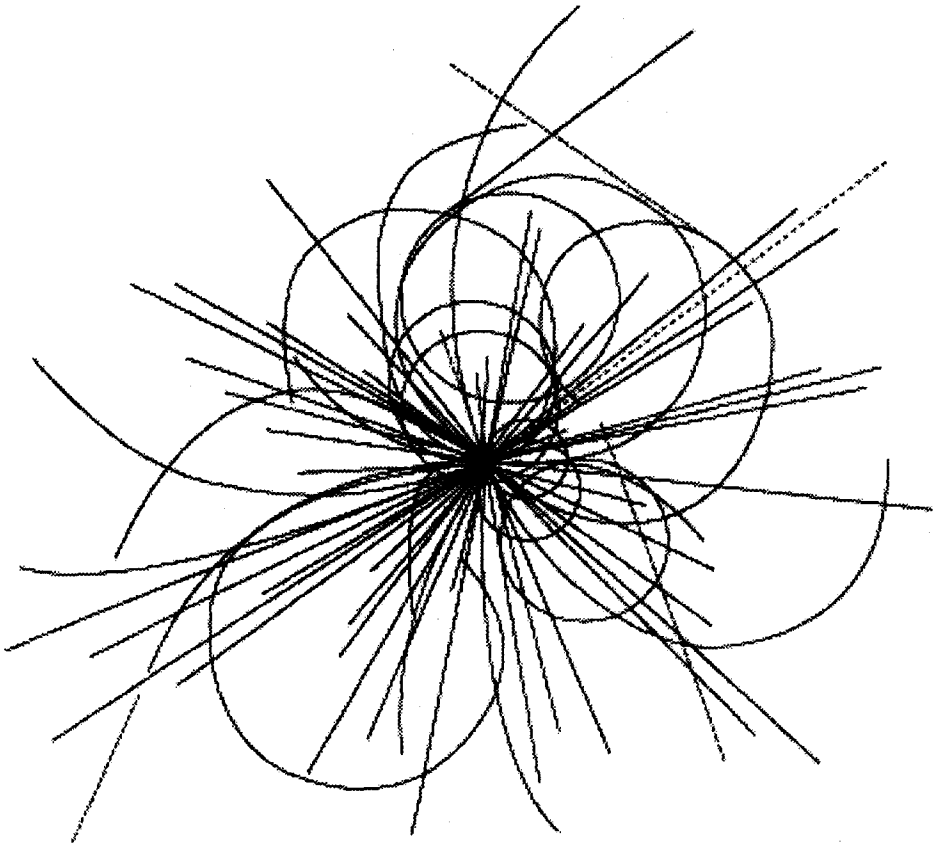
SSCL-SR-1227

SSCL-SR-1227
September 1993
Distribution Category: 414

8th International Magnetic Measurement Workshop (IMMW-8) Presentations



Superconducting Super Collider Laboratory

SSCL-SR-1227

8th International Magnetic Measurement Workshop (IMMW-8) Presentations

Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave.
Dallas, TX 75237

27–30 September 1993

*Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

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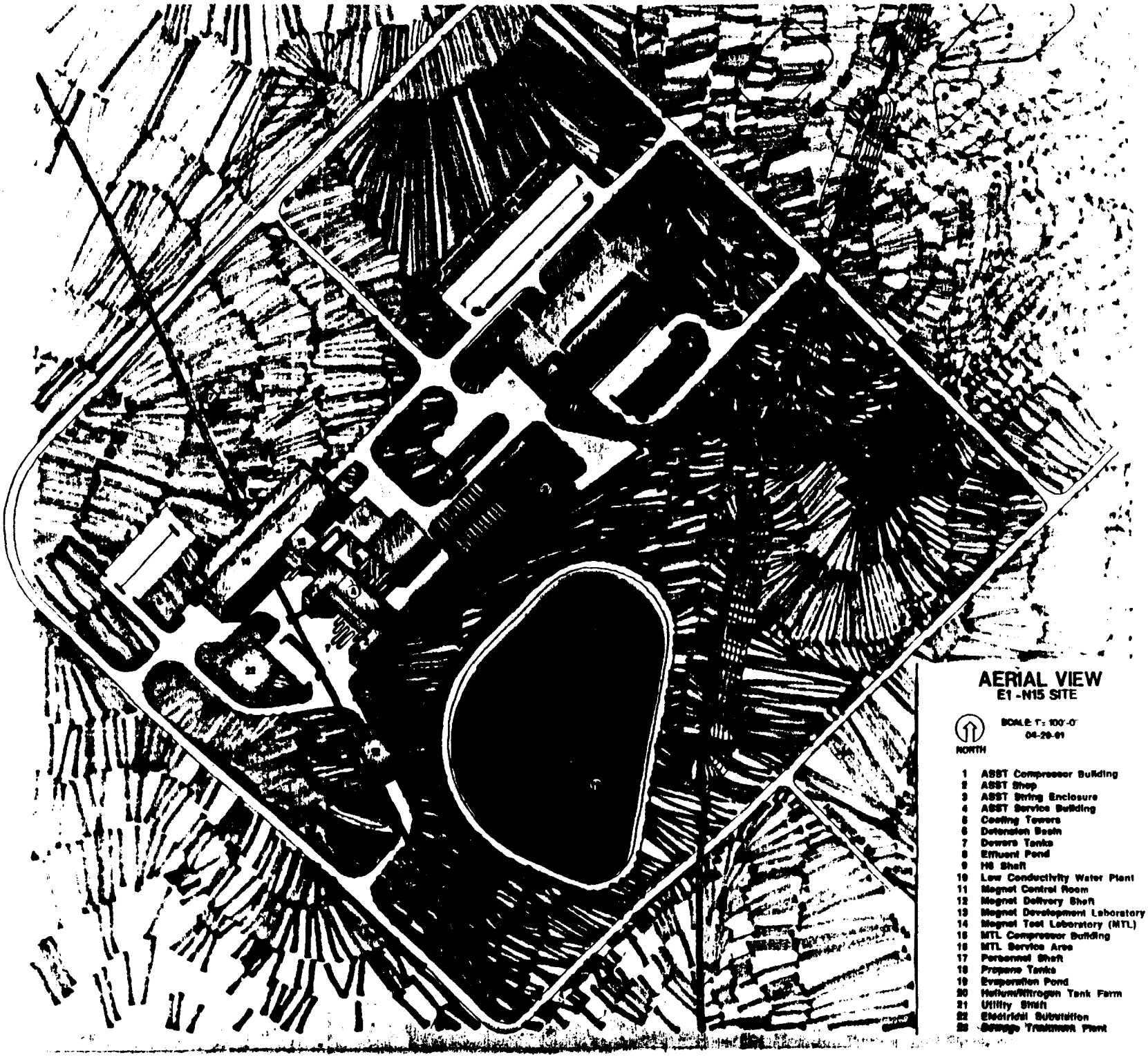
Overview of Magnetic Multipole Measurements at the SSC

Mark Coles

27 Sept. 1993

Topics Covered

- Operating charge of Test Dept (Magnet Test Lab, Subcontractor, program requirements)
- Brief overview of measurement apparatus, data acquisition, software
- Systematic measurement uncertainties (sources, solutions, data)
- Random error; signal conditioning (more in other talks - Sharanov, Krzywinski
- Other apparatus - very long drive rotating coils, NMR arrays



AERIAL VIEW
E1 - N15 SITE

SCALE: 1" = 100'-0"
04-29-91

1 ASST Compressor Building
2 ASST Shop
3 ASST String Enclosure
4 ASST Service Building
5 Cooling Towers
6 Detention Basin
7 Dewars Tanks
8 Effluent Pond
9 H6 Shaft
10 Low Conductivity Water Plant
11 Magnet Control Room
12 Magnet Delivery Shaft
13 Magnet Development Laboratory
14 Magnet Test Laboratory (MTL)
15 MTL Compressor Building
16 MTL Service Area
17 Personnel Shaft
18 Propane Tanks
19 Evaporation Pond
20 Helium/Nitrogen Tank Farm
21 Utility Shaft
22 Electrical Substation
23 Sewage Treatment Plant

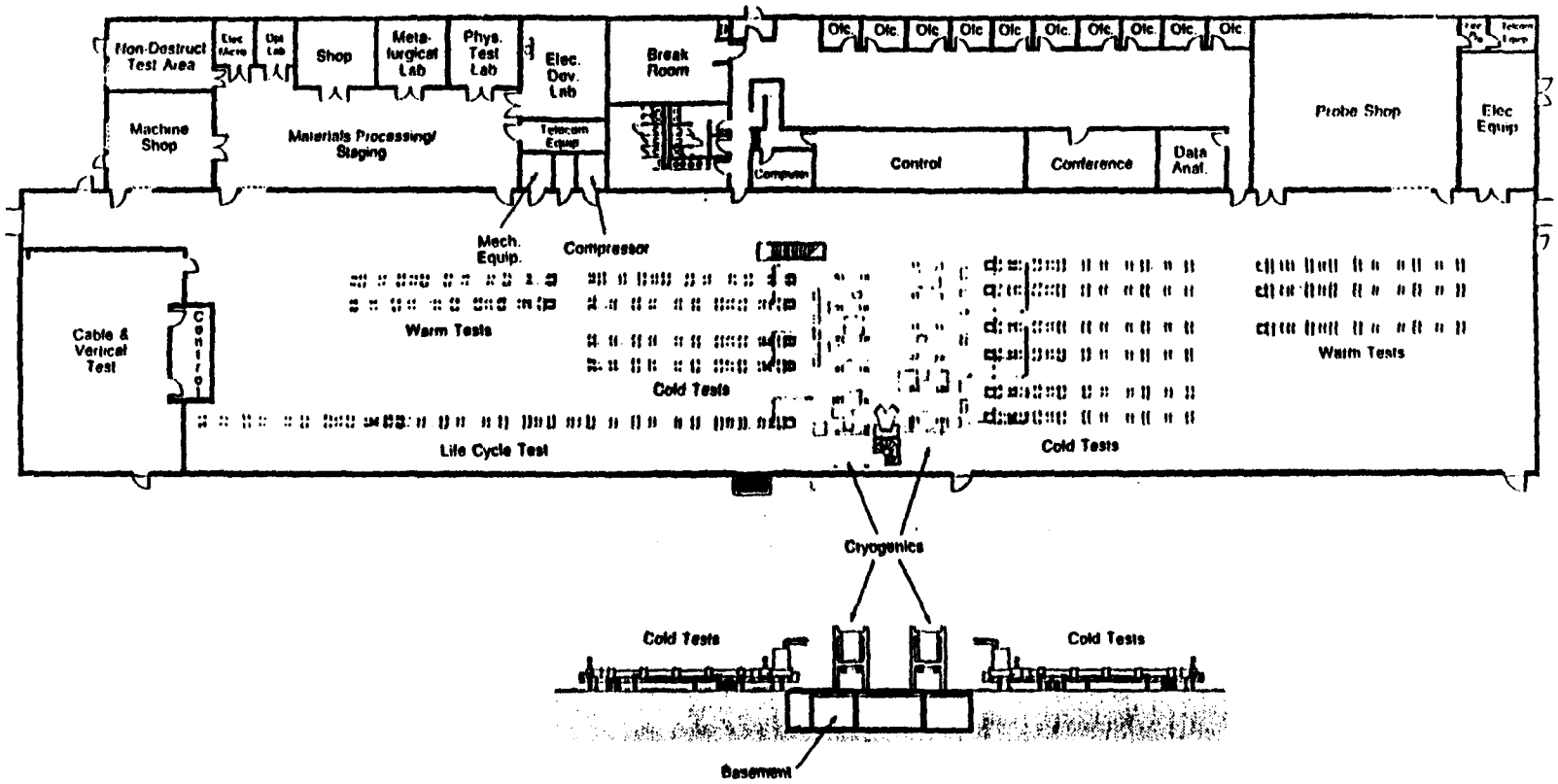
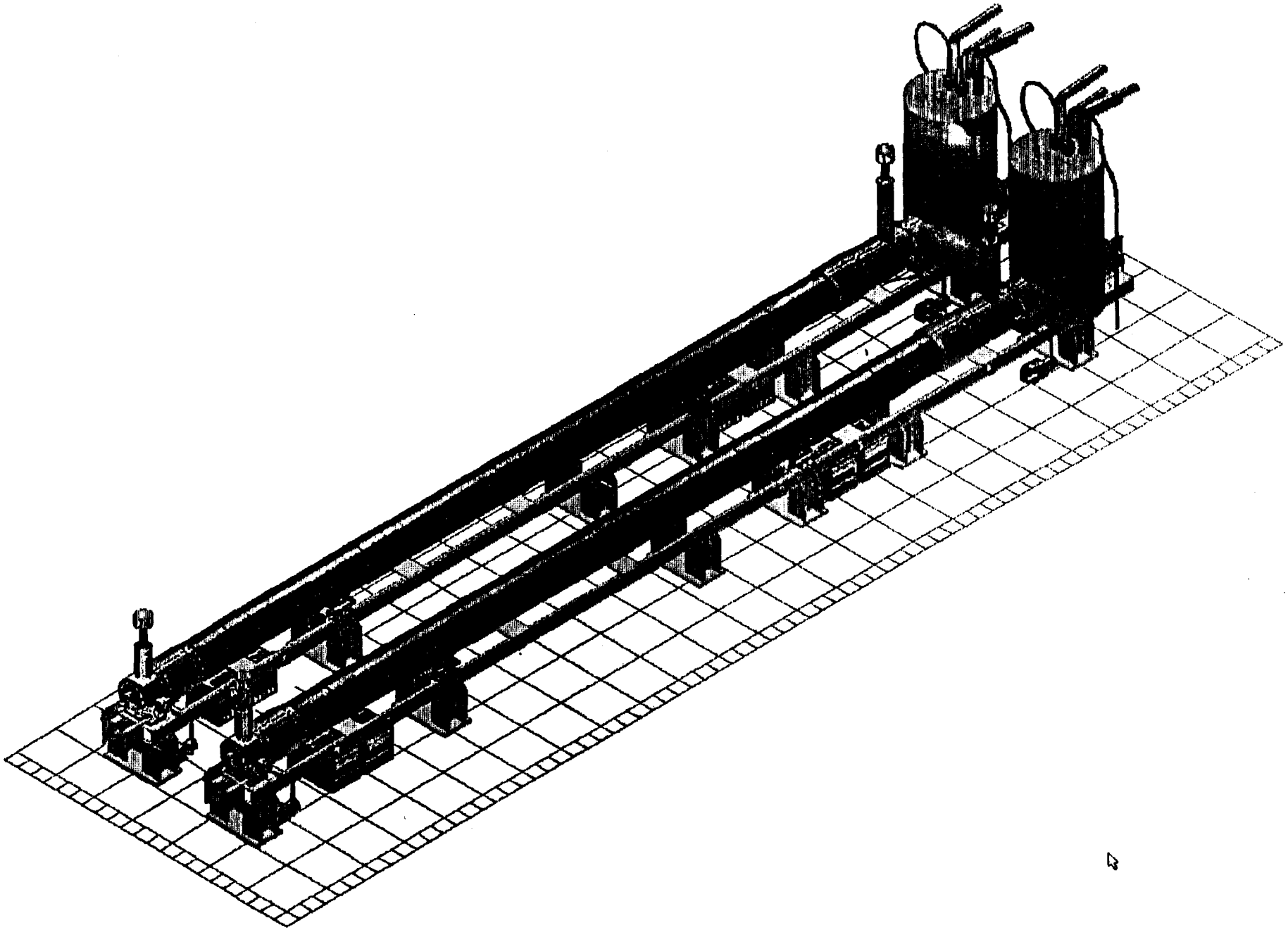


Figure 3. Floor plan of Magnet Test Laboratory showing layout of magnet test stands and central cryogenic distribution boxes.



Objectives of the MTL

- Provide acceptance test facilities for superconducting magnets
- Test magnet design principles and establish limits on magnet capabilities (R&D testing)
- Verify and supplement testing of industrially produced magnets
- Test all superconducting magnets fabricated by the SSCL in the MDL

cold testing:

- vacuum test
- measurement of stress due to Lorentz forces
- determine magnetic field characteristics at various operating currents and at temperatures from 2.5K to 4.5K,
  - determination of field harmonics at constant current
  - time dependent field measurements
  - dipole angle measurement
  - total magnetic field intensity measurement
  - quadrupole gradient measurement
- determine quench characteristics (critical current, quench initiation location, propagation velocity, etc.) as a function of temperature,
- determine effects of conditioning at lower temperature on quench current at 4.35°K,
- verify operation of quench heaters,
- determine alignment of the magnetic field with respect to external magnet fiducials
- verify electrical isolation of conductor when cold.

<u>life test activities:</u>

- repetitive thermal and power cycling
- repetitive quenching
- heat load tests
- quenching
- determine mechanical fatigue effects from repeated quenching,
- mechanical and electrical fatigue effects due to repeated energizing and ramping of magnets
- effects of repetitive thermal cycling on quench performance
- magnetic measurements (?)

Test Capacity:

- Ten single magnet test stands
  - 2 "R&D" test stands
  - 8 production test stands
  - stands designed to accomodate different length magnets.
- One life cycle test stand for use with three magnet string

Cold test throughput rate:

- Initial testing ~ 250 hours per test ==> 1 magnets/day
- Prototype testing ~ 150 hours/test ==> 1.3 magnets/day
- Production testing ~ 100 hours/test ==> 2 magnets/day

(assumes 8 stands used for prototype and production test)

Testing will always be conducted at the full capacity of the MTL

- all initial production and approximately 10% of total production magnets will be cold tested)

Types of long magnet tests planned for the MTL:

<u>warm test activities:</u>

- **hi-pot**
- **electrical continuity**
- **alignment check**
- **magnetic field harmonics at low current**
- **measurement of coil prestress**
- **verify these warm measurements on a "spot check" basis.**
- **establish correlations of warm/cold field characteristics**

ALSO:

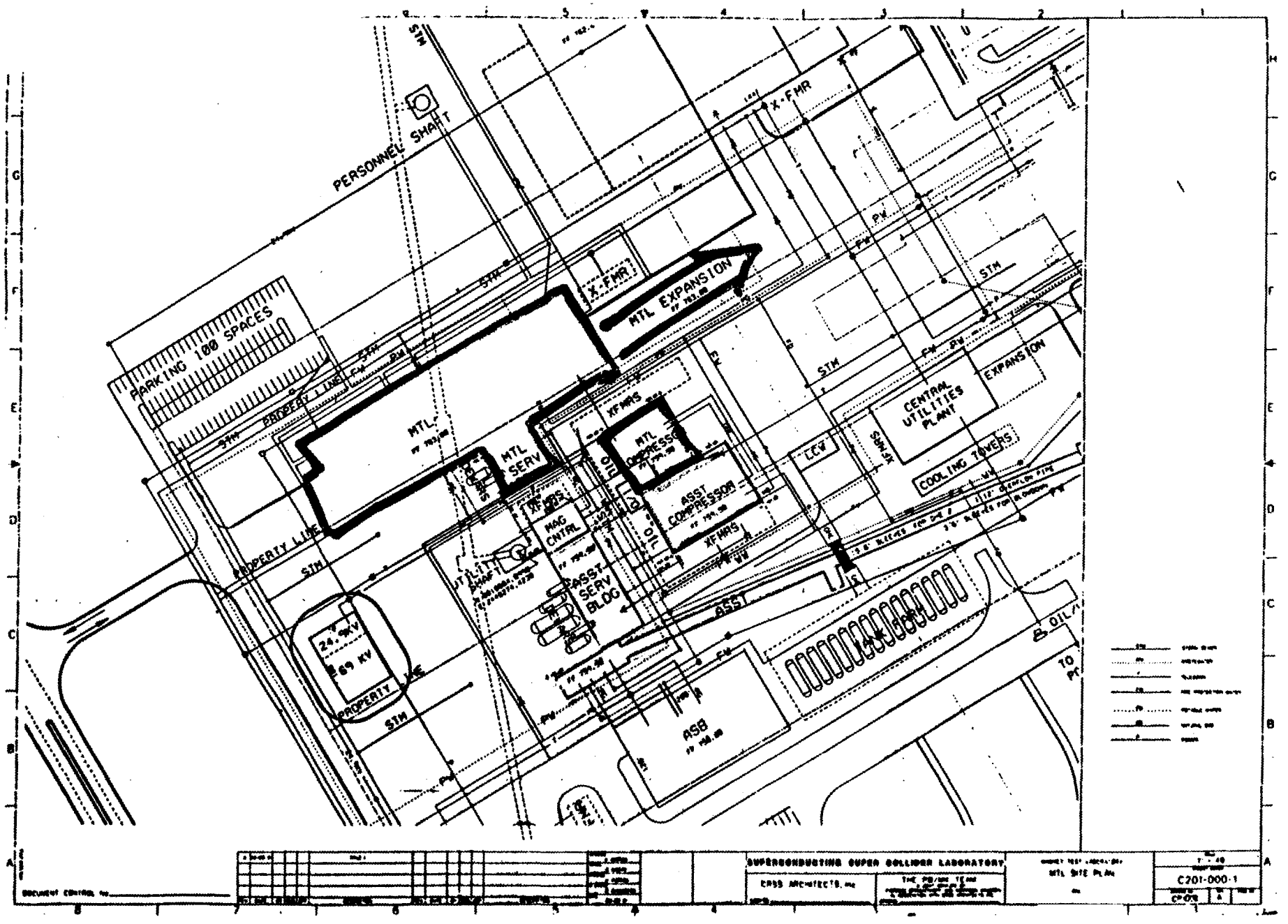
- **develop the warm measurement instrumentation to be used by industry**

Expansion of Cold Test Capacity

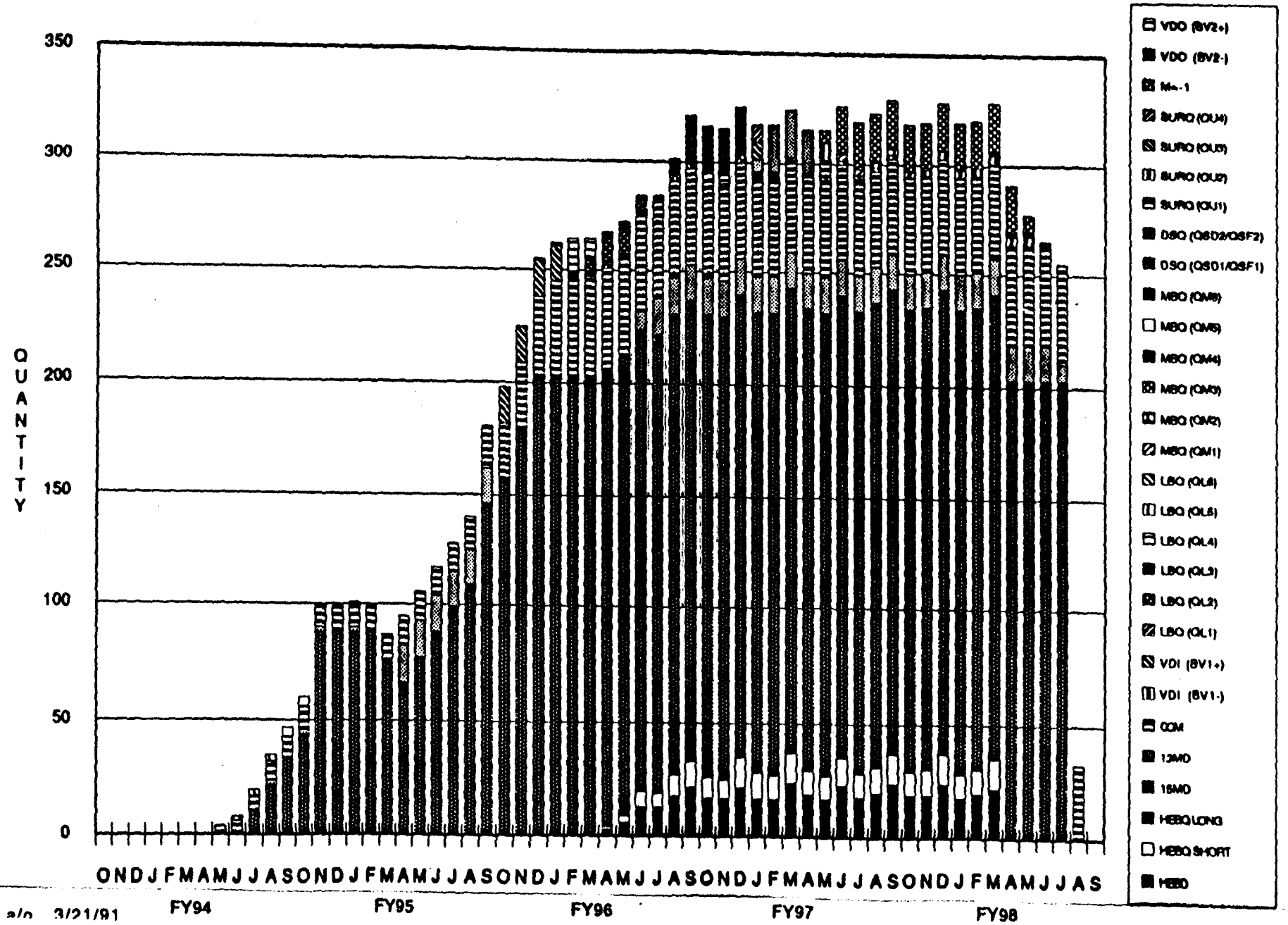
Ideal test capacity will be determined as a result of production experience and success of warm/cold correlations. MTL design must allow for capacity increase of required.

<u>Things to consider if capacity must be increased:</u>

- **refrigeration:**
  - **ASST refrigeration can be linked to MTL cold box with transfer lines.**
  - **Add additional bank of distribution boxes and convert warm test to cold test area.**
  - **move southwest wall out and add second pit for power supplies.**
- **Delivery:**
  - **MTL has two delivery areas so to minimize interference of contruction on testing.**
  - **control room trivially expands into conterence room.**
  - **warm test area is oversized to provide space for instrumentation development. This work should be completed by the time expansion might be required.**


PERSONNEL SHAFT
PARKING 100 SPACES
PROPERTY LINE
MTL EXPANSION
X-FMR
MTL
MTL SERV
XFMRS
MTL COMPRESSOR
ASST COMPRESSOR
MAG CNTRL
ASST SERV BLDG
ASST
ASB
CENTRAL UTILITIES PLANT
EXPANSION
COOLING TOWERS
24.9KV
69 KV
STM
FW
PW
OIL
TO PT
SUPERCONDUCTING SUPER COLLIDER LABORATORY
CRSS ARCHITECTS, INC
MTL SITE PLAN
C201-000-1

MAGNET MONTHLY DELIVERIES



a/o 3/21/91

Percent magnets tested at 60 magnets/month test capacity

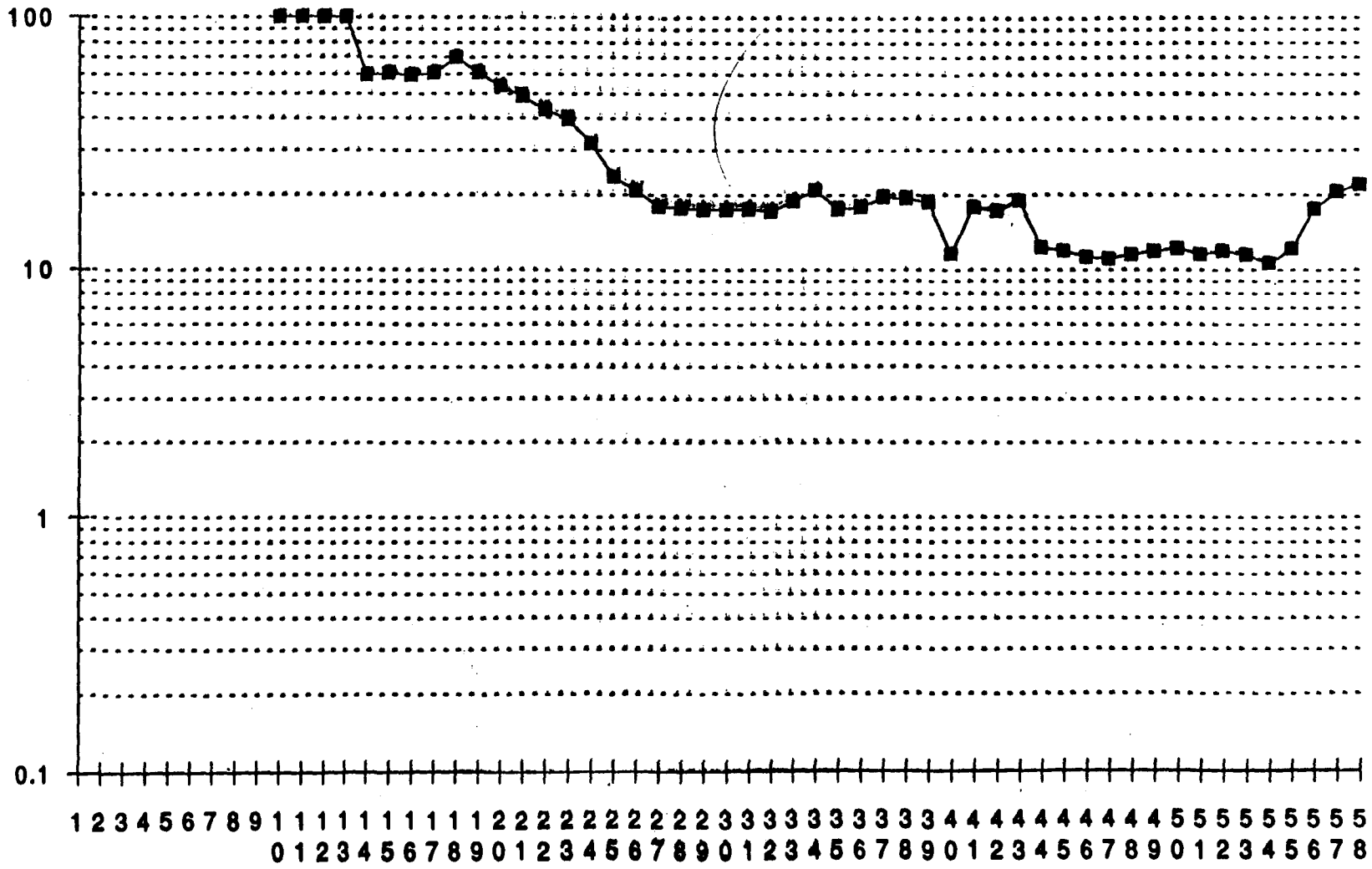


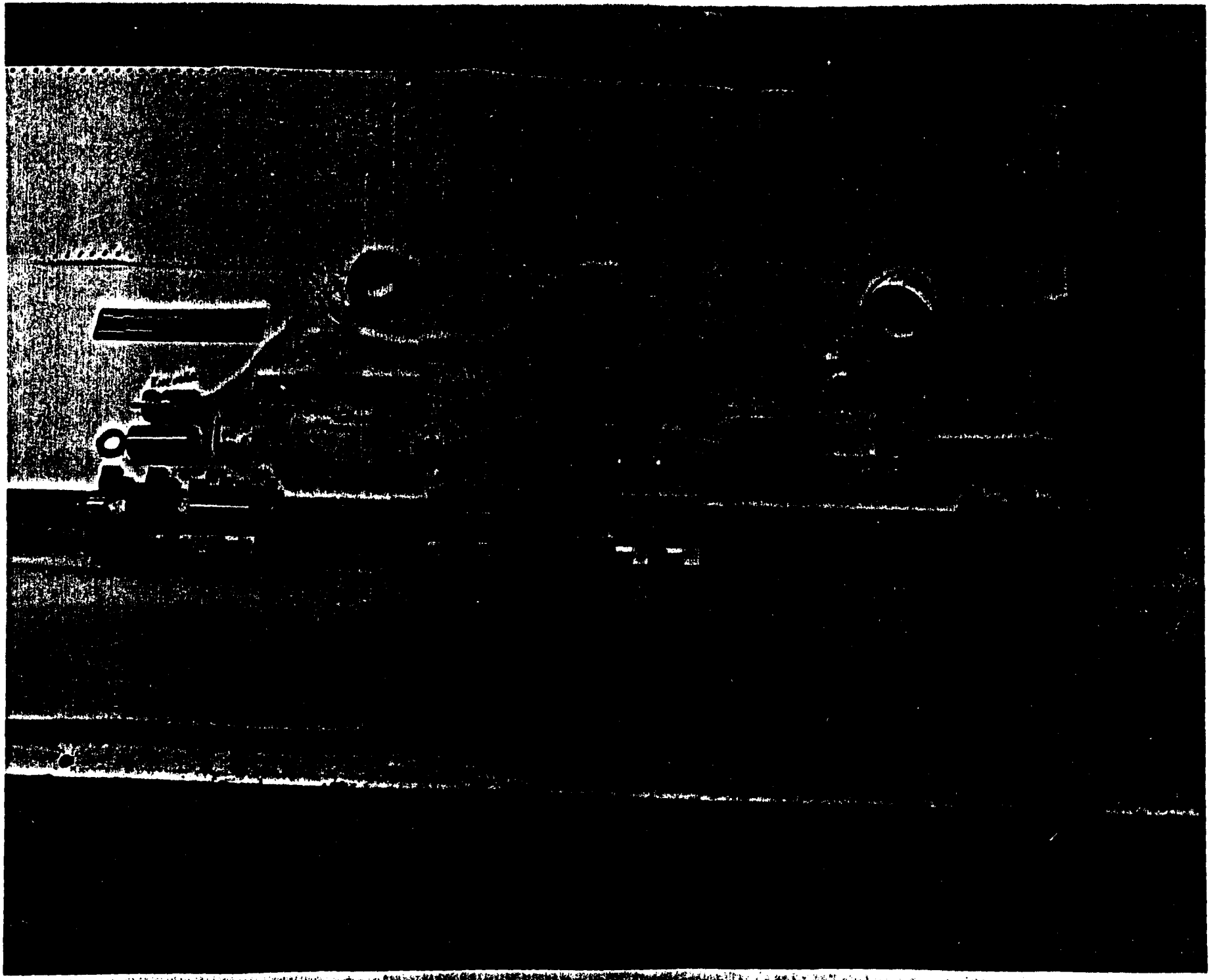
Table 1. Approximate schedule requriements for GFE mole equipment.

Activity	Warm moles	Cold moles	Approx. date of first delivery
CDM program*			
Prototype	2	2	11/92
Pre-prod	6	2	11/93
LRIP	6	2	7/94
Full production	14	2	7/95
CQM			
Prototype	2	1	4/93
Pre-prod	2	1	11/93
LRIP	2	1	7/94
Full production	4	2	5/95
HEBDM			
Prototype	1	1	2/94
Pre-prod	1	1	7/95
LRIP	2	1	2/96
Full production	2	2	7/96
HEBQM			
Pre-prod	1	1	11/94
LRIP	1	1	7/95
Full production	1	1	1/96
MTL			
	2	2	9/92
	2	4	9/93
MDL			
	1	0	1/94
Spares**	8	6	
Total	32	17	

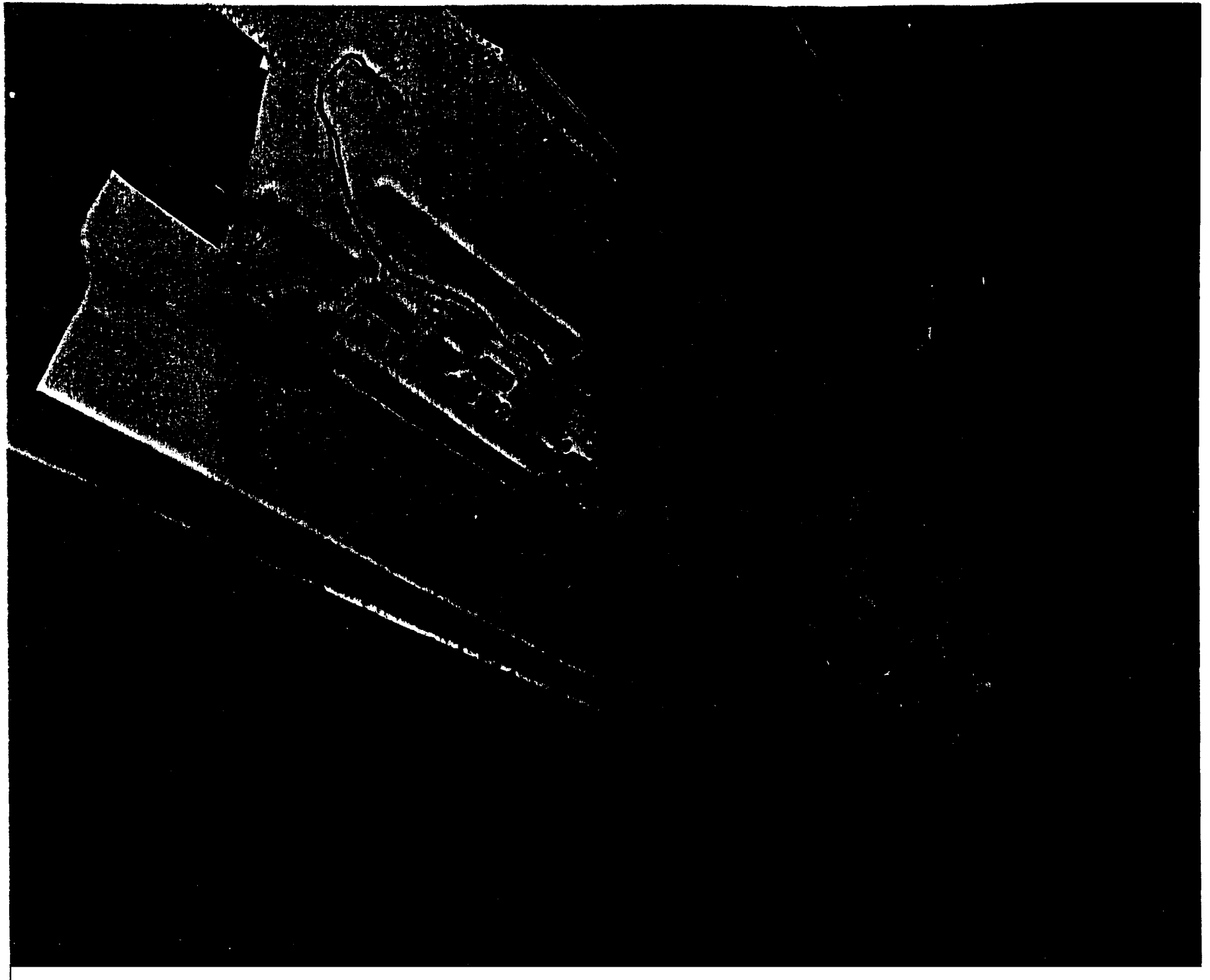
*estimates from Ron Jones, GD.
**assume one spare device per test site for warm and cold test.

Mole requirements
Number of moles
0
5
10
15
20
25
30
35
40
45
50
Sep-93
Nov-93
Jan-94
Mar-94
May-94
Jul-94
Sep-94
Nov-94
Jan-95
Mar-95
May-95
Jul-95
Sep-95
Nov-95
Jan-96
Mar-96
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Total required
Projected on Hand

Figure 1



CJ1-397-93



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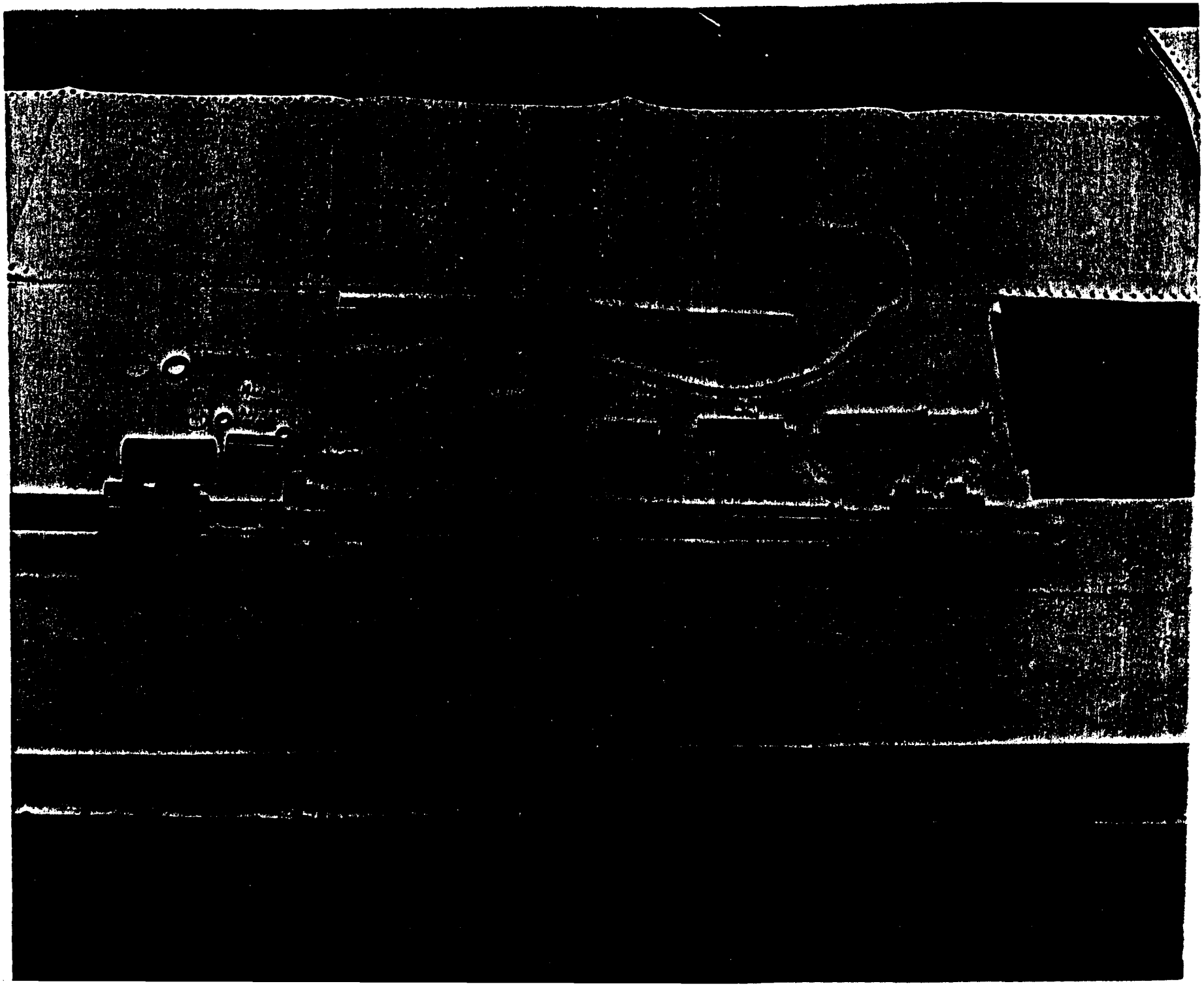
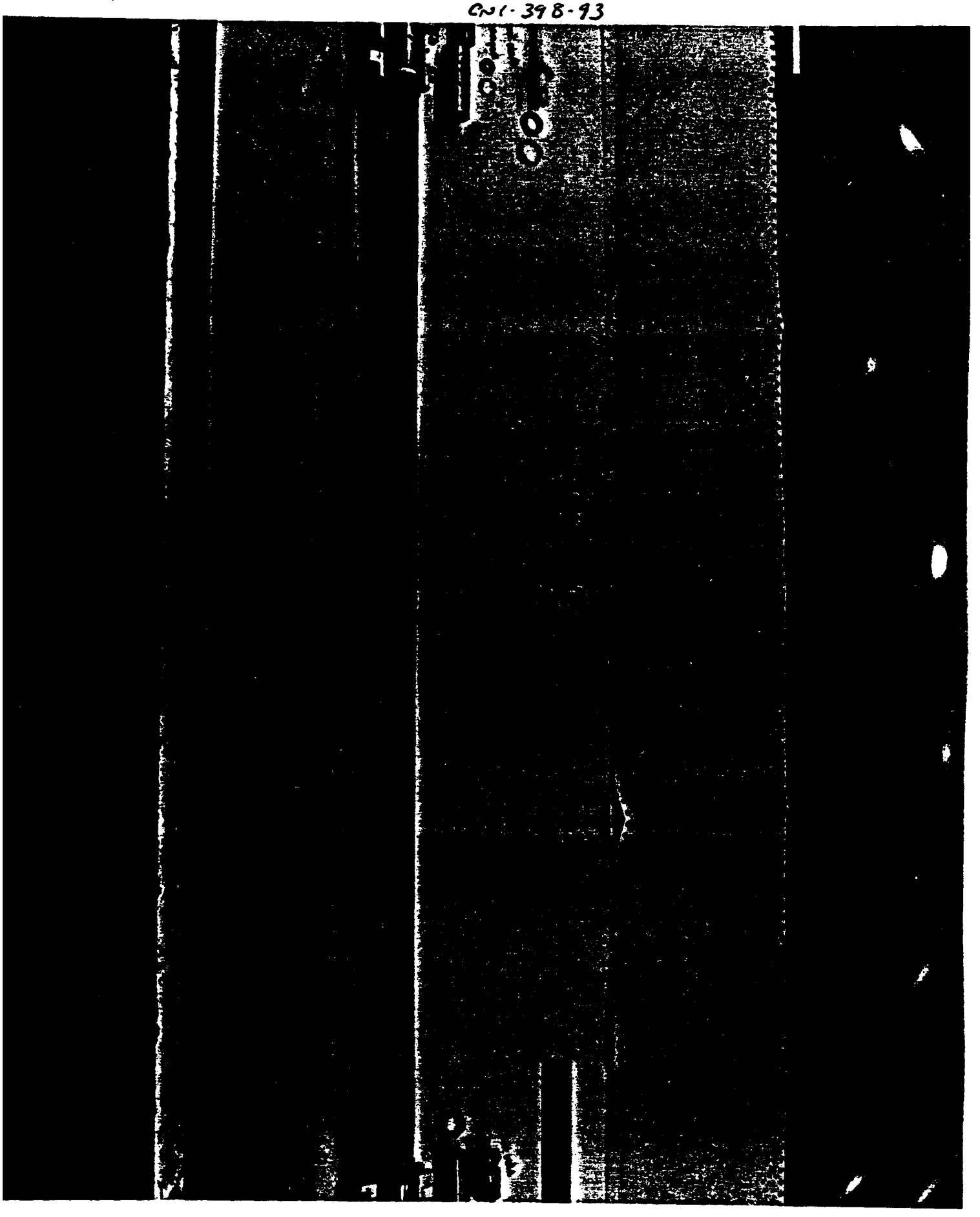


GN1-398-93



Mole program history

- B2 (built by BNL) used for 4 years at FNAL to measure SSC magnets

- Previous and current SSCL - BNL lab agreements included fabrication of moles in support of the SSCL program

- This has resulted in the "F" mole design - contains many improvements which resulted from operational experience with B mole

- EVERYONE HAS AN OPINION:
  - radial coils
  - integrators
  - other construction materials, techniques, etc.

- WE KNOW WHO OUR FRIENDS ARE (i.e. where we can get help)

- Strategy has been, and is, to help complement BNL's efforts so that they (and therefore we) are successful

Mole history

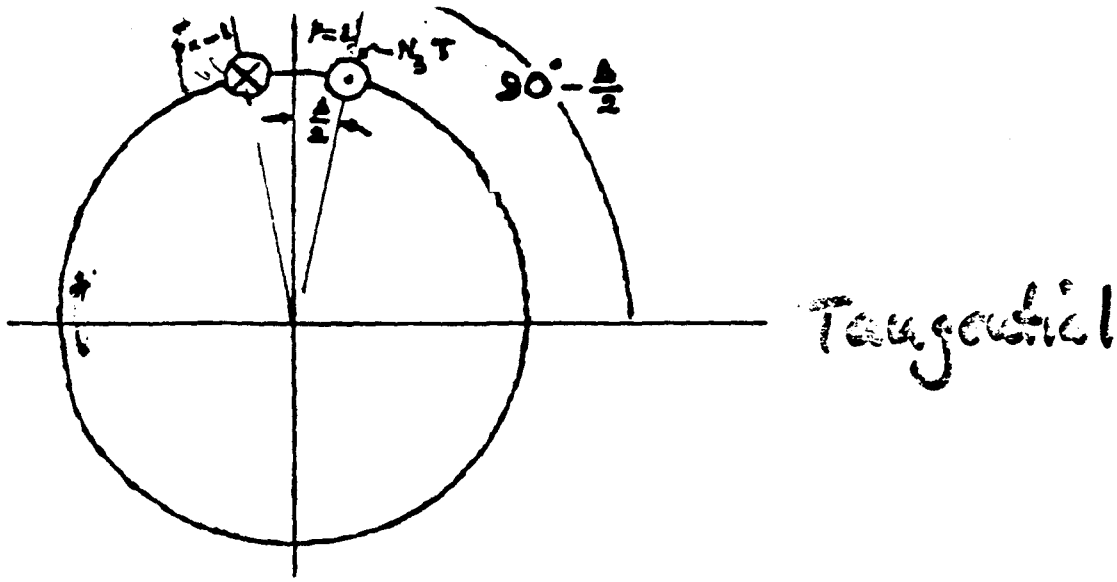
- More than ten years of development at BNL - how to measure within very small very long magnet where external references are not available

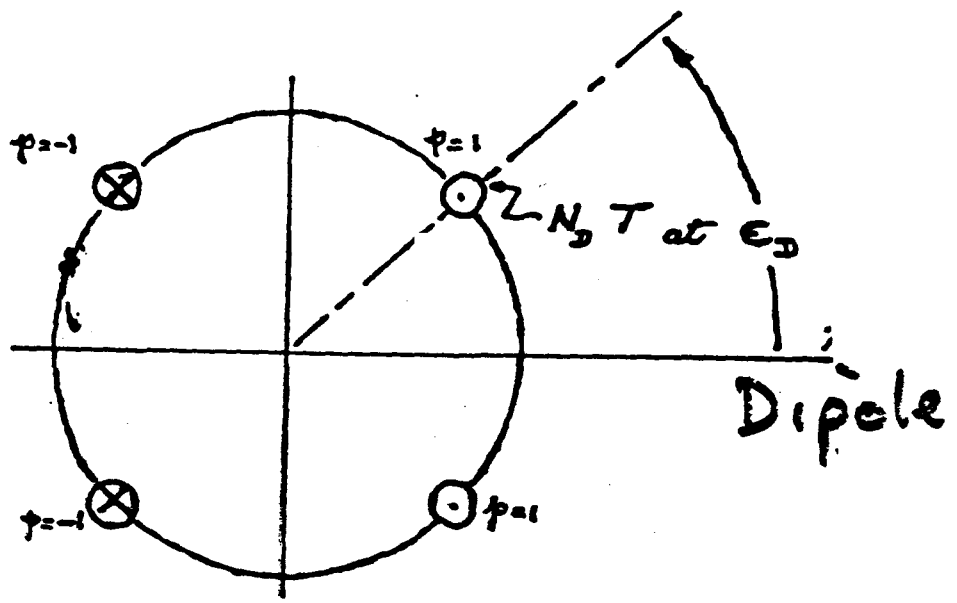
- Development milestones:
  - coil fabrication
  - components requried for very small design circle ~ 25 mm
    - slip rings
    - encoder
    - bearings
    - air motors

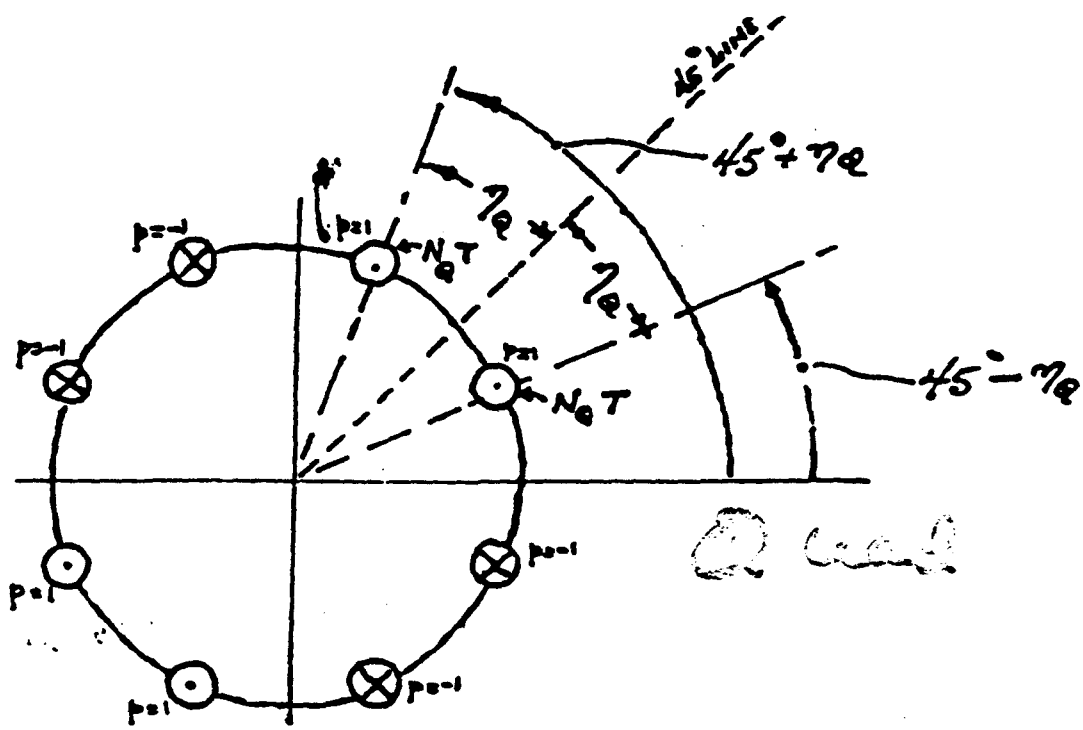
  All had to be non-magnetic and non conductive for moving parts

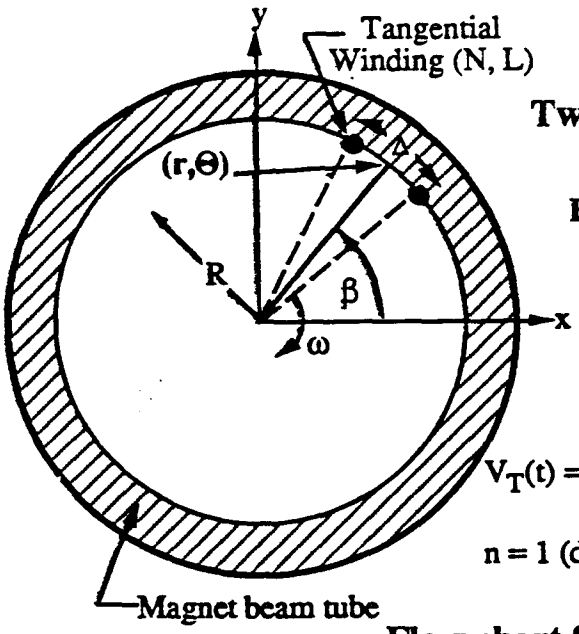
- Ancestors of present mole design used at BNL and FNAL to evaluate SSCL dipoles

- Understanding of performance characteristics has slowly been built up during this period


p=-1
p=1
$N_S T$
$90° - \frac{\Delta}{2}$
$\frac{\Delta}{2}$
Tangential


p=-1
p=1
$N_D T$ at ϵ_D
Dipole
p=-1
p=1


45° LINE
$45° + \eta_Q$
η_Q
η_Q
$45° - \eta_Q$
p=-1
p=1
$N_Q T$
p=-1
p=1
$N_Q T$
p=1
p=-1
p=1
p=-1
Quad



Two dimensional field representation in aperture

$$B(r,\Theta) = \sum_{n=1}^{\infty} C(n)\left(\frac{r}{R}\right)^{n-1} r \sin n(\Theta - \alpha_n) + \Theta \cos n(\Theta - \alpha_n)]$$

Voltage induced in the tangential winding

$$V_T(t) = -2\sum_{n=1}^{\infty} N_T r_T L_T \omega C(n)\left(\frac{r_T}{R}\right)^{n-1} \sin\left(\frac{n\Delta}{2}\right)\cos[n(\omega t - \beta + \alpha_n)]$$

n = 1 (dipole)

Flow chart for the digital harmonic analysis

Tangential coil digitized voltage → FFT → $X_T(n) = \sum_{k=0}^{N/2-1} A_k^T \cos\left(\frac{2\pi nk}{N} + \Phi_k^T\right)$

Buck 1 coil digitized voltage → FFT → $X_{D1}(n) = \sum_{k=0}^{N/2-1} A_k^{D1} \cos\left(\frac{2\pi nk}{N} + \Phi_k^{D1}\right)$

Buck 2 coil digitized voltage → FFT → $X_{D2}(n) = \sum_{k=0}^{N/2-1} A_k^{D2} \cos\left(\frac{2\pi nk}{N} + \Phi_k^{D2}\right)$

Bucking Condition
for k = 1
$X_T(n) + f_1 X_{D1}(n) + f_2 X_{D2}(n) = 0$
↓
(f_1, f_2)

Total digitized bucked voltage
$V_B(n) = X_T(n) + f_1 X_{D1}(n) + f_2 X_{D2}(n)$

Bucked Voltage $V_B(n)$ → FFT → $V_B(n) = \sum_{k=0}^{N/2-1} B_k \cos\left(\frac{2\pi nk}{N} + \Theta_k\right)$ → **C(n), α_n**

Where C(n) and α_n are the magnitude and angular phase of the nth multipole

$$a_n = \frac{C(n+1)\sin[-(n+1)\alpha_{n+1}]}{C(1)R^n} \qquad b_n = \frac{C(n+1)\cos[(n+1)\alpha_{n+1}]}{C(1)R^n}$$

n = 0 (dipole)

Where a_n and b_n are the skew and normal coefficients of the 2(n + 1) pole.

Figure 1-3a Formalism for Digital Harmonic Analysis for Dipole Magnets

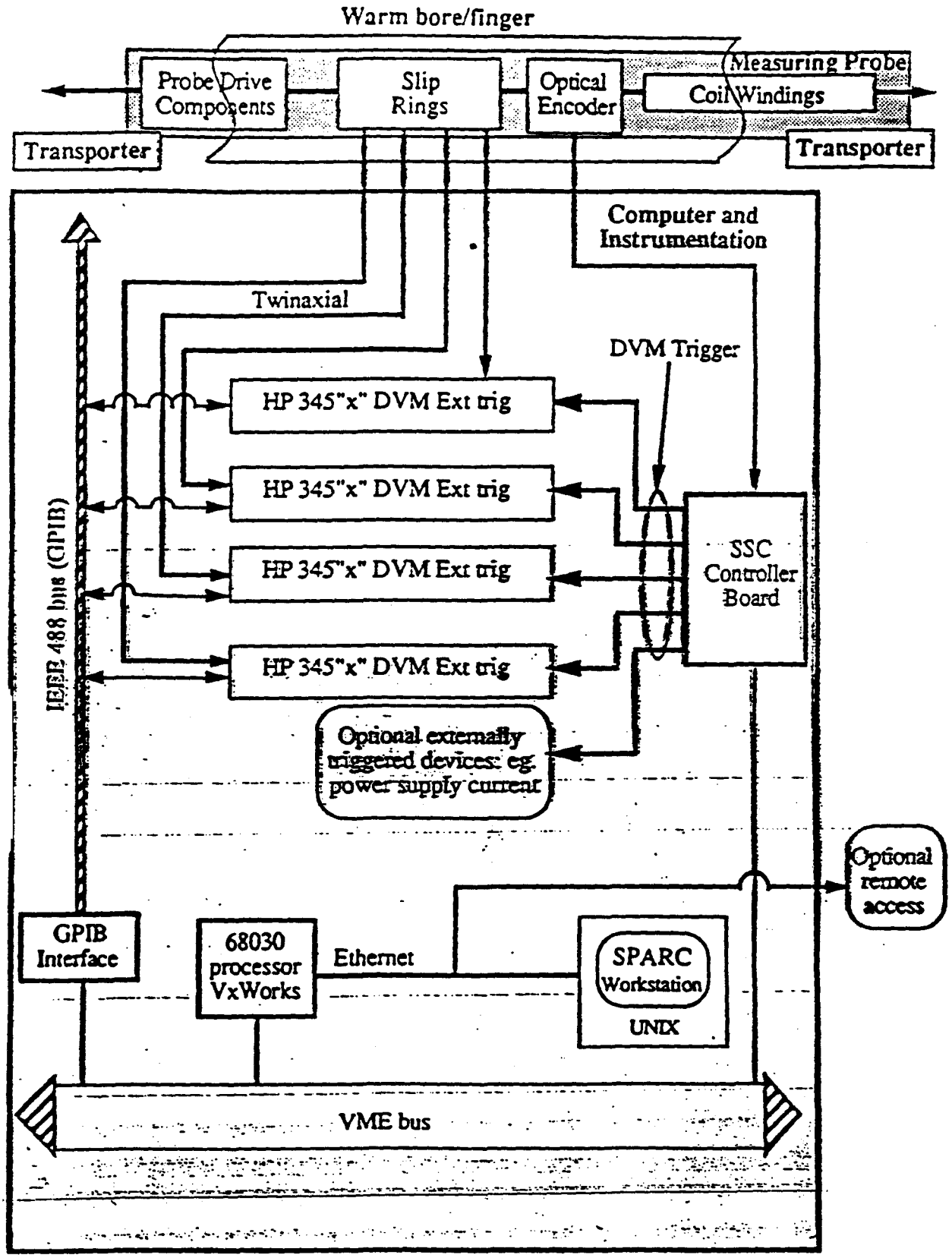
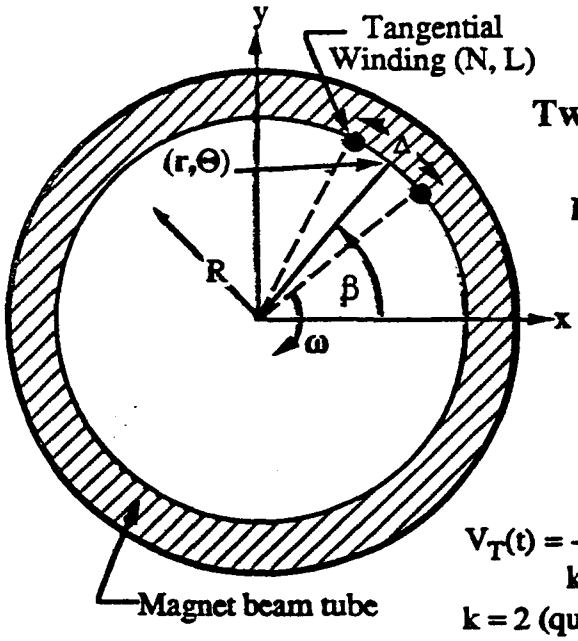


Figure 1-4 Block diagram of the mole instrumentation system



Two dimensional field representation in aperture

$$B(r,\Theta) = \sum_{n=1}^{\infty} C(n)\left(\frac{r}{R}\right)^{n-1} r \sin n\,(\Theta - \alpha_n) + \Theta \cos n\,(\Theta - \alpha_n)]$$

Voltage induced in the tangential winding

$$V_T(t) = -\sum_{k=1}^{\infty} C(k)\left(\frac{r_T}{R}\right)^{k-1} 2\, L_T r_T N_T\, \omega\, \sin\left(\frac{n\Delta}{2}\right)\cos[\,k\,(\omega t - \beta + \alpha_k)]$$

$k = 2$ (quadrupole)

Voltage induced in quadrupole buck winding 1

$$V_{Q_1}(t) = -\sum_{k=1}^{\infty} C(k)\left(\frac{r_{Q_1}}{R}\right)^{k-1} 2\, L_{Q_1} r_{Q_1} N_{Q_1}\, \omega\, \sin\left(\frac{k\pi}{4}\right)\cos[\,k\,(\omega t - \beta + \varepsilon_1 + \alpha_k)][\,1 + (-1)^k\,]$$

Voltage induced in quadrupole buck winding 2

$$V_{Q_2}(t) = -\sum_{k=1}^{\infty} C(k)\left(\frac{r_{Q_2}}{R}\right)^{k-1} 2\, L_{Q_2} r_{Q_2} N_{Q_2}\, \omega\, \sin\left(\frac{k\pi}{4}\right)\cos[\,k\,(\omega t - \beta - \varepsilon_2 + \alpha_k)][\,1 + (-1)^k\,]$$

Voltage induced in the dipole buck windings

$$V_D(t) = -\sum_{k=1}^{\infty} C(k)\left(\frac{r_D}{R}\right)^{k-1} 2\, L_D r_D N_D\, \omega\, \sin\left(\frac{k\pi}{2}\right)\cos[\,k\,(\omega t - \beta + \alpha\ )]\; 2\cos(k\,\varepsilon_D)$$

Figure 1-3b Formalism for Digital Harmonic Analysis for Quadrupole Magnets

Flow chart for the digital harmonic analysis

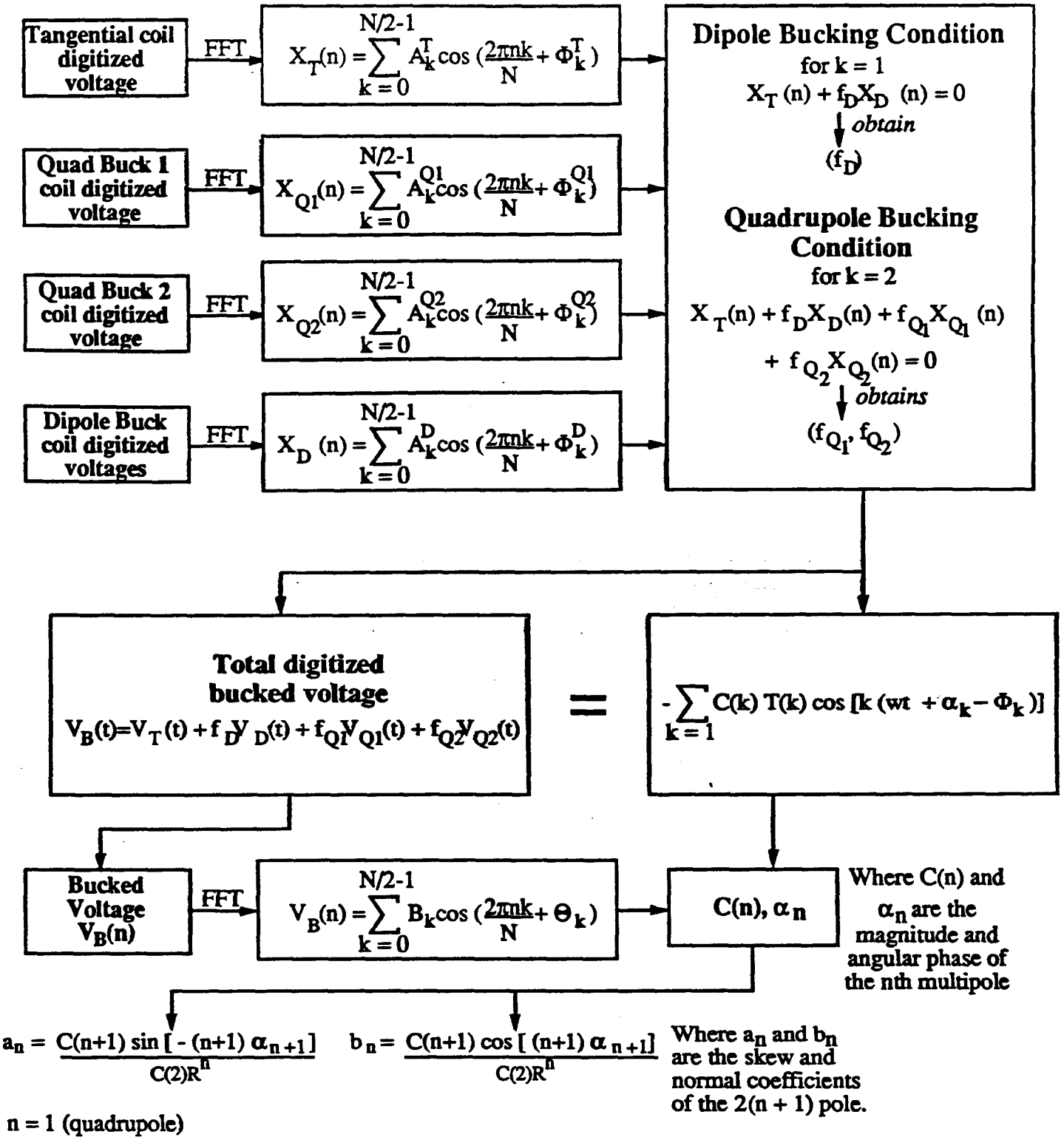


Figure 1-3c Flow Chart for Digital Analysis of Quadrupole Magnets

Figure 4 Voltage versus angular position for nominal input

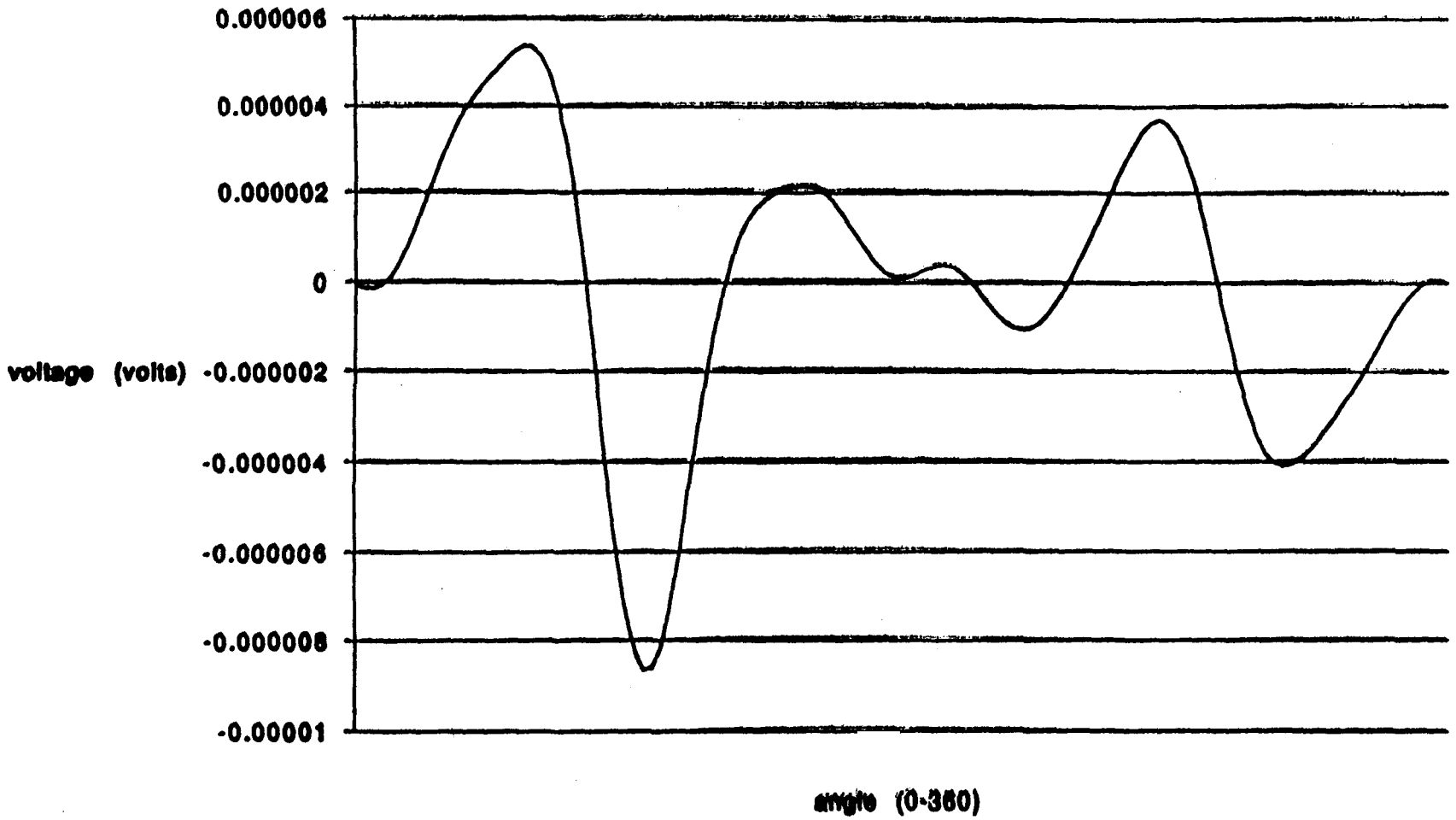
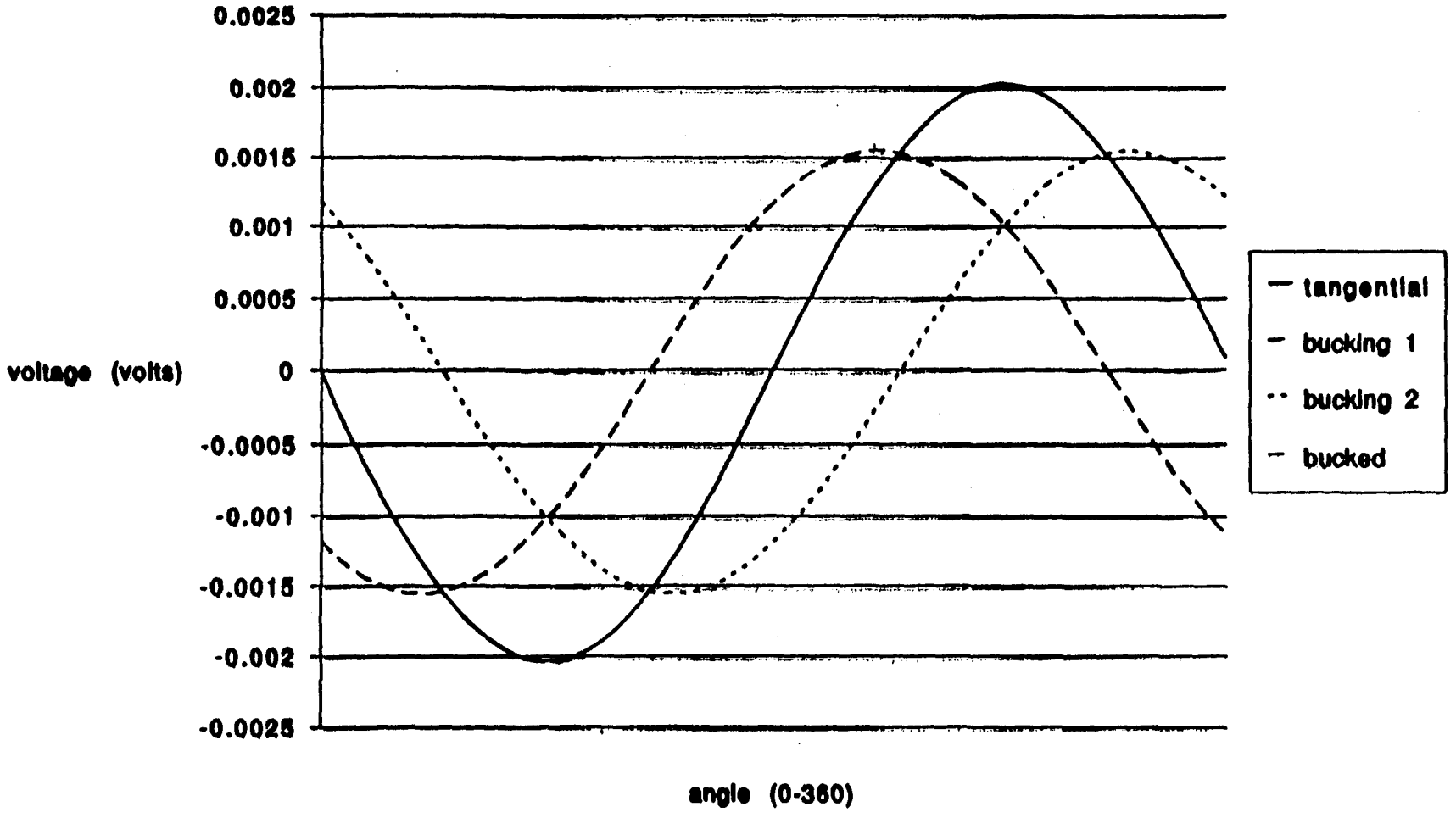


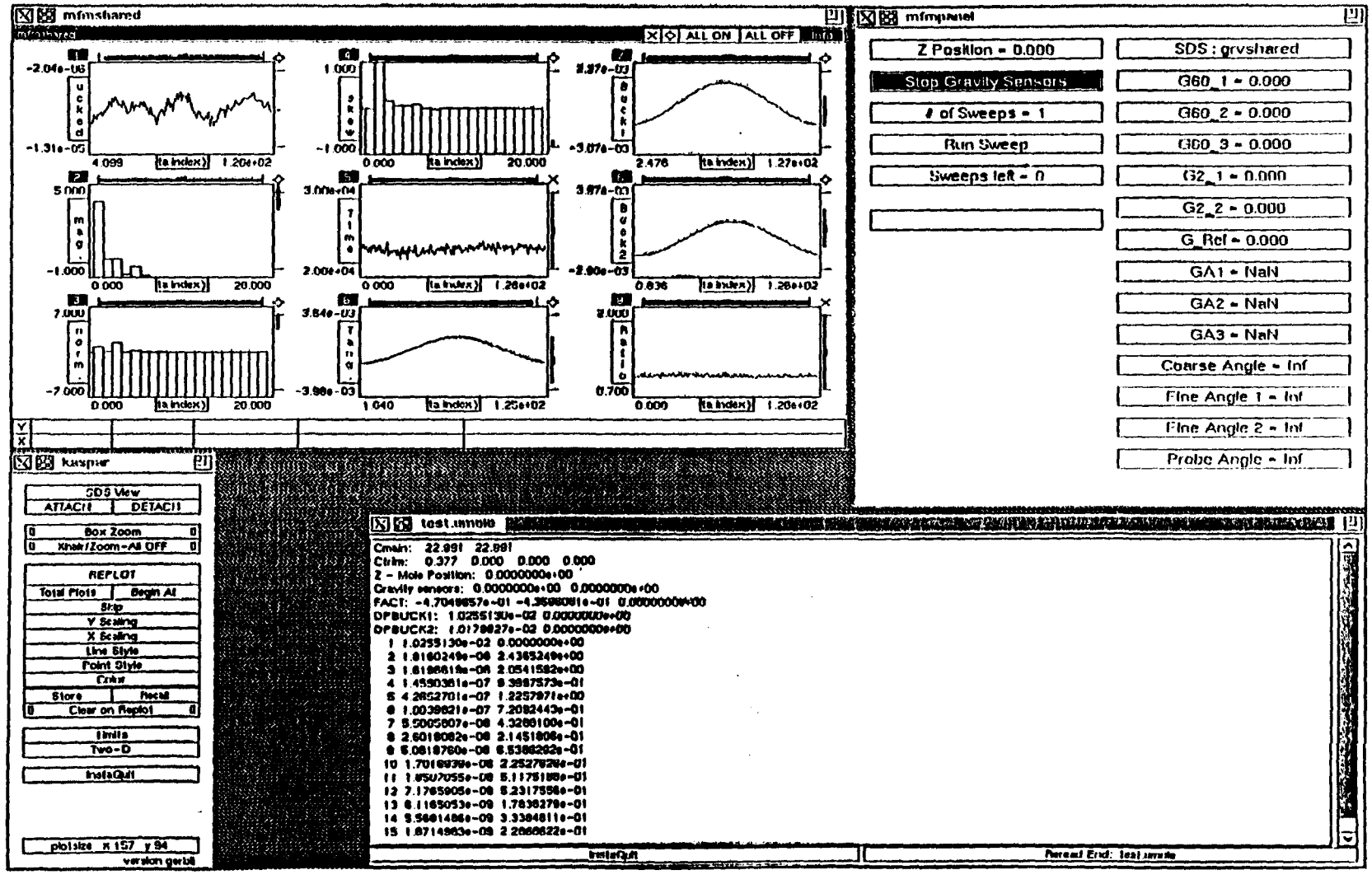
Figure 3 Voltage versus angular position for nominal input



bucking factor, cold, 4000Amp				
5 DVMs for QSH803				
quad Bucking factor		dipole Bucking factor		
1.66E+07		2.73E+07		
4 DVMs for QSC405				
2.88E+06		23.8		
bucking factor, warm, 10Amp				
5 DVMs for QSH803, 128 gain amplifier used				
quad Bucking factor		dipole Bucking factor		
6.05E+06		8.25E+06		
4 DVMs for QSC405, no amplifier used				
3.76E+06		15.2		

MTL Software

Typical B2 mole system screen at FNAL MTF



Measurement system to be given to Vendors

- SSC will supply:

  Measurement system hardware and software.

  Operator Manual.

- Vendor will supply

  Networks - WAN preferable, Internet needed for on-line support.

  Measurement Initiation Interface (GLISH).

  Test Results Capture Interface (SDS).

Mole Data acquisition system software

History:

- ISTK tools, ASD support for MTL software as a test bed for accelerator controls (Chris Saltmarsh)

- Data base interface unified with other test and fabrication software

- Initial LBL contract in support of accelerator controls and MTL software suggested VME buss and VxWorks real time kernel

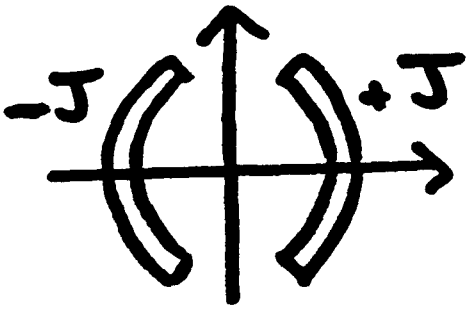
- Dave Lambert, Joe Garbarini, Wei-chuan Li, Paul Craker, and Jim Ivey wrote the SSCL software which implements these ISTK tools (GLISTK, SDS structures, GLISH)

- features:
  - raw data handling
  - analysis features
  - ISTK tools
  - P.S. digitization

- basic analysis software is BNL's - rewritten from HPBasic to C on the SUN

Allowed and Unallowed Multipoles

- Perfect Dipole Coil



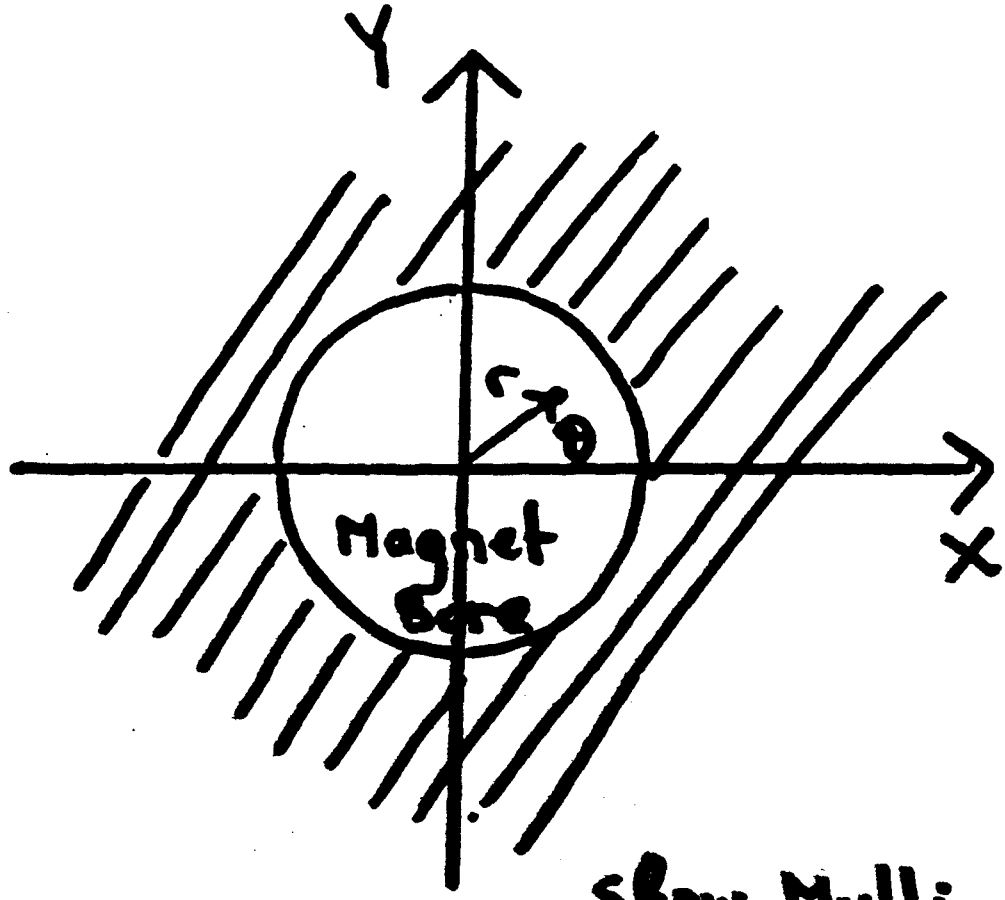
By symmetry, the only allowed multipoles are $B_0, b_2, b_4, b_{2\ell}$

- Real Magnets

Violations of dipole symmetry due to manufacturing errors result in unallowed multipoles.

e.g., Top/Bottom asymmetry results in a_1
Left/Right asymmetry results in b_1.

Fourier Decomposition



Skew Multipole

$$B_r(r,\theta) = B_0 \sum_{n=0}^{+\infty} \left(\frac{r}{r_0}\right)^n \left[a_n \cos(n+1)\theta + b_n \sin(n+1)\theta \right]$$

Normal Multipole

$$B_\theta(r,\theta) = B_0 \sum_{n=0}^{+\infty} \left(\frac{r}{r_0}\right)^n \left[b_n \cos(n+1)\theta - a_n \sin(n+1)\theta \right]$$

a_n, b_n coefficients of $2(n+1)$-pole

(1 unit $= 10^{-4}$)

3.2.1.3.3 Systematic Multipole Tolerance. Upper limits of the absolute values of the systematic multipole errors shall meet the specifications in Table 3.2.1.3–II. The systematic multipole error is defined as the average value of the multipole taken over the sample of magnets installed in the ring.

TABLE 3.2.1.3–II. ABSOLUTE VALUE LIMIT OF SYSTEMATIC MULTIPOLES FOR THE MAGNET FAMILIES.

Multipole	CONFIGURATION ITEMS		
	CDM 15m, CDM 13m		CQM
(Absolute Value)	Injection 2.0 TeV	High Field	
$\lvert a_1 \rvert$*	< 0.04	< 0.04	
$\lvert b_1 \rvert$*	< 0.04	< 0.04	
$\lvert a_2 \rvert$*	< 0.032	< 0.032	<0.23
$\lvert b_2 \rvert$	< 2.00[A]	< 0.80	<0.23
$\lvert a_3 \rvert$*	< 0.026	< 0.026	<0.13
$\lvert b_3 \rvert$*	< 0.026	< 0.026	<0.13
$\lvert a_4 \rvert$*	< 0.01	< 0.01	<0.15
$\lvert b_4 \rvert$	< 0.08[B]	< 0.08	<0.15
$\lvert a_5 \rvert$*	< 0.005	< 0.005	<0.18
$\lvert b_5 \rvert$*	< 0.005	< 0.005	<1.40[C]
$\lvert a_6 \rvert$*	< 0.005	< 0.005	<0.10
$\lvert b_6 \rvert$	< 0.02	< 0.013	<0.10
$\lvert a_7 \rvert$*	< 0.005	< 0.005	<0.12
$\lvert b_7 \rvert$*	< 0.005	< 0.005	<0.12
$\lvert a_8 \rvert$*	< 0.005	< 0.005	<0.13
$\lvert b_8 \rvert$	< 0.01	< 0.01	<0.13
$\lvert a_9 \rvert$*	< 0.005	< 0.005	<0.15
$\lvert b_9 \rvert$*	< 0.005	< 0.005	<0.61
$\lvert a_{10} \rvert$*	< 0.02	< 0.02	<0.15
$\lvert b_{10} \rvert$	< 0.02	< 0.02	<0.13

*Non-Allowed Multipoles (Units for a_n or b_n are defined as 10^{-4} cm^{-n})

Note A: The value of systematic b_2 shall not change by more than 0.5 units during the one hour injection interval.

Note B: The value of systematic b_4 shall not change by more than 0.04 units during the one hour injection interval.

Note C: The value of systematic b_5 shall not change by more than 0.2 units during the one hour injection interval.

Figure 6 Coil Sag Diagram

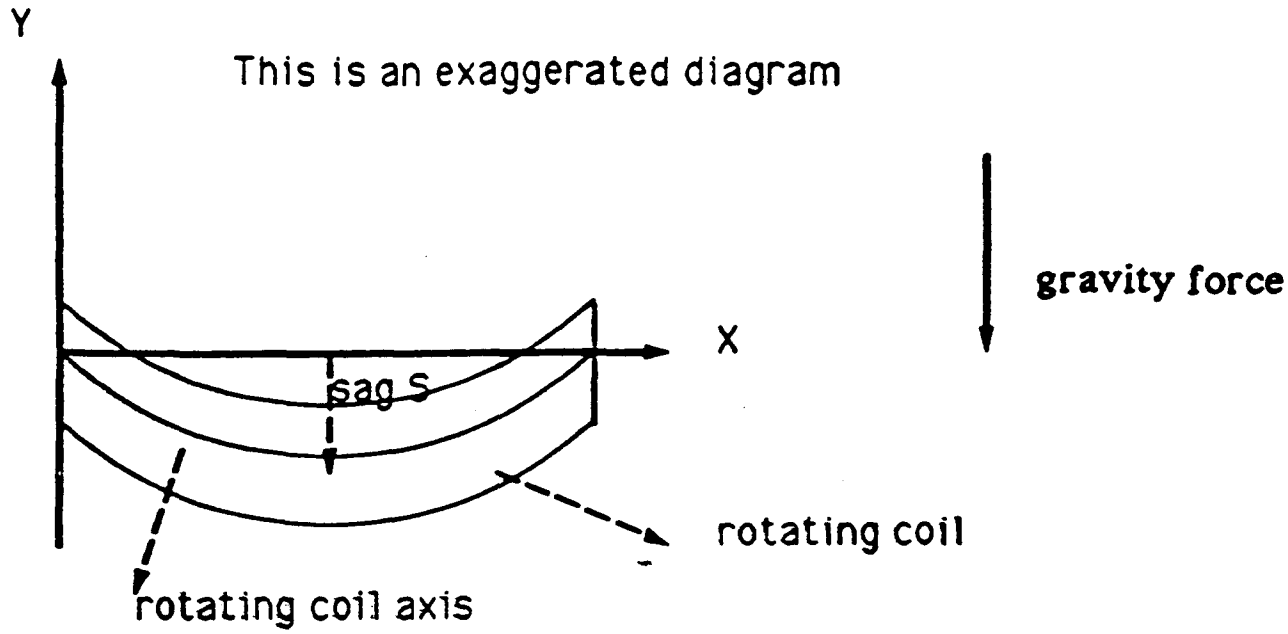


Figure 7 Bowing on a rotating coil

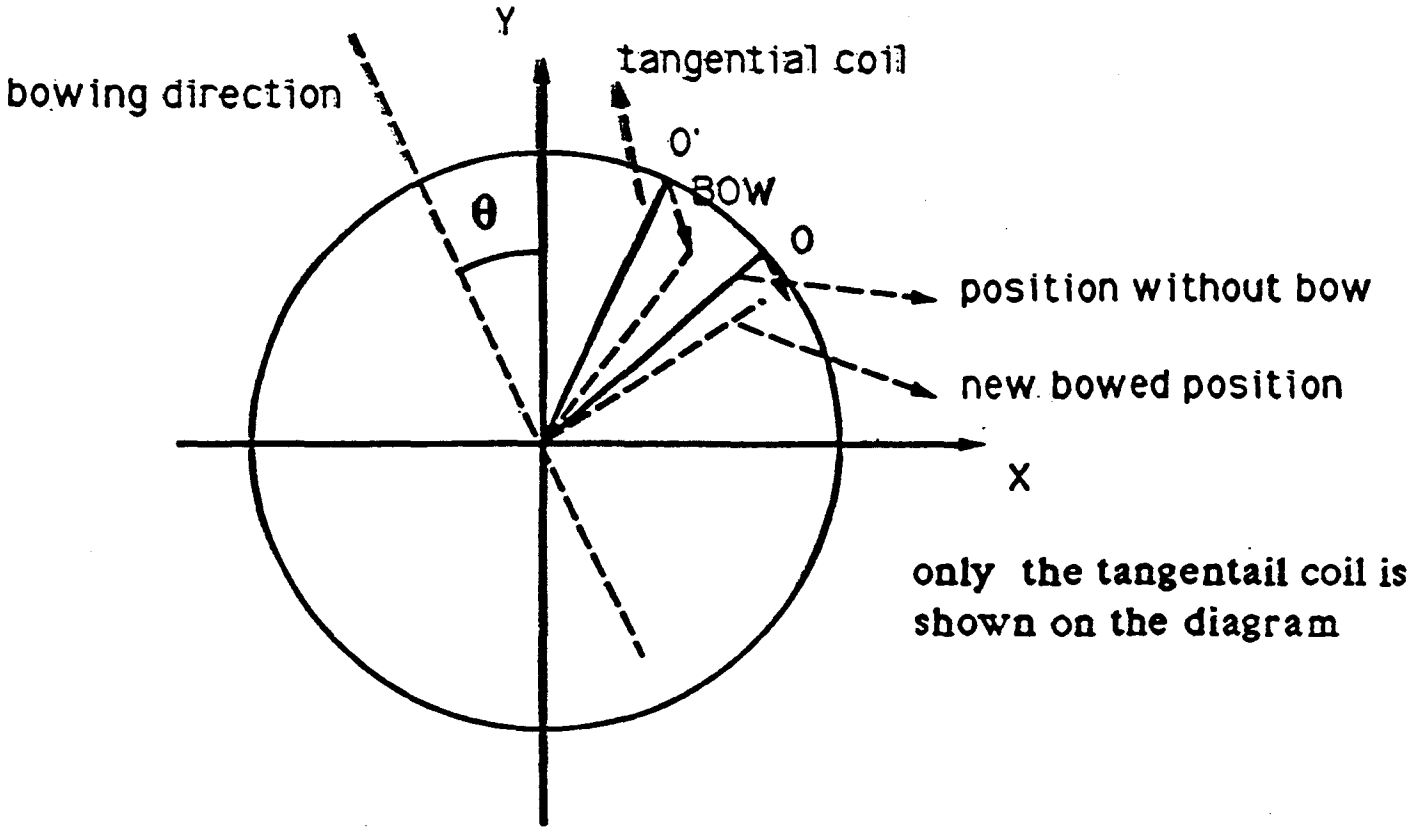


Figure 10 Bowing at 0 degree

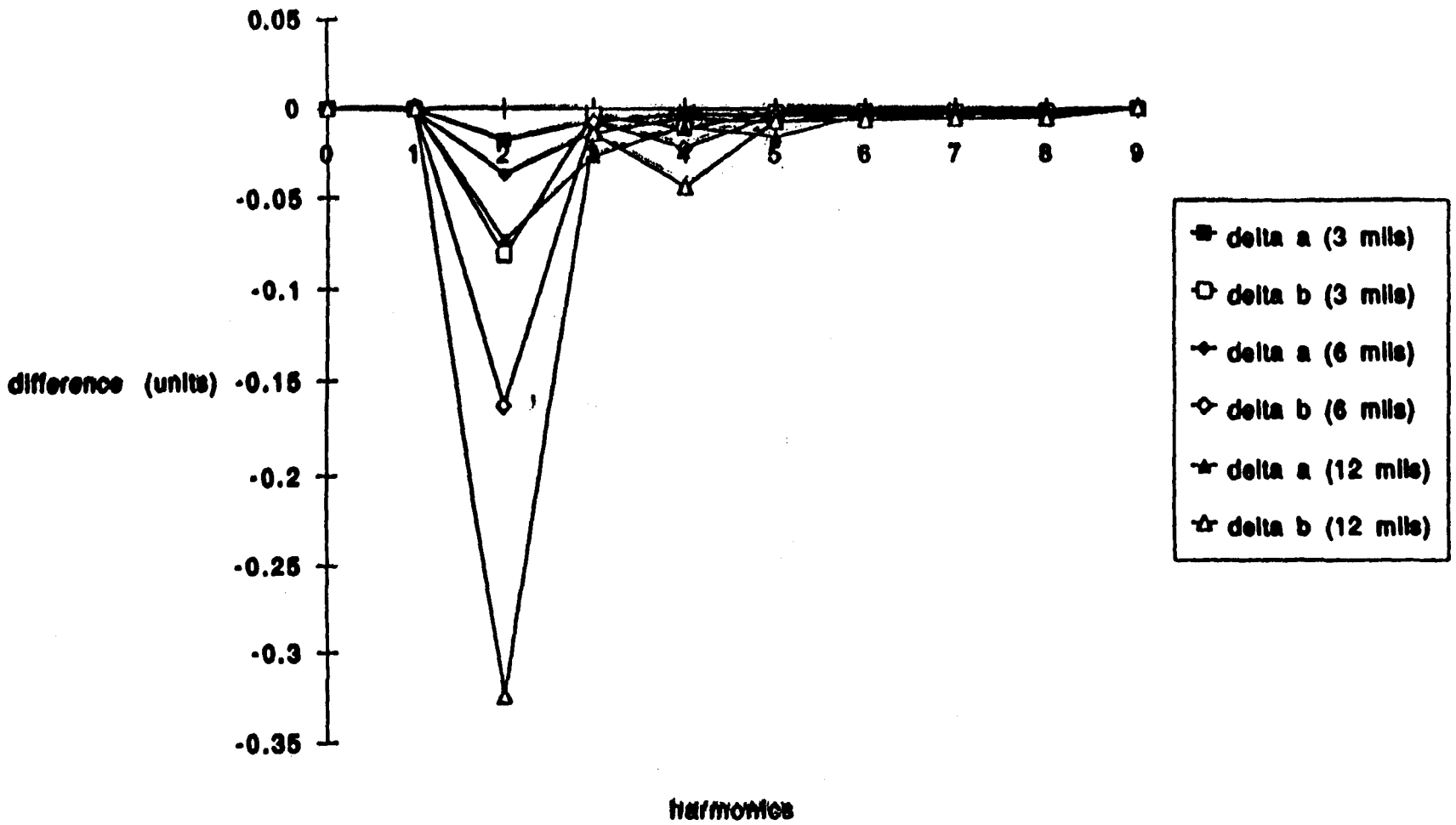


Figure 13 The radius of the tangential winding is off set

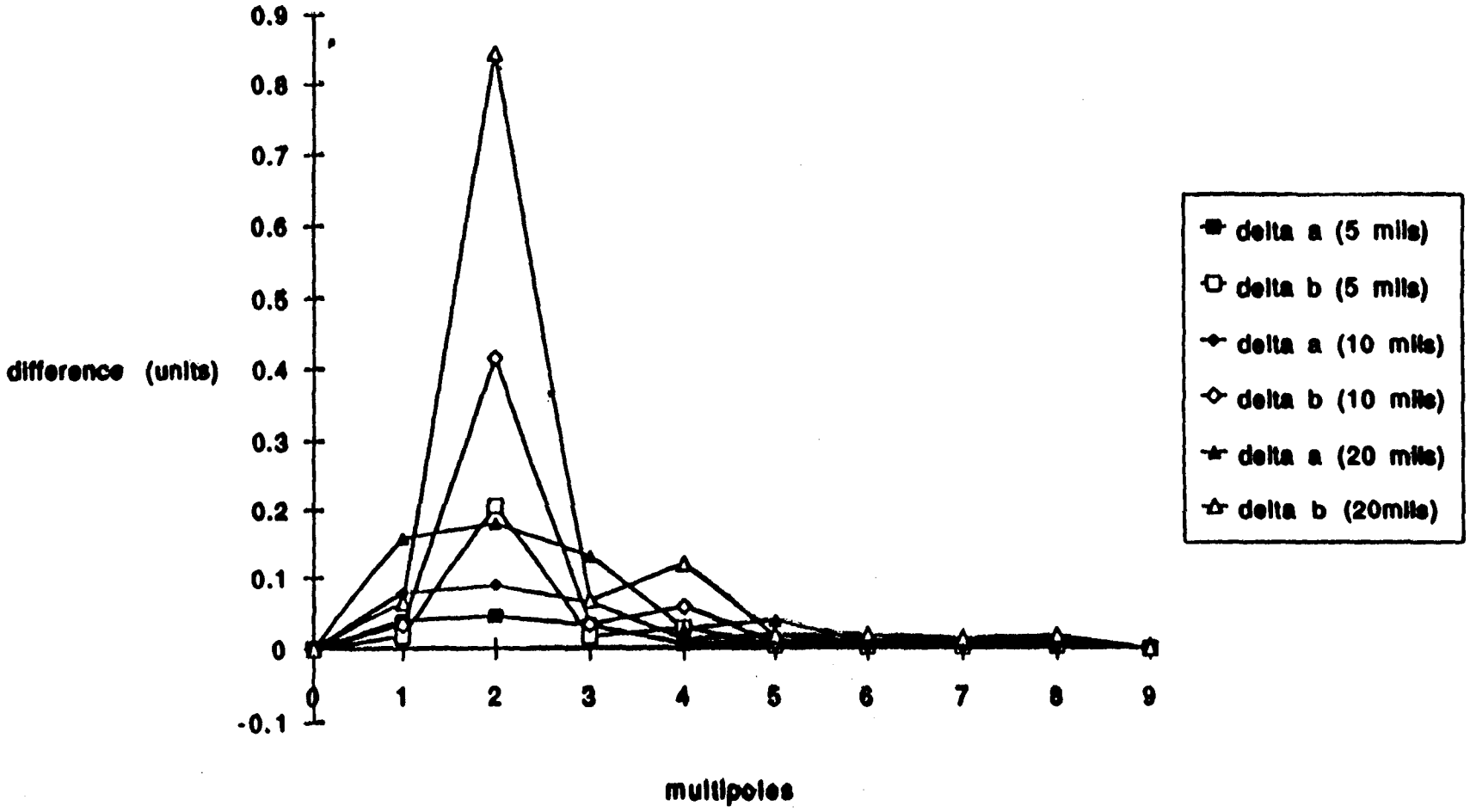


Figure 12 The angle of the bucking 1 winding is offset

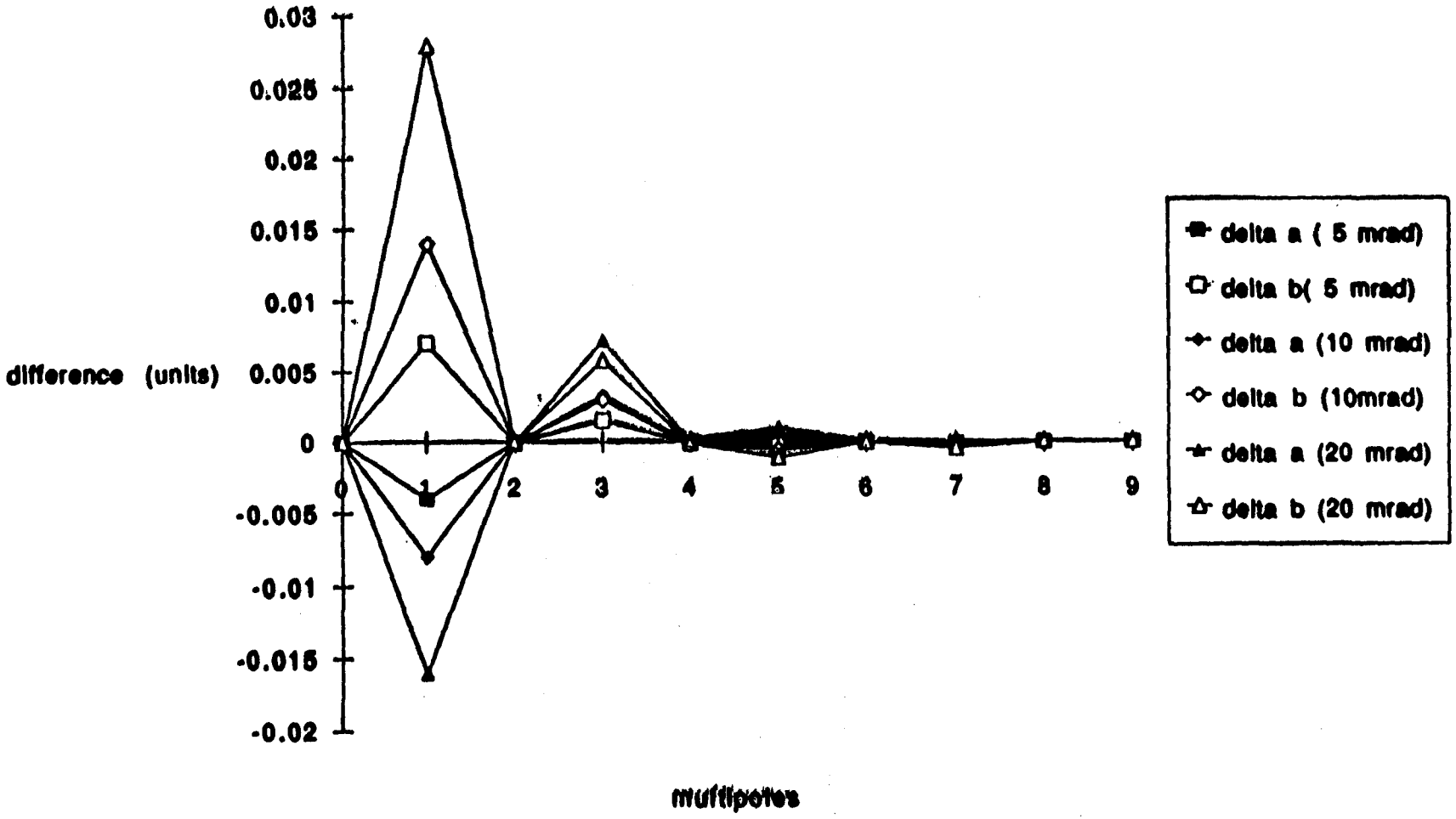
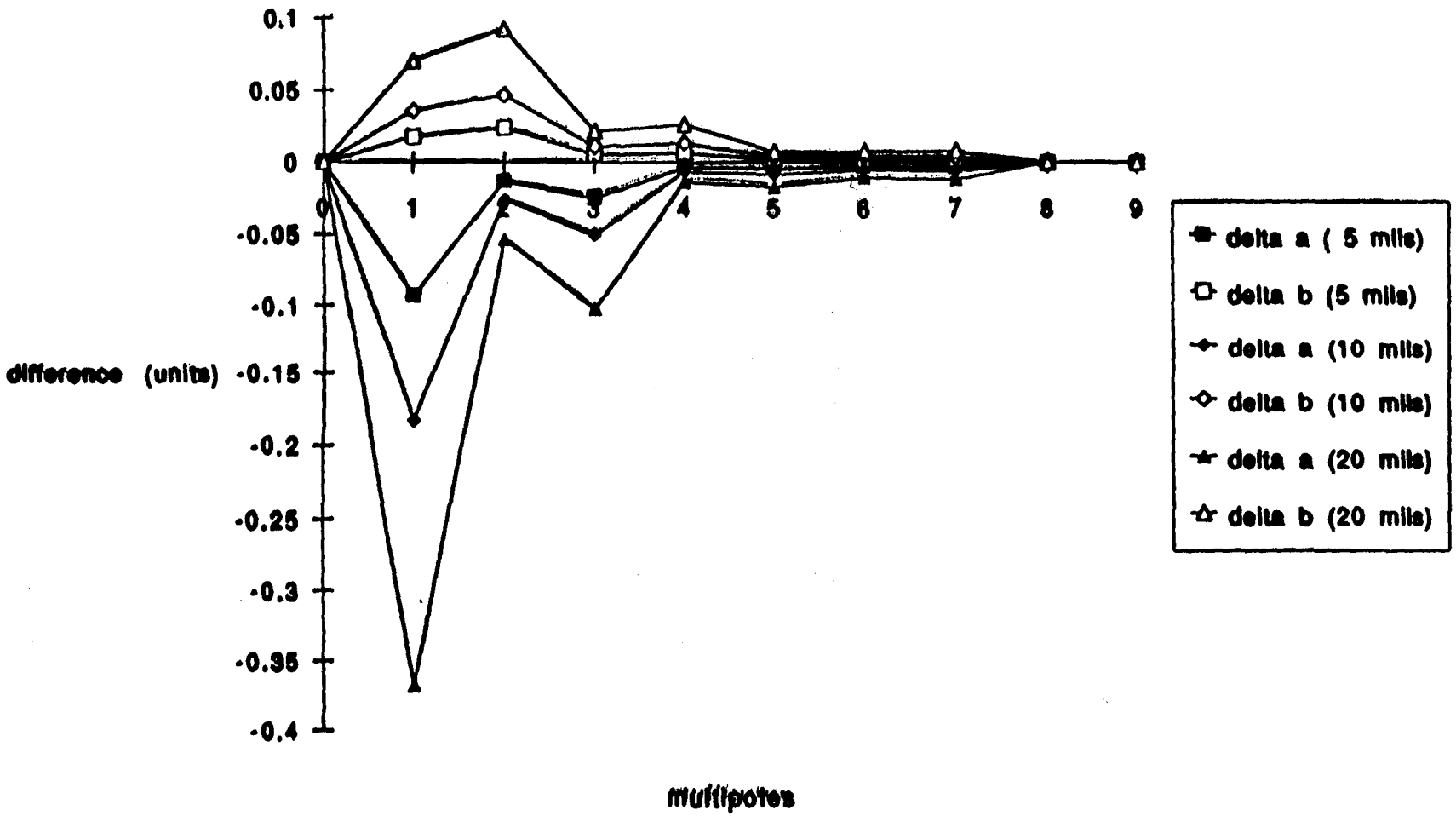
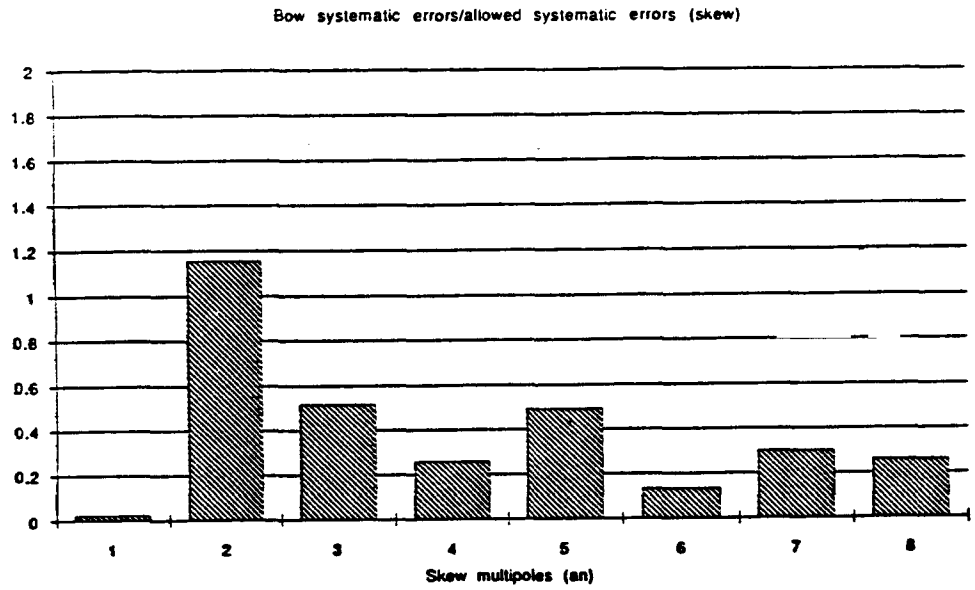
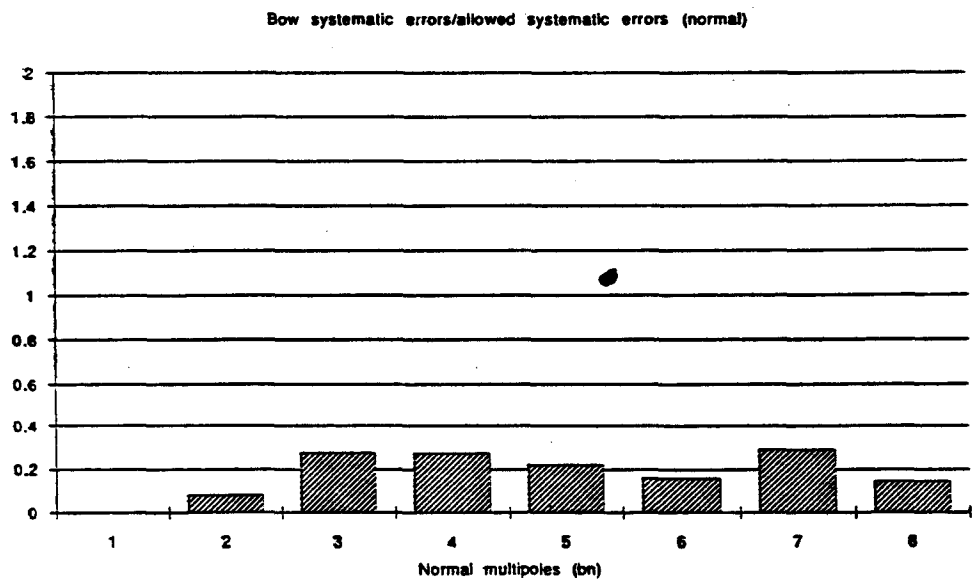


Figure 6 Gravity sag




Bow systematic errors/allowed systematic errors (skew)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
8
Skew multipoles (an)


Bow systematic errors/allowed systematic errors (normal)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
8
Normal multipoles (bn)

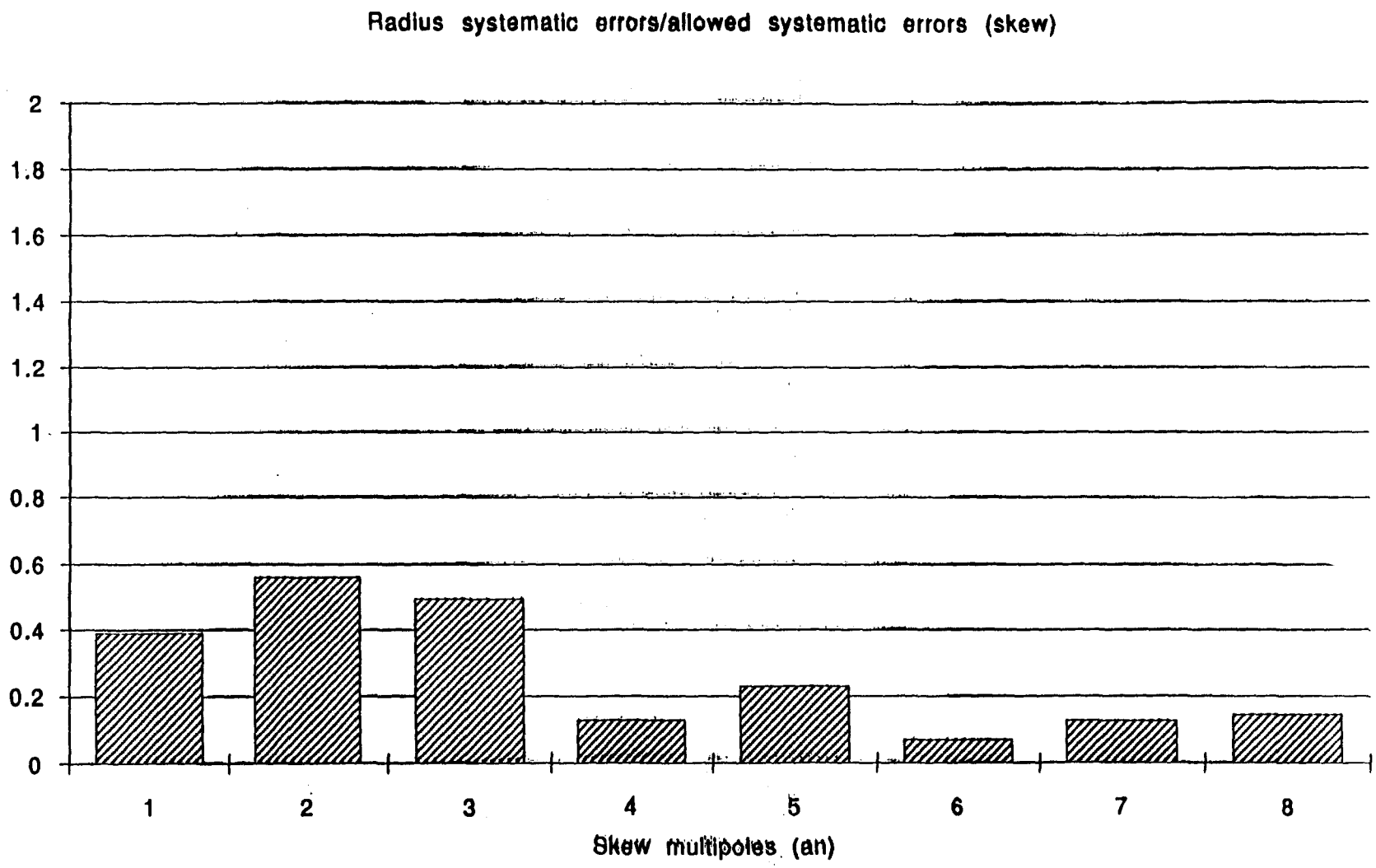

Radius systematic errors/allowed systematic errors (skew)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
8
Skew multipoles (an)

Figure 9 Gravity sag after ideal centering correction

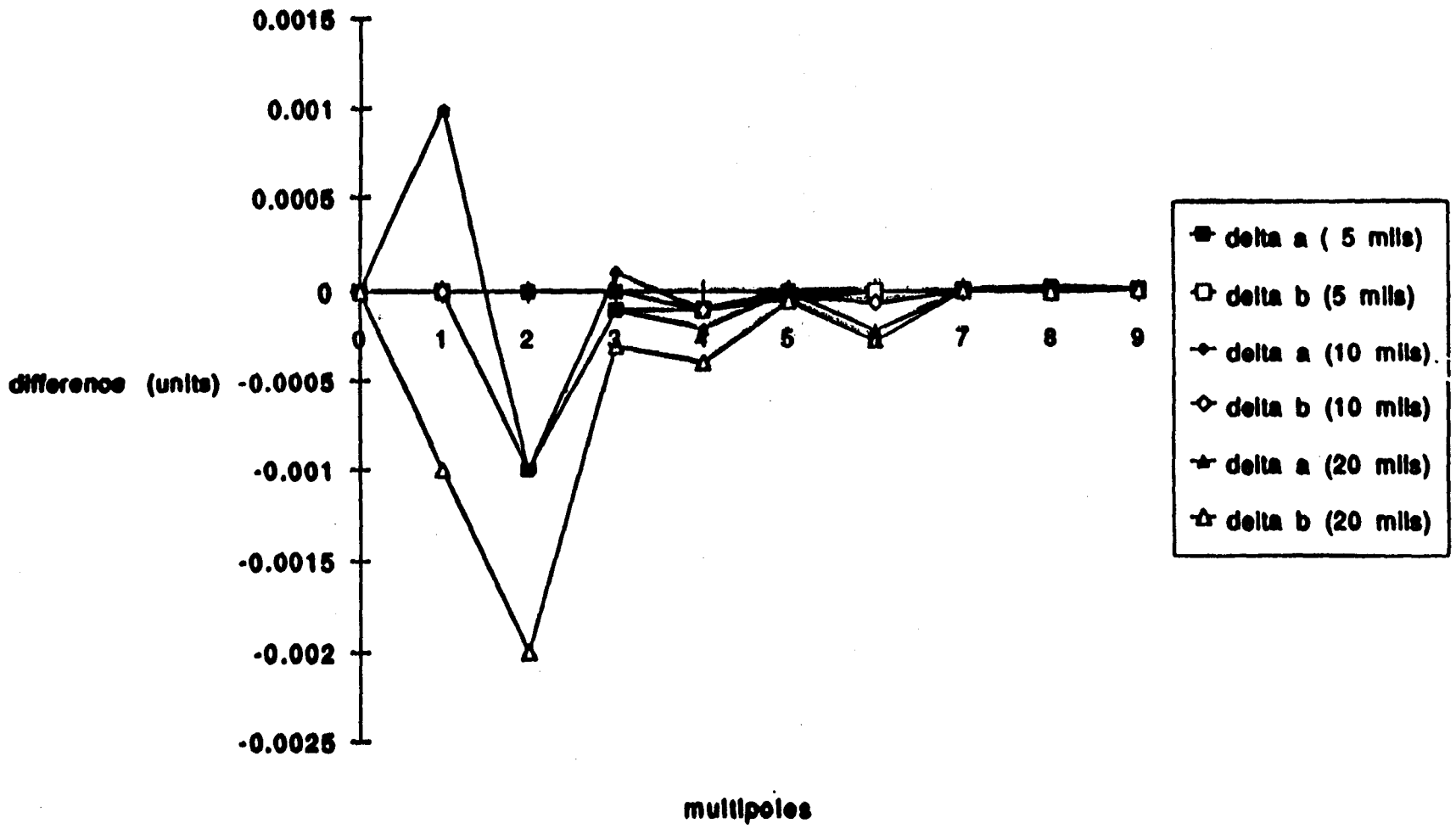


Figure 14 The radius of the bucking winding is offset

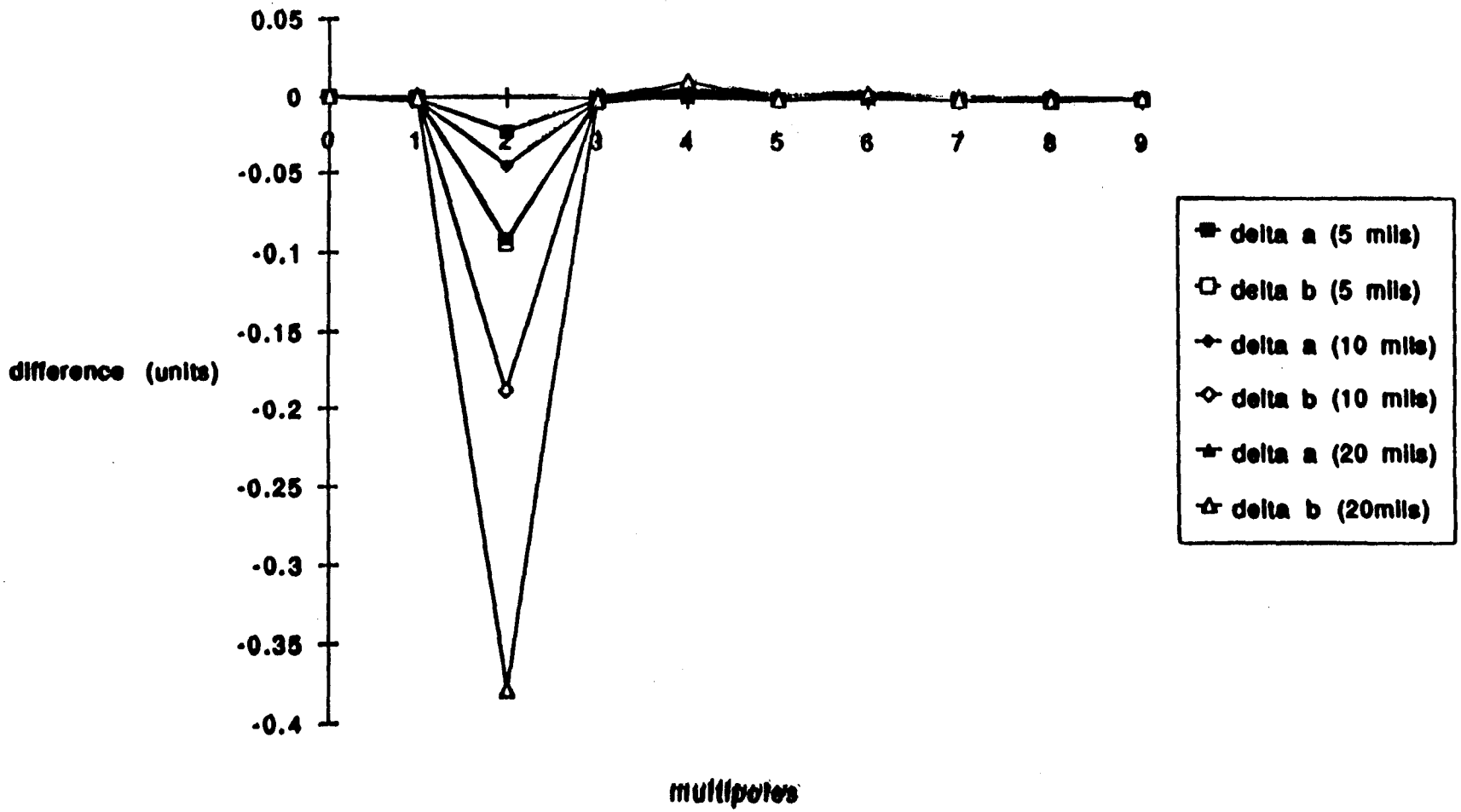


Figure 17 The twist of the coil form

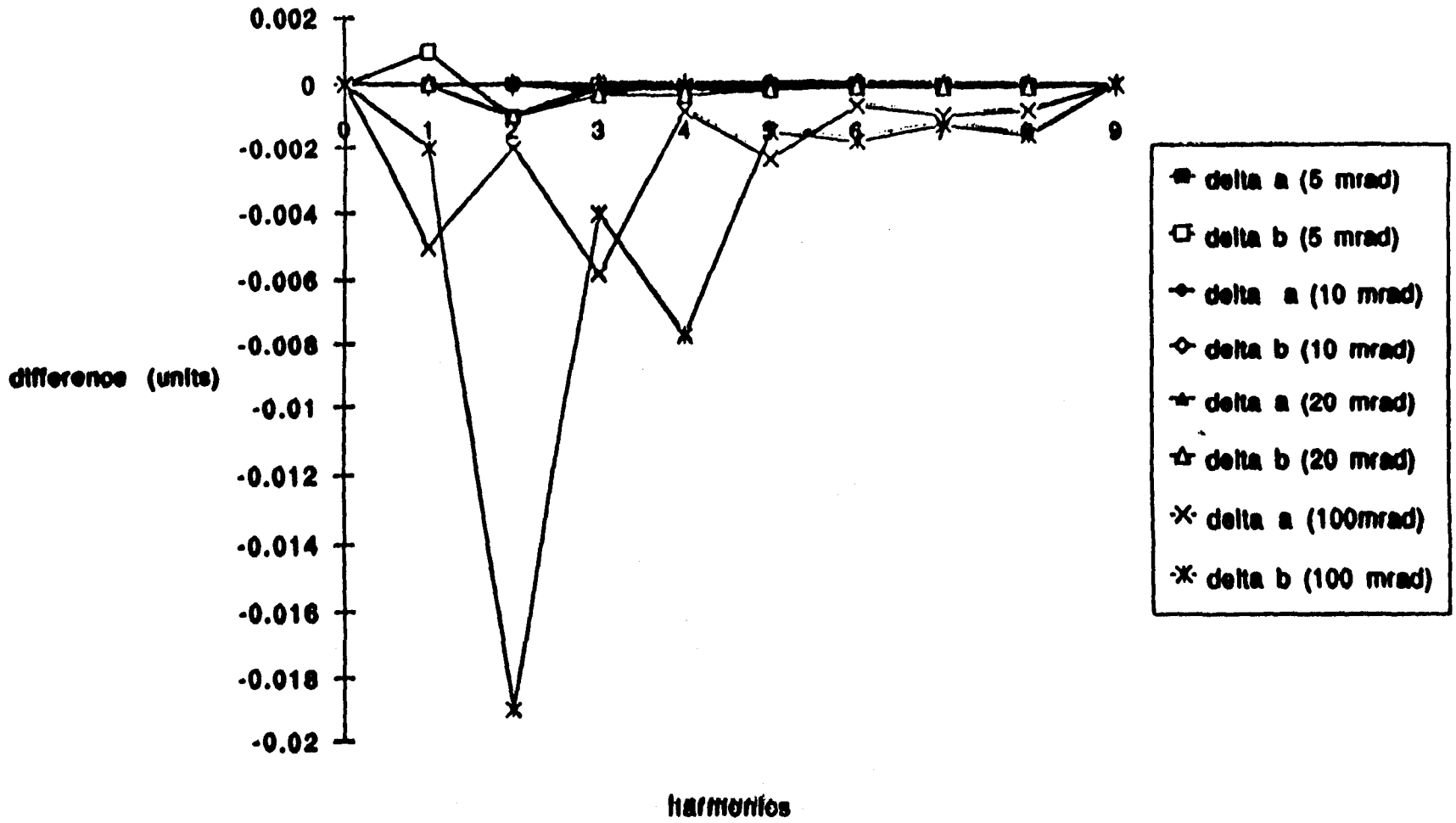


Figure 15 The cone effect on tangential coil

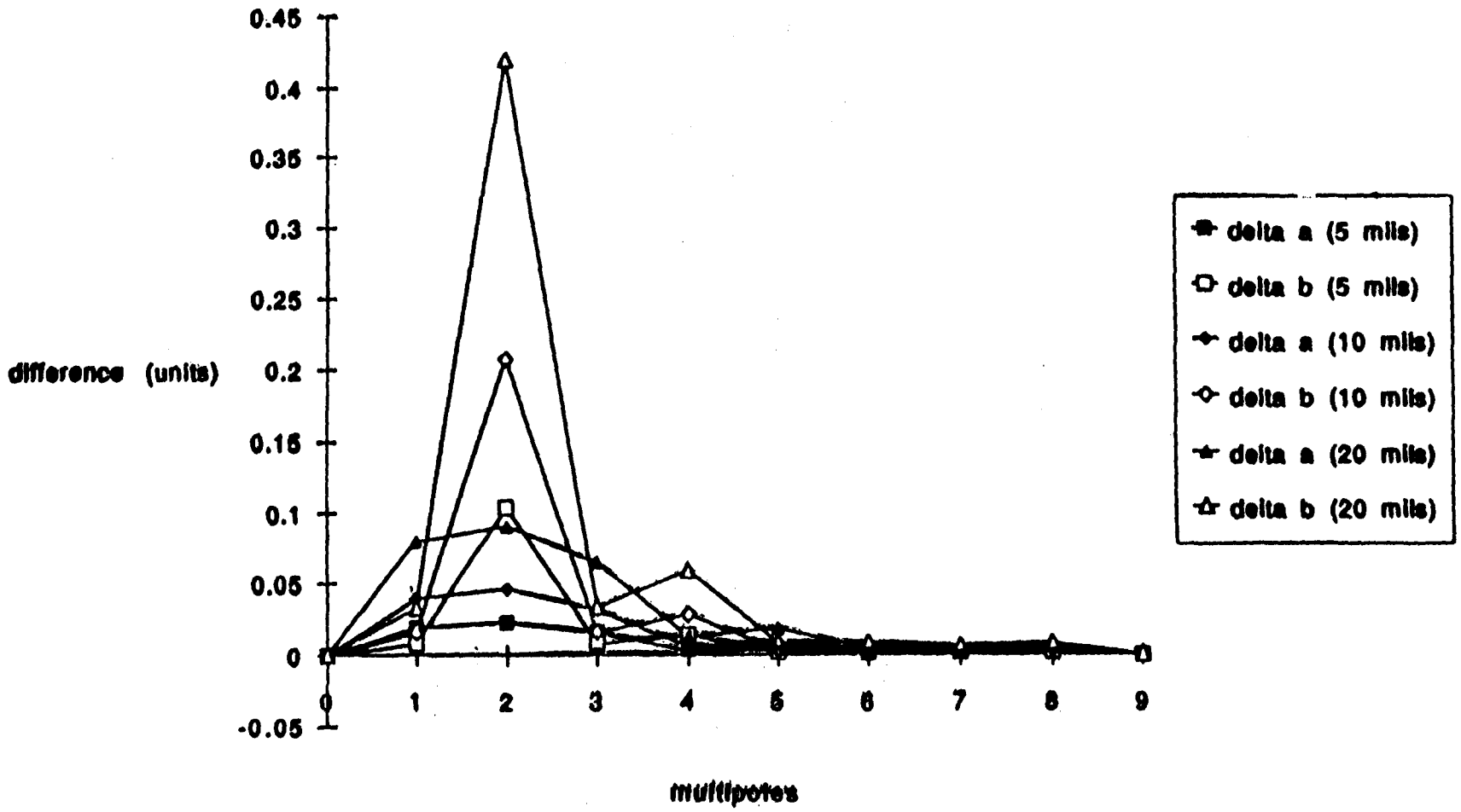


Figure 16 The cone effect on bucking 1 coil

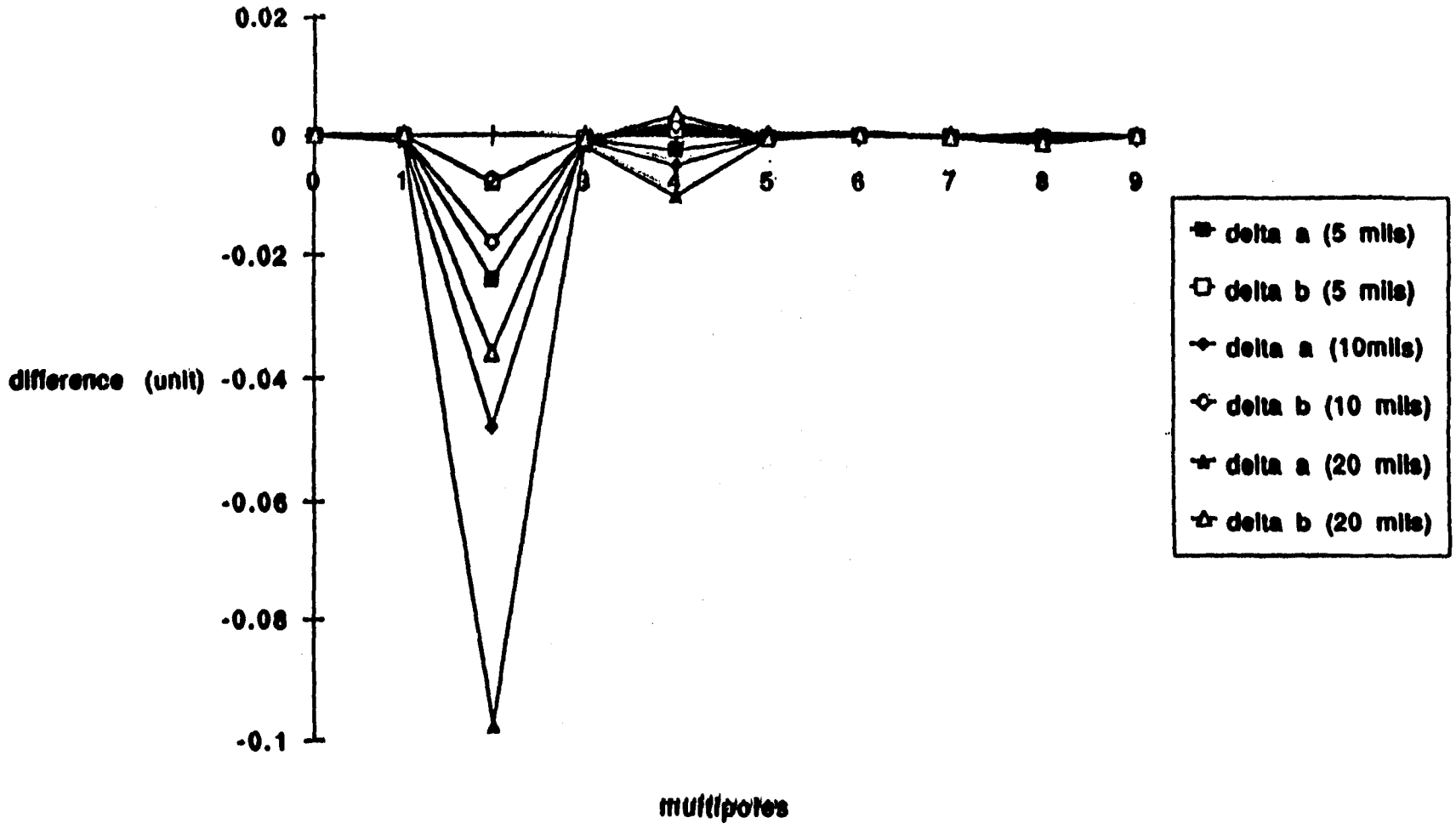


Figure 23 The center of coil is offset in Y direction

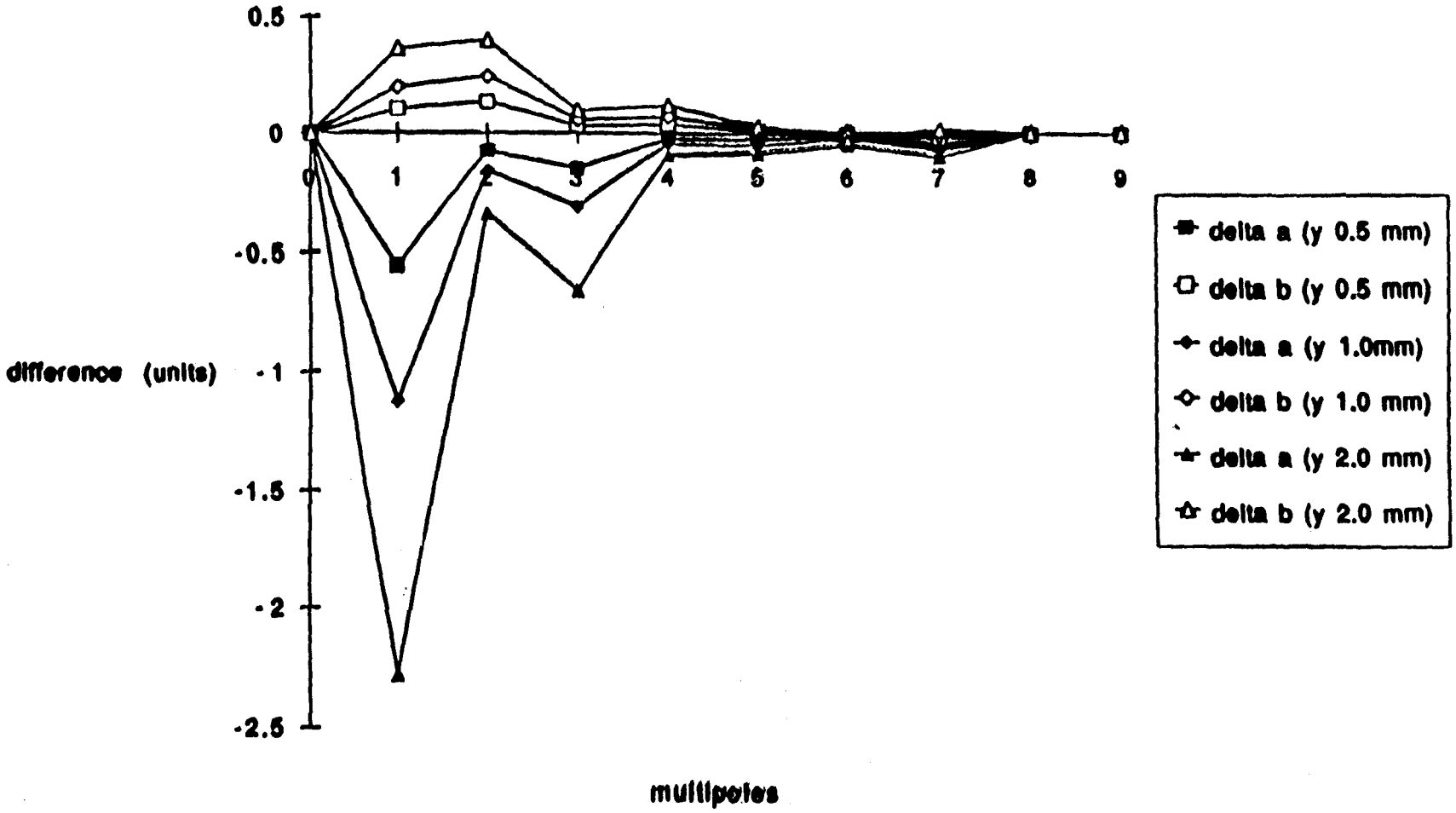


Figure 24 The center of coil is offset in Y direction, after ideal centering correction

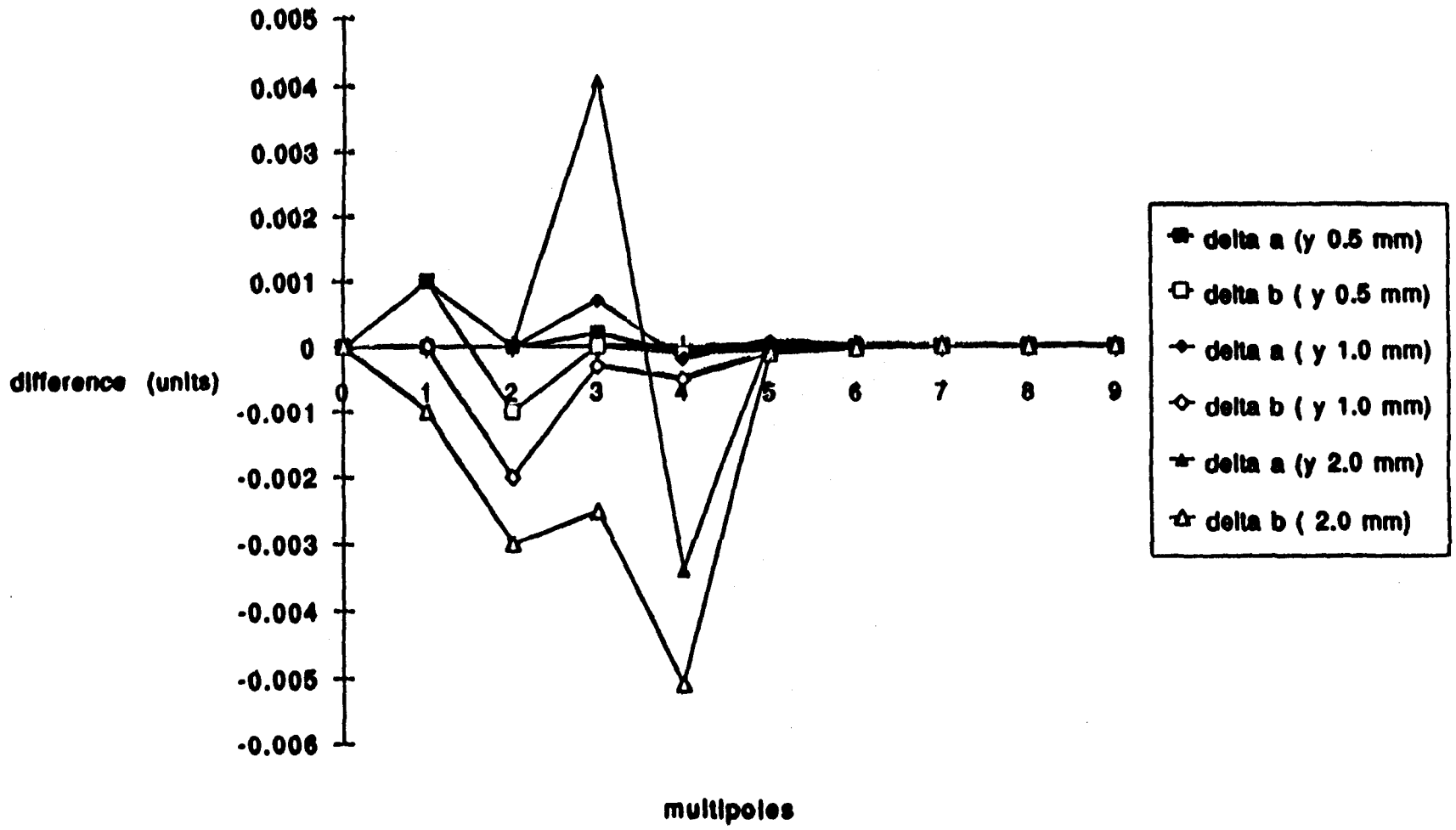


Figure 25 The center of coil is offset in Y directon, after centering correction

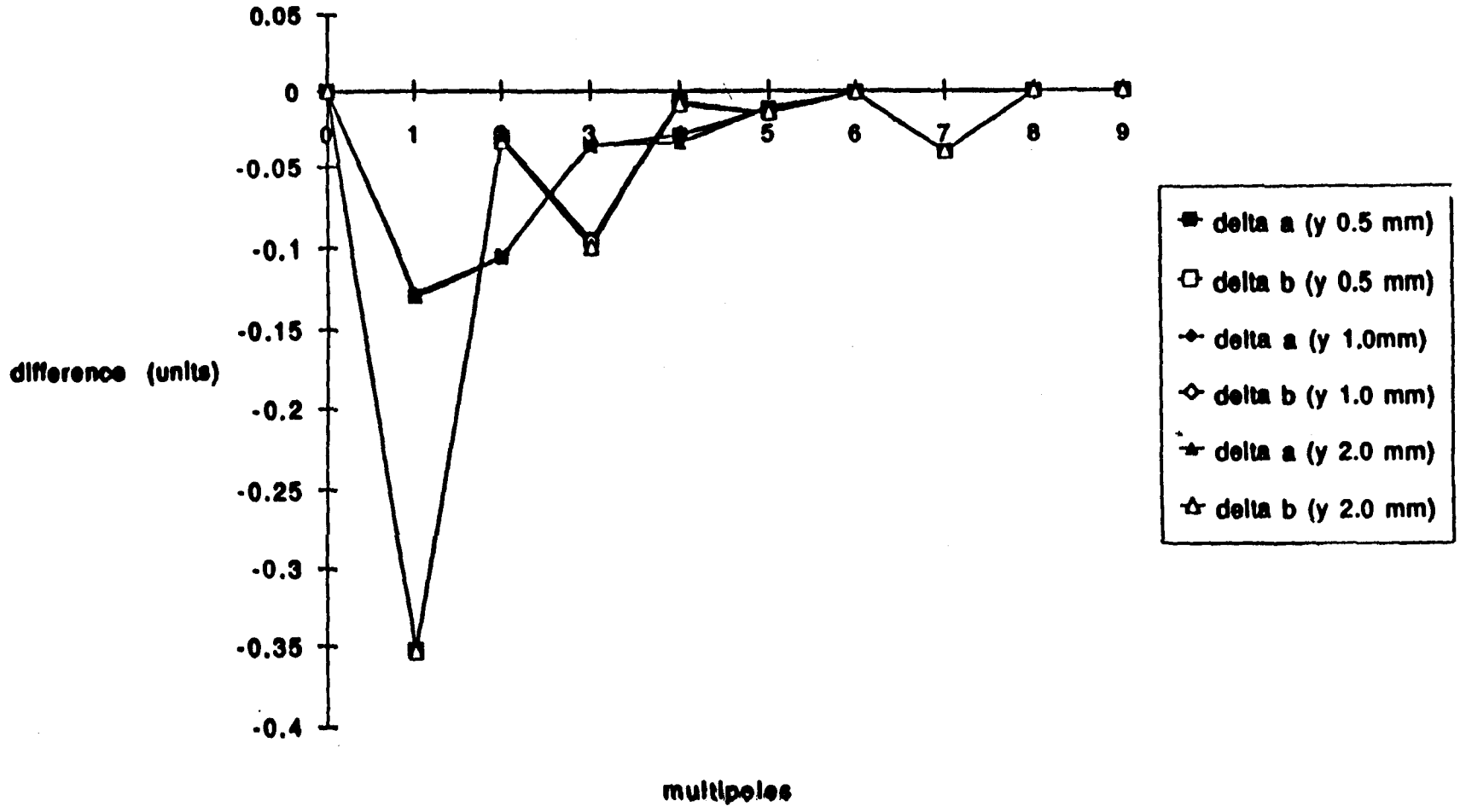


Figure 26 The center of coil is offset in both X and Y direction, Y offset is fixed to -1.0 mm

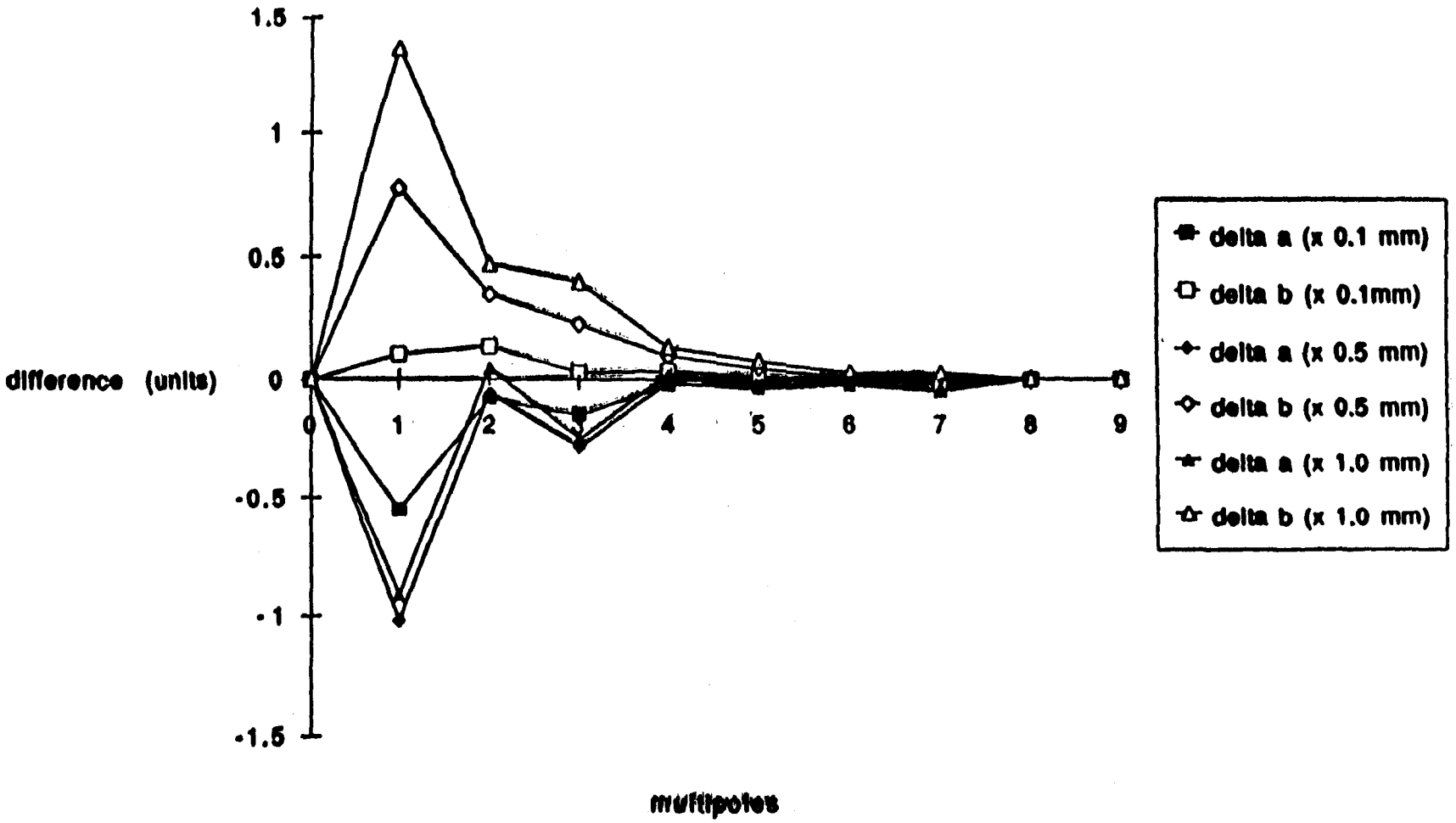


Figure 27 The center of coil is offset in both X and Y , Y offset fixed to -1mm, after centering correction

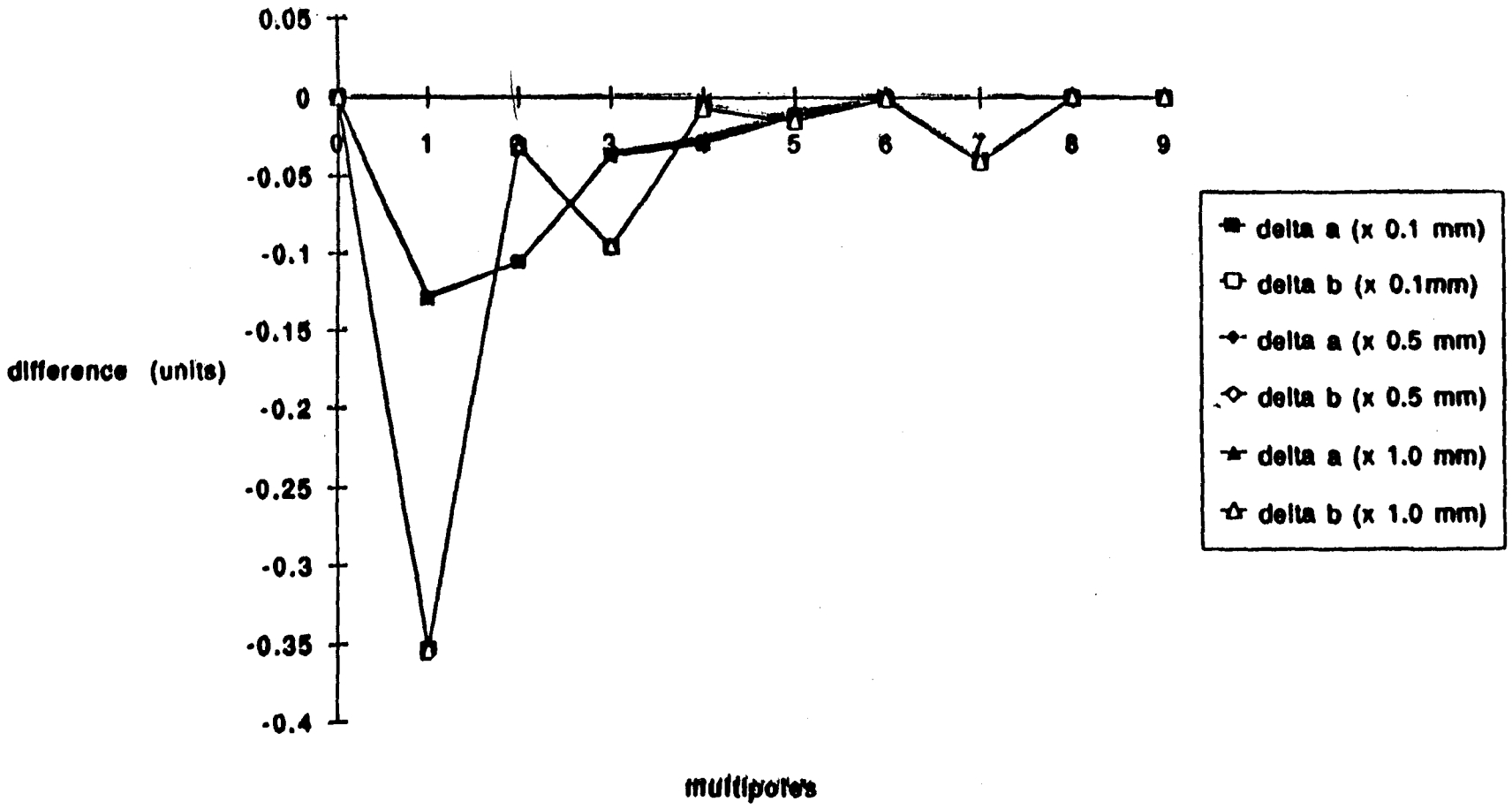


Figure 28 The center of coil is offset in both X and Y direction, Y offset is fixed to 1.0 mm, after ideal centering correction

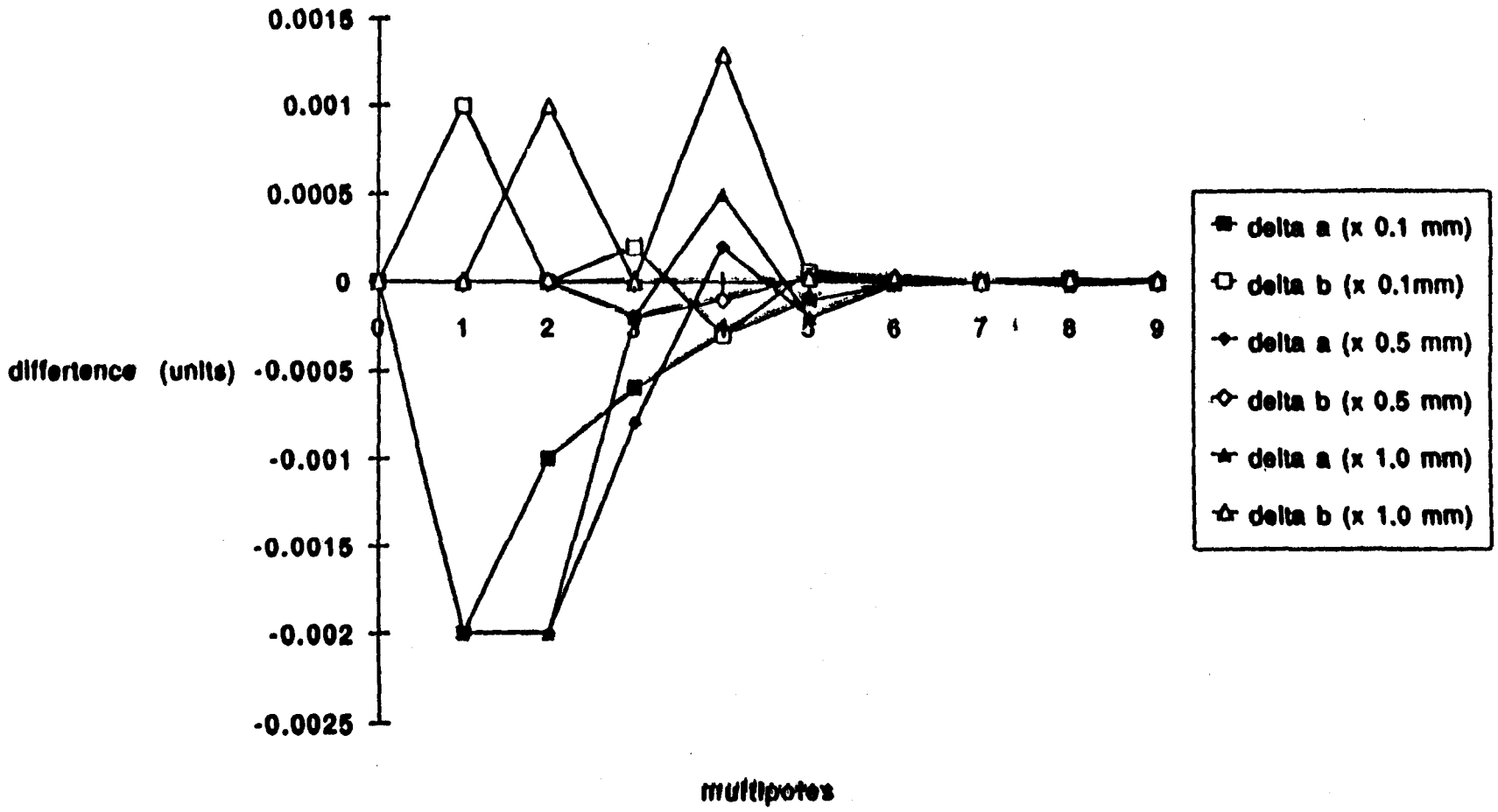


Figure 29 The bearing is offset in Y direction

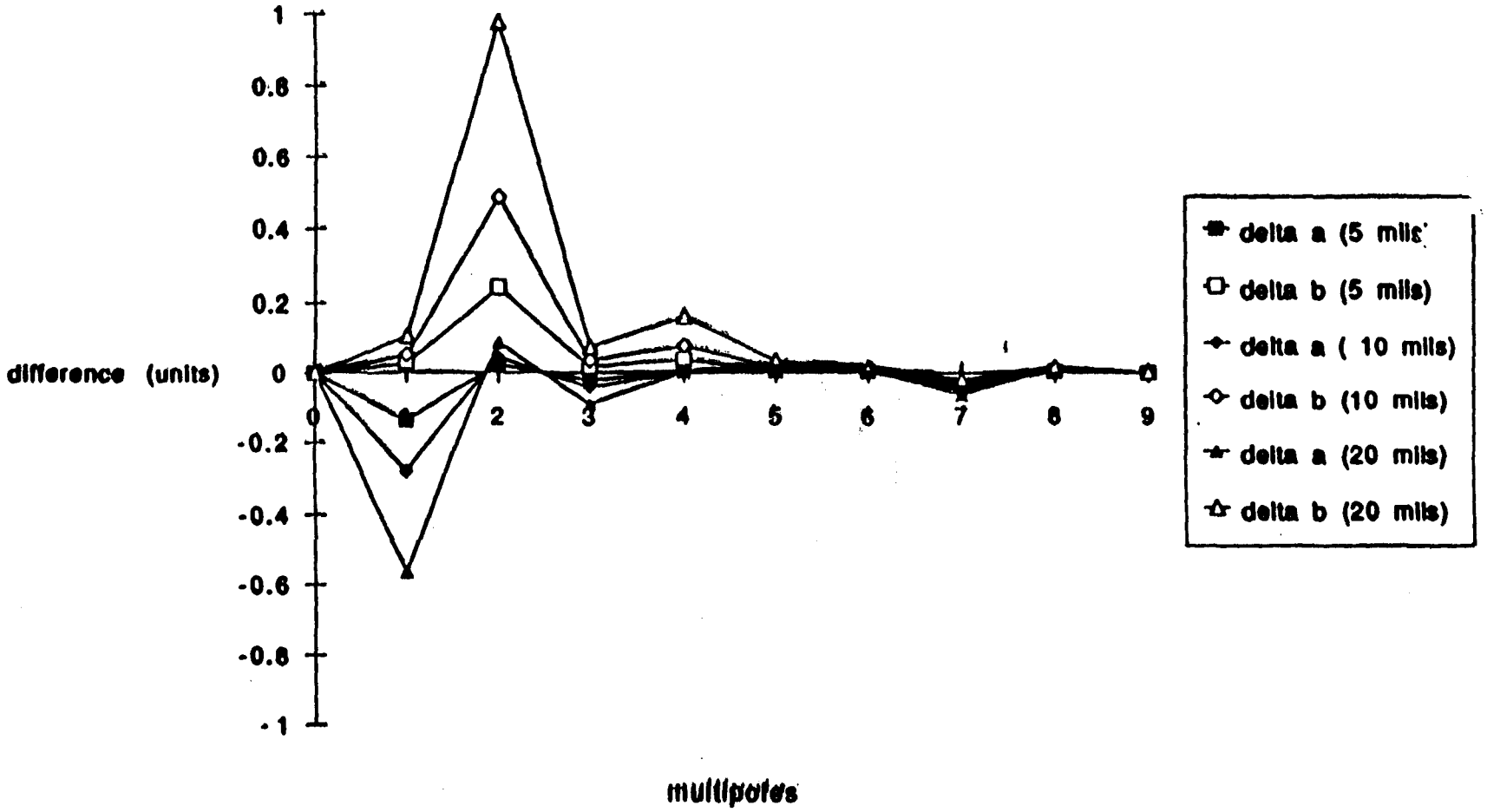


Figure 31 The bearing is offset in Y direction after ideal centering correction

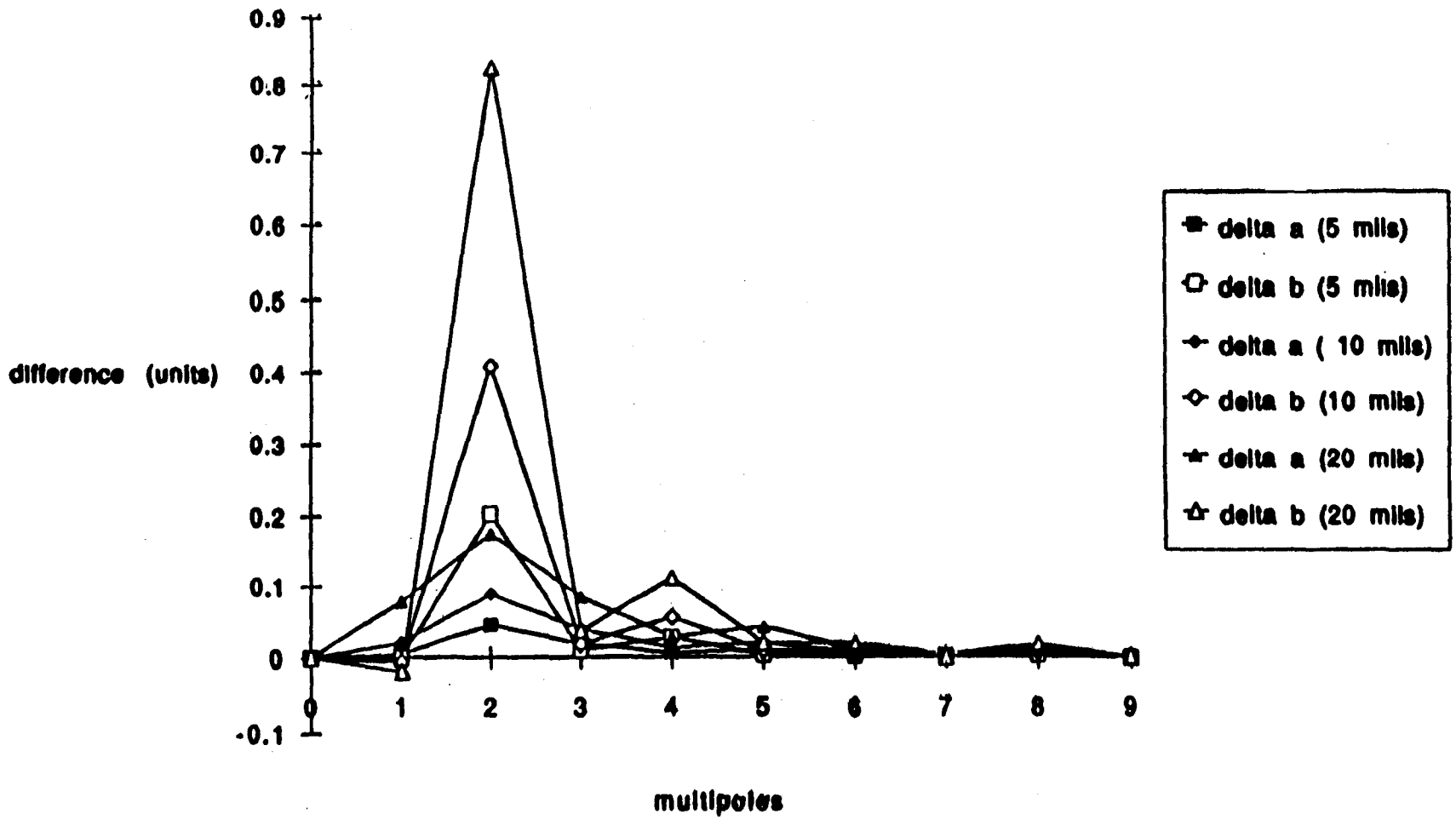


Figure 32 The bearing is offset in Y direction with smaller change after ideal centering

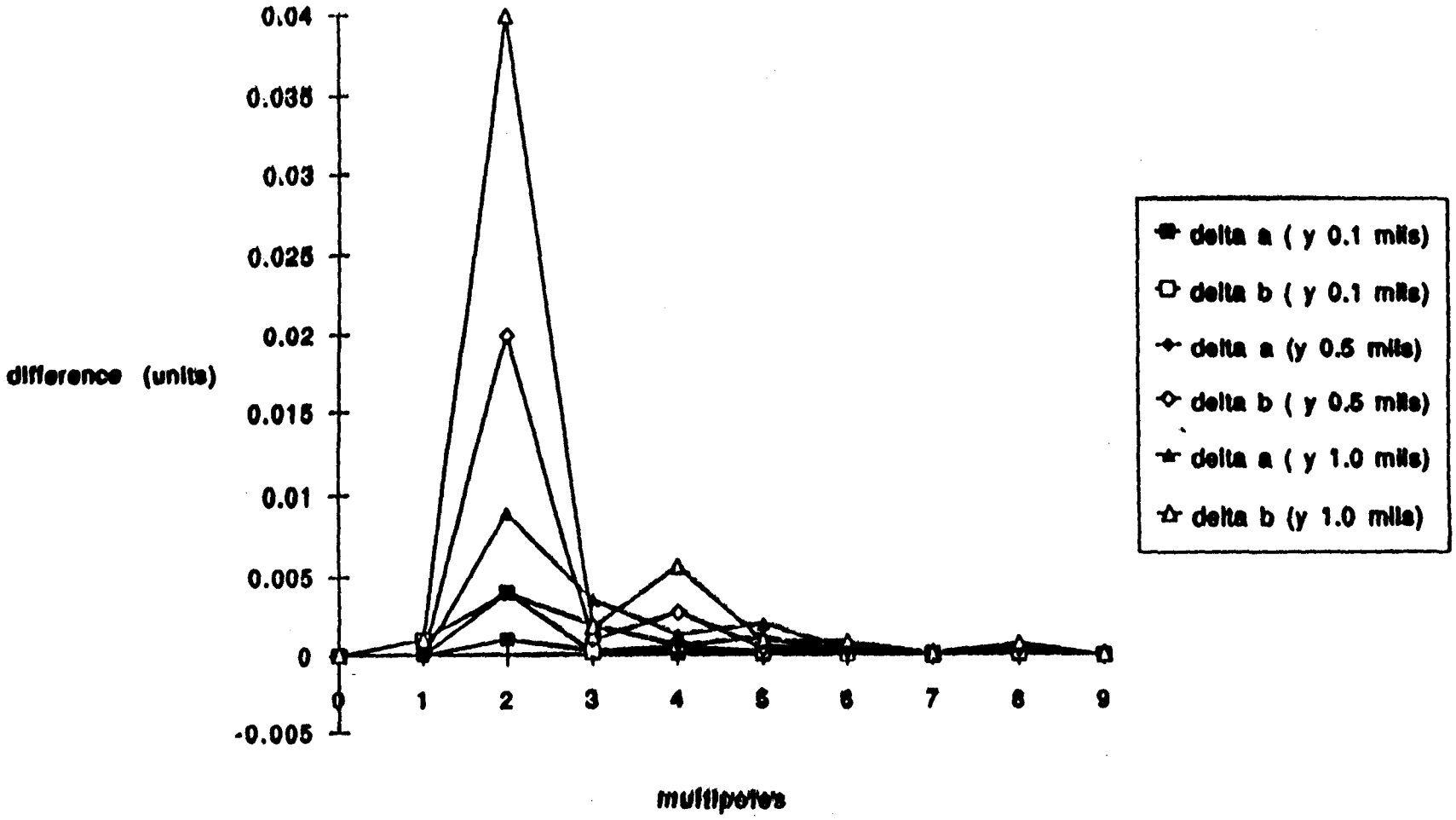


Figure 33 The bearing is offset in X direction, after ideal centering correction

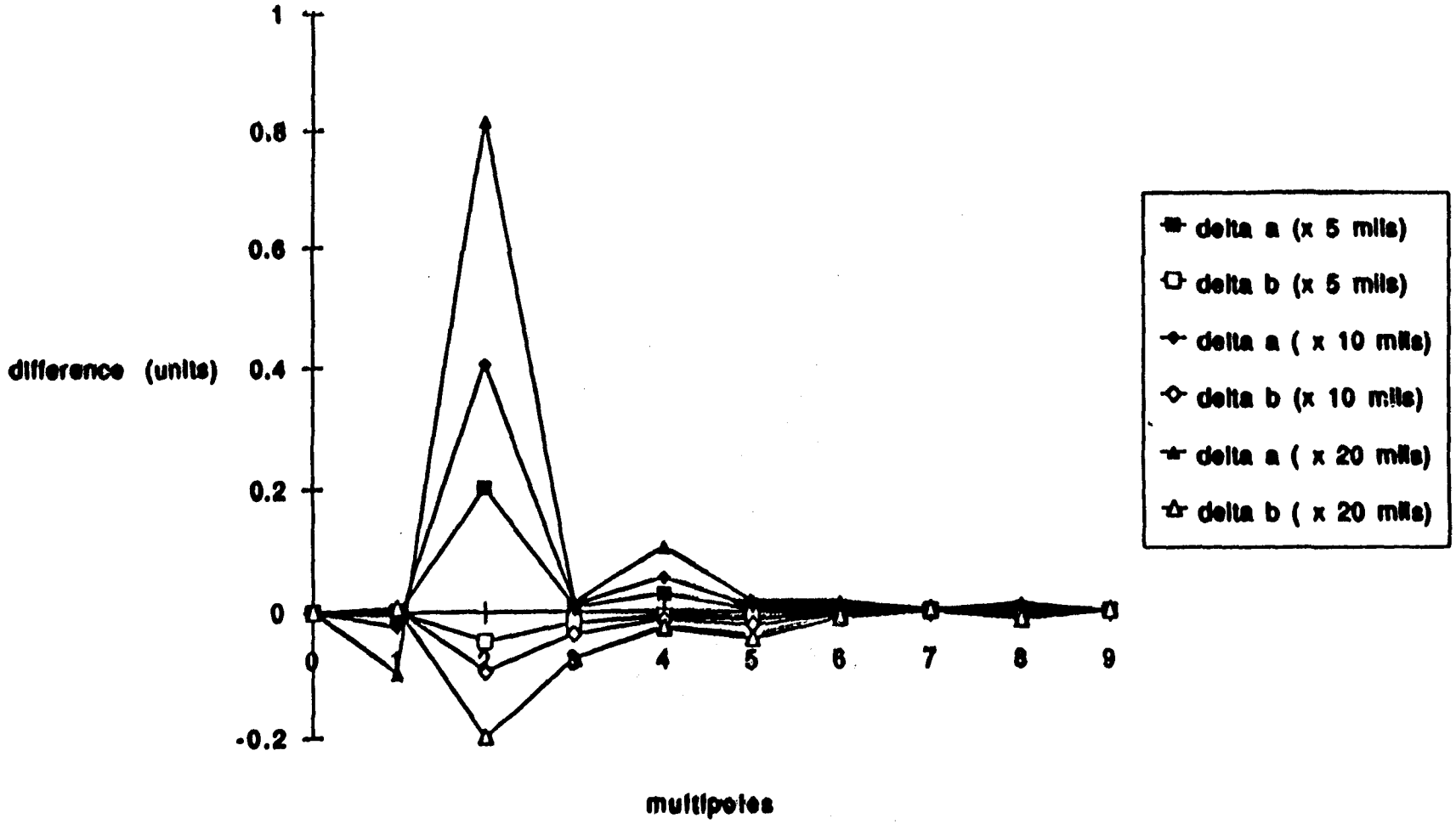
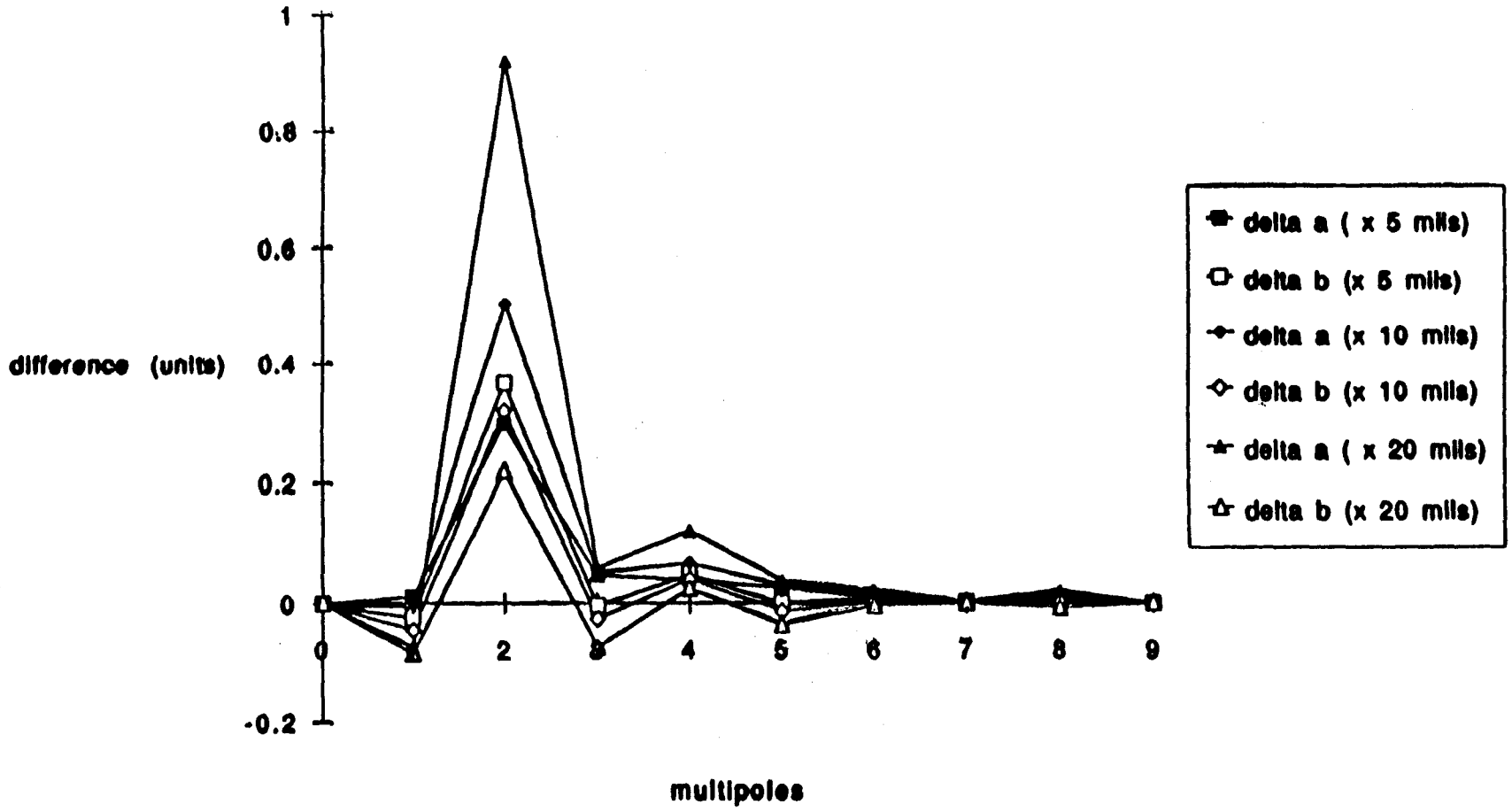


Figure 34 The bearing offset in both X and Y direction, Y offset is fixed to 10 mils. Ideal centering correction used.



AMPAD 22-141 50 SHEETS 22-142 100 SHEETS 22-144 200 SHEETS

	Mean depth	Radius of Rotation
20° 9'	-0.02514 ± .00035	0.48462 ± .00035
49° 15'	-0.02567 ± .01034	0.49160 ± .00034
69° 50'	-0.02558 ± .00022	0.48177 ± .00022
110° 9'	-0.02560 ± .00030	0.49176 ± .00030
130° 44'	-0.02559 ± .00038	0.49176 ± .00038
159° 50'	-0.02563 ± .00038	0.49172 ± .00038
200° 9'	-0.02560 ± .00045	0.49175 ± .00045
229° 15'	-0.02520 ± .00025	0.49216 ± .00025
249° 50'	-0.02415 ± .00042	0.49123 ± .00042
290° 9'	-0.02546 ± .00046	0.49149 ± .00046
310° 44'	-0.02515 ± .01025	0.49221 ± .00025
339° 50'	-0.02512 ± .01027	0.49153 ± .00027
T < 90	-0.03982 ± .00027	0.46754 ± .00027
T > 90	-0.03974 ± .00026	0.46762 ± .00026
T < 270°	-0.03971 ± .00022	0.46765 ± .00022
T > 270°	-0.03958 ± .00018	0.46777 ± .00018

Tangential Depth -0.03978 ± .00026
Rotation Radius 0.46758 ± .00026
Aver. Radius for coil

DB1 Depth -0.02537 ± .00039
Rotation Radius 0.48199 ± .00039
Aver Radius of coil 0.48554

DB2 Depth -0.02545 ± .00041
Rotation Radius 0.48184 ± .00041
Aver Radius of Coil 0.48543

QB1 Depth -0.02570 ± .00040
Rotation Radius 0.48166 ± .0004

QB2 Depth -0.02579 ± .00039
Rotation Radius 0.48156 ± .00039

Rotating Coil Simulation Study

Wei-Chuan Li, Mark Coles
April 2, 1992

SSC Laboratory
2550 Beckleymeade Ave.
Dallas, TX 75237

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92 5830 R M****

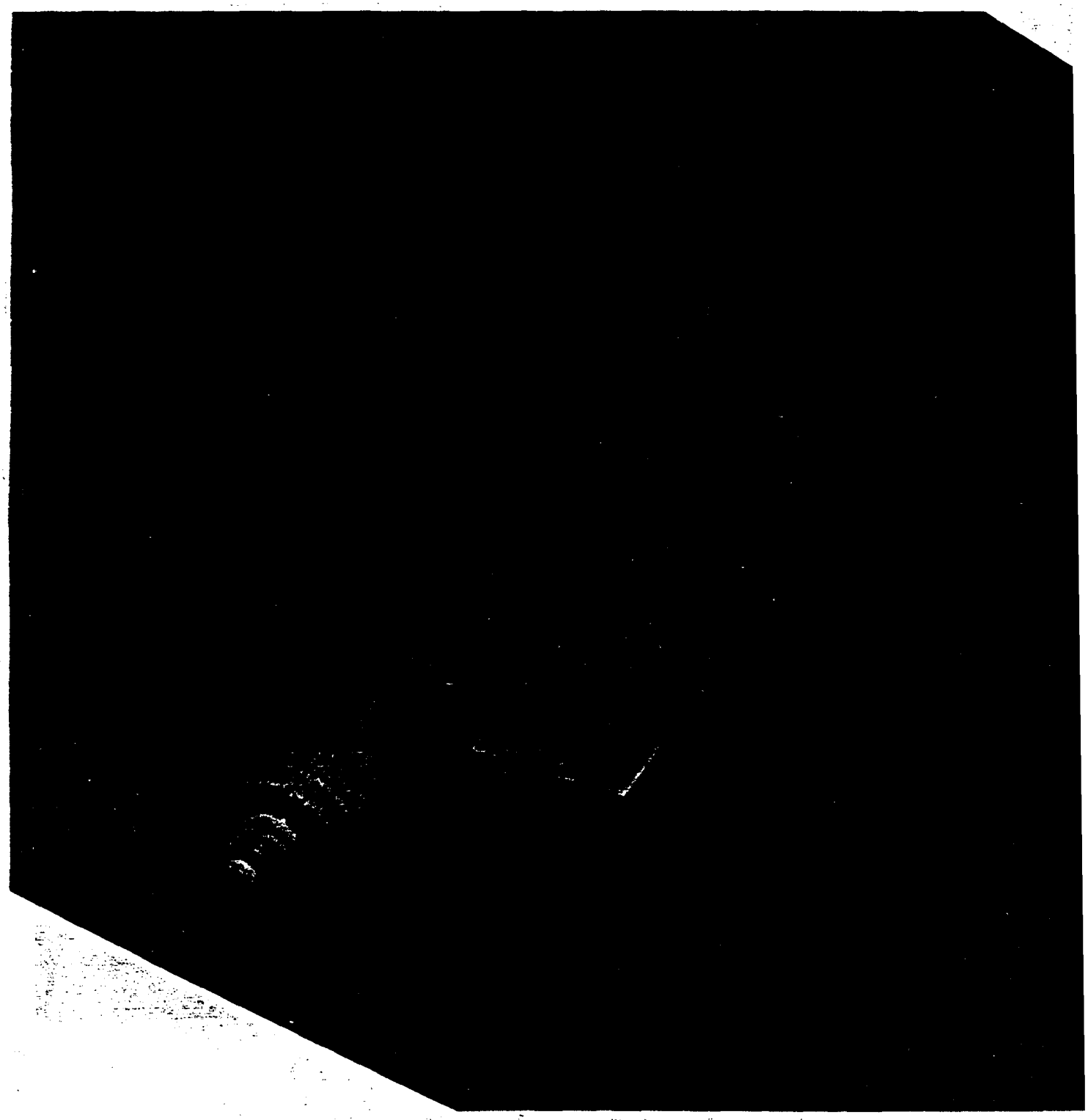
ABSTRACT

This report describes a study of the systematic and random measurement uncertainties of magnetic multipoles which are due to construction errors, rotational speed variation, and electronic noise in a digitally bucked tangential coil assembly with dipole bucking windings. The sensitivities of the systematic multipole uncertainty to construction errors are estimated analytically and using a simulation program "MOLESIM" which simulates the operation of the F series mole. The coil mechanical device tolerances required to achieve less than 0.01 units of systematic error for any multipoles have been determined. Also, random error limits on speed variation and electrical noise have been determined which are necessary to achieve less than 0.01 units of random uncertainty on any multipole measurement. These results are summarized in table 1.

Parameter	Nominal value	tolerance
bow	0.0	1.6 mils or 0.041 mm
sag	0.0	4 mils or 0.1 mm
twist	0.0	40 mrad
bearing misalignment	0.0	0.24 mils or 0.0061 mm
radial error of tangential winding	12.3063 mm	0.24 mils or 0.0061 mm
radial error of bucking winding	12.3063 mm	0.53 mils or 0.014mm
angular error of tangential winding	0.262 rad	130 mrad
angular error of bucking winding	3.141 rad	7.1 mrad
parallelism error of tangential winding	0.0	0.48 mils or 0.012 mm
parallelism error of bucking winding	0.0	2.0 mils or 0.052 mm
angular velocity of coil	2.0943 rad/s	0.021 rad/s
random electrical noise	0.0	2.8 nv (rms)

Table 1: The tolerance requirements for the coil

66



BBC 924-2991

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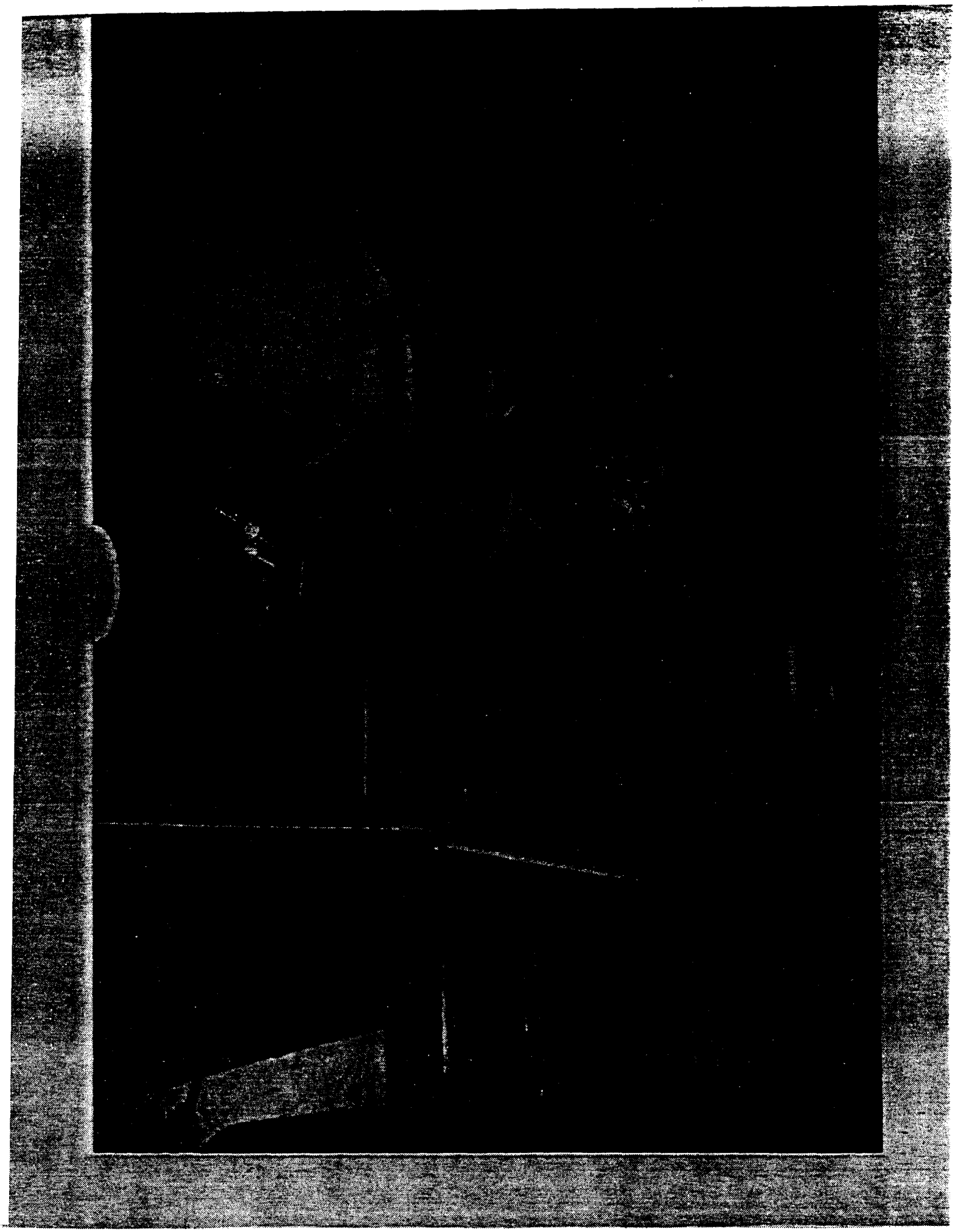

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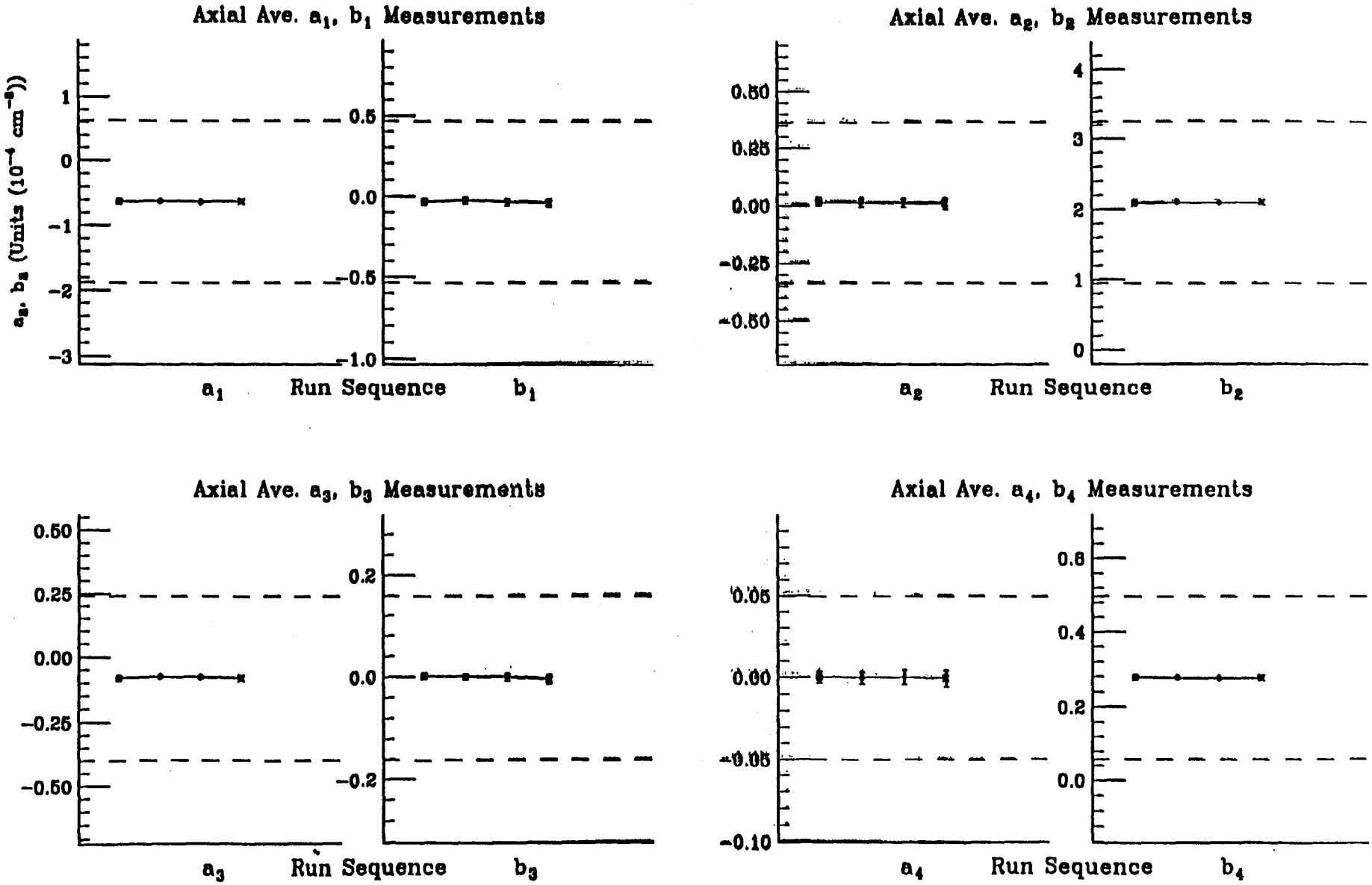
DCA312 Ave. a_n, b_n Z-scan Summary

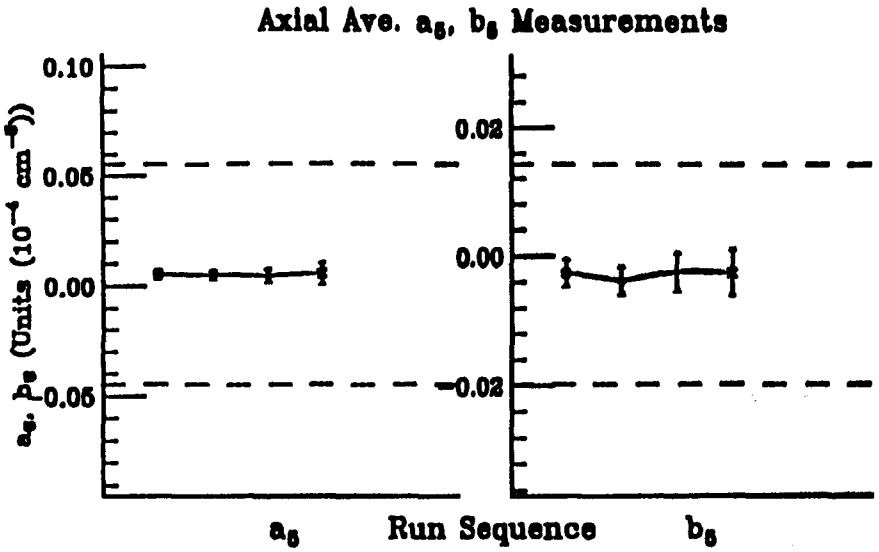


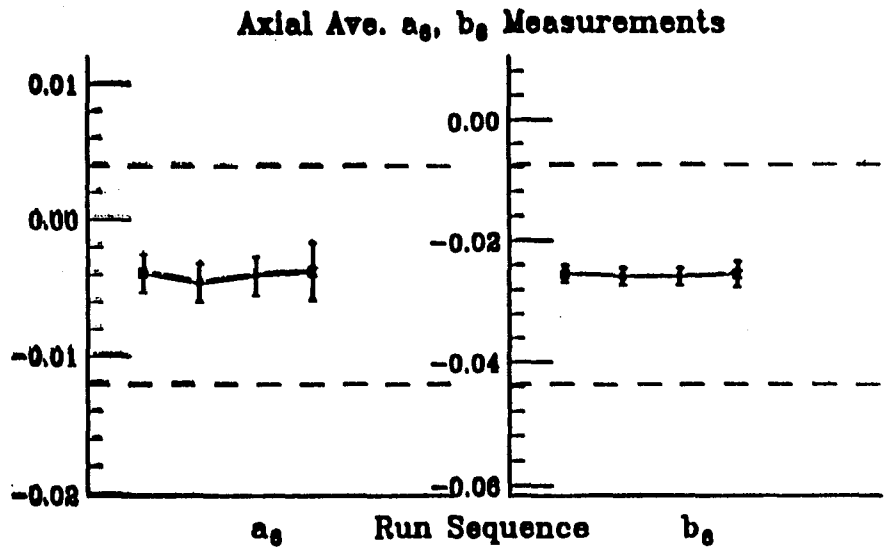
□ DCA312 901 930223 warm 10.A
+ DCA312 903 930224 warm 10.A

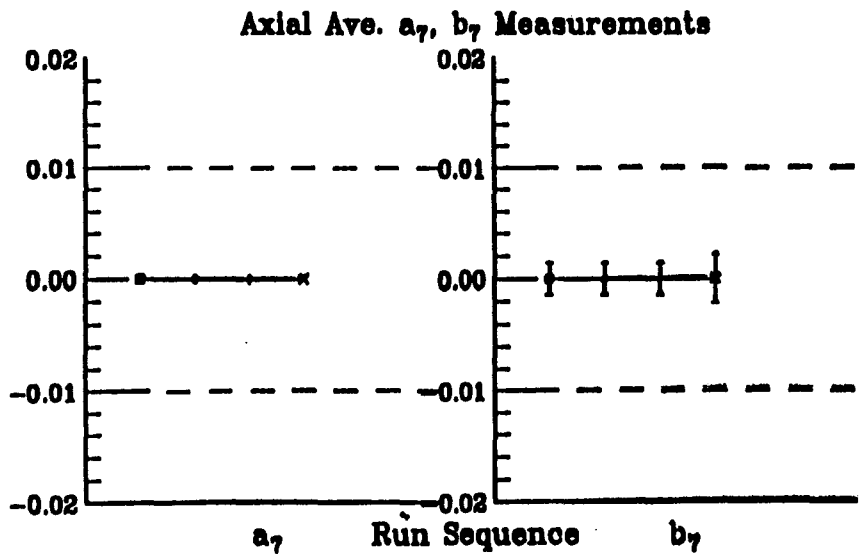
◇ DCA312 902 930224 warm 10.A
× DCA312 904 930224 warm 10.A

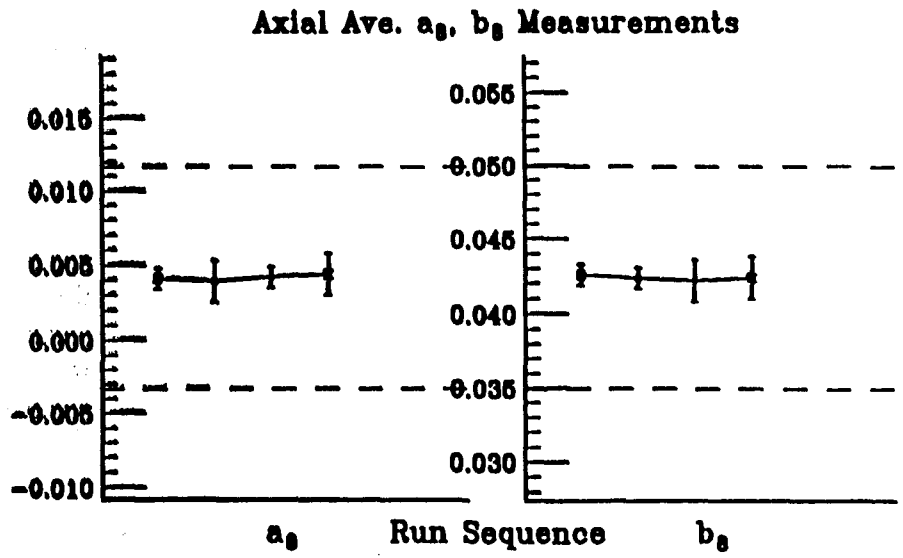
1-MAR-93 06:53:36

DCA312 Ave. a_n, b_n Z-scan Summary







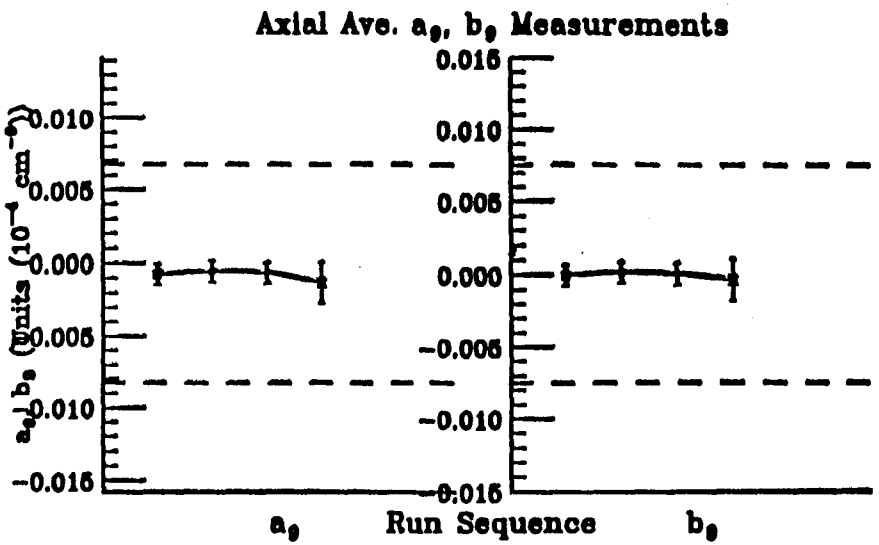


□ DCA312 901 930223 warm 10.A
+ DCA312 903 930224 warm 10.A

◇ DCA312 902 930224 warm 10.A
× DCA312 904 930224 warm 10.A

1-MAR-93 06:53:36

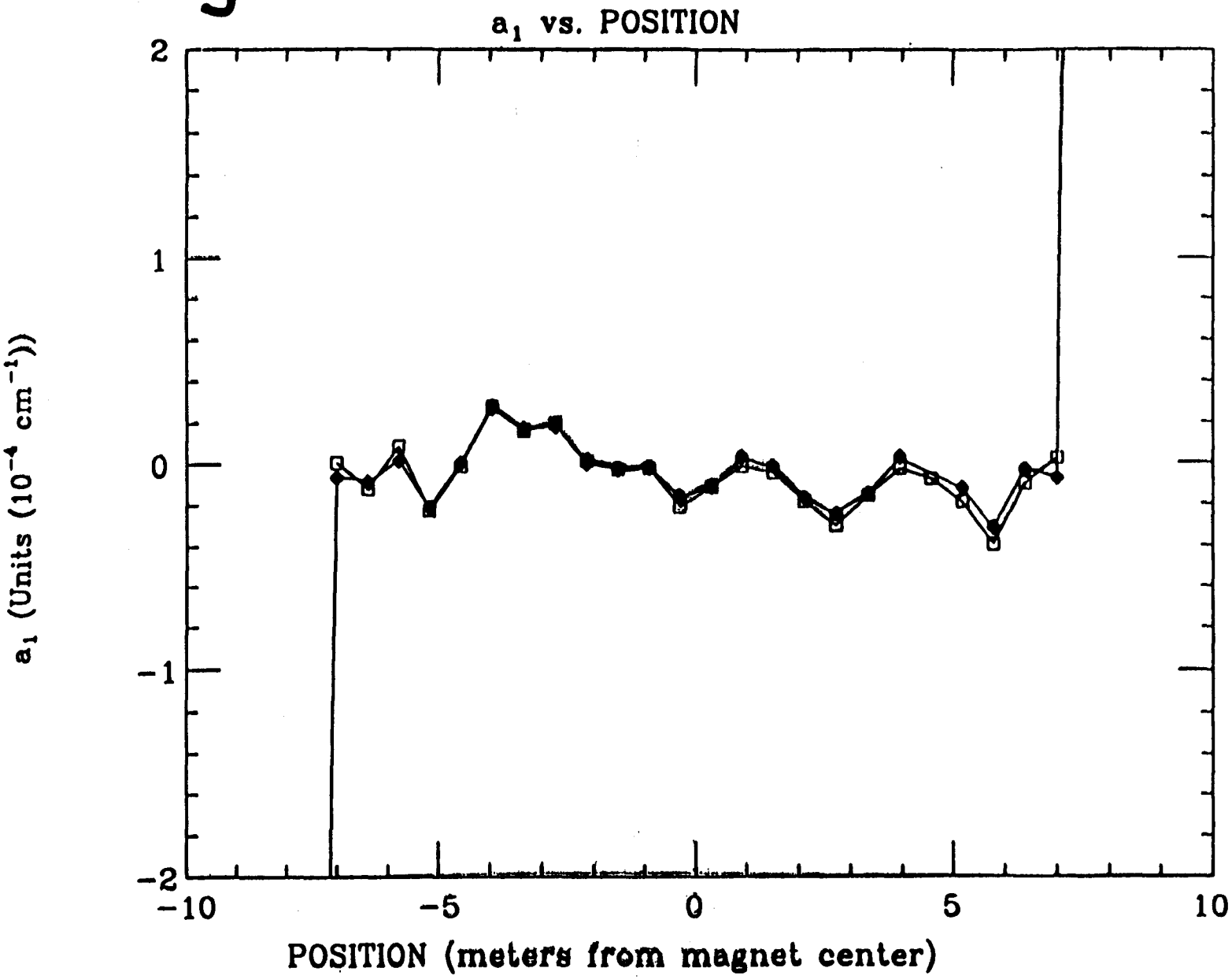
DCA312 Ave. a_n, b_n Z-scan Summary



□ DCA312 901	930223 warm	10.A	◆ DCA312 902	930224 warm	10.A
+ DCA312 903	930224 warm	10.A	× DCA312 904	930224 warm	10.A

FINAL Magnet DCA315

22-APR-92 14 :05



◇ DCA315 519 17 Feb 1992 cold data 1994. Amps Cold z-scan TC2, 16/18/It corr.
□ DCA315 15 11 Feb 1992 cold data 1994. Amps cold z-scan - 16/18/It corr.

	b0	b1	b2	b3	b4	b5
FA1	-0.390	-610.0	-17.57	-11.880	1.933	5.357
FA2	-0.390	-606.2	-17.68	-11.930	1.992	5.517
FA3	-0.391	-607.4	-17.90	-11.920	2.005	5.682
FA4	-0.388	-608.2	-17.45	-11.860	1.994	5.405
FA5	-0.372	-601.2	-17.11	-11.900	2.047	5.593
FE1	-0.395	-610.8	-18.77	-12.280	2.138	5.824
FE3	-0.395	-608.3	-18.87	-12.310	1.986	5.848
FE5	-0.387	-607.5	-18.75	-12.790	1.869	5.744
calculated multipole	-0.396	-604.6	-17.95	-11.930	2.148	5.585
measurement mean	-0.388	-607.4	-17.96	-12.085	1.995	5.609
std dev/|mean|	0.019	0.0048	0.038	0.027	0.039	0.033
|mean-calc|/calc	0.020	0.0046	0.001	0.013	0.071	0.004
	a0	a1	a2	a3	a4	a5
FA1	-9209.9	-286.4	33.37	-9.38	13.22	0.061
FA2	-9207.3	-287.2	33.71	-9.37	13.45	0.090
FA3	-9204.3	-285.2	33.96	-9.35	13.67	0.224
FA4	-9214.9	-289.4	33.49	-9.35	13.29	0.039
FA5	-9280.6	-294.4	34.31	-8.98	13.41	-0.046
FE1	-9187.0	-287.0	34.72	-9.52	14.00	0.118
FE3	-9188.9	-281.6	34.80	-9.44	14.02	0.183
FE5	-9222.9	-291.6	35.65	-9.26	13.92	0.183
calculated multipole	-9182.7	-282.6	33.33	-9.69	13.42	0.024
measurement mean	-9214.5	-287.9	34.25	-9.33	13.62	0.107
std dev/|mean|	0.0035	0.019	0.028	-0.037	0.015	3.438
|mean-calc|/calc	0.0032	0.014	0.023	0.017	0.024	0.838

multipole component. The deviation of a multipole component for a given magnet from the ensemble average is called a random error.

3.2.1.3.1 RMS Width of Multipole Distribution

Upper limits on the RMS widths of the multipole distributions shall meet the specifications in Table 3.2.1.3–I. These requirements shall be met at all times throughout the operating cycle defined in Section 3.1.4.1.

TABLE 3.2.1.3–I. MULTIPOLE RMS DISTRIBUTION LIMITS FOR MAGNET CONFIGURATION TYPES.

MULTIPOLE	CONFIGURATION ITEM	
	CDM 15m, CDM 13m (σ spec)*	CQM (σ spec)*
a_1	1.25	
b_1	0.50	
a_2	0.35	2.47
b_2	1.15	2.47
a_3	0.32	1.42
b_3	0.16	1.42
a_4	0.05	0.49
b_4	0.22	0.49
a_5	0.05	0.56
b_5	0.017	0.28
a_6	0.008	0.11
b_6	0.018	0.11
a_7	0.01	0.12
b_7	0.01	0.12
a_8	0.0075	0.14
b_8	0.0075	0.14
$> a_9, b_9$	0.0075	0.16

*Units for a_n or b_n are defined as $10^{-4}.cm^{-n}$.

The ensemble of magnets of each configuration type in the collider rings shall meet th applicable specifications above at all times/places throughout the magnetic cycle. In particular, shall meet this specification throughout the one hour long injection period. These specification are based on the integral field of the magnet inclusive of ends and interconnect regions.

$$V_N = L \omega r B_0 \gamma_n \left(\frac{z}{r_0}\right)^n n_T \sin\left(\frac{n\Delta}{2}\right)$$

$L =$ coil length $\simeq 1\,m$

$\omega \simeq \frac{2\pi}{3\,sec}$

$\gamma_n \rightarrow 1$ unit

$B_0 \rightarrow 1\,T$

$$\boxed{L \omega r B_0 \gamma_n \simeq 8\,\mu V}$$

$\Rightarrow$ use $n_T = 30$, $\Delta = 15°$ to get a $1\,mV$ signals

$$\boxed{V_n(\lambda z) = \lambda^n V_n(z)}$$

<u>Throw away signal rapidly for large n</u>

RMS multipole 1 sigma values, corresponding peak voltages, and noise floor

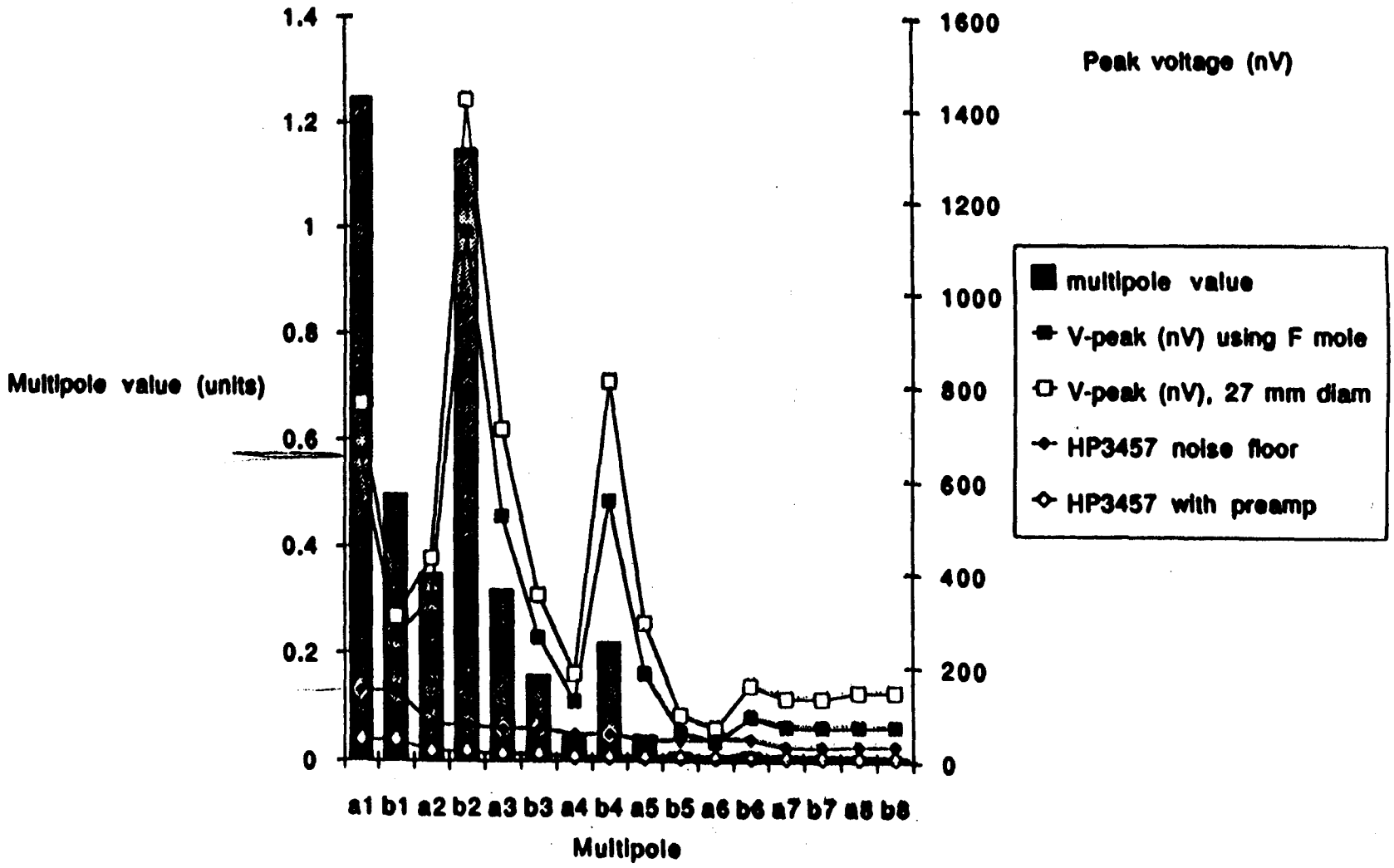
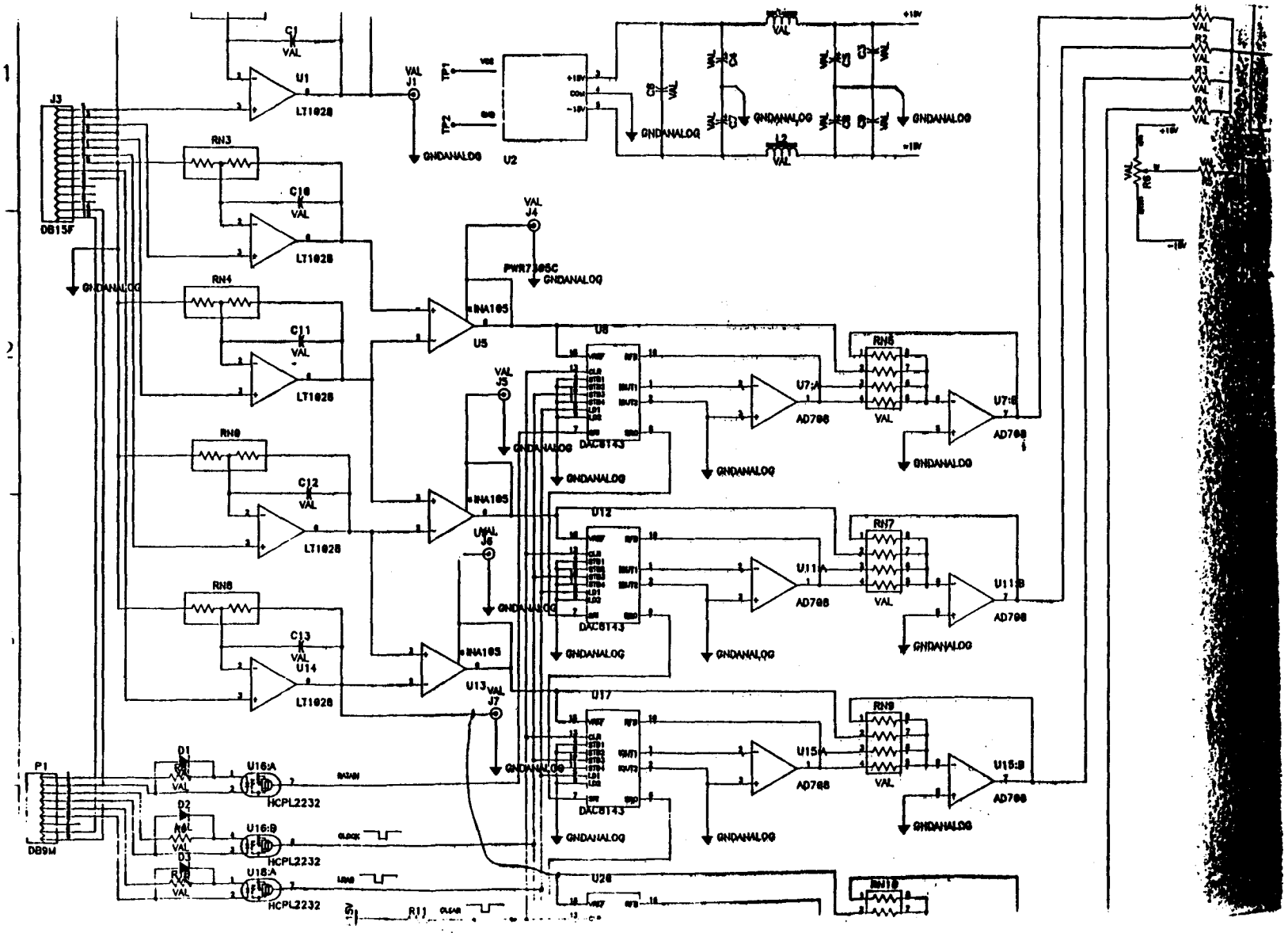
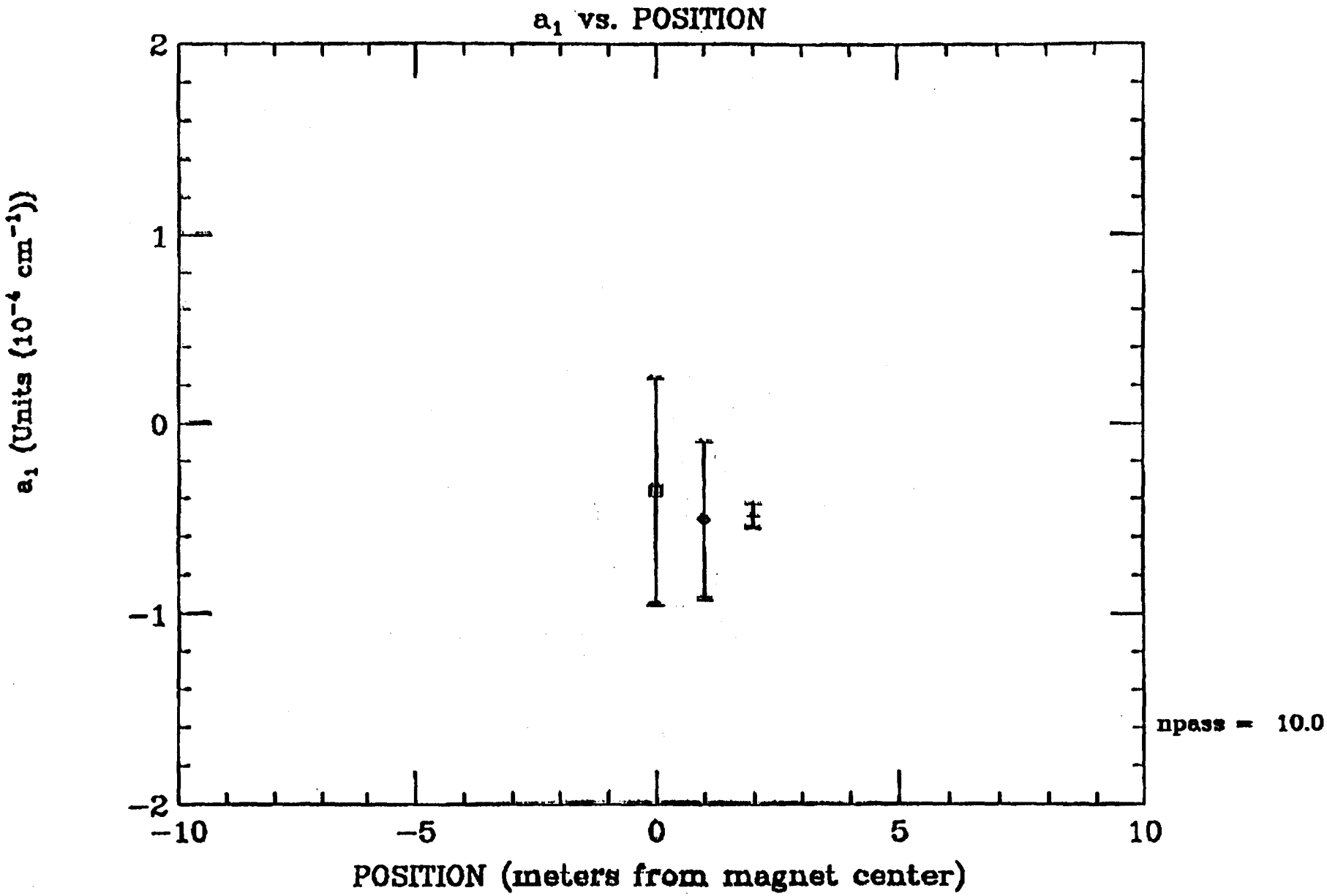


figure 1

From S Sharanov

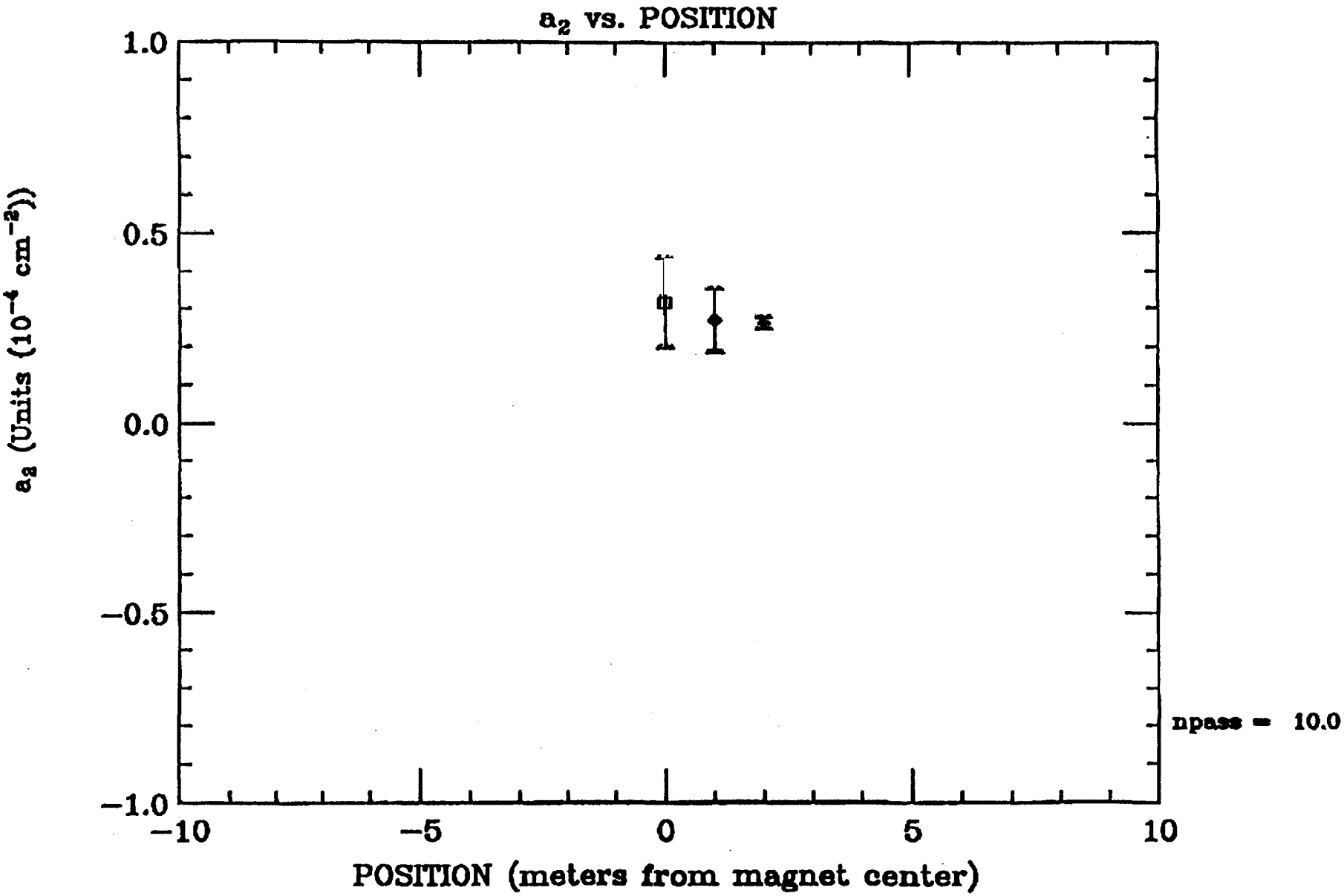


29-APR-92 15:37:22



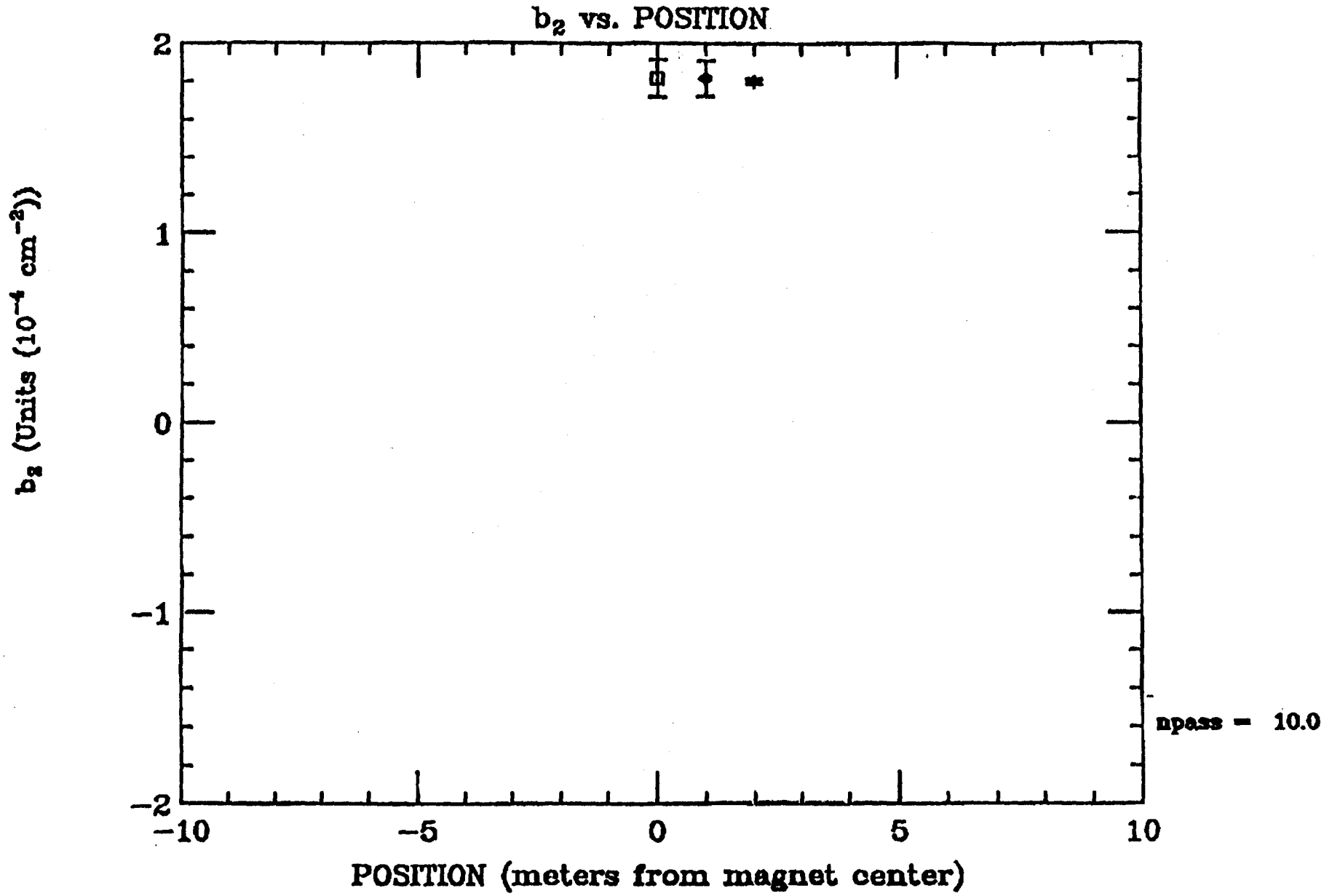
+ DSA329	2	29 Apr 1992 warm data	10. Amps	modified software, w/ amp., 16/18/lt corr.
◇ DSA329	1	29 Apr 1992 warm data	10. Amps	modified software, no amp., 16/18/lt corr.
□ DSA329	0	29 Apr 1992 warm data	10. Amps	standard software, no amp., 16/18/lt corr.

29-APR-92 15:37:23



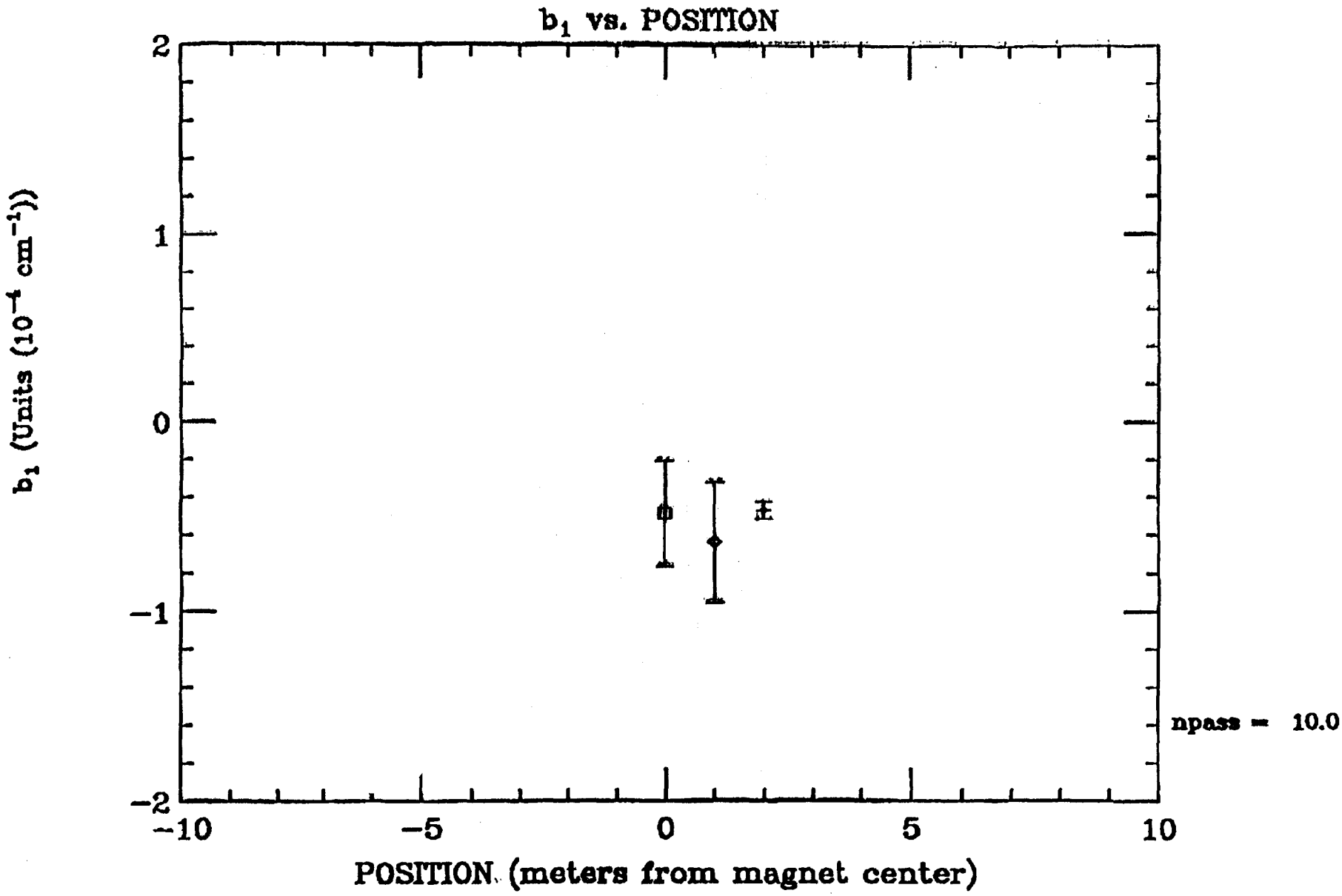
+ DSA329	2	29 Apr 1992 warm data	10. Amps	modified software, w/ amp., 16/18/It corr.
◇ DSA329	1	29 Apr 1992 warm data	10. Amps	modified software, no amp., 16/18/It corr.
□ DSA329	0	29 Apr 1992 warm data	10. Amps	standard software, no amp., 16/18/It corr.

29-APR-92 16:37:23



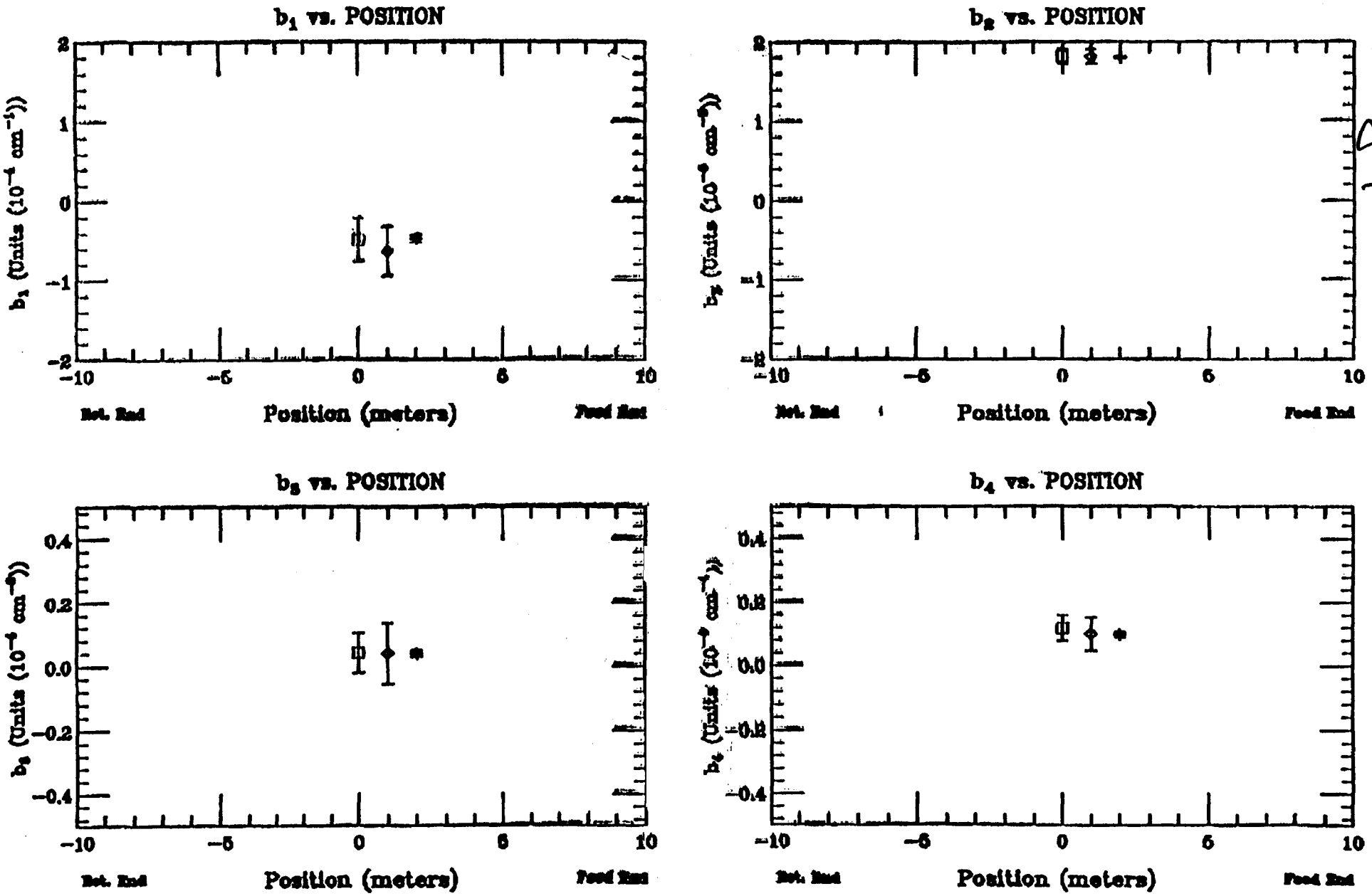
+ DSA329	2	29 Apr 1992 warm data	10. Amps	modified software, w/ amp., 16/18/lt corr.
◇ DSA329	1	29 Apr 1992 warm data	10. Amps	modified software, no amp., 16/18/lt corr.
□ DSA329	0	29 Apr 1992 warm data	10. Amps	standard software, no amp., 16/18/lt corr.

29-APR-92 15:37:23



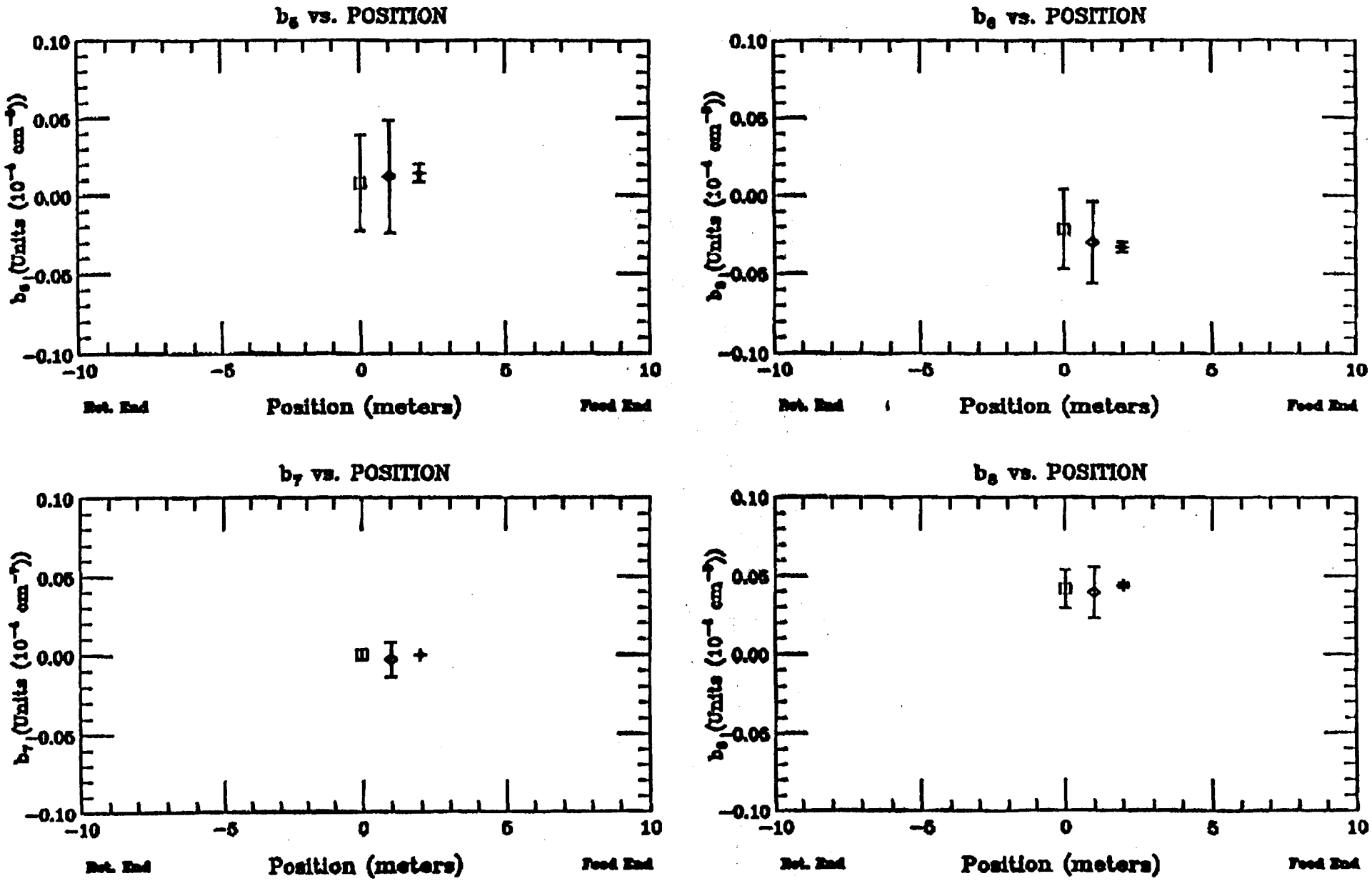
+ DSA329	2	29 Apr 1992 warm data	10. Amps	modified software, w/ amp., 16/18/It corr.
◇ DSA329	1	29 Apr 1992 warm data	10. Amps	modified software, no amp., 16/18/It corr.
□ DSA329	0	29 Apr 1992 warm data	10. Amps	standard software, no amp., 16/18/It corr.

b_n vs Position for magnet DSA329 – files 0, 1, 2



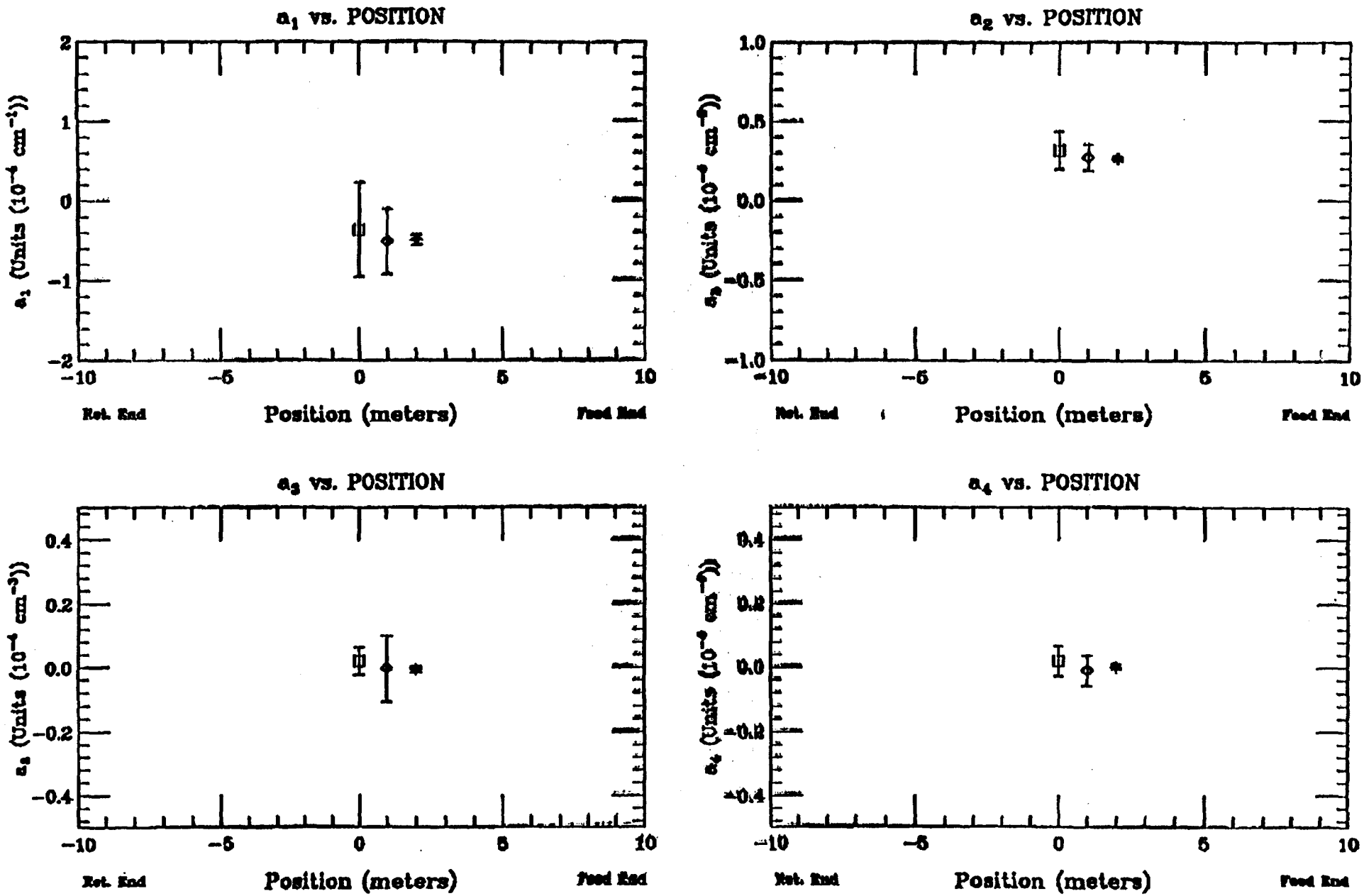
Warm measurement, 16/18/It. corrected

b_n vs Position for magnet DSA329 – files 0, 1, 2



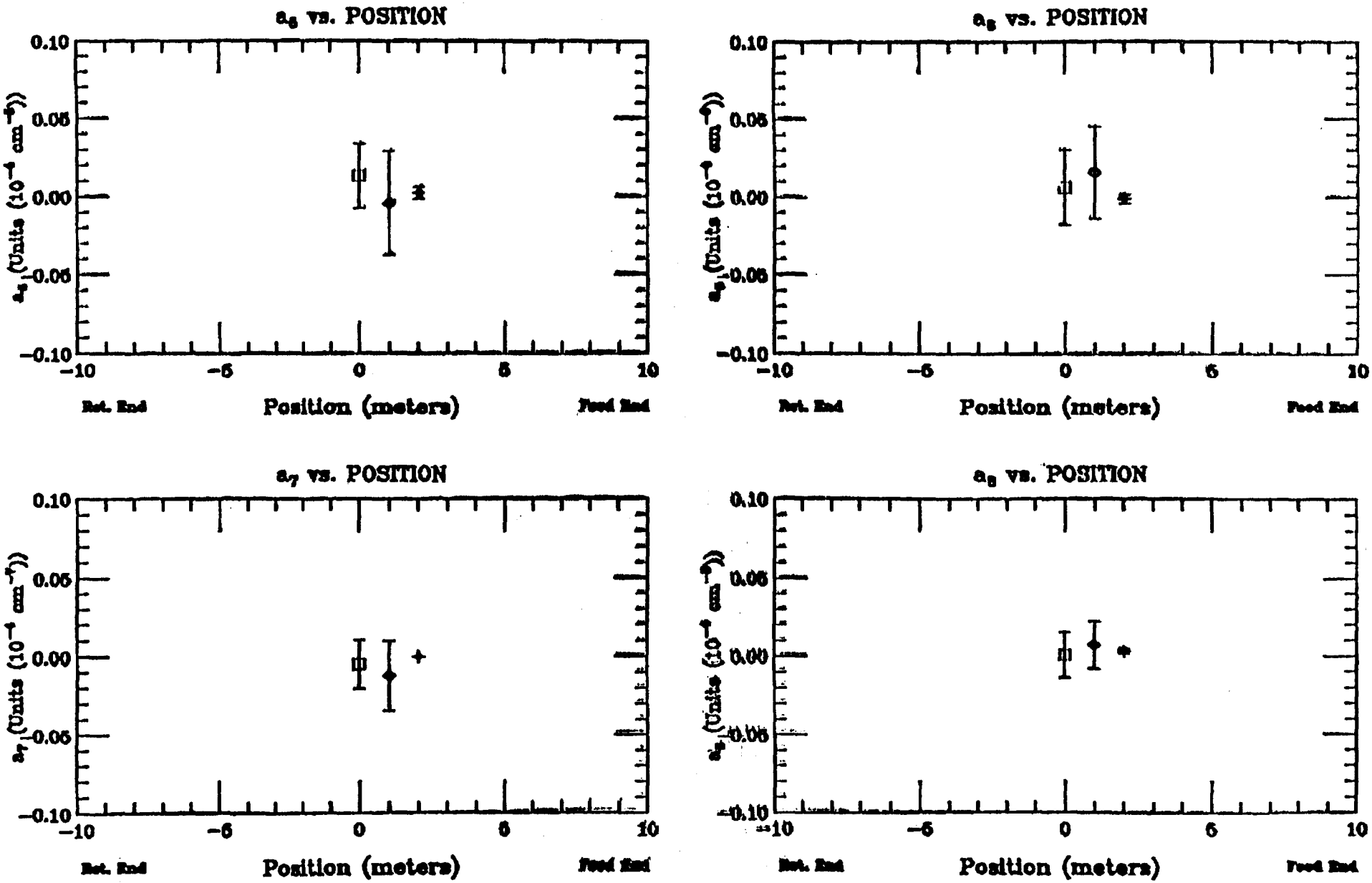
Warm measurement, 16/18/It. corrected

a_n vs Position for magnet DSA329 – files 0, 1, 2



Warm measurement, 16/18/lt. corrected

a_n vs Position for magnet DSA329 – files 0, 1, 2



Warm measurement, 16/18/It. corrected

Estimated multipole error per point

multipole	Uncertainty (units)	% of std. dev.	Uncert(units) w preamp	% of std. dev.
a1	0.286	40	0.0858	12
b1	0.286	99	0.0858	30
a2	0.079	39	0.0213	11
b2	0.079	12	0.0213	3
a3	0.043	23	0.0098	5
b3	0.043	46	0.0098	11
a4	0.023	81	0.0040	14
b4	0.023	18	0.0040	3
a5	0.012	42	0.0024	8
b5	0.012	105	0.0024	21
a6	0.009	156	0.0019	33
b6	0.009	78	0.0019	16
a7	0.004	75	0.0011	19
b7	0.004	75	0.0011	19
a8	0.004	81	0.0008	19
b8	0.004	81	0.0008	19

	A	B	C	D	E	F	G	H	I
1	WARM MEASUREMENTS, DSA329 (+/-10 Amper)								
2		Without Amplifier				With Amplifier			Improvment
3		an	sd			an	sd		
4	"Quadrupole 1	-0.3612	0.5945			-0.493	0.0642		9
5	2	0.3166	0.1186			0.2614	0.0149		8
6	3	0.0209	0.0433			-0.007	0.0098		4
7	4	0.0203	0.0471			0.0012	0.0079		6
8	5	0.0135	0.0206			0.0027	0.0038		5
9	6	0.0062	0.0237			-0.0009	0.0028		8
10	7	-0.0051	0.0155			0	0		
11	8	0.0007	0.0145			0.0032	0.0016		9
12	9	0.0043	0.0177			0.0015	0.0016		11
13	10	0.0022	0.007			0.0022	0.0013		5
14	11	-0.003	0.0085			-0.0001	0.0013		7
15									
16									
17		bn	sd			bn	sd		
18	"Quadrupole"1	-0.4839	0.2792			-0.4679	0.0462		6
19	2	1.8165	0.098			1.8001	0.0123		8
20	3	0.0426	0.0626			0.0395	0.0111		6
21	4	0.1178	0.0414			0.0981	0.0092		5
22	5	0.008	0.0307			0.0146	0.006		5
23	6	-0.0214	0.0253			-0.033	0.0032		8
24	7	0.0003	0.0032			0	0		
25	8	0.0417	0.0123			0.0441	0.0016		8
26	9	-0.0012	0.0161			-0.0007	0.0019		8
27	10	0.0222	0.0139			0.0174	0.0009		15
28	11	-0.0039	0.0076			-0.0005	0.0013		6

Fe2 means and stds

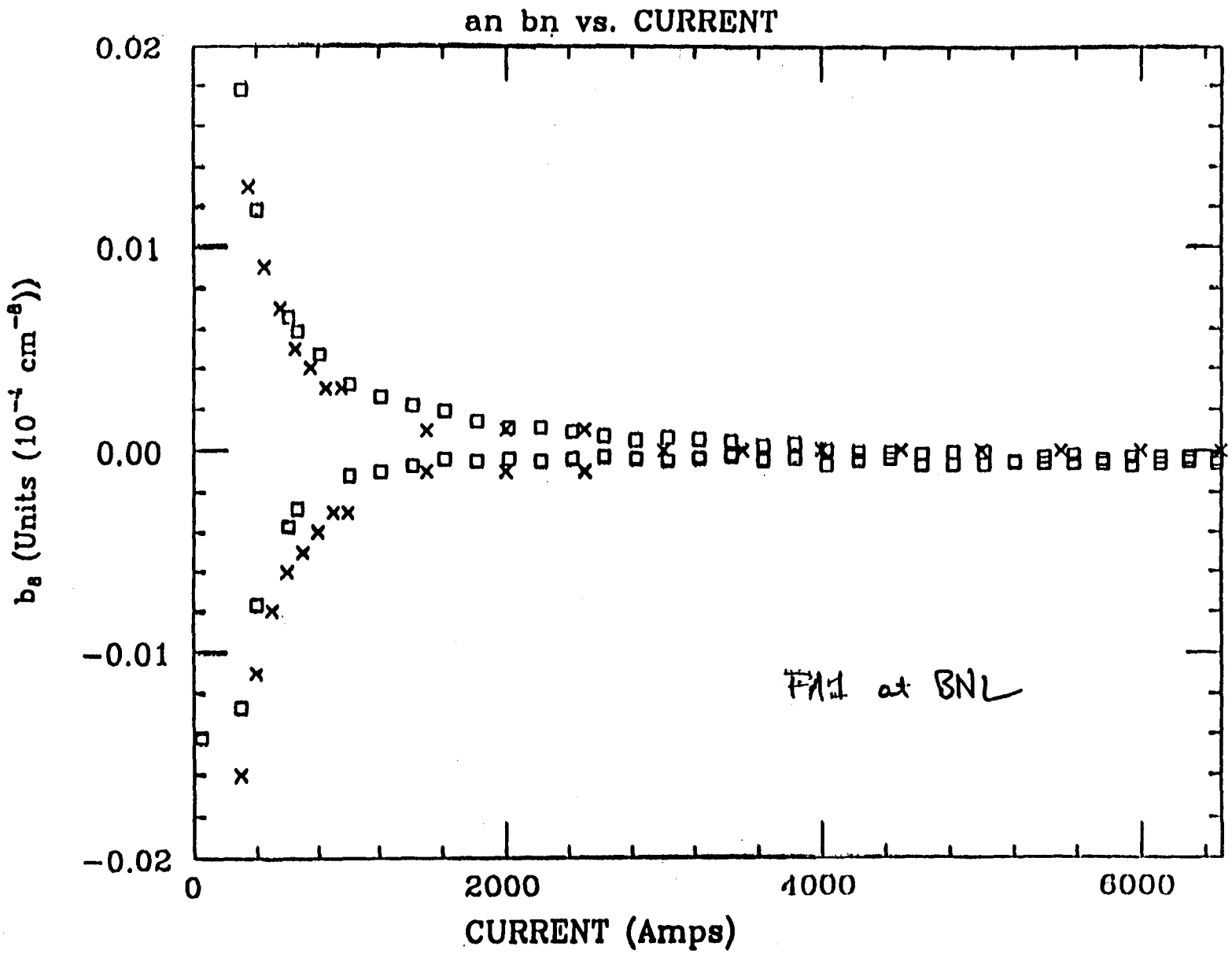
Multipole	max meas sigma	allowed mag std	allowed/max meas
b1	0.0232	0.5	22
b2	0.0177	1.15	65
b3	0.0033	0.16	49
b4	0.0047	0.22	47
b5	0.0015	0.017	11
b6	0.0017	0.018	10
b7	0.0011	0.01	9
b8	0.0008	0.0075	10
b9	0.0010	0.0075	7
a1	0.0202	0.5	25
a2	0.0165	1.15	70
a3	0.0056	0.16	29
a4	0.0035	0.22	63
a5	0.0024	0.017	7
a6	0.0013	0.018	14
a7	0.0011	0.01	9
a8	0.0011	0.0075	7
a9	0.0007	0.0075	10

II. Statistical study of random uncertainty

review of standard deviations in the measurements of
- DCA312
- DSH701
- DSD101

mole and 25 cm coil comparisons
- DCA312
- DSH701

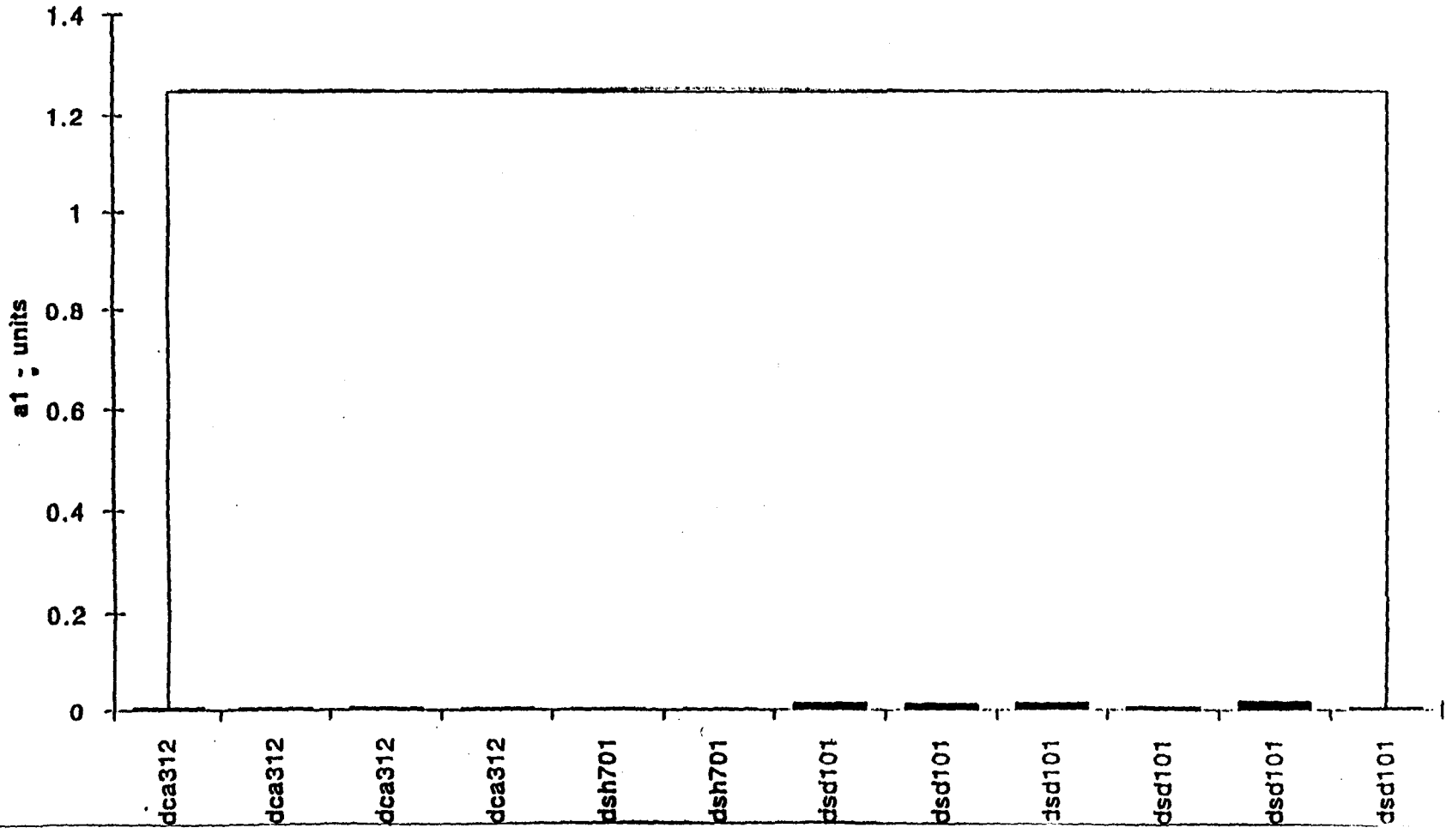
quadrupole standard deviations
- QSE101
- QSE102

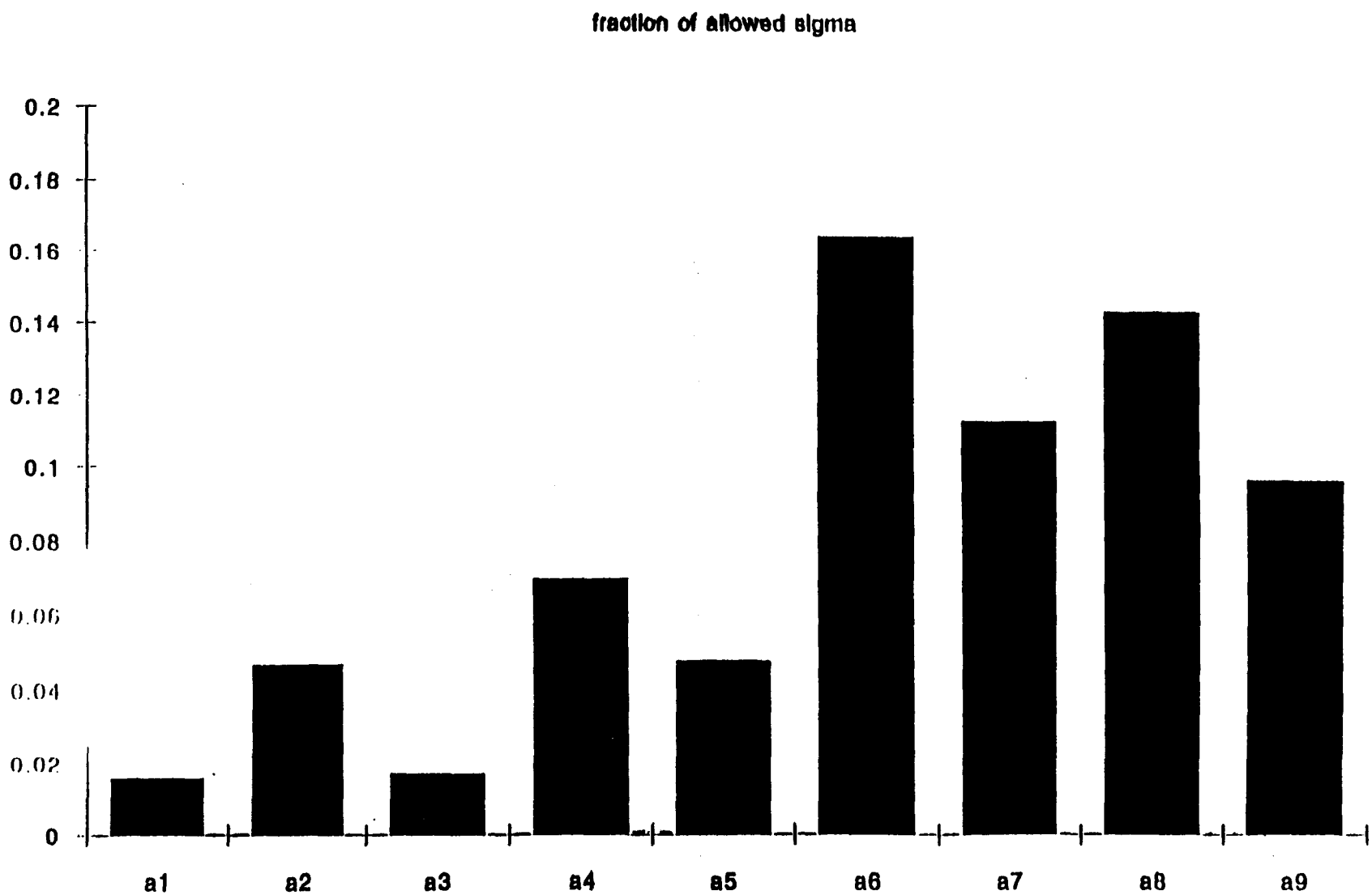


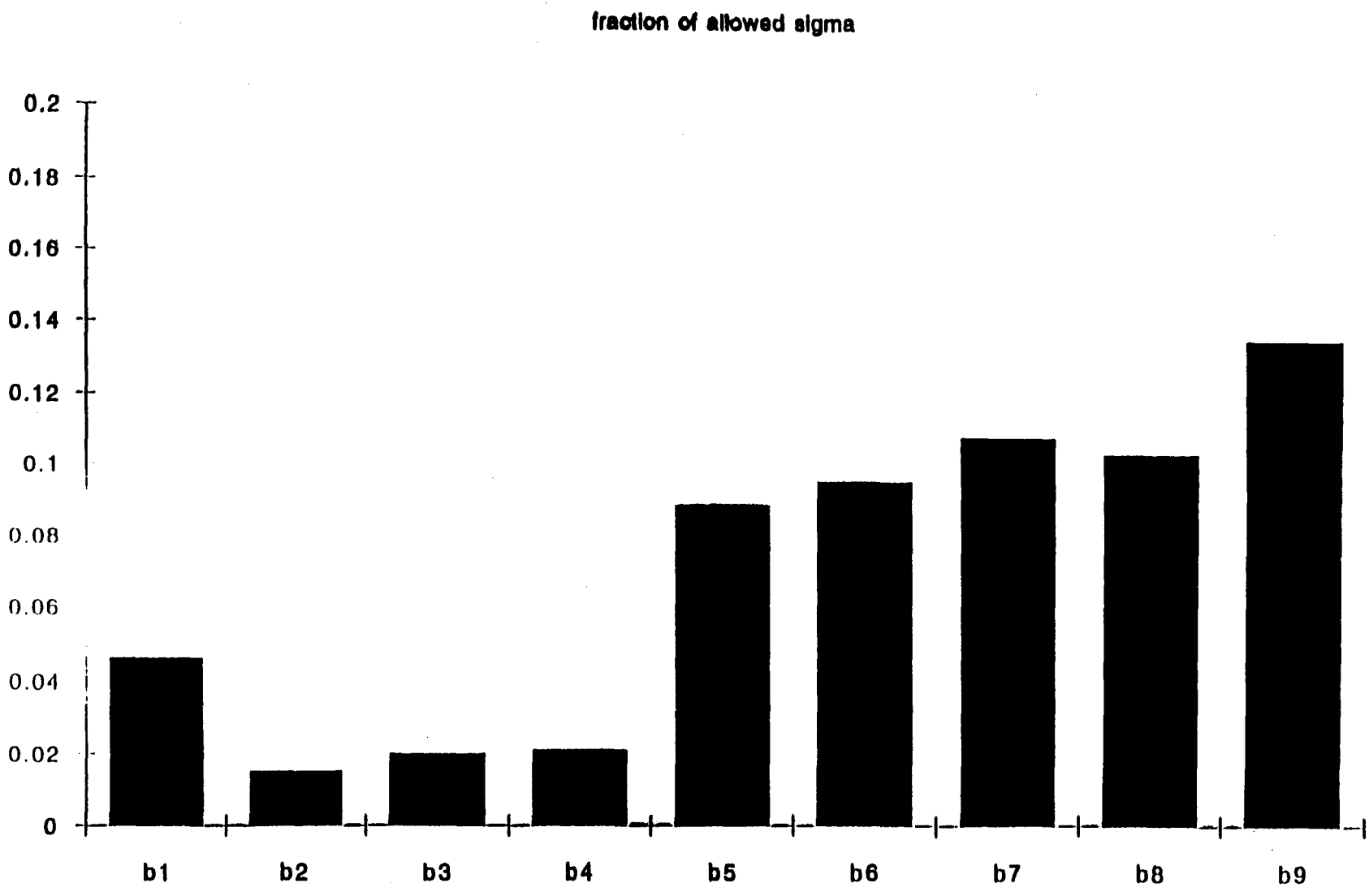
DCA210 131 20 Mar 92 cold position (M) : −0.498000
Jc(IU)=2991 A/mm² Jc(IL)=2961 A/mm²
Jc(OU)=2851 A/mm² Jc(OL)=2878 A/mm²

× Theoretical model
□ Measurement results

a1 - standard deviation of the mean of 10 measurements and sigma s

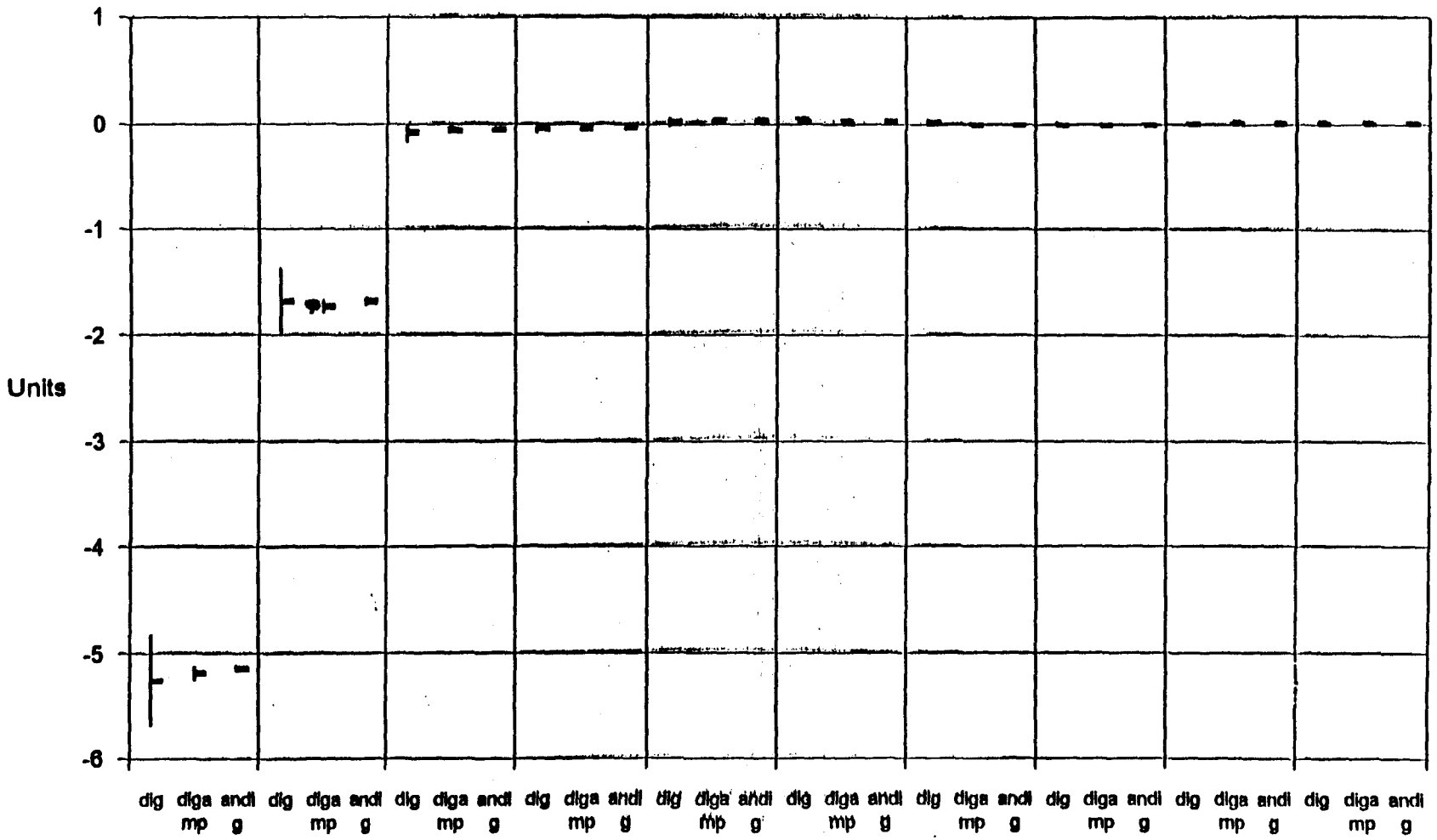



fraction of allowed sigma
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
a1
a2
a3
a4
a5
a6
a7
a8
a9


fraction of allowed sigma
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
b1
b2
b3
b4
b5
b6
b7
b8
b9

From Sergey Sharamov

SLAC Dipole, 50 Gaus Residual Field, Normal Components



quadrupole data qse101 102

multipole	max field	max field/a	allowed field
b1			
b2	0.0213	2.47	116
b3	0.0047	1.42	302
b4	0.0038	0.49	130
b5	0.0075	0.28	37
b6	0.0010	0.11	107
b7	0.0010	0.12	116
b8	0.0010	0.14	137
b9	0.0007	0.16	239
a1			
a2	0.0223	2.47	111
a3	0.0052	1.42	272
a4	0.0031	0.49	156
a5	0.0064	0.56	88
a6	0.0014	0.11	78
a7	0.0010	0.12	118
a8	0.0009	0.14	158
a9	0.0004	0.16	367

QSH803 Ave. Harmonic Magnitude Summary

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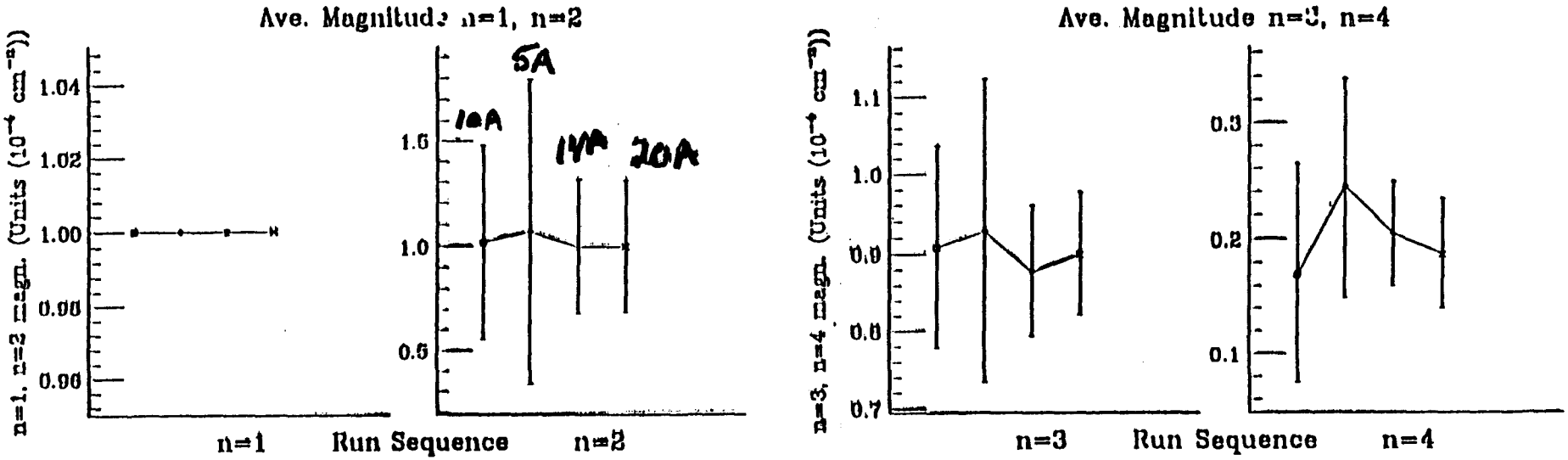
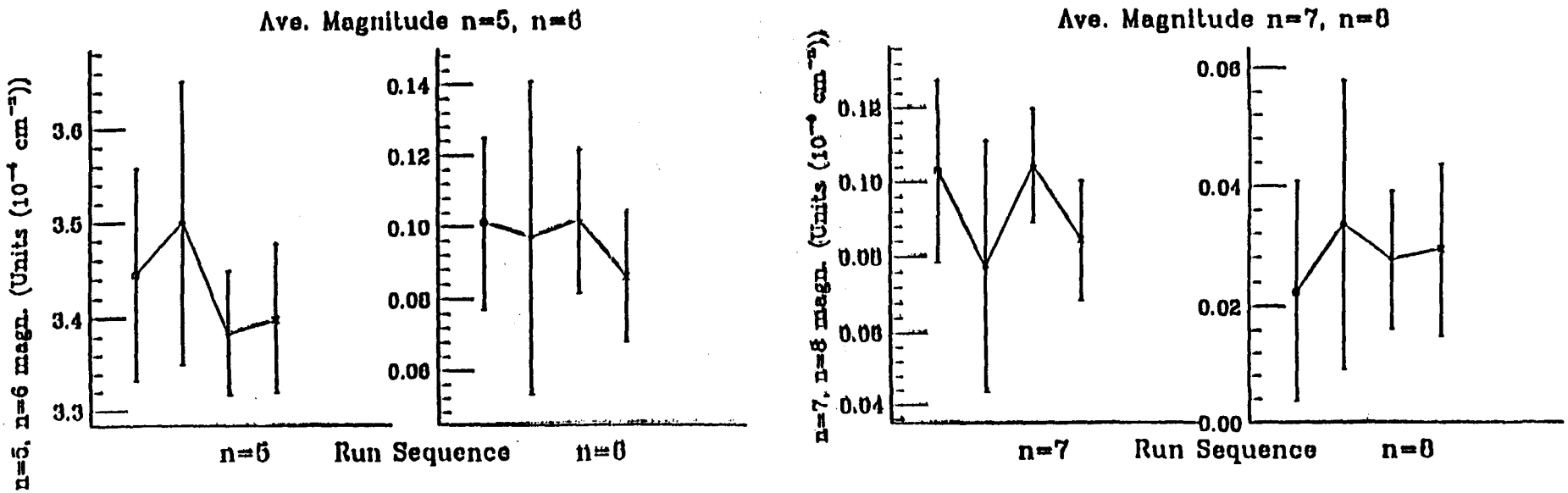




□ QSH803 30 930108 warm 10.A
+ QSH803 34 930108 warm 14.A

◇ QSH803 32 930108 warm 5.A
× QSH803 36 930108 warm 20.A

MOLBAY brass WBT

+.11m pos (Same as MEDL)

Average and Ave S. dev./√nmeas for Axial a_n and b_n

Magnet QSH803 file: 048 (Warm data) Cur. : 10.00 Nmeas. = 3 Npass = 9

n	1	2	3	4	5	6	7	8	9	10	11
an	0.000	−1.056	0.756	−0.046	0.341	0.012	0.062	0.002	0.008	0.000	0.000
STD	0.000	0.127	0.042	0.026	0.037	0.000	0.009	0.006	0.004	0.000	0.000
bn	1.000	0.298	0.197	0.279	−0.285	−0.030	0.008	0.003	−0.103	0.000	0.000
STD	0.000	0.180	0.062	0.027	0.088	0.00[illegible]	0.009	0.006	0.004	0.000	0.000

Summary of Axial Scans Average a_n and b_n

Magnet QSH803 file: 042 (Warm data) Cur. = 10.00 Pos. : 0.25 Npass = 10

n	1	2	3	4	5	6	7	8	9	10	11
an	0.000	−1.934	0.808	−0.114	0.098	−0.020	0.070	−0.017	−0.017	0.000	0.000
STD	0.000	0.170	0.063	0.052	0.074	0.019	0.016	0.013	0.008	0.000	0.000
bn	1.000	−0.962	0.264	0.096	−3.850	−0.096	0.017	−0.004	−0.101	0.000	0.000
STD	0.000	0.279	0.103	0.051	0.066	0.017	0.021	0.010	0.007	0.000	0.000

Magnet QSH803 file: 042 (Warm data) Cur. = 10.00 Pos. : 0.00 Npass = 10

n	1	2	3	4	5	6	7	8	9	10	11
an	0.000	0.016	0.923	0.104	0.516	0.059	0.080	0.015	0.024	0.000	0.000
STD	0.000	0.245	0.087	0.036	0.052	0.015	0.015	0.009	0.007	0.000	0.000
bn	1.000	1.074	0.145	0.159	−3.356	−0.011	0.014	−0.001	−0.105	0.000	0.000
STD	0.000	0.312	0.125	0.039	0.061	0.015	0.015	0.012	0.007	0.000	0.000

Magnet QSH803 file: 042 (Warm data) Cur. = 10.00 Pos. : −0.25 Npass = 9

n	1	2	3	4	5	6	7	8	9	10	11
an	0.000	−1.255	0.544	−0.133	0.414	−0.002	0.026	0.006	0.015	0.000	0.000
STD	0.000	0.237	0.071	0.043	0.065	0.012	0.013	0.008	0.007	0.000	0.000
bn	1.000	0.782	0.162	0.561	−3.141	0.018	−0.006	0.013	−0.104	0.000	0.000
STD	0.000	0.345	0.093	0.050	0.058	0.017	0.011	0.012	0.007	0.000	0.000

Average and Ave S. dev./√nmeas for Axial a_n and b_n

Magnet QSH003 file: 041 (Warm data) Curr. : 10.07 Nmeas. = 3 Npass = 10

n	1	2	3	4	5	6	7	8	9	10	11
an	0.000	−1.057	0.776	−0.042	0.387	0.010	0.059	0.001	0.011	0.000	0.000
STD	0.000	0.091	0.024	0.017	0.017	0.005	0.006	0.005	0.002	0.000	0.000
bn	1.000	0.241	0.204	0.275	−8.859	−0.028	0.011	0.001	−0.104	0.000	0.000
STD	0.000	0.093	0.033	0.016	0.021	0.005	0.005	0.004	0.003	0.000	0.000

Summary of Axial Scans Average a_n and b_n

Magnet QSII003 file: 041 (Warm data) Cur. = 19.97 Pos. : 0.25 Npass = 10

n	1	2	3	4	5	6	7	8	9	10	11
an	0.000	−2.007	0.050	−0.094	0.094	−0.011	0.060	−0.023	−0.008	0.000	0.000
STD	0.000	0.236	0.067	0.045	0.045	0.015	0.014	0.014	0.005	0.000	0.000
bn	1.000	−1.168	0.303	0.068	−3.286	−0.092	0.026	−0.017	−0.099	0.000	0.000
STD	0.000	0.228	0.072	0.032	0.060	0.011	0.013	0.011	0.008	0.000	0.000

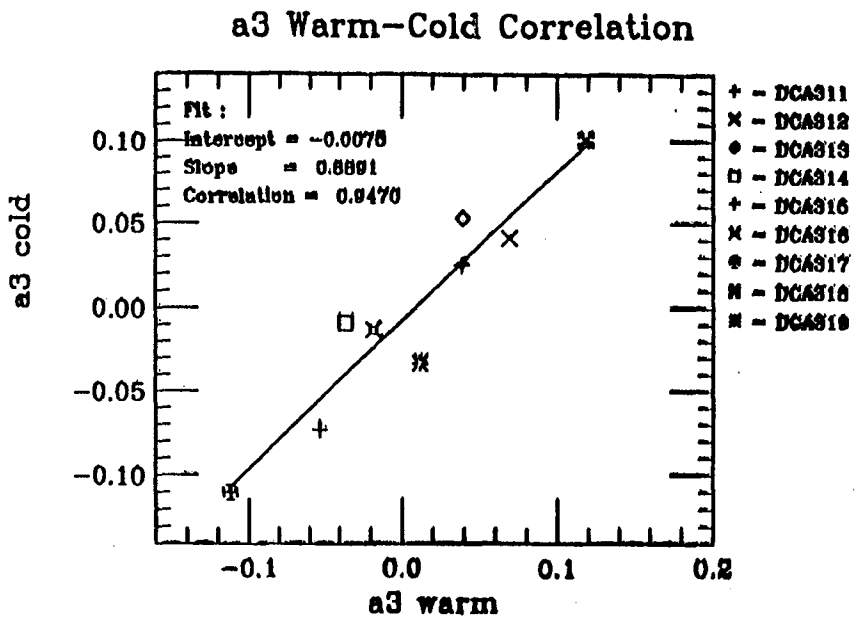
Magnet QSII003 file: 041 (Warm data) Cur. = 19.97 Pos. : 0.00 Npass = 10

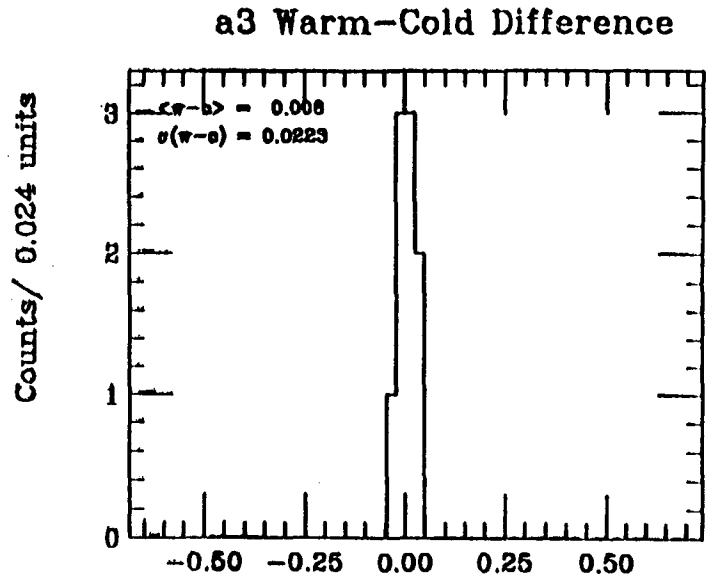
n	1	2	3	4	5	6	7	8	9	10	11
an	0.000	0.034	0.035	0.110	0.500	0.053	0.077	0.016	0.024	0.000	0.000
STD	0.000	0.118	0.037	0.023	0.023	0.007	0.009	0.008	0.004	0.000	0.000
bn	1.000	1.194	0.138	0.161	−3.335	−0.006	0.010	−0.004	−0.106	0.000	0.000
STD	0.000	0.157	0.065	0.031	0.026	0.010	0.008	0.005	0.005	0.000	0.000

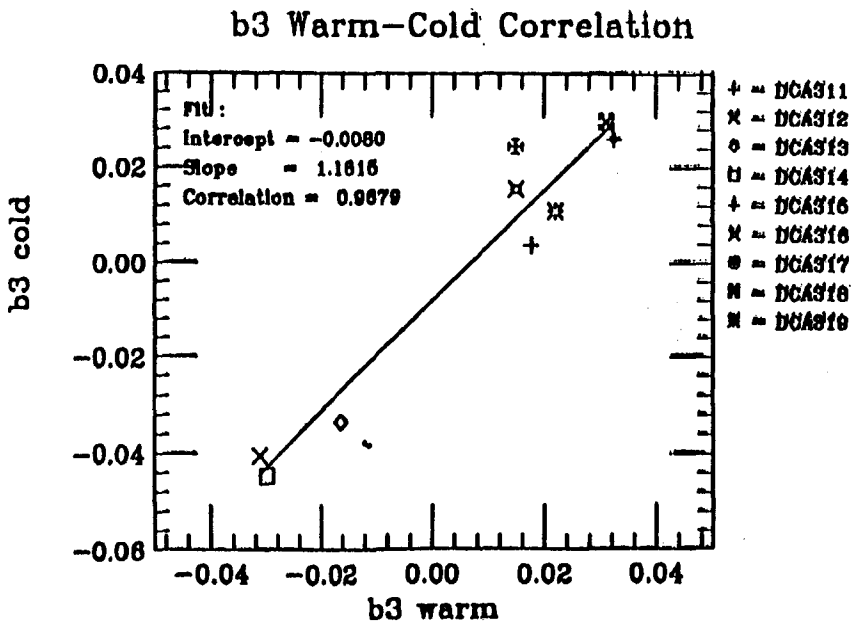
Magnet QSII003 file: 041 (Warm data) Cur. = 19.97 Pos. : −0.25 Npass = 10

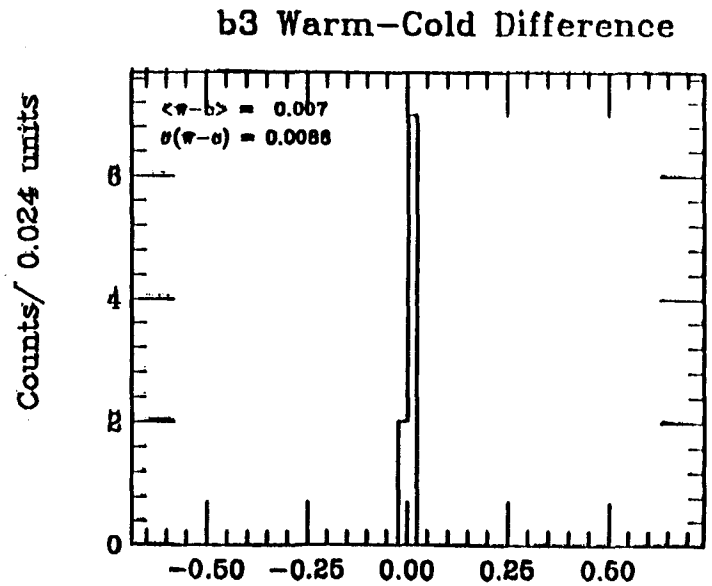
n	1	2	3	4	5	6	7	8	9	10	11
an	0.000	−1.199	0.548	−0.140	0.378	−0.013	0.030	0.007	0.018	0.000	0.000
STD	0.000	0.120	0.022	0.018	0.020	0.006	0.006	0.005	0.002	0.000	0.000
bn	1.000	0.698	0.171	0.576	−3.096	0.014	−0.003	0.023	−0.105	0.000	0.000
STD	0.001	0.096	0.033	0.019	0.021	0.006	0.004	0.005	0.003	0.000	0.000

Warm-Cold Correlations Warm data: asst_warm_before_mpole.dat Cold data: asst_cold_mpole.dat 09:01:44 16-FEB-93

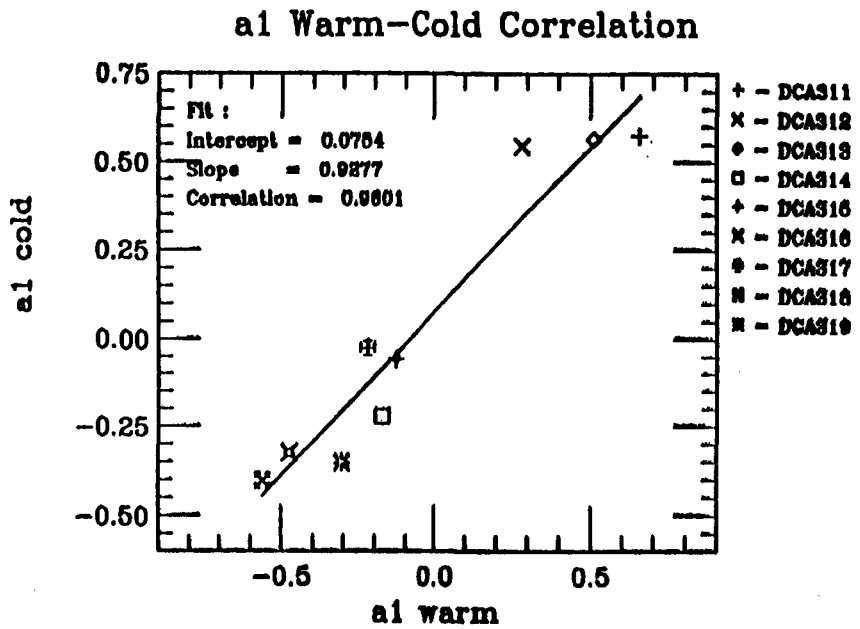


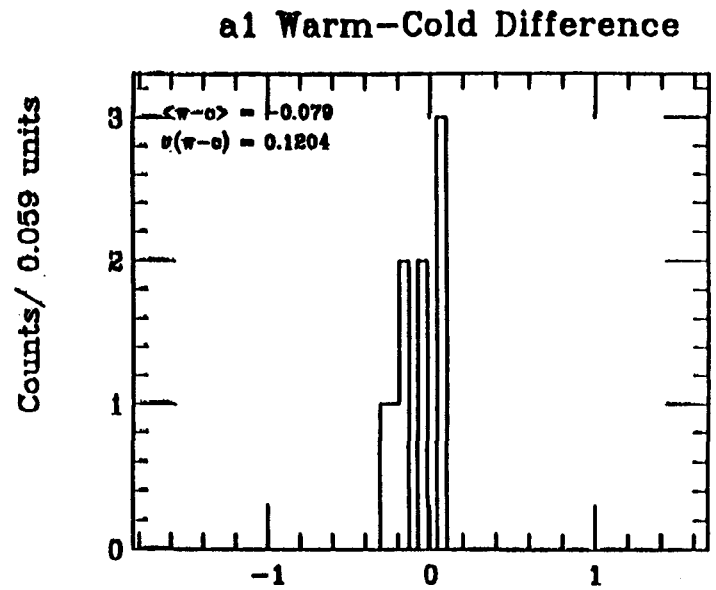


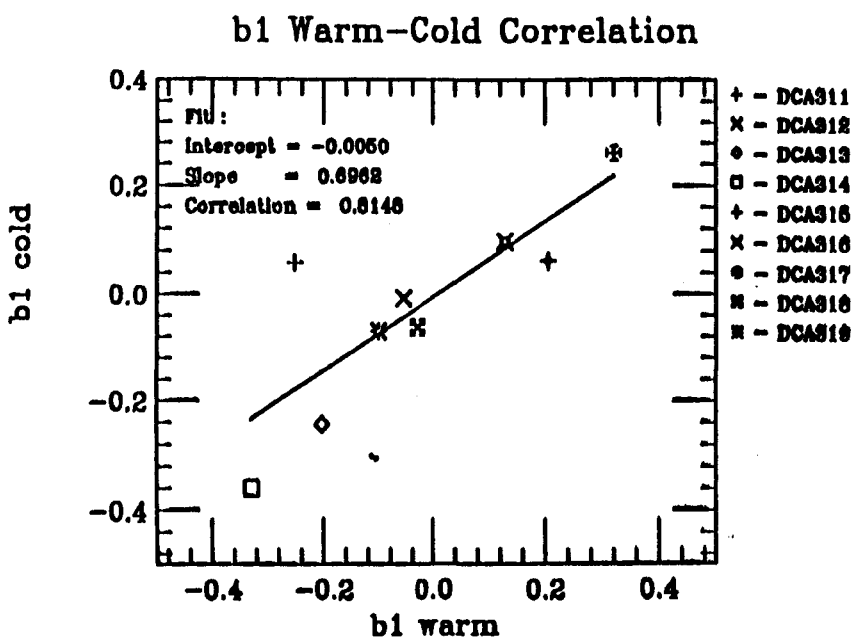


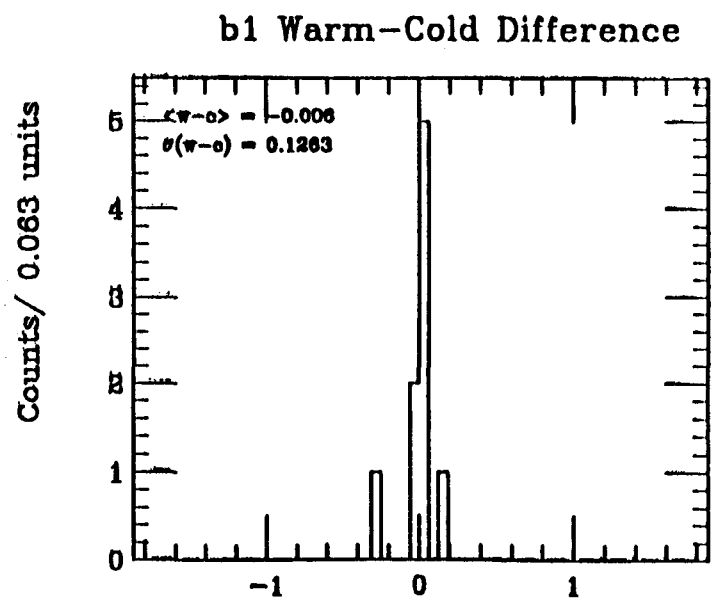


Warm-Cold Correlations Warm data: asst_warm_before_mpole.dat Cold data: asst_cold_mpole.dat 09:01:44 16-FEB-93

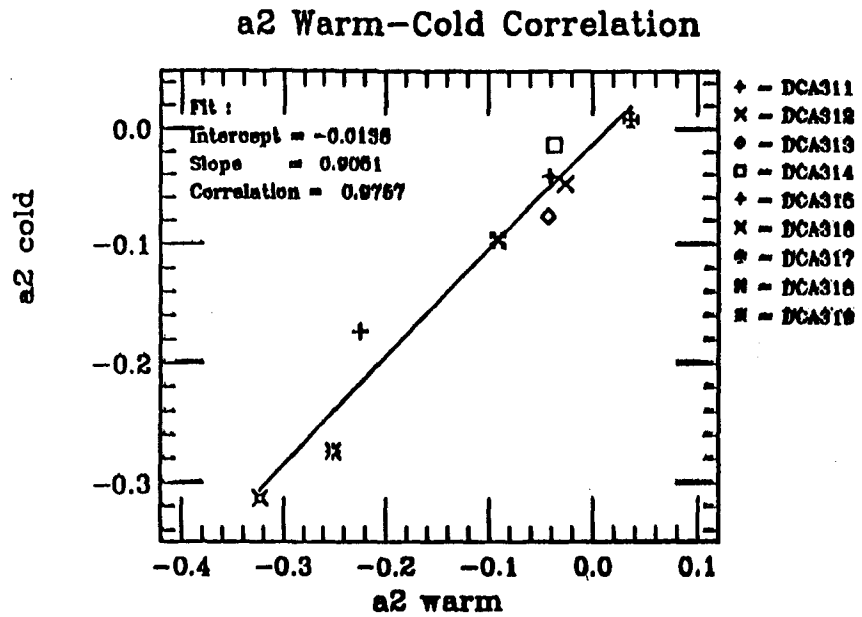


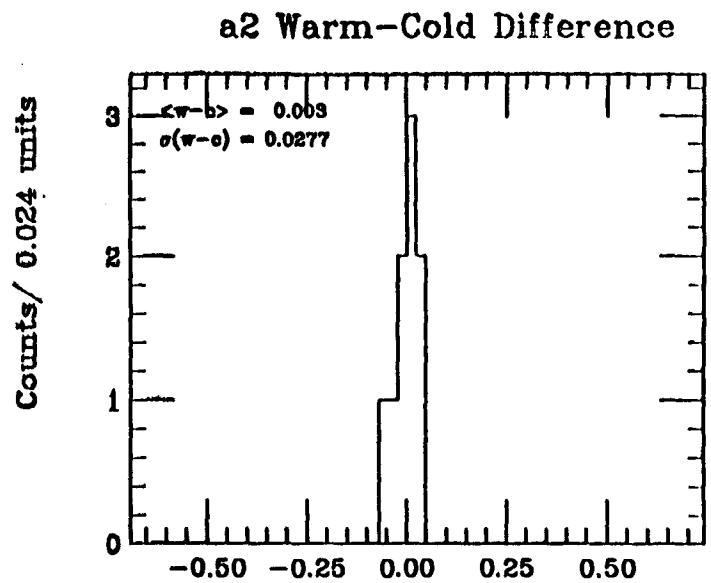


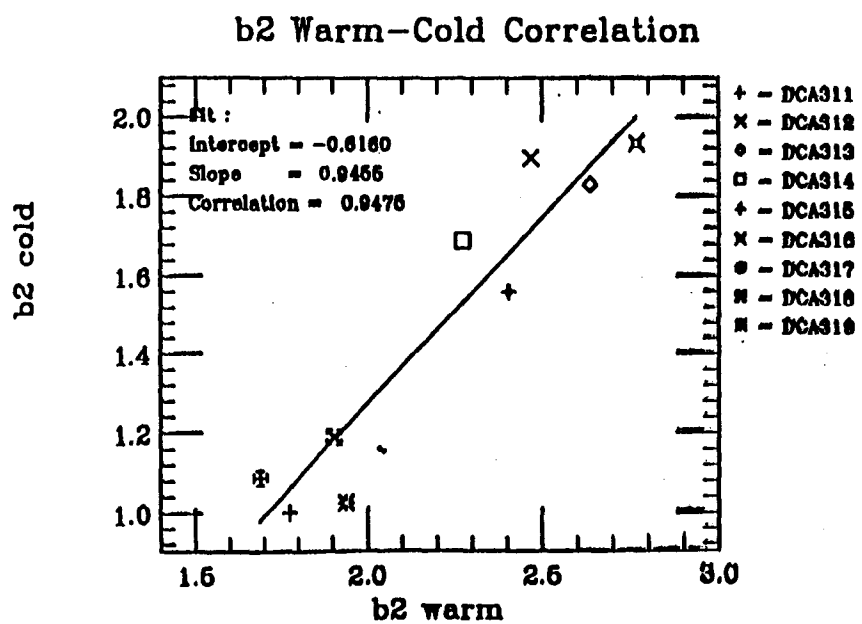


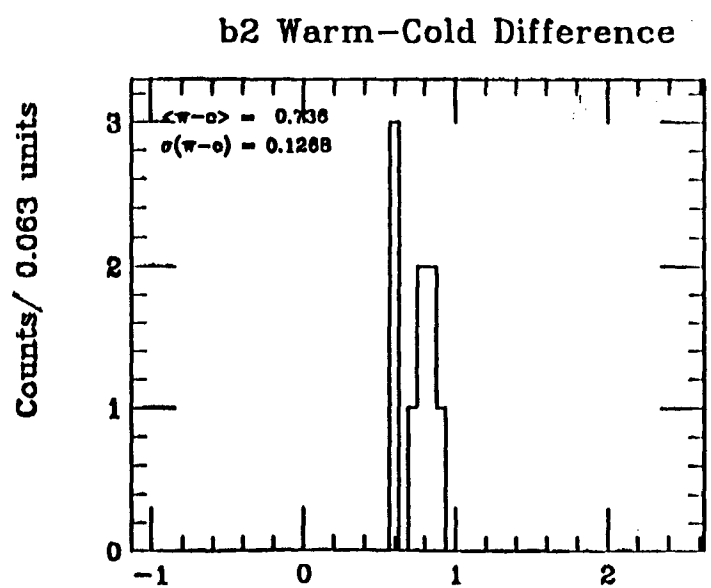


Warm-Cold Correlations Warm data: asst_warm_before_mpole.dat Cold data: asst_cold_mpole.dat 09:01:44 15-FEB-93

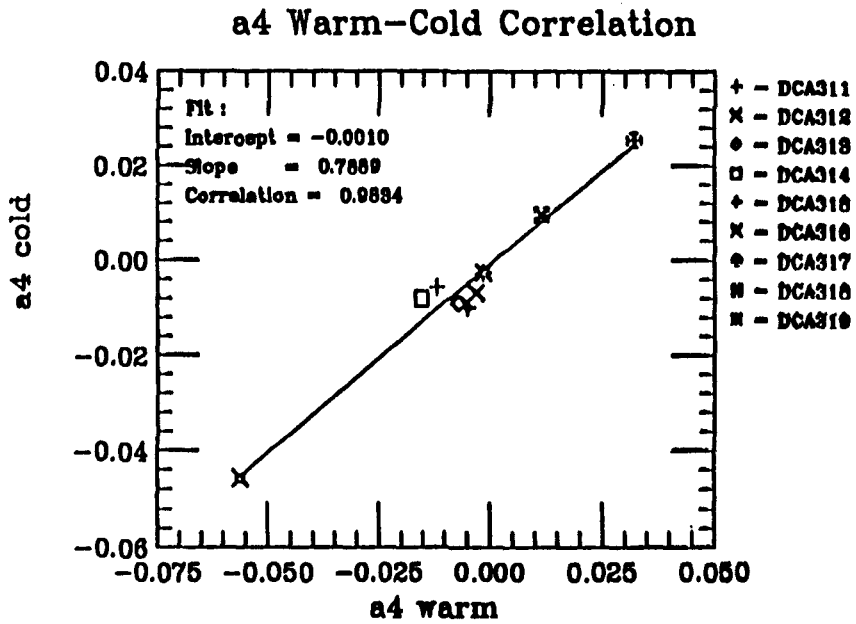


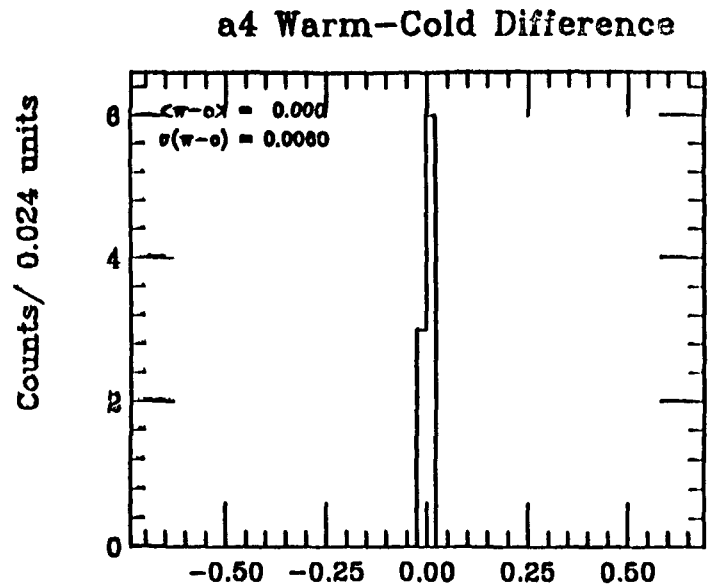


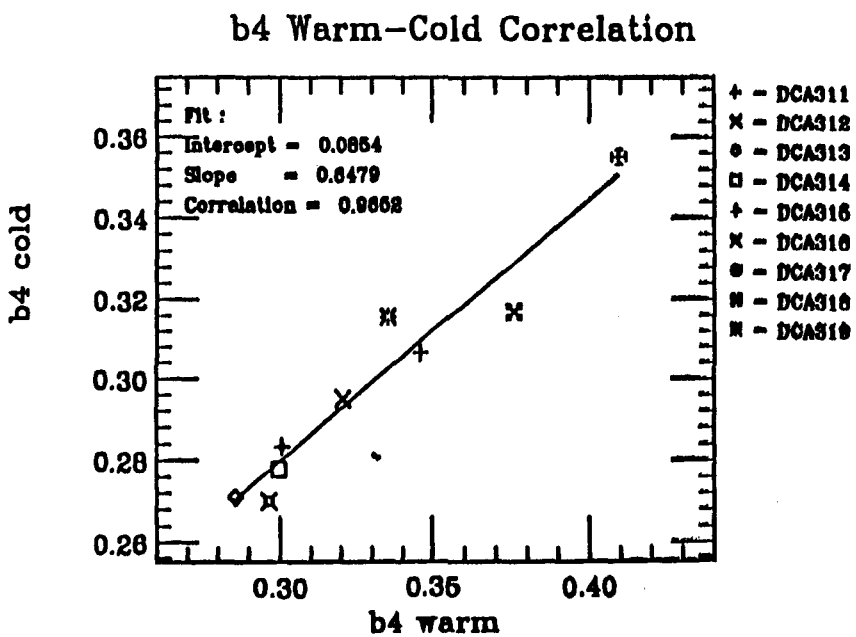


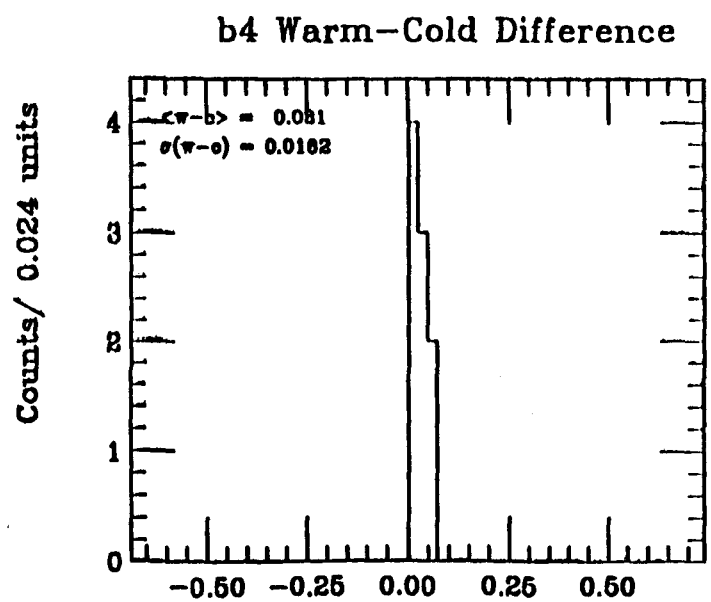


Warm-Cold Correlations Warm data: asst_warm_before_mpole.dat Cold data: asst_cold_mpole.dat 09:01:44 15-FEB-93

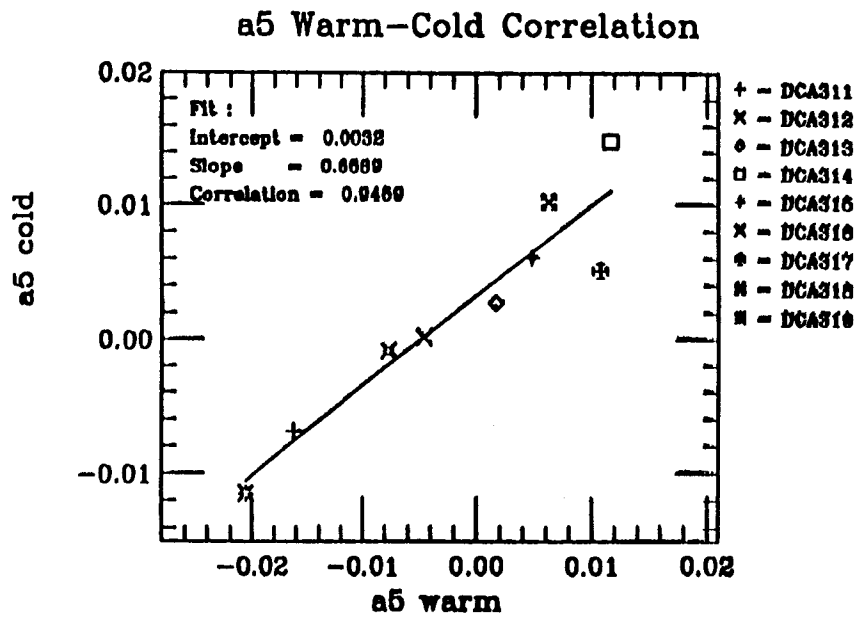


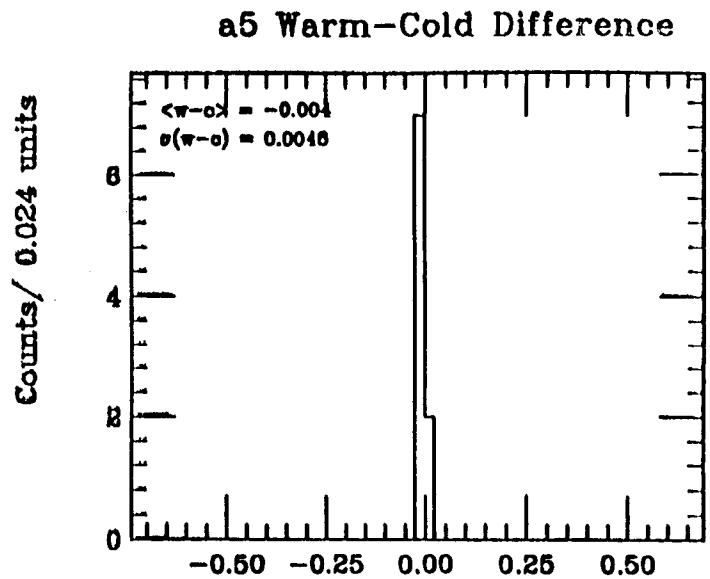


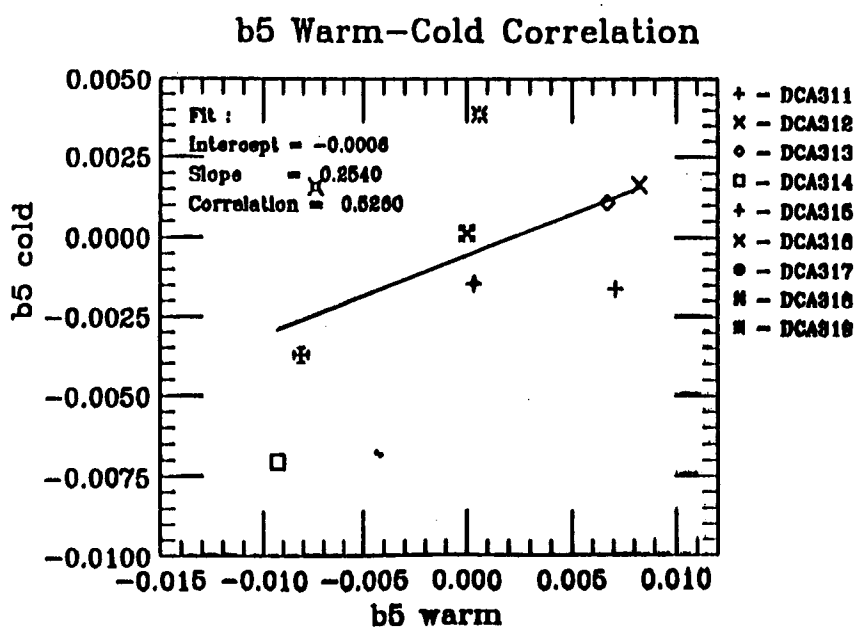


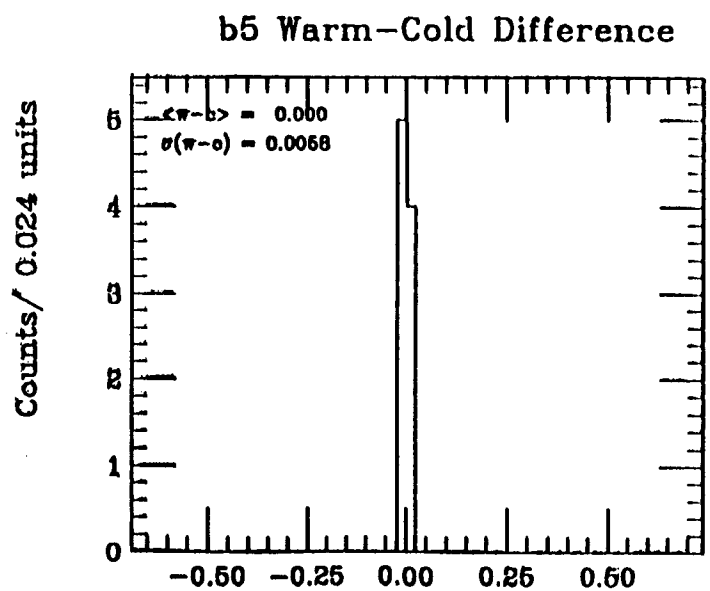


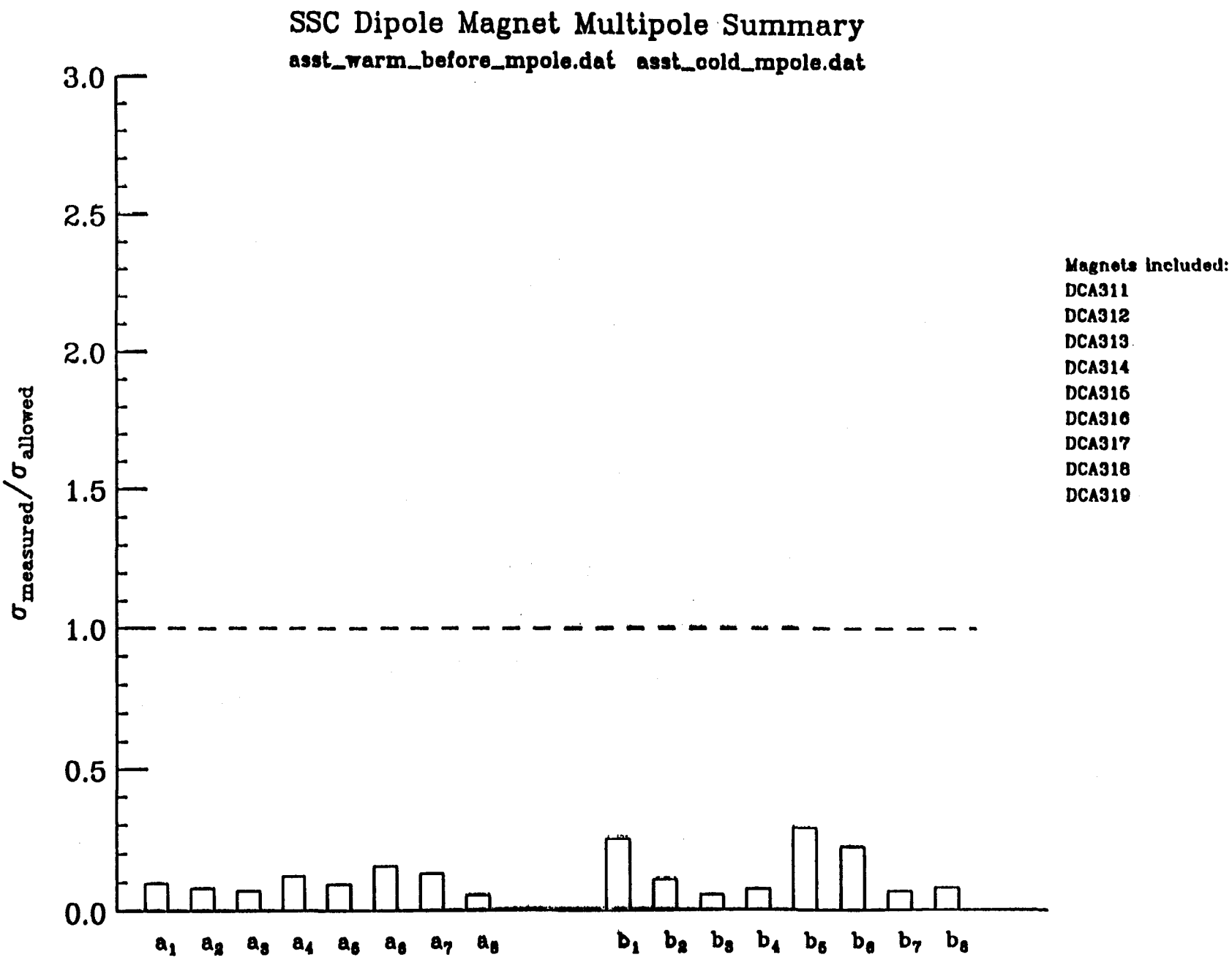
Warm-Cold Correlations Warm data: asst_warm_before_mpole.dat Cold data: asst_cold_mpole.dat 09:01:44 16-FEB-93







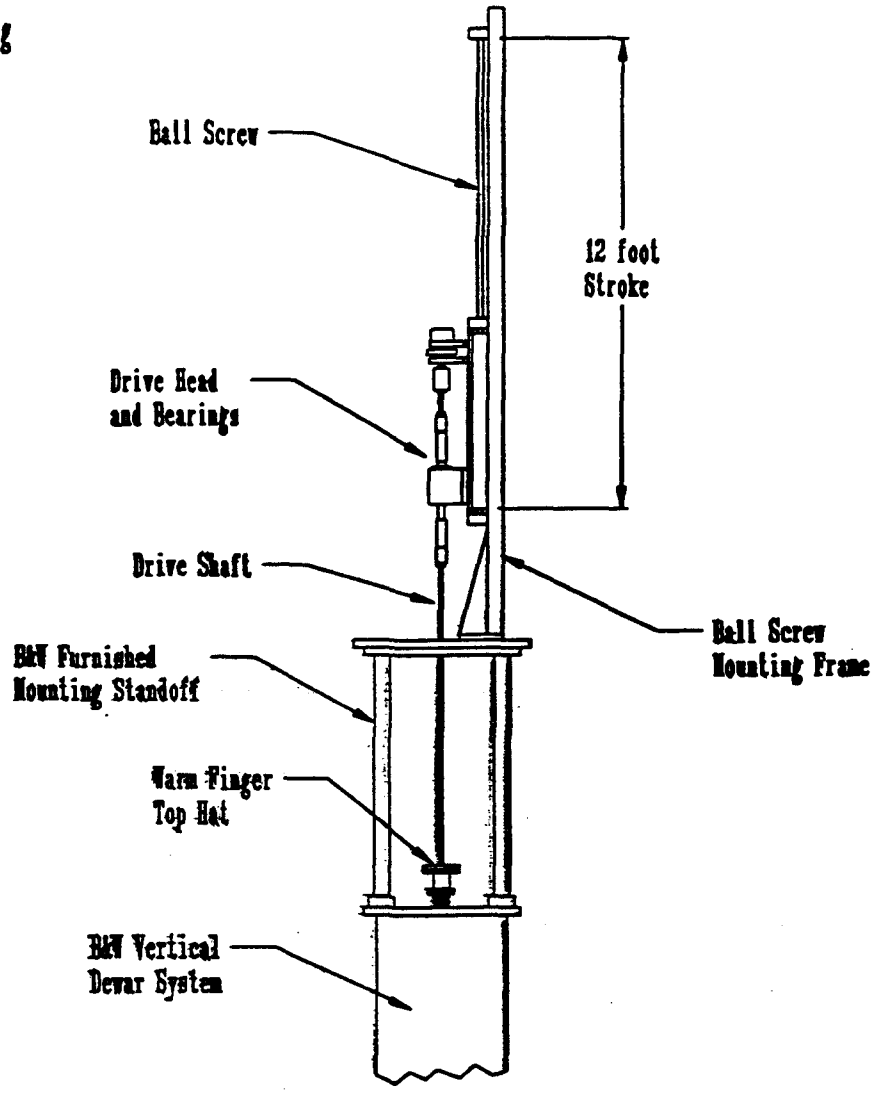



SSC Dipole Magnet Multipole Summary
asst_warm_before_mpole.dat asst_cold_mpole.dat
3.0
2.5
2.0
1.5
1.0
0.5
0.0
σmeasured/σallowed
a1 a2 a3 a4 a5 a6 a7 a8
b1 b2 b3 b4 b5 b6 b7 b8
Magnets included:
DCA311
DCA312
DCA313
DCA314
DCA315
DCA316
DCA317
DCA318
DCA319

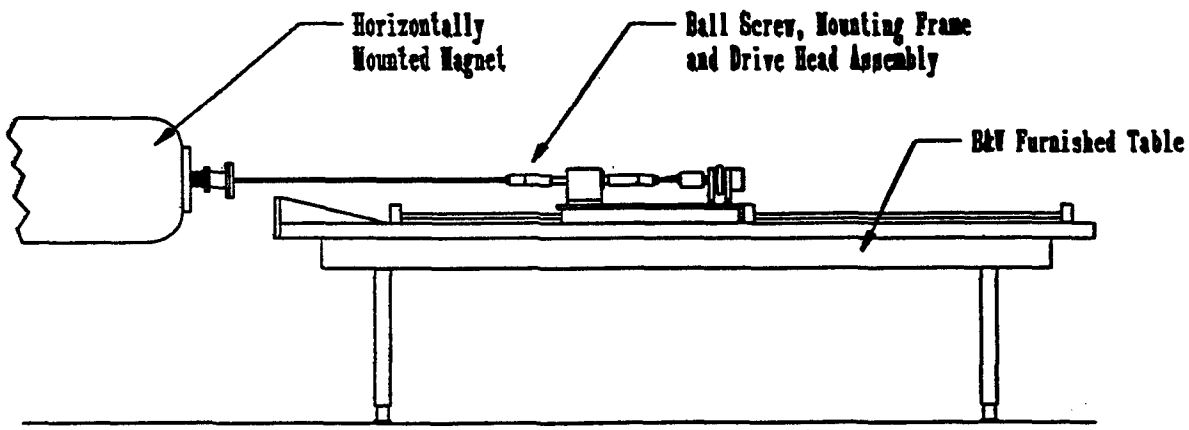
Other notable components

- PMI torque motor
  - uses same closed loop velocity control as mole system
- Teledyne Gurley encoder
- Airflyte slip rings
- stainless steel drive shaft outside magnetic field
- G-10 inside
- 25 cm ceramic coil

B&W Vertical Coil Transporter Mounting Concept



B&W Horizontal Coil Transporter Mounting Concept



I. B&W rotating coil

(Ray Fuzesy, Rick Dorman, Ted Gathright, Kim Shirley, Joe Dryer, Kiseon Kim, Sergey Sharanov, Tony Mann - B&W)

- angular alignment adjustment
- parallel alignment provided by B&W
- 170 inch stroke to get coil totally out of dewar
- powered Z-positioning with external controller - can be remotely controlled
- 25 cm coil with shield
- dummy warm finger provided for pre-alignment
- closed loop motor control

E-LINE•ORIGA

Series 6000 Electric Linear Actuator

Compact rodless design for industrial continuous duty service and strokes to 12 feet of travel.

Superior positioning capability with up to +/-0.003" repeatability.

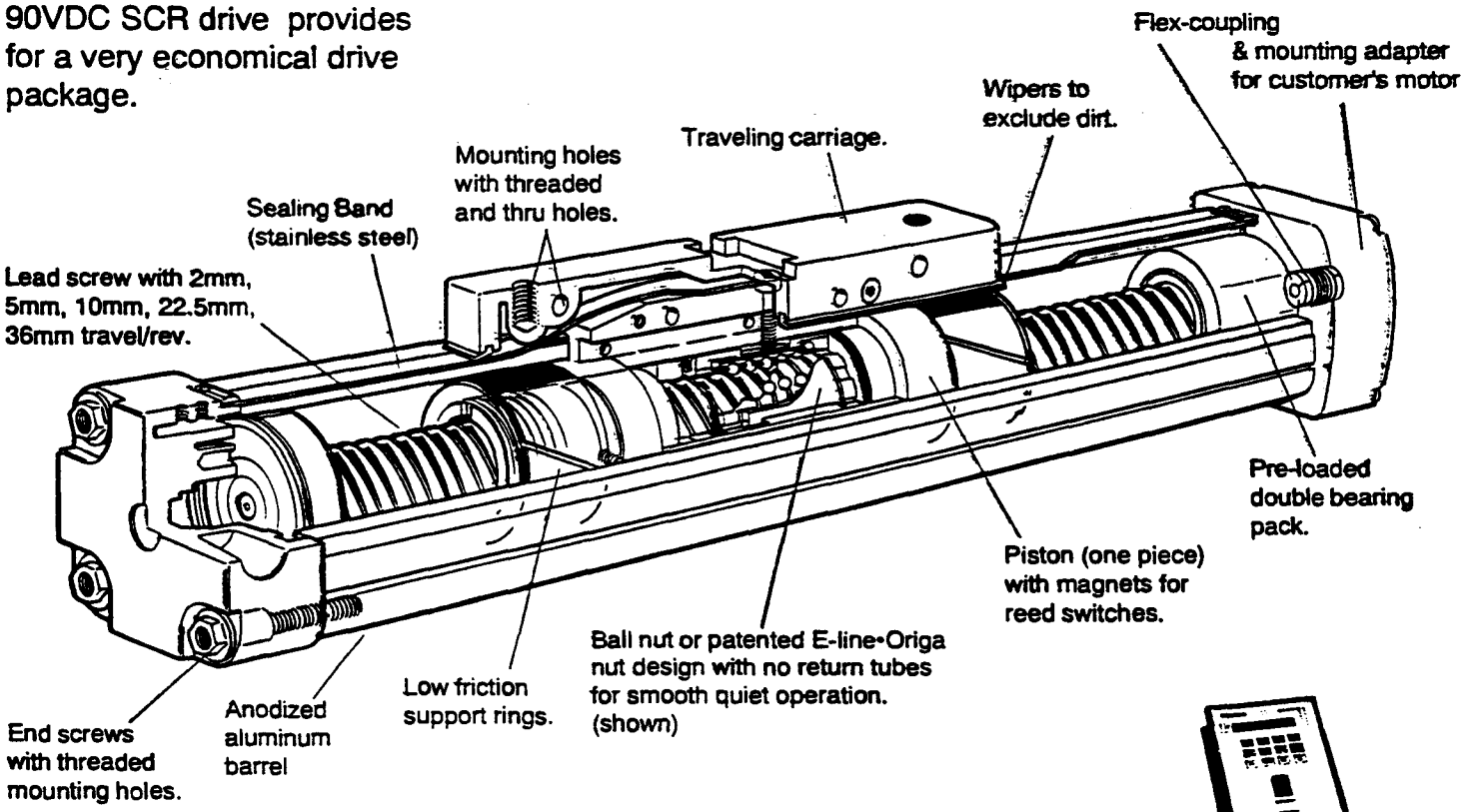
E-Line•Origa brushless servo drive available with integrated control system 6000-SC. 90VDC SCR drive provides for a very economical drive package.

Packaged enclosed construction with guided carriage for easy to mount assembly.

Speeds to 60 in./sec and thrust loads to 250 lbs. Brushless models provide constant velocity performance with varying loads.

Motor mounting adapters for most brushless servo, NEMA 23 and 34 steppers and DC motors up to 3/4 HP @ 2800 RPM are standardized.

Drive shaft model for timing belt pulley also available.

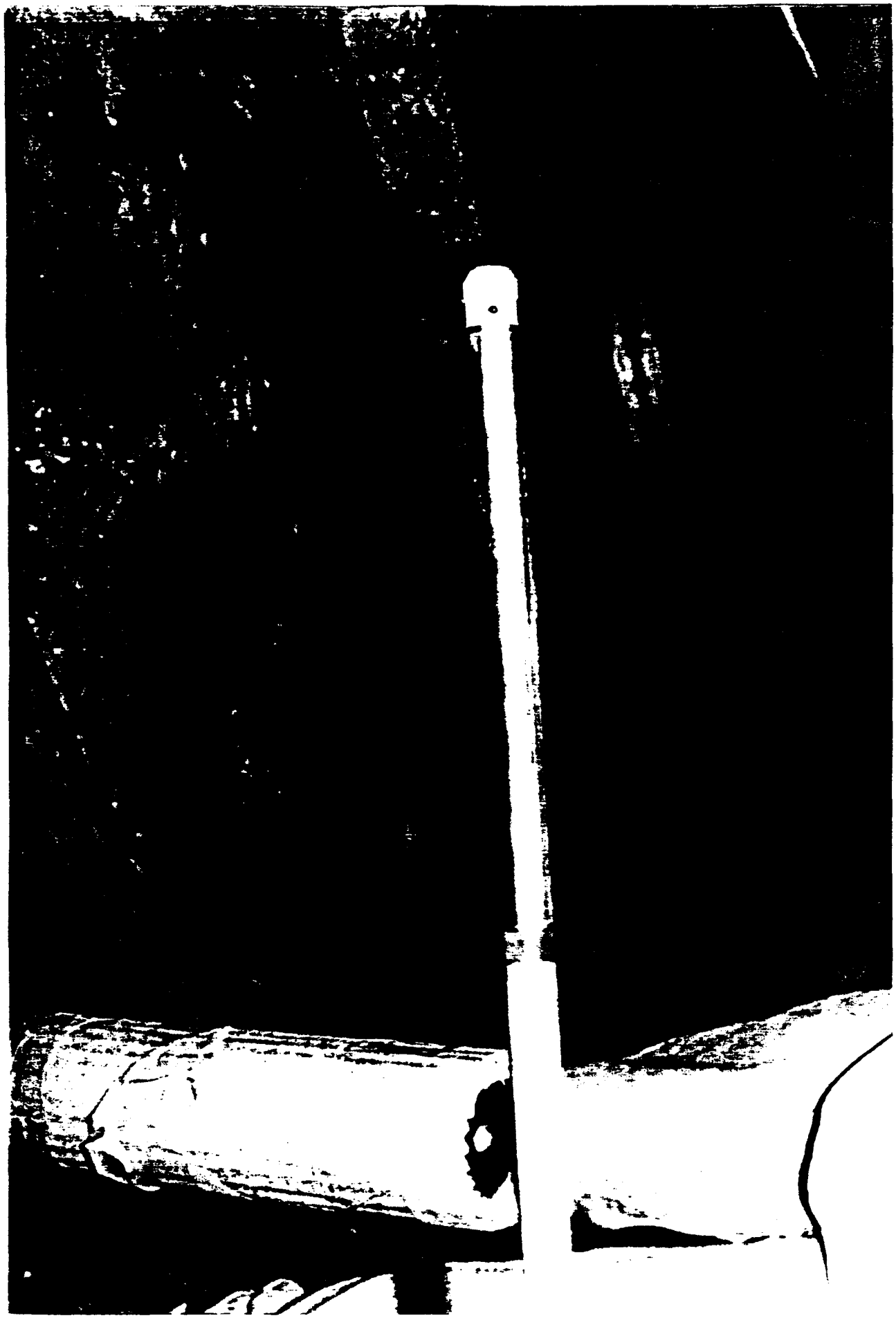


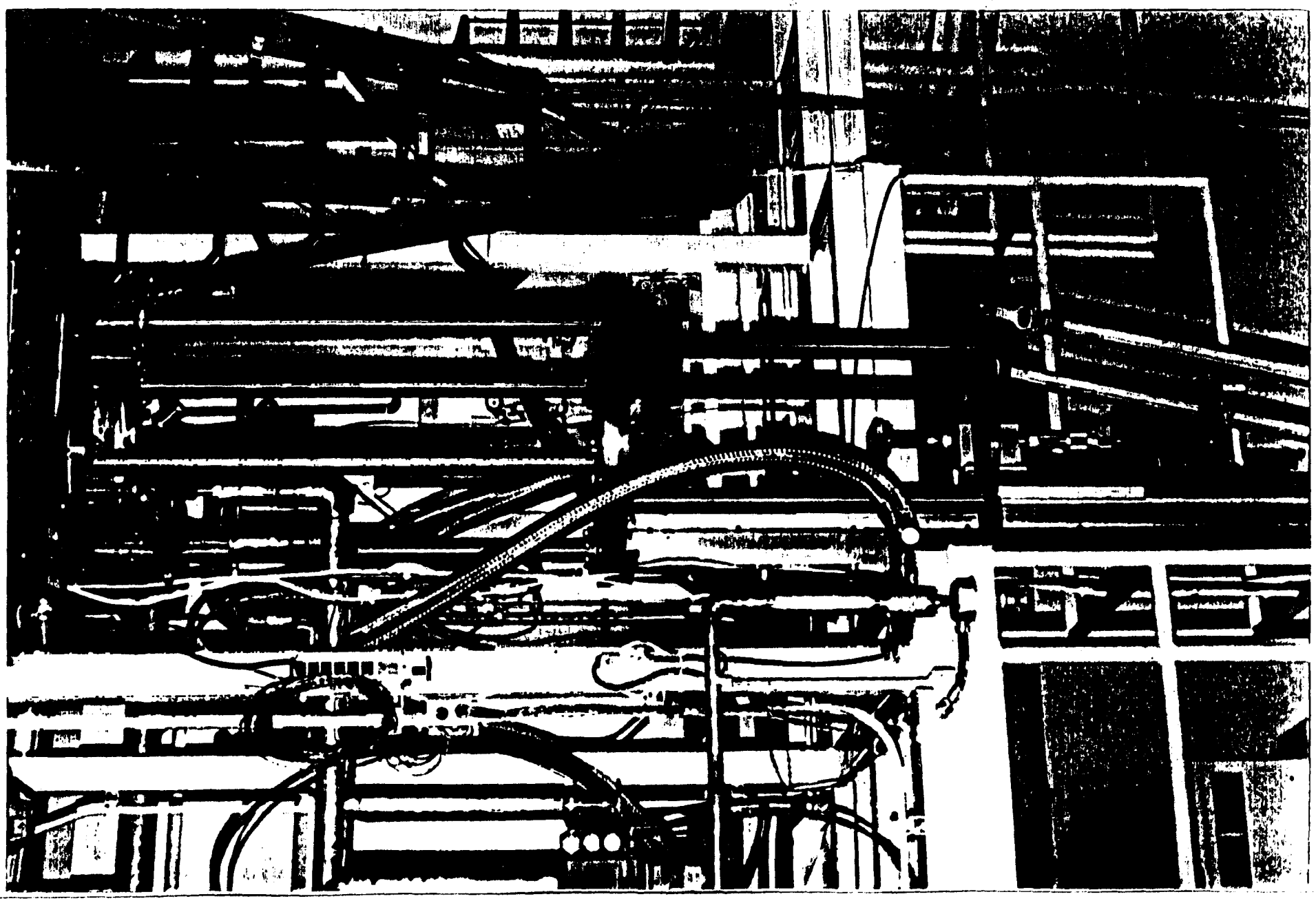
6000-SC programmer for brushless drive.

- 10 program memory
- keyboard programmer
- position display
- I/O @ 24VDC
- interfaces to PLC two axis capability

DESIGN AND MATERIALS

Housing	Anodized Aluminum
Actuator End Caps	Aluminum
Piston Mounting	Anodized Aluminum
Ball Screw	Rolled thread (4150 Steel) hardened to RC56
Ball Nut	Threads hardened to RC56



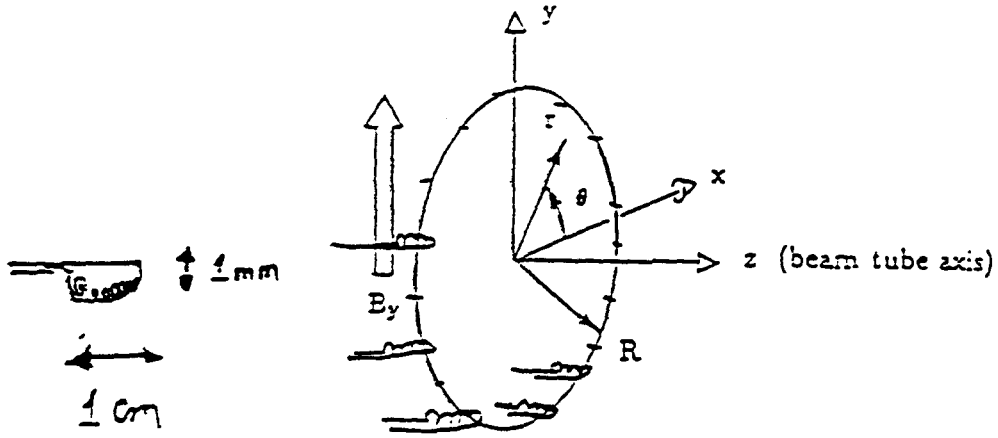


II. NMR array data with DSB701

(Ernest Wong - UCLA, Joe Dimarco, Joerg Marks)
32 channel pulsed NMR array

From Gil Clark & Ernest Wong - UCLA

B. Implement NMR in Magnetic Field Mapping



$$B_y(R,\theta) = B_0 + B_0 \sum_{n=1}^{\infty} R^n [b_n \cos(n\theta) - a_n \sin(n\theta)]. \tag{1}$$

The coefficients a_n and b_n are the multipole moments that are used for trajectory stability modeling. They are calculated using the Fourier inversion formulas:

$$b_n = \frac{1}{\pi B_0 R^n} \int_0^{2\pi} B_y(R,\theta)\cos(n\theta)d\theta, \quad n = 1,2,..., \tag{2}$$

$$a_n = \frac{-1}{\pi B_0 R^n} \int_0^{2\pi} B_y(R,\theta)\sin(n\theta)d\theta, \quad n = 1,2.... \tag{3}$$

- Instead of being measured continuously on the boundary, it is done with a large number (M) of discrete field sensors placed at the angles $\theta_m = 2\pi m/M$; $m = 1, 2, ..., M-1$ on the boundary circle. The inversion formulas for the MMC are:

$$b'_n = \frac{2}{M B_0 R^n} \sum_{\theta_m} B_y(R,\theta_m) \cos(n\theta_m)$$

and

M = 32

$$a'_n = \frac{-2}{M B_0 R^n} \sum_{\theta_m} B_y(R,\theta_m) \cos(n\theta_m)$$

I. Basic Principles of MCPMR
(Multiple Coil Pulse Magnetic Resonance)

A. Basic Principles of Nuclear Magnetic Resonance
(Classical Treatment) (NMR)

$$\vec{\mu} = \gamma \vec{J}$$

$\vec{\mu}$ is magnetic moment

$\vec{J}$ is angular momentum

γ is gyromagnetic ratio

magnetic moment $\vec{\mu}$ precesses in a magnetic field H_0 with a angular frequency ω_L. It is so called "Larmor frequency" ω_L.

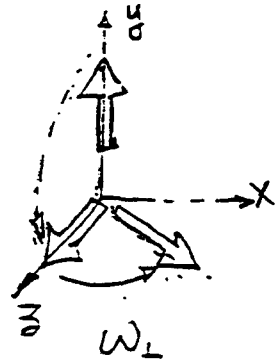
ω_L	$=$	γ	$\times$	H_0
(Resonance Frequency)		(Gyromagnetic Ratio)		(Magnetic Field)

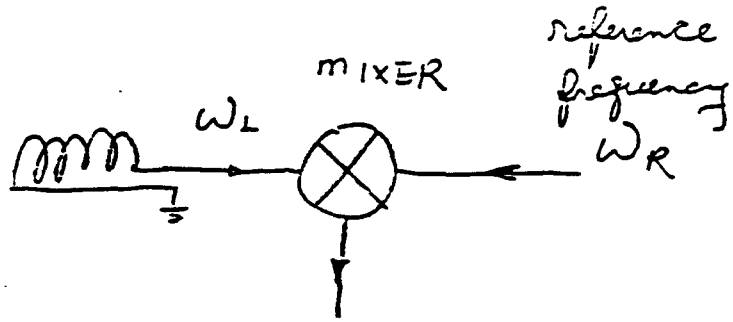
$\gamma/2\pi(^1H) = 42.5759$ MHz/T

C. Measure Resonance Frequency with MCPMR

M_0 $\qquad$ B_y

Apply a "$\pi/2$" pulse,

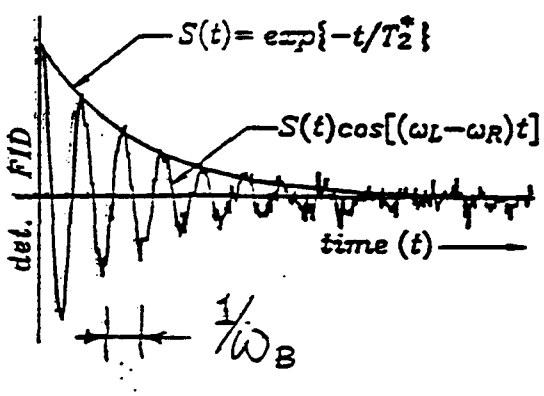




precessing mag. moment induces EMF at ω_L in the coil

$$V(t) = S(t)\left[\cos(\omega_L - \omega_R)t + \cos(\omega_L + \omega_R)t\right]$$

filtered out



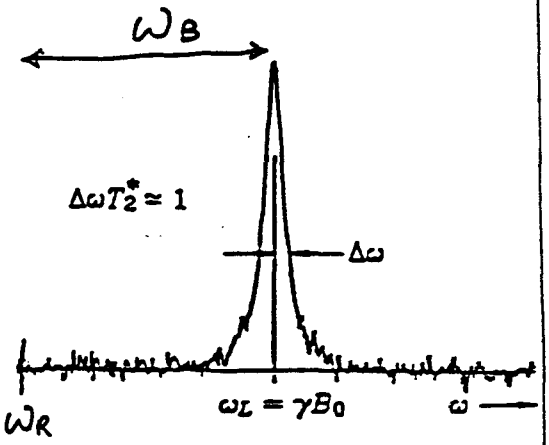
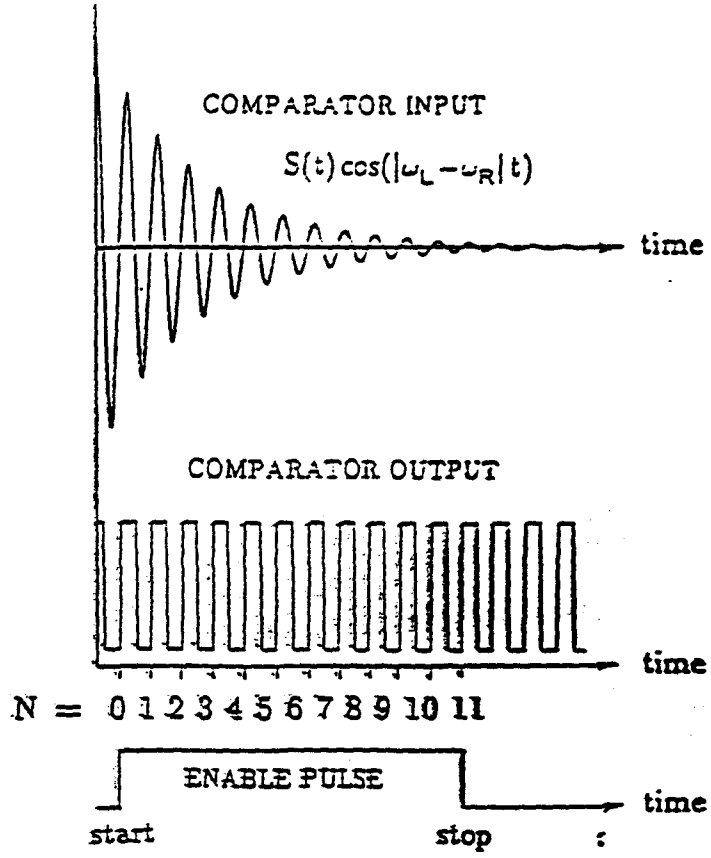


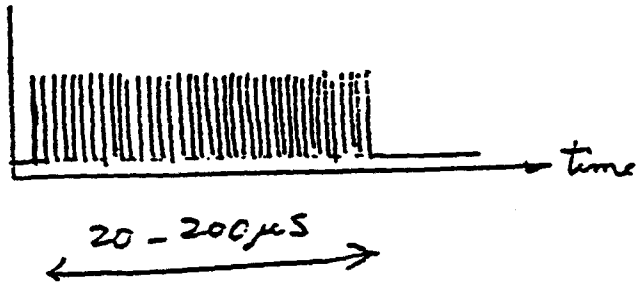
Fig. 3 Form of the signals from a pulsed magnetic resonance instrument (left) and a steady state absorption apparatus (right).

$$\omega_L = \omega_R + \omega_B$$

Zero Crossing Detection



N

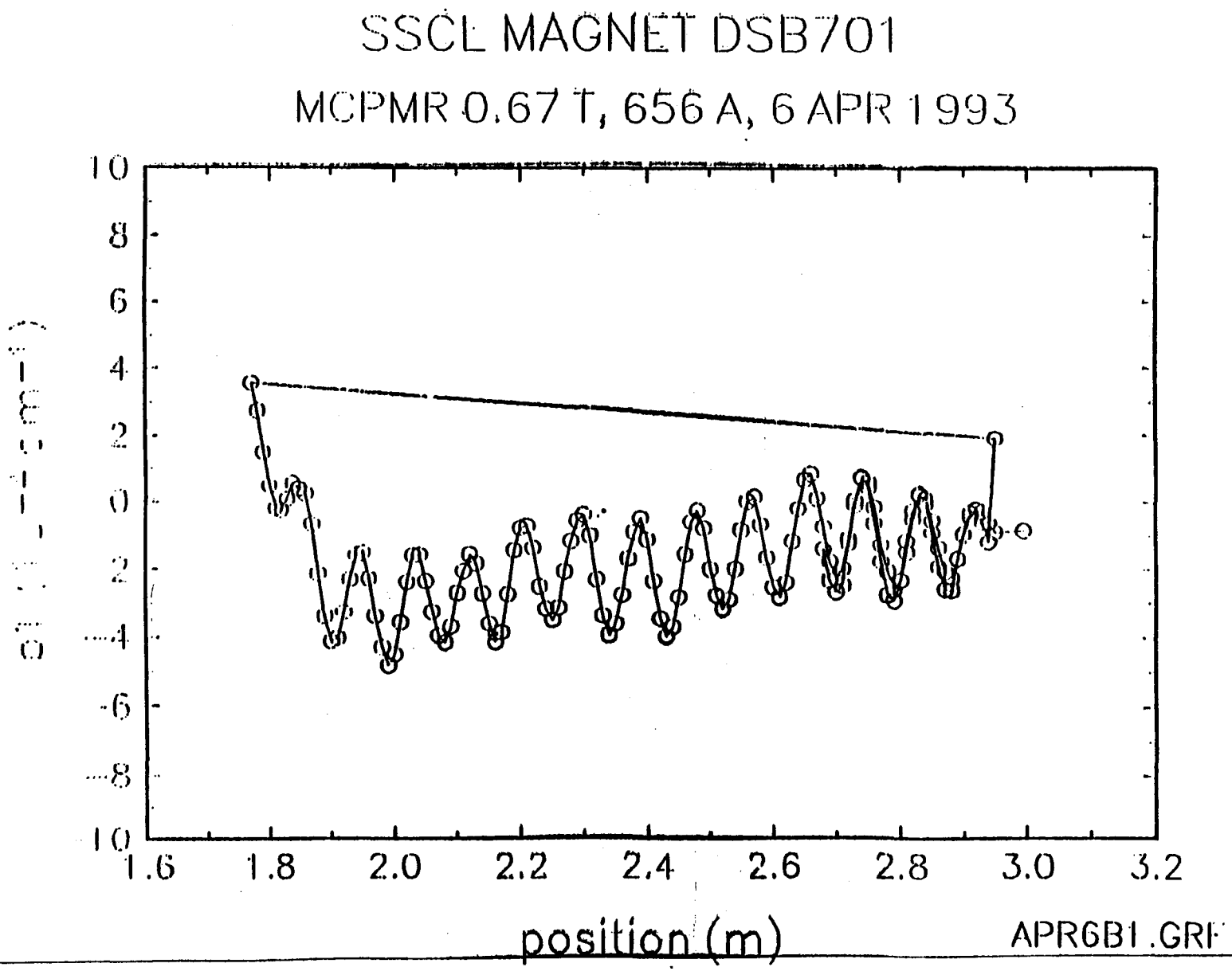


T "tic
of c

ω_{clock}

$$\omega_L = \omega_R + \omega_B$$

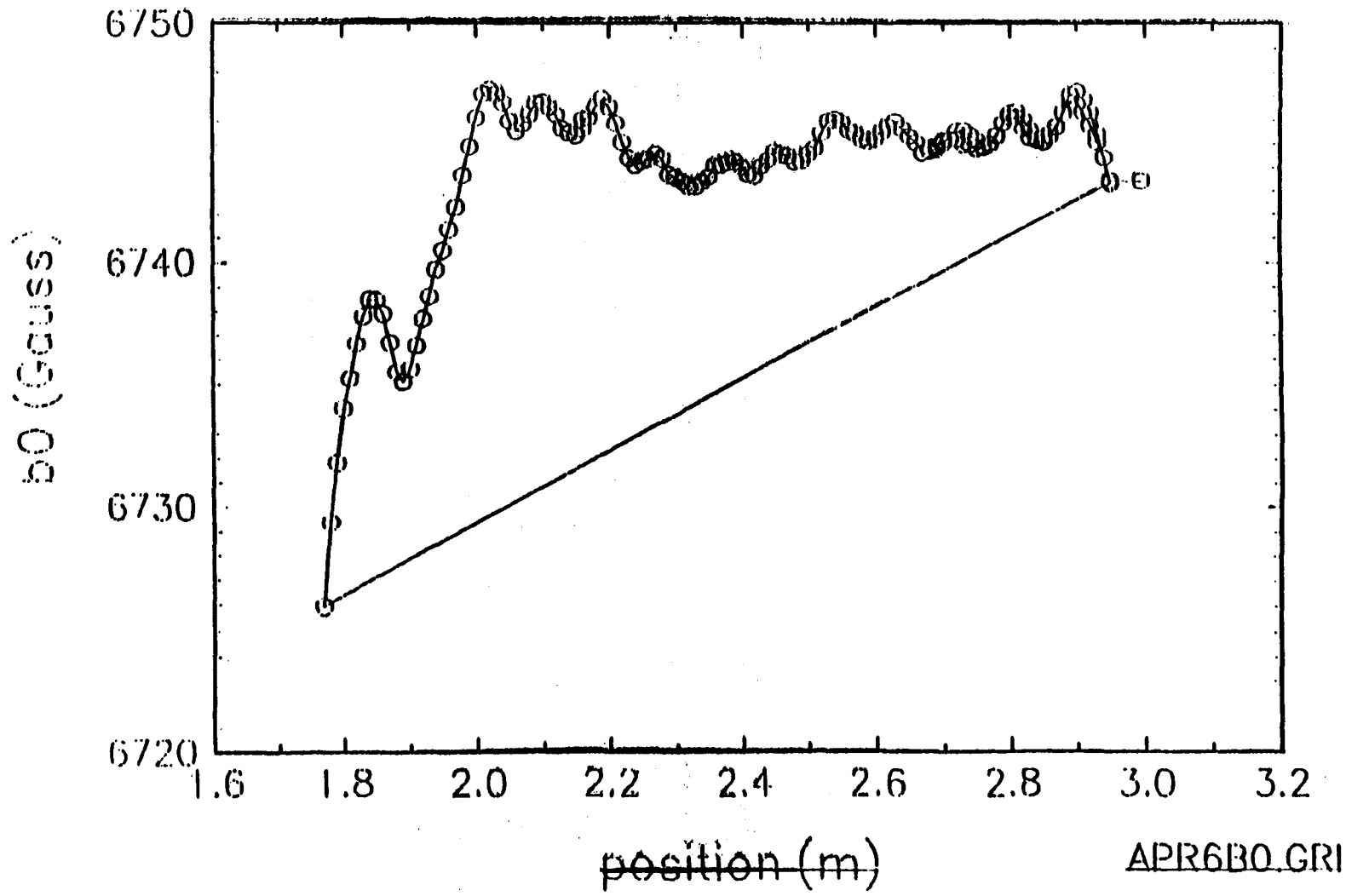
$$= \omega_R + \omega_{clock} * (N/T)$$

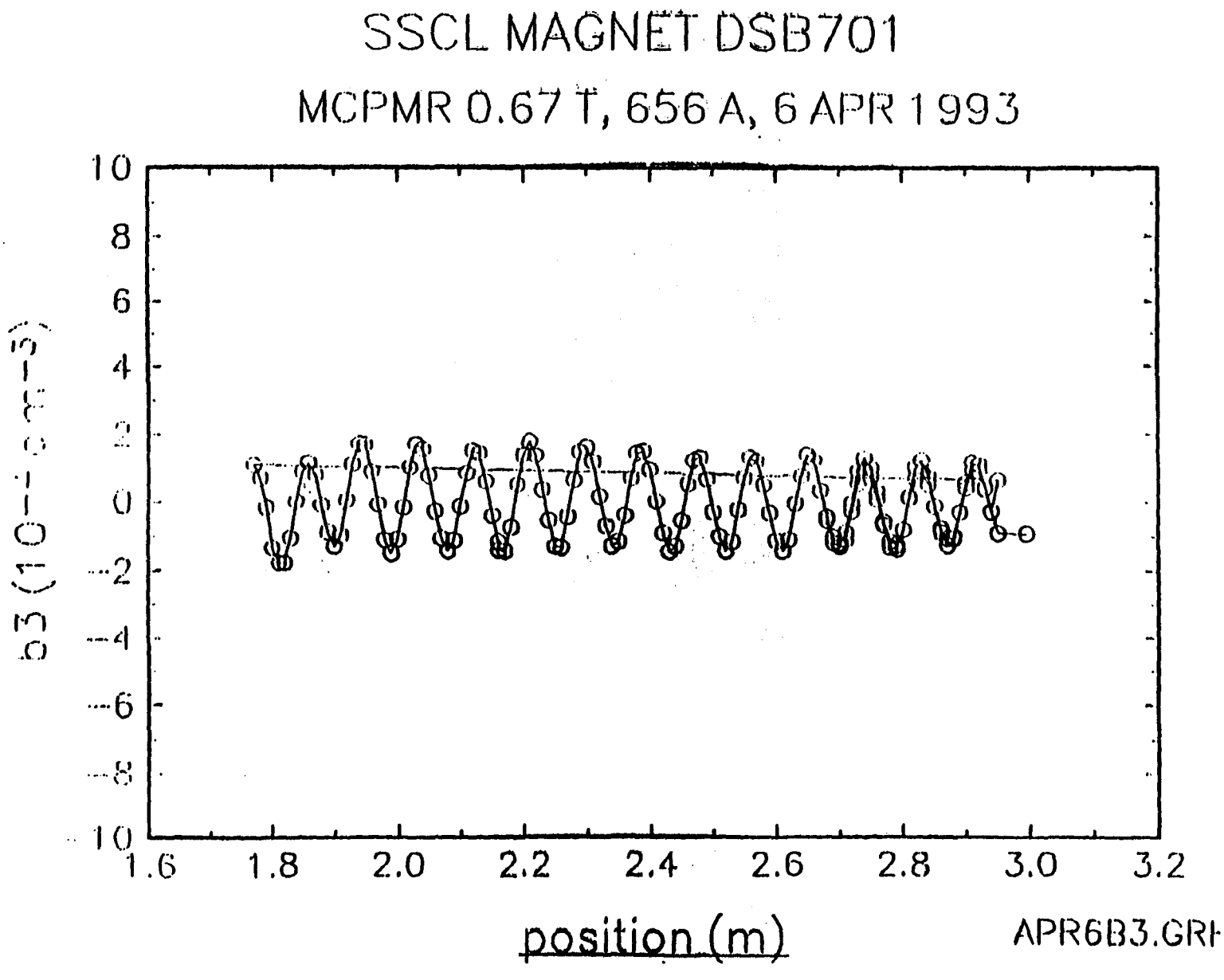

SSCL MAGNET DSB701
MCPMR 0.67 T, 656 A, 6 APR 1993
10
8
6
4
2
0
-2
-4
-6
-8
-10
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
position (m)
APR6B1.GRF

host W. H. Wong (UCLA)

SSCL MAGNET DSB701

MCPMR 0.67 T, 656 A, 6 APR 1993




SSCL MAGNET DSB701
MCPMR 0.67 T, 656 A, 6 APR 1993
10
8
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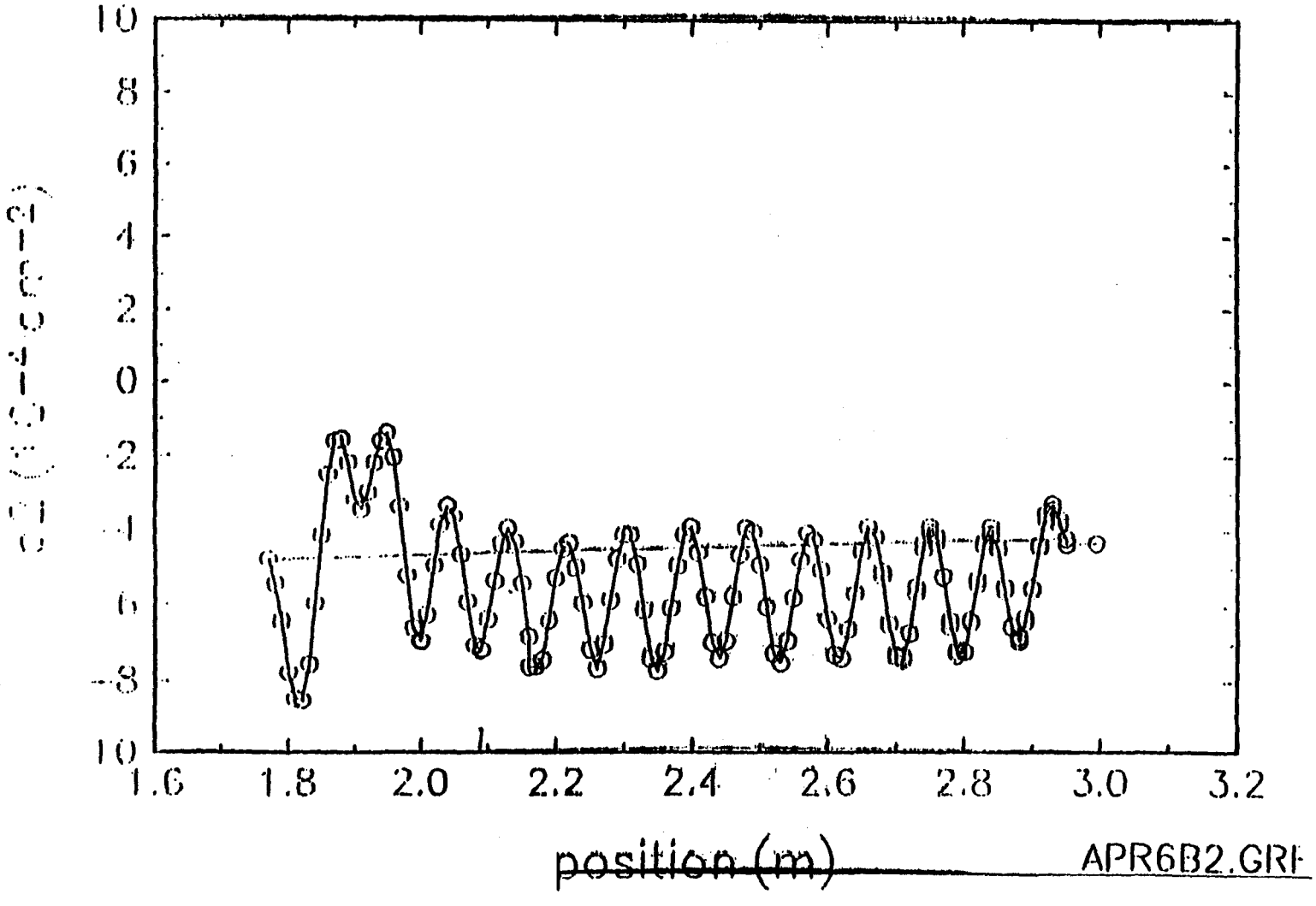
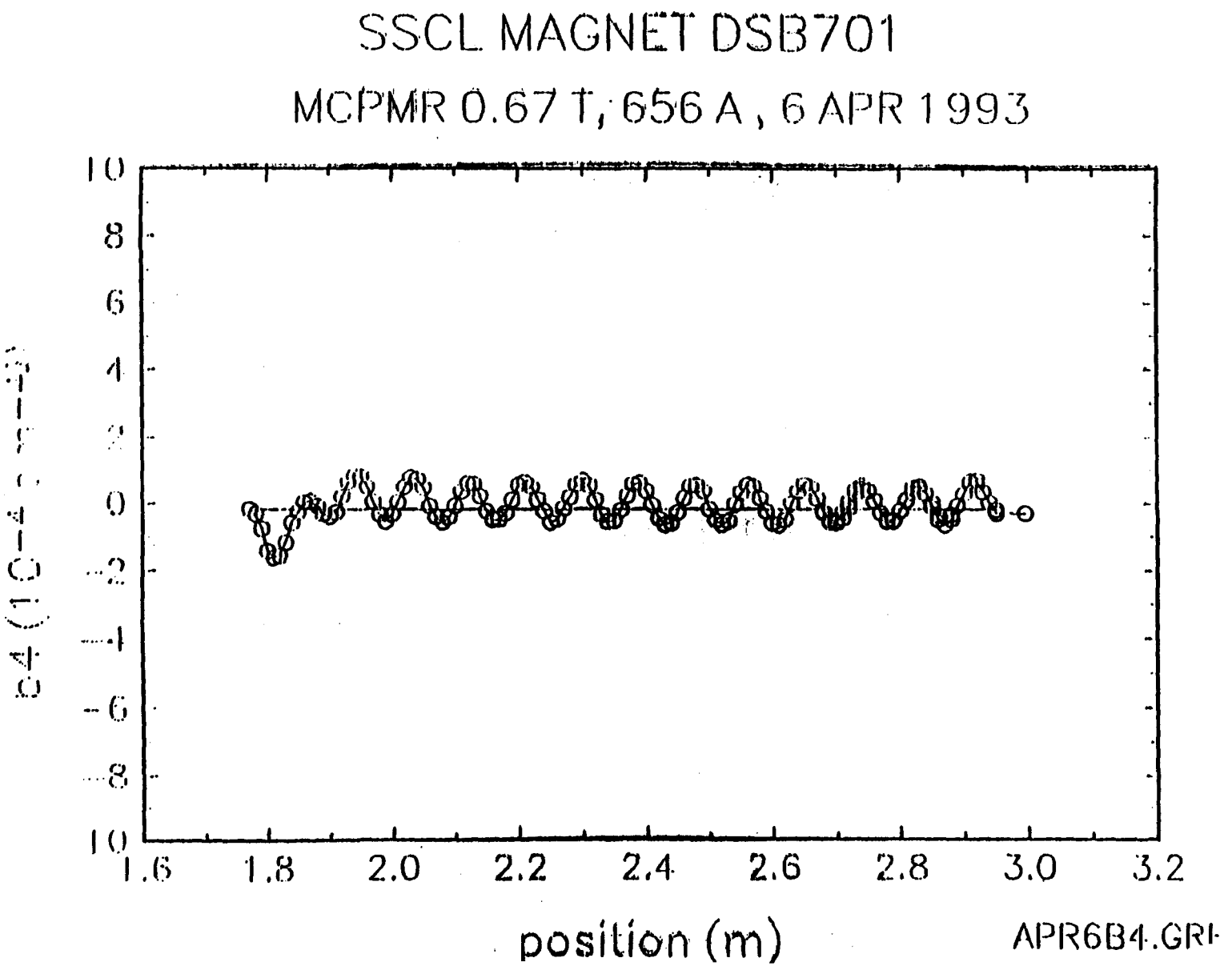
0
-2
-4
-6
-8
-10
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
position (m)
APR6B3.GRF

SSCL MAGNET DSB701

MCPMR 0.67 T, 656 A, 6 APR 1993




SSCL MAGNET DSB701
MCPMR 0.67 T, 656 A , 6 APR 1993
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-2
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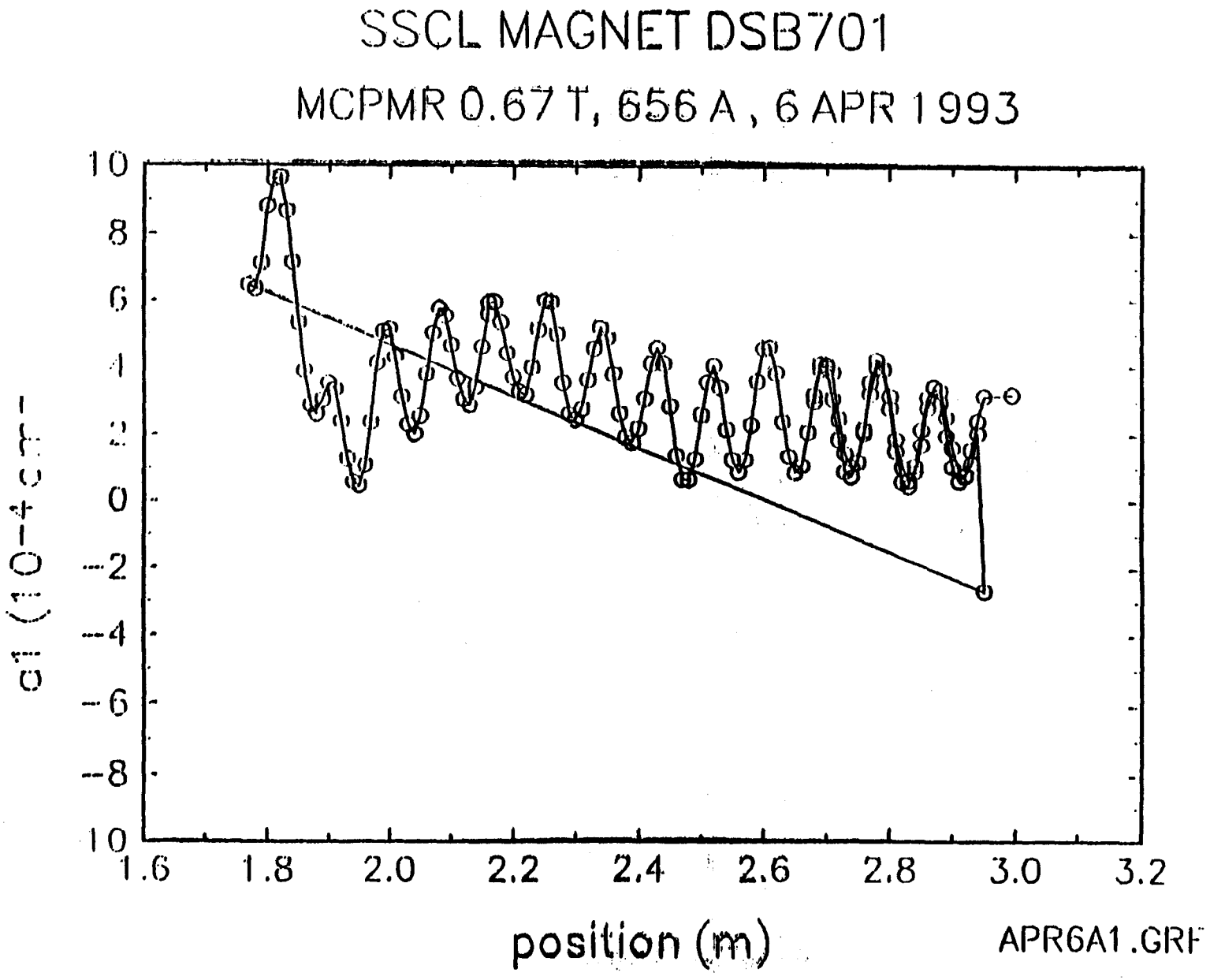
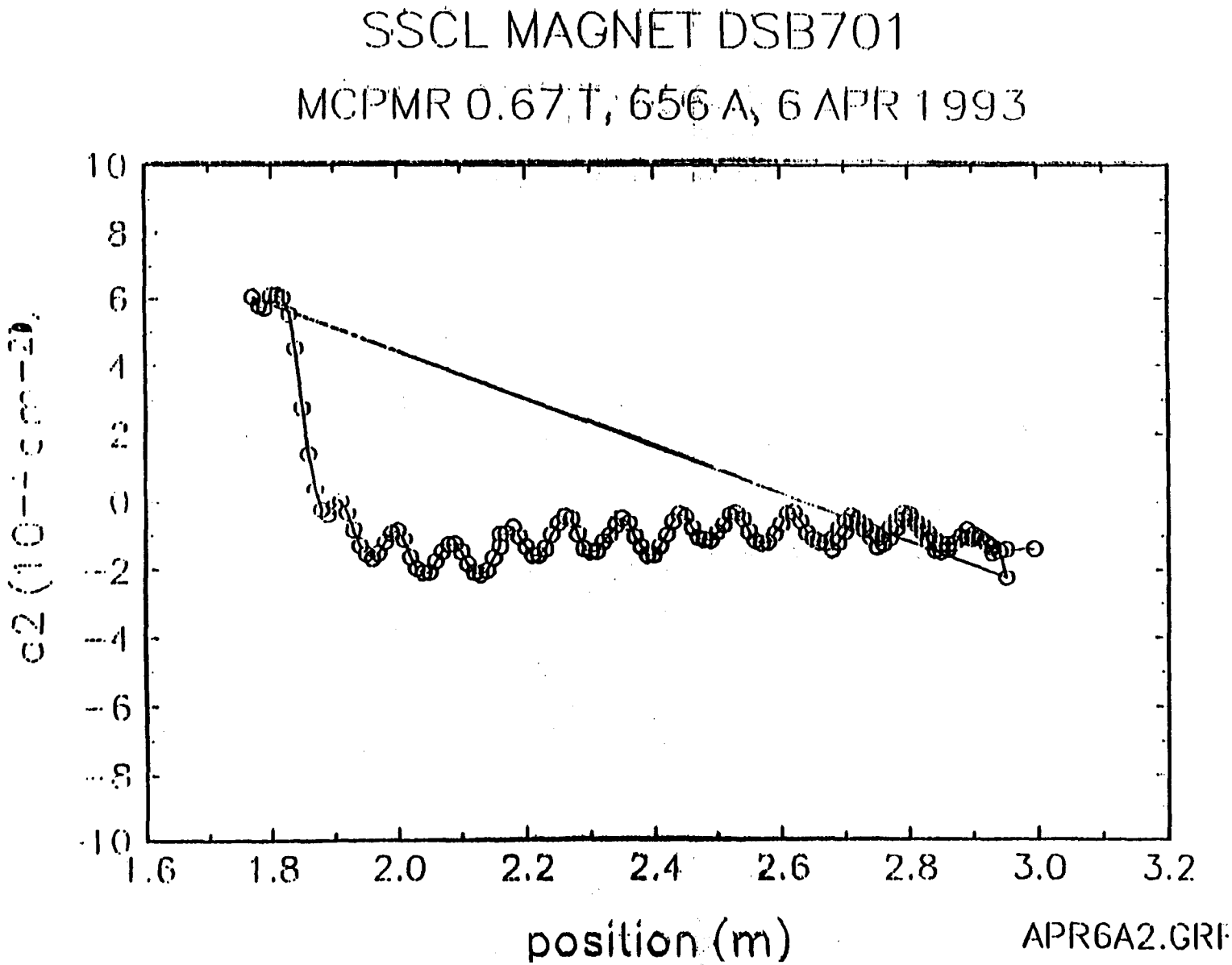
-6
-8
10
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
position (m)
APR6B4.GRF


SSCL MAGNET DSB701
MCPMR 0.67 T, 656 A , 6 APR 1993
10
8
6
4
2
0
-2
-4
-6
-8
10
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
position (m)
APR6A1.GRF


SSCL MAGNET DSB701
MCPMR 0.67 T, 656 A, 6 APR 1993
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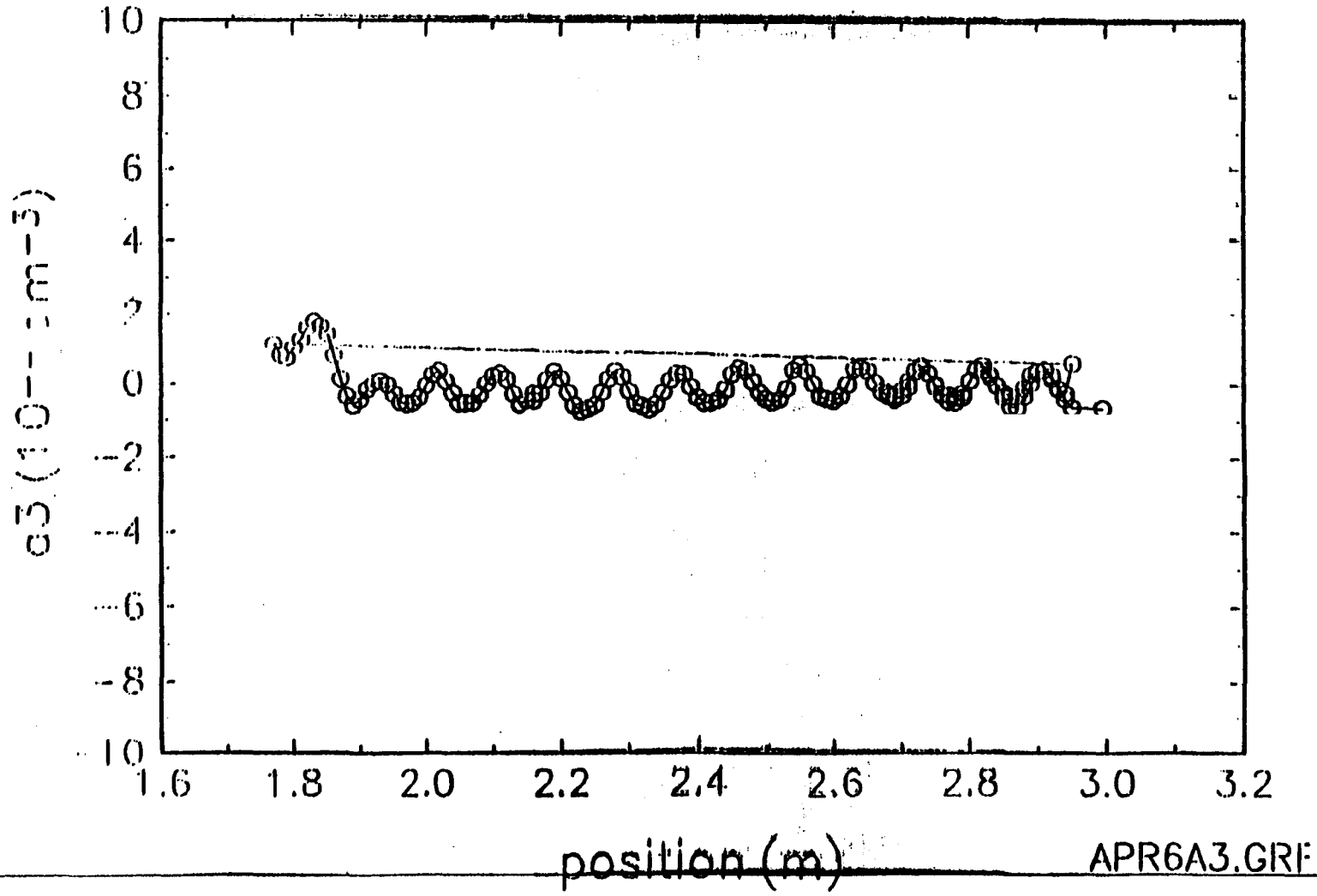
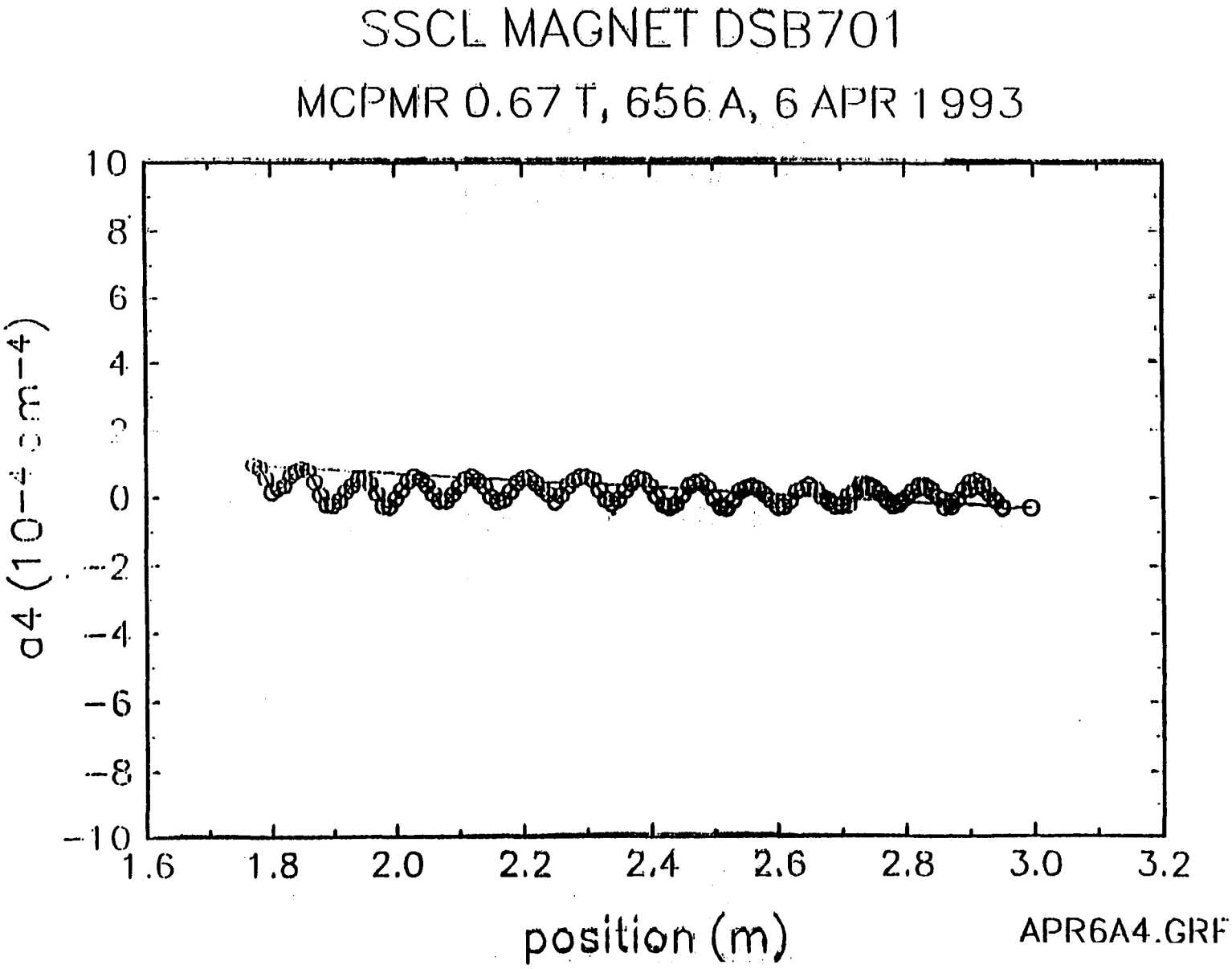
8
6
4
2
0
-2
-4
-6
-8
-10
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
position (m)
APR6A2.GRF

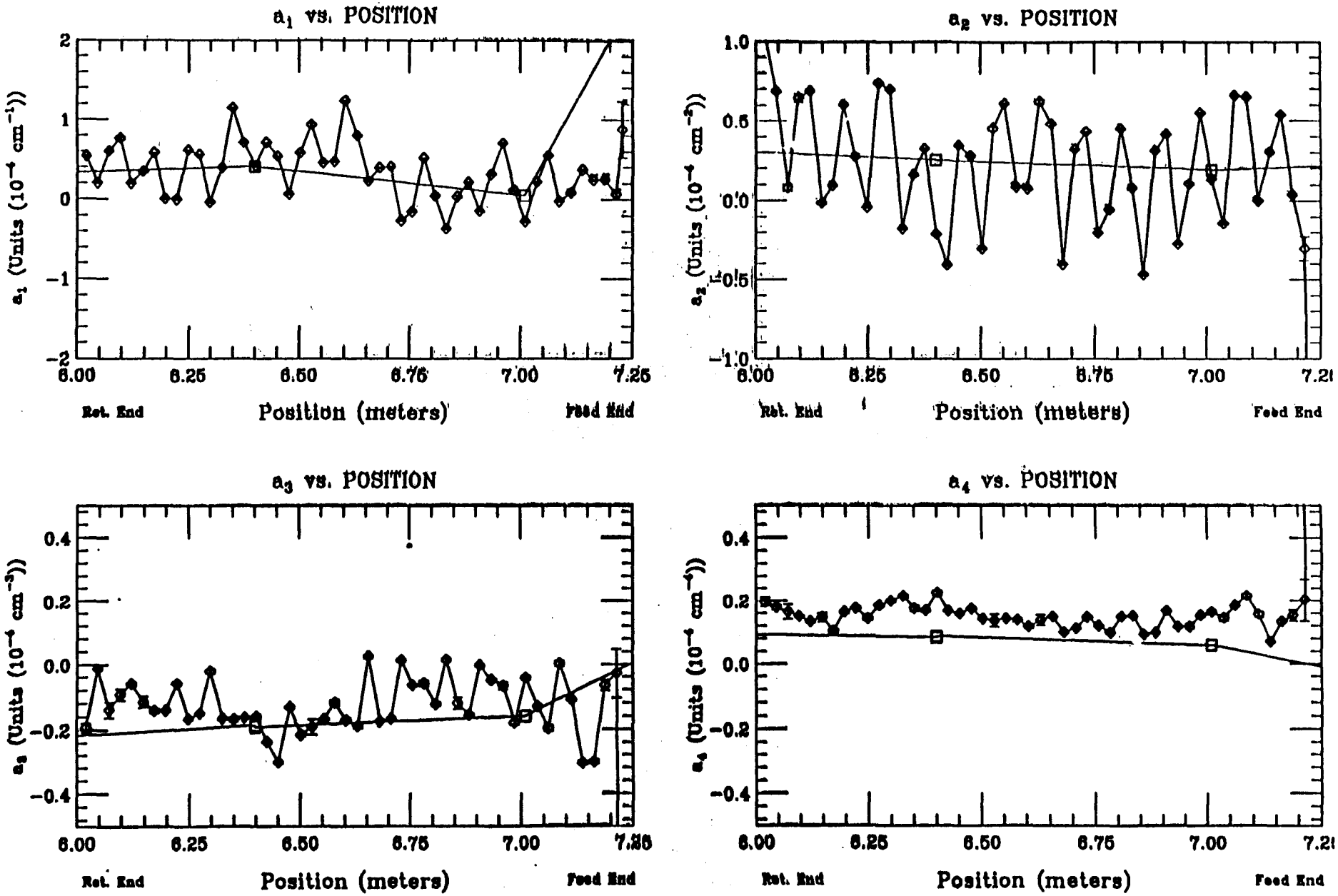
SSCL MAGNET DSB701

MCPMR 0.67 T, 656 A, 6 APR 1993



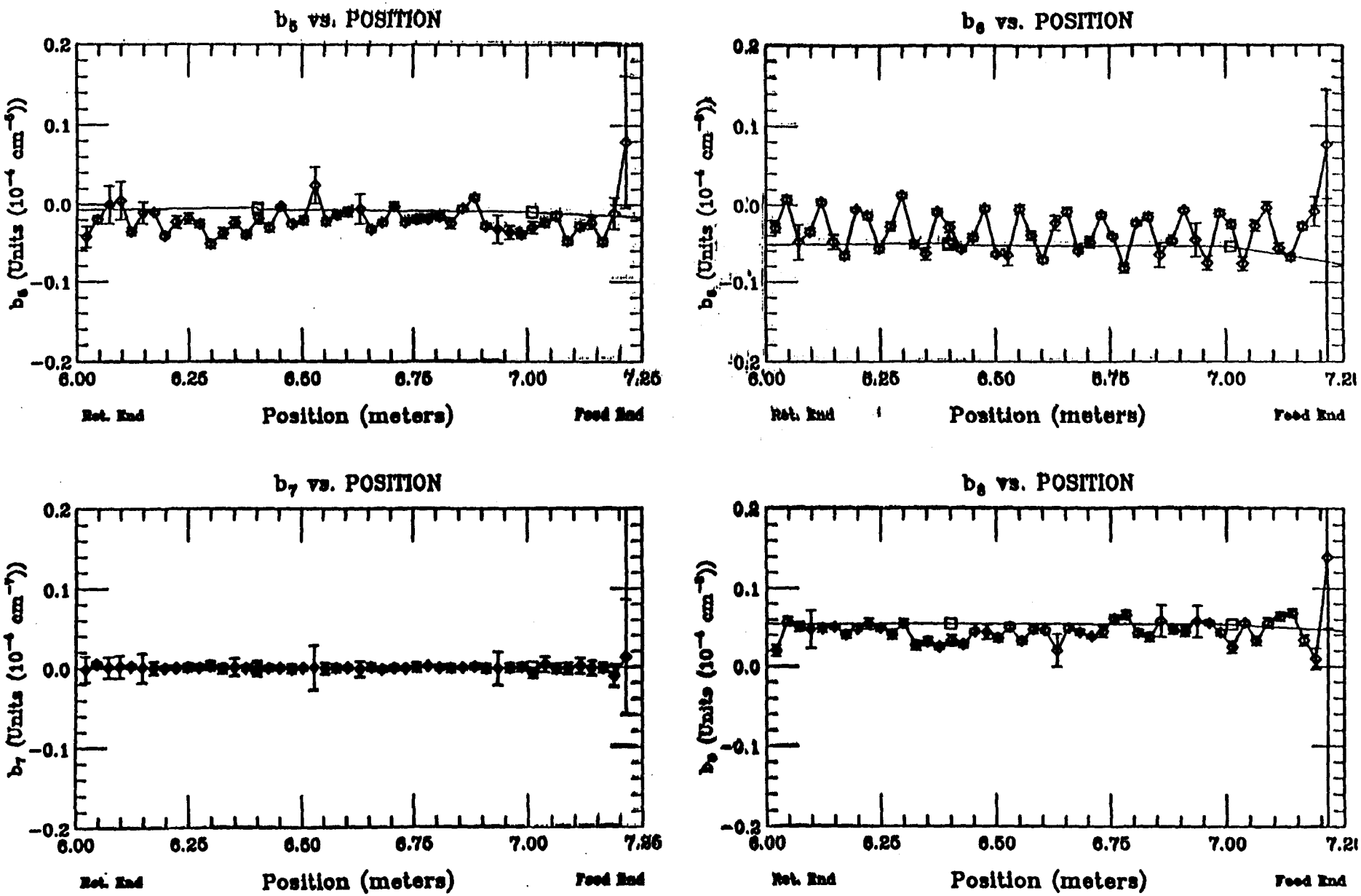

SSCL MAGNET DSB701
MCPMR 0.67 T, 656 A, 6 APR 1993
a4 (10−4 m−4)
10
8
6
4
0
−2
−4
−6
−8
−10
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
position (m)
APR6A4.GRF

a_n vs Position, DCA317 – file 520 and MCPMR series–A



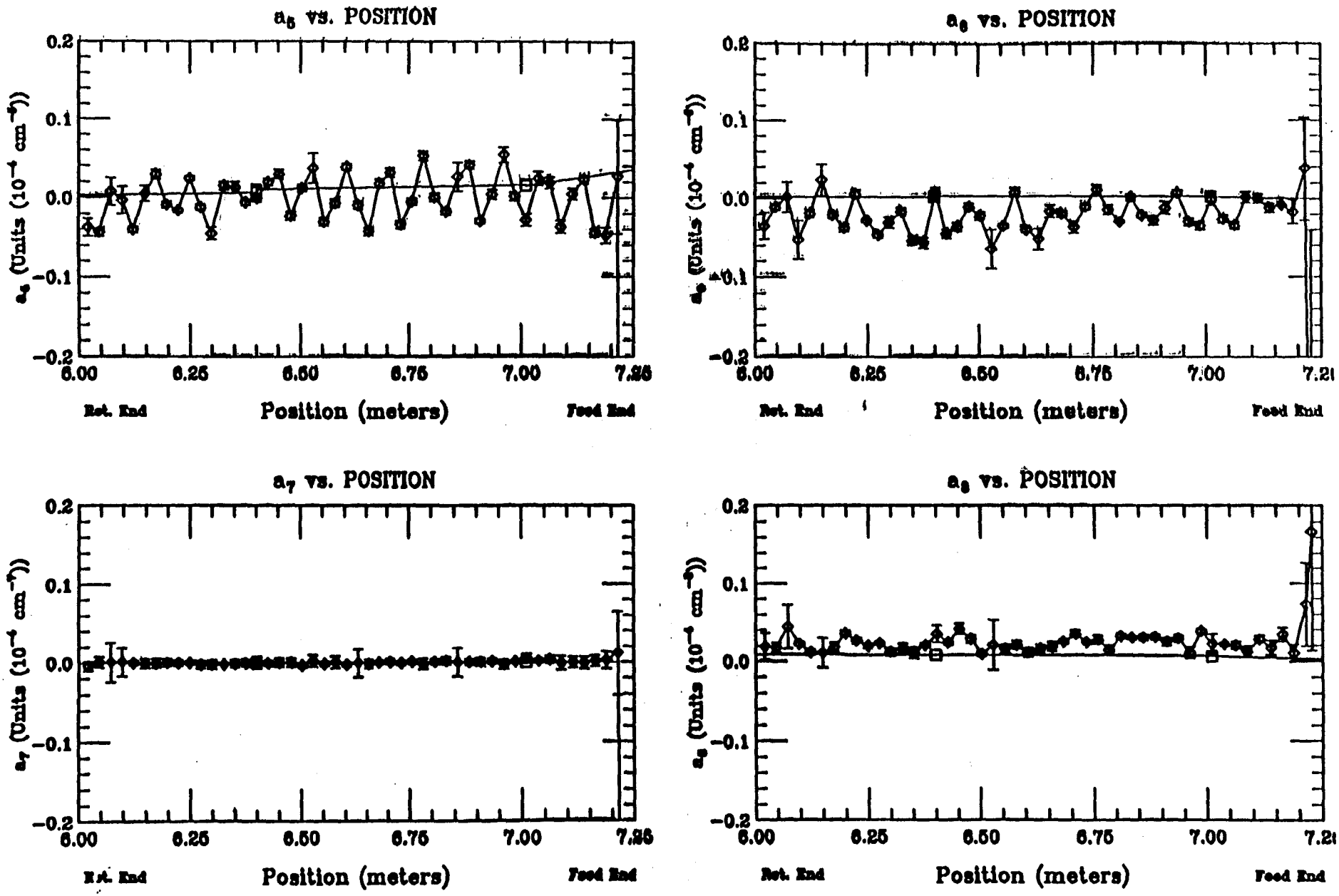
Cold measurement at .66T, 16/18 corrected

b_n vs Position, DCA317 – file 520 and MCPMR series–A



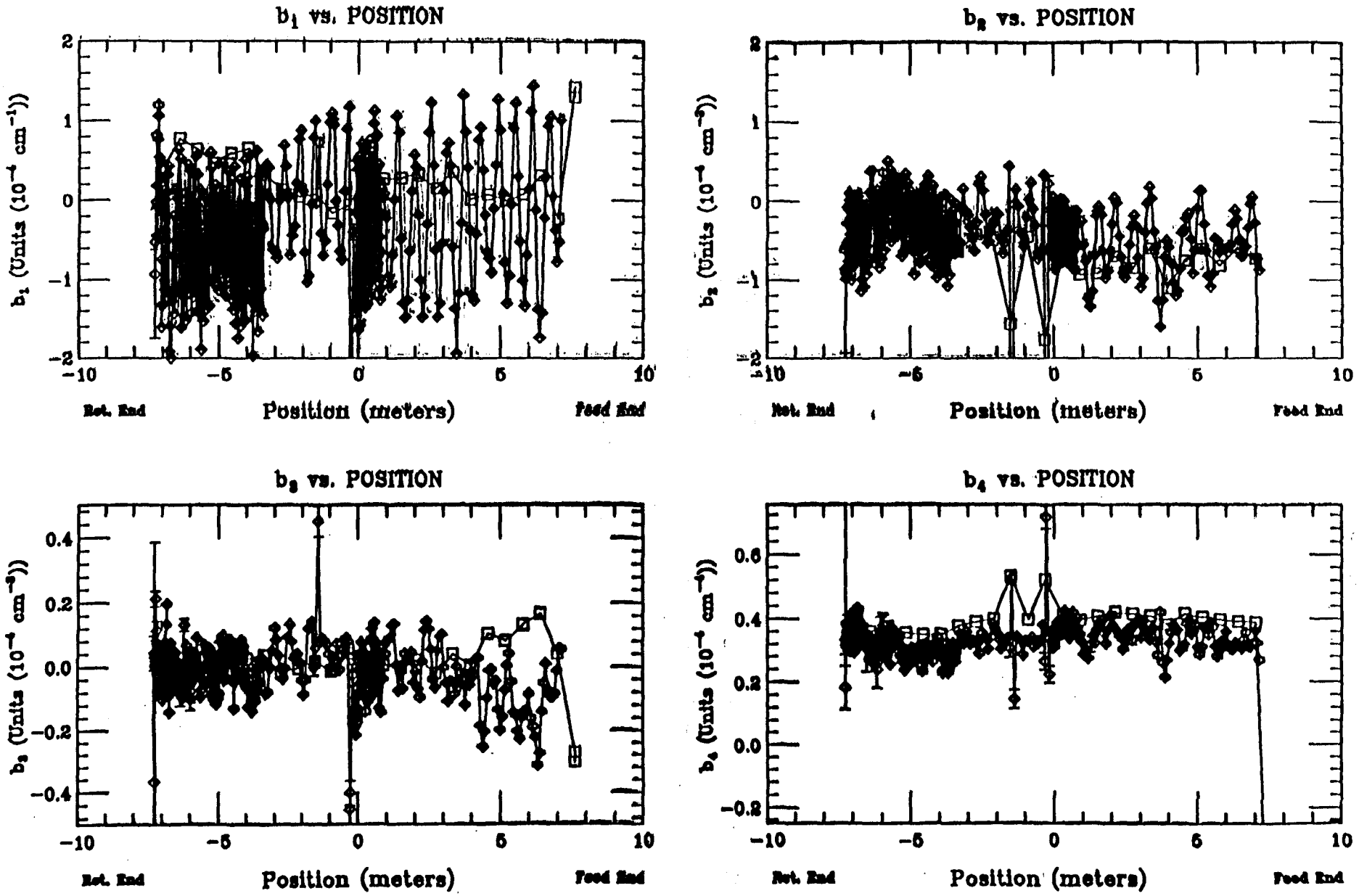
Cold measurement at .66T, 16/18 corrected

a_n vs Position, DCA317 – file 520 and MCPMR series–A



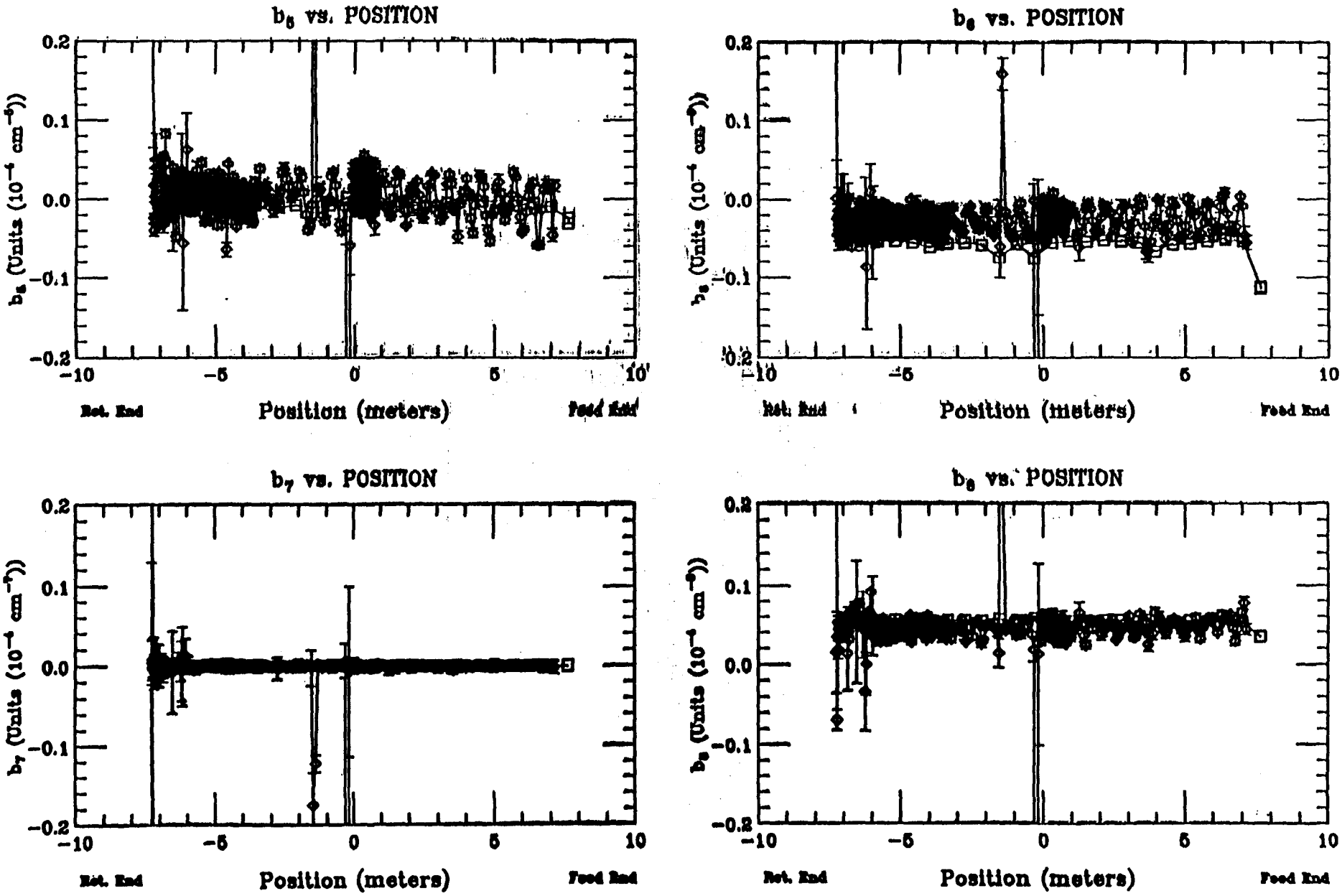
Cold measurement at .66T, 16/18 corrected

b_n vs Position, DCA317 – file 520 and MCPMR series–B



Cold measurement at .66T, 16/18 corrected

b_n vs Position, DCA317 – file 520 and MCPMR series–B



Cold measurement at .66T, 16/18 corrected

Summary

- Mole is a joint effort of BNL & SSCL
  SSC contributions are:
  - signal conditioning
  - data acquisition and control hardware and software
  - Precision coil construction, ceramics

- Lots of work ahead to reproduce moles at SSC (J. Krzywinski et al). All mole assembly to date done at BNL

- NMR (and soon ESR!) will be helpful to estimate high order multipole systematic uncertainties

- Maintaining calibrations will be a big effort. Does anybody have a long (72") dipole or quadrupole they can give us?

Bean

Pipe

ND

Beam pipe size

- 33 mm beam pipe makes field quality measurements very difficult
- Mole OD is 29.6 mm
- Cannot be easily reduced below 28.2 mm without major NRE
  - encoder size limitation
  - quite fragile at 28.2
- Estimate heat leak from anticryostat (Q.S. Shu)
- 30-60 watt heat leak depending on surface emissivity and centering supports

IV. Conclusions

- standard-deviations of uncentered data are well below one sigma tolerances for magnet construction

- errors due to centering must be considered -

- We are working on a statement of a conservative error budget for multipole measurements which can be always be met in a production environment.

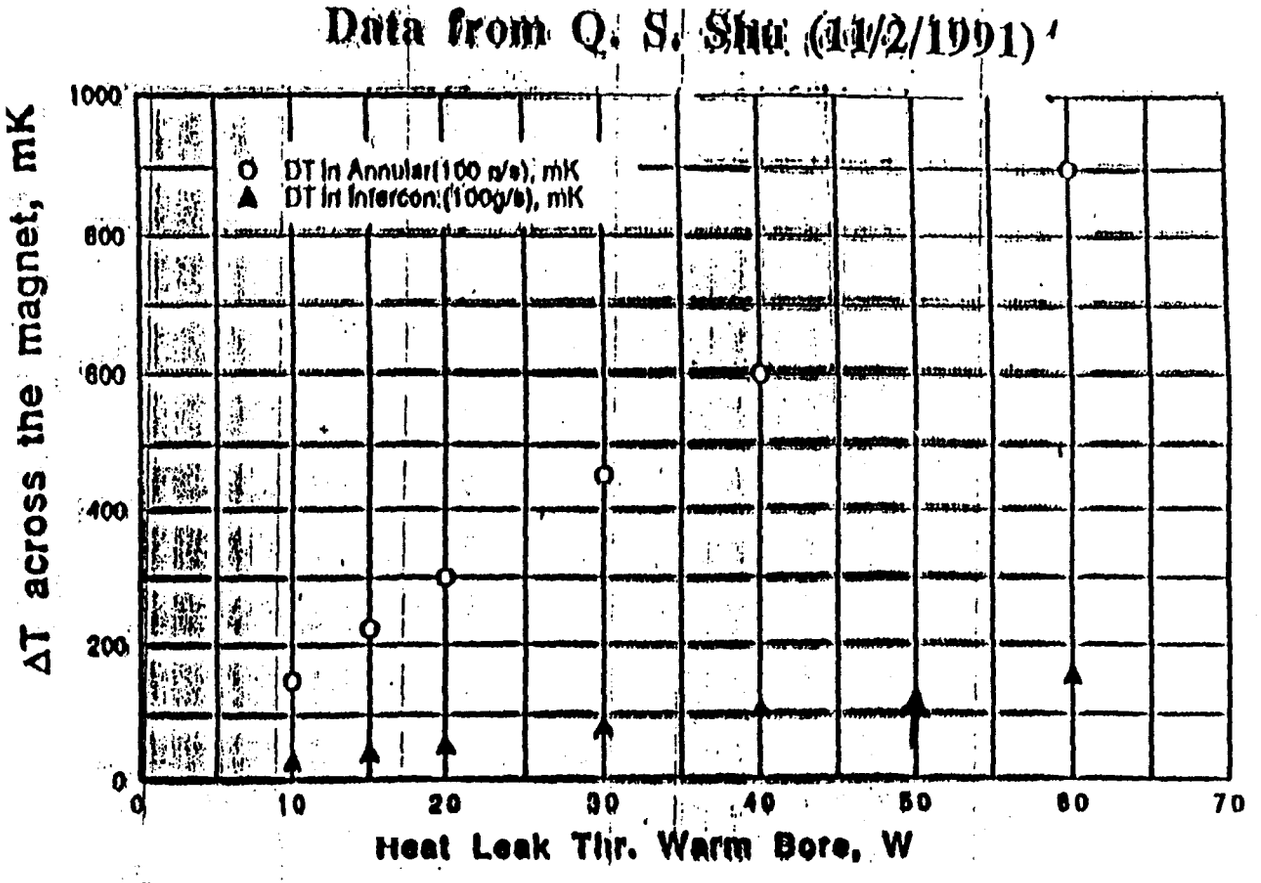


Fig. 4 Temperature increasing of single phase He across the magnet due to heat gain through beam tube by the warm bore.

Summary

Performance:

Systematic errors	~ 0.01 units	(b2)
Random errors	< 0.05 units	(a1- 10 meas)
Stability (100 days)	< 0.01 units	
	< 0.2 mrad	

Technology transfer from BNL in progress

SSCL data acquisition electronics
Coil form construction and winding
Mechanical drawings
Assembly training

Beam pipe

Increase heat load - tough design problem
Risk to downsize, cost, no obvious solution

L V L Mag. Meas. Group

GROUP LEADER: Bob Schermer R
DEPUTY G.L. : Don Nelson R
Physicist : Mike I. GREEN R
Computer Scientist : Paul Barale T
Technician : Dave Van Dyke

R ≡ retire November 1 1993
T ≡ Transfered

Mike Green & Bob Schermer
LBL GUEST SCIENTISTS
SSC
SLAC

Advanced Light Source

~ 200 Magnets

DIPOLES

Combined Function - DP/QD

QUADRUPOLES

sextupoles (ALS only)

Harmonic Analysis

Point H. P. Maps

Short Line Integral coils

ALS now commisioned

ALS Insertion Devices

- UNDULATORS -

Supercon Group

Clyde Taylor

10 T Dipole

SSCL Collider Ring
Prototype Quadrupoles
5 m long
40 mm bore

UNIX - VxWorks - VME
BNL Tangential coil

JULY

1) LEB QD
Fabricated & Tested

2) Several Resistive Magnets

3) Permanent Magnet Multipole
Magnets - Short
Single Block, DP, QD. 5X
50 & 100 mm bore

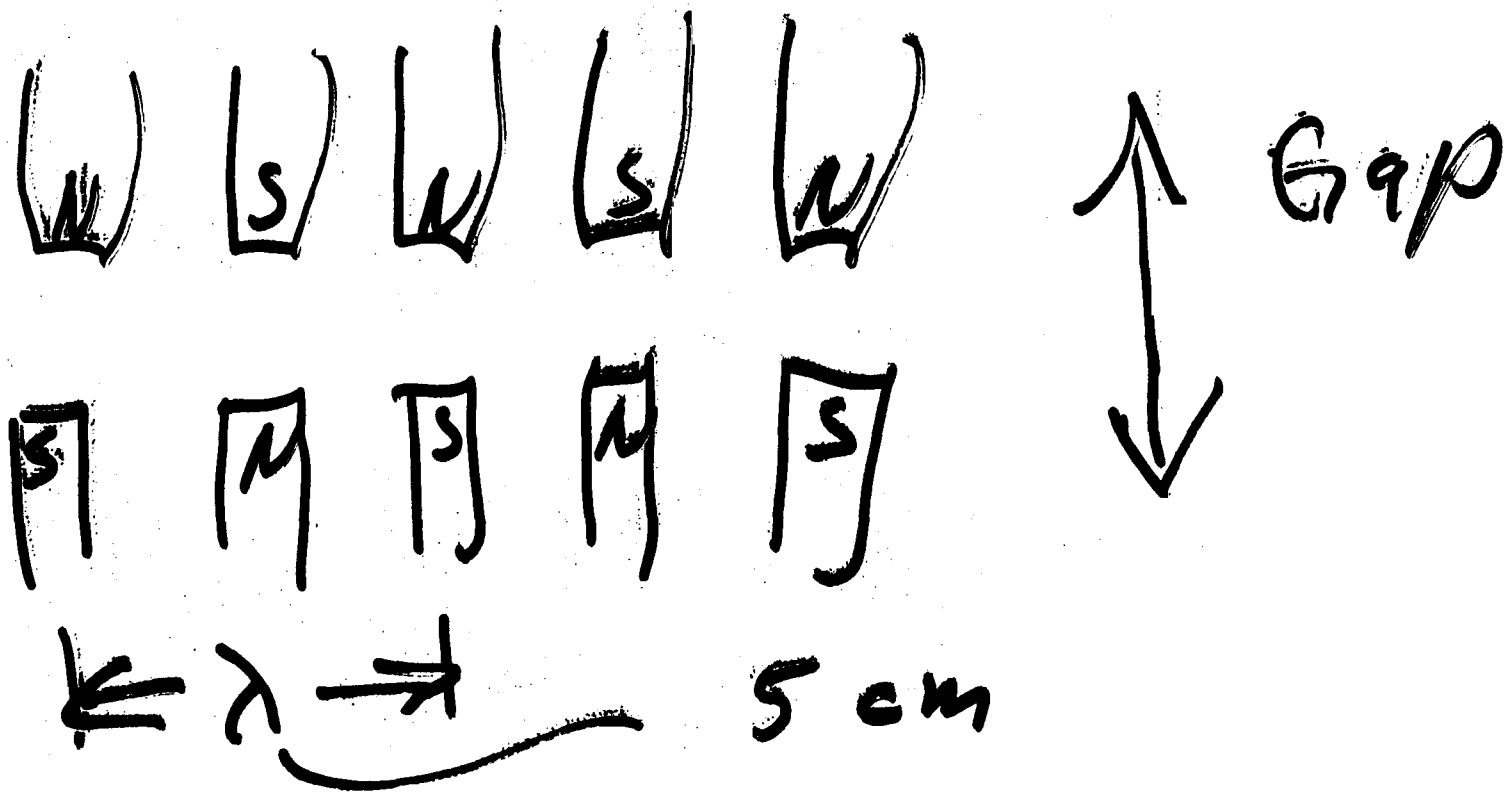
4) Bob Scherner
Chief Magnet Scientist - MSD

5) Mike Green
Accelerator Systems Division
Magnet Testing - Fiducialization

HLS Insertion Device Group

Steve Marks, Bill Hassenzahl
Carl Cook, AL Rubber
Paul Kownacki, Johanes Bahrdt
Dave Platte, John Carrieri
Brian Kincaid
Minor help from Paul Barale
and Mike Green

UNDULATOR / WIGGLER



~ 5 m long

ALS Insertion Device Requirements

Accelerator Requirements

Integrated Normal Dipole	< 100 G-cm
Double Integral of Normal Dipole	< 100 G-cm^2
Integrated Skew Dipole	< 500 G-cm
Integrated Normal Quadrupole	< 100 G
Integrated Skew Quadrupole	< 100 G
Integrated Sextupole	< 50 G/cm

Spectral Requirements

RMS Random Field Error	< 0.25%
Degradation of 5th Harmonic	< 30%

ALS Insertion Device
Magnetic Measurement Requirements

Hall Probe Measurements

Peak Field	±2.5 T
Accuracy, Repeatability	±1 G, ±0.5 G
Positioning Accuracy: z	2.5 μm
Positioning Accuracy: x, y	25 μm
Scan Range: z	6 m
Scan Range: x, y	±30 mm, ±105 mm
Temperature Variation	< 1° C

Integral Coil Measurements

Signal (dipole)	~100 μV-sec
Resolution	~10 μV-sec
Position Accuracy	< 1 mm

ALS ⊥ V Mapping

Hall Probe Scans

± 2.5 T peaks

± 1 G accuracy, ± 0.5 G repeatability

± 2.5 μm z accuracy

6 meter z scan

~40 seconds

~2500 points, $\Delta z \approx 2.2$ mm

2 ms integration time

~20 ms between points

Group 3 Hall Probe / Gauss Meter

OVERVIEW OF SLAC

M. I. GREEN

27 SEPTEMBER 1993

SLAC – SSRL Mag. Meas.

Group Leader: Joe Cobb Retired

Lead Tech: Dave Jensen Retired

Tech: Dan Jones Retired

Student: Louis Jaquez

M.I. Green helping until replacement for Joe is hired.

---

1) Replacement Magnets

2) B-Factory ?

3) Palladin Free Electron Laser from LLNL

SLAC - SSRL

IBM 286 & XT machines
Interpretive Basic
Harmonic Analysis
64 samples / Rev ⇒ DVM
average ~32 Revolutions
No Bucking Coils
Klinger x, y, z stage for
Hall Probe mapping.
NMR magnet - Metrolab
Schlumberger - only integrator
Halbach permeameter (LBL)

CEBAF MAGNET MEASUREMENT

Leigh Harwood and Jeffery Karn

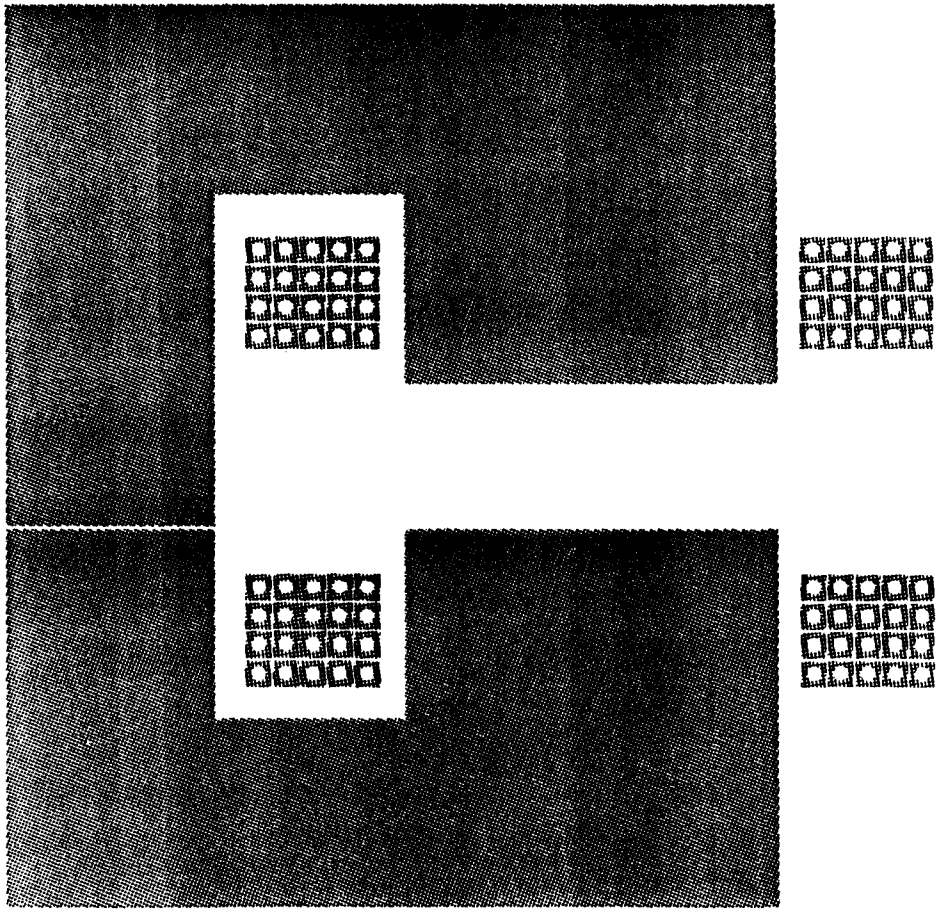
→ management → operations

OUTLINE

- Magnets and specifications
- Hardware
- Problems
- Results
- Summary

Typical dipole cross section

Core constructed from machined blocks of solid 1006 steel



MAGNET SPECIFICATIONS

- Major Dipoles
  - 382 magnets (1-3 m, 1-6 kG, "C", solid)
  - 12 circuits
    - Like magnets on a given circuits must match $\int Bdl$ ±0.1%
  - Common dipoles must $\int B(x)dl$ flat to 0.1% of 7 cm width
- Focusing & steering magnets
  - 1015 steering dipoles (need $\int Bdl$ to 5%)
  - 712 quadrupoles (most laminated, "hyperbolic" pole; B_2 accurate to 1%, B_6< 0.1% and B_{10}<0.2% at pole,and sum of others <0.1% at half-aperture
  - 104 sextupoles (B_6<0.5% and B_{10}<1% at pole)

HARDWARE

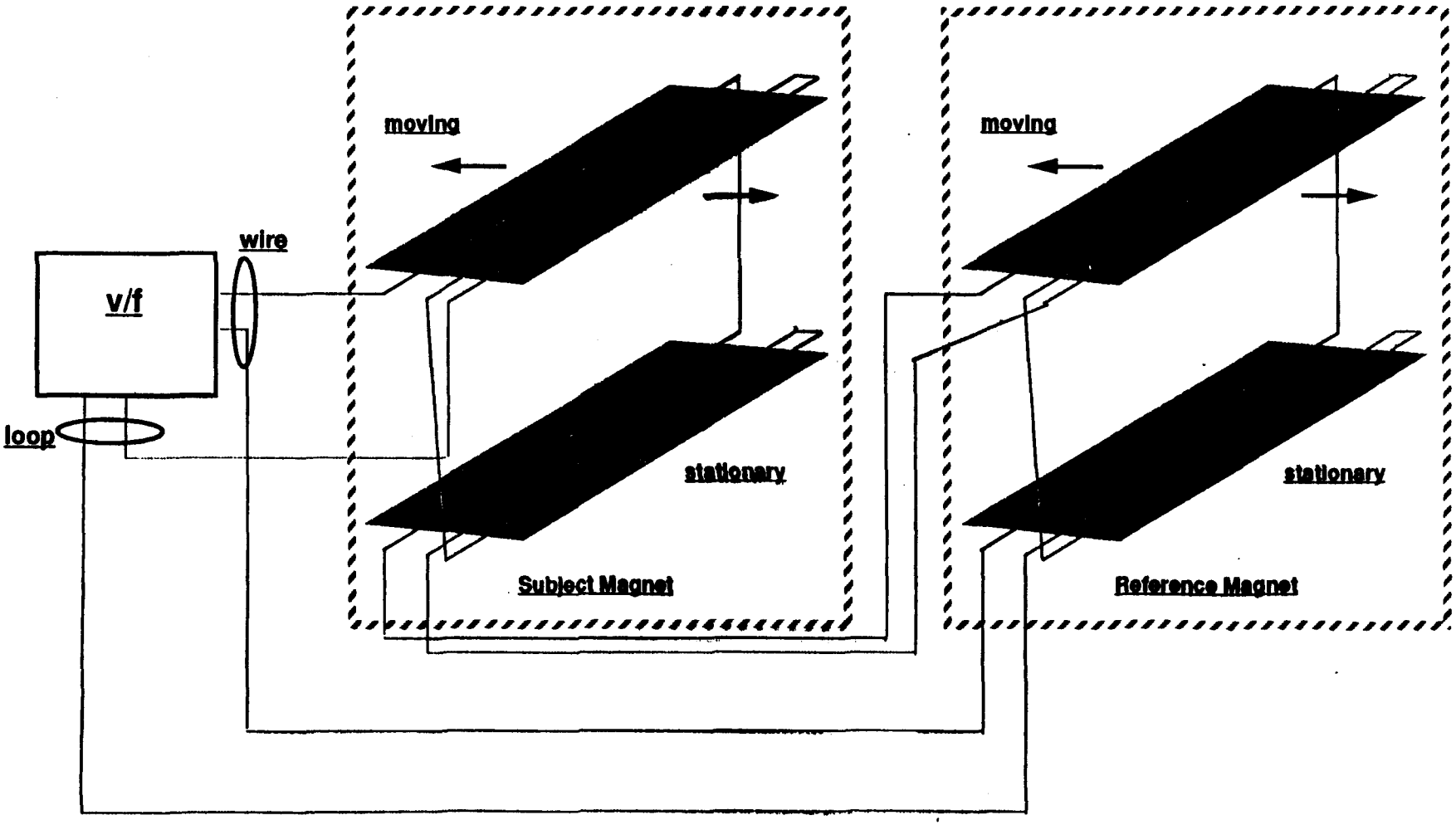
- General
  - Primarily interested in differences or errors -> signal-to-noise problems
    - Try for "zero" measurements whenever possible
    - Use bucking
    - Use a control ("standard") magnet to check for systemic changes
  - Interested infield integrals
    - Use stretched wire
      - 50-200 strand Litz wire loops (extra cost for E-tech's glasses after soldering)
      - Bipolar v/f
      - Electronic strobe for latching the scaler
      - Horizontal translation for dipoles; rotating for quads/sexts.

HP- UNIX - GPIB- CAMAC

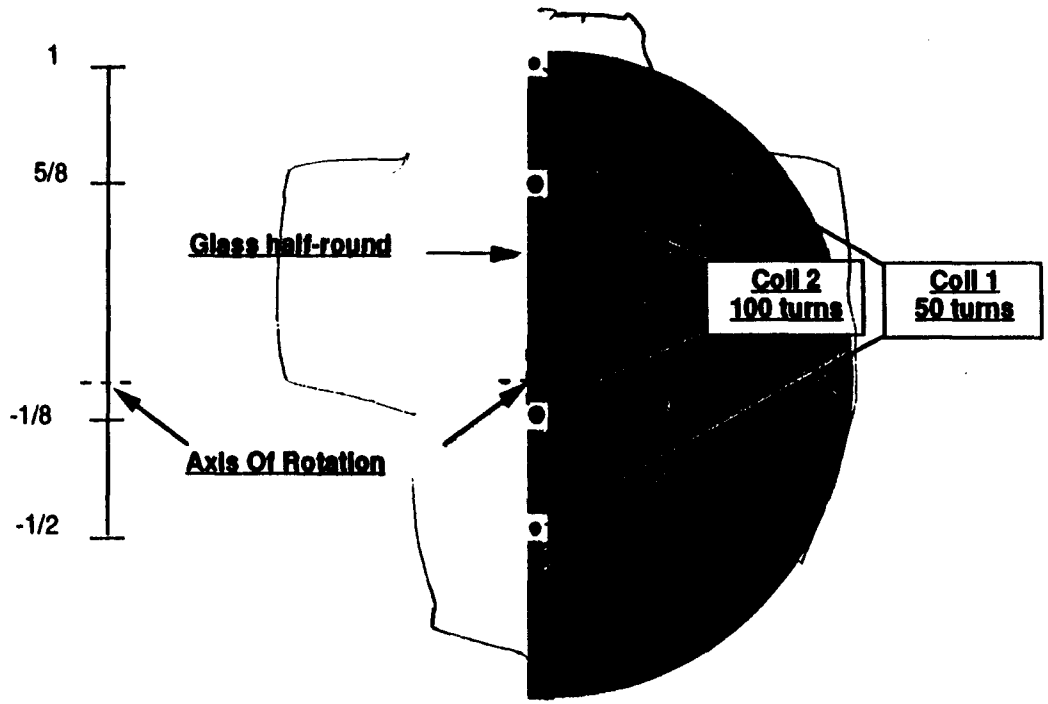
HARDWARE (cont'd)

- Dipoles
  - 3m long magnets -> 3.4 m stretched wire (magnet gap ≈ 2.5 cm)
  - Try loop and "single" wire circuits
    - Duplicates on both moving and stationary arms
    - Replicate above in a second ("reference") magnet; arms are physically joined
- Quadrupoles
  - "Halbach" coil for basic tests
  - "Full radius" coil for production
    - Bucking comes from having 2 magnets on the probe together

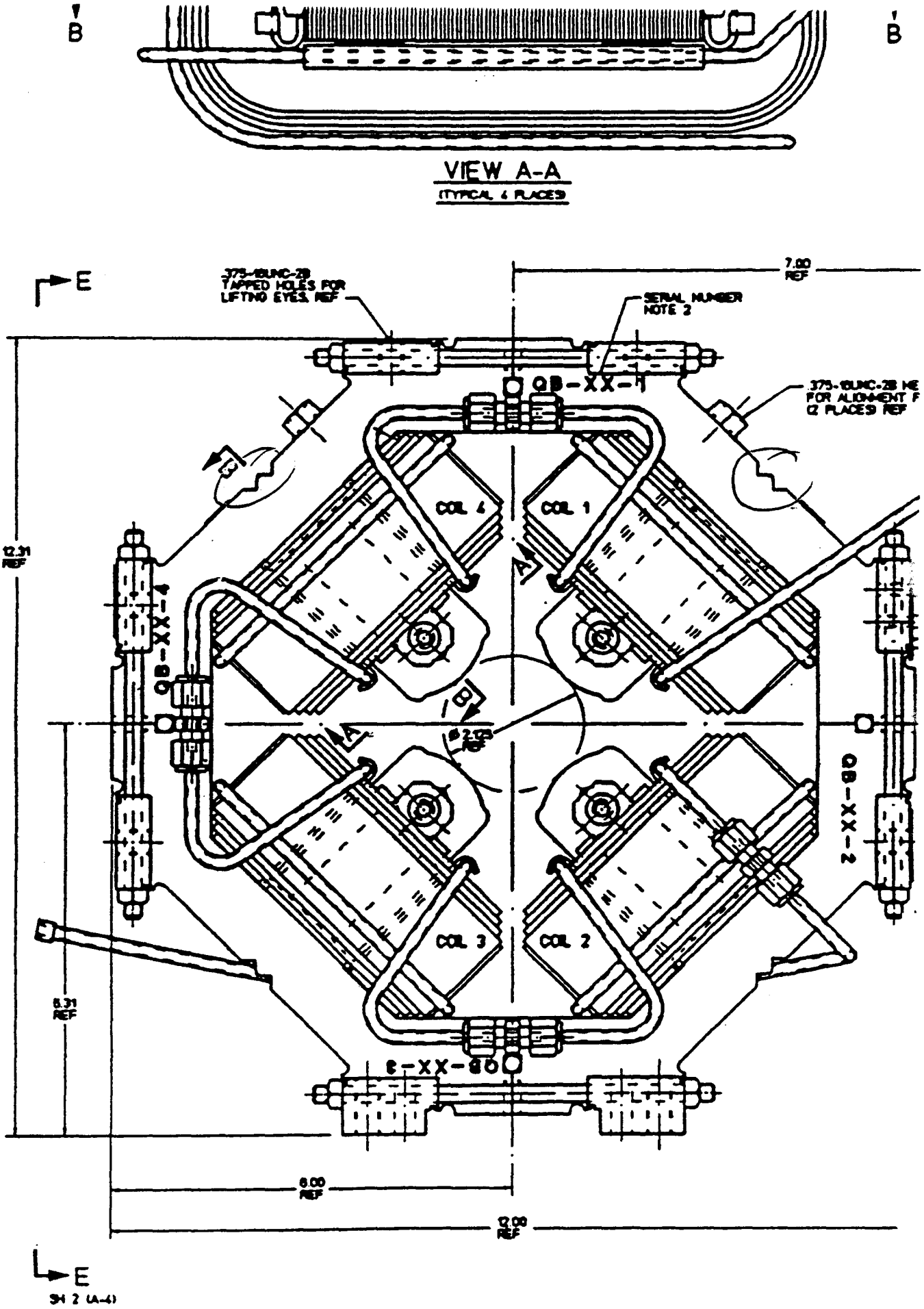
Circuit diagram for dipole field measurement stand



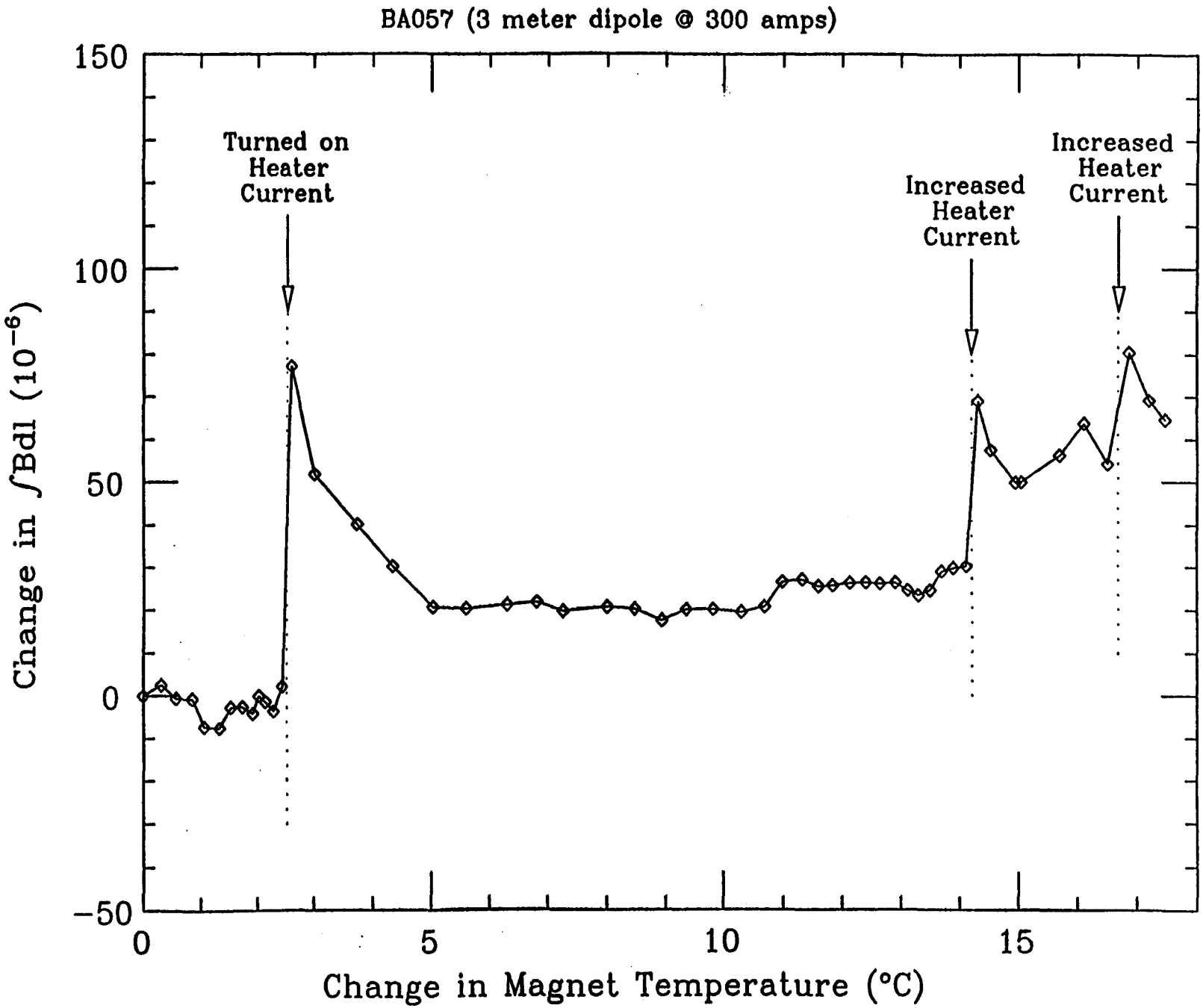
"Halbach" Bucked Coil Geometry



Coil 1 - Coil 2 ⟶ Dipole and quadrupole signals are cancelled


B
B
VIEW A-A
(TYPICAL 4 PLACES)
E
.375-16UNC-2B
TAPPED HOLES FOR
LIFTING EYES, REF
SERIAL NUMBER
NOTE 2
7.00
REF
QB-XX-1
COIL 4
COIL 1
COIL 3
COIL 2
QB-XX-4
QB-XX-2
QB-XX-3
12.31
REF
8.31
REF
6.00
REF
12.00
REF
E
SH 2 (A-4)

Arc Dipole – Thermal Effect on Field Integral



Relations used to extract ∫Bdl differences

$$\Delta_i^j = \int Bdl_i - \int Bdl_j$$

$$= \left[\int Bdl_i - \int Bdl_{\text{reference magnet}}\right] - \left[\int Bdl_j - \int Bdl_{\text{reference magnet}}\right]$$

$$= \left\{\left[\int Bdl_i - \int Bdl_{\text{reference magnet}}\right] - \left[\int Bdl_{\text{standard magnet}} - \int Bdl_{\text{reference magnet}}\right]\right\}_n -$$

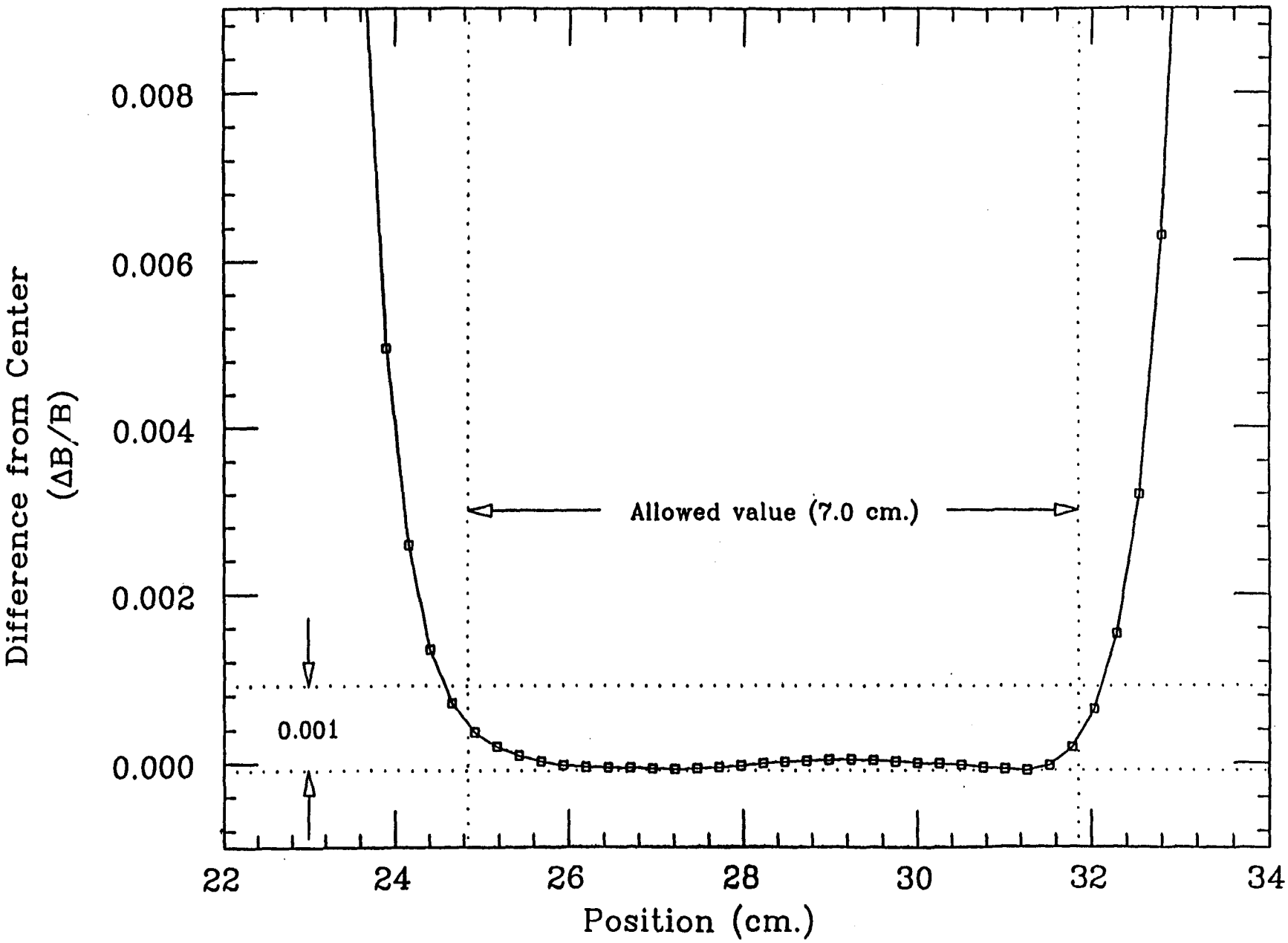
$$\left\{\left[\int Bdl_j - \int Bdl_{\text{reference magnet}}\right] - \left[\int Bdl_{\text{standard magnet}} - \int Bdl_{\text{reference magnet}}\right]\right\}_m$$

PROBLEMS

- General
  - Lots of "hash"
  - green site
- Dipoles
  - Non-uniform step sizes
- Quadrupoles
  - Radius of "full radius" probe varied by a few parts in a thousand at different long. positions
    - » Optimized bucking needed a shunt across the "reference"

Dipole Field Profile

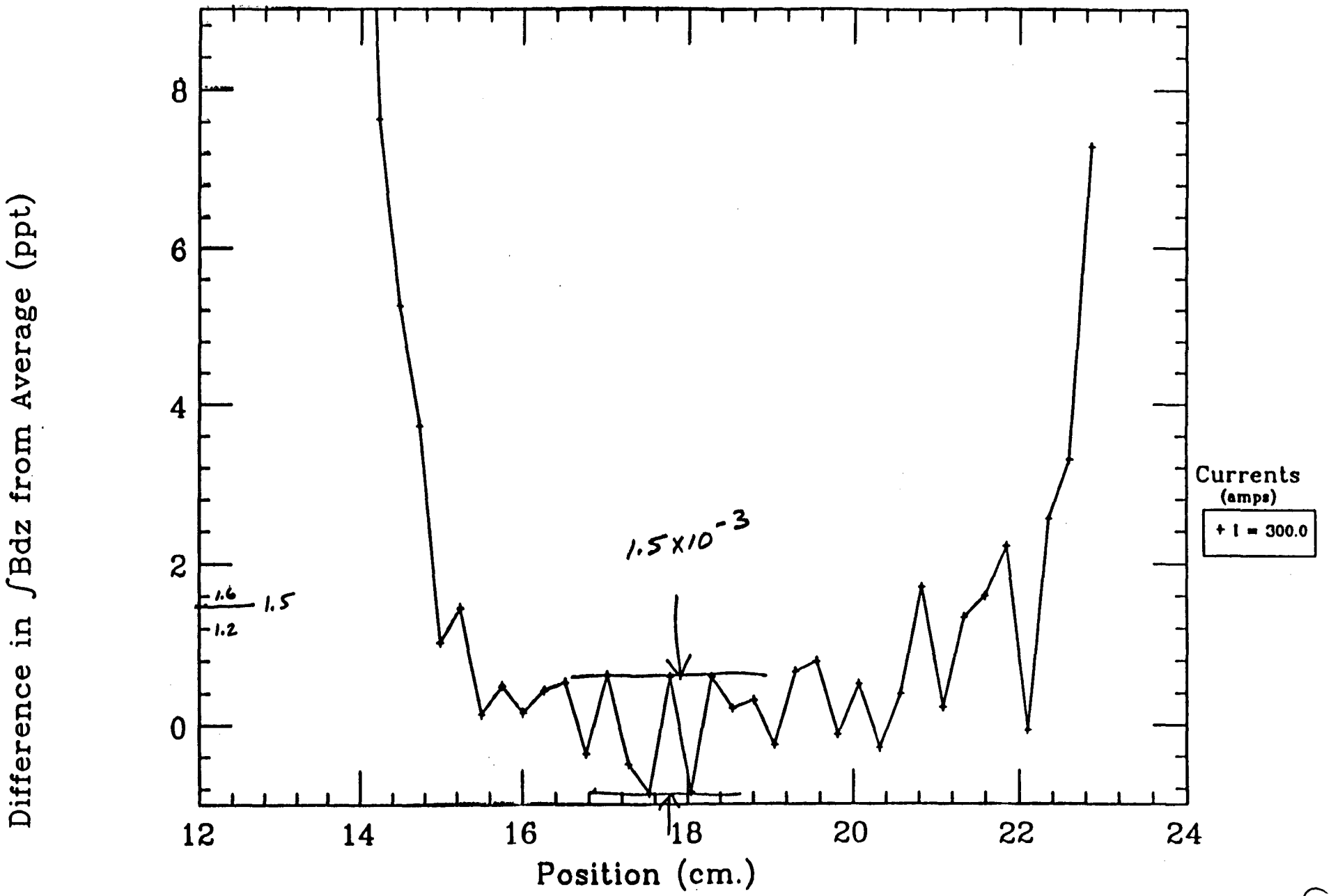
Data : 03/21/92
Plot : 03/17/92
JC3_D.TOP



Transverse Deviation Profile

Data : 07/16/93
Plot : 09/13/93

BA05102 (Single Wire Coil - Unbucked)

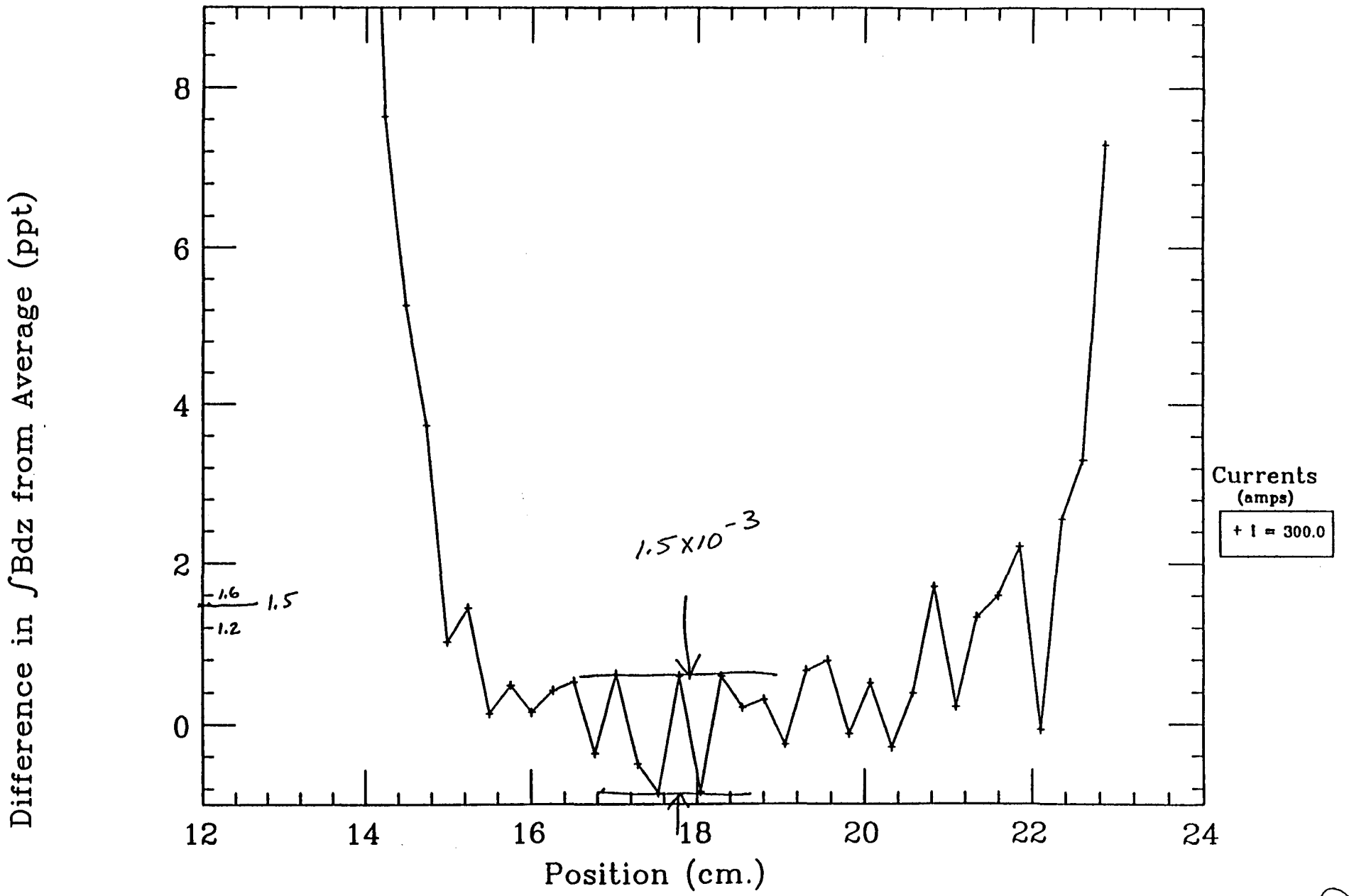


05102-03_DEV_PROF.TOP

Transverse Deviation Profile

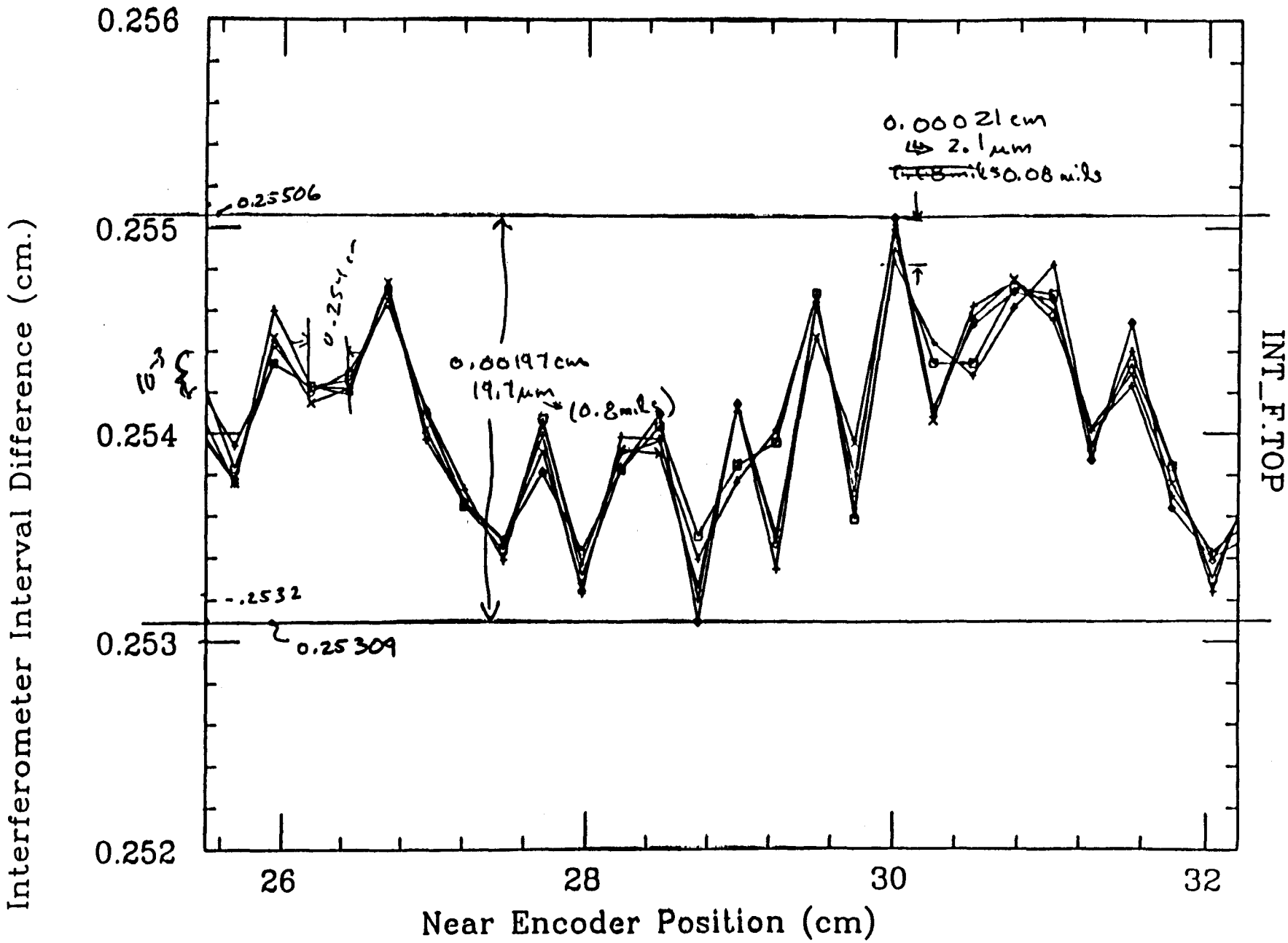
Data : 07/16/93
Plot : 09/13/93

BA05102 (Single Wire Coil – Unbucked)



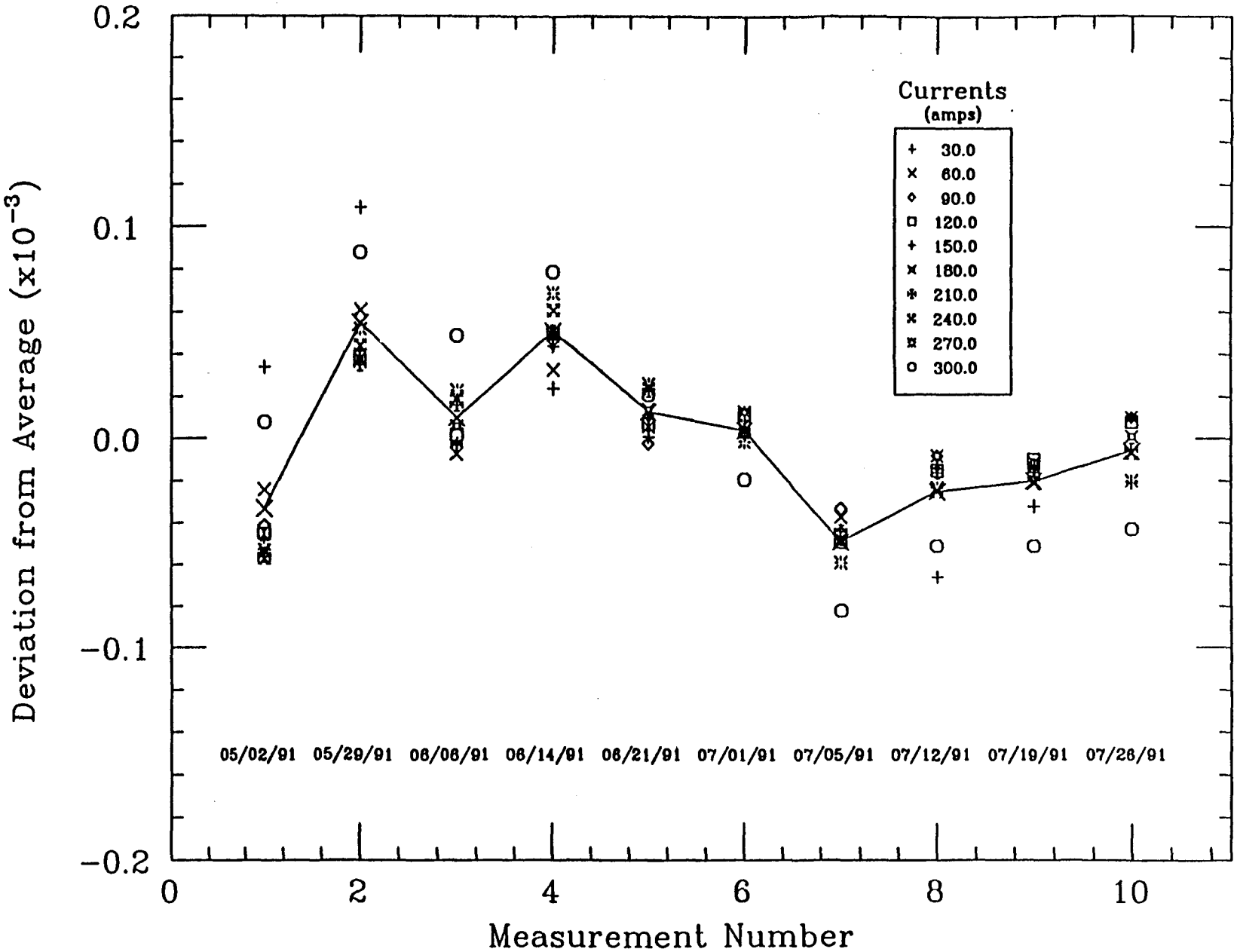
BA05102-03_DEV_PROF.TOP

Interferometer vs. Encoder Position (Forward)



Arc Dipole – Standard Magnet Comparison

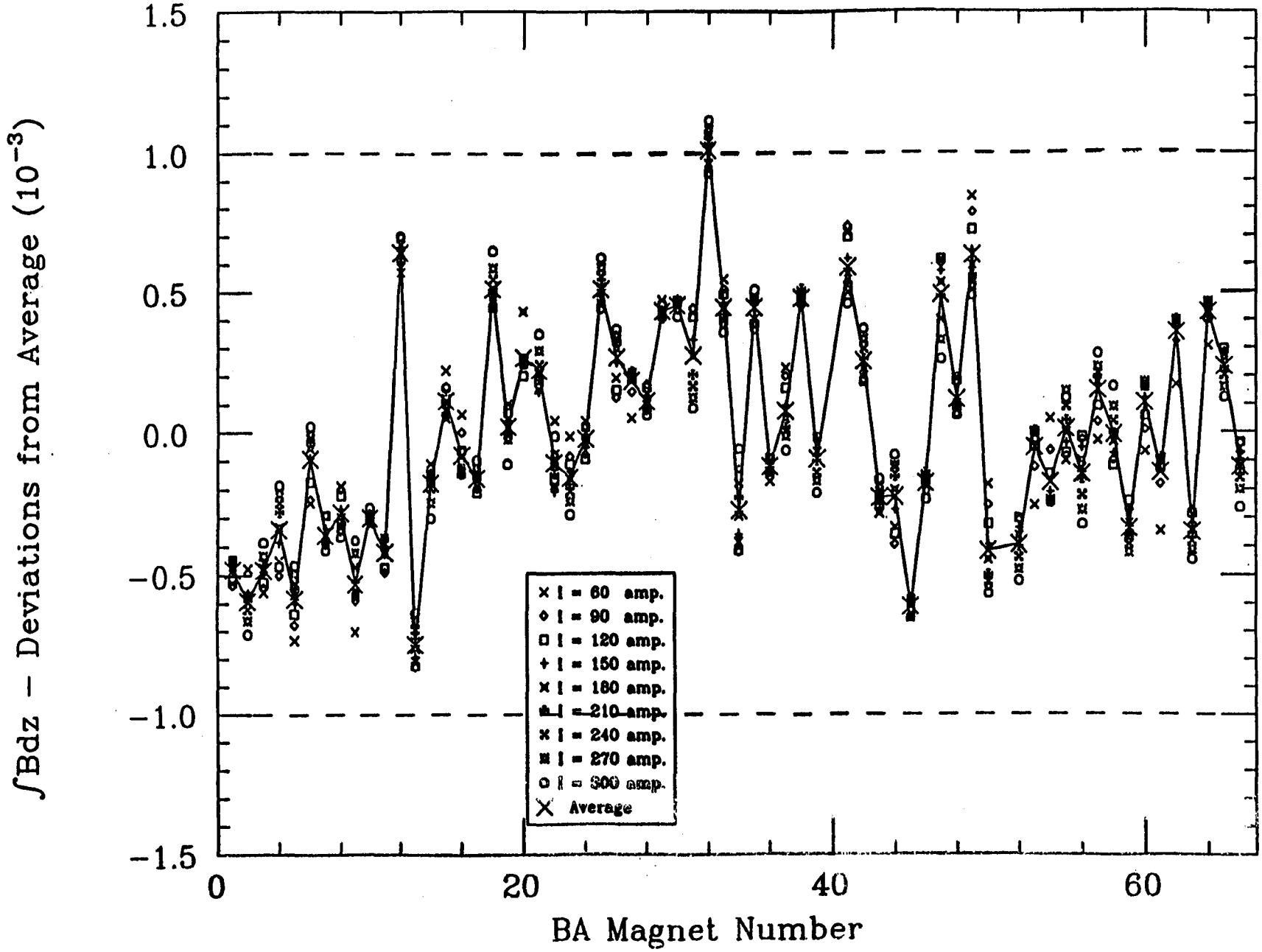
BE036 (Single Wire Coils – Bucked)



BA Magnet Comparison

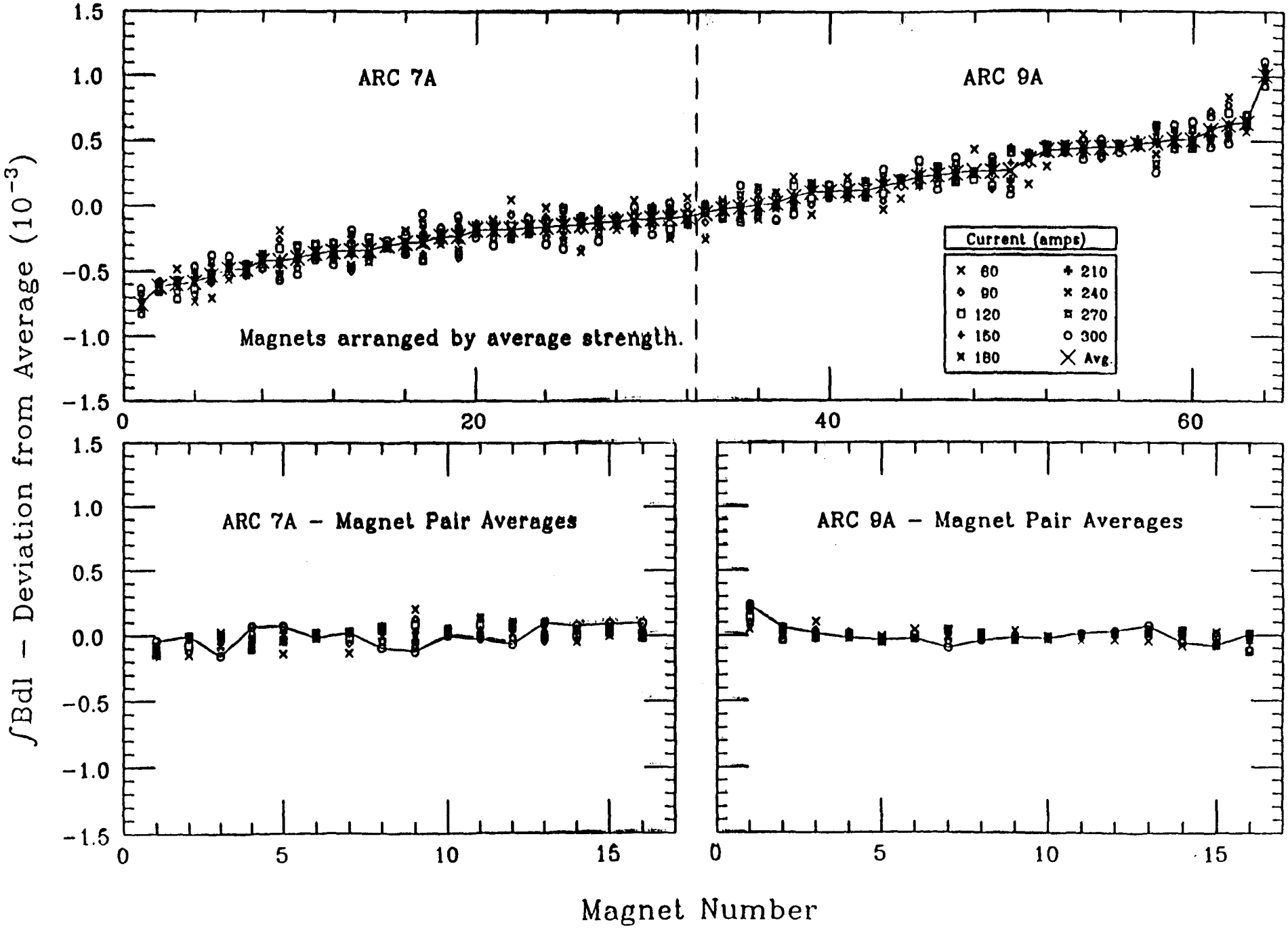
(Single Wire Coils – Bucked)

Plot : 01/24/92
PLOT_43.TOP



Arc Dipole – Production Comparison

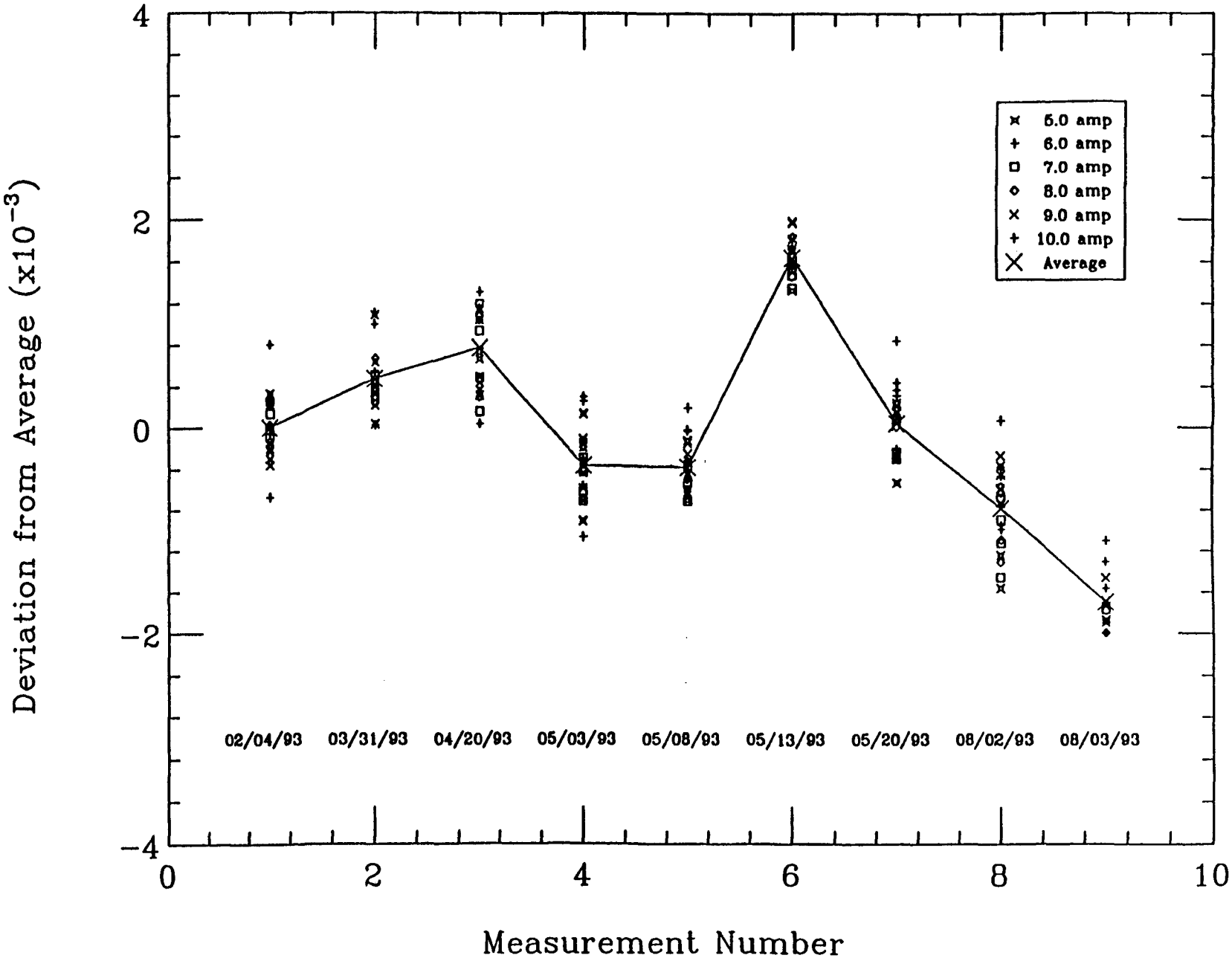
(64) – 3 meter, BA Magnets



Type	Number	Style	Effective length (cm)	Aperture diameter (cm)	Field @ pole (G)	Allowed multipole content (Spec/achieved) (@ 1/2 aperture unless otherwise noted; 0.1% of fundamental harmonic)		
Quadrupoles						Dodecapole (@full aperture)	Icosapole (@ full aperture)	Sum of symmetry breaking multipoles
QA	472	laminated, iron dominated	30	2.9	4200	1.0/0.25	1.0/1.2	1.0/0.25
QB	137	"	15	5.4	2450	1.0/0.5	1.0/1.2	1.0/0.25
QC	75	"	30	5.4	1930	1.0/0.25	1.0/1.2	1.0/0.25
QD	18	solid, "Panofsky"	15	4.1	200	4.0/3.0	2.0/0.8	1.0/0.4
QJ	5	"	7.5	11.6	25	4.0/2.0	2.0/0.6	1.0/1.0
Sextupoles							Sum of octupole and higher	
SA	56	solid, 3 coils	15	2.9	551		5.0/1.8	
SB	48	"	15	5.4	292		5.0/1.2	
Correctors						Quadrupole (@ full aperture)	Sum of sextupole and higher	
BD	32	solid,"window", backleg coil	15	4.1	933	0.5/0.5	1.0/0.8	
BS	10	"	15	4.1	230	5.0/3.0	5.0/4.0	
BC	642	solid, "C", backleg coil	15	2.9	630	15.0/6.0	15.0/6.0	
BM	48	"	15	5.4	550	27.0/0.6	27.0/0.7	
BT	276	"	15	5.4	110	27.0/6.0	27.0/6.0	

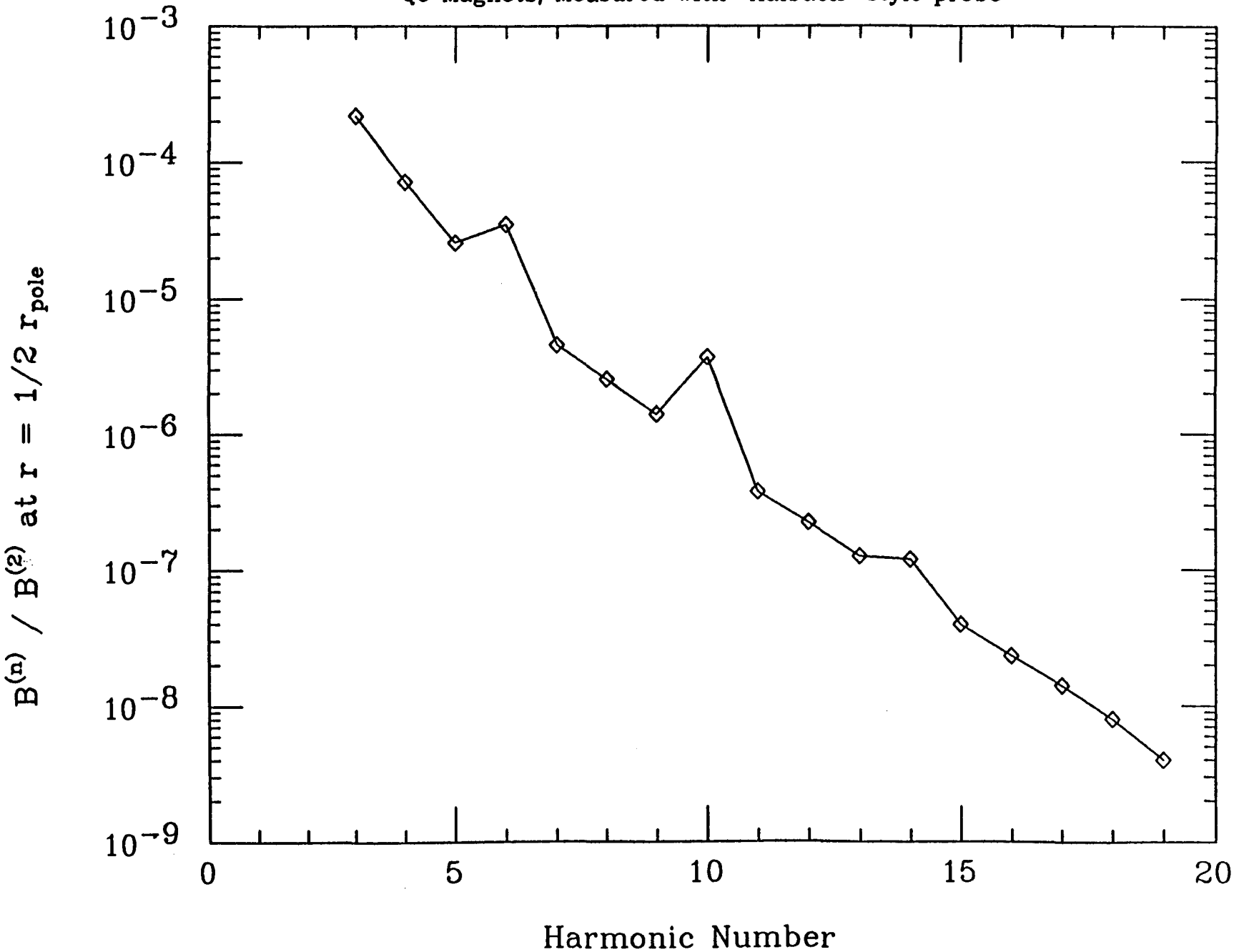
Quadrupole – Standard Magnet Comparison

QA079 (Bucked Magnets)



Quadrupole – Harmonic Summary

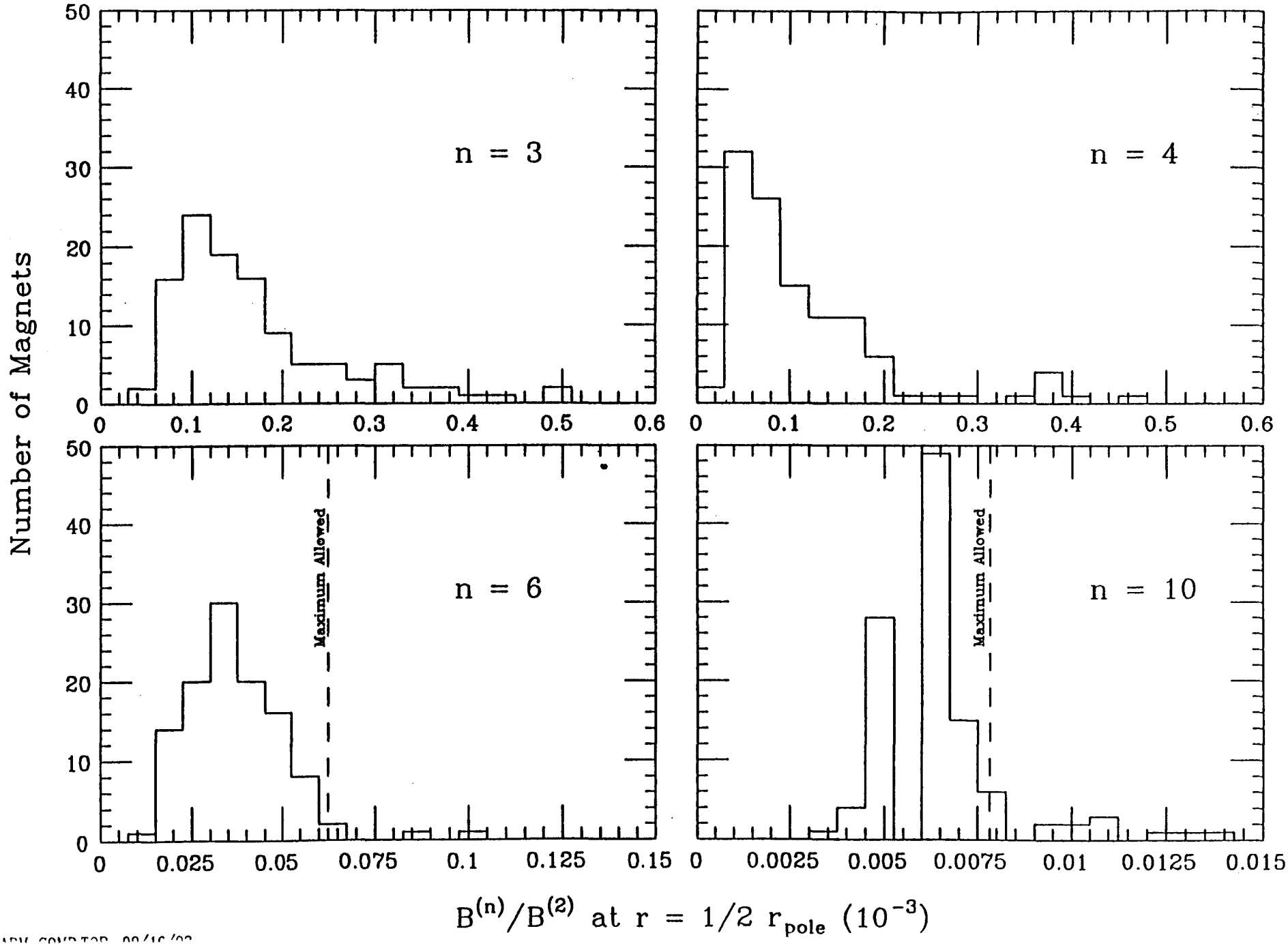
QC Magnets, Measured with "Halbach" style probe



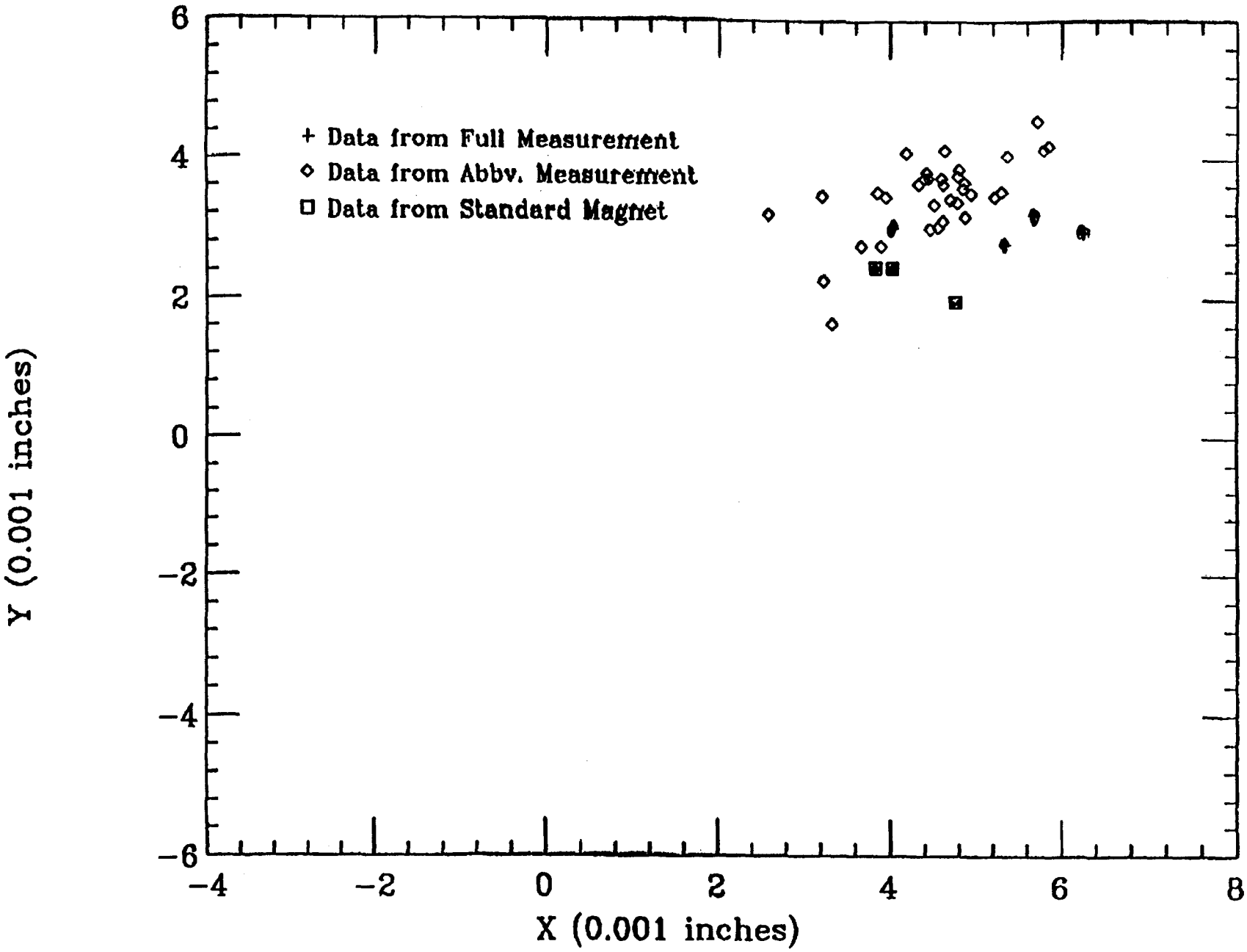
QC_07.TOP (09/16/93)

Quadrupole – Production Harmonic Comparison

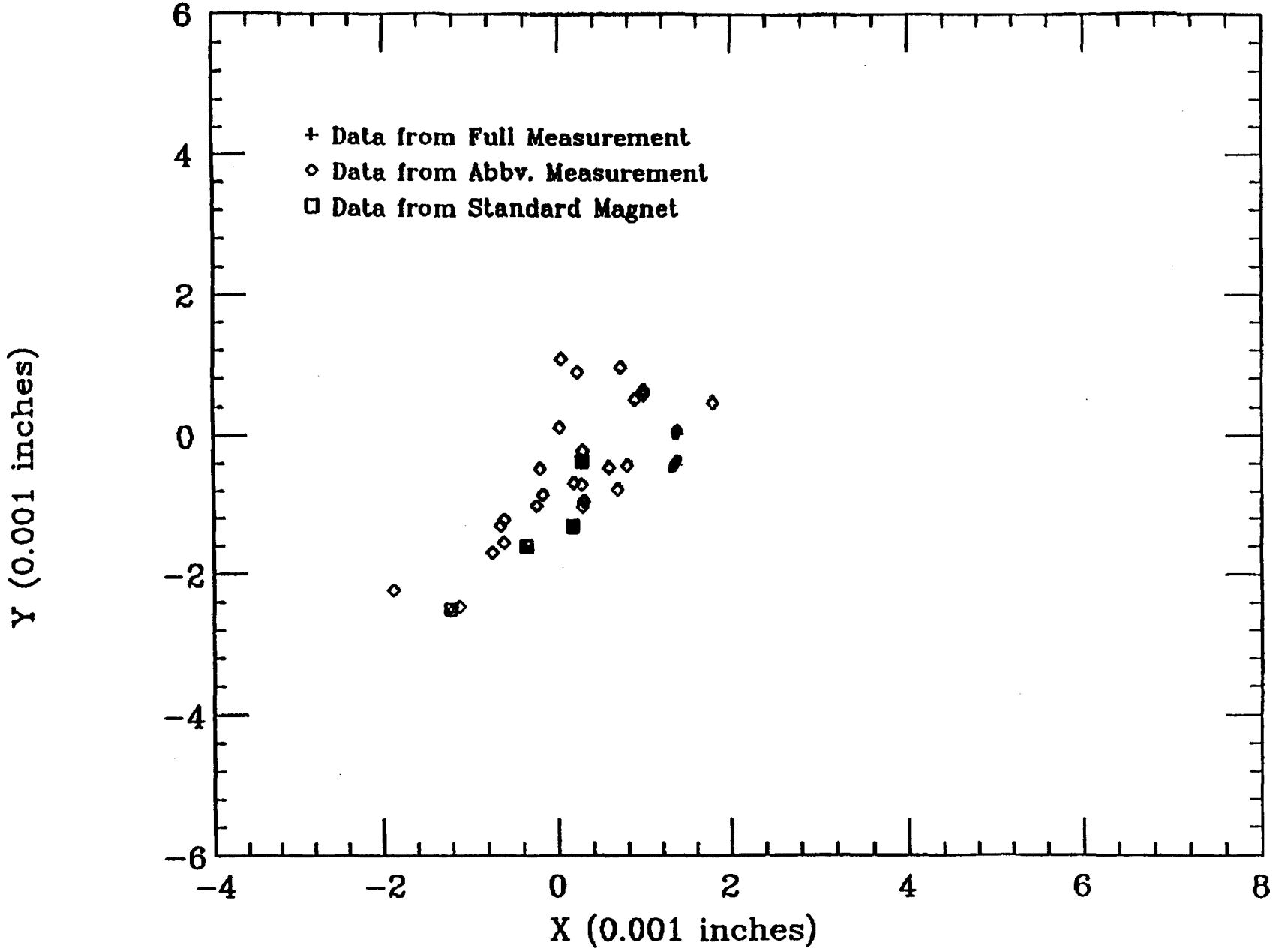
(113 QA Magnets)



AVERAGED MAGNETIC CENTER (QA's)



AVERAGED MAGNETIC CENTER (QA's)

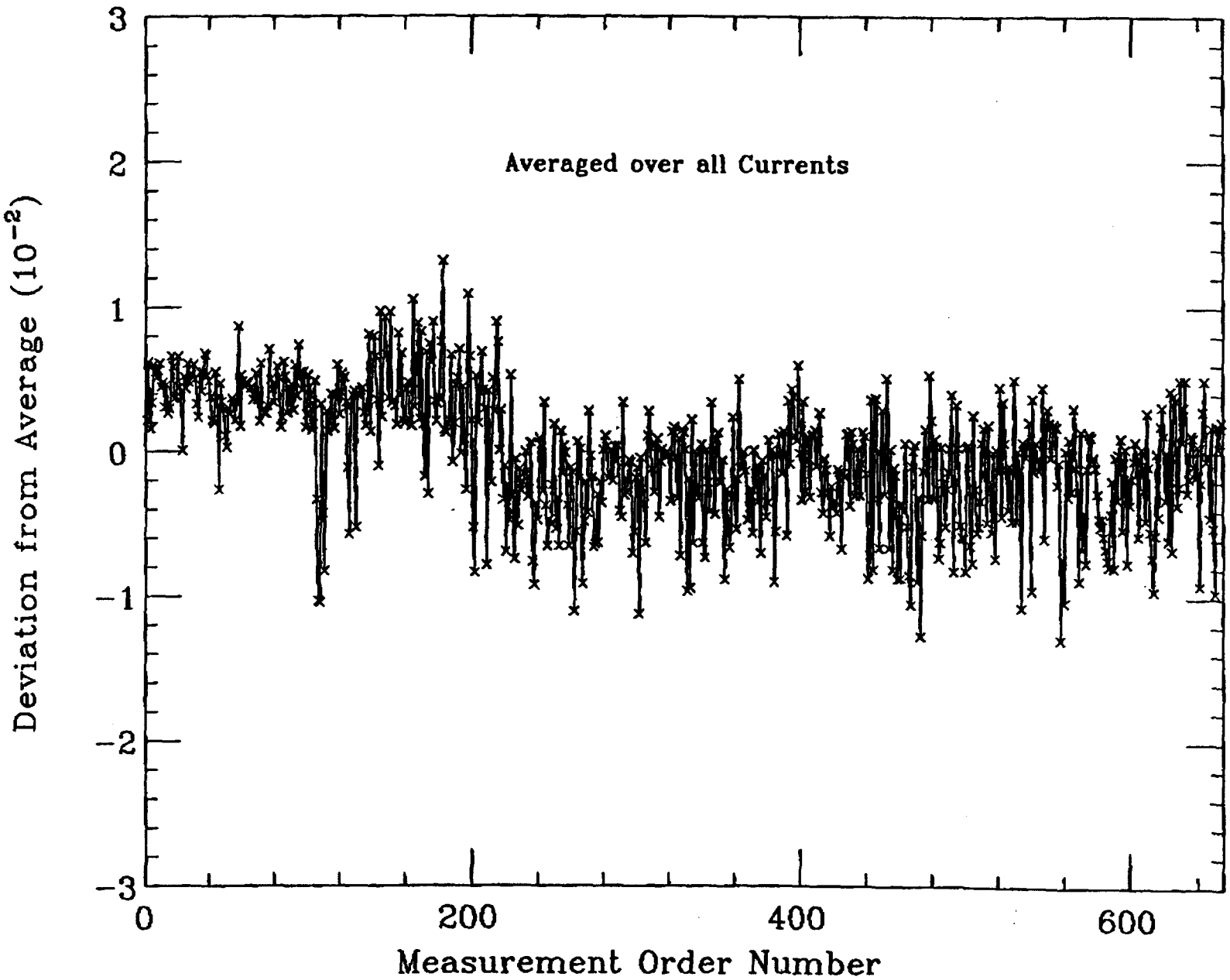


SUMMARY

- We're done
- System worked
  - Good precision
  - Good rate
- Anybody know how to do 10^{-5} absolute? $\int B dl \lesssim 0.1\ Tm$ $(0.04\ T \times 3m)$
-

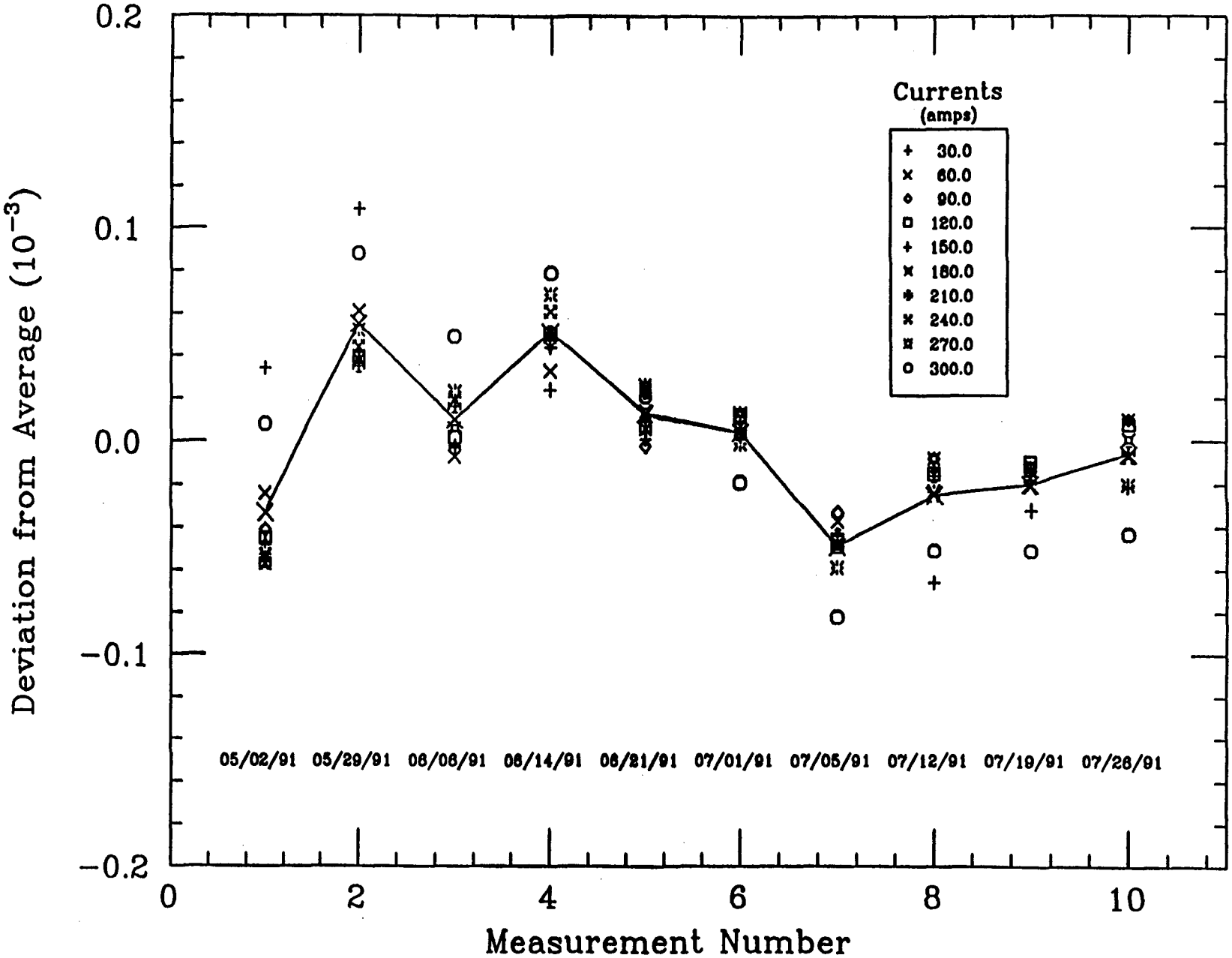
Corrector Dipole – Central Field Comparison

654 BC Magnets

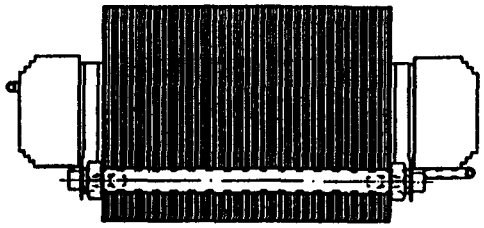


Arc Dipole – Standard Magnet Comparison

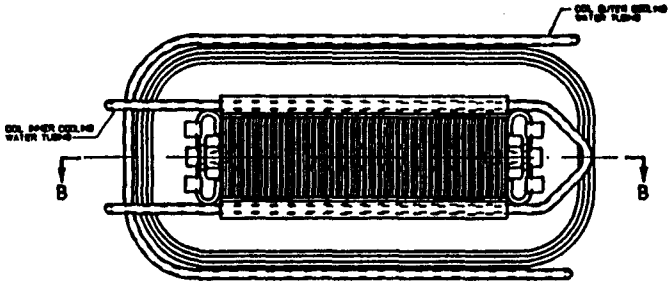
BE036 (Single Wire Coils – Bucked)



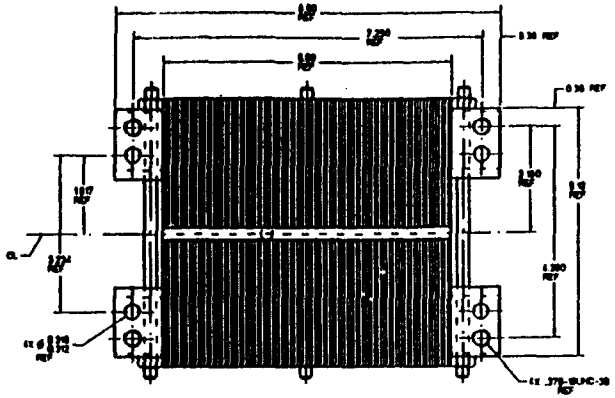
BE036_DEV.TOP (09/16/93)



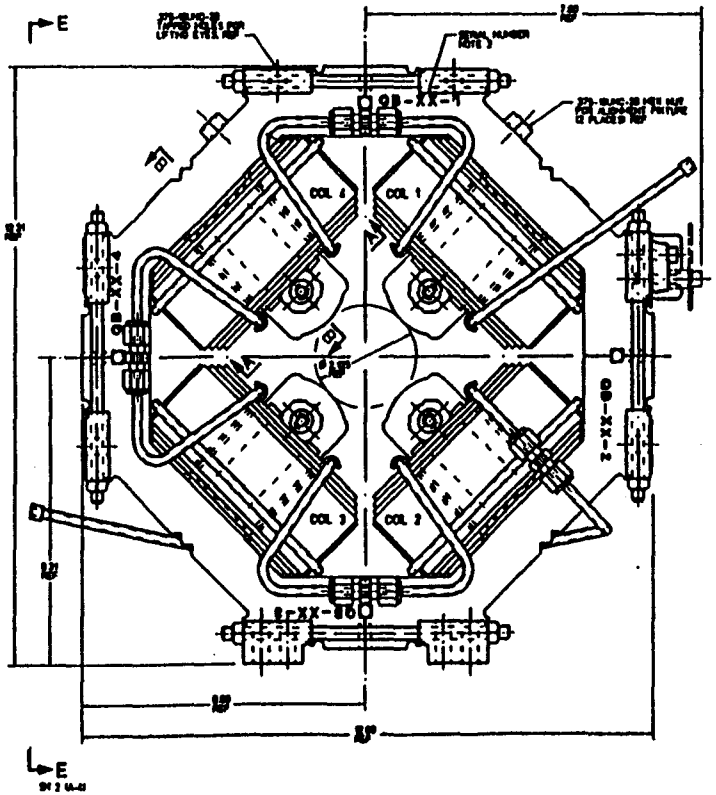
SECTION B-B

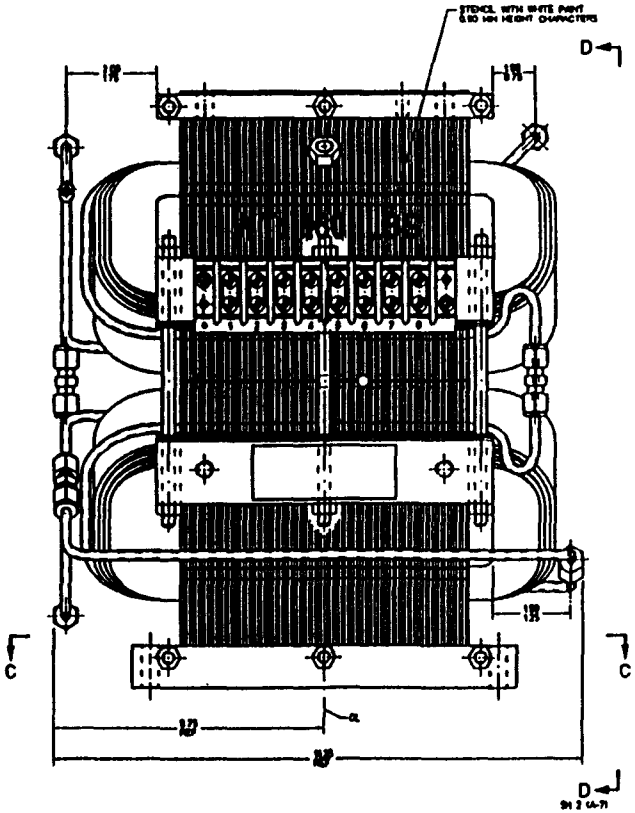


VIEW A-A



SECTION C-C





ARCS SCOPE DETAIL

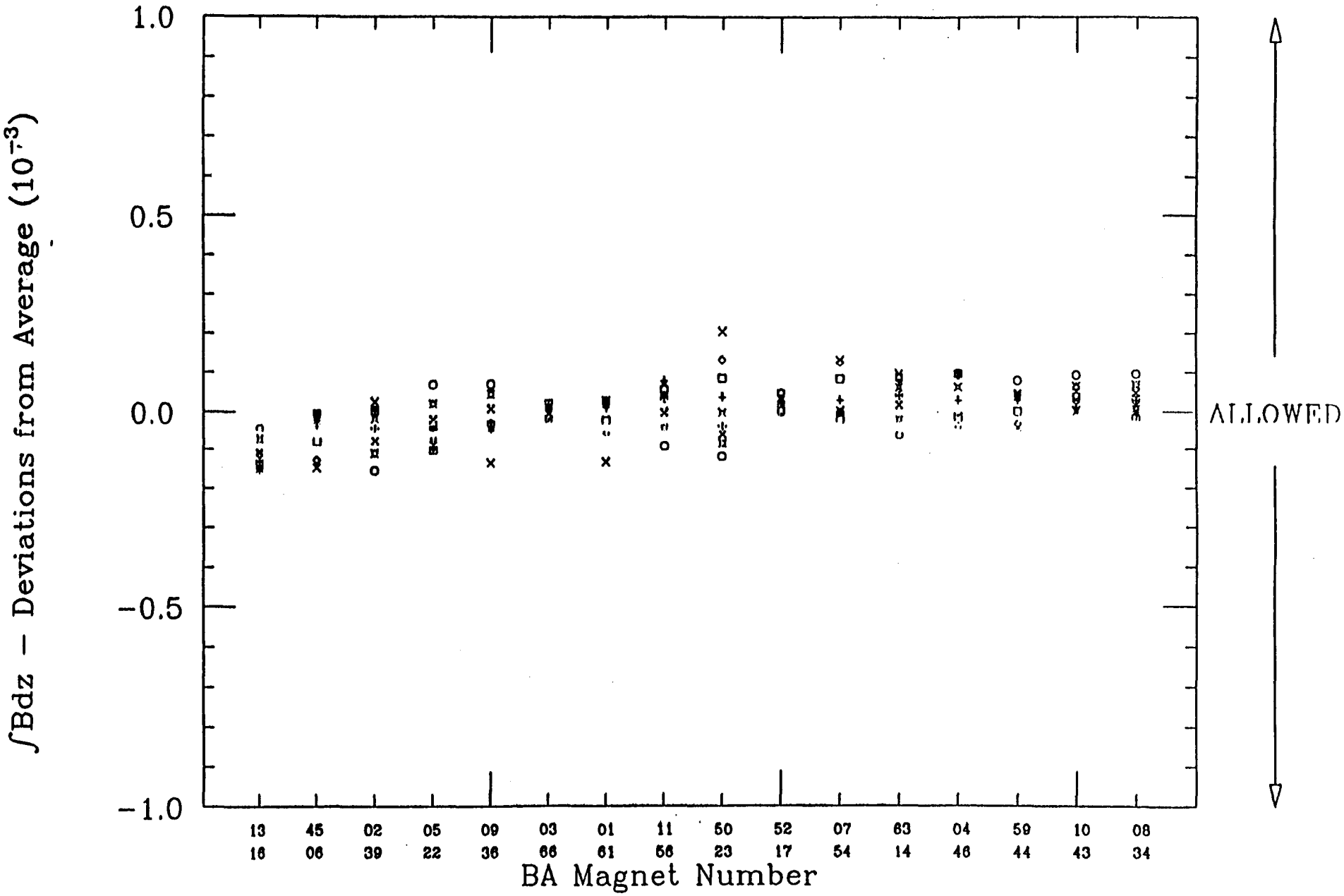
Magnet Element Summary and Characteristics

Quantity	Type	Characteristics
382	main dipoles	≥ 1m x 1 kG ≤ 3m x 7 kG solid construction, "C" type 1006 steel water cooled copper conductor ~ 300 amp max current
1041	corrector dipoles	15 cm x 0.8 kG solid construction 10 amp max. current
712	quadrupoles	< 4 kG max laminated construction 10 amp max. current
104	sextupoles	< 0.16 kG max for 1" dia. 15 cm long laminated construction 10 amp max current
25	septa	1-2 m
2264	all types	

BA Magnet Pair Averages (Arc 7)

(Single Wire Coils – Bucked)

Plot : 12/16/91
BA-GRP1_41.TOP

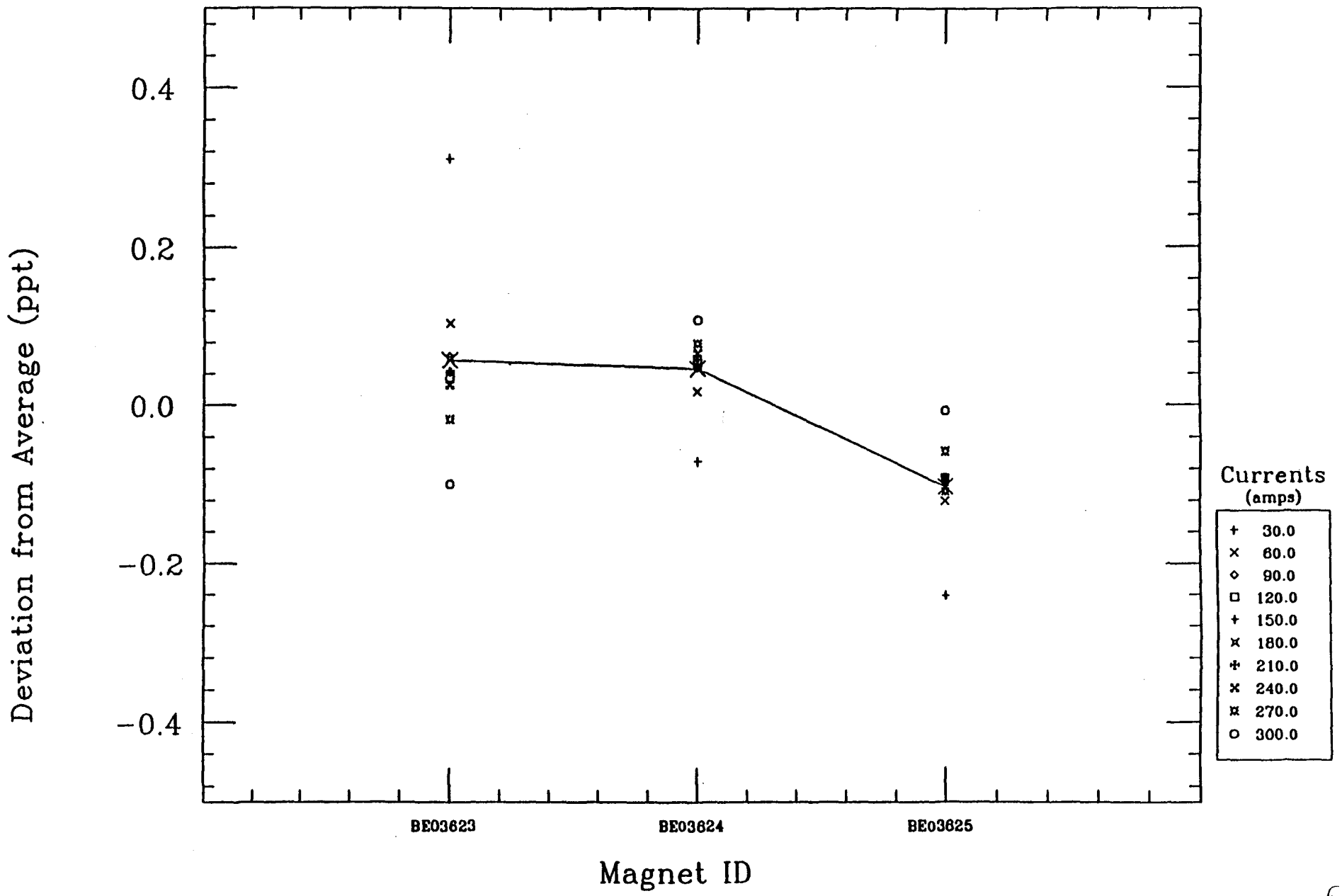


Measurements on CEBAF Beam Transport magnets

Leigh Harwood and Jeffery Karn

Deviations from Population Average

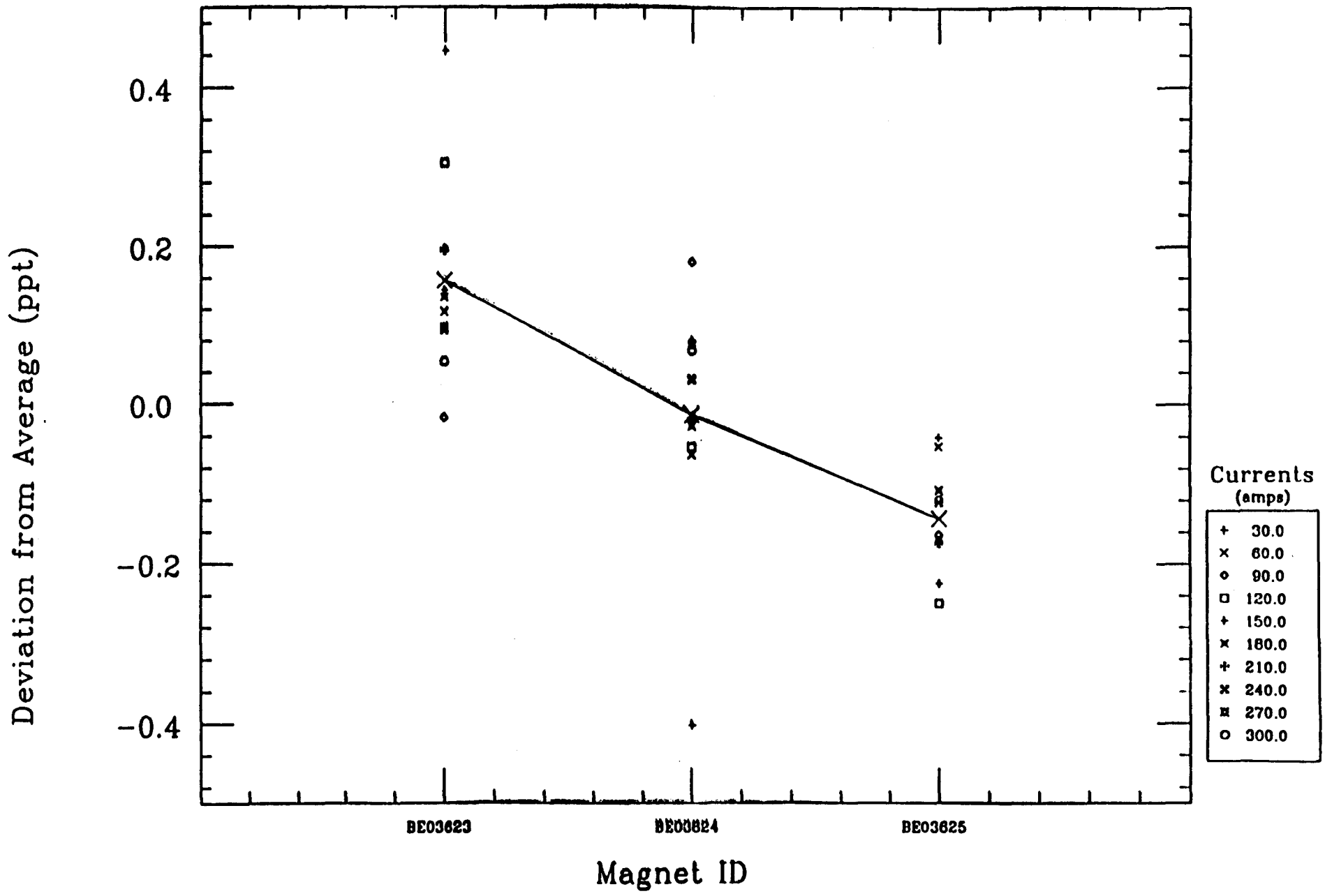
BE Magnets (Single Wire Coils – Bucked)



Plot : 09/14/93

Deviations from Population Average

BE Magnets (Looped Coils – Bucked)



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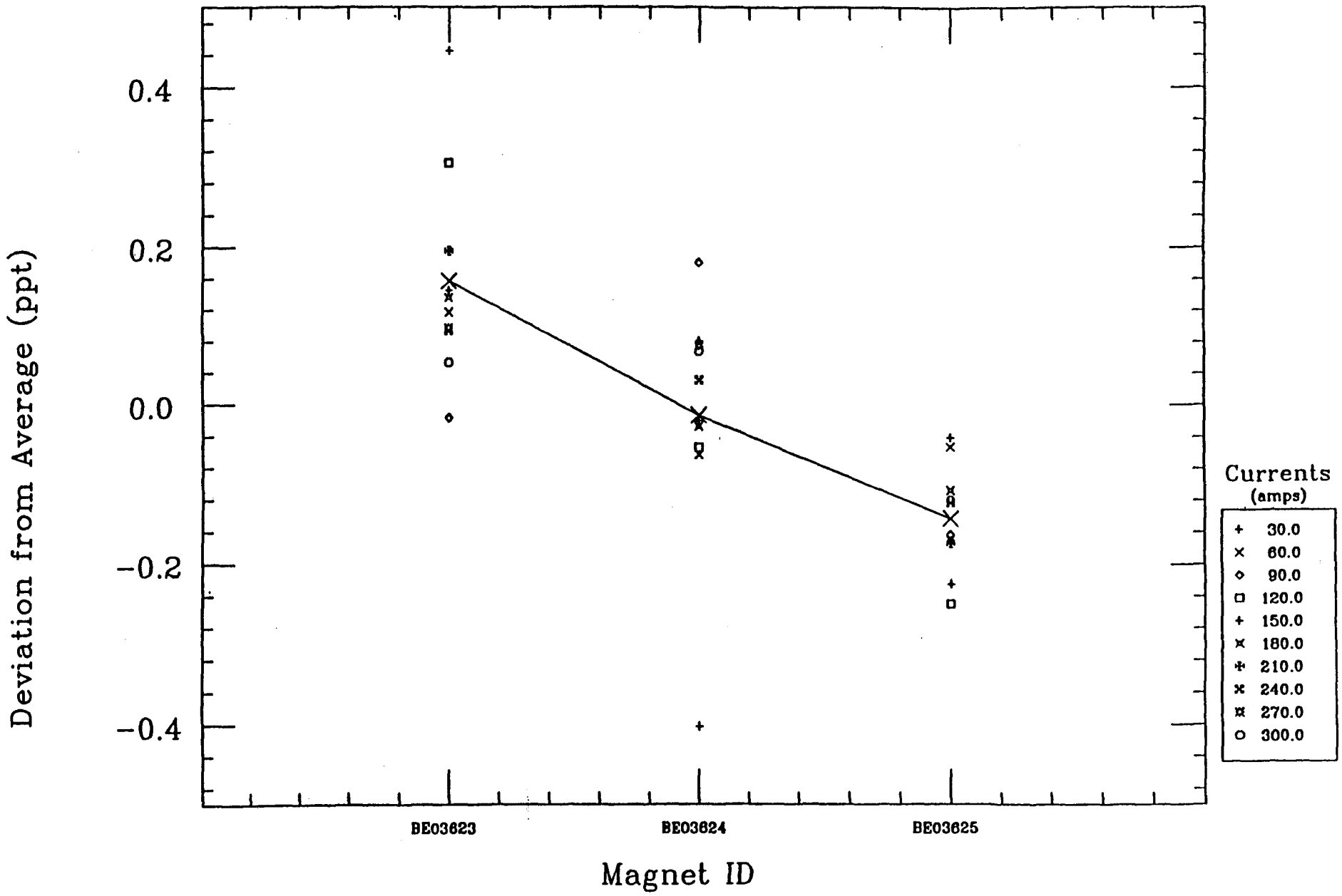
Deviations from Population Average

BE Magnets (Looped Coils – Bucked)

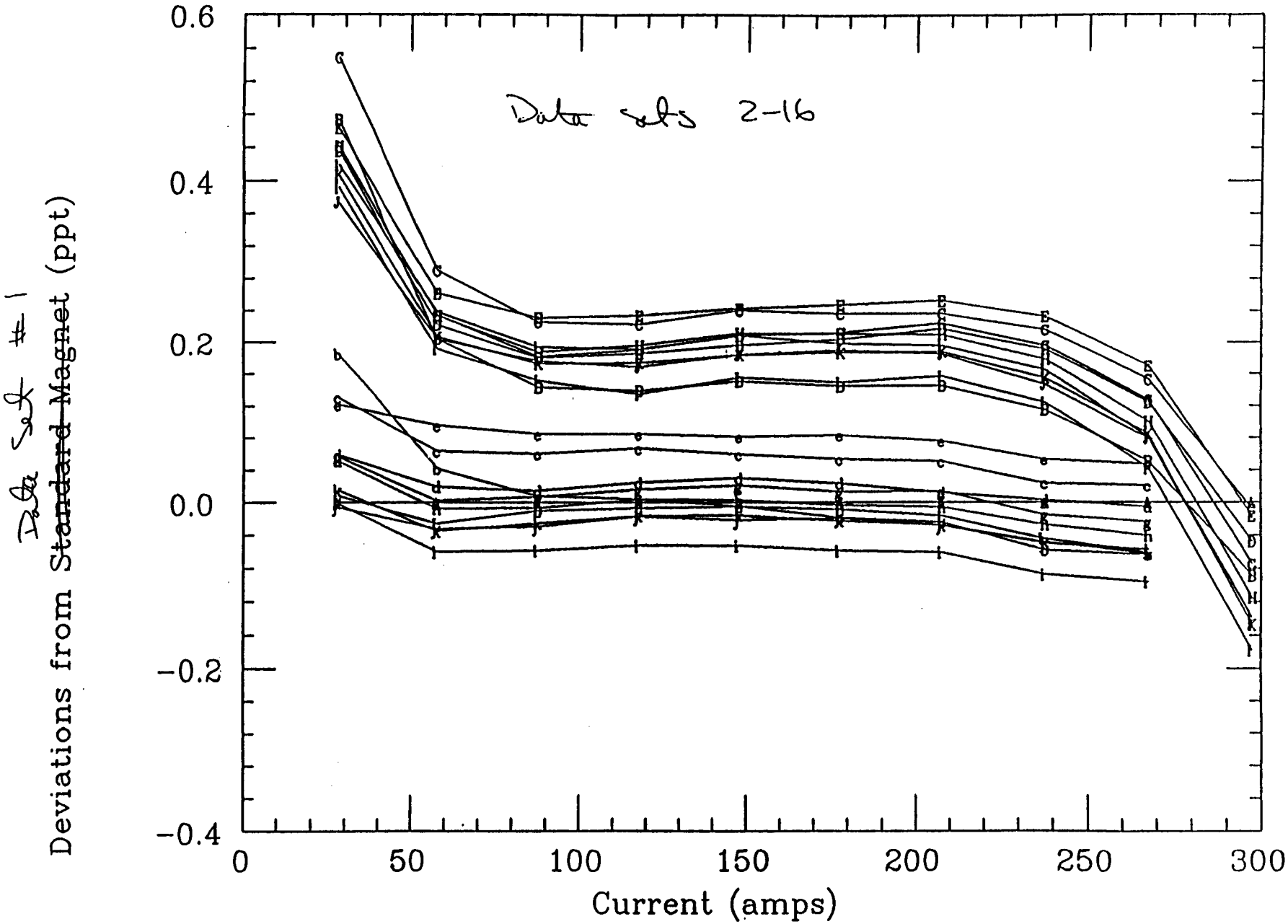


Plot : 09/14/93

Field Ratios vs Current

BE036 (Single Wire Coils - Bucked)

Plot : 07/29/91
BE036_30.TOP



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MEASUREMENT PROGRAM FOR RHIC

Animesh K. Jain
Brookhaven National Laboratory, Upton, NY 11973-5000

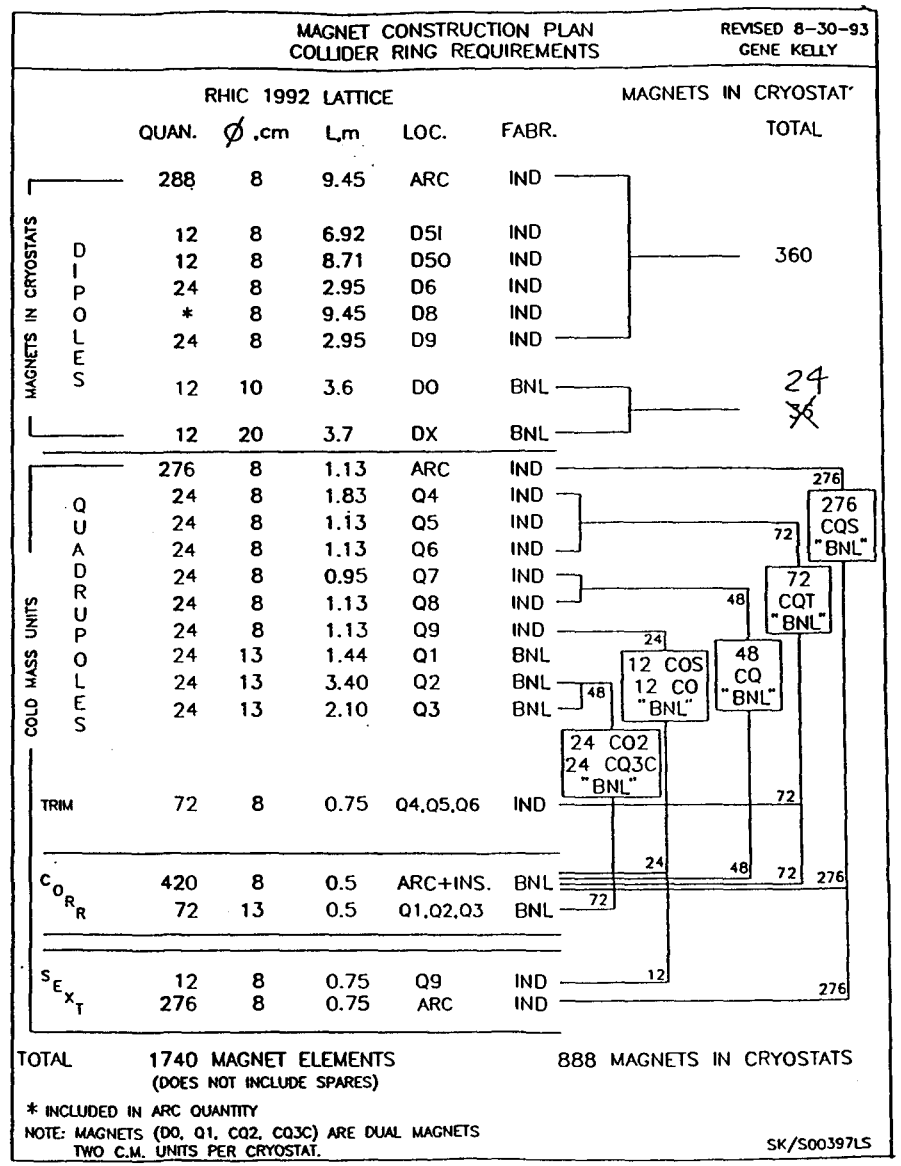
OVERVIEW:

- ❒ INTRODUCTION
- ❒ MEASURING COILS
  - Calibration in Reference Magnets
  - Air Core Magnet
- ❒ DATA ANALYSIS
  - Bucking for Measuring Quadrupoles, Sextupoles, etc.
  - Body and End Harmonics in Insertion Quadrupoles
  - Centering of Data:

    QCD Method for Dipoles

    Higher order Calculation of (r_0, ω)

8th International Magnetic Measurement Workshop (IMMW-8), Superconducting Super Collider Laboratory, Dallas, TX, Sept. 27-30, 1993.



- All 8cm Dipoles will be Measured Warm by the Vendor
- All magnets, including 8cm Dipoles, will be Measured Warm at BNL
- A fraction of the Magnets will be Measured Cold

MEASURING COILS FOR MAGNETIC FIELD MEASUREMENT

- ❒ Rotating Coils (RHIC Mole, External Drive Coils) for Harmonic Measurements
- ❒ Full Length, Non-rotating Coil for Integral Dipole Field Measurements.
- ❒ Approximately 12 different types of External Drive Coils to suit various Magnet Lengths and Apertures.

ISSUES IN USING ROTATING COILS:

1. Fabrication
2. Reliable Operation
3. Calibration
4. Data Analysis (Bucking etc.)

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	*Measuring Coils for RHIC Production Magnets*												
2			Coil	Name	Magnet	Status	BL,m	# Mag	Beam Tube	Warm Fngr	# VT	# HT	Coil Length, m
3	Fixed drive coils												
4		A. 13 cm, maximum diameter											
5			Short	S13M	Q1	CM	1.44	26	N	N			2.76M
6					Corr	CM	tbd	52	N	N			2.76M
7			Long	L13M	Q2	CM	3.4	26	N	N			4.74
8					Q3	CM	2.1	26	N	N			4.74
9		B. 13 cm, reduced diameter											
10			Short	S13R	Q1	CM	1.44	26	N	Y	10		2.76
11					Corr	CM	tbd	52	N	Y	52		2.76
12			Long	L13R	Q2	CM	3.4	26	N	Y	10		
13					Q3	CM	2.1	26	N	Y	10		
14					CQ1	CM		26	Y	N,Y	N3		
15					CQ3	CM		26	Y	N,Y	N3		
16					CQ1	Cry		26	Y	N,Y		N4	
17					Q2	Cry		26	Y	N,Y		N4	
18					CQ3	Cry		26	Y	N,Y		N4	
19		C. 8 cm, maximum diameter											
20			Short	S8M	Arc Q	CM	1.13	380	N	N			
21					Q6	CM	0.95	25	N	N			
22					Sext	CM	0.75	300	N	N			
23					Trim Q	CM	0.75	78	N	N			
24					Corr	CM	0.5	430	N	N			
25		D. 8 cm, reduced diameter											
26			Short	S8R	Arc Q	CM	1.13	380	N	Y	N1		
27					Q6	CM	0.95	25	N	Y	N1		
28					Sext	CM	0.75	300	N	Y	N2		
29					Trim Q	CM	0.75	78	N	Y	N2		
30					Corr	CM	0.5	430	N	Y	71		
31			Long	L8R	CQS+CQT+CQ	CM		405	Y	N,Y	N3		3.58
32					Q4	CM	1.83	25	N	N,Y	N3		3.58
33					CQS+CQT+CQ	Cry		405	Y	N,Y		N4	3.58
34			Ex long	XL8R	CQT4	CM		25	Y	N,Y	N3		
35					CQT4	Cry		25	Y	N,Y		N4	
36		E. 11 cm, reduced diameter											
37			Long	L11R	D0 (11 cm)	CM	3.6	25	Y	N,Y	2		
38						Cry		25	Y	N,Y		25	
39		F. 20 cm, reduced diameter											
40			Long	L20R	DX (20 cm)	CM	3.5	13	Y	N			
41						Cry		13	Y	N,Y		13	
42	Notes												
43		N1	Total of 70 vertical cold tests of these elements										
44		N2	Total of 65 vertical cold tests of these elements										
45		N3	Total of 79 vertical cold tests of these elements										
46		N4	Total of 123 horizontal cold tests of these elements										
47		N5	All cold masses (CM) and all cryostated magnets (Cry) are measured warm.										
48		N6	N,Y in column J means: no warm finger/warm finger for warm/cold tests										
49		N7	Measuring coil length is magnetic length of longest element plus 8 magnet coil diameters										

CALIBRATION OF MEASURING COILS

- Calibration for Amplitudes
  (Radii, Lengths, Opening Angles)
- Calibration for Phase Angles
  (Azimuthal Positions of Windings)

A "Reference Dipole" and a "Reference Quadrupole" are used for Calibration. These are normal conducting magnets with well surveyed and aligned yokes for zero phase angles

Reference Dipole:

1.374 Tesla at 1500A : Air Motor Moles/External Drive Coils

362.7 Gauss at 40A : Electric Motor Moles

Reference Quadrupole:

4.905 Tesla/m at 1500 A

CALIBRATION PROCEDURE

1. Radii Estimated from Coil-form Diameter, Measured Groove Depths, wire diameters, and the arrangement of layers.
2. Lengths Estimated from the drawings and inspection reports.
3. Opening Angles of the Dipole and the Quadrupole Buck Windings are assumed to be 180 degrees and 90 degrees respectively. Amplitudes of allowed terms are not very sensitive to small errors in these angles.
4. Opening Angle of Tangential Winding is estimated by comparing the Dipole signal amplitude with those of the Dipole Buck Windings.
5. Azimuthal angles of Windings from the Measured Phase Angles in Reference Magnets.

Extensive checks are carried out to ensure stability of Amplitudes and Phases over short term measurements.

All Measuring Coils are periodically checked for Calibration.

RHIC Moles used in Dipoles will have an on-line check of calibration using a specially built permanent magnet.

ADJUSTMENT OF RADII AND OPENING ANGLE

A small correction can be made to the radii and the opening angle of the tangential winding by demanding self-consistent values of C(1) from the Dipole buck and the tangential windings in a dipole magnet, and of C(2) from the Quad Buck Windings and the Tangential in a Quadrupole Magnet.

DB1=1 DB2=2 Tang. = 3 QB1=4 QB2=5

$$V_1(1) = 2L_1N_1|\omega|R_1C(1) \quad (1)$$

$$V_2(1) = 2L_2N_2|\omega|R_2C(1) \quad (2)$$

$$V_3(1) = 2L_3N_3|\omega|R_3\sin(\Delta_3/2)C(1) \quad (3)$$

$$V_4(2) = 4L_4N_4|\omega'|R_4^2C(2)/R_{ref} \quad (4)$$

$$V_5(2) = 4L_5N_5|\omega'|R_5^2C(2)/R_{ref} \quad (5)$$

$$V_3(2) = \left[2L_3N_3|\omega'|R_3^2C(2)/R_{ref}\right]\sin(\Delta_3) \quad (6)$$

By Eliminating $C(1)$ and $C(2)$ from the above equations, we can find the four unknowns:

$$(R_2/R_1), \quad (R_5/R_4), \quad R_3, \quad \Delta_3$$

OBTAINING ACTUAL RADII FROM THE RATIOS

- Make use of the Measured Groove Depths, etc.
- Adjust the two radii in a pair (R_1,R_2) and (R_4,R_5) by equal and opposite amounts to match the estimated ratios.

EXAMPLE (Coil-85: RHIC Coil for Sextupoles, etc.):

Winding	Turns	Radius Before Correction (mm)	Radius After Correction (mm)	Δ Before Correction (deg.)	Δ After Correction (deg.)
DB1	3	35.676	35.6745	180	180
DB2	3	35.666	35.6675	180	180
Tangential	30	35.624	35.5346	14.985	15.023
QB1	3	35.655	35.6538	90	90
QB2	3	35.661	35.6622	90	90

The corrected parameters ensure full agreement between the Dipole amplitudes from DB1, DB2, and Tangential, and also the Quadrupole amplitudes from QB1, QB2 and Tangential. Before correction, the agreement in Quad Amplitudes is only within 0.3%.

The corrected parameters also give a slightly better agreement (0.16% instead of 0.34%) for the sextupole strengths from the DB1, DB2 and the Tangential windings.

BUCKING OF SIGNALS IN DIFFERENT TYPES OF MAGNETS

MEASURING COILS HAVE DIPOLE AND QUADRUPOLE BUCK WINDINGS. HARMONICS OTHER THAN DIPOLE AND QUADRUPOLE ARE OBTAINED FROM BUCKED SIGNAL.

BUCKING SHOULD REMOVE THE PRIMARY FIELD COMPONENT, AND IF APPLICABLE, THE NEXT LOWER HARMONIC (WHICH MAY BE LARGE DUE TO FEED DOWN)

"TRADITIONAL" DIGITAL BUCKING:

$$\text{BUCK-1} = V_{Tang} + f_1 V_{DB1} + f_2 V_{DB2}$$

f_1 AND f_2 CHOSEN TO MAKE THE DIPOLE TERM ZERO.

$$\text{BUCK-2} = \text{BUCK-1} + f_3 V_{QB1} + f_4 V_{QB2}$$

f_3 AND f_4 CHOSEN TO MAKE THE QUADRUPOLE TERM ZERO.

THE ABOVE SCHEME CAN RUN INTO PROBLEMS FOR MAGNETS OTHER THAN A DIPOLE

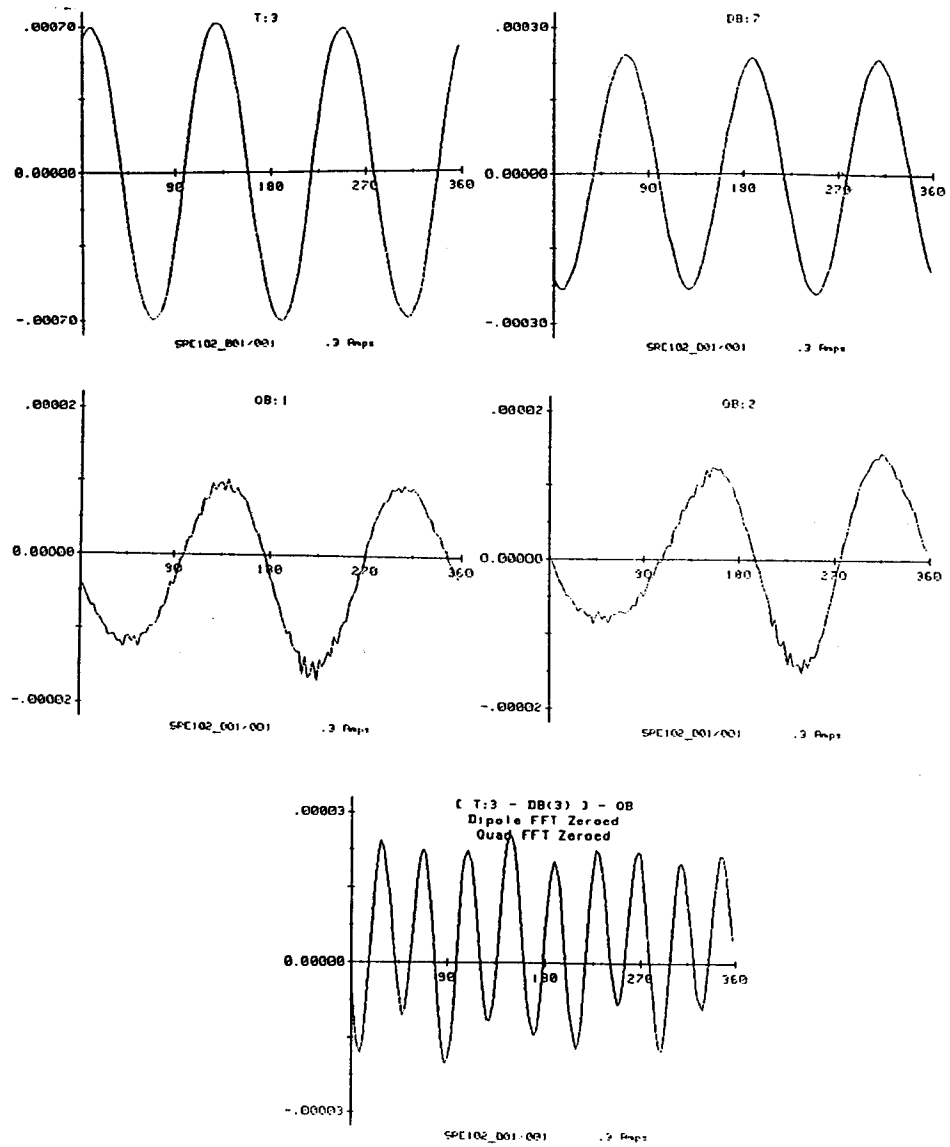
QUAD SHOULD BE BUCKED FIRST IN A QUADRUPOLE

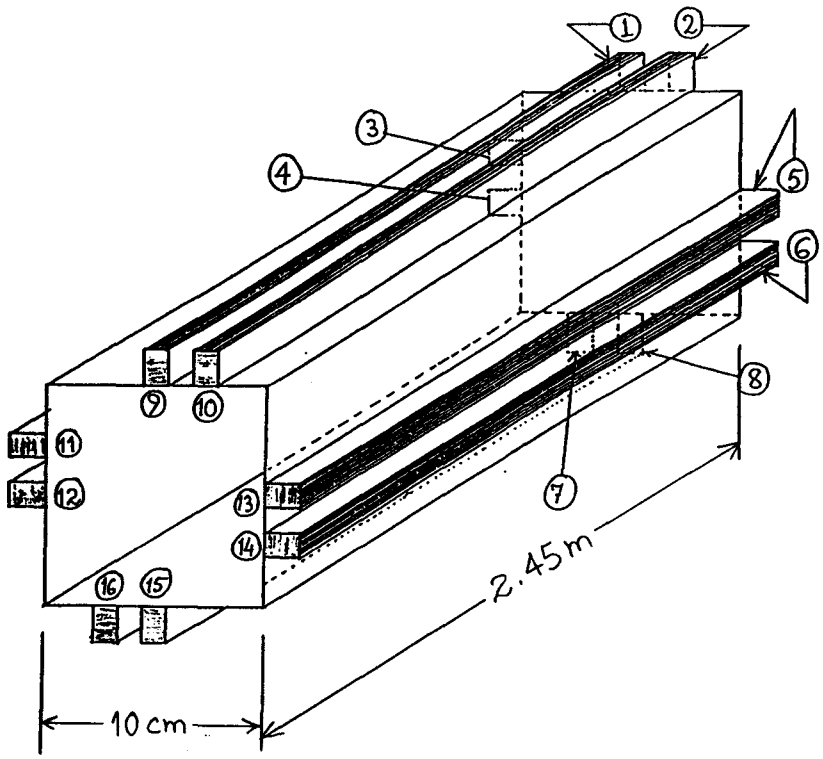
IN A SEXTUPOLE OR DECAPOLE MAGNET:

f_1 AND f_2 CAN BE CHOSEN TO MAKE THE SEXTUPOLE (OR THE DECAPOLE) TERM ZERO.

THE SEXTUPOLE (OR DECAPOLE) AMPLITUDE **MUST BE** OBTAINED FROM THE **UNBUCKED** SIGNAL. THE BUCKED SIGNAL MAY HAVE UNSCRUPULOUS AMOUNTS OF SUCH FIELDS DUE TO COIL CONSTRUCTION ERRORS.

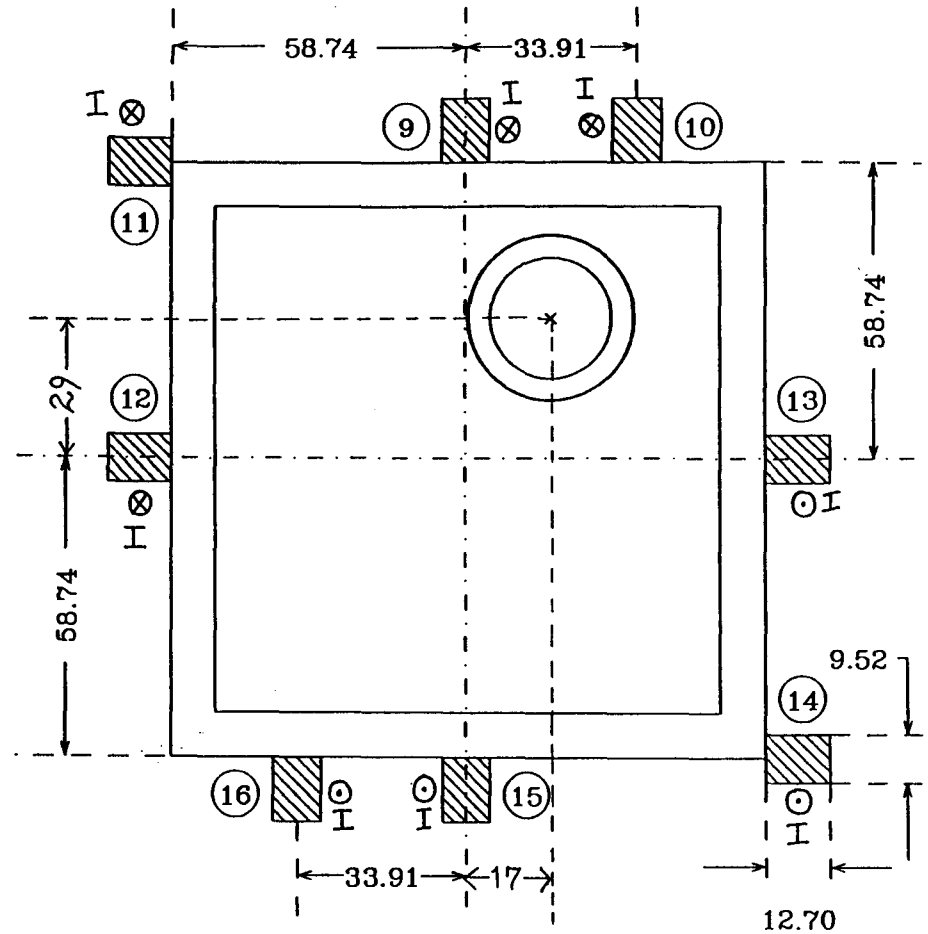
ILLUSTRATION OF BUCKING IN A SEXTUPOLE MAGNET





SCHEMATIC OF AIR-CORE MAGNET SHOWING THE LOCATIONS OF THE 8 CONDUCTORS

- A LARGE VARIETY OF FIELD CONFIGURATION
- THE MULTIPOLES CAN BE ANALYTICALLY CALCULATED



LOCATIONS (in mm) OF CONDUCTORS
IN THE CALIBRATION MAGNET
(Looking from the 9,10,11,12,... end)

The Currents Shown Correspond to "Configuration 1"

Comparison of Harmonics with Various Moles

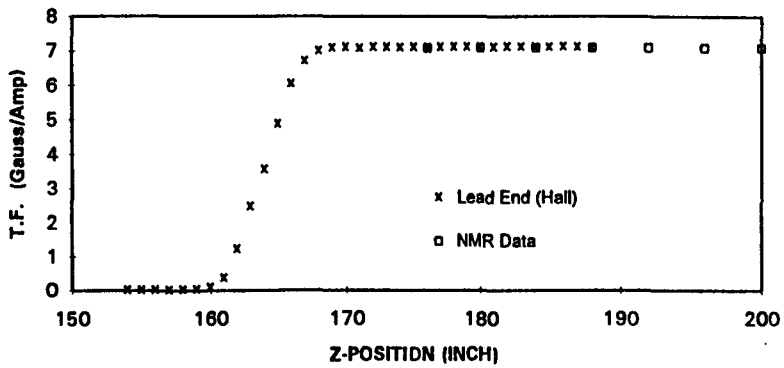
Air Magnet in Configuration 1 at 1000A

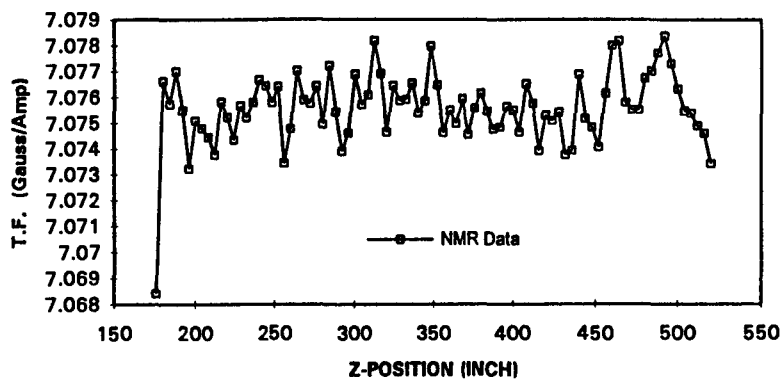
Normal Terms

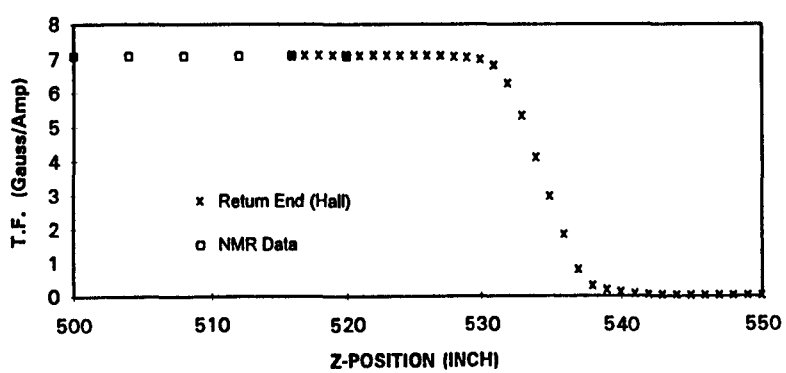
Mole _Run	b0	b1	b2	b3	b4	b5	b6	b7	b8	b9
FA1001.029	-3896	-610.0	-17.57	-11.88	1.933	5.357	0.057	-0.325	0.002	0.004
FA2001.005	-3902	-606.2	-17.68	-11.93	1.992	5.517	0.067	-0.329	0.001	0.003
FA3001.036	-3909	-607.4	-17.90	-11.92	2.005	5.682	0.059	-0.350	-0.003	0.008
FA4001.008	-3884	-608.2	-17.45	-11.86	1.994	5.405	0.056	-0.330	-0.006	0.001
FA5001.009	-3724	-601.2	-17.11	-11.90	2.047	5.593	0.069	-0.350	-0.002	0.005
BE1001.021										
FE1001.017	-3950	-610.8	-18.77	-12.28	2.138	5.824	0.052	-0.369	-0.003	0.005
FE3001.007	-3945	-608.3	-18.87	-12.31	1.986	5.848	0.065	-0.360	0.000	0.006
FE5001.003	-3865	-607.5	-18.75	-12.79	1.869	5.744	0.054	-0.366	-0.015	-0.005
Average	-3884	-607.4	-18.01	-12.11	1.996	5.621	0.060	-0.347	-0.003	0.003
STD DEV	71	2.9	0.69	0.33	0.078	0.185	0.006	0.017	0.006	0.004
Calculated	-3960	-604.6	-17.95	-11.93	2.148	5.585	0.042	-0.344	0.000	0.006

Skew Terms

Mole _Run	a0	a1	a2	a3	a4	a5	a6	a7	a8	a9
FA1001.029	-9210	-286.4	33.37	-9.38	13.22	0.061	-1.424	0.011	0.059	-0.001
FA2001.005	-9207	-287.2	33.71	-9.37	13.45	0.090	-1.449	0.011	0.063	0.004
FA3001.036	-9204	-285.2	33.96	-9.35	13.67	0.224	-1.472	0.004	0.069	0.003
FA4001.008	-9215	-289.4	33.49	-9.35	13.29	0.039	-1.410	0.012	0.063	-0.001
FA5001.009	-9281	-294.4	34.31	-8.98	13.41	-0.046	-1.440	0.022	0.064	0.000
BE1001.021										
FE1001.017	-9187	-287.0	34.72	-9.52	14.00	0.118	-1.525	0.006	0.065	0.001
FE3001.007	-9189	-281.6	34.80	-9.44	14.02	0.183	-1.530	-0.005	0.068	-0.001
FE5001.003	-9223	-291.6	35.65	-9.26	13.92	0.183	-1.480	-0.010	0.044	-0.015
Average	-9214	-287.9	34.25	-9.33	13.62	0.107	-1.466	0.006	0.062	-0.001
STD DEV	29	3.9	0.77	0.16	0.32	0.089	0.044	0.010	0.008	0.006
Calculated	-9183	-282.6	33.33	-9.69	13.42	0.024	-1.457	0.013	0.064	0.000







Transfer Functions at 2400A in DRE011

Comparison of Mole and (NMR+Hall) Data

A. Straight Section Average:

Measured with Mole Z-Scans:	0.7085	Tesla/kA
Measured with NMR:	0.7076	Tesla/kA
(Mole - NMR)/NMR	0.1377	(%)

B. Integral Transfer Function:

Measured with Mole Z-Scans:	6.6692	T.m/kA
Measured with NMR and Hall Probes:	6.6604	T.m/kA
(Mole - NMR)/NMR	0.1314	(%)

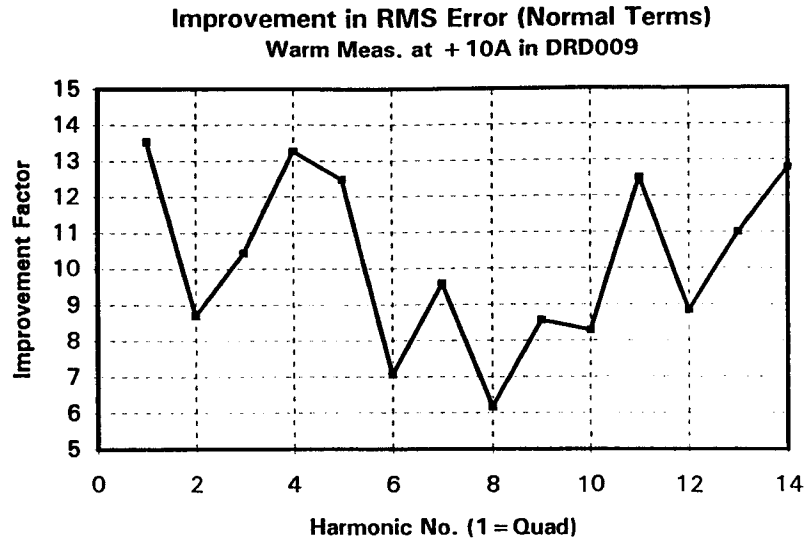
WARM MEASUREMENTS ISSUES

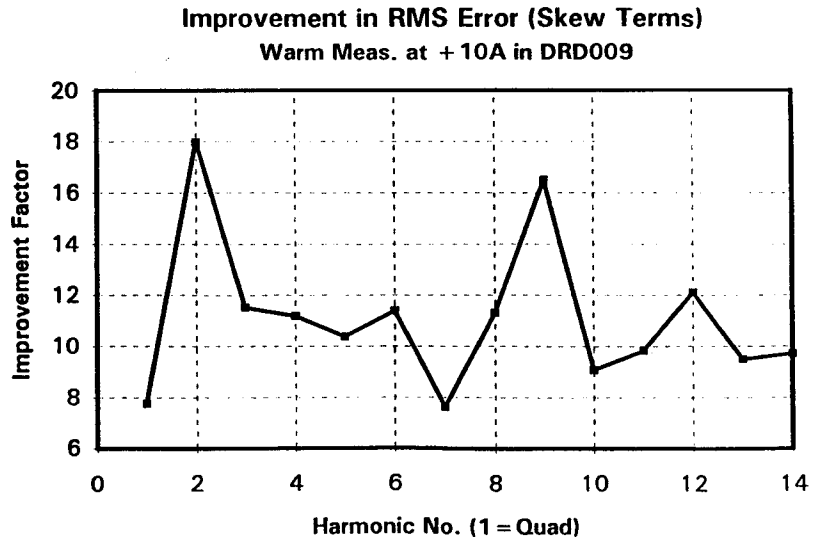
MOST MAGNETS WILL BE MEASURED WARM ONLY

- GOOD WARM-COLD CORRELATIONS ARE REQUIRED (CONVINCING DATA FROM 8 IDENTICALLY BUILT, 8 cm QUADRUPOLES)

- IMPROVE SIGNAL-TO-NOISE RATIO BY USING AN AMPLIFIER (SUCCESSFUL TEST IN DRD009 WITH A VOLTAGE GAIN OF 26)

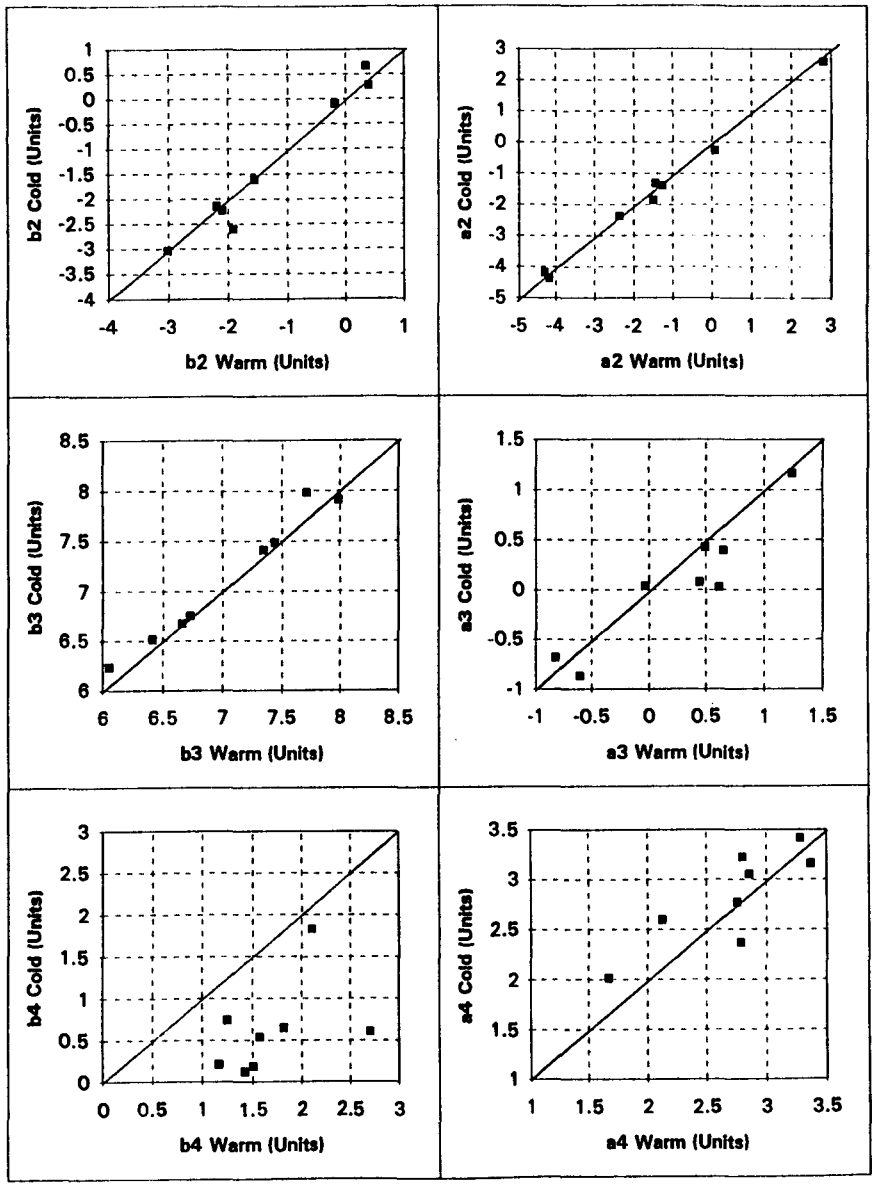
WARM MEASUREMENTS WITH AMPLIFIERS (GAIN=26)





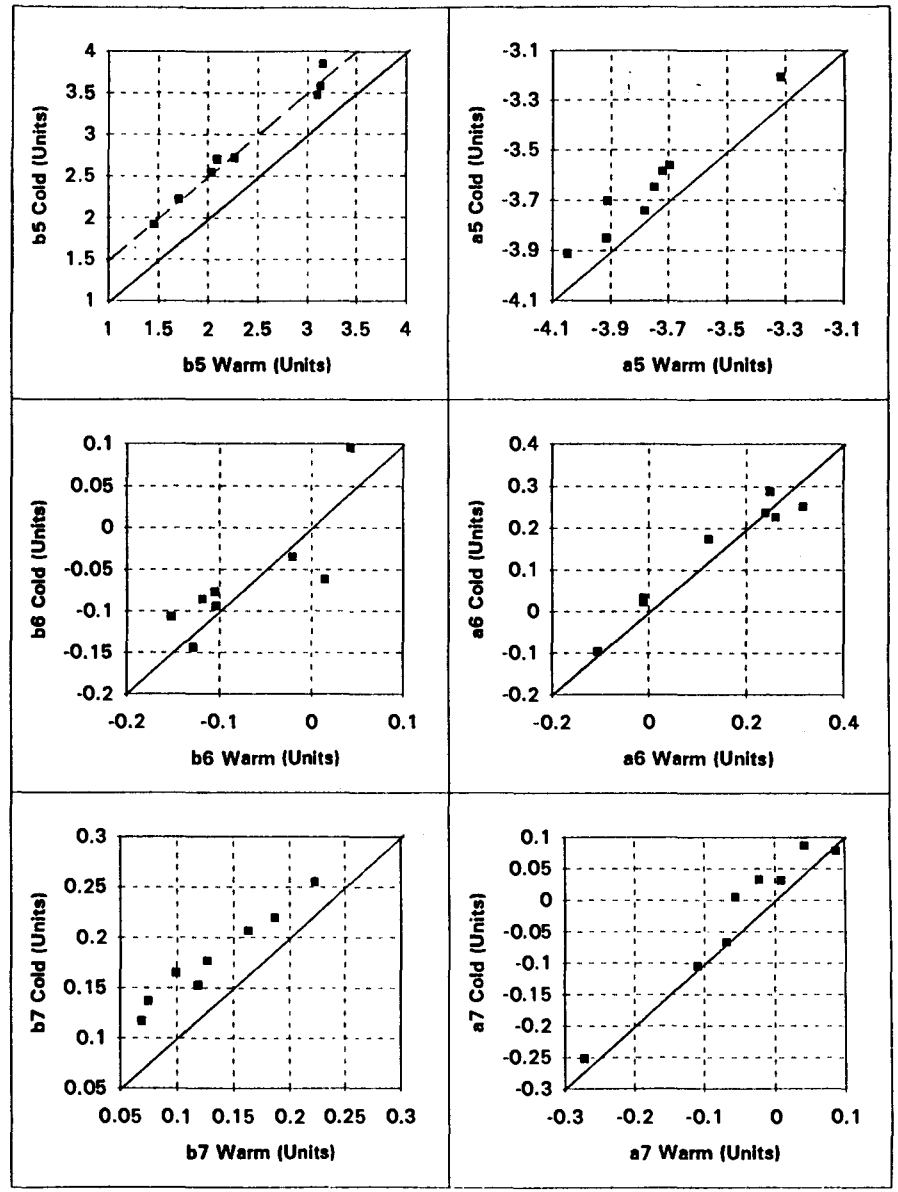
Warm-Cold Correlations In Magnets QRB005-QRB012

Warm=10A Cold=3kA (Avg. of Up and Dn Ramps)



Warm-Cold Correlations In Magnets QRB005-QRB012

Warm=10A Cold=3kA (Avg. of Up and Dn Ramps)



Warm-Cold Correlations in Magnets QRB005-QRB012
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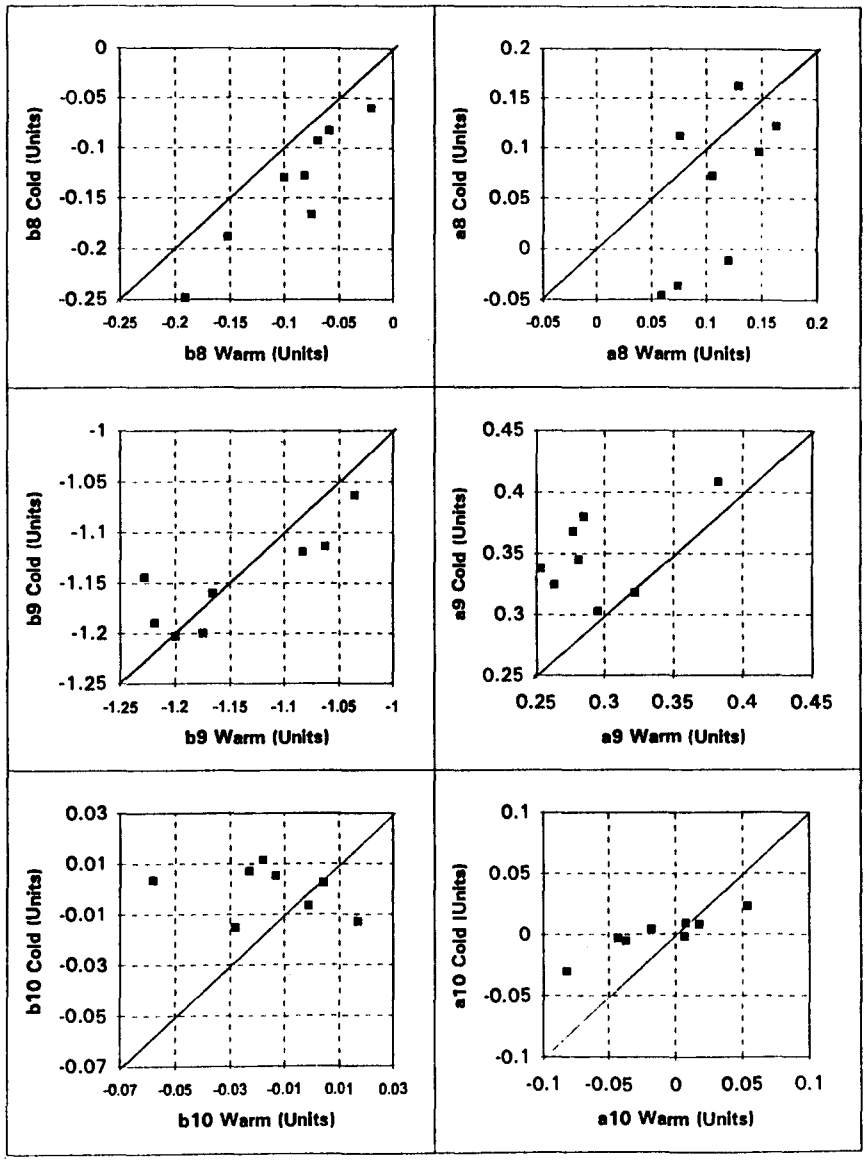

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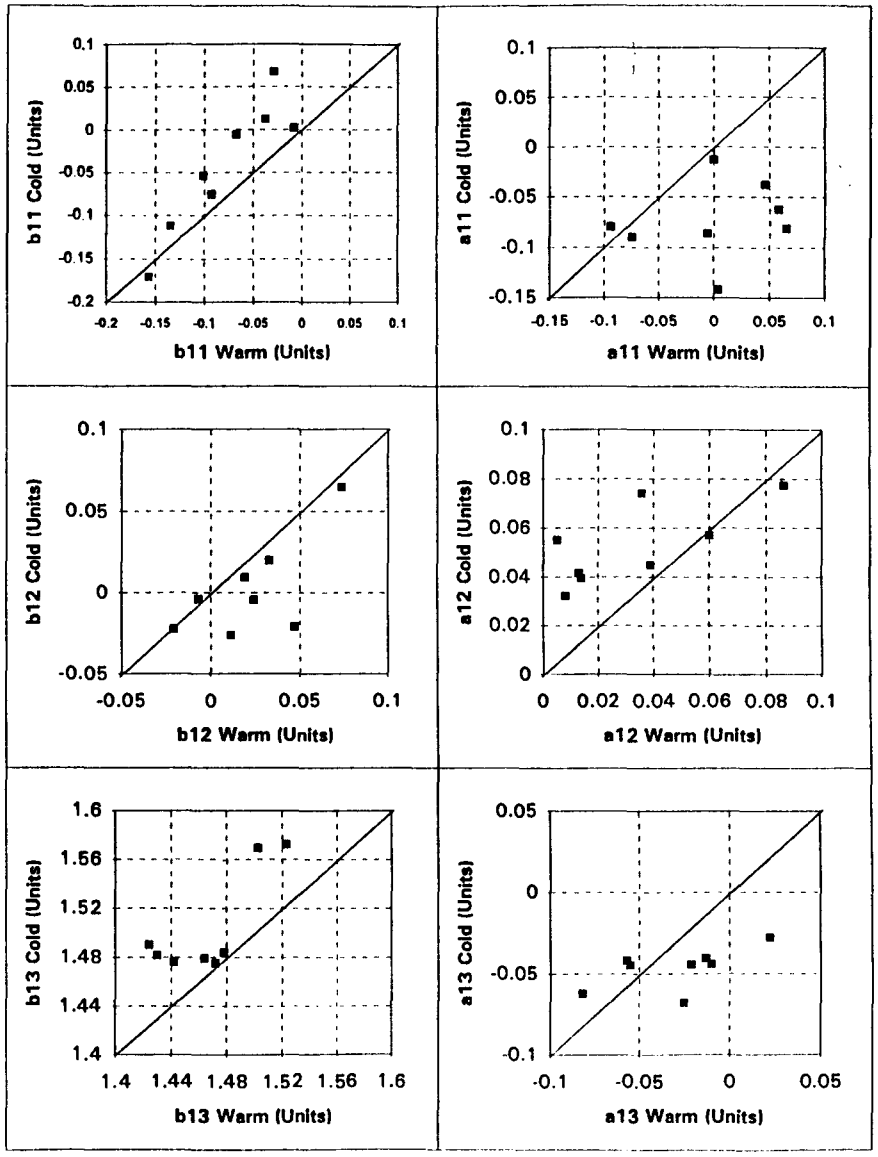


CENTERING OF FIELD DATA

THE MEASURING COIL AXIS MAY NOT COINCIDE WITH THE MAGNETIC AXIS.

THE MEASURED FIELD COEFFICIENTS MUST BE "CENTERED".

ALMOST ALL CENTERING ALGORITHMS RELY ON MAKING ONE OR MORE UNALLOWED HARMONICS ZERO.

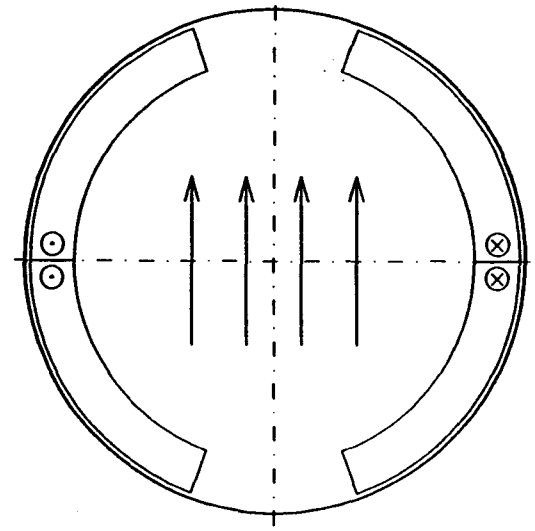
DIPOLES:

- ❒ MINIMIZE ONE OR MORE OF THE HIGH ORDER UNALLOWED TERMS (SUCH AS 16-POLE, 20-POLE, 24-POLE, ETC.)
  - REQUIRES PRECISION MEASUREMENT OF HIGHER HARMONICS – COULD BE A PROBLEM FOR WARM MEASUREMENTS
  - MUST CONSIDER FEED DOWN FROM SEVERAL HIGHER HARMONICS FOR CALCULATING THE OFFSETS –

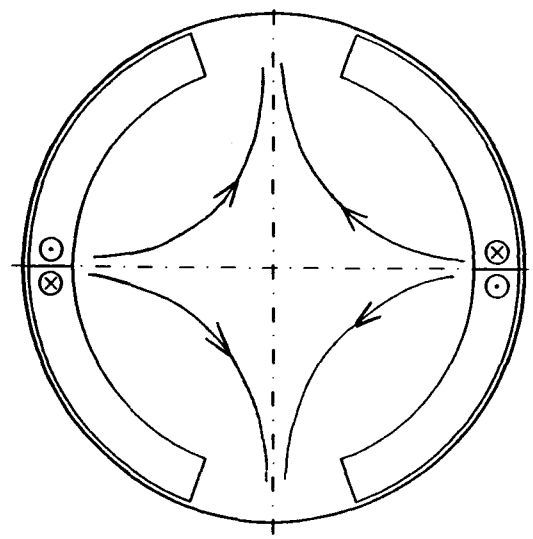
    UP TO A THIRD ORDER FEED DOWN IS NOW ROUTINELY USED. HIGHER THAN THIRD ORDER SOMETIMES USED FOR LARGER OFFSETS.
- ❒ USE A QUADRUPOLE CONFIGURED DIPOLE (QCD) CONFIGURATION, JUST TO MEASURE THE COIL OFFSETS.

OTHER TYPES OF MAGNETS:

- ❒ USE FEED DOWN FROM THE PRIMARY FIELD, OR ONE OF THE HIGHER ALLOWED TERMS FOR CENTERING. GENERALLY, THIS HAS NO PARTICULAR PROBLEMS



DIPOLE MODE

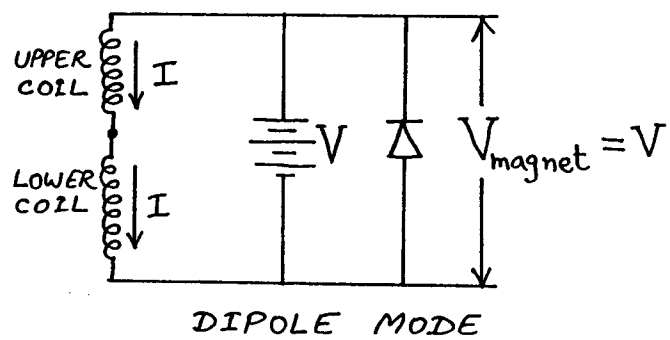


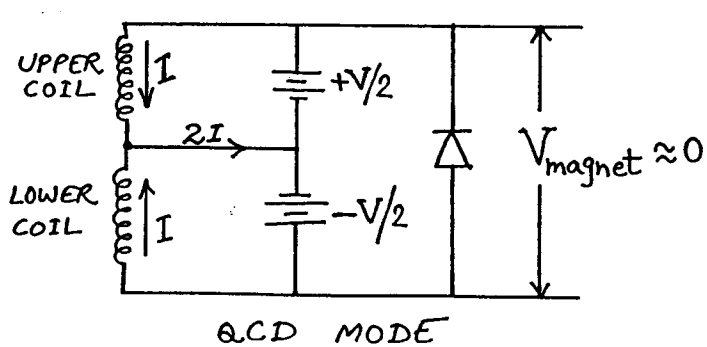
QUADRUPOLE CONFIGURED DIPOLE (QCD)

QCD MEASUREMENTS IN PRODUCTION MAGNETS

UPPER AND LOWER COILS ARE ALREADY SPLICED:

- A CENTER TAP TERMINAL IS NECESSARY
- TWO SEPARATE POWER SUPPLIES MUST BE USED





$V_{magnet} \approx 0 \Rightarrow$ BOTH +I AND -I MEASUREMENTS POSSIBLE

QCD CENTERING WITH UNBALANCED CURRENTS

IF THE CURRENTS IN THE TWO MAGNET HALVES ARE NOT IDENTICAL, THERE MAY BE SOME ERROR IN OBTAINING THE CENTERING PARAMETERS.

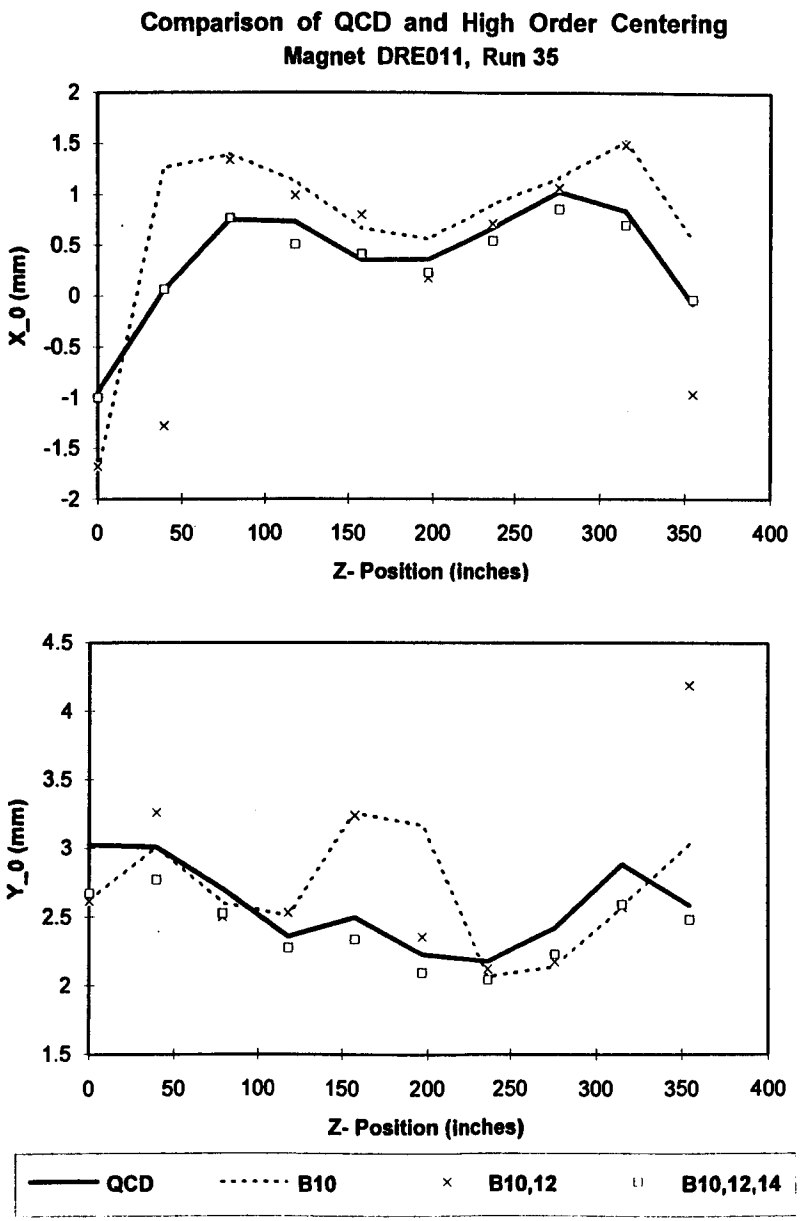
IF THE CURRENTS ARE (I+ΔI) AND (I-ΔI) IN THE TWO HALVES, THE ERROR IN CALCULATING THE OFFSET, r_0 IN THE RHIC DIPOLES IS:

$\Delta r_0 \approx 62.6\left(\frac{\Delta I}{I}\right)$ mm : Feed Down from Quad to Dipole

$\Delta r_0 \approx 0.02 b_2\left(\frac{\Delta I}{I}\right)$ mm : Feed Down from Octupole to Sextupole

WHERE b_2 IS THE AMOUNT OF SEXTUPOLE IN UNITS, WHEN POWERED IN THE DIPOLE MODE.

THE ERRORS ARE NEGLIGIBLE EVEN FOR "NOT SO WELL MATCHED" SUPPLIES, PARTICULARLY IF OCTUPOLE TO SEXTUPOLE FEED DOWN IS USED.



FIELD MEASUREMENTS IN INSERTION QUADRUPOLES

BEAM SIZE VARIES DRAMATICALLY OVER THE LENGTH OF THE QUADRUPOLES

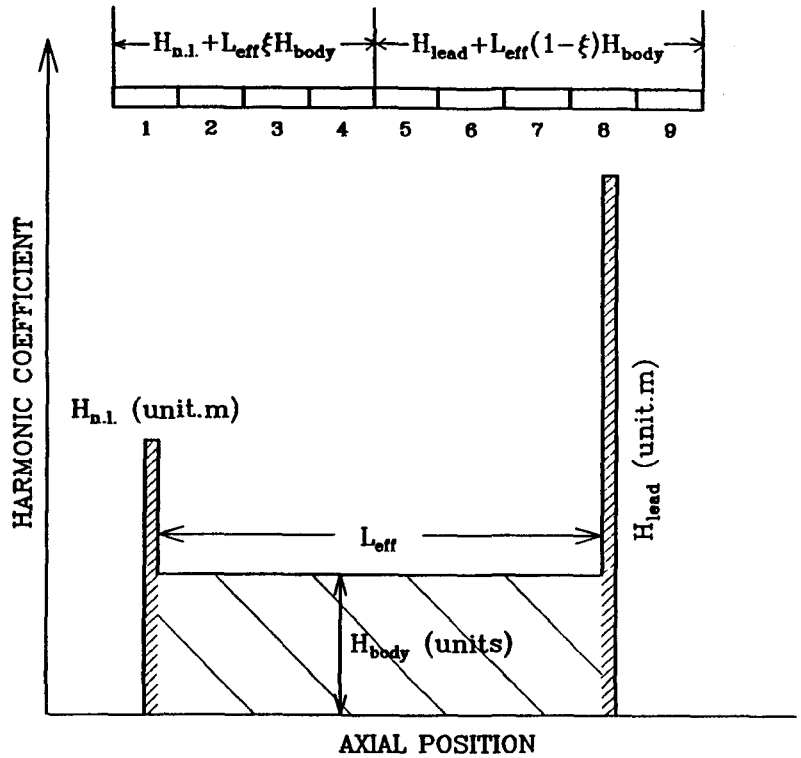
⇒ HARMONICS IN THE ENDS DO NOT HAVE THE SAME EFFECT AS HARMONICS IN THE BODY OF THE MAGNETS.

BODY AND END HARMONICS ARE OBTAINED FROM A SERIES OF MEASUREMENTS WITH A 9" (0.23m) LONG COIL

STRINGENT REQUIREMENTS ON THE HARMONICS

⇒ MAGNETS WILL BE MEASURED WARM AND THEN SHIMMED ACCORDINGLY, TO REDUCE HARMONICS THAT ARE OUT OF TOLERANCE

MEASUREMENTS ARE THUS AN INTEGRAL PART OF THE MANUFACTURING PROCESS.

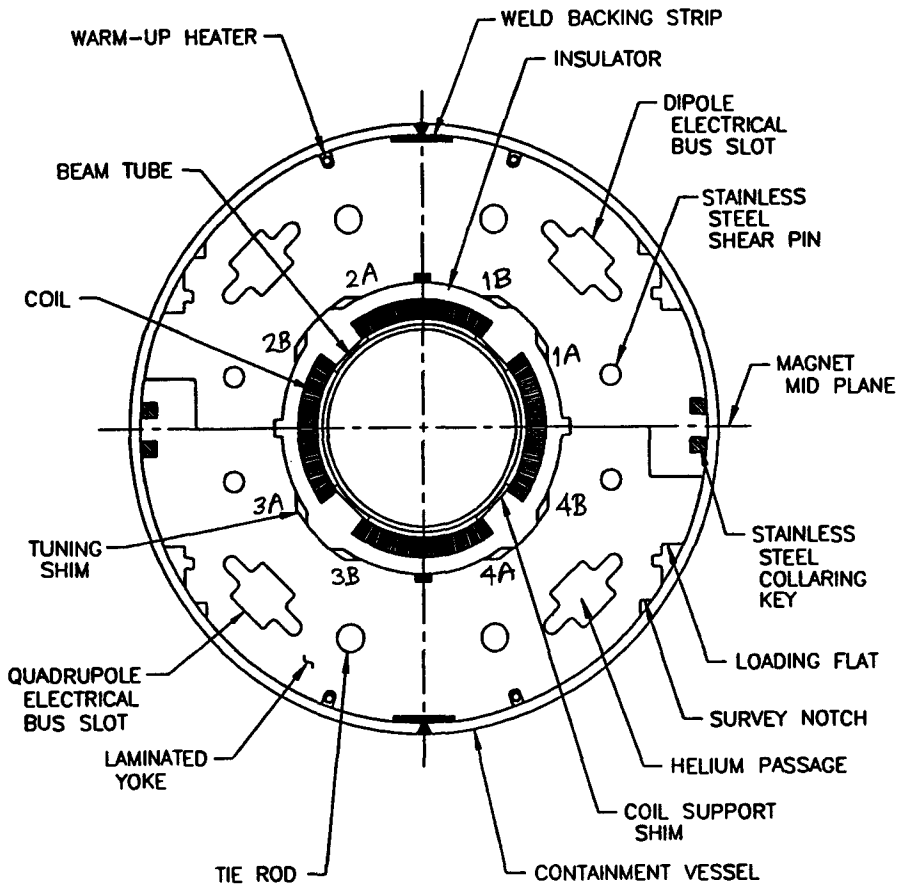


SCHEMATIC SHOWING CALCULATION OF BODY AND END HARMONICS IN 13cm QUADS

Harmonics in QRI103

Harmonic	Warm Integ. Run 4/02	Integral Up Ramp (Run 22/01) 660A	1450A	5000A	Body 5000A	Lead End 5000A	NL End 5000A
T.F.	13.592	13.641	13.658	13.626	9.465	---	---
b2	-2.11	-2.44	-2.46	-2.50	-3.22	0.68	-0.34
b3	-0.70	-0.69	-0.80	-0.67	-0.43	-0.05	-0.42
b4	0.04	0.33	0.32	0.29	0.26	0.12	0.20
b5	6.46	3.94	6.25	6.51	2.74	4.73	0.77
b6	0.16	0.20	0.19	0.20	0.15	-0.07	0.01
b7	-0.36	-0.30	-0.30	-0.32	-0.29	0.00	0.00
b8	0.02	-0.02	-0.02	-0.03	-0.02	-0.02	-0.03
b9	0.32	0.31	0.30	0.43	0.85	-0.44	-0.14
b13	-0.04	-0.07	-0.05	-0.04	---	---	---
a2	1.20	1.53	1.51	1.54	1.44	-0.01	-0.42
a3	-1.21	-1.08	-1.06	-1.04	-0.41	-1.22	0.61
a4	0.07	0.22	0.22	0.17	0.01	0.19	0.08
a5	0.21	0.15	0.17	0.11	0.68	-1.51	-0.16
a6	0.11	0.10	0.11	0.11	0.19	-0.10	-0.05
a7	-0.04	-0.08	-0.08	-0.08	-0.13	-0.02	0.09
a8	-0.02	-0.01	-0.02	-0.03	0.03	-0.03	-0.01
a9	0.13	0.14	0.14	0.14	0.02	0.24	0.00
a13	-0.02	-0.02	-0.02	-0.02	---	---	---
		Units			Units	unit.m	

RHIC INSERTION QUADRUPOLE



sk/s00488ml

Shimming Experiment in QRI103 (Warm) - Effect of Individual Shims

Loc. of Shim	Del-b2 (units)	Del-b3 (units)	Del-b4 (units)	Del-b5 (units)	Del-b6 (units)	Del-b7 (units)	Del-b8 (units)	Del-b9 (units)	Del-b13 (units)
1A	-6.05	2.63	-0.45	-0.31	0.43	-0.27	0.13	-0.05	0.00
1B	-0.92	-2.67	2.04	-0.41	-0.34	0.27	-0.06	-0.01	0.01
2A	0.91	-2.71	-2.03	-0.28	0.37	0.30	0.05	-0.06	0.00
2B	6.44	2.82	0.51	-0.43	-0.44	-0.29	-0.15	-0.03	0.01
3A	5.91	2.71	0.53	-0.20	-0.44	-0.29	-0.12	-0.05	0.00
3B	1.26	-2.71	-2.07	-0.45	0.38	0.30	0.06	-0.03	0.00
4A	-1.12	-2.62	1.95	-0.30	-0.36	0.25	-0.05	-0.05	0.01
4B	-6.06	2.72	-0.50	-0.30	0.42	-0.27	0.13	-0.04	0.00
Total	0.37	0.16	-0.03	-2.69	0.02	-0.01	-0.02	-0.33	0.03

Loc. of Shim	Del-a2 (units)	Del-a3 (units)	Del-a4 (units)	Del-a5 (units)	Del-a6 (units)	Del-a7 (units)	Del-a8 (units)	Del-a9 (units)	Del-a13 (units)
1A	-1.16	2.54	-1.96	0.99	-0.36	0.02	0.05	-0.06	0.00
1B	-5.97	2.55	0.41	-1.03	0.44	0.03	-0.12	0.06	0.00
2A	-6.02	-2.51	0.54	1.07	0.44	-0.05	-0.14	-0.06	0.00
2B	-1.08	-2.63	-2.12	-1.08	-0.38	-0.06	0.05	0.06	-0.01
3A	1.03	2.50	2.03	1.01	0.36	0.06	-0.03	-0.05	0.01
3B	6.28	2.68	-0.48	-0.98	-0.44	0.01	0.12	0.06	0.00
4A	5.92	-2.53	-0.46	1.01	-0.43	-0.03	0.13	-0.05	-0.01
4B	0.99	-2.48	1.96	-1.05	0.36	-0.04	-0.06	0.04	-0.01
Total	-0.01	0.11	-0.08	-0.06	-0.01	-0.05	0.00	0.01	-0.01

Note: Measuring Coil from NL End. Coil End 2" Inside the End Plate on Lead End.

CONCLUSIONS

- A BUSY PRODUCTION MEASUREMENTS SCHEDULE AHEAD INVOLVING A VARIETY OF MAGNETS
- MAJOR EFFORT UNDERWAY IN BUILDING MEASURING COILS AND "MOLES"
- RELIABLE OPERATION OF ROTATING COILS
- IMPROVED COIL CALIBRATION PROCEDURES
- IMPROVED DATA ANALYSIS -- BUCKING, CENTERING, ...
- MEASURE → SHIM → MEASURE : INTEGRAL PART OF THE MANUFACTURING PROCESS FOR THE INSERTION QUADS.

September 24, 1993

SSCL

Resistive Magnet Measurement Facility Status

Ted Hunter

ASD Mechanical Engineering

ABSTRACT

The number and types of magnets to be measured will be presented. The present status of the measurement facility and measurement results of a few LEB magnets will be shown.Expected magnet delivery will be discussed.

September 24, 1993

DIPOLES

- Want To Know

  $B_y(X,Z)$ vs. I

  $\int Bdl$ vs. I

  $\int Bdl$ vs. X, Y

  End Effects (Harmonics)
  Beam tube effects
  A.C. effects
  Magnetic center line vs. Fiducials
  Voltage vs. Current
  Water flow
  Pressure drop
  Temperatures
  History

- Will Need

  NMR
  Hall Probes
  Precision Current Transformer
  DVM
  Power Supply
  Integrators (analog, digital)
  Search Coils (point, integral)
  X-Y-Z-Theta motion
  Motion Control
  Data Acquisition System
  Data analysis/display
  Temperature monitors
  Data Base
  Alignment tools

September 24, 1993

Quadrupoles

- Want to Know

  G vs. I

  $\int G dl$ vs. I

  Harmonic content ($\%B_n/B_2$), ends and integral

  L_{eff} vs. I

  $B_{Pole\ Tip}$ vs. I

  Beam tube effects

  A.C. effects

  Magnetic center-line vs. Fiducials

  Voltage vs. Current

  Water flow

  Pressure drop

  Temperatures

  History

- Will Need

  Harmonics Measurement System

  Hall Probes

  PCT

  DVM

  Power Supply

  Data analysis/display

  Temperature monitors

  Data Base

  Alignment tools

September 24, 1993

Table 1: # Resistive Magnets

Beam Line	Quads	Dipole	Sext.	Bump	Septa	Sym Lamb	Assy Lamb	"C"	Total
Linac	109								109
Linac/Leb	17	6							23
Lin/LEB Trim		17							17
LEB Inj.				5	1				6
LEB	101	101							202
LEB Corrector	100	96	56						252
LEB Extr.				5	2				7
LEB/MEB	20	12							32
LEB/MEB Corr		15							15
MEB Inj.						1			1
MEB	248	381							629
MEB Corrector	20	228	181	12					441
MEB/HEB	90	26				2	2	2	122
MEB/HEB Trm		85							85
MEB Abort						9	5	15	29
Test Beams	24	33			6	2	5		70
Test Bms Trim		15							15
HEB Inj.				6		2	2	2	12
HEB Extr.						10	4	6	20
HEB/SSC	28	56				20	8	36	148
HEB/SSC Trim		40							40
SSC Inj.						10	4	6	20
SSC Abort	22	8				30	20		80
Special-Misc.									100
Total	779	1119	237	28	9	86	50	67	2475

Table 2: LEB Corrector Magnets

Beam Line	Aperature mm	Gradient T/m	Leff m	Max Current	Qty
High Field Quad	100	6	0.33	90	24
Low Field Quad	100	2	0.33	15	78
Steering Dipole	100/50	2 Kg	0.15	25	92
Chromaticity Sextupole	100	1.5 Kg Pole Tip	0.35	25	50

Table 3: LEB/MEB

Beam Line	Aperature mm	Gradient or Field	Leff m	Max Current	Qty
LEB Extr Bumps	80	4 Kg	.45	1625	1 5
LEB Extr Septa	20/80 20/85	2.5 Kg 12.5 Kg	0.8 1.6	3981 20,080	1 1
LEB/MEB Dipoles	48	13.4 Kg	2	1500	12
LEB/MEB Quads	53	15 T/m	0.5	200	20
Correction Dipoles	100/50	1.3 Kg	0.25	15	13
MEB Inject-Lambertson					1

Table 4: MEB Corrector Magnets

Type	Aperature mm	Gradient or Field	Leff m	Max Current	Qty
Chromaticity Sextupole	100/50	57.5Tm/m^2	0.4	600	2 166
Horizontal Dipole	100/50	1.3 Kg	0.25	15	2 115
Verticle Dipole	100/50	0.9	0.2	15	2 109
Skew & Trim Quads	100	2	0.33	15	20
Skew & Trim Sextu-pole	100/50	2.8Tm/m^2	0.2	15	1 16

Table 5: Beam Line Quadrupoles

Beam Line	Aperture mm	Gradient T/m	B_{Pole} Tesla	L_{eff} m	Max Current	#
Linac	23	1			80	109
Linac/LEB	75	13.5	1.013	0.3	273	17
LEB	100	14.9	0.745	0.7564	3919	12
LEB	100	14.9	0.745	0.5919	3919	24
LEB	100	14.9	0.745	0.5983	3919	24
LEB	100	14.9	0.745	0.6127	3919	9
LEB	100	14.9	0.745	0.6568	3919	6
LEB	100	14.9	0.745	0.5552	3919	3
LEB	100	14.9	0.745	0.6980	3919	6
LEB	100	14.9	0.745	0.6858	3919	6
LEB H.F.	100	6	0.3	0.33	90	24
LEB L.F	100	2	0.1	0.33	15	78
LEB/MEB	53	15	0.4	0.5	200	20
MEB	86.9	21.4	0.93	2.4	5200	206
MEB	86.9	21.4	0.93	2.802	5200	12
MEB	86.9	21.4	0.93	0.544	5200	12
MEB Sk&T	100	2	0.1	0.33	15	20
MEB/HEB	46	30.7	0.707	1.5		80
HEB/SSC	30-40	40	0.6-0.8	3		4
HEB/SSC	30-40	40	0.6-0.8	6		18

Table 6: Sextupoles

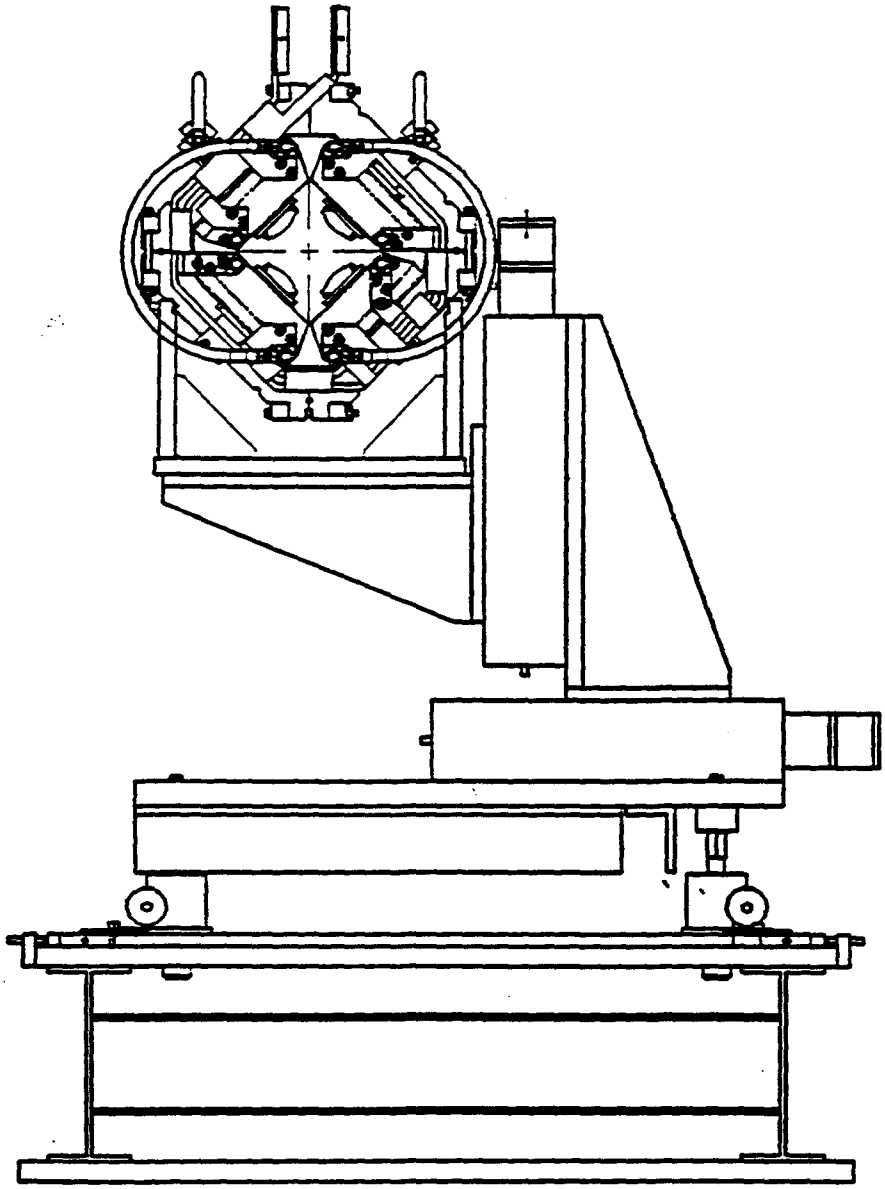
Type	Aperature mm	Gradient or Field	Leff m	Max Current	Qty
LEB Chromaticity Sextupole	100	1.5 Kg Pole Tip	0.35	25	56
MEB Chromaticity Sextupole	100/50	57.5Tm/m^2	0.4	600	165
MEB Skew & Trim Sextupole	100/50	2.8Tm/m^2	0.2	15	16

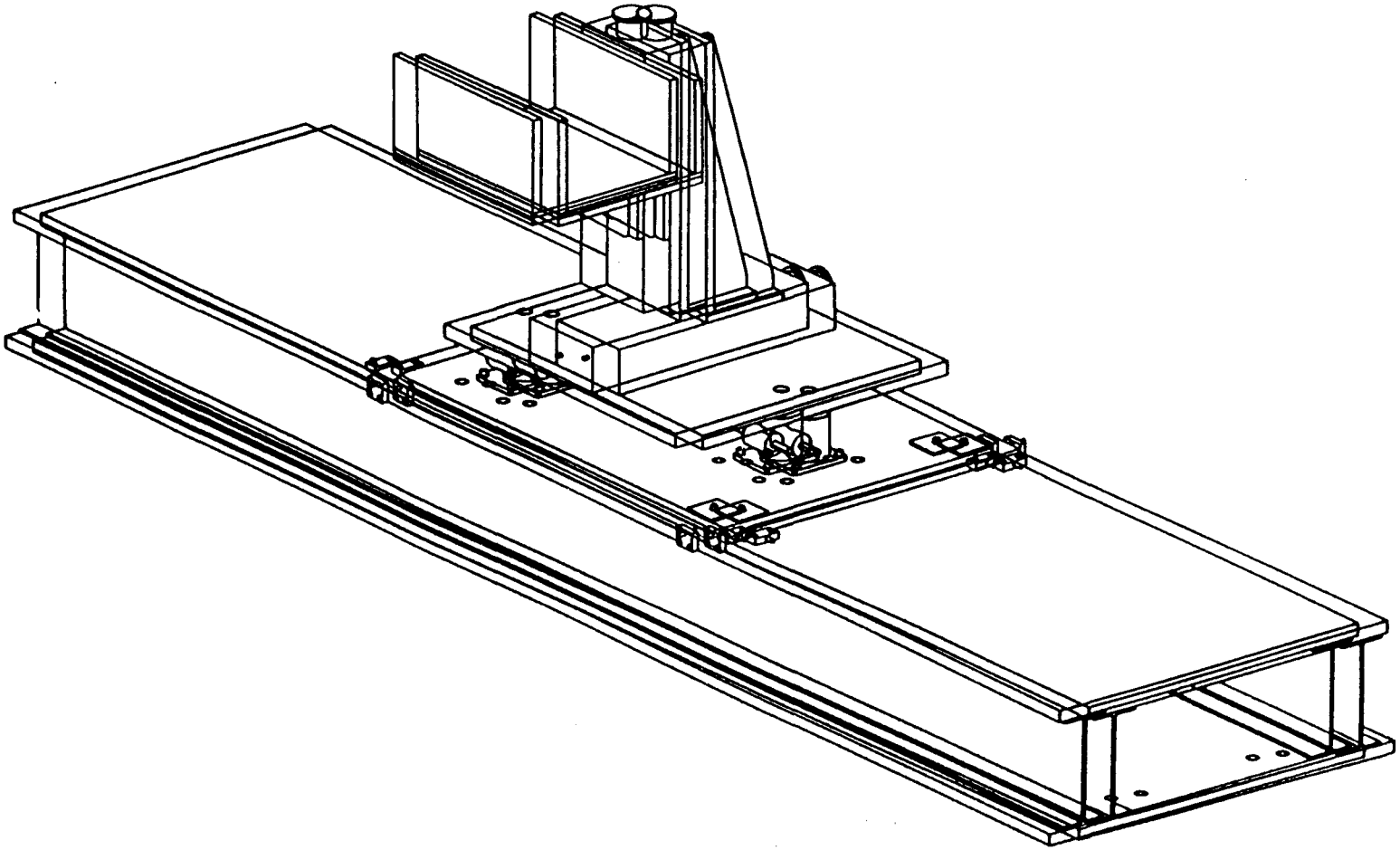
Table 4: Hardware Required & Status

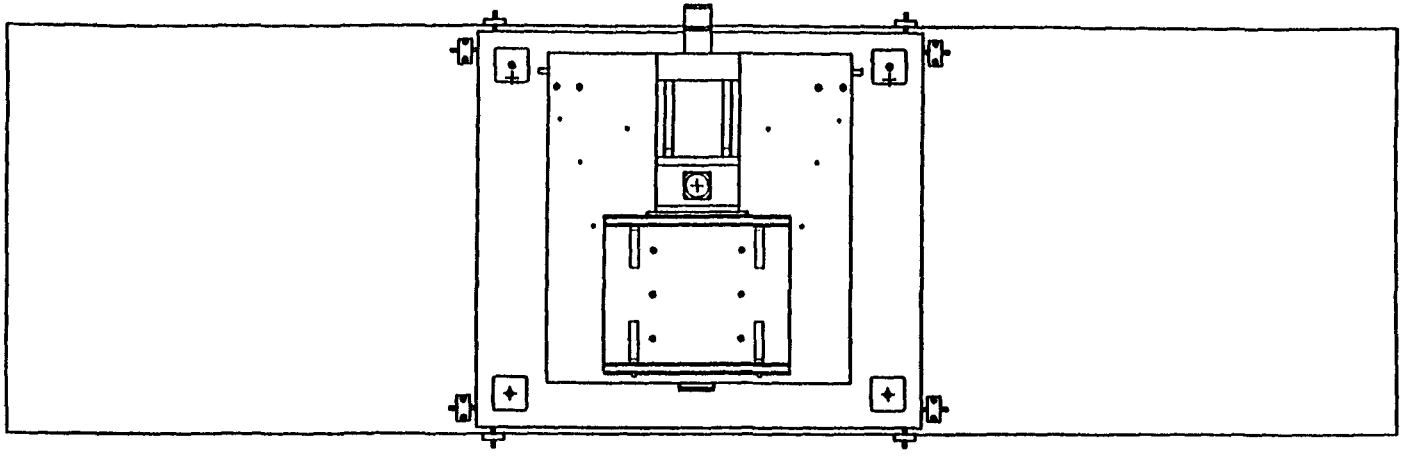
Component	# Required	Designed	Ordered	Delivered	Installed	Tested
Floor Space	5000 ft.^{2}	NA	NA	Cf	NA	
Clean Power	2	No				
8000amp/ 40volt	2	Yes	Yes	Yes	50%	
PCT	2	Yes	Yes	Yes		
D.C. Bus	2	Yes	Yes			
LCW Mani-folds	2	Yes	Yes			
LEB Quad Harmonics	1	Yes	Yes	Yes	90%	
LEB Quad Bench	1	Yes	RFQ Placed			
X-Y Slide	1	Yes	RFQ Placed			
LEB Dipole Probe	3?	10%				
LEB Dipole Bench	1	25%				
Reference Quadrupole	1	Spec.	Placed			
MEB Quad Bench	1	No				
MEB Dipole Probe	1	FERMI?				
MEB Dipole Bench	1	No				
Pulsed (A.C.) Systems	1	No				
Optical Fidu-cialization	2	No				

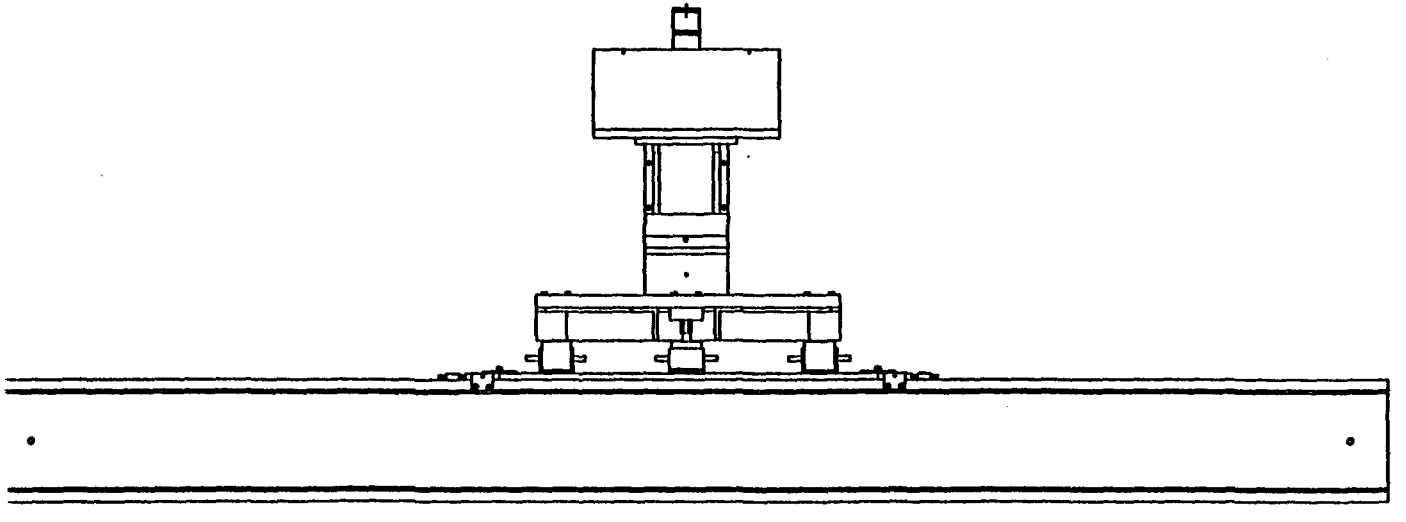
Table 4: Hardware Required & Status

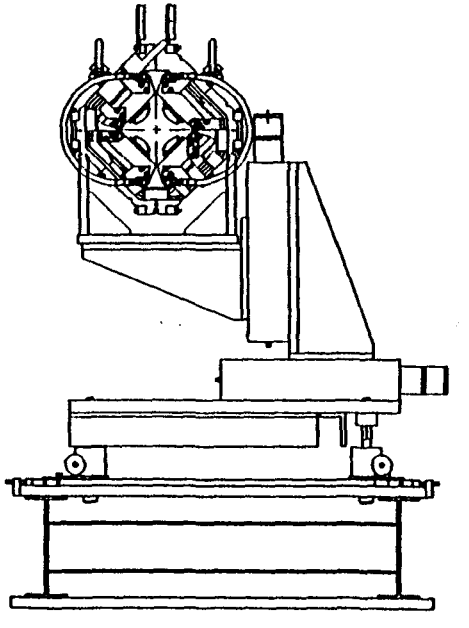
Component	# Required	Designed	Ordered	Delivered	Installed	Tested
Floor Space	5000 ft.^{2}	NA	NA	Cf	NA	
Clean Power	2	Yes	Yes	Yes	Yes	Yes
8000amp/ 40volt	2	Yes	Yes	Yes	Yes	Yes
PCT	2	Yes	Yes	Yes	Yes	Yes
D.C. Bus	2	Yes	Yes	Yes	Yes	Yes
LCW Mani-folds	2	Yes	Yes	Yes	Yes	Yes
LEB Quad Harmonics	1	Yes	Yes	Yes	Yes	Yes
LEB Quad Bench	1	Yes	Yes	Yes	Yes	Yes
X-Y Slide	1	Yes	Yes	Yes	Yes	Yes
LEB Dipole Probe	1	Yes	Yes	Yes	Yes	Yes
LEB Dipole Bench	1	Yes	Yes	Yes	90%	
Reference Quadrupole	1	Yes	Yes	Yes	Yes	Yes
MEB Quad Bench	1	50%	50%			
MEB Dipole Probe	Flat Coil Streched wire	FERMI No				
MEB Dipole Bench	1					
Pulsed (A.C.) Systems	1	No				
Optical Fidu-cialization	1	Yes	Canceled			

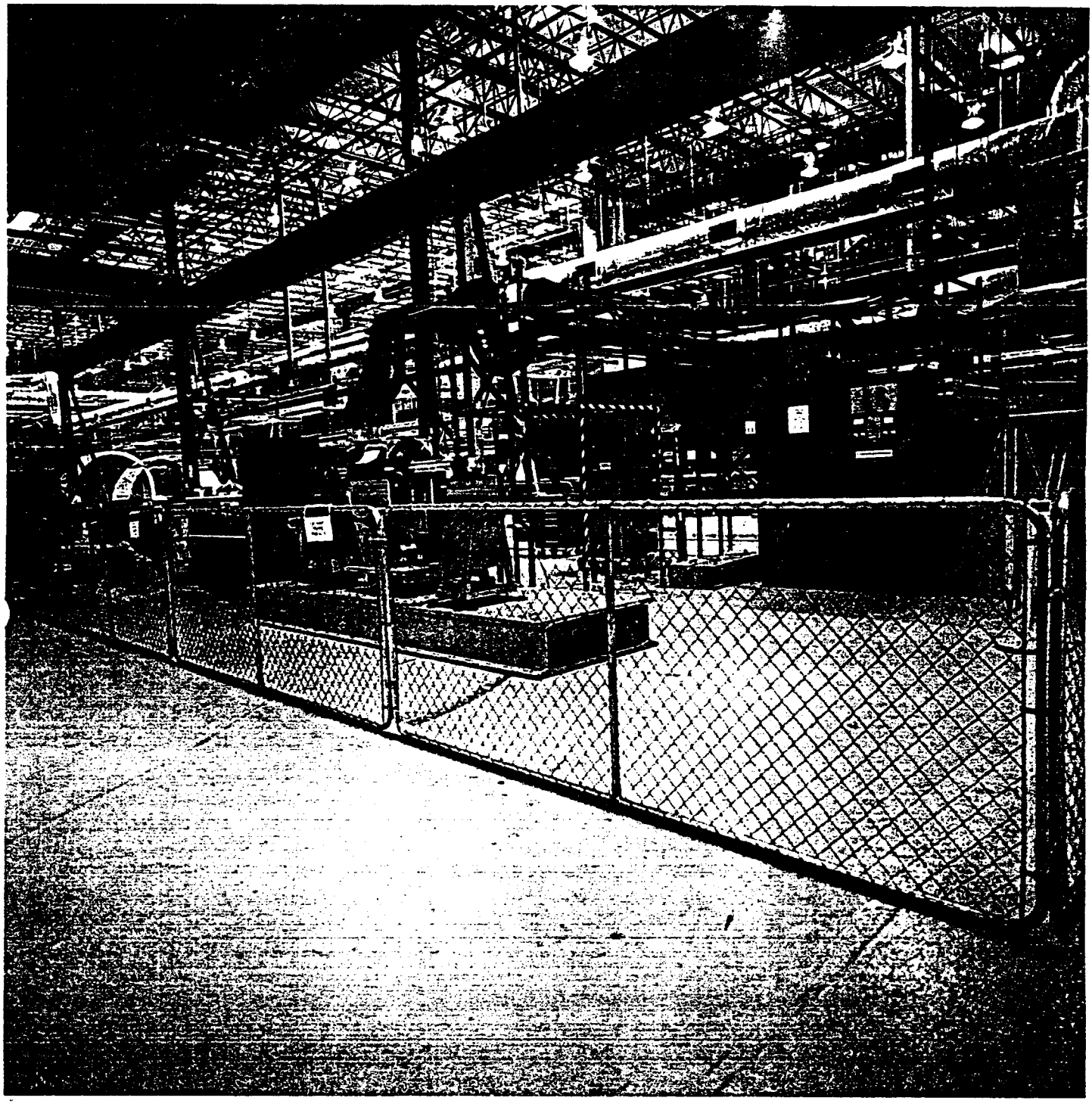






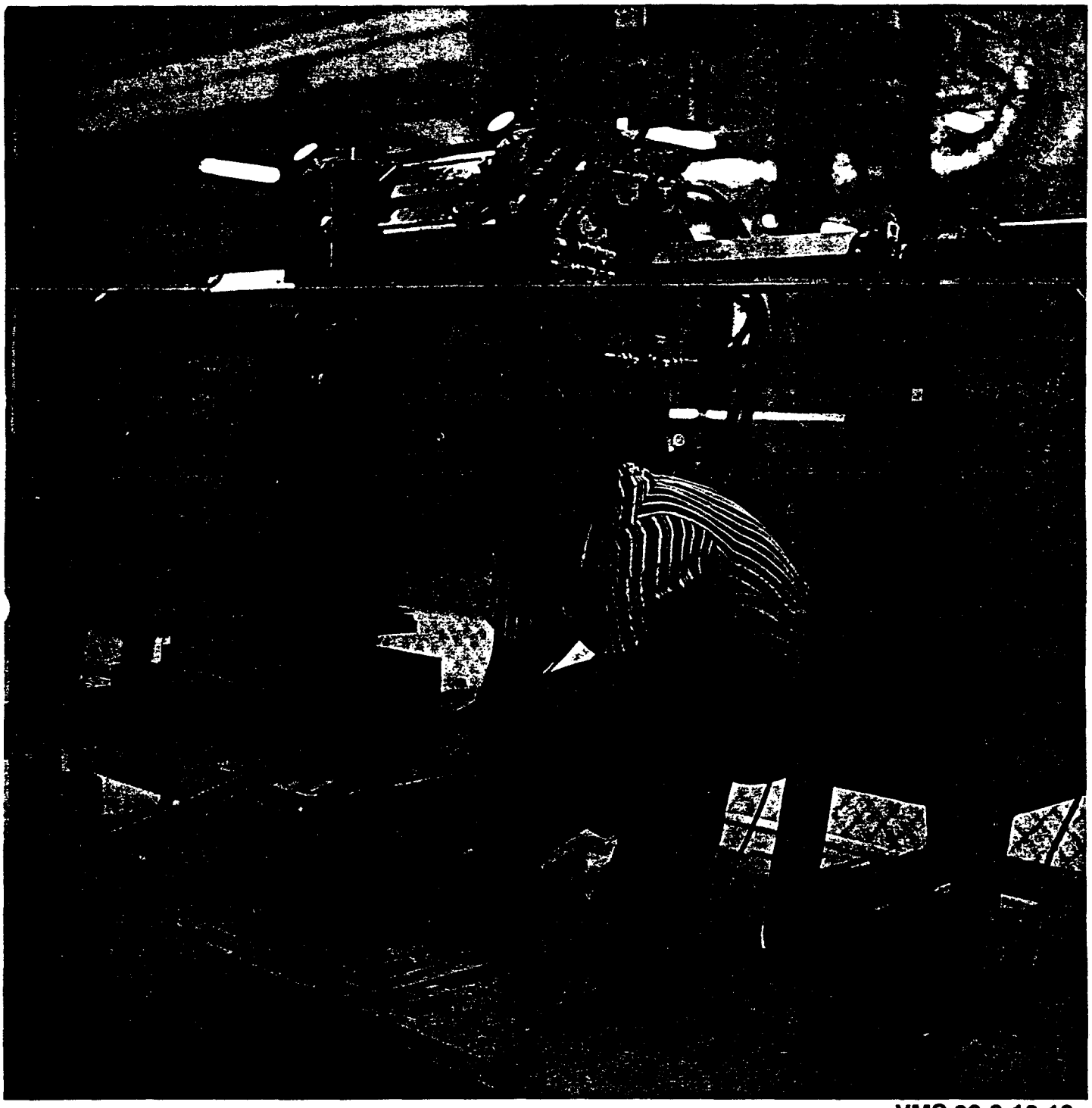






VMS 93-9-9-15
3-16-93
Magnets

VMS 93-9-10-3
3-16-93
Magnets



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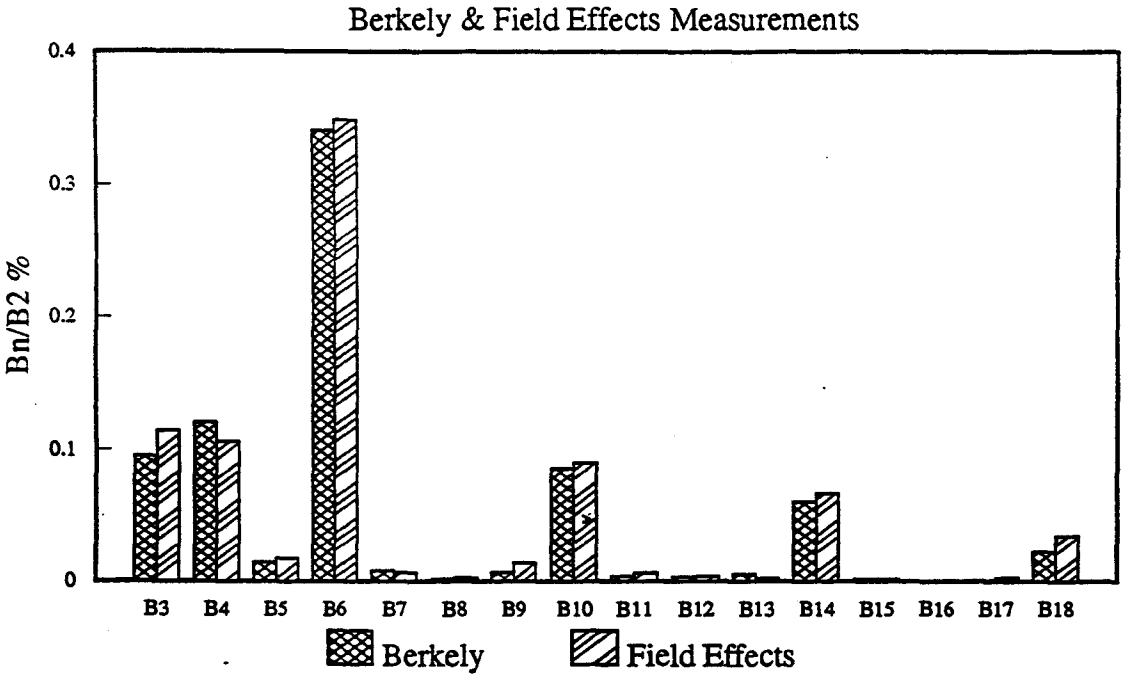
3-16-93
Magnets

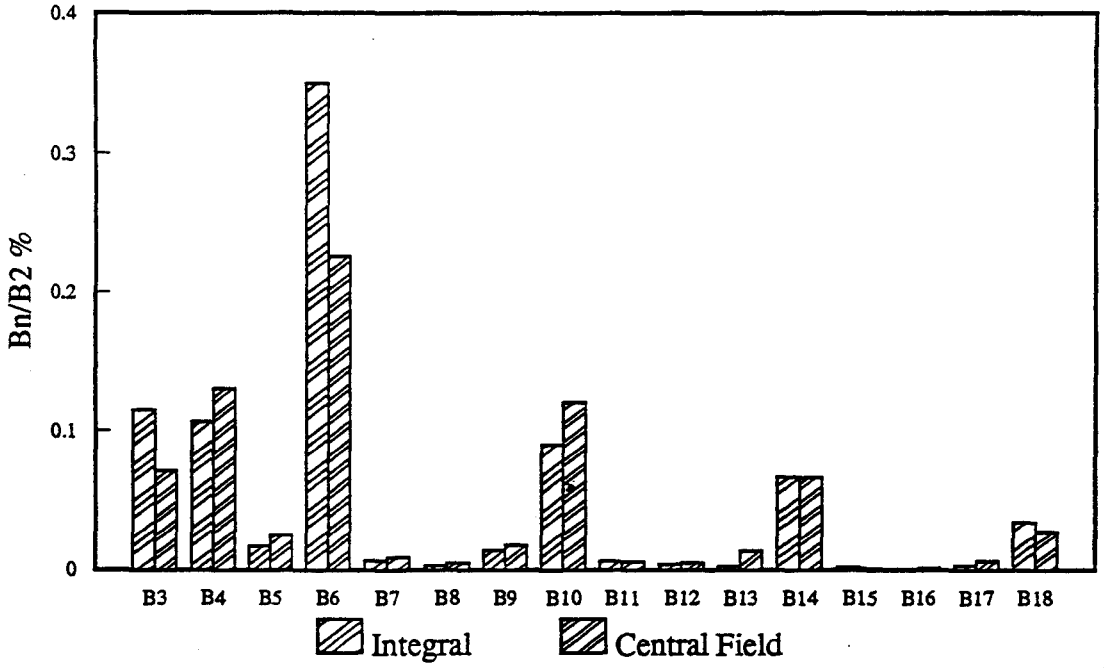
Quad SLCB1A



Berkely R0=4.25 cm
Field Effects R0=4.25 cm

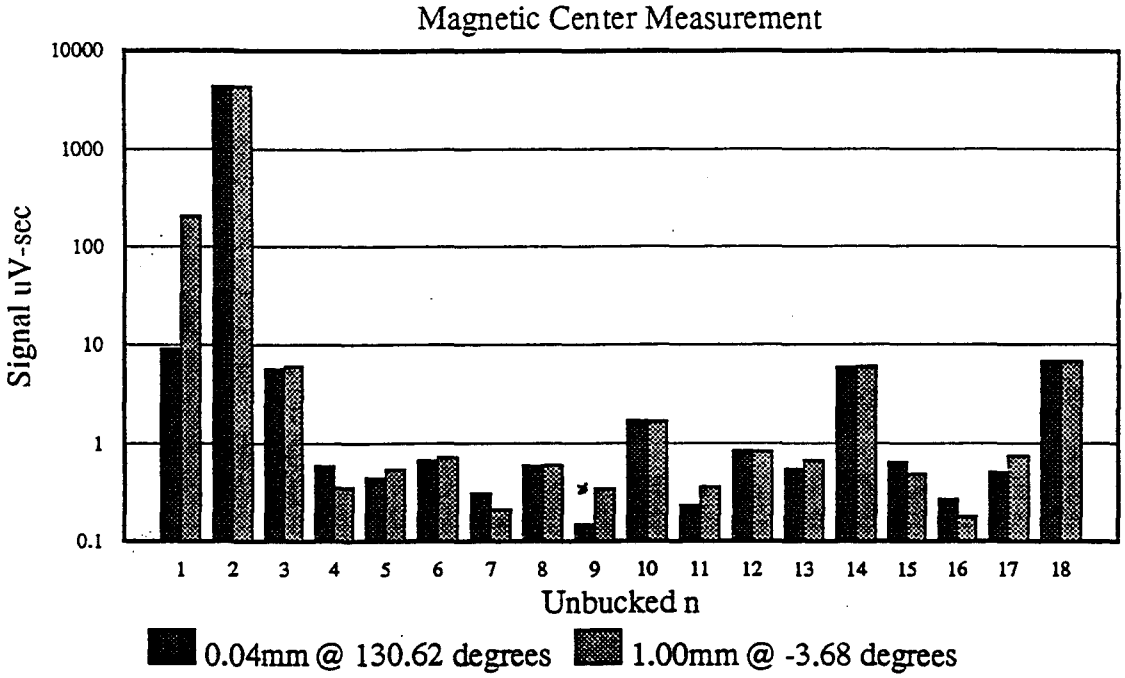
Quad SLCB1A

Field Effects Measurements



Field Effects R0=4.25 cm

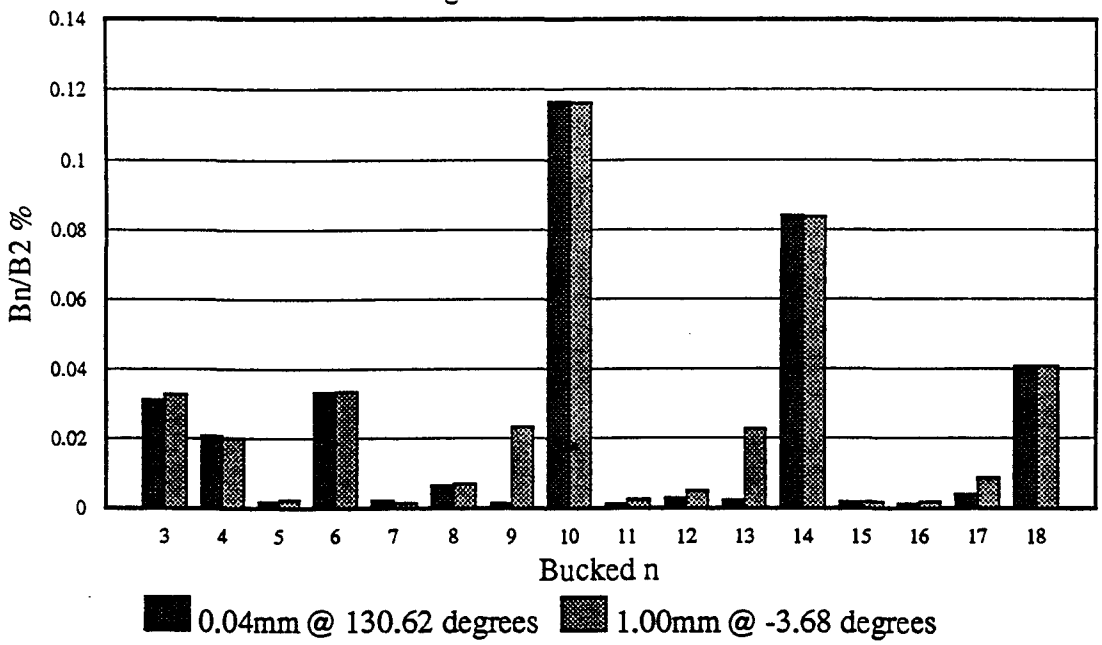
Berkeley Quad



We moved the magnet 1 mm between measurements
2000 amps, 4/30/93 data

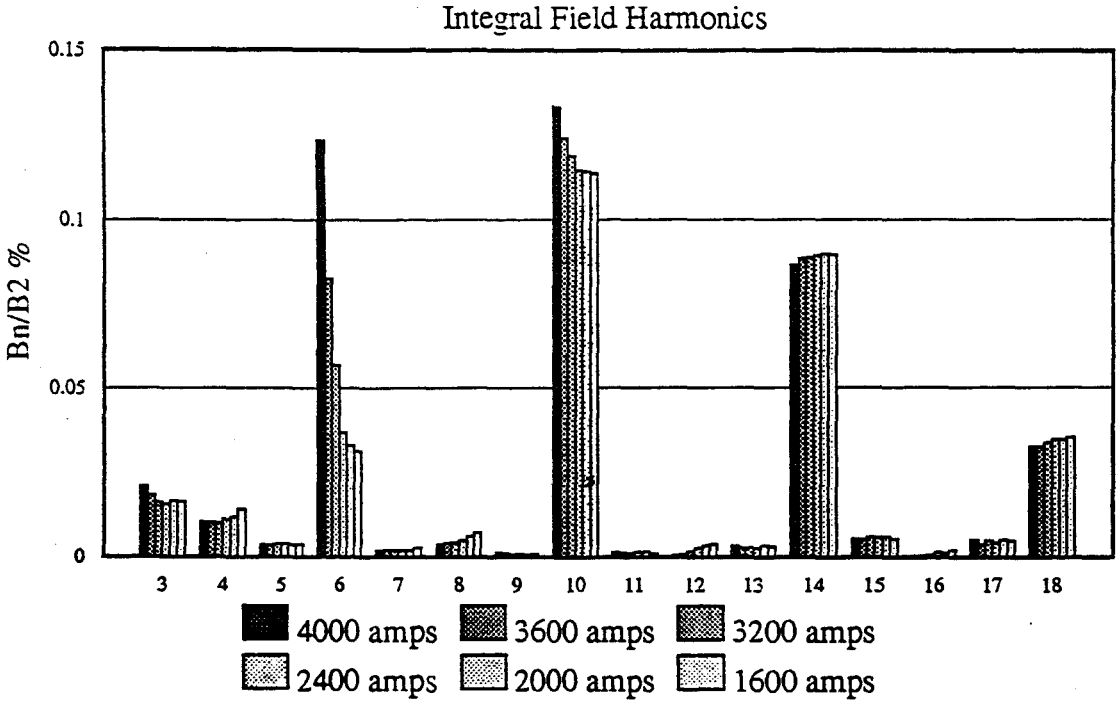
Berkeley Quad

Magnetic Center Measurement



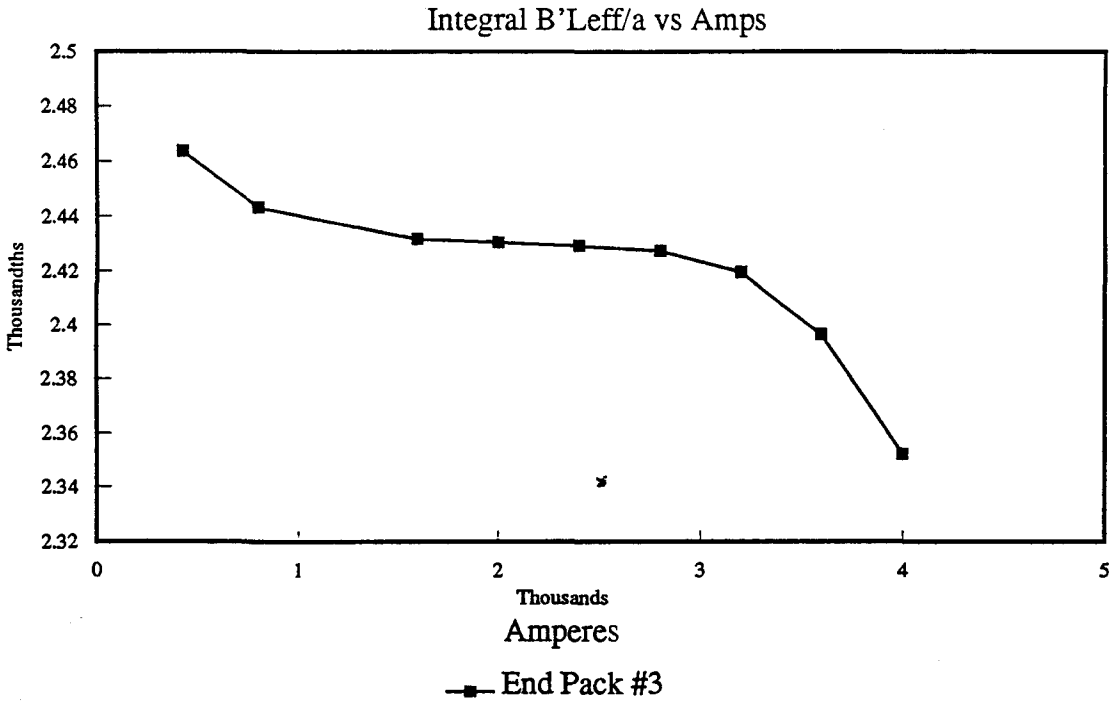
We moved the magnet 1 mm between measurements
2000 amps, 4/30/93 data

INP Quad Prototype #1

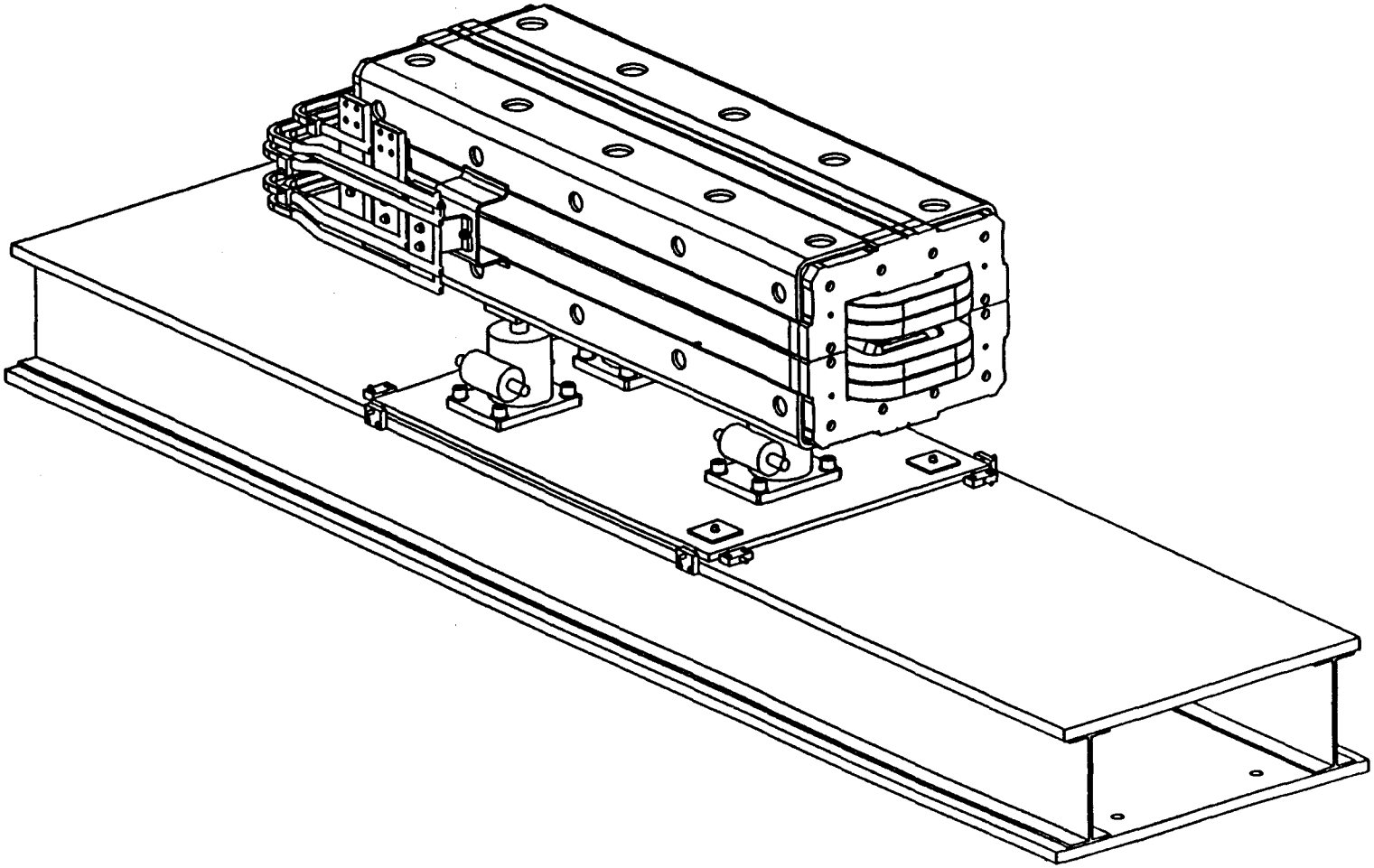


5/27/93 Field Effects Measurements

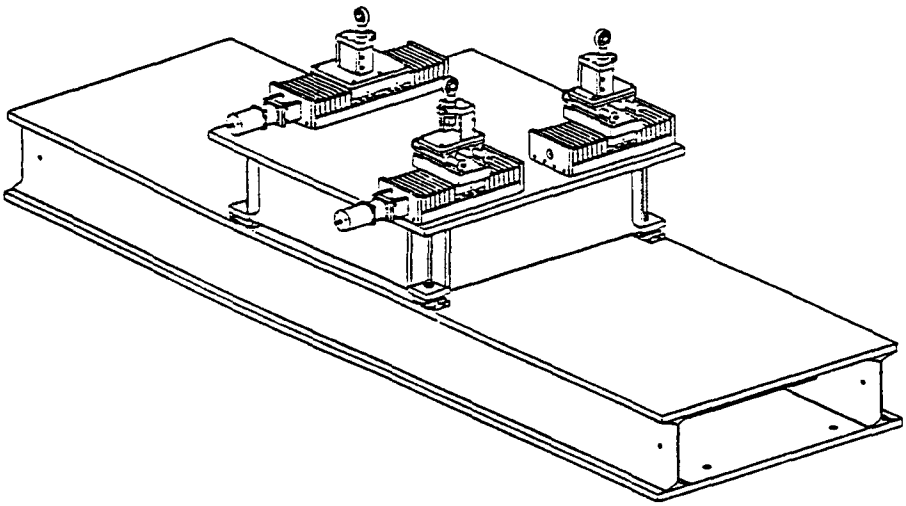
Berkeley Quad

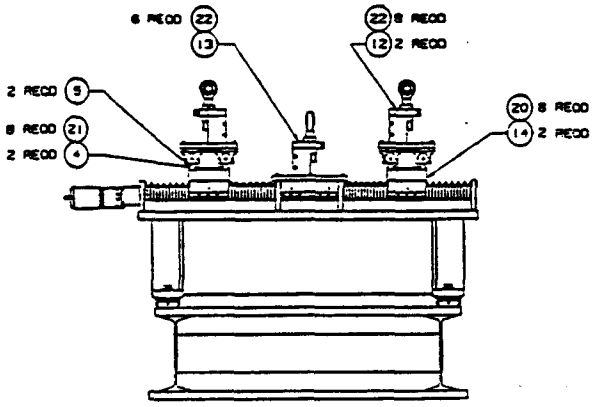


./26/93 data



ZONE	REV	REVISIONS DESCRIPTION	DATE	APPROVED





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QTY	QTY	QTY	PART NUMBER	DESCRIPTION	CAGECO	ZONE	ITEM
		14		.375-24 UNC X 1.25 SHCS, SST		E3	22
		8		.250-28 UNF X .375 HHCS, SST		D4	21
		8		.375-24 UNF X 1.75 SHCS, SST		D3	20
		20		.375-16 UNC X 1.75 SHCS		G6	19
		4		.750-10 UNC X 4.25 HHCS		D5	18
		4	9009K73	LEVELING MOUNT		D5	17
		4	91131A080	SPHERICAL WASHER SET		D6	16
		1	5518A403	5/8" HEX SOCKET RATCHET WRENCH (NOT SHOWN)			15
		2	AMS-2210020	PLATE, ADAPTER		D3	14
		1	AMS-221013-003	ASSY, SUPPORT JACK LEB DIPOLE		D4	13
		2	AMS-221013-001	ASSY, SUPPORT JACK LEB DIPOLE		D2	12
		1	AMS-2210012	BASE, MAGNET MEASUREMENT MACHINE		D5	11
		1	AMS-2210011	TABLE, MAGNET SUPPORT		D6	10
		1	AT8400	COMPUMOTOR MULTI AXIS INDEXER (NOT SHOWN)			9
		2	6600	COMPUMOTOR DRIVER (NOT SHOWN)			8
		2	583-62NO	COMPUMOTOR NEMA 34 STEPPING MOTOR	P7681		7
		2	NE34-05	BAYSIDE NEMA 34 511 GEAR REDUCER	P7681		6
		2	TRCA16-8-CUSTOM	LINTECH CARRIGE, W/INSERTS, .375-24		D4	5
		2	TRSA16-12-E4	LINTECH TWIN RAIL W/END STOPS		D4	4
		1	MI-250812-CUSTOM	LINTECH TABLE, NO DRIVE/MOTOR		G6	3
		1	MI-250812-LE12 X	LINTECH TABLE, 8" CARRIAGE		F6	2
		1	MI-251212-LE12 X	LINTECH TABLE, 12" CARRIAGE		G6	1
		-001	-	LIST OF MATERIALS / PARTS LIST			

REF ONLY-NOT TO BE MAINTAINED

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

TOLERANCE OF WHOLE NUMBERS ±1

TOLERANCE OF DECIMALS .X ±0.5 .XX ±0.25 .XXX ±0.125

1. DIMENSIONS SHOWN THUS (XXX) ARE REFERENCE DIMENSIONS.
2. DO NOT SCALE THIS DRAWING.

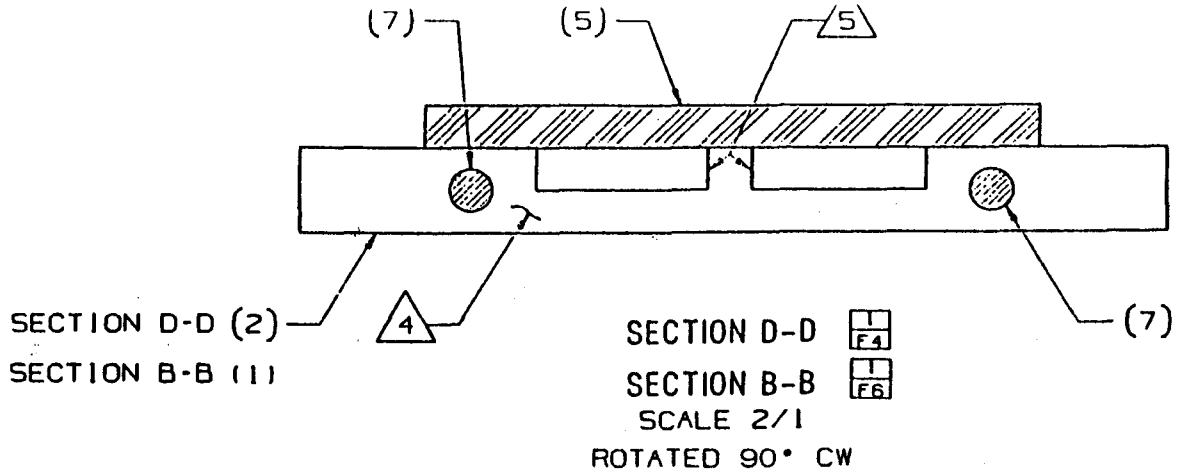
DRAWN W. SIAZ 03-22-93
CHECK 03-22-93
ENG 03-25-93
APPD
APPD
APPD
APPD

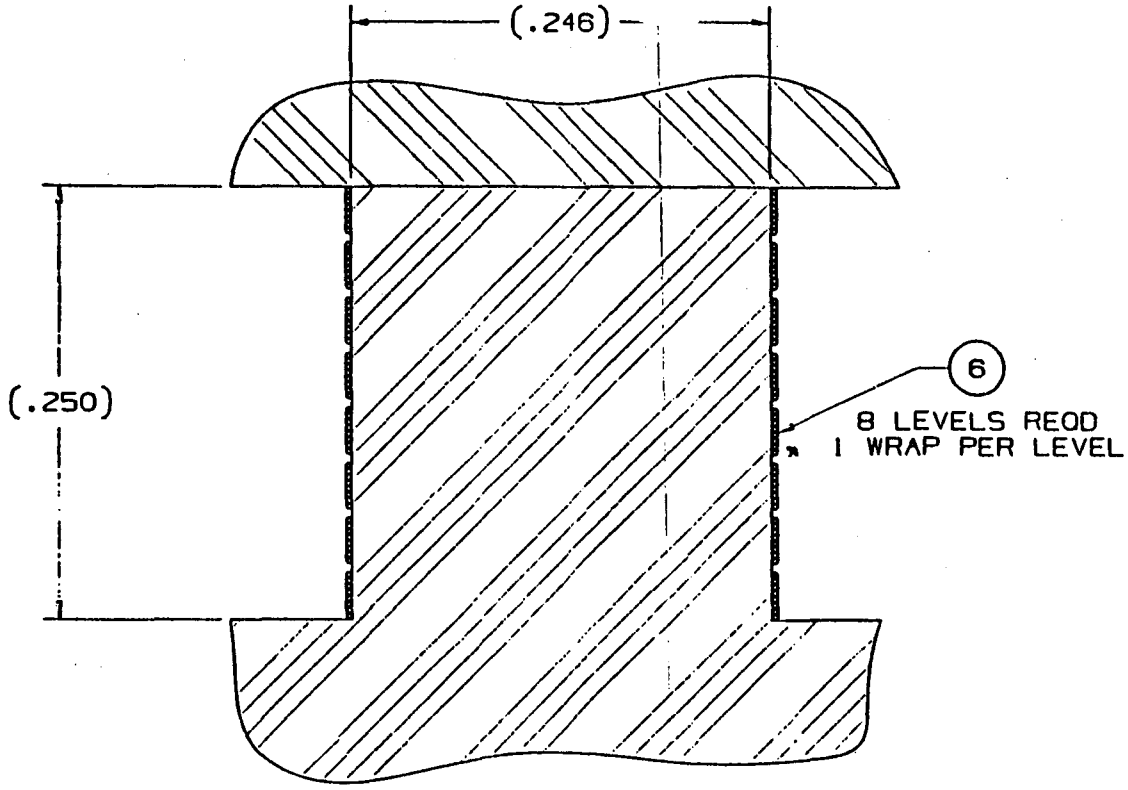
SSC

ASSY, MAGNETIC MEAS MACHINE - LEB DIPOLE

INCH / SI-METRIC

SIZE | DRAWING NO | REV





DETAIL C 1/E6

THIS IS A C
MAKE MANUA

3

QTY	QTY	QTY	PART NUMBER	
		70		SCREW, CAP, H
		6	·003	PIN, DOWEL, 0
		A/R	8-8401291	MULTIFILAR MA
		1	AMA-2210282-001	COVER, CENTER
		2	AMA-2210281-001	COVER, END
		1	AMA-2210279-002	FORM, END, RI
		1	AMA-2210280-001	FORM, CENTER
		1	AMA-2210279-001	FORM, END, LE
		·001		LIST OF

INCH

SYMETRIC

THIRD ANGLE PROJECTION

REF ONLY-NOT TO BE MAINTAINED

DASH NO	NEXT ASSY	USED ON
·001	AMA-2210290	

APPLICATION

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS

TOLERANCE OF HOLE DIAMETERS

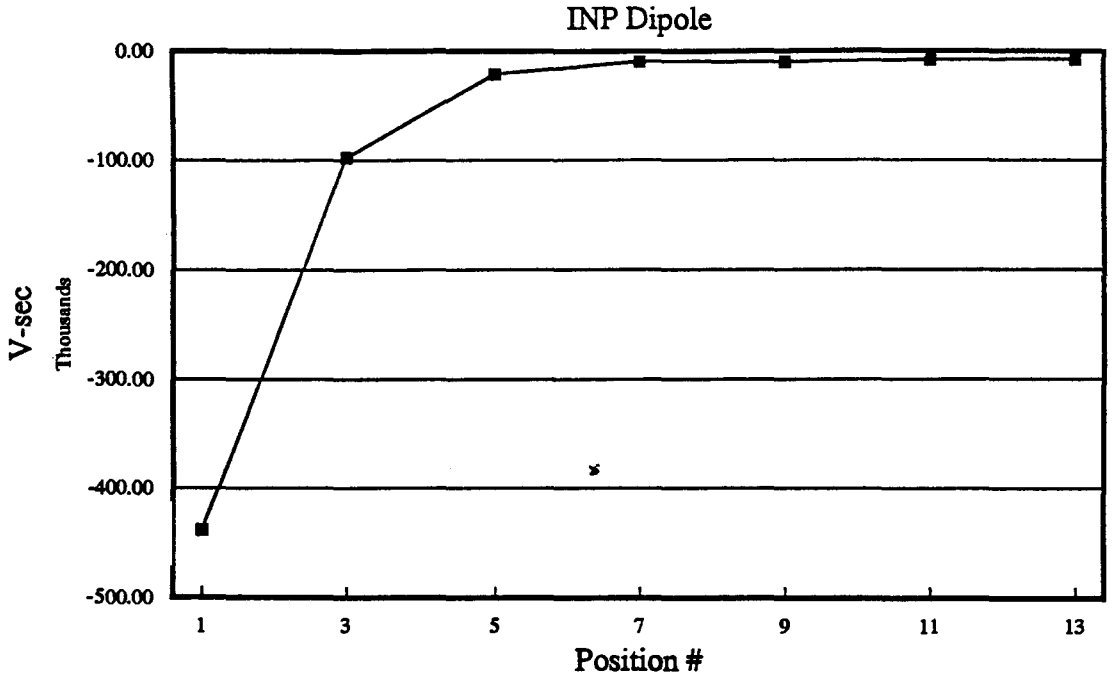
TOLERANCE OF DECIMALS

1. BREAK ALL SHARP EDGES 0.5 MAX.
2. DO NOT SCALE THIS DRAWING
3. DIM. TO AMA-15.SM-1982
4. ALL MACHINED SURFACES

3.2

DRAWN R. HARTNED
CHKD
APPD
APPD
APPD
APPD
APPD
CONTRACT NO. DE-AC35-8

Flat Coil Data

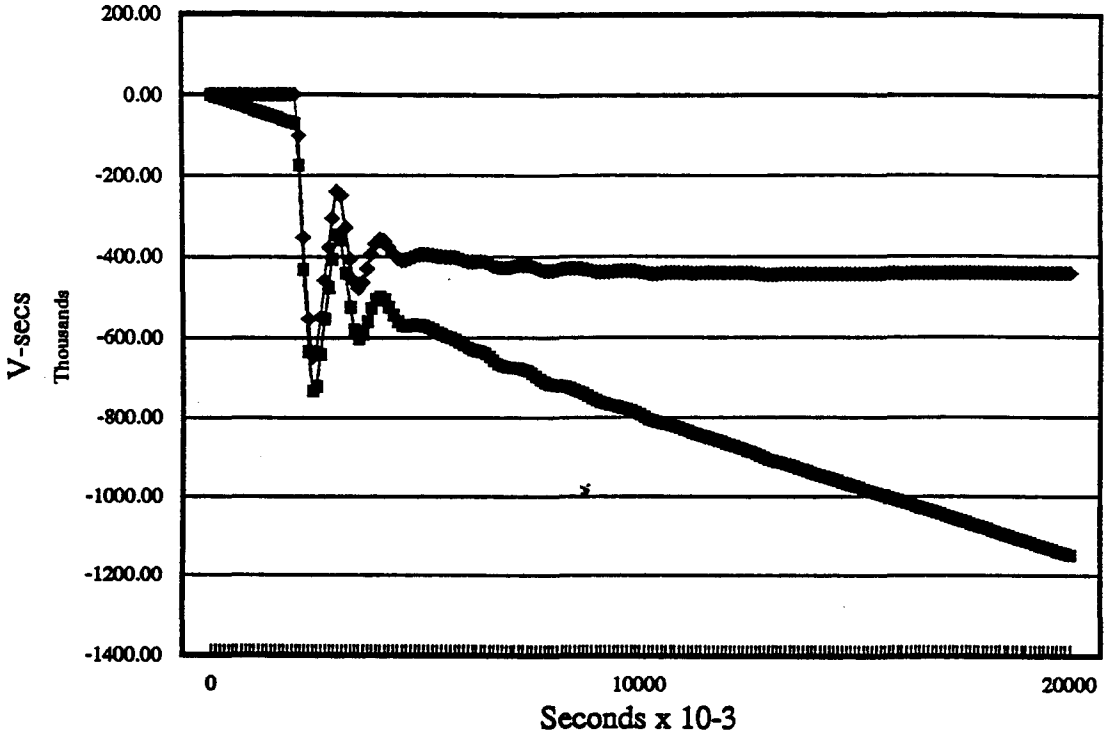


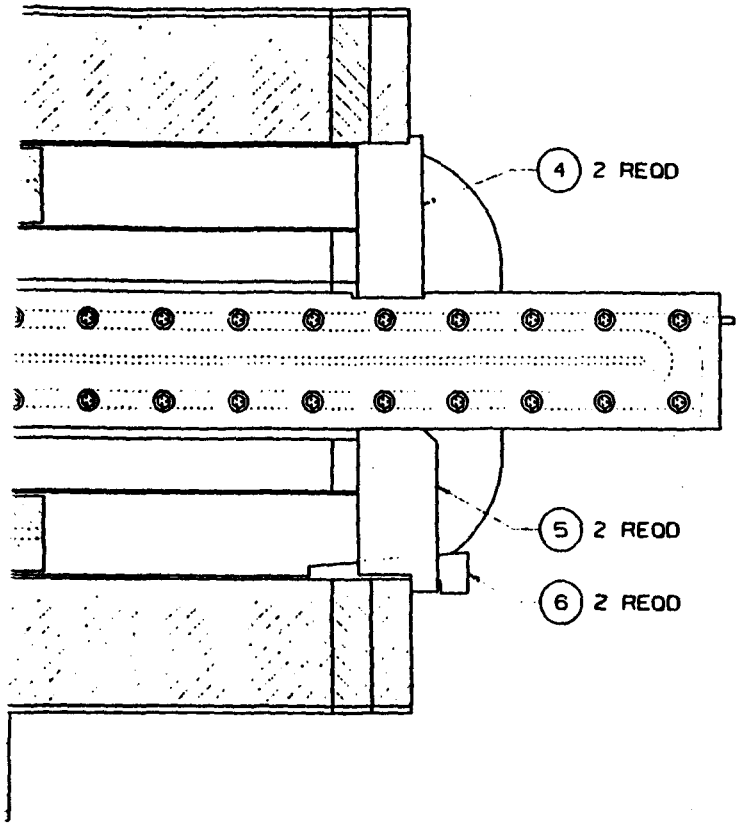
flatcoil9-21-93.wk
426 amps

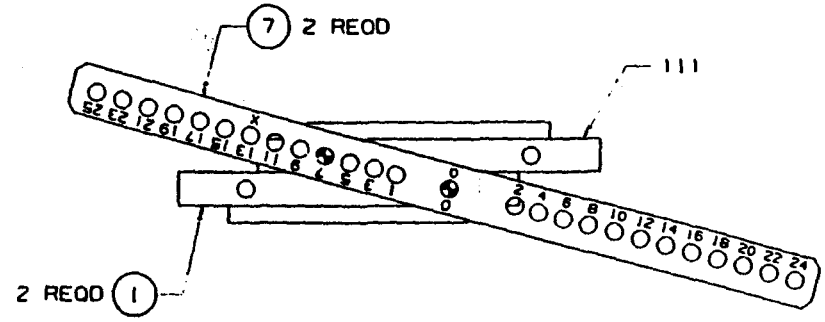
Magnets that will arrive next year:

- 100 Linac Quadrupoles
- 6 Linac/LEB dipoles
- 17 Linac/LEB Trim dipoles
- 17 Linac/LEB Quads
- 100 LEB Main Quads
- 100 LEB Main Dipoles
- 250 LEB Corrector magnets
- LEB Injection Bumps and Septa
- 3 MEB prototype dipoles
- 1 MEB prototype quad

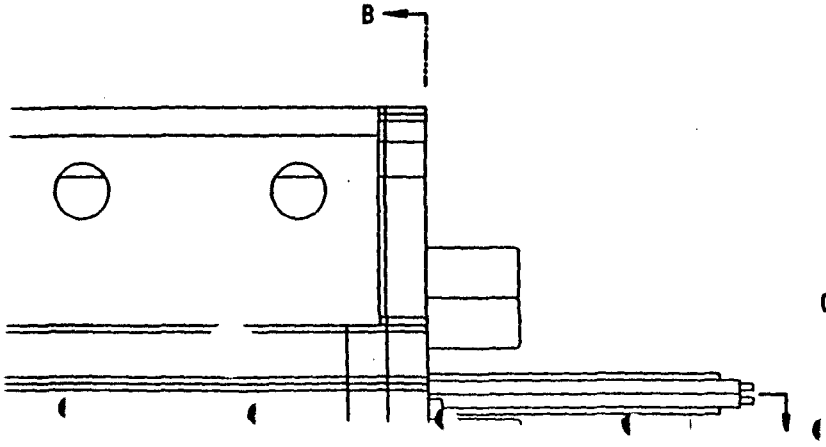
Flat Coil Data

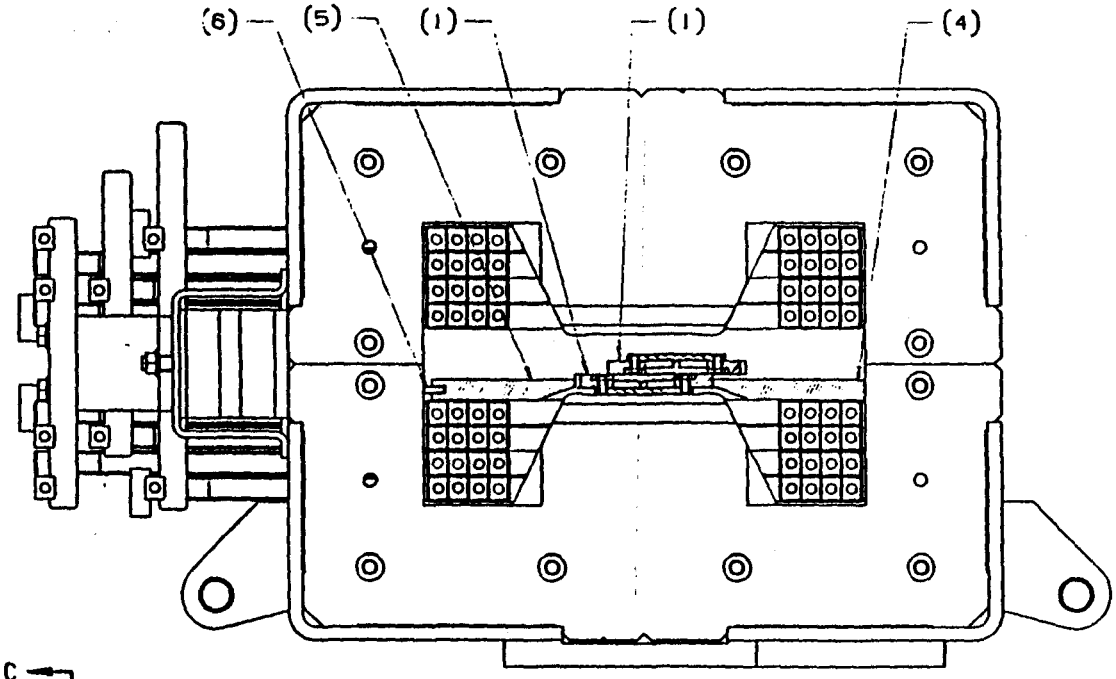






VIEW C-C
SCALE 1:1





SECTION B-B

IMMW-8

SSCL September, 1993

Cosmore Sylvester

Superconducting Corrector Magnets
Magnetic Measurements Systems

IMMW-8

SSCL 9-93

Cosmore Sylvester

INTRODUCTION

The SSCL collider arc and the High Energy Booster corrector magnets are 50 mm bore cryogenic magnets. The integral strength and harmonics will be measured at full current at 4.2K and at plus and minus 400 mA at room temperature. Dipoles, quadrupoles, and sextupoles have error tolerances of a few tens of units. The required field quality of the error harmonics is 10 to 30 units. A unit is defined as 10^{-4} of the fundamental field evaluated at a reference radius of 1 cm. Magnet lengths vary from 0.2 meters to 1.8 meters.

MAGNET MEASUREMENT REQUIREMENTS

HEB Dipole Corrector Magnets

REQUIREMENT	VERTICAL	HORIZONTAL
Quantity	184	178
Field Integral @ max current and 1 cm ref. radius	2.5 T-m	2.5 T-m
Operation	Bipolar	Bipolar
Multipole error, Sum	< 0.3% at 1 cm	< 0.3% at 1 cm
Clear Aperture diameter (mm)	50	50
Max Operating current	< 100 A	< 100A
Maximum dI/dt	10 A/s	10 A/s

HEB Quadrupole Corrector Magnets

REQUIREMENT	QUADRUPOLE	SKEW QUAD
Quantity	348	40
Field Integral @ max current and 1 cm ref. radius	0.25 T-m	0.25 T-m
Operation	Bipolar	Bipolar
Multipole error, Sum	< 0.1% at 1 cm	< 0.1% at 1 cm
Clear Aperture diameter (mm)	50	50
Max Operating current	< 100 A	< 100A
Maximum dI/dt	10 A/s	10 A/s

HEB Sextupole Corrector Magnets

REQUIREMENT	SEXTUPOLE	SKEW SEXT
Quantity	282	8
Field Integral @ max current and 1 cm ref. radius	0.15 T-m	0.15 T-m
Operation	Bipolar	Bipolar
Multipole error, Sum	< 0.3% at 1 cm	< 0.3% at 1 cm
Clear Aperture diameter (mm)	50	50
Max Operating current	< 100 A	< 100A
Maximum dI/dt	10 A/s	10 A/s

COLLIDER Dipole Corrector Magnets

REQUIREMENT	CBH, CBV	CBH1, CBV1
Quantity	782 (H), 782(V)	2 (H1), 2 (V2)
Field Integral @ max current and 1 cm ref radius	3.00 T-m	TBD T-m
Operation	Bipolar	Bipolar
Multipole error, Individual	< 0.3% at 1 cm	< 0.3% at 1 cm
Clear Aperture diameter (mm)	50	50
Max Operating current	< 100 A	< 100A
Maximum dI/dt	1A/s	1A/s

COLLIDER Quadrupole Corrector Magnets

REQUIREMENT	CQF/CQD	SKEW QUAD
Quantity	782/782 (1564 total)	TBD
Field Integral @ max current and 1 cm ref radius	0.65 T-m	0.65 T-m
Operation	Bipolar	Bipolar
Multipole error, Individual	< 0.1% at 1 cm	< 0.1% at 1 cm
Clear Aperture diameter (mm)	50	50
Max Operating current	< 100 A	< 100A
Maximum dI/dt	1 A/s	1 A/s

COLLIDER Sextupole Corrector Magnets

REQUIREMENT	SX/D	SX/F
Quantity	784	784
Field Integral @ max current and 1 cm ref. radius	0.23 T-m	0.15 T-m
Operation	Bipolar	Bipolar
Multipole error, Individual	< 0.3% at 1 cm	< 0.3% at 1 cm
Clear Aperture diameter (mm)	50	50
Max Operating current	< 100 A	< 100A
Maximum dI/dt	1 A/s	1 A/s

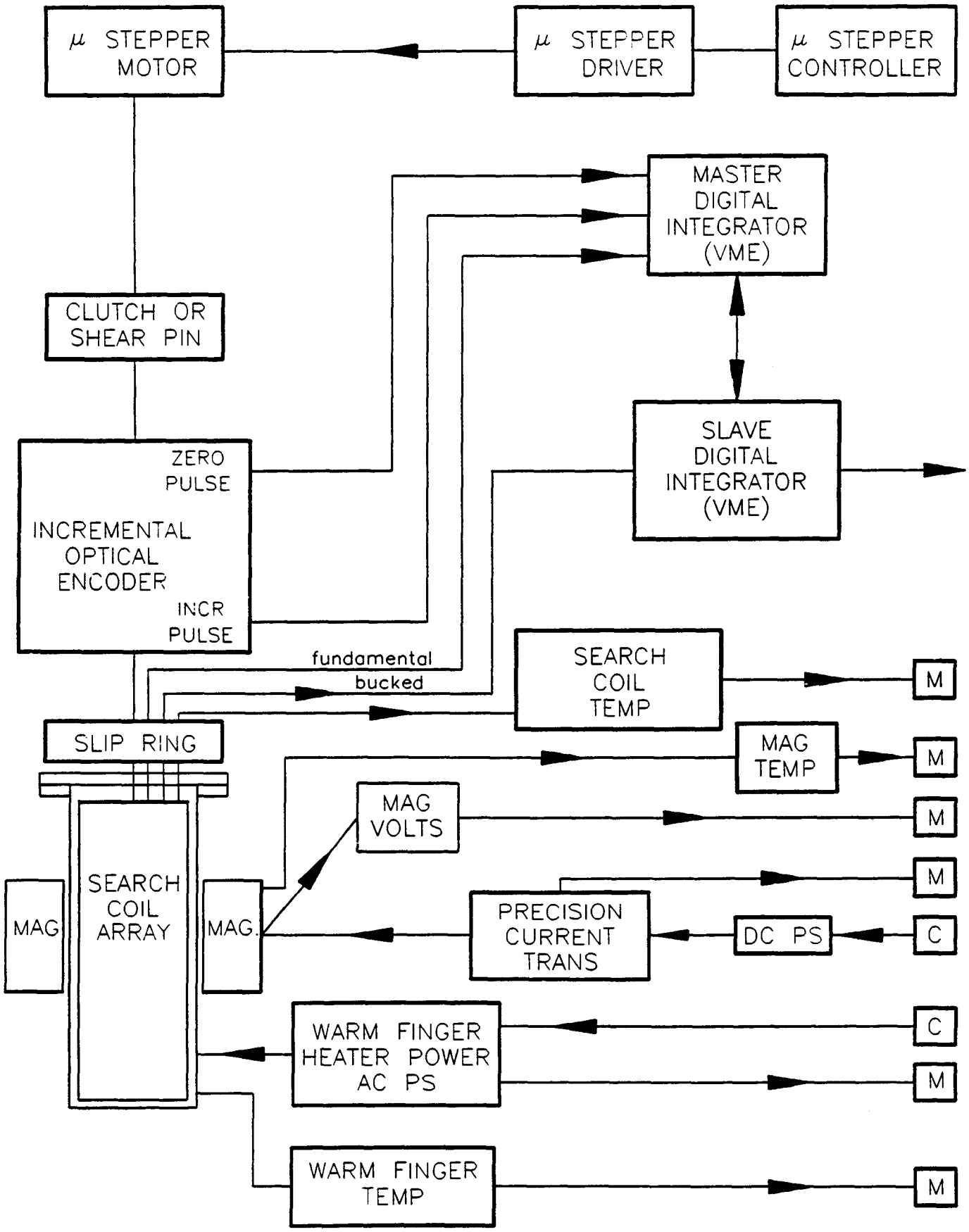
INSTRUMENTATION

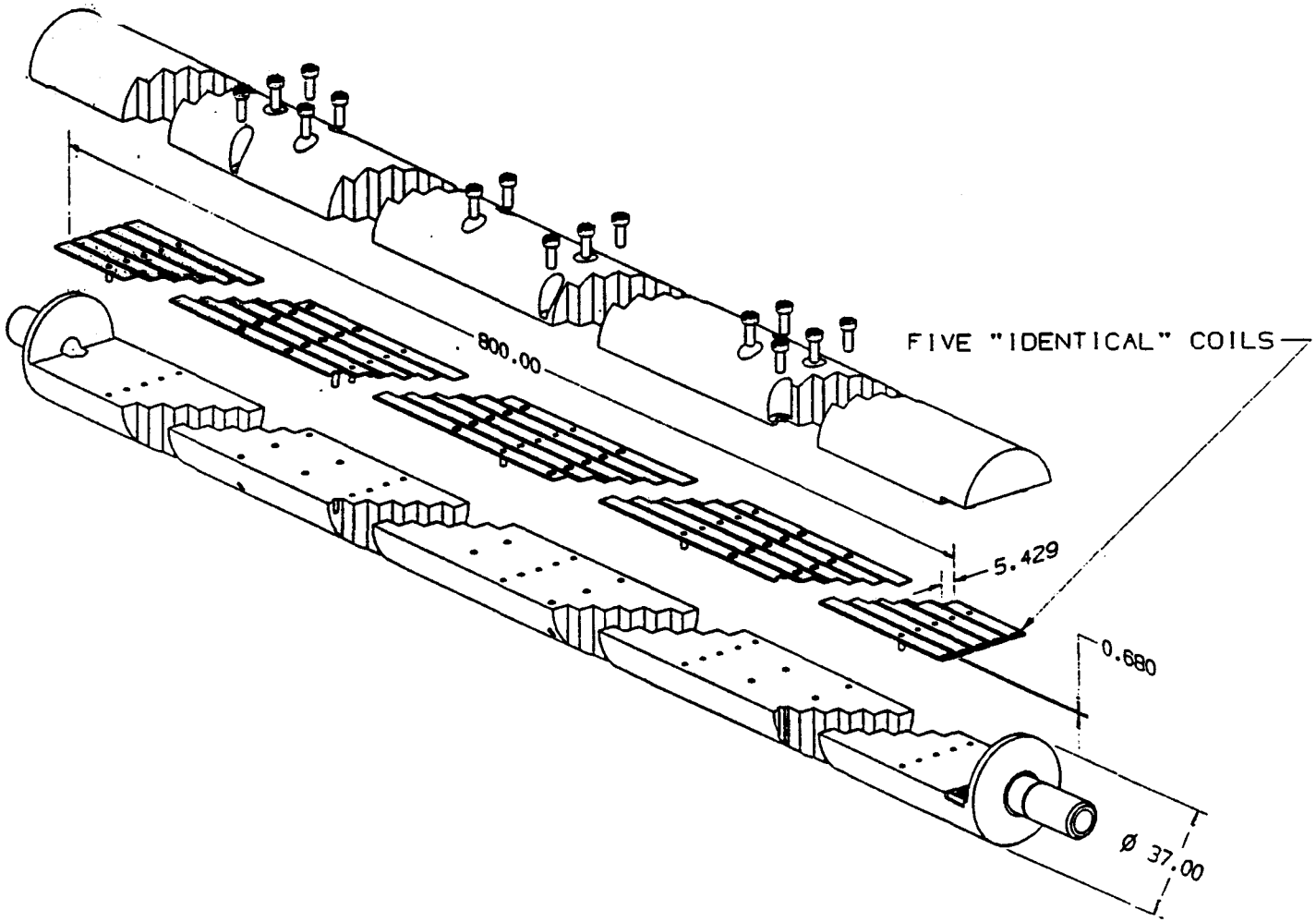
The voltage from rotating radial coil arrays is fed to digital integrators which are latched by an incremental optical encoder. The decision to use radial rather than tangential coil arrays is based on the higher sensitivities obtainable with radial coil arrays. Tangential coil arrays have the coil bundles on the surface of a cylinder, whereas radial coil arrays typically have their coil bundles in a plane going through the axis of rotation. Using integrators rather than reading the voltage directly eliminates the need to correct the coil voltages for rotational speed variations. Measurements of the error harmonics will be facilitated by utilizing analog bucking,.i.e., connecting coils in series opposing to cancel out the fundamental, and one lower harmonic. As the digital integrators have a high input impedance, the system will be able to simultaneously obtain data from the fundamental coil by itself and the fundamental coil output bucked by the output of the compensating coils.

Slip rings will allow continuous rotation of the coils. This will facilitate more comprehensive data acquisition during current ramps.

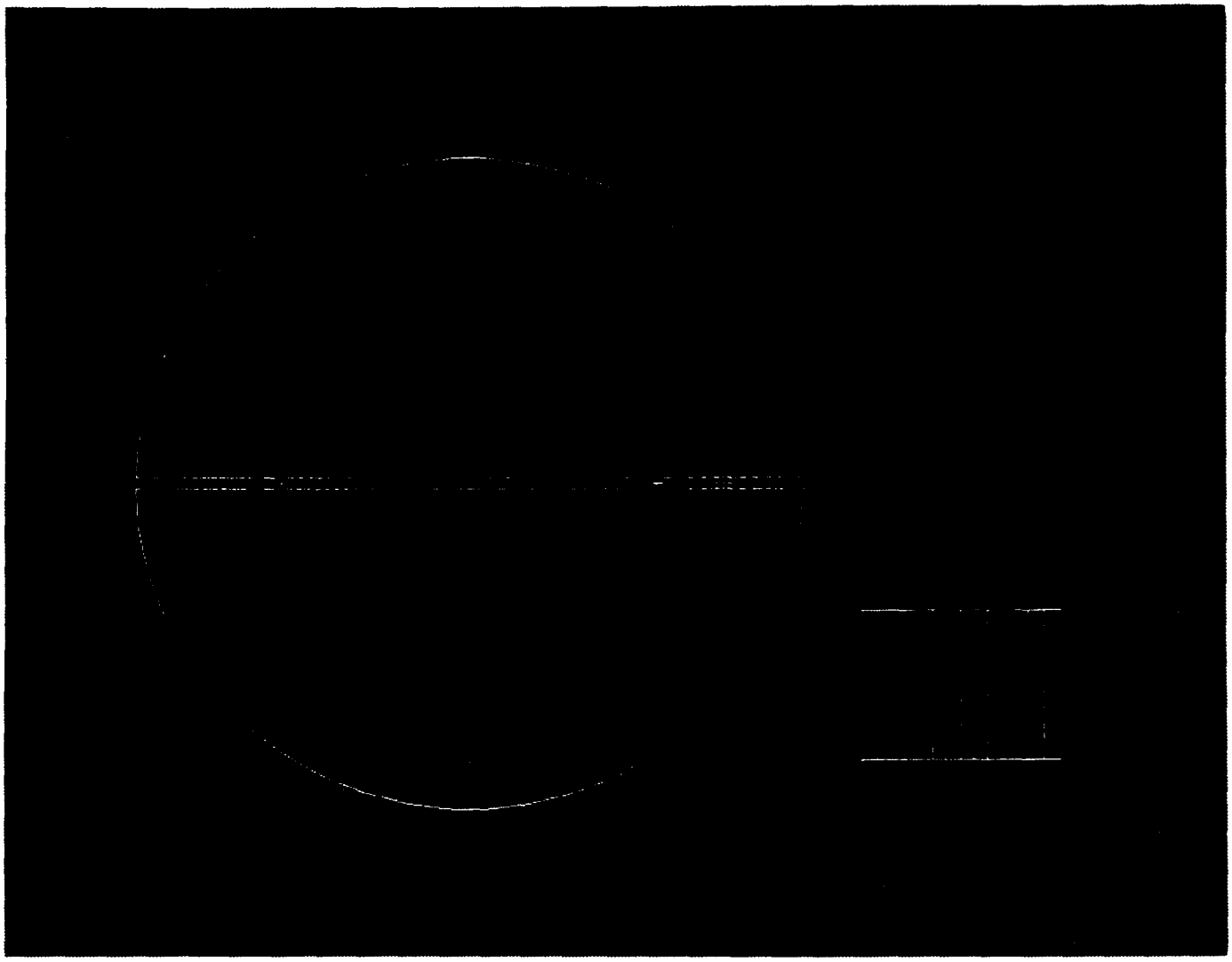
The data acquisition instrumentation is VME based. A Motorola MVME-167 will control the VME bus. The digital integrators are Metrolab PDI 5035 VMEbus models which are based upon a voltage to frequency converter developed at CERN.

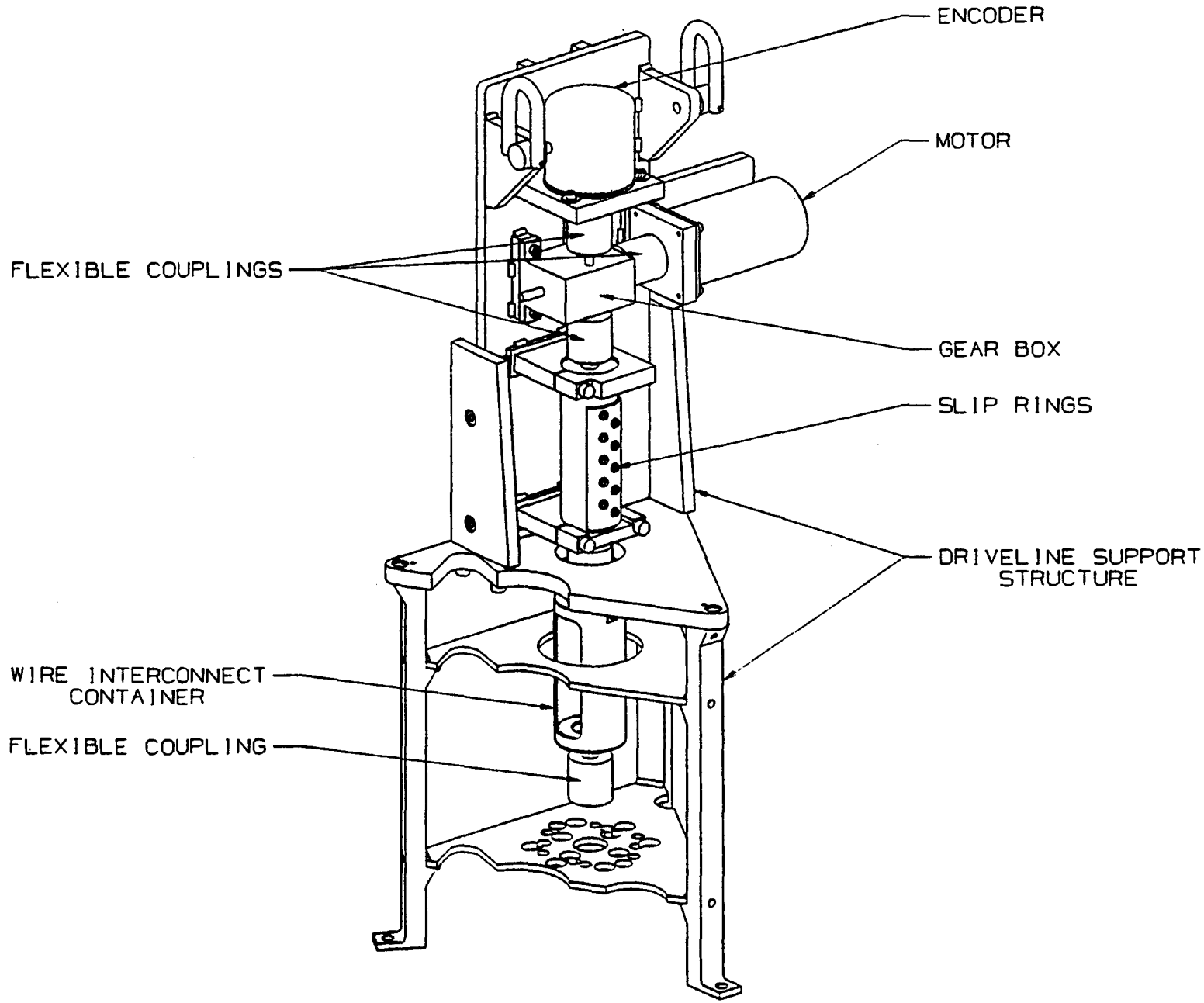
CRYOGENIC CORRECTOR MAGNET HARMONIC ANALYSIS SYSTEMS



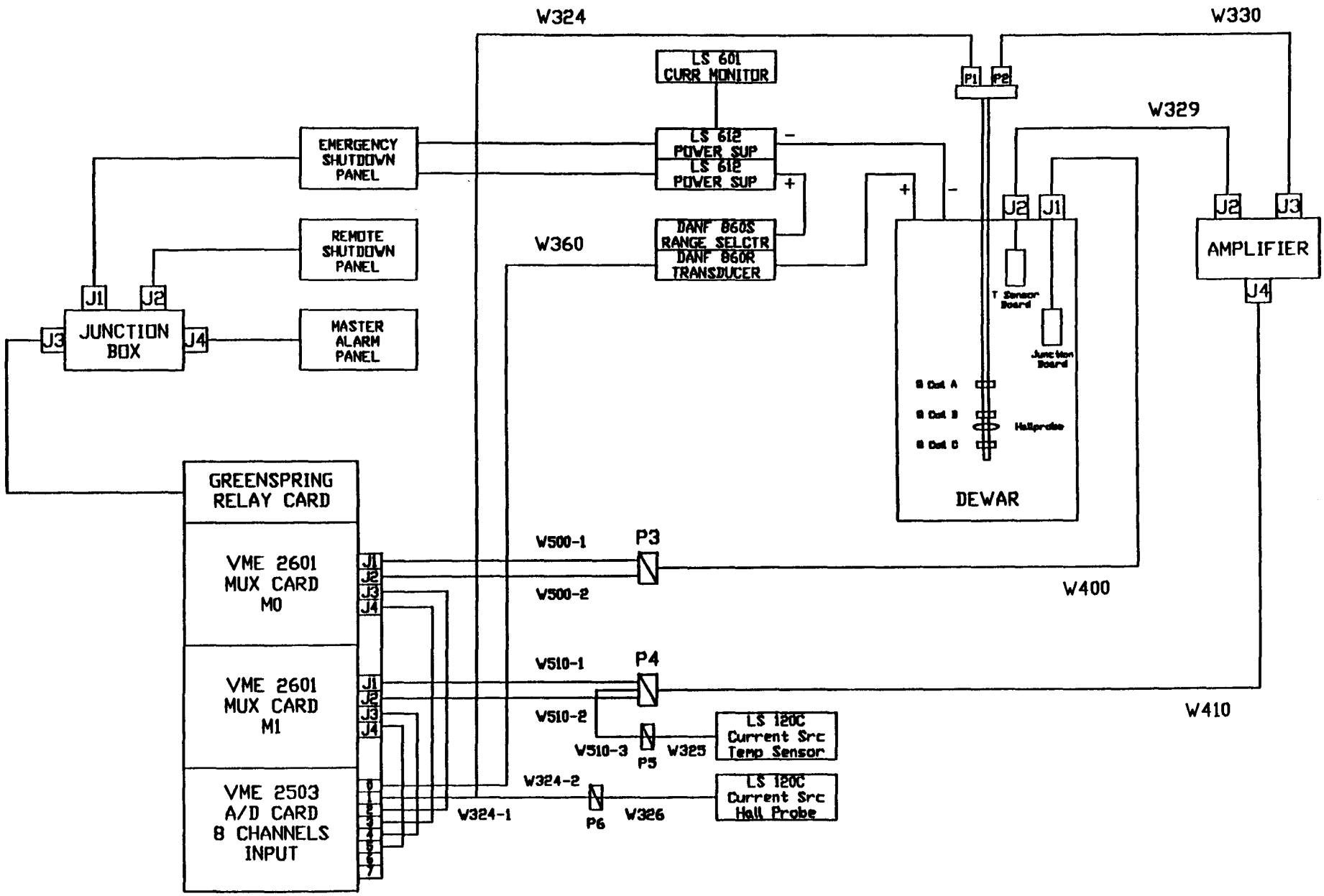


Quad Coil Array

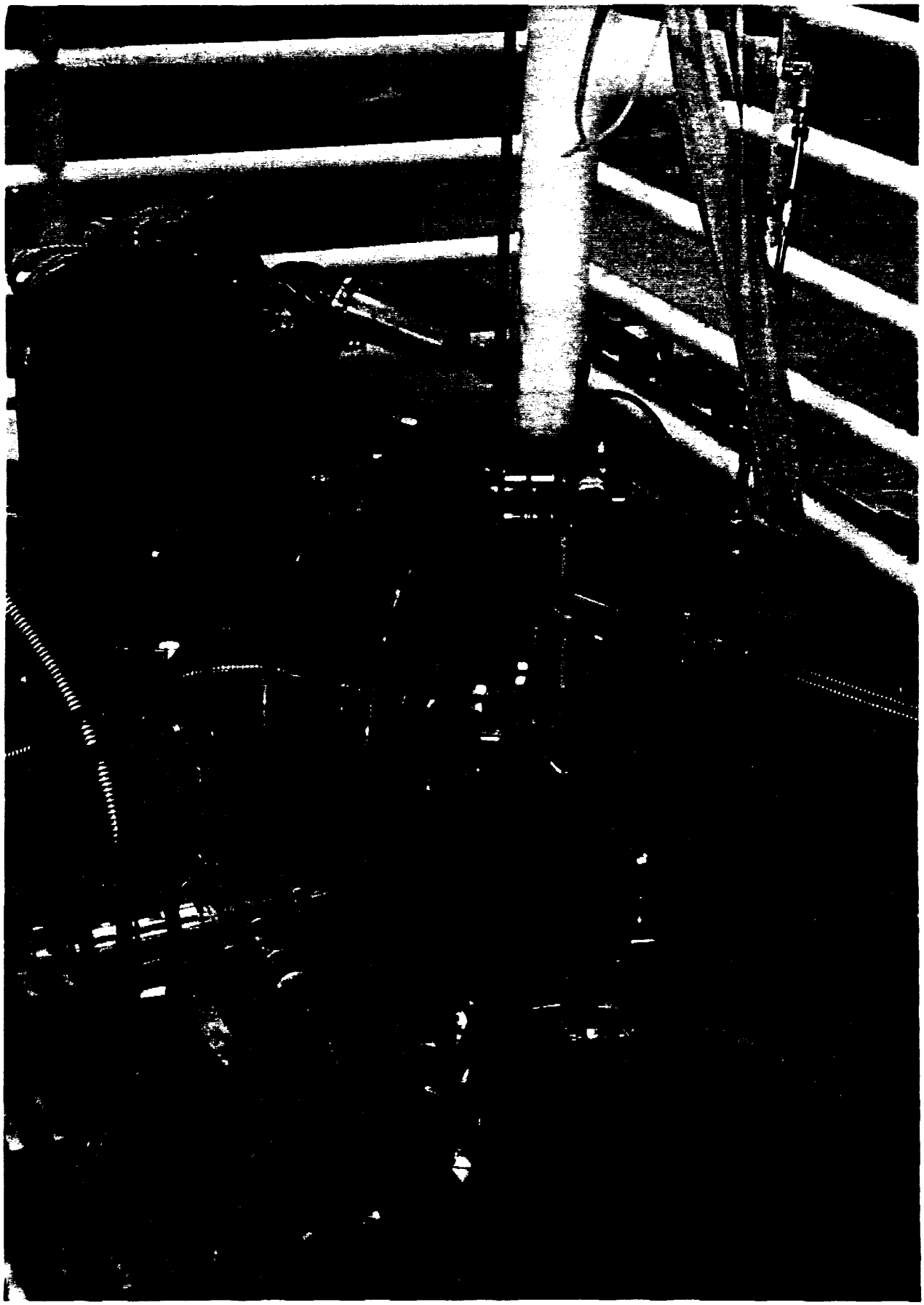




Drive Assembly

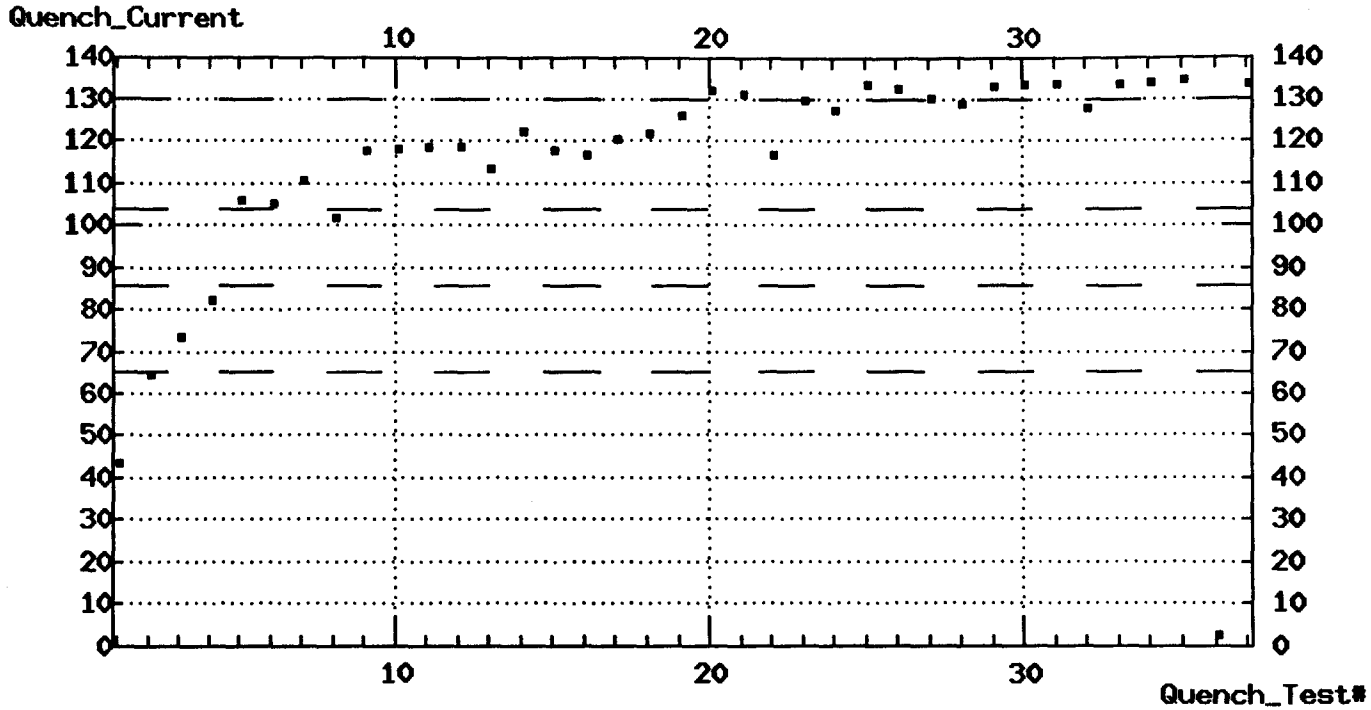


Existing Quench Testing Block Diagram



VMS 92-2-49-8
9-4-92
Corrector Magnet Lab

MAGNET: supmagnets/BCDb2/12 SERIES: 1 DATE: 08/23/93 I(C): 130.000000



1	44.11	0.50	2	65.23	0.50	3	74.00	0.50	4	82.61	1.00
5	106.50	1.00	6	105.85	1.00	7	111.35	1.00	8	102.64	1.00
9	118.17	1.00	10	118.96	1.00	11	119.04	1.00	12	119.37	1.00
13	113.99	1.00	14	122.76	1.00	15	118.46	1.00	16	117.33	1.00
17	121.21	1.00	18	122.59	1.00	19	126.79	1.00	20	132.88	1.00
21	131.62	1.00	22	117.24	1.00	23	130.21	1.00	24	128.01	1.00
25	134.29	1.00	26	133.24	1.00	27	131.06	1.00	28	129.33	1.00
29	133.89	1.00	30	134.35	1.00	31	134.01	2.00	32	128.74	2.00
33	134.21	5.00	34	134.71	5.00	35	135.01	10.00	36	2.92	10.00
37	134.30	10.00									

File: MCOb11.9

Magnet ID MCOb11

Meas. Number 8
Meas. Date: August 31,1993
Meas. Time: 17:06:31

Remark:
Collider Superconducting Corr. Quadrupole
0.0cm at magnet center.
2.0 bar air bearing pressure.
Coil #4 (38mm Quadrupole coil).

ref. radius:	1.00	(cm)
Current:	+281	(mA)
B'1.eff:	3.25892E-01	(Tesla)
Bo @ 1cm	0.00326	(Tesla)

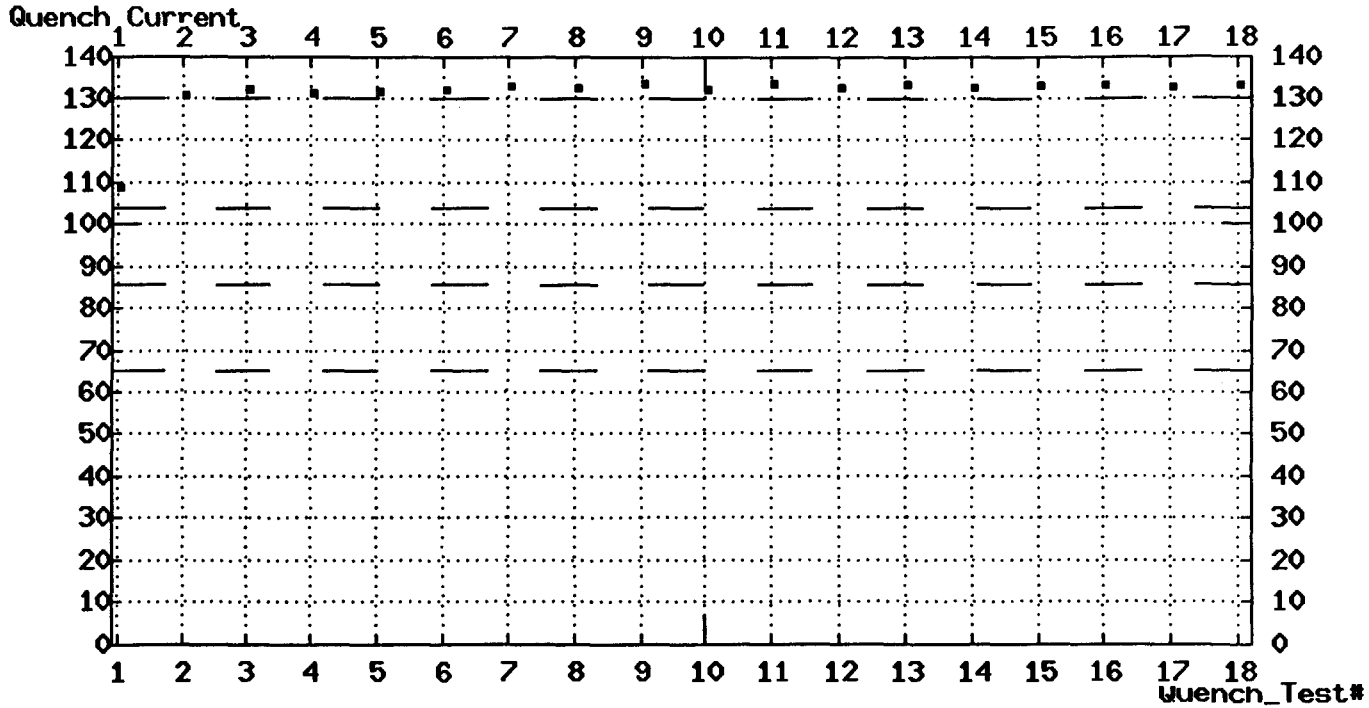
Compensated Harmonics:

N	An	Bn	err.real	err.imag	Bn/B2	Bn/B2[%]
1	9.16549E-07	-3.36579E-06	0.00000E+00	0.00000E+00	1.07040E-03	1.070E-01
2	1.62946E-01	-1.01406E-04	1.00000E+00	-6.22418E-04	1.00000E+00	1.000E+02
3	1.27177E-02	3.49014E-02	2.34144E-03	6.42579E-03	3.41950E-03	3.420E-01
4	-5.64842E-01	-4.63635E-01	-2.07991E-03	-1.70731E-03	8.96929E-04	8.969E-02
5	1.50123E+01	-6.92514E+00	9.21328E-04	-4.25032E-04	2.53651E-04	2.537E-02
6	-7.85548E+02	7.12684E+02	-7.23126E-04	6.56083E-04	1.95278E-04	1.953E-02
7	-2.28579E+04	-2.84371E+03	-2.94602E-04	-3.66591E-05	4.94761E-05	4.948E-03
8	6.56115E+05	-9.25715E+05	1.12748E-04	-1.59084E-04	2.78534E-05	2.785E-03
9	4.75643E+07	1.65660E+07	1.05089E-04	3.66003E-05	1.39095E-05	1.391E-03
10	-1.39642E+10	9.55575E+08	-3.85645E-04	2.63893E-05	4.29492E-05	4.295E-03
11	-2.30513E+10	-1.17753E+11	-7.78129E-06	-3.97493E-05	4.05001E-06	4.050E-04
12	4.33617E+12	1.08593E+12	1.75644E-05	4.39756E-06	1.64597E-06	1.646E-04
13	-1.04340E+14	2.04571E+14	-4.99498E-06	9.79231E-06	9.16059E-07	9.161E-05
14	-1.24534E+15	-8.37280E+15	-6.95842E-07	-4.67654E-06	3.63644E-07	3.636E-05
15	5.70695E+17	-4.03695E+16	3.67765E-06	-2.60485E-07	2.63333E-07	2.633E-05
16	-6.56944E+17	1.83147E+19	-4.83069E-08	1.34877E-06	8.99754E-08	8.998E-06
17	-1.05728E+21	-2.64600E+20	-8.82533E-07	-2.20991E-07	5.68534E-08	5.685E-06
18	4.88250E+21	-3.26032E+22	4.58609E-08	-3.06232E-07	1.82085E-08	1.821E-06

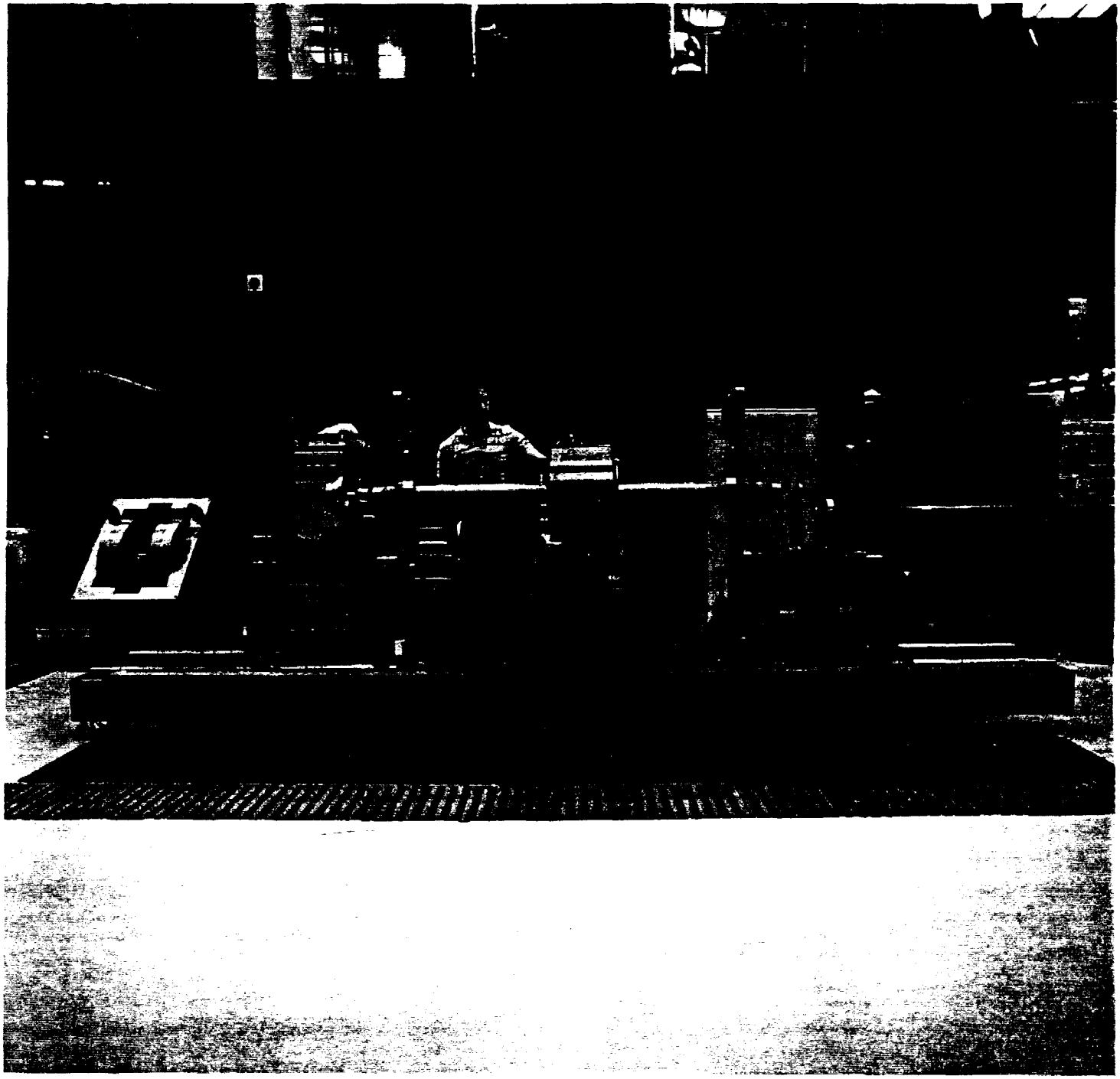
* The Average value of 5 readings

Print Date: 09/20/93 17:02:29

MAGNET: supmagnets/BCDb2/12 SERIES: 2 DATE: 09/14/93 I(C): 130.000000



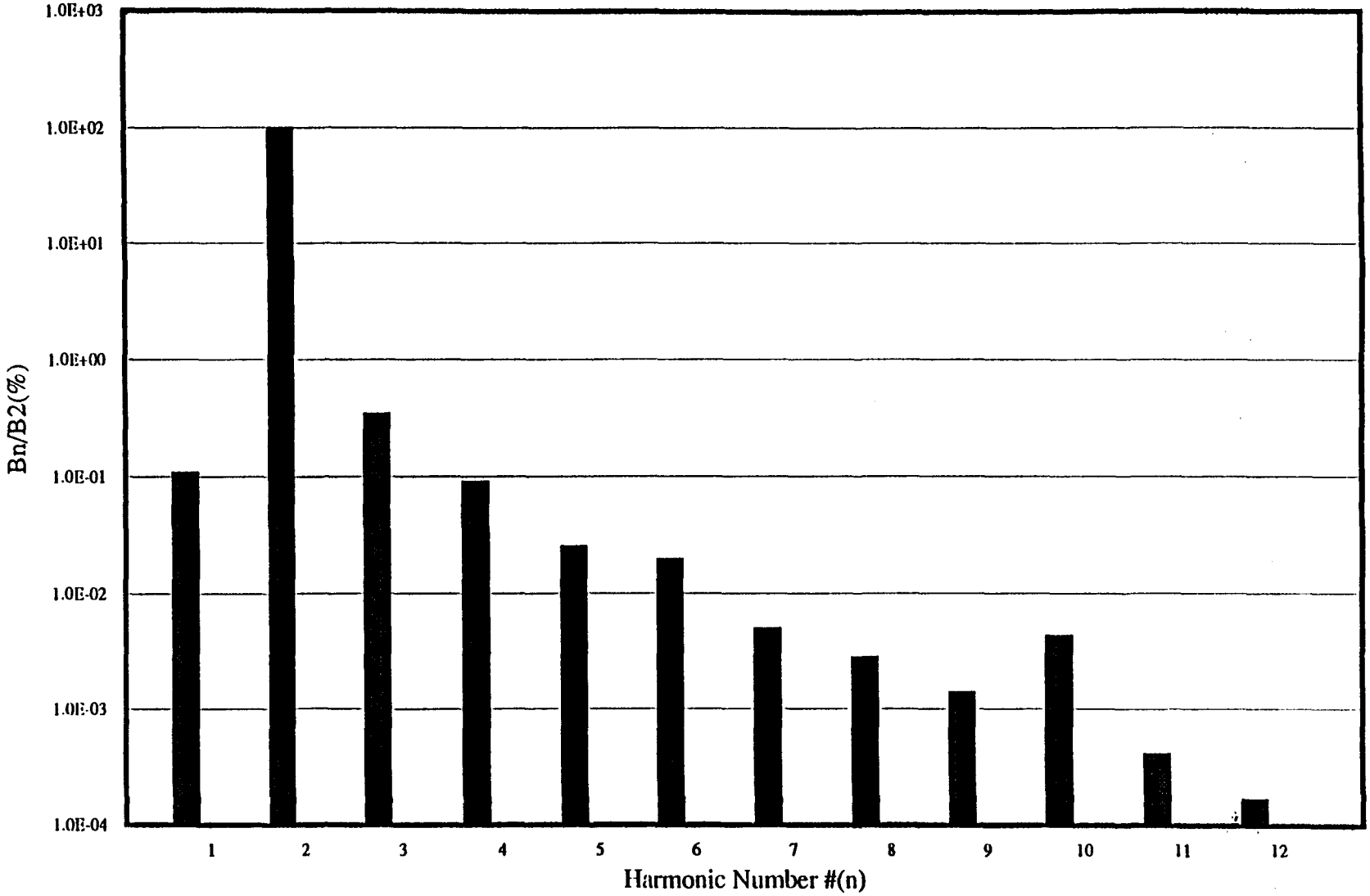
1	109.41	0.50	2	131.56	0.50	3	132.57	1.00
4	131.78	1.00	5	132.52	1.00	6	132.98	1.00
7	133.54	1.00	8	133.11	1.00	9	134.21	1.00
10	132.84	1.00	11	134.37	1.00	12	133.09	1.00
13	134.13	2.00	14	133.45	2.00	15	133.70	5.00
16	133.93	5.00	17	133.36	10.00	18	133.51	10.00



VMS 93-9-11-8
3-16-93
LEB Quadrupole Magnet

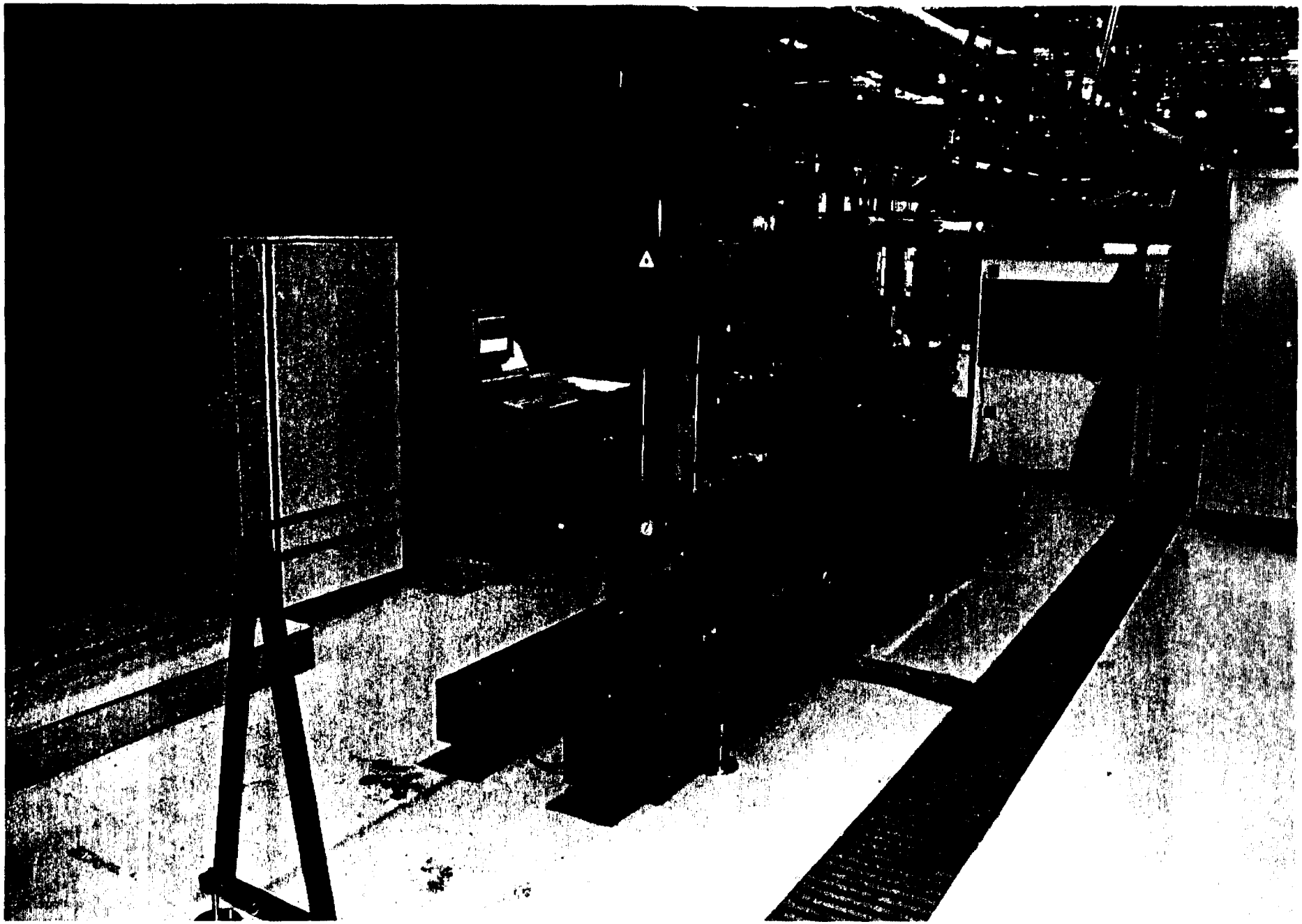
MCOb1.1-Warm Measurement

(I=+281mA)



File: MCOb11.9 Meas. Date: 8/31/93

2.0 bar, coil #4, Speci. radius =1.0(cm), Compensated Meas., Average 5 readings. print date: 9/7/93



VMS 93-2-19-1
1-27-93
Corrector Magnet

VMS 93-9-11-1
3-16-93
Harmonics Measuring Device

MAGNET TESTING ACTIVITIES AT FERMILAB

(A RANDOM WALK THROUGH MTF)

SEPTEMBER 27, 1993

PETER O. MAZUR

SSC 50MM COLLIDER DIPOLE PROGRAM COMPLETED WITH THE TEST OF A FERMILAB DIPOLE, A FERMILAB-GD DIPOLE, SEVEN GD DIPOLES, AND FOUR FERMILAB R+D DIPOLES. THIS COMPLETES A LONG FERMILAB-BROOKHAVEN-LBL-SSCL COLLABORATION. THE PROGRAM WAS SUCCESSFUL AND RELATIVELY UNEVENTFUL: MAGNETS REACHED DESIGN OPERATING CURRENT WITH ZERO OR ONE QUENCH; MEASUREMENTS WITH MOLE (HARMONICS), HALL-NMR PROBE (STRENGTH AND UNIFORMITY), AND FIELD ANGLE PROBE BECAME ROUTINE. FIELD STRENGTH RECORD WAS 9.5 T AT 1.8 K. (DESIGN FIELD WAS 6.6 T AT 4.35 K.) SOME OF THE THINGS WE LEARNED DURING THIS:

* OPERATION AT 1.8 K WAS STRAIGHTFORWARD.
* HEAT LEAK DROPPED FROM ABOUT 40W TO LESS THAN 10W GOING FROM SINGLE LAYER WARM BORE TO TWO LAYER WARM BORE.
* MOLE (BY BNL) IMPROVED MUCH OVER THE PERIOD.
* THE CHALLENGES OF ELECTRICAL NOISE AND GROUNDING IN AN INDUSTRIAL ENVIRONMENT WERE DISCOVERED. REPEATEDLY.
* CURRENT READOUT AT 10000 A IS A CHALLENGE.

TEVATRON DIPOLES WERE RETESTED AT 3.6K IN PREPARATION FOR AN UPGRADE OF THE TEVATRON CRYOGENIC SYSTEM THIS YEAR. ALL DIPOLES NOT INSTALLED IN THE RING WERE TESTED, A TOTAL OF ABOUT 50. ONE OR TWO FAILED TO PERFORM WELL ENOUGH TO REACH 1.1 TEV AT 3.6K (WE HAVE BEEN RUNNING ABOUT .9 TEV AT 4.6K.) THE PROBLEM WITH THESE WAS HEAT LEAK RATHER THAN MECHANICAL WEAKNESS OF THE COIL STRUCTURE.

THE TIME DEPENDENCE OF THE SEXTUPOLE WAS MEASURED BY AKBAR MOKHTARANI AND DAVID HERRUP USING THE RAMPS ACTUALLY USED IN THE TEVATRON. THE RESULT WAS PROGRAMMED INTO THE SEXTUPOLE CORRECTORS AND THE LUMINOSITY WAS SIGNIFICANTLY INCREASED.

MEASUREMENT TECHNIQUE BASED ON PDP11-34. NEW MEASUREMENTS OF TIME DEPENDENCE BASED ON CONCURRENT COMPUTER (REAL-TIME UNIX) SPINNING A PROBE AT 3-6 HZ.

OUR "TRADITIONAL" TECHNIQUE FOR MEASURING RESISTIVE ACCELERATOR MAGNETS IS BASED ON VAX COMPUTERS RUNNING VMS. DATA IS COLLECTED LARGELY WITH HOMEMADE SOFTWARE AND STORED IN DEC'S "DATATRIEVE" DATA BASE. THIS SYSTEM HAS BEEN USED SINCE 1984, WAS THE SYSTEM USED FOR TEVI AND MAIN RING MEASUREMENTS AND LOMA LINDA UNIVERSITY THERAPY SYNCHROTRON ELEMENT MEASUREMENTS. MEASUREMENTS USE A PRESTON CHOPPER-STABILIZED AMPLIFIER, AN ANALOG INTEGRATOR, AND READOUT BY A DVM ("FLATCOIL", A SLOW TECHNIQUE) OR BY AN ADC ("HARMONICS", A BIT FASTER, UP TO 0.1 HZ PROBE ROTATION SPEED.)

VAX FLATCOIL CONSISTS OF TRANSLATING A COIL ACROSS THE APERTURE OF A MAGNET WHILE READING THE VOLTAGE ON THE INTEGRATOR. THE COIL IS SUPPORTED AND MOVED BY STEPPING MOTOR DRIVEN STAGES AT ONE END (FOR ENDFIELD STUDIES) OR AT BOTH ENDS OF THE MAGNET. THE COIL MAY BE A STRETCHED WIRE LOOP (TYPICALLY 25.4 MM WIDE) OR A SHAPED COIL (TYPICALLY 6.4 MM WIDE AND CURVED TO MATCH THE MAGNET CURVATURE.) ALTERNATELY, THE COIL IS HELD FIXED AT THE CENTER OF THE APERTURE AND THE MAGNET IS RAMPED TO FIELD. LIMITATIONS: STRETCHED WIRE DOESN'T WORK FOR CURVED DIPOLES AND SHAPED COILS SUPPORTED ONLY AT THE ENDS ARE WET NOODLES.

VAX HARMONICS USES A STEPPING MOTOR TO ROTATE A PROBE IN THE APERTURE. WE USE BOTH MORGAN COILS, PRINCIPALLY ON QUADS, AND "DDL" COILS, ON DIPOLES.

THE DDL, OR "DIPOLE DOUBLE LITZ", COIL CONSISTS OF A TANGENTIAL WINDING OF 20 TURNS BUCKED AGAINST AN EQUATORIAL WINDING OF 4 TURNS. BOTH WINDINGS CONSIST OF A LITZ WIRE TURN WITH THE REQUIRED NUMBER OF STRANDS SOLDERED IN SERIES TO MAKE UP THE COIL. IN ADDITION, THERE ARE SINGLE STRAND DIPOLE COILS AT +/- 45 DEGREES FOR TRIMMING.

WE HAVE OBSERVED THE "DEADLY SKEW QUAD EFFECT" ON DDL PROBES IN WHICH THE BEAM TUBE IS OTHER THAN CIRCULAR. THIS EFFECT OCCURS REGARDLESS OF INTEGRATION TECHNIQUE. IT IS REDUCED BY MOVING THE SURFACE OF THE PROBE SEVERAL MM AWAY FROM THE INSIDE OF THE BEAM TUBE AND BY WRAPPING THE PROBE IN A CONDUCTING MATERIAL SUCH AS SUPER MONOKOTE (TAT AGAIN.)

WE STILL DO NOT UNDERSTAND THE DEADLY SKEW QUAD EFFECT AND HOPE TO STUDY IT FURTHER AT LEISURE.

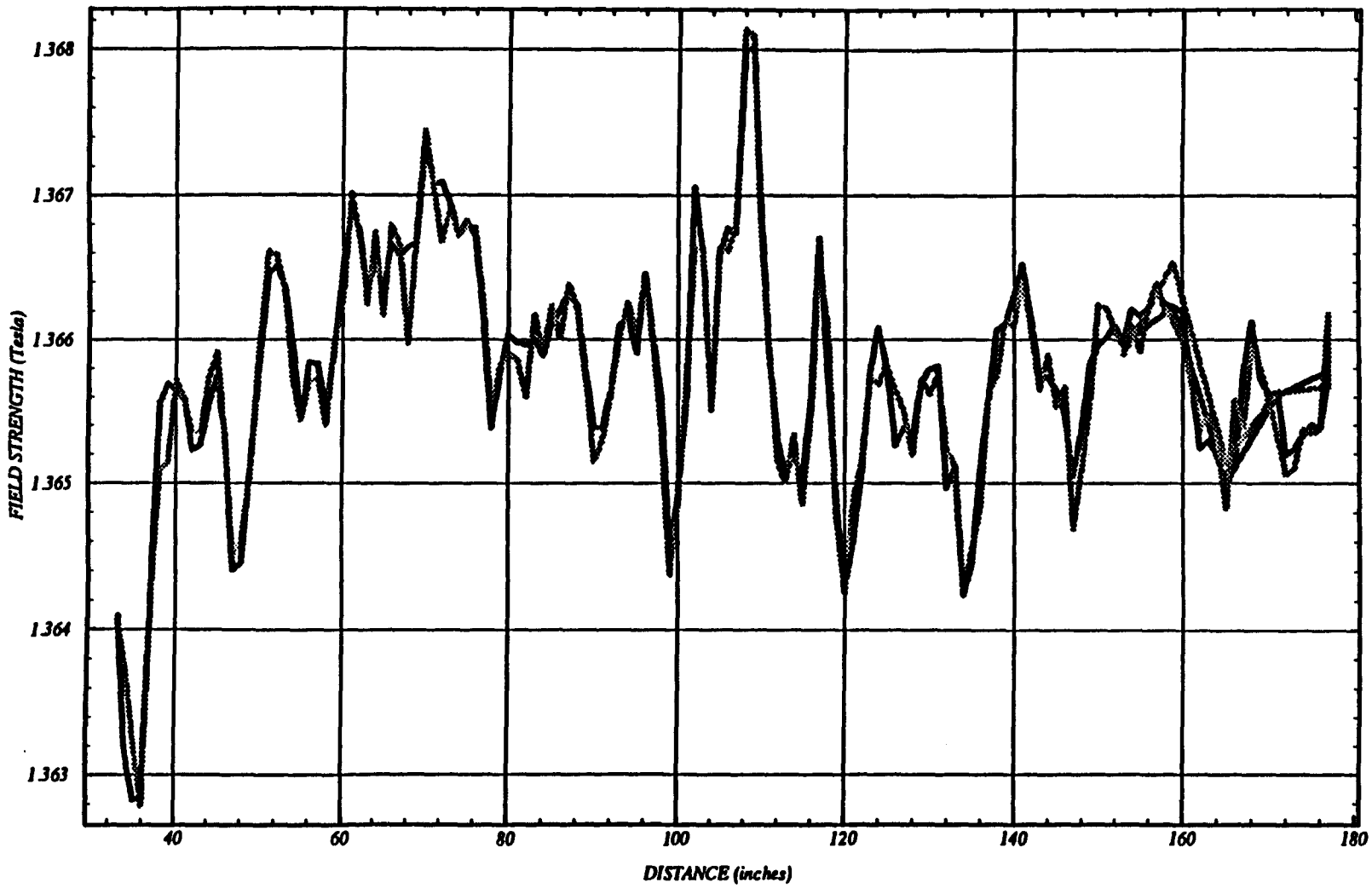
WE HAVE BEEN DEVELOPING NEW MEASURING SYSTEMS BASED ON UNIX PLATFORMS AND THE SYBASE DATABASE SYSTEM. (PROJECT LEADER IS BRUCE BROWN, FLATCOIL CZAR AND CHIEF ANALYST IS HANK GLASS, HARMONICS CZAR IS DANA WALBRIDGE, POINTSCAN CZAR IS AKBAR MOKHTARANI. LEAD PROGRAMMER IS JIM SIM. DARRYL ORRIS, PENNIE HALL, KELLEY TROMBLY-FREYTAG, RICH GLOSSON, DAVE HARDING AND A CAST OF THOUSANDS ARE WORKING ON THIS AS WELL.)

THIS SYSTEM IS FOR THE FERMILAB MAIN INJECTOR, A NEW 150 GEV RESISTIVE ACCELERATOR TO REPLACE THE ORIGINAL MAIN RING. THE INTERESTING CHALLENGE IS THE DIPOLE: 10000 A, SLIGHTLY CURVED HARDWARE DEVELOPED WITH A BEAM TUBE IN MIND, BUT MEASUREMENTS WILL BE PERFORMED BEFORE THE BEAM TUBE IS INSTALLED.

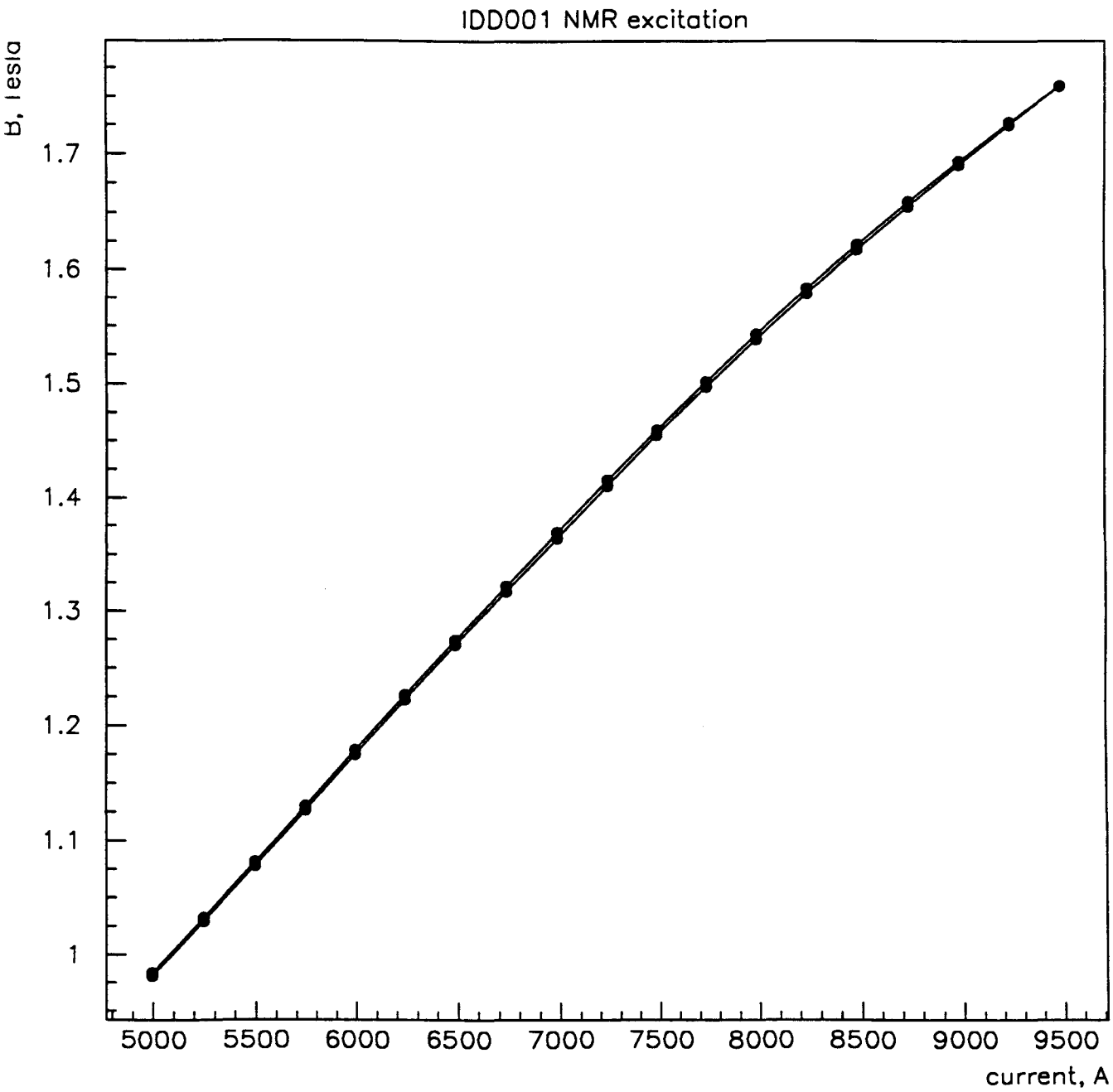
STRENGTH MEASUREMENTS ARE MADE USING THE "Z-POINTSCAN" SYSTEM CONSISTING OF A WHEELED CART ON A RAIL PULLED THROUGH THE MAGNET BY A KEVLAR-REINFORCED TIMING BELT PASSING OVER A PULLEY DRIVEN BY A STEPPING MOTOR. REDUNDANT POSITION READOUT IS PROVIDED BY A STRING OR BELT DRIVING AN ENCODER, AND BY PROXIMITY SENSORS AT THE ENDS OF THE TRACK. THE CART CARRIES A NMR PROBE AND A TWO-AXIS HALL ARRAY. BOTH FIELD INTEGRAL AND STRUCTURE ARE DETERMINED BY THIS METHOD.

HALL & NMR FIELD STRENGTH MEASUREMENTS vs. Z-POSITION

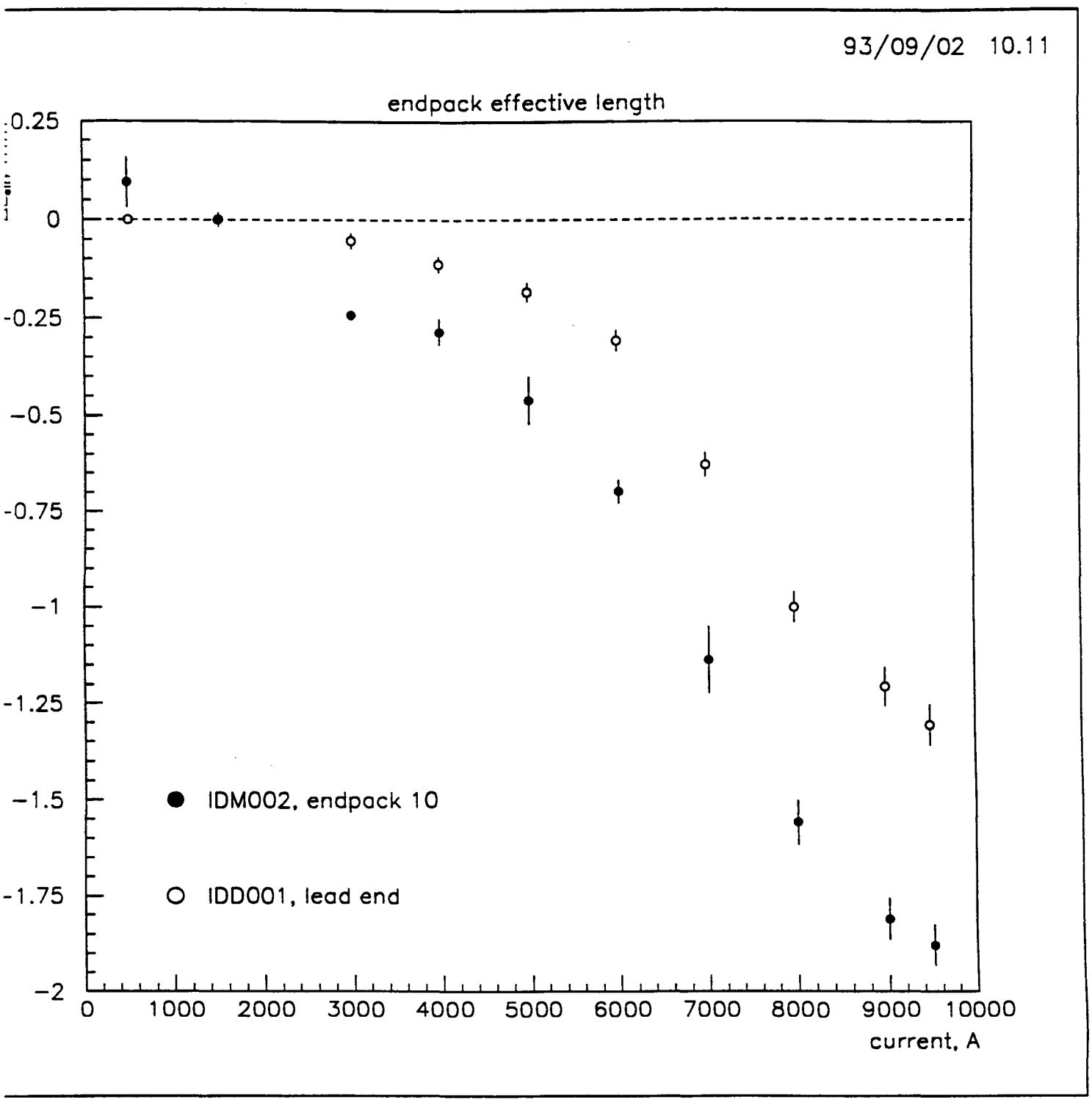
Magnet Current @7000 Amps

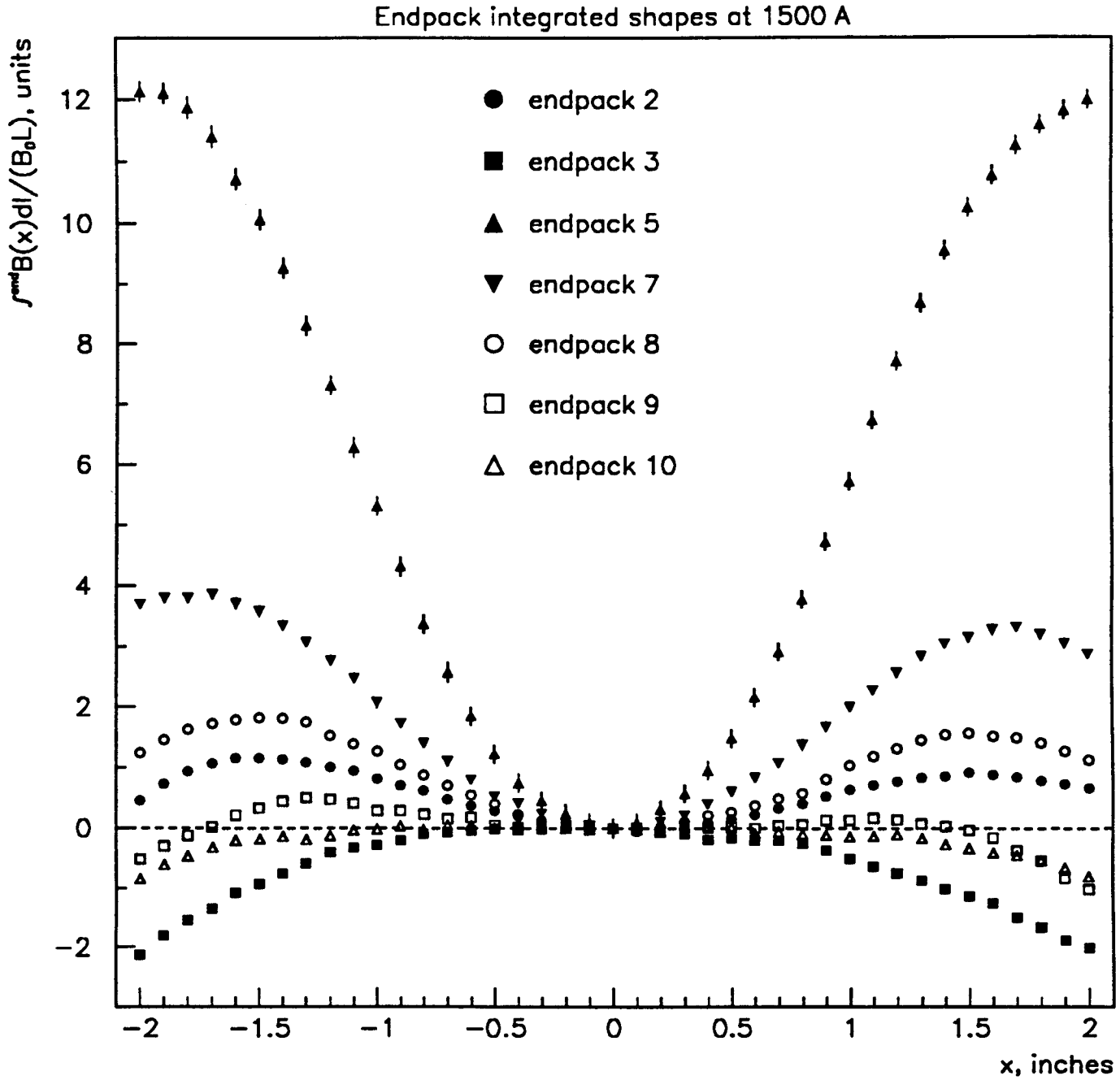


93/09/22 15.03


IDD001 NMR excitation
B, Tesla
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500
current, A

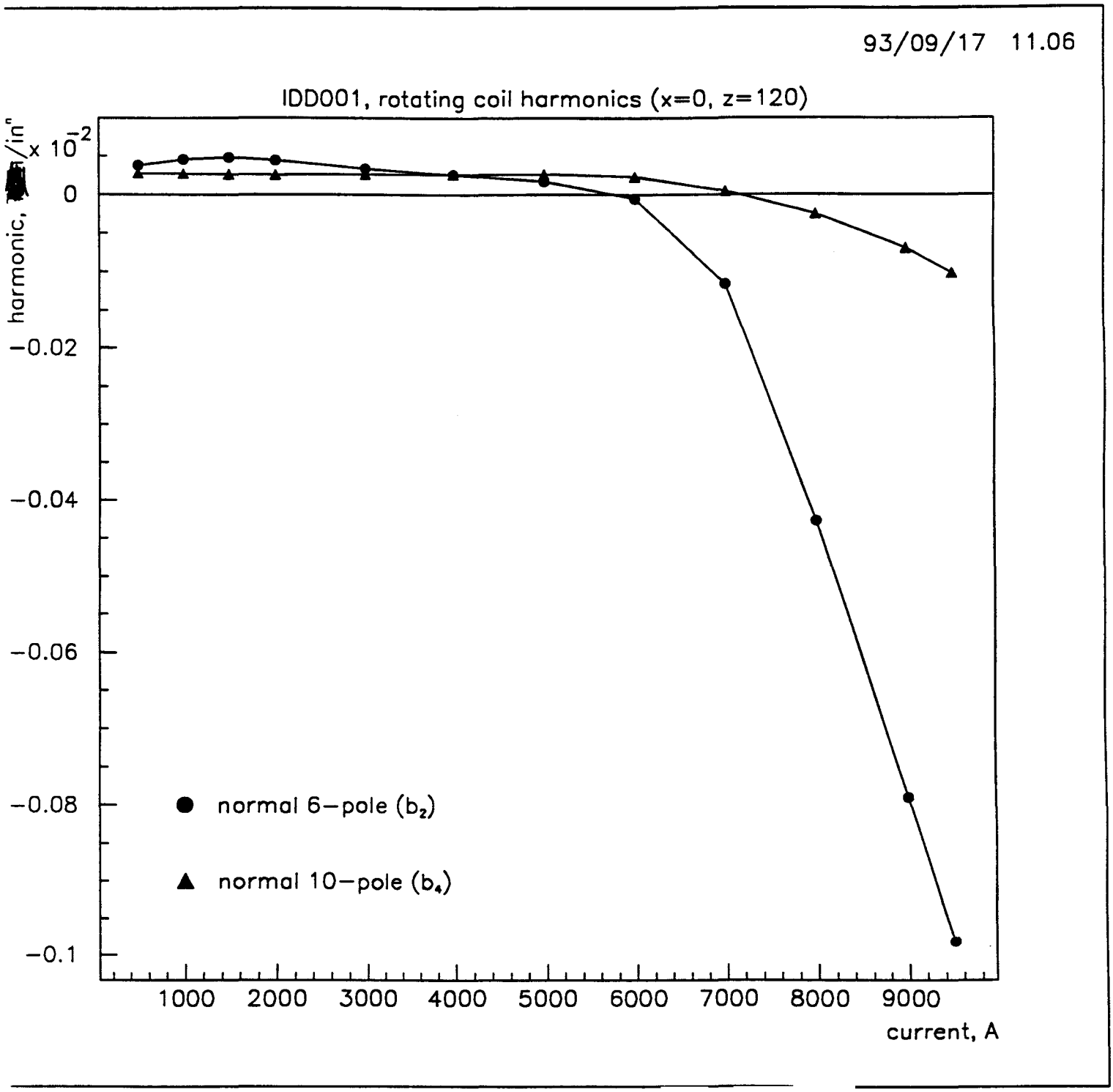
THE END FIELDS OF THE MAGNET HAVE BEEN STUDIED EXTENSIVELY USING THE 2-METER FLATCOIL. THIS CONSISTS OF A PROBE 2 M LONG AND 6.4 MM WIDE WHICH SCANS THE WIDTH OF THE APERTURE WHILE PROTRUDING ONLY PART WAY INTO THE MAGNET APERTURE. A DESIGN OF ENDPACKS FOR THE DIPOLE WAS DEVELOPED LARGELY USING THIS TECHNIQUE.


93/09/02 10.11
endpack effective length
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
current, A
IDM002, endpack 10
IDD001, lead end


Endpack integrated shapes at 1500 A
$\int^{end} B(x)dl/(B_0L)$, units
12
10
8
6
4
2
0
−2
endpack 2
endpack 3
endpack 5
endpack 7
endpack 8
endpack 9
endpack 10
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
x, inches

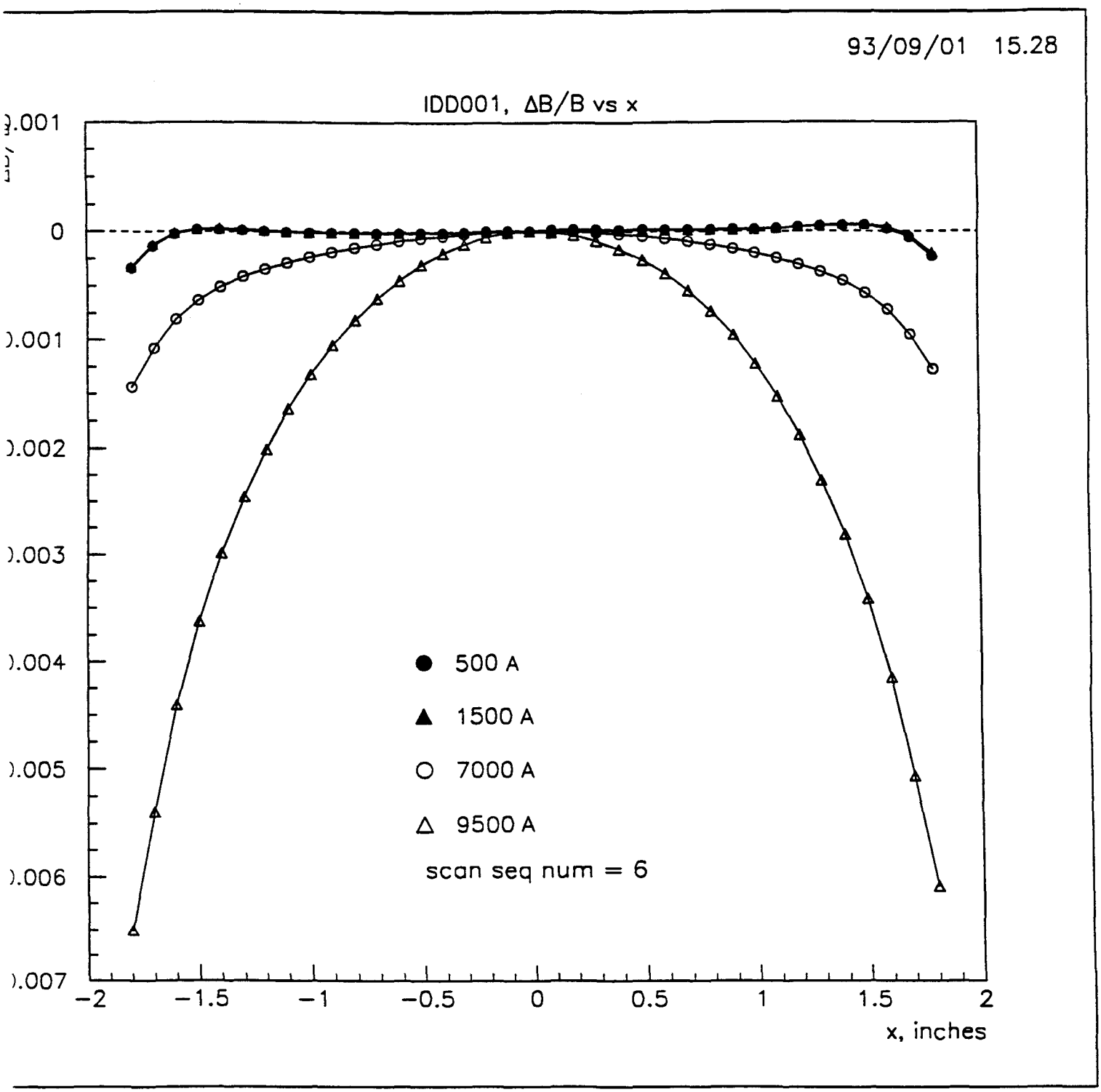
A/C HARMONICS MEASUREMENTS WERE PERFORMED (AND REPORTED BY DANA WALBRIDGE AT THE ACCELERATOR CONFERENCE AT HAMBURG). THE METHOD WAS TO USE A PROBE WITH MORGAN COIL GEOMETRY FOR SEXTUPOLE AND DECAPOLE SENSITIVITY, BUT WOUND WITH LITZ WIRE. THE MAGNET WAS RAMPED WHILE THE VOLTAGE ON THE PROBE WAS SAMPLED BY A FAST DVM. THE RESULT WAS A MEASUREMENT OF SEXTUPOLE GENERATED IN THE BEAM PIPE DUE TO THE RAMPING MAGNET.

AN INTERESTING ASIDE: NOISE IN THE POWER SUPPLY AT 720 HZ PRODUCES SEXTUPOLE NOISE IN THE BEAM PIPE. AS A RESULT, THE NOISE SEEN ON THE SEXTUPOLE-SENSITIVE PROBES WAS SUBSTANTIALLY LARGER THAN SEEN ON THE DIPOLE. THIS MAY CAUSE NOISE ON OTHER MEASUREMENT DEVICES WITH CONDUCTING STRUCTURAL PARTS, E.G., IN OUR NEW FLATCOIL SYSTEM.


93/09/17 11.06
IDD001, rotating coil harmonics (x=0, z=120)
x 10^-2
0
−0.02
−0.04
−0.06
−0.08
−0.1
1000
2000
3000
4000
5000
6000
7000
8000
9000
current, A
normal 6−pole (b2)
normal 10−pole (b4)

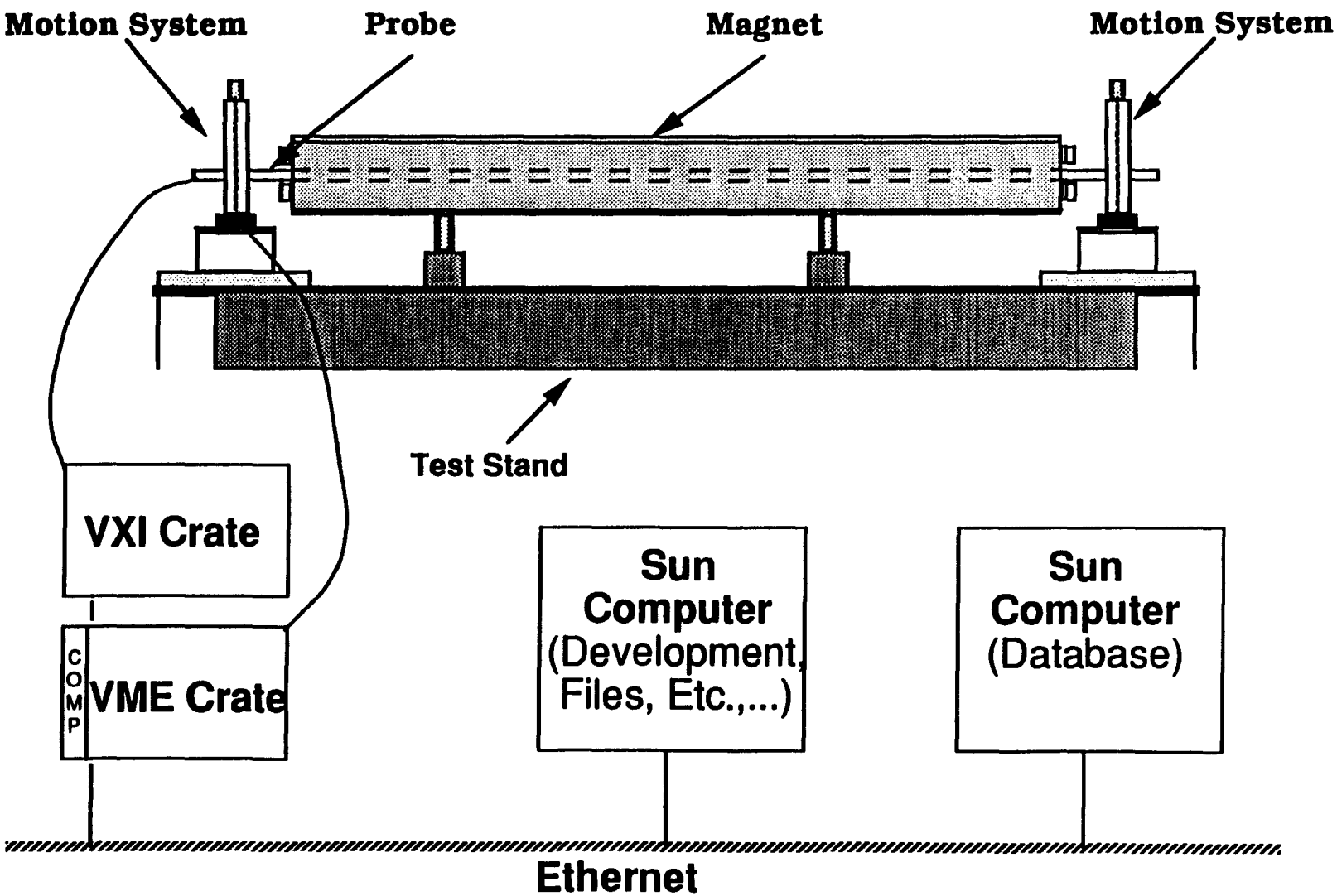
THE NEW FLATCOIL SYSTEM CONSISTS OF A 6.4 MM WIDE ALUMINUM BAR ON WHICH IS WOUND AN 18 TURN COIL. THIS COIL IS MOVED LATERALLY WHILE CURVATURE IS MAINTAINED. THERE IS REFERENCE PROBE IN A FIXED POSITION BELOW THE PLANE OF MOTION OF THE MEASUREMENT COIL WITH A SIMILAR GEOMETRY AND NUMBER OF TURNS. THE MEASUREMENT AND REFERENCE COILS ARE BUCKED AGAINST EACH OTHER DURING SCAN MEASUREMENTS TO REDUCE POWER SUPPLY NOISE.

THIS SYSTEM WILL BE THE PRIMARY MEASUREMENT DEVICE FOR THE MAIN INJECTOR DIPOLES, PRODUCING A MEASUREMENT OF THE STRENGTH AND OF THE NORMAL HARMONICS. SKEW HARMONICS ON AXIS WILL BE MEASURED WITH A 7 M LONG, CURVED, ROTATING DDL COIL HARMONICS PROBE.


93/09/01 15.28
IDD001, ΔB/B vs x
0.001
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
x, inches
500 A
1500 A
7000 A
9500 A
scan seq num = 6

Schematic Diagram

The Magnet Measurement System



Precision required

Numbers from Steve Peggs (after some jawboning):

Flatcoil excitation:

Current (A)	Field (kG)	Strength $dB/B \times 10^4$	Shape $dB/B \times 10^4$
505	1.0	2.0	0.5
1260	2.5	2.0	0.5
1770	3.5	2.0	0.5
4290	8.5	1.5	
7100	13.8	1.0	0.2
8400	16.0	1.0	
9420	17.3	1.0	0.2

Harmonics at 505 A

n	db_n (units)
1	0.2
2	0.2
3	0.4
4	0.8
5	1.4
6	3.0
7	6.6
8	15.0

Metrolab SPECS.

Drift[1)]

Gain	Manual offset adjustment effect [2)]		temperature coefficient after 1h30 warm up	
	µV	ppm of input range	µV/°C	ppm of input range/°C
1	±70	±7	+10	+1
10	±7	±7	+1	+1
100	±1.5	±15	+0.15	+1.5
1000	±1	±100	+0.1	+10

1) All values are referred to input.
2) Refer to an operator with an average skill level.

Drift variation vs time: max. per month: 200µV
max. per year: 500µV
Divide by gain in order to refer to input

Gain:

Gain linearity: max. gain deviation from straight line crossing the zero, in ppm of input range.

Gain	VFC		
	100 KHz	500 KHz	1 MHz
1-200	±10	±20	±60
1000	±50	±60	±100

Gain stability vs temp.: +7 ppm/°C (VFC 100 KHz)
(max.temp.coefficient) +9 ppm/°C (VFC 500 KHz)
+25 ppm/°C (VFC 1 MHz)
Gain stability vs time: per month: ±30 ppm
per year: ±50 ppm

Gain ratio error: max. ±100 ppm when interchanging the gain setting.

Gain adjustment: factory adjusted at 10 with ±10ppm accuracy. The non linearity is balanced for the input voltage +0.4 V and -0.4 V.

Noise

Gain	Noise (0.1 Hz to 10 Hz; referred to input)	
	(µV)	ppm of input range
1	±10	±1
10	±1	±1
100	±0.3	±3
1000	±0.2	±20

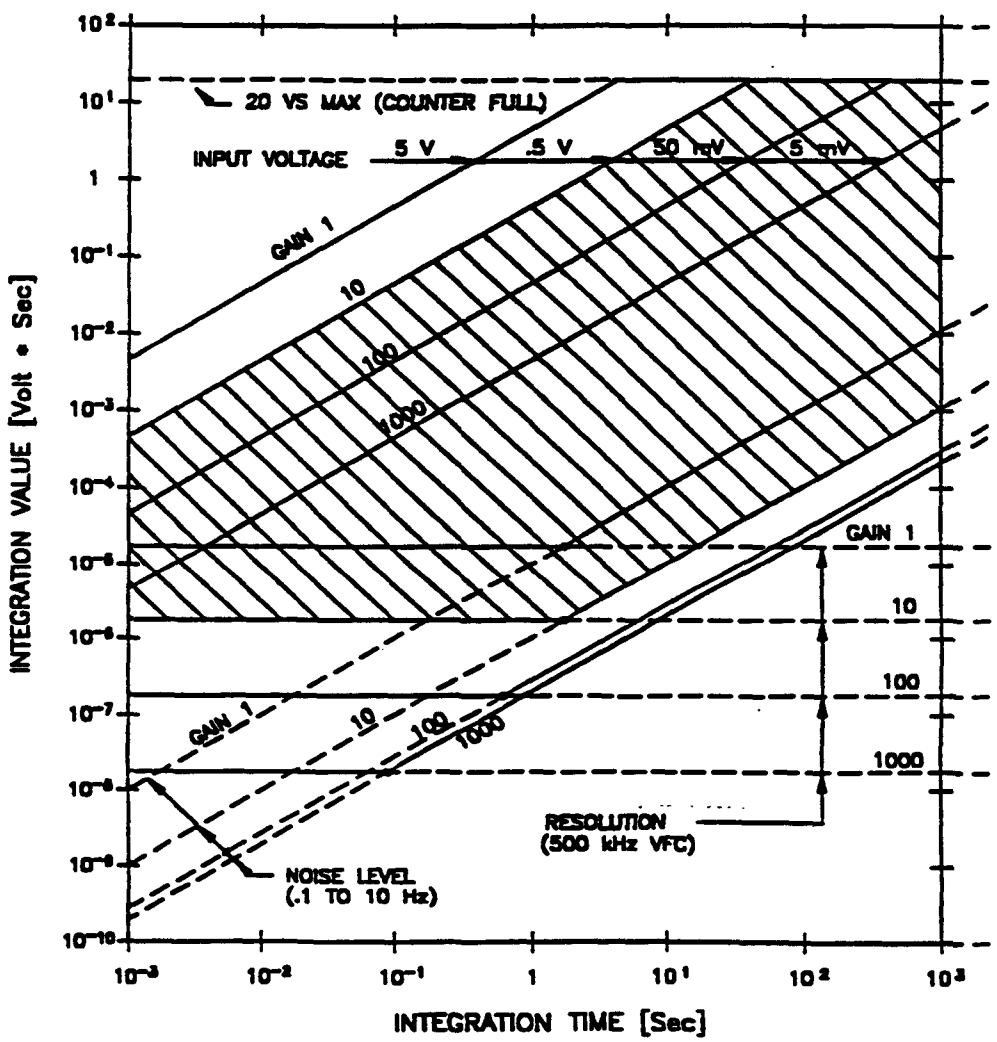
Metrolab Specs.

Resolution and max. range:

VFC	Gain									
	1	2	5	10	20	50	100	200	500	1000
100 KHz	10000	5000	2000	1000	500	200	100	50	20	10
	20	20	20	20	20	20	20	10	20	10
500 KHz	2000	1000	400	200	100	40	20	10	4	2
	20	20	20	20	20	20	20	10	20	10
1 MHz	1000	500	200	100	50	20	10	5	2	1
	20	20	20	20	10	20	10	5	10	5

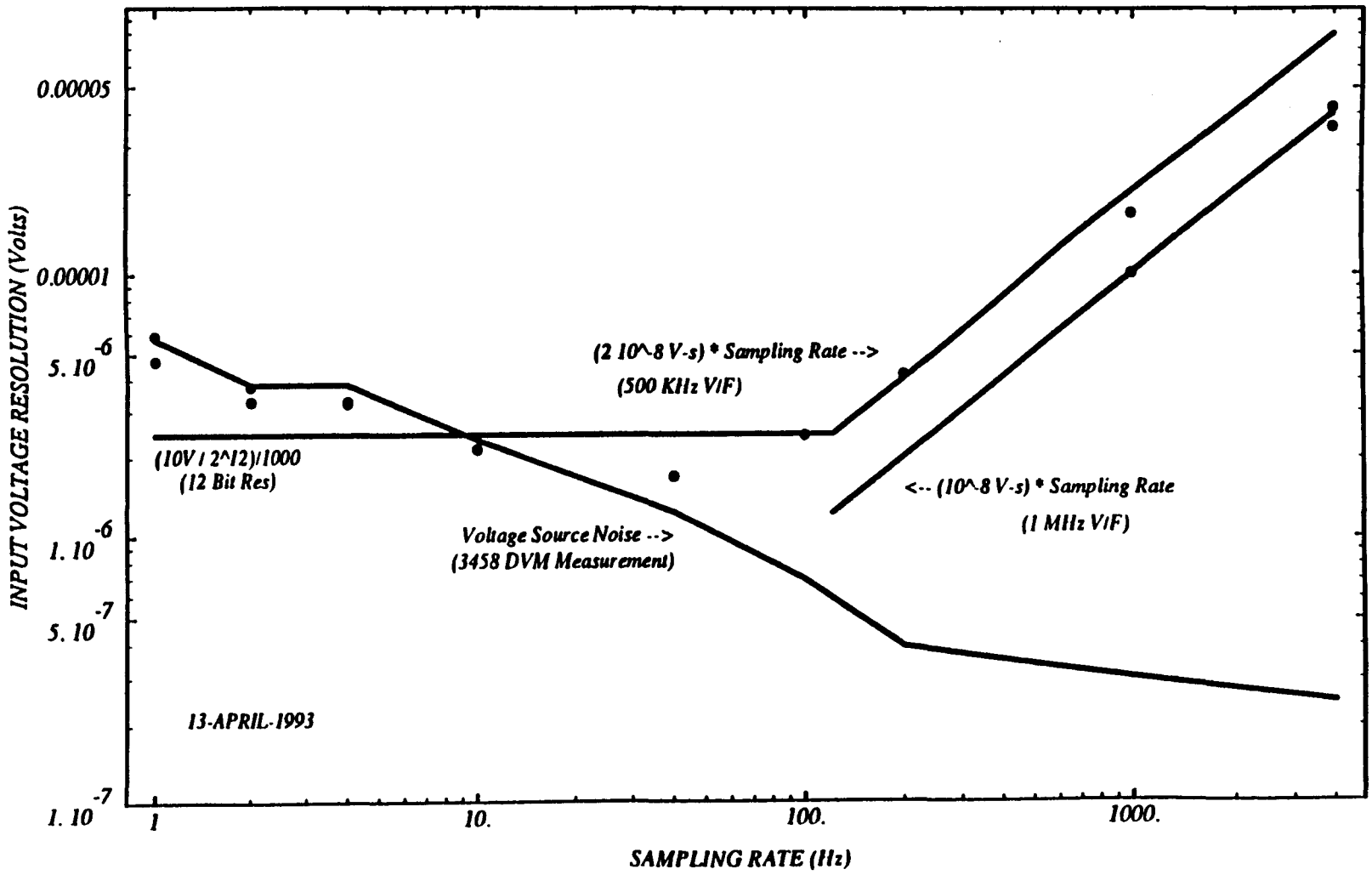
In each box in the table, the upper number gives the resolution in units of 10^{-8} Vs and the lower number the max. range in Vs.

The following diagram shows the measurement domains at different gains (hatched: G = 10) and noise levels.



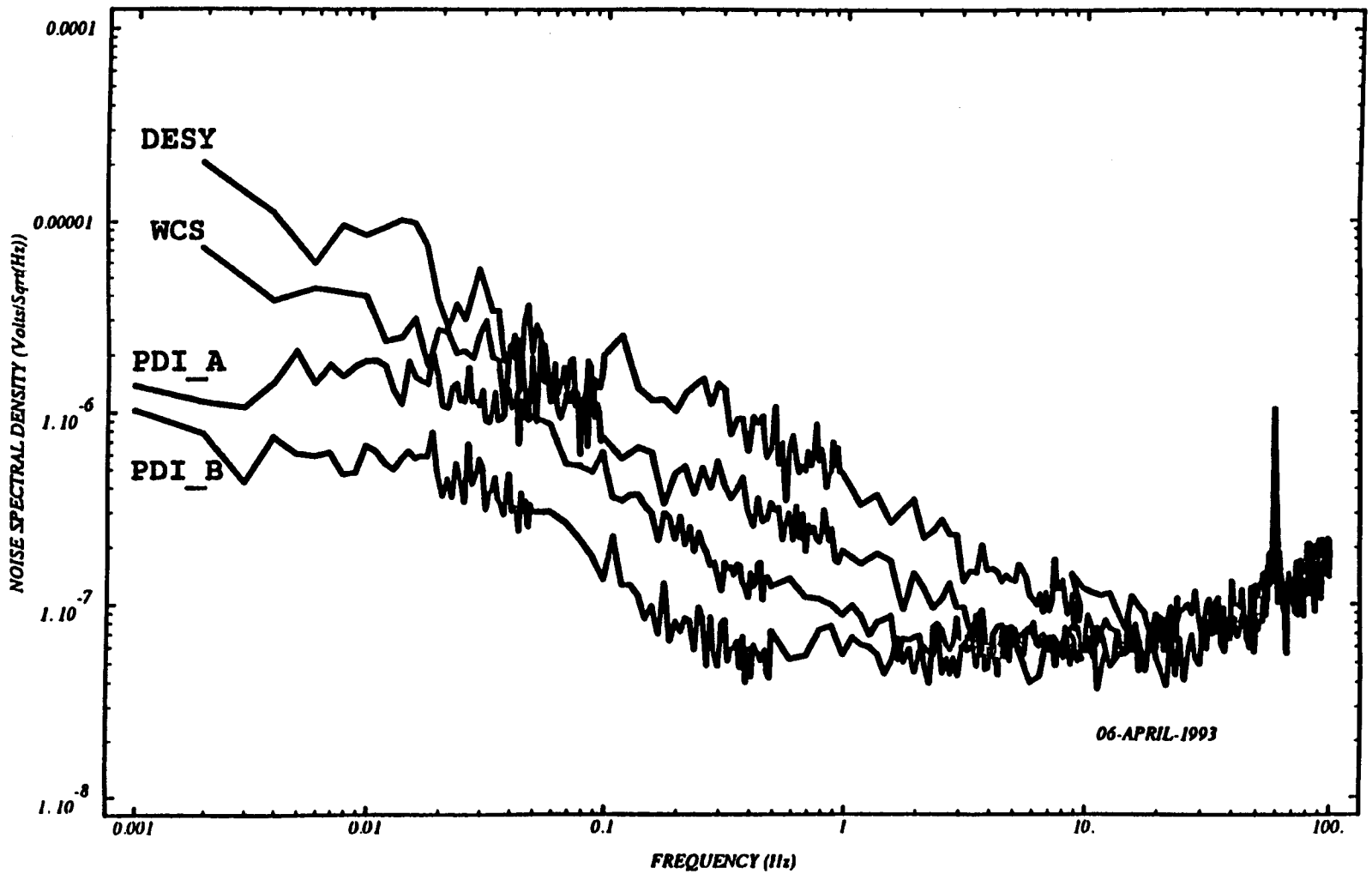
INPUT VOLTAGE RESOLUTION vs. SAMPLING RATE (PDI_A & PDI_B)

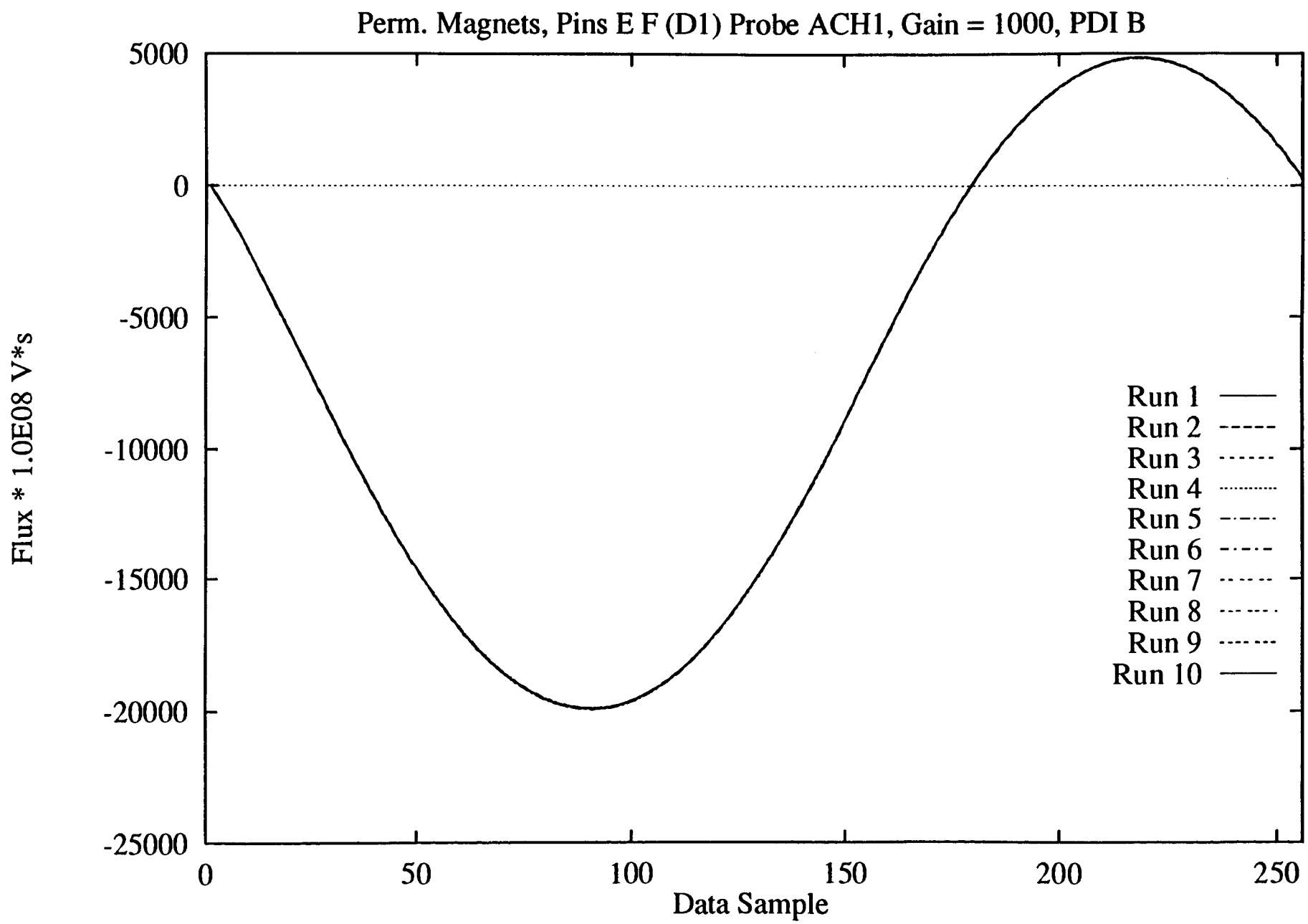
(500 SAMPLES at EACH DC INPUT VOLTAGE (9 MEASUREMENTS TO SPAN INPUT RANGE), G = 1000)



NOISE SPECTRAL DENSITY vs. FREQUENCY

*(10 Measurements over 4096 SAMPLES (8192 SAMPLES for PDI Modules), @8Hz, 80Hz, 800Hz, & 4000Hz *** SHORTED INPUTS)*

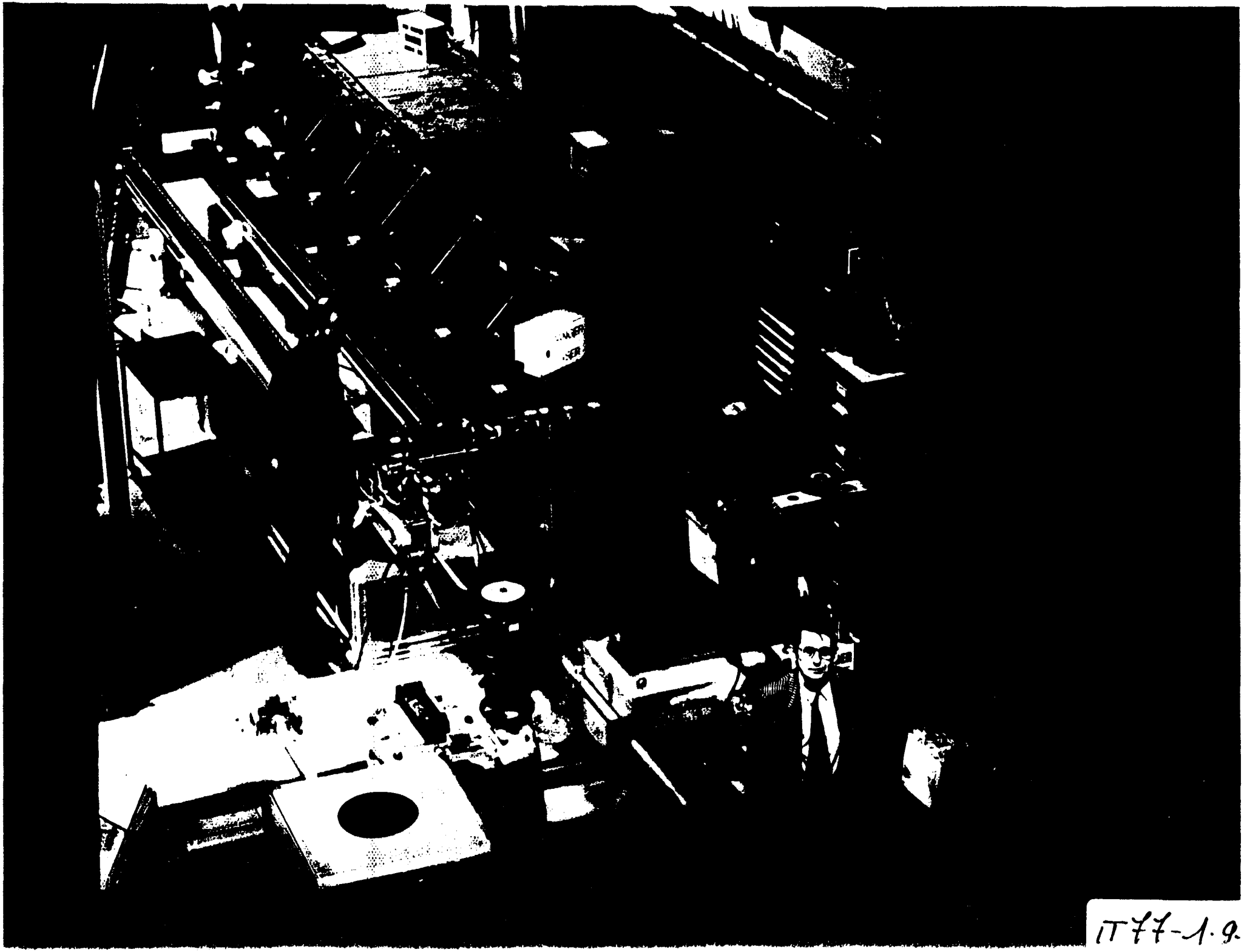



Perm. Magnets, Pins E F (D1) Probe ACH1, Gain = 1000, PDI B
5000
0
-5000
-10000
-15000
-20000
-25000
Flux * 1.0E08 V*s
0
50
100
150
200
250
Data Sample
Run 1
Run 2
Run 3
Run 4
Run 5
Run 6
Run 7
Run 8
Run 9
Run 10

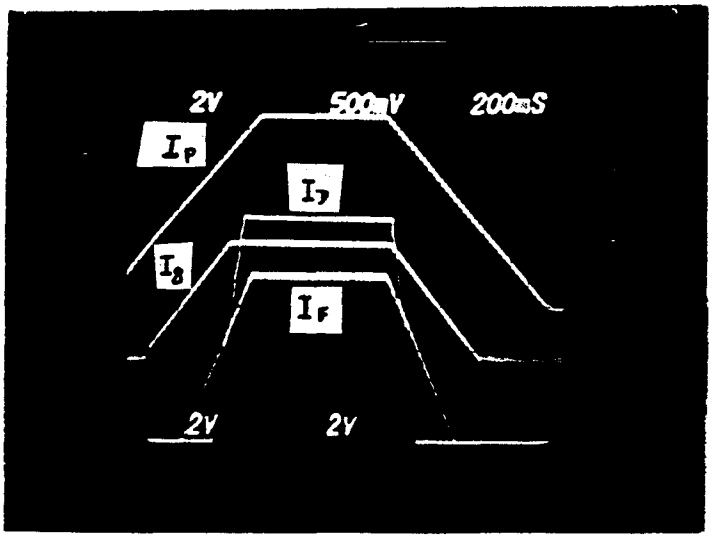
PULSED MAGNETIC MEASUREMENT BENCHES FOR THE CERN PS COMPLEX

D. Cornuet

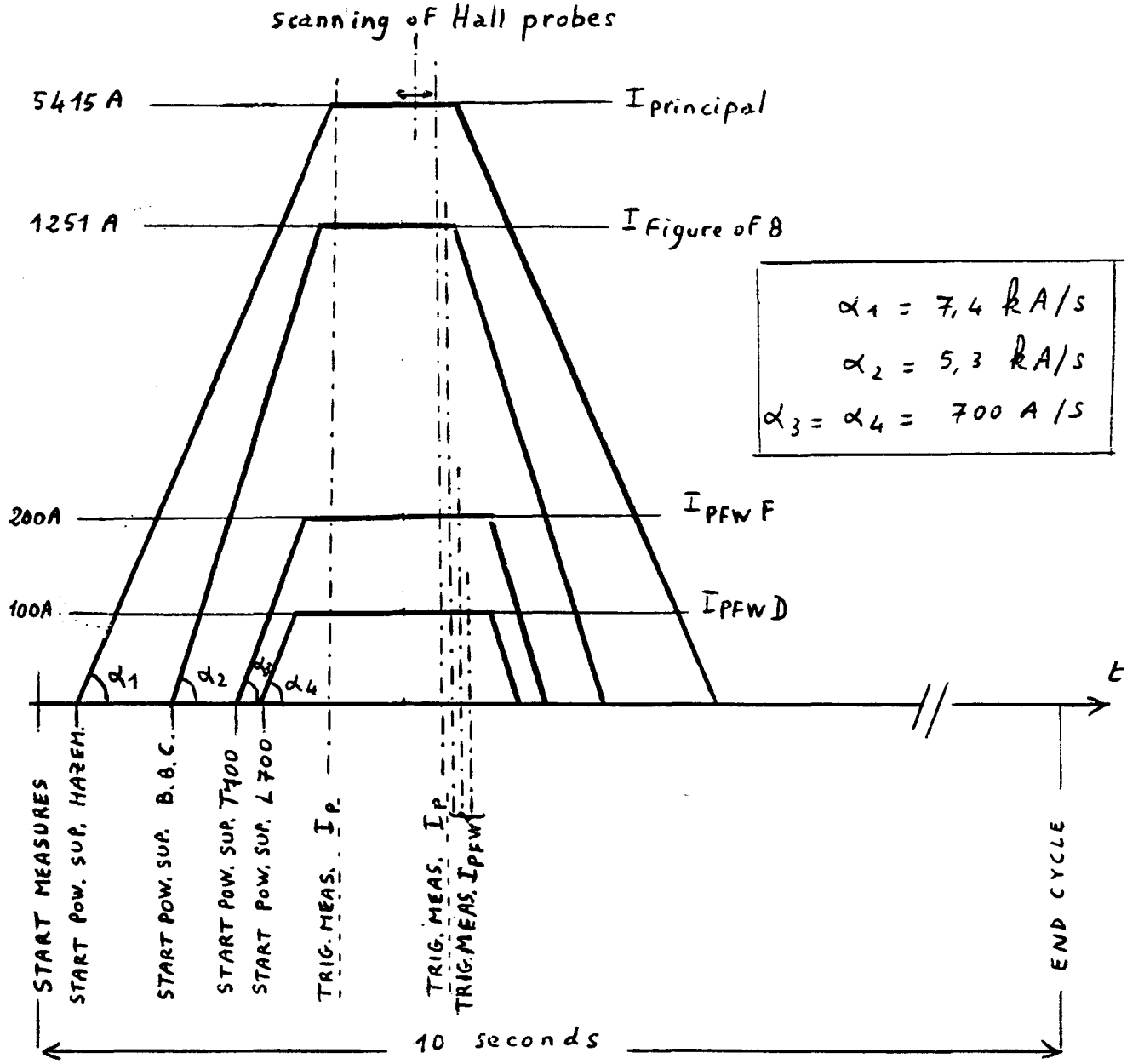
1. General purpose magn. meas. stand
   - 1.1 PS magnet Unit
   - 1.2 Deflection magnet
2. LINAC quadrupole stand
3. Mobile systems
   - 3.1 "Double integration" principle
   - 3.2 Septum magnet



IT 77-1.9.



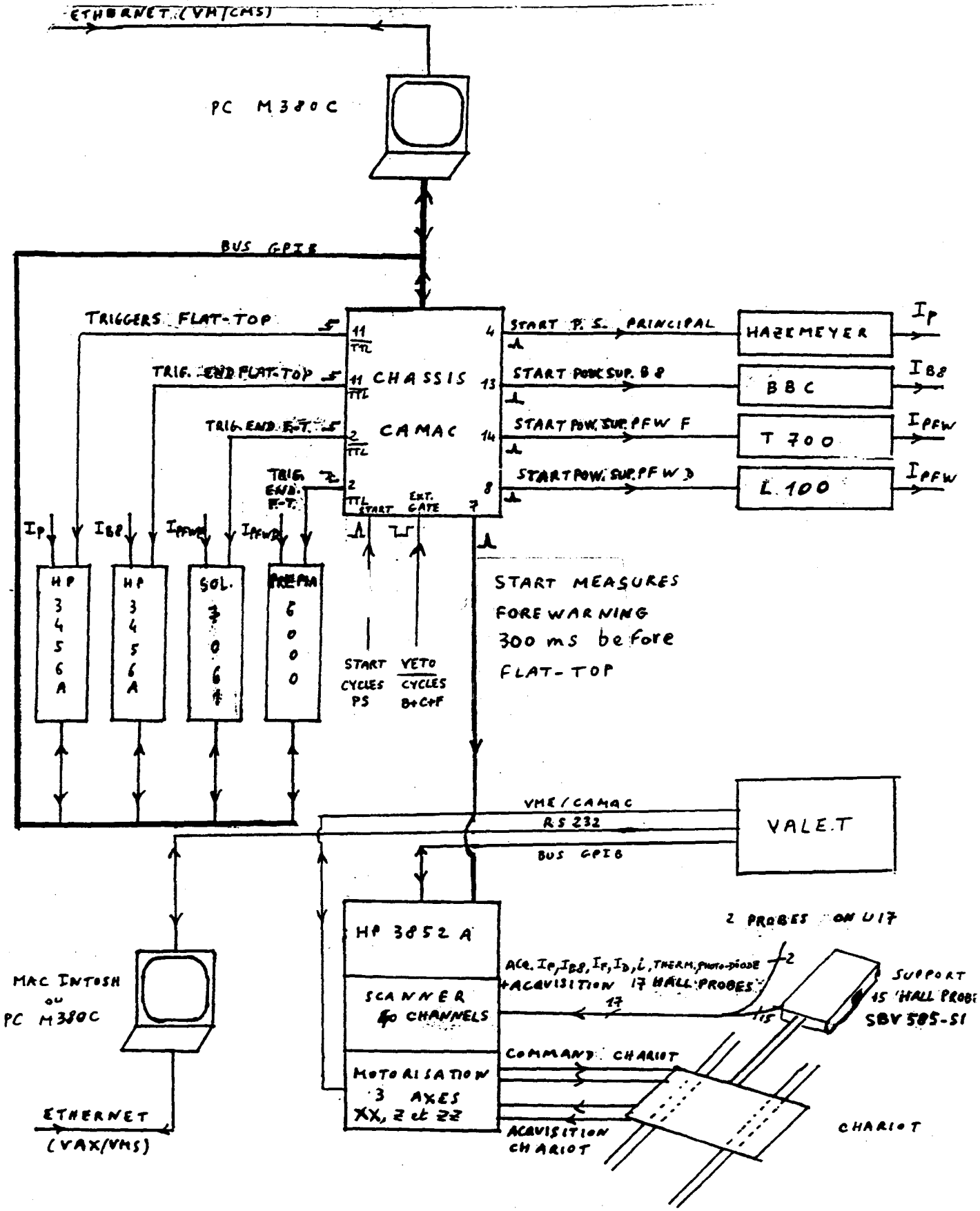
IP = 5415 A		Hazem
I8 = 1251 A		B.B.C
IF = 200 A		T700
ID = 100 A		L100



TIMING FOR MAGNETIC MEASUREMENT OF CPS MAGNET

D.C

OF CERN PS MAGNET UNIT N° U 17



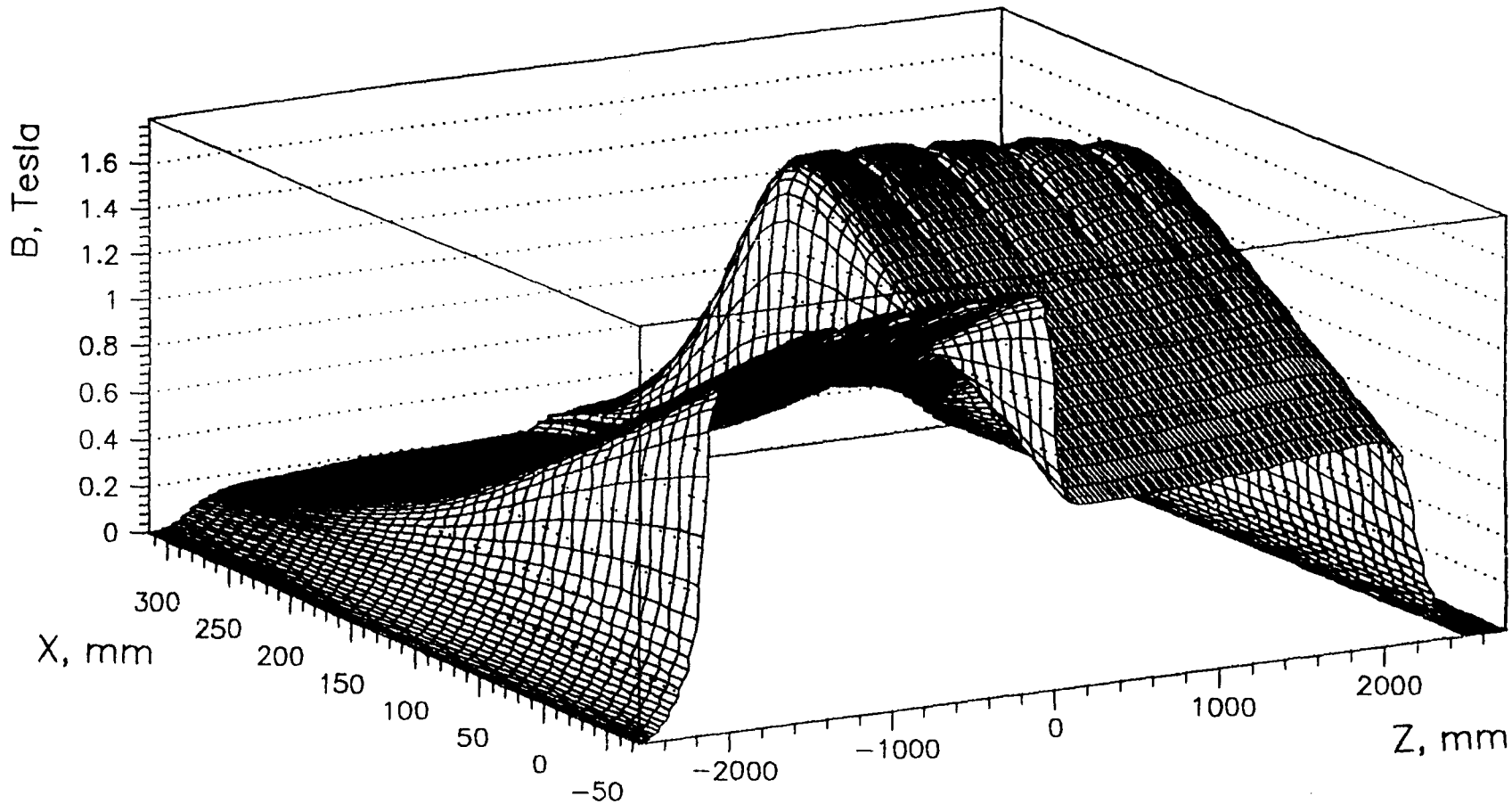
MEASUREMENT WITH HALL PROBES

D. Cornuet

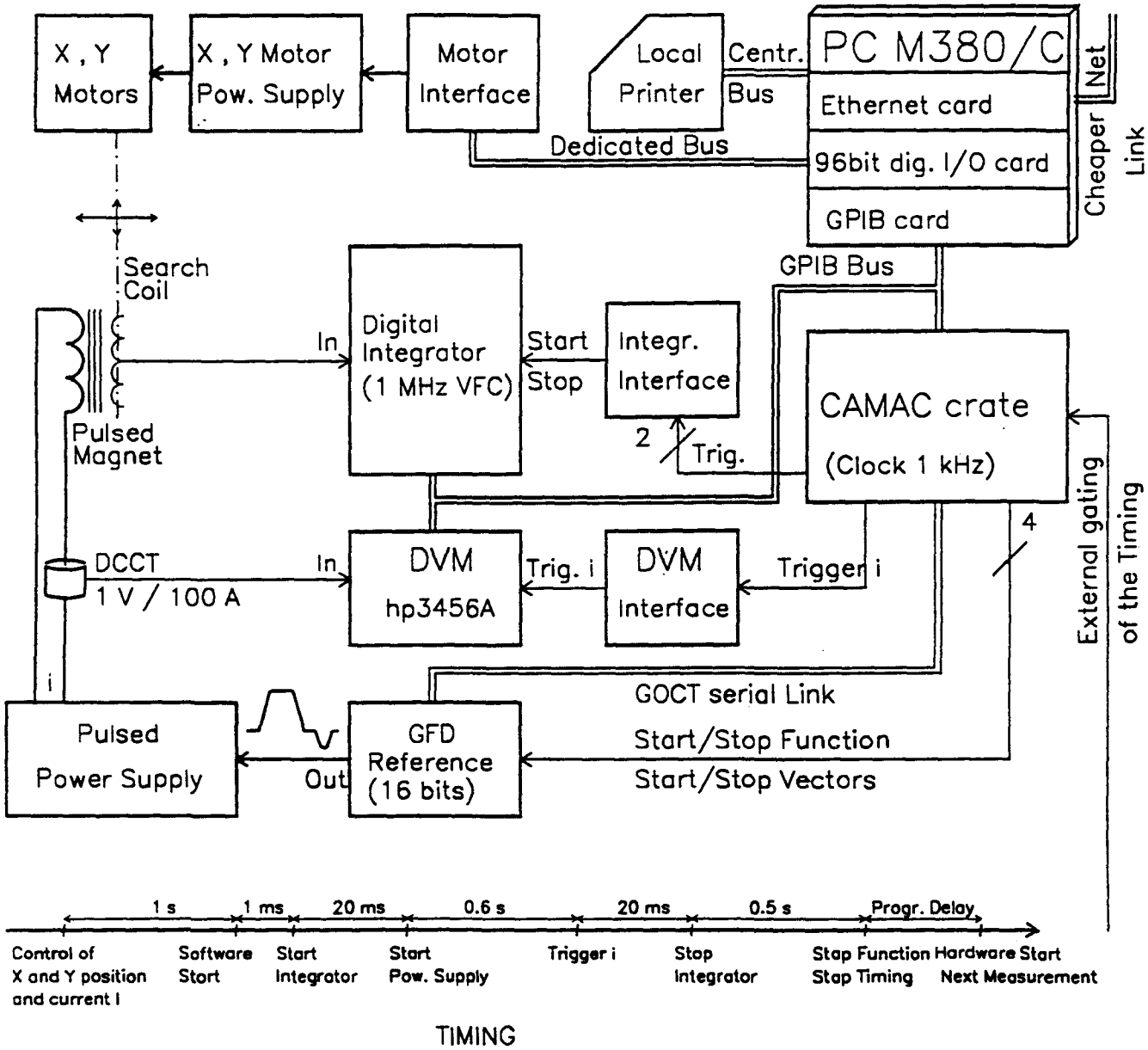
le 24 juillet 1990

04/06/91 22.03

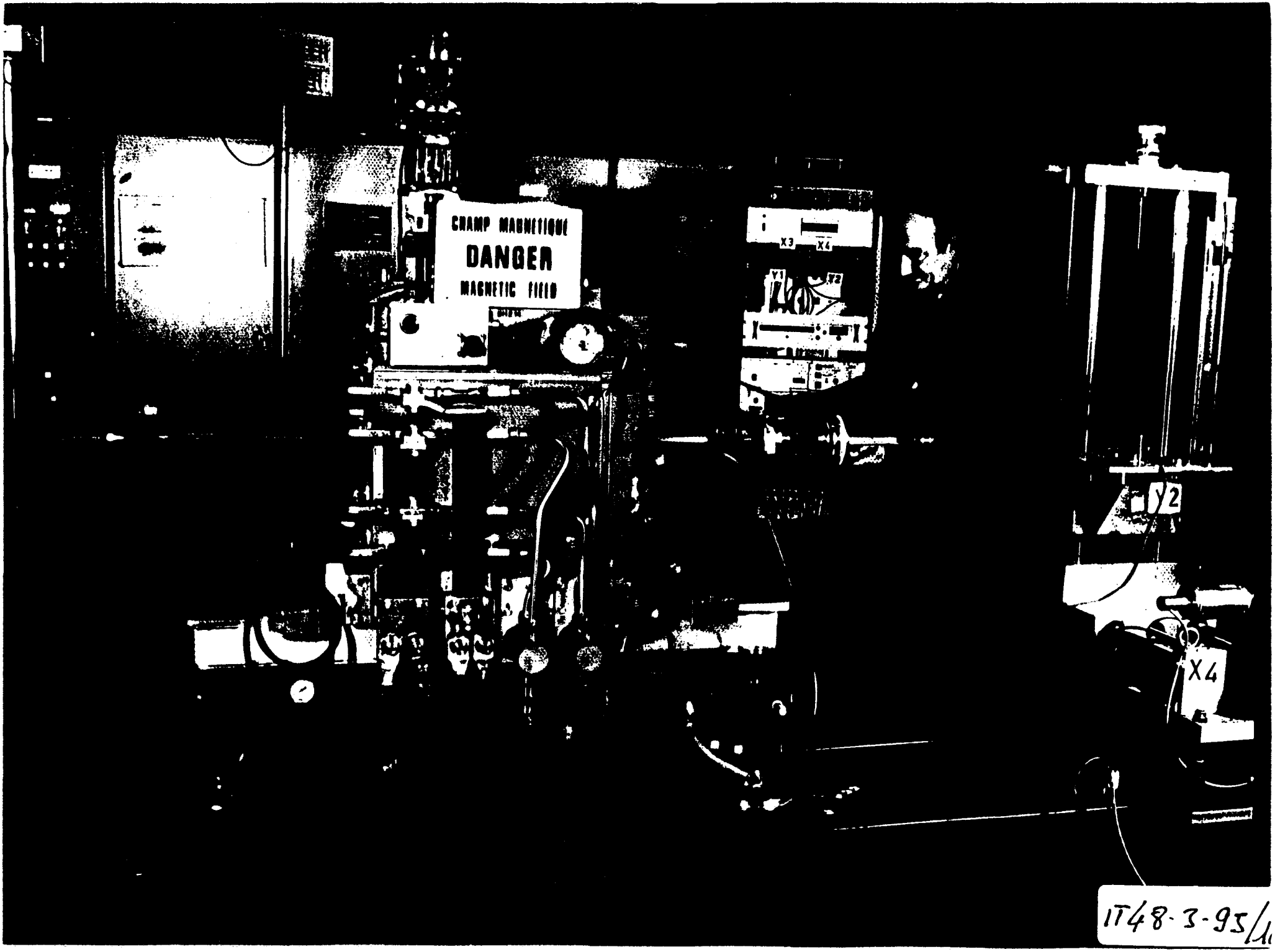
Cycle_C, Outside yoke, (files CLE58.cor,CLED96.cor,CLEDD54.cor)



Accuracy ~ 8×10^{-4} essentially due to alignment (high G)



Pulsed Magnet Measurement System


CHAMP MAGNETIQUE
DANGER
MAGNETIC FIELD
X3
X4
Y1
Y2
Y2
X4
IT48-3-95/1

et l'erreur relative aléatoire est :

$$|\varepsilon_r| \leq 1 \times 10^{-4} .$$

Il a été constaté qu'avec les cycles de démagnétisation choisis, l'influence des courants de Foucault devient négligeable 50 ms après le retour à zéro du courant du deuxième trapèze.

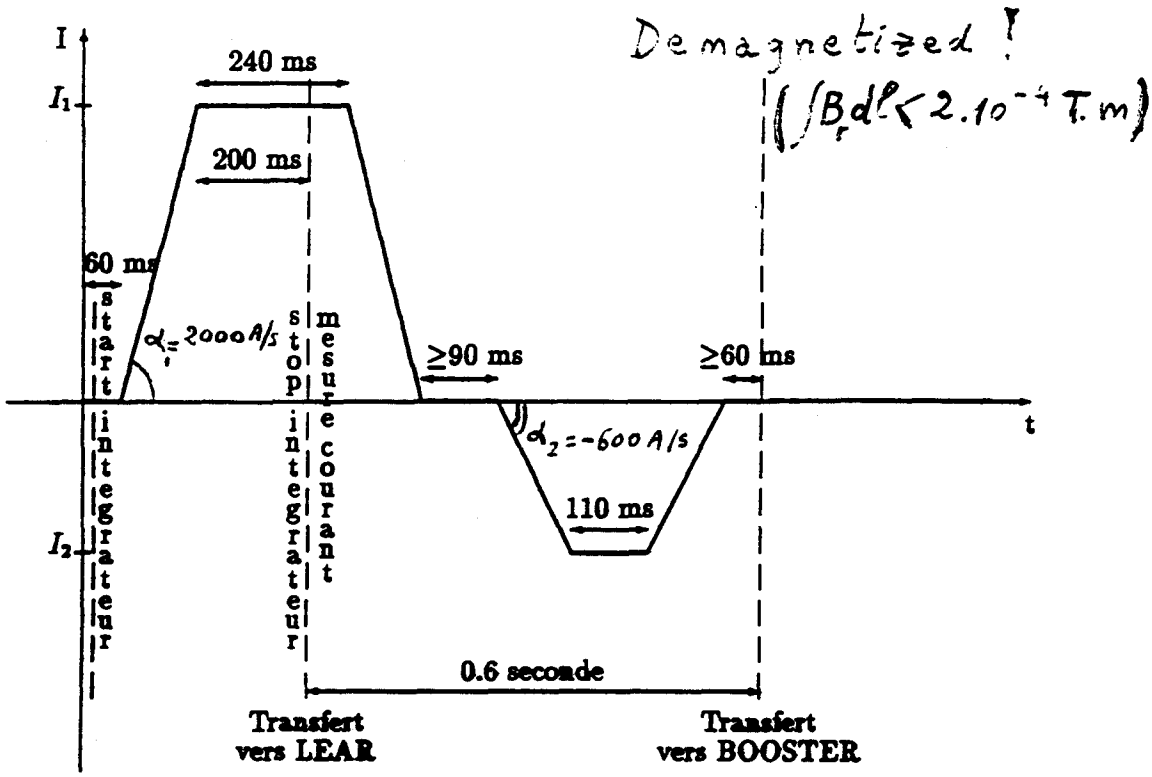


Figure 2: Séquence de mesure

2.3 Mesure de l'induction et de l'induction intégrée

La mesure de l'induction B(X,0) est faite avec la bobine courte BLC1/C de 3 cm :

$$B(X,0) = \frac{I_{th}}{A} \cdot \left| \frac{\int_0^{t_m} e_n(t)dt}{I_{mes}(t_m)} \right| \tag{1}$$

avec :

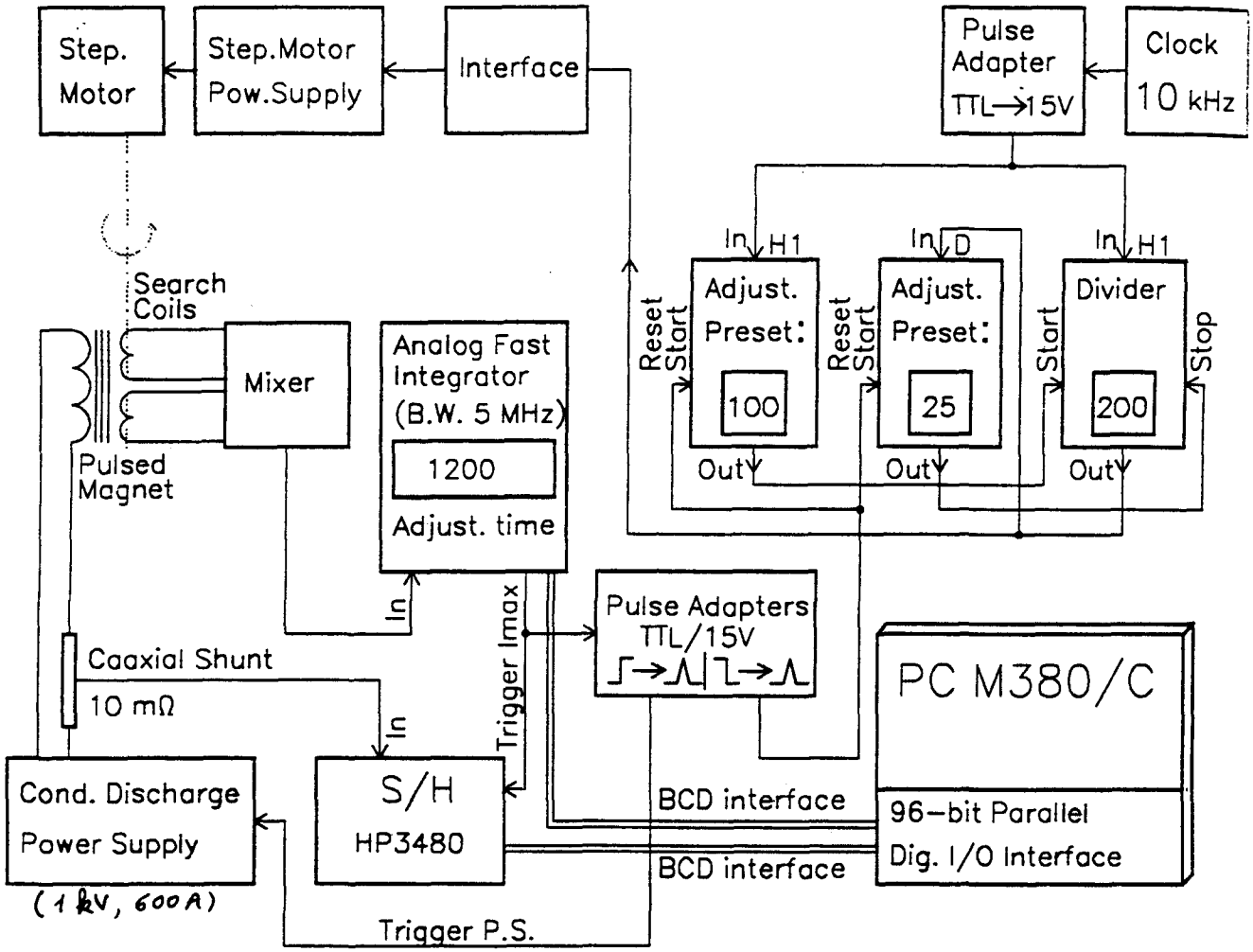
I_{th}	:	courant théorique auquel on souhaite faire la mesure,
I_{mes}	:	courant effectivement mesuré (voisin à ±0,2% près de I_{th}) ,
A	:	constante du capteur BLC1/C ($A = 4,8005 * 10^{-2} m^2$),
t_m	:	temps auquel on mesure le courant ,
		temps auquel on arrête l'intégration ,
$\int_0^{t_m} e_n(t)dt$	:	intégrale de la tension induite dans le capteur.

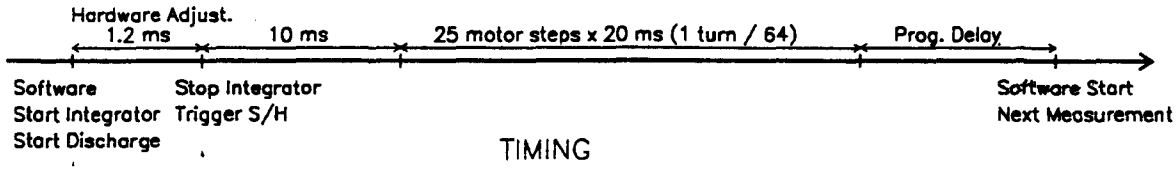
Dans la plage

$$100A \leq I \leq 250A ,$$

l'erreur relative sur la valeur absolue est :

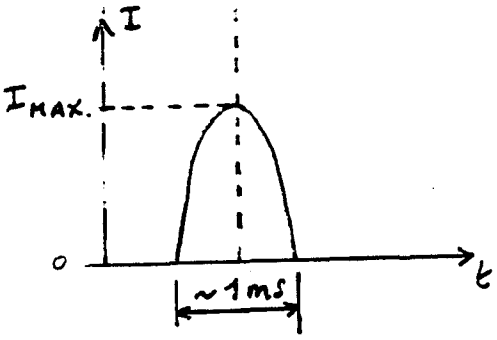
$$|\varepsilon_a| \leq 1 \times 10^{-3}$$





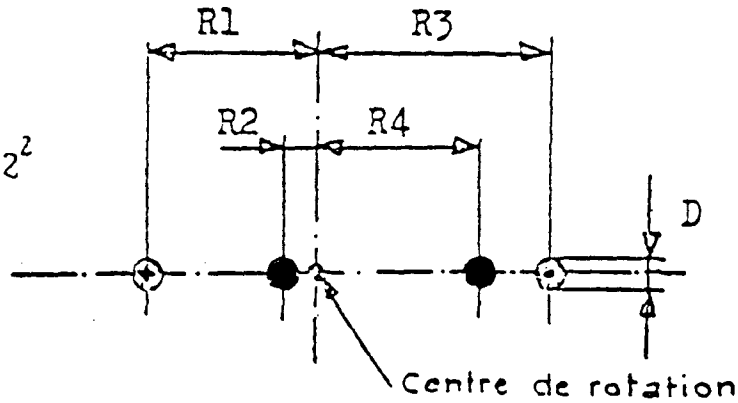
TIMING

Pulsed Quadrupole Measurement System



QUADRUPOLES LINAC

$R1 = R4$
$R2 = R3/10$
$R3^2 = R1^2 + R4^2 - R2^2$
$R1 = R3\sqrt{1.01/2}$
$N1 = N2 = N$



DIAM. SONDE mm	R1 mm	R2 mm	R3 mm	R4 mm	NOMBRE DE SPIRES N	DIAM. DU FIL mm	DIAM. TORSADE D ~ mm	MATIERE
19	6,04	0,85	8,5	6,04	30	0,1	0,75	Al_2O_3
24	7,82	1,1	11	7,82	20	0,1	0,7	"
29	9,59	1,35	13,5	9,59	14	0,1	0,6	"
46	15,63	2,2	22	15,63	10	0,1	0,5	Vetresit
68	23,45	3,3	33	23,45	6	0,2	0,7	"
100	34,82	4,9	49	34,82	6	0,2	0,7	"

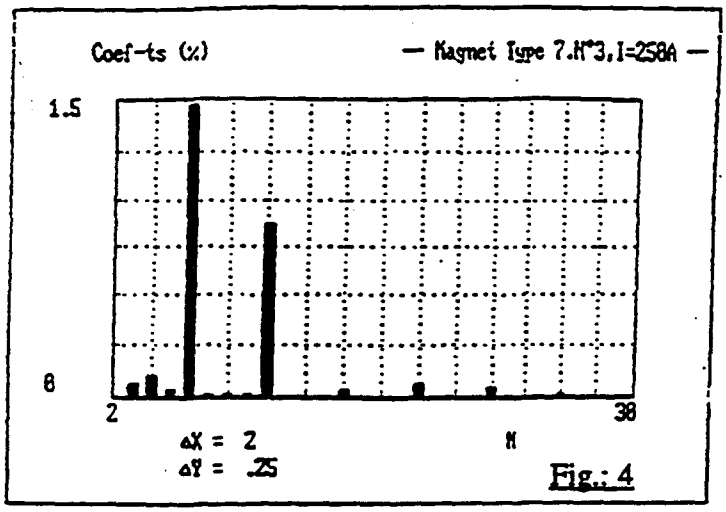


Fig.: 4

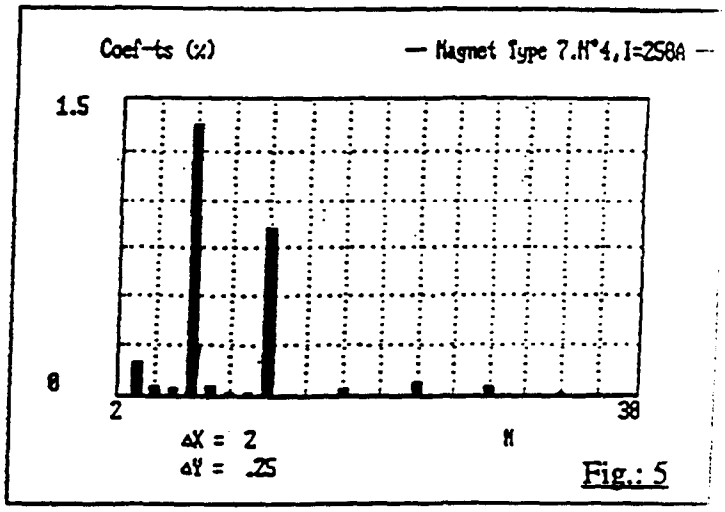


Fig.: 5

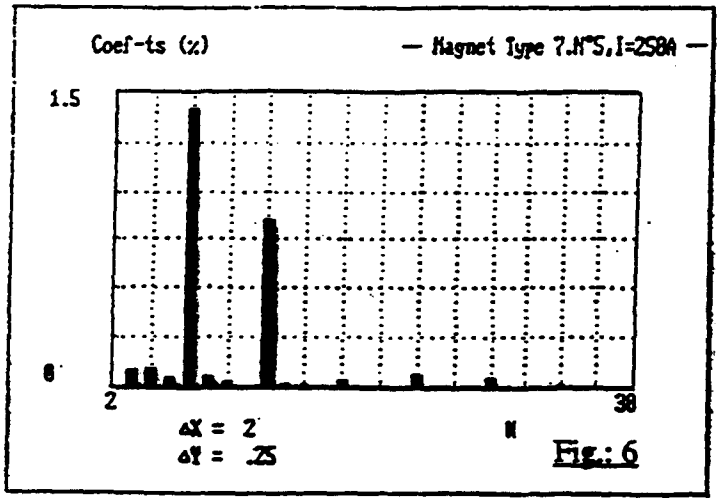


Fig.: 6

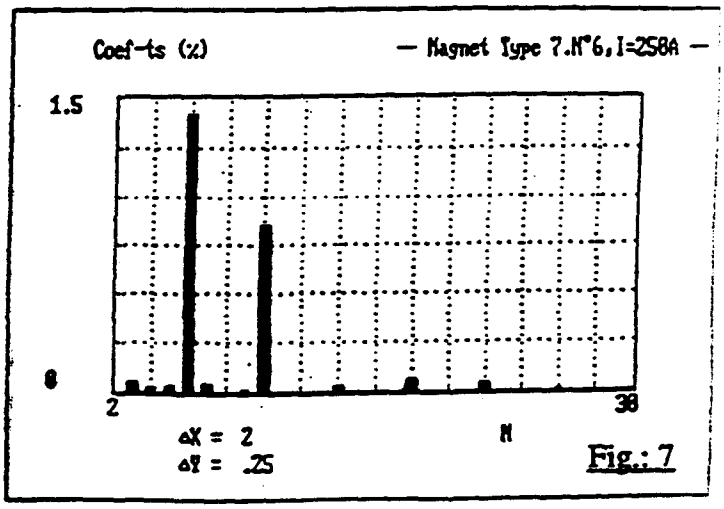
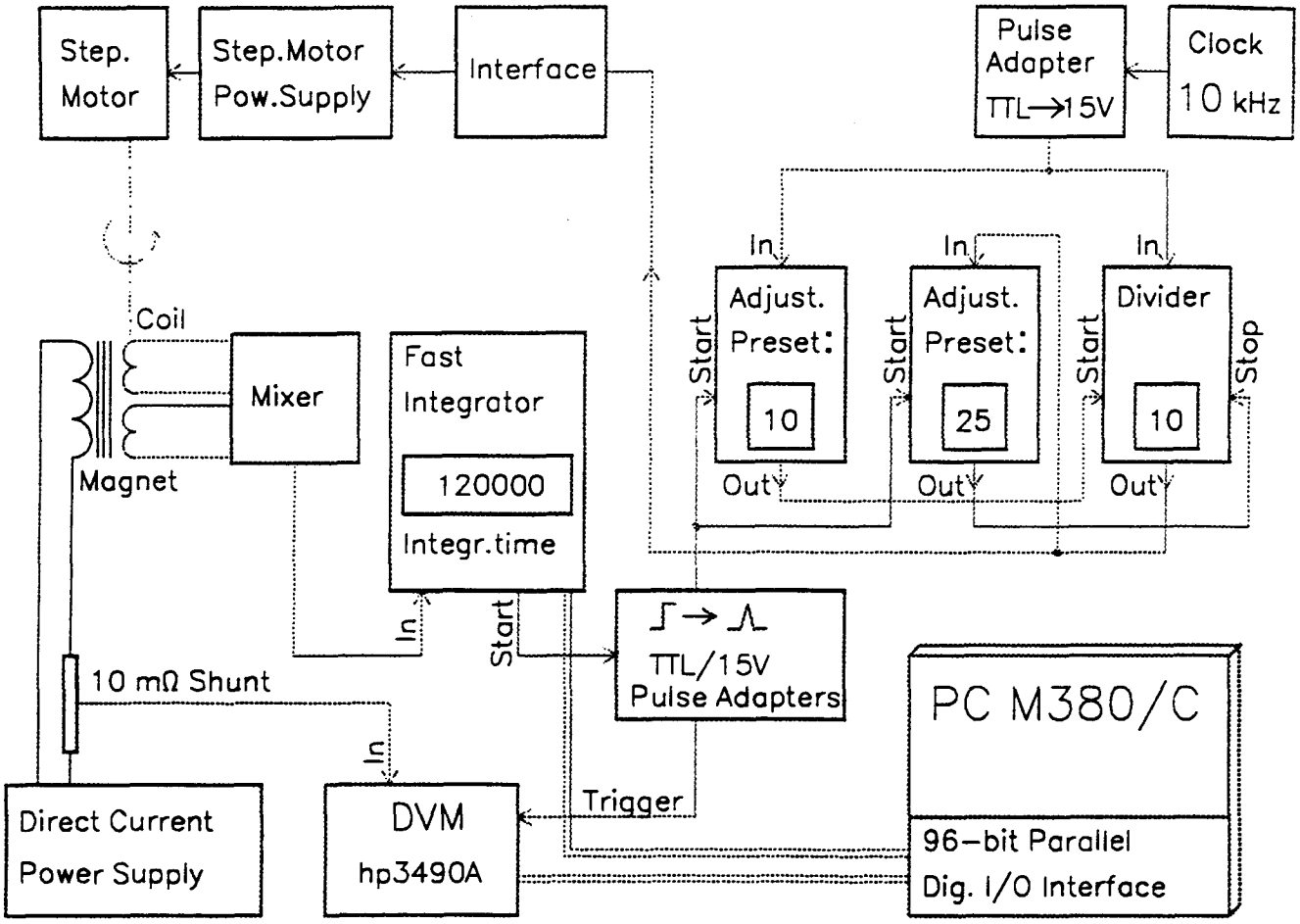


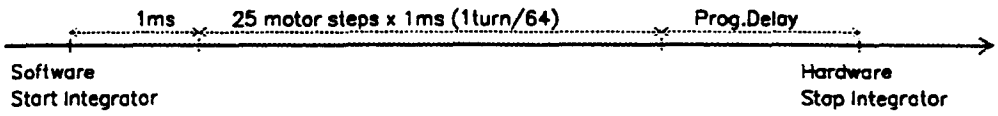
Fig.: 7

5.2 Centres magnétiques et plans médians à $I_N = 250$ A

N° de série	Centre magnétique		Inclinaison du plan médian en degré
	ρ (mm)	α (degré)	
01	0,029	- 84,0	+ 0,06
02	0,044	+ 5,7	+ 0,09
03	0,031	- 33,0	- 0,02
04	0,017	- 89,5	+ 0,04
05	0,033	- 109,2	+ 0,31
06	0,033	- 55,0	+ 0,01

Accuracy ~ 2 ‰

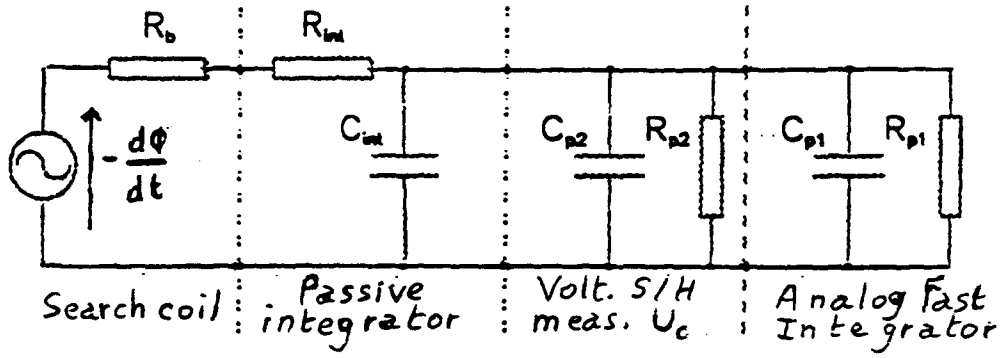




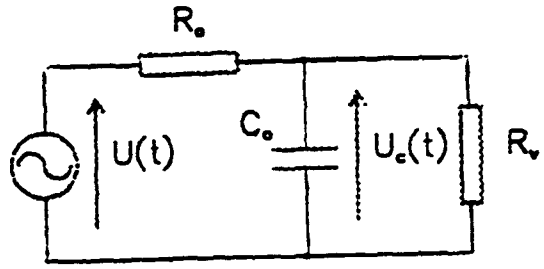
TIMING

DC–Quadrupole Measurement System

"Double integration" principle



Equivalent diagram :



$R_o = R_b + R_{int}$

$C_o = C_{int} + C_{p1} + C_{p2} \# C_{int}$

$R_v = \frac{R_{p1} R_{p2}}{R_{p1} + R_{p2}} \# R_{p1}$

Exact equation: $$\boxed{\int_0^{t_2} U(t)dt = R_o C_o U_c(t_2) + (1 + \frac{R_o}{R_v}) \int_0^{t_2} U_c(t)dt}$$

- First term : passive integration
- Second term : mere divider

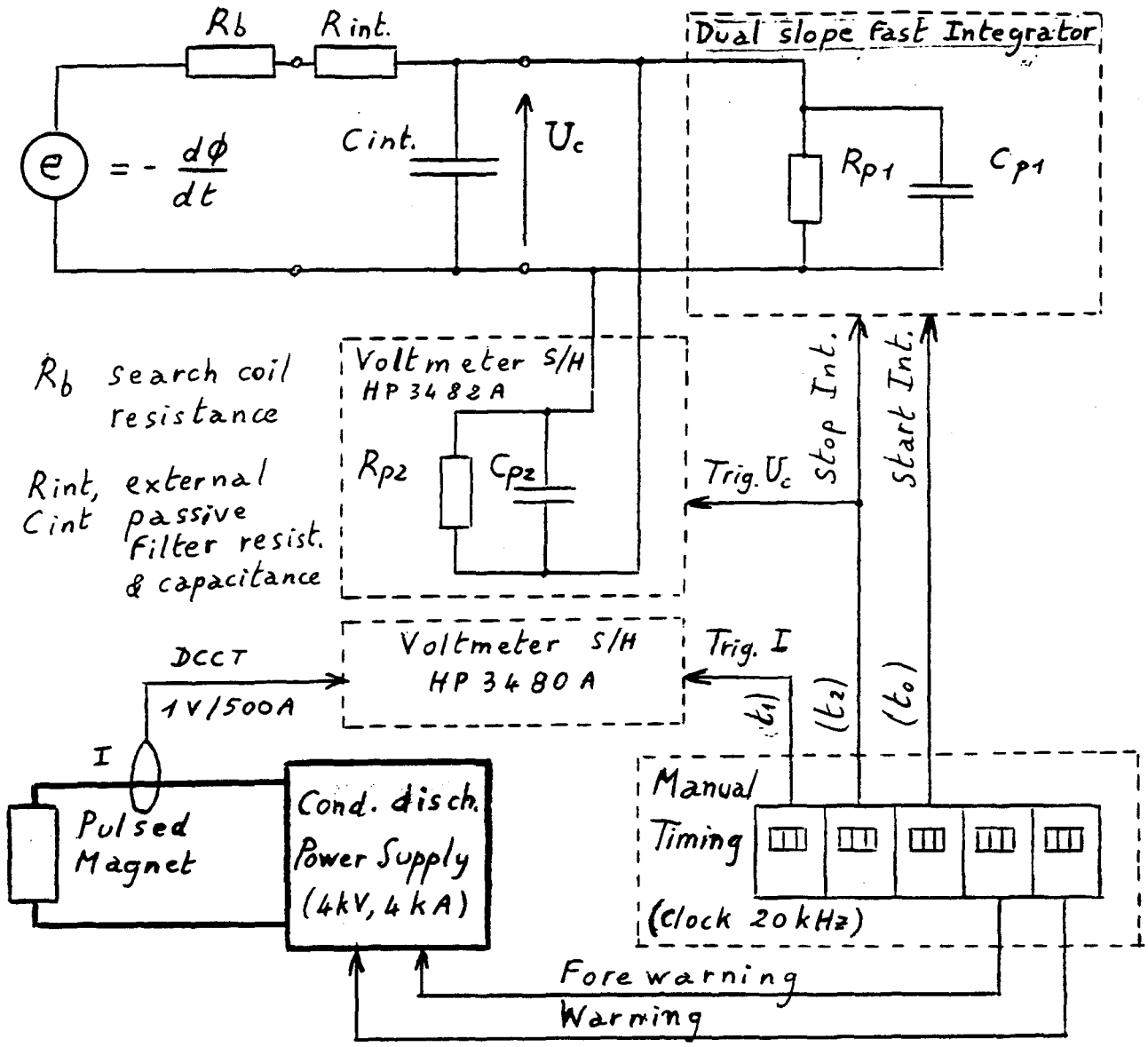
Interest of "double integration":

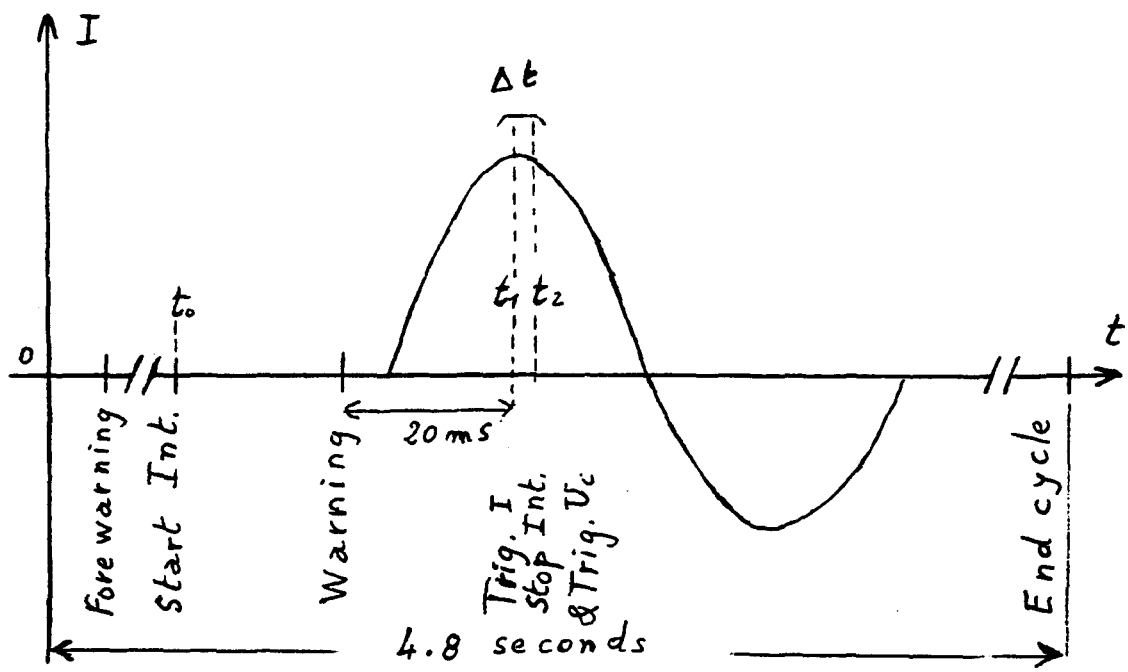
- High induced voltages ($\frac{d\Phi}{dt}$ several tens, hundreds volts)
- Medium Frequencies (several tens, hundreds Hz)
- Capacitance of integrator, of cables not negligible (several hundreds pF) choose Cint high enough
- Noisy environment
- Inductance of coil negligible if Rint chosen high enough

BUT accuracy relies on quality of Rint and Cint and be sure that Cint completely discharged before next pulse.

(Second term is only few % of the first)

Mobile pulsed Measurement System





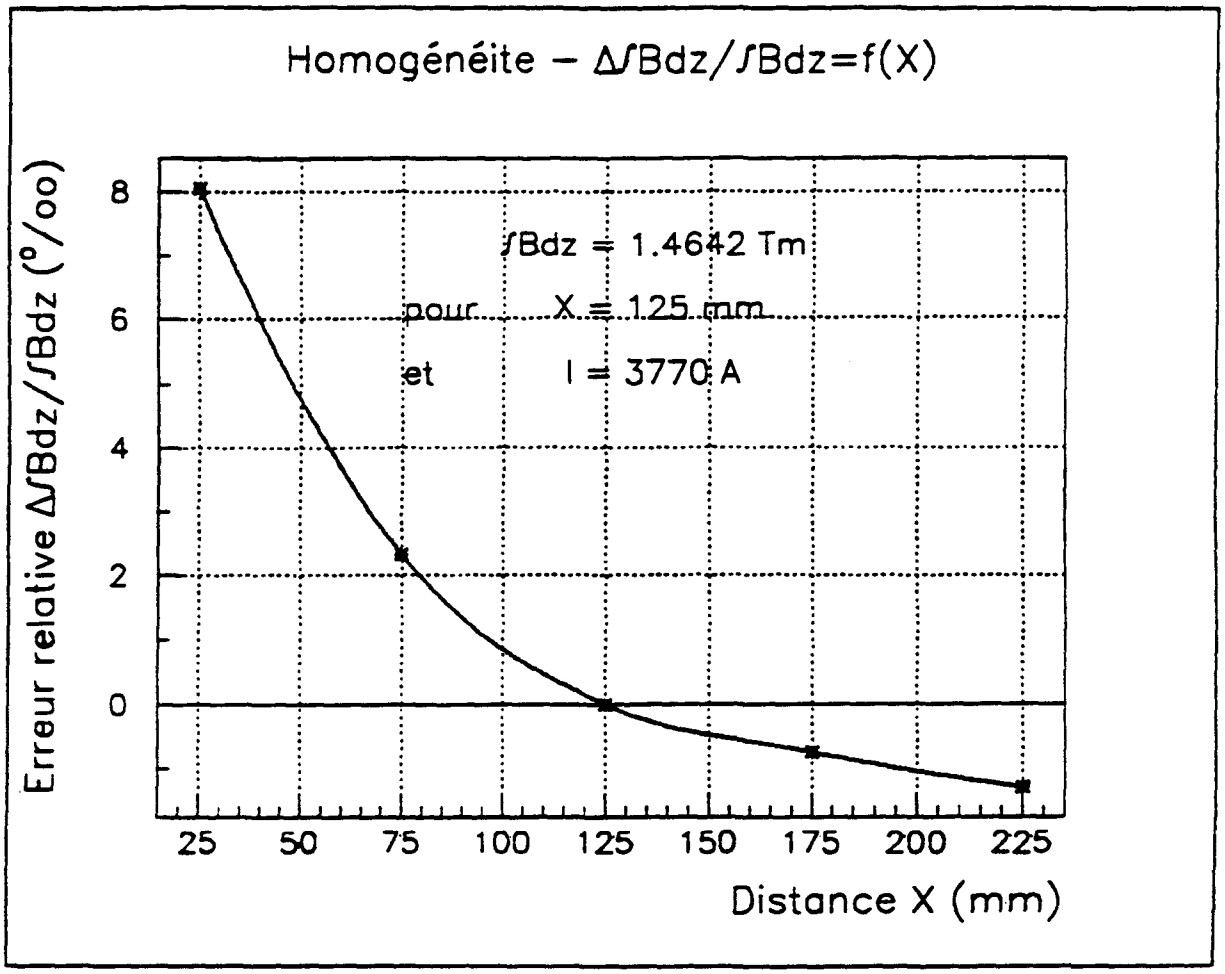
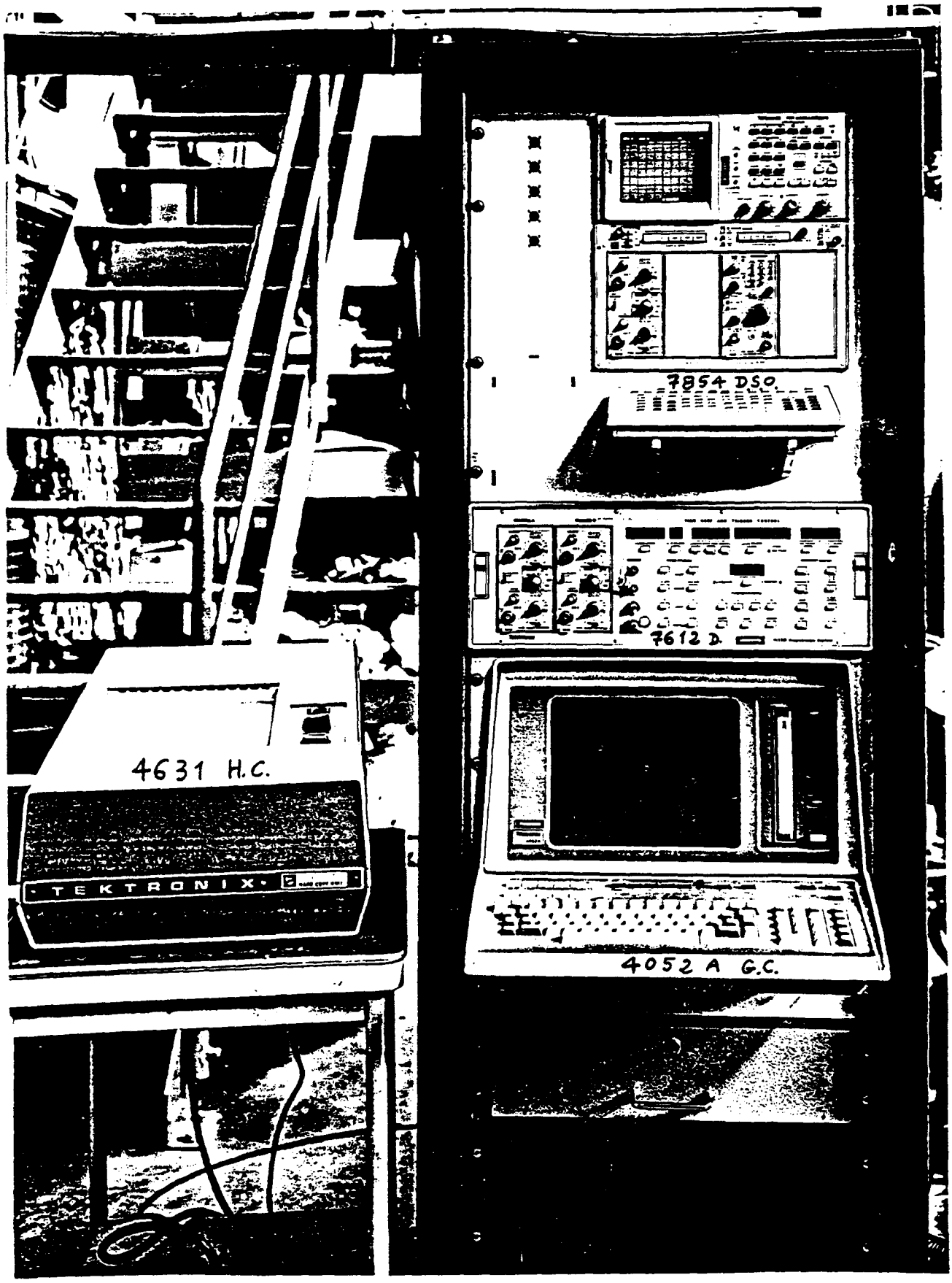


Figure 5: Courbe d'homogénéité

Cette courbe montre que l'homogénéité est meilleure que ±0,5 % sur Δx = 200 mm.

Ex. : 8 kA - 60 μs pulse
: 30 kA - 200 μs pulse

Figure



Calibration of double search coils

→ Integral coils : Field and Gradient coil..

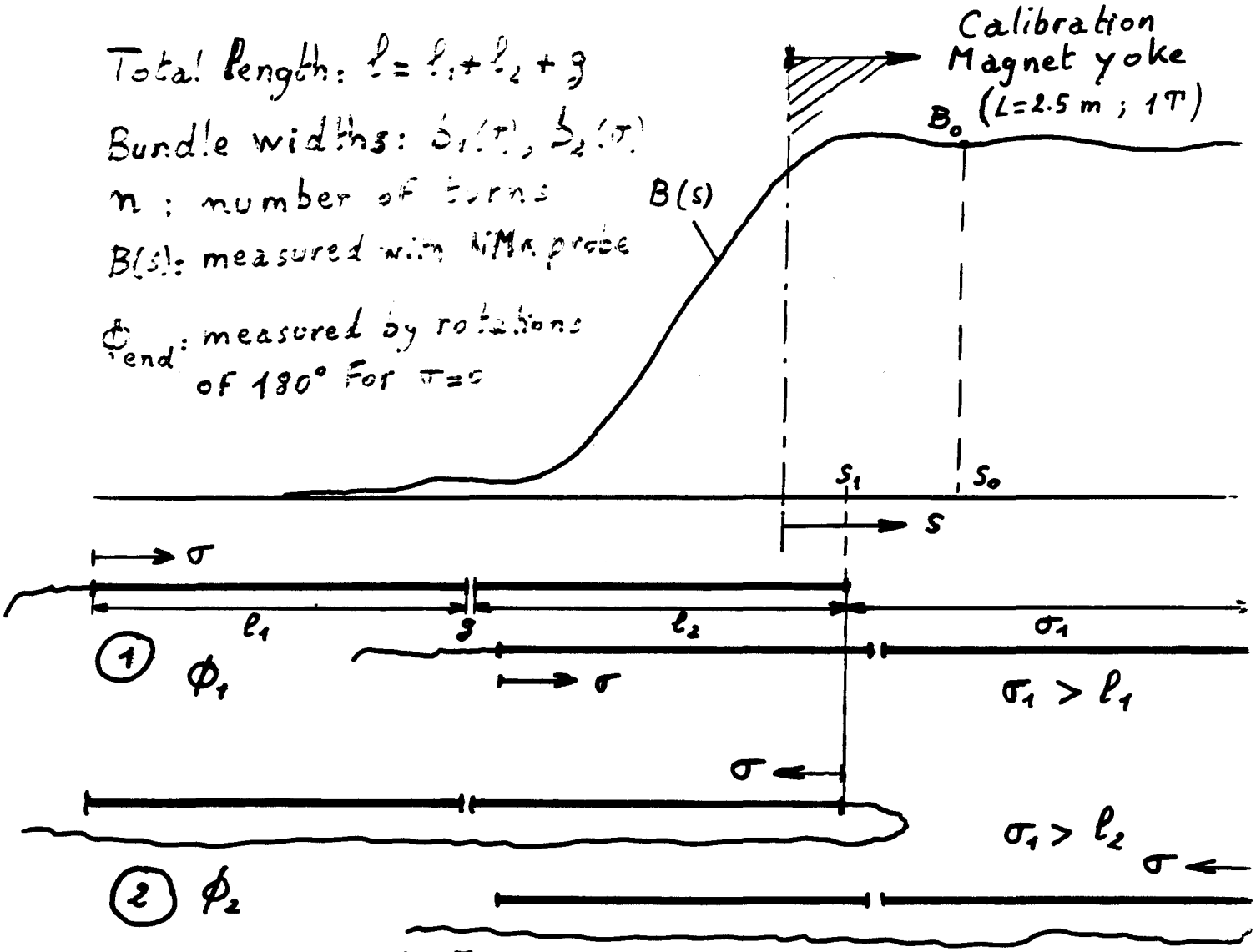
Total length: $\ell = \ell_1 + \ell_2 + g$

Bundle widths: $b_1(\sigma)$, $b_2(\sigma)$

n : number of turns

$B(s)$: measured with NMR probe

Φ_{end}: measured by rotations of 180° for $\sigma = 0$



$$B_m = \frac{1}{\sigma_1}\int_{s_1}^{s_1+\sigma_1} B(s)\,ds$$

10^{-4} accuracy $\Rightarrow \varepsilon_{\sigma_1} < 0{,}1\,m$ if $\ell_1, \ell_2 \simeq 1\,m$

σ_1 measured with length gauge

$$\Phi_{end} = \frac{n(\bar{b}_1+\bar{b}_2)}{2}\cdot\int_{s_1-\ell}^{s_1-\ell+\sigma_1} B(s)\,ds$$

$$\left[A_s(\sigma_1) = \frac{1/2(\Phi_1+\Phi_2)+\Phi_{end}}{B_m\,\sigma_1} = \frac{n(\bar{b}_1+\bar{b}_2)}{2}\left(1-\frac{g}{\sigma_1}\right)\right\}$$

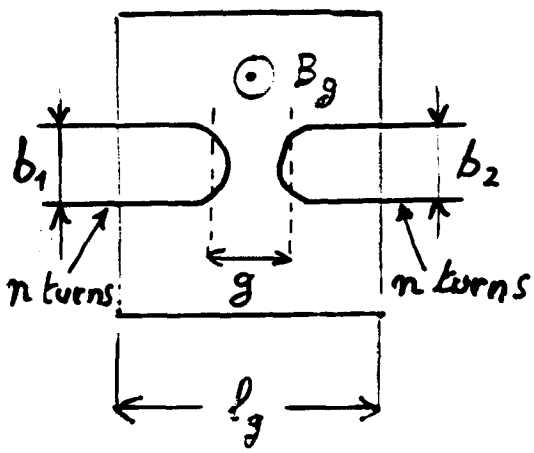
Specific constant of search coil For $\ell_1 = \ell_2$

For a magnet where $\ell_{eq} \neq \sigma_1$, take :

$$A_s(\ell_{eq}) = A_s(\sigma_1) \times \frac{1-g/\ell_{eq}}{1-g/\sigma_1} \quad \text{(in meter)}$$

D. Cornuet

Measurement of the gap g of the double search coil



Use of a short magnet:
permanent magnet moved
or pulsed small dipole

$$\int B\,dl = B_g \cdot l_g \simeq \text{constant}$$

over width b_1, b_2 and length g

$$\phi_1 = n\,\bar{b}_1\,B_g\,l_g$$

$$\phi_2 = n\,\bar{b}_2\,B_g\,l_g$$

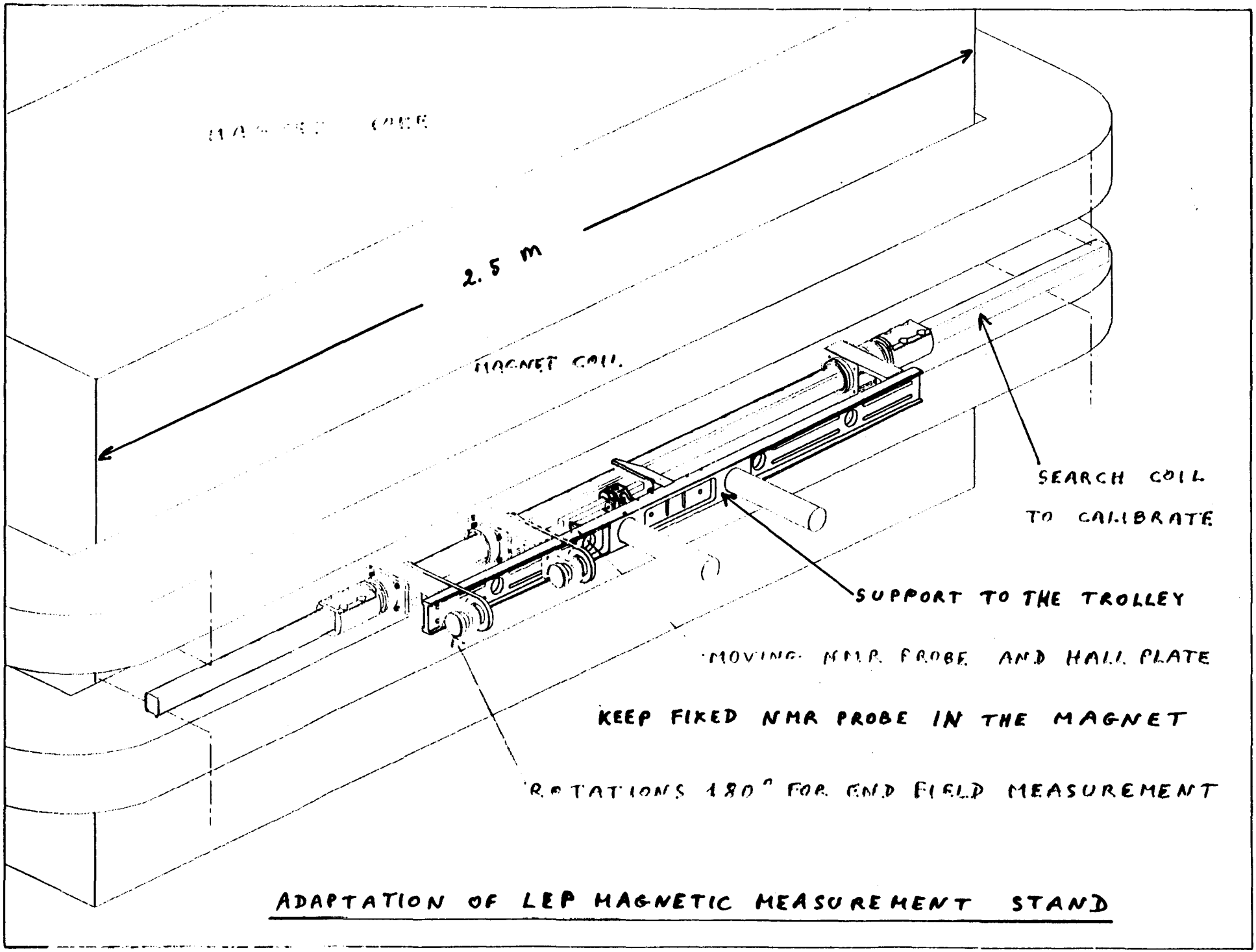
In between

$$\phi_3 = n\,\frac{\bar{b}_1+\bar{b}_2}{2}\,B_g\,(l_g - g)$$

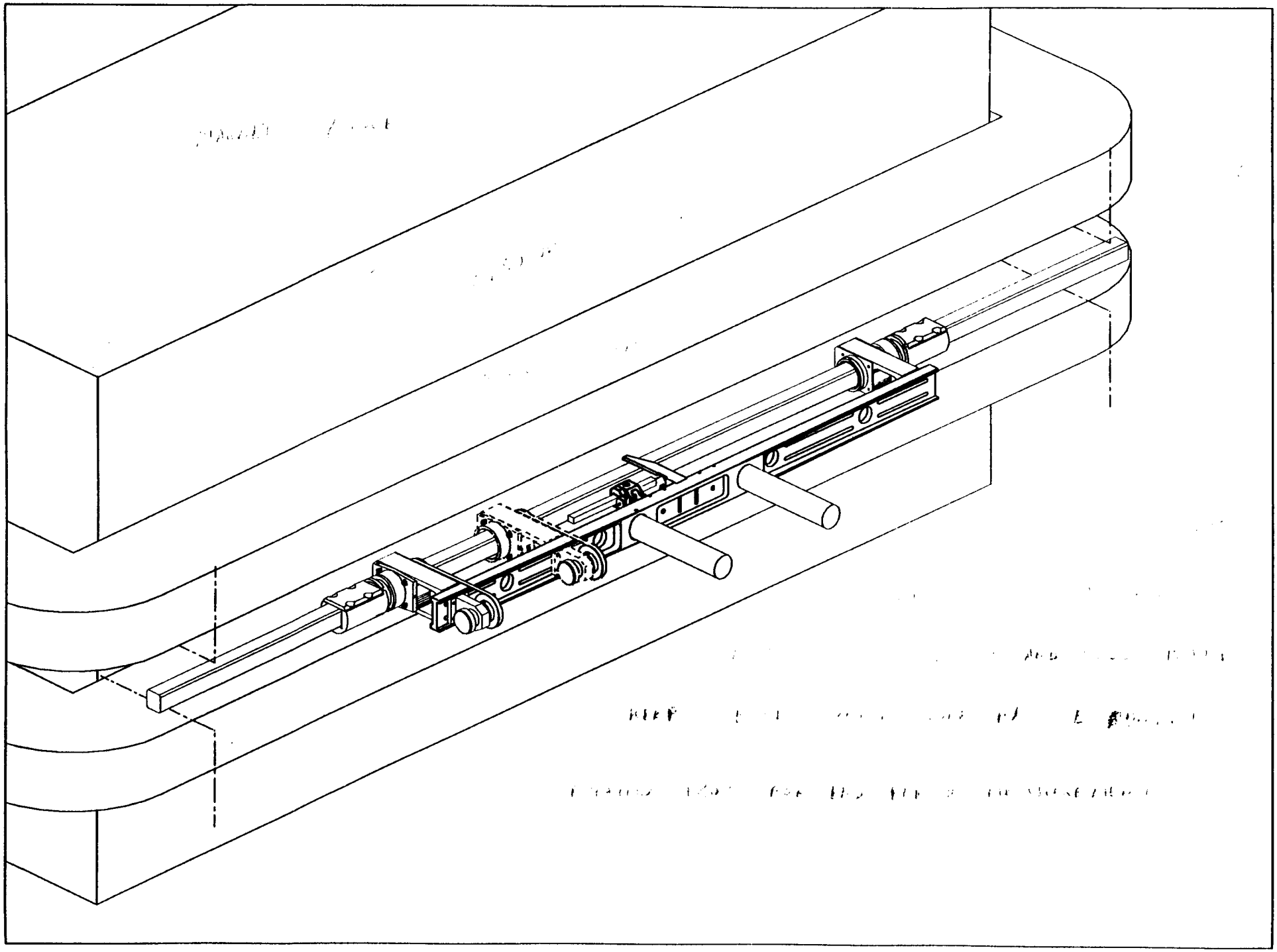
B_g measured with Hall plate

$$\left[\; g = \frac{1/2\,(\phi_1+\phi_2) - \phi_3}{n\,\frac{(\bar{b}_1+\bar{b}_2)}{2}\cdot B_g} \;\right]$$

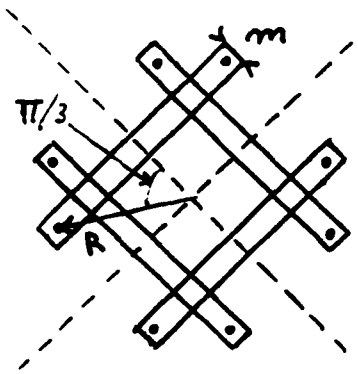
The above method determines $n\,\frac{(\bar{b}_1+\bar{b}_2)}{2}$ and g purely magnetically and doesn't need to know the exact geomety (which is often unknown) of the integral coils.
(Only hypthesis : $l_1 = l_2$)



ADAPTATION OF LEP MAGNETIC MEASUREMENT STAND



Double gradient coils



Ironless magnet used for additional calibration :

$F \simeq 70\ Hz$

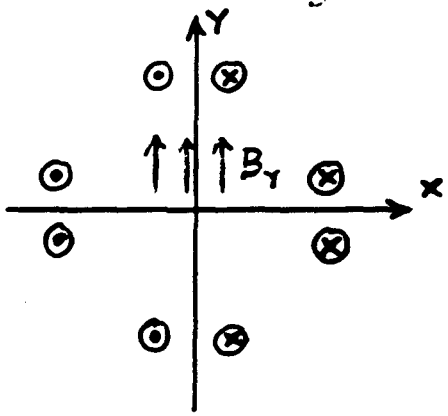
$L = 2.40\ m$

$R = 12\ cm$

$m = 6.2\ mm$

$B \simeq 50$ Gauss

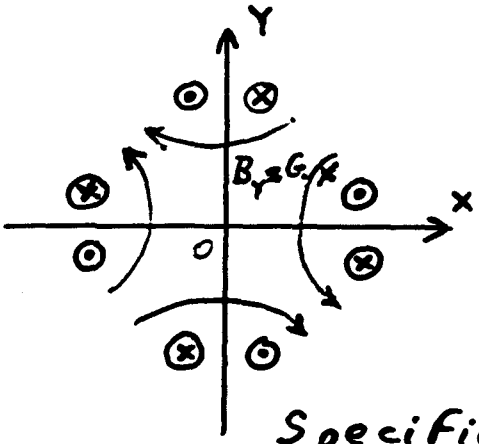
- Configuration as Helmholtz coil :



For matching coils' constan with <u>equilizing resistors</u> (~99,9 10^{-3})

(Suppose $n_1 = n_2$; $\ell_1 = \ell_2$ and only spread over b_1 and b_2, checked by meas. of surfaces A_1 & A_2, and fluctuations of b_1 & b_2).

- Configuration as Gradhelm coil :



For measurement of d_1, d_2 distances between coils of one pair (accuracy better 0.01 mm) $\sim 10^{-3}$

Specific constant of gradient coils

(in m^2) $$\left[V_S(\sigma_1) = \frac{[1/2(\phi_1+\phi_2)+\phi_{end}}{B_m\ \sigma_1} . d = \frac{n(\bar{b}_1 . \bar{d}_1 + \bar{b}_2 \bar{d}_2)}{2} \left(1 - \frac{g}{\sigma_1}\right) \right.$$

{ Of course resonance frequency of the search coil is supposed far above 70 Hz.

Performance of a Stretched Wire Fiducialization System for SSC Magnets

Zachary Wolf
Pierre Pellissier
Lars Jensen
Suzanne Averitte

SSC Laboratory
September 28, 1993

Required Measurement Accuracy

Quadrupole Center:
0.21 mm w.r.t. fiducials

Quadrupole Roll Angle:
0.46 mrad w.r.t. fiducials

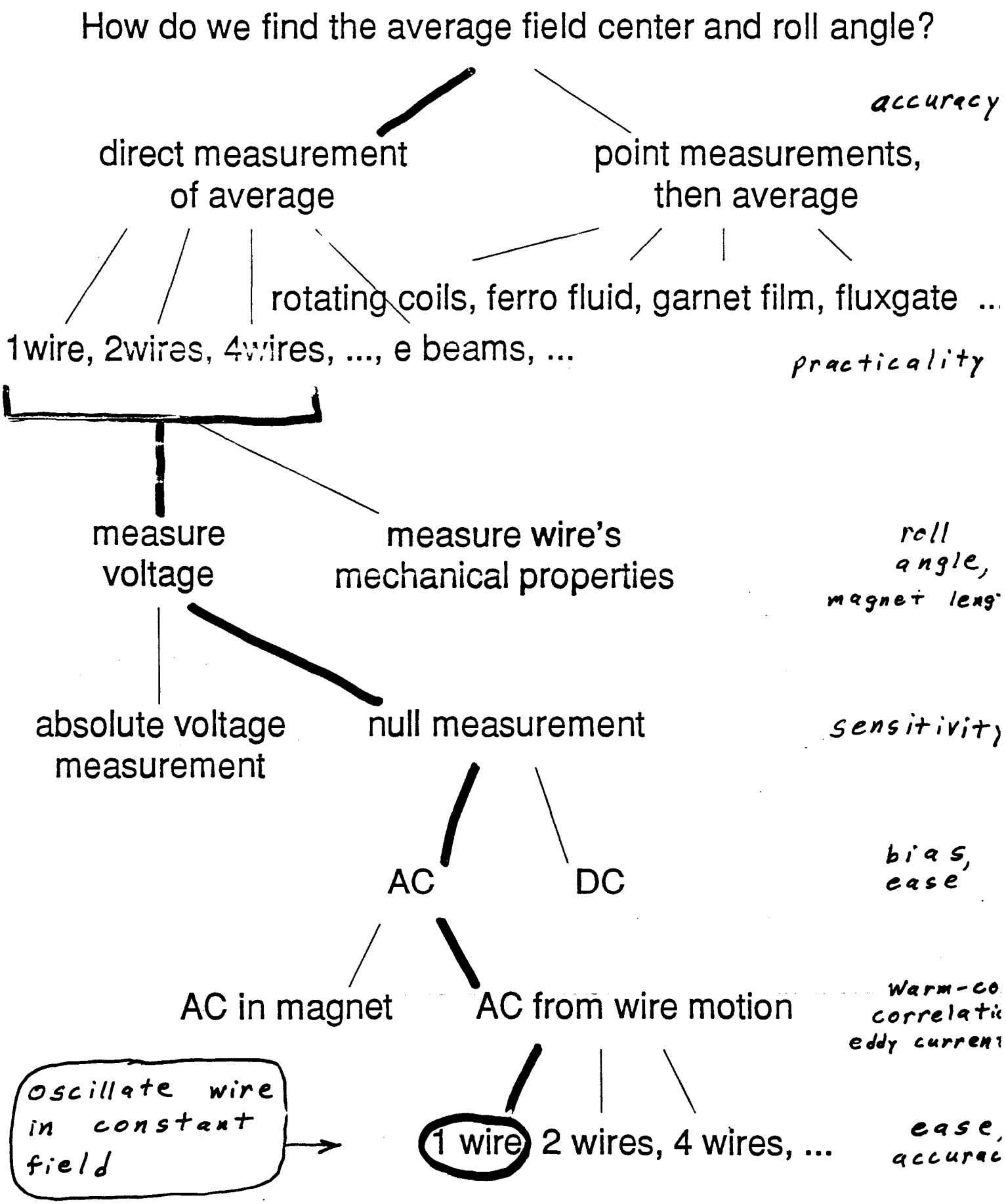
Quadrupole Integrated Gradient:
0.1%

Dipole Roll Angle:
1 mrad w.r.t. fiducials

Dipole Integrated Field Strength:
0.1%

Dipole Center:
1 mm w.r.t. fiducials

NB These accuracies refer to cold magnets in the tunnel.


How do we find the average field center and roll angle?
accuracy
direct measurement of average
point measurements, then average
rotating coils, ferro fluid, garnet film, fluxgate ...
1wire, 2wires, 4wires, ..., e beams, ...
practicality
measure voltage
measure wire's mechanical properties
roll angle, magnet leng
absolute voltage measurement
null measurement
sensitivity
AC
DC
bias, ease
AC in magnet
AC from wire motion
Warm-co correlati eddy curren
oscillate wire in constant field
1 wire
2 wires, 4 wires, ...
ease, accurac

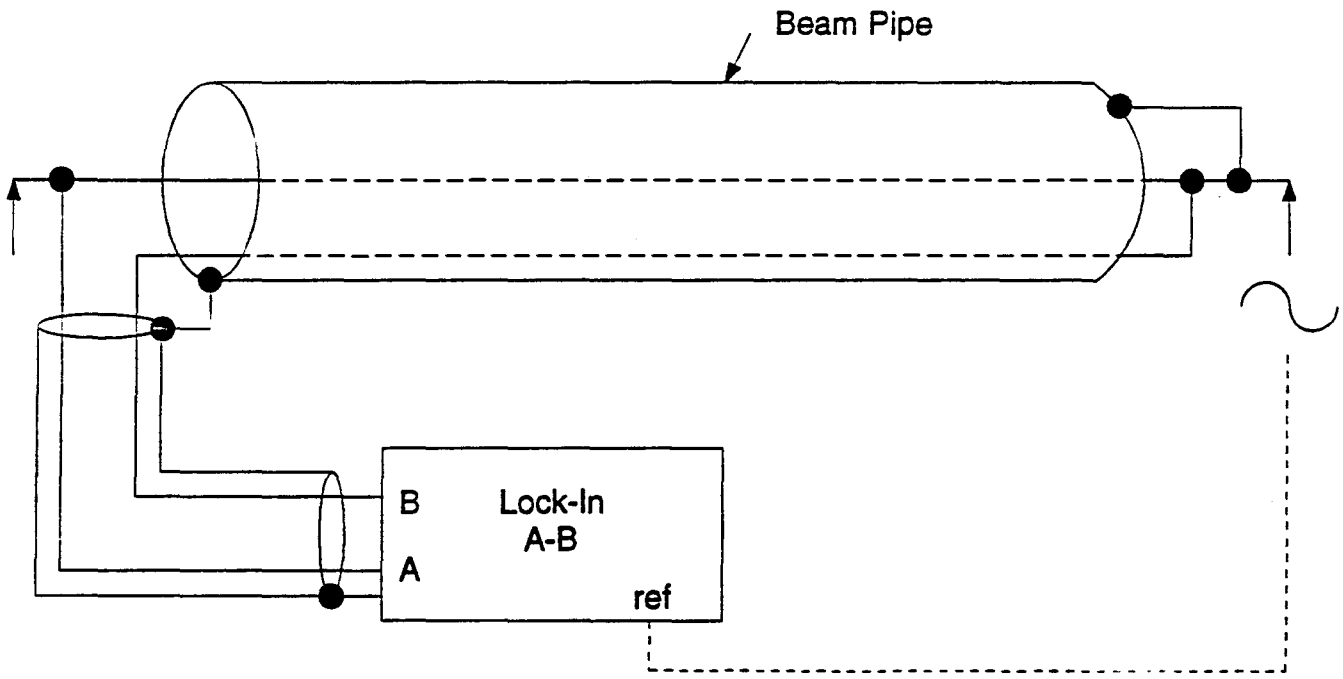
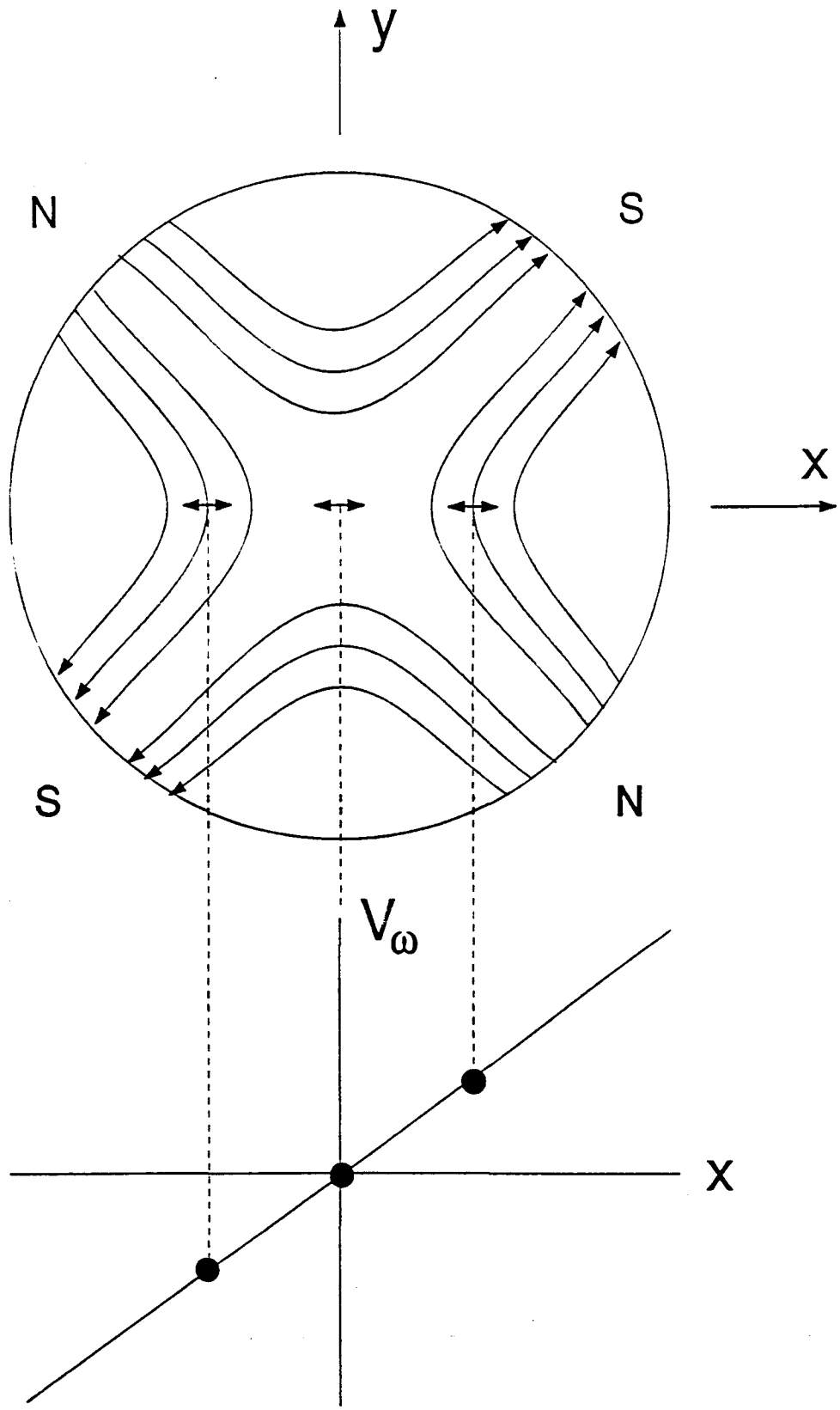
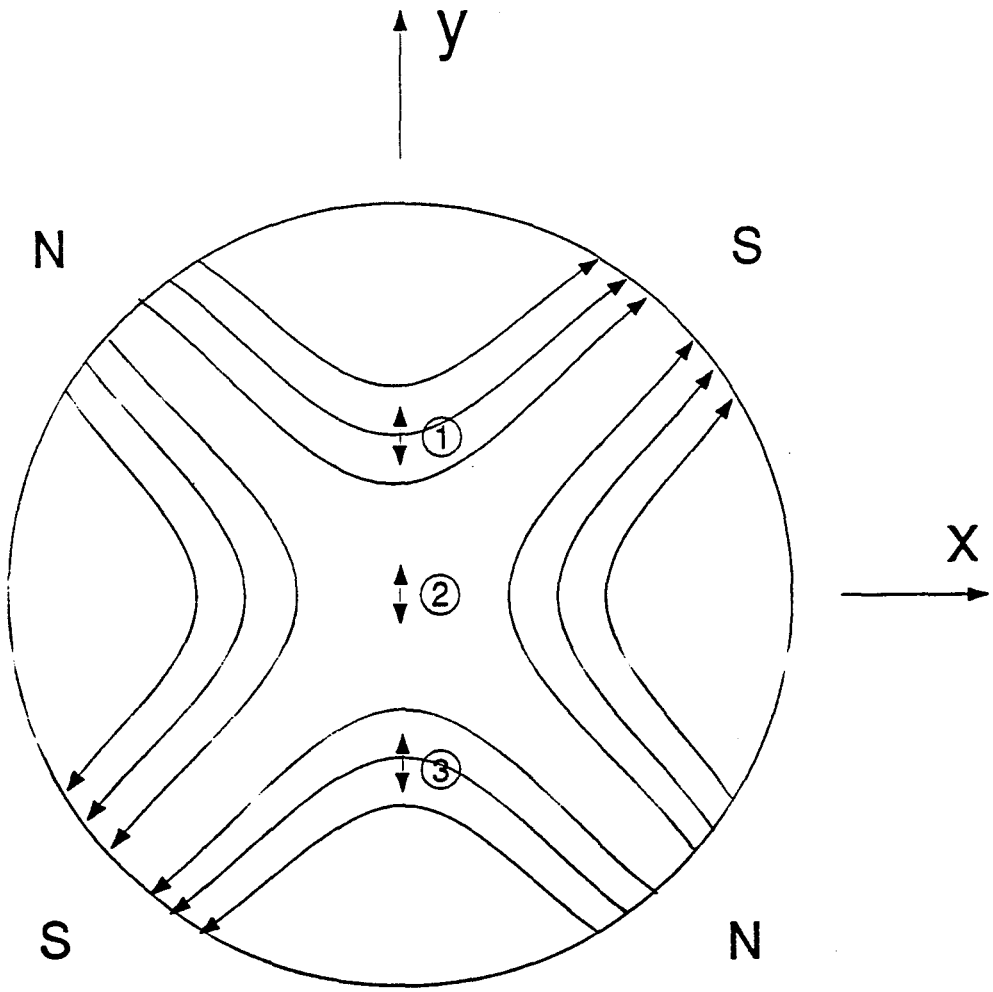
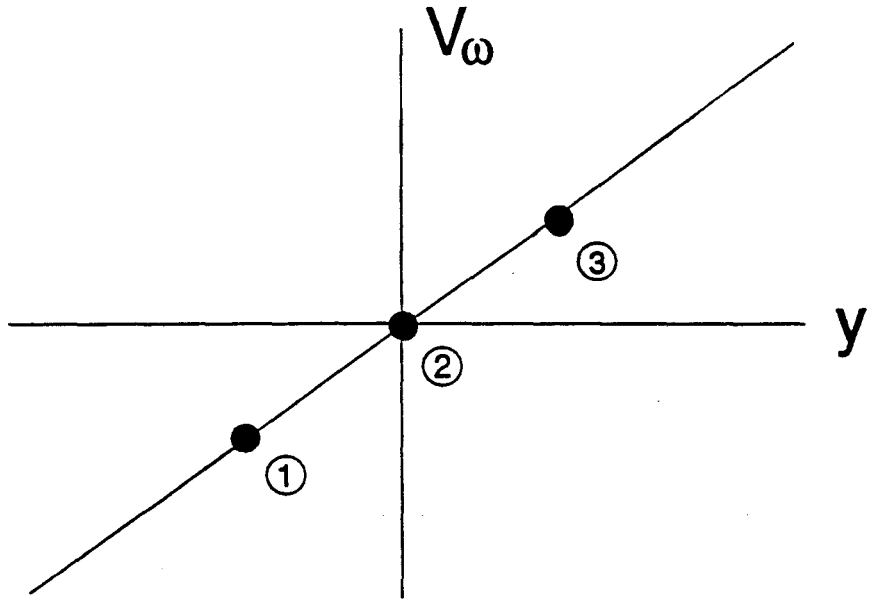
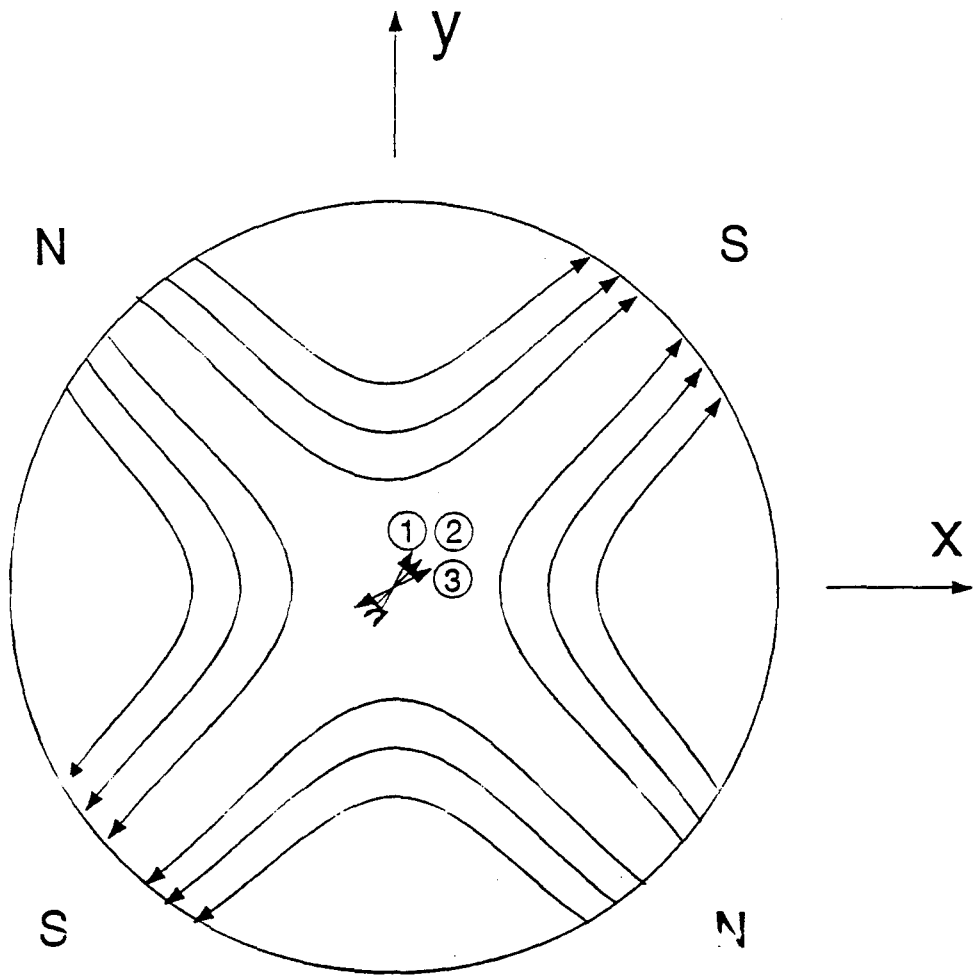


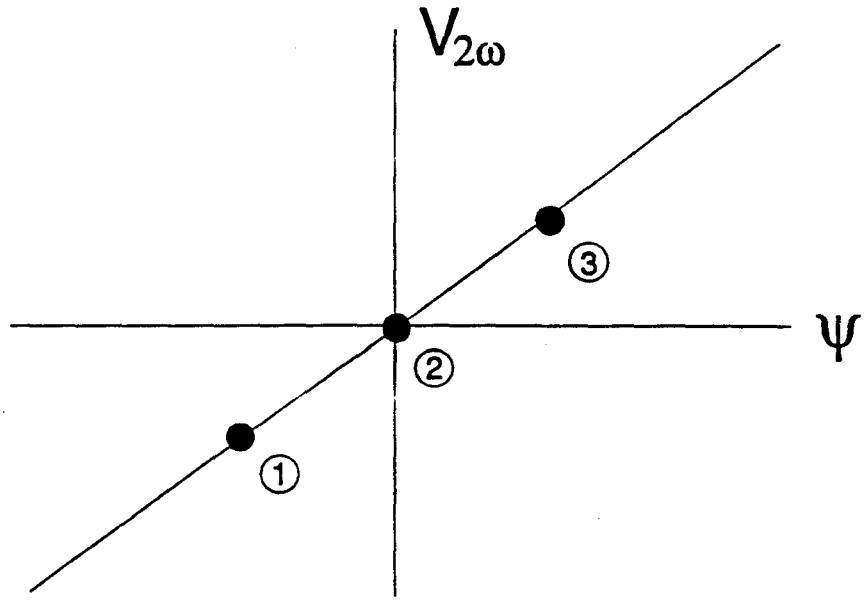
Figure 4


y
N
S
x
S
N
V_ω
x


y
N
S
1
2
3
x
S
N


Vω
3
y
2
1


y
N
S
1
2
3
X
S
N


$V_{2\omega}$
3
ψ
2
1

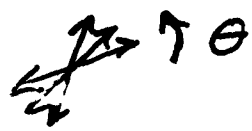
Types of Motion Required

1) sinusoidal $\longleftrightarrow$
   a) variable amplitude
   b) variable frequency

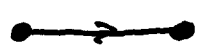
2) x y translations

$\leftrightarrow \quad \leftrightarrow \quad \leftrightarrow \quad \leftrightarrow \qquad \rightarrow x$

3) θ rotations



4) linear between fixed endpoints



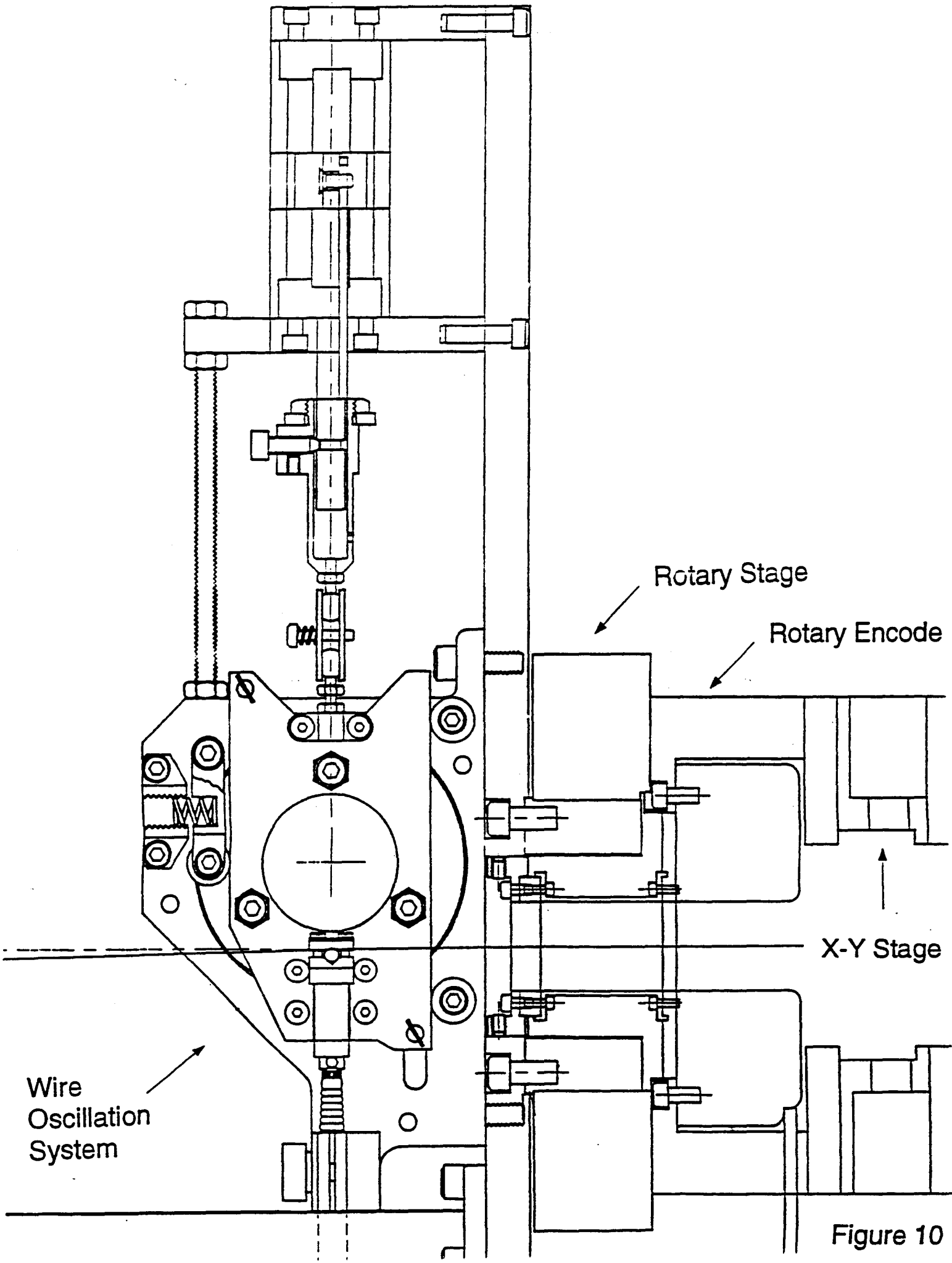

Rotary Stage
Rotary Encode
X-Y Stage
Wire
Oscillation
System

Figure 10

Figure 5

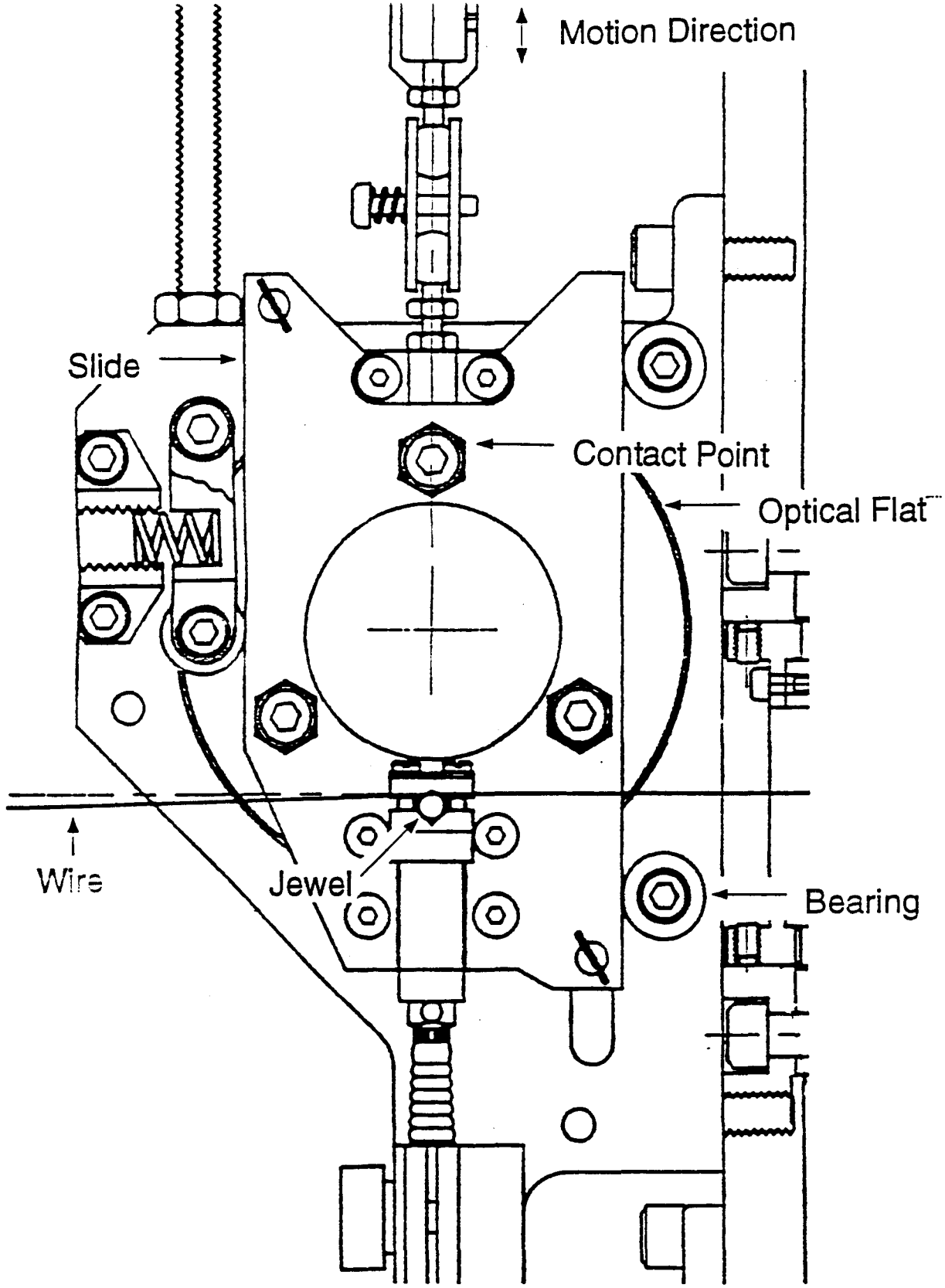

Motion Direction
Slide
Contact Point
Optical Flat
Wire
Jewel
Bearing

Figure 6

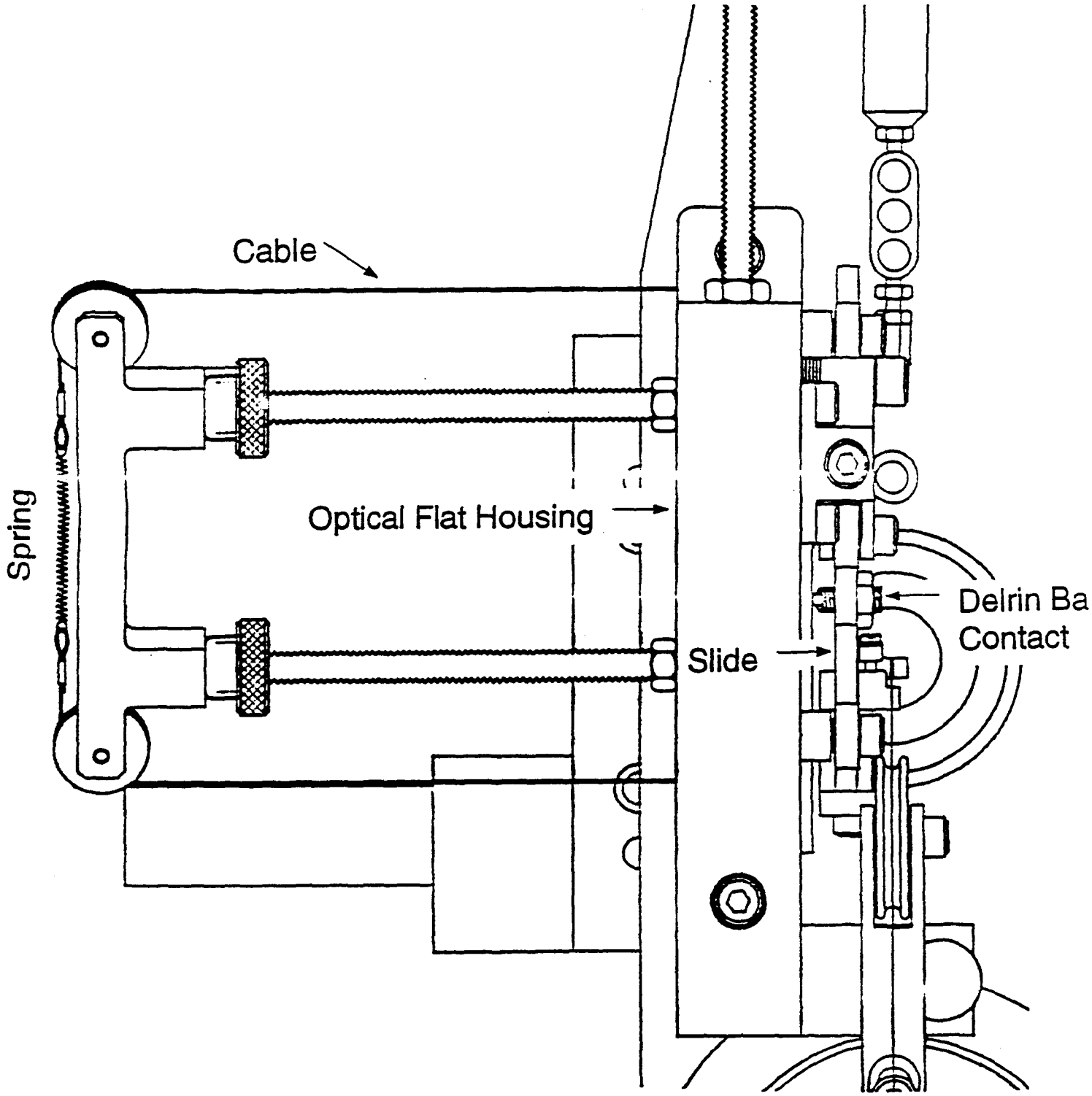


Figure 7

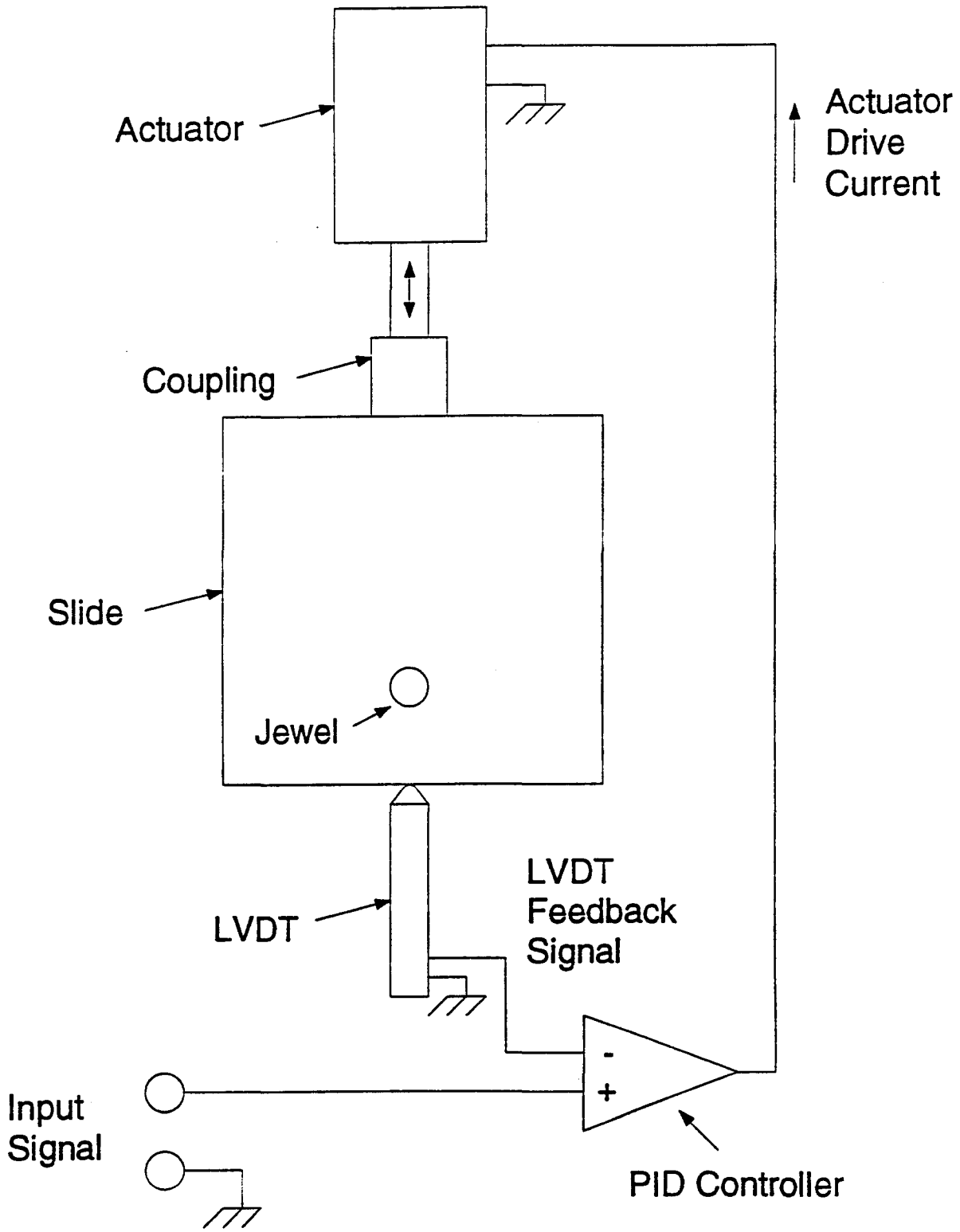

Actuator
Actuator
Drive
Current
Coupling
Slide
Jewel
LVDT
LVDT
Feedback
Signal
-
+
Input
Signal
PID Controller

Figure 8

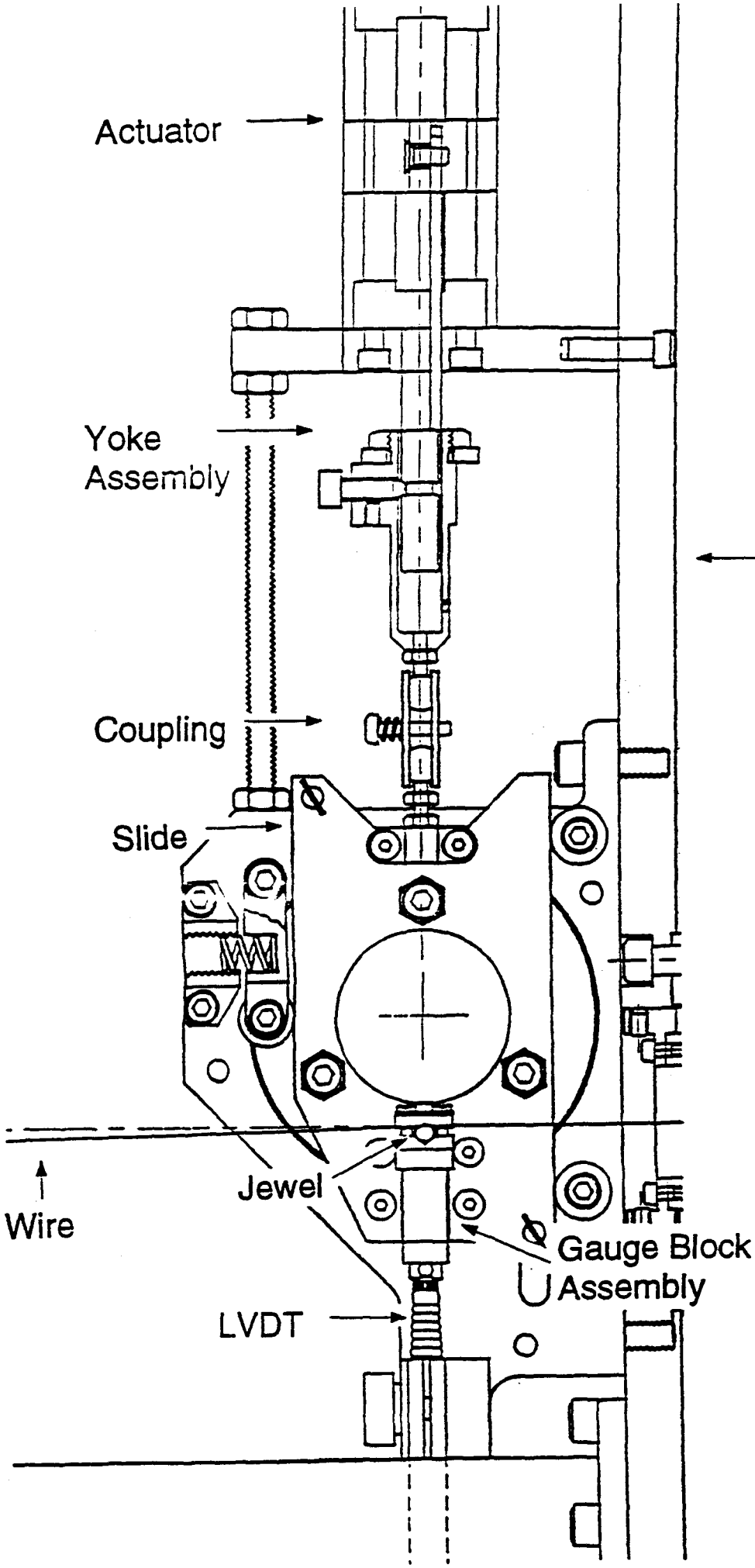

Actuator
Yoke
Assembly
Base
Plate
Coupling
Slide
Jewel
Wire
Gauge Block
Assembly
LVDT

Figure 9

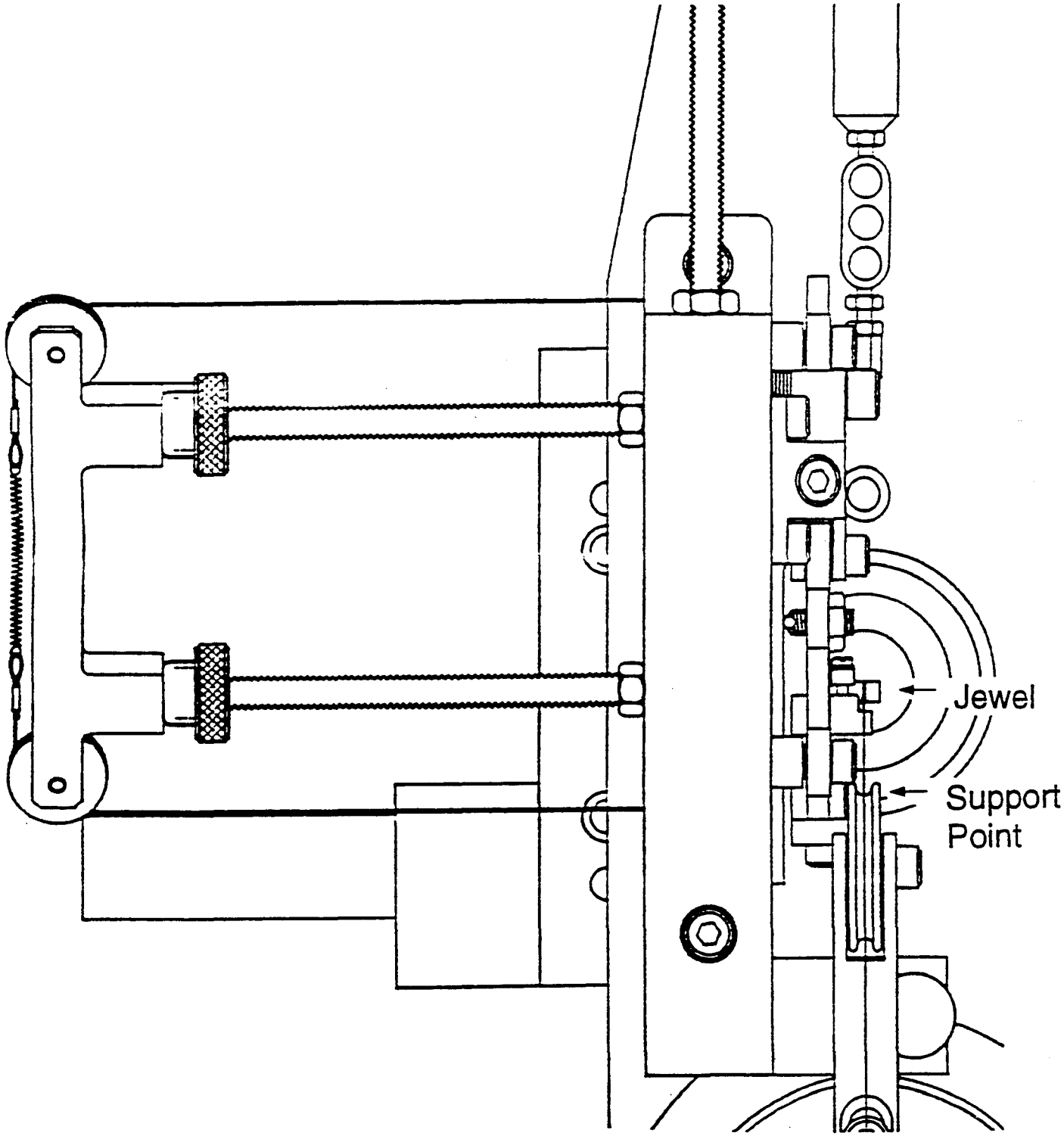


Figure 11

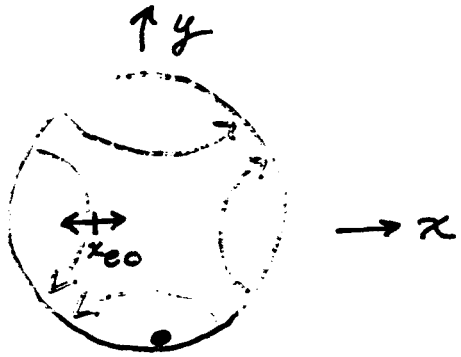
Complimentary System
Finds Fiducials

Take advantage of
Applied Geodesy Group's
work.
(They Place magnets in the
tunnel.)

Plan to use laser
tracker.

x - position of center

no roll center at $x=0$



$$V = -\frac{d\Phi}{dt}$$

$$-\Phi = \Phi_o + \int_{x_{eo}}^{x_{eo}+A\sin\omega t} B_y L_m \, dx$$

$$= \Phi_o + \int_{x_{eo}}^{x_{eo}+A\sin\omega t} G x \, L_m \, dx$$

$$= \Phi_o + \frac{1}{2} G L_m \left[(x_{eo} + A\sin\omega t)^2 - x_{eo}^2 \right]$$

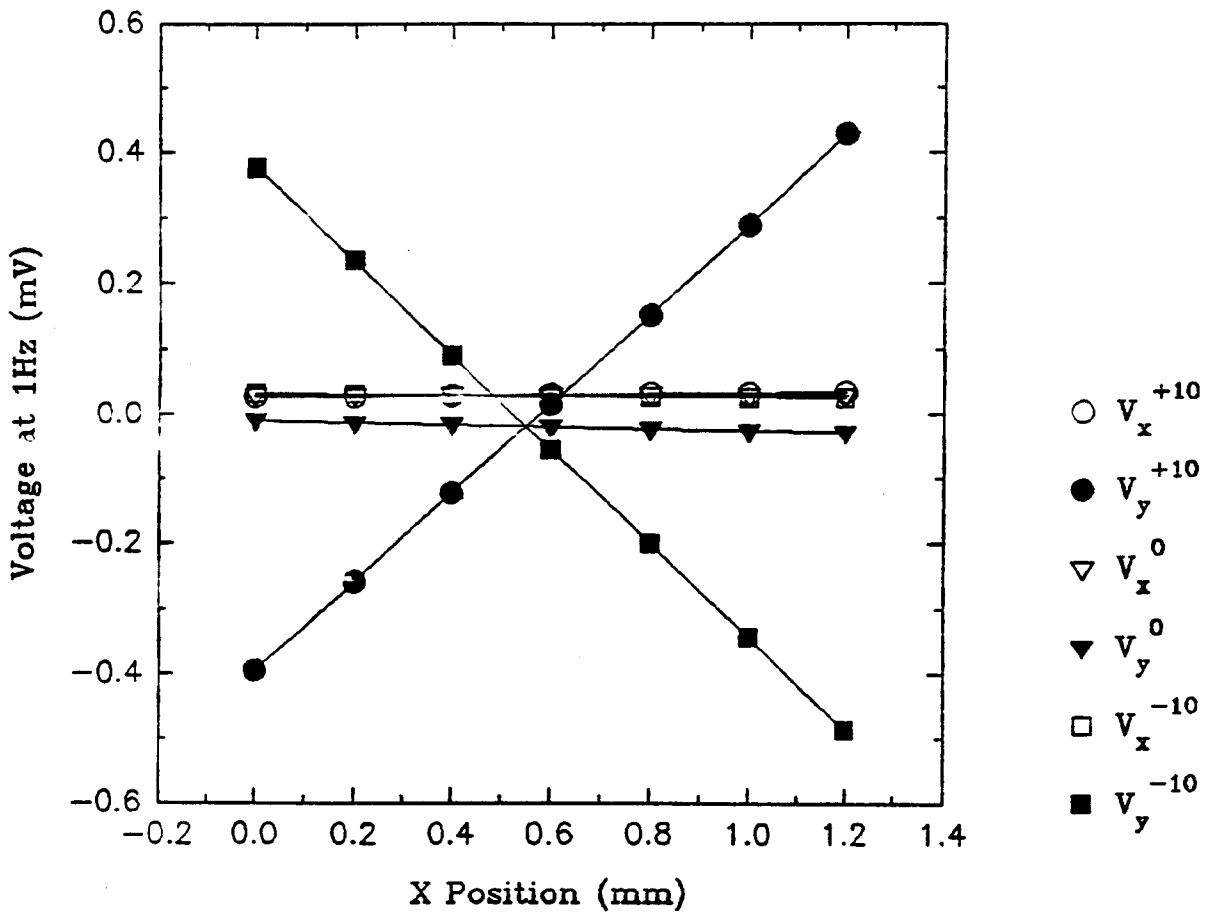
$$= \Phi_c' + \frac{1}{2} G L_m \left[-\frac{1}{2} A^2 \cos 2\omega t + 2 x_{eo} A \sin \right.$$

$$+V = +\frac{1}{2} G L_m \omega A^2 \sin 2\omega t + G L_m \omega A x_{eo} \cos \omega t$$

$$\boxed{V_\omega^{rms} = \frac{1}{\sqrt{2}} G L_m \omega A x_{eo}}$$

MTL-92-002

Stretched Wire Measurement #1 for X Field Center



$$\frac{dV_\omega^{rms}}{dx} \simeq 7 \ \mu V/mm$$

$G = .33$ T/m

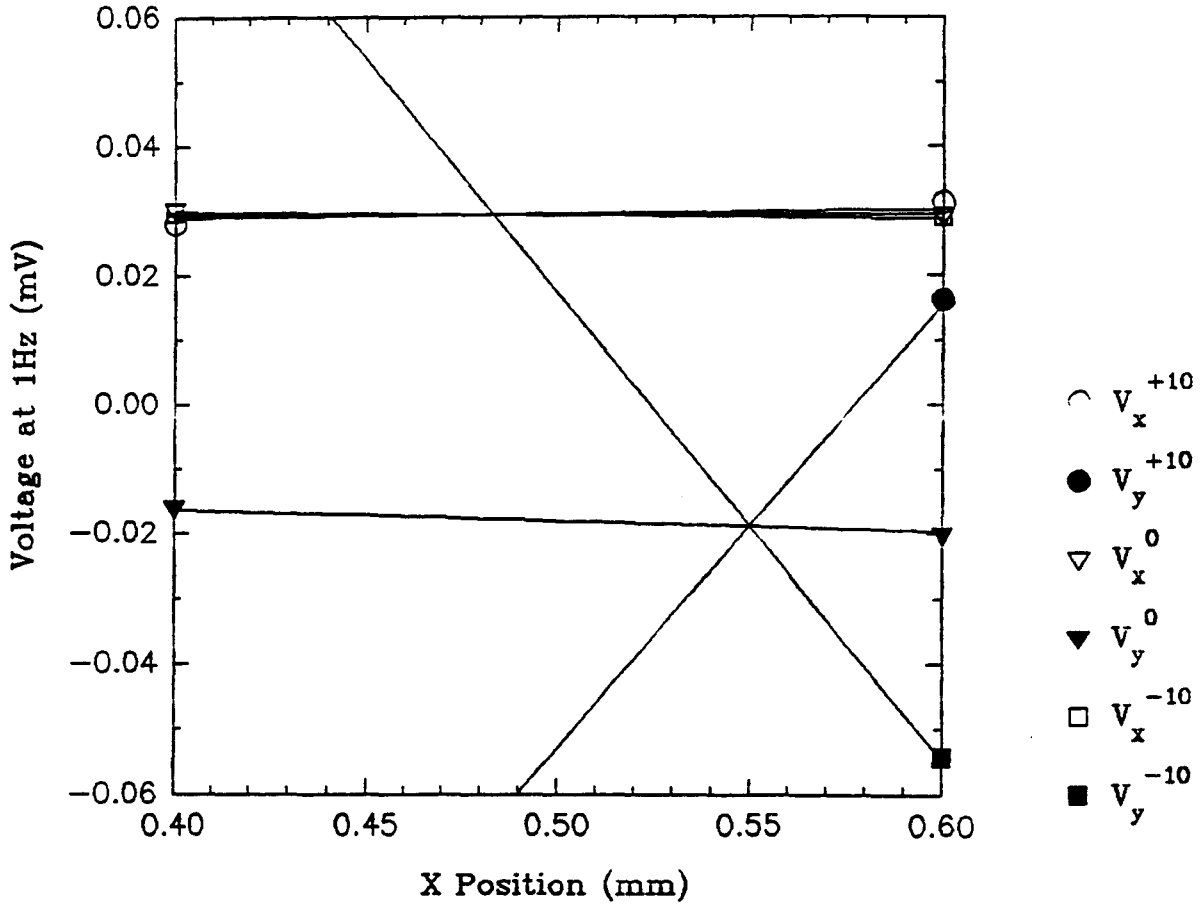
$L_m = 5.1$ m

$f = 1$ Hz

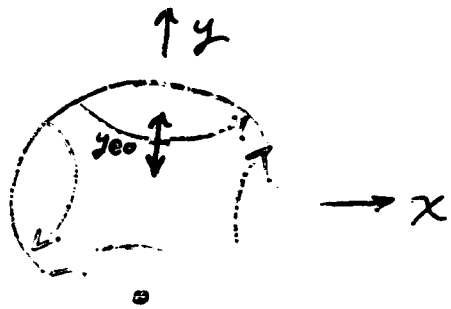
$A = 2$ mm

preamp $G = 100$

Stretched Wire Measurement #1 for X Field Center



y - position of center



Similar to x

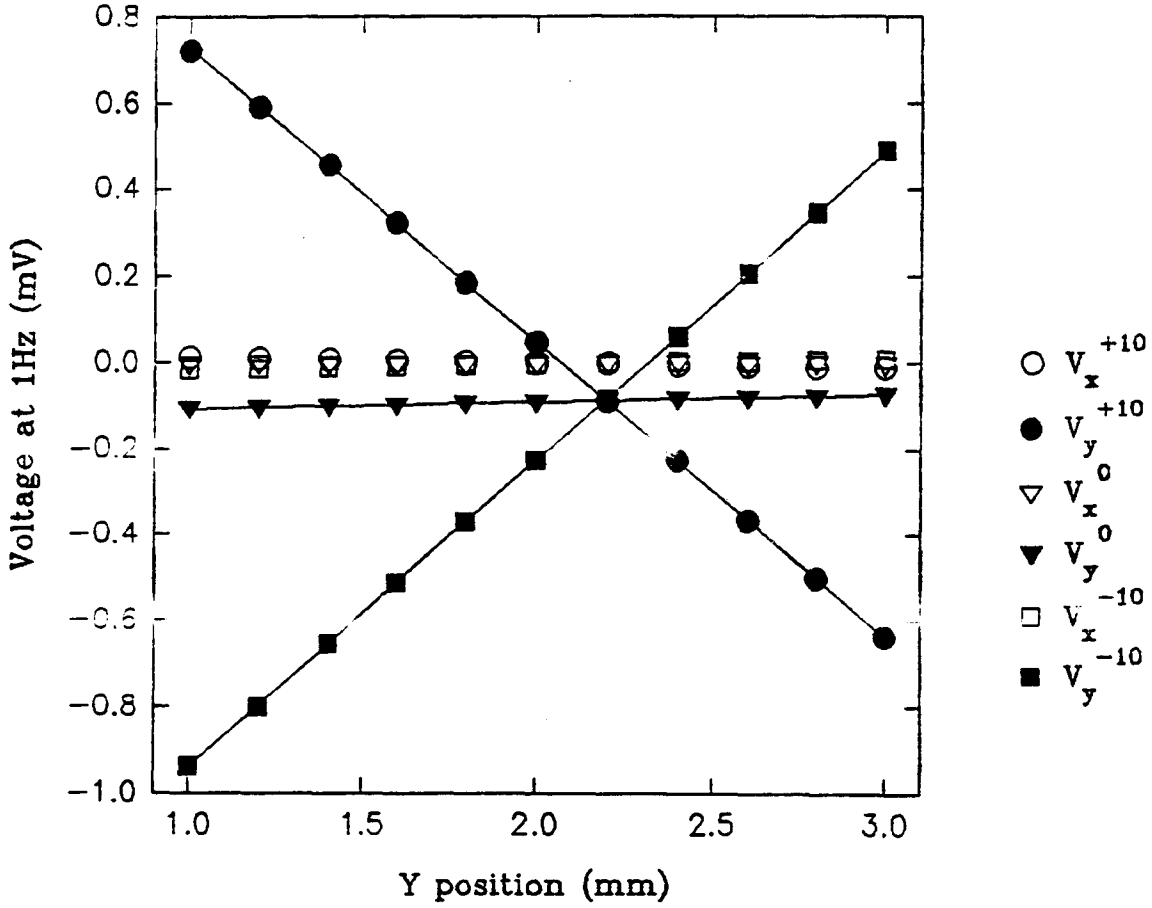
$$\tilde{V}_w^{rms} = -\frac{1}{\sqrt{2}} G L_m \omega A y_{eo}$$

<u>except</u>, the wire is below yeo due to sag

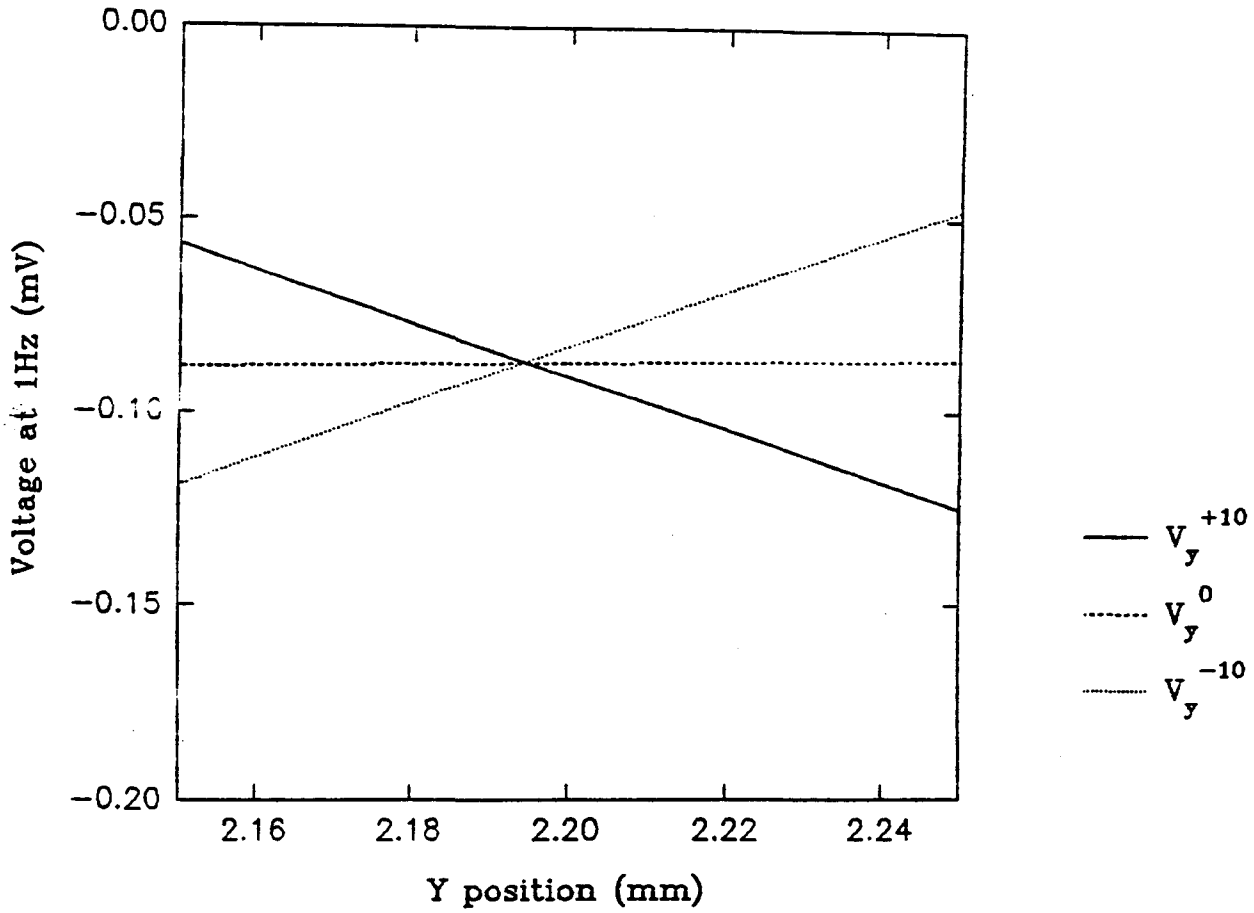
$$\boxed{V_w^{rms} = -\frac{1}{\sqrt{2}} G L_m \omega A \left(y_{eo} - \frac{2}{3} \underbrace{\delta}_{\text{sag}}\right)}$$

Correct using DESY technique of varying tension and extrapolating to infinite tension.

Stretched Wire Measurement (#1) for Y Field Center



Stretched Wire Measurement (#1) for Y Field Center



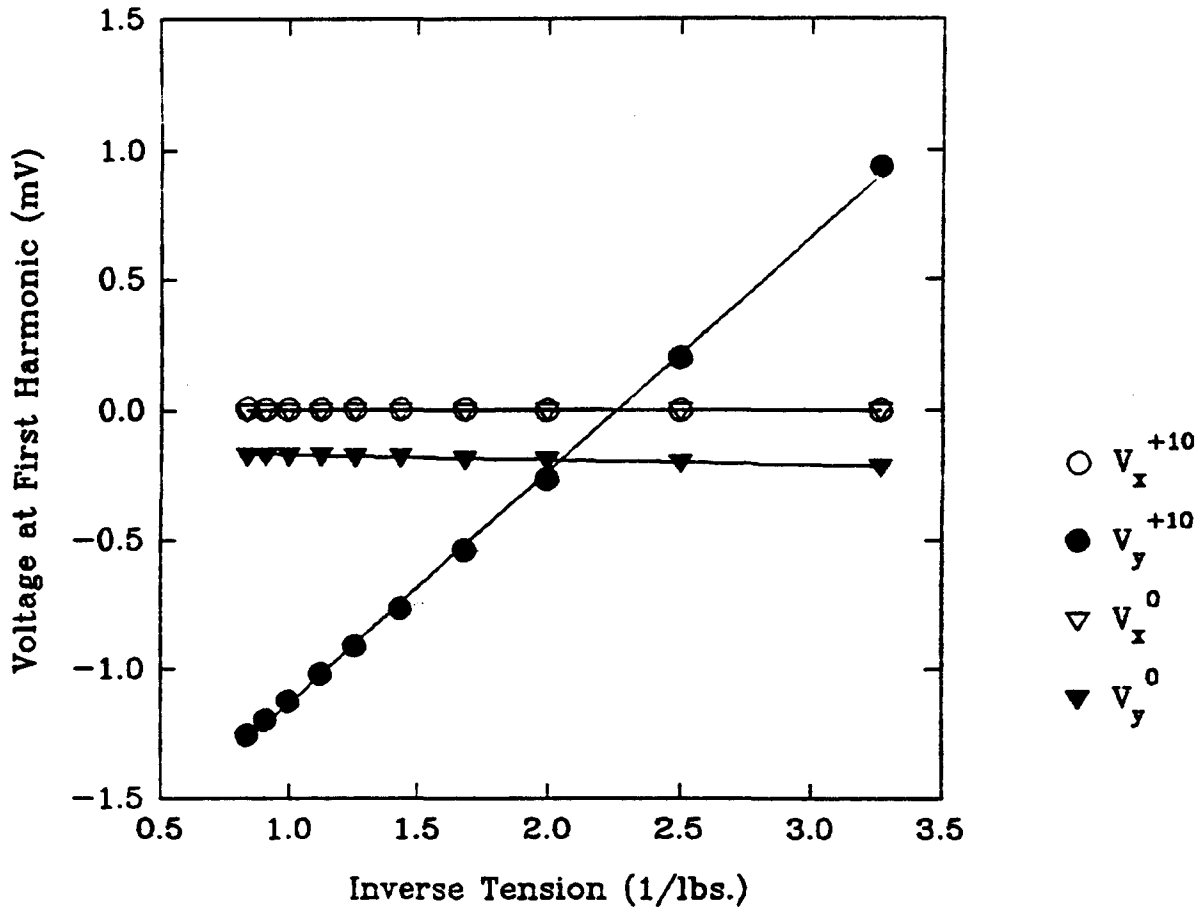
Parameter Studies

Over the summer we measured $V_{\substack{\omega \\ 2\omega}}^{rms}$ as a function of all the relevant parameters:

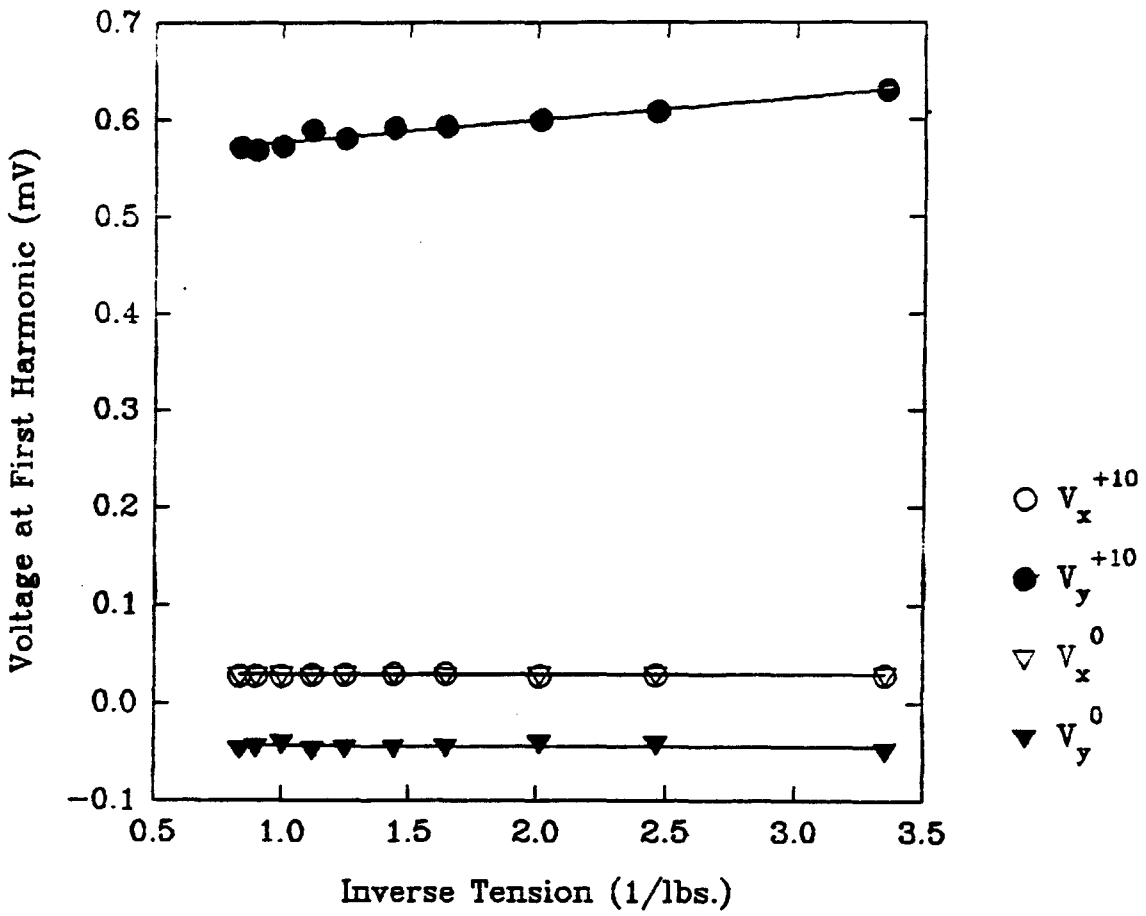
$$I, f, A, T, x, y, \theta$$

Results agree with calculations at the few percent level.

Tension Dependency of Wire voltage in Y Field Component



Tension Dependency of Wire Voltage in X Field Component

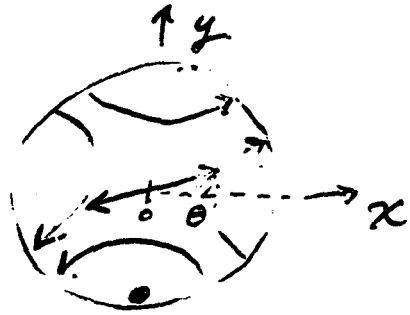


Roll Angle

$$B_x = G y \quad , \quad B_y = G x$$

polar coordinates

$$B_r = G r \sin 2\theta \quad , \quad B_\theta = G r \cos 2\theta$$



$$-\Phi = \Phi_0 + \int_0^{A \sin \omega t} B_\theta \, L_m \, dr$$

$$= \Phi_0 + G L_m \cos 2\theta \int_0^{A \sin \omega t} r \, dr$$

$$= \Phi_0 + \frac{1}{2} G L_m \cos 2\theta \, A^2 \sin^2 \omega t$$

$$= \Phi_0 - \frac{1}{4} G L_m A^2 \cos 2\theta \, \cos 2\omega t$$

$$V = \frac{d(-\Phi)}{dt} = \frac{1}{2} G L_m \omega A^2 \cos 2\theta \, \sin 2\omega t$$

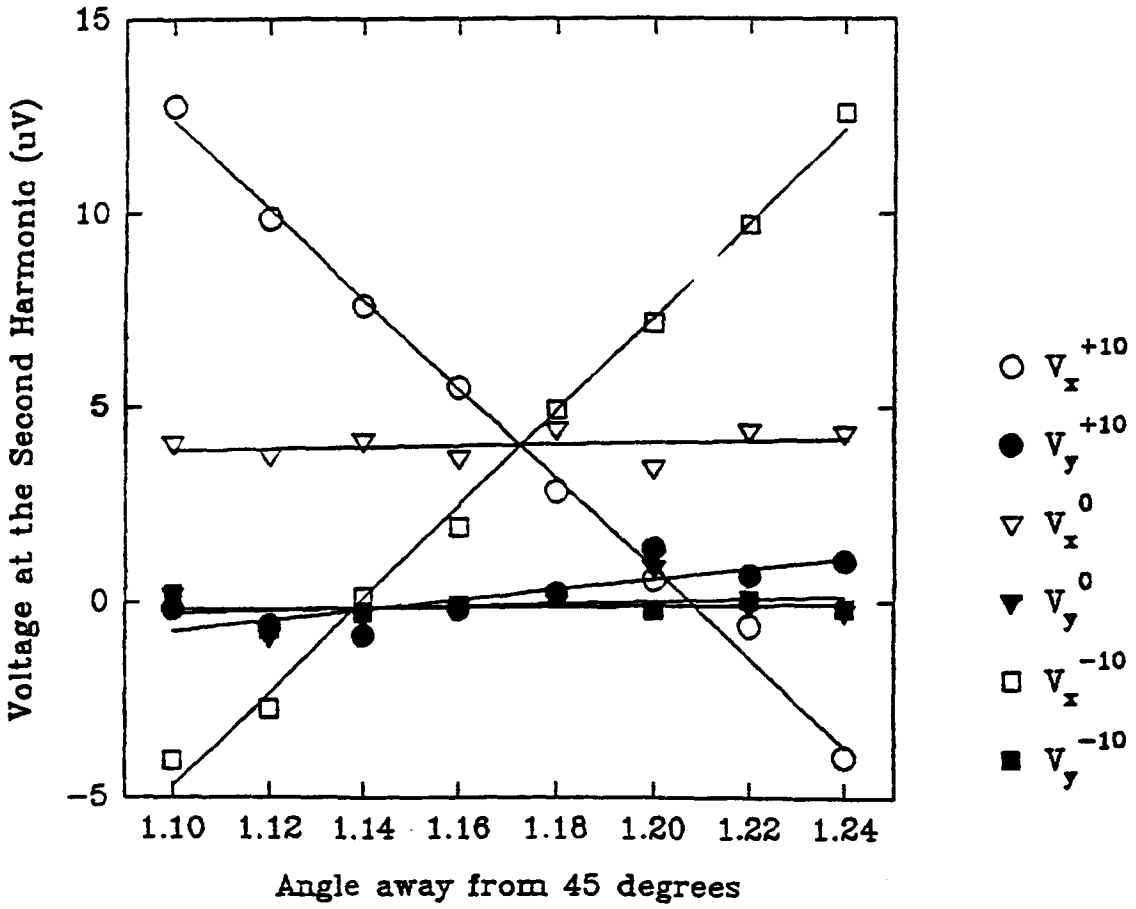
$$\boxed{V_{2\omega}^{rms} = \frac{1}{2\sqrt{2}} G L_m \omega A^2 \cos 2\theta}$$

$$\theta = 45^\circ + \psi$$

$$\cos 2\theta \simeq -2\psi$$

$$\boxed{V_{2\omega}^{rms} = -\frac{1}{\sqrt{2}} G L_m \omega A^2 \psi}$$

Roll Angle Measurement at +45 degrees



$$\frac{dV_{2\omega}^{rms}}{d\psi} \simeq 67 \frac{nV}{mrad}$$

$G = .33\ T/m$

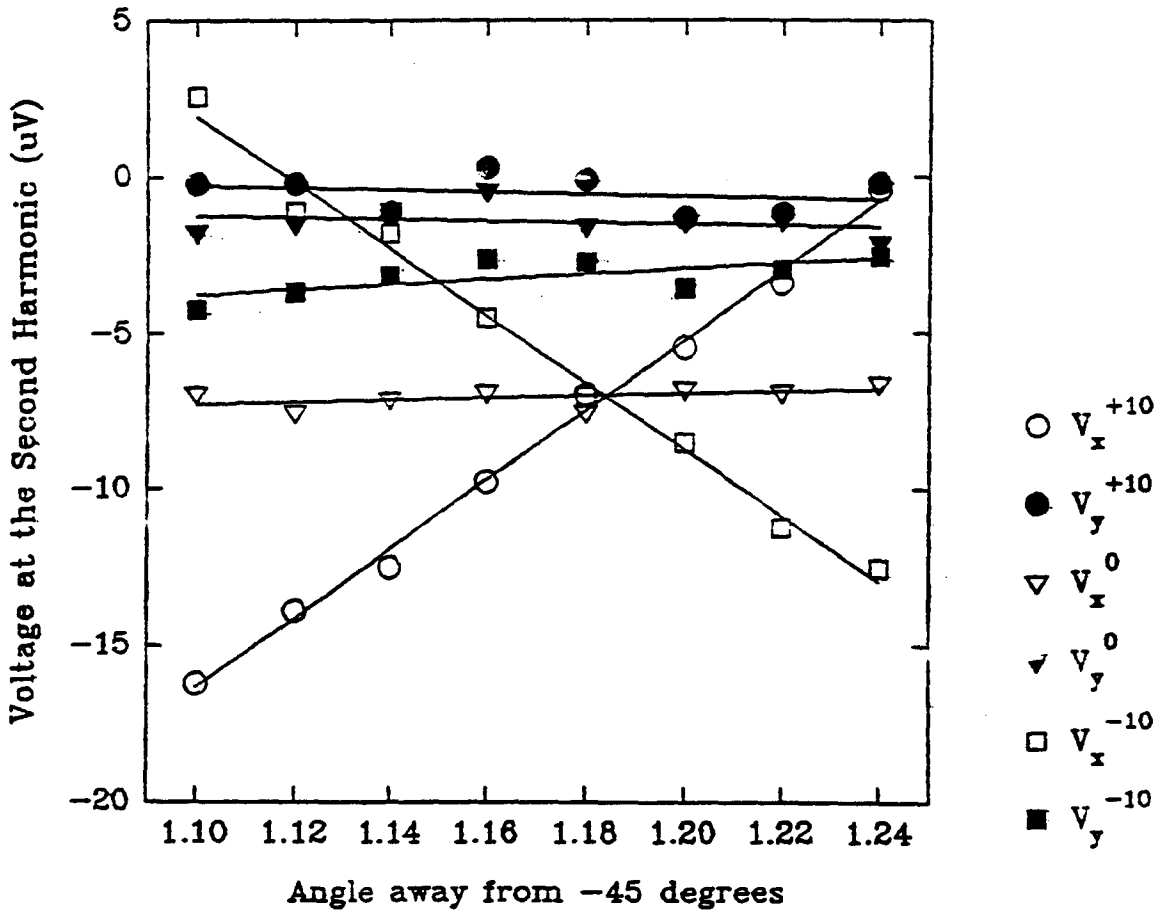
$L_m = 5.1\ m$

$f = 1\ Hz$

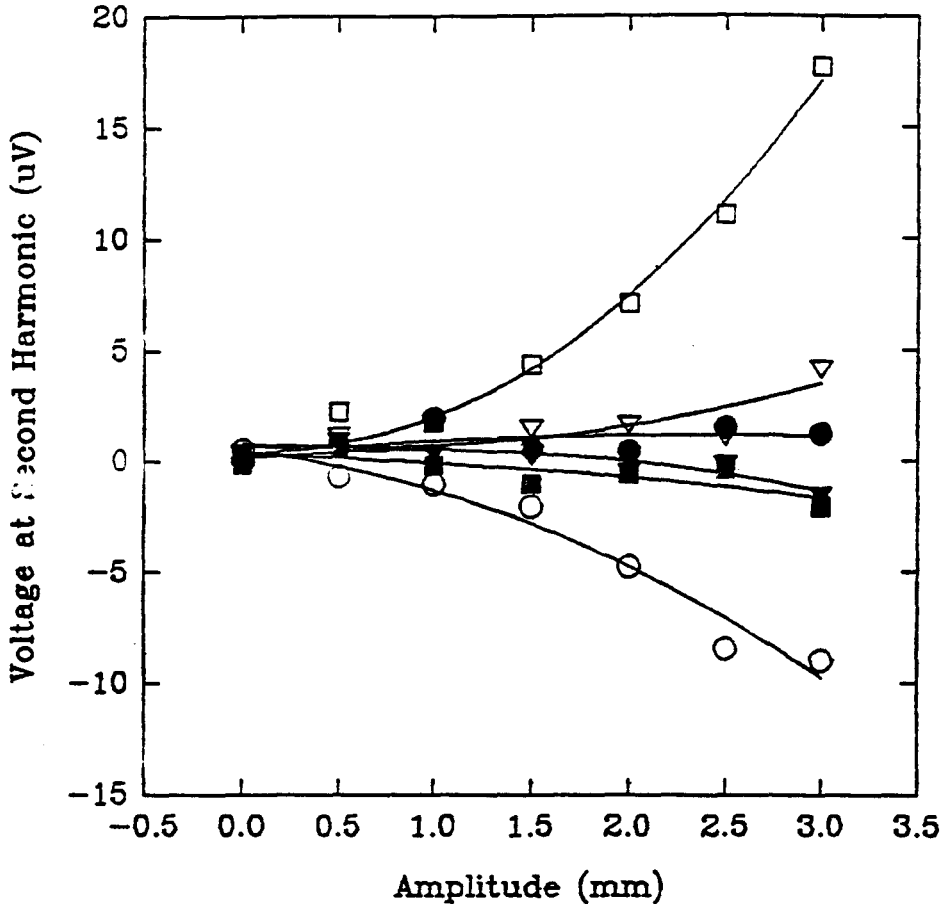
$A = 3\ mm$

assume $G = 100$

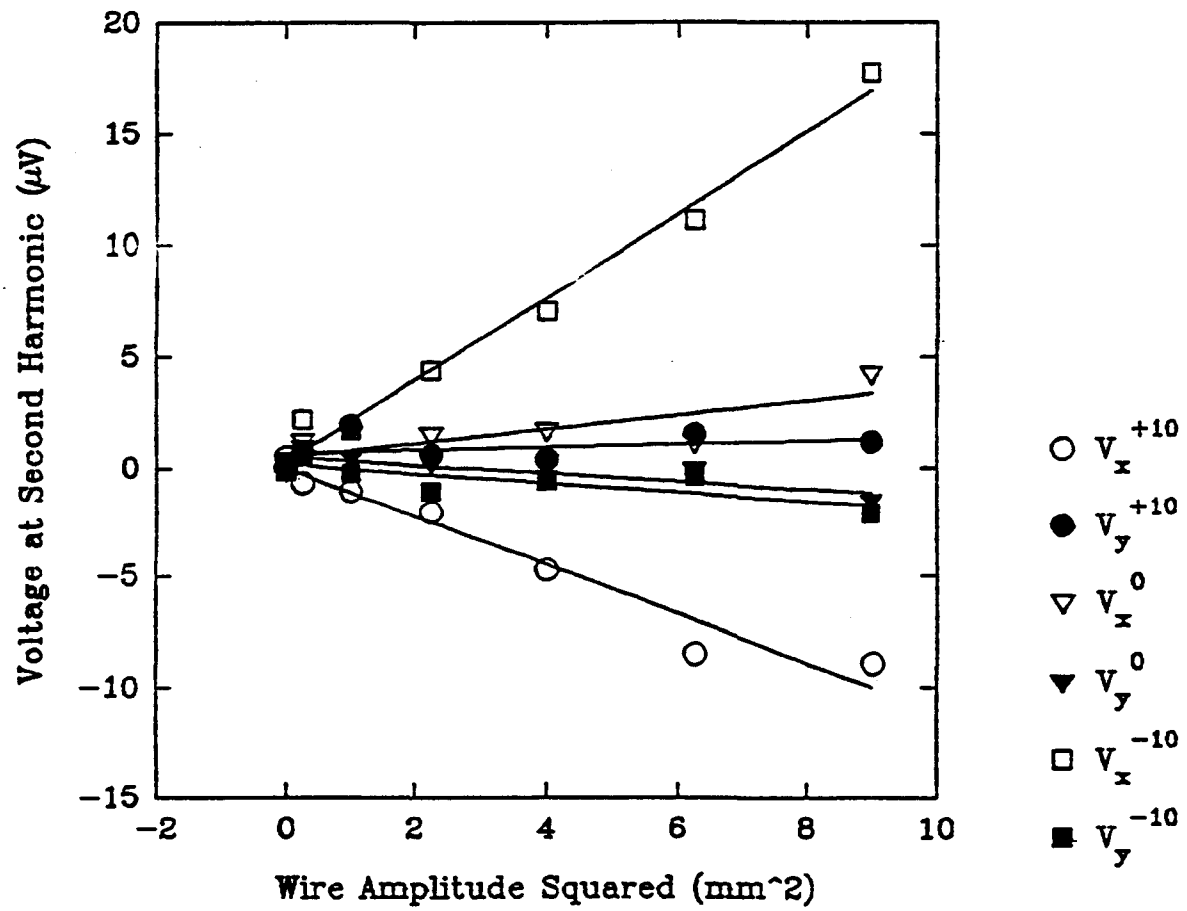
Roll Angle Measurement at −45 degrees

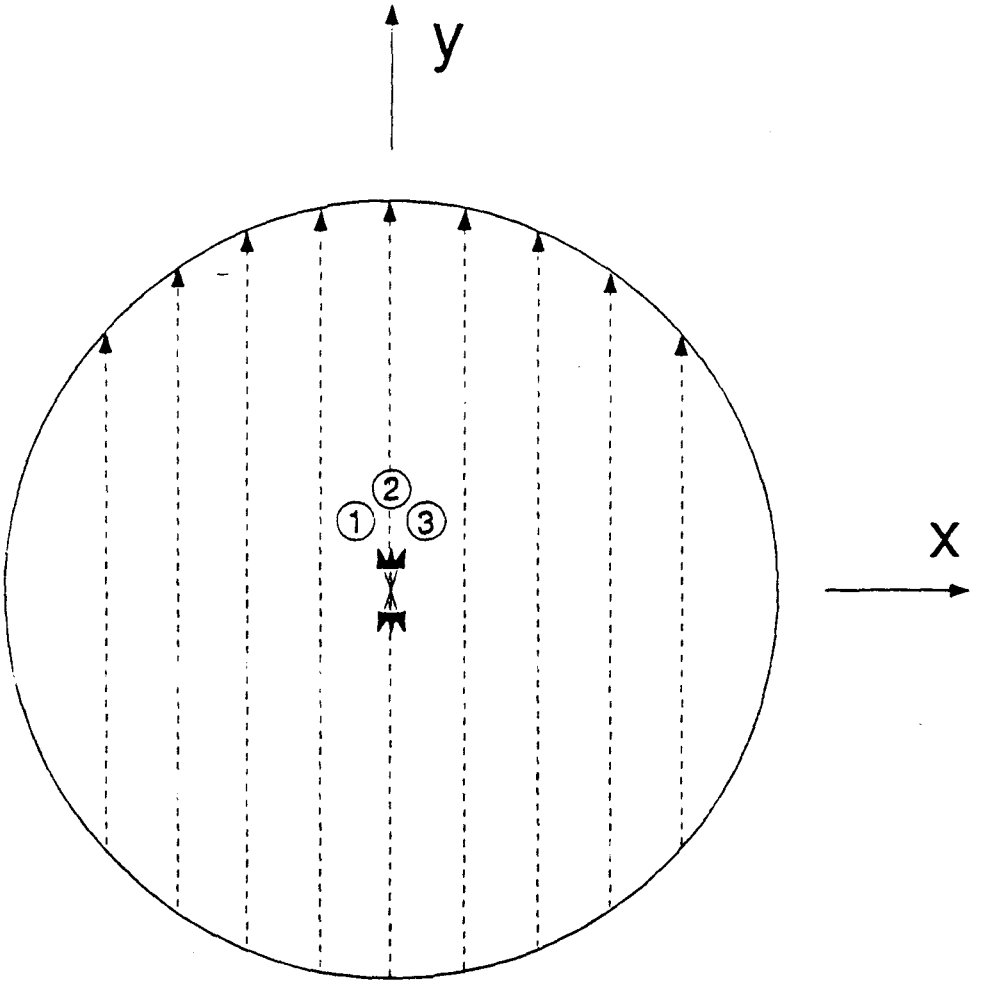


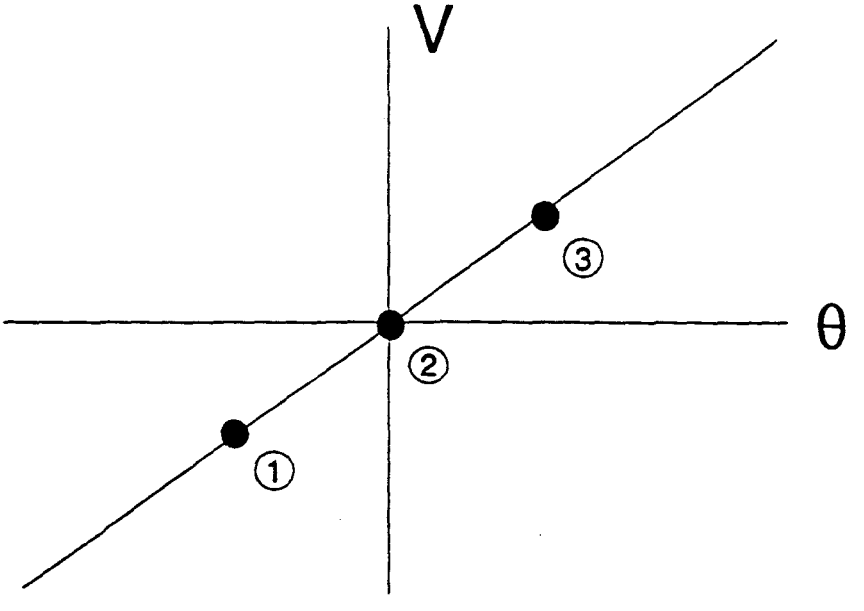
Voltage vs Amplitude



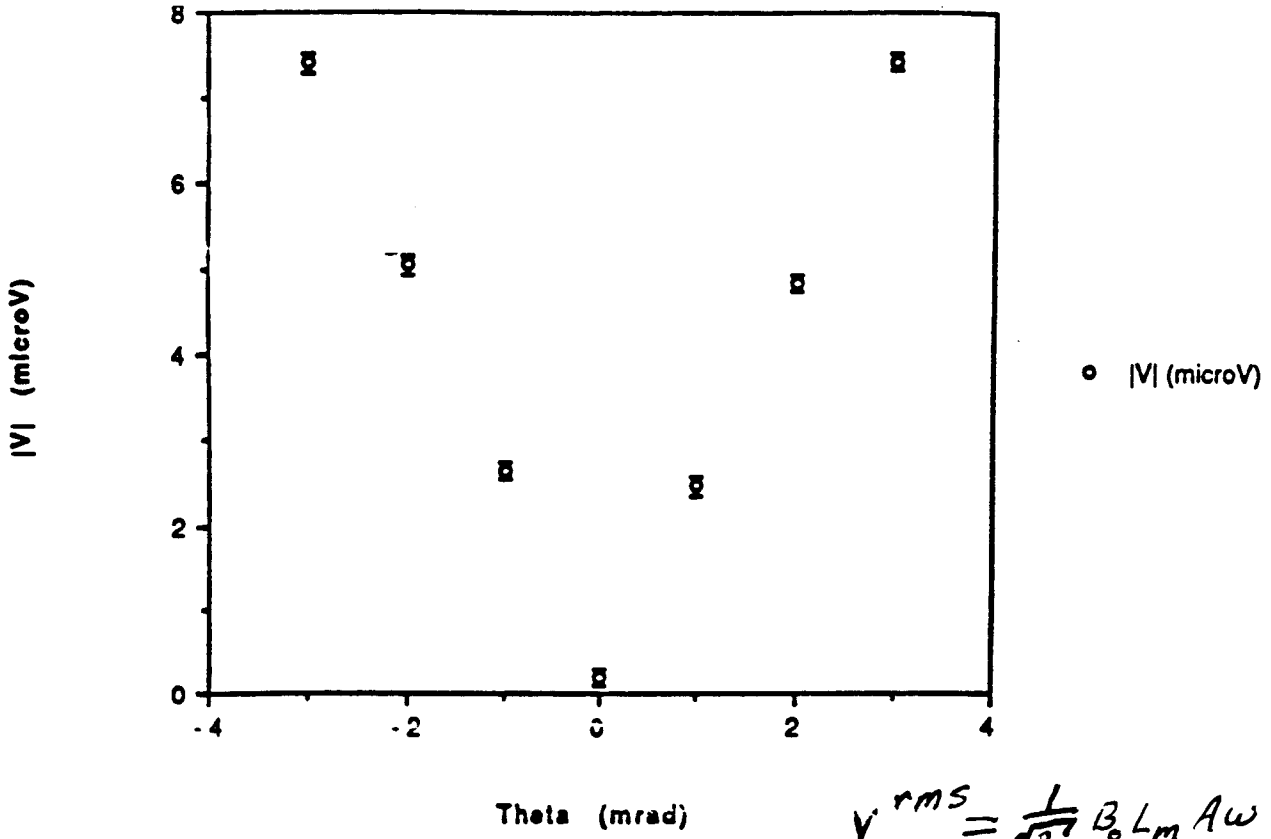
Amplitude Dependence of Second Harmonic Near the Roll Angle




y
x
1
2
3

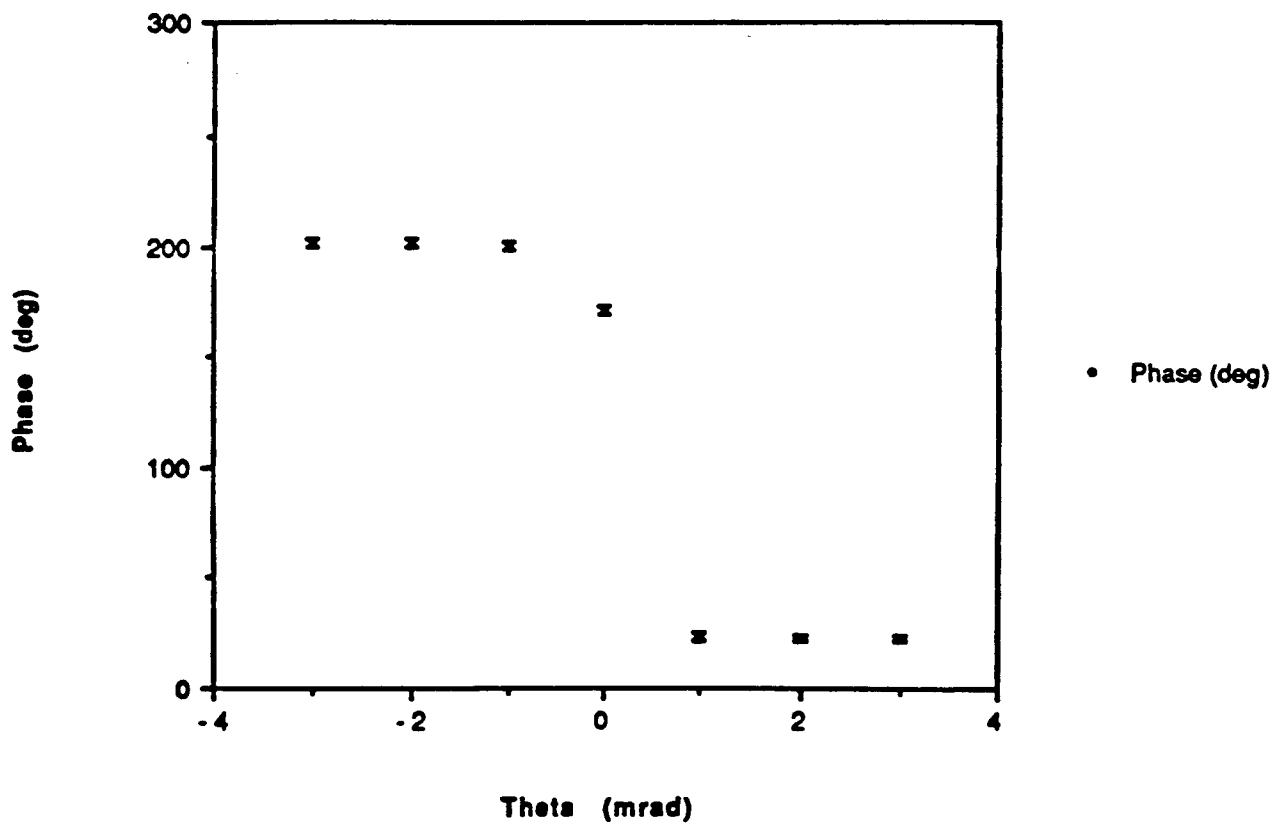

V
θ
1
2
3

|V| vs Magnet Angle for D0001



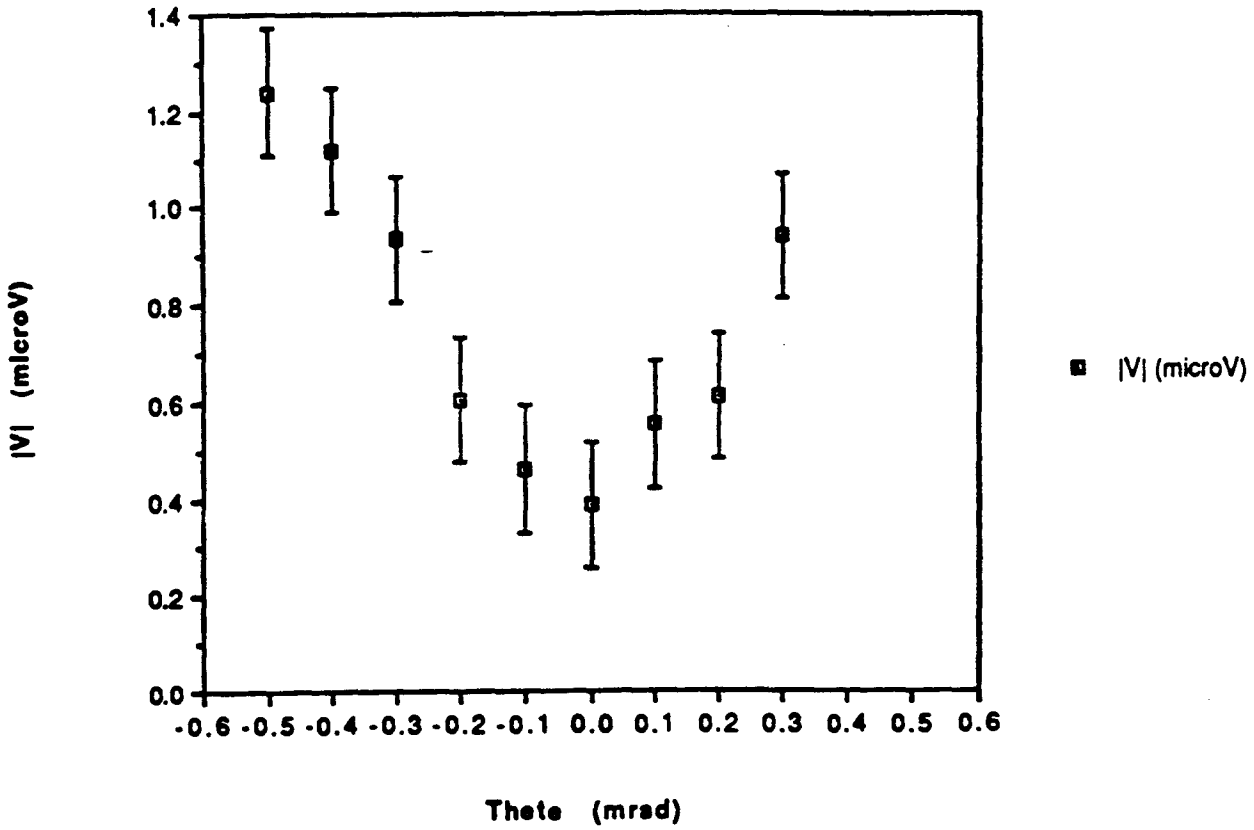
$$V^{rms} = \frac{1}{\sqrt{2}} B_0 L_m A\omega (\theta - \theta_0)$$

Phase of V vs Magnet Angle for D0001

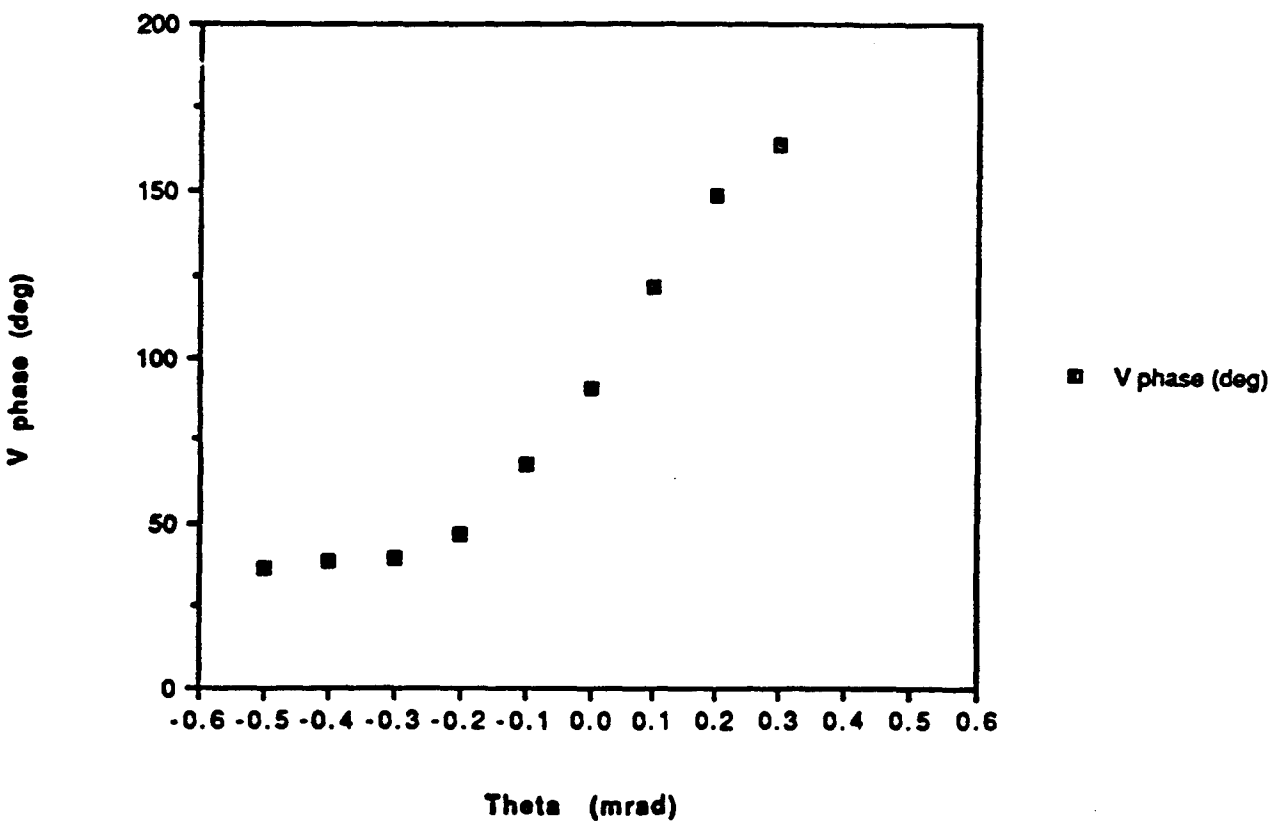


IISSC '92

|V| vs Magnet Angle for D0001



V Phase vs Magnet Angle for D0001



Status

The concept appears to be sound.

A second "home made" prototype system is under construction.

We will buy a third prototype system in an effort to find a vendor for future systems.

system automation

HP sampling integrator

LHC-DIPOLE MEASURING BENCH

(MT-13)

J. BILLAN, J. BUCKLEY, R. SABAN, P. SIEVERS,
L. WALCKIERS

IGNORE: COIL → J.B.
ELECTR. → L.W.
COMP.

MECHANICAL DESIGN
INITIAL EXPERIENCE
PROBLEMS

LHC: ~ 1600 DIPOLES ($L \sim 10 \cdots 15$ m, ~ 9T, $\phi_i = 43. \cdots \leq 49.$ mm)
~ 600 QUAD'S ($L \sim 3.5$ m, 250 T/m, $\phi_i = 43. \cdots 49.$ mm)

!! DOUBLE APERTURE !!

USERFRIENDLY-AUTOMATIC SYSTEM!!

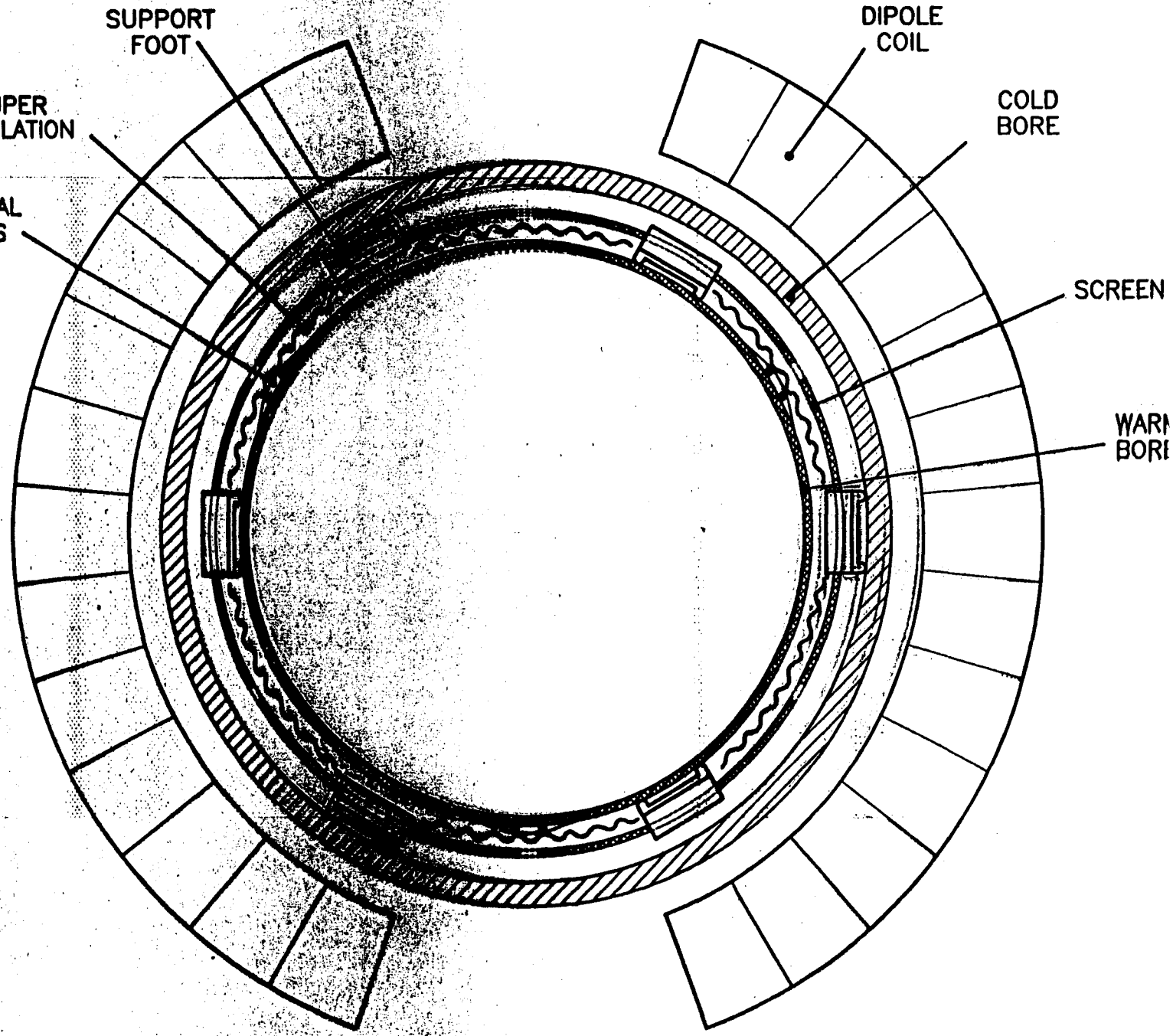
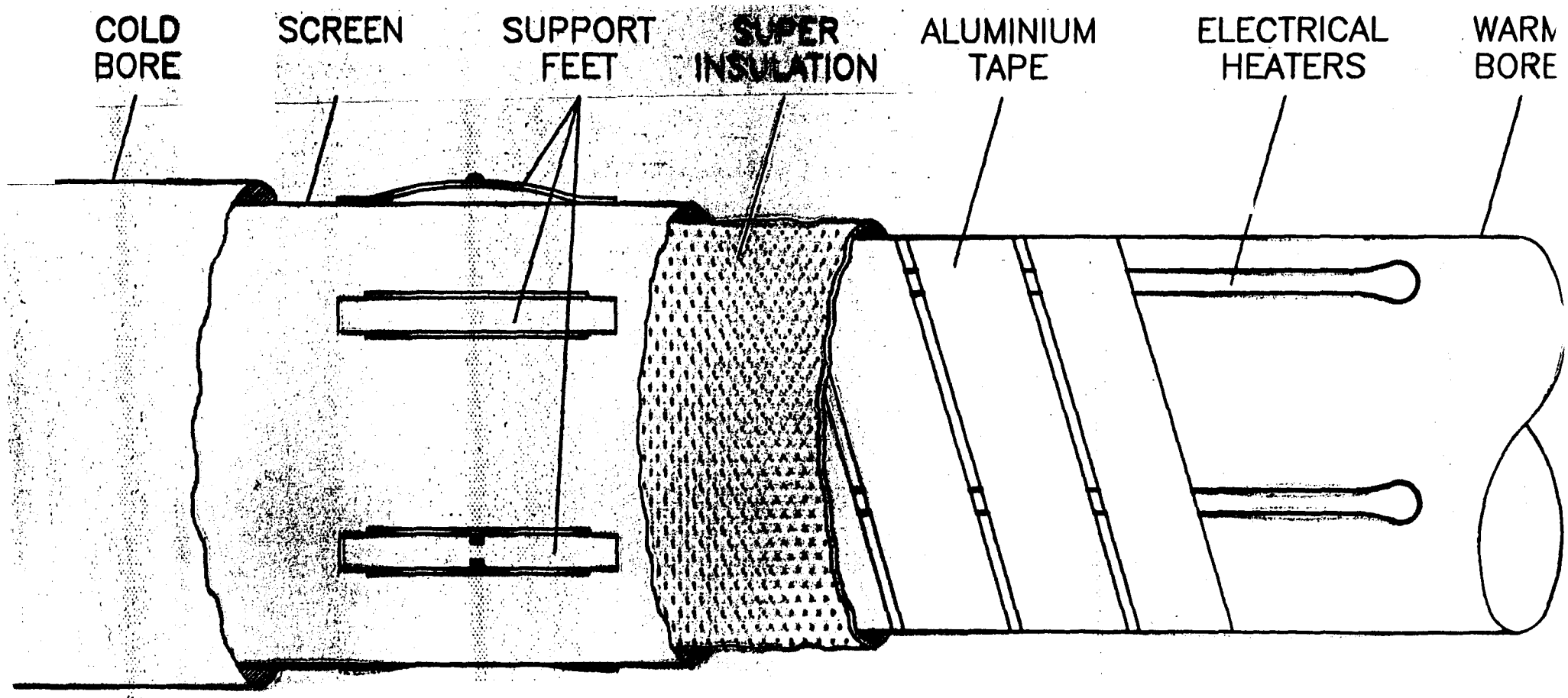
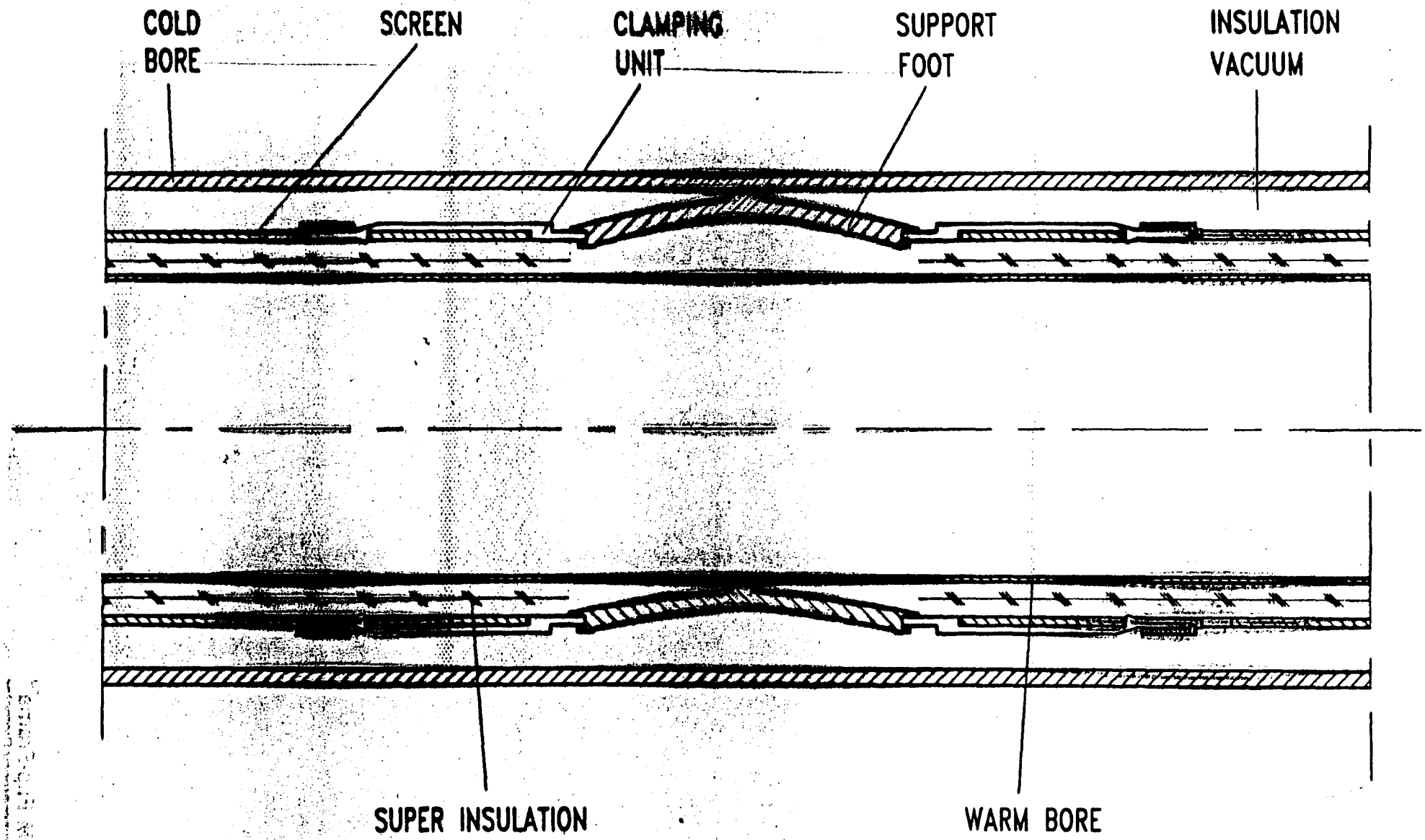
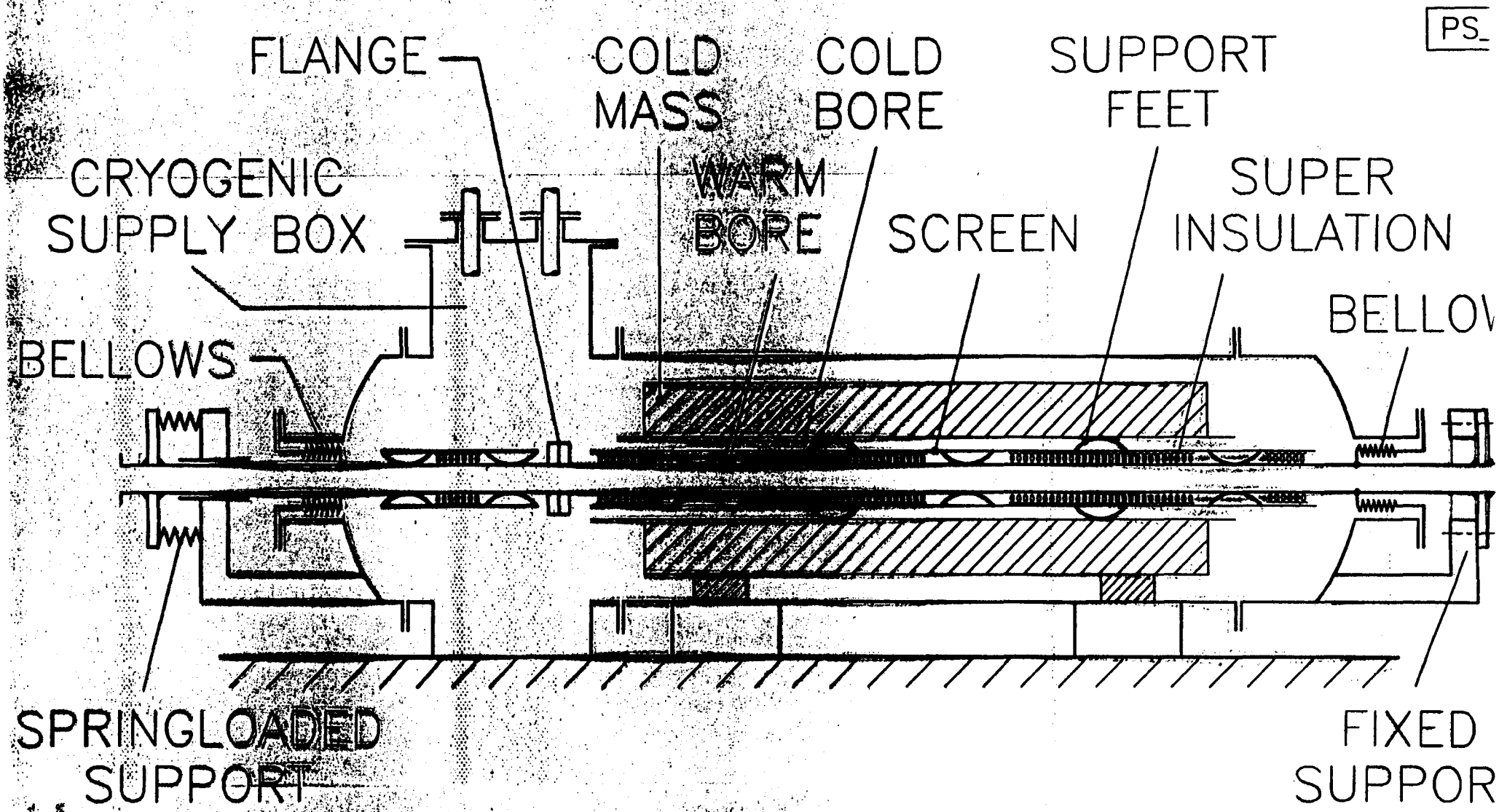

SUPPORT
FOOT
SUPER
INSULATION
ELECTRICAL
HEATERS
DIPOLE
COIL
COLD
BORE
SCREEN
WARM
BORE

Figure 4

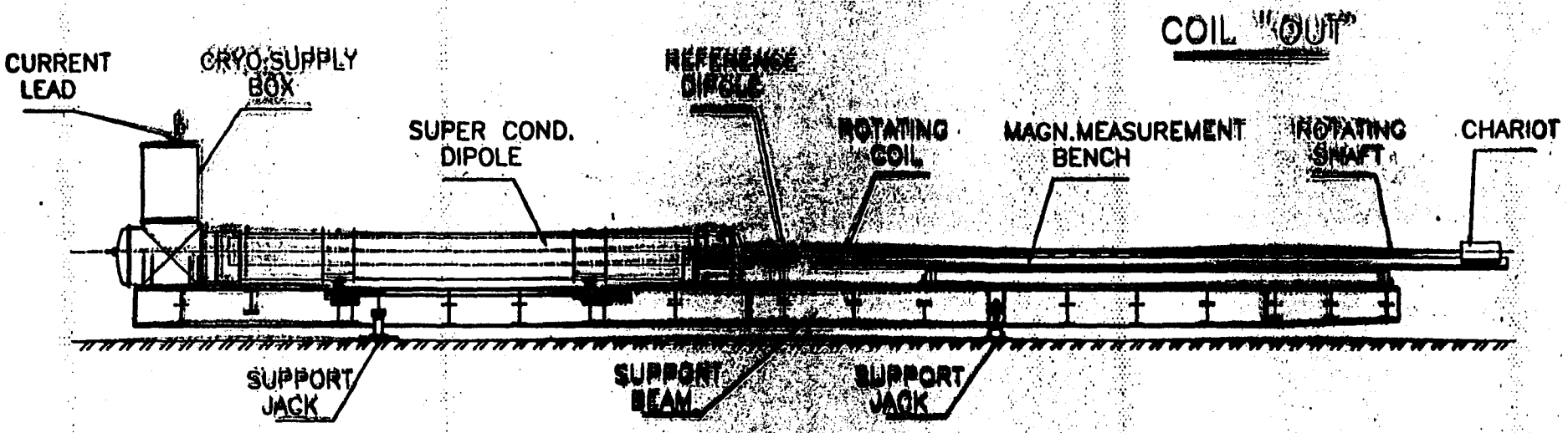

COLD BORE
SCREEN
SUPPORT FEET
SUPER INSULATION
ALUMINIUM TAPE
ELECTRICAL HEATERS
WARM BORE

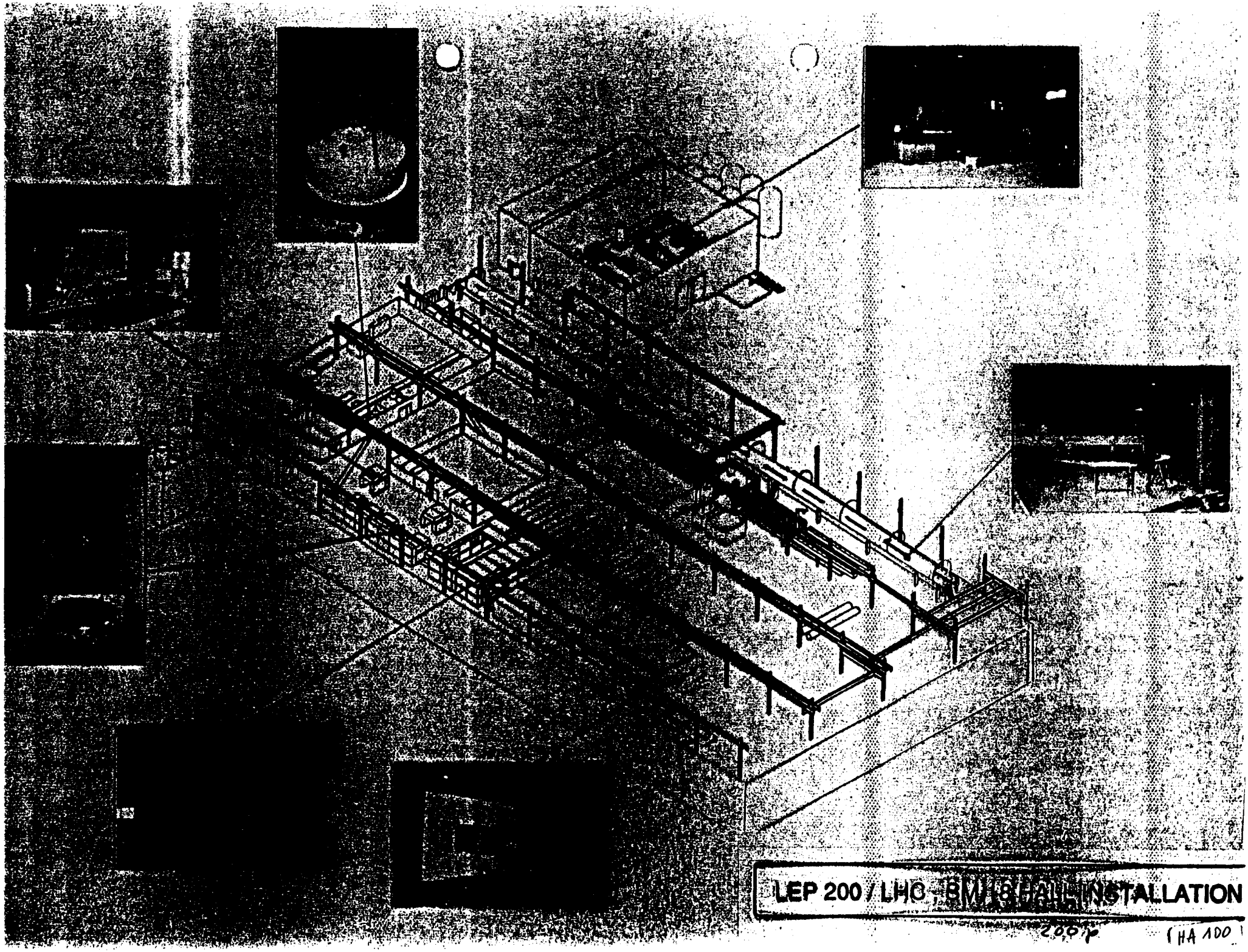

COLD BORE
SCREEN
CLAMPING UNIT
SUPPORT FOOT
INSULATION VACUUM
SUPER INSULATION
WARM BORE

IT48-6-9.


PS_
FLANGE
COLD MASS
COLD BORE
SUPPORT FEET
CRYOGENIC SUPPLY BOX
WARM BORE
SCREEN
SUPER INSULATION
BELLOV
BELLOWS
SPRINGLOADED SUPPORT
FIXED SUPPOR

LHC-DIPOLE TEST STAND

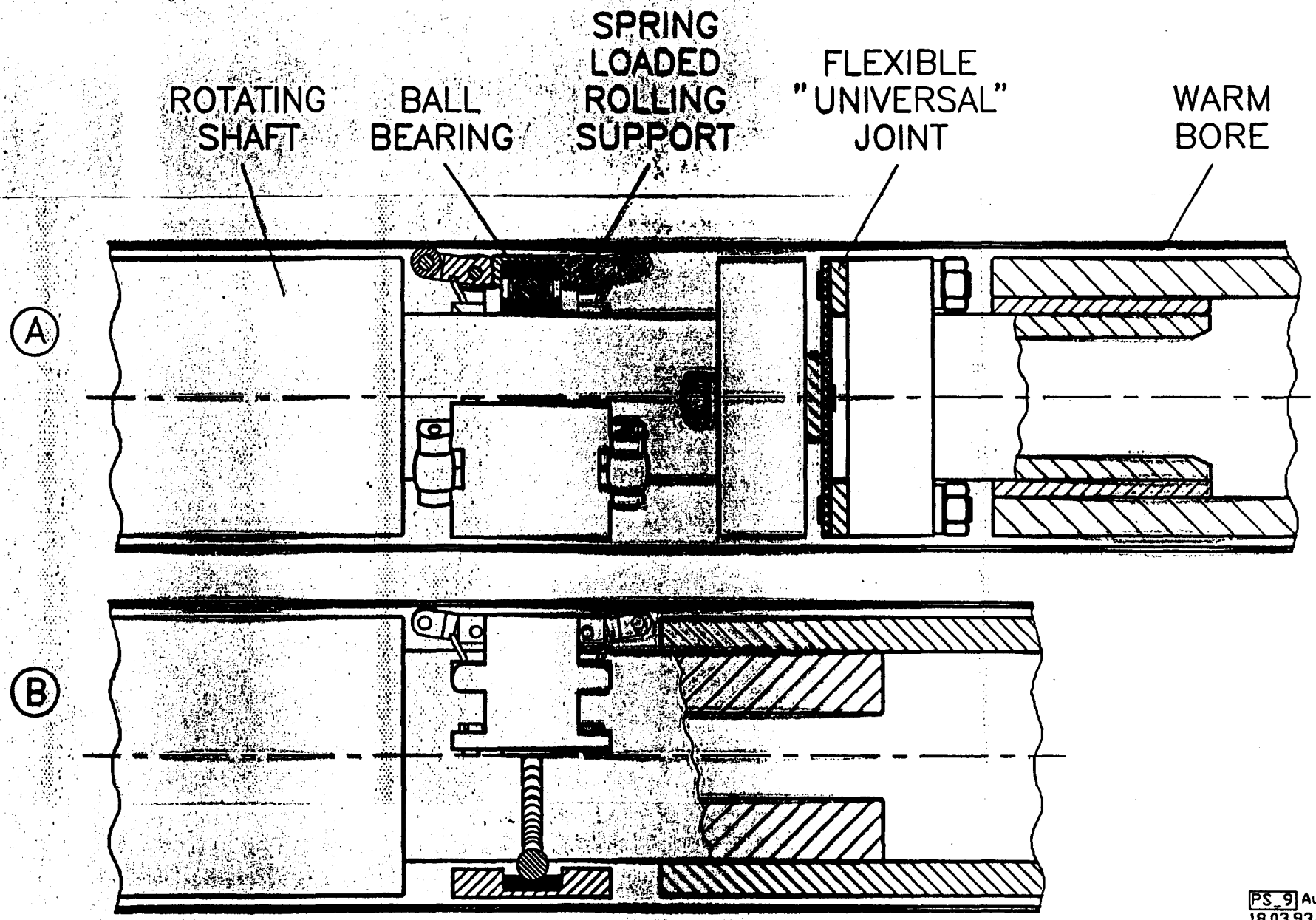




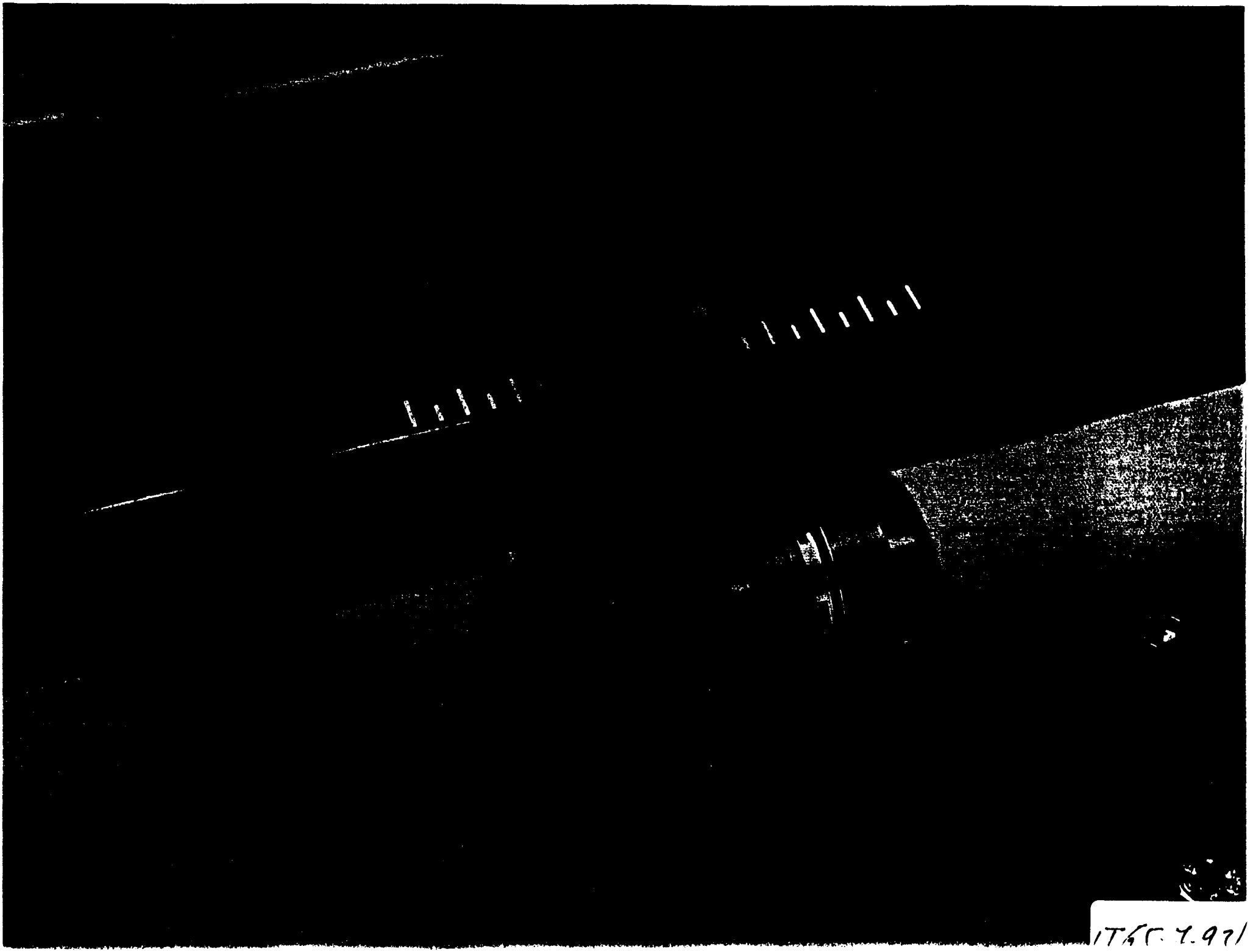
LEP 200 / LHC - SM18 HALL INSTALLATION

2007

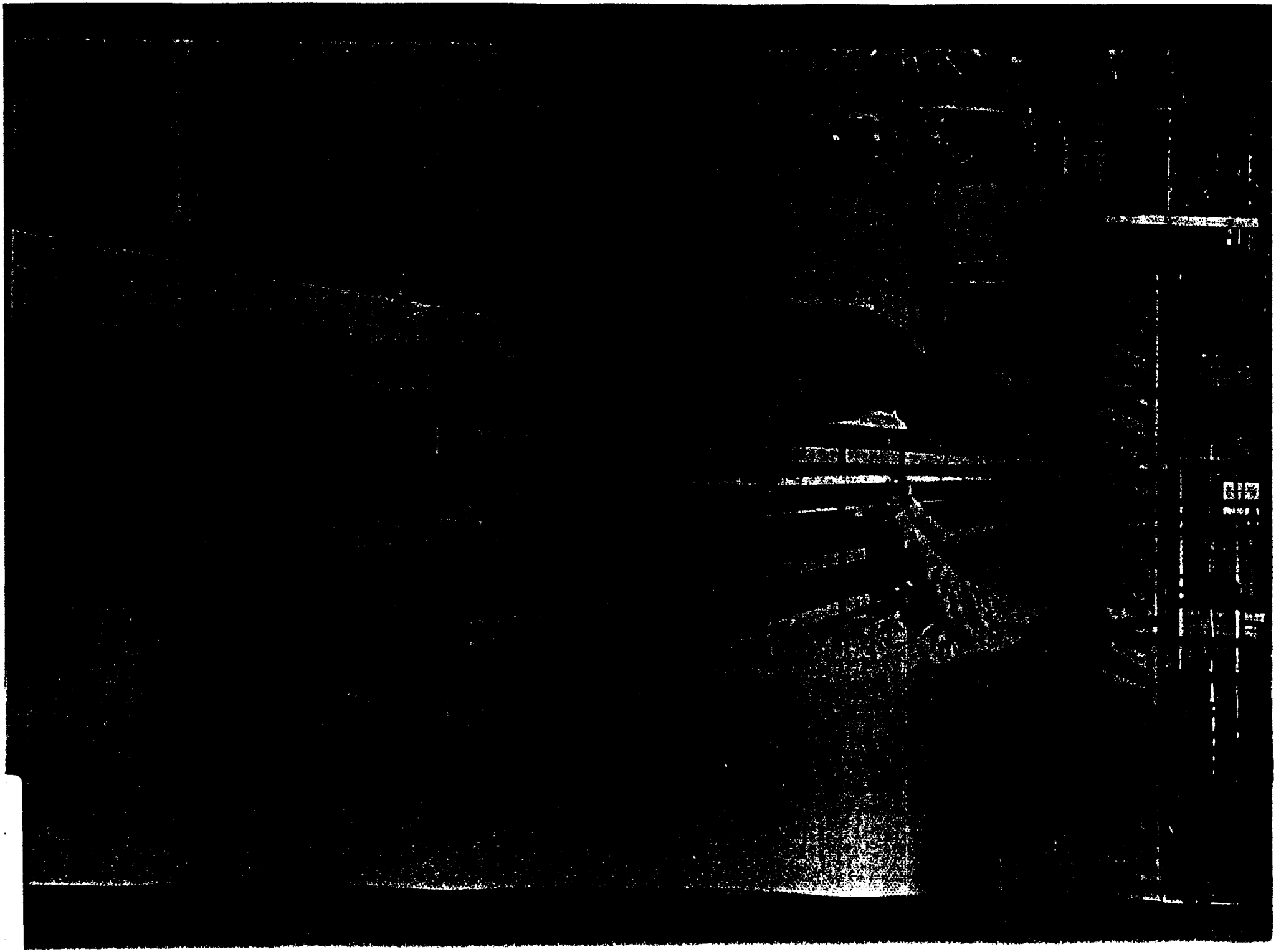
CHA 100



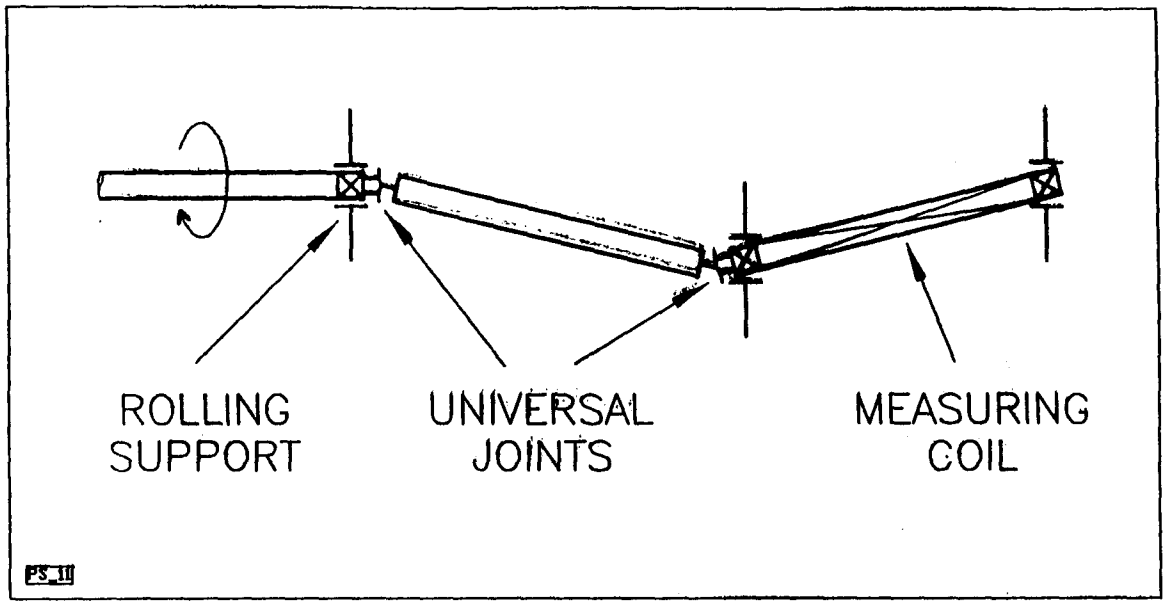
PS_9 AutoCAD
18.03.93/AR

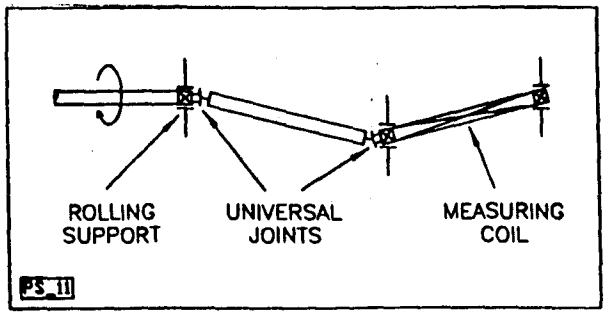


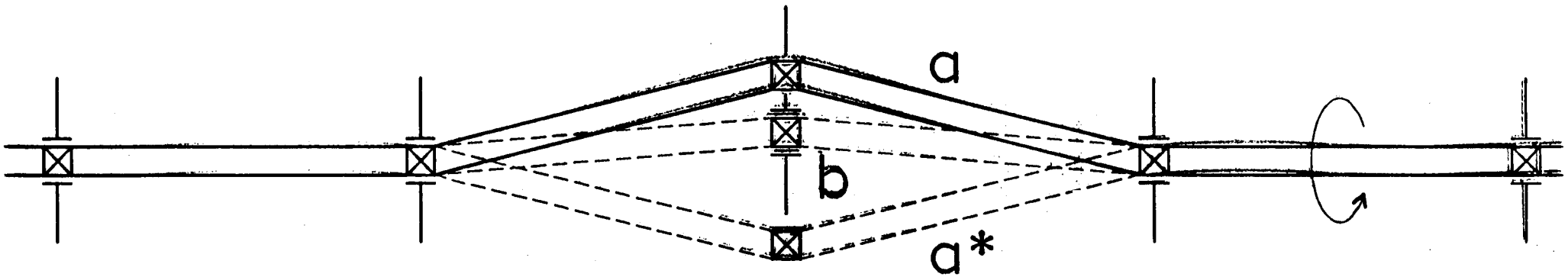
ITAC 7.971



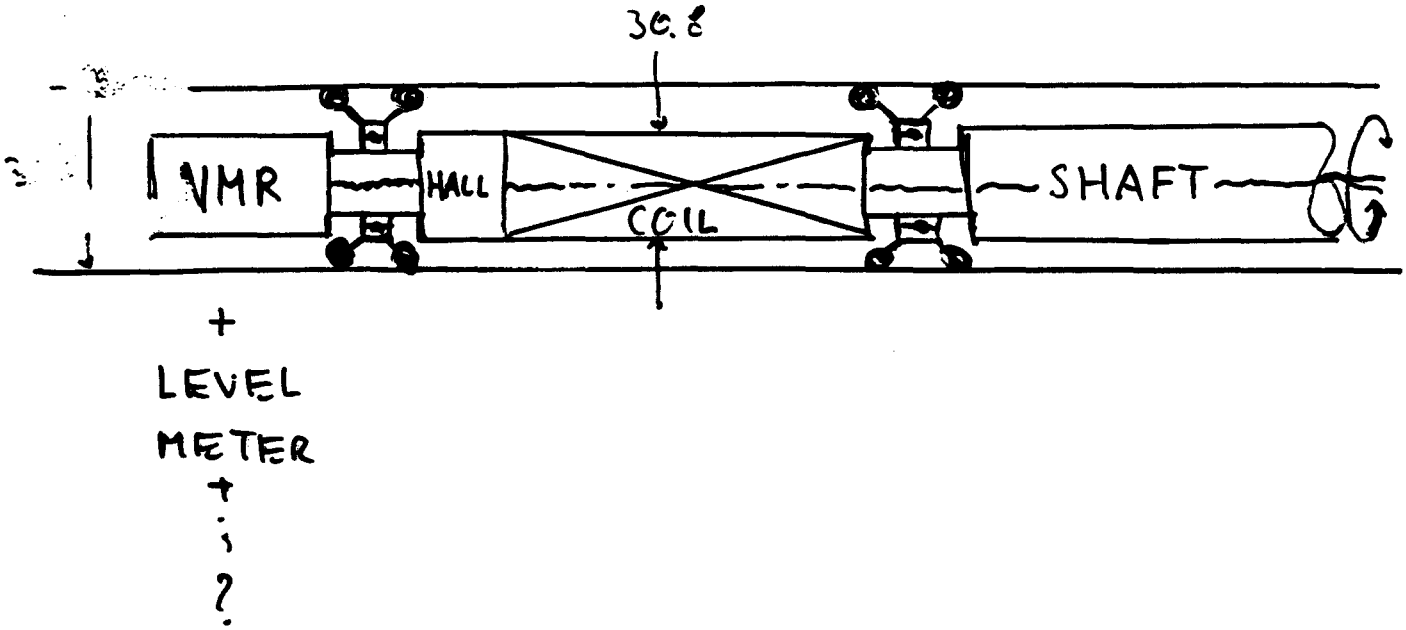
IT 50-6-97


ROLLING
SUPPORT
UNIVERSAL
JOINTS
MEASURING
COIL
PS_11

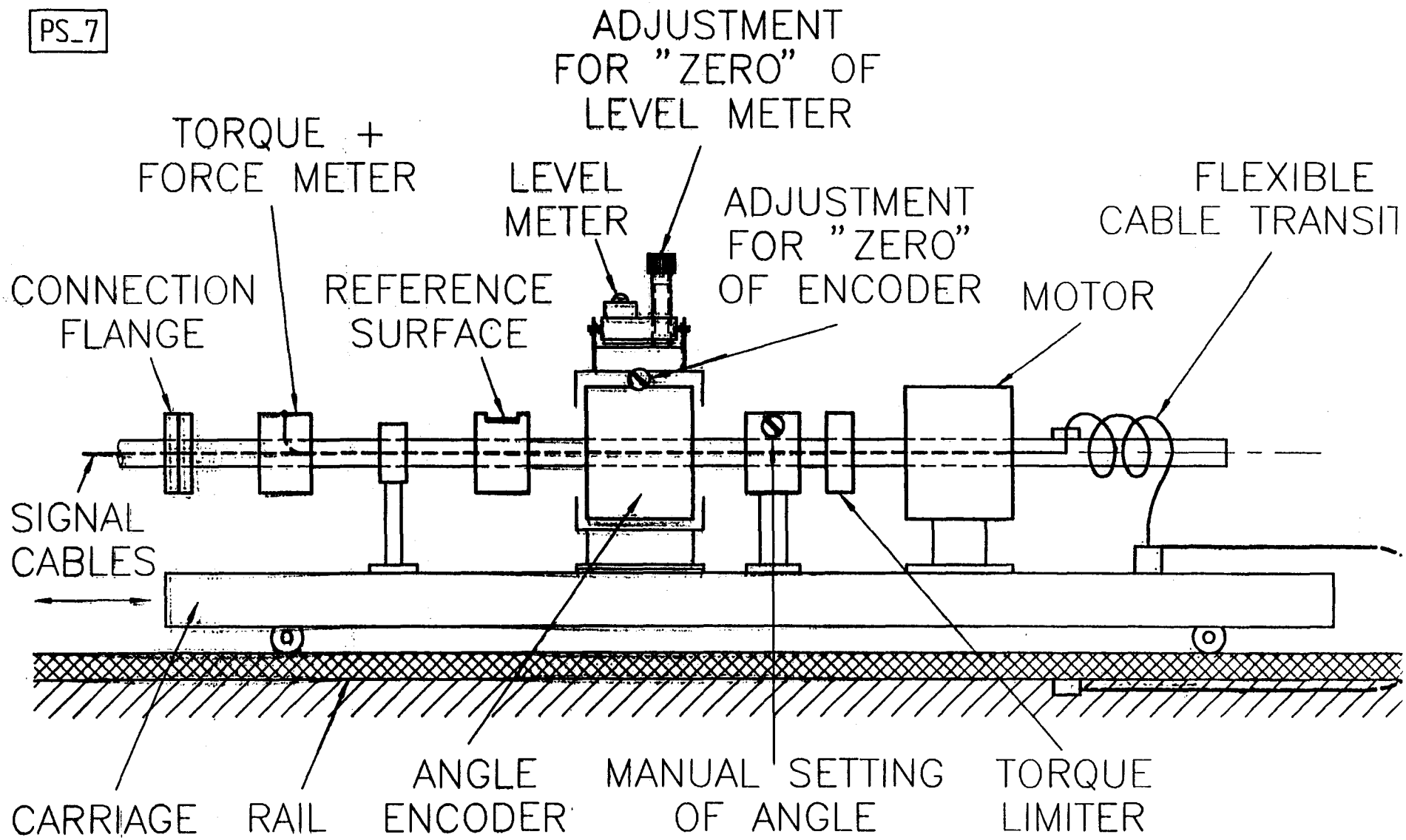

ROLLING
SUPPORT
UNIVERSAL
JOINTS
MEASURING
COIL
PS_11

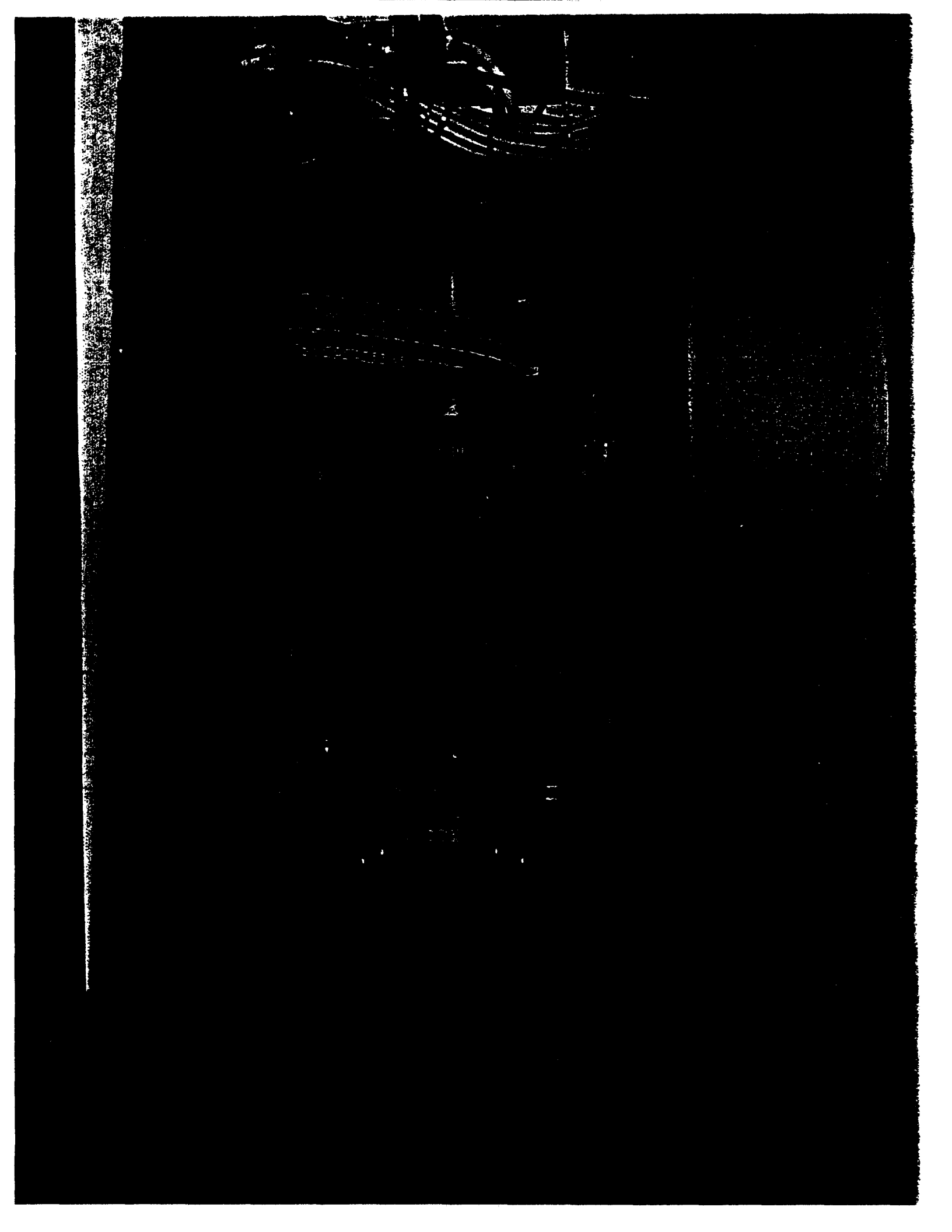


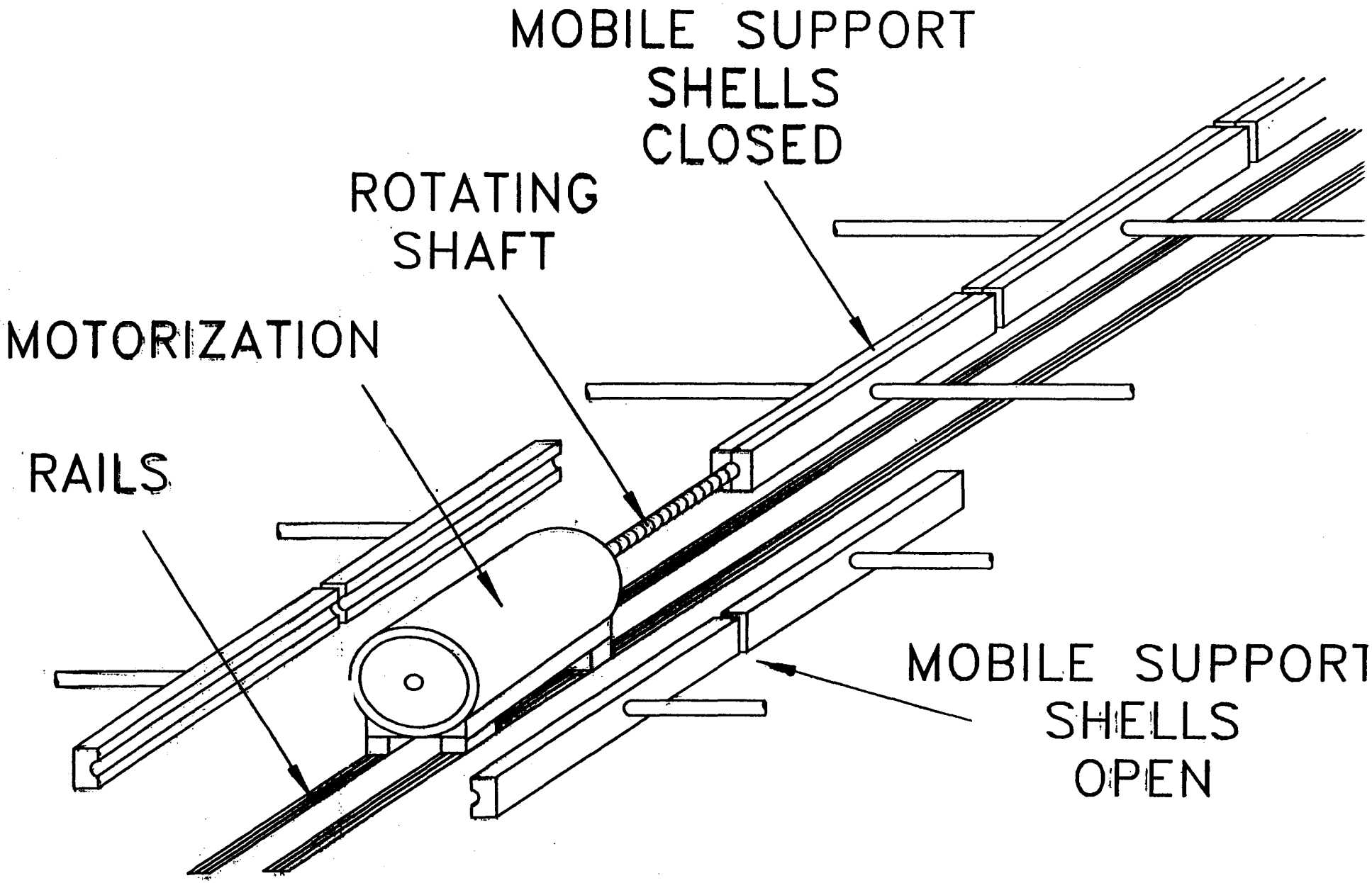
PS_II
AutoCAD
14.06.93/AR

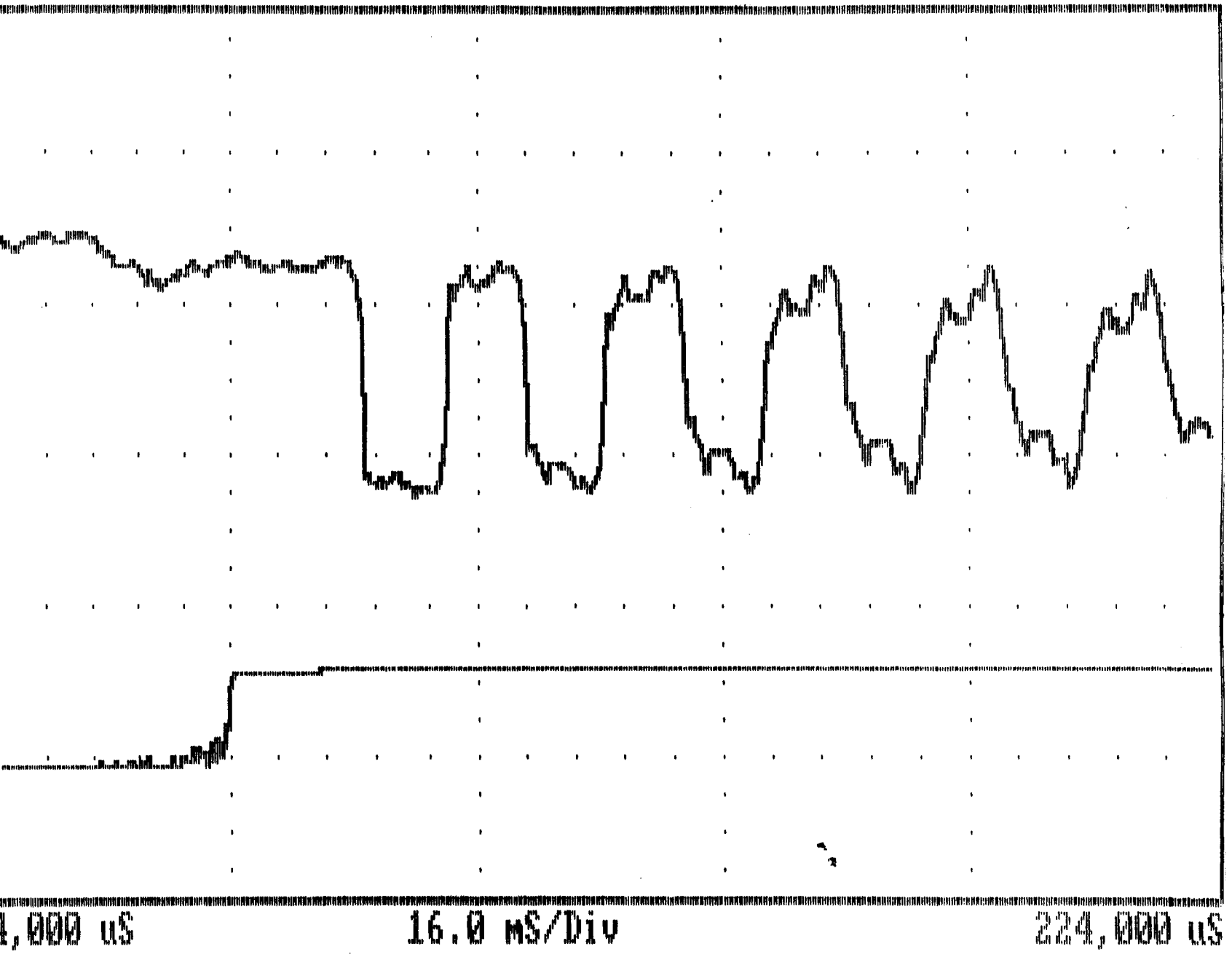

30.8
VMR
HALL
COIL
SHAFT
+
LEVEL
METER
+
?

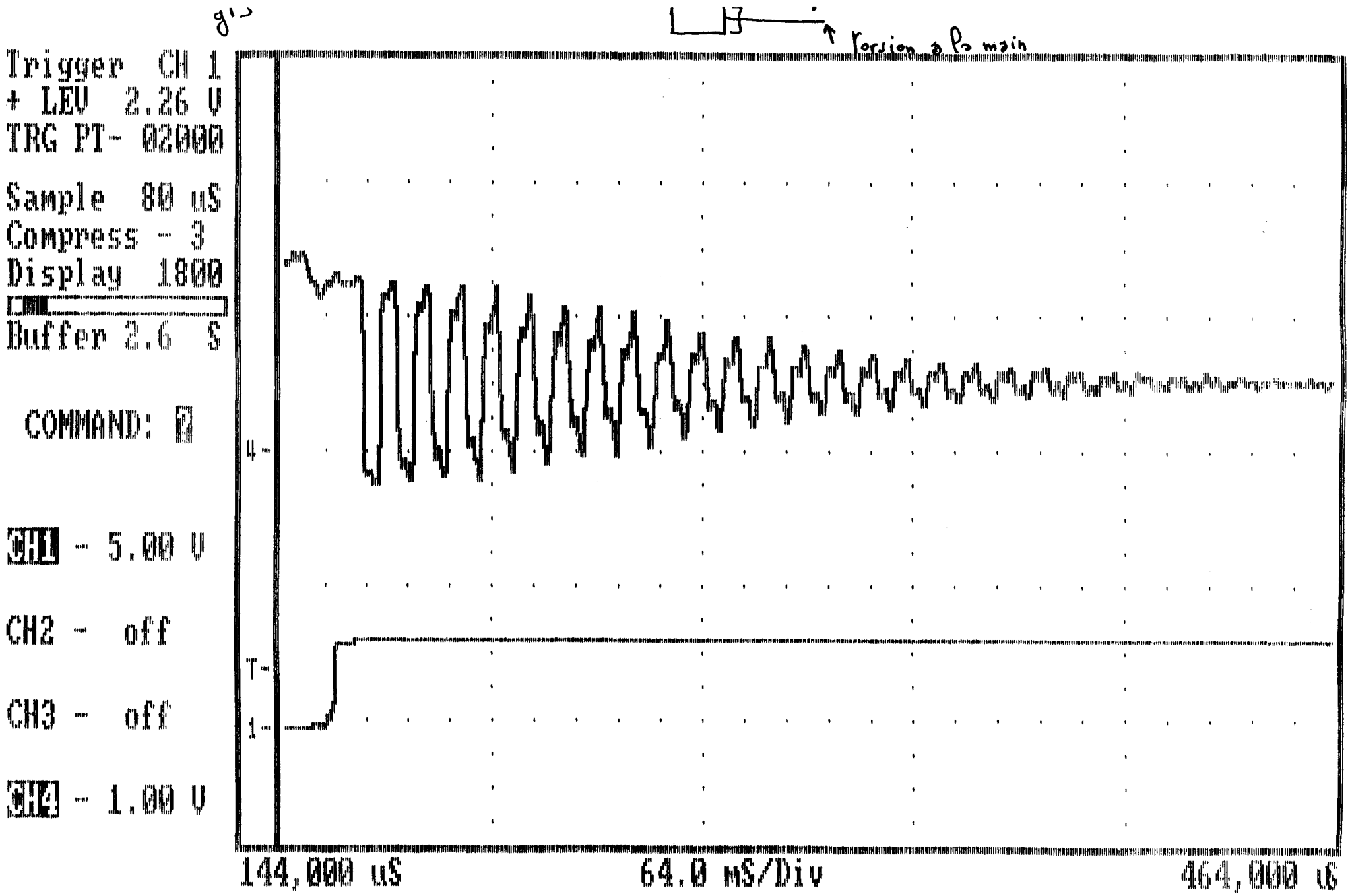
PS_7

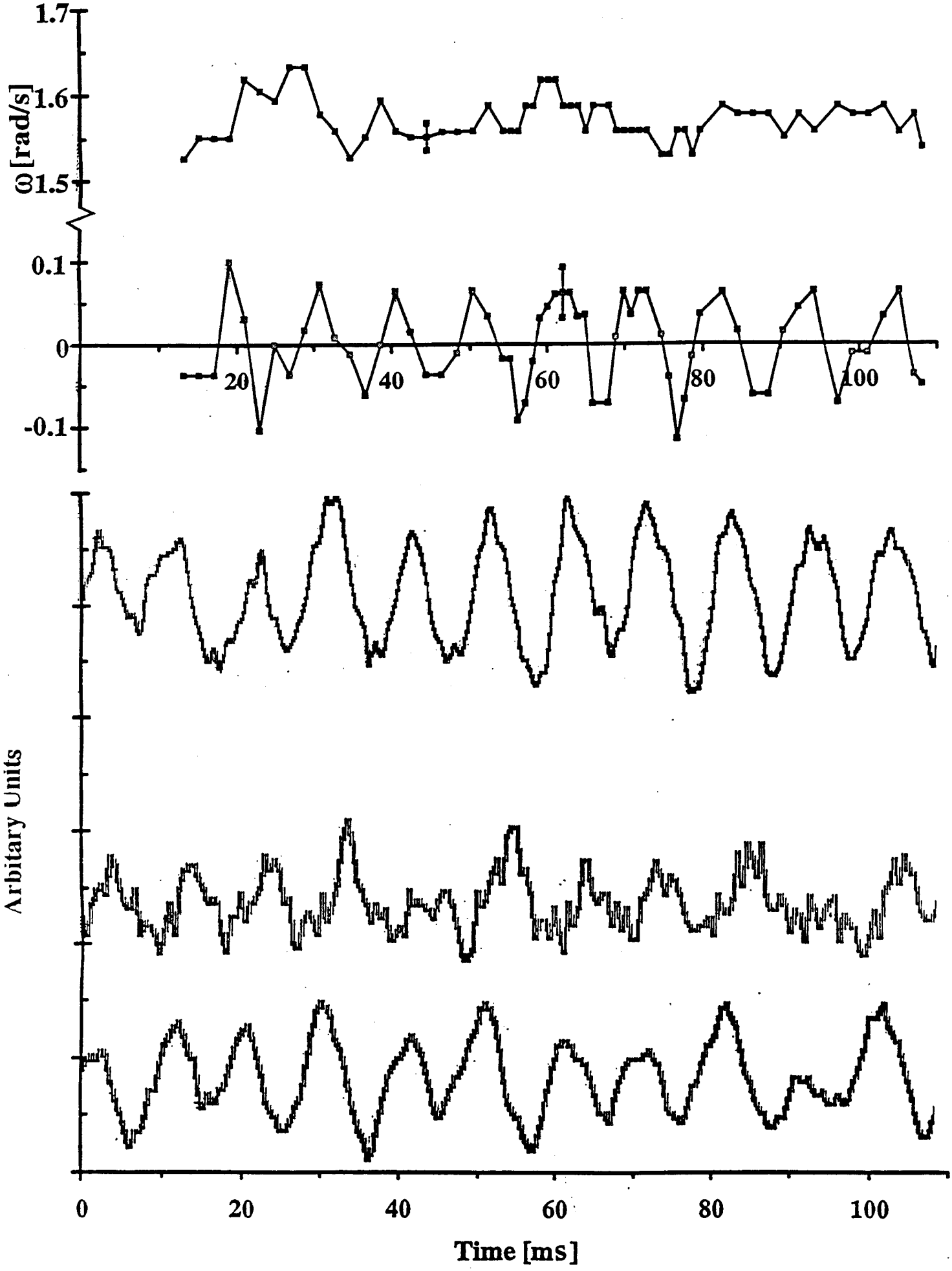

ADJUSTMENT FOR "ZERO" OF LEVEL METER
TORQUE + FORCE METER
LEVEL METER
ADJUSTMENT FOR "ZERO" OF ENCODER
FLEXIBLE CABLE TRANSIT
CONNECTION FLANGE
REFERENCE SURFACE
MOTOR
SIGNAL CABLES
CARRIAGE
RAIL
ANGLE ENCODER
MANUAL SETTING OF ANGLE
TORQUE LIMITER




MOBILE SUPPORT
SHELLS
CLOSED
ROTATING
SHAFT
MOTORIZATION
RAILS
MOBILE SUPPORT
SHELLS
OPEN


1,000 uS
16.0 mS/Div
224,000 uS


g's
torsion a la main
Trigger CH 1
+ LEV 2.26 V
TRG PT- 02000
Sample 80 uS
Compress - 3
Display 1800
Buffer 2.6 S
COMMAND:
CH1 - 5.00 V
CH2 - off
CH3 - off
CH4 - 1.00 V
4-
T-
1-
144,000 uS
64.0 mS/Div
464,000 uS


1.7
1.6
1.5
ω [rad/s]
0.1
0
-0.1
20
40
60
80
100
Arbitary Units
0
20
40
60
80
100
Time [ms]

Design and Test of the Benches for the Magnetic Measurement of the LHC Dipoles

J. Billan, J. Buckley, R. Saban, P. Sievers, L. Walckiers
CERN, European Organization for Nuclear Research
CH-1211 Geneva 23, Switzerland.

Abstract - **The magnetic measurement of more than 1300 LHC dipoles comprises the content of higher harmonic field components, field direction and field integrals. The measurements will be carried out along a warm bore installed inside the magnet cold bore, thus allowing the use of rotating coils at room temperature. This coil, together with Hall and NMR detectors is mounted at one end of a 12.5 m long shaft which is specially designed for very high rotational stiffness and which is controlled from its far end by a motor, an angular encoder and a level meter, all standard components placed outside the magnetic field without space restrictions. Particular emphasis has been put on the user-friendliness of the bench and its automated, computer-controlled operation requiring a minimum of staff, an important issue during production measurements of large series of magnets. The bench and its performance and precision achieved during its commissioning are described.**

I. Introduction

The measurement of the magnetic field of long, high strength superconducting dipoles forms an important part of the commissioning of the magnets for accelerators, as recently experienced at the HERA $e^- p^+$ collider, and for the future SSC and LHC $p^+ p^+$ colliders. Although the basic techniques for the actual measurement and analysis of the field quality, using rotating coils, Hall plates and Nuclear Magnetic Resonance (NMR) devices, are well suited also for the measurement of multi-tesla fields, they have to be adapted to the particular environment imposed by long superconducting magnets. In order to avoid measurements inside the evacuated cold bores, warm bore anti-cryostats are inserted into the cold bores, allowing for measurements to be made at ambient temperature and atmospheric pressure.

Basically two measuring principles exist. The first consists of a mole-type device [1],[2] which travels along the aperture and which uses flexible cables from the outside, field free region for the input and output signals. This mole is fitted in addition to the actual field sensors, with motors, angle encoders, gravity level meters, etc., which all have to operate properly in an extremely limited space and in elevated magnetic fields. The second solution consists of a probe, equipped with only the field sensors, while all other services (motors, encoder, level meters) are placed at the outside of the magnet in the field free region with no limitations on space. This allows the use of standard components. In this latter case, the transmission of the required displacements, orientations and rotations is established mechanically via a long shaft. To achieve the necessary precision, in particular of the rotation of the coil, the shaft must have a very high torsional stiffness and rotating supports with low friction. It must also be made of material of high electrical resistivity to avoid eddy currents, magnetic forces and twists induced during its rotation. In view of the very limited time allowed for R+D of the LHC prototype dipole measuring system, the second solution was pursued since the only essential and critical item to be newly developed, was the shaft. Moreover, this solution also allowed the design of a measuring bench with a high degree of ruggedness, automatization, user-friendliness and with minimum content of labour of the measurements, which is an important aspect in view of the production measurement of a large series of magnets.

II. General Layout

Fig. 1 shows a side view of the dipole measuring stand. The cryostat-dipole unit to be tested at superfluid helium temperature has a length of nearly 12 m and a weight of 23 t. Current and cryogenics are connected through the supply box on its left side.

Along each of the two apertures, 180 mm apart, a warm bore anti-cryostat [3] is installed which allows for an accessible diameter of 35 mm at ambient temperature over the total length of 13.8 m of the structure. On the downstream side of the dipole the magnetic measuring bench with an overall length of 14.7 m and a weight of 5.6 t is installed. It consists essentially of a carriage with a unit to rotate the 12.5 m long drive shaft and the measuring coil at its opposite end. This unit is axially mobile to position the coil along the magnetic field over its length of nearly 10 m inside the anti-cryostat. Prior to each scan the coil, and in particular its orientation, is checked in the field of a short normal conducting

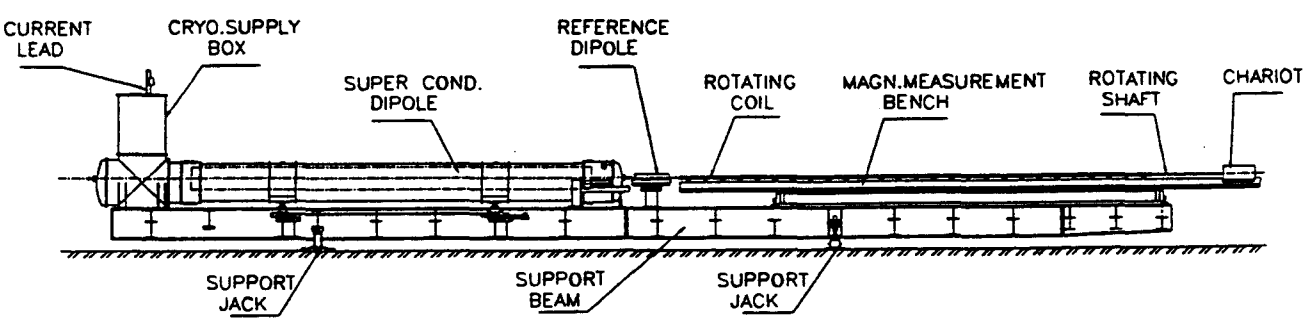


Fig. 1. Test stand for LHC prototype dipoles. The supply box, the magnet and the measuring bench are installed on a common girder which allows to make tests with the magnets tilted by at most ± 1.5%.

Manuscript received September 20, 1993.

SUBMITTED TO MT-13

reference dipole (see Fig. 1) with well known field strength and direction. All components are placed onto a common support girder of 27 m length, which permits measurements with the magnet inclined by ± 1.5 %, to simulate the tilt of the LEP/LHC tunnel.

III. MEASURING BENCH

The carriage, carrying the rotating unit for the shaft, is driven on linear ball bearings and precision rails by a d.c. motor, also mounted onto the carriage and engaged via a pinion to a rack on the stationary support of the bench. The axial position is recorded with an angular encoder on the carriage and engaged to the same rack. A precision and reproducibility of ± 0.1 mm is readily achieved over the total range of 13.5 m. Its absolute length, independent of temperature variations of the structure will be measured by stretching along the bench an invar-wire of well defined length. This should allow to obtain the field integral $\int B\,dl$ with a precision of better than 10^{-4}.

The layout of the rotating unit on the mobile carriage is shown in Fig. 2 . The signal cables from the coil pass through the hollow shaft and through the rotating unit and emerge at its end in form of a spiral which allows for 3 turns of the unit of which one is used for smooth acceleration before activating the measurement of the field over one turn. The rotation is made by a micro-stepping motor (5×10^4 steps/turn) and a 1:4 reduction. This provides also the possibility to place the shaft into precise and reproducible angular positions, opening further options for the measurements of field direction and the axis of quadrupoles at a later stage. Upstream of the motor, a hollow shaft encoder with a resolution of better than 10^{-4} rad measures the angular position of the coil, the central issue of harmonic field analysis. The housing of this encoder can be oriented manually around its axis in order to "zero" the encoder at the angular reference position of the coil as defined by the reference magnet. The housing of the encoder is fitted with a high precision electronic level meter, which again can separately be adjusted to "zero" around the axis of the rotation. Thus the zero of the encoder and of the level meter can be made to coincide with the angular zero position of the coil as defined by the field orientation of the reference magnet. Any change in orientation of the carriage during its axial travel relative to the vertical is precisely measured by the level meter.

Between the shaft and the rotating unit, a piezo torque meter is installed which monitors the friction in the rotating supports of the shaft, and thus its twist and angular precision. Moreover, this detector measures axial forces. By setting predefined maximum values triggering an interlock, the system is well protected against mechanical faults, and in particular errors in angular position.

Two types of rotating shafts were developed. The first consists of eight segments of extruded alumina (Al_2O_3) pipes with an OD = 32 mm and an ID = 24 mm and a length of 1.5 m each. The second shaft is made from shorter pipe segments (1.3 m) of high strength carbon fiber pre-pregs [4]. A particular fiber orientation in combination with intermediate insulating glass layers had to be selected to minimise eddy currents and magnetic torques in the shaft when rotating with an angular velocity of 1 turn /s in a dipole field of up to 10 T. The pipe segments are connected together with fittings of reduced diameter to provide sufficient radial space for the supporting ball bearings as shown in Fig. 3. Again to reduce magnetic and mechanical torques, high quality ball bearings of Si_3N_4 ceramic were used. In addition to the rotation, easy axial displacement of the shaft is provided by clamping around the outer race of each ball bearing a ring fitted with spring loaded axial rollers (see Fig. 3). Since these units are stationary during the magnetic measurement they could be made of brass. To suppress any lateral forces due to angular errors or kinks at the fittings a flexible universal joint can be mounted between the flanged connections close to the measuring coil. A photograph of a coupling is shown in Fig. 4.

The stiffness of both types of shafts completely assembled, were 580 Nm/rad and 210 Nm/rad for the ceramic and reinforced carbon respectively. The torque required to rotate the shaft with about 1 turn/s was at most 6×10^{-3} Nm which should lead to an angular twist of at most 0.03 mrad between both ends.

Clearly, the long slender shaft has continually to be supported on the bench all along its length during its axial travel. Pairs of mobile half shells with a length of 1.3 m and with an open inner diameter of 35 mm (equal to the warm bore inside the dipole) are progressively removed horizontally by pneumatic jacks (see Fig. 5), thus liberating the space for the rotating unit during its advance. The reverse, closing procedure is applied during the return of the carriage. The coordination between the movements of the carriage and the support shells forms part of the process control system of the bench and is in addition hardwire protected against malfunction and errors. Fig. 6 shows a view along the measuring bench with the magnet at its far end.

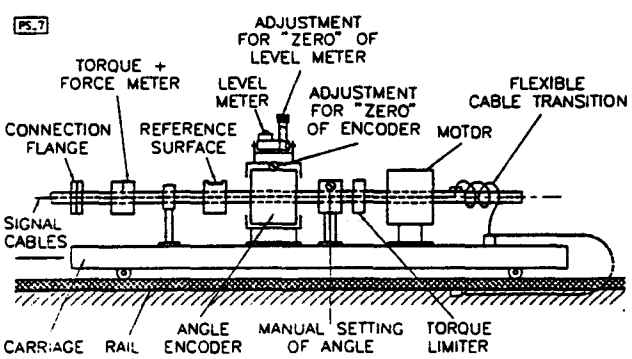


Fig. 2.. Rotating unit to drive the shaft, mounted on the mobile carriage.

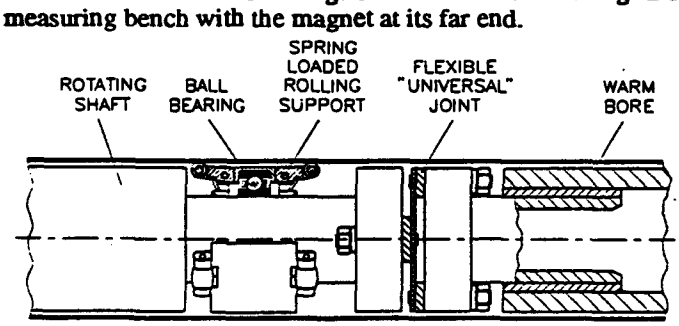


Fig. 3. Coupling between segments of the rotating shaft with ball bearings for the rotation and with spring loaded rolling supports for the axial displacement along the warm bore.

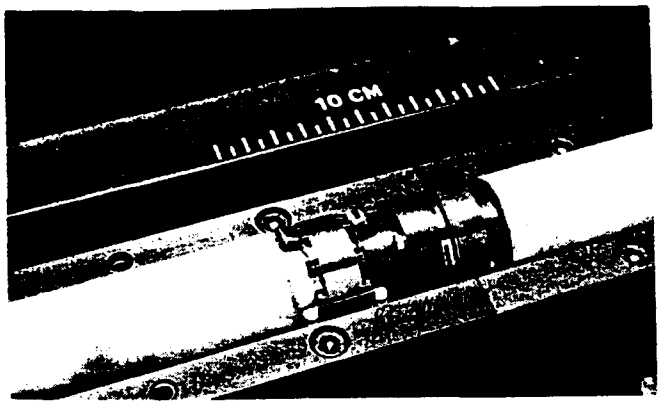


Fig. 4 . Flanged coupling between two ceramic segments of the rotating shaft as schematically shown in Fig.3.

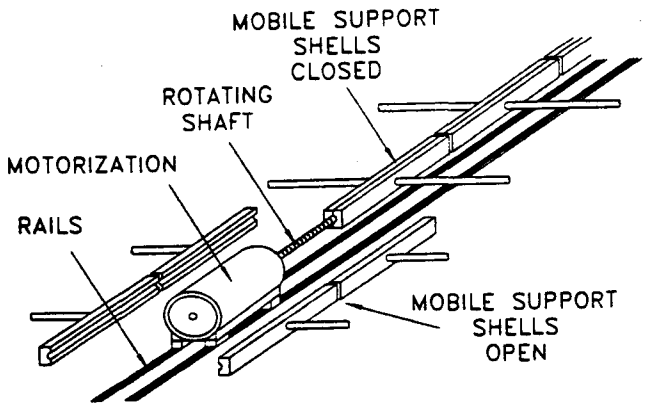


Fig. 5. Segmented, mobile support system for the shaft, progressively liberating the space for the motorization unit during its advance.

The measuring head, shown in Fig. 7 at the end of the rotating shaft, is composed of an NMR probe, two perpendicular Hall plates and a set of three radial harmonic coils wound onto a fiber glass reinforced epoxy structure. The coils are made identical in area and in parallelism to within 10^{-3} by precise machining of their core, and windings are made with flat multiwire cables. No skew coil for compensating their lack of parallelism is foreseen. The external windings of the measuring coils rotate on a radius of 15.4 mm inside the radius of the warm bore of 17.5 mm. The arrangment of three coils is used for ease of fabrication, symmetry and redundancy and to determine the off-centering of the measuring coils with respect to their true axis of rotation [5]. In order to maintain the sag below 0.1 mm, the length of the unit has been limited to 750 mm.

The motorization of the test bench has followed the industrial control line adopted for all the equipment associated to the dipole test stand namely, the cryogenics infrastructure and demineralized water plant. This implied the usage of commercially available industrial PLCs, communication and supervision systems. Together with the functionality of the equipment, the data structures for the exchange of information between the operator and the equipment were specified and agreed with the suppliers. The applications for the supervision were designed and developped in house using a workstation based commercial industrial supervision package.

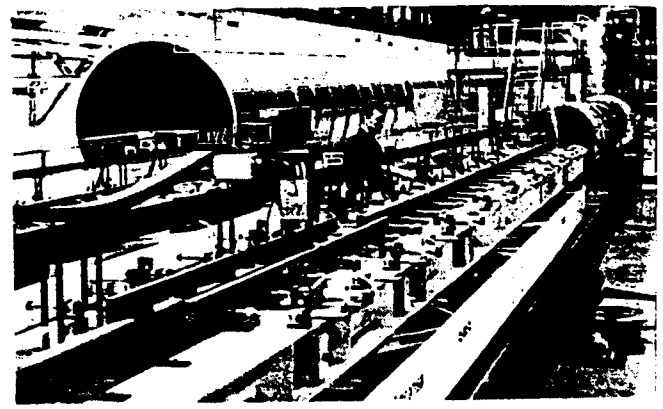


Fig. 6. The measuring bench with the carriage half way down its stroke between the opened support shells of the shaft and with the magnet cryostat and cryogenic supply at the far end.

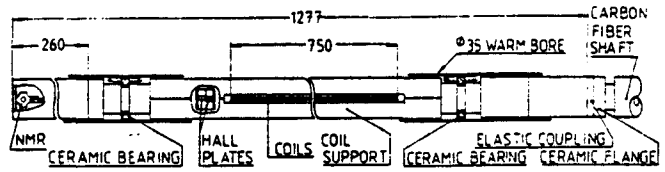


Fig. 7. Measuring head at the end of the rotating shaft fitted with the various field probes (Dimensions in mm).

VI. Measurements

To assess the initial performance and precision of the magnetic measurement system and in particular the crucial item, the shaft, we investigated its dynamic response to the rotation [6]. A second encoder was mounted provisionally at the downstream end of the carbon reinforced shaft which allowed to measure rotational velocities and relative angular oscillations between the two ends of the shaft. Fig. 8 shows clearly a relative oscillation of 100 Hz which corresponds well to the torsional natural frequency of the shaft [6] and its oscillation amplitude is ± 0.1 mrad. They are correlated to the oscillations of the torque, measured at the upstream end which are shifted, as expected by 90 degrees. At rotation speeds below 0.1 turns/s the upstream end starts to turn less regular, while at velocities between 0.25-1 turns/s the oscillation amplitude remains about constant. Smaller vibrations have been observed with the ceramic shaft due to its much higher stiffness. The torque driving these oscillations comes mainly from the pinions at the motor and damping elements are being prepared to reduce these oscillations. Further measurements with the completed carbon fiber shaft unit rotating inside the dipole reference magnet at 0.13 T revealed again oscillations of the coil during its rotation, clearly visible when passing parallel to the dipole field. As before they are correlated to the torque at the upstream end (see Fig. 8).

Consecutive measurements of the angle of the dipole field at 0.13 T gave a short term reproducibility of better than 0.1 mrad with the carbon as well as with the ceramic shafts. Since the average temperature along the shaft may vary with its axial position due to different thermal conditions along the bench and inside the anti-cryostat of the magnet, the twists of both shafts as a function of their temperature was measured. The carbon shaft when heated over its total length showed a pronounced temperature related twist of about 0.6 mrad/K,

which is most likely due to its strongly non uniform fiber structure, although the fiber layers were placed with alternating orientation. Even if the precise temperature regimes of the bench and the anti-cryostat are not yet known the improvement of the thermal stability of this shaft will be pursued. To the contrary, the ceramic shaft showed, within the measurement errors, no such thermally induced twists, as expected from the uniform structure of its material.

The relative field harmonics expressed at 15.4 mm, the outer radius of the measuring coil, were measured with a reproducibility of 10^{-5} for all orders. This precision is expected to improve since the coil surfaces and the electronics are adapted for the much higher field level of the superconducting dipoles.

V. Conclusion and Outlook

The basically simple concept developed at CERN for the measuring benches of the LHC prototype dipoles allowed for design and fabrication of these benches entirely by industry in turnkey style, following a CERN performance specification. The main issue of these benches, the long, slender rotating shaft made of ceramic performed well within the required specification. For the carbon shaft further development is needed to reduce its thermally induced twist.

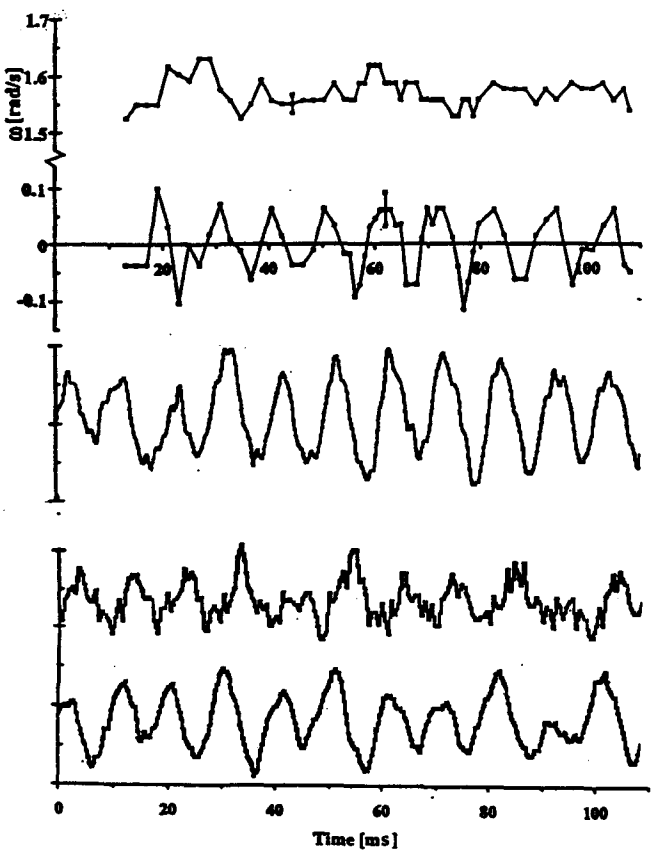


Fig. 8. Rotation velocity ω at the upstream end of the shaft, and the difference in ω between both its ends and the torque at its upstream end versus time (top). Below are shown for a different run the voltage induced in the coil rotating inside the reference magnet at the downstream end and the torque at the upstream end.

Small residual rotational oscillations of the measuring coil of about 100 Hz, inherent in the system, are sufficiently rejected by the harmonic analysis. In view of the increased magnetic length of the future LHC dipoles of above 13 m with a slightly bent aperture, tests have shown that shafts of increased length can still be used, in particular since their diameters, and thus their rigidity, can be increased due to the enlarged aperture of these magnets.

Thanks to the fully automatic measurement cycles, later during production measurement one operator will be able to supervise simultaneously several measuring benches. Since the actual time devoted to the field measurement of each dipole is only about 20-30 % of the turn around time of a test stand these benches should be rendered easily mobile from one stand to another which could limit the number of required benches to four if in total 16 tests stands are envisaged.

Finally the developed system can naturally be extended to the magnetic measurement of the short straight section units with an overall length of 6.5 m, comprising the main quadrupole and correction magnets, where, in addition to the multipole content of the fields and the orientations, the field axis has to be measured. By adding an appropriate laser tracking system, detecting the lateral position of the coil, the dipole measuring benches can also serve to measure quadrupoles. This laser tracking system is presently being developed.

Acknowledgment

We should like to acknowledge the excellent collaboration with the firms CHACONSA / Murcia, Spain and ISLER / Zurich, Switzerland which designed and manufactured the measuring benches. Thanks are also due to CERN staff, too numerous to mention them all by name, of the CERN MT and AT Divisions and in particular of the AT-Magnet Group.

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Prototype Development of a Warm Bore Insert for the LHC Magnet Measurements

F. Clari, O. Dunkel, M. Genet, Ch. Gregory, P. Sievers
CERN, European Organization for Nuclear Research
CH-1211 Geneva 23, Switzerland.

Abstract -To allow the measurements of the superconducting LHC magnets up to their nominal field with well-proven, standard techniques, easy access into the apertures is required at ambient temperature and atmospheric pressure. A warm bore anti-cryostat is inserted into the cold bore vacuum pipe of the magnet, where the evacuated radial gap between these two parts serves as thermal insulation. To allow for maximum accessible cross-section during the measurements, the small radial gap of 3.5 mm has to accommodate superinsulation, support spacers and electrical heaters for the thermalization. Design aspects, related to the high magnetic fields, quenches, mechanical loads, vacuum, reliability and ease of handling have to be addressed. The design of the anti-cryostat and the cryogenic test of a prototype model are described. The heat load on the cold mass of the magnet by this prototype was below one watt per meter.

I. Introduction

For the magnetic measurements of the LHC dipoles, standard rotating coil techniques will be applied [1]. In order to avoid technical complications, caused by the very long and narrow magnet aperture and in particular by its vacuum chamber kept at liquid helium temperature, a thermally insulated tube is inserted into this cold bore, which allows to perform the magnetic measurements at ambient temperature and pressure along the warm bore of this anti-cryostat [2]. Similar approaches have been adopted previously at FERMILAB and DESY and recently also at SSCL [3].

II. Operational Conditions

The anti-cryostat must be designed for maximum free inner diameter, vital for high precision magnetic measurements, while still minimising the heat inleak into the 1.8 K liquid helium bath of the magnet. Straightforward estimates indicate that heat inleaks through radiation of well below 1.5 W/m should be achieved with the envisaged geometry.

In order not to interfere with high precision magnetic measurements inside the anti-cryostat non magnetic components and in particular low permeability stainless steels have to be used. Clean, inorganic components with low outgassing have to be applied in order to prevent contamination of the cold bore during the magnet test by absorbed gas which later during operation might be desorbed through the synchrotron radiation of the circulating proton beams.

At this moment of time it cannot be excluded that the heat input through the anti-cryostat raises slightly the average temperature of the superconducting coil, which would lead to lower quench levels than during normal operation of the magnet without anti-cryostat. Therefore provision must be made to evacuate temporarily the anti-cryostat, thus cutting all heat input into the magnet which allows quench studies under realistic conditions.

The force F per unit length L acting on the warm bore in its horizontal plane induced during a possible quench of the magnet by eddy currents is given by :

$$F/L = (2R^2 d/\rho)\cdot B\cdot dB/dt$$

with R = Radius of the pipe, d = Wall thickness of the pipe, ρ = Specific electrical resistance, B = Magnetic field density, dB/dt = Decay of the magnetic field during the quench. With R = 17.75 mm, d = 0.5 mm, $\rho = 7 \times 10^{-7}\ \Omega$ m and with a maximum dB/dt = 70T/s at B = 7 T [4] a maximum lateral force of 220 N/m will occur. Tests with such force have shown a temporary ovalization of the cross section of the pipe of + 0.98 mm with no residual, plastic deformation thereafter.

III. Layout and Design

A cross section and a side view of the anti-cryostat are shown in Fig.1 and Fig.2. The warm bore tube with an inner diameter of 35 mm and a wall thickness of 0.5 mm is placed inside the magnet cold bore with an inner diameter of 43 mm, thus leaving a radial insulating vacuum gap of only 3.5 mm. The warm bore consists of a seamless, drawn pipe of non magnetic stainless steel (AISI TYPE 316LN) with a total length of 13 m.

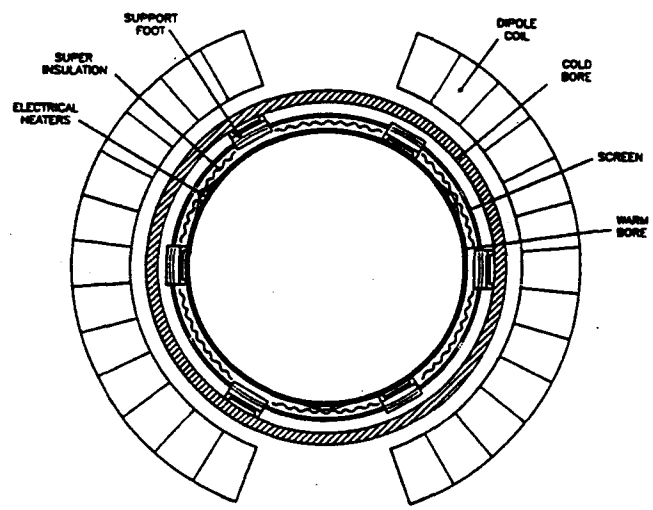

Fig. 1. Cross section of the anti-cryostat inside the cold bore vacuum pipe of the dipole (not to scale).

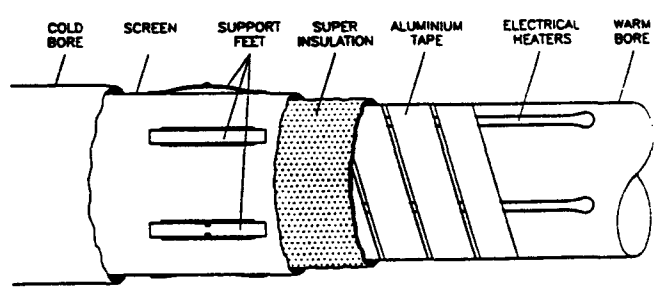

Fig. 2. Side view of the anti-cryostat.

Manuscript received September 20, 1993.

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To maintain the temperature of the warm bore at room temperature while the magnet is cold, three independent, mineral insulated, coaxial, electrical heating cables with an outside stainless steel jacket with a diameter of 0.3 mm are soft soldered onto the outside of this pipe each forming a loop over its total length. With a current of 0.4 A and a voltage of 13 V over each loop a power of 1.5 W/m is dissipated. The same power could, in the limit, be dissipated by only one of the three heaters which provides sufficient redundancy in case of failure of one of the three.

Around the outside of the warm bore and the heaters, shiny aluminium tape is wound which serves to reduce the emissivity of this surface and to distribute the heat supplied by the heating elements uniformly around its circumference. A small gap is left between the turns of the tape to help outgassing and pumping. On top of this Al-tape three layers of perforated aluminised mylar superinsulation are wrapped which thereafter are covered by an auxiliary thin walled stainless steel pipe, the screen. To facilitate assembly it consists of short segments with a length of 650 mm each which are progressively mounted together with the superinsulation. The inner and outer surfaces of each screen are mechanically polished to high brilliance and holes are drilled into it, again to improve outgassing and cryopumping towards the outside cold bore. The segments of the screens are joined together axially by special connecting units (see Fig.3) each fitted with six claws which are locked and secured into holes at each end of each screen.

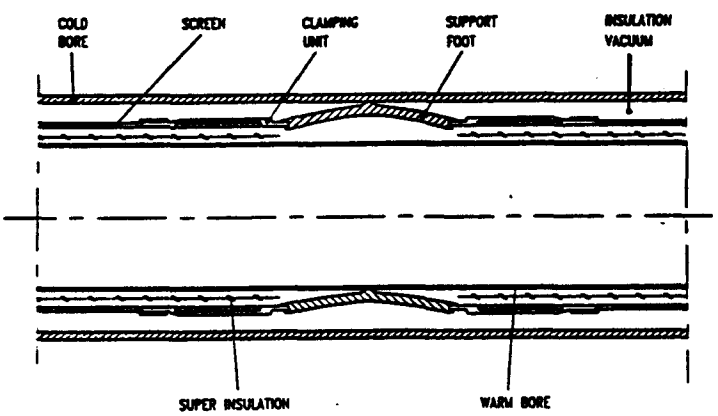

Fig. 3. Cut through the connecting unit, equipped with the support feet and clamps fitted to the screens on either side.

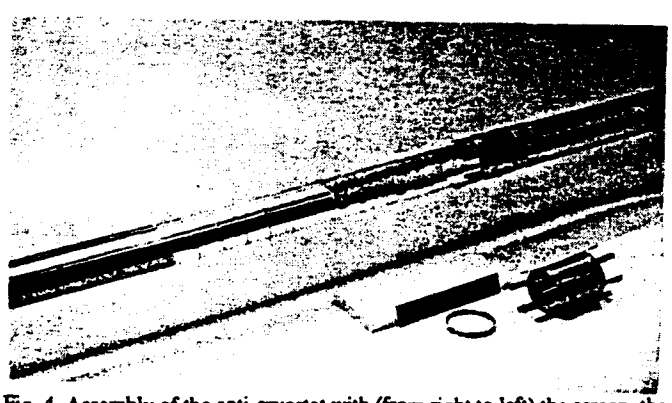

Fig. 4. Assembly of the anti-cryostat with (from right to left) the screen, the connecting unit, the layers of the superinsulation and Al-tape wrapped around the warm bore.

Fig. 4 shows a photograph of the various layers between the warm bore and the screen with its connecting unit. The warm bore is centered radially within these junction pieces and thus within the screens by three support feet which are placed symmetrically around the circumference of the unit (see Fig.3). They are shaped like spring blades protruding towards the inside and made of low thermal conducting polyimide. Their geometry has to be optimised with respect to their mechanical rigidity and the capability to pick up tolerances in diameter of the warm bore as well as with respect to their thermal resistance.

An additional set of three support feet is mounted on this junction unit which are now oriented towards the outside, thus centering radially the total anti-cryostat within the cold bore. With a global radial spring constant of each support unit of 330 N/mm, a radial displacement of 0.06 mm is expected due to the weight of about 40 N of the magnetic field sensor passing along the warm bore. The total force to pull the anti-cryostat into the magnet is 160 N.

Fig.5. shows the layout of the anti-cryostat inside the magnet test stand. The anti-cryostat consists of one short part with a length of 2 m installed permanently inside the cryogenic supply box on the left side. The other 11 m long part is introduced from the right side through the cold bore of the magnet, which requires for the intermediate junction between the two parts of the warm bore a miniaturised flange. This has an outside diameter of 42 mm, fitted with a metallic gasket, which allows in the limit also the warm bore to cool down to cryogenic temperatures. The warm bore is axially fixed at the right side (see Fig.6) but can laterally, via a flexible bellows, be displaced to align it with respect to the magnet aperture. The opposite end is axially loaded by three springs with a total pulling force of 520 N and a spring constant of 2.5 N/mm to allow for differential thermal expansion between the magnet cryostat and the warm bore, in particular when cooled to cryogenic temperature. Fig.7 shows a photograph of the spring loaded end flange.

IV. Measurements on a Prototype

A prototype of the anti-cryostat with a reduced length of 6 m has been built and tested in an assembly simulating the geometry of the magnet cold bore, however, at 4.2 K boiling helium temperature. The heat input from the anti-cryostat into the helium bath could readily be measured via the power dissipated in the electrical heaters during the steady state of the warm bore. Fig.8 shows the power per unit length of the anti-cryostat versus the steady state temperature of the warm bore for two types of screens (gold plated:top, mechanically polished:bottom).

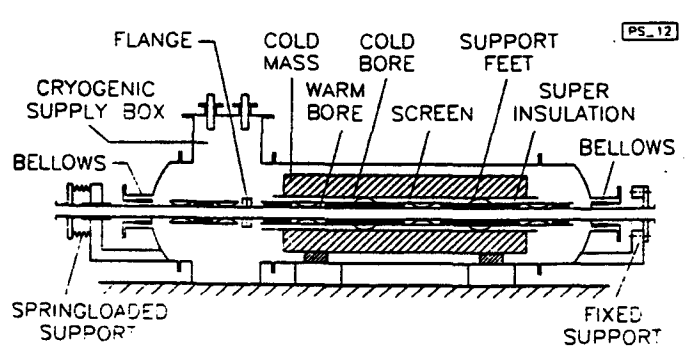

Fig. 5. Layout of the magnet test stand fitted with the anti-cryostat (not to scale).

Thus, values of at most 1 W/m can be expected in the final layout of the test stand. Fig.9 shows the temperature measured along the inside surface of the warm bore at a heat input of 1.04 W/m. Cryopumping of the small gaps between the warm and the cold bores along the anti-cryostat should lead to increased vacuum and thus to higher steady state temperatures at its axial center than at its ends, where thermal conduction through rest gas from the "warm" environment at these locations occurs.

The time constant dK/dt of the temperature of the warm bore when after reaching the steady state the heating power is cut, is also significant for the thermal quality of the anti-cryostat. A value of 8.5 K/h has been measured. This allows also in the case of failure of the heating system, sufficient time to intervene before condensation of humidity or formation of ice sets in inside the warm bore. The average temperature along the warm bore can readily be followed via the temperature dependence of the resistance of the copper heating wires. A temperature coefficient of the resistance of about 3.5×10^{-3}/K was measured which should allow the monitoring and control of the temperature of the warm bore within a precision of ± 5 K.

V. Conclusion

The very tight geometrical constraints imposed on the anti-cryostat and especially on the evacuated thermal insulating gap of only 3.5 mm between the warm bore at 295 K and the cold bore at 1.8 K, required particular effort and high precision for the construction of the anti-cryostat prototype. The selected design proved to comply well with these constraints. Moreover, the heat inleak through this anti-cryostat into the helium bath was well within the expected value of below 1 W/m which still depended significantly on the relatively poor global insulating vacuum in the test set-up. Thus, even lower heat inleaks should be reached with improved vacuum, as expected in the final magnet test stands. The total heat load caused by two anti-cryostats on the cryogenic system of twin-aperture dipoles, 10 m long will thus amount to about 20 W. Clearly, when more radial space for the insulating gap around the anti-cryostat can be made available, as one may expect from the increase of the inner diameters of the superconducting coils from 50 mm to 56 mm, as presently foreseen, this heat load will be substantially reduced.

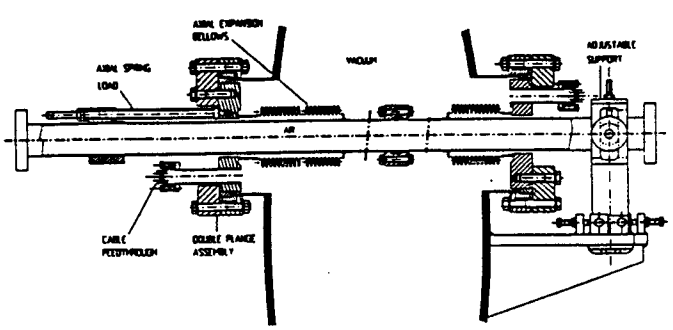

Fig. 6. Details of the fixed (right side) and axially spring loaded (left side) end flanges of the warm bore.

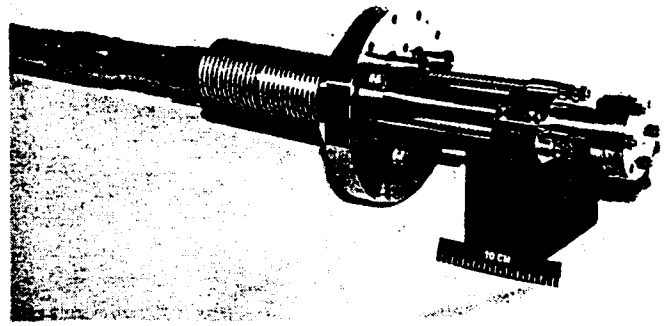

Fig. 7. Overall view of the axially spring loaded end flange of the warm bore.

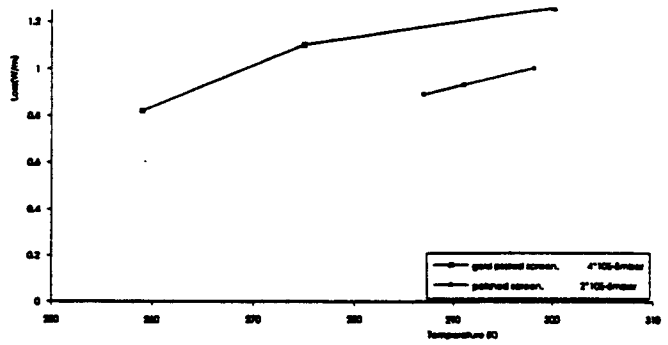

Fig. 8. Average heat inleak through the anti-cryostat into the Helium bath versus the steady state temperature of the warm bore for two differents types of screens.

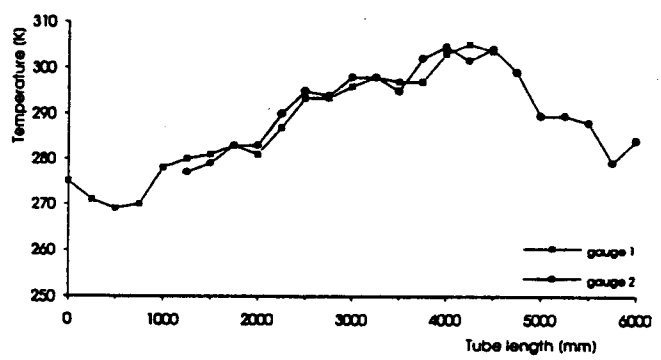

Fig. 9. Steady state temperature along the warm bore of the anti-cryostat thermalized against the He bath with a power of 1.04 W/m.

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Knud N. Henrichsen
CERN

Experience with cryogenic Hall plates

IMMW-7

Siemens, RHY 17

- no oscillatory effect
- not very linear
- significant temperature coefficient
- but, no longer produced

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- linear
- small temperature coefficient
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Features:
Temperature range - 1,5 K up to 350 K
Magnetic field range - 0 T up to 30 T

Linearity error:
In magnetic fields up to 1 T, 300 K ..... < 0,2 %
In magnetic fields up to 5 T, 4,2 K ..... < 1,0 %

Unpackaged as well as packaged units are available.
Normal and low active area electric systems.

DESCRIPTION

This series of Hall probes has been developed for operation at room as well as cryogenic temperatures.

Two basic types of Hall probes are available:

- Hall probes for liquid N_2 temperatures with sensitivity about 100 mV/T at control current 100 mA
- Hall probes for liquid He temperatures with sensitivity about 10 mV/T at control current 100 mA

Both types can be used at room temperatures as well. Hall probes with higher sensitivity have higher temperature dependence of the Hall voltage at room temperatures.

The units can be supplied as unpackaged or packaged. The basic type of the probes has an electric system with the active area of 0,625mm^2. Also Hall probes with small active area (0,01 mm^2) for measurements of inhomogeneous magnetic fields have been developed. Transverse or axial package modification is available.

Great attention was paid to the low value of the off-set voltage U_O, as well as to the stability of Hall probes parameters during the thermal cycling from 300 K to 77 K and 4,2 K. Laboratory specimens have withstood 100 cycles from 300 K to 77 K without considerable change of parameters. The change of sensitivity after this cycling did not exceed ± 0,04 %, off-set voltage change was of the order of ± 5 μV.

CALIBRATION

As a standard the Hall probes are supplied with following measured parameters:

- input and output resistance at 300 K and 77 K in zero magnetic field
- off-set voltage at 300 K and 77 K
- sensitivity at 300 K and 0,2 T
- change of sensitivity due to reversing of magnetic field

On customer's request the calibration of the Hall probes up to 5 T at 4,2 K or up to 0,4 T at 77 K or up to 0,8 T at 300 K can by make.

The Hall probes described are intended for the precise measurements of magnetic fields in the temperature interval from 350 K down to liquid helium temperatures. High linearity of the Hall voltage U_H versus magnetic field and small temperature dependence of sensitivity represents an advantage for physical and technical experiments.

GUARANTEE

Probes that not meet specifications must be returned within 30 days of shipment, in which case either the full purchase price will be refunded or a replaced unit sends, as preferred, unless the unit has been damaged by rough handling or improper mounting.

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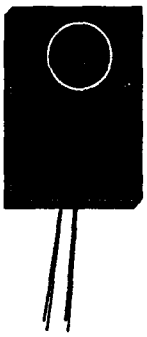
PARAMETER			TYPE			
			LHP-Nx	LHP-Mx	HHP-Nx	HHP-Mx
Magnetic field range		[T]	0-33	0-33	0 - 5	0 - 5
Temperature range		[K]	1,5 - 350	1,5 - 350	1,5 - 350	1,5 - 350
Nominal control current In		[mA]	100	20	100	20
Maximum control current		[mA]	150	50	150	50
Sensitivity at In		[mV/T]	>10	>5	>100	>20
Linearity error	T[K]	B[T]				
	300	0 - 1	<0,2	<0,1		
[%]	77	0 - 0,2		<0,05		
Mean temperature coefficient of sensitivity : $[K^{-1}]$	4,2	0 - 5	<1	<1	<1,5	<1,5
	Temperature range : [K]	4,2 - 77	2.10^{-5}	2.10^{-5}	3.10^{-5}	3.10^{-5}
		77 - 300	3.10^{-5}	3.10^{-5}	1.10^{-4}	1.10^{-4}
Residual voltage		[μV]	< 20	< 20	< 50	< 50
Temperature coeff. of residual voltage		[μV/K]	< 0,02	< 0,02	< 0,3	< 0,3
Input resistance [Ω] at T[K] (in zero field, including leads)		4,2	0,9	1,8	1,9	2,8
		77	1,1	2,2	2,3	4,7
		300	1,5	4	3	7
Output resistance [Ω] at T[K] (in zero field, including leads)		4,2	1,3	1,9	2,7	2,9
		77	1,8	2,6	3,8	4
		300	3	6	7	8
Quantum oscilations begining		[T]	>2	>2	>1,5	>1,5
Amplitude of q. oscilations		[%]	<0,1	<0,1	<0,1	<0,1
Active area		[mm2]	0,625	0,01	0,625	0,01
Overall dimensions		[mm]	6 x 4 x 0,5	6 x 4 x 0,5	6 x 4 x 0,5	6 x 4 x 0,5
Axial Hall probe overall dimensions :			⌀ = 7 mm, L = 8 mm			

Characterisation Of The Hall Probes

12 various types of the probes are available:



❶HP-❷❸

❶ *Sensitivity:*

H - higher - N type > 100 mV/T
M type > 20 mV/T

L - lower - N type > 10 mV/T
M type > 5 mV/T

❷ *Active area size:* **N** - normal
M - micro

❸ *Construction of the probe :*

U - unpackaged
P - packaged in synthetic resin - transverse
A - packaged in synthetic resin - axial

Example

LHP-NP is the lover sensitivity probe with normal size electrical system, packaged.

Leads

Colour code: Control current - green, black
Hall voltage - orange, red

Leads are made from copper wires:
⌀ 0,10 mm - current leads
⌀ 0,08 mm - Hall leads

Applications

For technical assistance with your specific needs and problems, contact applications engineers at

Institute Of Electrical Engineering, Bratislava

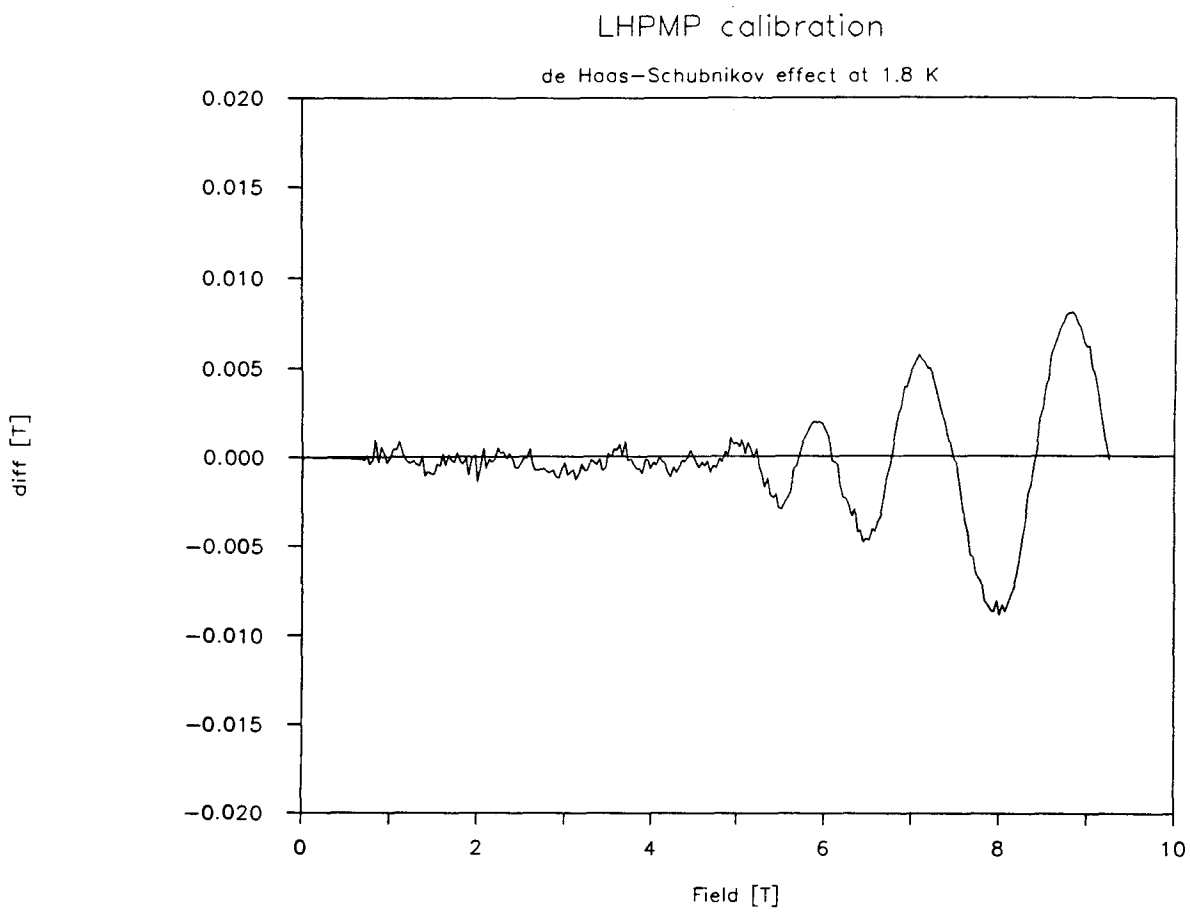
TEL: ++42 7 375806
FAX: ++42 7 375816

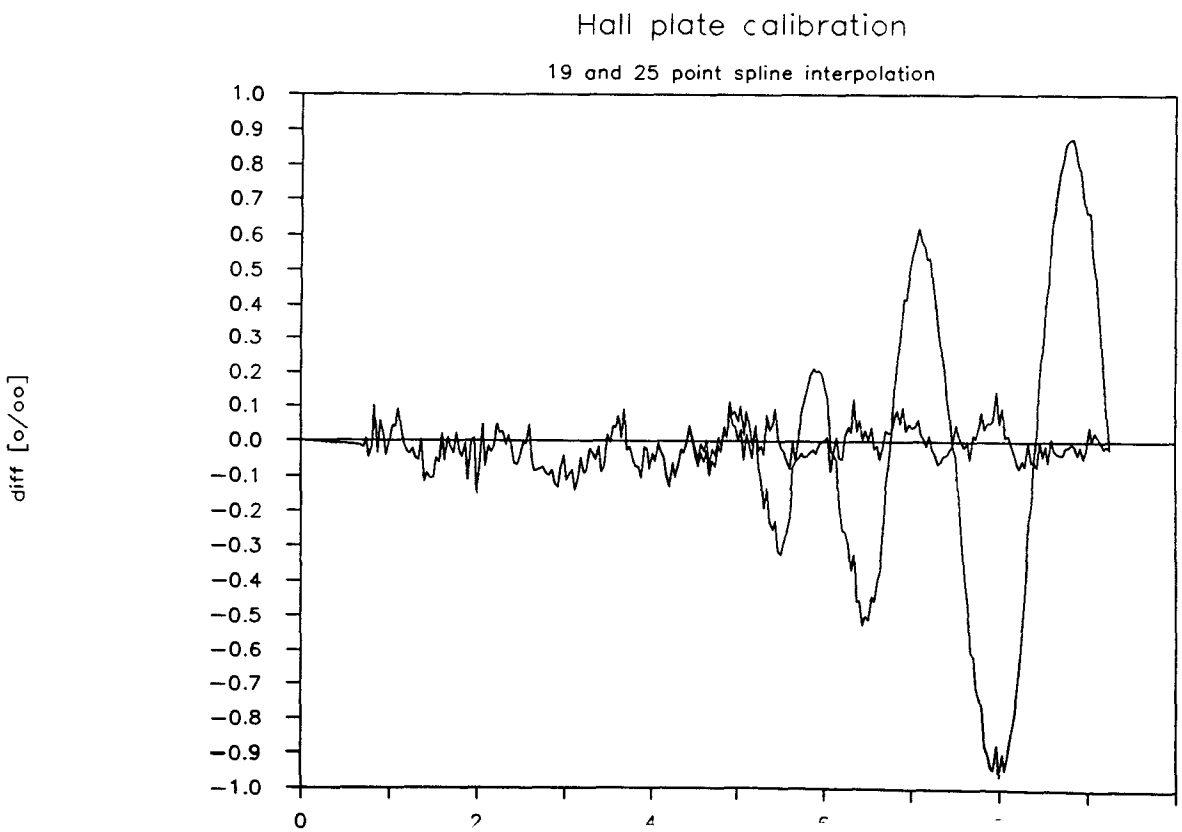
Sales Representative

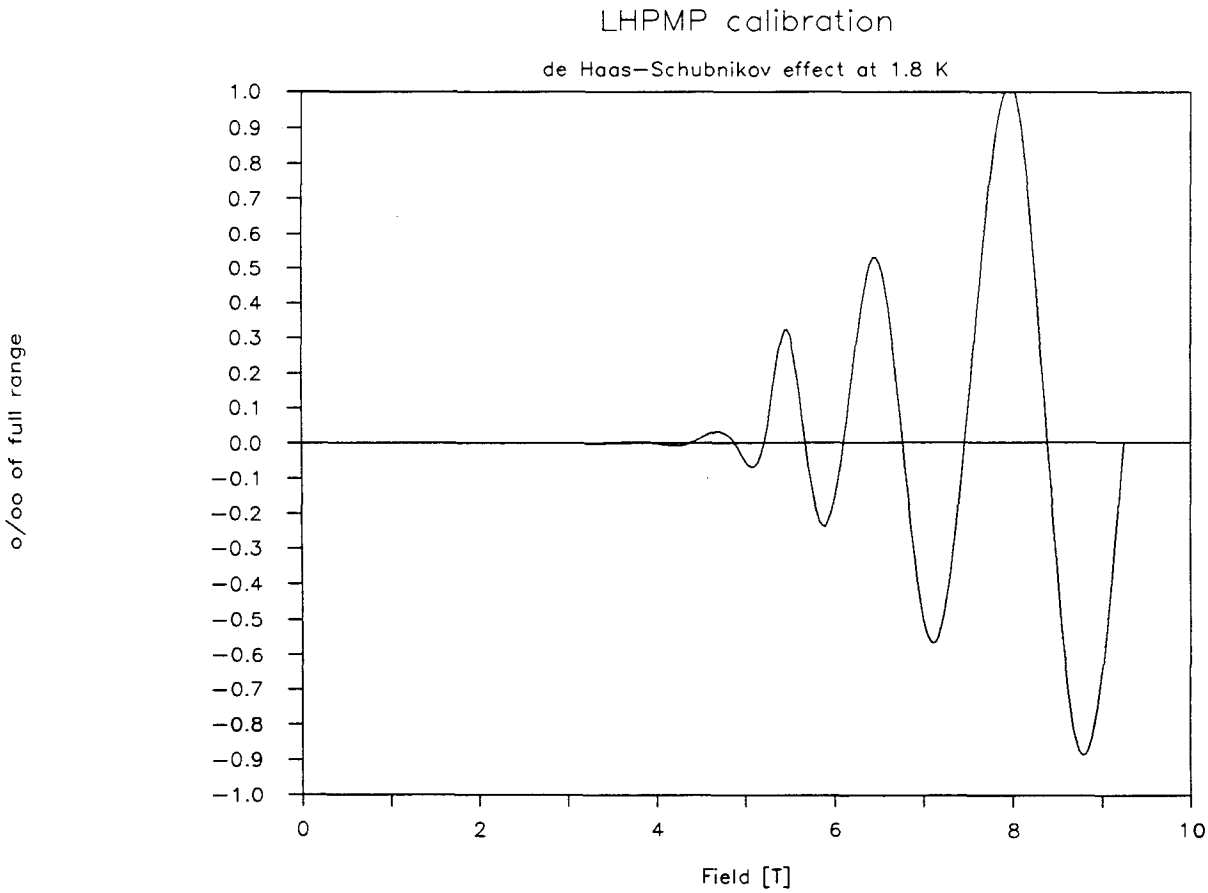
For current pricing information, terms and conditions, call or fax to :

Arepoc - Lubo Kopera, Bratislava

TEL/FAX: ++42 7 824613


LHPMP calibration
de Haas–Schubnikov effect at 1.8 K
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
−0.020
diff [T]
0
2
4
6
8
10
Field [T]


Hall plate calibration
19 and 25 point spline interpolation
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
−0.7
−0.8
−0.9
−1.0
diff [o/oo]
0


LHPMP calibration
de Haas–Schubnikov effect at 1.8 K
o/oo of full range
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
−0.7
−0.8
−0.9
−1.0
0
2
4
6
8
10
Field [T]

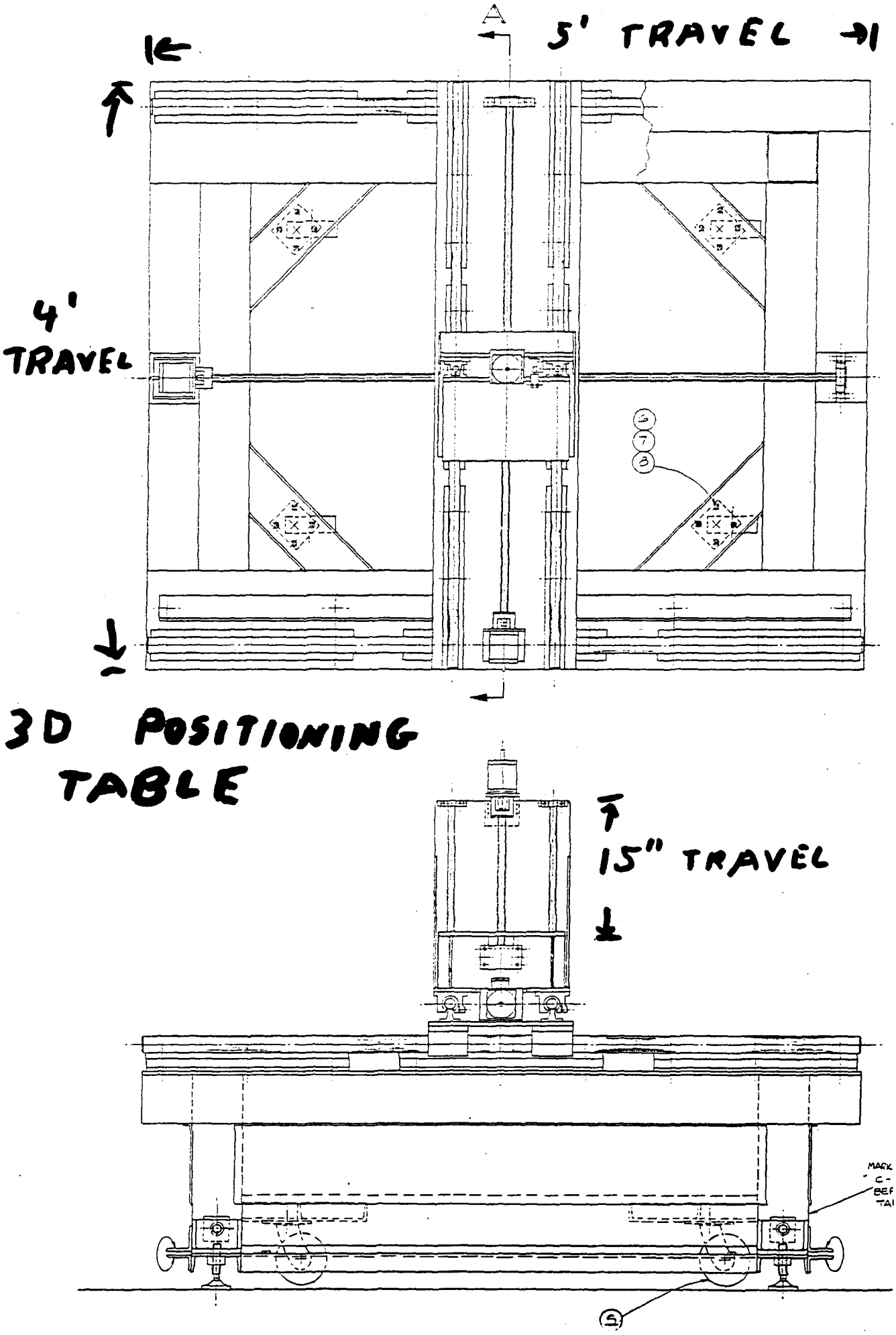
"NEXT GENERATION AUTOMATED MAGNET MEASUREMENT SYSTEM FOR TRIUMF."

PAUL REEVE
MIKE BARNES
DOUG EVANS
DAVE MORRIS

ation of automated magnet measurement equipment, to replace the present system, at TRIUMF. The four main aims are:

1. Review the stepping motor and 3D positioning system requirements to see if they can be met by a commercial system.
2. Review the acquisition system requirements for both dc and ac measurements. Consider improvements in setting up the measurement parameters and on-line verification of the data.
3. Determine how best to set up a database management and analysis system for the magnetic field data.
4. Determine the optimum computer system and software to use for this work, assuming integration with the present central computing facility is necessary.

The magnet measurement system considered is a general purpose system, but it is also considered to be a prototype for KAON. Thus, in order to ensure that the next generation of magnet measurement systems would also be suitable for KAON, the specifications of KAON factory magnets are considered.


A
5' TRAVEL
4' TRAVEL
3D POSITIONING TABLE
15" TRAVEL
MARK
C-
BEF
TAI

OLD TRIUMF MAGNET MEASUREMENT SYSTEM.

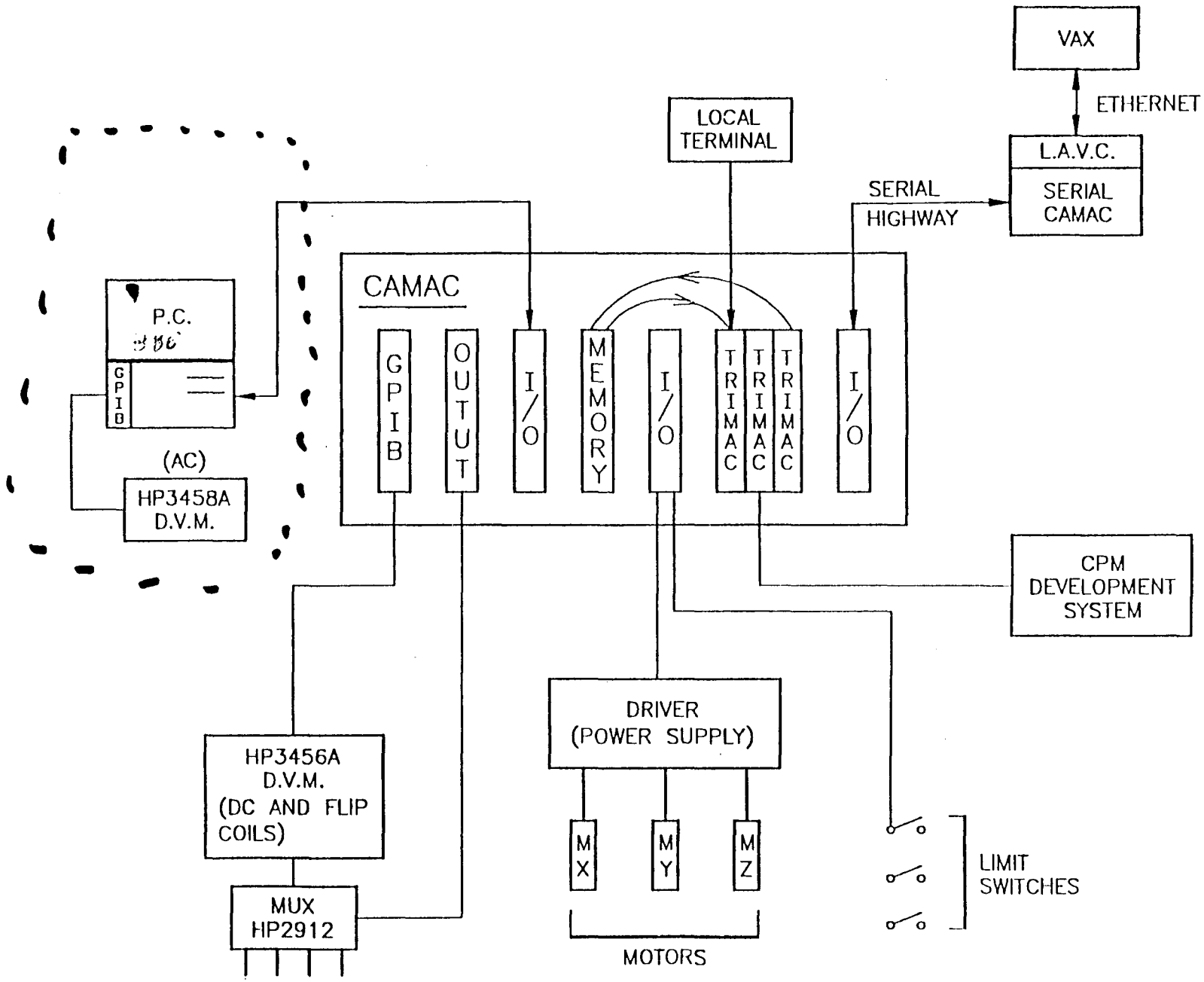


Table 2: Present and Proposed Instrumentation

'Type' of Measurement	Present Instrumentation and Computer	Proposed Instrumentation and Computer	Comments re Proposed Instrumentation
Hall Probe - ac	HP3458A DVM & pc	HP3458A DVM & pc or DECstation	exists
Hall Probe - dc	HP3456A DVM & TRIMAC	HP3458A DVM & pc or DECstation	exists
Flip Coils	Electronic Integrators HP2912 MUX, HP3456A DVM & TRIMAC	Electronic Integrators[1] HP3488A MUX, HP3458A DVM & pc or DECstation	or integrating DVM exists exists
Rotating Coils	Quan-Tech Wave Analyzer Pen and Paper	HP3458A DVM & FFT on data logging computer (pc or DECstation) OR: HP35665A Wave Analyzer & pc or DECstation	exists $15,800
Morgan Coils	RMS meter, HP3458A DVM & pc	HP3458A DVM & pc or DECstation OR: Rotating Coils[2]	exists

7 Optimum Computer System and Software to use for Measurement System

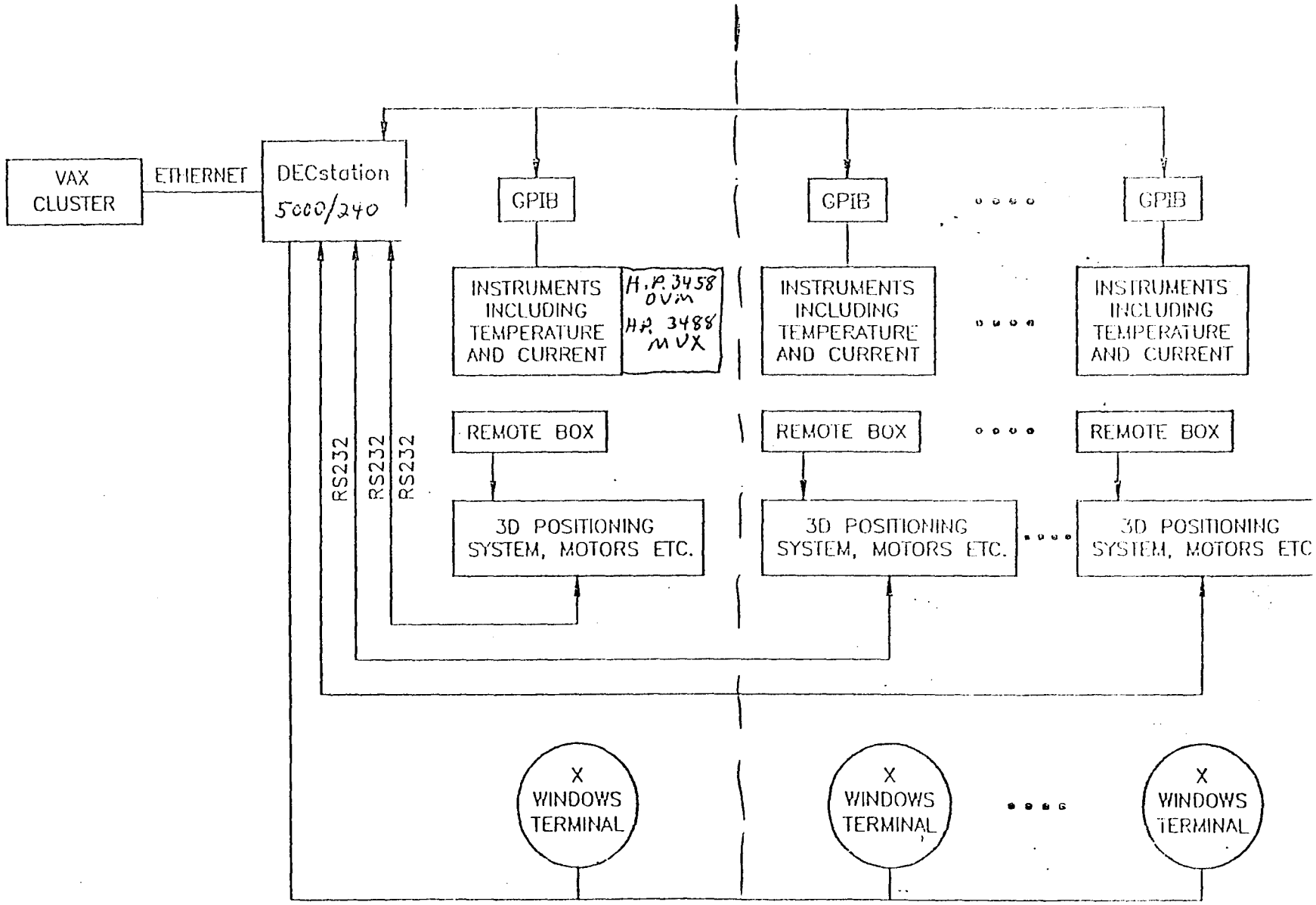
7.1 Platform for Magnet Survey Workstation

Table 3 briefly compares several aspects of IBM compatible pc's, Sun SPARCstations, DEC VAXstations, and DECstations. Silicon Graphics workstation are generally only used for intensive number-crunching, and are not recommended for this application. In addition Plotdata is not supported on Silicon Graphics workstation.

Table 3: Comparison of 4 computer platforms

Platform	pc	SPARCstation	VAXstation	DECstation
Initial Cost with colour monitor	$5,000 (33MHz 486)	$10,000 (SPARC 2)	$10,000 (4000 model 60)	$13,000 (5000 model 240)
Spares & Availability	readily available	may require off-site personnel to repair	may require off-site personnel to repair	may require off-site personnel to repair
# Personnel Familiar with platform	Lots	Some	Lots	Some
Learning Curve	Short	Long	Long	Long
Graphics	available commercially $2,000	available commercially	Plotdata & Opdata (Free)	Plotdata & Opdata (Free)
Database: Oracle Sybase	Yes Yes	Yes Yes	Yes Yes	Yes Yes
Preemptive Multi-tasking	Not with DOS or windows 3 OS2/2 - Yes	Yes	Yes	Yes
Ethernet card	$300	Standard	Standard	Standard
Interface Cards: IEEE-488 # channels or instruments	$660 to $790 13	$1325 to $1990 14	$1325[1] 14[1]	$1,325 14
RS232	Standard	Standard	Standard	Standard

DEC STATION 5000/240
- RUNS EXISTING CLUSTER SOFTWARE DIRECTLY (PLOTDATA ETC.)
- X-WINDOWS
- UNIX OP. SYSTEM
- DIRECT ON-LINE ANALYSIS
- OPERATE UP TO 3 SURVEY TABLES WITH SEPARATE X-WINDOW TERMINALS.


VAX CLUSTER
ETHERNET
DECstation 5000/240
GPIB
GPIB
GPIB
INSTRUMENTS INCLUDING TEMPERATURE AND CURRENT
H.P. 3458 DVM
HP 3488 MUX
INSTRUMENTS INCLUDING TEMPERATURE AND CURRENT
INSTRUMENTS INCLUDING TEMPERATURE AND CURRENT
RS232
RS232
RS232
REMOTE BOX
REMOTE BOX
REMOTE BOX
3D POSITIONING SYSTEM, MOTORS ETC.
3D POSITIONING SYSTEM, MOTORS ETC.
3D POSITIONING SYSTEM, MOTORS ETC
X WINDOWS TERMINAL
X WINDOWS TERMINAL
X WINDOWS TERMINAL

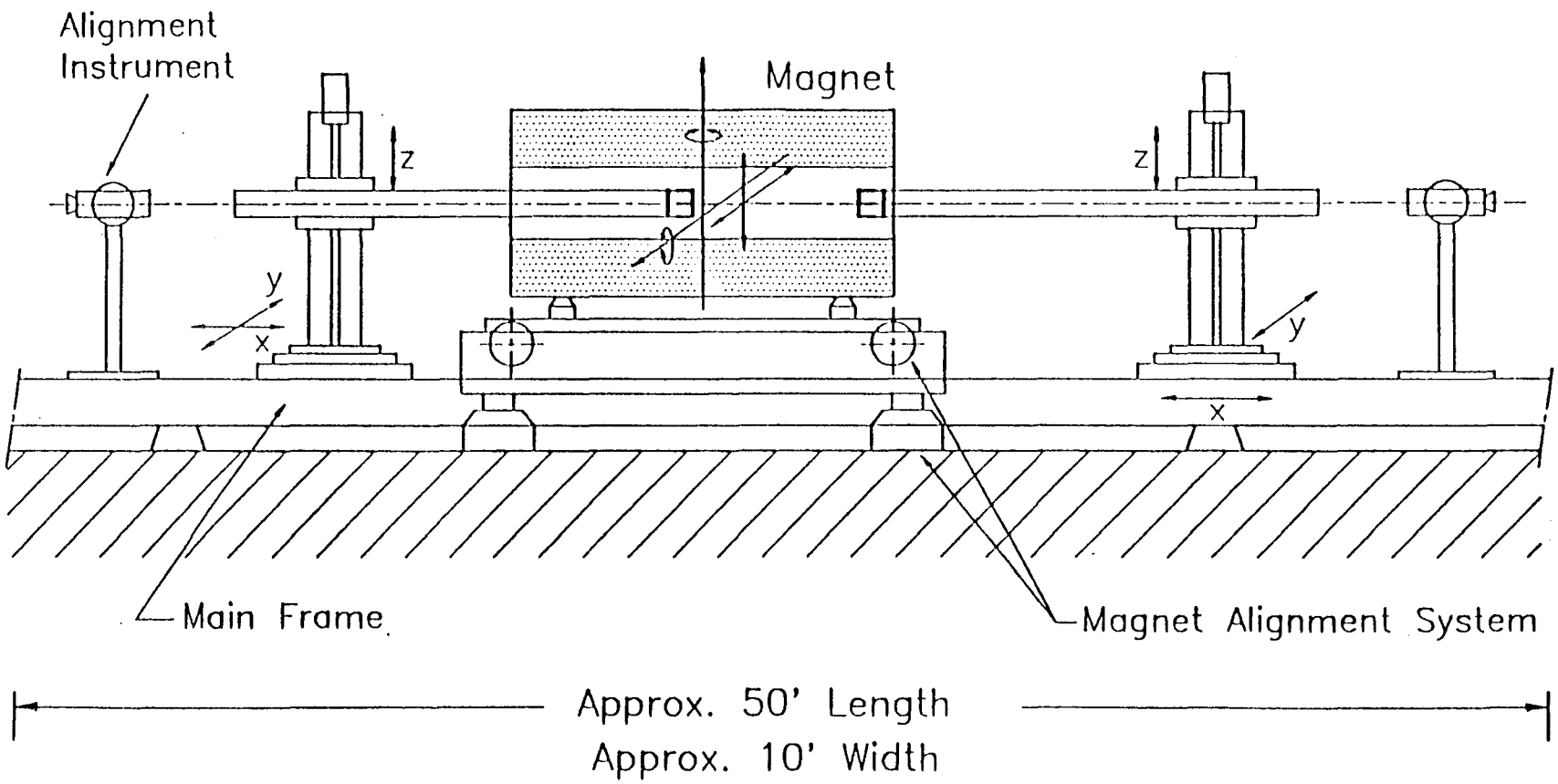


Fig 2: Proposed Magnet Measurement Table.

CONCLUSIONS

) 1ST PRIORITY IS TO REPLACE COMPUTER AND SOFTWARE.
- DEC STATION 5000/240 SO WE CAN USE ALL EXISTING ANALYSIS SOFTWARE AND ALSO RUN UNIX. SOFTWARE WRITTEN IN "C" SO THE LANGUAGE IS WIDELY KNOWN AND VERY PORTABLE.

) MAGNET GROUP ALREADY OWNS NECESSARY UPGRADE INSTRUMENTS FOR FASTER DATA ACQUISITION AND THEY HAVE BEEN IMPLEMENTED IN THE DEC STATION SYSTEM
IE. HP 3458A DVM & HP 3488A MULTIPLEXER.

) NO COMERCIAL SYSTEM HAS BEEN IDENTIFIED TO REPLACE 3D POSITIONING SYSTEM SO IT WILL BE BUILT. CONCEPT DRANING COMPLETED.

) DATABASE WILL BE ORACLE AS IT IS TRIUMF SITE STANDARD AND PROGRAMMERS FAMILIAR WITH IT ARE AVAILABLE.

J. BILLAN
CERN

LHC dipole magnet measurement system at room temperature

Aim

- To control the quality of the superconducting coils

  --> as soon as possible in the fabrication process (collaring)
  --> acceptance test during fabrication
  --> reduced operation time (fabrication cost)

- Fermilab and Hera showed a good **correlation** between warm and cold measurements

Design criteria

- Designed for the LHC prototype dipole magnets

  --> Seven **10 m** long prototypes have been ordered,

    --> 1st delivered at CERN towards the end of 1993.

  --> Inner coil diameter: **50 mm** (56mm for the next)

    --> cold bore tube inner diameter: **43 mm**
    Choosing this last diameter will permit the system to be tested not only on collared coils but also on coils mounted in their iron yoke or even on the finished magnet.

  --> **"Two-in-one"** or separate coils mounted in the same yoke

    --> The system should be able to measure the field direction with respect to the reference surfaces of the collars : **parallelism**

Principle of the measurement

--> **DC current** : 20A (150 gauss, 39 times less than injection level: 5800 gauss)

--> **Radial** search coils: measuring radius: 19 mm, (15.4 mm at 4K)

--> Coil length: 750 mm (< 0.1 mm sag)
14 measurement positions to cover the length

--> **Reference magnet** to calibrate periodically the tilt sensor with respect to the coil-encoder system (tilt sensor drift limitation)

  --> small dipole magnet: 500 gauss @ 3.5 A

Description of the mole

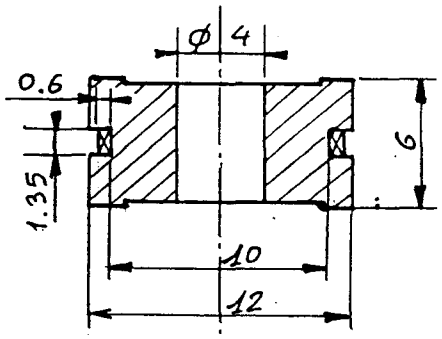
Self-contained mole equipped with coils, encoder and tilt sensor
long shaf mechanically driven from one end
all cabling on the other end

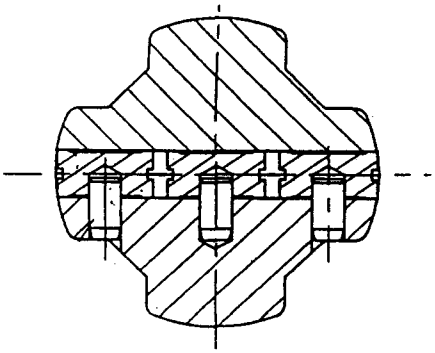
Search coil system

- **Radial** - 3 identical coils
  - measuring radius: 19 mm
  - normal and skew bucking > 1000
  - no skew coil

- Core:
  - Epoxy-glass fiber material (mat): Vetresit 300 (Micafil - CH)
  - CNC machining --> reproducibility

- winding:
  - 20 conductor flat cable (MWS - USA) - 44 AWG (0.05 mm diam.)
  - 200 turns (10 layers)
  - very regularly placed inside their grooves --> reproducibility
  - interconnexion --> specially developped technique - with microscope
    - no extra area
    - robust





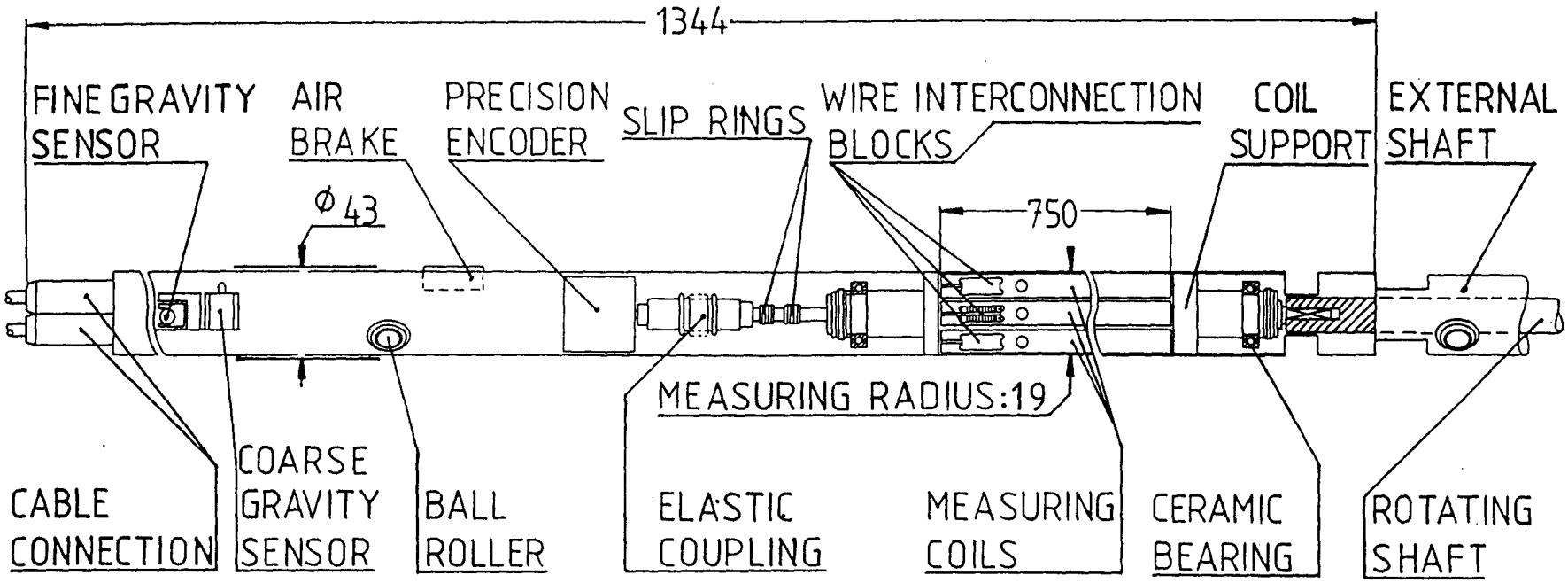
Encoder:
- Minirod 450 (Heidenhain - GE)
- incremental
- 3600 step/turn
- 72000 step/turn after interpolation (16 bit, < 0.1 mrad accuracy)
- calibrated with reference to an absolute 17 bit encoder (ROC 717)
- diameter: 36.5 mm

Tilt sensors:

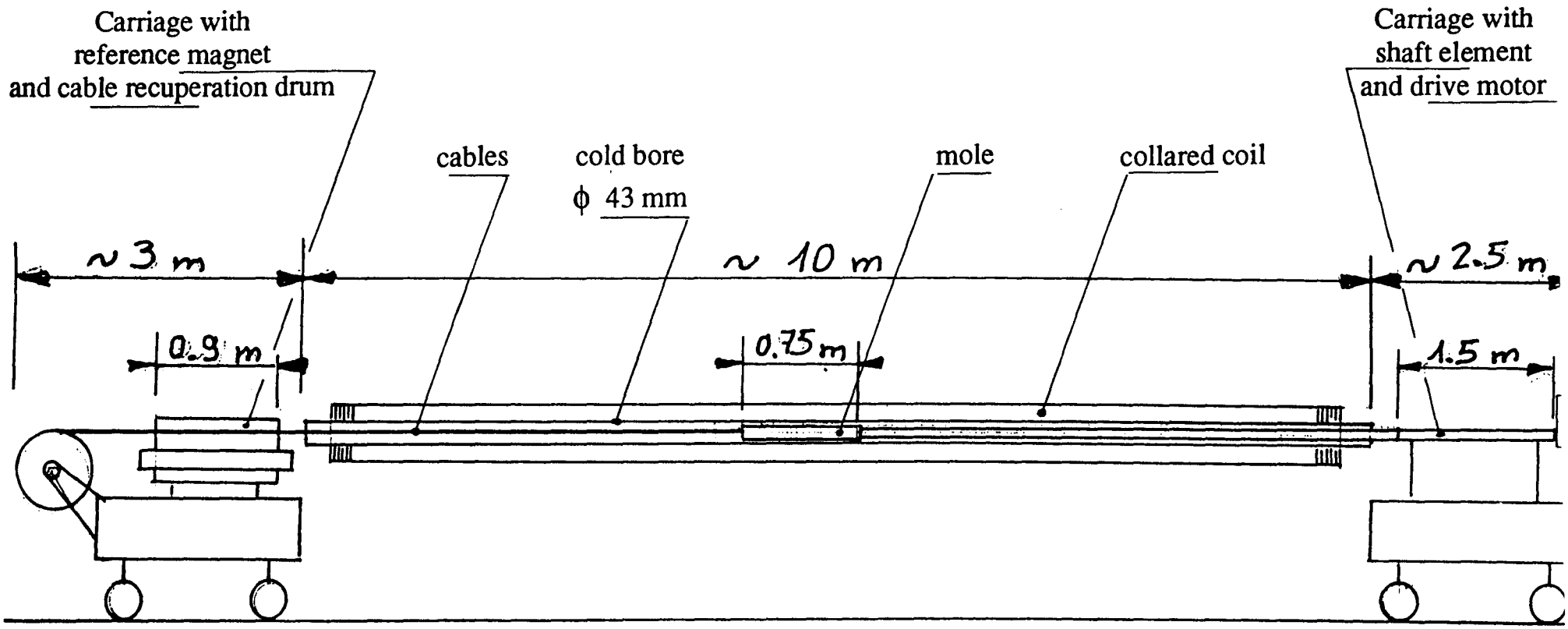
-Fine:
- electrolytic ±1° (Spectron RG-33N - USA)
- 0.03 mrad resolution
- possibly CG-10N ±4° - 0.005 mrad resolution

- Coarse:
  - electrolytic ±60° (Spectron L-211U)
  - possibly capacitive - (Access DTT - CH)
    - ±30° - 0.02 mrad resolution
    - 18 x 18 x 5 mm
    - but noisy (0.1 mrad) ??

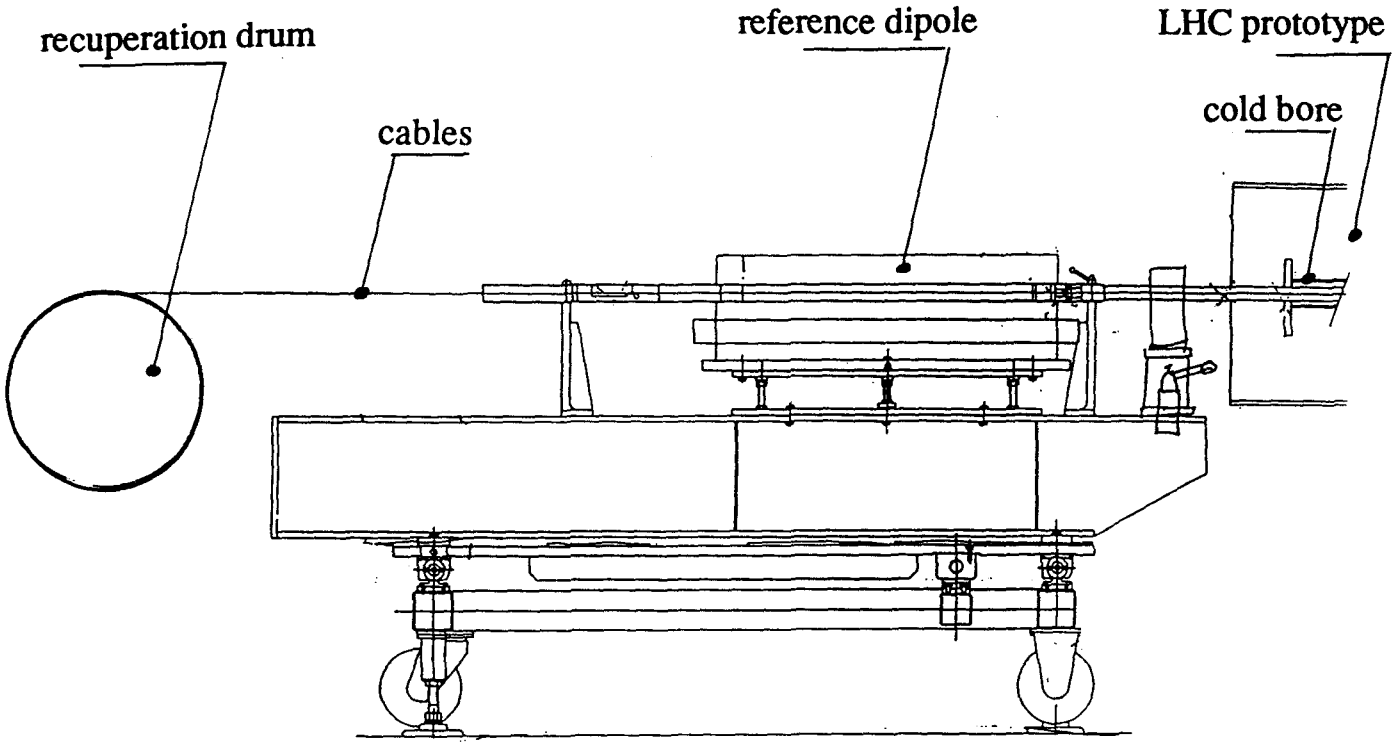
- Still problems with temperature dependence
- Field dependence still to be checked - but not for our application

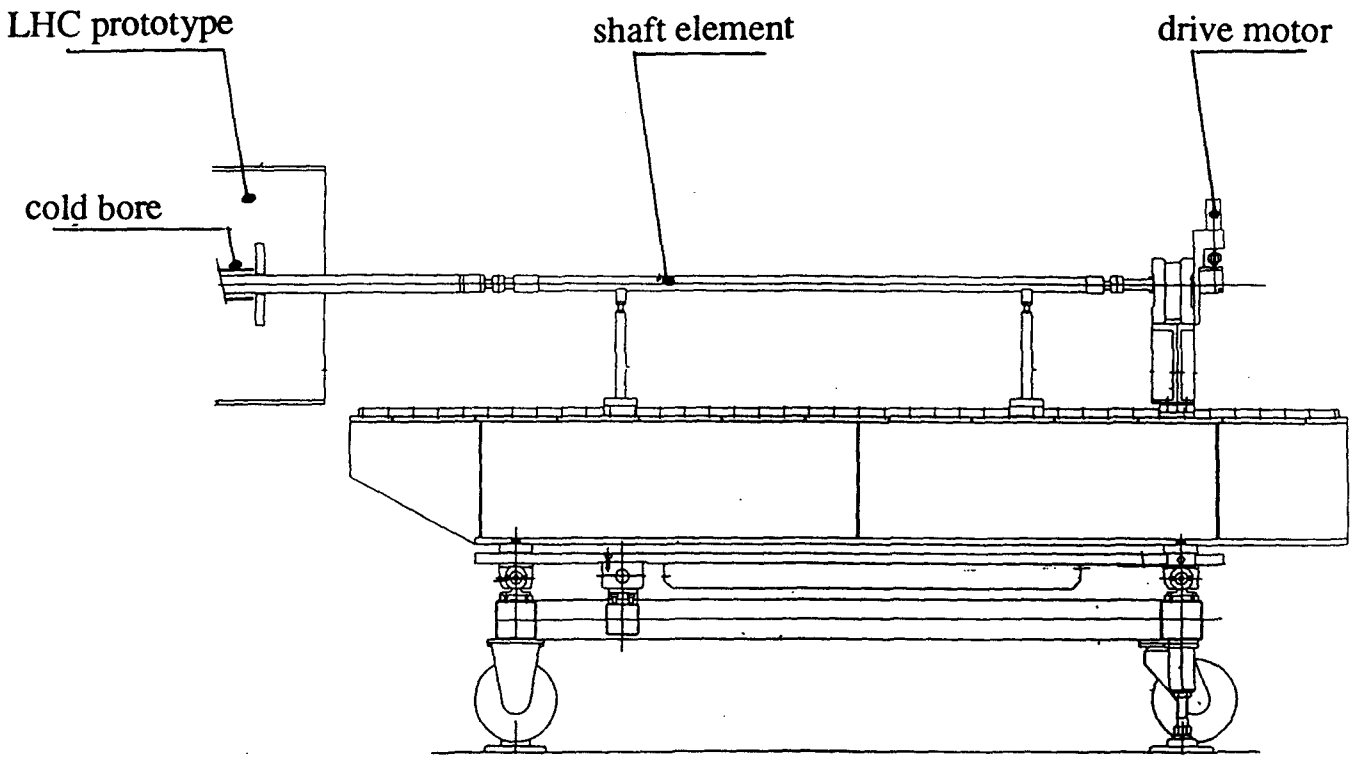


Schematic view of the mole



General view of the measuring system





Detail of the carriages

IR 5

The operation

1. Calibration in the reference magnet

   - tilt sensor zero
   - search coil area
   - global test of the system ("finger-print")

2. Collared coil measured in 14 positions

   - longitudinal translation with a long shaft - manual operation
     - divided in 1.5 m long elements (7 elements)
     - 2 search coil length per element

   - search coil driven by a DC motor
     - 1 turn for rotation stabilization
     - 1 turn for measuring
     - 1 turn for stopping
     - idem in the other direction

3. Idem 1. and 2., in the second coil ("two-in-one" case)

4. Results - tilt with respect to reference surfaces of collars
   - at every position - twist
   - mean value
   - harmonic content - integral
   - transfer function (B/I)

5. Remote communication at CERN - by modem and telephone line

Planning

- The system has been designed to work at the firm with a minimum of intereference

- But it will not be used at the firms for the first prototypes, in order not to complicate their task.

- Measurements are presently made at CERN on short models (1.3 m),
  - with iron yoke
  - mainly to test the system.

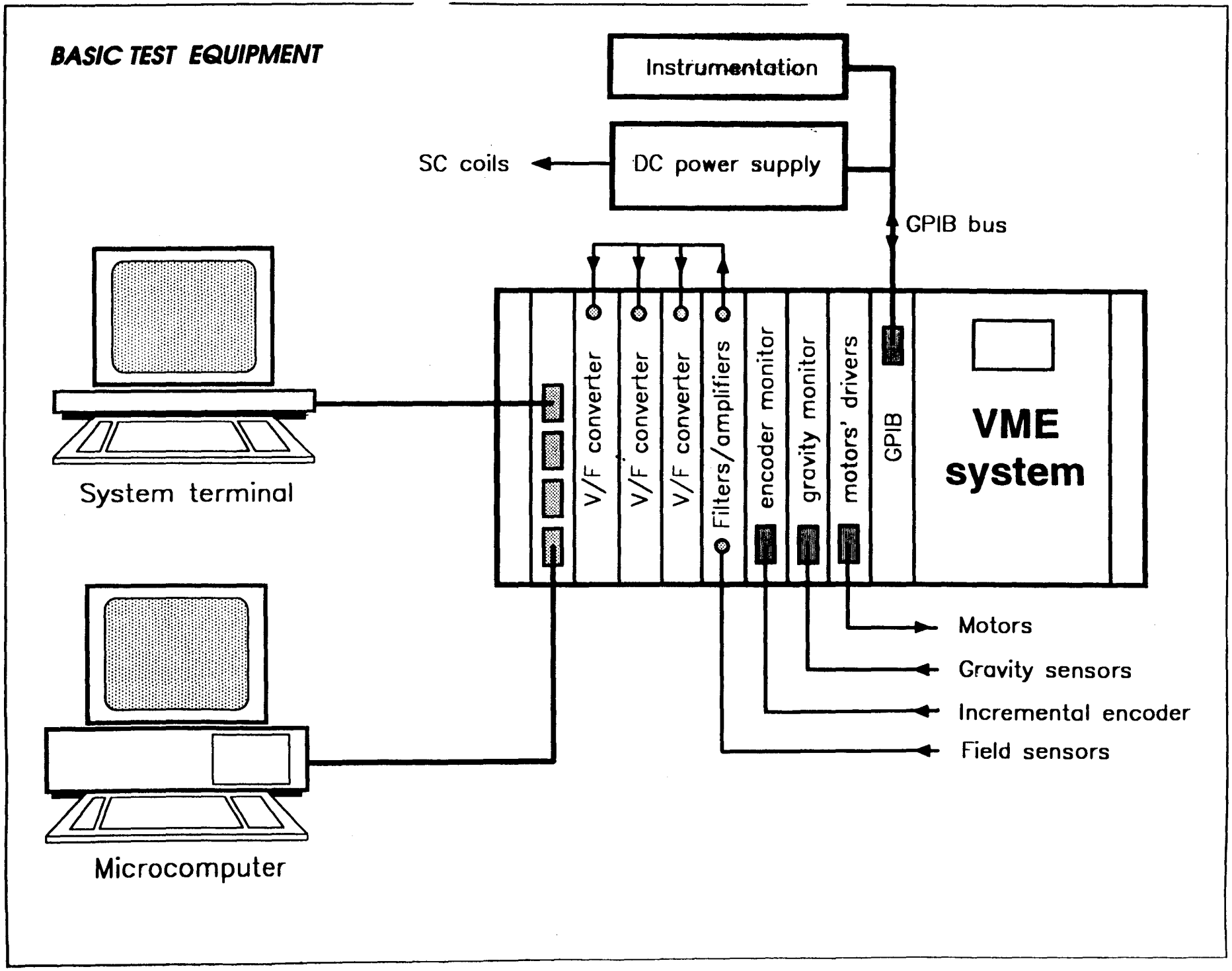
- Measurement on short model coils - without iron yoke

- Measurement on a long copper coil (Holec-Elin prototype: separated coils)

- Measurement at CERN of the finished prototypes

First prototype early in 1994

Should permit the system to be tested and improved in view of the series


BASIC TEST EQUIPMENT
Instrumentation
SC coils
DC power supply
GPIB bus
System terminal
V/F converter
V/F converter
V/F converter
Filters/amplifiers
encoder monitor
gravity monitor
motors' drivers
GPIB
VME system
Motors
Gravity sensors
Incremental encoder
Field sensors
Microcomputer

UPDATE ON THE MEASUREMENT SYSTEMS FOR THE ACCELERATOR MAGNETS AT APS

S. KIM

29 SEPTEMBER 1993

APS - 7-GeV Advanced Photon Source
at Argonne Nat'l Lab
(not the American Physical Society)

Linac
Positron Accumulator Ring
Booster Synchrotron (0.45 GeV → 7.0 GeV)
v Storage Ring : 40-sector Chasman-Green Lattice,
1104-m circumference.

- 80 Dipoles
- 400 Quads
- 280 Sexts
- 320 correctors

30~35 Insertion Device Beam Lines
40 Bending magnet " "

Magnet Measurement Group
Suk H Kim
David Carnegie
Charles Doose
Roger Hogrefe
Keeman Kim
Robert Merl
8 + (2) Technicians

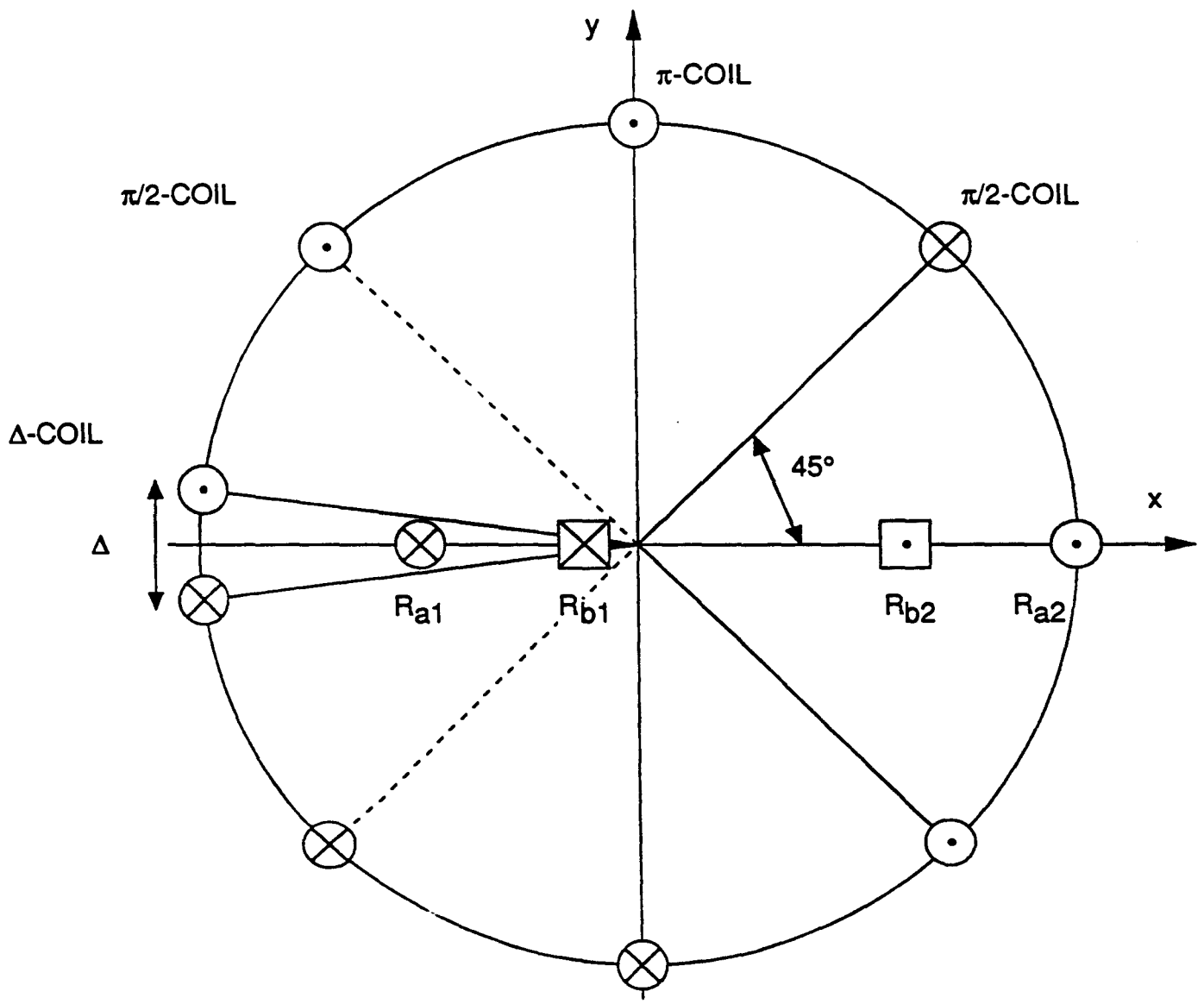
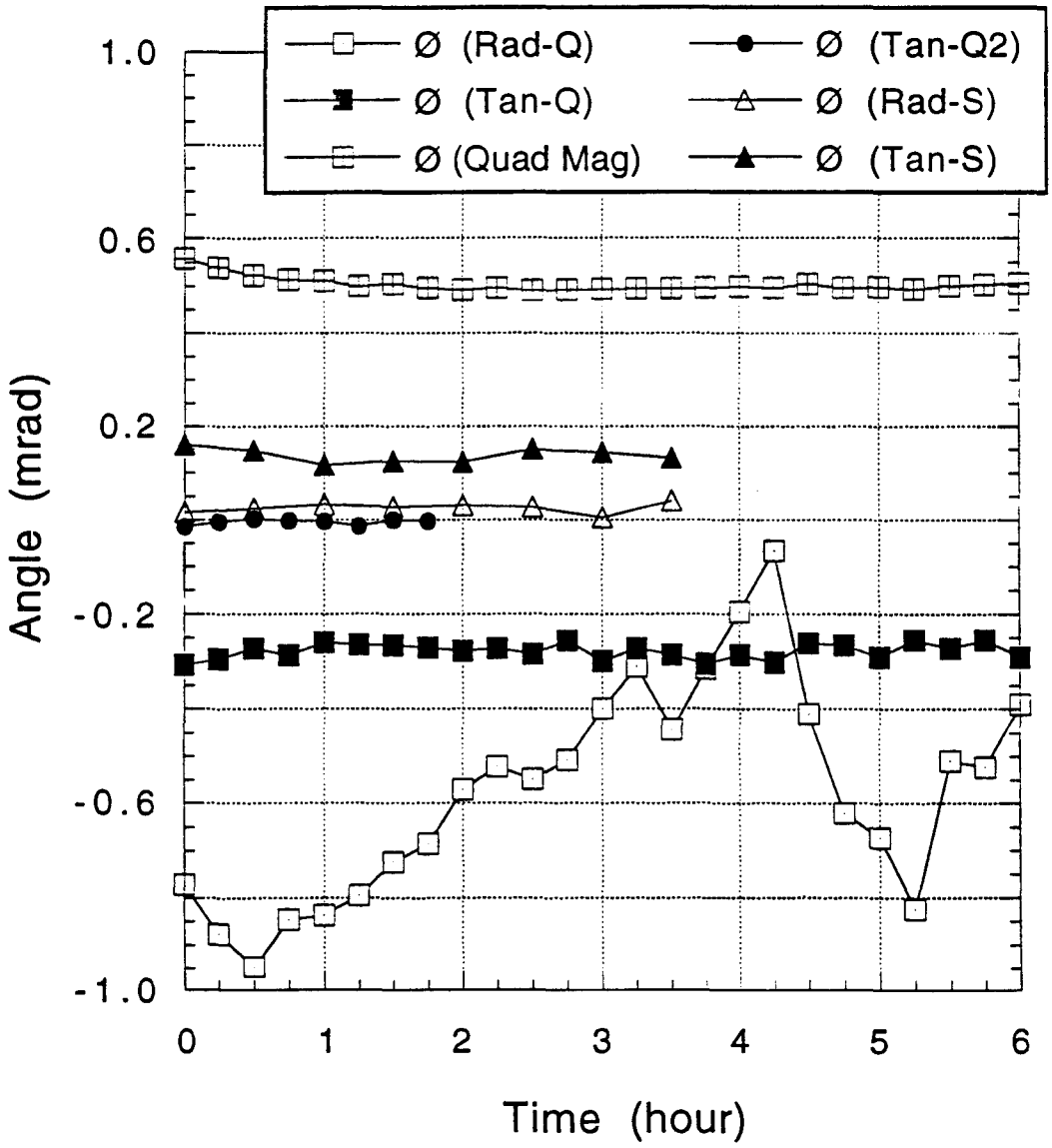
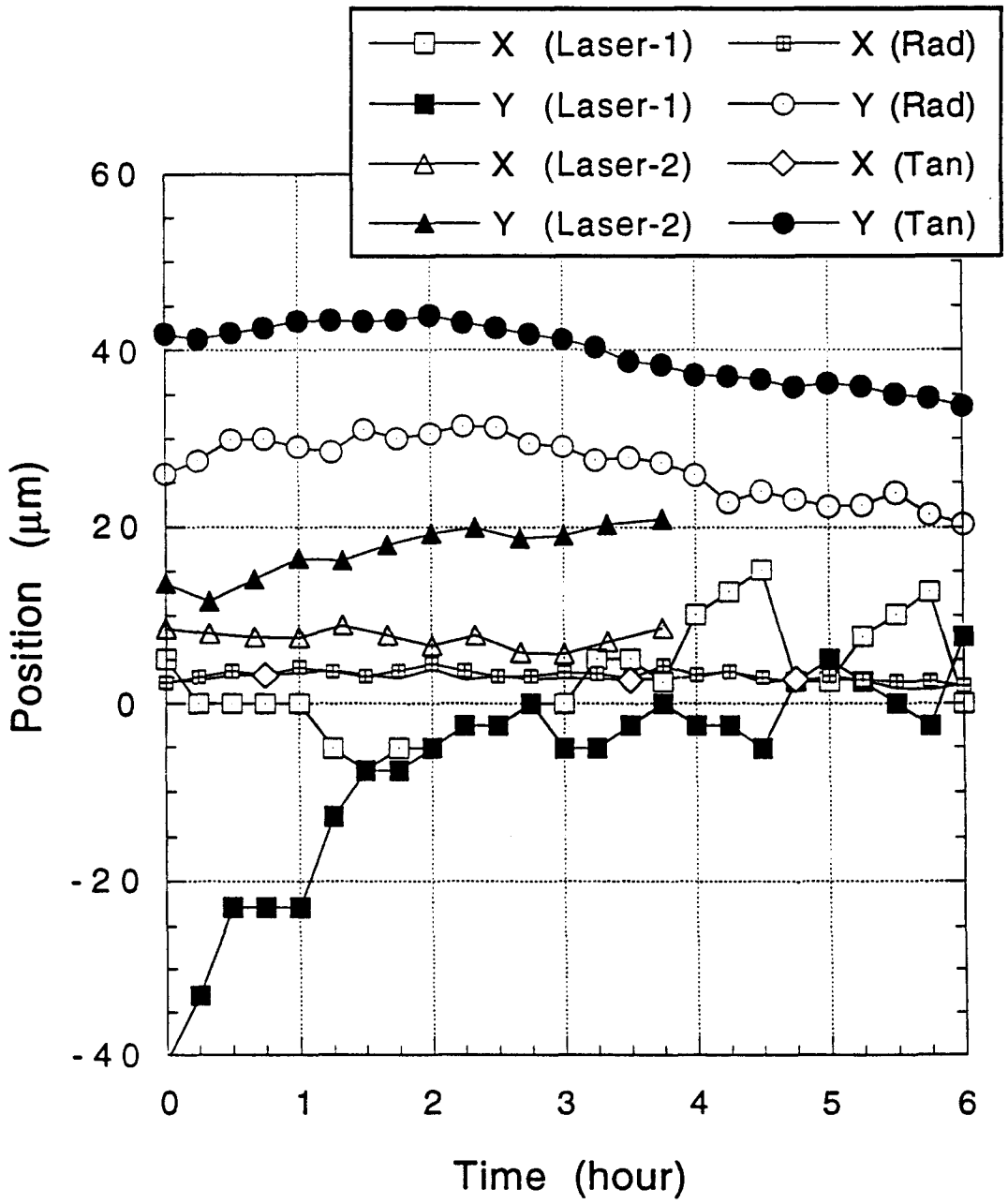
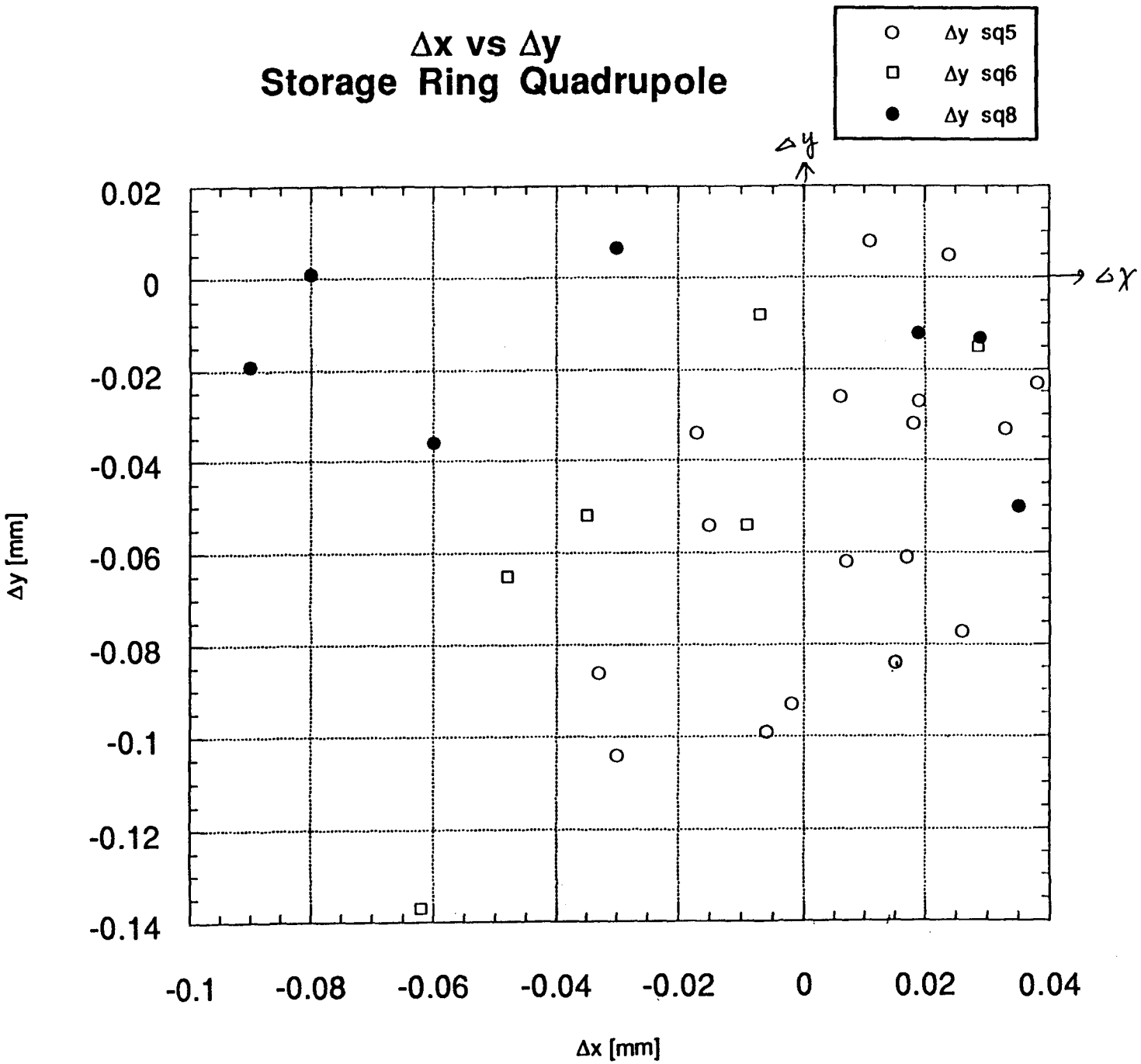


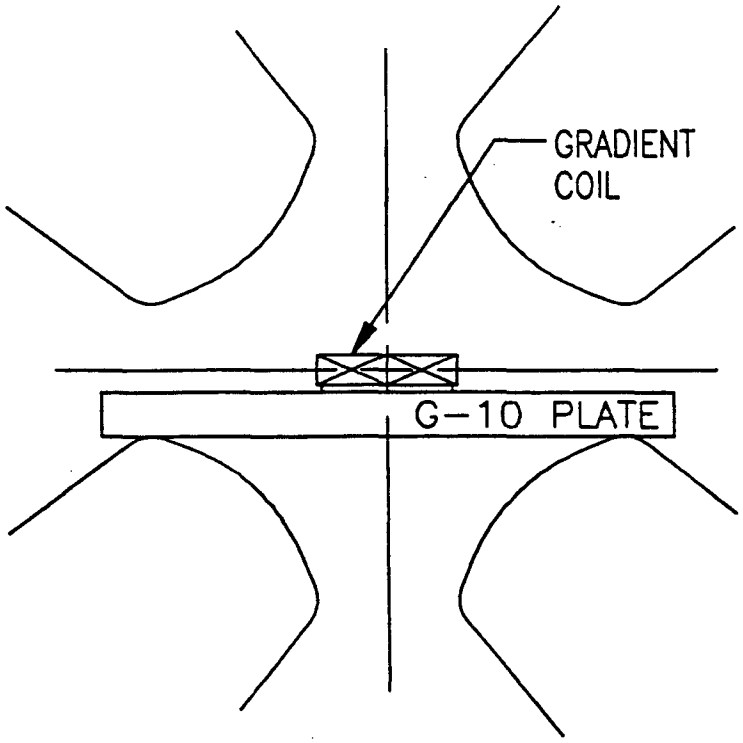
Fig. Cross section of the radial and tangential coil geometries. The radial coil set is located on the x-axis.

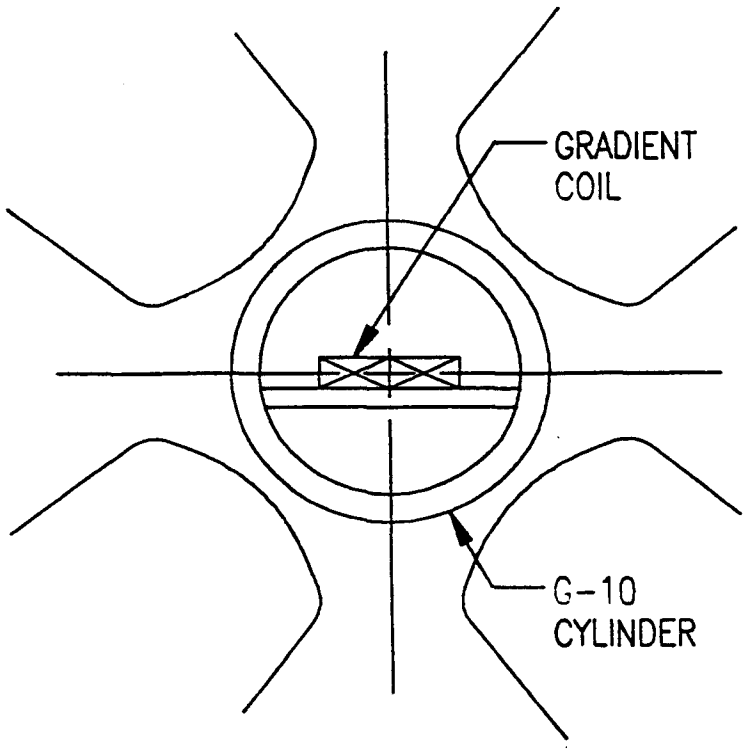

Ø (Rad-Q)
Ø (Tan-Q2)
Ø (Tan-Q)
Ø (Rad-S)
Ø (Quad Mag)
Ø (Tan-S)
1.0
0.6
0.2
-0.2
-0.6
-1.0
Angle (mrad)
0
1
2
3
4
5
6
Time (hour)


X (Laser-1)
X (Rad)
Y (Laser-1)
Y (Rad)
X (Laser-2)
X (Tan)
Y (Laser-2)
Y (Tan)
60
40
20
0
-20
-40
Position (µm)
0
1
2
3
4
5
6
Time (hour)


Δx vs Δy
Storage Ring Quadrupole
Δy sq5
Δy sq6
Δy sq8
Δy
Δx
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
Δy [mm]
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
Δx [mm]

GRADIENT COIL





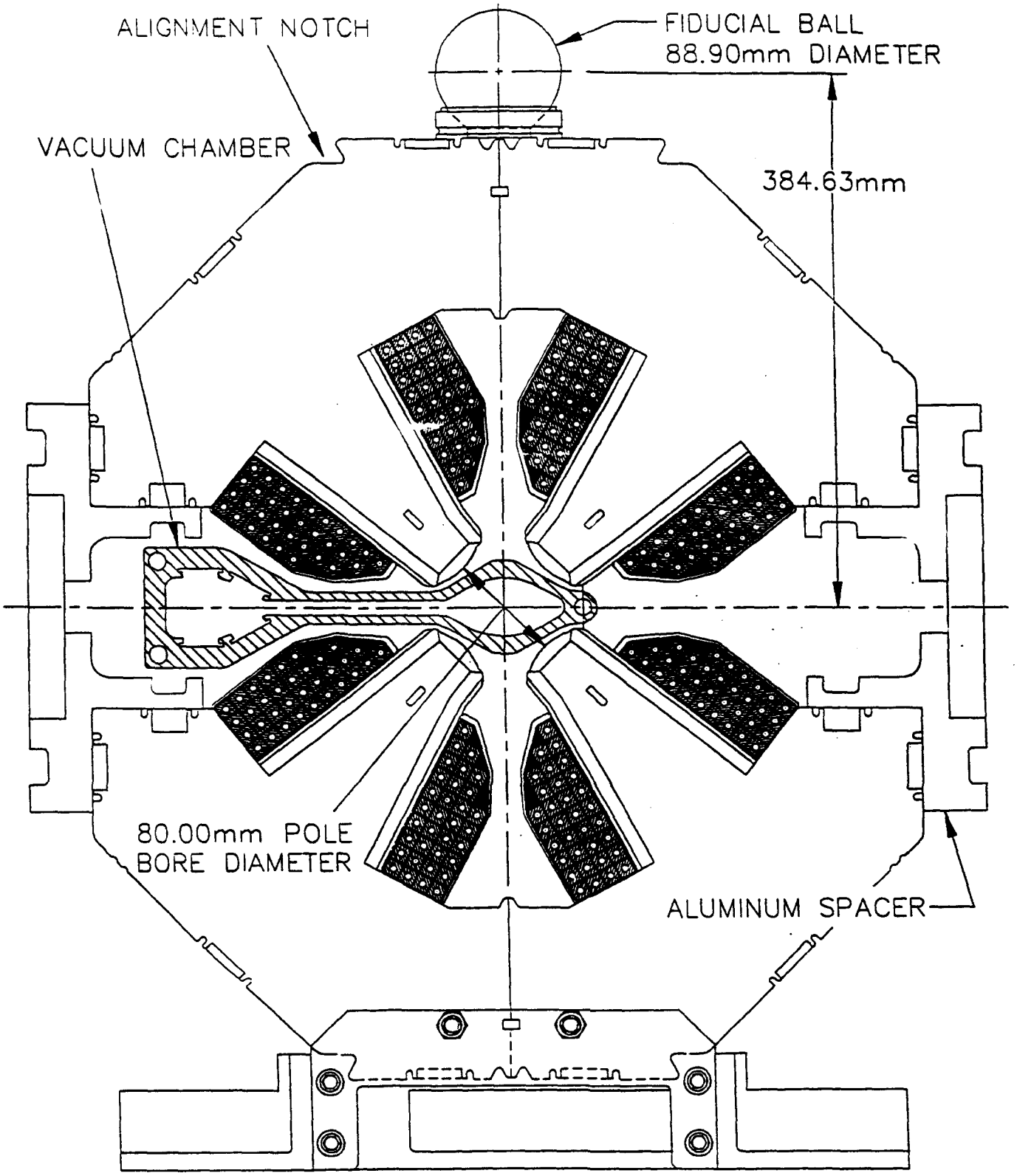
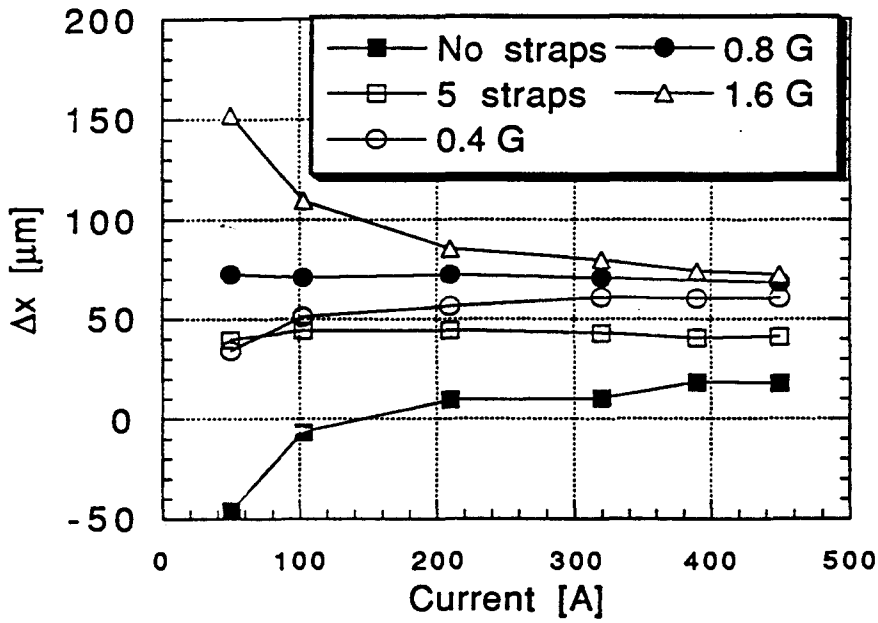
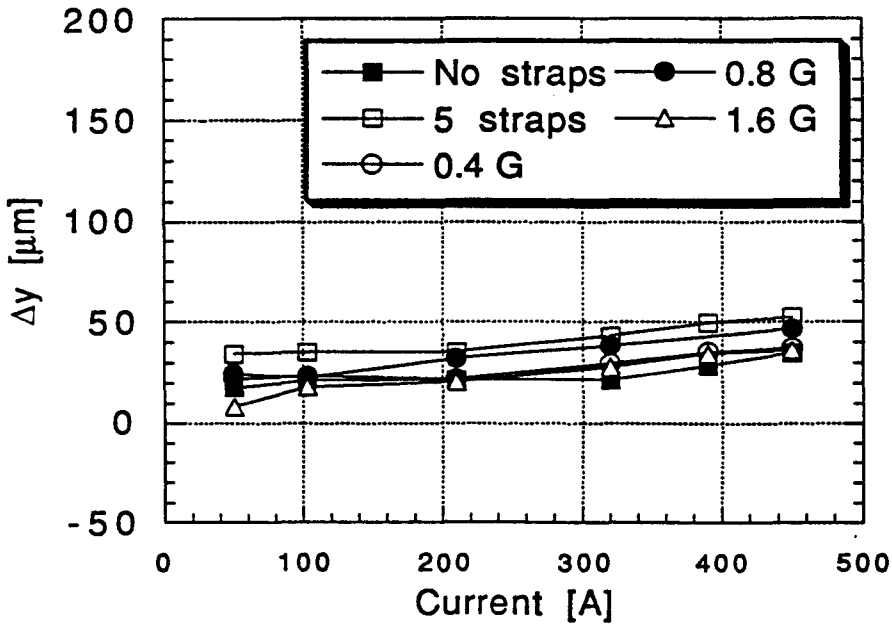
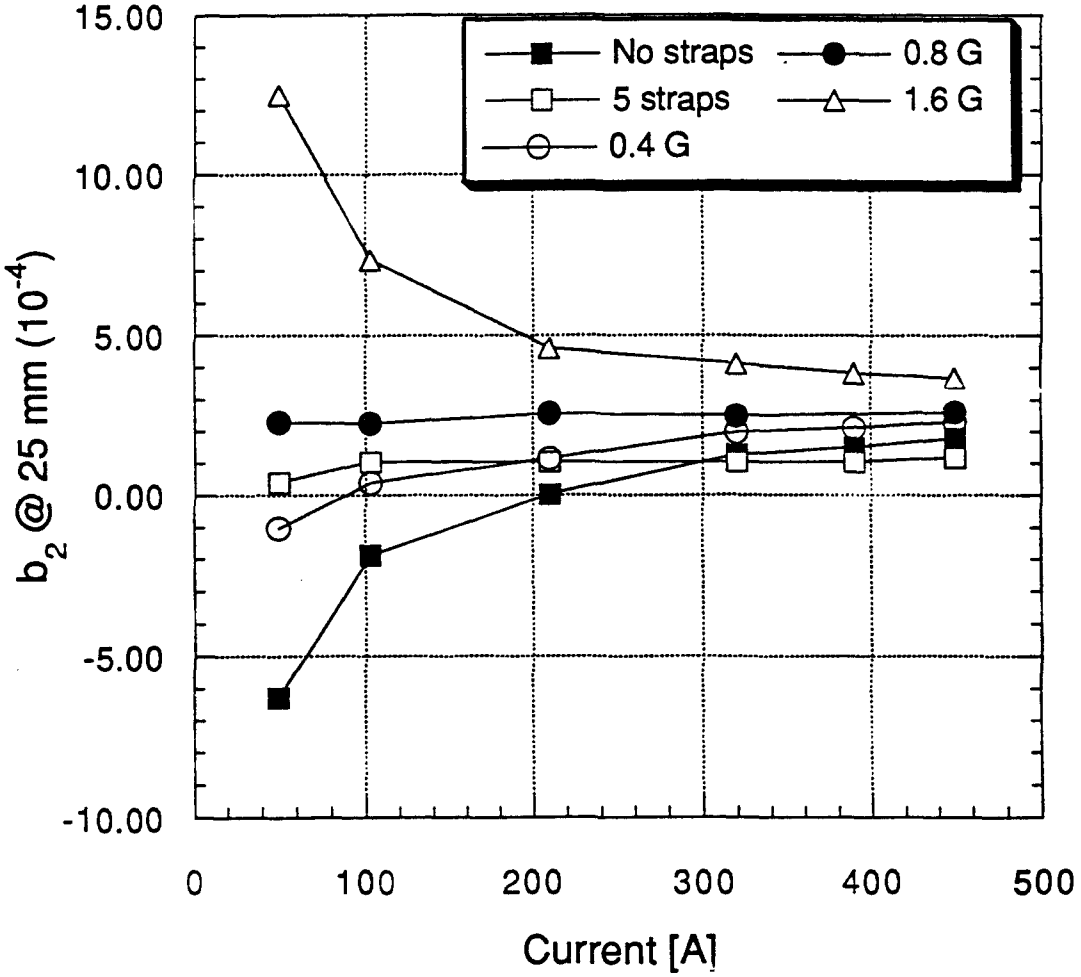


Fig. Cross section of the SR quad with the vacuum chamber.


No straps
0.8 G
5 straps
1.6 G
0.4 G
Δx [μm]
200
150
100
50
0
-50
0
100
200
300
400
500
Current [A]


No straps
0.8 G
5 straps
1.6 G
0.4 G
Δy [μm]
200
150
100
50
0
-50
0
100
200
300
400
500
Current [A]


15.00
10.00
5.00
0.00
-5.00
-10.00
b_2 @ 25 mm (10^{-4})
0
100
200
300
400
500
Current [A]
No straps
5 straps
0.4 G
0.8 G
1.6 G

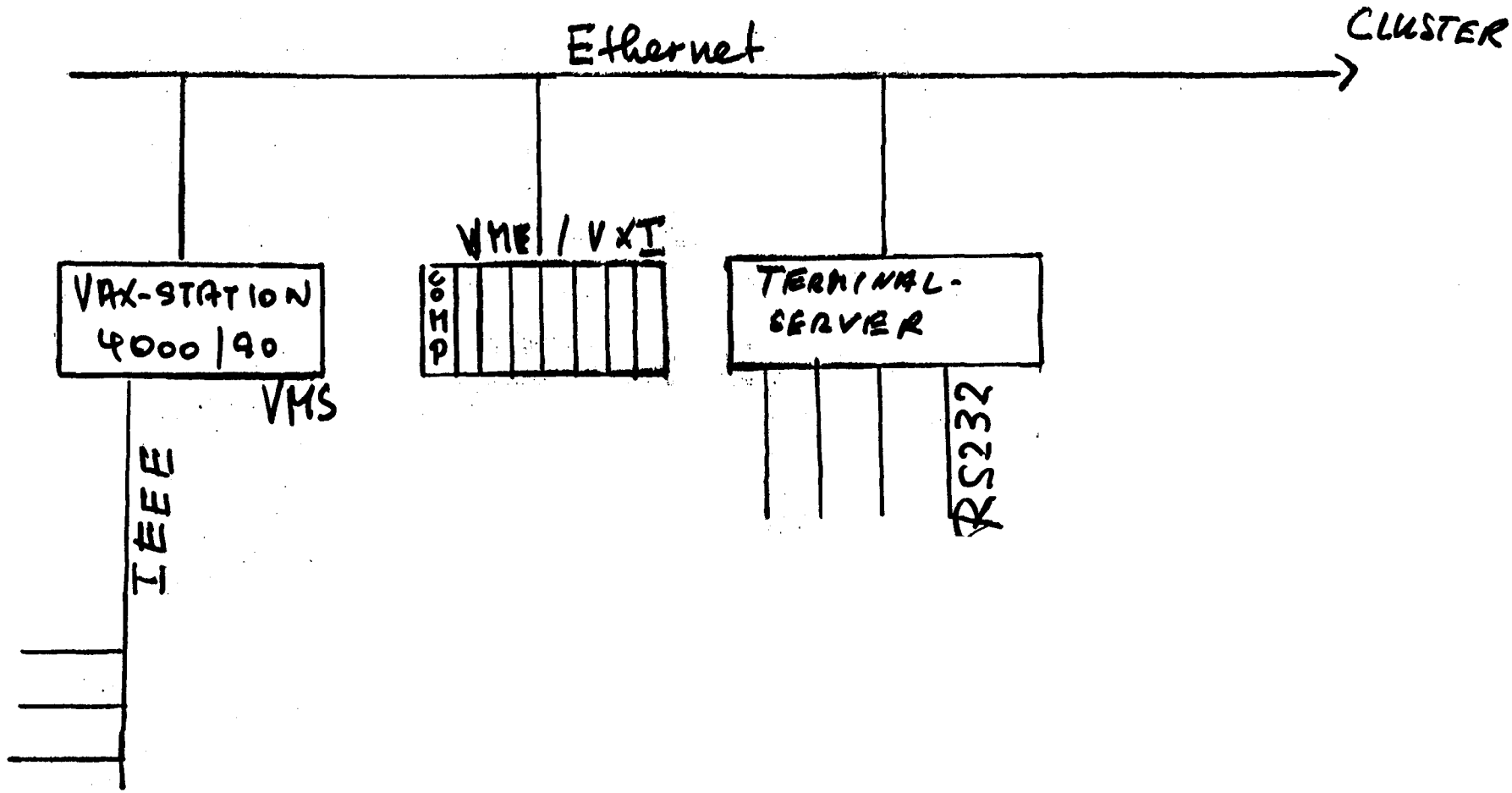
PLANNED MEASUREMENT, CONTROL AND DATA ACQUISITION AT GSI

G. MORITZ

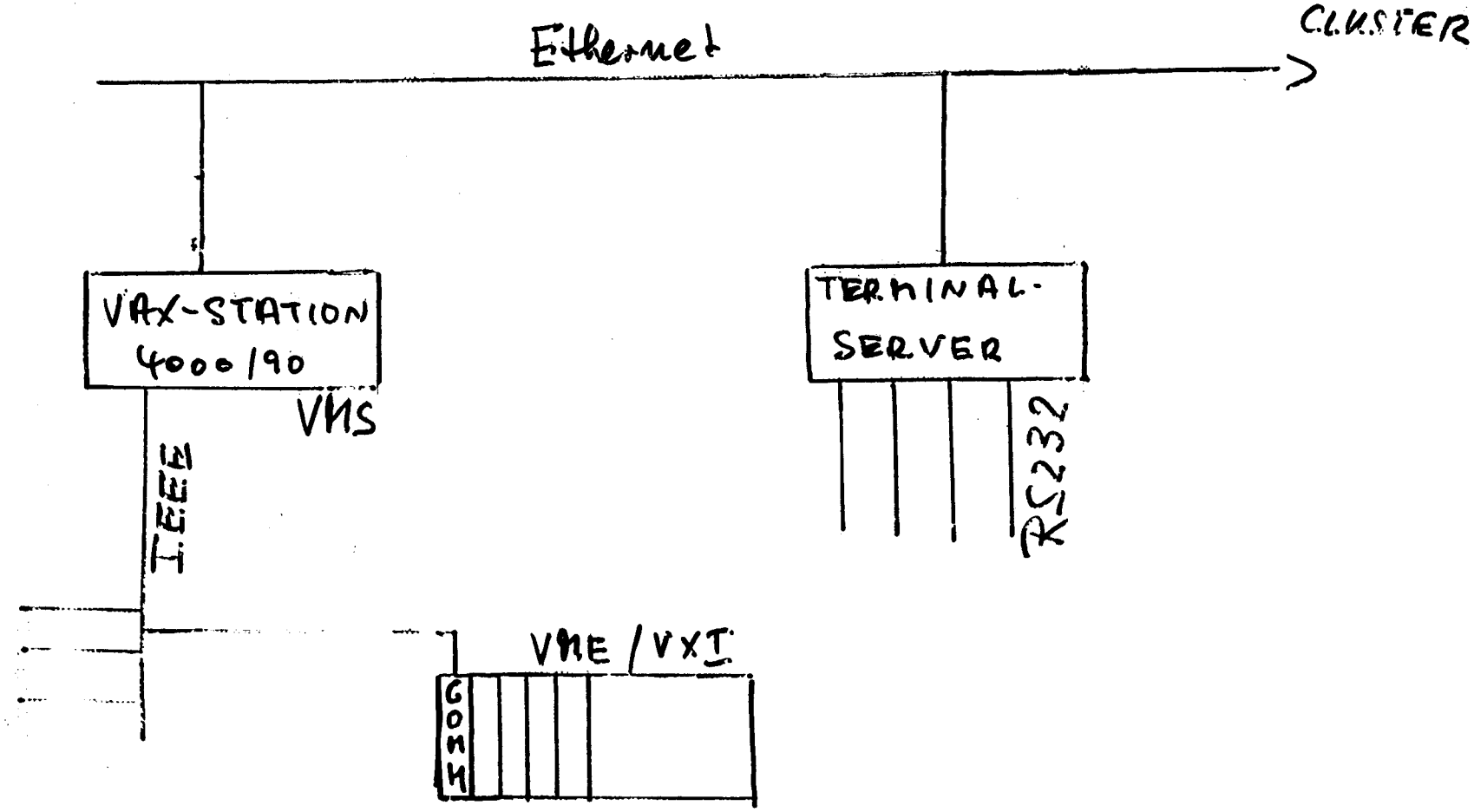
29 SEPTEMBER 1993

Software : limited man power !

- Keep as much as possible of the already existing code
- Use as much as possible software support of other groups


Ethernet
CLUSTER
VAX-STATION
4000/90
VMS
IEEE
VME / VXI
COMP
TERMINAL-
SERVER
RS232

Preferred Solution



7 Optimum Computer System and Software to use for Measurement System

7.1 Platform for Magnet Survey Workstation

Table 3 briefly compares several aspects of IBM compatible pc's, Sun SPARCstations, DEC VAXstations, and DECstations. Silicon Graphics workstation are generally only used for intensive number-crunching, and are not recommended for this application. In addition Plotdata is not supported on Silicon Graphics workstation.

Table 3: Comparison of 4 computer platforms

Platform	pc	SPARCstation	VAXstation	DECstation
Initial Cost with colour monitor	$5,000 (33MHz 486)	$10,000 (SPARC 2)	$10,000 (4000 model 60)	$13,000 (5000 model 240)
Spares & Availability	readily available	may require off-site personnel to repair	may require off-site personnel to repair	may require off-site personnel to repair
# Personnel Familiar with platform	Lots	Some	Lots	Some
Learning Curve	Short	Long	Long	Long
Graphics	available commercially $2,000	available commercially	Plotdata & Opdata (Free)	Plotdata & Opdata (Free)
Database: Oracle Sybase	Yes Yes	Yes Yes	Yes Yes	Yes Yes
Preemptive Multi-tasking	Not with DOS or windows 3 OS2/2 - Yes	Yes	Yes	Yes
Ethernet card	$300	Standard	Standard	Standard
Interface Cards: IEEE-488 # channels or instruments	$660 to $790 13	$1325 to $1990 14	$1325[1] 14[1]	$1,325 14
RS232	Standard	Standard	Standard	Standard

DEC STATION 5000/240
- RUNS EXISTING CLUSTER SOFTWARE DIRECTLY (PLOTDATA ETC.)
- X-WINDOWS
- UNIX OP. SYSTEM
- DIRECT ON-LINE ANALYSIS
- OPERATE UP TO 3 SURVEY TABLES WITH SEPARATE X-WINDOW TERMINALS.

Bestellungen für Umrüstung Meßdatenerfassung Magnetlabor:

	Pos			
	1	1 St.	VAXstation 4000/90	23401,00
	2	2 St.	Speichererweiterung à 32 MB }	8920,50
	3	1 St.	Plattenlaufwerk 2,1 GB }	
	4	1 St.	Bandlaufwerk 1/2"	6975,00
Labor	5	1 St.	Laserprinter mit Postscript	3303,36
	6	1 St.	Laserprinter ohne Postscript	2176,20
	7	1 St.	Hitachi Farbmonitor	5147,60
Labor	8	1 St.	Graphic-Station VXT2000+	8171,91
Labor	9	1 St.	Speichererweiterung	346,75
	10	1 St.	DECserver 700DL	4110,60
				DM 62552,92

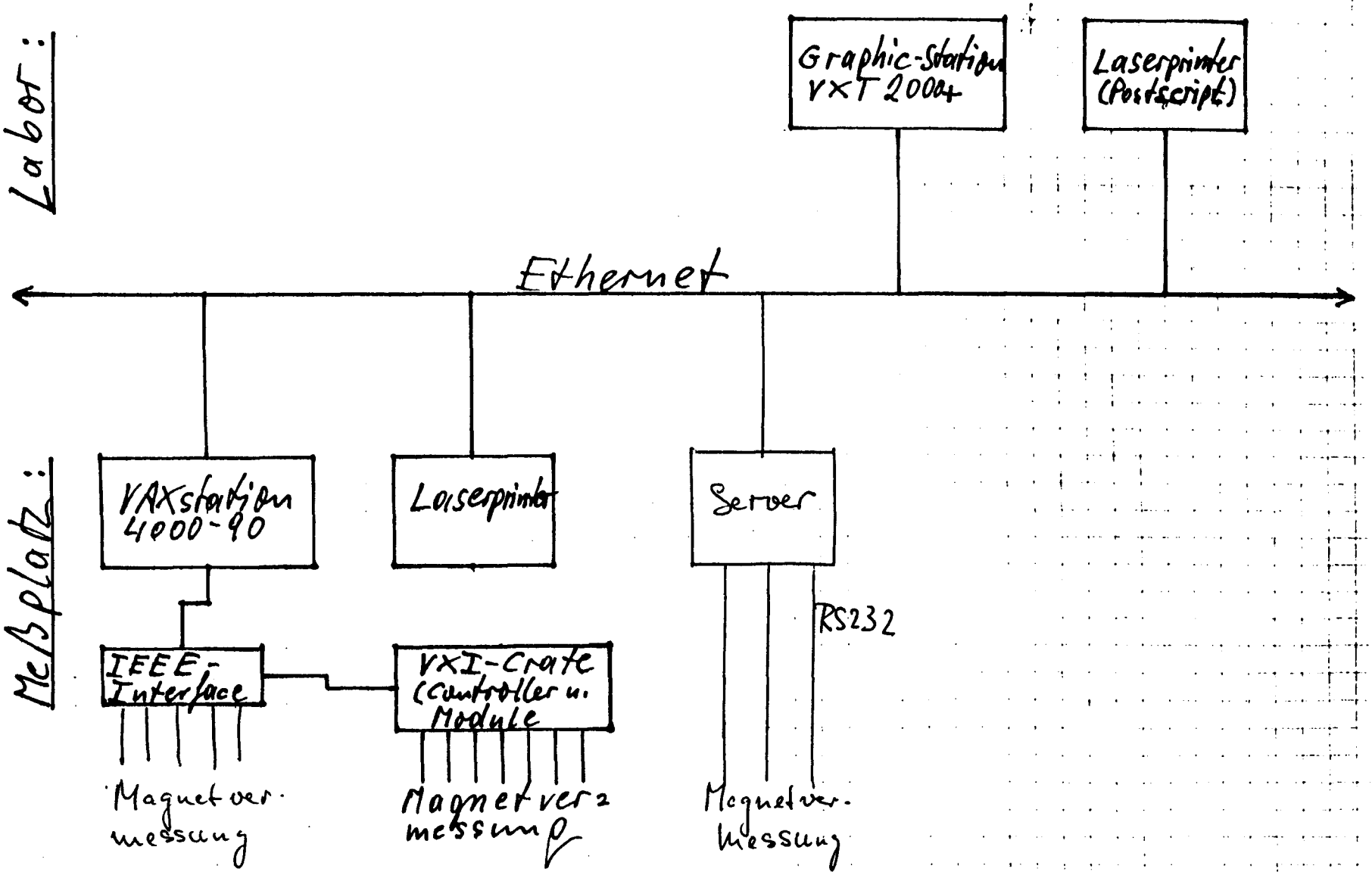
11	*1	St.	IEEE-Interface	ca. 3000,00
12	1	St.	VXI-Crate	11208,00
13	1	St.	GPIB-VXI Interface	4610,00
14	*?	St.	VXI-Module	ca. 20000,00
				ca. DM 38818,00
			Σ total	101370,92

* Noch keine Angebote vorhanden, Preis geschätzt!

Bemerkung GBr:
Das 2. System benötigt Pos. 5, 8, 9 nicht, d.h. Gesamtkosten 89548,90

F. Roth 26.07.93

Magnetvermessung

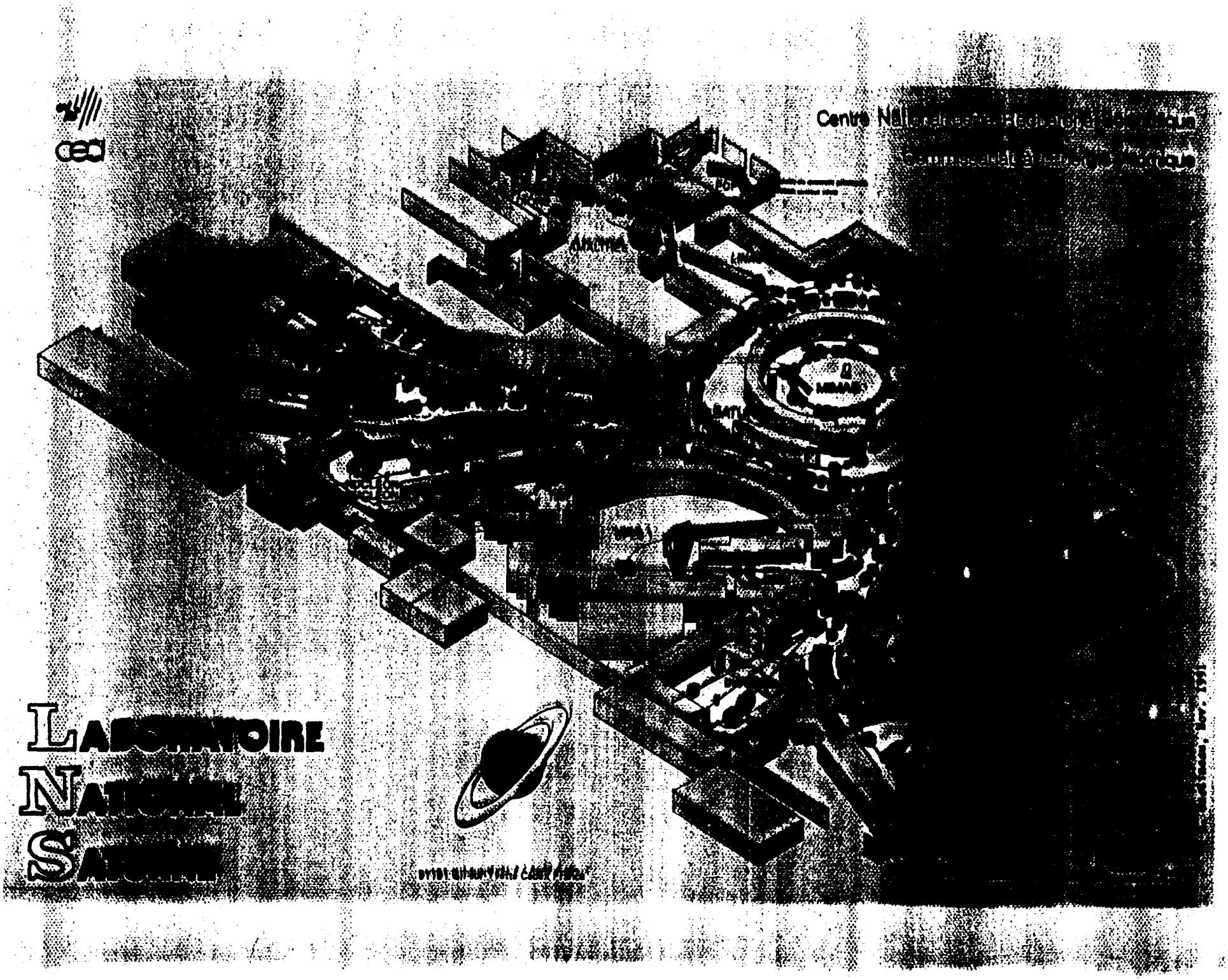


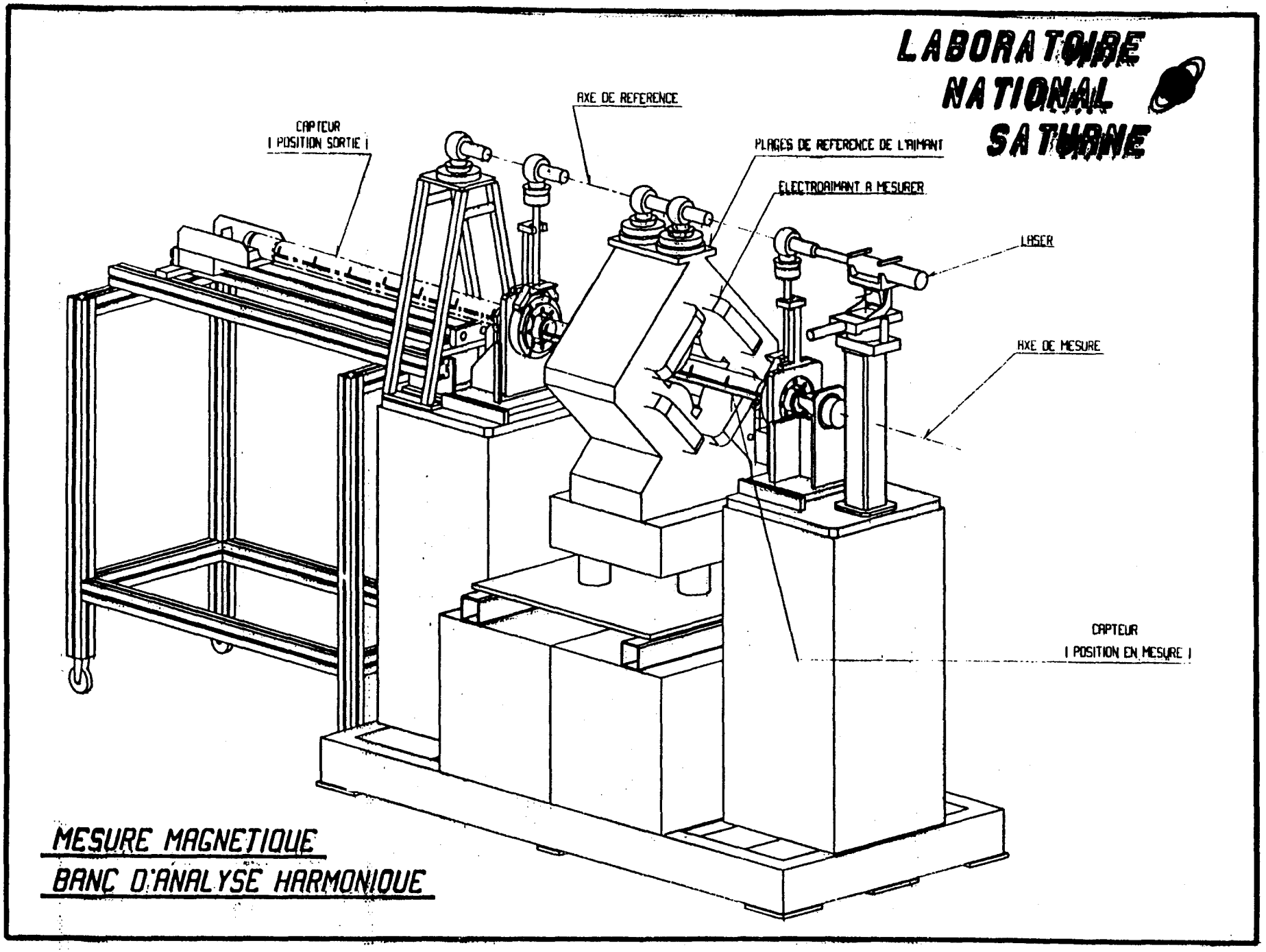
Harmonic analysis bench experience

M. TKATCHENKO

LNS - SACLAY

29/09/93


Centre National d'Etudes Spatiales
Commission des Satellites Météorologiques
LABORATOIRE
NATIONAL
SATELLITE


LABORATOIRE
NATIONAL
SATURNE
AXE DE REFERENCE
CAPTEUR
(POSITION SORTIE)
PLAGES DE REFERENCE DE L'AIMANT
ELECTROAIMANT A MESURER
LASER
AXE DE MESURE
CAPTEUR
(POSITION EN MESURE)
MESURE MAGNETIQUE
BANC D'ANALYSE HARMONIQUE

ANALYSE HARMONIQUE : PERFORMANCES

- **Précision :**

fidélité à 10^{-5} & justesse à 10^{-3}. ----------> *Etalonnage magnétique du capteur.*

- **Sensibilité :** n = 32 soit 10 nWb.

- **Signal/Bruit** : 200 dB.

- **Durée** : 30 s après installation de l'aimant.

- **Détections des défauts ponctuels novatrice.**

- **Banc compétitif.**

- **Réponds à la demande industrielle.** ----------> *Universalisation du capteur*

- **Publication en cours :** "New performance in harmonic analysis device generation used for magnetic field measurements".

Sondes R.M.N.

La sonde à Résonance Magnétique Nucléaire est une technologie récente pour l'analyse harmonique du champ magnétique. Elle se développe actuellement aux Etats Unis pour la mesure du S.S.C. [24, page 69] et devrait permettre des mesures de grande précision.

Dans les champs inhomogènes, on utilise de petites sondes à l'hélium, ^{3}He, exitées par un oscillateur pulsé. On fait les mesures en des points équidistants sur un cercle de rayon R centré sur l'axe Os de l'aimant, comme indiqué dans le cas 1 pour les mesures avec sondes de Hall.

2.2. Capteurs

On étudie les signaux délivrés par des capteurs sensibles à la mesure du flux de la composante radiale et azimutale du champ magnétique.

2.2.1- Grandeurs physiques mesurées

Selon l' équation *I.7* et la figure *II-12*, dans un système de coordonnées polaires, on décompose le champ magnétique en deux composantes, l'une radiale B_r et l'autre azimutale B_θ

$$\vec{B} = B_r \vec{r_0} + B_\theta \vec{\theta_0}$$

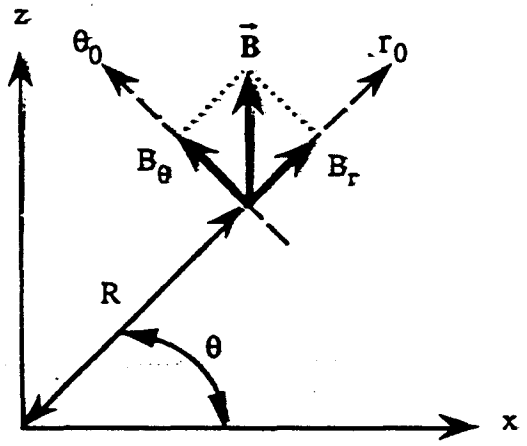


Figure II-12 : Composantes radiale et azimutale du champ magnétique.

On peut donc mesurer :

- La composante azimutale en plaçant la normale de la surface sensible du conducteur parallèle à celle-ci.
- La composante radiale lorsque la normale de la surface sensible du conducteur lui est parallèle.

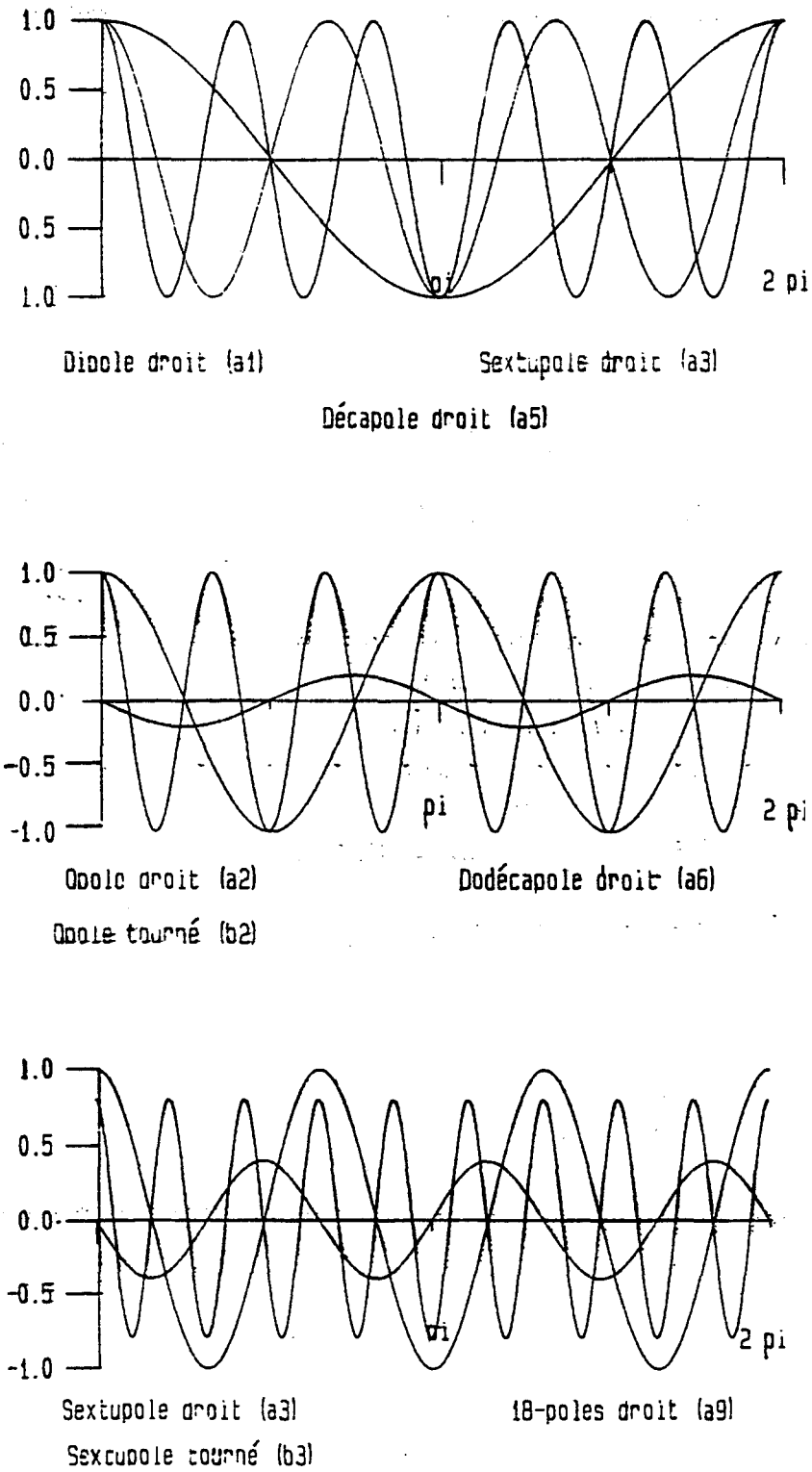
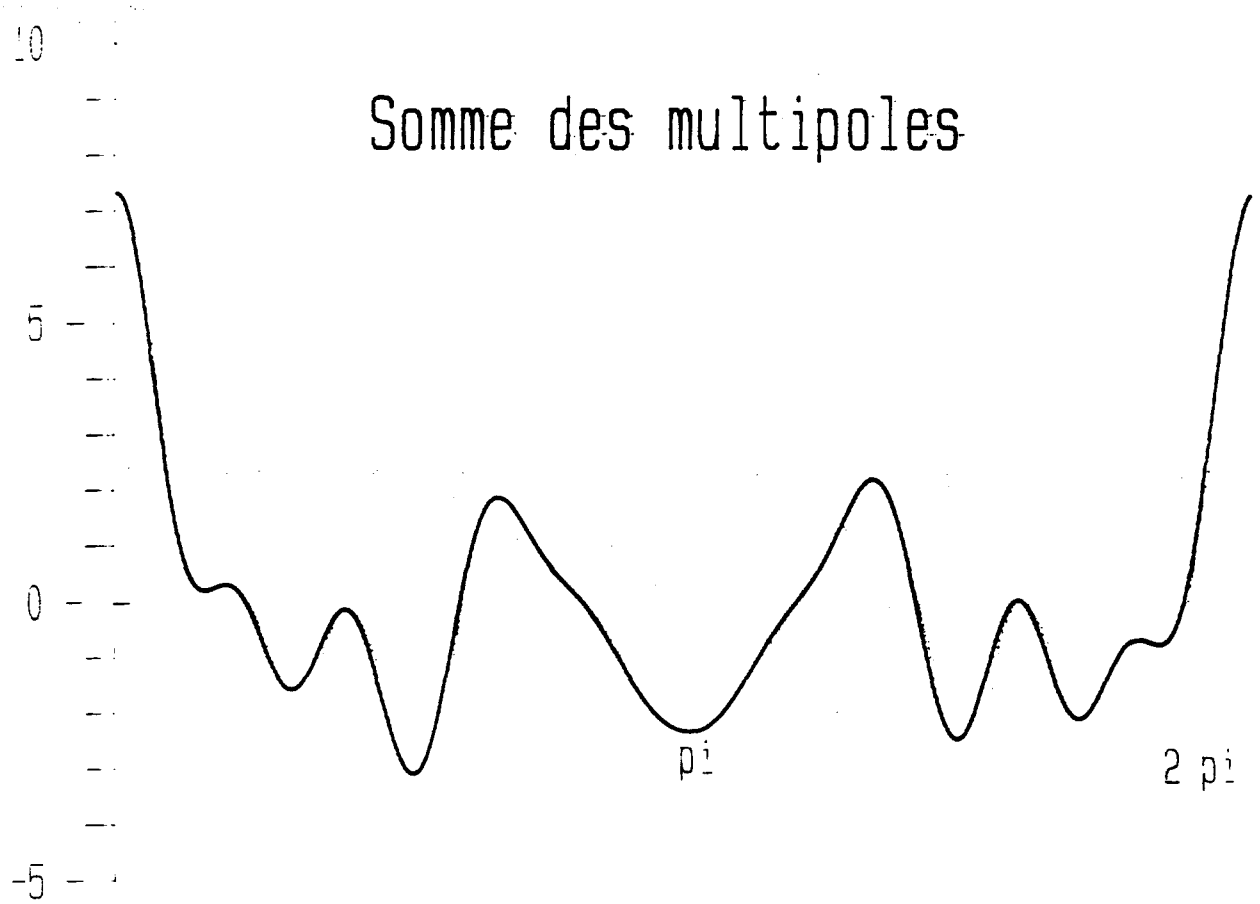
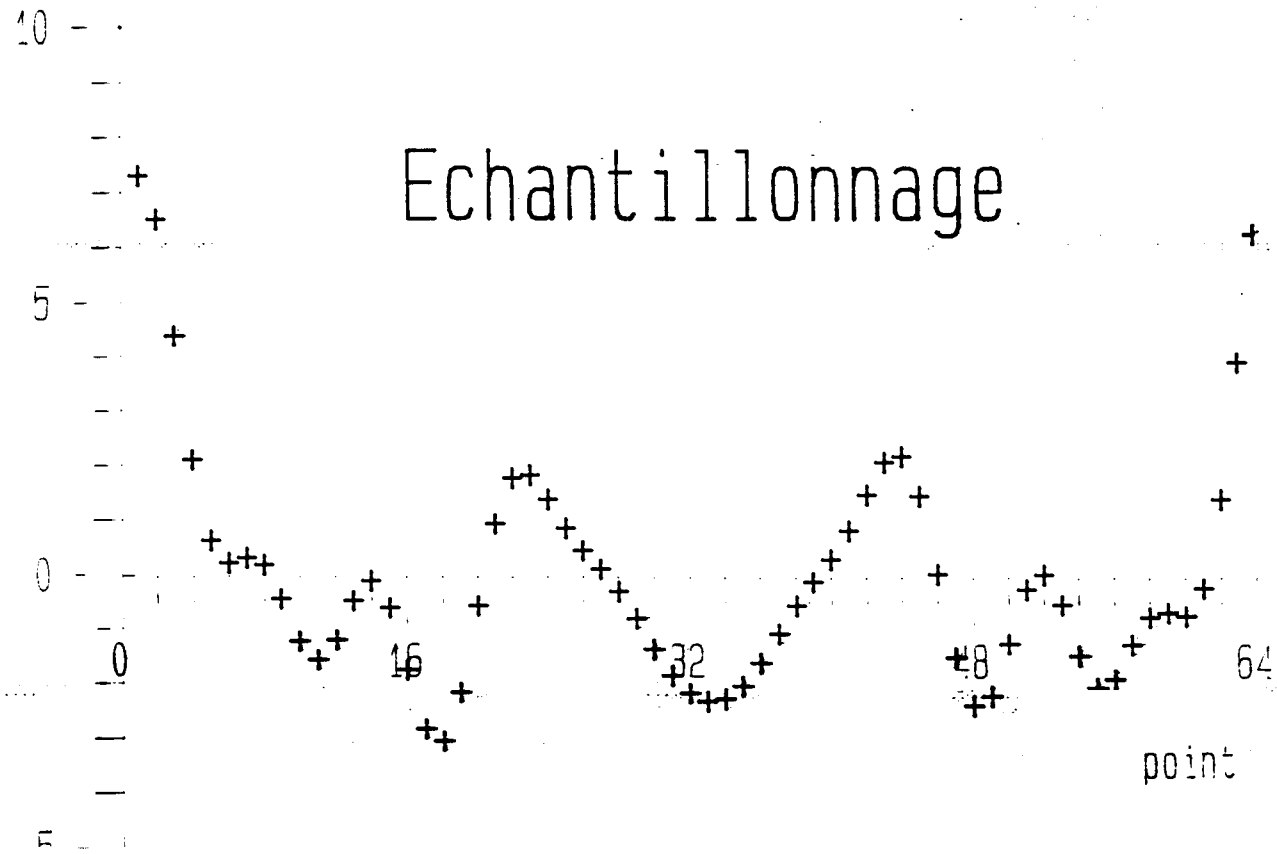
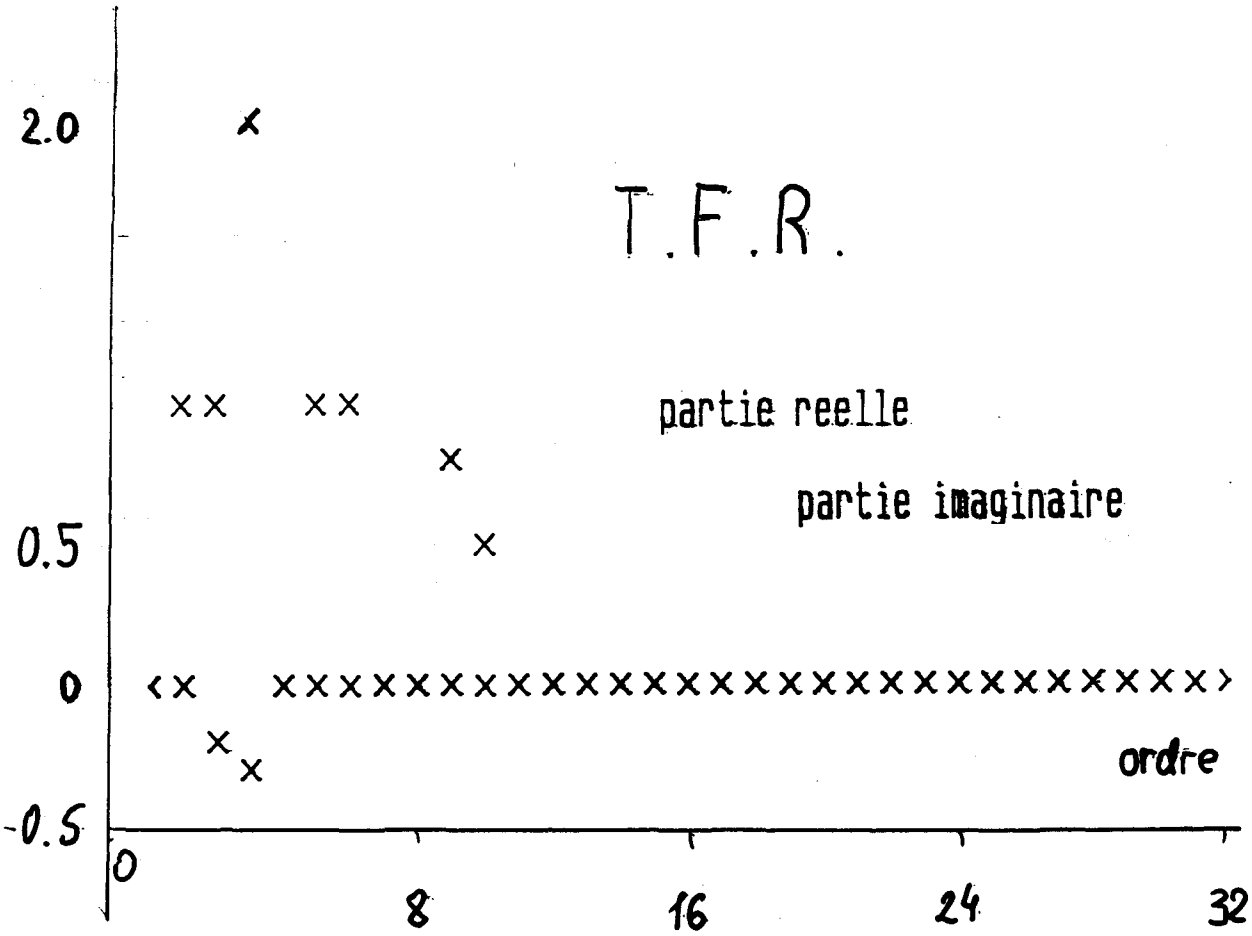
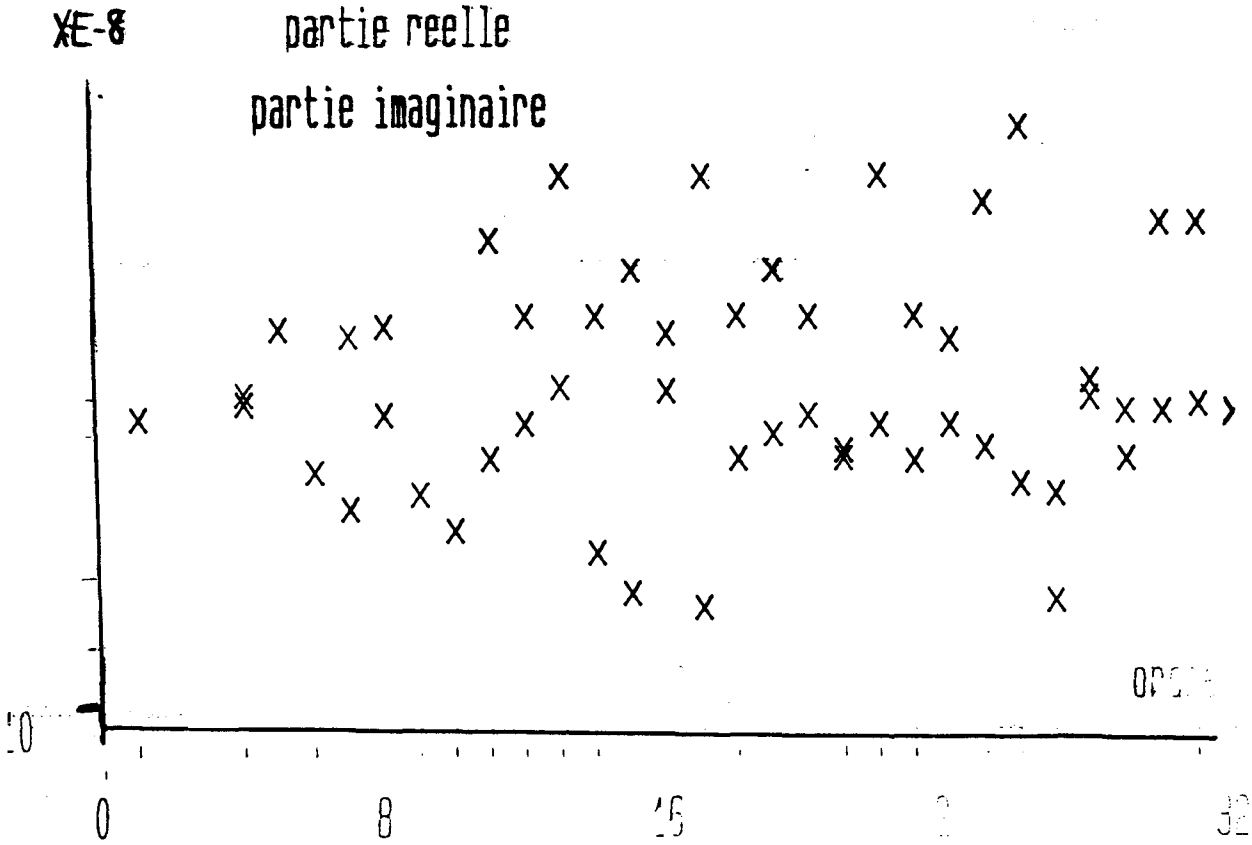


Figure I-8 : Composantes multipolaires azimutales $B_\theta = f(\theta)$.


Somme des multipoles
10
5
0
-5
pi
2 pi


Echantillonnage
10
5
0
5
0
16
32
48
64
point


T.F.R.
partie reelle
partie imaginaire
ordre
2.0
0.5
0
-0.5
0
8
16
24
32


XE-8
partie reelle
partie imaginaire
0
8

Q = 4

Row	TE.1	Im_FFT_of_TE.1.1	Re_FFT_of_TE.1.1
1	1	0	0
2	-1	0	[illegible]
3	1	0	0
4	-1	[illegible]	[illegible]

Q = 8

Row	TE	Im_FFT_of_TE.1	Re_FFT_of_TE.1
1	1	0	-1.326792416-17
2	2.653584817e-17	0	-3.752735646-17
3	-1	-1.06143393e-16	1
4	-7.960754456-17	0	3.752735637e-17
5	1	0	1.326792409e-17
6	1.326792409e-16	[illegible]	[illegible]
7	-1	[illegible]	[illegible]
8	[illegible]	[illegible]	[illegible]

Q = 16

Row	TE	Im_FFT_of_TE	Re_FFT_of_TE
1	1	0	-1.876367 9e-17
2	0.707107	-5.307169634e-17	1
3	2.65e-17	0	1.876367 9e-17
4	-0.70711	0	1.326792409e-17
5	-1	0	1.876367 99e-17
6	-0.70711	5.307169634e-17	0.5571358435e-09
7	2.65e-17	0	-1.876367 9e-17
8	0.707107	0	[illegible]
9	1	0	-6.433962 [illegible]e-18
10	0.707107	[illegible]	[illegible]
11	1.3[illegible]e-16	[illegible]	[illegible]
12	-0.70711	[illegible]	[illegible]
13	[illegible]	[illegible]	[illegible]
14	-0.70711	[illegible]	[illegible]
15	-1.9e-16	[illegible]	[illegible]

Q = 32

	Im_FFT	Re_FFT
1	0	-4.7e-18
2	1.44e-11	1
3	0	4.69e-18
4	0	3.32e-18
5	0	4.69e-18
6	2.06e-12	2.6e-09
7	0	-4.7e-18
8	0	-3.3[illegible]-18
9	0	-4.7e-18
10	[illegible]	[illegible]-09
11	0	4.69e-18
12	0	3.32e-18
13	0	-4.69e-18
14	2.06e-12	2.9e-09
15	0	-4.7e-18
16	0	-3.3e-18
17	0	-4.7e-18
18	2.1e-12	2.06e-09
19	0	4.69e-18
20	0	3.32e-18
21	0	4.69e-18
22	2.06e-12	2.48e-09
23	0	-4.7e-18
24	0	-3.3e-18
25	0	-4.7e-18
26	2.1e-12	7.34e-09
27	0	4.69e-18
28	0	3.32e-18
29	0	4.69e-18
30	2.06e-12	-1.9e-10
31	0	-4.7e-18
32	0	-1.[illegible]-18
		-1.7[illegible]-18

Le banc de test

☞ Ses fonctions

- → Faire tourner le capteur
- → Repérer les positions angulaires
- → Aligner chaque élément
- → Supporter l'ensemble

- → Préserver la justesse et la fidélité

- → Contraintes pratiques

☞ Les qualités de chaque élément

Application de la loi de composition des variances aux termes multipolaires :

➡ mesure radiale $\left(\frac{\sigma_{an}}{a_n}\right)^2 = \left(\frac{\sigma_{\Delta Kn}}{\Delta Kn}\right)^2 + \left(\frac{\sigma_e}{e}\right)^2 + (n\,\Delta\theta\,\mathrm{tg}\,n\Delta\theta)^2\left(\frac{\sigma_{\Delta\theta}}{\Delta\theta}\right)^2$ + traitement

➡ mesure azimutale $\left(\frac{\sigma_{an}}{a_n}\right)^2 = \left(\frac{\sigma_{\Delta Kn}}{\Delta Kn}\right)^2 + \left(\frac{\sigma_e}{e}\right)^2 + (n\,\Delta\theta\,\mathrm{cotg}\,n\Delta\theta)^2\left(\frac{\sigma_{\Delta\theta}}{\Delta\theta}\right)^2$ + environnement

$\approx 10^{-5}$?

$\Leftrightarrow n\frac{\sigma_r}{r}$ rotation : rayons

acquisition des signaux

repères des positions angulaires

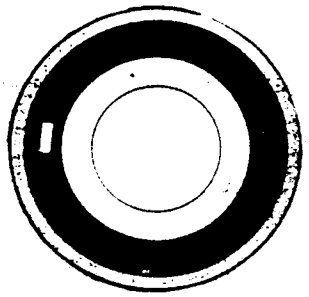
Repère des positions angulaires

$\frac{\sigma_{\Delta\theta}}{\Delta\theta} \Leftrightarrow$ codeur & origine angulaires

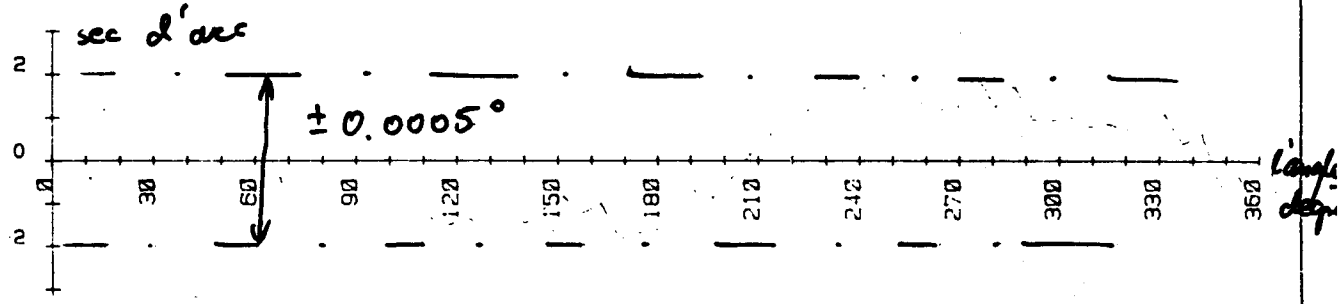
$Q = 64 \iff \Delta\theta = 5{,}625$ degrés

☞ Codeur incrémental binaire

➡ **N = 8192 traits <==> mesure de flux entre 128 traits**



➡ **étalonné par le constructeur**



$$\frac{\sigma_{\Delta\theta}}{\Delta\theta} = 3.10^{-5}$$

☞ Origine angulaire : Plan bobine = Plan médian aimant

➡ **réglage mécanique**

➡ **réglage magnétique**

$\pm 0.02°$

☞ Termes systématiques

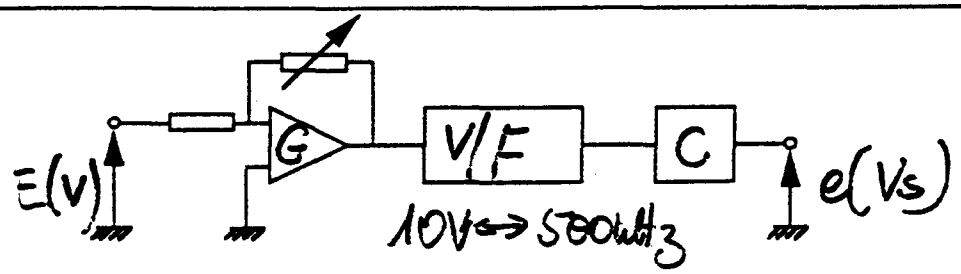
$n\Delta\theta$ tg $n\Delta\theta$ en mesure radiale

$n\Delta\theta$ cotg $n\Delta\theta$ en mesure azimutale

Acquisition des signaux

$\frac{\sigma_e}{e} \Leftrightarrow$ intégrateur & connectique

☞ Intégrateur

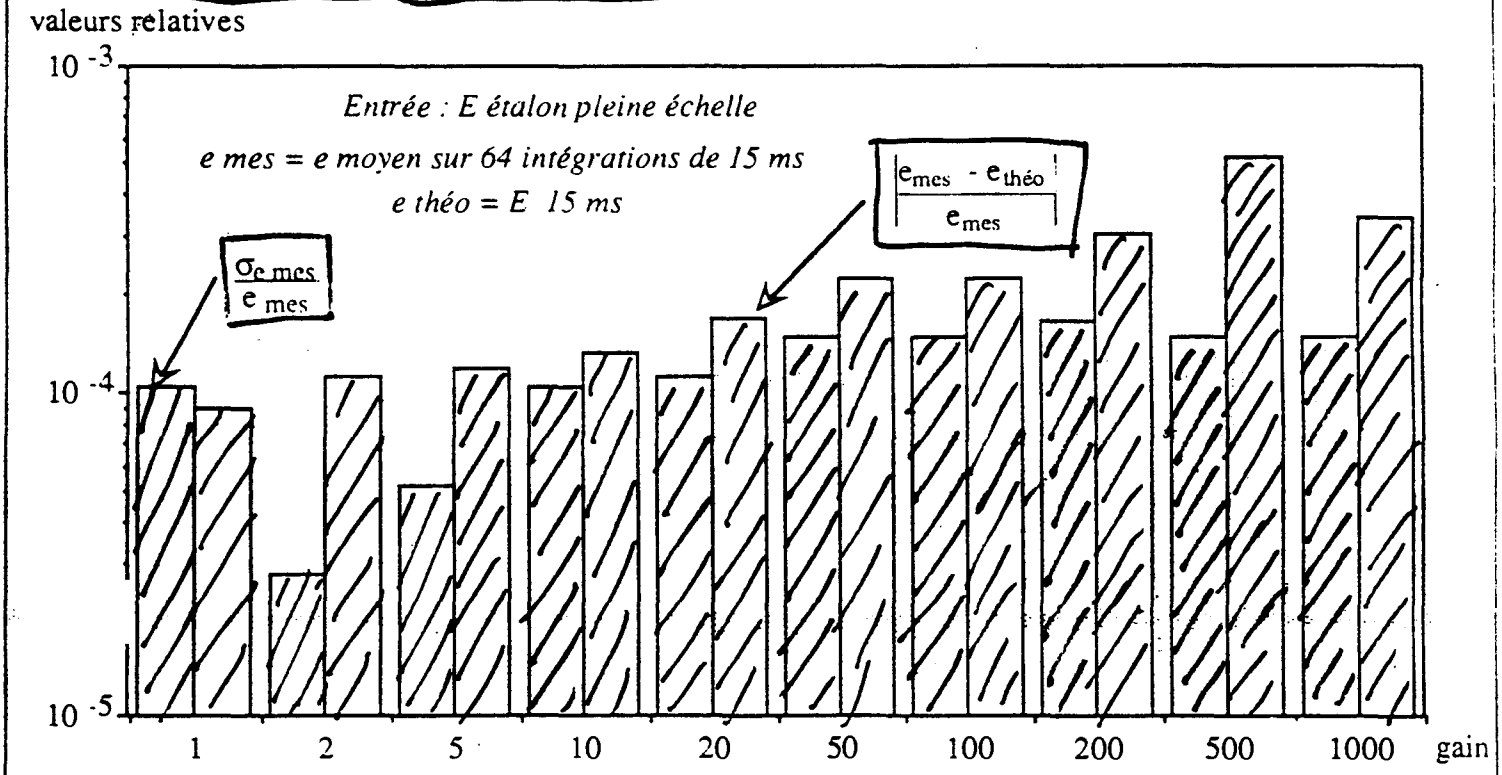


➜ **résolution**

$$\tau = \frac{V}{F} \cdot \frac{1}{G}$$

→ bruit blanc + erreur systématique

➜ **exactitude et dispersion statistique**



$G \leq 20$

$\frac{\sigma_e}{e} \simeq 10^{-4}$

☞ Connectique

Optimisée expérimentalement

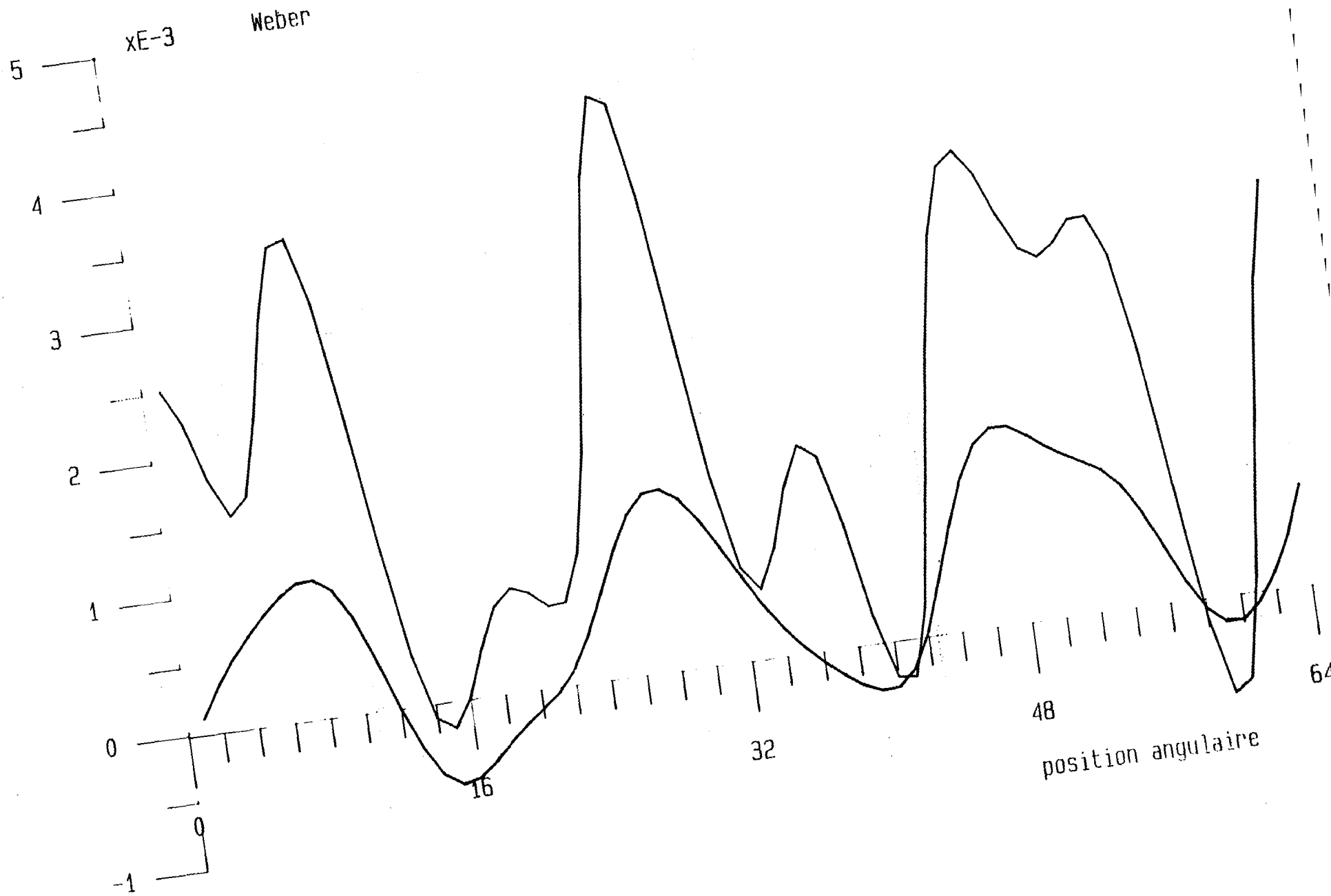
$\simeq 0{,}5\,\mu V/s$

Rayons de rotation des bobinages

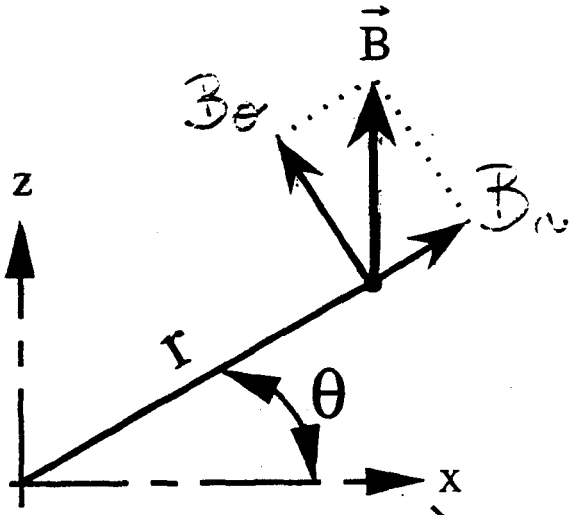
$$\frac{\sigma_{Kn}}{Kn} \Leftrightarrow n\,\frac{\sigma_r}{r}$$

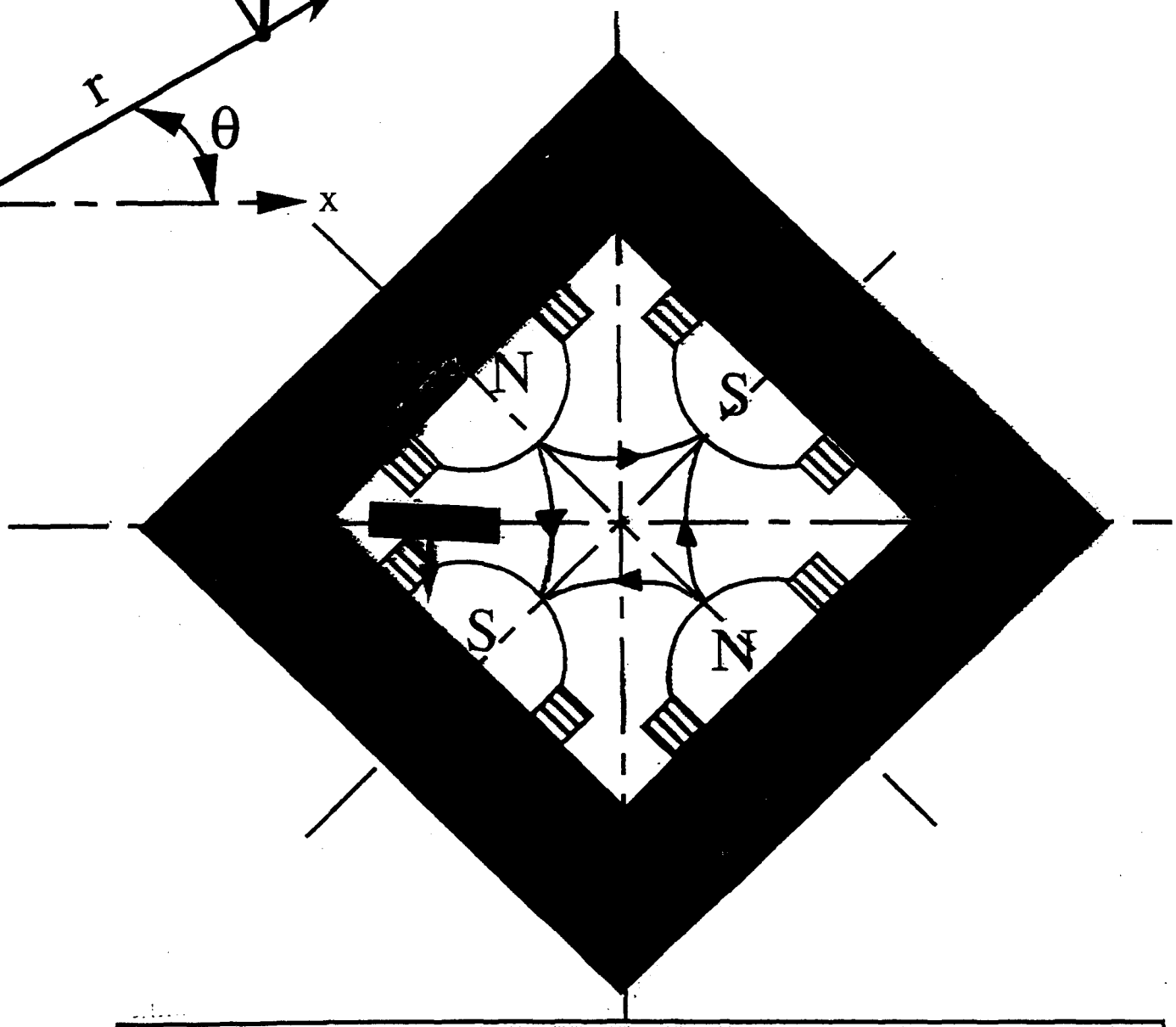
Sources d'incertitudes	Solutions adoptées
☞ **Position des conducteurs :**	Fil multibrins ... $\phi = 50\,\mu m$ tendu et collé dans la rainure 60 conducteurs 30 conducteurs *échelle 10*
☞ **Support des conducteurs :**	amagnétique construction homogène profil circulaire matériaux rigide (E/p grand) tolérances sérrées contrôles rigoureux → ΔK_n : $2\,\mu m$
☞ **Vibrations :**	absorbeurs moteur continu : $5\,\mu m$
☞ **Concentricité de la rotation**	paliers à air : $5\,\mu m$
☞ **Alignement banc - aimant** — **mécaniquement :**	faisceau laser & photodiode silicium : $4\,\mu m$
☞ **Alignement banc - aimant** — **magnétiquement :**	bobines mesures : $1\,\mu m$

$$\frac{\sigma_{\Delta K}}{\Delta K} \simeq 10^{-3} \longleftarrow \frac{\sigma_r}{r} = 4 \cdot 10^{-4}$$


xE-3
Weber
5
4
3
2
1
0
-1
0
16
32
48
64
position angulaire

Détection d'un défaut ponctuel





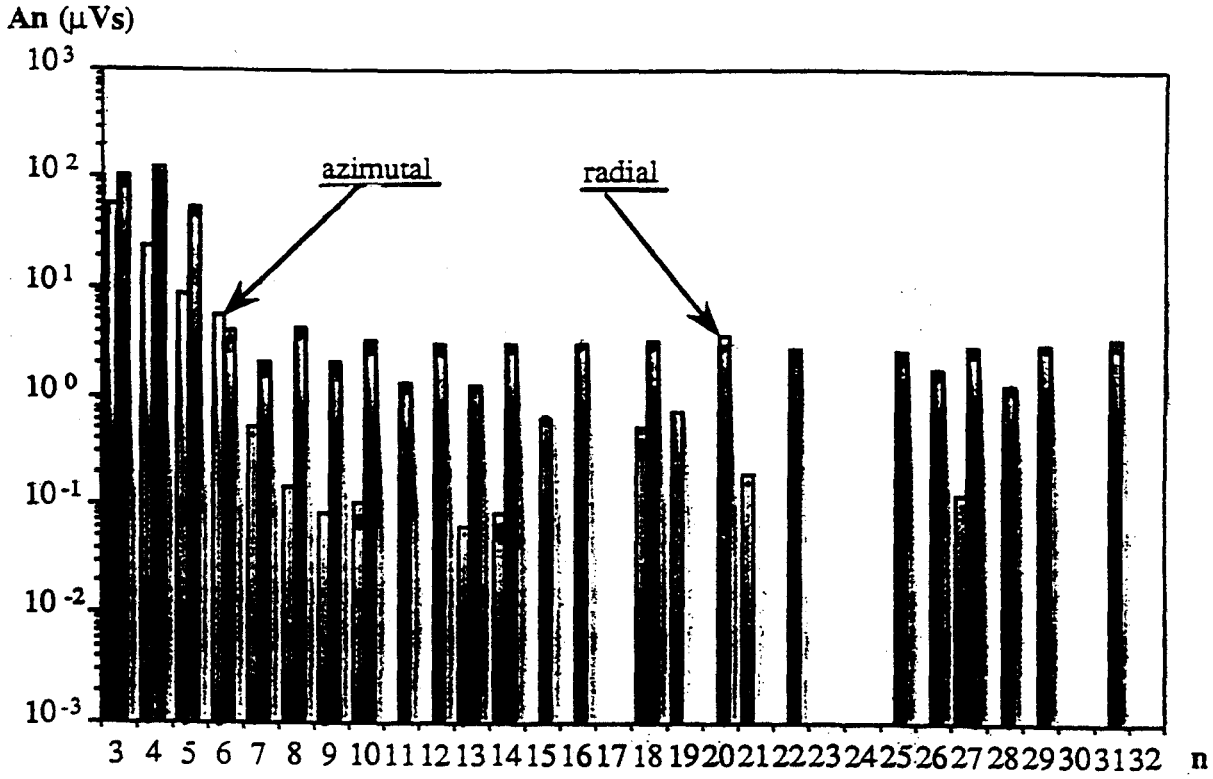
☞ **Localisation du défaut** $\alpha = \operatorname{arctg} \frac{b_m}{a_m}$

☞ Complémentarité des deux bobines

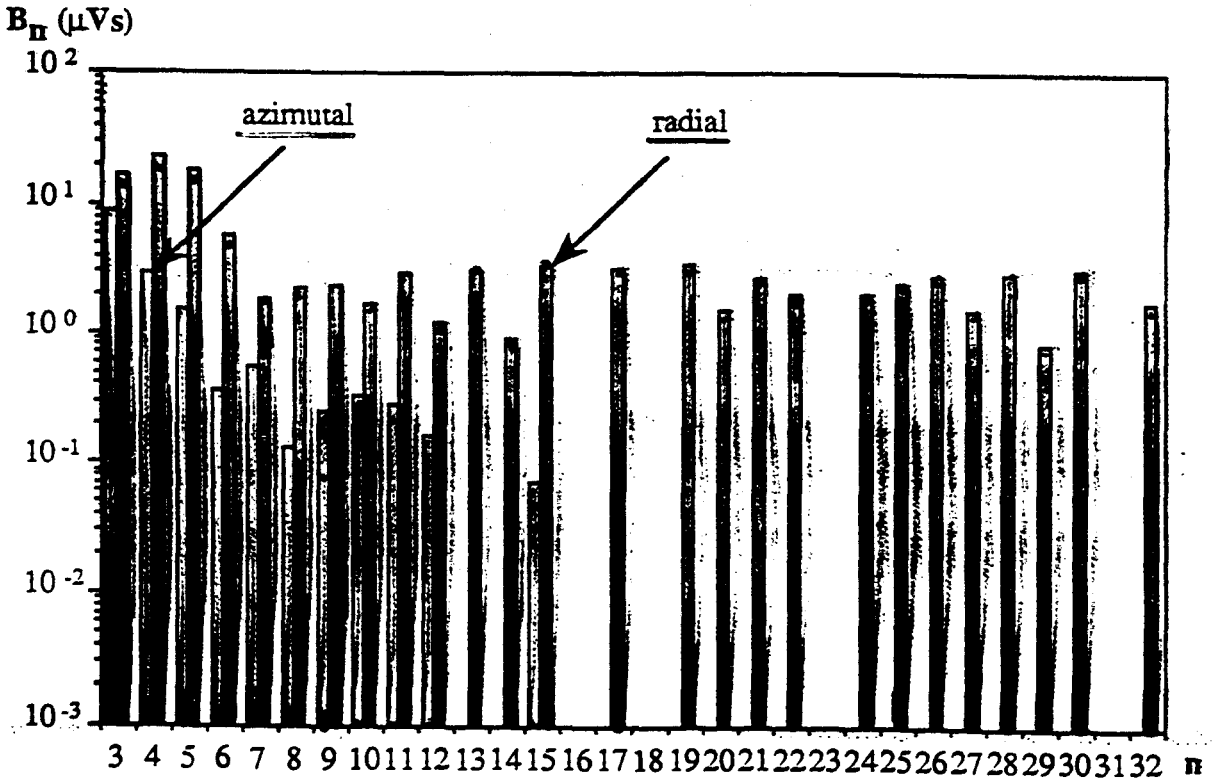
Défaut ponctuel de longueur de pôle

dans le quadrupôle

☞ **Termes droits**



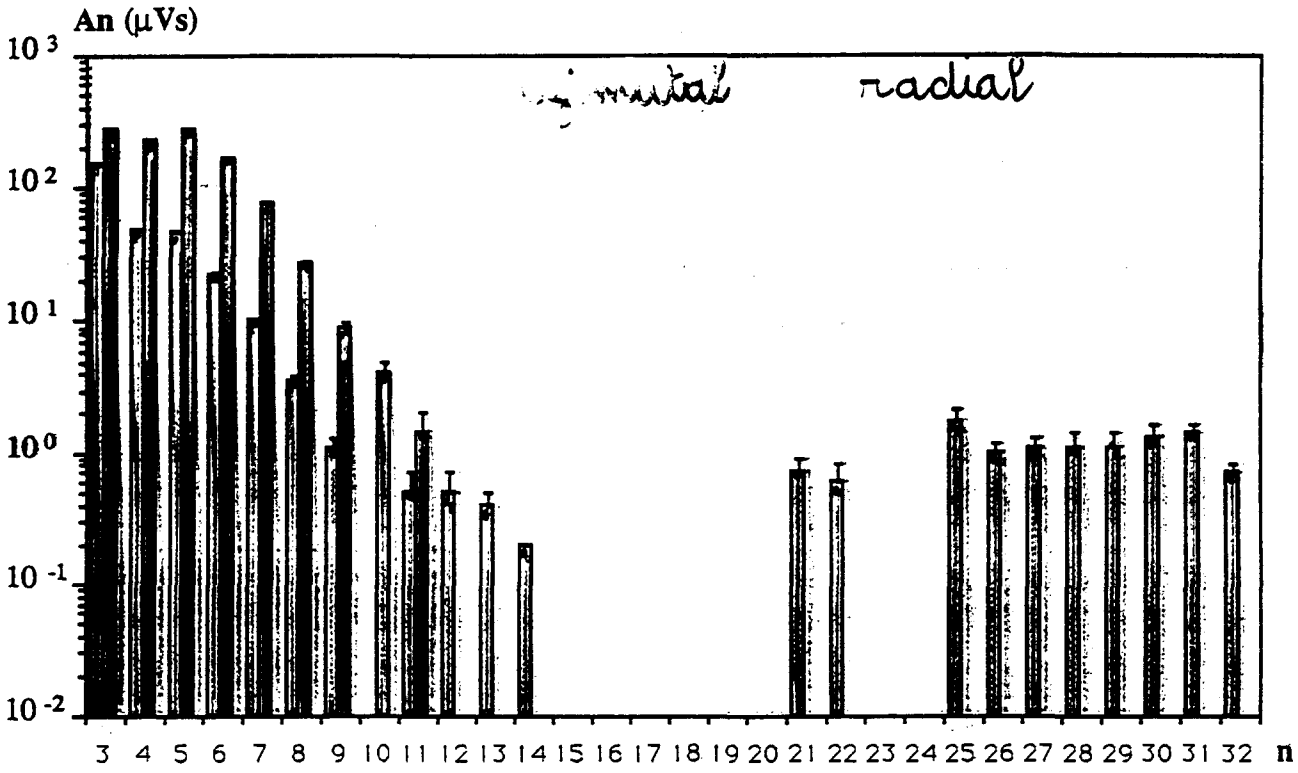
☞ **Termes tournés**



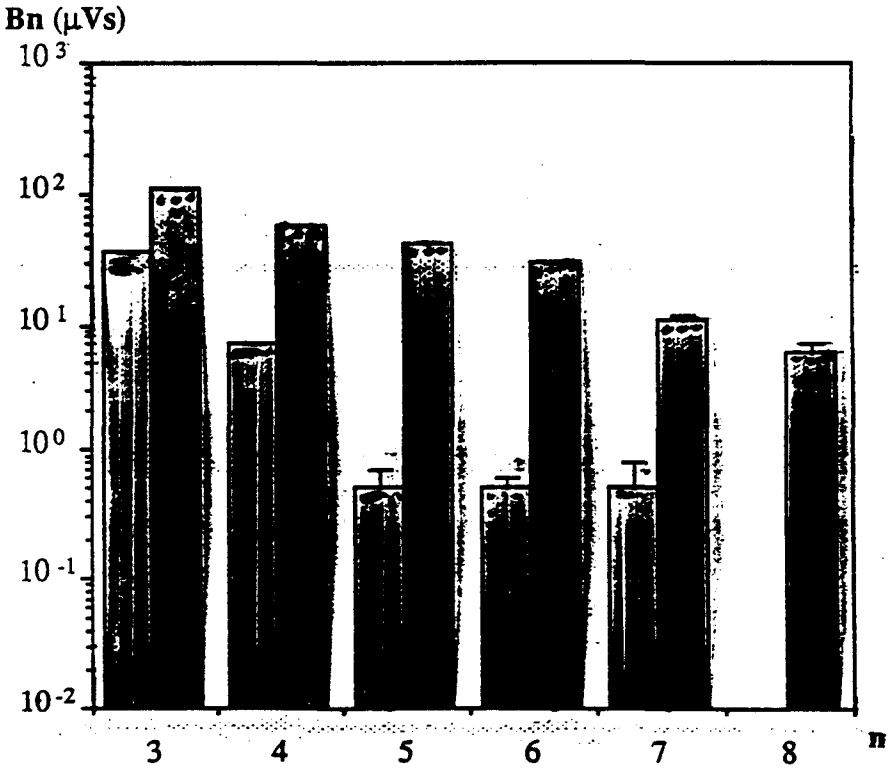
Défaut de plan médian

dans le quadrupôle

☞ **Termes droits**

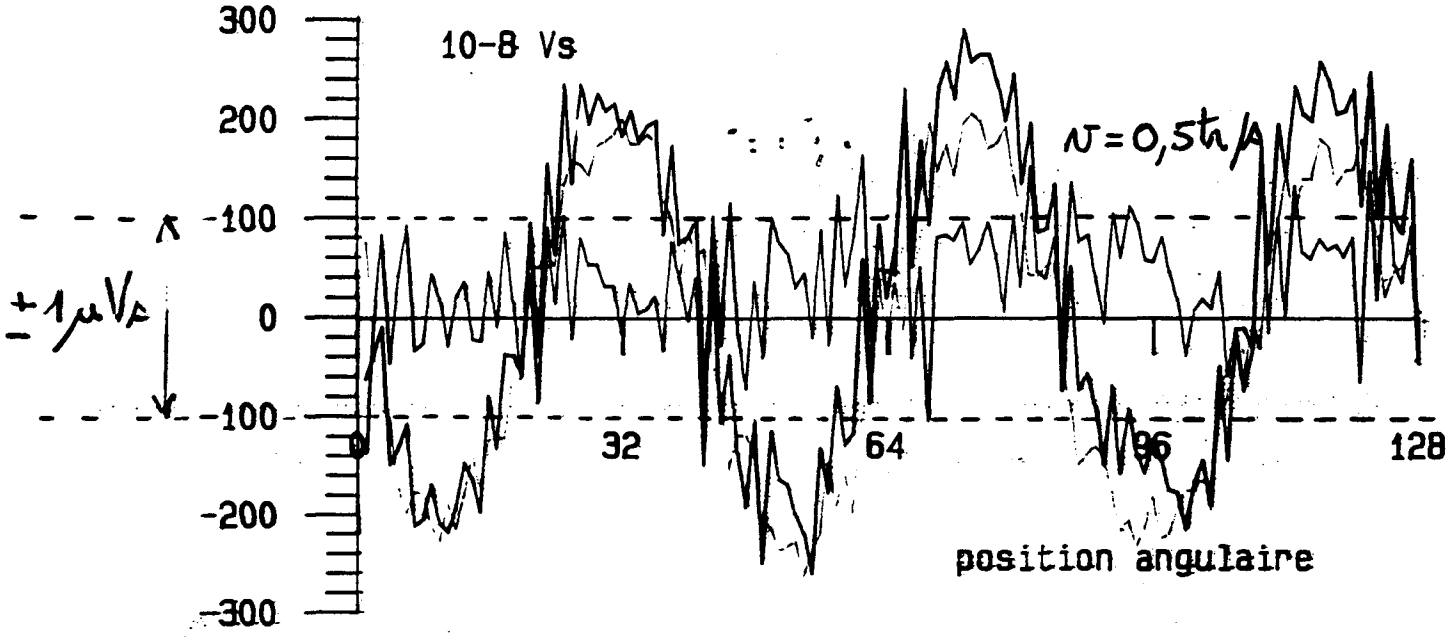


☞ **Termes tournés**

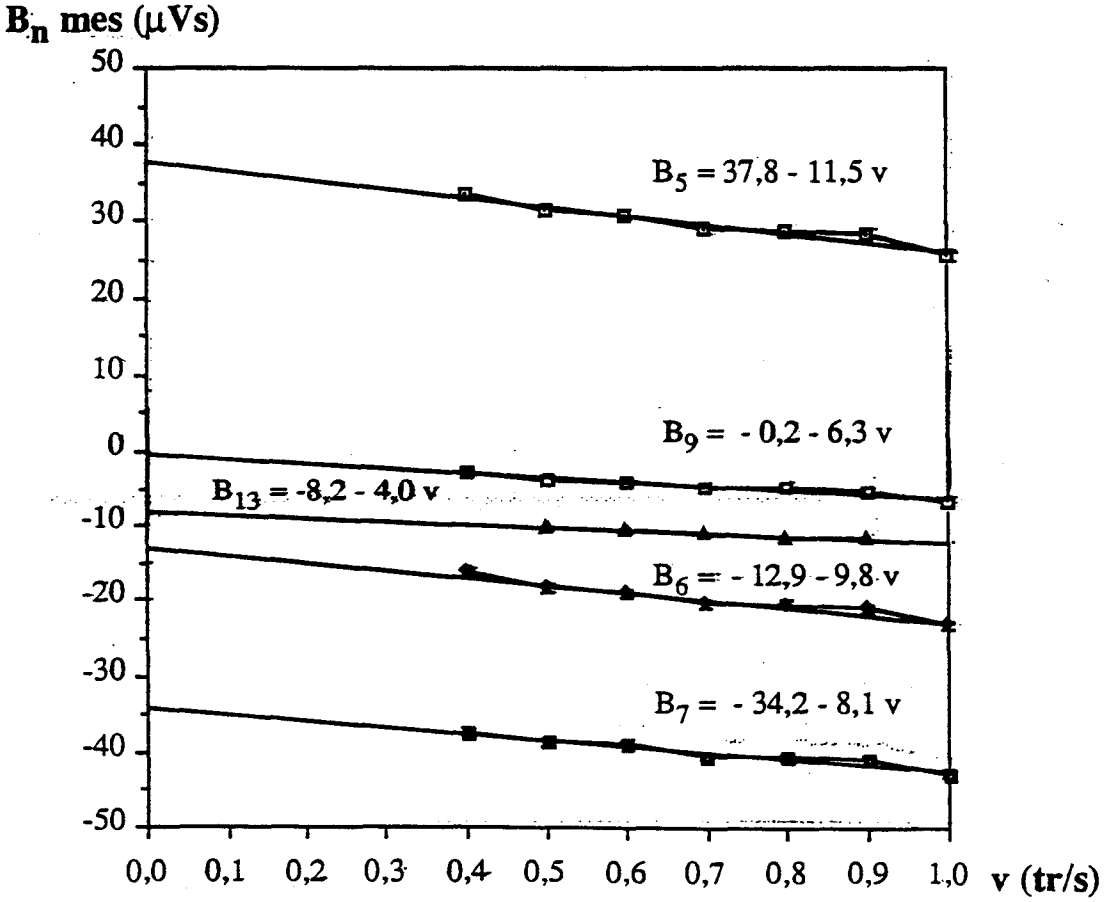


Effets de la vitesse

☞ **Effets sur le flux rémanent**



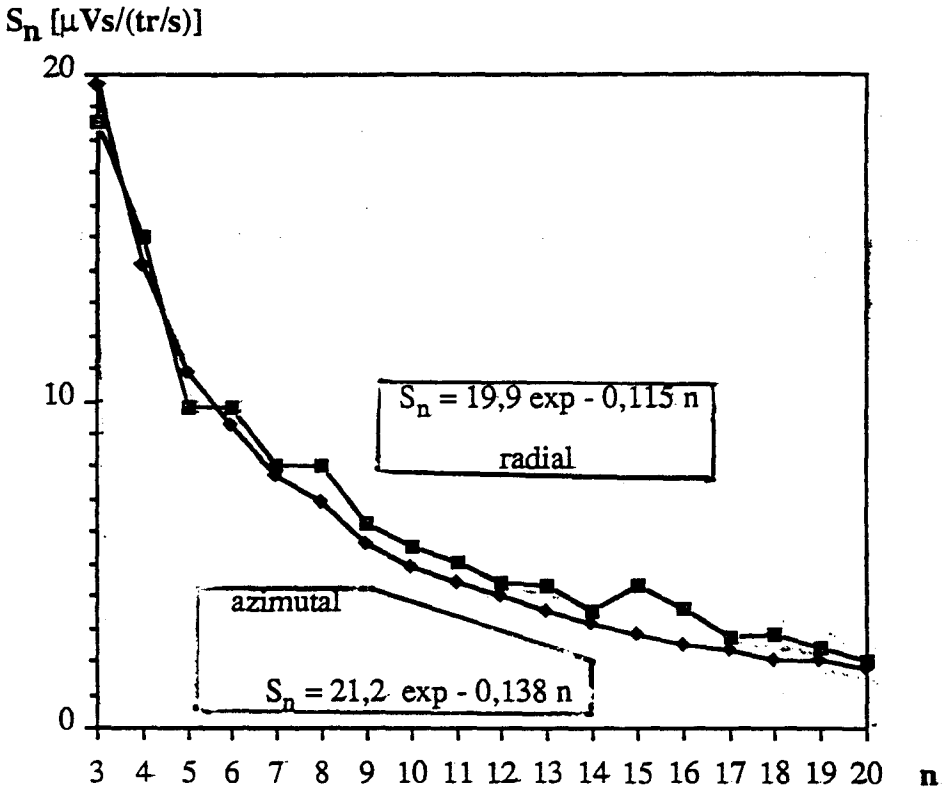
☞ **Effets sur les termes imaginaires**



$$B_n \text{ mes} = B_n \text{ réel} + S_n v$$

Correction de la vitesse

☞ **Loi de variation**



$$S_n = \rho \exp - n \Delta\theta$$

☞ **Correction**

$$B_{n\,réel} = B_{n\,mes} - \rho\, v \exp - n \Delta\theta$$

SLIP RING
BRASS CONTACT RING
SIDE
ENCODER
BEARING RING
TANGENTIAL COIL GROOVES
RADIAL COIL GROOVES
CENTRAL CHANNEL COILS
T STRUCTURE
BEARING RING
SIDE
MOTOR
FIXATION SCREWS
COVER

n \ σ_r		20 µm	10 µm	1 µm
Bucking coils	3	$3,7\ 10^{-3}$	$1,9\ 10^{-3}$	$1,9\ 10^{-4}$
	5	$4,0\ 10^{-3}$	$2,0\ 10^{-3}$	$2,0\ 10^{-4}$
	10	$6,2\ 10^{-3}$	$3,1\ 10^{-3}$	$3,1\ 10^{-4}$
	20	$4,8\ 10^{-2}$	$2,4\ 10^{-2}$	$2,4\ 10^{-3}$
Measuring coil	2	$1,2\ 10^{-3}$	$6,0\ 10^{-4}$	$6,0\ 10^{-5}$

n \ σ_r		20 µm	10 µm	1 µm
Bucking coils	3	$5,6\ 10^{-3}$	$2,8\ 10^{-3}$	$2,8\ 10^{-4}$
	5	$3,8\ 10^{-3}$	$2,0\ 10^{-3}$	$2,0\ 10^{-4}$
	10	$6,3\ 10^{-3}$	$2,7\ 10^{-3}$	$2,7\ 10^{-4}$
	20	$8,0\ 10^{-3}$	$6,3\ 10^{-3}$	$6,3\ 10^{-4}$
Measuring coil	2	$1,5\ 10^{-3}$	$7,2\ 10^{-4}$	$7,2\ 10^{-5}$

Figure 7 : Variation of $\sigma_{Kn}/Kn = f(\sigma_r)$ for coils measuring radial (r = 33 mm) and azimuthal (r = 32 mm) components.

Name	E (GPa)	ρ (gcm^{-3})	y (µm)
Steel	210	7,8	9
Duraluminum	72	2,8	9
	Ceramics		
Macor	65	2,52	9
Alumina	330	4,0	3
Silicon carbide	350	3,15	2
Silicon nitride	280	3,11	3
Boron carbide	440	2,45	1
	Composite materials		
Fiberglass epoxy	40	1,9	11
Carbon fiber epoxy	200	1,55	2
Kevlar	90	1,45	4

Figure 8 : Comparison of many materials features and saggita.

QUENCH OBSERVATION
BY
MAGNETIC FIELD PERTURBATION MEASUREMENTS

L. WALCKIERS

29 SEPTEMBER 1993

Quench Observation by Magnetic Field Perturbation Measurements

No voltage taps inside the coils on the first series of LHC models
=> No way to localise, then understand the training quenches

Spikes on voltage taps = Signature of mechanical movement

Idea :
detect the position of the associated magnetic perturbation with magn. meas. coils mounted in the apertures

Luckily :

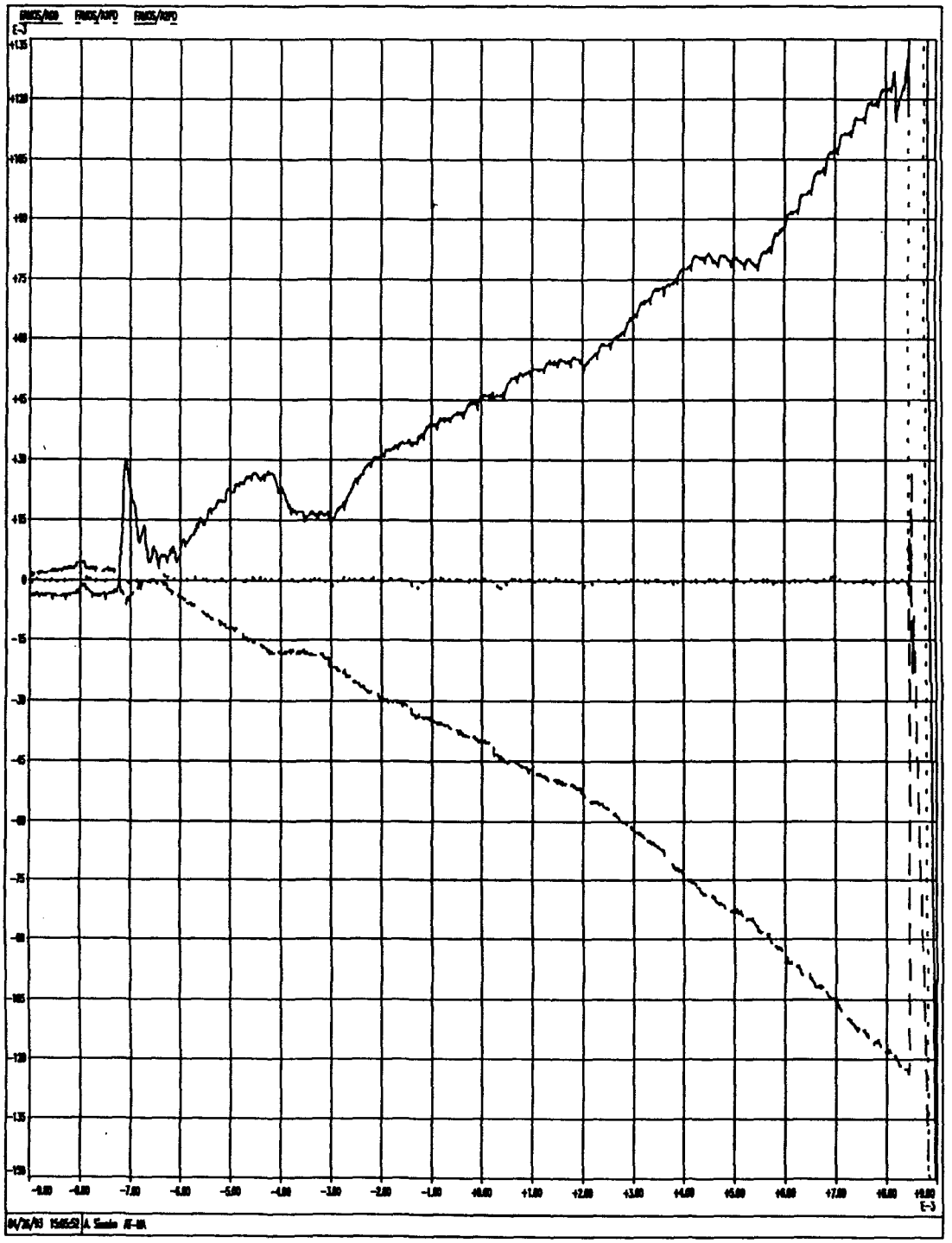
- **Twin Aperture Structure => noise cancellation**

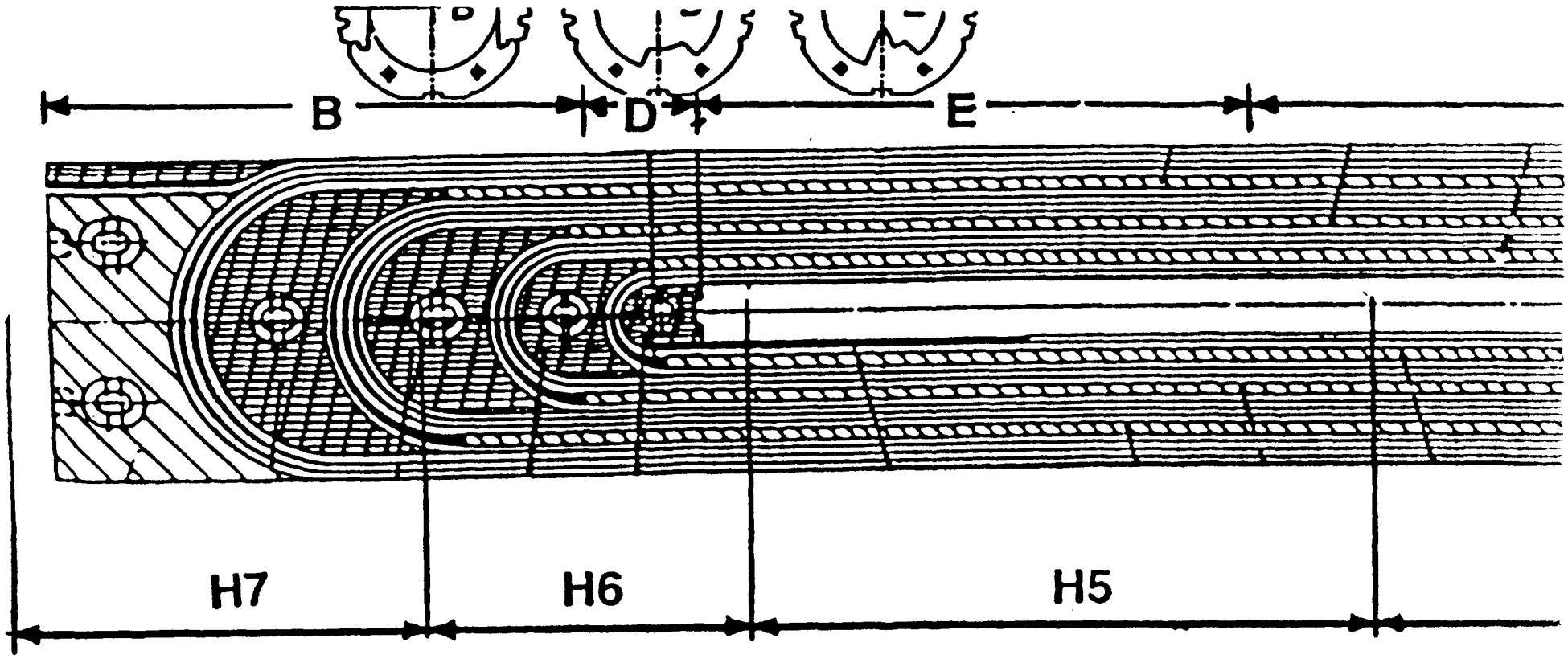
- **Discovery of " Bumps " = Perturbation due to the transition into a superconducting cable**

(LHC)		(SSC)
Pick-up Coils	=	Quench Antenna

Quench No 4 MTACERN
file "C1003085.004" bl-4

Spike on AD, A1PD, A2PD





MTACERN

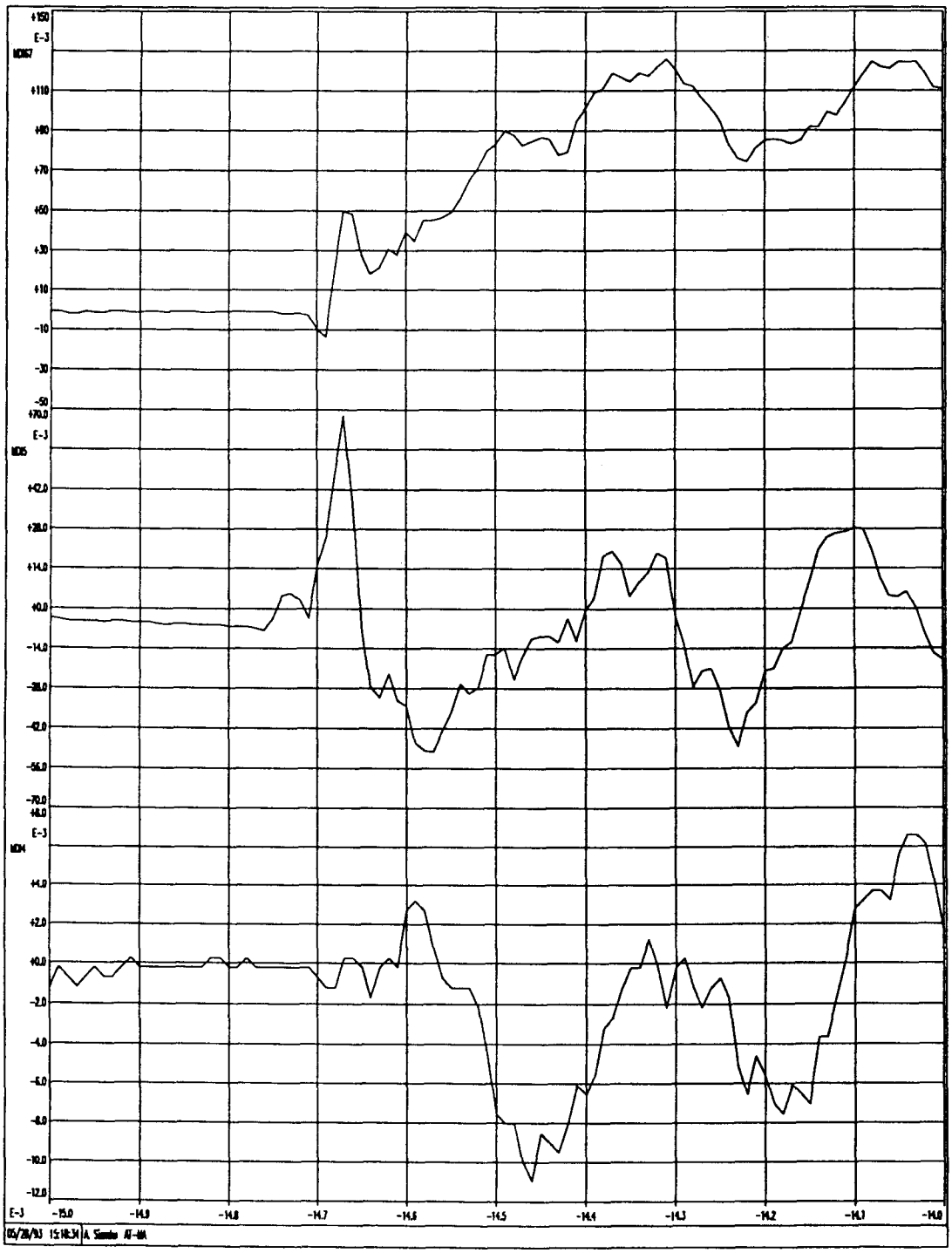
March-May 1993

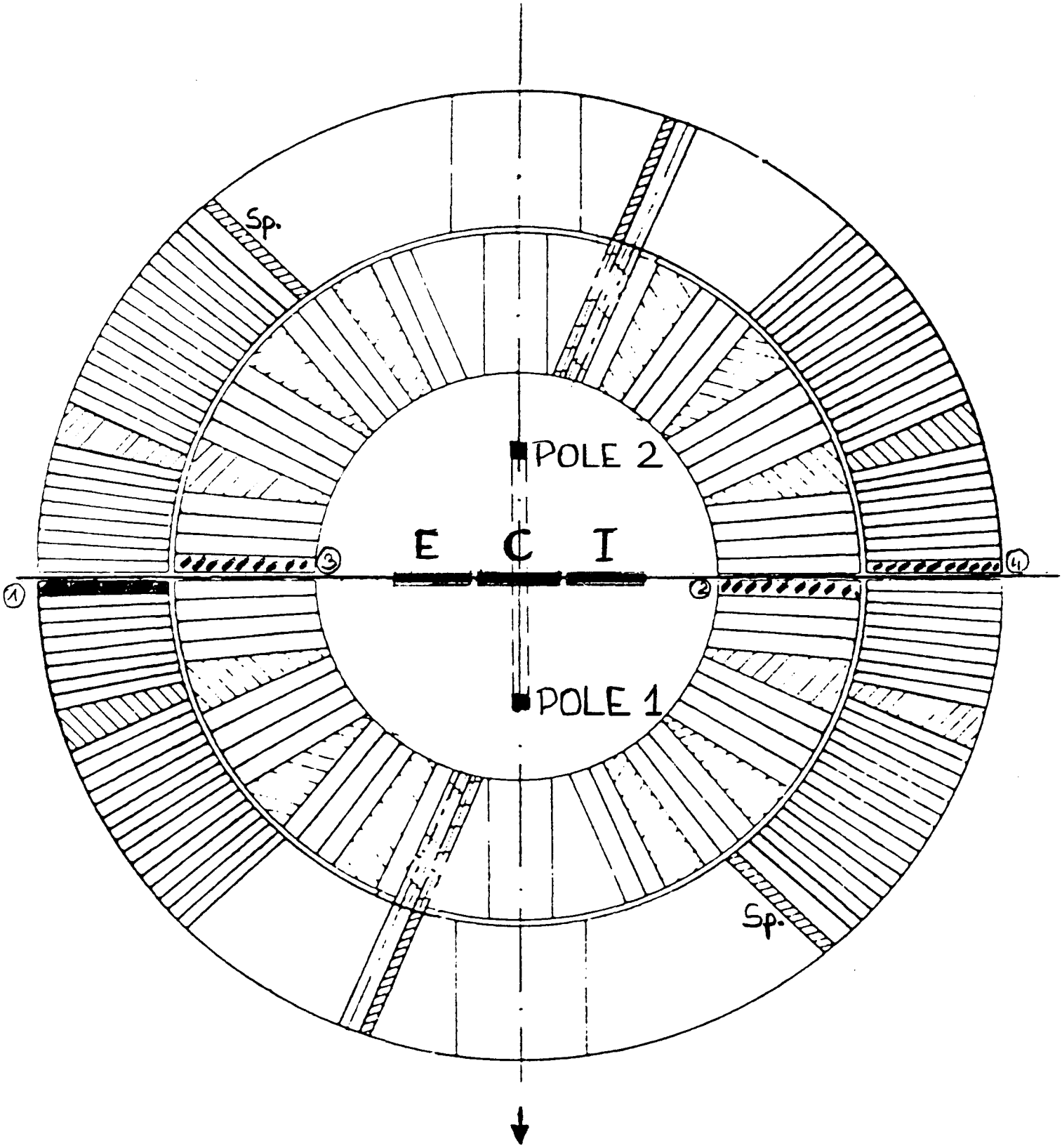
A1 P1
(coil 3)

Drawing pos. No	Quench No in coil	Quench No training	Field Meas. [T]	Quen type
1	1	2	8.06	B
2	2	8	8.12	B
	3	9	8.12	B
3	4	43	8.13	B
	5	44	8.13	B
	6	45	8.13	B

Quench No 13 MTACERN
file "C2303143.104"

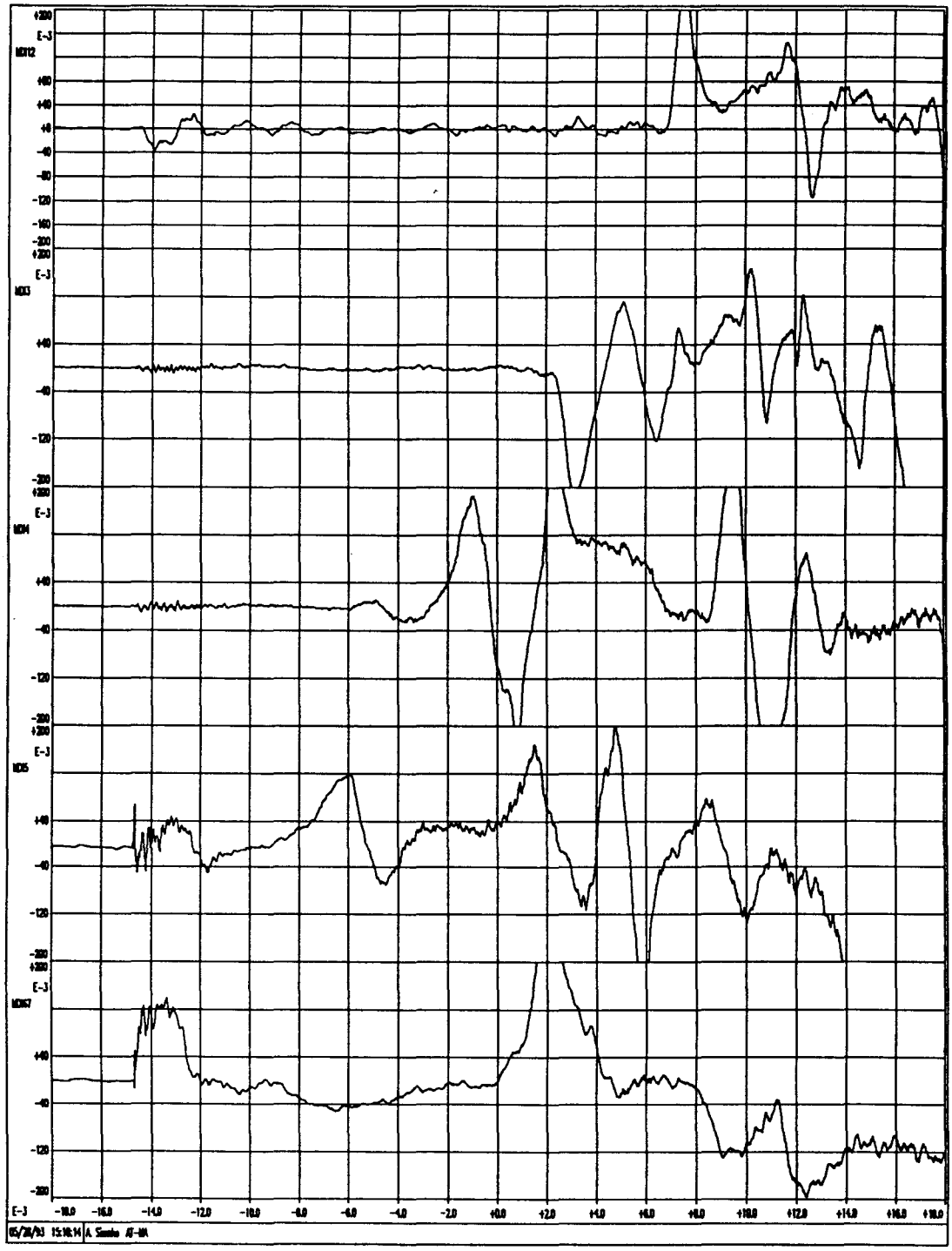
Spike propagation MD167, MD15, MD14




Sp.
POLE 2
E
C
I
3
4
1
2
POLE 1
Sp.

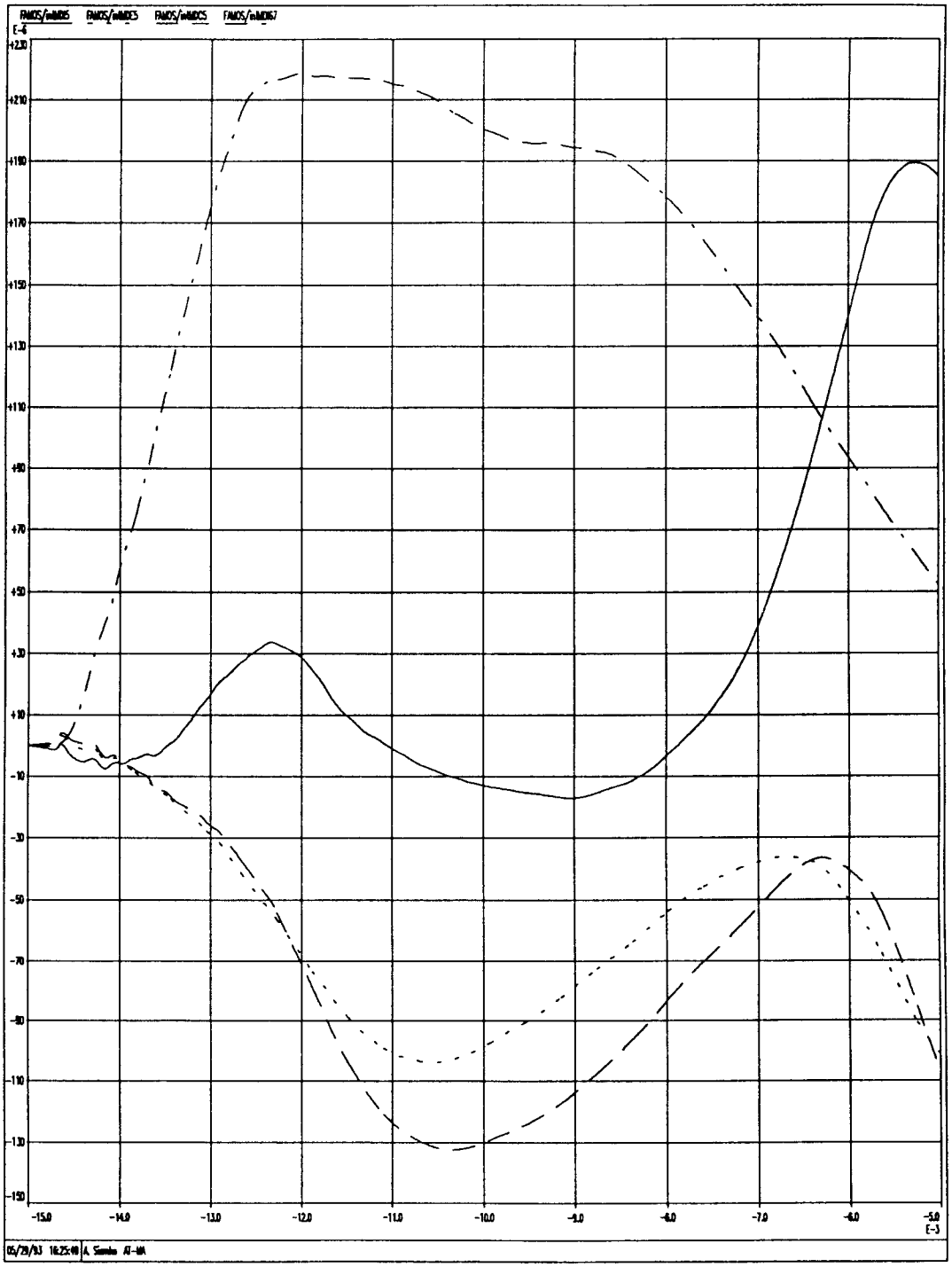
Quench No 13 MTACERN
file "C2303143.104"

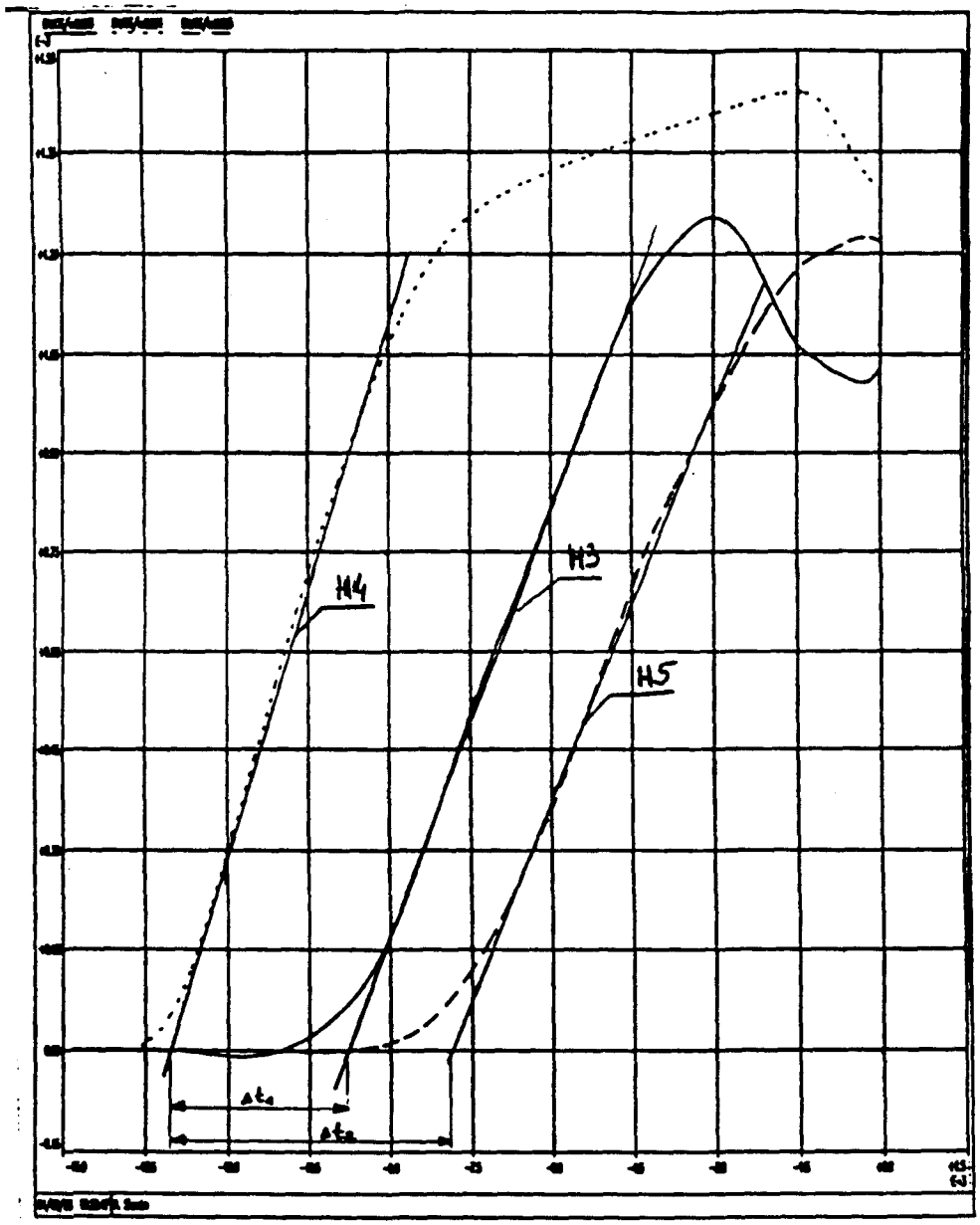
MDIxx



Quench No 13 MTACERN
file "C2303143.104"

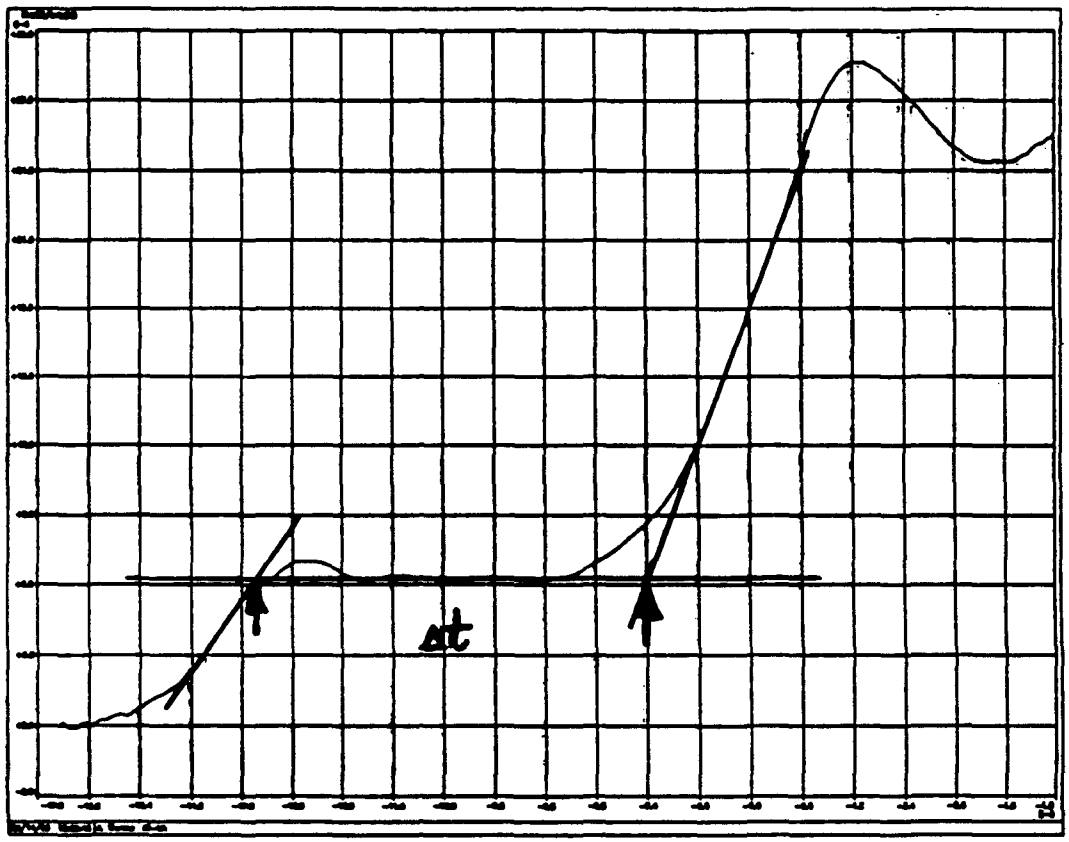
intMDx5 & intMDI67





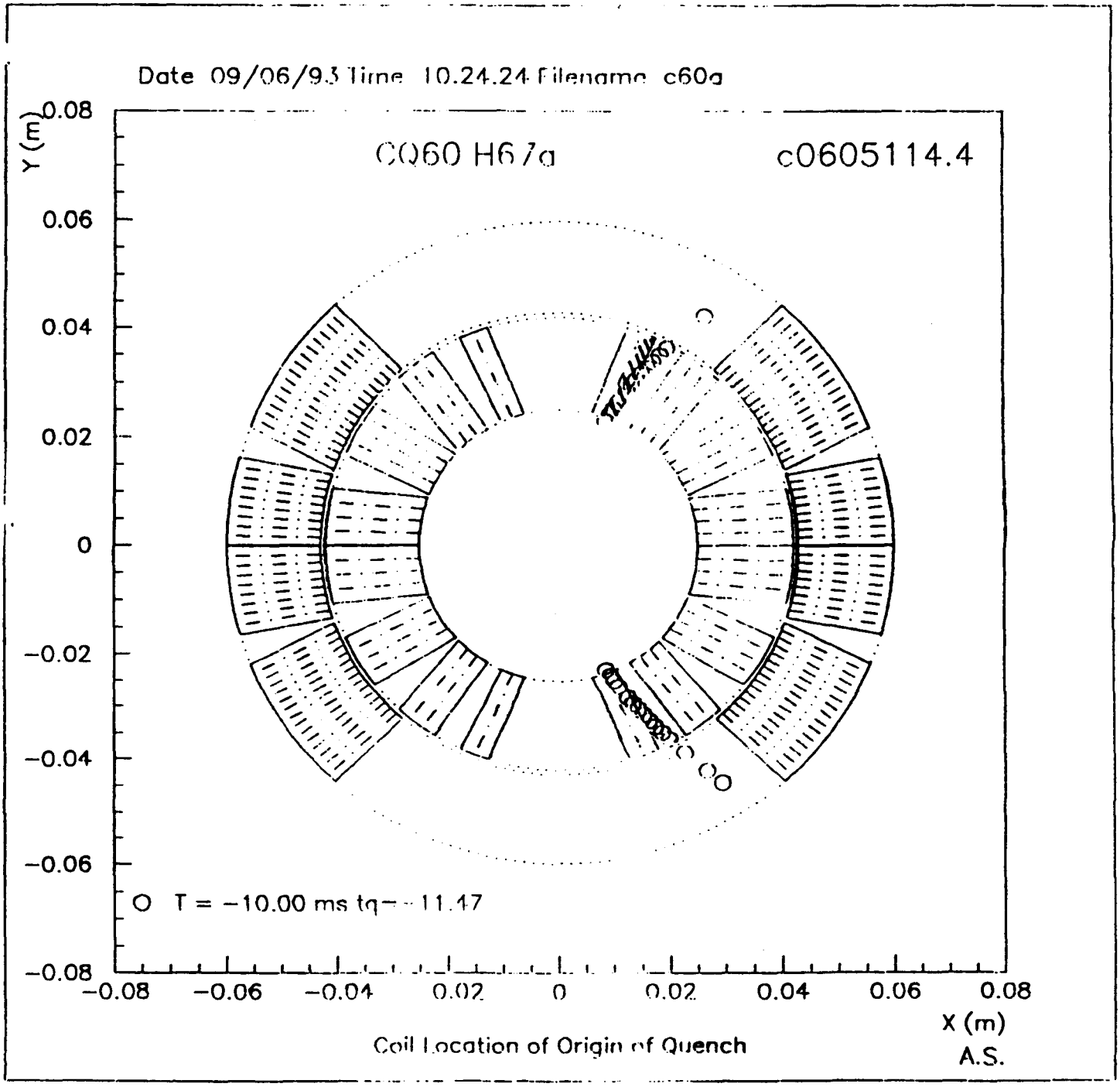
QUENCH LOCATION BY MEANS OF RELATIVE PROPAGATION TIME MEASUREMENT
(CENTRAL PART OF MAGNET)

Quench No 5 MTACERN
file "C1003113.005"

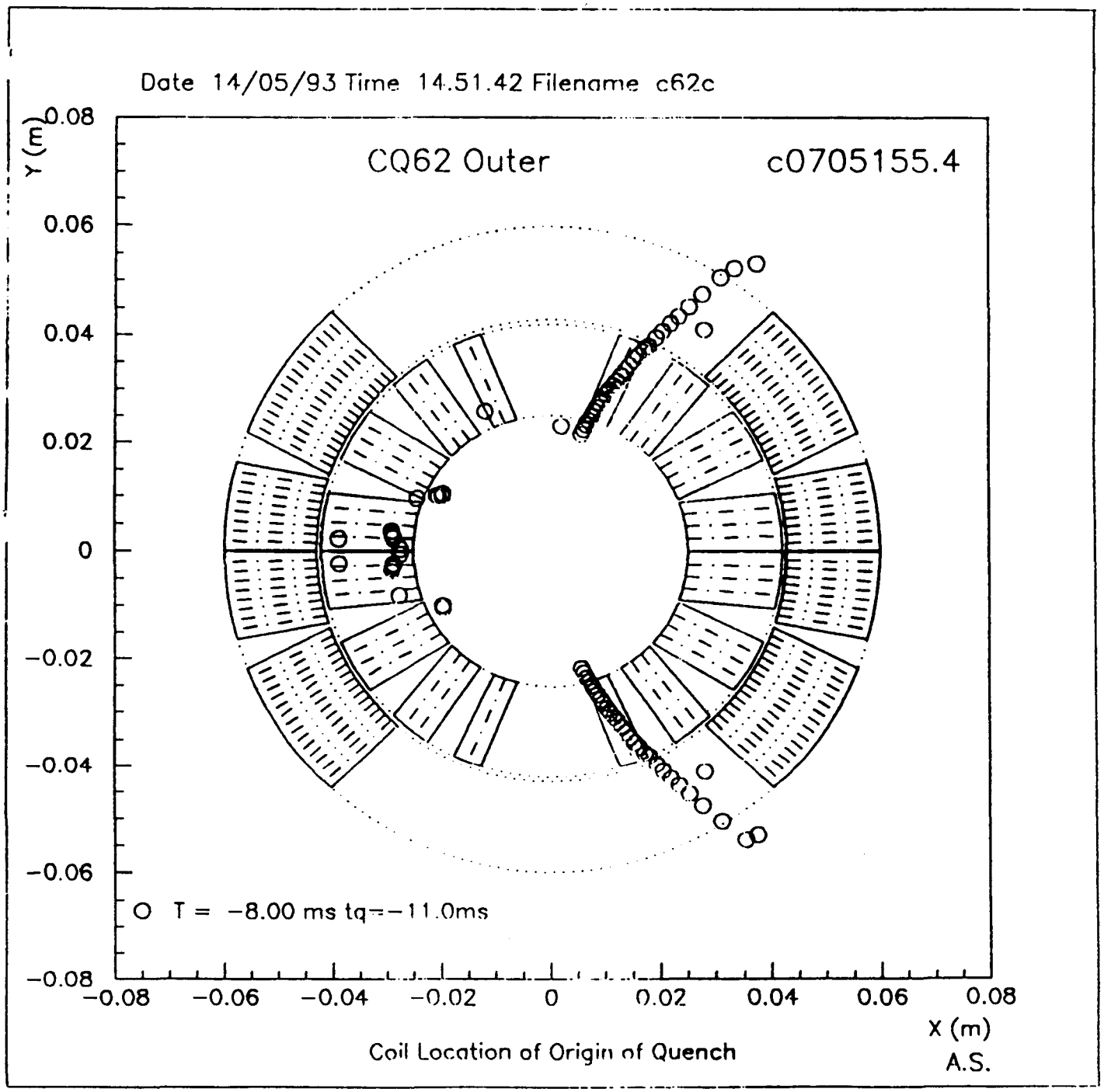


ESTIMATION OF BLOCK NUMBER IN WHICH QUENCH APPEARED (Q. SHOULD START CLOSE TO MAGNET END) BY OBSERVATION OF PROPAGATION OF BOTH PROPAGATION FRONTS (ONE FRONT AFTER

BL 1 T2


Date 09/06/93 Time 10.24.24 Filename c60a
C060 H67a
c0605114.4
Y (m)
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.08
−0.06
−0.04
0.02
0
0.02
0.04
0.06
0.08
X (m)
O T = −10.00 ms tq= 11.47
Coil Location of Origin of Quench
A.S.

Outer layer


Date 14/05/93 Time 14.51.42 Filename c62c
CQ62 Outer
c0705155.4
Y (m)
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.08
−0.06
−0.04
−0.02
0
0.02
0.04
0.06
0.08
X (m)
O T = −8.00 ms tq=−11.0ms
Coil Location of Origin of Quench
A.S.

Achieved

Longitudinal Localisation within 1 cm
(resolution 1 mm)

Measurement of the propagation velocity of the transition
(straightforward compared to growth of resistance)

Localisation of the starting bloc by

- **Signals from different coils in the transverse plane**
- **Propagation time through the end**
  (does not require a precise knowledge of the velocity)

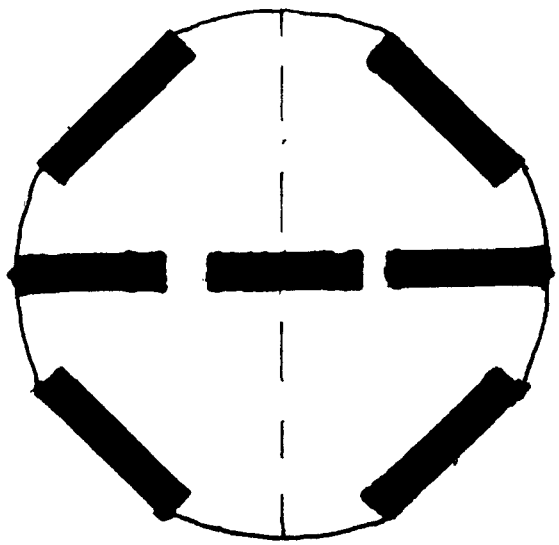
Discrepancy between layers :
Need inter layer voltage taps
(at least to qualify the different signatures)

Complementary to voltage taps in the windings :
allow to diminish the number
applicable if no voltage taps are present

Future

Models (1m long) tested in vertical cryostat

same shaft for magnetic measurements and pick-up coils



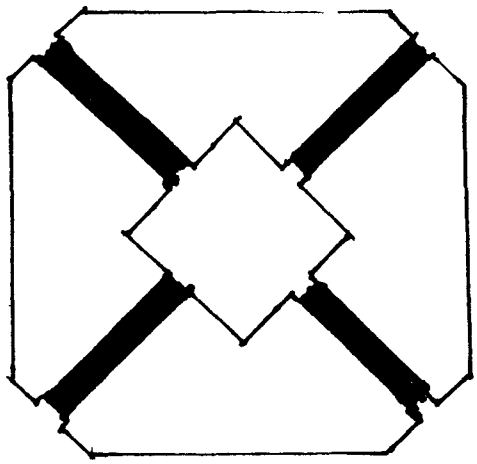
10 m prototypes : warm aperture for the magnetic meas.

Dedicated shaft that could be cold or warm

Resolution in 10 longitudinal intervals

2 * 3 for the ends

4 for the straight part



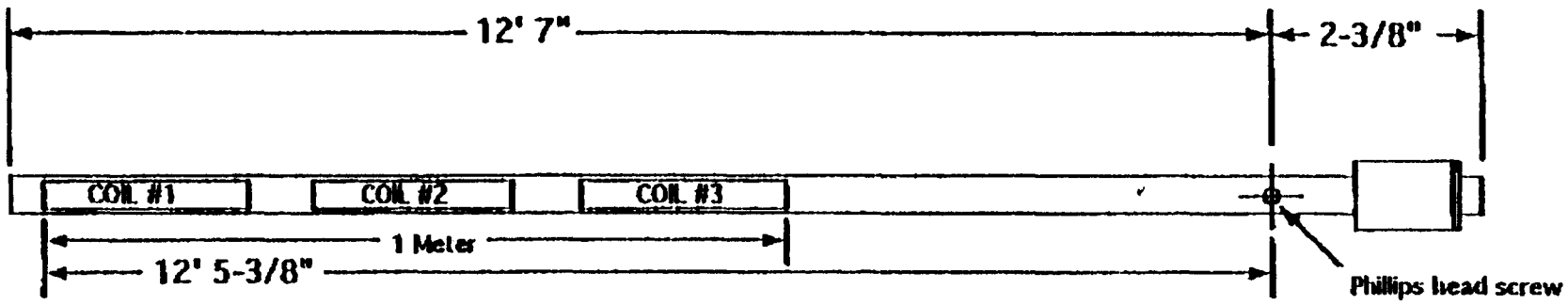
Jacek KRZYWINSKI

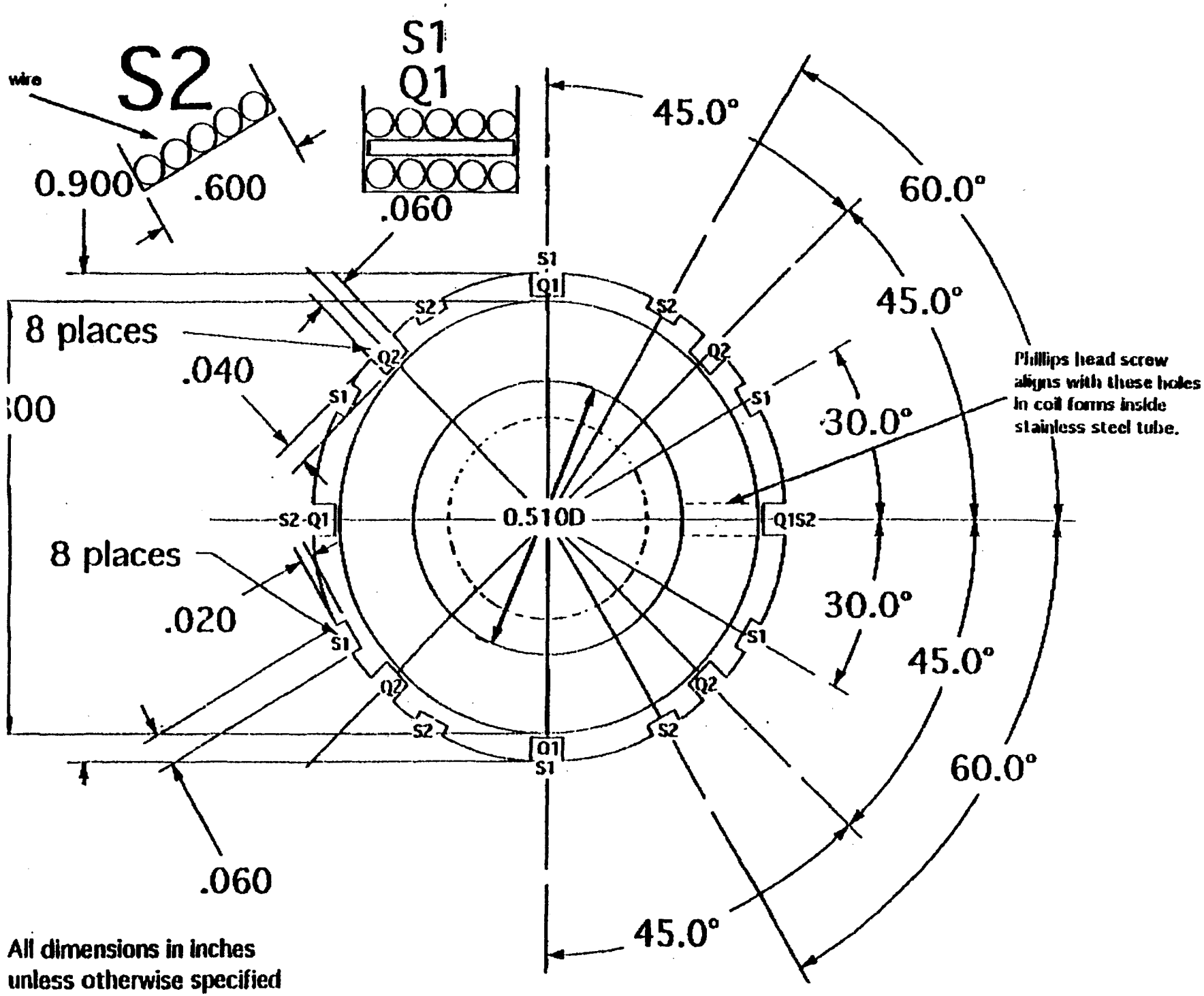
Quench Antenna

quench detection using pick-up wils

credits:

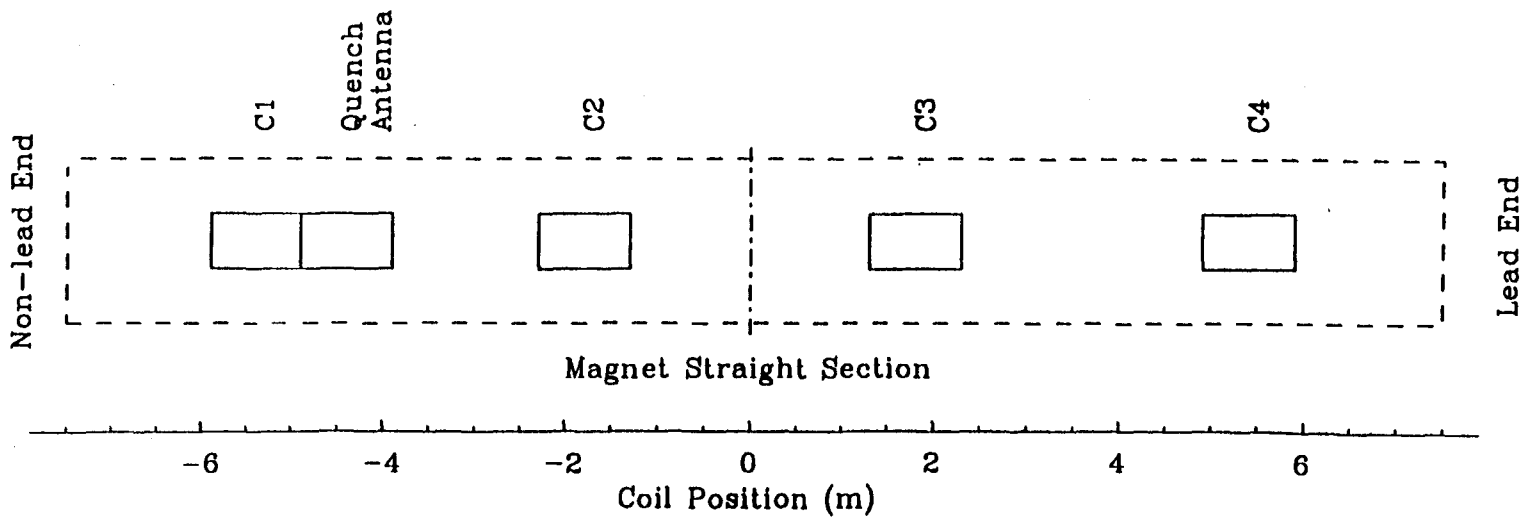
T. Ogitsu SSC
A. Devred SSC
A. Labarge SSC
R. Schermer LBL
K. Tsuchiya KEK
P. Wanderer BNL

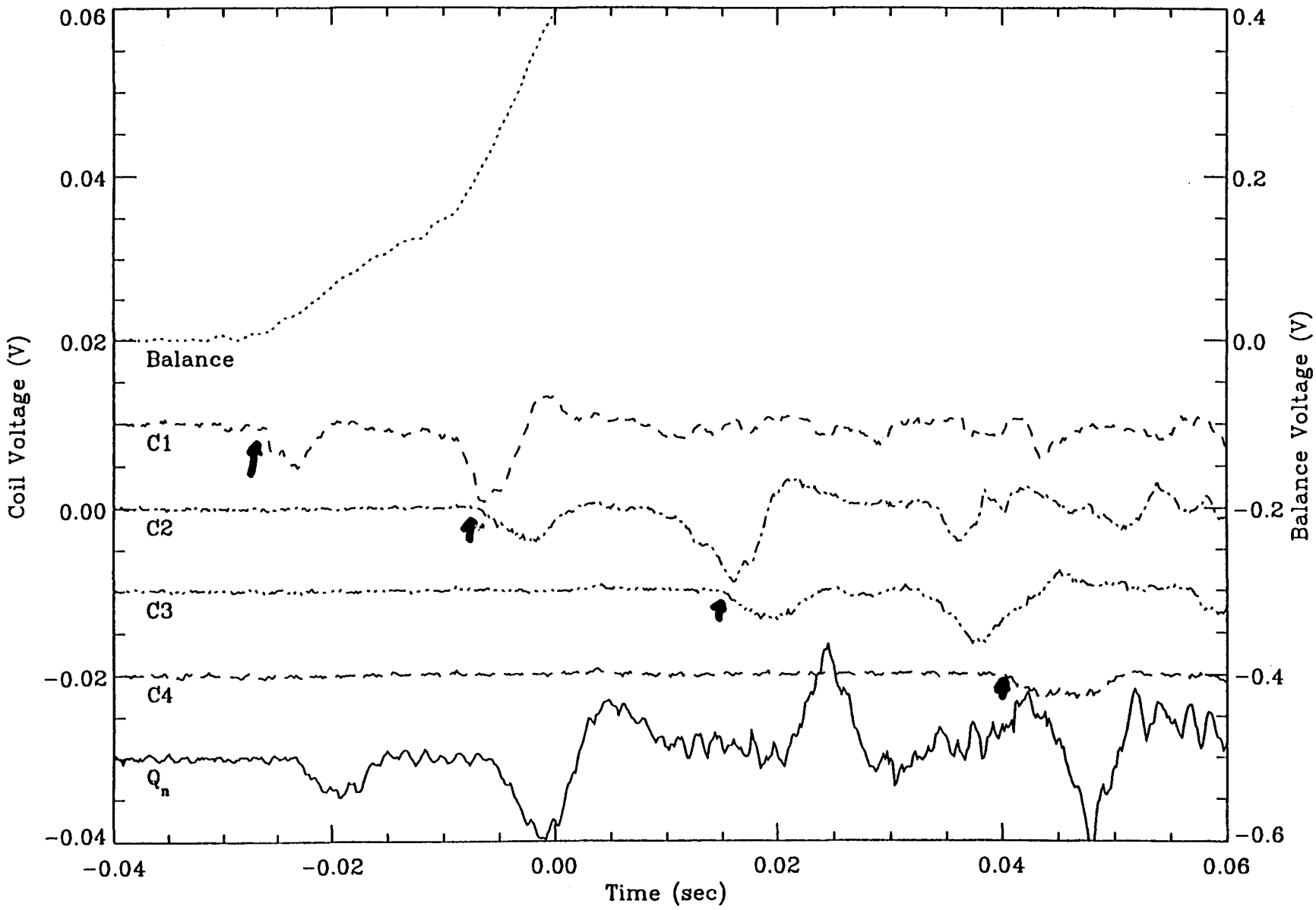

12' 7"
2-3/8"
COIL #1
COIL #2
COIL #3
1 Meter
12' 5-3/8"
Phillips head screw

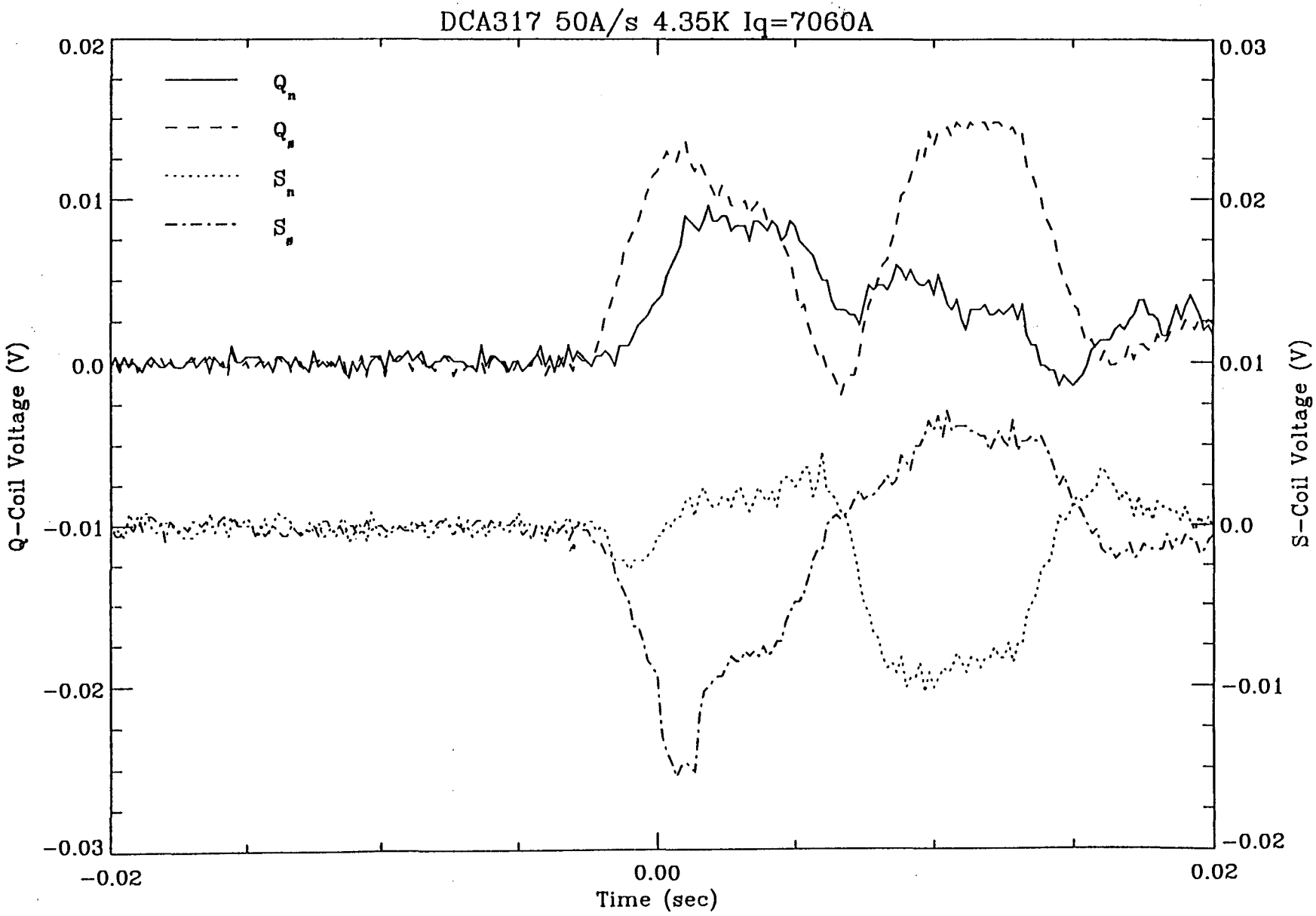


All dimensions in inches
unless otherwise specified

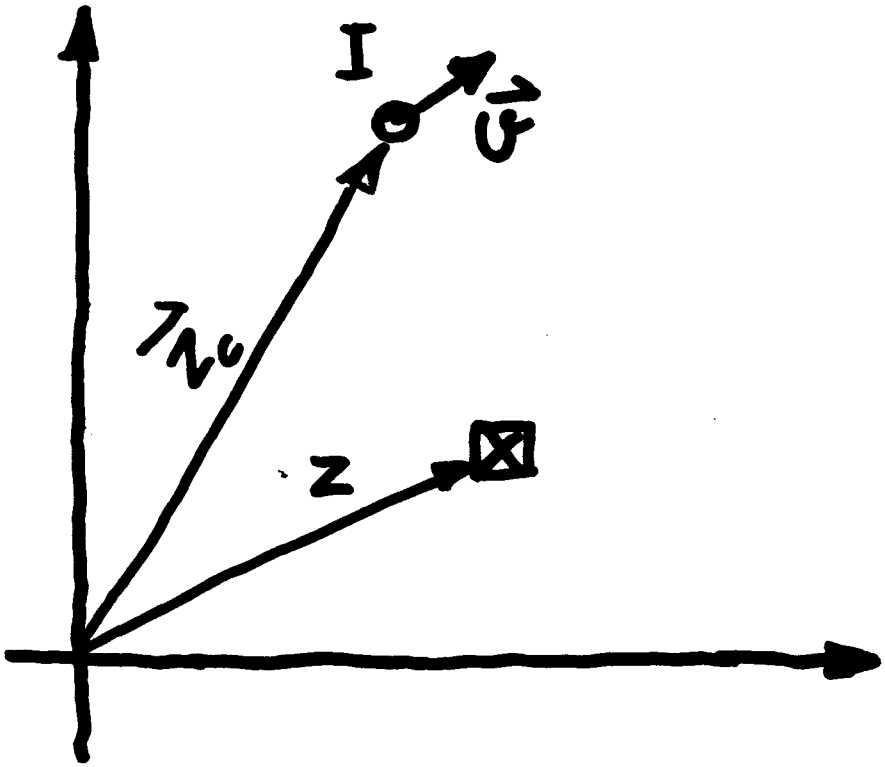
DCA318 Setup




0.06
0.04
0.02
0.00
−0.02
−0.04
Coil Voltage (V)
0.4
0.2
0.0
−0.2
−0.4
−0.6
Balance Voltage (V)
Balance
C1
C2
C3
C4
Q_n
−0.04
−0.02
0.00
0.02
0.04
0.06
Time (sec)


DCA317 50A/s 4.35K Iq=7060A
Q_n
Q_s
S_n
S_s
0.02
0.01
0.0
−0.01
−0.02
−0.03
0.03
0.02
0.01
0.0
−0.01
−0.02
−0.02
0.00
0.02
Time (sec)
Q−Coil Voltage (V)
S−Coil Voltage (V)

coil length $\gg |z - z_c|$!

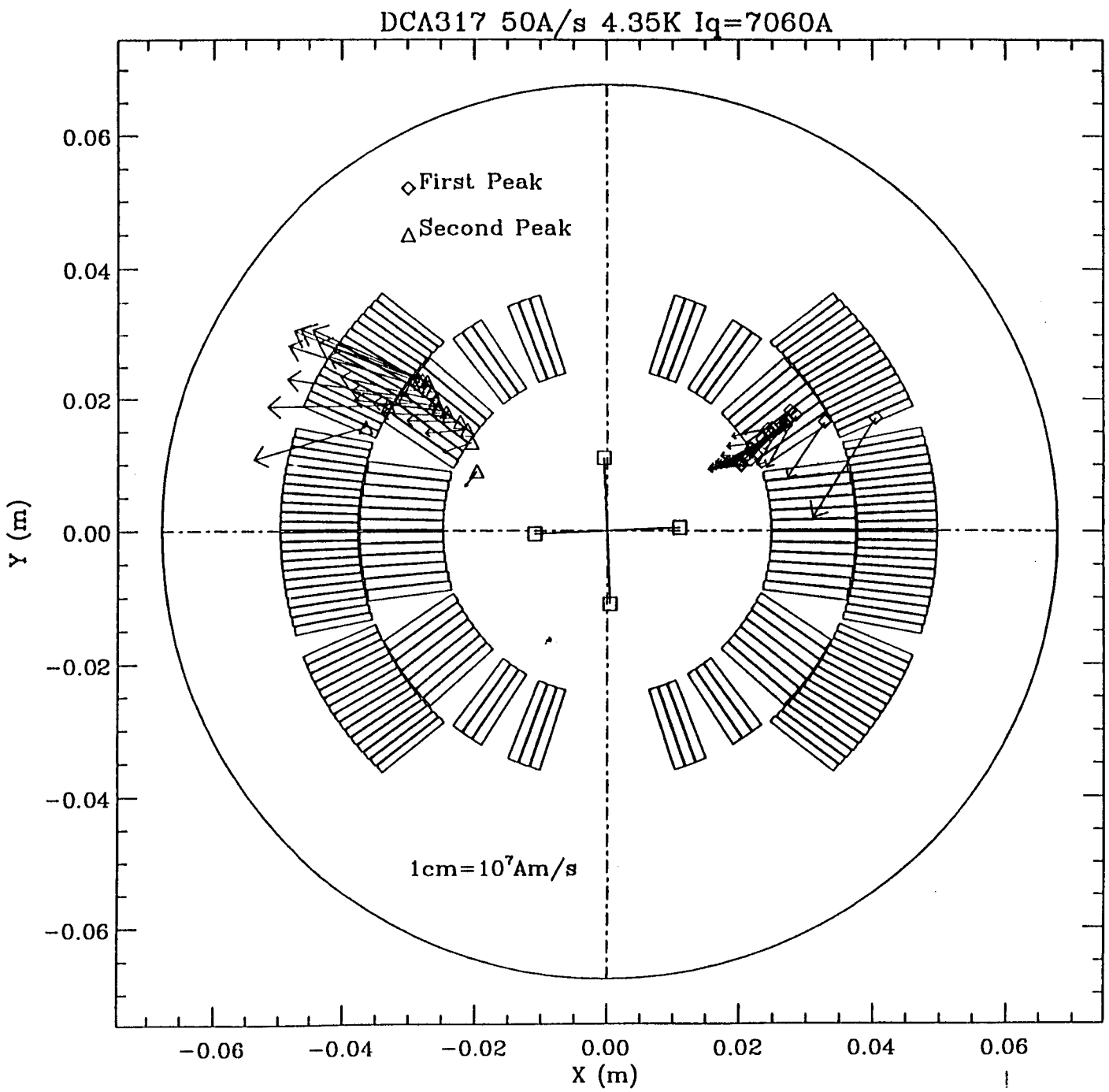


$$V = -j A_z$$

voltage $\sim \dot{V} = -j \dfrac{v \cdot \text{const}}{z - z_c} =$

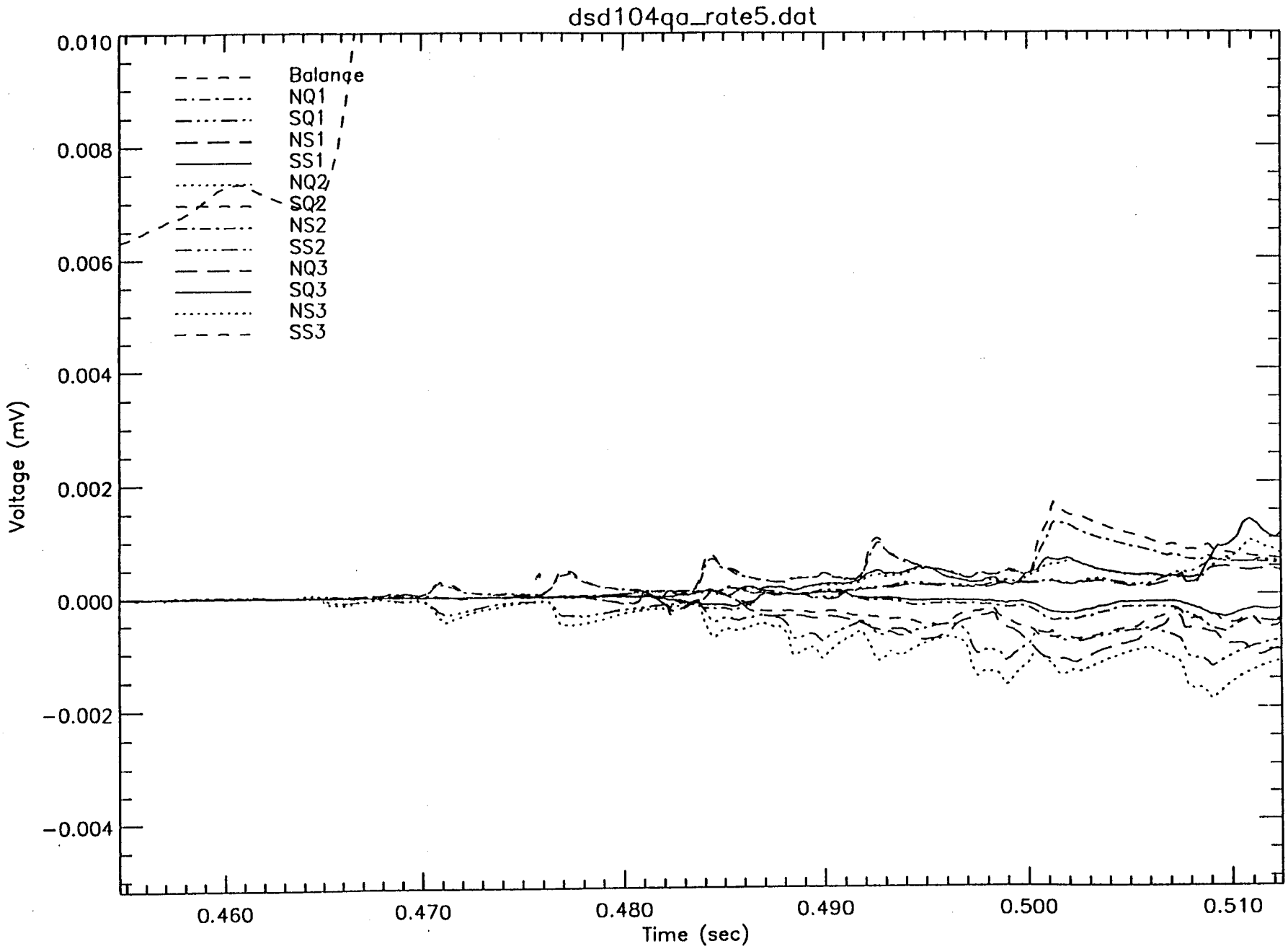
for $|z| < |z_c|$

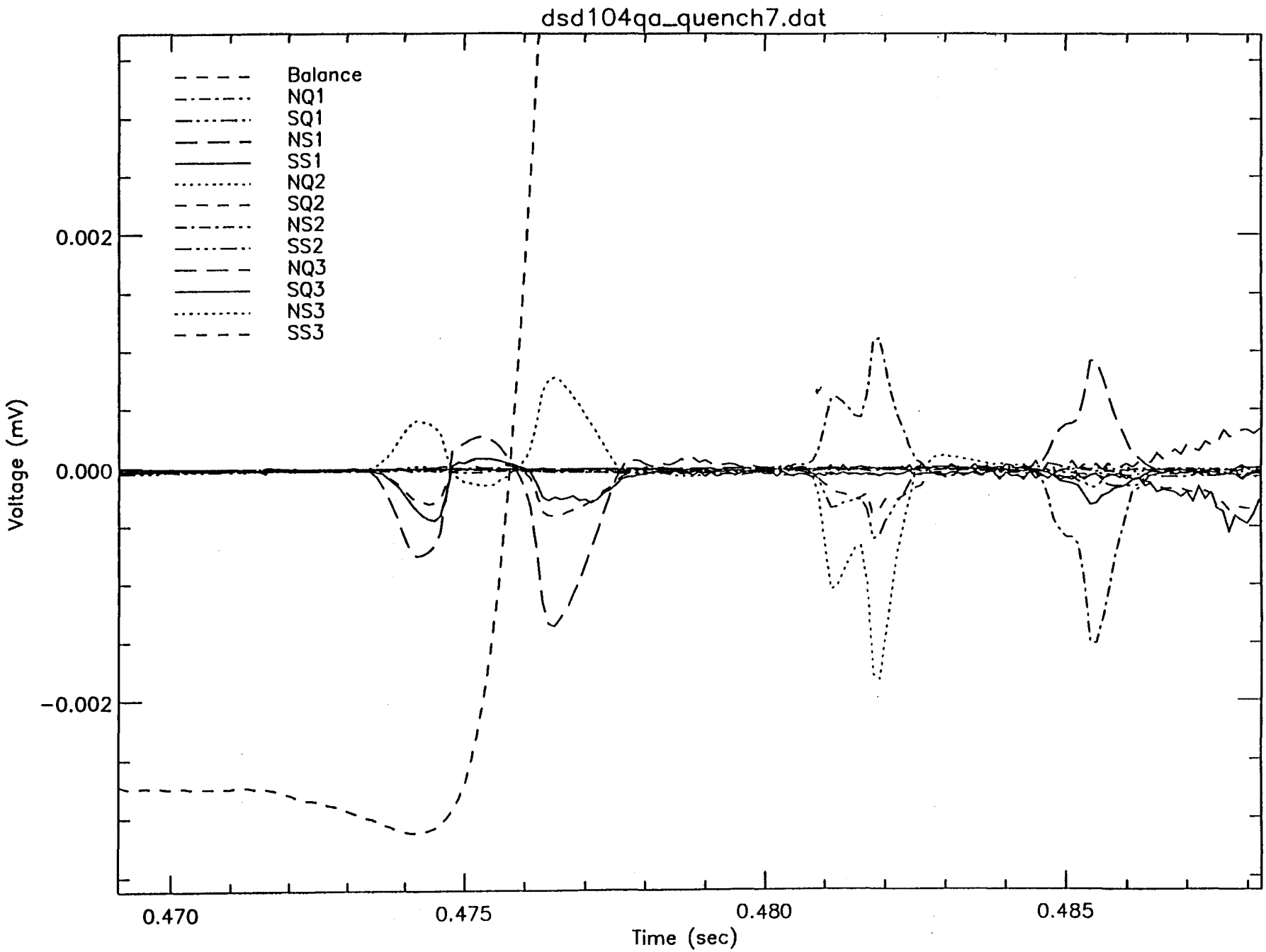
$$= -j \, \text{const} \cdot v \cdot \sum_{1}^{\infty} \frac{z^{n-1}}{z_c^{n}}$$

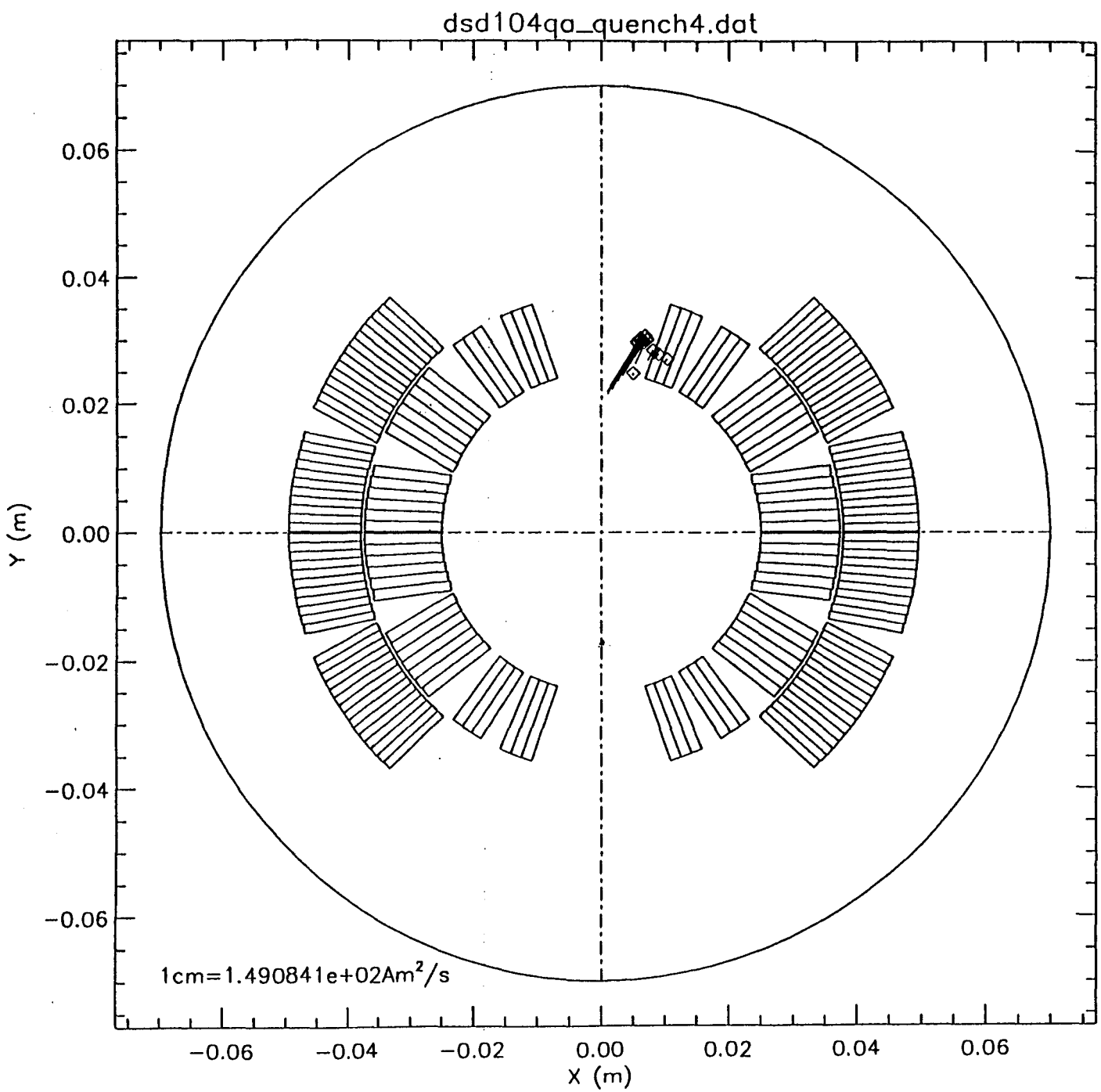

DCA317 50A/s 4.35K Iq=7060A
First Peak
Second Peak
1cm=10^7Am/s
Y (m)
X (m)
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06

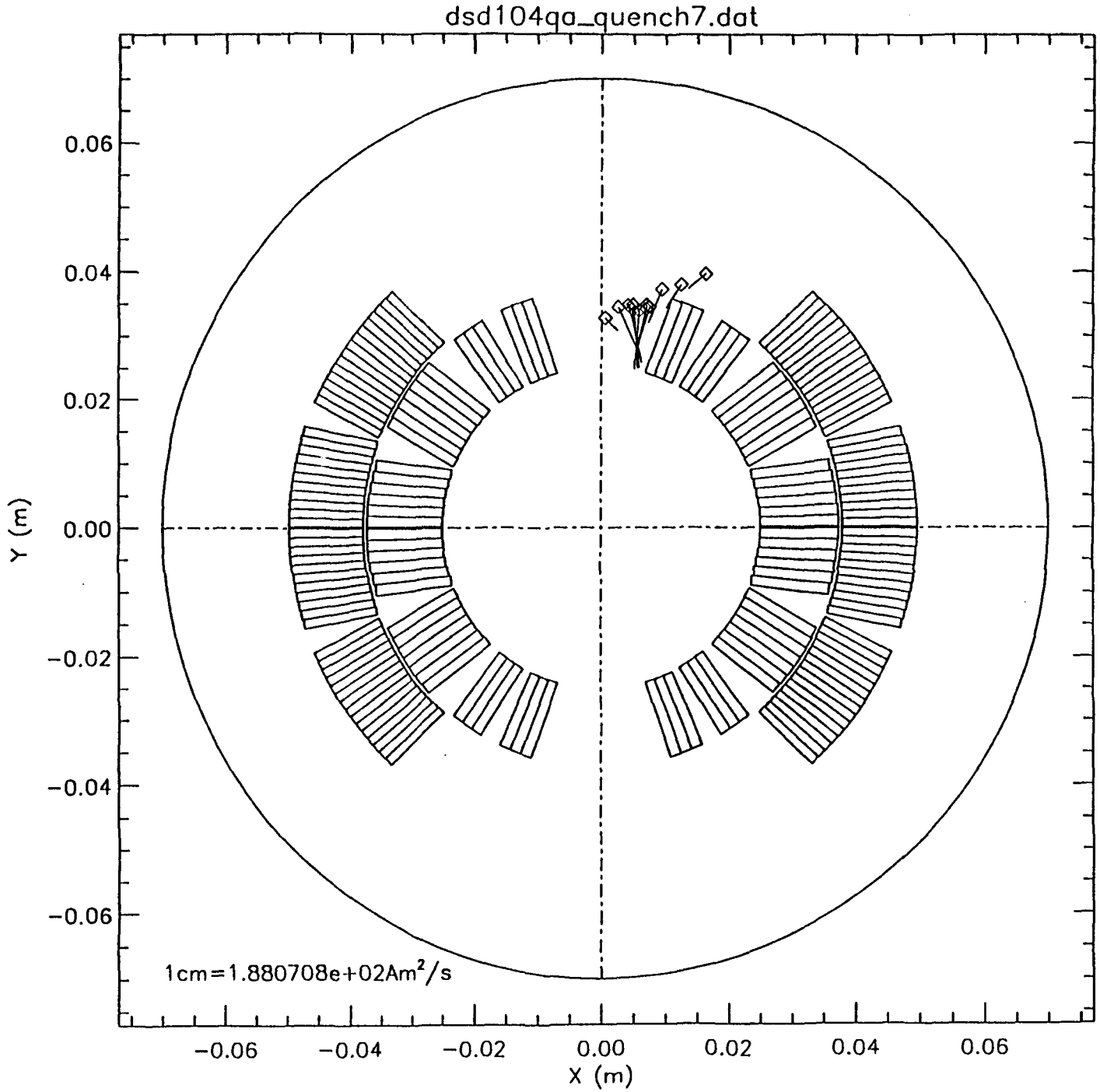
SEQ	TEST TYPE	QUENCH I (A)	RAMP RATE	BETWEEN TAPS	LOC: (see convention)*					
					I O	U L	S L/R	MT GRP	TRN #	L R
1	STRAIN2	5385	16	U13A:U13B	I	U	L	2	13	-
2	QUENCH 1	5659	16-0-4	U13A:U13B	I	L	L	2	13	-
3	QUENCH2	6218	16-0-4	Centertap:L27	Lower Outer Coil					
4	QUENCH3	6682	16-0-4	L27:L19B	Lower Coil Ramp Splice					
5	QUENCH4	6782	16-0-4	U19C:U19D	I	U	R	1	19	-
6	QUENCH5	7053	16-0-4	Centertap:L27	Lower Outer Coil					
7	QUENCH6	7299	16-0-4	L19C:L19D	I	L	R	1	19	-
8	QUENCH7	7359	16-0-4	L27:L19B	Upper Coil Ramp Splice					
9	QUENCH8	7539	16-0-4	Centertap:U27	Upper Outer Coil					
10	RAMPRATE1	1942	100	UOA:U13A and	I	U	-	3 & 4	1-13	-
				L13A:LOA	I	L	-	3 & 4	1-13	-
11	RAMPRATE2	2418	64	UOA:U13A and	I	U	-	3 & 4	1-13	-
				L13A:LOA	I	L	-	3 & 4	1-13	-
12	RAMPRATE3	5524	48	UOA:U13A and	I	U	-	3 & 4	1-13	-
				L13A:LOA	I	L	-	3 & 4	1-13	-
13	RAMPRATE4	7611	16	L27:L19B	Lower Coil Ramp Splice					
14	RAMPRATE5	5295	-100	UOA:U13A and	I	U	-	3 & 4	1-13	-
				L13A:LOA	I	L	-	3 & 4	1-13	-
15	RAMPRATE8	2071	80	UOA:U13A and	I	U	-	3 & 4	1-13	-
				L13A:LOA	I	L	-	3 & 4	1-13	-
16	RAMPRATE9	7122	32	UOA:U13A and	I	U	-	3 & 4	1-13	-
				L13A:LOA	I	L	-	3 & 4	1-13	-
********** Subcool to 3.85 K **********										
17	QUENCH9	7873	16-0-4	U27:U19B	Upper coil ramp splice					
18	QUENCH10	7191	16-0-4	U27:U19B	Upper coil ramp splice					

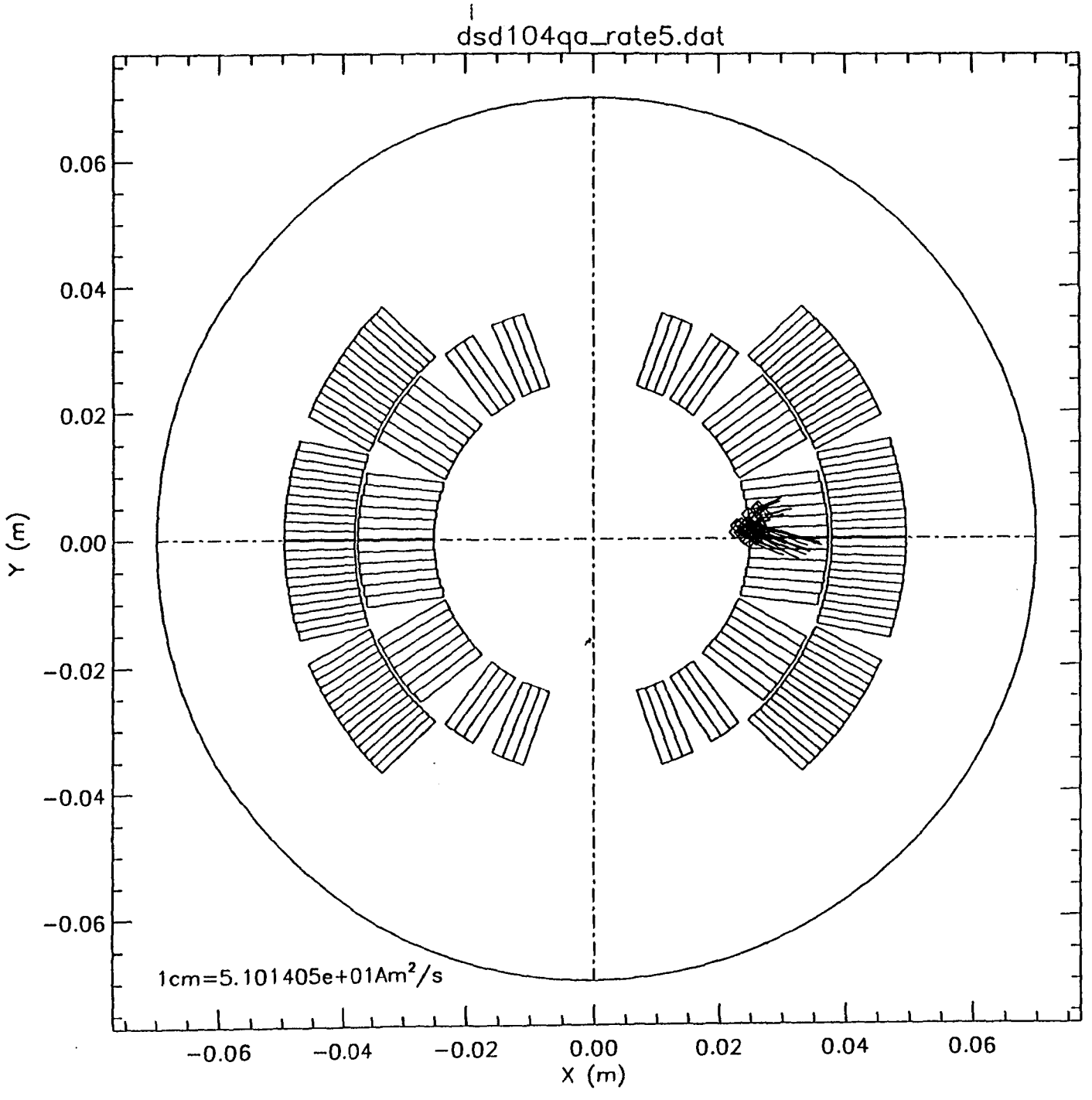
Table 3. Quench localization data for DSD104 (Continues)

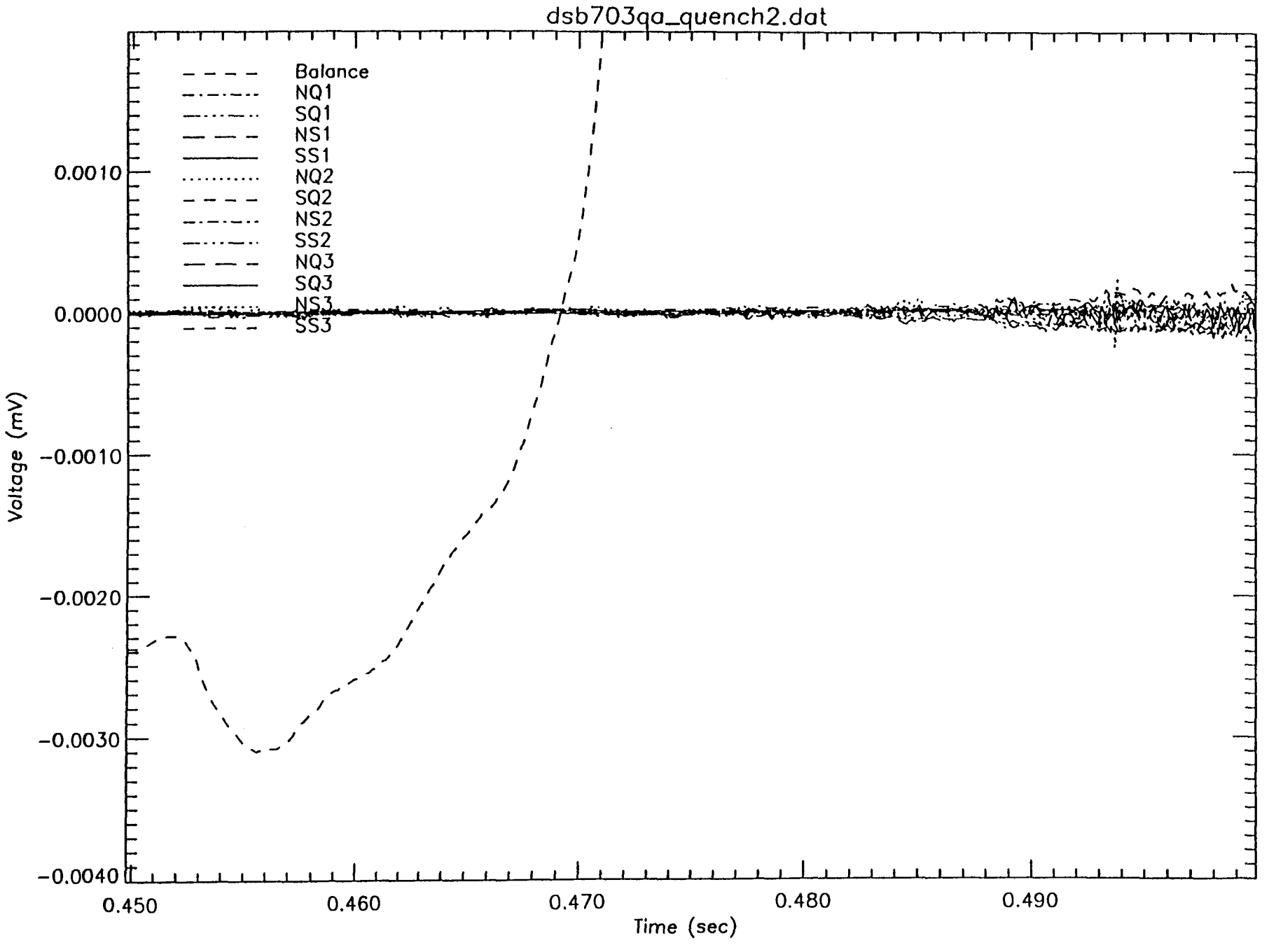

dsd104qa_rate5.dat
Balance
NQ1
SQ1
NS1
SS1
NQ2
SQ2
NS2
SS2
NQ3
SQ3
NS3
SS3
0.010
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
Voltage (mV)
0.460
0.470
0.480
0.490
0.500
0.510
Time (sec)


dsd104qa_quench7.dat
Balance
NQ1
SQ1
NS1
SS1
NQ2
SQ2
NS2
SS2
NQ3
SQ3
NS3
SS3
0.002
0.000
−0.002
Voltage (mV)
0.470
0.475
0.480
0.485
Time (sec)


dsd104qa_quench4.dat
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
Y (m)
1cm=1.490841e+02Am²/s
−0.06
−0.04
−0.02
0.00
0.02
0.04
0.06
X (m)


dsd104qa_quench7.dat
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
Y (m)
1cm=1.880708e+02Am²/s
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
X (m)


dsd104qa_rate5.dat
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
Y (m)
1cm=5.101405e+01Am²/s
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
X (m)


dsb703qa_quench2.dat
Balance
NQ1
SQ1
NS1
SS1
NQ2
SQ2
NS2
SS2
NQ3
SQ3
NS3
SS3
0.0010
0.0000
-0.0010
-0.0020
-0.0030
-0.0040
Voltage (mV)
0.450
0.460
0.470
0.480
0.490
Time (sec)

SSCL

HEB Quadrupoles

URA Saclay

CEA/STCM

HEB Quadrupole Cold Mass Critical Design Review

WARM MAGNETIC MEASUREMENTS

BY

JOSETTE LEBARS

Description :

MAGNETIC CONFIGURATION

There are five different magnetic configurations which vary in effective magnetic length and five different magnetic measuring coils

Magnet lattice designation HEB Quadrupole	Length of the coil including the connections mm	Length total of the measuring coils mm	Length of the end coils mm	Length of the central coils mm
HQM	1768	2000	500	1000
HQM 1	1067	1500	500	500
HQM 2	1340	1500	500	500
HQM 3	2469	2650	700	1250
HQM 4	3522	3750	1250	1250

HEB Quadrupole Cold Mass Critical Design Review

- Test conditions :

  * On the 3 prototypes built by the CEA

  * In the Saclay test facility (vertical position)

2 - MEASURING METHOD :

- Saclay's previous experiences for magnetic measurements at room temperature : LHC*, UNK.

- The selected principles are :

  * Amplitude and phase of the voltage induced in the pick-up coil are measured then FOURIER analyzed

  * Measurements are taken from 20 to 32 or 100 to 128 different angular positions

  * During a measurement, the pick-up coil is stationary

  * To cover the whole length of a quadrupole magnet, one measurement using 3 sets of 3 coils is needed

  * Semi automatic process

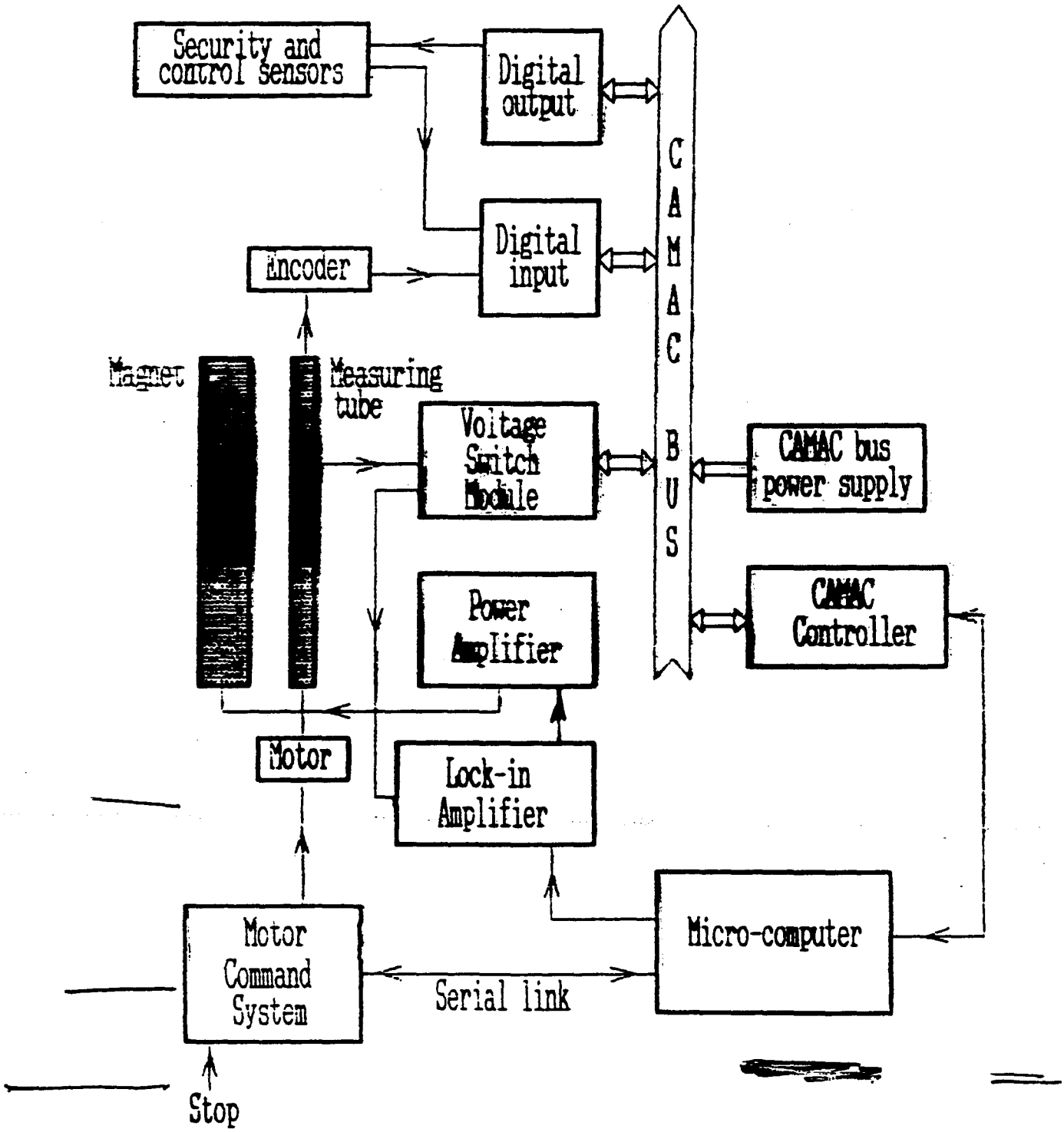
  * Data processing enables to calculate the harmonics

* results are given in table 1

HEB Quadrupole Cold Mass Critical Design Review

Mult. meas. RMS = 0.1 * Random mult. RMS tolerance :

σ meas.	n
0.18 unit	2
0.08	3
0.02	4.5
0.01	6 to 9


Security and control sensors
Digital output
Digital input
Encoder
CAMAC BUS
Magnet
Measuring tube
Voltage Switch Module
CAMAC bus power supply
Power Amplifier
CAMAC Controller
Motor
Lock-in Amplifier
Micro-computer
Motor Command System
Serial link
Stop

*Lock-in amplifiers tested :

.PA 5302 ;Princeton applied research
calculated error :$<9.2*10^{-6}$; $\Delta T=20°$

.SR 850 ;Stanford research system
calculated error :$<6.7*10^{-6}$; $\Delta T=20°$

If measurement cabinet is temperature regulated, errors for SR 850 are less important :$<5.6*10^{-6}$; $\Delta T=2°$

3 - SPECIAL EFFORTS :

Why ?

- To compare with the HERA results : we have to increase all the precisions due to the systematic mechanical imperfections

minimum factor 4

MECHANICAL IMPERFECTIONS

- To design the measuring tube, we have to think that it is necessary to reduce these imperfections in comparison with the HERA coils.

Vertical position is chosen instead of horizontal position

- To reduce - the sagitta of coil axis - under it own weight

SSC coils Ø 39.5	HERA coils 53
SSC magnetic length > 4m	HERA coils 2,3

- To avoid the hyperstaticity of the tube in the horizontal position (3 or 4 supports necessary inside the measuring tube in horizontal position).

  => deflection of the axis of rotation no symetrics along the magnetic axis : twist.

- To increase the Ø of the coil. No necessity of a tube around the coils and in fact to increase the precision of the measures.

- We have also Ø of the room measurement coils = Ø at cold temperature. It means : good comparison_ between the harmonic and correlation.

IN VERTICAL POSITION

Where to avoïd what:

MECHANICAL ERROR
Error on coil radii
Angle between coil planes
~~Sagitta~~ of coil axis (Bow)
Movement of coil axis
Twist about the axis, i.e deviation of coil winding from straight line

In the :

- Measuring tube

  - material : - high mechanical strength
    - isotropic
    - able to be machined with an high accuracy

  - Alignment : between measuring tube axis and mechanical guide axis (air bearing support and radial guide in the lower part), has to be perfect. (<50μ)

COLD MAGNETIC MEASUREMENTS

BY

JOSETTE LEBARS

SSCL
HEB
Quadrupoles
URA Saclay
CEA/STCM

HEB Quadrupole Cold Mass Critical Design Review

Description :

- Magnetic configuration
  id = Warm measurements

There are five different magnetic configurations which vary in effective magnetic length and five different magnetic measuring coils

Magnet lattice designation HEB Quadrupole	Length of the coil including the connections mm	Length total of the measuring coils mm	Length of the end coils mm	Length of the central coils mm
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HQM 1	1067	1500	500	500
HQM 2	1340	1500	500	500
HQM 3	2469	2650	700	1250
HQM 4	3522	3750	1250	1250

and 4 wires added to measure the integral ~~determined.~~ $\int g\,dl$

1 - SPECIFICATION REQUIREMENT :

Test Objective :

- To measure with the magnet at Helium temperature supplied

a) with a DC current

- the field homogeneity in term of harmonic content
- the integrated field strength

b) with a HEB current cycle (F Kircher)

- the actual field homogeneity in term of harmonic content

Measurements to be done :

- using a DC current
- at 4.2K

- harmonic content of the field up to n=9 at different current levels between injection (656A) and nominal current (6650A).

-Integrated field strength with a design operating current of 6650A.

Expected accuracy specified for the multipoles content:

Mult. meas. RMS = 0.1*Random mult. RMS tolerance

σ meas	n
0.18 unit	2
0.08	3
0.02	4,5
0.01	6 to 9

For the integrated field strength:

Magnet Designator (F&D)	GdL @ 2TeV/c (Tesla)
HQM	298.69 ± 3
HQM1	168.38 ± 1.68
HQM2	219.00 ± 2.13
HQM3	421.50 ± 4.2
HQM4	624.71 ± 6.15

Acceptance ~1%

2 - MEASURING METHOD :

- Saclay has previous experiences on magnetic measurements of coil supplied at Helium temperature : LHC, UHK, HERA.

- The selected principles is to rotate in the He bath, the measuring coils continuously at a speed of :

    - 1.5 turns per min. with the DC current
    - 2.5 turns per sec. with the HEB current cycle

- The flux variations due to the rotation of the measuring coils - and or not - the current ramping, are integrated then Fourrier analyzed

- Data processing enables to discriminate the two sources of flux variations so as to calculate the harmonics at a finite number of current level, and the integrated field strength at the operating current

- Test conditions :

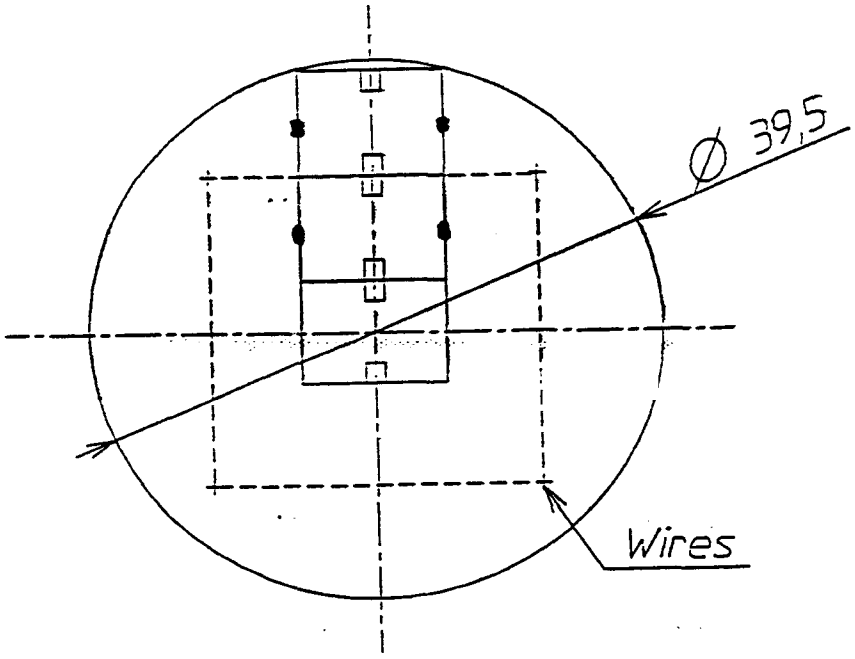
    * On the 3 prototypes built by the CEA

    * In the Saclay test facility (vertical position)

Measuring coils

Similary to the measuring coils at room temperature :

- same diameter
- same measuring coil lengths
- 4 wires added



MAGNETIC MEASURING EQUIPMENT

Requirement :

* Positionning the magnetic field sensor with respect to the magnet at Helium temperature

* Rotating in the Helium bath at a maximum speed of 2.5 turns/sec

Mechanical Quadrupole equipment :

What is changed comparing these measurements with the warm measurements ?

1 - Air bearing radial guide is not available
- Has to be studied but will be a mechanical system

2 - id.

3 - id.

4 - 4 wires added

5 - id.

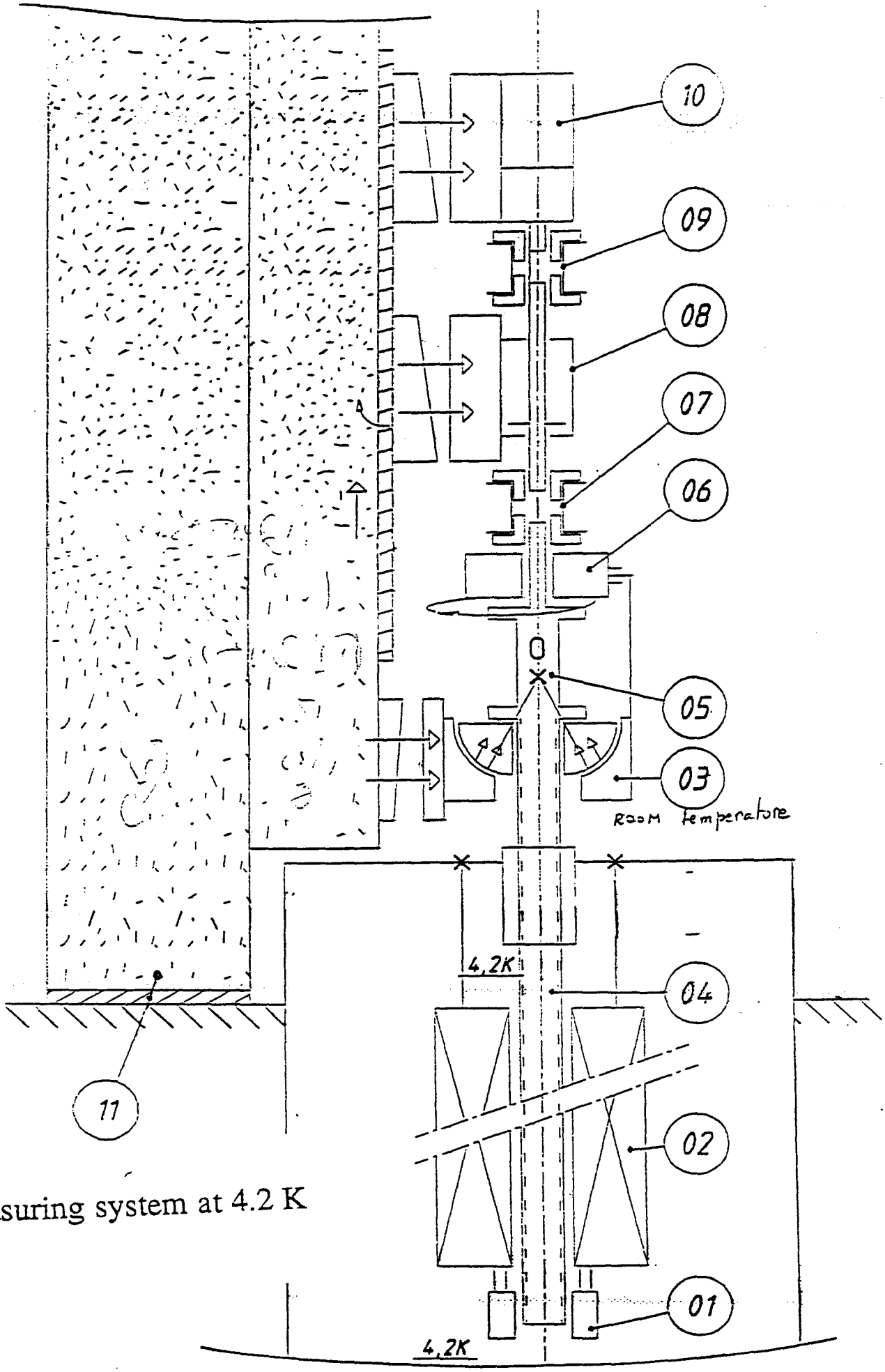
6 - slipping rings will be used to transmit the signal from the cryostat to outside

7 - id

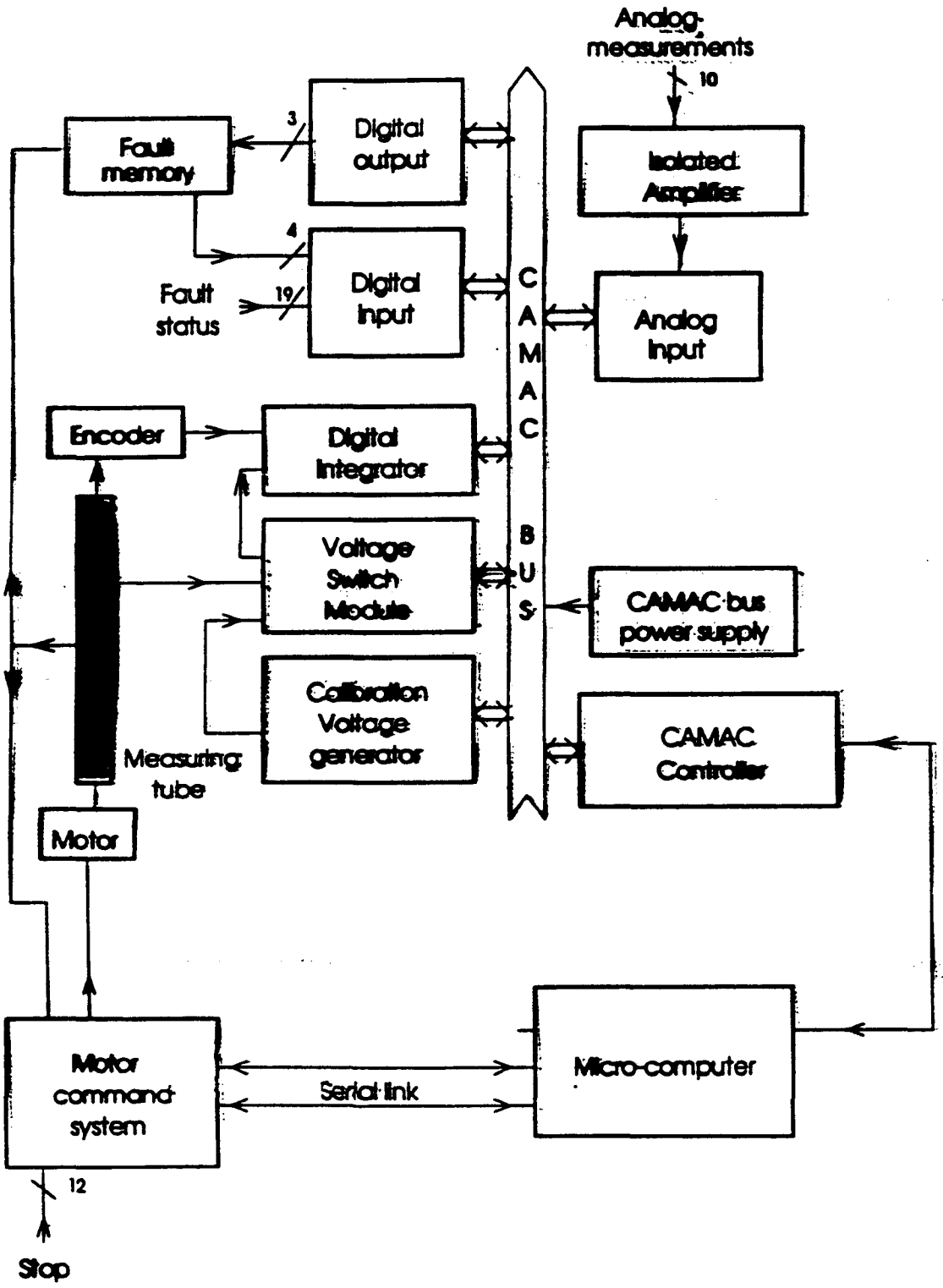
8 - id. for low speed measurements
≠ has to be determined for high speed measurements (less number of bits)

9 - id.

10 - id. for low speed measurements
≠ brushless continuous motor without reductor for high speed measurements



Measuring system at 4.2 K


Analog measurements
10
Fault memory
3
Digital output
Isolated Amplifier
4
Fault status
19
Digital Input
CAMAC BUS
Analog Input
Encoder
Digital Integrator
Voltage Switch Module
CAMAC bus power supply
Calibration Voltage generator
CAMAC Controller
Measuring tube
Motor
Motor command system
Serial link
Micro-computer
12
Stop

*Digital integrators have been used for:

- Low drift.
- Very important output range.

*Integrator design from CERN has been used and improved by :

-Noise and offset voltages reduction.
:1000 X voltage gain available.

-Readings by computer are triggered from angle given by encoder .
:Harmonics calculations improved.

-Calibration process has been integrated in software.
:calibrated voltage gains and offset are used to give accurate measured voltage.
Minimum input voltage ~ 100 nV

3 - SPECIAL EFFORTS :

Why ?

- Very high accuracy requested for harmonic content

- To compare with the HERA results : we have to reduce all the mechanical imperfections
  minimum factor 4

- First time this measurement will be done with the measuring coils rotating in liquid Helium!

Where and What ?

Measuring coils
. materials at 4.2 K : studies and test. - calibration -
. vibrations : measurements and to do the equilibration

Measurements improving must be introduced in the control/command and measurement software

1- SPECIFICATION REQUIREMENT:

Test objective:

To measure the actual field homogeneity in term of harmonic content when the magnet is supplied with the HEB current cycle, so as to determine the effects of the eddy and persistent currents.

Measurements to be done:

Harmonic content of the field up to n=9, at different current levels (Fig 1):

. for bipolar operation,

. between injection (650A) and nominal current (6650A),

. for up and down ramps (dI/dt =60 A/sec).

Expected accuracy:

Aim: to get almost the same accuracies (systematic and random) as for DC measurements on the integral field: for random accuracy:

Mult. meas. RMS= 0.1*Random mult. RMS tolerance

σ meas	n
0.18 unit	2
0.08	3
0.02	4,5

2- MEASURING METHOD:

- Saclay had a previous experience for mag. meas. during ramping with very high ramp-rate (1T/sec); with the present HEB cycle, this method would be too much time-consuming.

- The choosen principle is to rotate measuring coils continuously and at high speed :

. the flux variations due to the rotation of the measuring coils and the current ramping are integrated then FOURIER analyzed,

. data processing enables to discreminate the two sources of flux variation, so as to calculate the harmonics at a finite number of current levels.

- This method has already been used with different approaches (SSC workshop Feb 93).

Test conditions:

. on the 3 prototypes built by CEA,
. in the Saclay test facility (vertical position),
. with the Saclay bipolar PS, delivering a current cycle similar to the HEB one.

Description (Fig2):

- ***Measuring coils*** (J. Le Bars):

. Similar to those used for DC meas.

. **Rotating in the helium bath at a speed of 2.5 turns/sec.**

- ***Signal transmission:***

Slipping rings will be used to transmit the signal from the cryostat to outside.

- ***Triggering:***

An accurate encoder will be used to send periodic triggers corresponding to incremental steps (128 per turn) to the data acquisition system.

- ***Data Acquisition System*** (J.C. Sellier):

. Digital integrator :
5 MHz VFC
programmable gain
periodic calibration
. Camac I/O modulus + bus
. PC + printer

*Pulse current measurement apparatus has been used for UNK magnets.

*The electronic system is greatly similar to DC current measurement apparatus.

*Great voltage measurement accuracy needed due to harmonics variations versus quadrupole current.

*Fast integrator is necessary due to high coils rotation speed.

*Technical solutions .
(Brookhaven, DESY, Fermilab, UNK)
- Analog integrators with ADC
- Digital voltmeters
- Lock-in amplifiers
- FFT analysers
- Digital integrators.

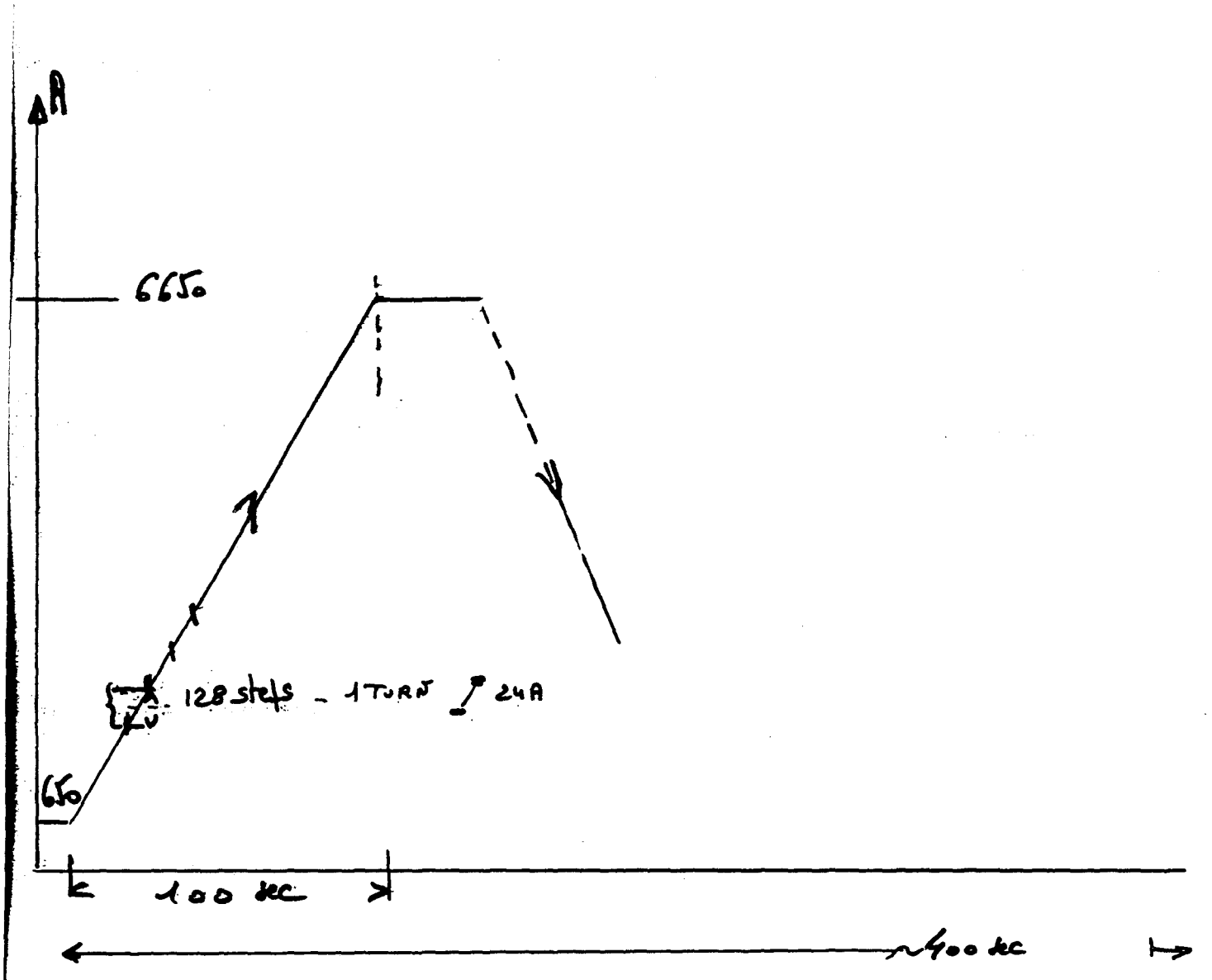
- *Data processing* (D. Orrell):

. main problem: to take into account the current change during one coil revolution;

. solution: linear interpolation of the voltage between cycles (Fig 3);

. accuracy (simulation): relative error in b5 <0.5% for 2 Hz rotation;

. data processing after each cycle + statistics on several cycles.


A
6650
650
128 steps - 1 TURN 24A
100 sec
~400 sec

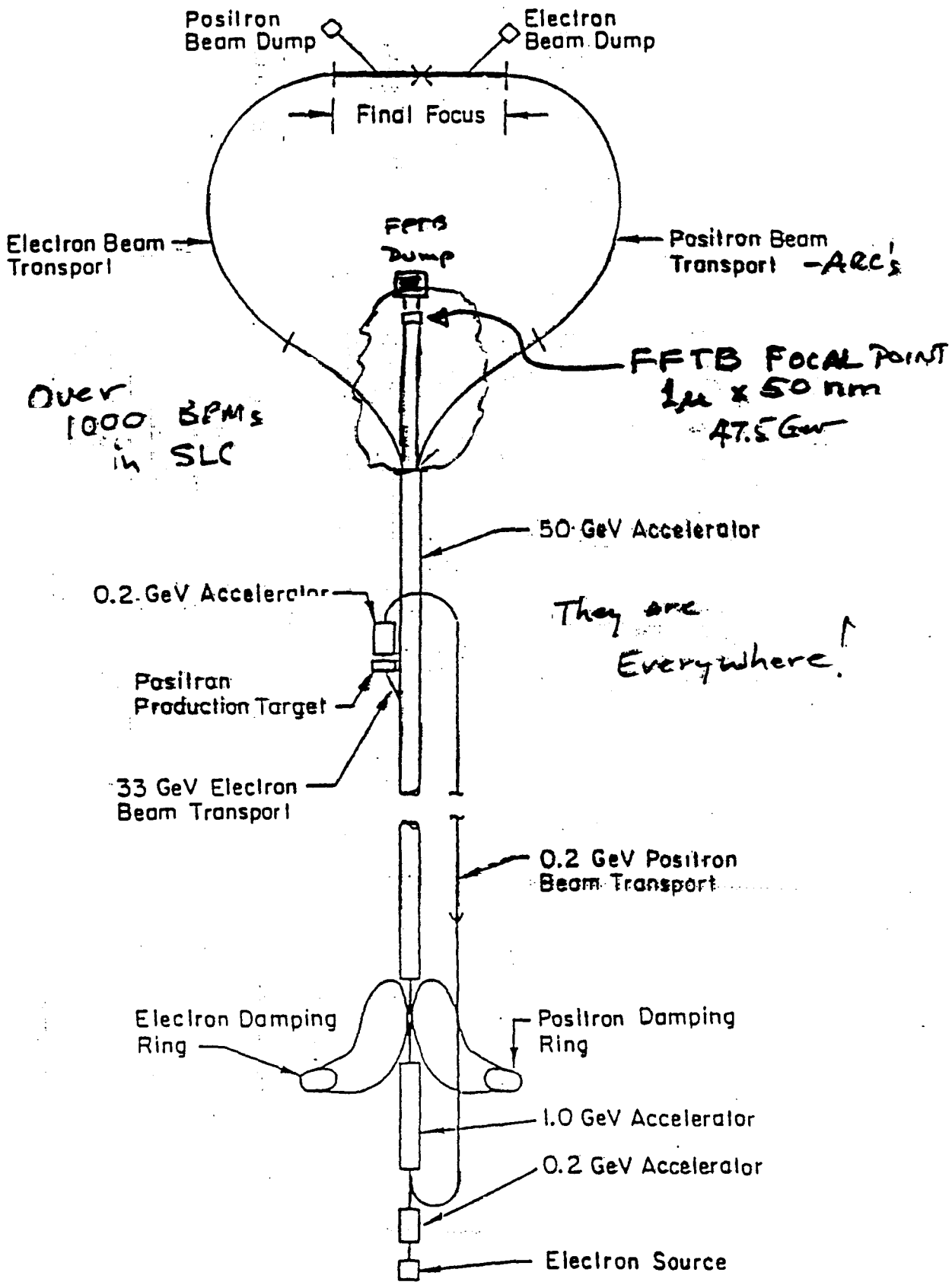
Vibrating Wire Method for Center Finding

FIDUCIALIZATION CONTRIBUTORS

Steve Williams
Yasunori Takeuchi
Gerry Fischer
Joe Cobb
Dave Jensen
Dan Jones
Helmut Walz
Dave Sawyer
Vince Bressler
Ed Askeland
Robert Ruland
Vern Smith

SLAC, KEK, ORSAY, DESY, ~~SOVIET~~ RUSSIA

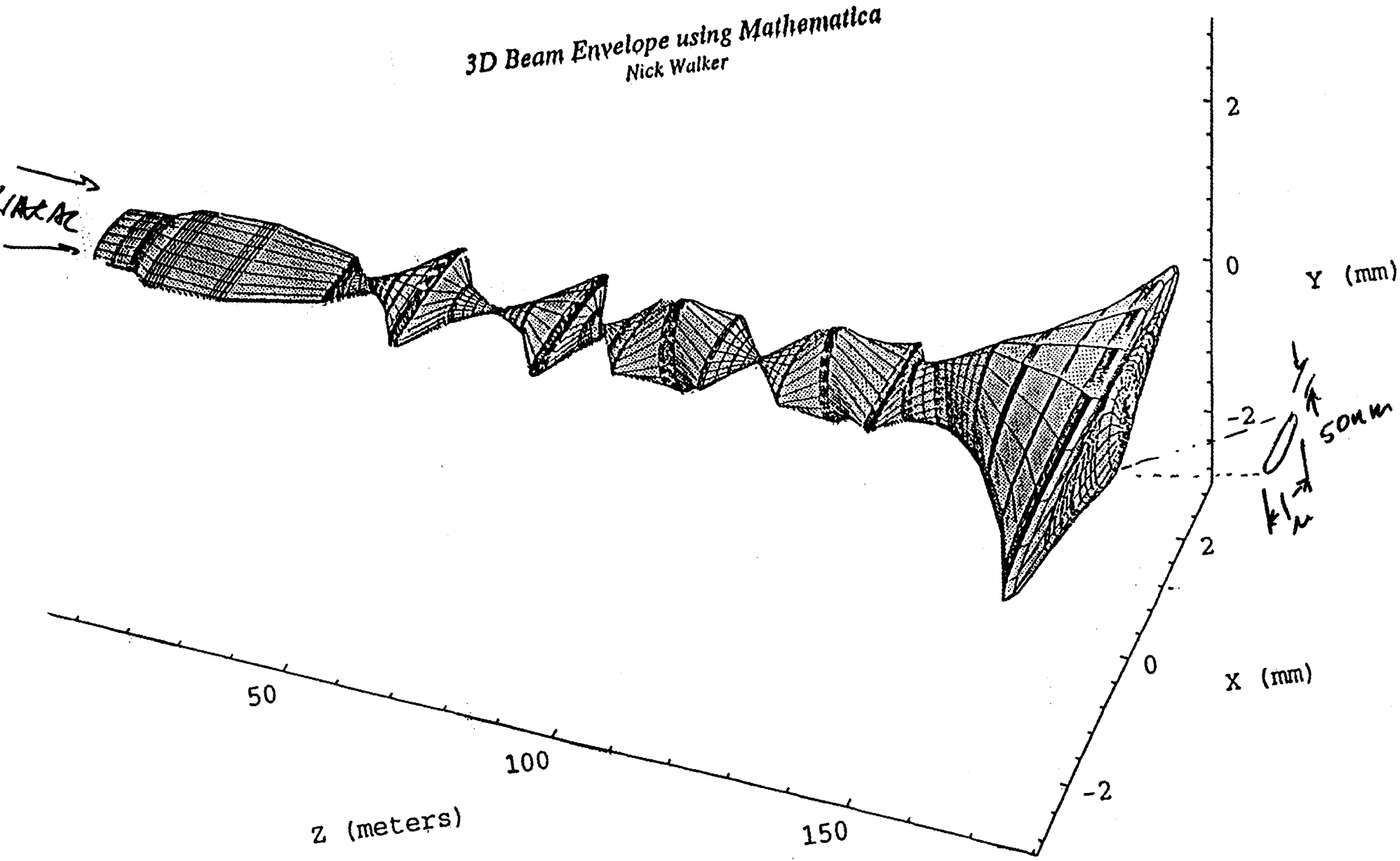
LINEAR COLLIDER TEST FACILITY



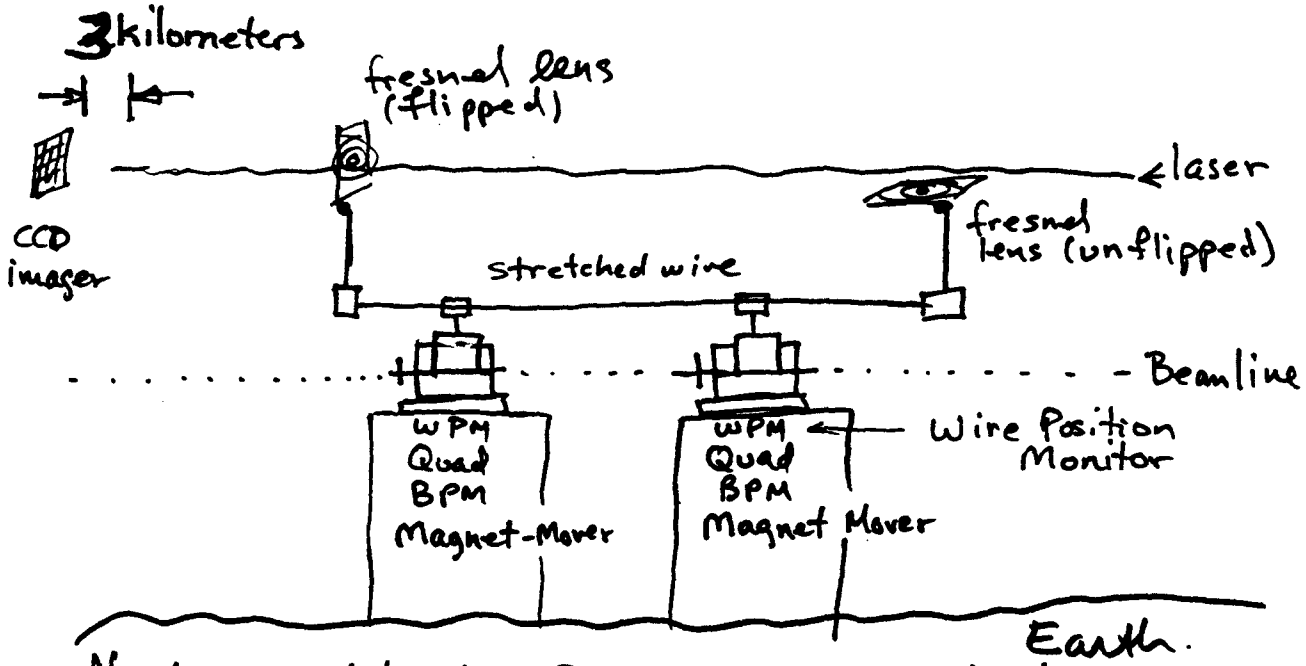
OVERALL SLC LAYOUT

5722A7

FFTB


3D Beam Envelope using Mathematica
Nick Walker
LINAC
Y (mm)
X (mm)
Z (meters)
50
100
150
2
0
-2
2
0
-2
50nm

Alignment System for FFTB



Need to calibrate BPM & Quad w.r.t. alignment system to $< 30\mu$

Alignment system can be remotely & dynamically operated to correct for earth & thermal movements.

FFTB QUAD/BPM FIDUCIALIZATION

Requirements:

* locate magnetic center wrt tooling balls to 10u

* locate bpm to magnetic center to 10u

Old method:

* assume magnetic center = mechanical center, fiducialize with optical survey

* machine bpm with tooling surface mating to magnet, use fixture to simulate beam pulse

* assemble magnet and bpm, move to beam line

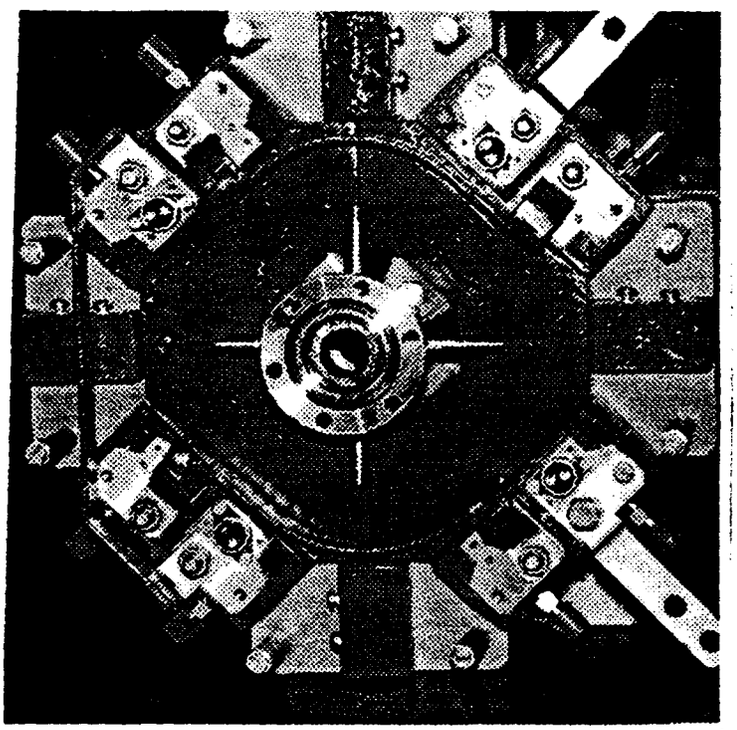
New method:

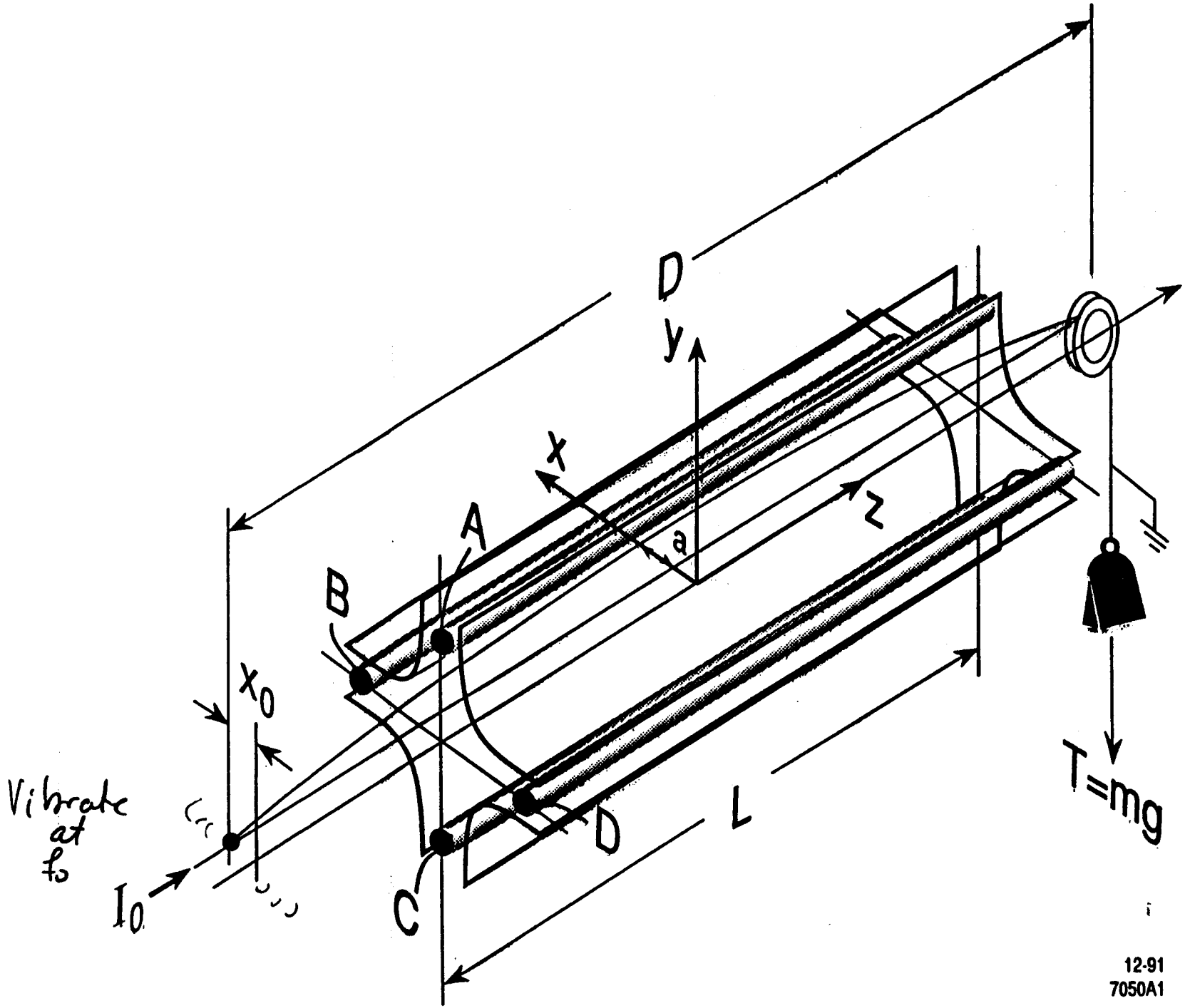
* assemble magnet and bpm

* find magnetic center and bpm electrical center in one fixture

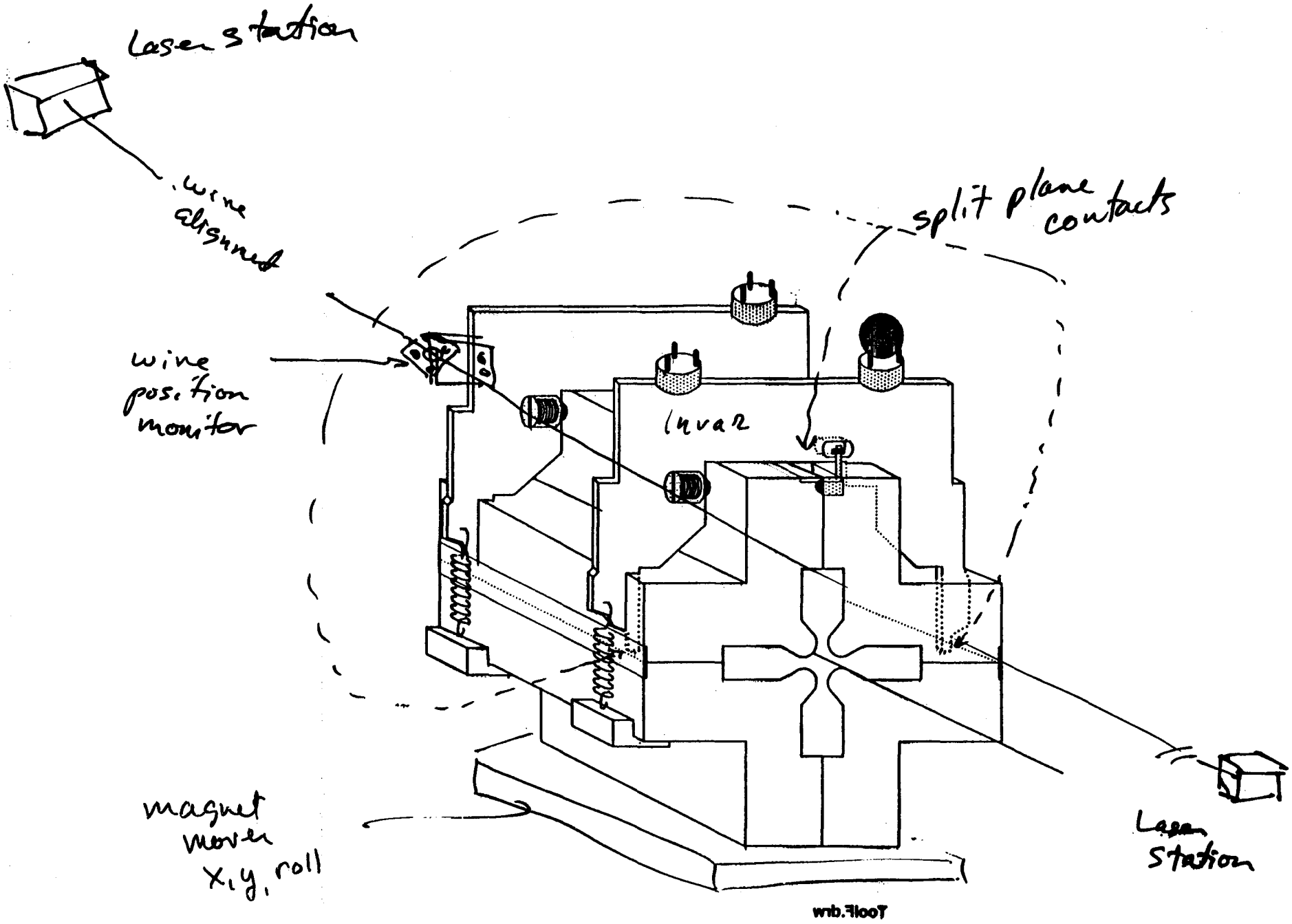
* move to beam line as one assembly

BPM IN QUAD





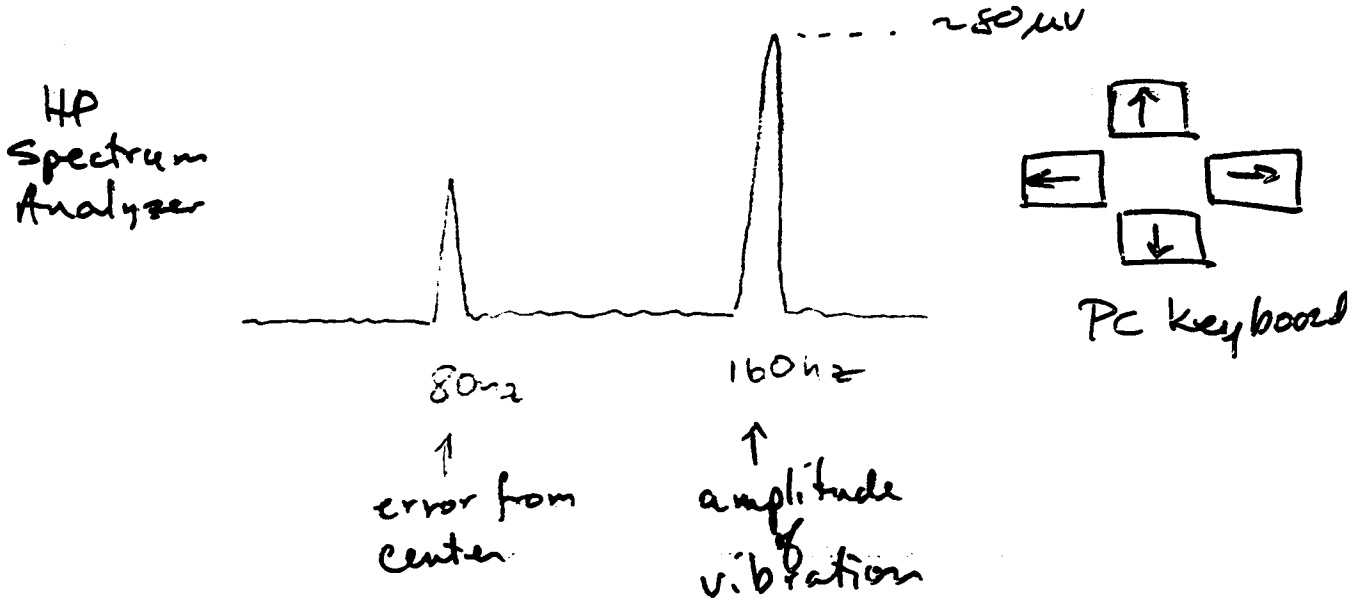
12-91
7050A1


Laser station
wire aligned
split plane contacts
wire position monitor
Invar
magnet mover
x, y, roll
Laser Station
wib.Tool7

METHODOLOGY

Magnetic center finding:

* stretched wire through magnet/bpm
* 2 meter 35u gold-plated tungsten,
  150 grams weight
* drive with audio voice coil at fundamental
* observe wire with spectrum analyzer 80-160 hz
* emf=2 k L a w (x cos(wt)+a sin(2wt)) => 1uv/u
  * at x=0, 1st harmonic,no fundamental
  * at x=a, fundamental = 1st harmonic
* adjust amplitude to 20u
* computer controlled micro motion stages
* 0.1u steps over 8 cm
* move ends of wire in x and y s.t. emf<2uv
  alternating between x and y vibration
* use microscope wire finder to locate wire
* use CMM to locate tooling balls and wire finder



FFTB Coordinate Measuring Machine
Status Report, 12/12/90
Bernard Bell

Our search has brought to light 3 horizontal arm CMMs:

1. Mitutoyo (Japanese)

Size	X range	600, 1000, 1500 mm
	Y range	450, 600 mm
	Z range	600, 800 mm
	Length	1150, ?, ? mm
	Base width	c. 300 mm

$42,000

Price:
Base price ranges from $14,200 (600x600x450) to $28,300 (1500x800x600).
Base price excludes probe, computer, software and interface box.

For comparison:	1000x600x800	Base price	24,600
		Computer & software	9,975
		Probe (PH8)	5,360
		Interface box	2,100
		Total	42,000

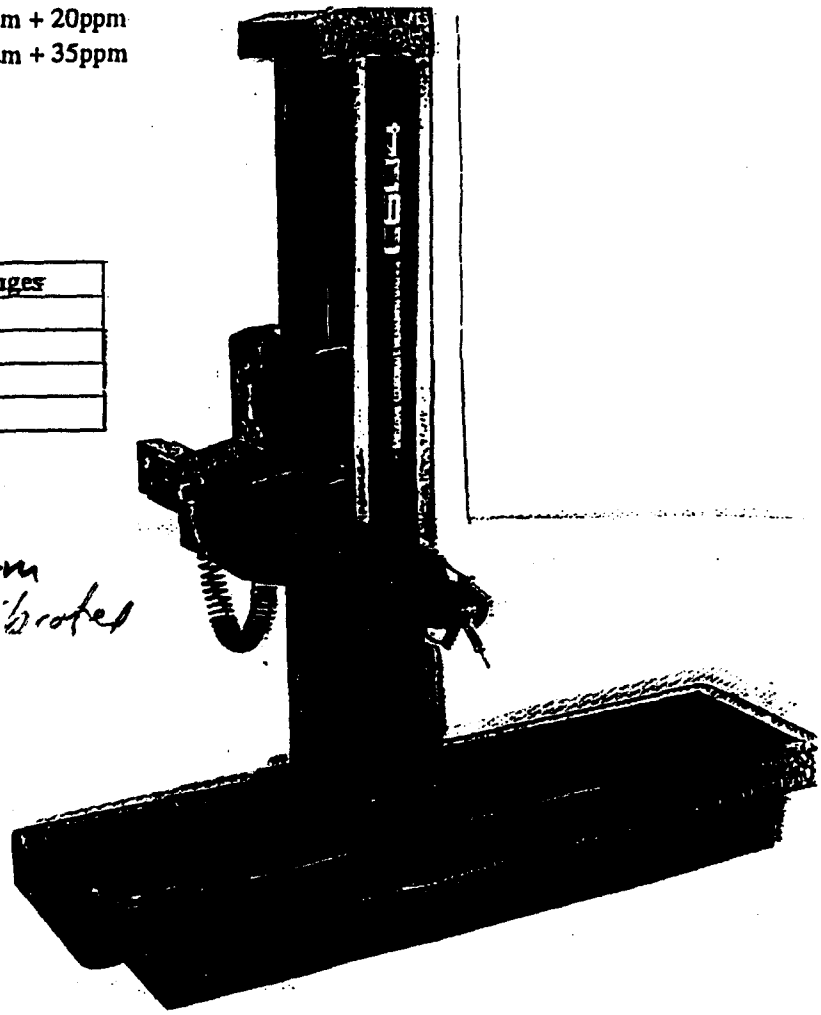
Accuracy	1D linear	15μm + 20ppm
	3D volumetric	30μm + 35ppm

Resolution: 0.0001"

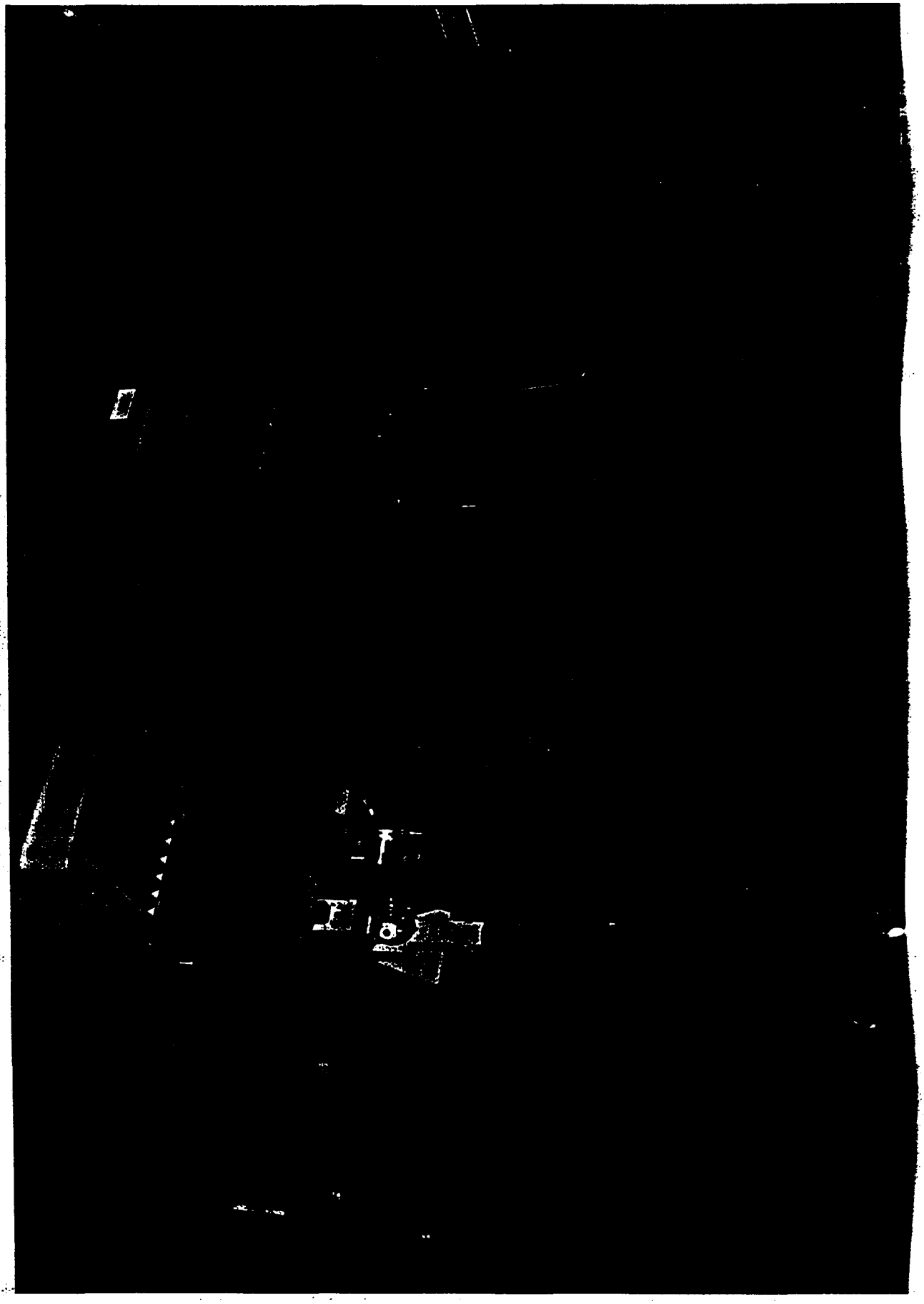
Pros & Cons

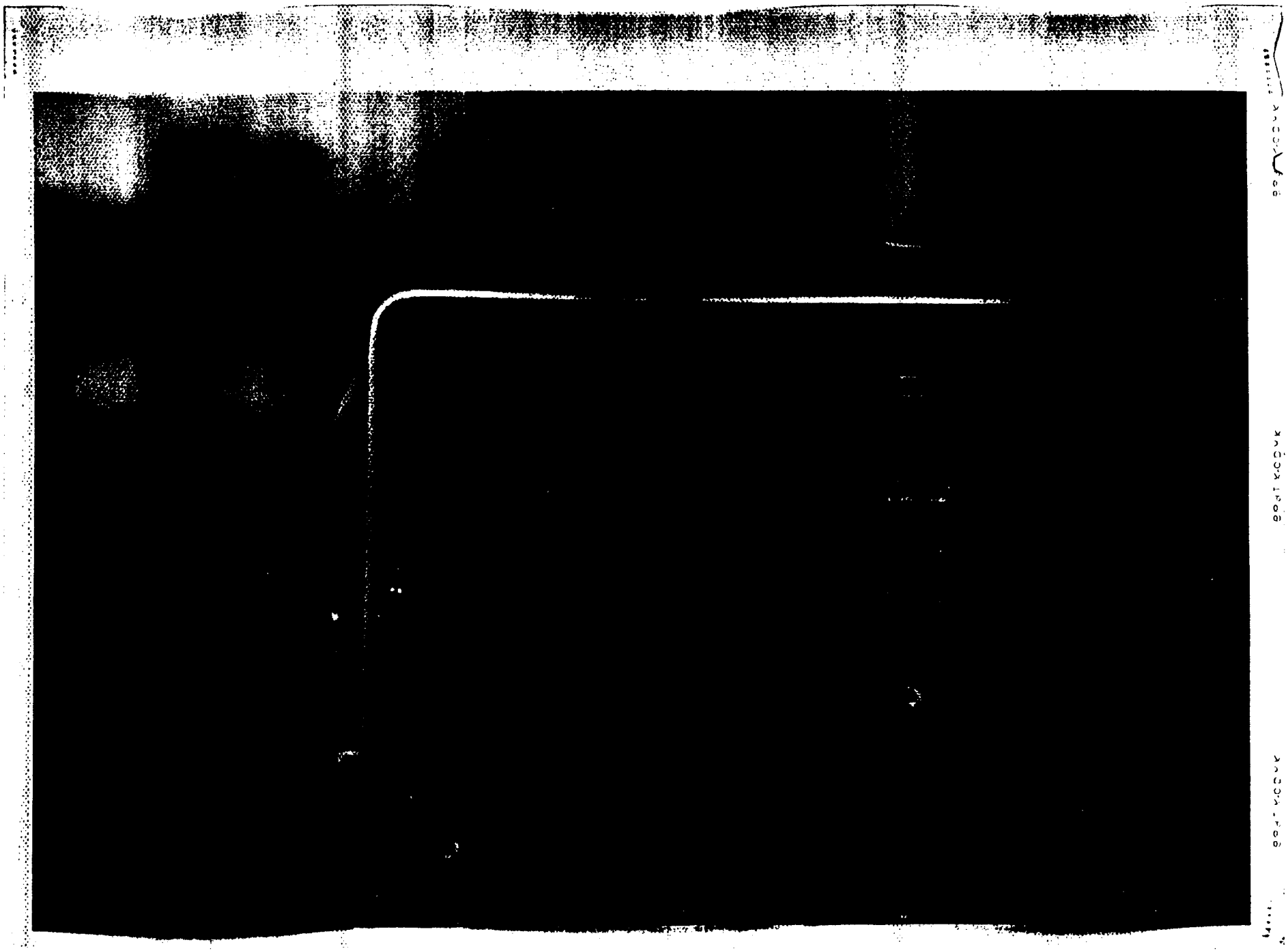
Advantages	Disadvantages
Good price	Foreign
Base c. 300 mm wide	
Initial test was promising	

Repeatability ~5-8μ
Accuracy 50μ/50cm
But we cross-calibrated
w Leitz CMM

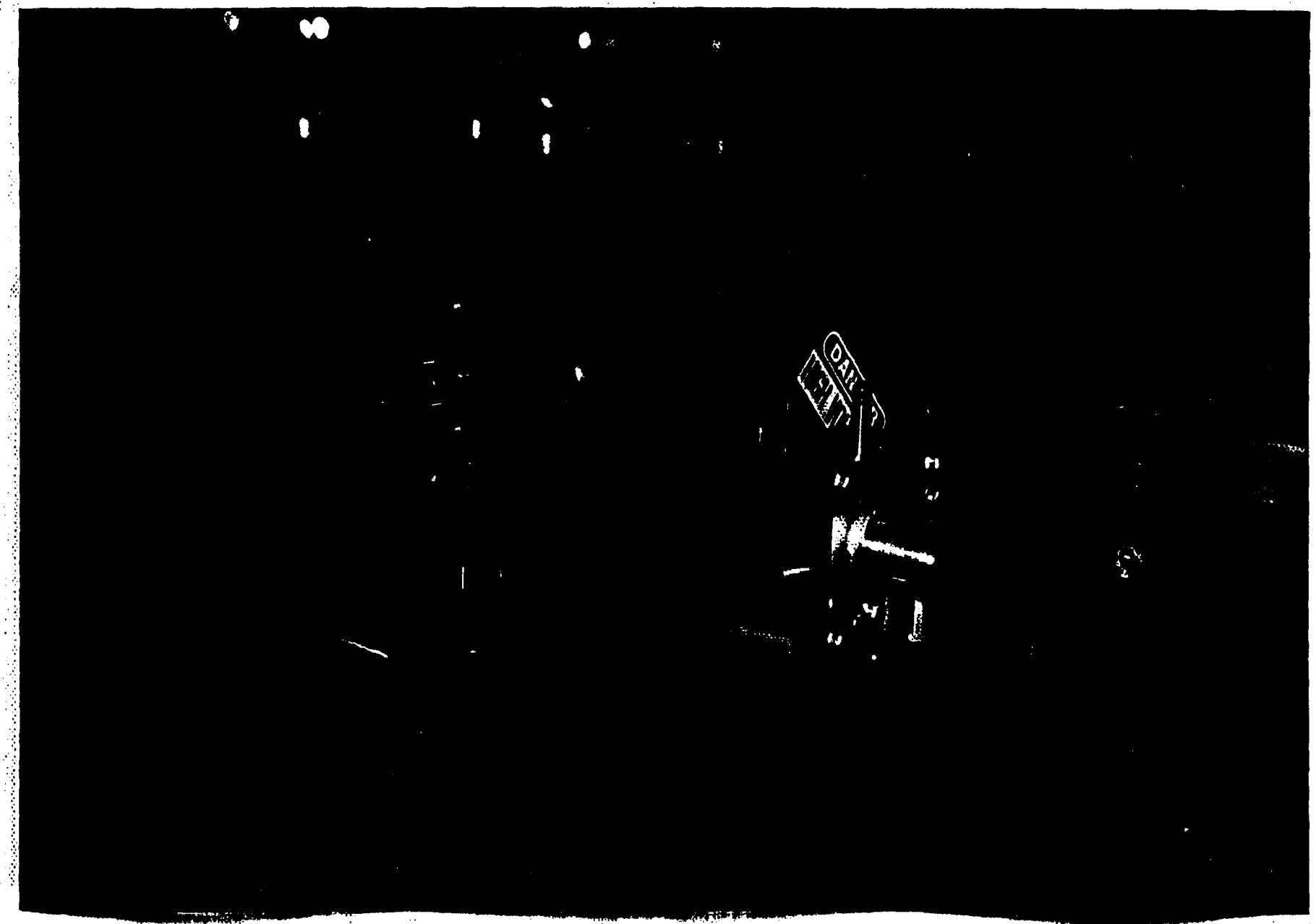


500000



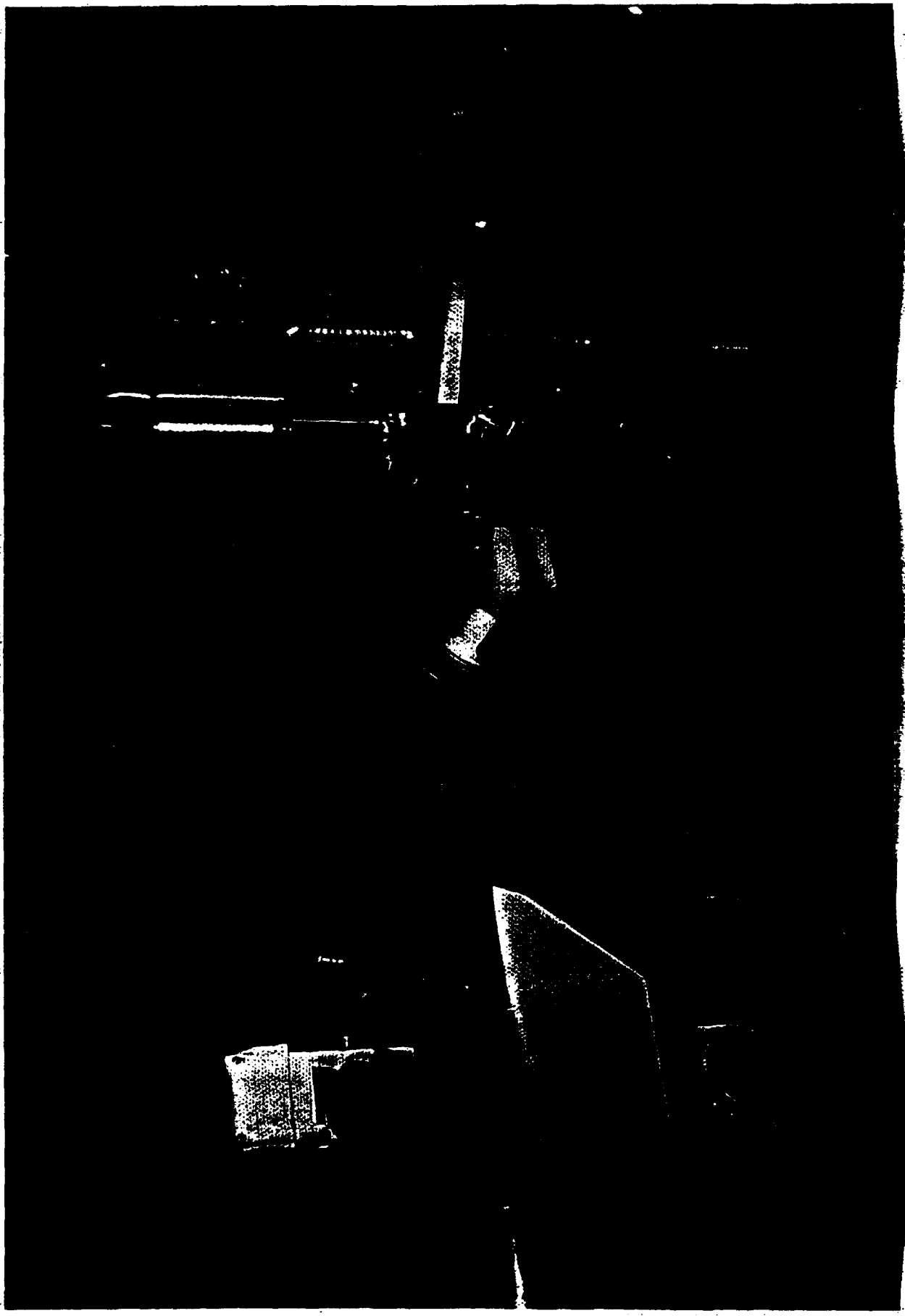


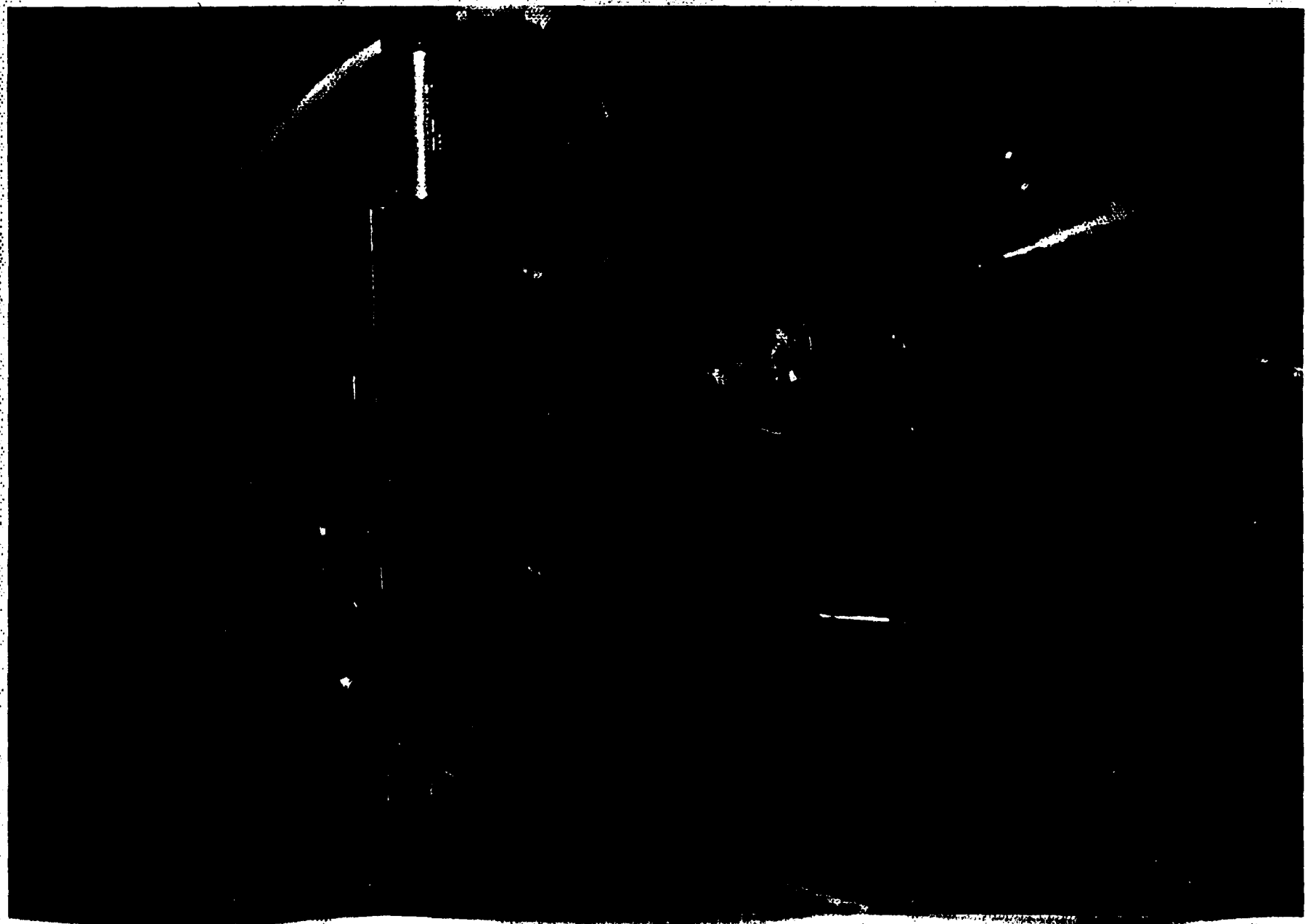
MISC. 153-25/25A



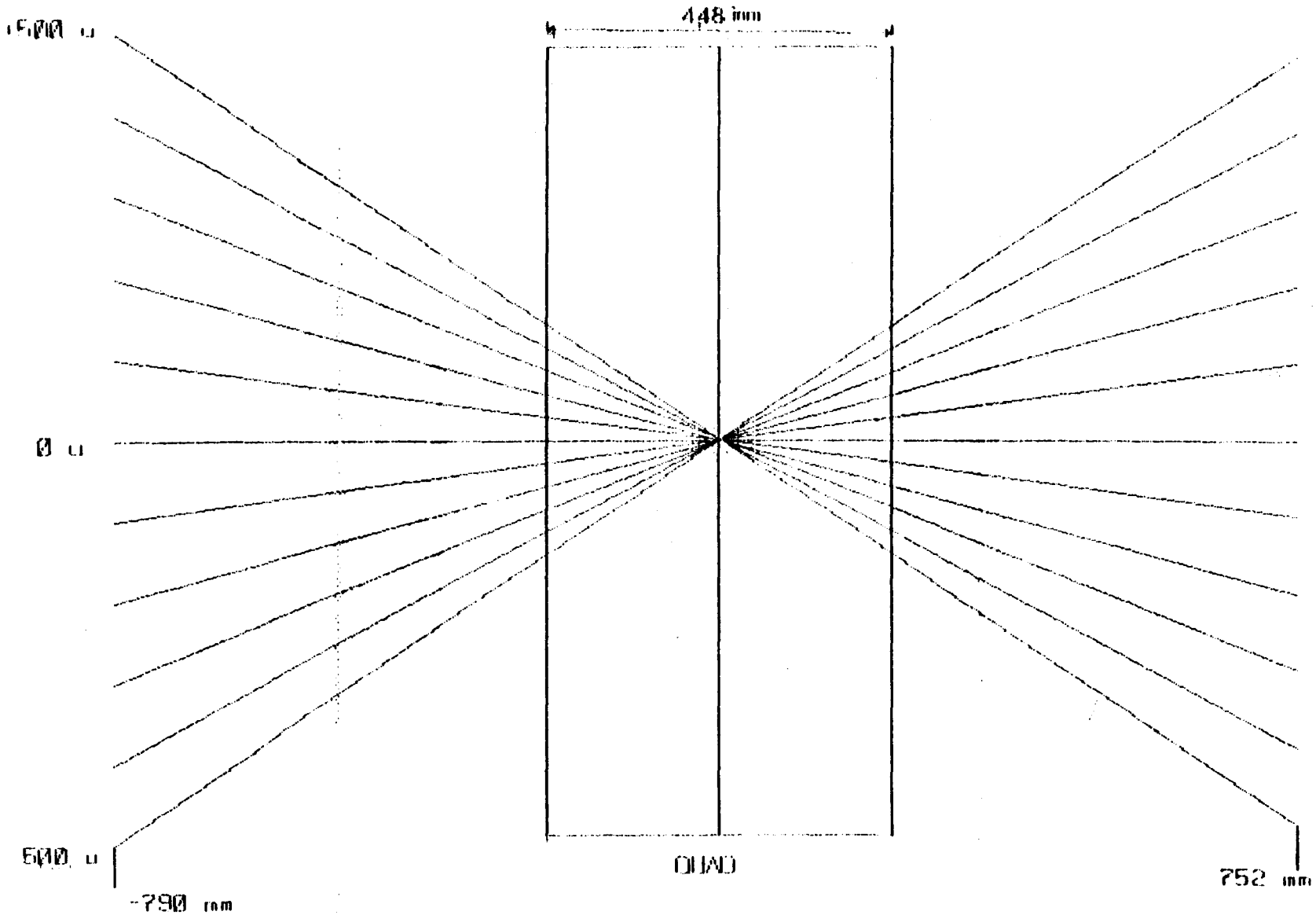
MISC. 153-Kellom

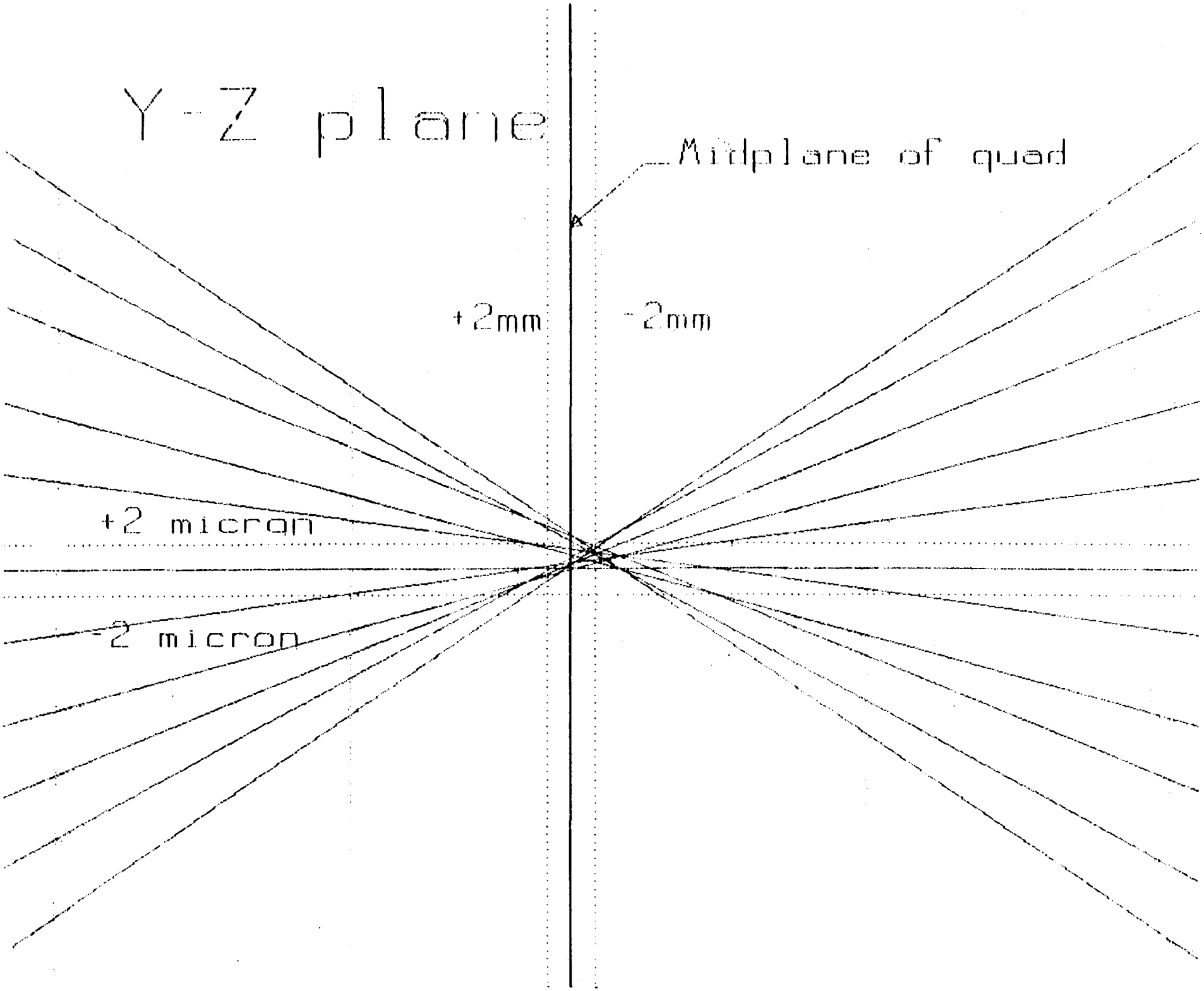
65 KODAK 65 KODAK 65 KODAK

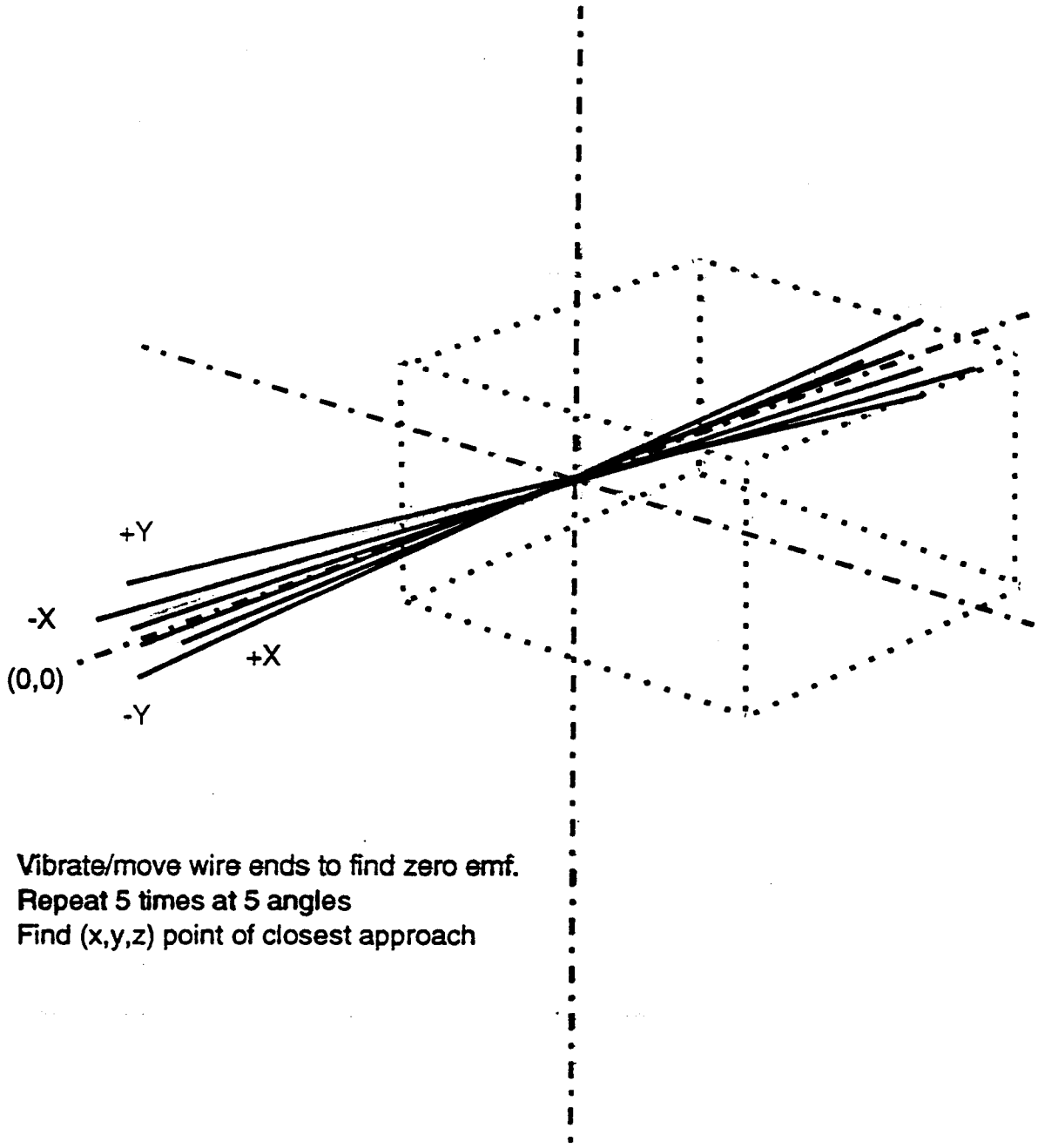




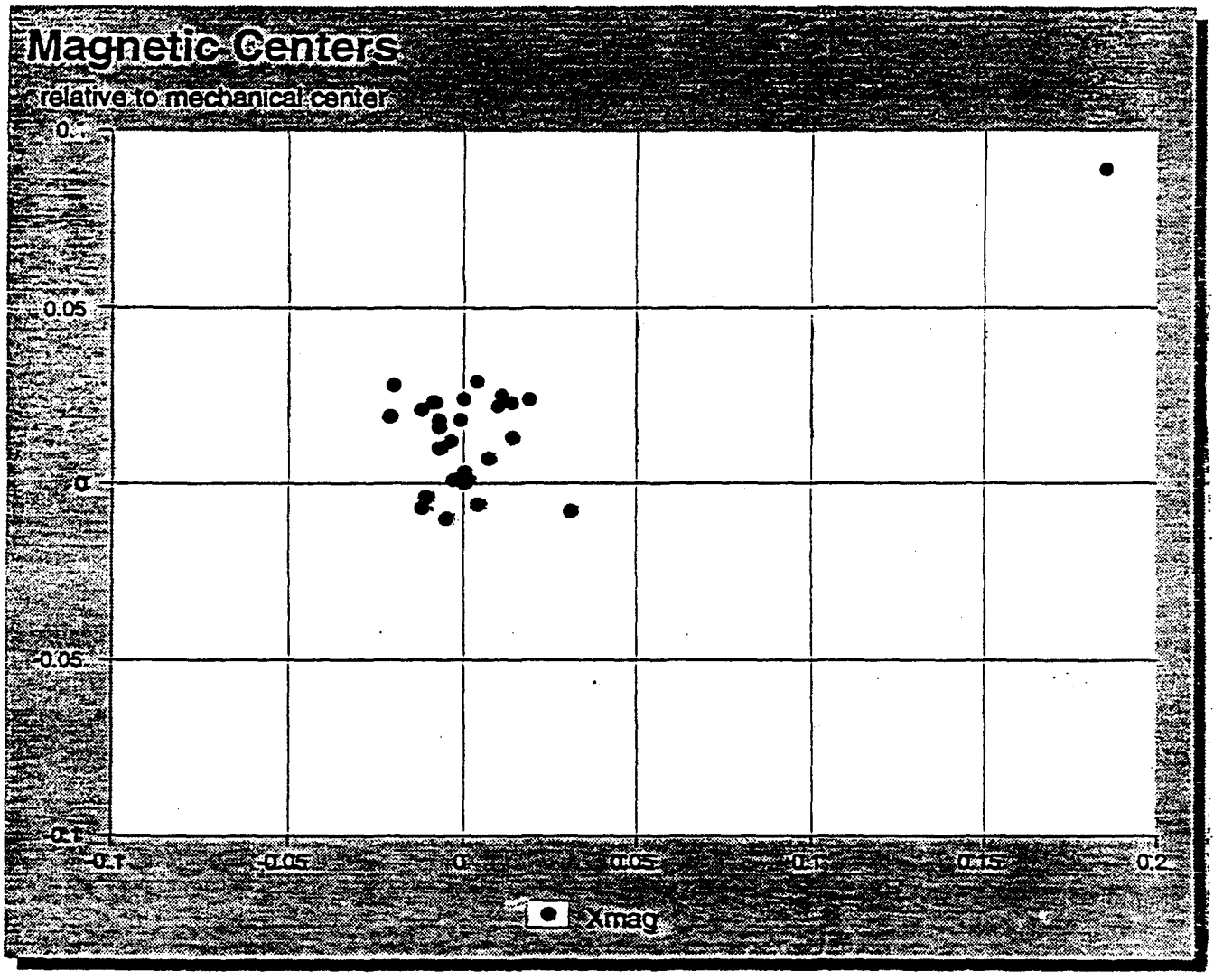
MISC. #153-14/14A


448 mm
+500 u
0 u
-500 u
-790 mm
OIAD
752 mm


Y-Z plane
Midplane of quad
+2mm
-2mm
+2 micron
-2 micron



Vibrate/move wire ends to find zero emf.
Repeat 5 times at 5 angles
Find (x,y,z) point of closest approach


Magnetic Centers
relative to mechanical center
0.1
0.05
0
-0.05
-0.1
-0.1
-0.05
0
0.05
0.1
0.15
0.2
Xmag

mm

Effect of TRIM COILS

As Dipoles

12 amps — 300 μ center motion

+12 amp to 0 — 13 μ
−12 amp to 0

Can produce non-mechanical motion

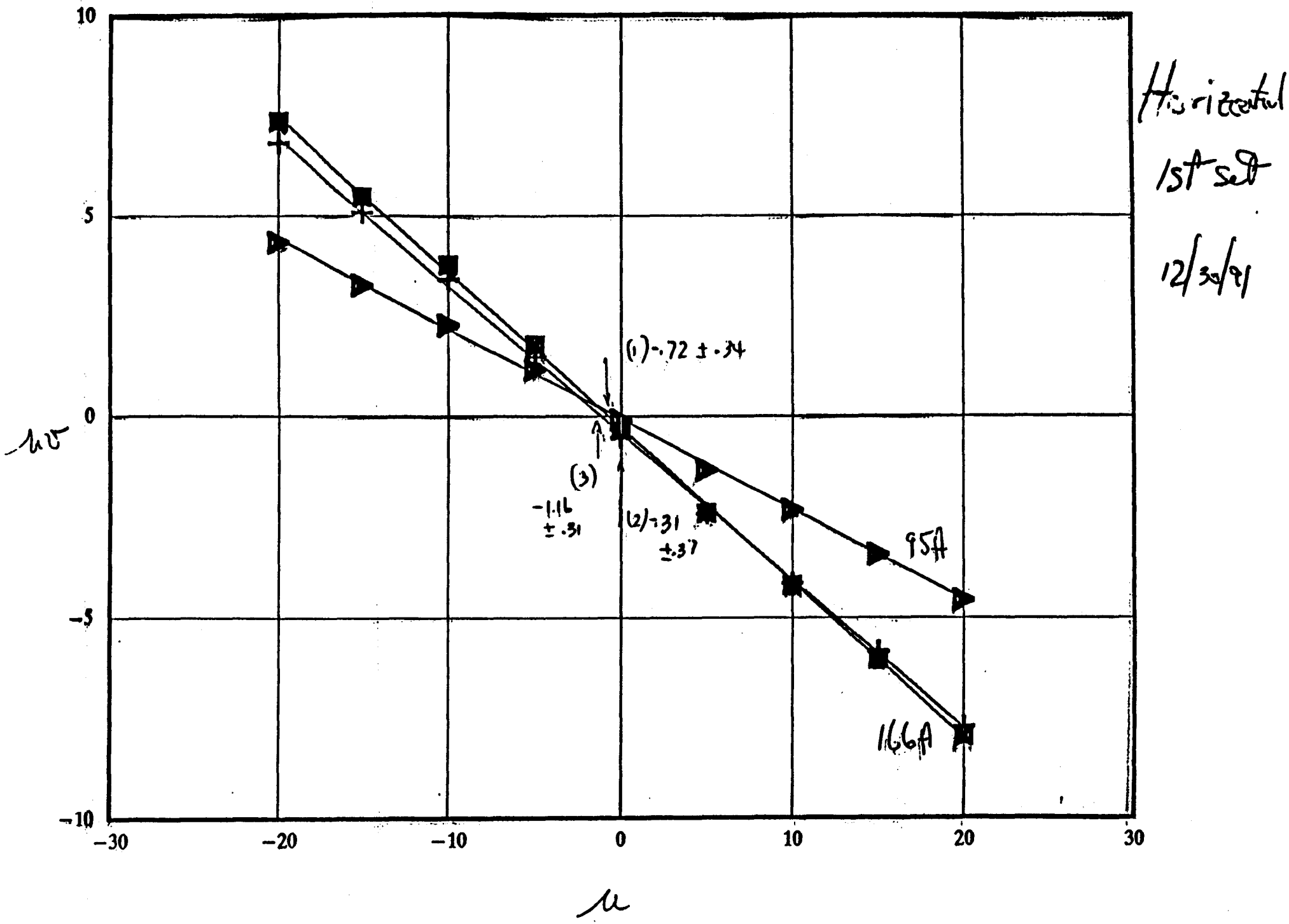
MAGNETIC CENTER MOTION

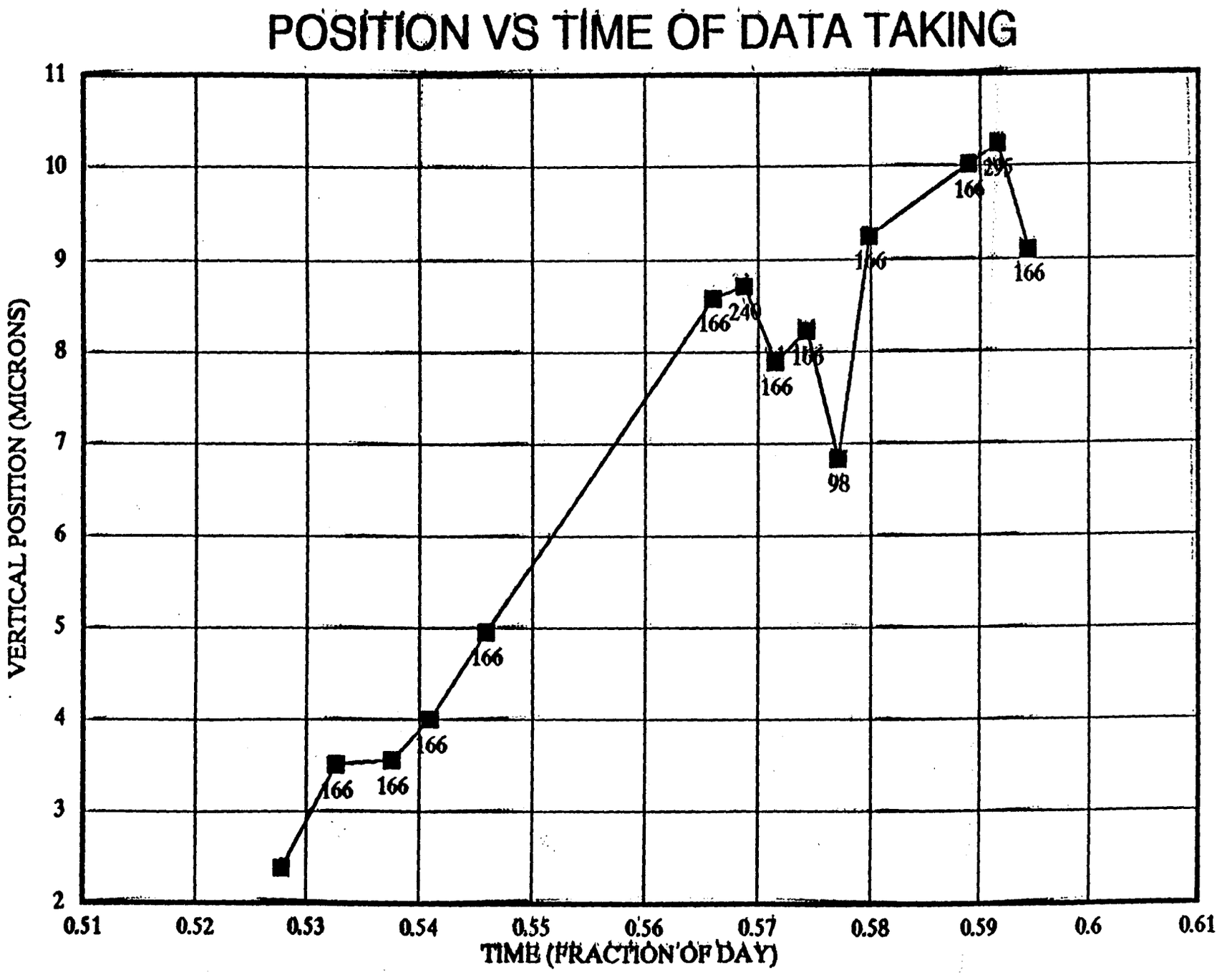
How much does the magnetic center move due to current and temperature?

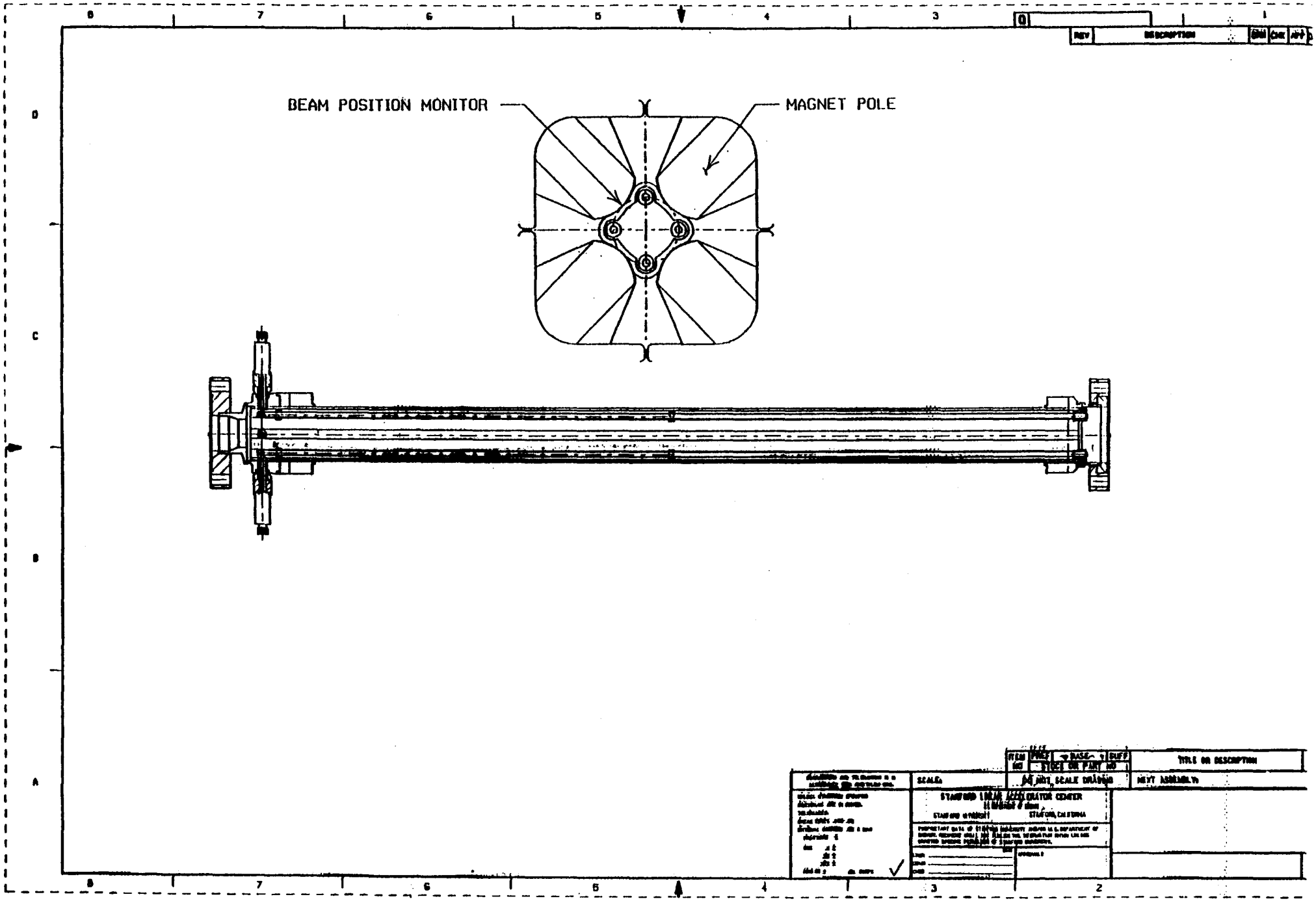
* No standardization of magnet
* use lockin voltmeter for greater precision
* locate center for several currents
* magnet heats - center rises over two hours by 8 microns
* rapid current excursions show 1-2 micron wiggles

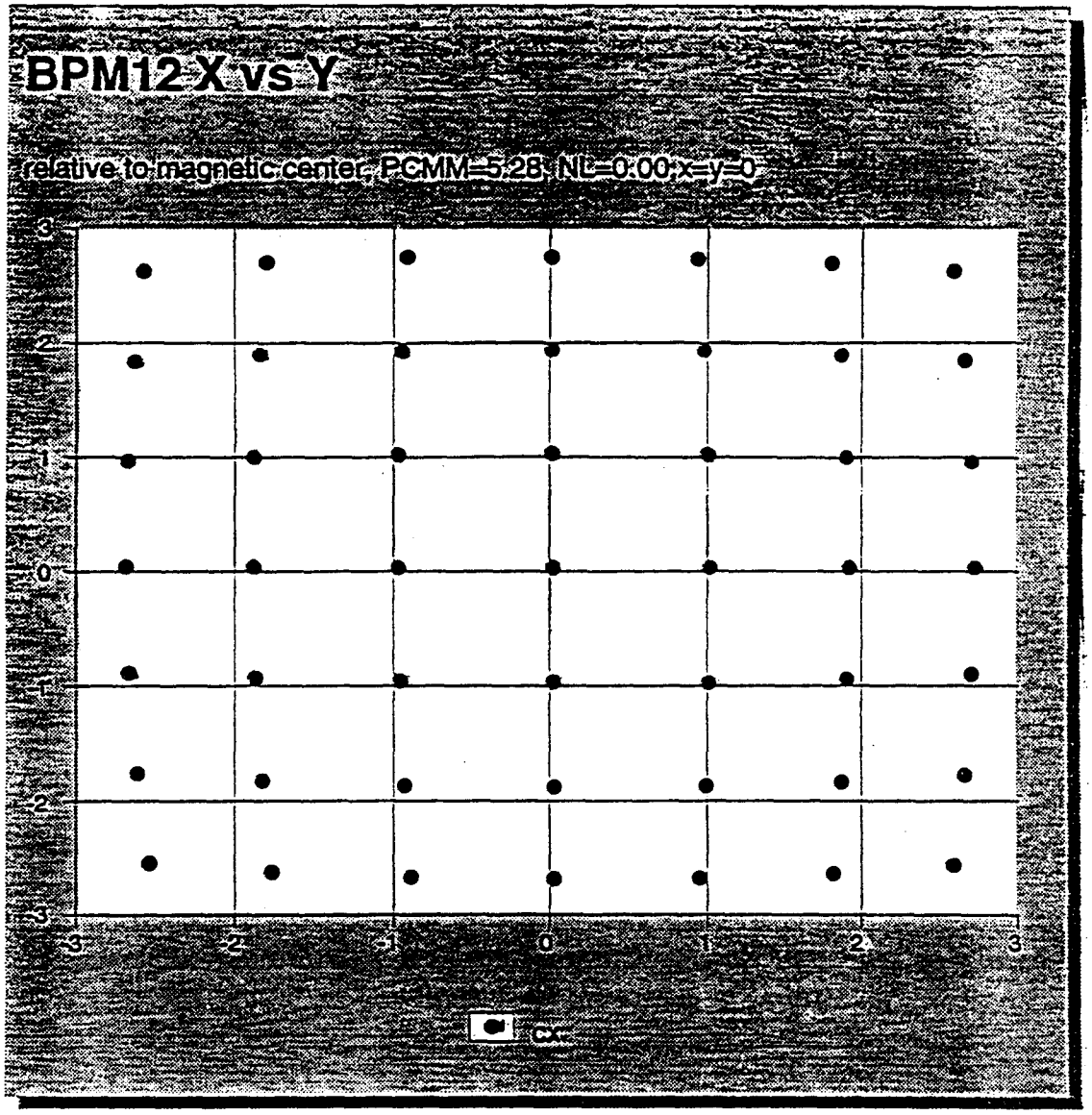
Conclusion:

* thermal motion significant but controllable by magnet movers
* 2 micron current wiggles w/o standardization


Horizontal
1st set
12/30/91
(1) -.72 ± .34
(3)
-1.16
± .31
(2) -.31
± .37
95A
166A
10
5
0
-5
-10
-30
-20
-10
0
10
20
30
v
u

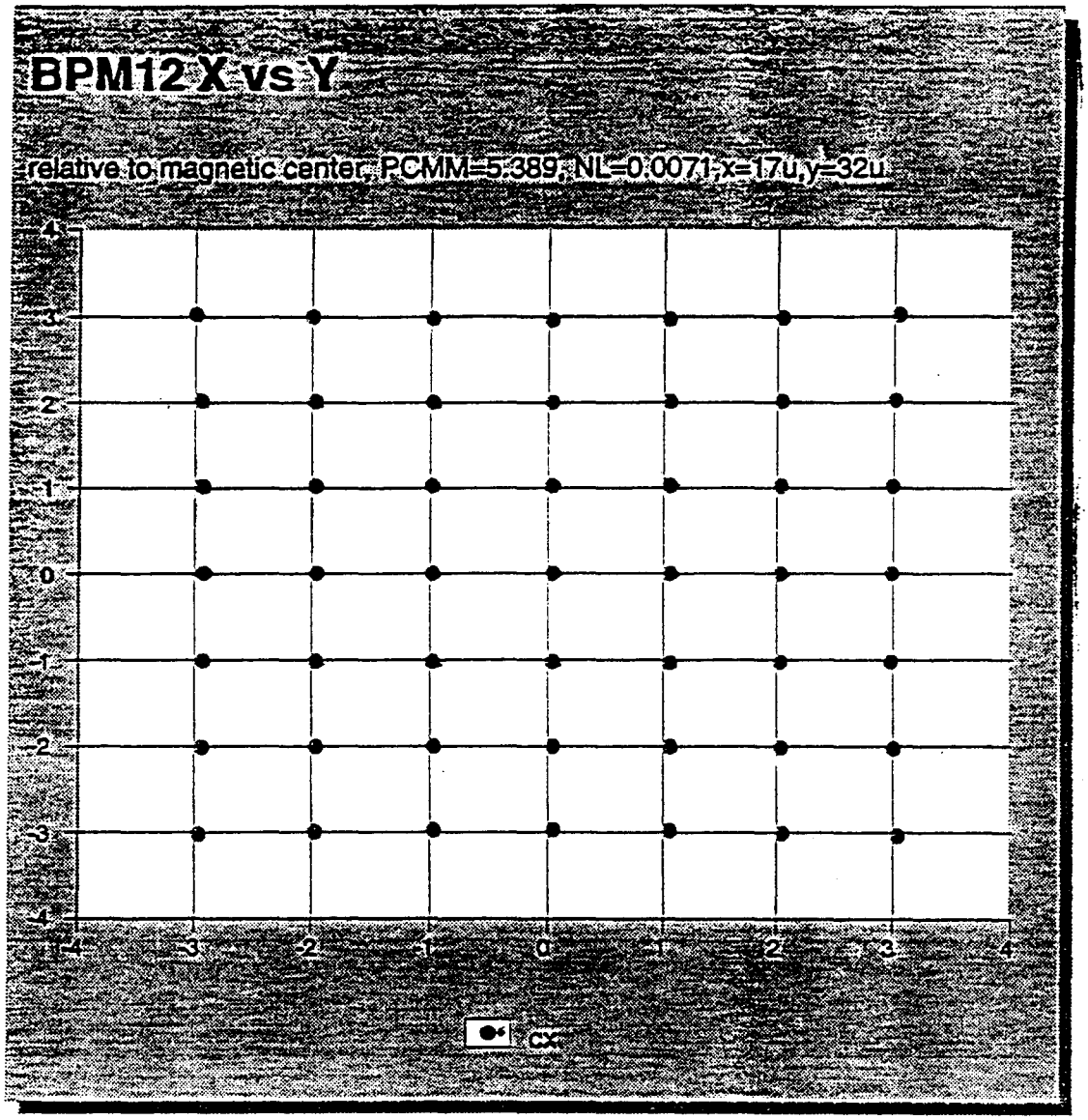

POSITION VS TIME OF DATA TAKING
VERTICAL POSITION (MICRONS)
TIME (FRACTION OF DAY)
11
10
9
8
7
6
5
4
3
2
0.51
0.52
0.53
0.54
0.55
0.56
0.57
0.58
0.59
0.6
0.61
166
166
166
166
166
240
166
166
98
166
166
166


BEAM POSITION MONITOR
MAGNET POLE
REV
DESCRIPTION
ITEM NO
PREF
BASE
BUFF
STOCK OR PART NO
TITLE OR DESCRIPTION
SCALE:
NOT SCALE DRAWING
NEXT ASSEMBLY
STANFORD LINEAR ACCELERATOR CENTER
STANFORD, CALIFORNIA



$$x = \frac{R}{2}\left(\frac{T-B}{T+B}\right) + x_0$$

$$+ \frac{1}{n^2}$$


BPM12 X vs Y
relative to magnetic center, PCMM=5.389, NL=0.0071,x=17u,y=32u
4
3
2
1
0
-1
-2
-3
-4
-4
-3
-2
-1
0
1
2
3
4
cx

QUAD/BPM Fiducialization Facility

Finds magnetic center of quad relative to fiducials

Eliminates need to know mechanical center

Finds electrical center of BPM relative to magnetic center

Measure PCMM(X,Y) over aperture

"One Step", i.e. no disassembly after fiducialization

Knud N. Henrichsen
CERN

Vibrating Particle Beam Measurement:

In-situ measurement of the magnetic centre of quadrupoles

Ref.: D.Rice et al., "Beam diagnostic instrumentation at CESR", IEEE Transactions on Nuclear Science, vol. NS-30, no.4 (1983) 2190-2192.

Modulation of the field in the LEP lattice quadrupoles

Modulation of the field in individual quadrupoles will permit the absolute calibration of their associated beam position monitors, thus providing a perfect knowledge of the closed orbit. Valuable information about the magnet alignment is obtained at the same time. A modulation of the order 0.3% r.m.s. of the set field at 45 GeV is adequate and may be obtained by excitation of back-leg windings.

A multicore cable wound twice around each pole of the magnet is employed. Values of impedance and resistance can be made compatible with a maximum excitation voltage of 50 V at frequencies between 12 and 20 Hz.

Two simple a.c. power supplies located in each of the eight LEP underground areas will power any of the quadrupoles located in the two adjacent half octants. A multicore control cable permits the multiplexing of the magnet excitation in each half octant through a matrix consisting of a diode and a relay installed near each quadrupole. Simultaneous measurements can take place in all half octants if 16 different frequencies are applied, f.ex. spaced at 0.5 Hz.

Local bumps of varying amplitude are then applied to the beam. The observed oscillations are Fourier analysed and the magnetic centre of the quadrupole is determined. A resolution in the micron range is obtained.

MAGNETIC AXIS
OF A SOLENOID
WITH A COMPOSITE INTEGRAL COIL

D. CORNUET

29 SEPTEMBER 1993

MAGNETIC AXIS

OF A SOLENOID

WITH A COMPOSITE INTEGRAL COIL

Search coil consisting in 2 coils (or 3

(ℓ_1 and ℓ_2 with gap g)

(or ℓ_1, ℓ_2 and ℓ_3 with total gaps g)

is rotated 180°.

As : specific constant of the integral coil (in m)

Fig. 1

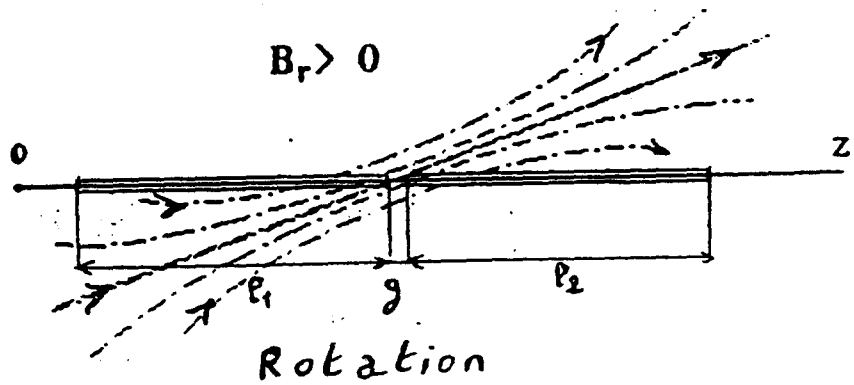
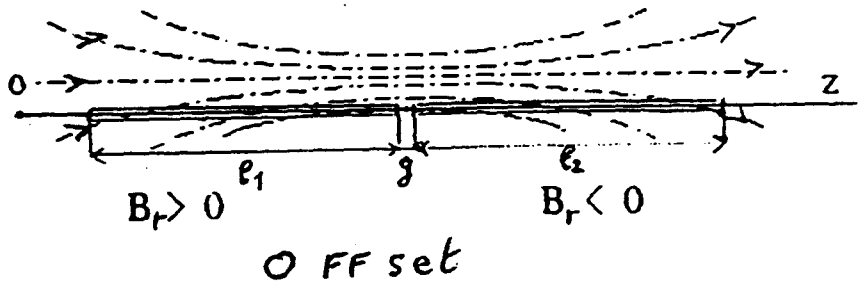
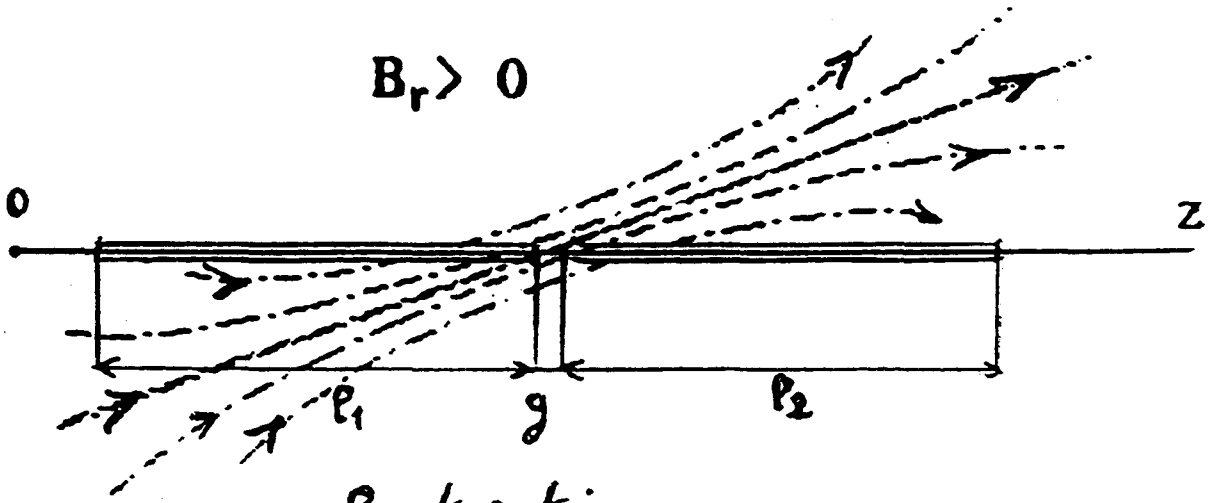
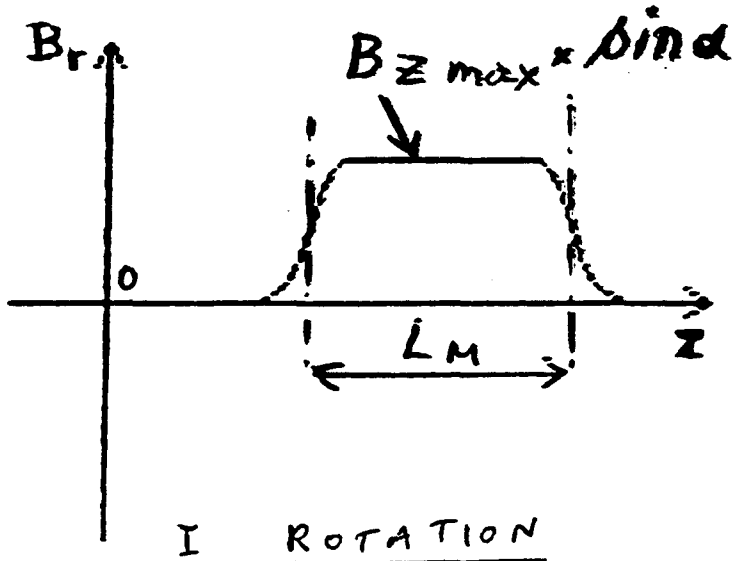


Fig. 2





Rotation



I ROTATION

Coils ℓ_1 and ℓ_2 series connected.

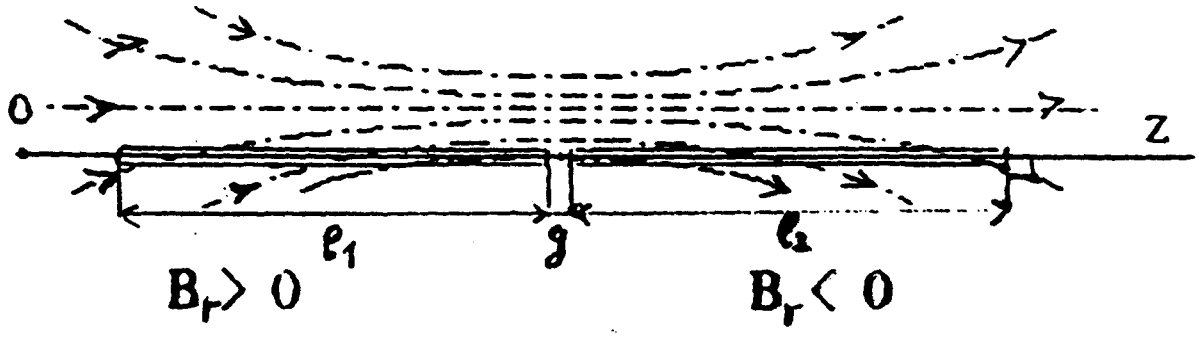
Ambiant Field MUST be taken into account!
(unless pulsed current)

(in V_x sec) $$V_{total} = 2 A_s \int_{-\ell_1 - g/2}^{+\ell_2 + g/2} B_z \, dz$$ Calculated From Hall probe (axial)

(in V_x sec) $$V_{x,Y} = 2 A_s \int_{-\ell_1 - g/2}^{-g/2} B_{x,Y} \, dz + 2 A_s \int_{+g/2}^{+\ell_2 + g/2} B_{x,Y} \, dz$$

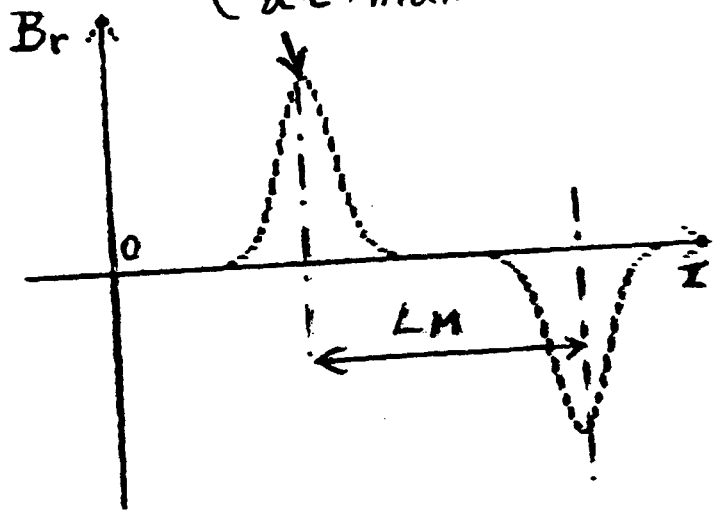
IF: $\alpha_{x,Y} \# 0$; $g \ll \ell_1, \ell_2$

" " " α ... ~ 1000 x $(V_{o\,x,Y} - V_{x,Y\,ambiant})$



II OFFsets

$$-\left(\frac{dB_z}{dz}\right)_{max} \times \frac{r}{2}$$



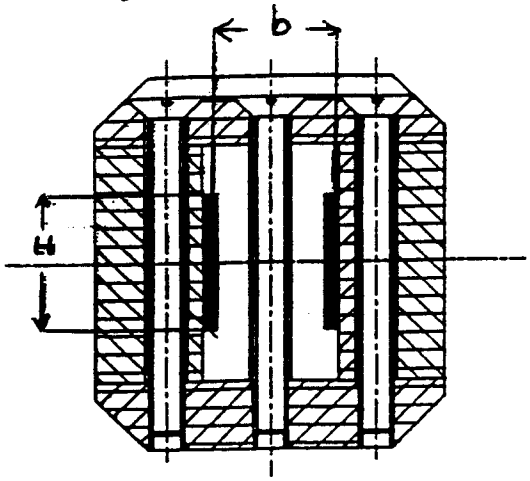
a) Lateral : Coils ℓ_1 and ℓ_2 opposite connections
Displacements $\delta_{x,y}$ until "zero" is detected.

b) Longitudinal: ℓ_1 and ℓ_2 series connections $\rightarrow g$ –
Measurement off center according X (or Y axis).
Displacement δ_z until "zero" is detected

Condition: Use special search coil where,
(or $g + \ell_3$) $g >$ B_z constant length $\left(\frac{dB_r}{dz} = 0\right)$
at L_M (still $dB_r = 0$)

COMPOSITE COILS

Field coils

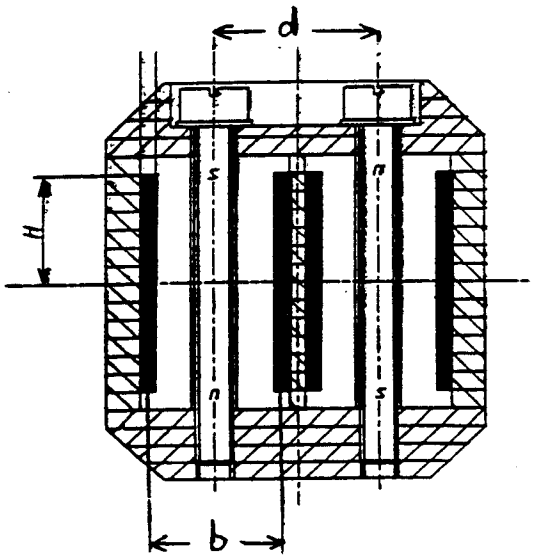


$\begin{cases} l_1 = l_2 = 1\,m \\ h = 5.5\,mm \end{cases}$ $g = 0.75\,mm$, $b = 6.2\,mm$, $n = 250$

$\begin{cases} l_1 = l_2 = 1\,m \\ h = 5.5\,mm \end{cases}$ $l_3 = 30\,mm$, $g = 1.5\,mm$, $b = 6.2\,mm$, $n = 250$

$\begin{cases} l_1 = l_2 = 1\,m\,20 \\ h = 6\,mm \end{cases}$ $g = 1\,mm$, $b = 6.5\,mm$

Gradient coils



$\begin{cases} l_1 = l_2 = 1\,m \\ h = 10\,mm \end{cases}$ $g = 1\,mm$, $b = 6.2\,mm$, $n = 450$, $d = 8\,mm$

$\begin{cases} l_1 = l_2 = 1\,m \\ h = 10\,mm \end{cases}$ $l_3 = 30\,mm$, $g = 1.6\,mm$, $b = 6.2\,mm$, $n = 450$, $d = 8\,mm$

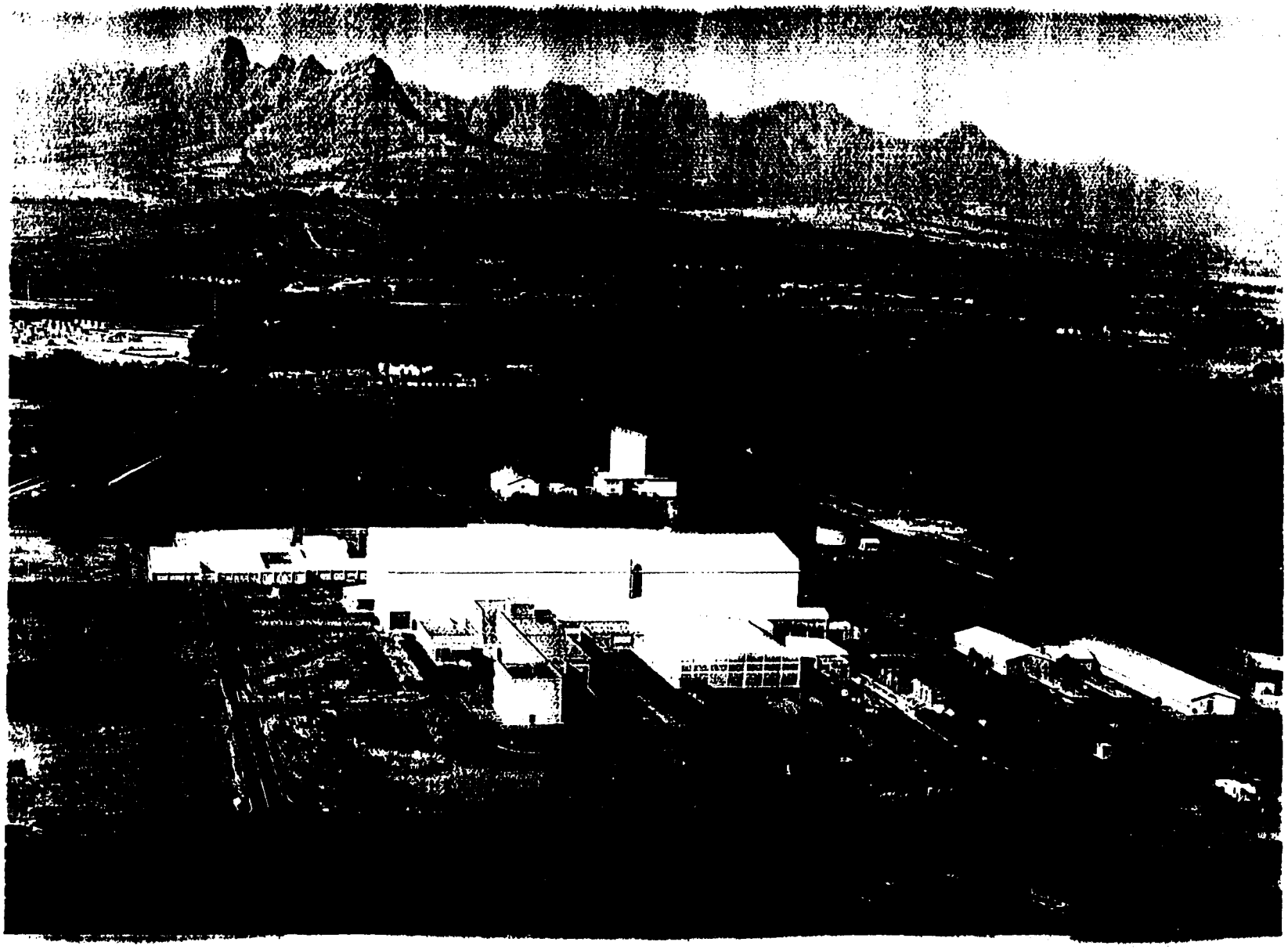
$\begin{cases} l_1 = l_2 = 0.95\,m \\ h = 6\,mm \end{cases}$ $l_3 = 100\,mm$, $g = 7\,mm$, $b = 6.5\,mm$, $n = 417$, $d = 9\,mm$

$\begin{cases} l_1 = l_2 = 0.8\,m \\ h = 6\,mm \end{cases}$ $l_3 = 400\,mm$, $g = 7\,mm$, $b = 6.5\,mm$, $n = 417$, $d = 9\,mm$

The 8th International Magnetic Measurement Workshop
September 27-30, 1993 Waxahachie, Texas

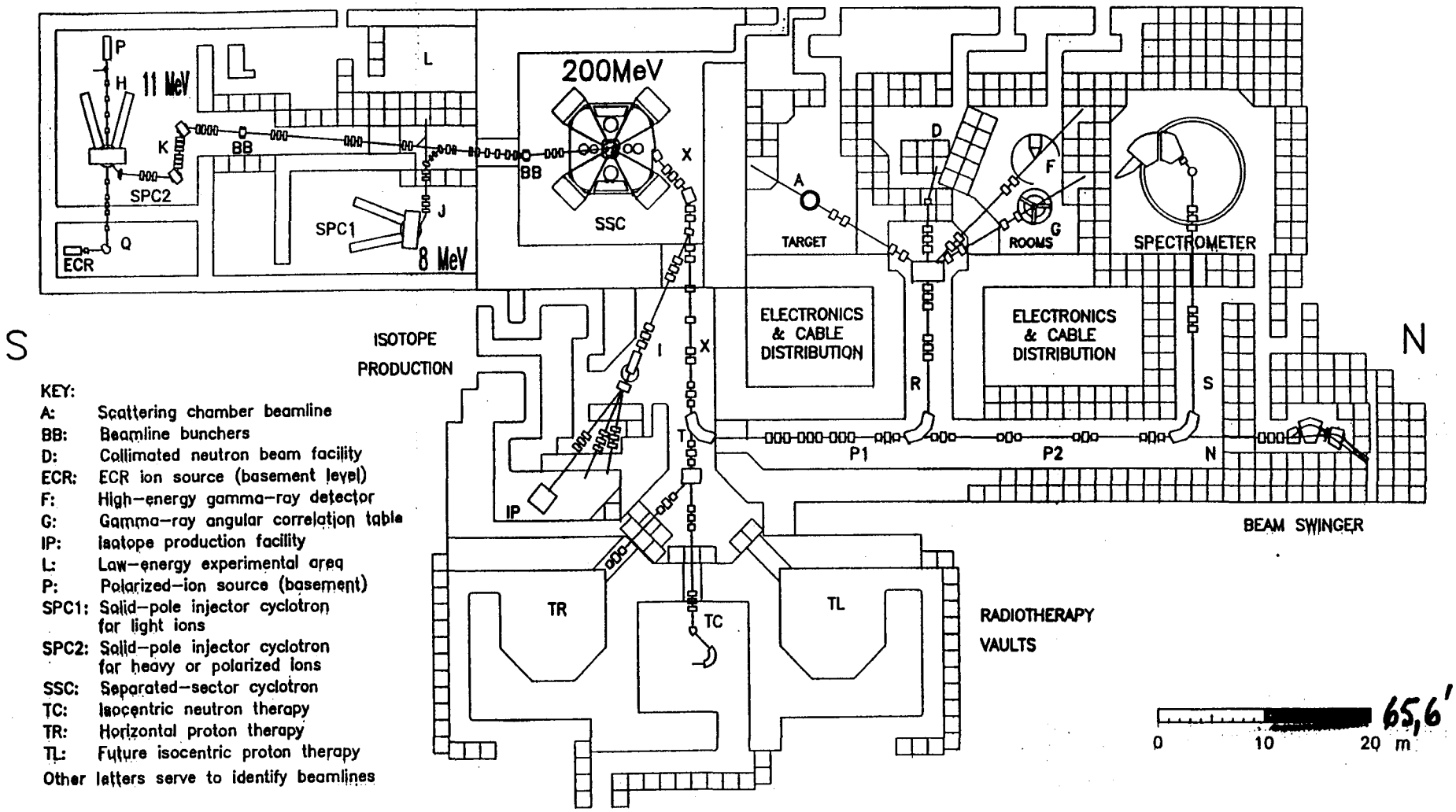
Median Plane Measurement Equipment at the NAC, using Hall Probes

Ludwig Schülein
National Accelerator Centre
P.O.Box 72 Faure
7131 South Africa
Tel/Fax +27 24 43820/525



NAC ACCELERATOR FACILITIES AT FAURE, 36km EAST OF CAPE TOWN

22,5m



KEY:

- A: Scattering chamber beamline
- BB: Beamline bunchers
- D: Collimated neutron beam facility
- ECR: ECR ion source (basement level)
- F: High-energy gamma-ray detector
- G: Gamma-ray angular correlation table
- IP: Isotope production facility
- L: Low-energy experimental area
- P: Polarized-ion source (basement)
- SPC1: Solid-pole injector cyclotron for light ions
- SPC2: Solid-pole injector cyclotron for heavy or polarized ions
- SSC: Separated-sector cyclotron
- TC: Isocentric neutron therapy
- TR: Horizontal proton therapy
- TL: Future isocentric proton therapy

Other letters serve to identify beamlines

THE AIM AND SEQUENCE OF THIS PROJECT

- To develop a multipurpose apparatus, that uses Hall generators, to measure the horisontal field components of the NAC cyclotrons.

- To evaluate the performance of and to gain experience in the use of the system.

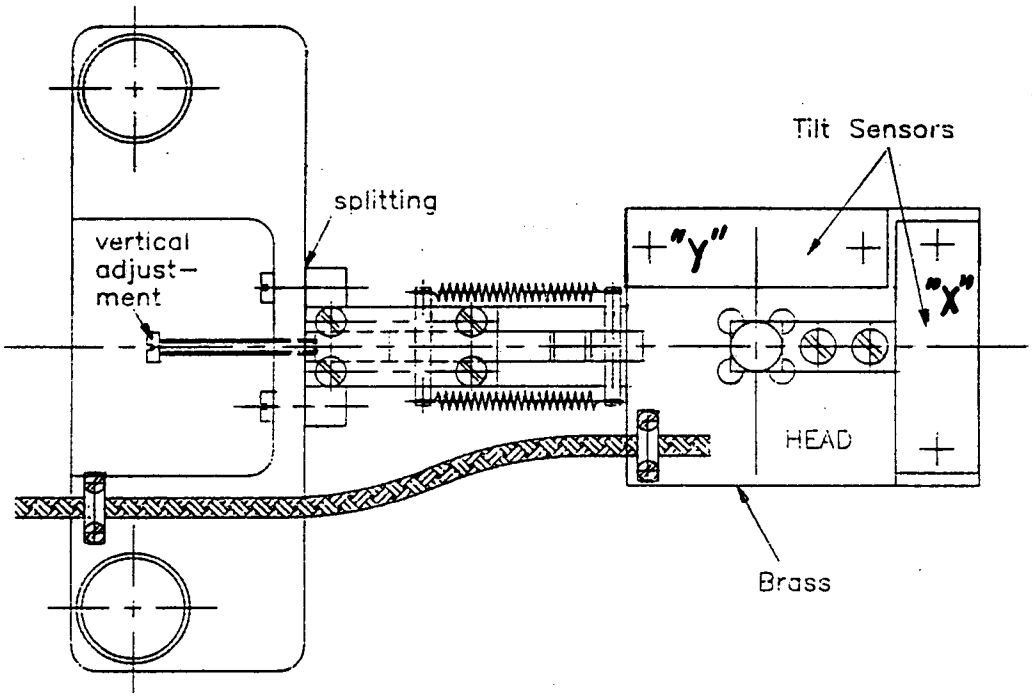
- To determine the displacement of the magnetic median plane from the geometric midplane in the magnets.

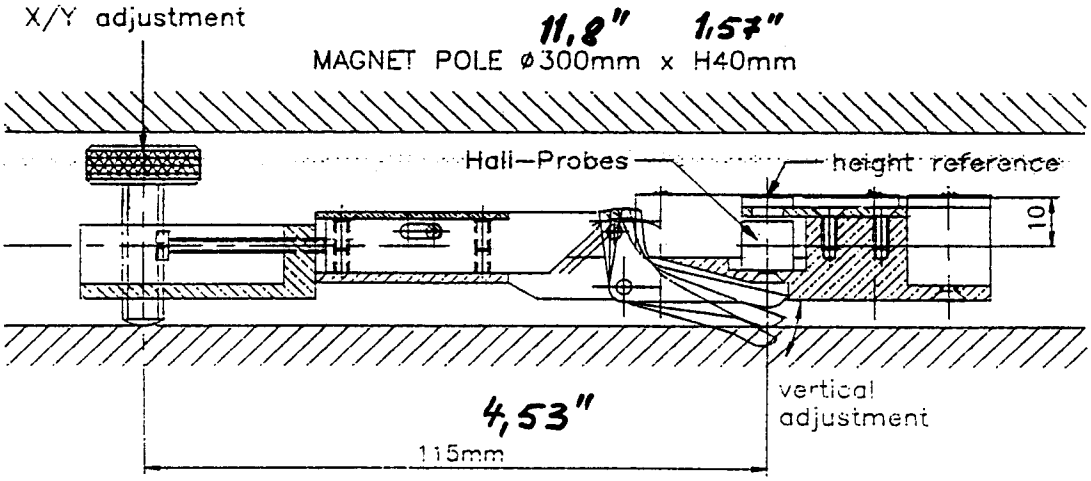
- To apply corrective measures to shift the magnetic median plane towards the midplane of each magnet.

In this talk, we are mainly concerned with the first two tasks, namely :

To develop a tilt/inclinometer and to evaluate its performance.

MEDIAN PLANE MEASUREMENT PROBE:
CALIBRATION MAGNET MODE

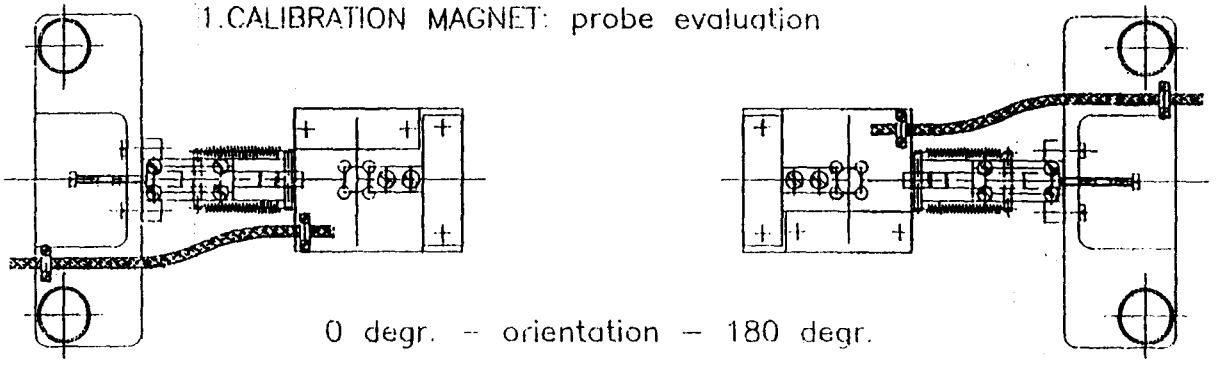




A.M.

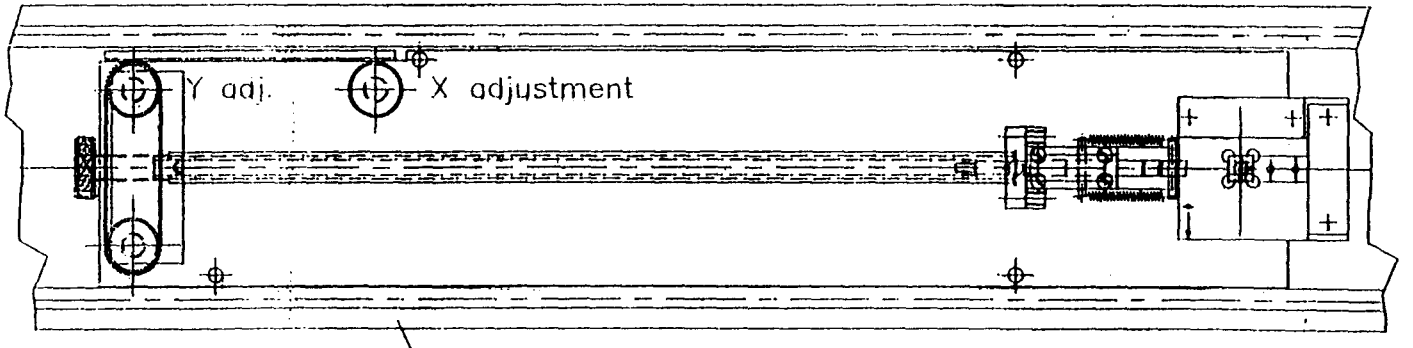
MEASUREMENT MODES

1.CALIBRATION MAGNET: probe evaluation



0 degr. – orientation – 180 degr.

2.INJECTOR I/II: measurements,aperture ~ 200 mm 7,87"

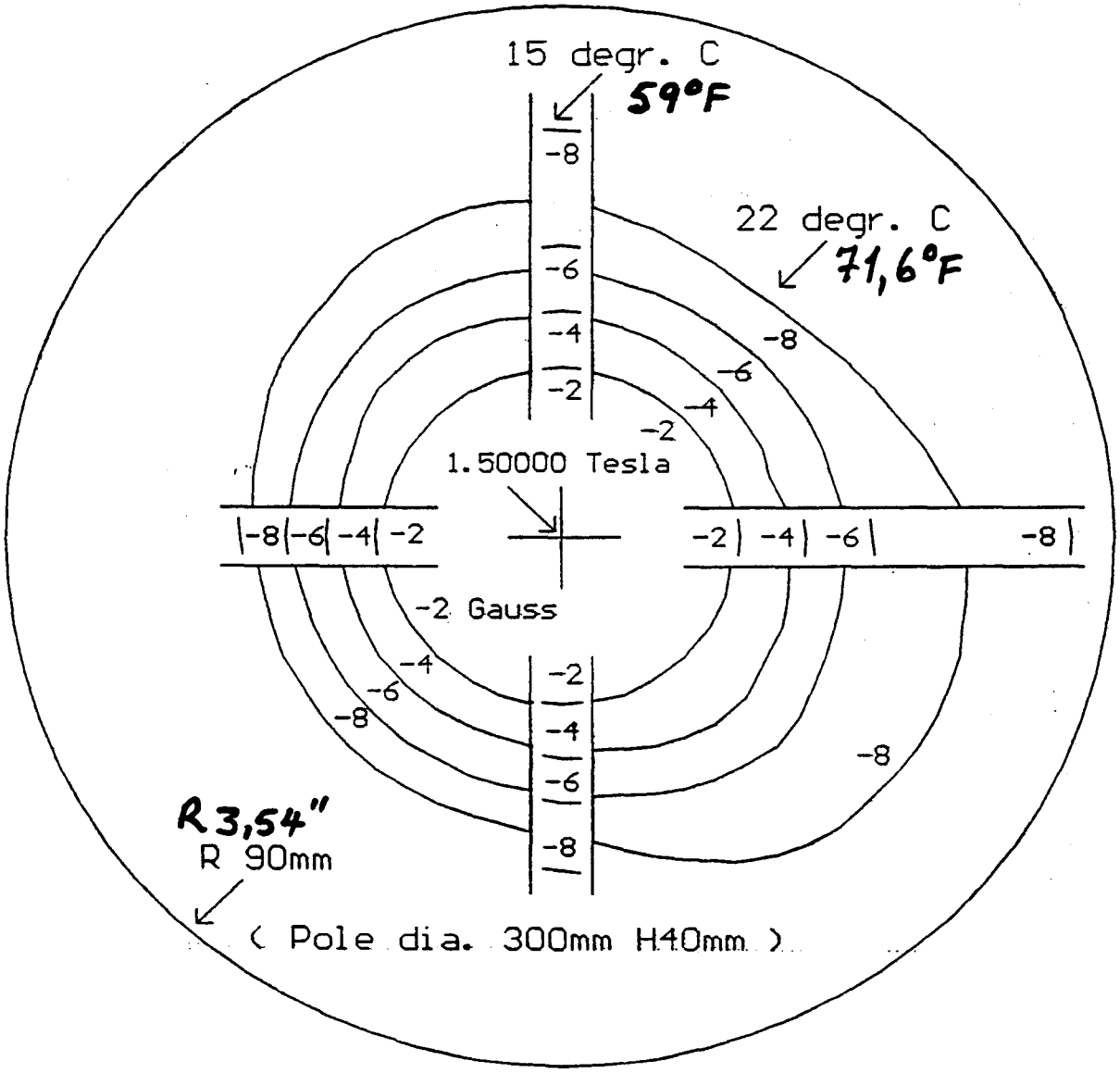


existing arm of field mapping equipment

3.RING CYCLOTRON: measurements of sector magnets, 1,18"
similar to (2),support on vacuumchamber, aperture ~ 30mm

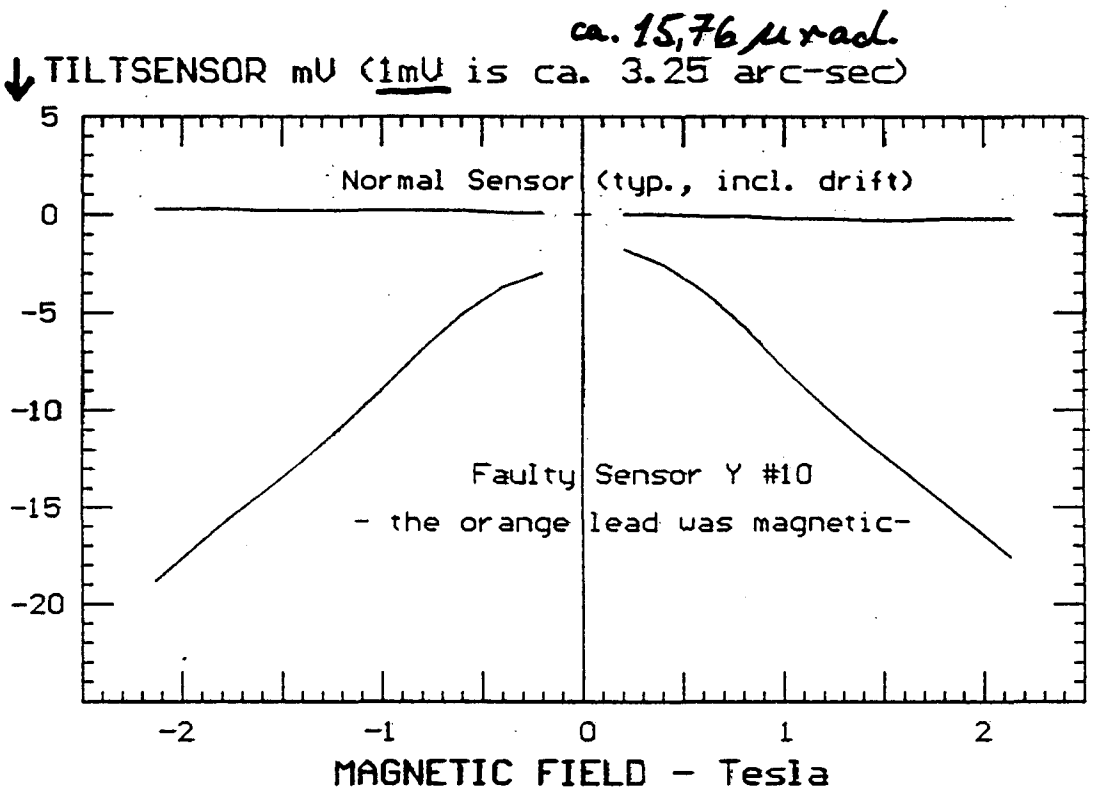
A.M.

CALIBRATION MAGNET FIELD CONTOURS
NMR PROBE IS 10mm ABOVE LOWER POLE



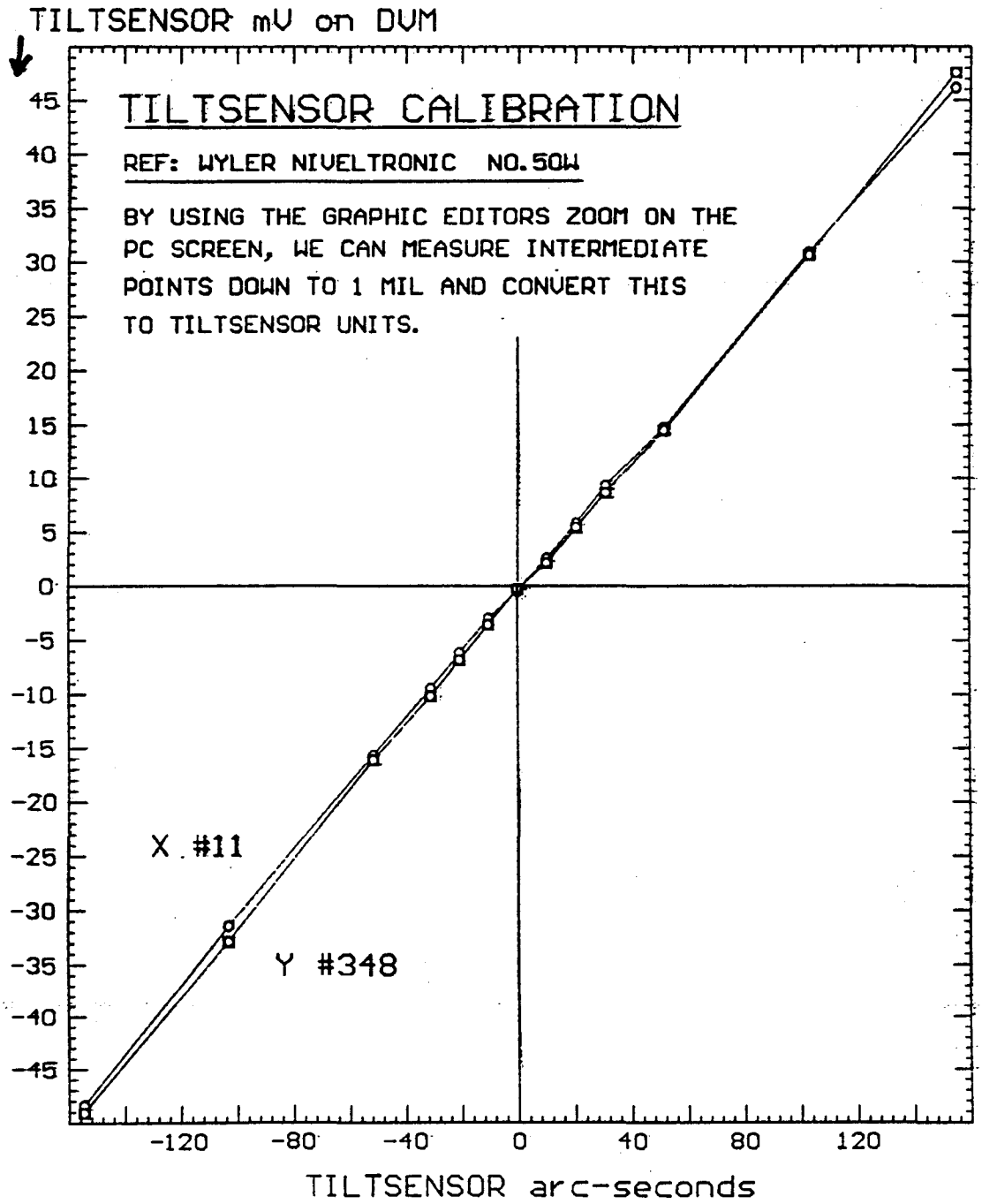
The contour lines change in form and position,
horisontally and vertically,
for changes in magnetic field,
ambient- and cooling water temperatures.

ERROR OF TILTSENSOR vs MAGNETIC FIELD



Virtually no error is detected up to 2 Tesla for very gradual changes in magnetic field.

The faulty sensor came as a surprise. In a magnetic field the sensor was deflected relative to its holder. The unit had to be replaced.



±160 SEC ≈ ±770 μrad.

SPECIFICATION OF THE READOUTS 1

TILTSENSOR TYPE CG57S:

Output on FLUKE 8502A DVM 10V range
DVM takes the average of 128 readings
DVM HI/LO peak memory may be used to monitor tiltsensor drift

RANGE: +– 12 degr.
(+– 1 degr. sensor would do, such as type RG33T)

SENSITIVITY: 308 micro Volt/arc second
(ca. 64 micro Volt/micro radian)

Adjustment of tiltmeter: in steps of 100 micro Volt $\approx 1,6 \mu$ rad.

RESOLUTION: 10 microVolt (tendency digit)

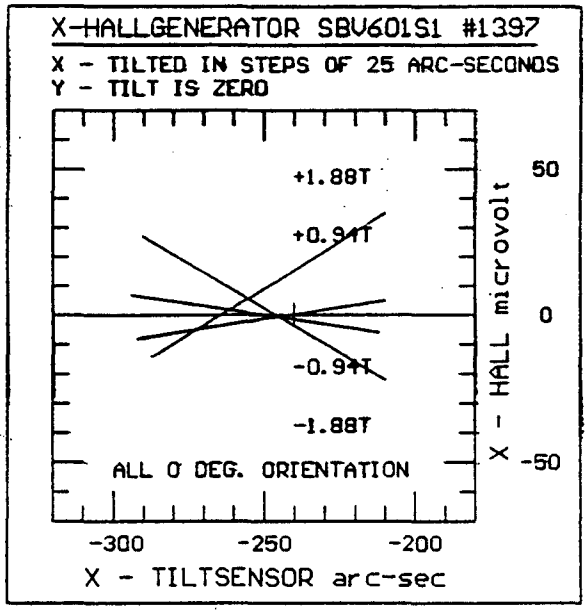
TILTSENSOR TYPE CG57S continued:

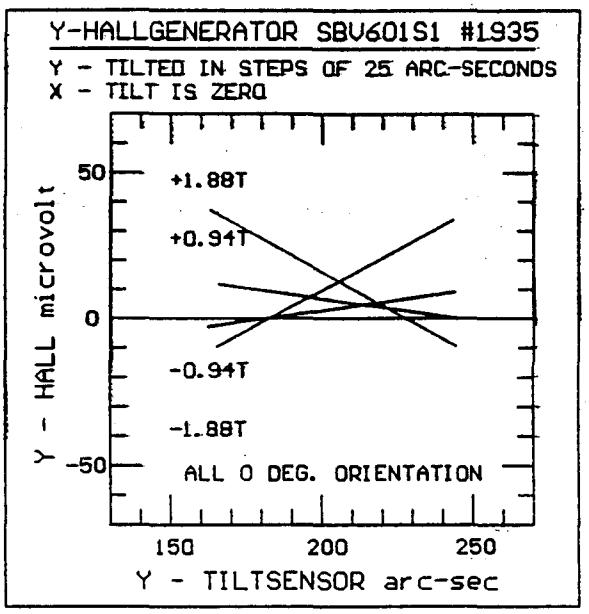
ACCURACY: Apart from time after calibration and temperature dependence, these sensors must also have a very stable support structure.

RELATIVE ACCURACY: We repeated the measurement of a few points at 1.84 Tesla after 18 hours under fairly stable condition and recorded a variation of 1.3 +— 0.3 arc seconds. For 3 to 7 days this would typically remain within +— 1.3 arc seconds; for a very stable environment we measure +— 0.5 arc seconds. (To do that just shut off the magnet supply and the cooling water circulation!)

Please note that for this accuracy, these tiltsensors may need 15 to 30 minutes SETTLING TIME after a full range (+— 12 degr.) excursion : (syrup effect).

PRIMARY EVALUATION (SELECTION) OF HALLGENERATORS





After the first assembly of the Hall/Tiltsensor combination we want to see:

- the magnitude of typical side effects of the Hall generators
- the alignment error between each Hall/Tiltsensor pair

Assuming that we already know the magnetic tilt characteristics of our magnet, we only need to measure at one (zero or 180 degr.) orientation.

The crosspoints for two selected values of magnetic field are determined as shown above and these will indicate if we can proceed with the alignment task.

Previously we did use Siemens type SBV585-S1 Hall generators and while one of them did show similar tilt variations like the present pair, the other one exceeded that level by a factor of 5. Tests at 90/270 degr. orientation confirmed these results.

The best Hall generators for this application are highly doped semiconductor types with small -resistivities and -temperature coefficients. The type 601 rates as a favo(u)rite also due to its low 'planar' Hall effect. Fortunately this effect did not complicate our evaluation process.

SPECIFICATION OF THE READOUTS 2

HALL GENERATOR TYPE SBV601-S1:

Constant current drive of 360mA, 3 probes in series.
Output on HP3457A DVM AUTO range, via 10 channel multiplexer.
SENSITIVITY: typ. 5.68 micro Volt/Gauss
as a tiltmeter:

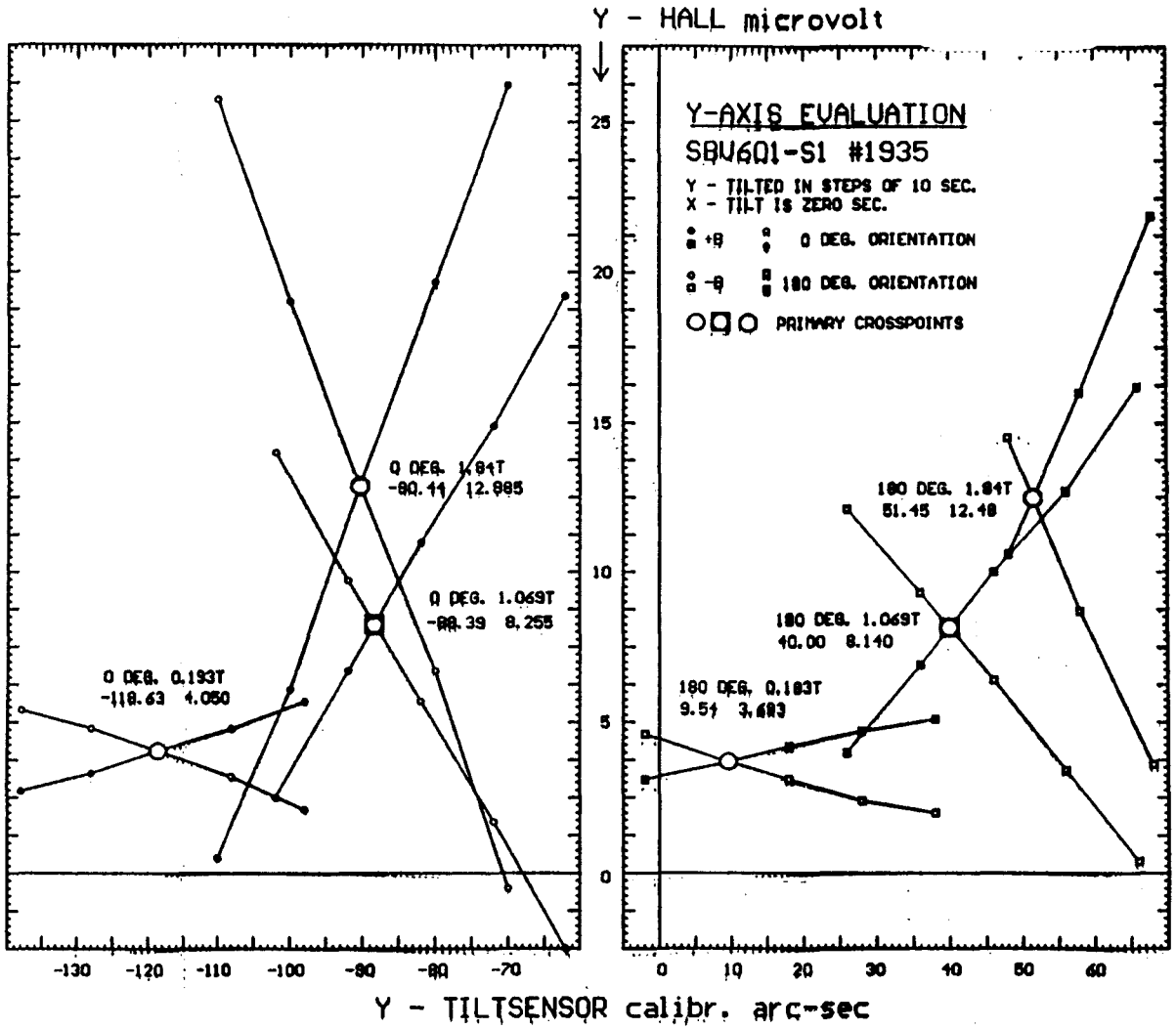
0.1 Gauss/arc second at 1.84 Tesla or
0.05435 Gauss/arc-sec/Tesla

RESOLUTION: 0.1 micro Volt
The HP's optional filter math operation reduces the effect of random noise while preserving long term trends.

HALL GENERATOR TYPE SBV601–S1 continued:

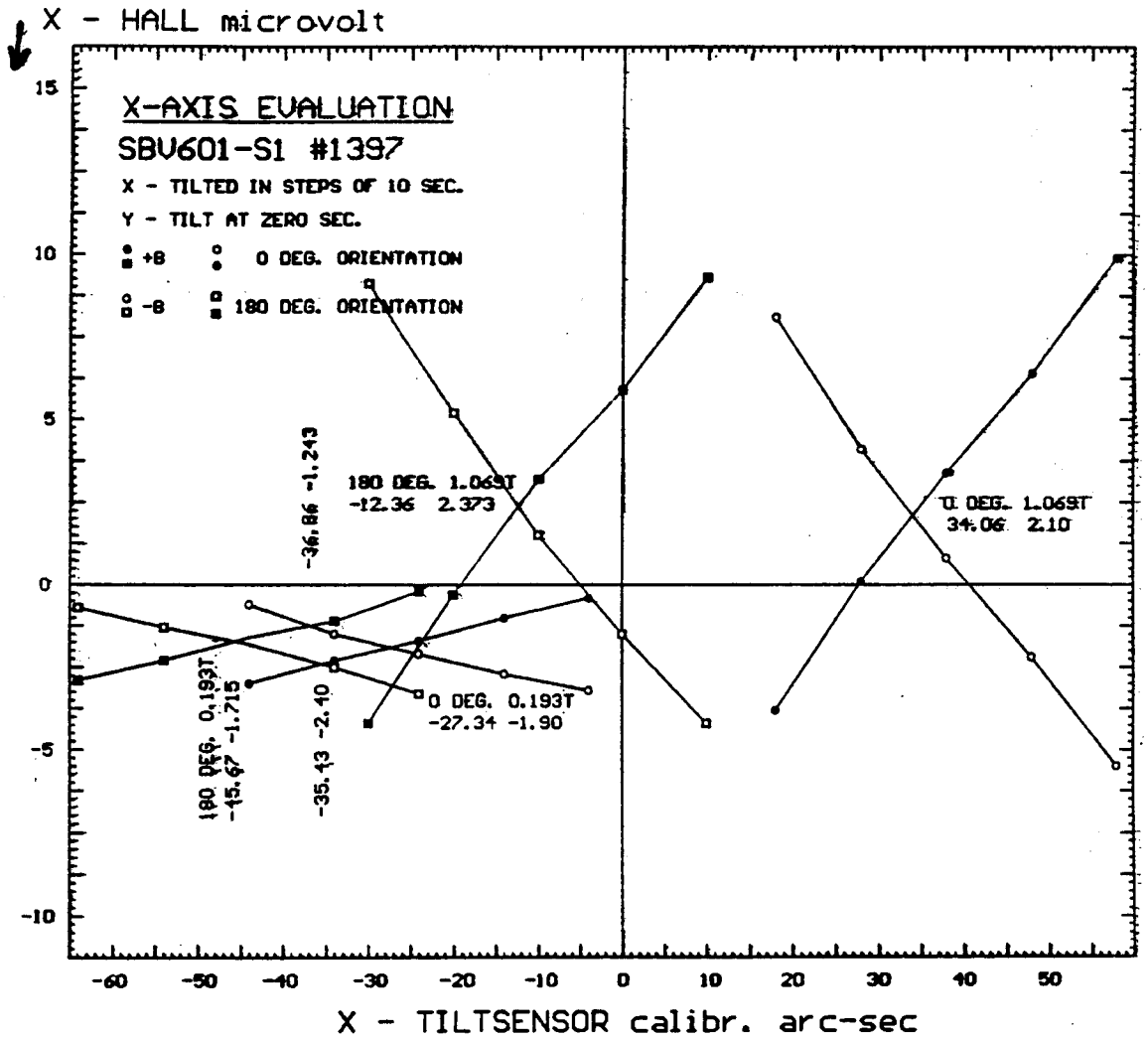
RELATIVE ACCURACY as a tiltsensor is proportional to the magnitude of the vertical (Z) field. Above 1 Tesla we achieve typ. 0.1 Gauss for a set of measurements.

Periodic RE–CALIBRATION as per requirement. It is fairly easy to calibrate the HALL OFFSET –VOLTAGES and –ANGLES in situ. Normal type of calibrations are labour intensive and are not really required in this application, except for the "Z" component.



For the Y-axis we now have the crosspoints for 3 different magnetic fields :

- The HALL OFFSET VOLTAGES are all positive values here and depend on the magnetic field.
- The HALL OFFSET ANGLES, including a fixed error of alignment, change with magnetic field. We could improve the alignment.
- The TILT of the magnetic field remains fairly constant. $0^\circ - 180^\circ$ sec/2.



For the X-Axis we first look at the crosspoints for 2 of the 3 magnetic fields :

- The HALL OFFSET VOLTAGES go from negative to positive values.
- The HALL OFFSET ANGLES again change with magnetic field and it is clear, that we need an additional calibration curve, that also takes into account the remaining alignment error.
- The TILT of the magnetic field changes visibly in magnitude over the field range.

HALL OFFSET VOLTAGE CALIBRATION continued:

The offset voltages of the Hall generators were obtained from the average of the 0/180 degr. orientation and +B/–B field values.

HALL OFFSET ANGLE + ALIGNMENT ERROR CALIBRATION:

This can be done by using the HALL OFFSET VOLTAGES as a basis to get the tilt angles after a full set of measurements. (This was the method used to align the tiltsensors.) It is also possible to tilt the Hall generators to any reference/offset level but this is thought to be less accurate.

To do these calibrations, we first want to improve the stability of our calibration magnet power supply as well as to have a more stable cooling water temperature regulation.

TO CONCLUDE

MEDIAN PLANE MEASUREMENTS:

We plan to do our first measurements on the SPC2 at the beginning of next year during the annual shutdown.

ACKNOWLEDGMENT:

I wish to acknowledge the help of Attie Mueller in the preparation of the mechanical drawings and for his design of the tilt/inclinometer. Also my thanks to the NAC management who supported my wish to participate in this workshop.

28/09/93

An Apparatus using the Faraday effect to locate the magnetic axis.

J. Le Bars
CEN-Saclay
FRANCE

MAIN CHARACTERISTICS OF THE EXPERIMENT

- **Magneto-optical properties :**
  - **Faraday effect :**

    an incident beam of linearly polarized light
    is changed into
    a transmitted beam of elliptically polarized light
  - **High uniaxial anisotropy field of the film**

- **Rotation of the mole around the Z axis - Translation along the Z axis**
  - **The angle of the film is measured at 4 points during the rotation at Z positions**

    $\left.\begin{matrix} dx \\ dy \end{matrix}\right\}$ Displacement of the magnetic axis with respect to the rotation axis

    β : Tilt of the magnetic plans with respect to the gravity direction.

  Are deduced

THE MOLE

ϕ = 32 mm Al alloy

Contains

Magneto optic film system ϕ = 2 mm

GARNET (Bi, Y, Fe, Ga, O)
Hc = 1,5 œ
Hs < 4 œ
thickness = 6 µm
SUPPLIER :
PHYSICAL TECHNICAL CENTER
PHYZICA - MOSCOW

and

- Polarizer film
- Analyser film
- 2 Bundles
- Glass fibers ϕ = 20 µm

- can be used in gradient up to : 2.5 T/m
  working G in a conventional quadrupole : 10 T/m
  or in a superconducting quadrupole : 100 T/m or more (will be tested)

Inclinometer to determine the gravity direction (at $\beta = 0$)
electrolytical level
± 8.7 mrd (± 10 v)
SUPPLIER : TECHTRIUM

Photodiode centroïde to have a reference axis
1 mV ⇒ 3 µm
SUPPLIER : OPTILAS - IR LASER

axe de la [illegible] = axe magnétique.

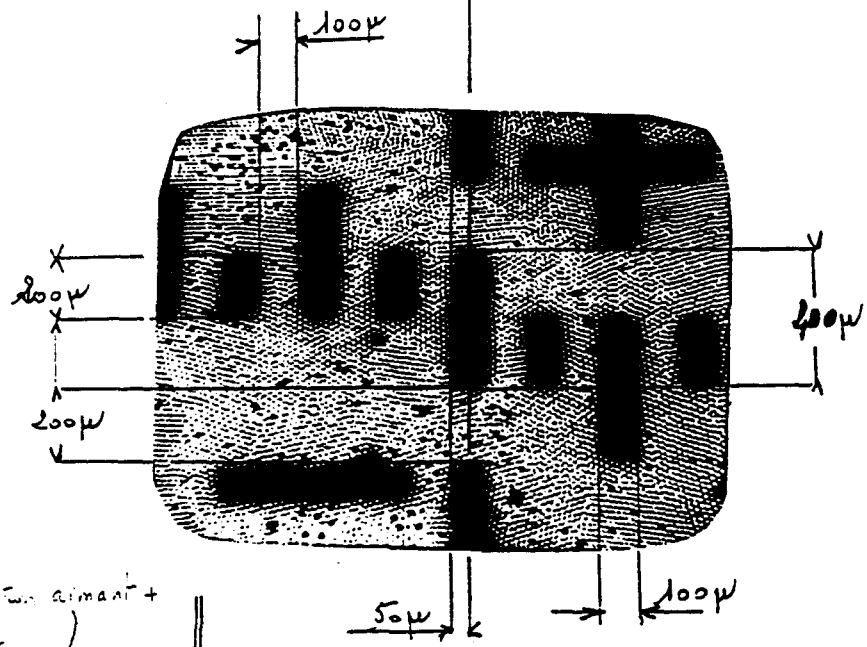
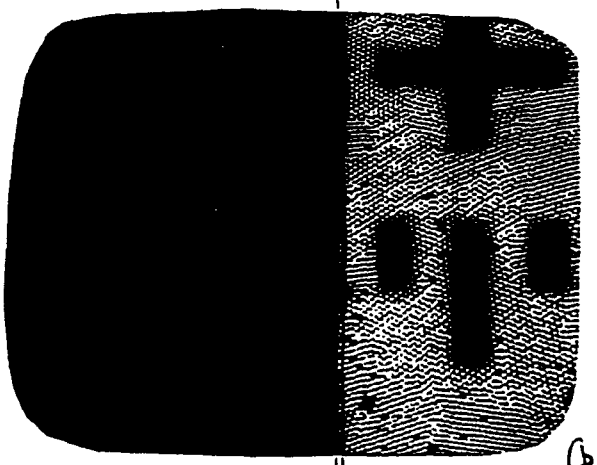


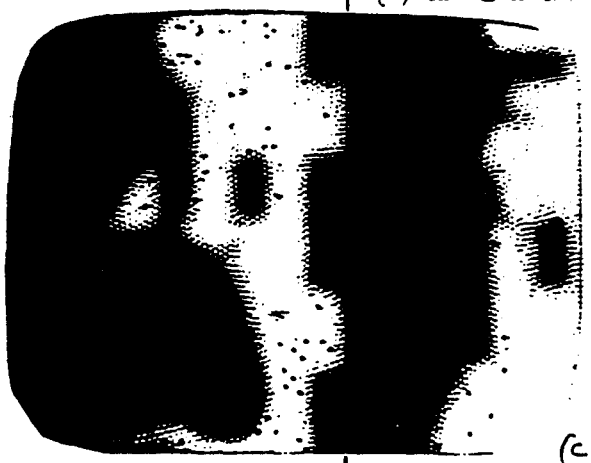
fig 4 (a)

polarisation aimant + (v. fig)



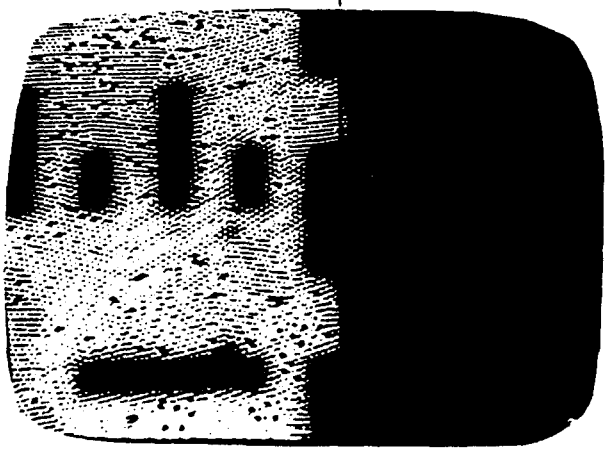
(b)

balayage de la polarisation + à − au cours de la magnétisation = (↗ du Gradient)



(c)

inversion de la polarisation (−) (v. fig)

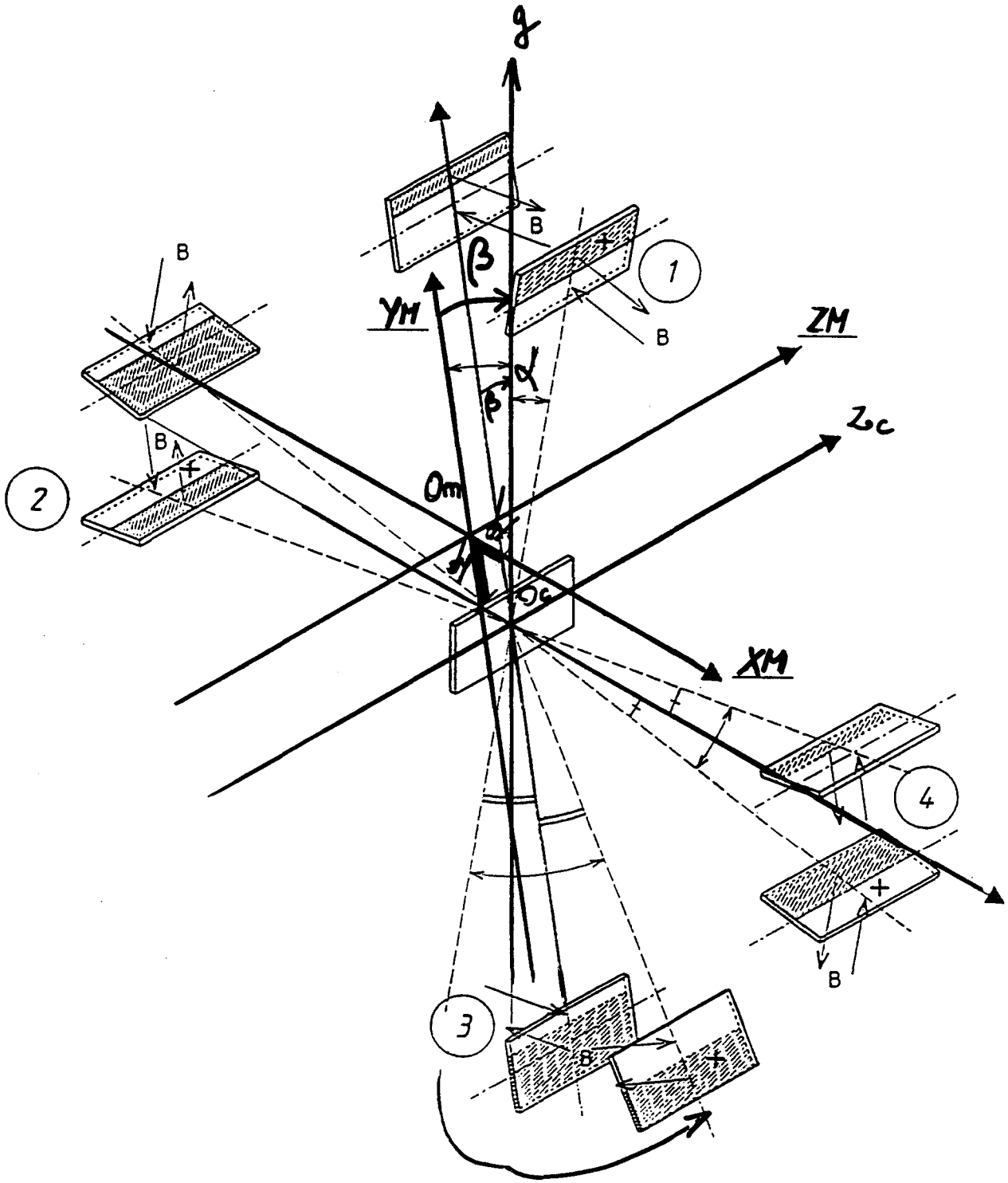


(d)

cobalt 6

Hc = 1.5 Oe

Hs = 4 Oe


g
YM
ZM
Zc
XM
Om
Oc
β
α
B
1
2
3
4

THE MOLE MOVES IN A TUBE AND ROTATES INSIDE THE QUADRUPOLE

- **Stepping motor + Reductor** 200 000 steps per turn
  (1 step = 0.03 mrd)
- **Tube**
  - inner diameter 36 mm
  - stainless steel (or al alloy)
  - centred inside the conventional quadrupoles
    (± 150 μm - x and y - with respect to the poles)
- **Mole**
  - diameter 32 mm
  - 2 teflon bearings outside $\phi = 36$ mm
- **IR laser**
- **2 Bundles** glass fiber $\phi = 20$ μm to collect and carry the light { • MOF • Analyser system

FOR RESULTS :
- microscope and video camera
- under study : analogic data acquisition system associated to an optical scanner

FORMULAE

$$\Delta\varphi y = \varphi_1 - \varphi_3 = 2k(G)\, dy \Rightarrow \boxed{dy}$$

$$\Delta\varphi x = \varphi_2 - \varphi_4 = 2k(G)\, dx \Rightarrow \boxed{dx}$$

$$\varphi_1 - \varphi_3 = 2\, d\varphi y$$

$\Delta\varphi y$ = Angle between the magnetic axis and the Y MOF axis at the point 1

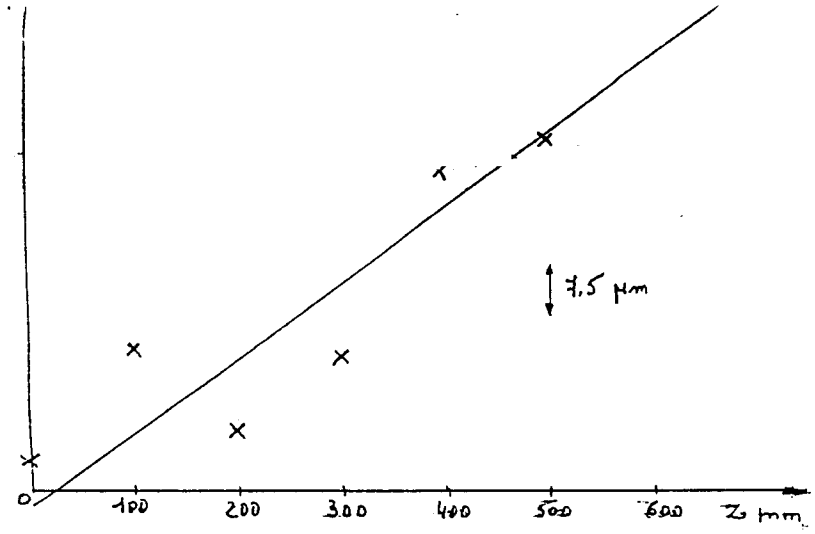
α = Gravity direction and Y MOF axis at point 1

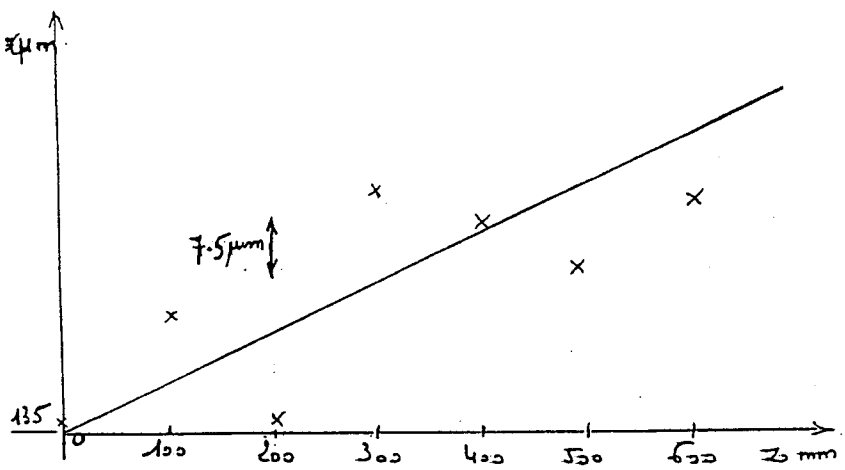
$\boxed{\beta}$ = $(\varphi_1 - \varphi_3)/2 \pm \alpha$ Angle between the magnetic axis and $\vec{G}$ Gravity

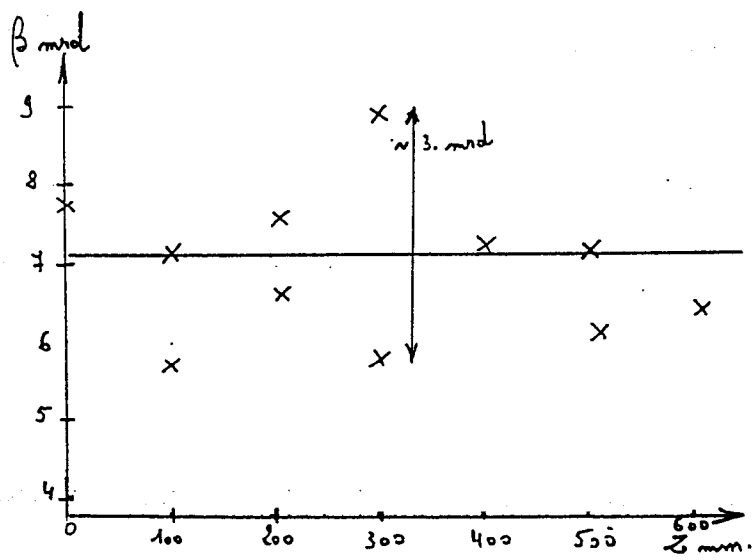
<u>RESULTS</u> : $\boxed{dx, dy, \beta}$

dx, dy : $\pm 20\ \mu m$

β : $\pm 1{,}5$ mrd







x and y in plane coordinates of Magnetic Axis = f(z)

β (tilt) Magnetic planes

CONCLUSIONS

Satisfying experiences and calculations

But : more developments would be necessary

- to increase the precision for the tilt determination
- to decrease the field working gradient < 1 T/m
  - to be able to do measurements at room temperature
- to analyze and compute the visual results

  (analogic data acquisition system)

VIBRATING WIRE SYSTEM FOR MAGNET FIDUCIALIZATION

H. YALLON

29 SEPTEMBER 1993

VIBRATING STRETCHED WIRE SYSTEM

- WE IMPLEMENTED A SYSTEM IN THE CORRECTOR MAGNET LAB.
- THE SETUP IS MIRRORED AFTER THE SYSTEM DEVELOPED AT SLAC BY JERRY FISHER AND STEVE WILLIAMS
- MECHANICAL DESIGNER: ELMORE SALISBURY
- TECHNICIANS: GERY CRAIG , DON RHODES
- MECHANICAL ENG.: DAVE SAWYER
- ASSISTANCE: ZACK WOLF, MIKE GREEN

VIBRATING WIRE SYSTEM FOR MAGNET FIDUCIALIZATION

1. OBJECTIVES

- DETERMINE THE MAGNETIC CENTERLINE OF DESCRETE MAGNETS
- DELIVER THE COORDINATES OF THE MAGNETIC CENTER TO FIDUCIALS
- DETERMINE THE ELECTRIC CENETERLINE OF BPMS
- DETERMINE THE COORDINATES OF THE ELECTRIC CENTERLINE RELATIVE TO THE MAGNETIC CENTERLINE.

2. CONCEPT

- SINGLE VIBRATING STRETCHED WIRE TECHNIQUE ADAPTED FROM SLAC.

3. SYSTEM ENHANCHEMENTS

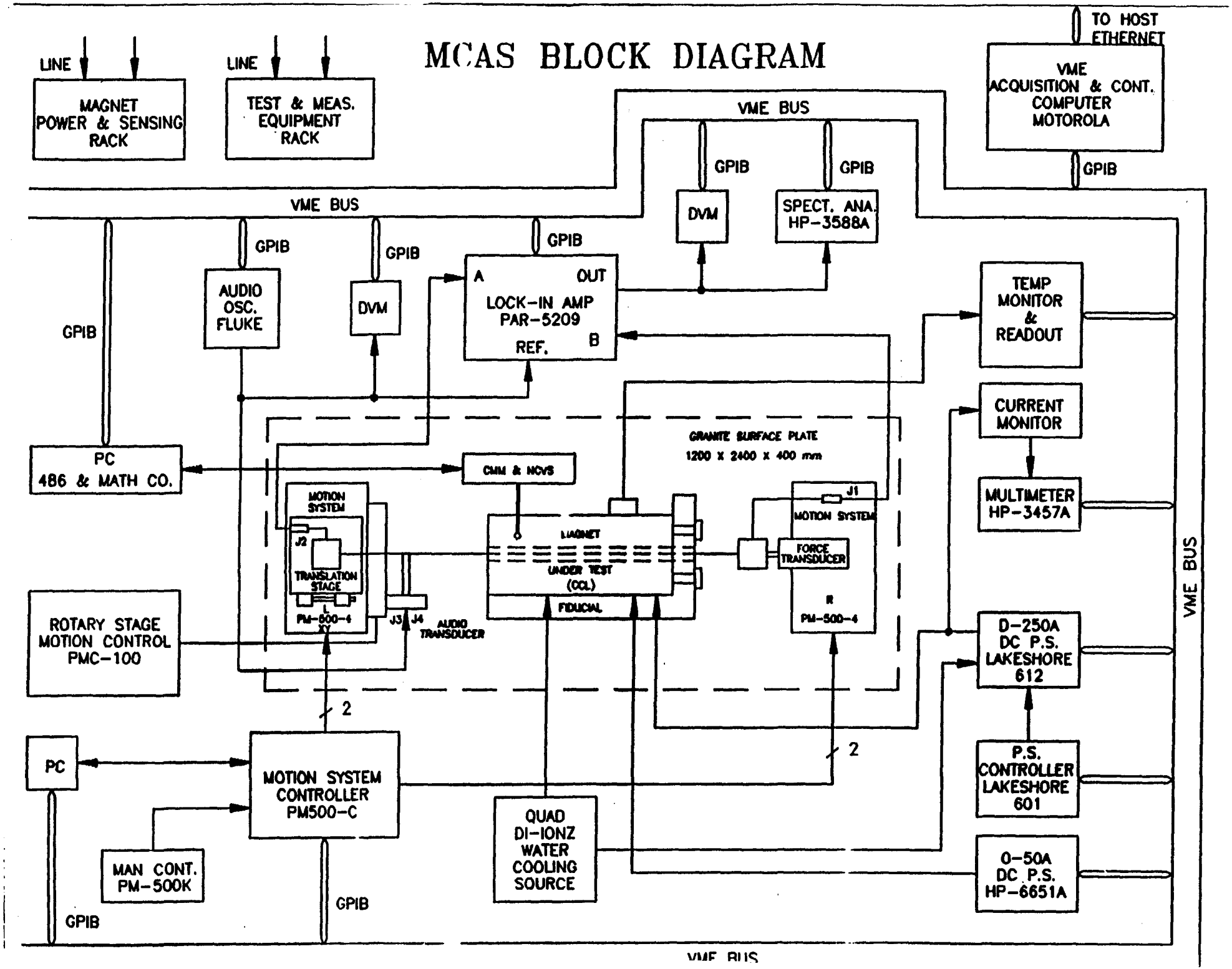
- NON CONTACT VIDEO SYSTEM FOR DETERMINATION OF WIRE COORDINATES USING EDGE DETECTION

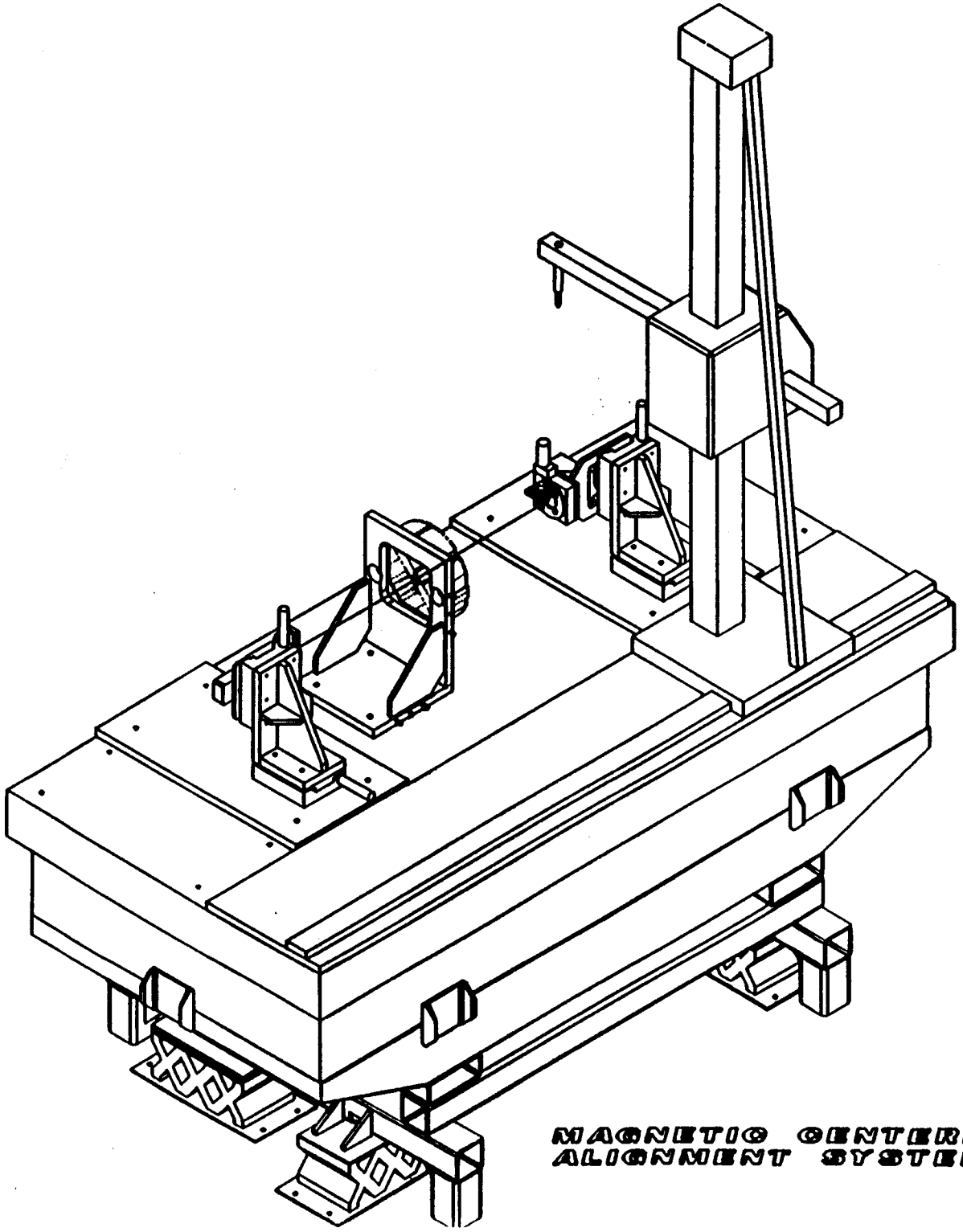
- ACCELEROMETER FOR SYSMIC VIBRATION DETECTION

- MOTORIZED ROTARY STAGE ALLOWS THE USE OF A SINGLE VIBRATION TRANSDUCER FOR BOTH HORIZONTAL AND VERTICAL PLANES

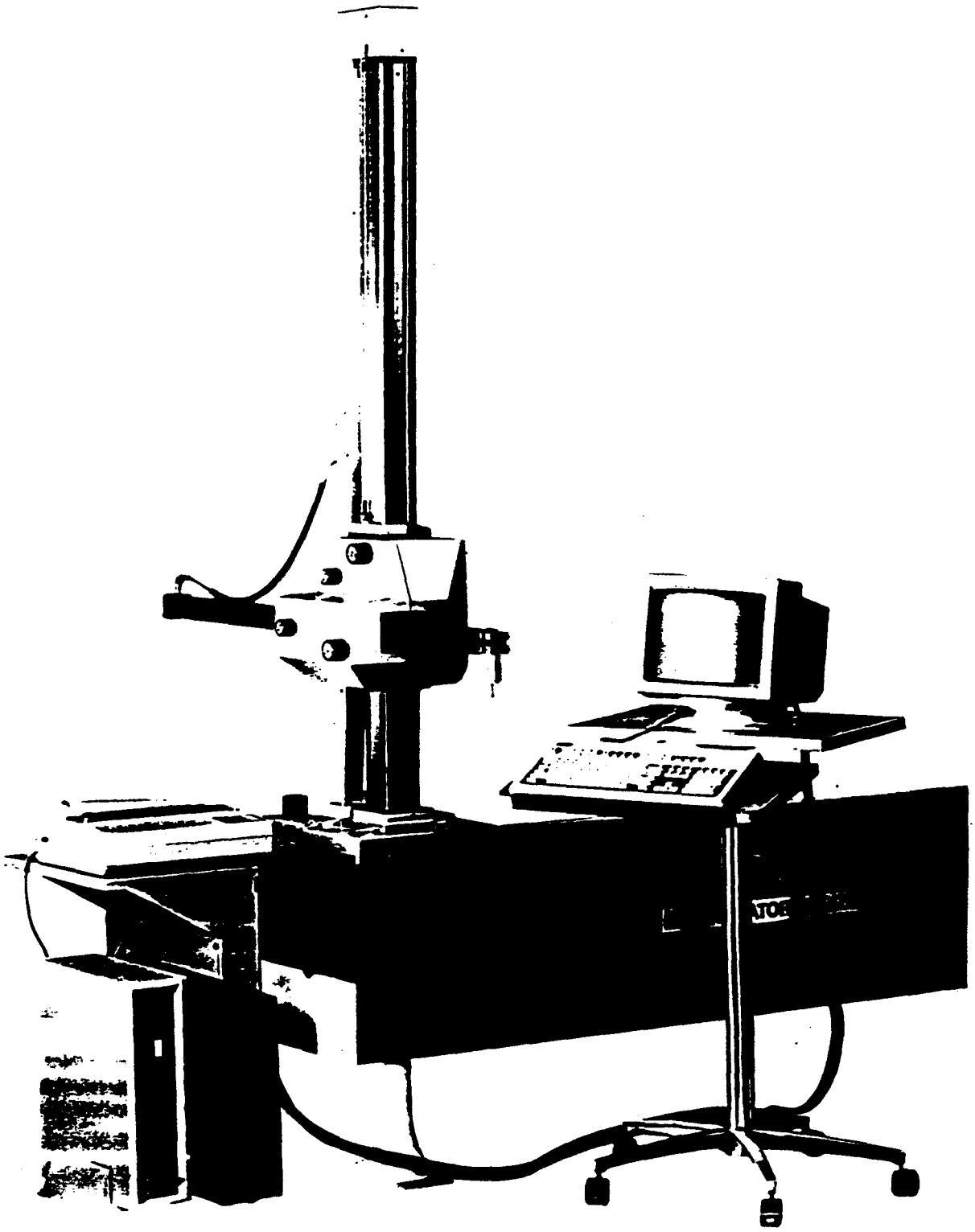
- FORCE TRANSDUCER FOR ACCURATE IMPLEMENTATION OF WIRE TENSION

MCAS BLOCK DIAGRAM





MAGNETIC CENTERLINE
ALIGNMENT SYSTEM



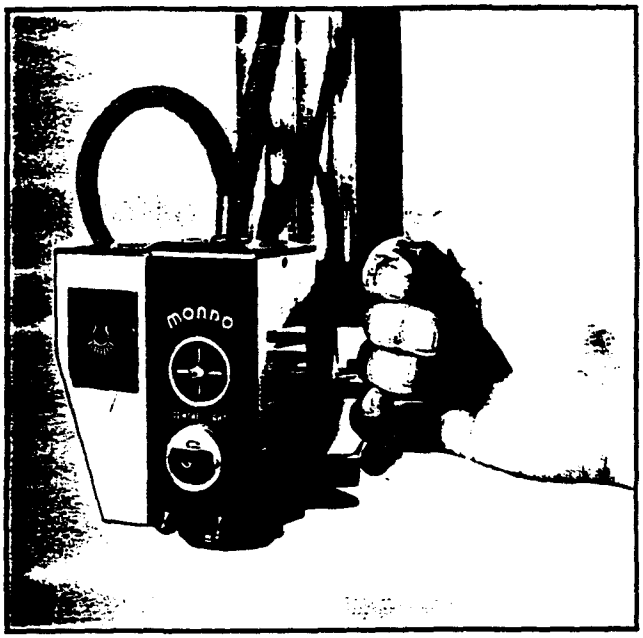
THE MICROPROBE 1000 is an accurate system of measurement capable of inspecting a wide range of components large or small, stable or flexible, with complete reliability. This is achieved by using a non-contact probe using remote control so that neither the component nor the measuring head is subject to any direct force, thereby removing all sources of component distortion and inaccurate reading. Additionally, the need for component clamping is reduced to a minimum.

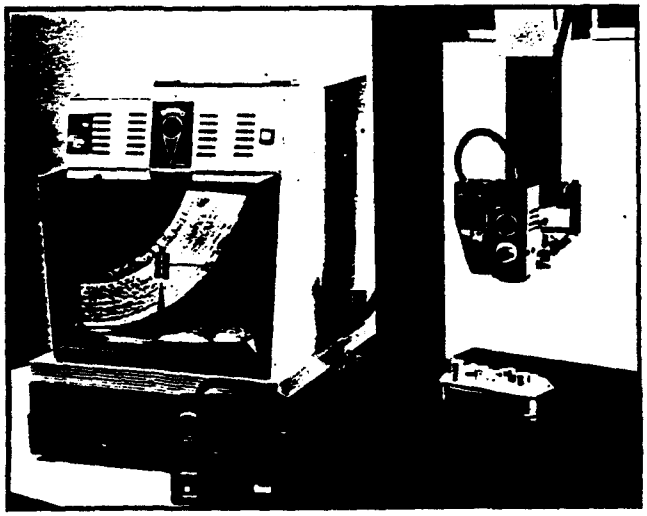
A specially designed light centreing facility affords improved component magnification. X and Y axes may be measured using lens ranging from x20 to x1000. The Z axis is a standard x20. The fibre optic "cold ring" lighting also ensures that no heat is applied to the component.

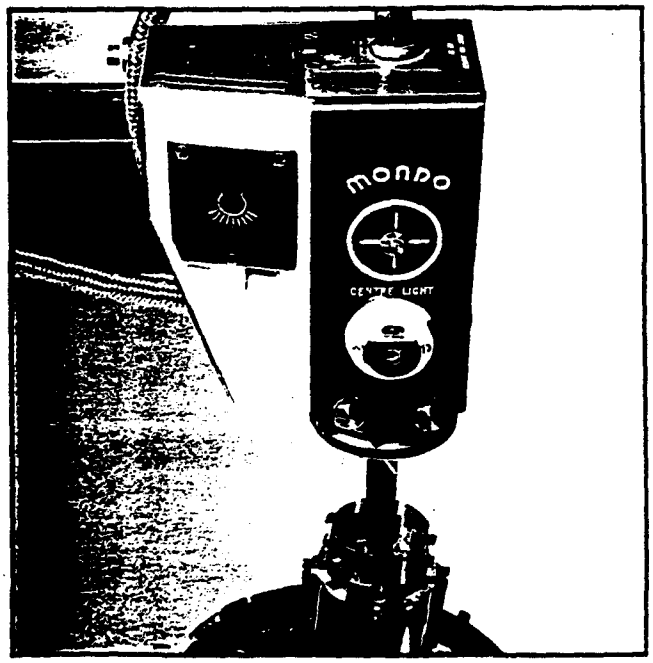
The system operates by means of a high quality solid state video camera coupled to either a monochrome or colour monitor.

The component to be measured is illuminated by an integral fibre optic cold ring light. The remote control unit has an eight button feather touch key pad. This operates the moveable lines of the electronic line generator allowing positive and negative grid boxes to be set up.

The resultant images are viewed on the TV monitor and measurements can be made to an accuracy of microns.





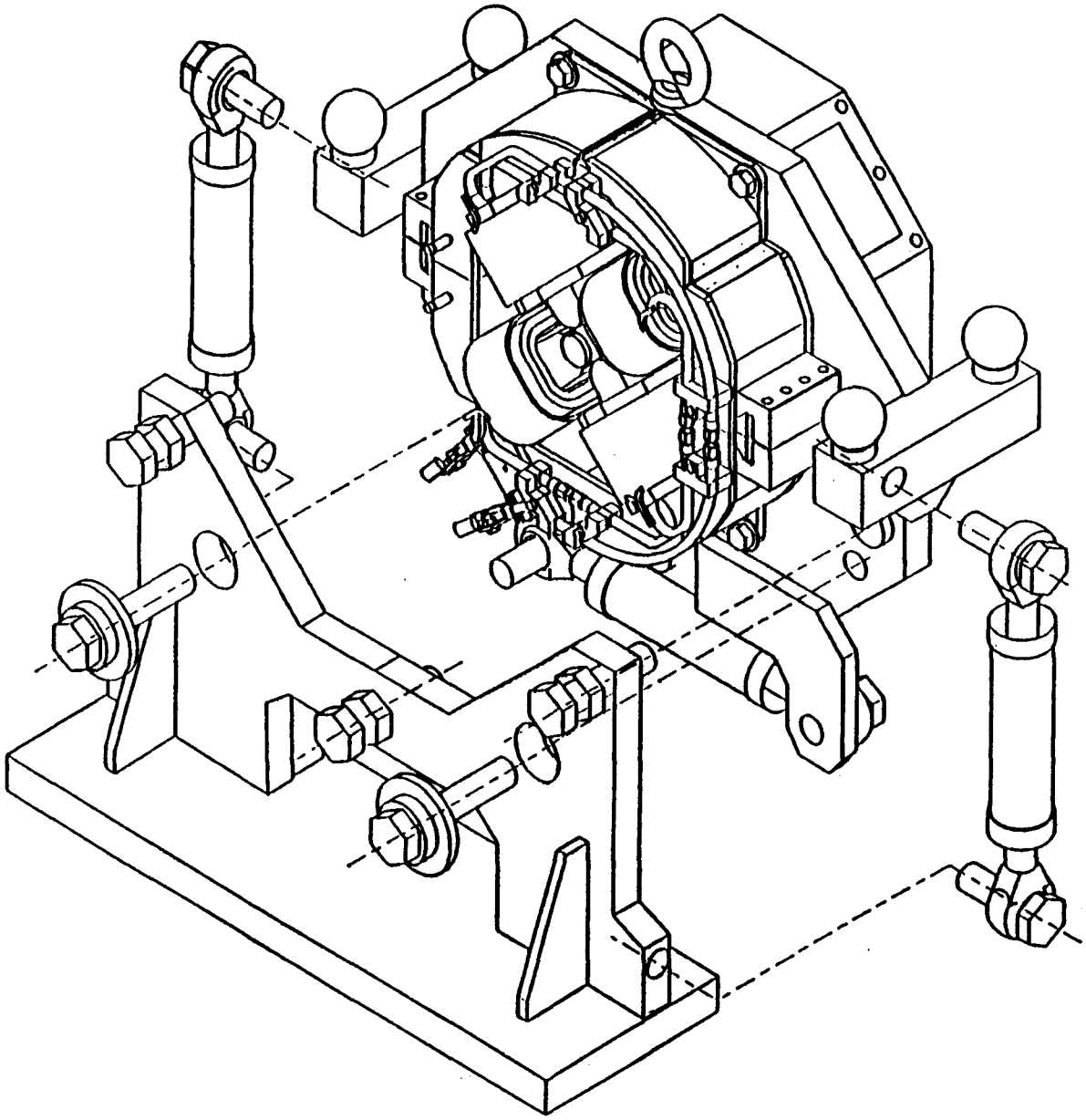


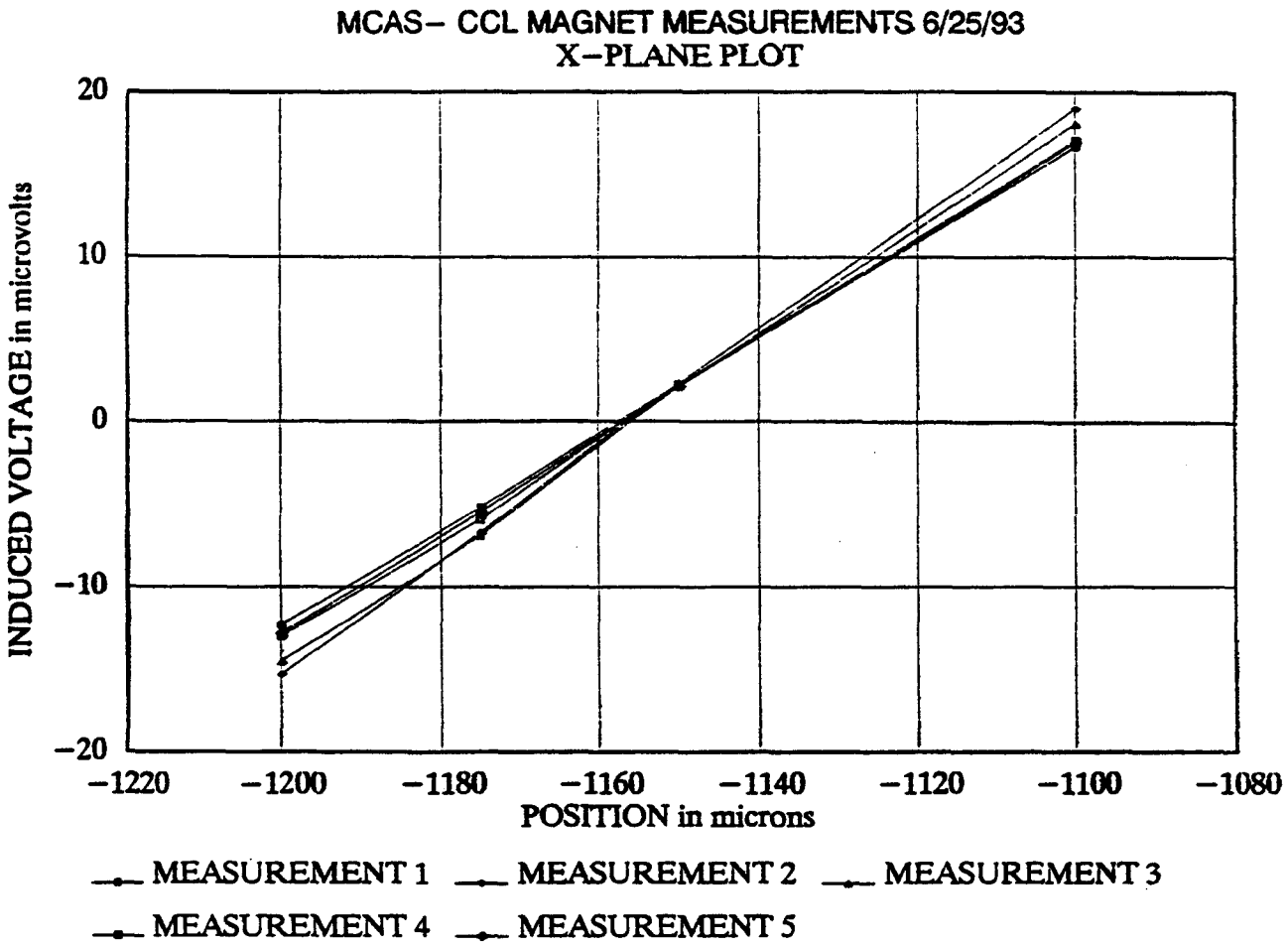
CCL SPECIFICATIONS

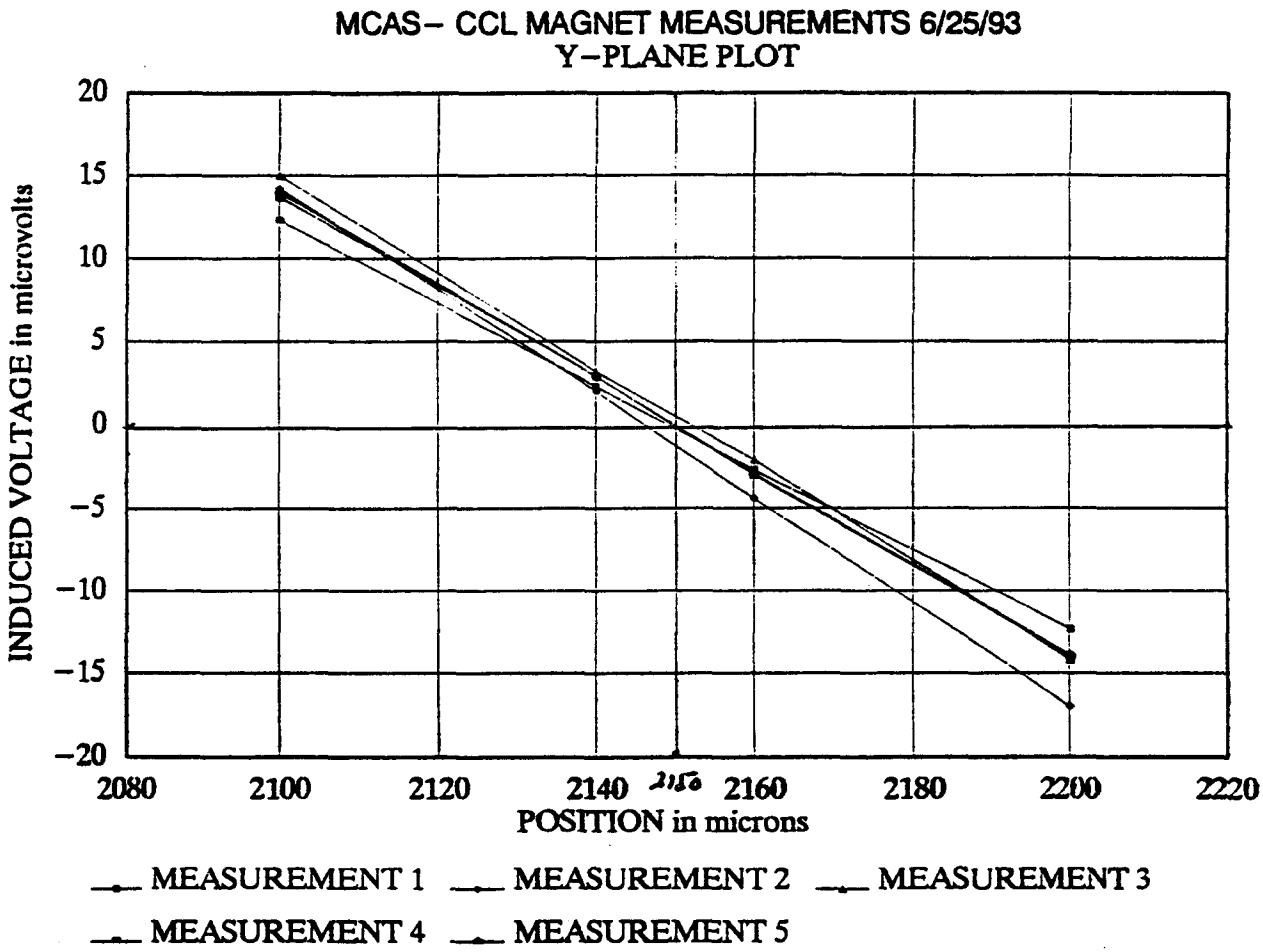
- FIELD GRADIENT: 31 T/m
- EFFECTIVE LENGTH: 7 Cm
- ID: 20 mm
- HEIGHT: 28 Cm
- WIDTH: 32 Cm
- OVERALL LENGTH: 12Cm
- CURRENT FOR G=31 T/m : 66 A

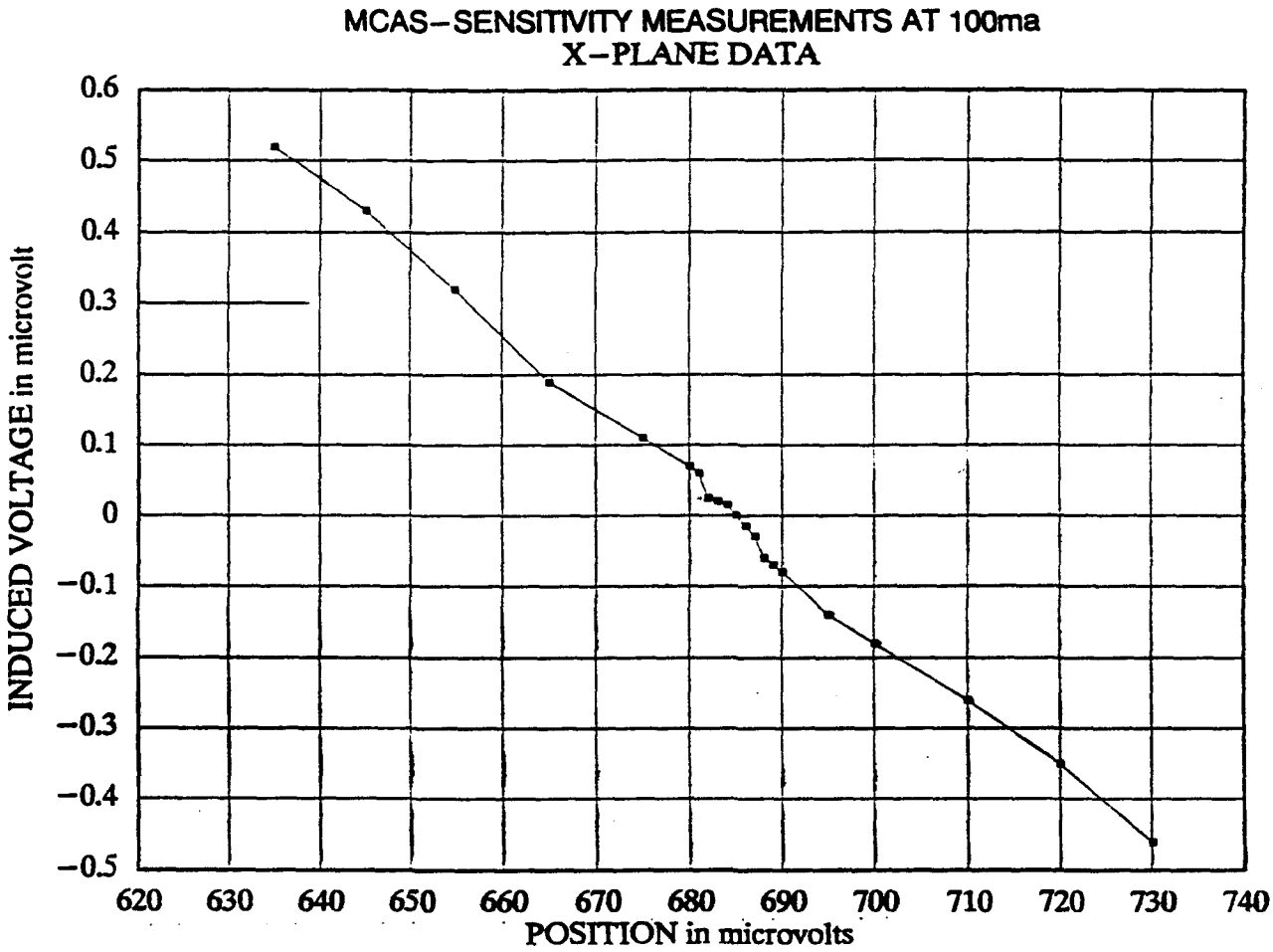
ALIGNMENT

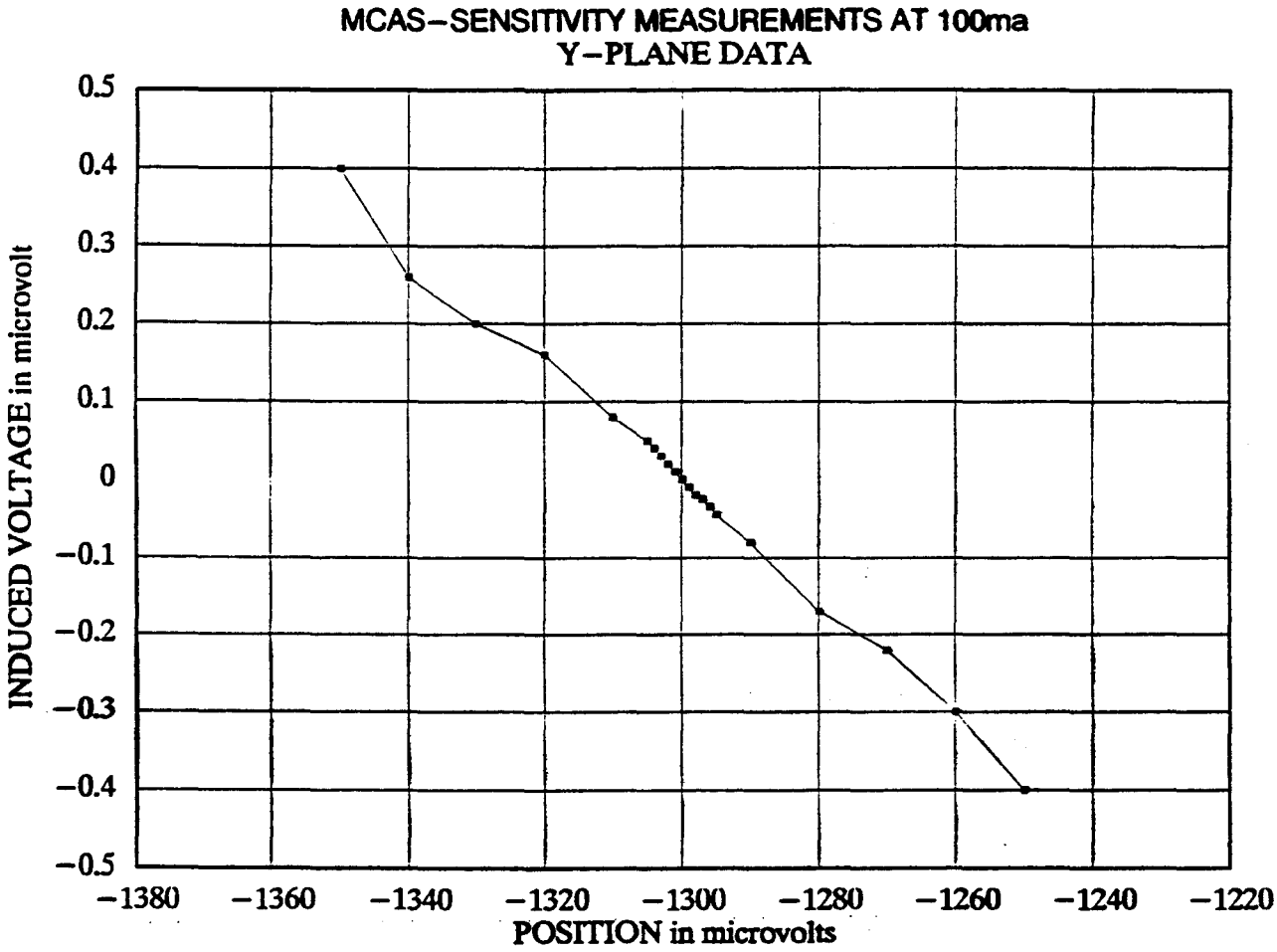
- ALONG BEAM AXIS: +/- 0.05mm
- TRAVERSE TO AXIS: +/-0.05mm
- CLOCKING: +/-0.1 deg.
- TILT AND YAW: +/-0.1deg.



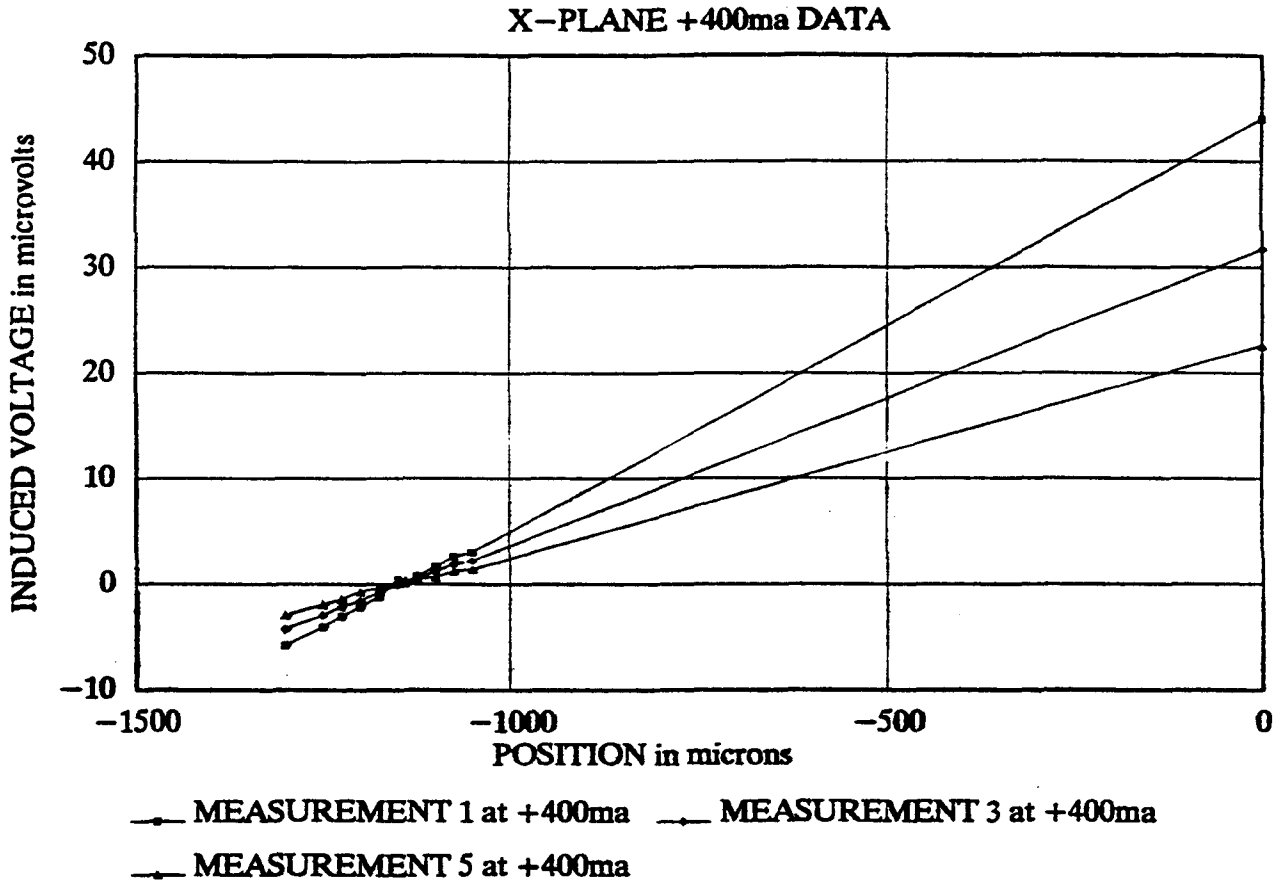

MCAS– CCL MAGNET MEASUREMENTS 6/25/93
X–PLANE PLOT
INDUCED VOLTAGE in microvolts
20
10
0
−10
−20
−1220
−1200
−1180
−1160
−1140
−1120
−1100
−1080
POSITION in microns
MEASUREMENT 1
MEASUREMENT 2
MEASUREMENT 3
MEASUREMENT 4
MEASUREMENT 5


MCAS– CCL MAGNET MEASUREMENTS 6/25/93
Y–PLANE PLOT
INDUCED VOLTAGE in microvolts
20
15
10
5
0
−5
−10
−15
−20
2080
2100
2120
2140
2150
2160
2180
2200
2220
POSITION in microns
MEASUREMENT 1
MEASUREMENT 2
MEASUREMENT 3
MEASUREMENT 4
MEASUREMENT 5


MCAS–SENSITIVITY MEASUREMENTS AT 100ma
X–PLANE DATA
INDUCED VOLTAGE in microvolt
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
620
630
640
650
660
670
680
690
700
710
720
730
740
POSITION in microvolts

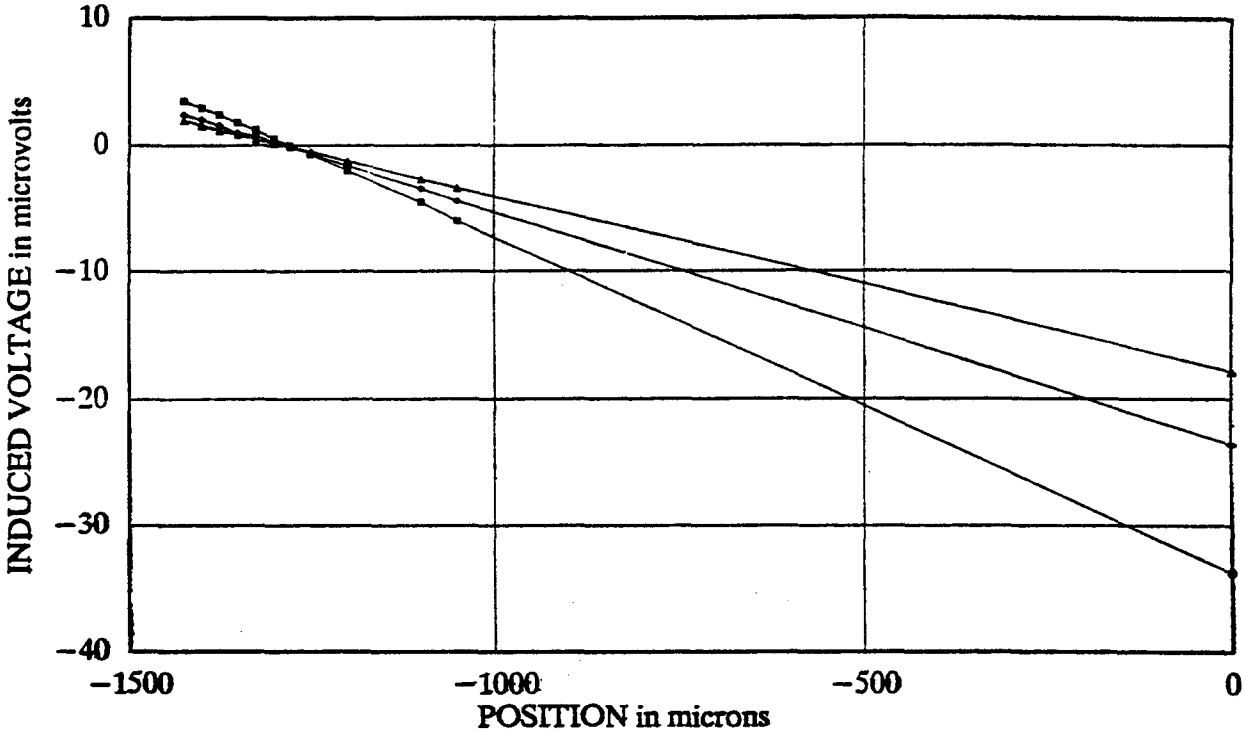

MCAS–SENSITIVITY MEASUREMENTS AT 100ma
Y–PLANE DATA
INDUCED VOLTAGE in microvolt
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
−1380
−1360
−1340
−1320
−1300
−1280
−1260
−1240
−1220
POSITION in microvolts

MCAS–SC MAGNET WARM MEASUREMENTS



MCAS–SC MAGNET WARM MEASUREMENTS

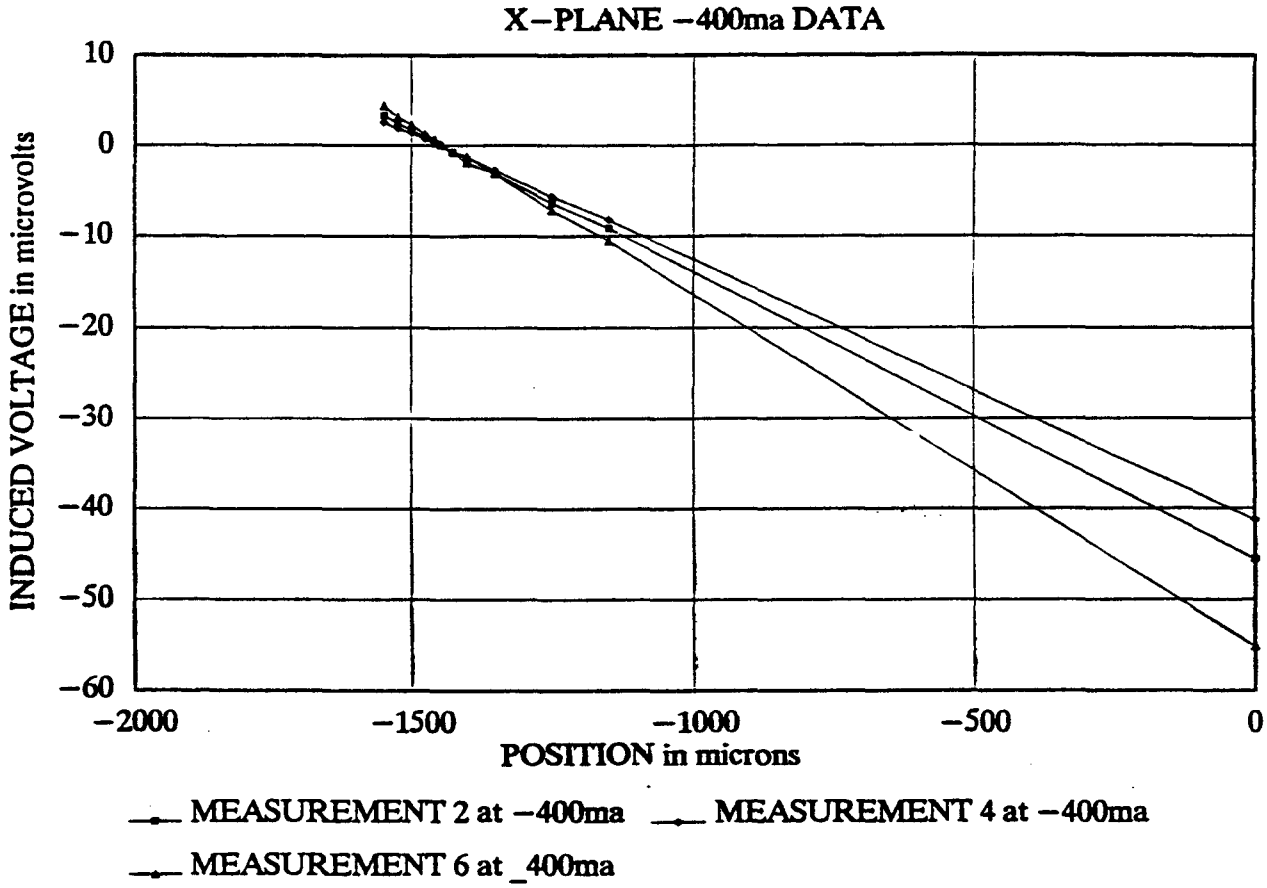
Y–PLANE +400ma DATA



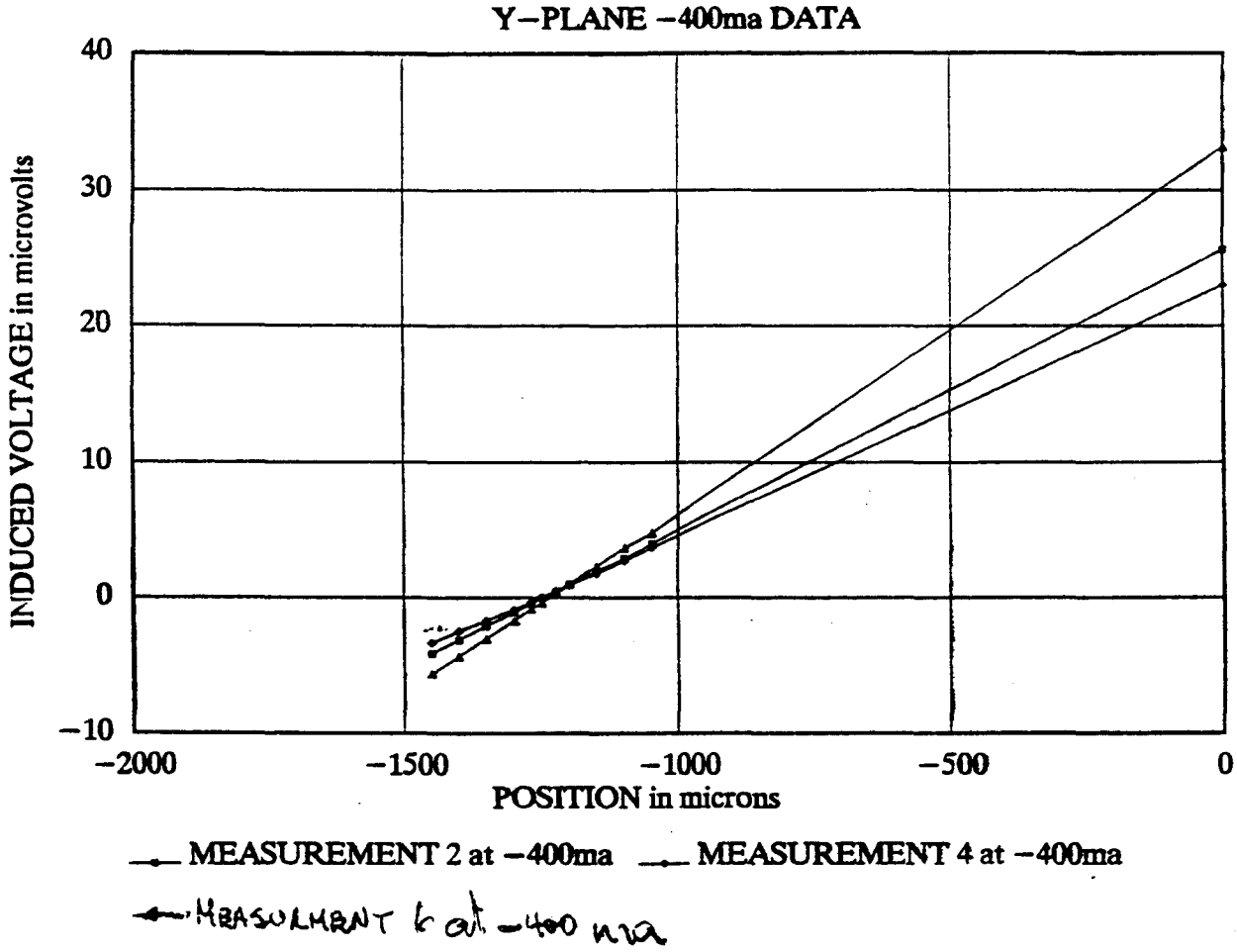
MEASUREMENT 1 at +400ma MEASUREMENT 3 at +400ma

MEASUREMENT 5 at +400ma

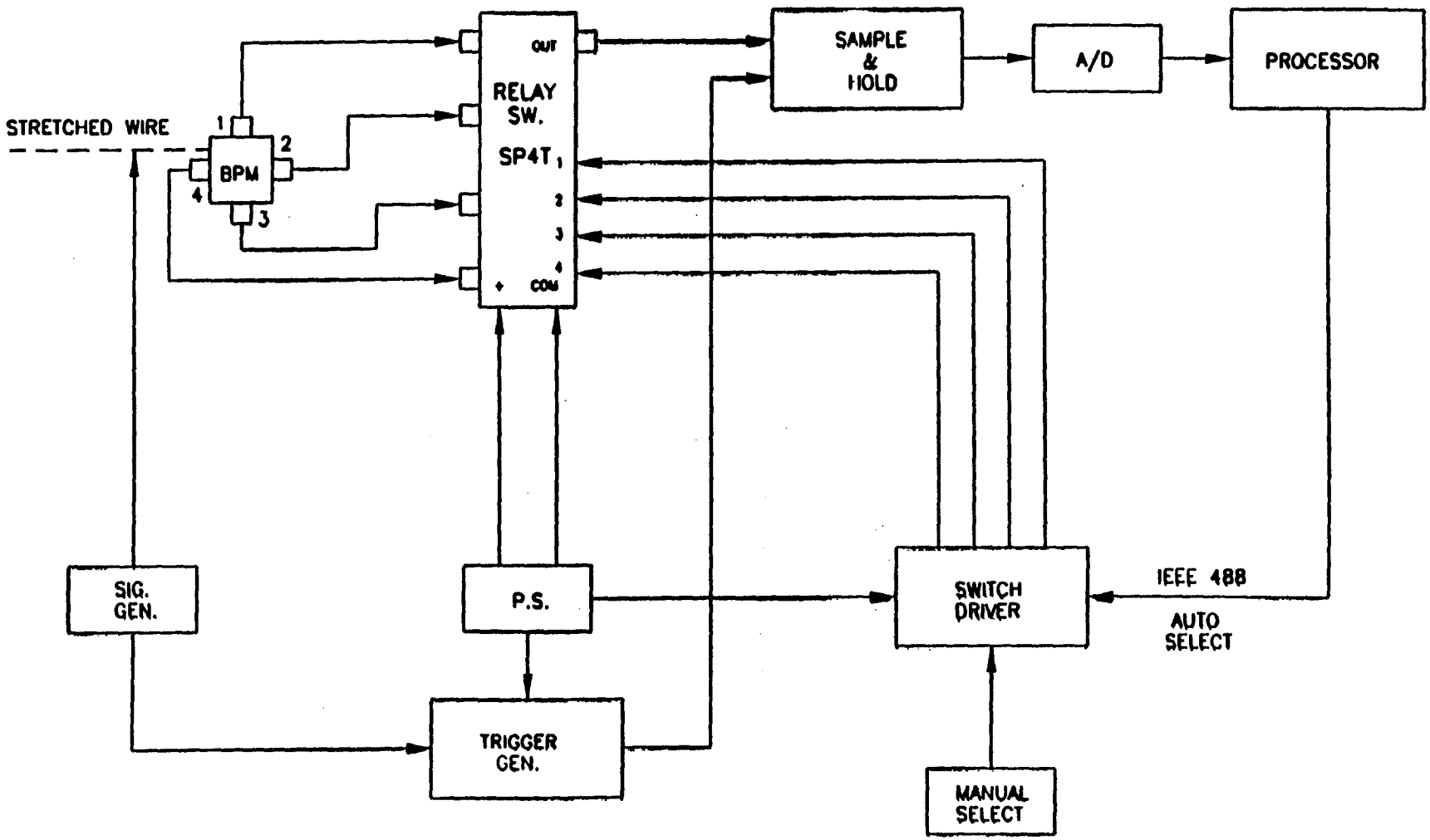
MCAS–SC MAGNET WARM MEASUREMENTS



MCAS–SC MAGNET WARM MEASUREMENTS



BPM TEST SET

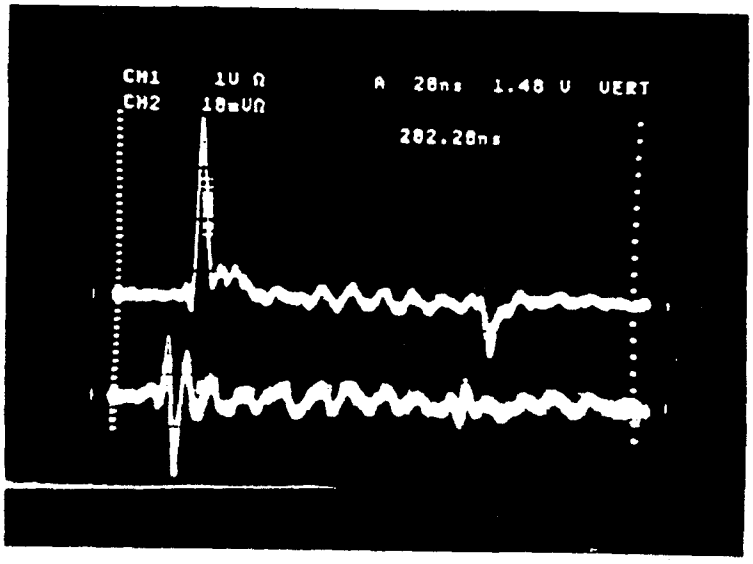

STRETCHED WIRE
BPM
1
2
3
4
RELAY SW.
SP4T
OUT
1
2
3
4
+
COM
SAMPLE & HOLD
A/D
PROCESSOR
SIG. GEN.
P.S.
TRIGGER GEN.
SWITCH DRIVER
IEEE 488
AUTO SELECT
MANUAL SELECT

PRELIMINARY BPM TEST 7/7/93

CCL MAGNET - PRELIMINARY BPM TEST.

INPUT SIGNAL: 20ns PULSES AT 10KHz and 1.5V AMPLITUDE.

OUTPUT: BPM DETECTOR A RESPONSE



CCL MAGNET - BPM TEST 7/7/93
TOP: INPUT SIGNAL
BOTTOM: BPM DET. OUTPUT A

VIBRATING WIRE SYSTEM FOR FOR SPOOL FIDUCIALIZATION

1. OBJECTIVE

- DETERMINE THE MAGNETIC CENTERLINE OF SPOOL SEXTUPOLE MAGNETS.
- DELIVER THE COORDINATES OF THE MAGNETIC CENTER TO FIDUCIALS.
- DETERMINE THE ELECTRIC CENTERLINE OF SPOOL BPMS.
- DETERMINE THE COORDINATES OF THE ELECTRIC CENTERLINE RELATIVE THE MAGNETIC CENTERLINE.

2.CONCEPT

- SINGLE MOVING STRETCHED WIRE TECHNIQUE.

3.MAJOR SYSTEM COMPONENTS

- TWO XYZ MOTION SYSTEMS WITH HORIZONTAL AND VERTICAL CAMERAS.
- TWO VIBRATION TRANSDUCERS.
- TWO MOTORIZED ROTARY STAGES.
- A FORCE TRANSDUCER
- ACCELEROMETERS

4.PRELIMINARY ANALYSIS

- MAX. TENSION FOR A 6mil WIRE T = SA = 7.46 Kg.

- THE FUNDAMENTAL FREQUENCY : $f = (1/(2D))\sqrt{T/\mu}$ = 19Hz

- THE SAG AT THE CENTER OF THE SPOOL IS: $dy = \vartheta \cdot \frac{X^2}{8T}$ = 844 um

AN ALTERNATE METHOD FOR SAG COMPENSATION IS THE DESY METHOD.

- NOISE REDUCTION IS ACHIEVED BY THE USE OF A LOCK IN AMPLIFIER.

- SEISMIC VIBRATIONS ARE DETECTED BY ACCELEROMETERS.

- EARTH'S MAGNETIC FIELD EFFECTS ARE DETERMINED BY DRIVING THE MAGNET'S COIL IN REVERSE DIRECTION.

- COLD MASS VIBRATION IMPACT WILL BE DETERMINED BY ENERGIZING THE SYSTEM WITH THE WIRE IN A NON VIBRATING MODE. THE FREQUENCY AND AMPLITUDE OF THE INDUCED VOLTAGE DUE TO VIBRATION WILL BE DETERMINED.

SPOOL SPECIFICATIONS

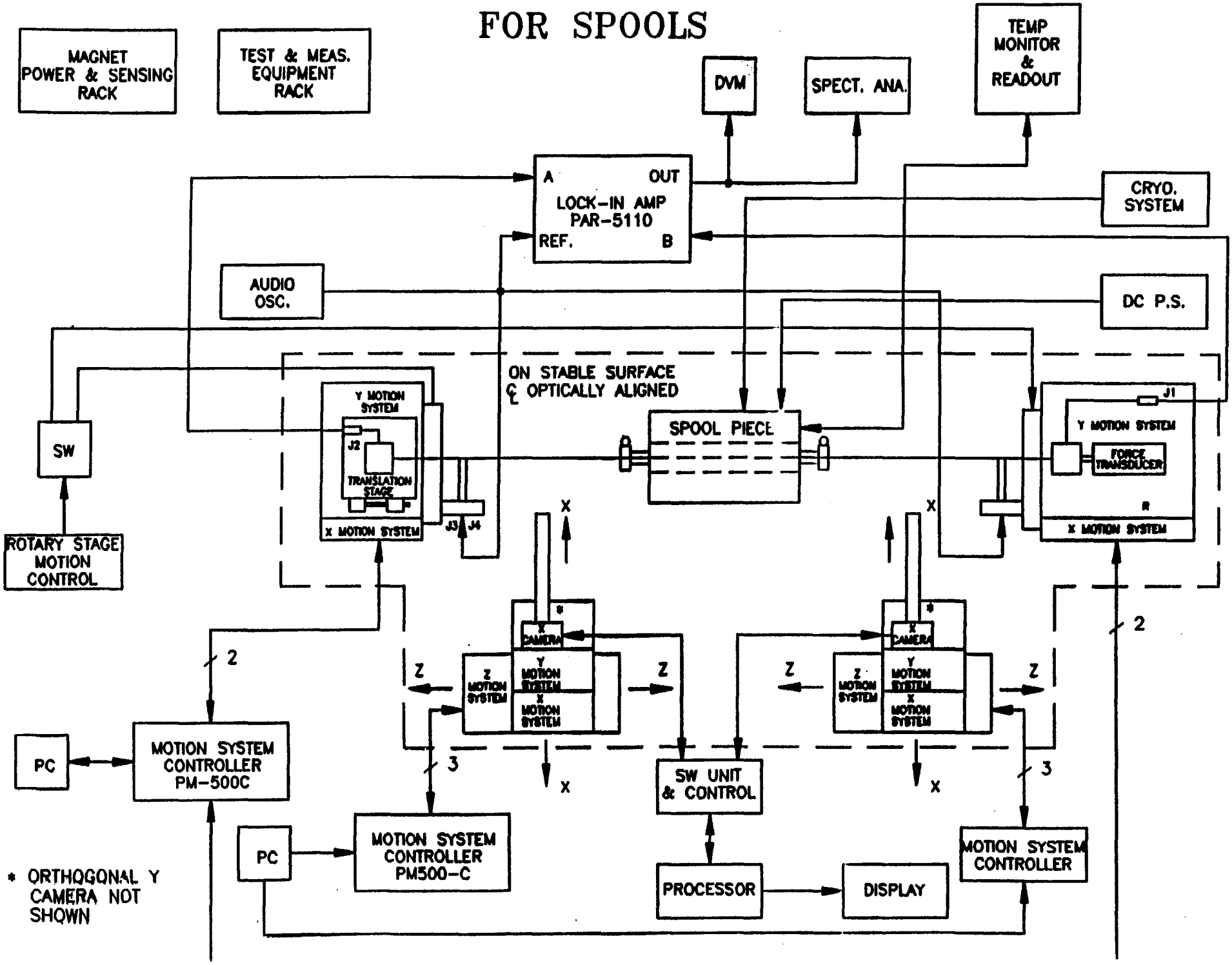
TEST SET UP DIMENSIONS

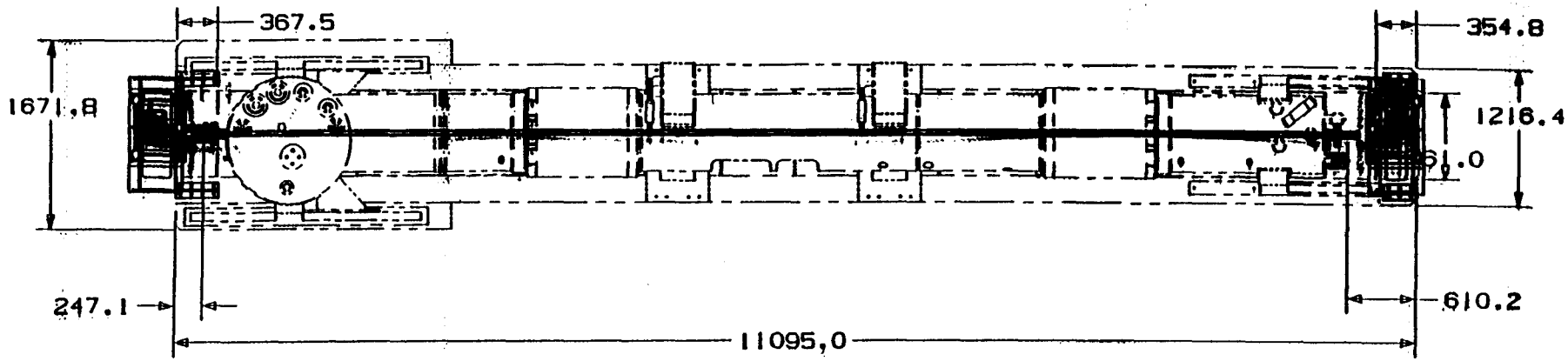
- SPOOL WITH END CANS: 10.019 m
- STAND: 11.095 m
- MU TUBE SHIELD DIA.: 10 mm
- STRETCHED WIRE LENGTH: 12 m (ESTIMATE)

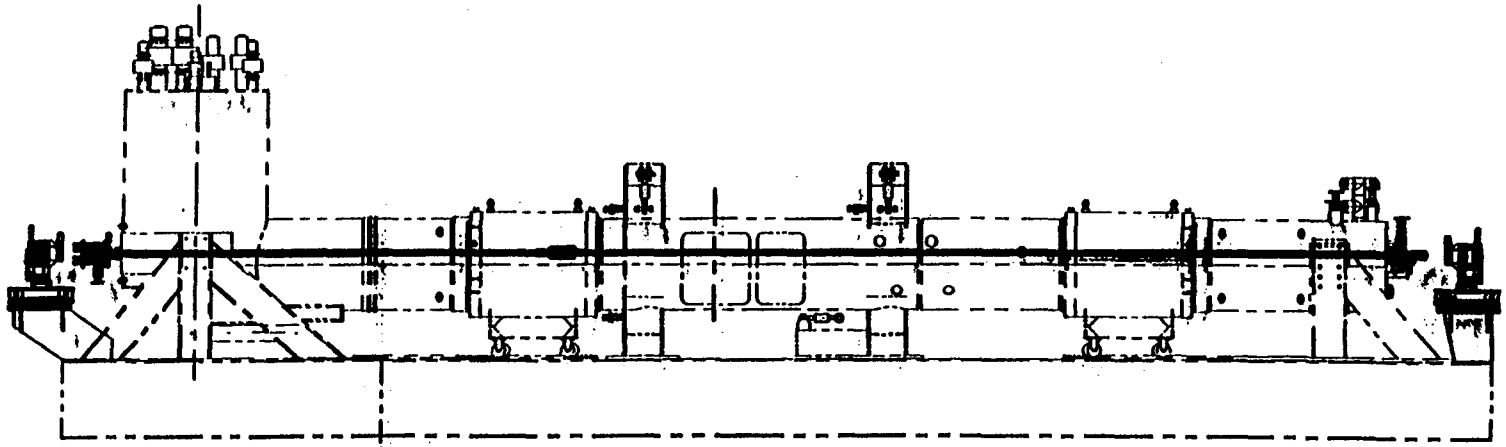
REQUIRED ACCURACIES

- BPM ELECTRIC CENTER relative to magnetic center: 1000 microns
- BPM ELECTRIC CENTER relative to primary fiducial: 200microns
- SEXTUPOLE MAGNETIC CENTER relative to primary fiducial: 200 microns
- MAGNETIC CENTER OF ALL OTHER MAGNETS RELATIVE TO SEXTUPOLE MAGNETIC CENTER: 1000 microns.

STRETCHED WIRE SYSTEM FOR SPOOLS




367.5
354.8
1671,8
1216.4
61.0
247.1
610.2
11095,0



930513

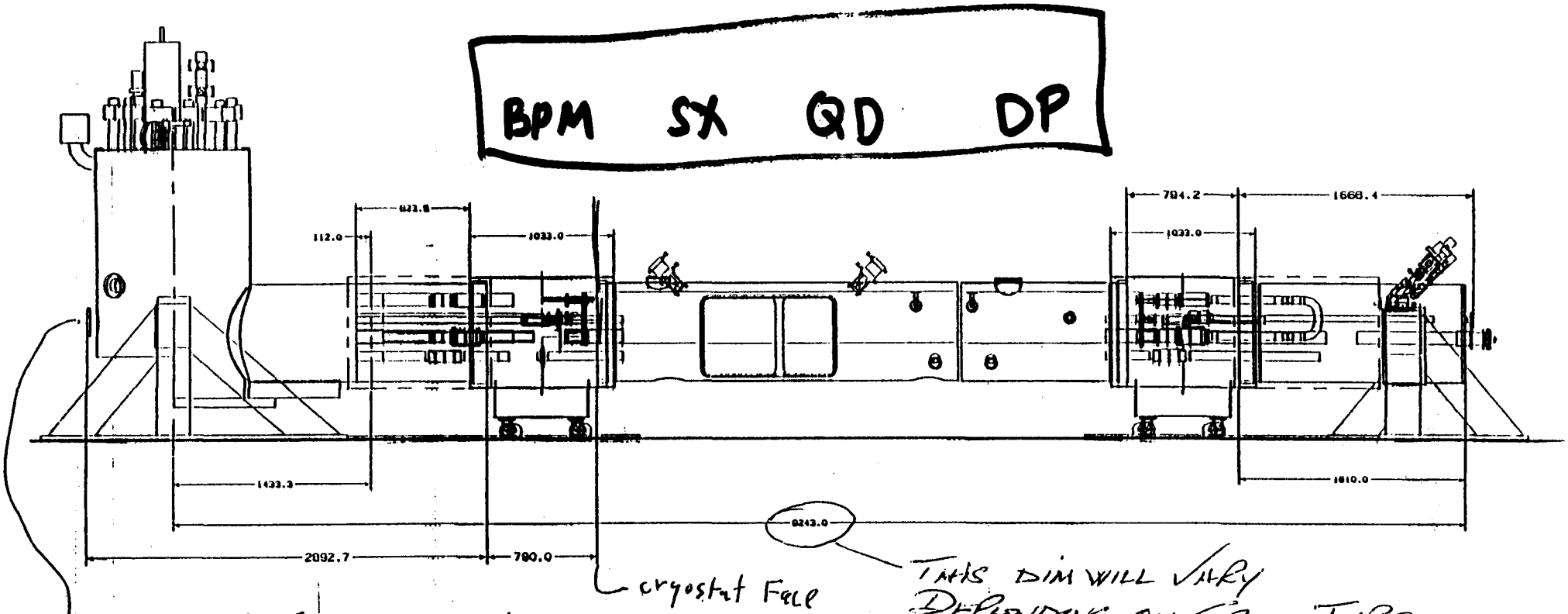
SX - BPM - spool piece Alignment
MTG May 13, 1993

Mike I. GREEN

1. FEASIBILITY
2. THEORY
3. HARDWARE
4. SOFTWARE
5. Cost ESTIMATES
   - Instrumentation
   - software
   - SYSTEM
   - MEASUREMENTS
6. SCHEDULE
7. PRO'S CON'S

To Mike Green
From Dave Powell
3/24/93

Warm/Cold Correlations



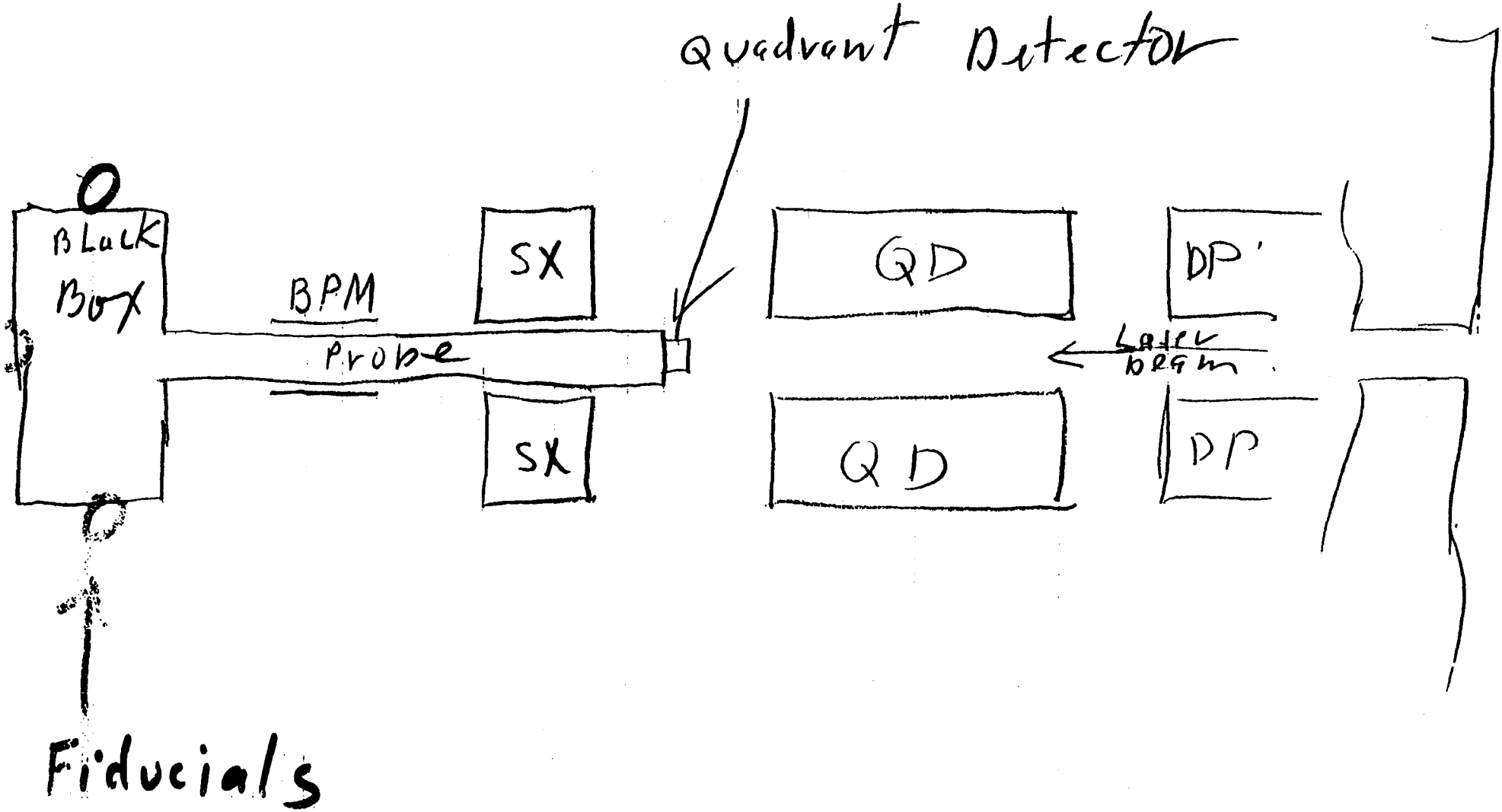
THIS DIM WILL VARY DEPENDING ON SPOOL TYPE
this is for collider SPR ANX

BEAM TUBE I/DIA. 1.640. INCHES
J.S. – ID of WF ~ 1.25" 930324

Philosophy

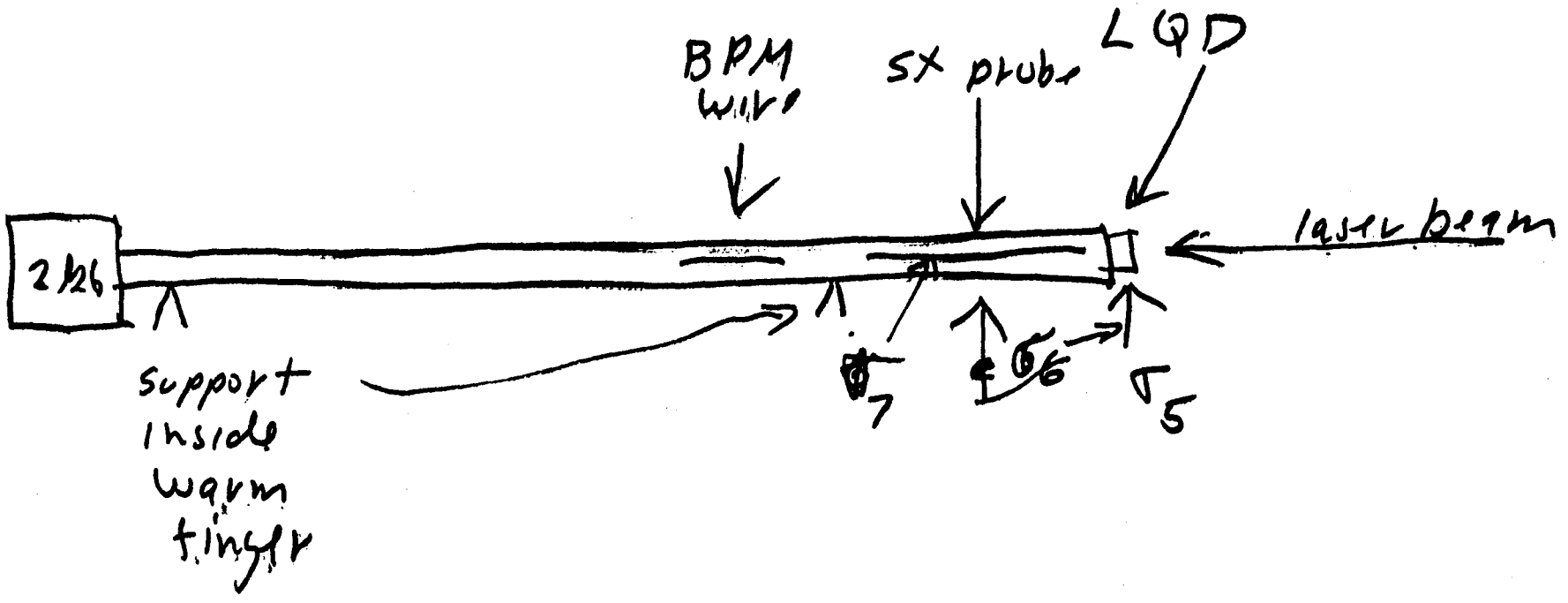
Calibrate Position

1. calibrate axis of SX Probe coils w/r/t Mounting Flange
2. ditto BPM wire
3. Measure SX Magnet axis w/r/t axis of SX Prob.
4. Measure/calibrate BPM w/r/t BPM probe wire.



T. Green 93 03 11

ERROR BUDGET



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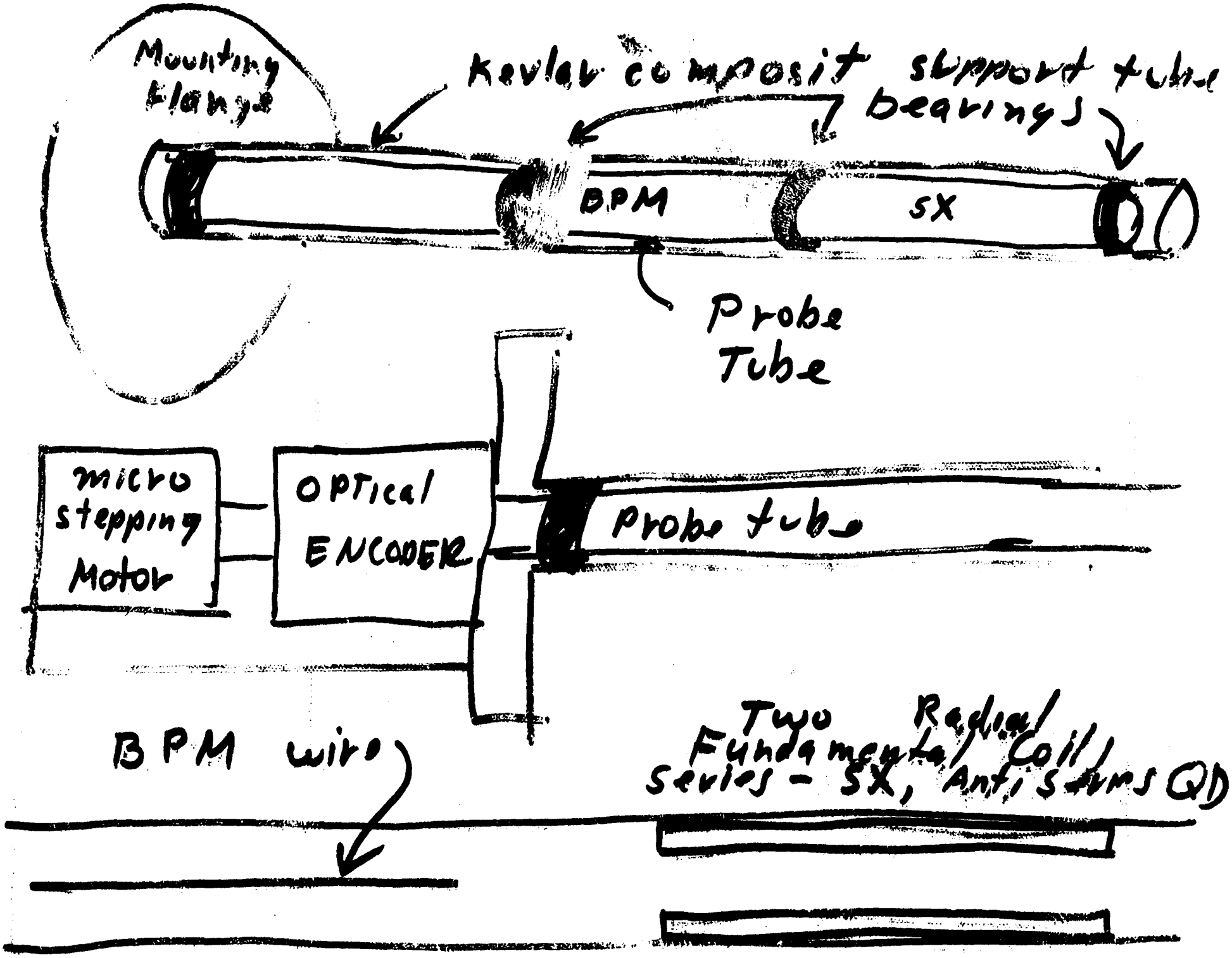
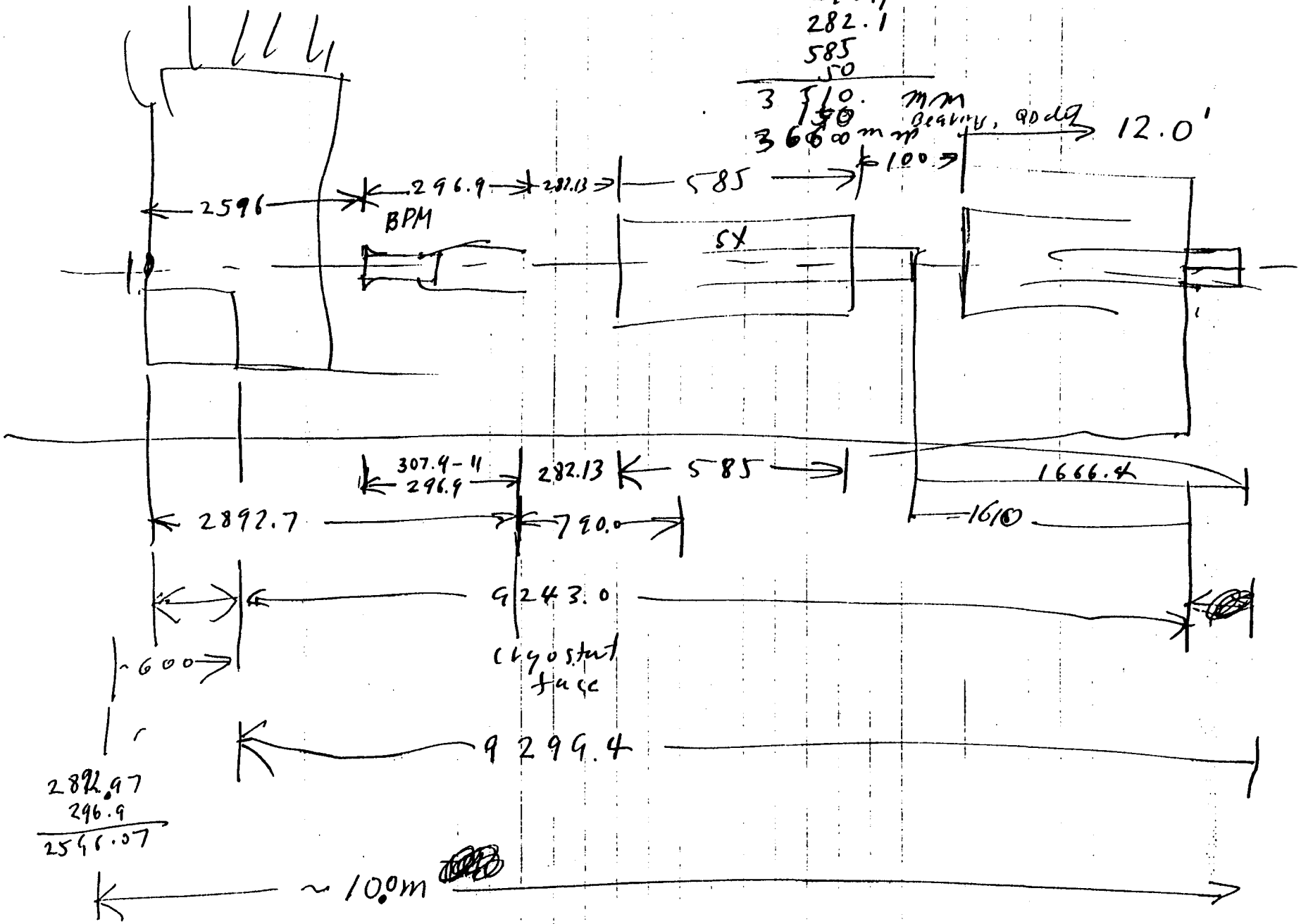

Mounting flange
Kevlar composit support tube
bearings
BPM
SX
Probe Tube
micro stepping Motor
OPTical ENCODER
Probe tube
BPM wire
Two Radial Fundamental Coil series - SX, Anti SXMS QD

296.9
282.1
585
50
3510. mm
150
3660 mm



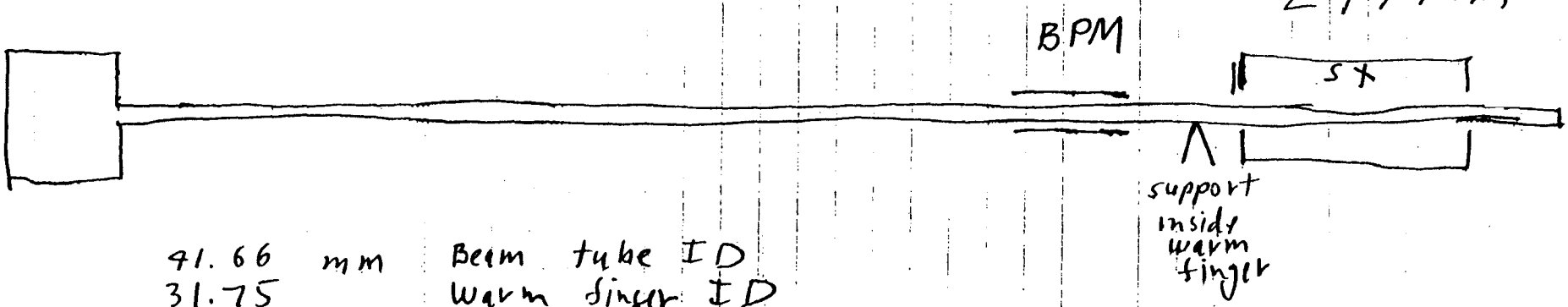
Some distances + dimensions

$\frac{585}{2} = 292.5$

3660.0	To end of Probe (bearing, Quadrant detector)
3510.0	To end of SX coil of probe
3460.0	To end of SX magnet
3167.5	To middle of SX
2875.0	To beginning of SX
2825.0	To beginning of SX coil of probe
2750.0	bearing and support
2592.9	To end of BPM
2444.45	? To middle of BPM
2296.0	To beginning of BPM
10,000.0	Warm Finger length

3460
292.5
3167.5
292.5
2875.0

2875.0
282.1
2592.9
296.9
2296.0
2592.9
2 | 4888.9
2444.45



41.66	mm	Beam tube ID
31.75		Warm finger ID
? 25.0		Probe tube OD

The complex potential is defined as

(1) $F(z) = A(z) + i\,V(z)$ (TM)

where

(2) $z = x + iy = re^{i\theta}$; $i^2 = -1$

$A(z) \equiv$ Vector potential

$V(z) \equiv$ Scalar potential

The Complex field

(3) $B = B_x + i B_y$

and is calculated from the complex potential by

(4) $B = -\dfrac{dF}{dz} = -F'$

The complex potential can be expanded in a Taylor series about any point P

(5) $F(z) = \sum_{n=1} F_n \left(\dfrac{z}{R}\right)^n$

where R is called the reference radius.

$n = 1 \Rightarrow$ dipole, etc

The Taylor series for the complex field

(6) $B = -\dfrac{dF}{dz} = -\sum_{n=1} \dfrac{n F_n}{R}\left(\dfrac{z}{R}\right)^{n-1}$

or

(7) $B = \sum_{n=1} C_n \left(\dfrac{z}{R}\right)^{n-1}$

(8) where $C_n = -\dfrac{n F_n}{R} = B_n + i A_n$

where:

$B_n \equiv$ real multipole component of the field

$A_n \equiv$ imaginary (Skew) component of the field.

and also from 8

(9) $$F_n = -C_n \frac{R}{n}$$

For a pure sextupole $(n=3)$

(10) $$F(z) \Rightarrow F_3 \left(\frac{z}{R}\right)^3$$

and if there is an axis offset

(11) $$F(z+\Delta z) \rightarrow F_3 \left(\frac{z+\Delta z}{R}\right)^3$$

(12) $$= \frac{F_3}{R^3} z^3 + \frac{3F_3}{R^3} z^2 \Delta z + \frac{3F_3}{R^3} z \Delta z^2 + \frac{3F^3}{R^3} \Delta z^3$$

Ignoring higher order terms of Δz

(13) $$F(z+\Delta z) \Rightarrow \frac{F_3}{R^3} z^3 + \frac{3F_3}{R^3} z^2 \Delta z$$

and the complex field becomes

(14) $$B = -\frac{dF}{dz} = -\frac{3F_3}{R^3} z^2 - \frac{6F_3 z \Delta z}{R^3}$$

and substituting from 9

(15) $$B = -\frac{3z^2}{R^3}\left(-C_3\frac{R}{3}\right) - \frac{6z\Delta z}{R^3}\left(-C_3\frac{R}{3}\right)$$

(16) $$B = \frac{C_3}{R^2}z^2 + \frac{2C_3}{R^2}z\Delta z$$

But we also have Taylor Series

(17) $$B = C_1 + C_2\frac{z}{R} + \frac{C_3 z^2}{R^2} + \dots$$

and equating terms linear in z

(18) $$\frac{C_2}{R} = \frac{2C_3\Delta z}{R^2}$$

or

(19) $$C_2 = \frac{2C_3\Delta z}{R}$$

But $C_n = B_n + iA_n$

(20) $$B_2 + iA_2 = \frac{2(B_3 + iA_3)}{R}(\Delta x + i\Delta y)$$

(21) and if we assume that $A_3 \ll B_3$, ie, the Sextupole phase is aligned, then

(22) $$\Delta x + i\Delta y = \frac{RB_2}{2B_3} + i\frac{R}{2}\frac{A_2}{B_3}$$

then

(23) $$\Delta x = \frac{RB_2}{2B_3}, \quad \Delta y = \frac{R}{2}\frac{A_2}{B_3}$$

SX & BPM Design with Issues

Concerns

150/1 Probe Aspect ratio — Wet noodle?

Probe vibrations
Audio noise — resonant frequencies
cryo fluids — Beam pipe transmission
rotation induced

Probe "set" — Temperature & Humidity & time

Drive end support
How to do reproducibly
cables & wires
Rigid or "loose" coupling

Warm finger — Non-conductor in region of BPM

EFFECT of three Non-conducting tubes on BPM System

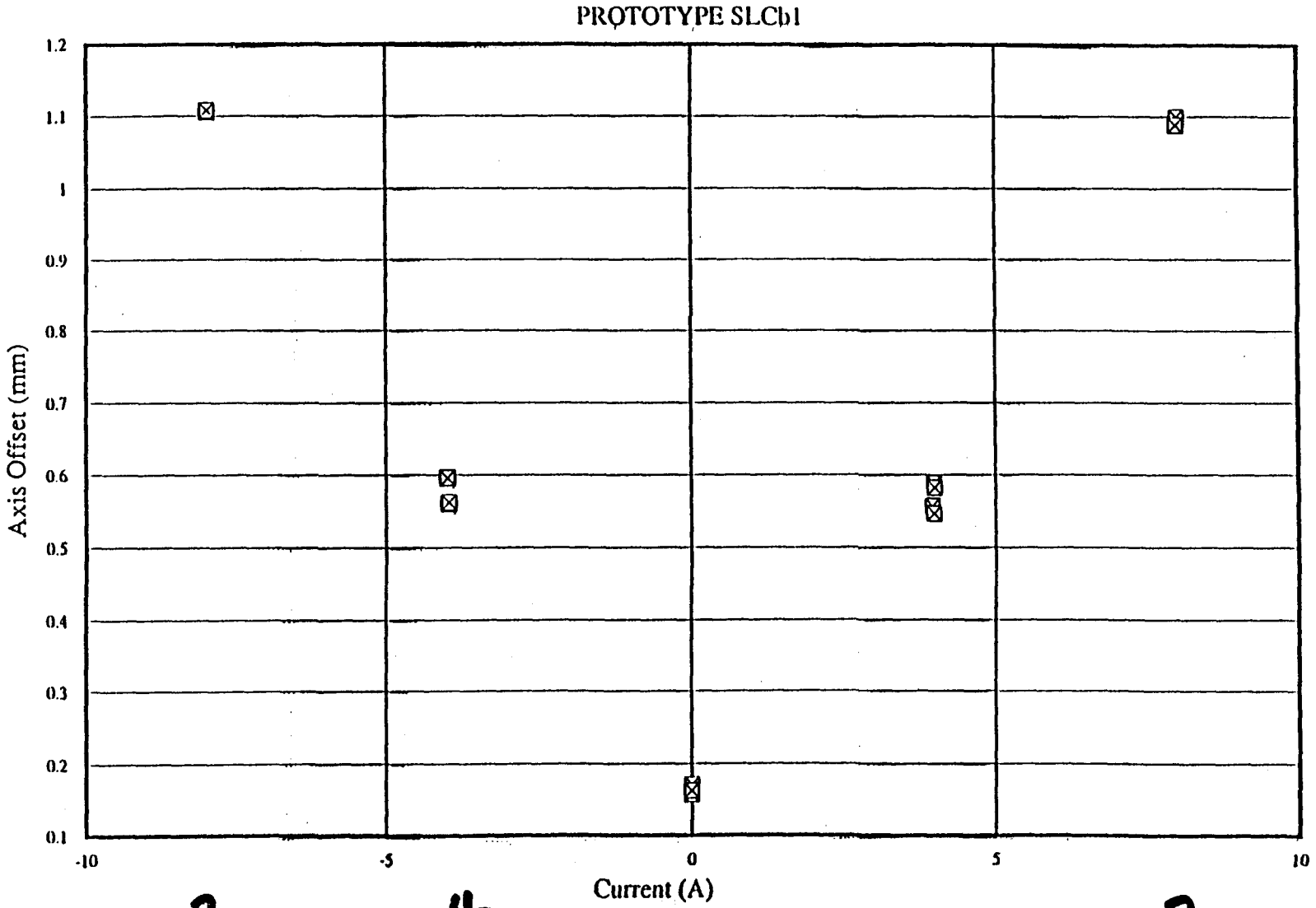
Goodies

Warm finger support between BPM & SX

BPM Rigid wire, rotatable with offset?

SX Probe — not sensitive to other magnets or ambient magnet fields.

SSCL CCL COMB. FUNCT. QUAD



1022a4.wk3
Page 1

2 4 5 4 2

Independent measurements

'SA ' ' Align' ' ' ' '

σ
(μm)

10 Rotating Coil Center Measurement reproducibility

Location of axis of revolution

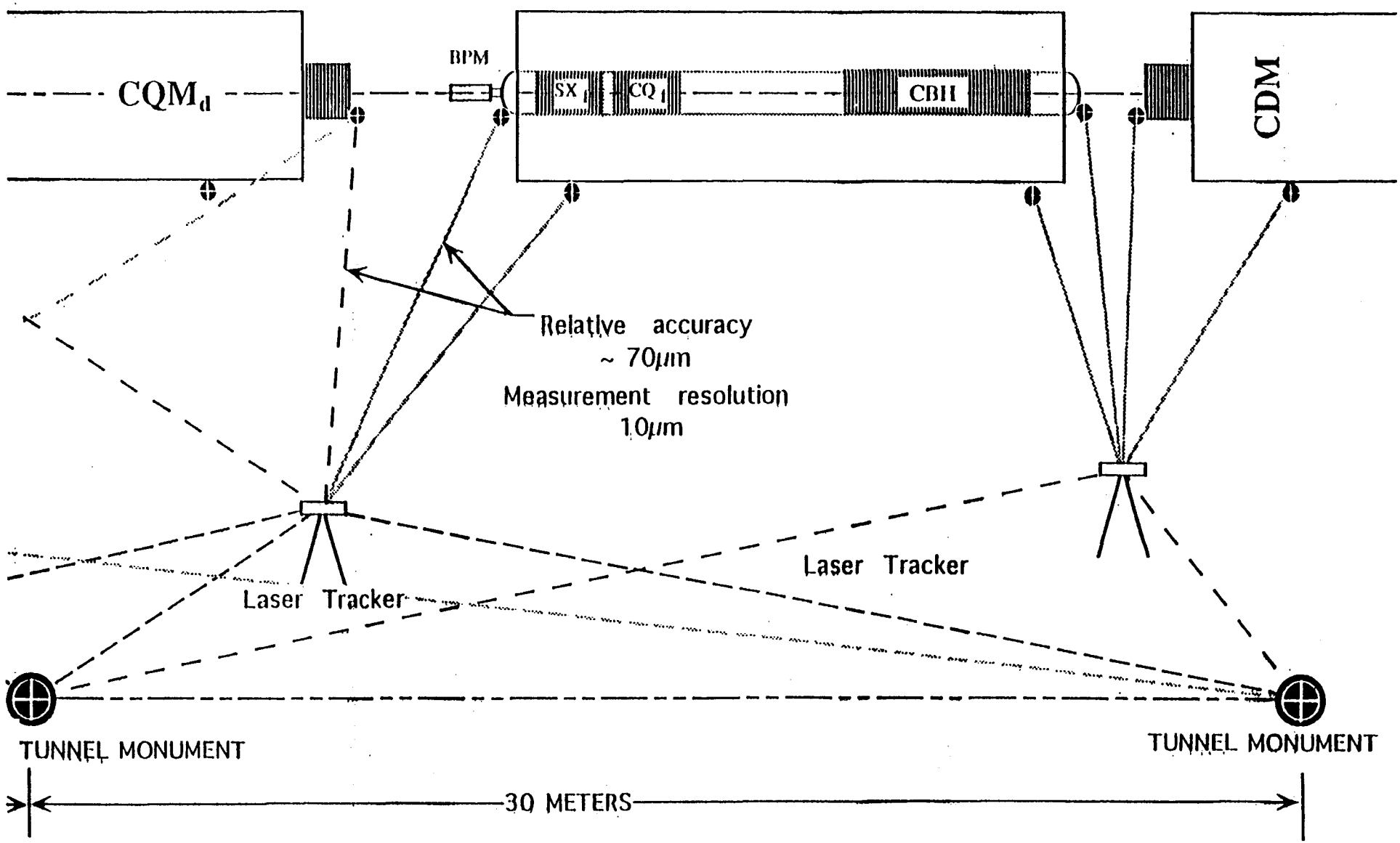
Axis of revolution to Probe fiducials

Probe Fiducials To external Fiducials

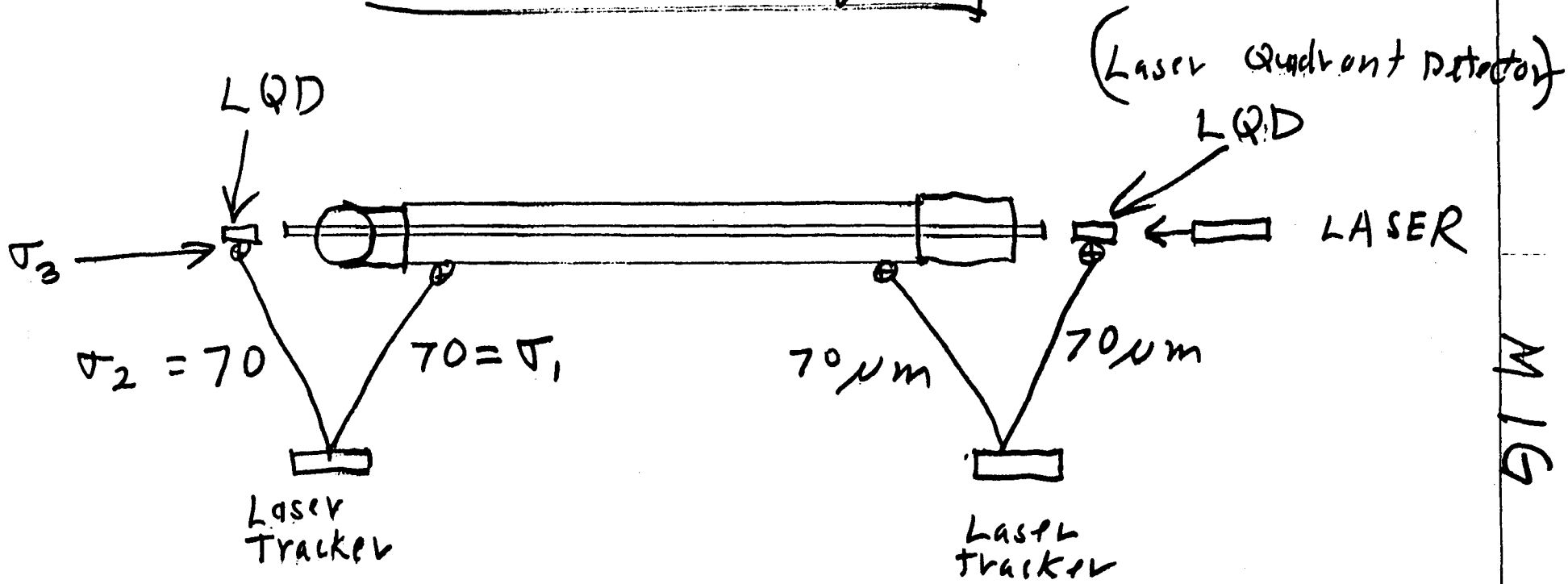
Laser QUADRANT Detector reproducibility

~~Laser Quadrant Detector to Laser~~

Laser beam to Fiducials


CQM$_d$
BPM
SX$_1$
CQ$_1$
CBH
CDM
Relative accuracy
~ 70μm
Measurement resolution
10μm
Laser Tracker
Laser Tracker
TUNNEL MONUMENT
TUNNEL MONUMENT
30 METERS

ERROR Budget



MIG 93051 3A

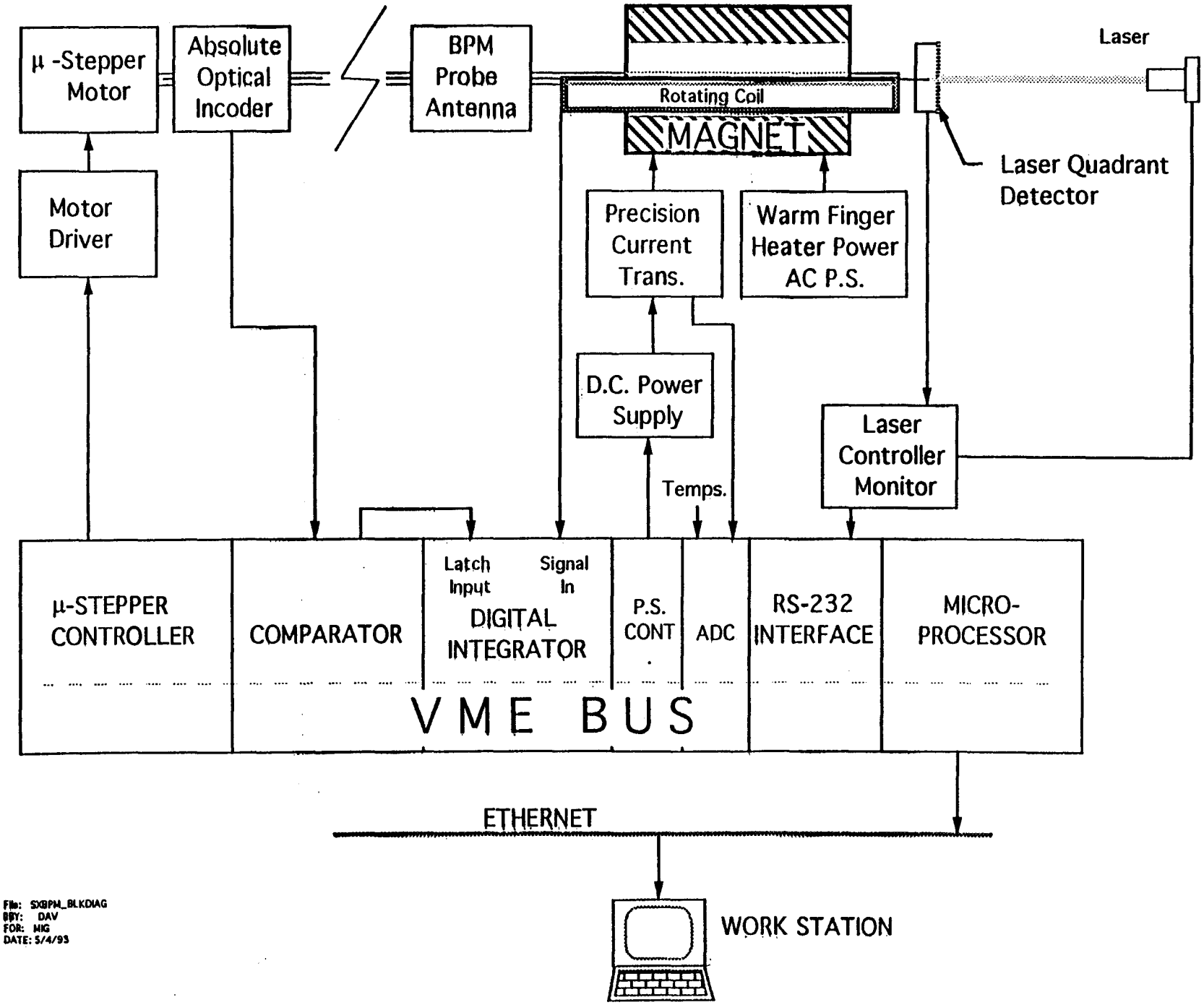
ERROR BUDGET

		μm
σ_1	cryostat to Laser Tracker	70
σ_2	Laser Tracker to LQD	70
σ_3	LQD Accuracy + LT → LQD	20
σ_4	Laser beam stability (5 μm/M/hr/°C)	50 – 100
σ_5	Probe LQD	20
σ_6	LQD → SX	40
σ_7	SX reproducibility	10
	[redacted]	
σ_8	LQD → BPM	40
σ_9	BPM	?

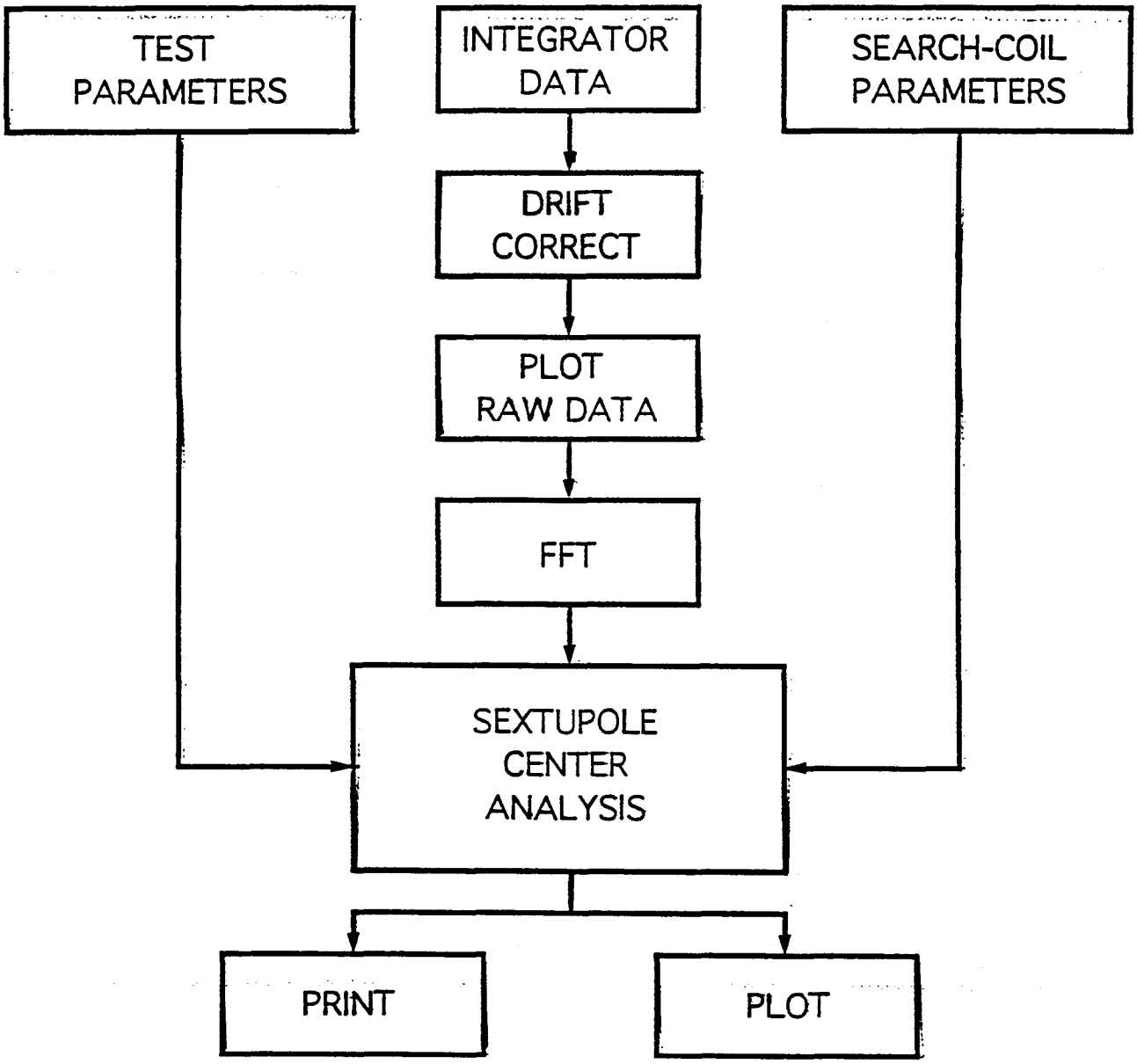
$$\sigma = \left(2\sigma_1^2 + 2\sigma_2^2 + 2\sigma_3^2 + \sigma_4^2 + \sigma_5^2 + \sigma_6^2 + \sigma_7^2\right)^{\frac{1}{2}}$$

$$\sigma = 181\ \mu m$$

M16 9305 13 A2



File: SXBPM_BLKDIAG
BY: DAV
FOR: MIG
DATE: 5/4/93



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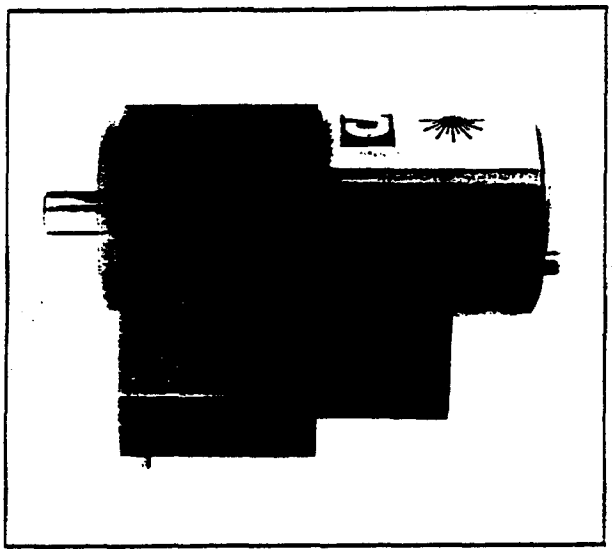
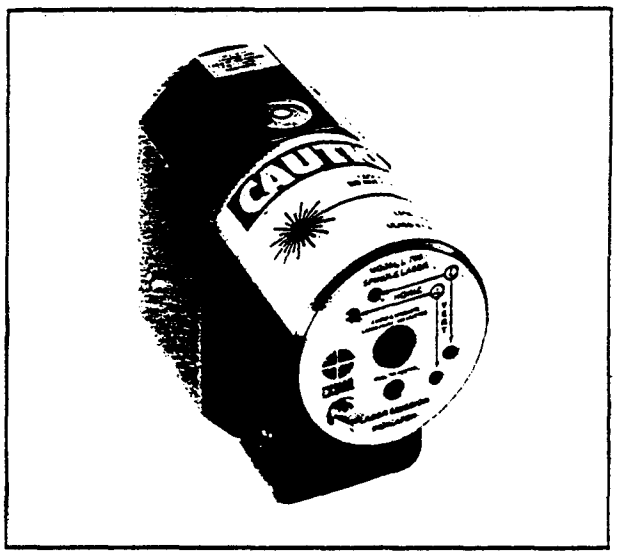
BY: DAV
FOR: MIS
DATE: 5/5/93

Model L-700

Visible Light Spindle Laser





Project Spindle Axis of Rotation
The L-700 Laser was designed to mount in the spindle of a machine tool to project its axis of rotation, allowing rapid and accurate alignment.

User-Adjustable
Vertical and horizontal controls on the front for both angle and centering allow the user to fine-adjust the laser to the spindle's precise axis of rotation.

Visible Light Beam
The low-power, visible light laser beam makes coarse alignment much easier — no viewing devices required.

Battery Operation
The L-700 runs for up to 8 hours on a standard, replaceable 9-volt battery, making the unit completely self-contained.

Compact and Rugged
This compact laser (4"L x 2.9"H x 1.75"W) is made of durable materials to withstand the shop floor environment.

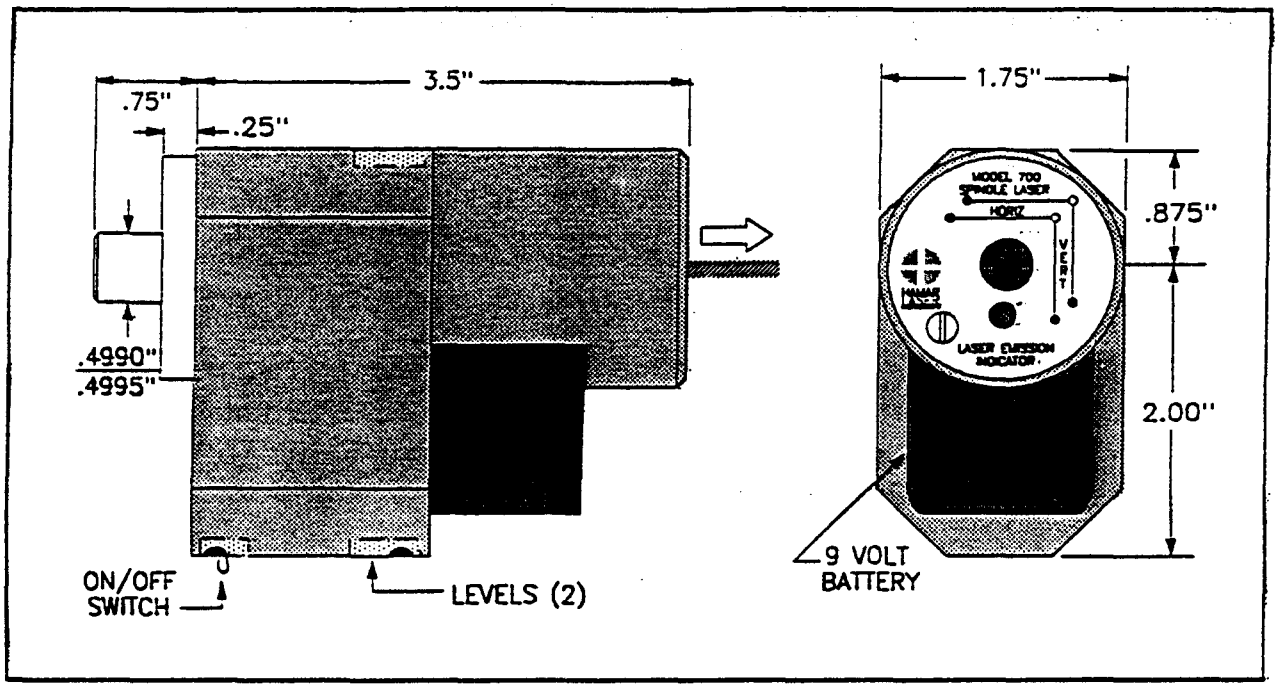
Simple Mounting Hardware
The 1/2" mounting stud can be used with most spindles. Fixtures are inexpensive and simple to design and build — a 1/2" hole reamed square to a face is all that is required to adapt the stud for larger spindles. The mounting stud can also be removed and replaced with custom mounting hardware.

Multiple Applications
The L-700 works with any Hamar Laser target, readout, or interface. It can be used for many types of alignment jobs, including spindle, coupling, and bore alignment, and measuring and correcting the alignment of a workpiece on the machine.

HAMAR LASER®

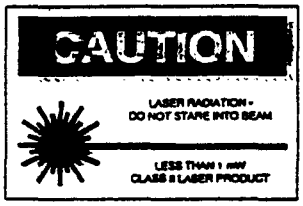
HAMAR LASER INSTRUMENTS, INC.

1047 DANBURY ROAD
WILTON, CT 06897 USA
PHONE: (203) 544-9321
FAX: (203) 544-9326



Applications

- Transfer Line Spindles
- On-Machine Part Alignment
- General Machine Tool Alignment
- Bore Alignment/Measurement
- Printing Press Side Frames
- Cam and Crankshaft Bore Alignment/Inspection
- Motor, Turbine, and Generator Shaft Alignment
- Jigs and Fixtures



This safety label is attached to every L-700 laser.

Specifications

Mounting Dimensions	.500" (12.7 mm) dia. concentric mounting stud, replaceable
Weight	18 oz. (510 g)
Material	Mounting Stud: 440C stainless steel, RC54-58 hardness Case: Aluminum
Power	9 volt battery
Range	30 feet (9 meters)
Beam Centering	.0005" (.013 mm) Center .0005"/ft. (.042 mm/M) Angle
Beam Stability	.0001"/hr/degree F Centering (.002mm/hr/°C) .0001"/ft/hr/deg F Squareness (.005mm/M/hr/°C)
Adjustment Resolution	.0001" (.003 mm) Center .0001"/ft (.008 mm/M) Angle
Adjustment Range	±.010" (.25 mm) Center ±0.25 degrees Angle

U.S. and foreign patented and/or patents pending.
Made in the USA.

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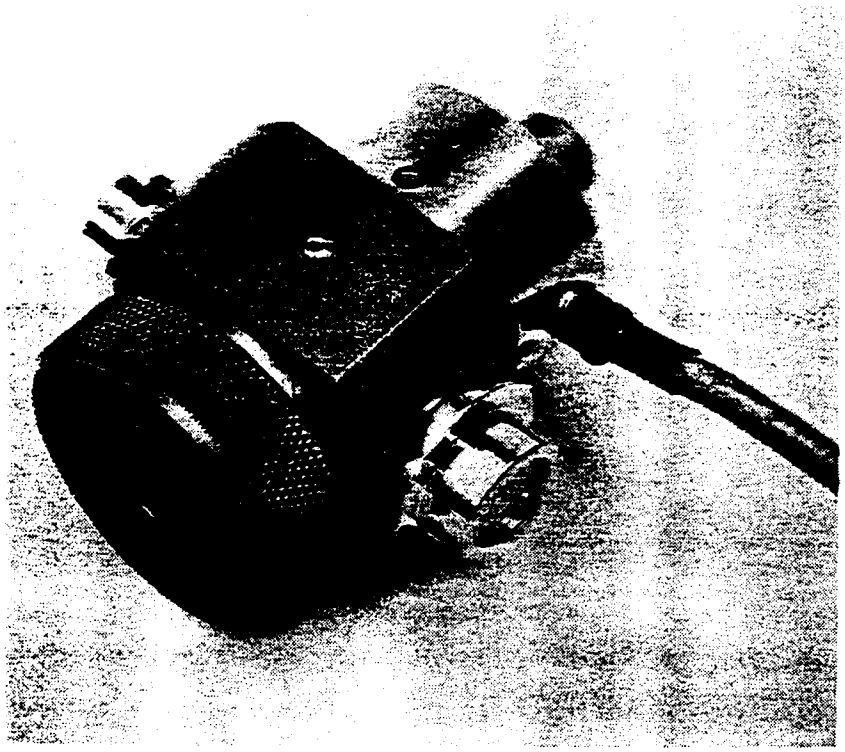
Wilton, CT 06897 USA

MODEL T-212
4-AXIS TARGET



The Model T-212 4-axis Target is the standard target of the Hamar Laser Alignment System and is used to give both two axis centering and squareness (pitch and yaw). It is extremely useful for centering and squaring headstock to tailstock, station alignment, tool station, boring bar supports, etc.

TARGET
The Model T-212 4-Axis Target is the general purpose target of the Hamar Laser target line, developed to meet the needs of most customers.

LASER BORE AND SHAFT ALIGNMENT
Lasers have simplified and increased the speed of bore and shaft alignment. Electronic targets were a great improvement, but these targets only measured bore or shaft lateral position at the target cell plane. The T-212 Target measures both position and squareness in one small self-contained rugged package.

TWO-AXIS CENTERING PLUS SQUARENESS (PITCH AND YAW)
The T-212 is an alignment target which can read both centering and squareness errors. Simply insert the precision lens system (1" focal length) and the target is converted from a centering to squareness mode. The readings in the squareness mode are in a .0001"/inch resolution. Measure both the vertical and horizontal off-center errors and the pitch and yaw errors with the same target.

SIMPLIFIED FIXTURING
The 1/2" diameter stud at the rear of the T-212 allows easy mounting and simplified fixture design. A simple .500" reamed hole square to a face is all that is needed to mount the T-212. Master pallets, face plugs for bores and other fixtures are now very simple and inexpensive to design and build.

COMPATIBLE WITH ALL READOUTS
The T-212 can be used with the R-307 Dual Axis Readout, the R-355 Computer Interface and with future readout designs.

TARGET ACQUISITION DIODE
When used with either the readout and/or interface, a special LED is provided, which lights when the laser beam is on target.

.0001" LEVEL ACCURACY
Readout stability is increased with the T-212 micro-circuitry making tenth-level work easier by the electronic elimination of misleading mechanical and electrical readings.

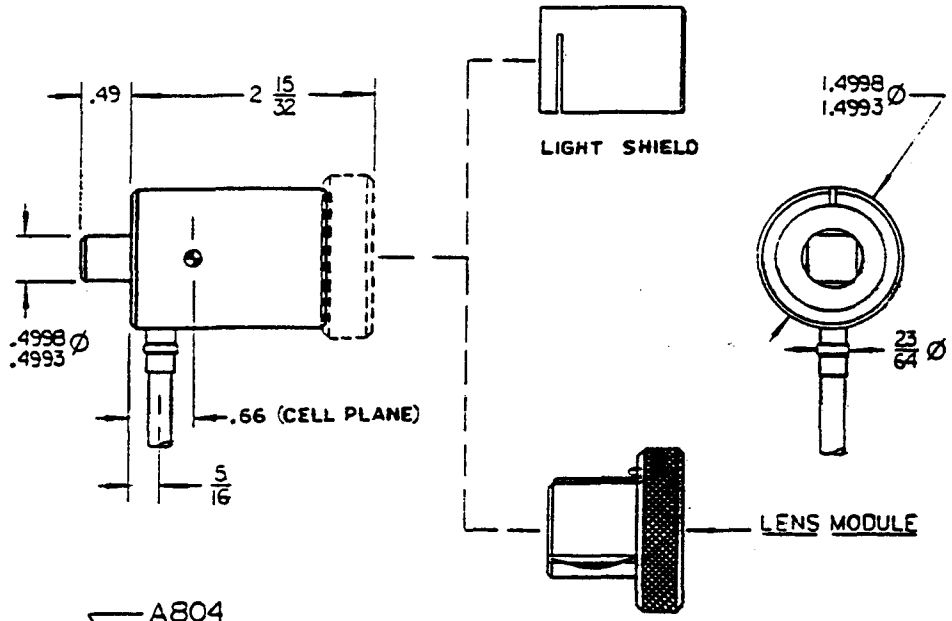
HAMAR LASER

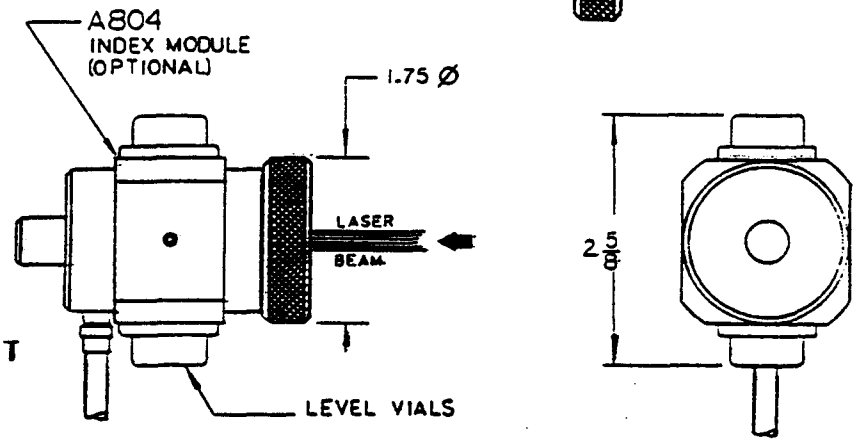
HAMAR LASER INSTRUMENTS, INC.

1047 DANBURY ROAD
WILTON, CONNECTICUT 06897
(203) 544-9321

APPLICATIONS

1. Machine tools
2. Lathe alignment
3. Boring bar alignment
4. Printing press side frames
5. Station alignment
6. Bore alignment/measurement
7. Motor, turbine, generator shaft alignment
8. Part and assembly alignment
9. Jigs and fixtures
10. Aerospace tooling & fixturing
11. Petrochemical — motors, compressors, blowers





T-212
FOUR AXIS TARGET

TARGET SPECIFICATIONS

SIZE:	See Drawing	**SENSITIVITY:**	.0001"
MOUNTING DIMENSIONS:	1.500" O.D. with .500" dia. concentric mounting stud	**REPEATABILITY OF LENS SYSTEM:**	±.0001"/inch
WEIGHT:	14 oz.	**RANGE:**	±.075" single axis; ±.050" combination both axis
MATERIAL HARDNESS:	440C stainless Rockwell RC55-60	**LINEARITY:**	Within 5%
TARGET CELL CONCENTRICITY:	.0005" T.I.R. to Stud of Target	**CALIBRATION:**	Indicated displacement within 5% of mechanical displacement @ .025"
LENS AXIS SQUARENESS:	.0005"/inch T.I.R. to Face of Target	**CORD DIMENSIONS:**	Target to connector 10 ft.

M1G 930513

Instrumentation Costs

UNIX Workstation	7,000
7 VME Modules	35,000
LASER System	25,000
PSupply	1,000
current Monitor	1,000
SX Probe Electrical	10,000
Probe Mechanical	20,000
	$99,000

Software

Based on existing system?
Hence

4 Man Weeks
$30/hr * 40 hrs/week * 4 weeks = $4,800

If not based on existing system $80,000

Assemble/test/Cal/debug $10,000
(8 MW)

M16 930513

Measurement Cost

Align Laser	4MH
Determine probe Position	1 MH
Measure	0.1 MH
Put away	0.4 MH
	5.5 MH
	× 30
	$165

Schedule

With existing manpower there is a slim possibility that a prototype system can be developed by 1999 !!!

With Adequate support, prototype system could be debugged and operational within 12 months.

MIG 930513

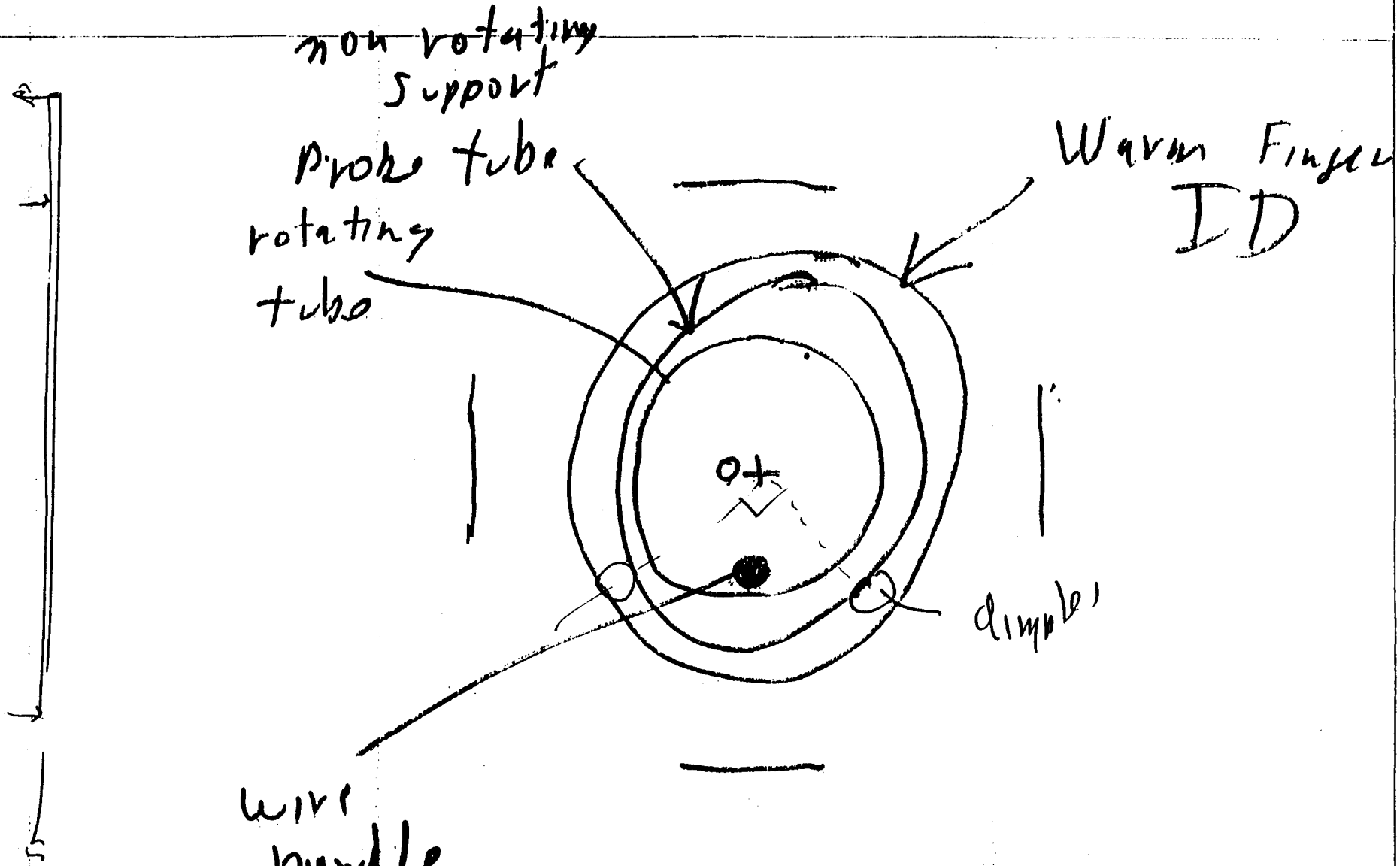
PRO'S

1. Rotating coil only sensitive to sextupole magnet
2. Rotating coil well understood
3. Short Measurement time

CON'S

1) Haven't the faintest idea if BPM measurement can be made inside of warm finger
Are We wasting our time?

2) error budget may be tight



1. Twisted pair from SX probe (#30 wire)
2. 4? wires from quadrant detector
3. Support for probe : Deflecti

42-381 50 SHEETS 5 SQUARE
42-382 100 SHEETS 5 SQUARE
42-389 200 SHEETS 5 SQUARE

MIG 930513 B1

Laser System Costs
(HAMAR)

L700 LASER	7350
T-212 Target (3@ 1500)	4500
R307 readout	1500
R355 computer intf	2745
cal	400
A801 Alignment Fixture	450
L104 stands (2@1070)	2140
L104A screw lift (2@750)	1500
	20585
+	?
	25,000

IMMW - 8 (SSC LAB)

SHORT UPDATE ON THE DANFYSIK MODEL 692 MULTIPOLE MAGNET MEASURING SYSTEM

THIS MEASUREMENT SYSTEM WAS MADE BY DANFYSIK ON BEHALF OF ESRF (EUROPEAN SYNCROTRON RADIATION FACILITY) GRENOBLE, FRANCE - BASED ON THE BENCHES DESIGNED BY CERN FOR MEASURING THE LEP MULTIPOLES.

POUL ABRAHAMSEN

D A N F Y S I K A/S.

Reference list for:

Multipole Magnet Measurement System

Model 692.

Bench # 1 & 2 : European Syncrotron Radiation Facility (ESRF)
Grenoble, France.
Delivered october 1990.
Ref: Marcel Lieuvin.

Bench # 3 : Argonne National Laboratory (ANL)
Advanced Photon Source (APS)
Argonne, Ill. USA.
Delivered september 1990.
Ref: Suk H. Kim.

Bench # 4 : Superconducting Super Collider Laboratory (SSCL)
Dallas, Texas USA.
Delivered january 1993.
Ref: Cosmore Sylvester.

Bench # 5 : Istituto Nazionale di Fisica Nucleare (INFN)
Laboratori Nazionale di Frascati (LNF)
Daphene Project.
Delivered february 1993.
Ref: Claudio Sanelli.

Bench # 6 : Berliner Electronenspeicherring - Gesellschaft
für Syncrotronstrahlung m.b.H.
Berlin, Germany.
Project BESSY II.
Projected delivery: october/november 1993.
Ref: Dieter Krämer.

THE FIRST 3 BENCHES WERE ALMOST IDENTICAL WITH RESPECT TO SOFTWARE AND HARDWARE.

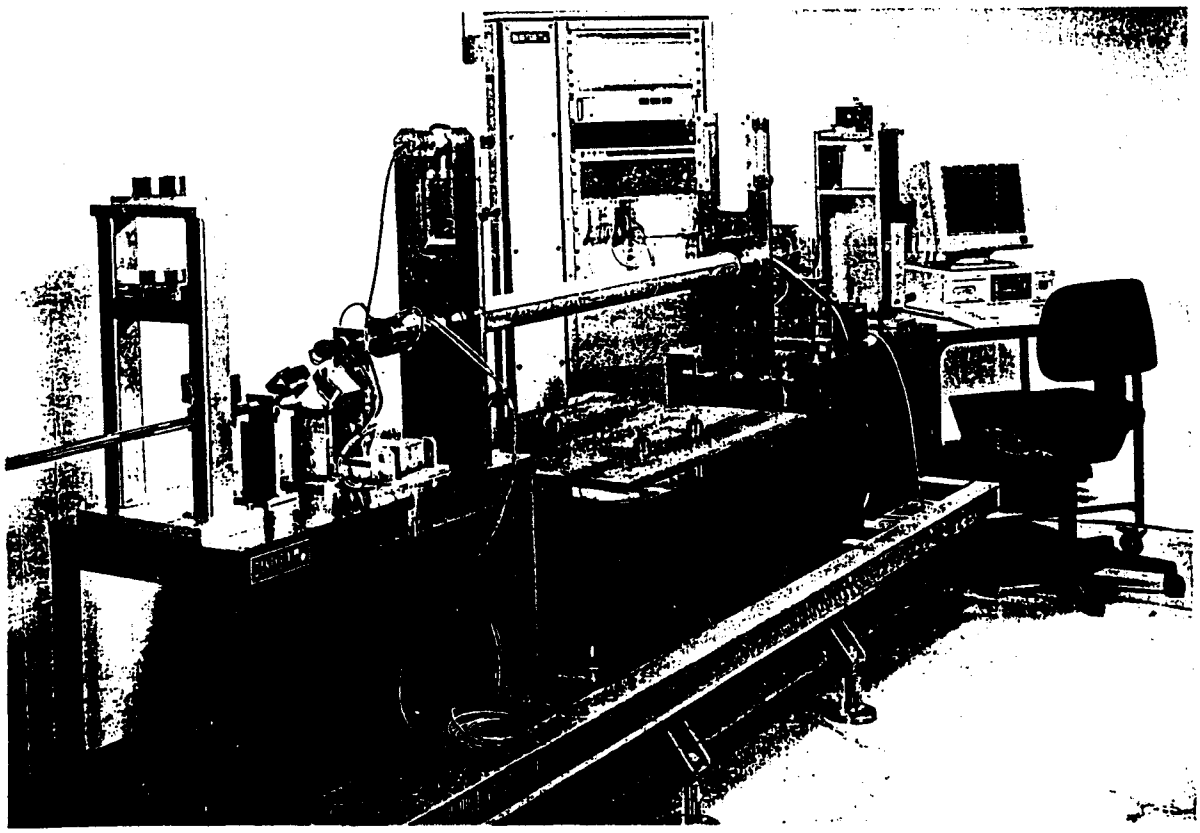
THE NEXT 3 BENCHES DID CONTAIN SOME IMPROVEMENTS - MOST IMPORTANT WAS THE ORIGINAL METROLAB PRECISION DIGITAL INTEGRATOR PDI 5050 REPLACED BY THE NEW VERSION PDI 5150 WITH GAIN CONTROLLABLE FROM THE G64-BUS.

SOFTWARE-CHANGES TAKING ADVANTAGE OF THIS GAINCONTROL WERE IMPLEMENTED. FINALLY HAS AIRCONTROL BEEN MADE AUTOMATIC

APENDIX

DANFYSIK

MULTIPOLE MAGNET MEASUREMENT SYSTEM MODEL 692



The DANFYSIK Multipole Magnet Measurement System, Model 692, is a high precision device for testing magnetic field quality of multipole magnets. Some of its features are:

* Magnetic flux integration using the harmonic coil method
* High resolution and accuracy of amplitude and angle measurement
* Compensating coil for high sensitivity of higher harmonics
* Fully automatic centering and measurement procedure
* Accurate positioning of alignment targets using laser and photo detector
* Power supply controller and magnet current measurement
* Custom designed coil dimensions to match specific magnets
* Design based on CERN (LEP) concept

MULTIPOLE MAGNET MEASUREMENT SYSTEM, MODEL 692

1. INTRODUCTION

The DANFYSIK Multipole Magnet Measurement System, Model 692 is developed for measurement of the strength and quality of multipole magnet fields, for magnetic centering, and for precise positioning of alignment targets on the magnets. The measurement system has been designed with the aim to perform precise, fast and reliable measurements of series of magnets. Care has been taken to ensure that the mechanical constructions have sufficient stability against or is insensitive to vibrations and thermal expansion. With computerized routines for prealignment, harmonic measurement and data analysis, magnetic centering and alignment, the need for operator intervention during the actual measurements and data evaluation is minimized.

The design of the Multipole Mgnet Measurement System, Model 692 is a slightly modified version of that used by CERN for the measurements of the magnetic lenses for LEP.

2. MEASUREMENT PRINCIPLE

The measurement system is based on the "harmonic coil method" in which a mechanically stable cylinder holding the main measuring coil is rotated inside the bore of the magnet. The induced voltage across the coil terminals is sampled and integrated over equally spaced angular intervals. This measurement provides an accurate determination of the integrated field and the magnet center position.

In order to achieve high sensitivity to higher order harmonic components and to reduce influence from mechanical vibrations a compensating coil with a different geometry is mounted on the cylinder. This coil is designed in such a way that a combination (subtraction) of the two coil signals is insensitive to the main and "main-1" harmonic while a high sensitivity of the higher harmonics is maintained.

3. DESCRIPTION

The mechanical layout of the magnet measurement bench is shown in fig.1. It consists of three major subassemblies, rotating coil assembly, magnet positioning system, and alignment system.

3.1 Rotating coil assembly

The rotating coil assembly consists of an epoxy impregnated Kevlar reinforced cylinder with two pick up coils (main and compensation coils) mounted on it. Each coil consists of a wire bundle suspended under spring tension force on two sets of rollers at each end of the coil cylinder. The coils will normally be designed individually for each magnet type to achieve maximum sensitivity. The coil cylinder is supported on air bearings and is rotated during measurements by a DC-motor. Its rotational angle is measured by a high resolution (15 BIT) absolute angular encoder. The encoder signal is used to trigger the integration of the pick up signals.

The coil assembly includes a "touch detector" system for interlock purposes to avoid damage to the coil during handling and operation of the system.

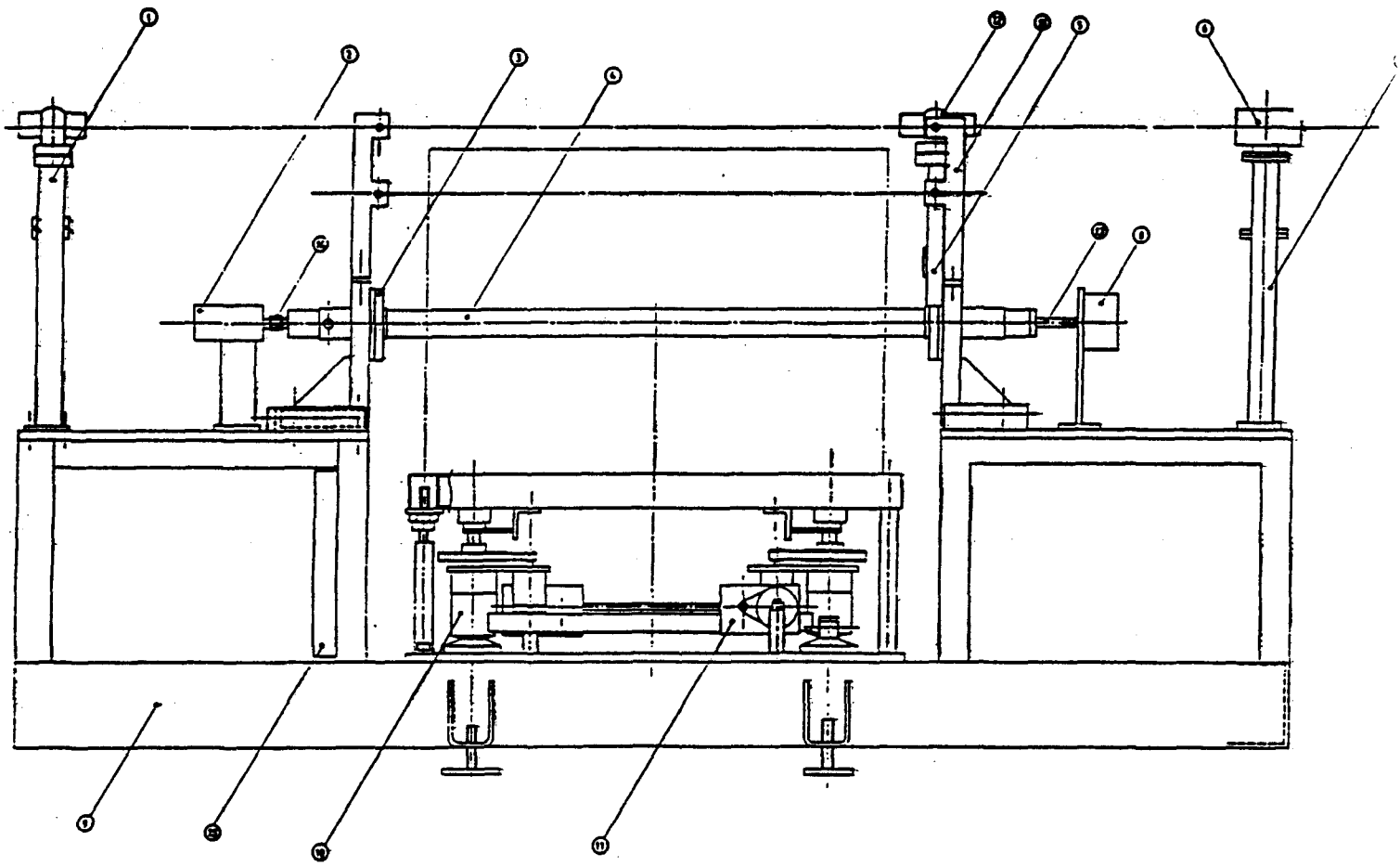


Fig.1. Side view of measurement bench. Rotating coil assembly consisting of measurement cylinder (4), air bearings (3), DC motor (2), and angular encoder (8). Magnet positioning system consisting of magnet support platform, horizontal movement gears and motors (11), vertical movement gears (mounted on air cushions) and motors (10). Alignment system consisting of laser (6), photo detector with Taylor Hobson ball (12), and calibration supports (1,5).

3.2 Magnet positioning system

When mounted on the bench the magnet can be moved by means of five step motors with corresponding gears and power supplies. Horizontal and vertical translation and rotation around three different axes are possible by simultaneous operation of two or three motors. During horizontal movements the magnet is supported on four air cushions to minimize the friction. The resolution of the movements is approximately 1 μ for the horizontal and 0.5 μ for the vertical movements. Position read out for each gear is provided by linear position potentiometers.

3.3 Alignment system

The alignment system consists of a laser, a position sensitive light detector (resolution ± 0.01 mm) mounted in a Taylor Hobson ball, and two electronic inclinometers (sensitivity 0.01 mrad). A calibration device is provided for initial alignment and maintenance checks of the laser. The alignment system is used for prealignment of the magnet before measurement and for final positioning of alignment targets on the magnet yoke.

3.4 Control system and software

The control system is designed to control the measurement sequence, and to provide information to the

operator when his interaction is required. The overall control system structure is illustrated in fig.2. The majority of the operations are controlled by the micro processor in the G64 crate, which is connected to the RS232C serial interface of the PC. The G64 crate contains electronic modules for magnet positioning, magnet measurements and alignment system. The descriptions and functions of the various modules are illustrated in fig 3. The microprocessor receives simple instructions and data from the PC initiating a series of actions, returns data to the PC and acknowledge that the task has been performed. The PC controls the overall magnet positioning, alignment and measurement procedures, it analyses, displays and stores the data. Furthermore, via the IEEE488 bus it controls the (optional) magnet power supply, sets and reads the magnet current from the Ultrastab Current Transducer.

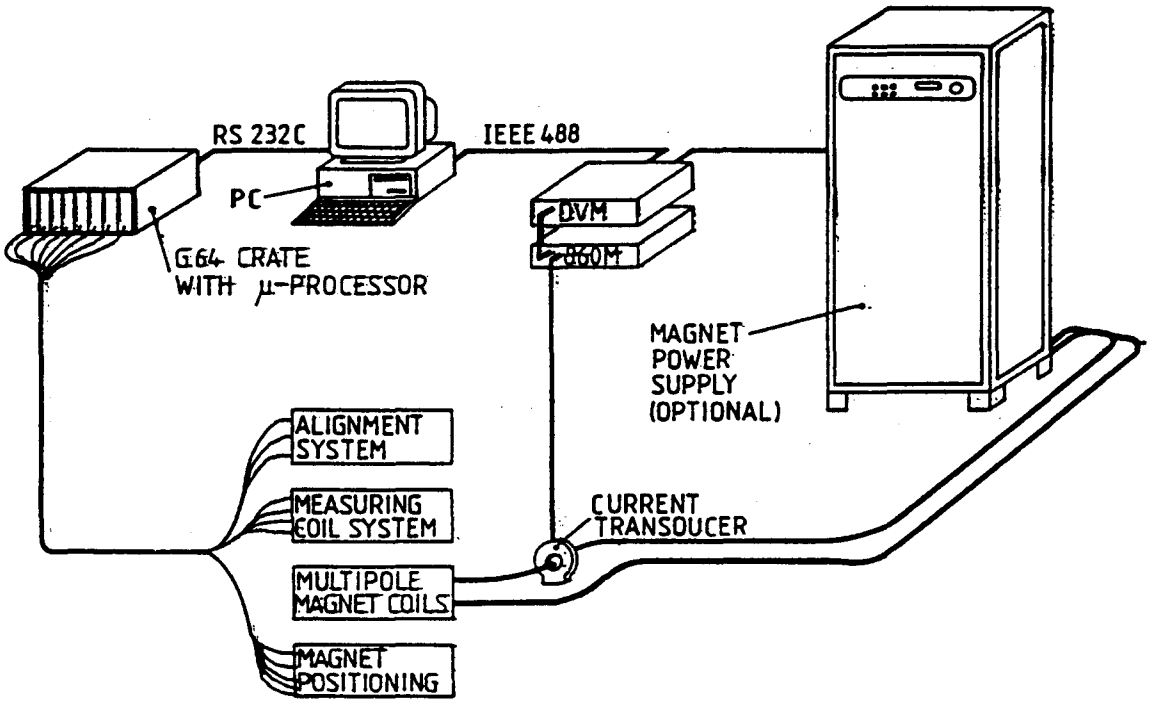


Fig.2. General layout of the control system for the Multipole Magnet Measurement System, Model 692.

4. OPERATION SEQUENCE

A typical measurement sequence will be the following:

1. *Mounting of the magnet, connection of current cables and water cooling. Manual task.*
2. *Prealignment in order to be able to insert measuring coil. Uses inclinometer, laser and photo detector positioned on coarsely mounted target holders. Position reading and motor movements are automatic.*
3. *Magnetic centering performed by consecutive main field measurements and motor movements. Performed fully automatic.*
4. *Measurement of main harmonic and higher order harmonics. Performed by one clockwise and one anti clockwise rotation of the coil. Data automatically transferred to PC, analyzed, displayed and stored.*
5. *Mounting of target holders and level mark in their fixed position using inclinometers, laser beam and photo detector. Manual task.*

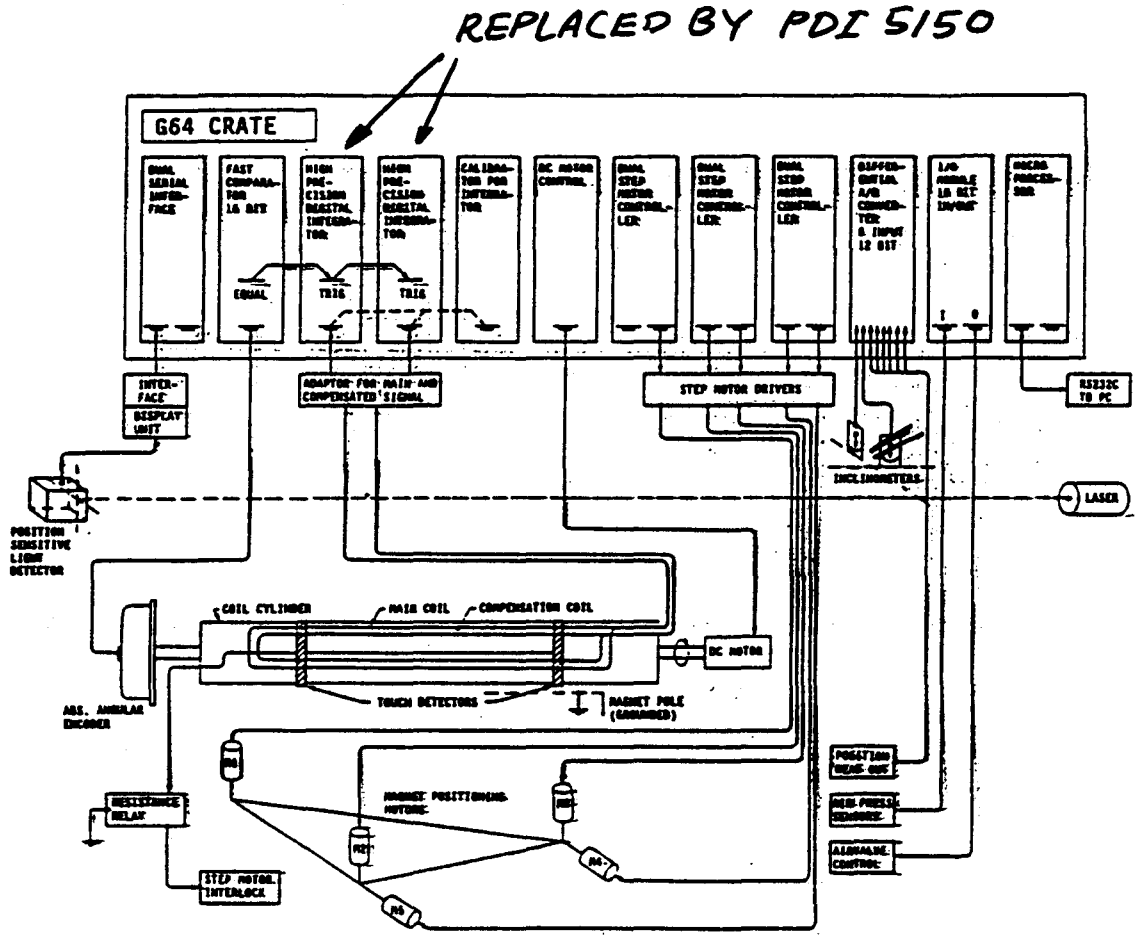


Fig.3. Block schematic of the micro processor controlled G64-system and its relation to the measurement bench components.

5. OVERALL SPECIFICATIONS

Relative accuracy of integrated main harmonic ..... $\pm\ 3 \cdot 10^{-4}$
Angular phase absolute accuracy ..... $\pm$ 0.2mrad
Lateral positioning of magnetic center with respect to rotation axis ..... $\pm$ 0.03 mm
Positioning accuracy of alignment targets with respect to coil axis ..... $\pm$ 0.03 mm
Accuracy of ratio between integrated field of a multipole component and the main component at the major coil radius ..... $\pm\ 3 \cdot 10^{-4}$

(Specifications are subject to change without notice)

DANFYSIK CAN ALSO OFFER YOU:

* Complete beamline systems covering Analyzing Magnets, Quadrupole Magnets and Switching Magnets
* Precision Magnet Power Supplies in 0.1, 1 or 10 ppm stability class
* Ion Implanters and a range of Ion Sources
* A wide program of Beam Diagnostic Instrumentation
* Complete consulting and design service from basic optics to finished documented products

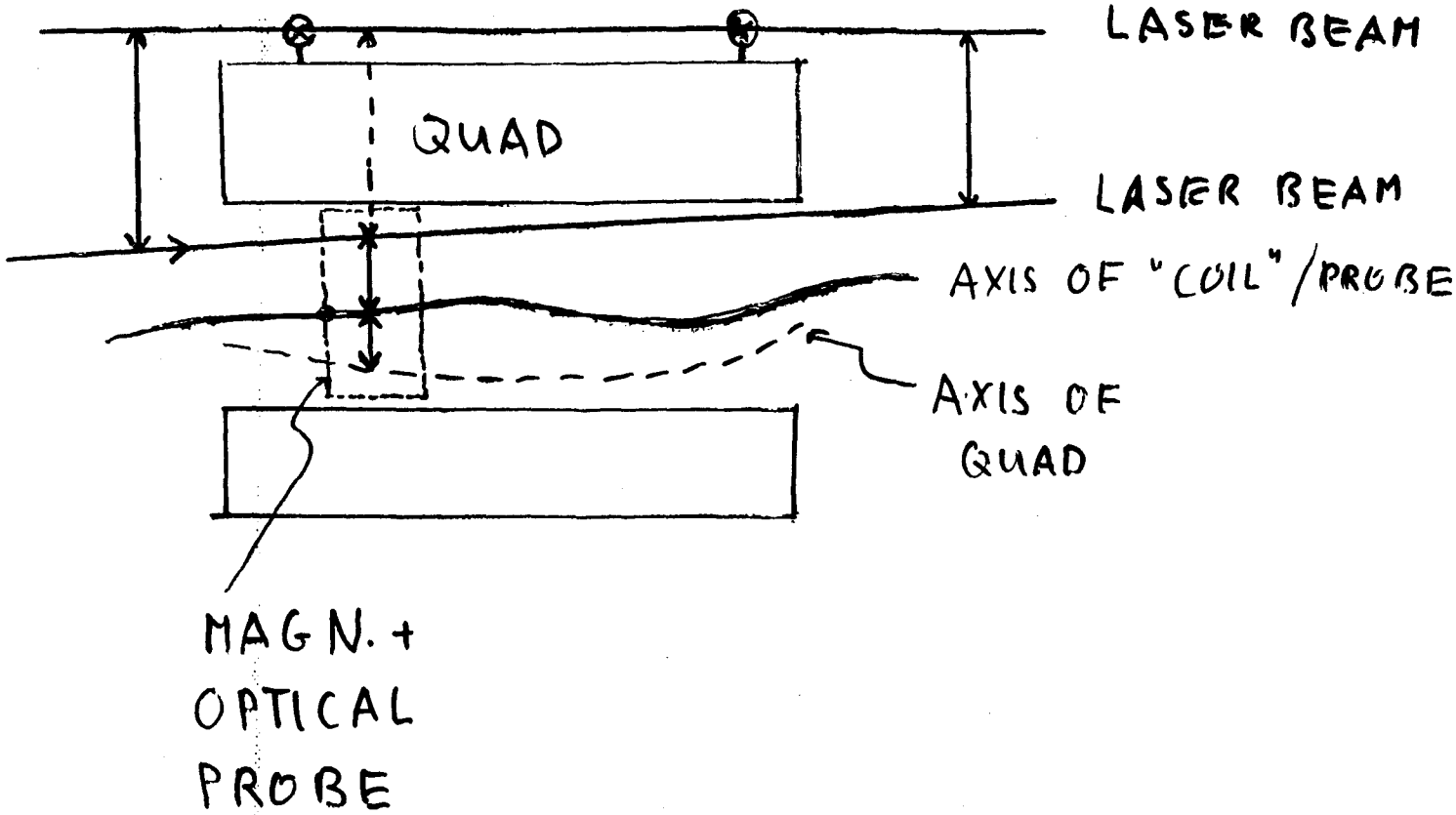
DANFYSIK A/S · DK-4040 Jyllinge · Denmark · Tel · +45 46 78 81 50 · Telefax · +45 46 78 81 15

R&D on LHC
QUADRUPLE MEASUREMENTS

P. SIEVERS

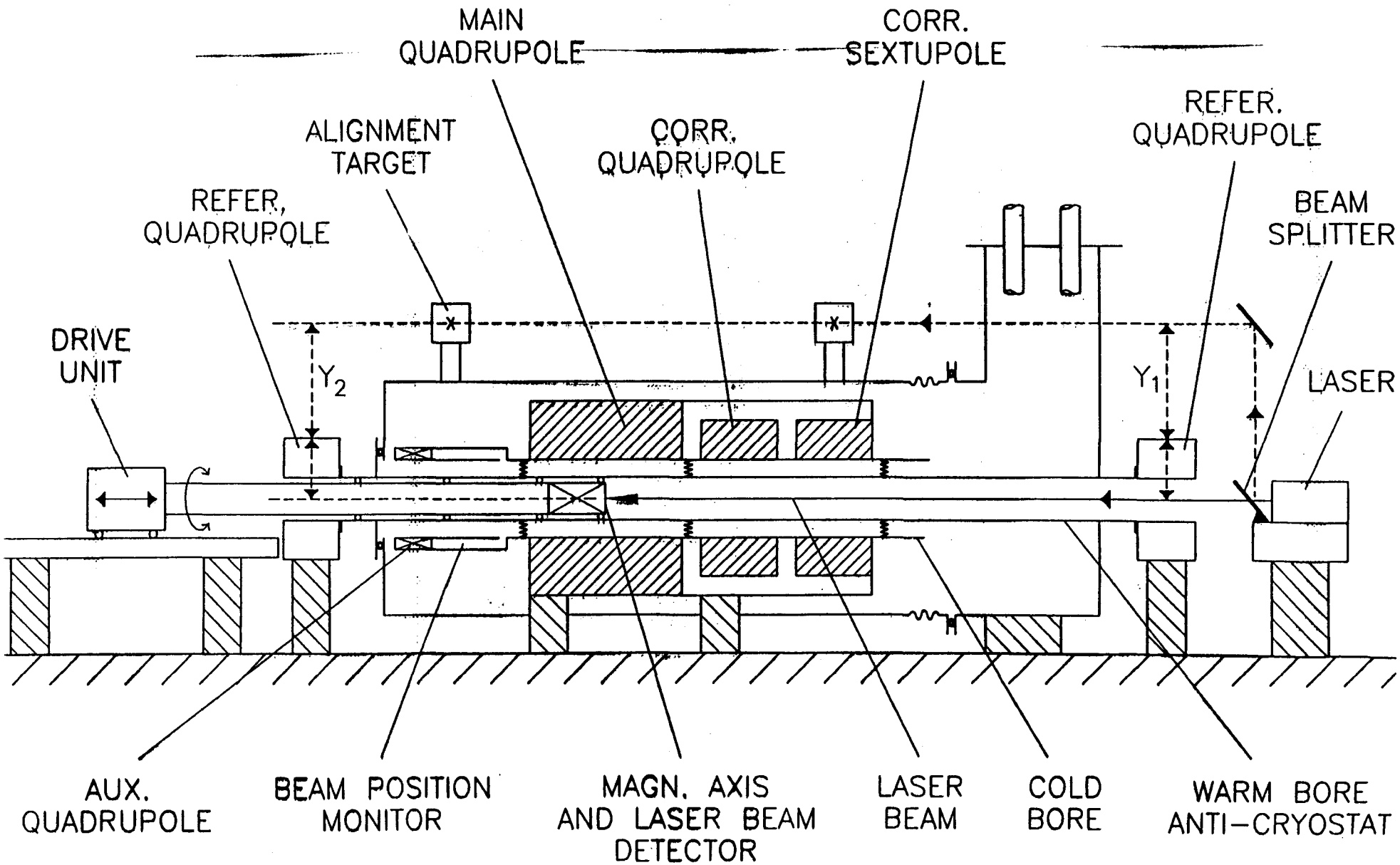
29 SEPTEMBER 1993

PRINCIPLE

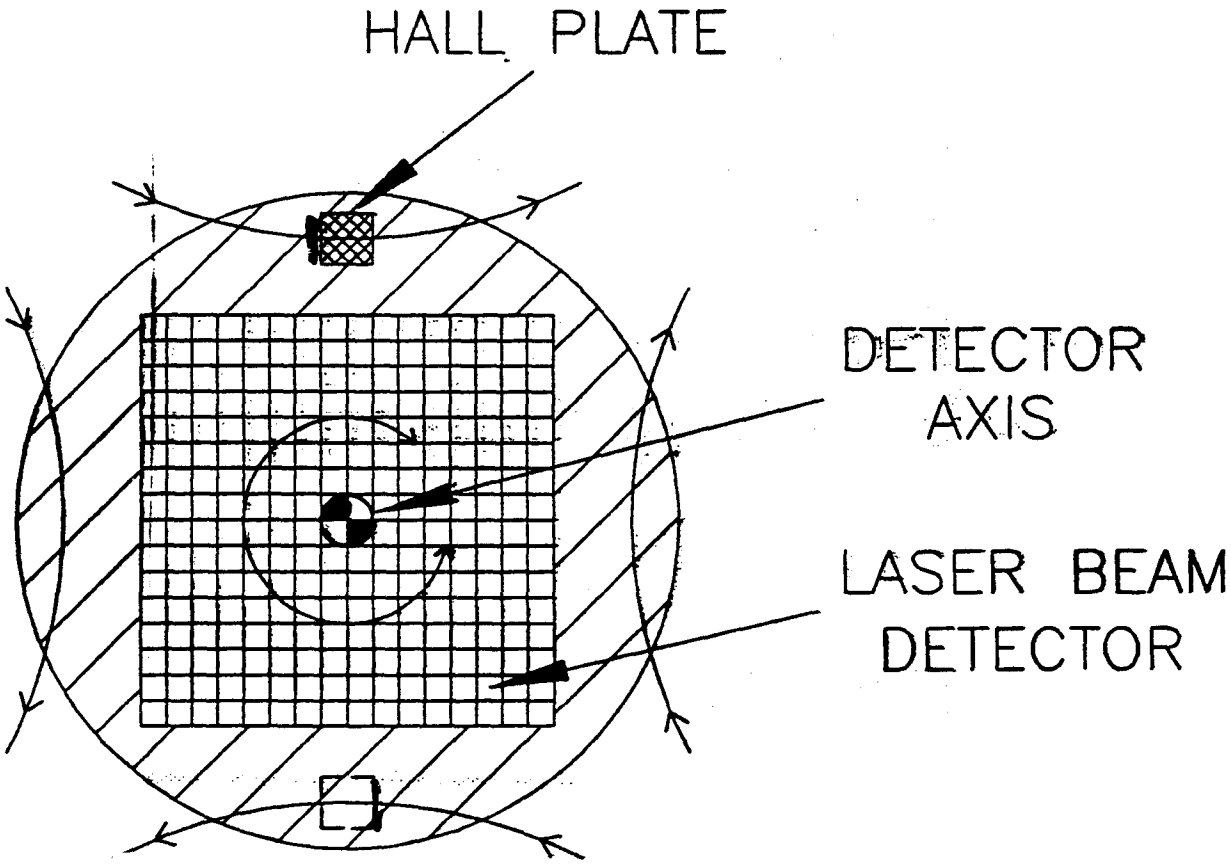

LASER BEAM
QUAD
LASER BEAM
AXIS OF "COIL"/PROBE
AXIS OF QUAD
MAGN. + OPTICAL PROBE

10
CAD
5.93/AR

QUADRUPOLE TEST STAND



DETECTOR FOR QUADRUPOLE AXIS



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AutoCAD
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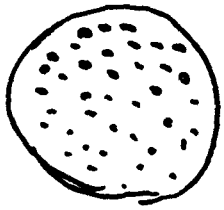
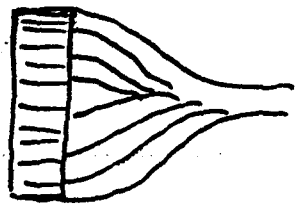
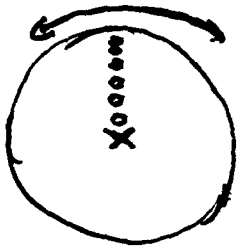
OPTICAL FIBER

LASER SPOT DETECTOR : ± 30μ in X, Y

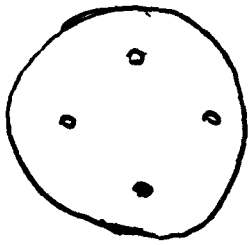




~1000 FIBERS

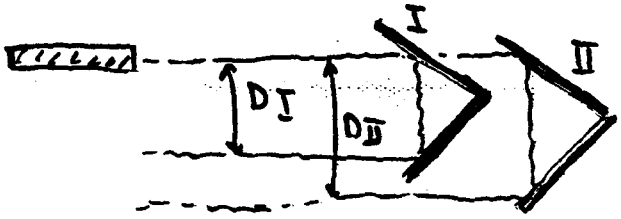


~10 FIBERS



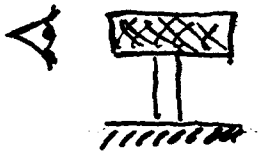
4 FIBERS, ROUND BEAM
NULLING

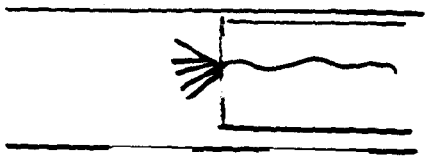
RETRO-REFLECTOR :

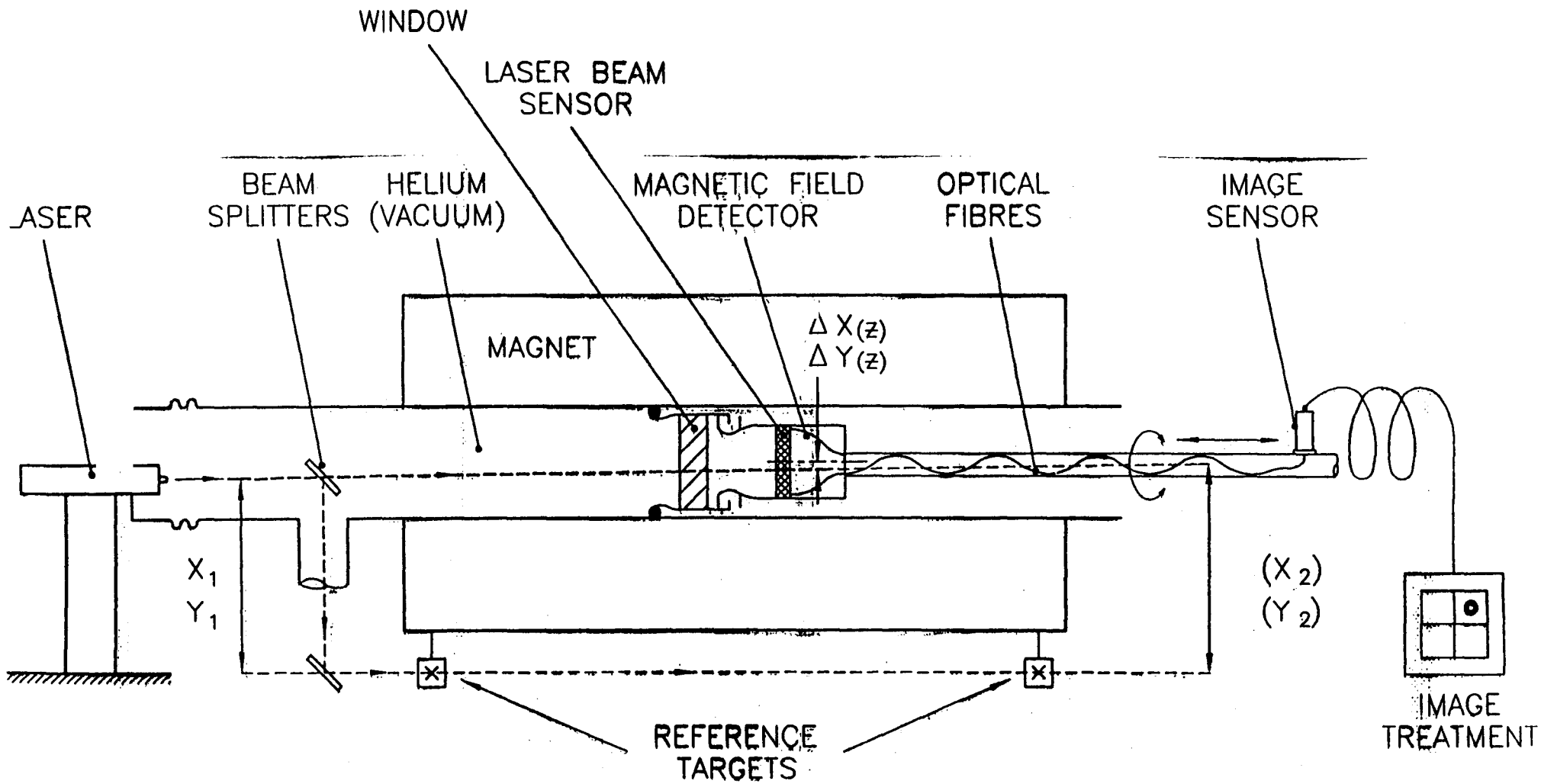


OR NULLING

LIGHT SPOT + TELESCOPE







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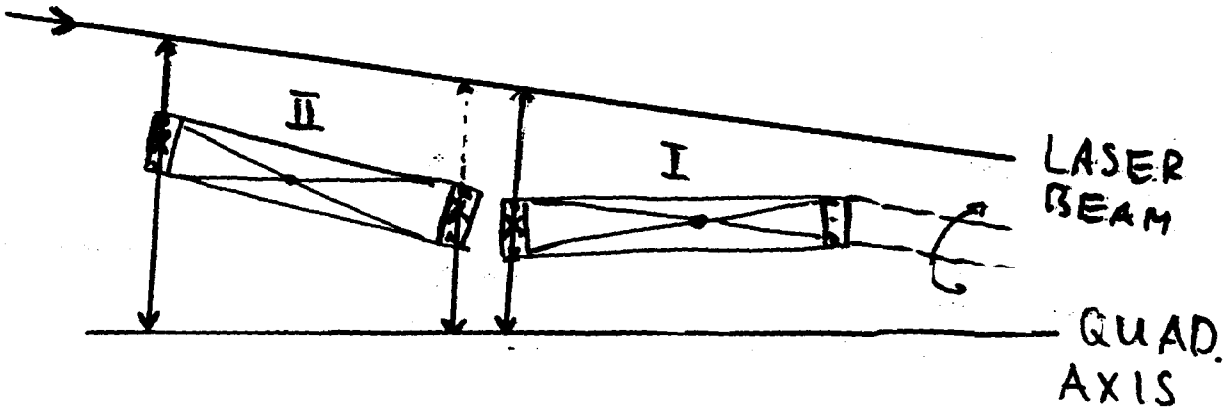
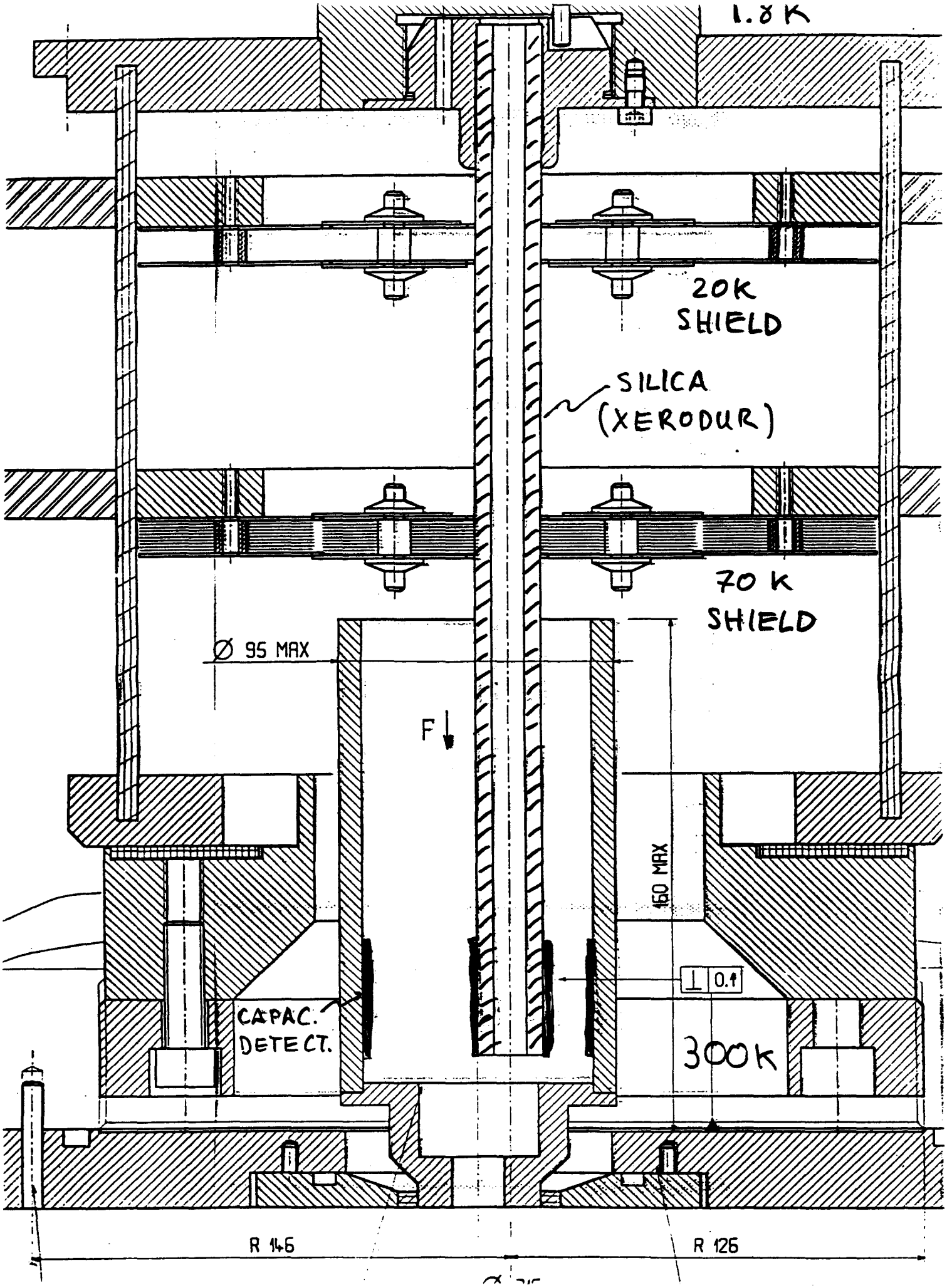
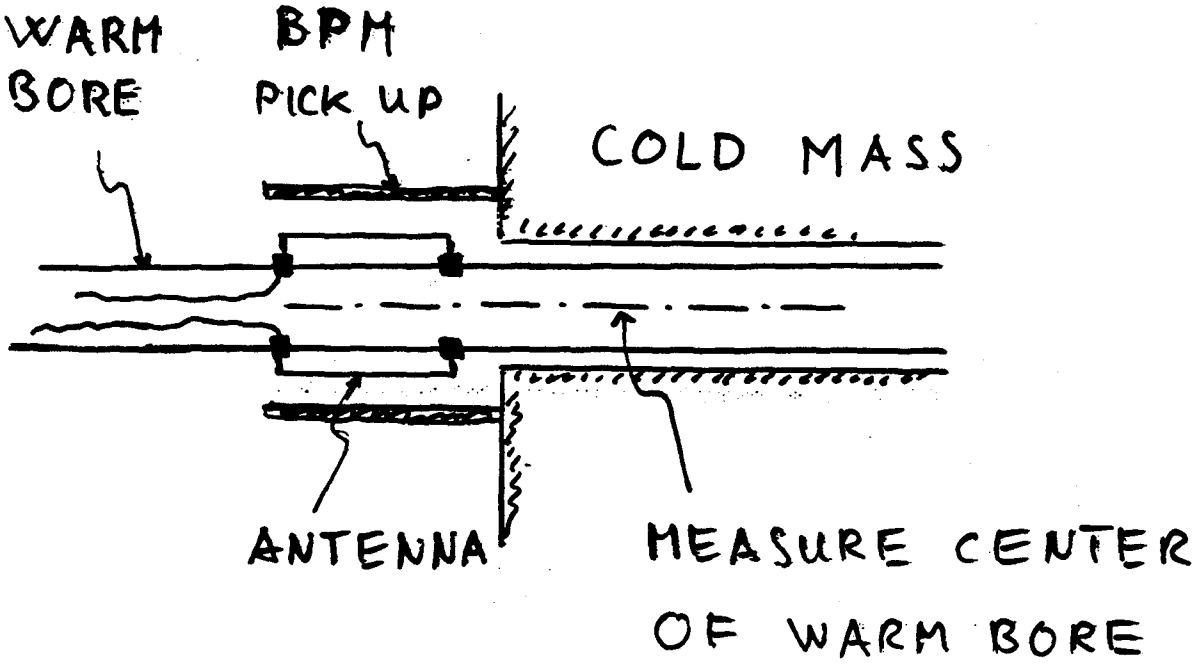
PS_8
AutoCAD


II
I
LASER
BEAM
QUAD.
AXIS


1.8 K
20K
SHIELD
SILICA
(XERODUR)
70 K
SHIELD
Ø 95 MAX
F
160 MAX
0.1
CAPAC.
DETECT.
300K
R 146
R 126


WARM BORE
BPM PICK UP
COLD MASS
ANTENNA
MEASURE CENTER OF WARM BORE

Stretched Wire Quadrupole Magnetic Field Measurements

Peter Tennenbaum, UCSC/SLAC
Steve Williams, SLAC
Dave Sawyer, SLAC *
* now SSCL

Method:

Use Magnetic Center Fiducialization Fixture to measure gradients & sextupoles.

Purpose:

Check/QC Quad/BPM units after assembly & before installation on beam line

(Review apparatus)

Equipment + Technique

Newport micron stages

Range : 8 cm

Leastmotion = 0.1 μ

Control + Data Acquisition:

MS DOS PC 286

MS Quick basic

National GPIB + driver

Integrator:

Schlumberger 7061

$\int V dt$ ≈ 5 sec integration time

GPIB:

2mm x + y

integrate −1mm to +1mm − 4 times AVG

~30 seconds / point

58 points (x + y)

~ 45 minutes / sweep

Repeat 10 times automatic, unattended for statiscal analysis + consistency check.

Fit for Gradient + Sextupole Moments

$$\int v\,dt = L_{eff}\Big\{ d_x\Big[B_{0y} + G_n x - G_s y + S_n(x^2-y^2) - 2S_s xy + S_n \frac{d_x^2}{12}\Big]$$

$$- d_y\Big[B_{0x} + G_n y + G_s x + 2S_n xy + S_s(x^2-y^2) - S_s d_y^2/12\Big]\Big\}$$

Measure $\int v\,dt$ at 58 $x+y$ for $x+y$ motion

Eliminate B_0 + Skew components
by introducing x_0, y_0 + θ.

Find G_n + S_n

Procedure:

1) Null wire (move to center of field by vibrating; move until electrical signal at vibration frequency vanishes).

2) For each sweep measurement:

a: Move wire to beginning of sweep: $(x, y - \varepsilon_y/2)$ or $(x - \varepsilon_x/2, y)$, check loc;

b: wait 3 seconds;

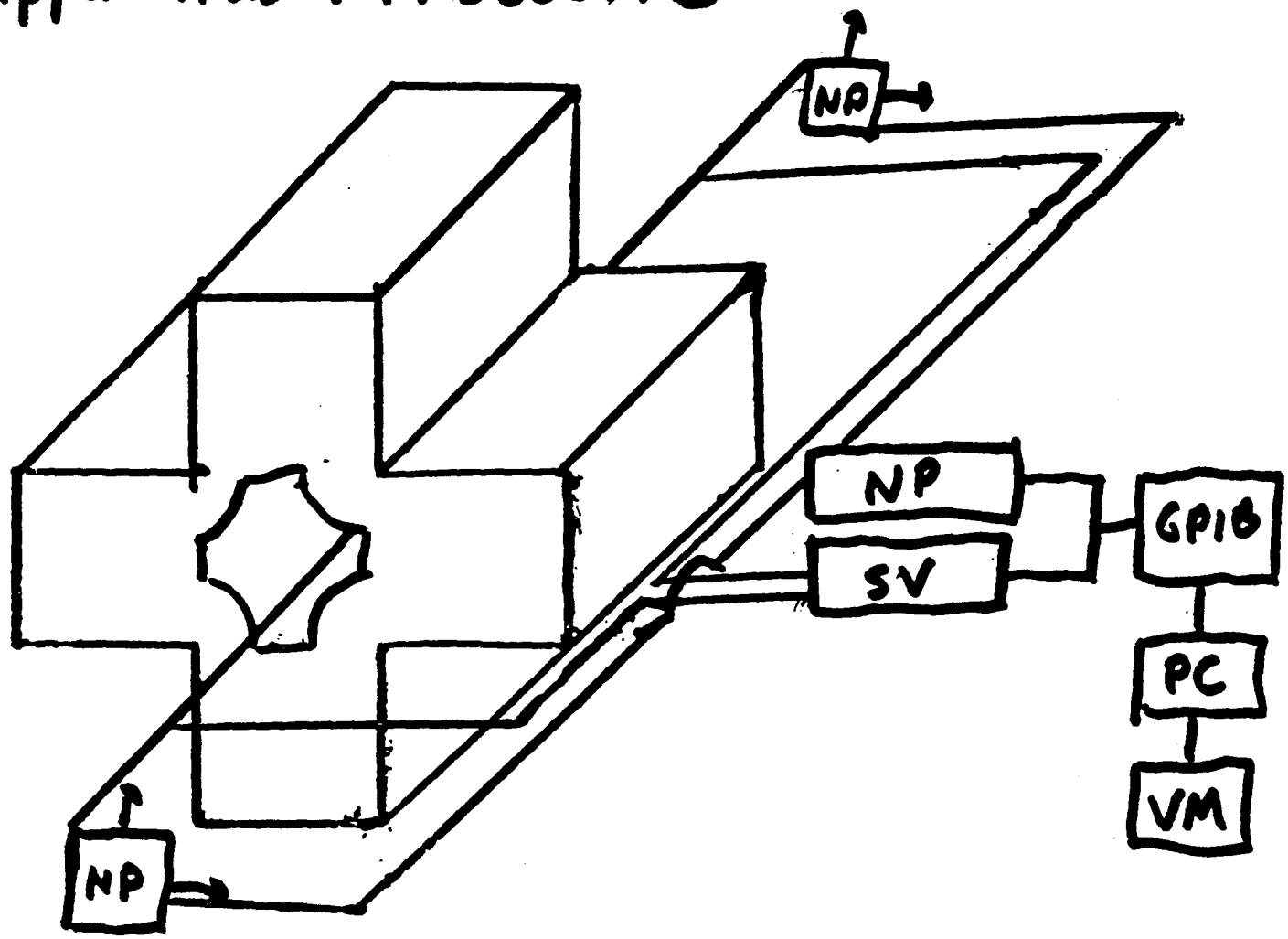
c: null voltmeter (zero offset);

d; Trigger 5 second integration on voltmeter;

e: Move wire to end of sweep: $(x, y + \frac{\varepsilon_y}{2})$ or $(x + \frac{\varepsilon_x}{2}, y)$, check loc;

f: repeat d + e 3 times and average to get saved $I(\vec{x})$ value.

Apparatus & Procedure



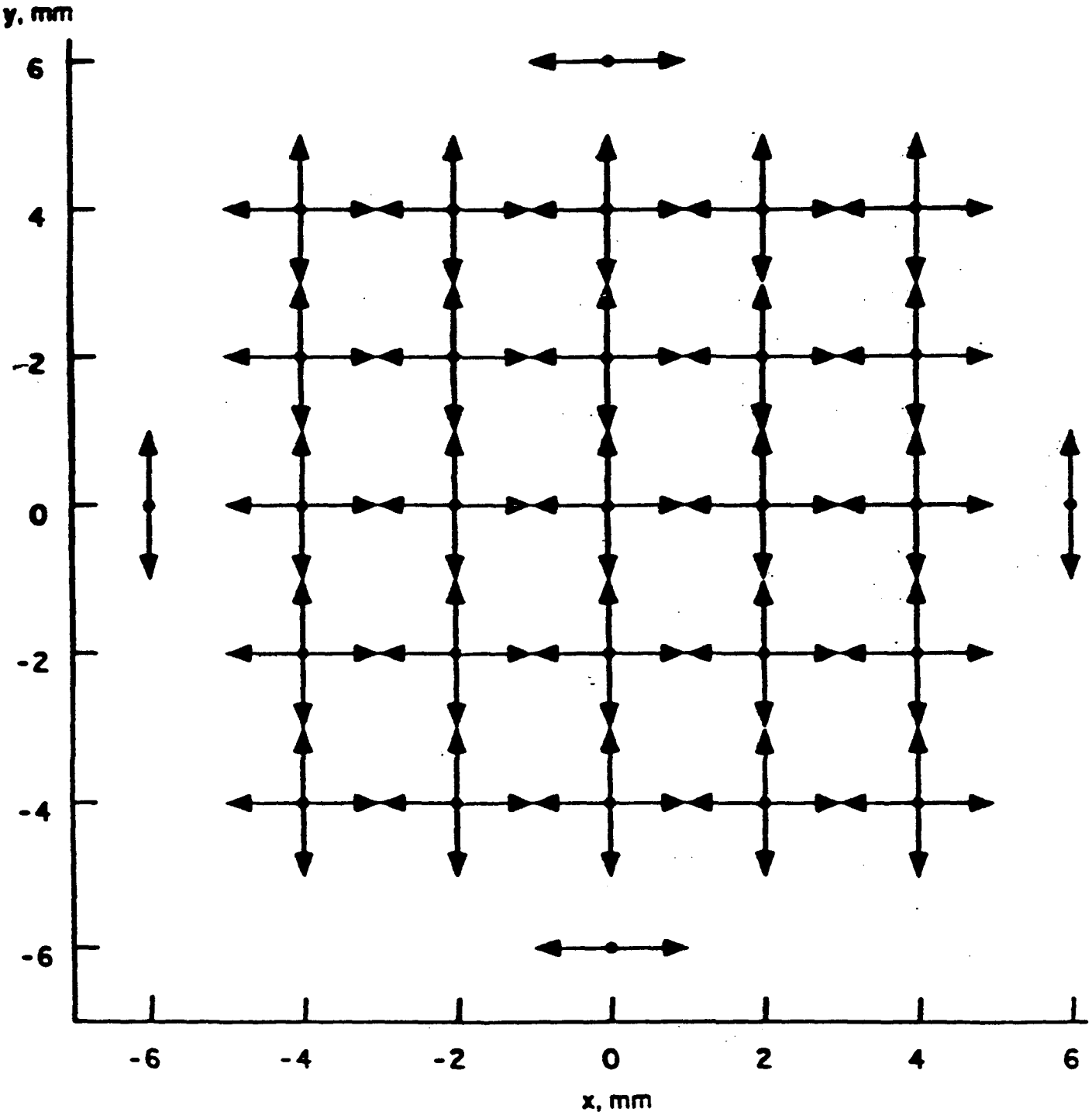
NP: Newport Stages + Controller; used to sweep wire.

SV: Systems Voltmeter, with time-integration function.

GPIB/PC: controls and reads out

VM: used for fitting program

Magnetic Measurement- Wire Sweep Pattern



Wire was swept over 2mm about center point in both x and y, except for points near edge of pipe. Quad bore=23 mm. diam.

The wire is swept around the pattern 10 times. The ten runs are then averaged, an RMS is computed, and the resulting 54 measurements of I are fit to a theoretical eqn, via Minuit.

Fit parameters:

δ_x

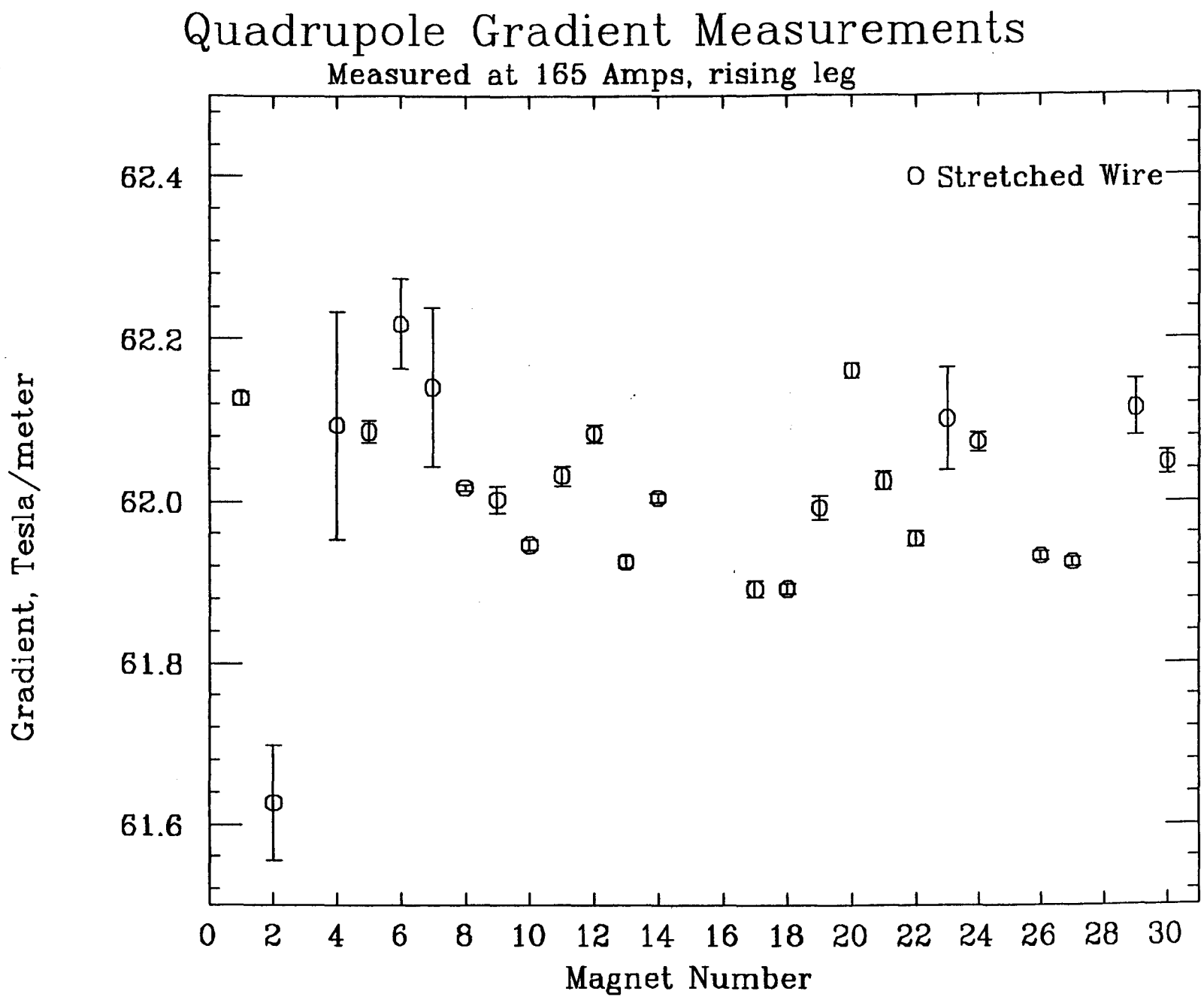
δ_y

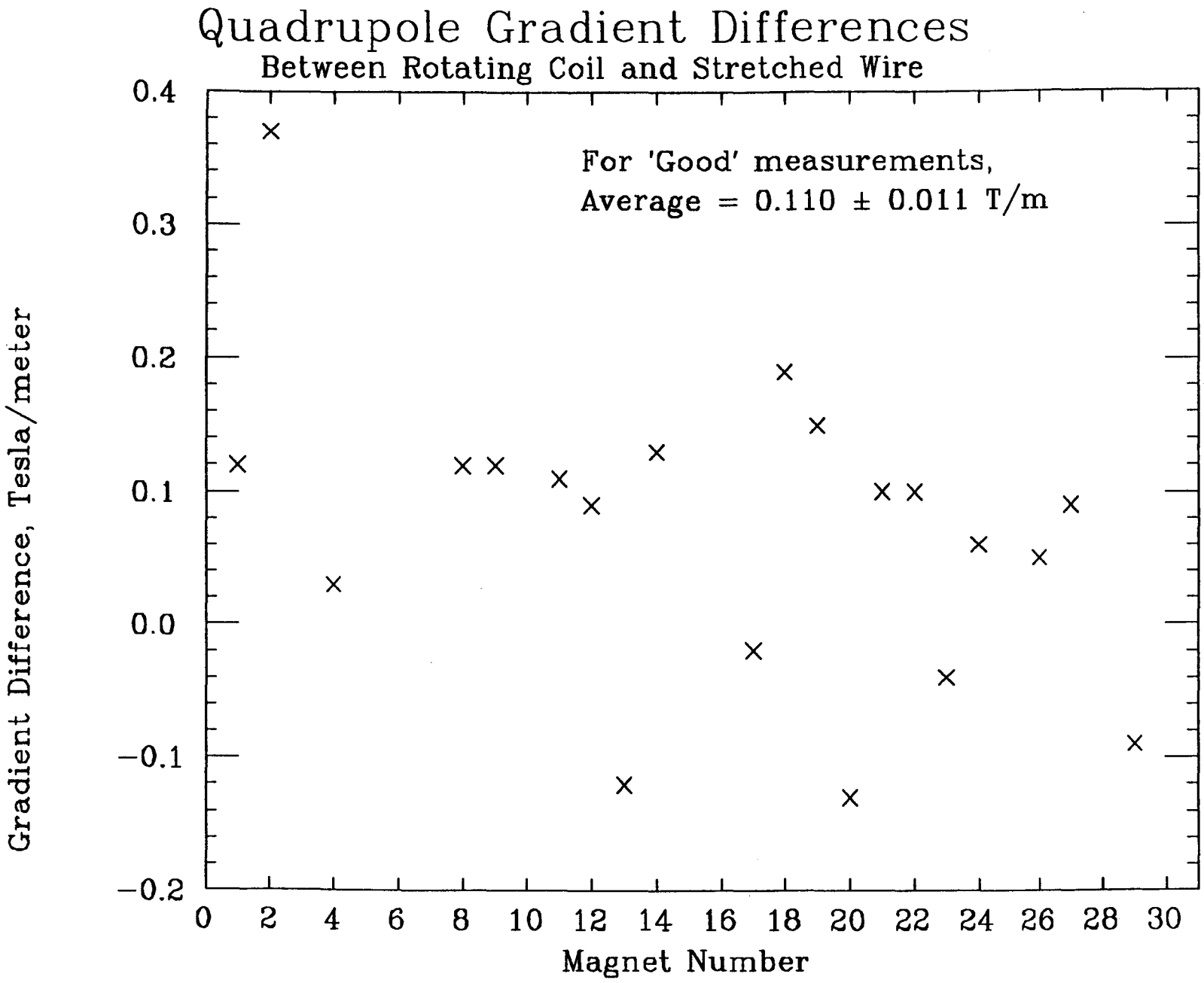
θ

g

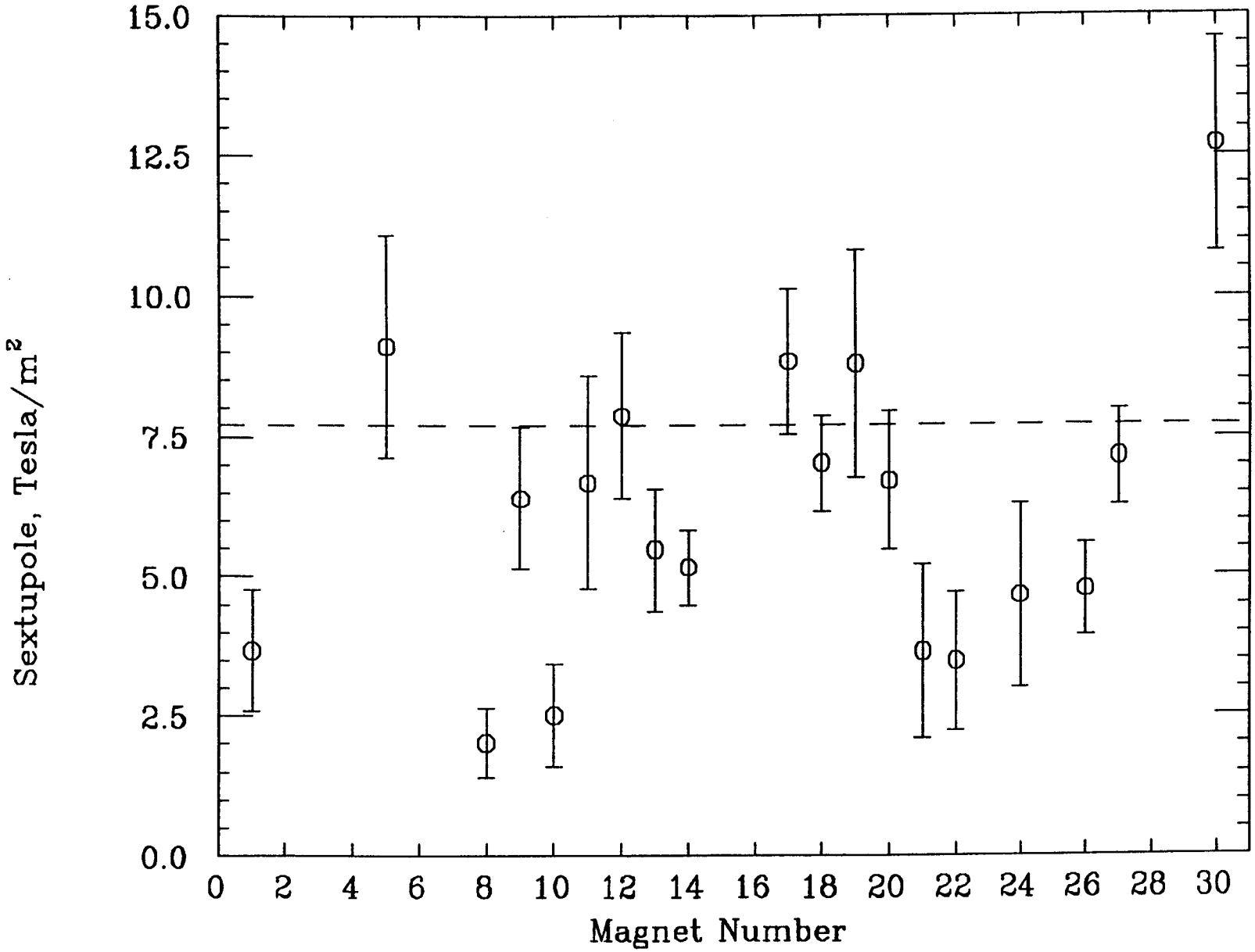
S

Fringe scale

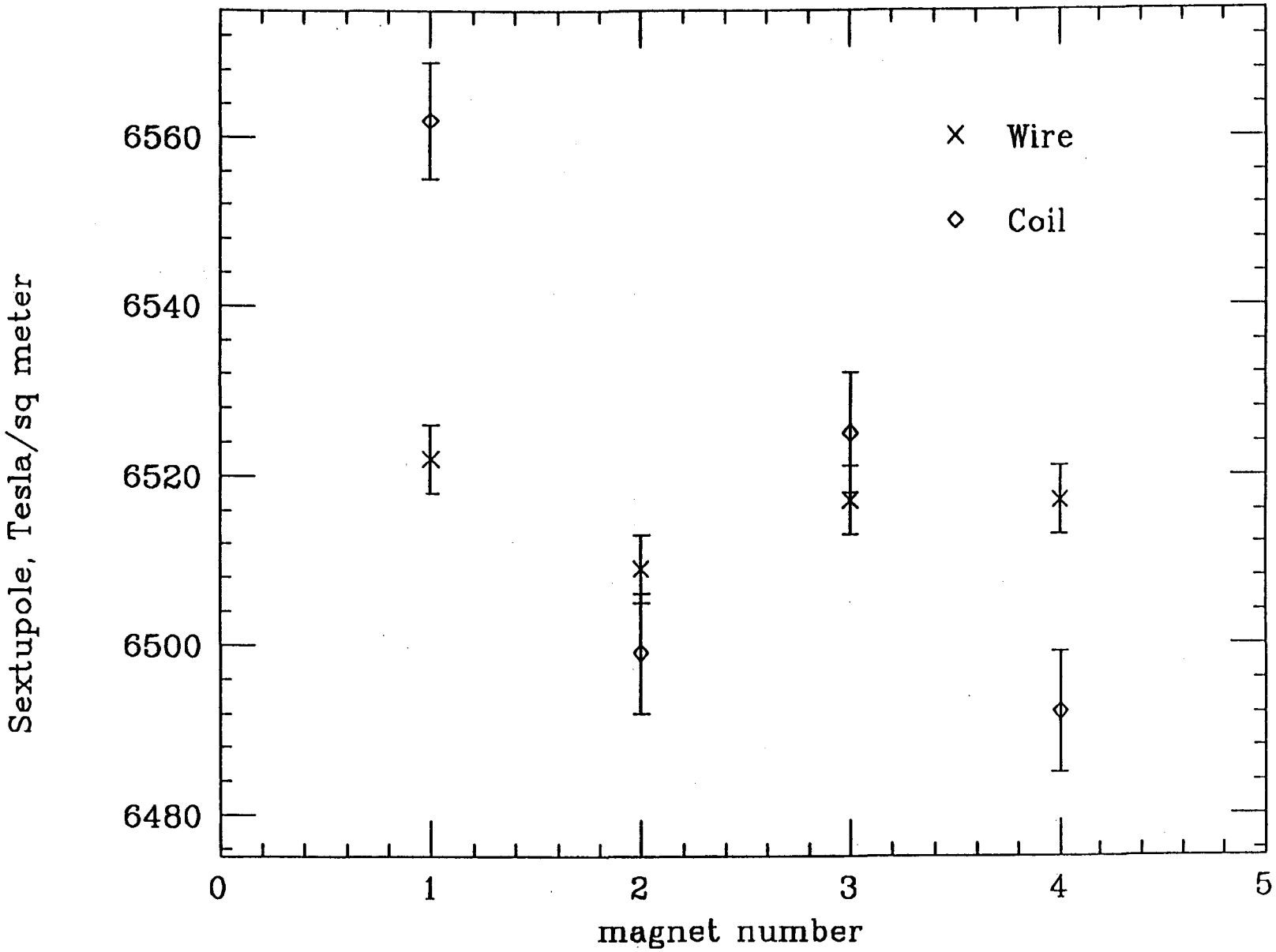

Quadrupole Gradient Measurements
Measured at 165 Amps, rising leg
Stretched Wire
Gradient, Tesla/meter
62.4
62.2
62.0
61.8
61.6
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Magnet Number


Quadrupole Gradient Differences
Between Rotating Coil and Stretched Wire
For 'Good' measurements,
Average = 0.110 ± 0.011 T/m
Gradient Difference, Tesla/meter
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Magnet Number

Quad Sextupole Content Measurements



Sextupole Field strengths, CCS magnets



Stretched Wire M Measurements.
vs Rotating Coil

- Takes more time but automatic, unattended
- Fits in smaller apertures
- Statistical error analysis straightforward
- Can measure skew angle accurately (75 μrad here)
- x + y sweep axes need to be orthogonal
- + accurate
- future: should have independent position readback, e.g. LVDT.

Conclusion:

For FFTB it was a good QC check of final assembly.

Superconducting Super Collider Laboratory
2550 Beckleymeade Avenue, MDL, MS-8002
Dallas, TX 75237-3946

Magnet Systems Division
Test and Data Management Department

Two Stage Bucking

Sergei Sharonov, Joe Dryer, Wei-Chuan Li

8/4/93

Abstract.

The rotating coil technique for magnetic measurements which is employed now in SSCL is based on the digital bucking idea. This assumes a high quality digitizer with a sampling rate of approximately 60 Hz and resolution of 1ppm. Modern technology leaves very few alternatives if any at all to a digital voltmeter (DVM) in this application. One possible variant we can think about is a sigma-delta converter, but it involves custom design, digitizer delay and synchronization problems. On the other hand, world practice knows a lot of successful applications of the integrators and lock-in amplifiers for magnetic measurements. Those devices are simple and cost effective, but lack the resolution (dynamic range) of DVMs. Integrators also provide direct measurement of integral instead voltage itself and solve synchronization and velocity correction problems pertinent to DVMs. Lock-in amplifiers have inherent filtering capability which can decrease the noise floor and are capable of high speed operation. A common solution for a dynamic range problem is an analog bucking idea. Requirements of a digitizer can be decreased 100 times easily. Some advanced approaches promise to increase this figure to several thousands or even more. We developed two alternative techniques based on both analog and digital bucking ideas: two stage bucking and enhanced analog bucking [1]. Implementing either of them will decrease the total cost of the system and in some cases will improve performance.

Two Stage Bucking.

The Two Stage Bucking (TSB) assumes course analog bucking on sequentially connected coils and fine digital bucking in the computer (See Fig1). DVM1 receives partially bucked signal - the fundamental is suppressed by the bucking ratio of the coils. Only the small amount of the signals received by the other DVMs is to be added at the digital stage.

The equation for the bucked signal is:

$$Bucked = DVM1 + \sum_i \alpha i \times DVMi$$

Note that now α_i's are small values (~0.01) and hence the resolution of the digitizers is not so demanding. Roughly, DVM1 should resolve ~0.01 unit signal (our accuracy requirement) riding on top of the residual fundamental (100 units for bucking ratio=100). Bucking DVMs should have comparable resolution, so that their quantization noise will not contribute to the total system noise. The field strength information can be extracted from the bucking signals. For the coils which can't perform direct analog bucking it is possible to use a resistor matrix embedded in an amplifier. Due to the fact that this matrix is located after the multichannel amplifier, it is possible to avoid additional noise contribution and stability problems pertinent to the resistor dividers connected directly to the coils. Preliminary tests were performed in dipole and quadrupole magnets (See Fig2-Fig7). "Dig" corresponds to pure digital technique, "digamp" to the digital with a preamplifier and finally "andig" to the TSB. The data obtained agrees well within the error bars with that of the standard digital bucking processing. Some noise figure improvement which TSB has against the digital system with preamplifier can be explained as a result of reduction of the effective number of measurement channels: DVM1 (or amplifier U1) is the major contributor to the system noise. Assuming that each channel generates noise E, and noise is uncorrelated between the channels we can derive the formula for the bucked signal total noise:

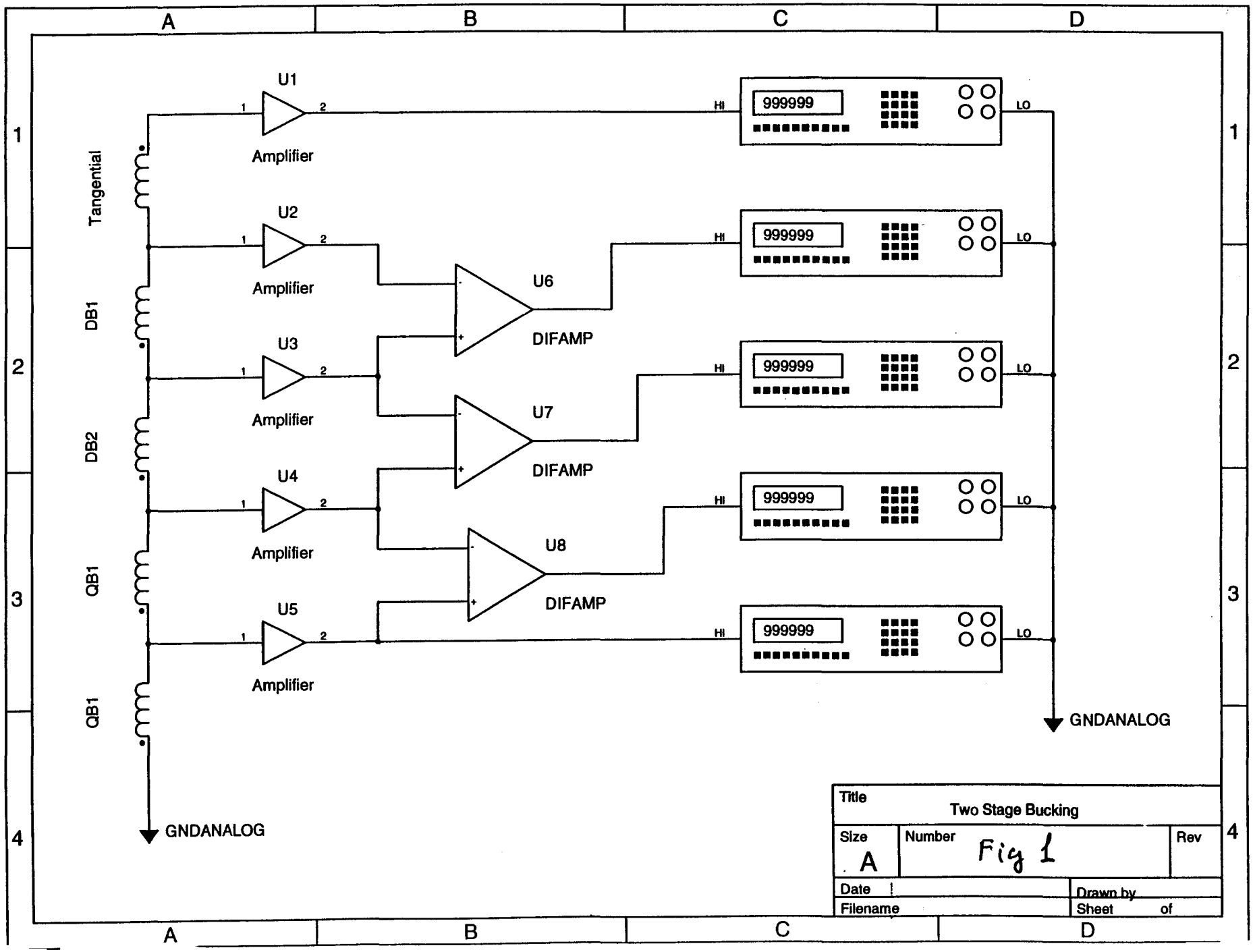
$$E_{total} = E\sqrt{1 + \sum \alpha^2}$$

Noise reduction was not observed in a quadrupole magnet and it means that an electrical noise is not a major degradation factor in this measurement.

Summary.

TSB technique is capable on the system cost reduction while maintaining or even improving the accuracy specifications. The harmonic measurements require only 14 bit A/D converter, but the desire to use the same device for field strength measurements moves us to 16 bit devices. Digitizer cost should drop 5 times approximately in comparison with the HP3458A DVMs we are currently using.

[1] MTL Note# 93-011 Bucking Techniques.
[2] MTL Note# 93-010 Preamplifier Design.


A
B
C
D
1
2
3
4
U1
U2
U3
U4
U5
Amplifier
Amplifier
Amplifier
Amplifier
Amplifier
U6
U7
U8
DIFAMP
DIFAMP
DIFAMP
Tangential
DB1
DB2
QB1
QB1
HI
LO
999999
GNDANALOG
GNDANALOG
Title
Two Stage Bucking
Size
A
Number
Fig 1
Rev
Date
Drawn by
Filename
Sheet
of

SLAC Dipole, 50 Gaus Residual Field, Normal Components

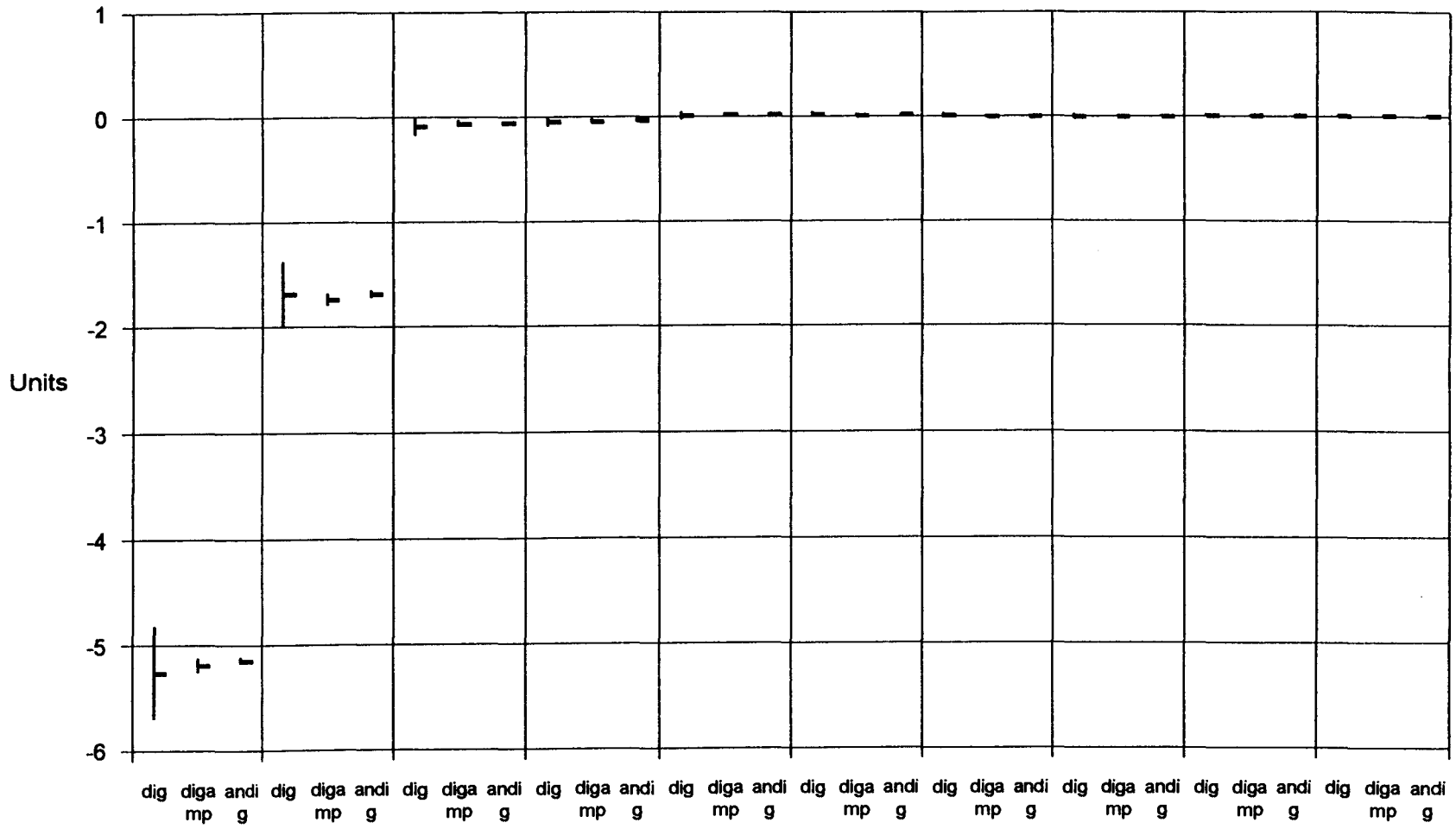


Fig 2

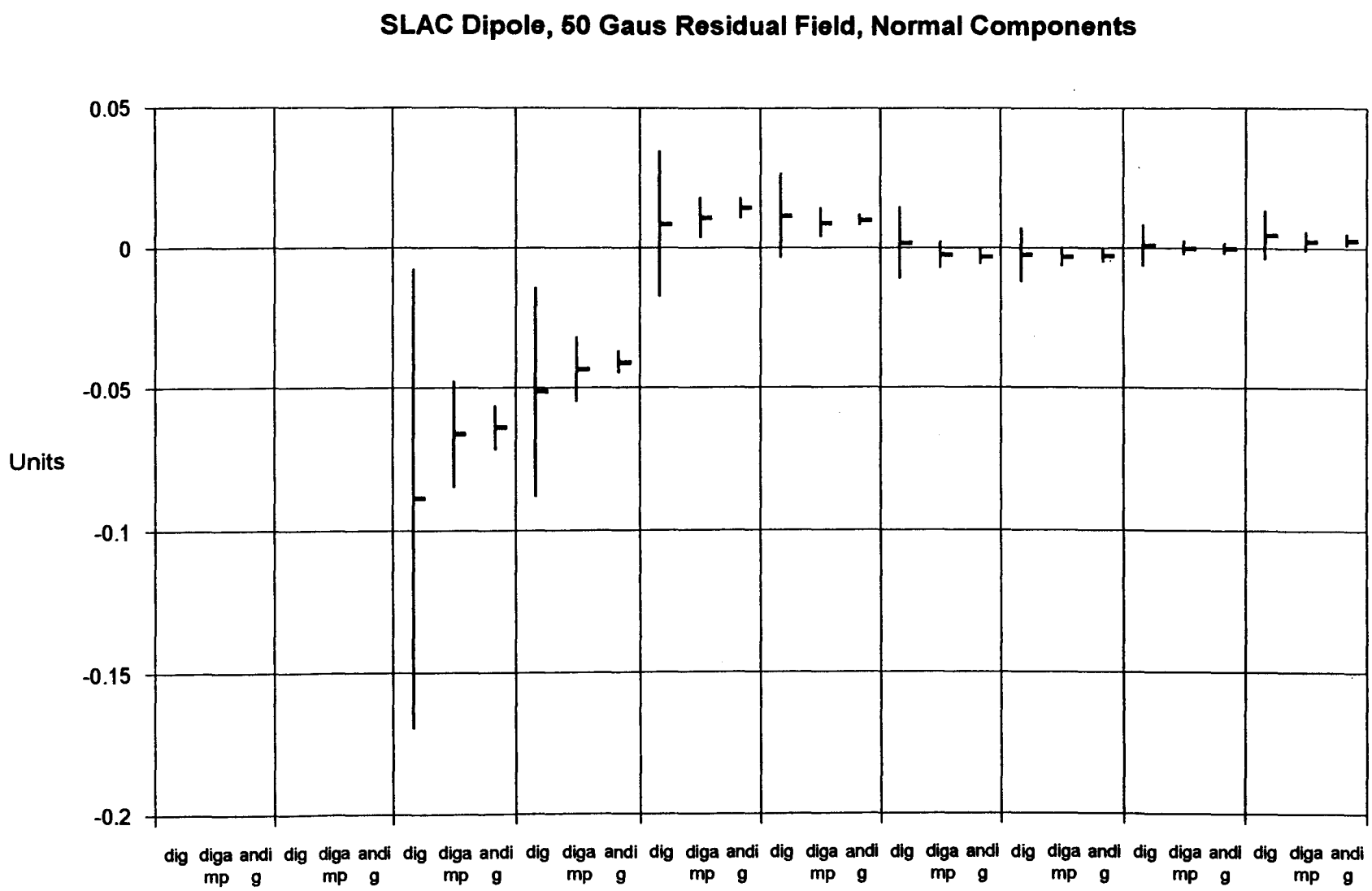

SLAC Dipole, 50 Gaus Residual Field, Normal Components
Units
0.05
0
-0.05
-0.1
-0.15
-0.2
dig
diga mp
andi g

Fig 3

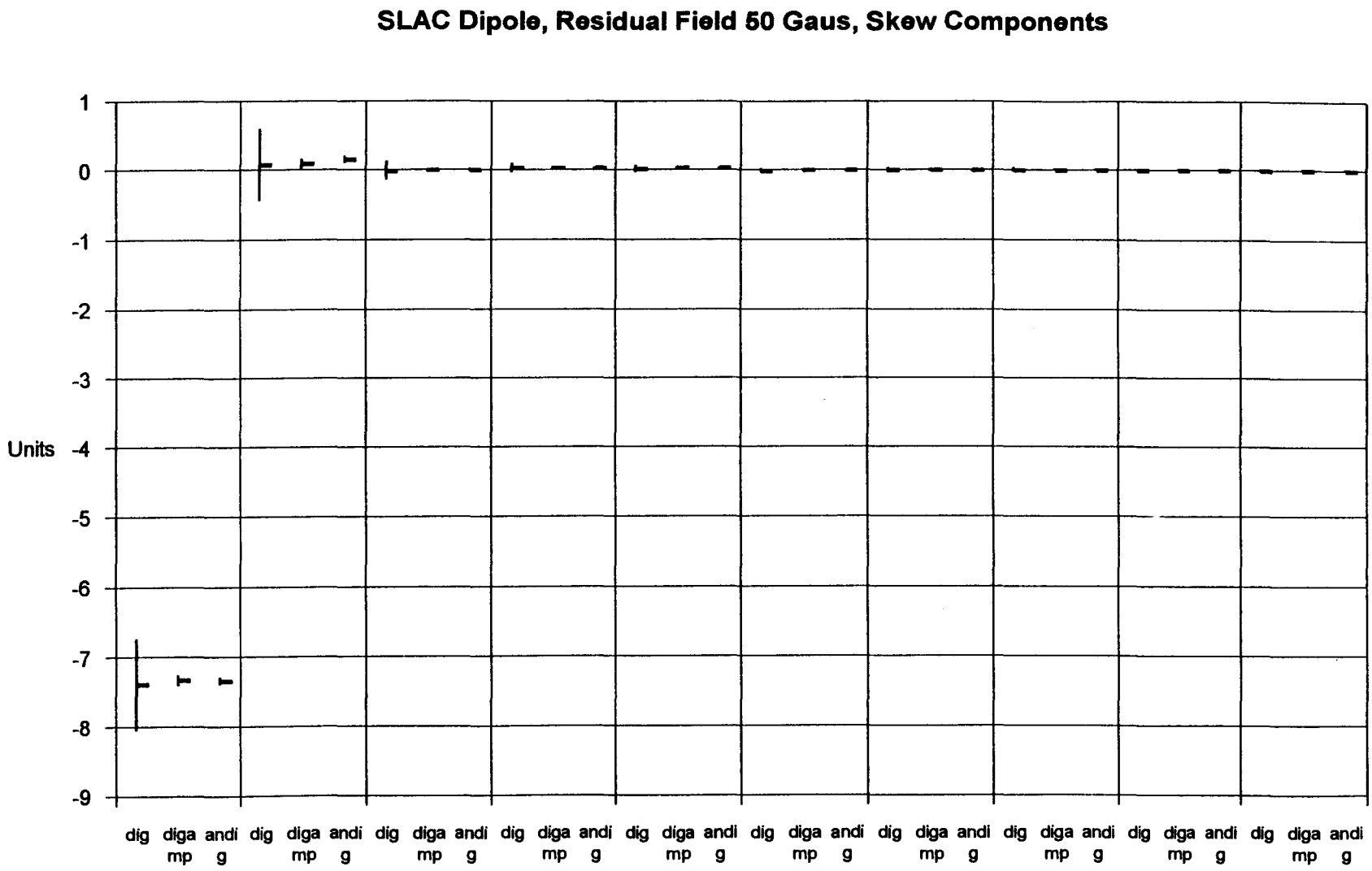

SLAC Dipole, Residual Field 50 Gaus, Skew Components
Units
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
dig
diga mp
andi g

Fig 4

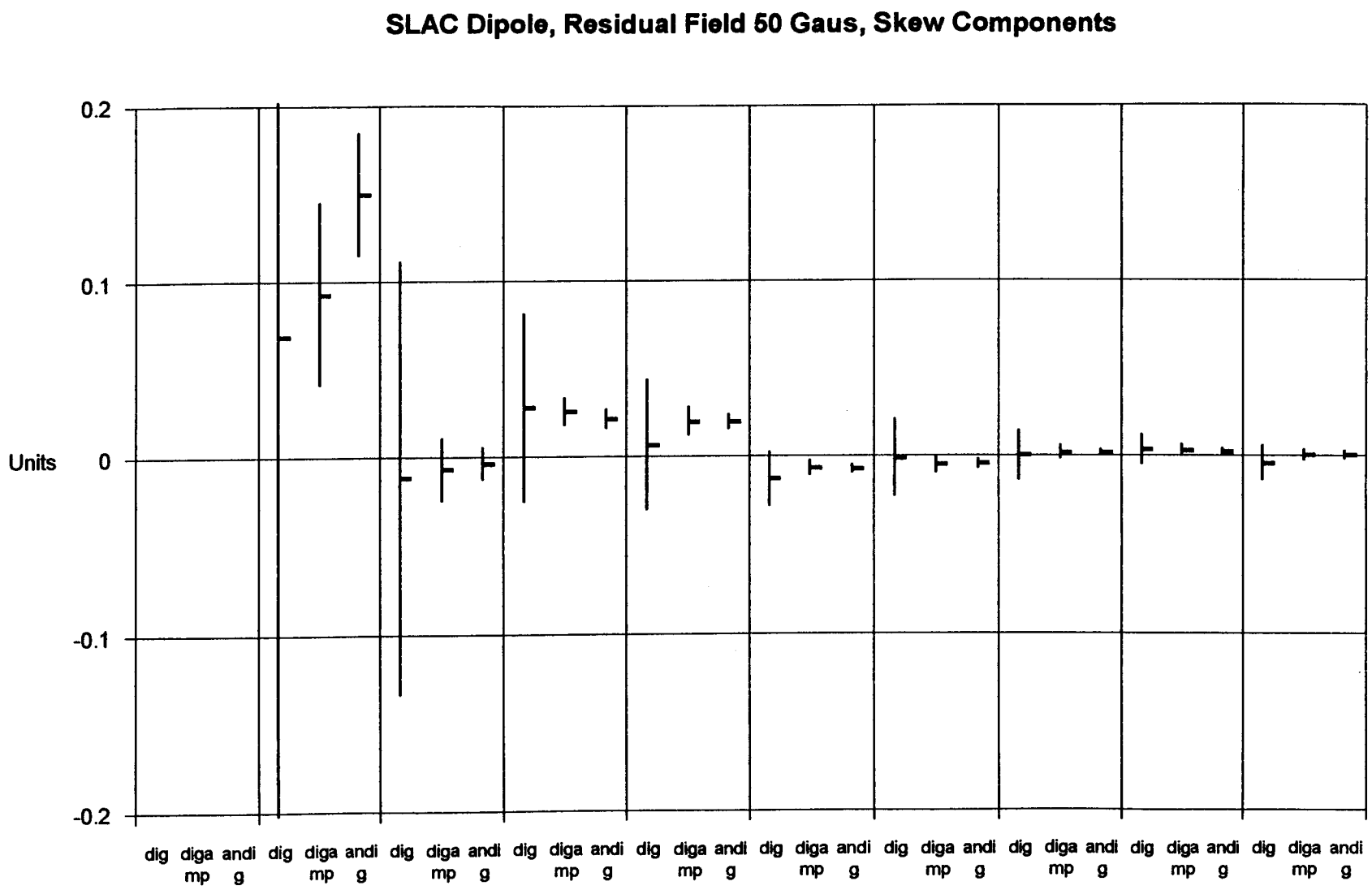

SLAC Dipole, Residual Field 50 Gaus, Skew Components
Units
0.2
0.1
0
-0.1
-0.2
dig
diga mp
andi g

Fig 5

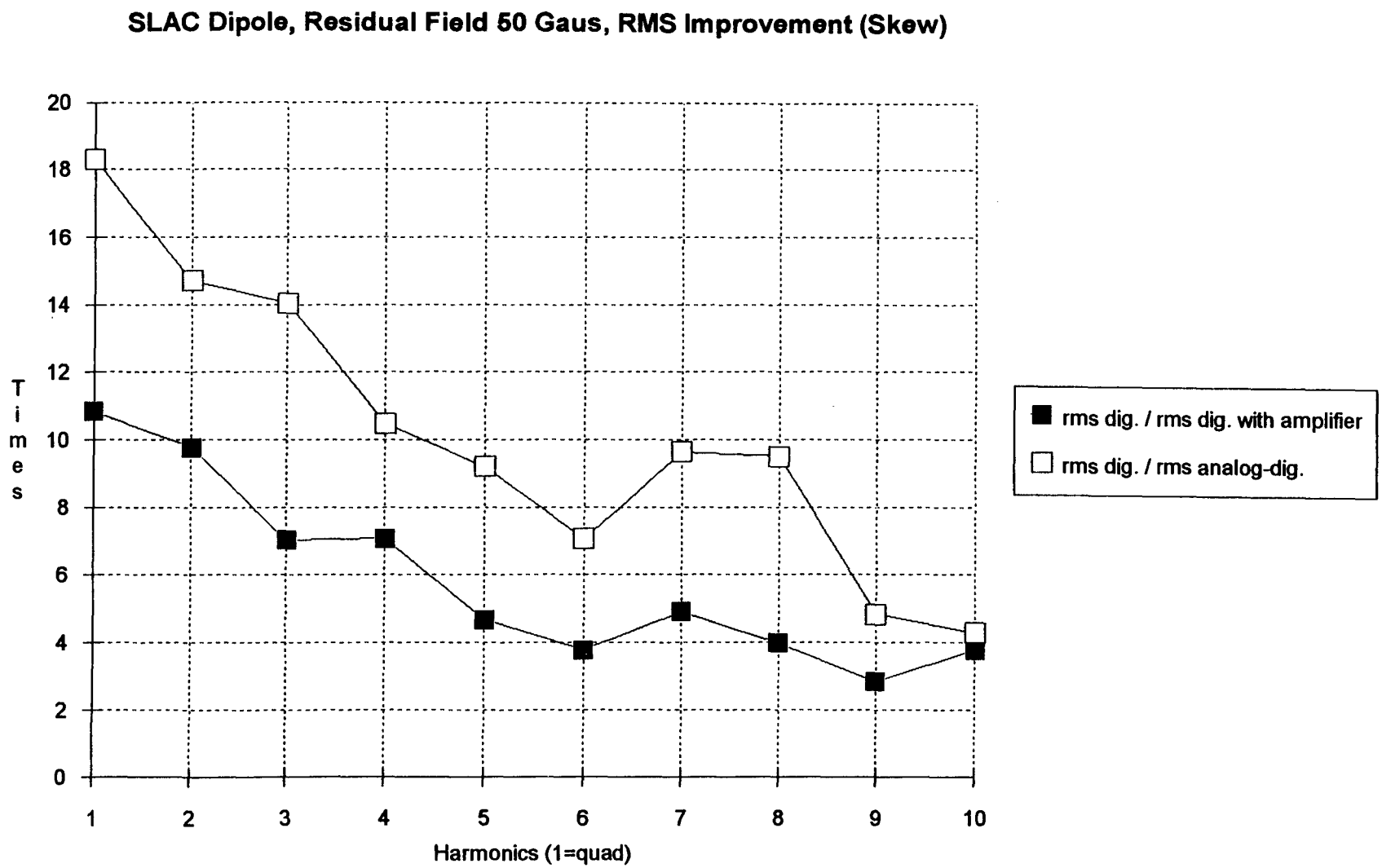

SLAC Dipole, Residual Field 50 Gaus, RMS Improvement (Skew)
Times
0
2
4
6
8
10
12
14
16
18
20
1
2
3
4
5
6
7
8
9
10
Harmonics (1=quad)
rms dig. / rms dig. with amplifier
rms dig. / rms analog-dig.

Fig 6

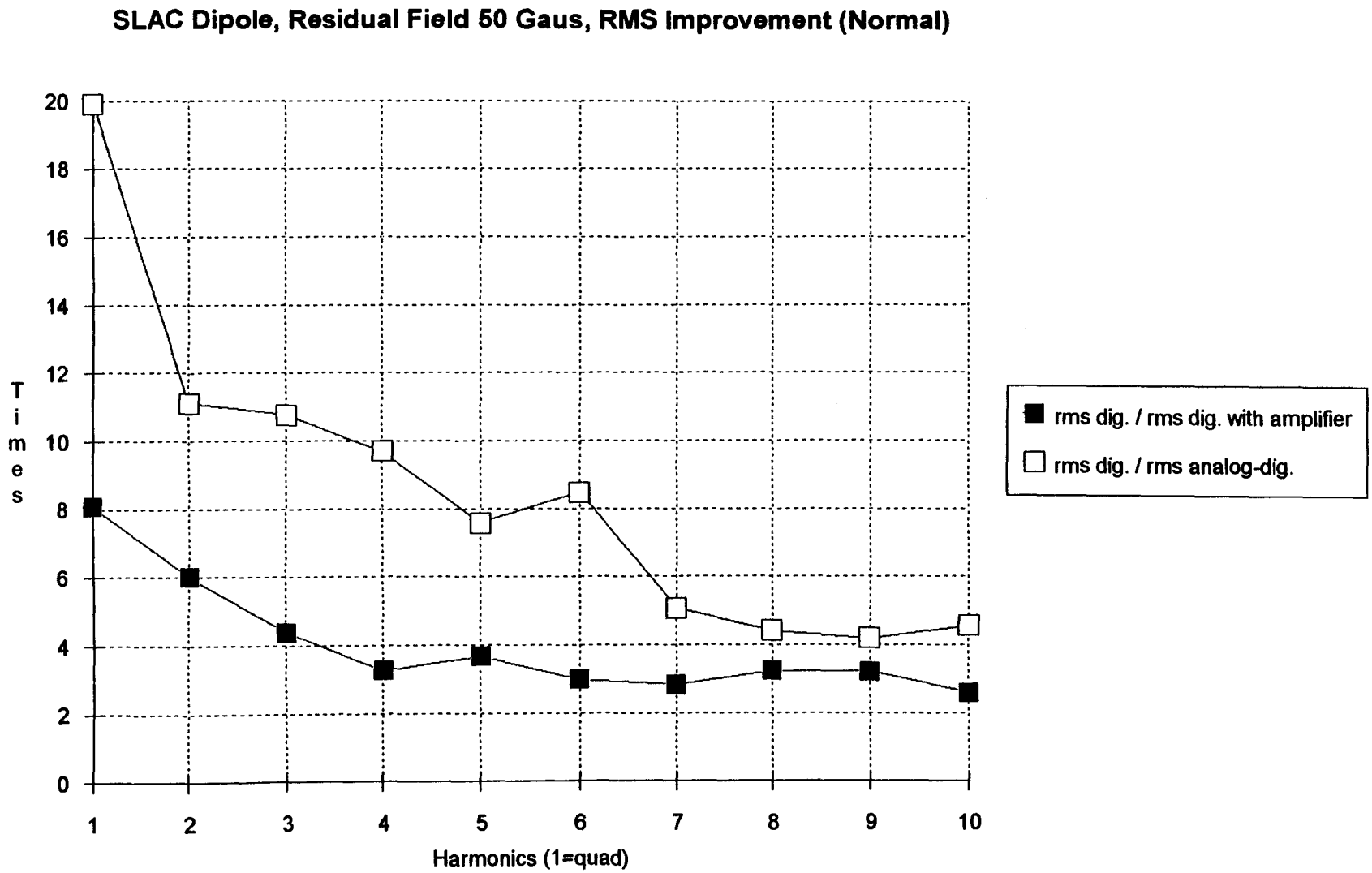

SLAC Dipole, Residual Field 50 Gaus, RMS Improvement (Normal)
Times
20
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
Harmonics (1=quad)
rms dig. / rms dig. with amplifier
rms dig. / rms analog-dig.

Fig 7

Superconducting Super Collider Laboratory
2550 Beckleymeade Avenue, MDL, MS-1002
Dallas, TX 75237-3946

Magnet Systems Division
Test and Data Management Department

An Integrator For The Stretched Wire System.

Sergei Sharonov, Joe Dryer

8/4/93

Abstract.

Any magnetic measurements that are based on an observation of the flux change through the loop of conductor require some sort of a device performing an integration of an induced voltage. The most common are analog integrators with a voltage output and the integrators based on VFCs (voltage to frequency converter). Analog integrators typically are made of an operational amplifier with a capacitive feedback (Fig. 1). While it is possible to find a precision operational amplifier and resistor, the capacitor is a source of all kind of errors: low absolute accuracy, temperature drift and dielectric absorption. Most VFCs use a charge balance technique (Fig. 2). This eliminates the capacitor imperfection effects but usually makes it hard to maintain stable gain in the converter. A VFC typically operates at a hundreds of kHz. If you multiply a single-shot pulse duration by the desired accuracy it will end up with pS requirements on the internal timing.

Testing Metrolab 5150.

It was our desire to use an of-the-shelf device for the stretched wire measurements. An integrator from Metrolab (model 5150) looked as a sensible choice. An number of tests were performed to clarify the actual precision of the 5150. The test setup shown on Fig. 3 was assembled and appropriate software written. As one can see both an integrator and a DVM (HP3458A) are fed by a medium accuracy programmable DC voltage source. Both the DVM and integrator were programmed to have the same aperture time (in the actual tests a 1S interval was used as a realistic one), and the integrator output was compared to the DVM. Such a scheme allows effective cancellation of the imperfection of a DC stan-

dard source, due to the superior accuracy of the HP voltmeter. Several tests were performed:

1. The integrator was set to the 5V input voltage range (gain=1) and the input voltage was scanned from -4.5V to 4.5V. Relative total error in ppm, that is

(Integrator - DVM) * 1.e6ppm / 5.V

is plotted as a function of input voltage in Fig.4. This error consists of slope (gain) error, offset error, linearity error and noise error. In order to reveal integrator features the next step was to make a linear fit and remove slope and offset errors (see Fig.5). Then an attempt was made to suppress the noise error by applying a walking window averaging filter. The filter width was set to 10 samples (see Fig.6).

2. Step 1. was repeated for the gain equal to 500. Data is presented on Fig 7-Fig 8.

3. The 8 hour stability was checked. A 166 uV signal which reflects an input in the warm measurements was applied to a DVM and an integrator. Data is presented on Fig 9. Top plot represents a DVM, the middle plot represents an integrator and a bottom one the difference between the DVM and integrator.

Considering precision requirements for the stretched wire system we can state that an integrator linearity error may be acceptable, but the gain and offset errors should be taken into account by using some calibration technique. It is worth noting, that linearity error should be mostly associated with a V to F converter as it doesn't depend on gain.

How we made one integrator from two DVMs.

An integrator can be constructed from a DVM, especially if the DVM uses an integration digitization method (dual slope, multi-slope, etc.). The DVM produces a reading which represents an average voltage during its aperture time. Multiplying this voltage by an aperture gives an integral value of the voltage. An obvious problem is that a DVM usually has a "dead" zone, that is a time interval between measurements when it doesn't integrate an input signal and any information during such intervals will be lost. An idea was to use two DVMs so that the first DVM would trigger the second one as soon as it finished integration of an input signal. And the second one, in his turn, would trigger the first DVM immediately after it goes into the "dead" zone. The algorithm should be clear from Fig 10. To prove the principle a setup shown on Fig 11 was assembled. Two DVMs are connected in a ring trigger chain and an external trigger which is needed to initiate the measurement sequence penetrates this chain via a ogical OR element. An HP8111A pulse generator was used to simulate this signal.

Special pulse generator G2 was designed to provide a pulse with a calibrated amplitude and duration. The pulse duration was switch programmable from 16.6666mS to 1S in 16.6666mS increments. The output amplitude was set to 5V by an external DC voltage standard source. The timing accuracy on 1S intervals was 2.5ppm. The zero pedestal was 40 uV and the very first reading produced by the DVMs was used to remove it. The pulse amplitude was adjusted so that the initial error of 80ppm (inter-calibration error between DVMs and standard source) was reduced to 3ppm.

The error versus aperature time is plotted on Fig 12. As expected this error is negative

since we are missing some gaps shown on Fig 10. The actual gap value estimated from this data is around 0.6uS. The absolute accuracy of a measurement cycle measured by a universal counter connected to the DVM1 trigger input (see Fig.12) was around 10ppm and jitter was substantially less.

Pros:

- We do not need to buy additional expensive equipment, we shall use the same DVMs we are using for the rotating coil measurements.
- We shall have a uniform system based on a reliable and high precision device, which is backed with a strong technical support.
- We achieve better accuracy, as one can see from the attached plots.

Cons:

- There is no possibility to stop integration at an arbitrary chosen point of time (external event). One should program the whole integration time beforehand, which is consistent with our stretched wire system. The measurement sequence will be performed as follows:
  a) a program starts the motion controller
  b) the motion controller issues an initial trigger signal to the DVMs.
  c) after a predetermined delay a wire motion begins.
  d) we continue to integrate for some time after the motion stops and use the first and/or the last reading to correct for possible pedestal errors.
- There are some gaps in the measurements, but for the reasonably chosen apertures they are insignificant.

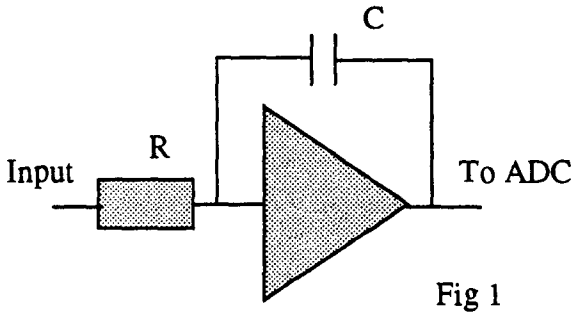


Fig 1

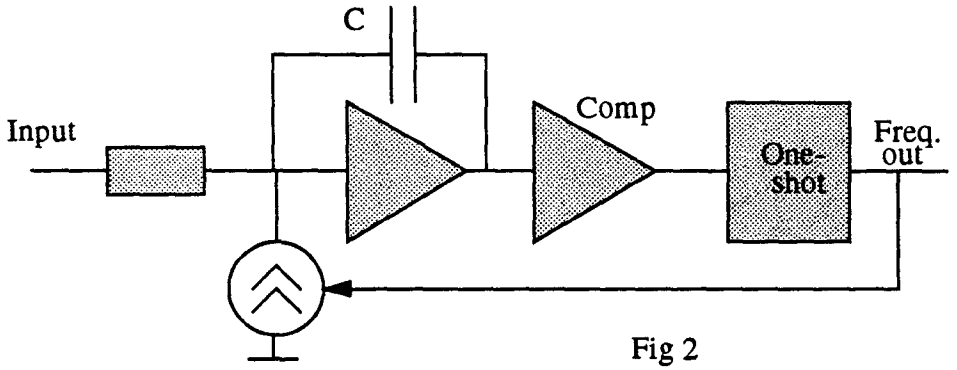


Fig 2

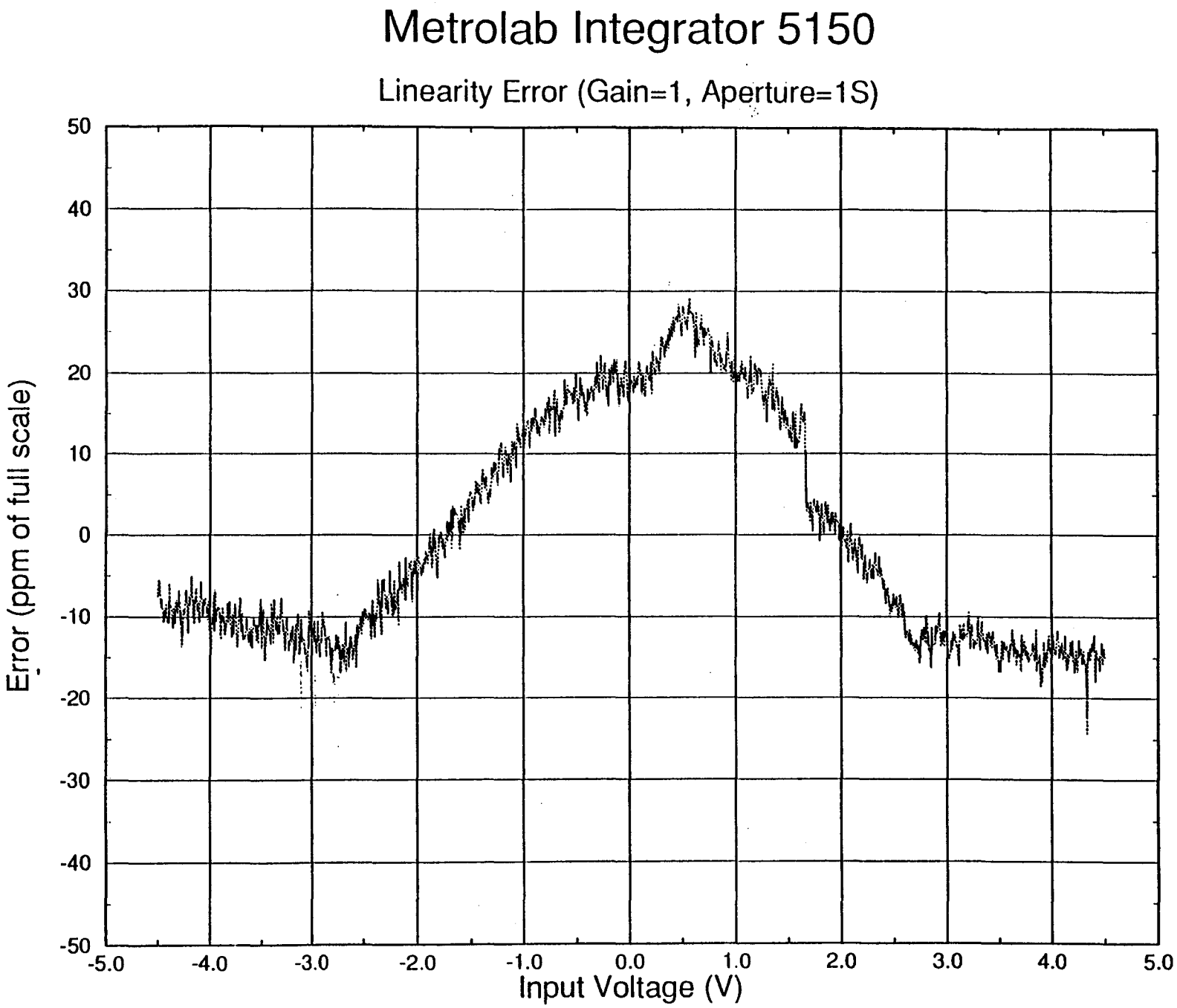

Metrolab Integrator 5150
Linearity Error (Gain=1, Aperture=1S)
Error (ppm of full scale)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
Input Voltage (V)

Fig 5

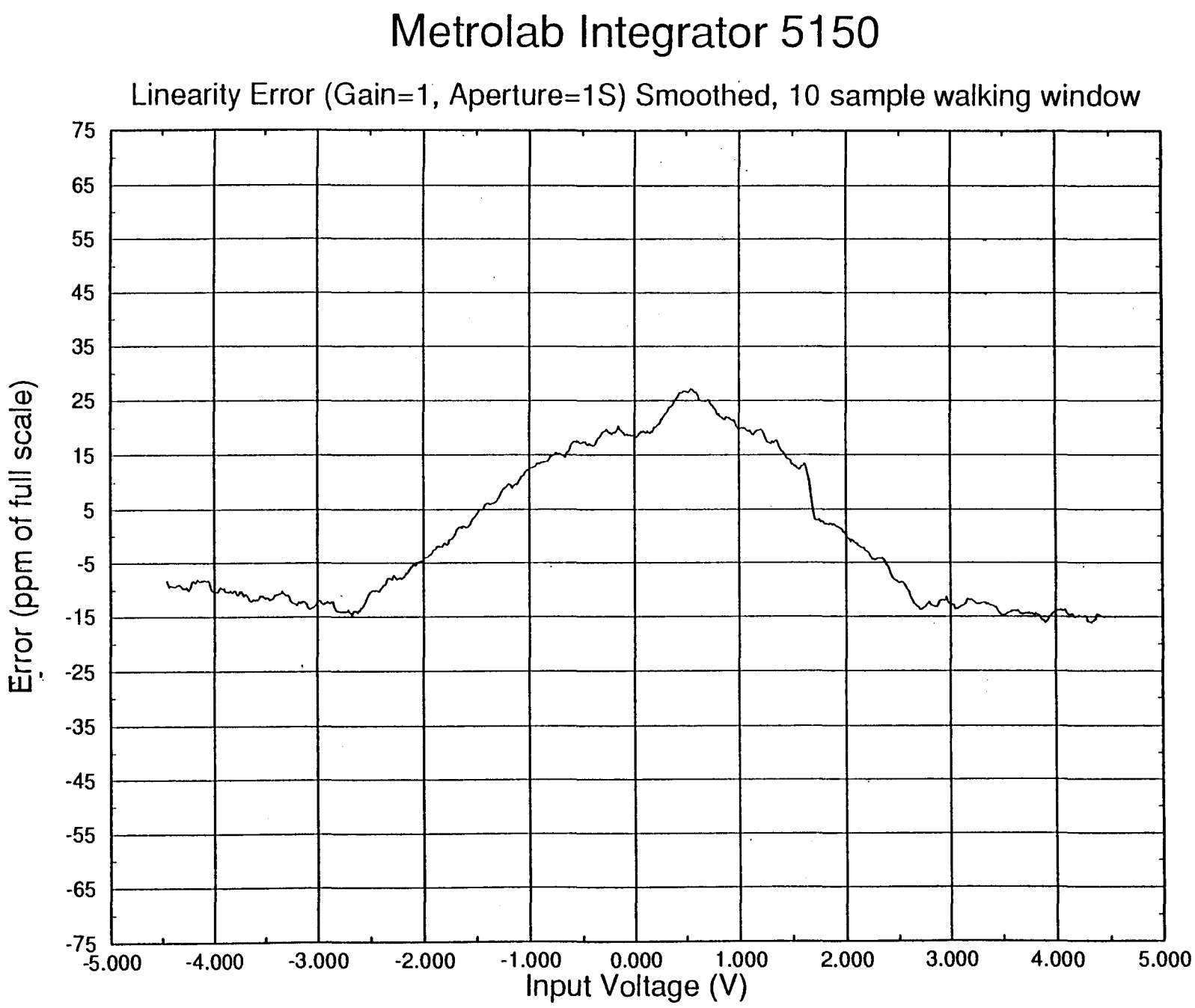

Metrolab Integrator 5150
Linearity Error (Gain=1, Aperture=1S) Smoothed, 10 sample walking window
Error (ppm of full scale)
75
65
55
45
35
25
15
5
-5
-15
-25
-35
-45
-55
-65
-75
-5.000
-4.000
-3.000
-2.000
-1.000
0.000
1.000
2.000
3.000
4.000
5.000
Input Voltage (V)

Fig 6

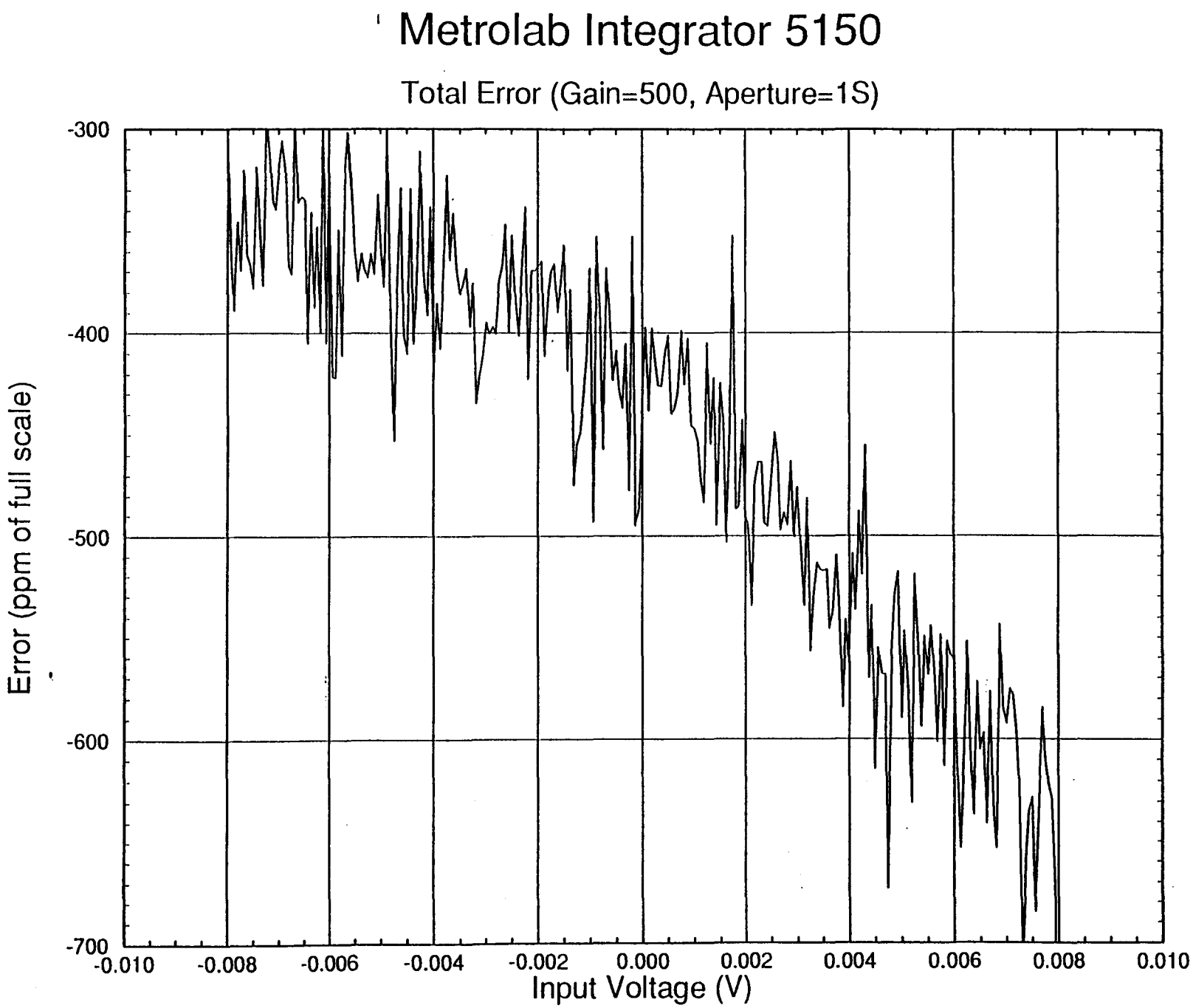

Metrolab Integrator 5150
Total Error (Gain=500, Aperture=1S)
Error (ppm of full scale)
-300
-400
-500
-600
-700
-0.010
-0.008
-0.006
-0.004
-0.002
0.000
0.002
0.004
0.006
0.008
0.010
Input Voltage (V)

Fig 7

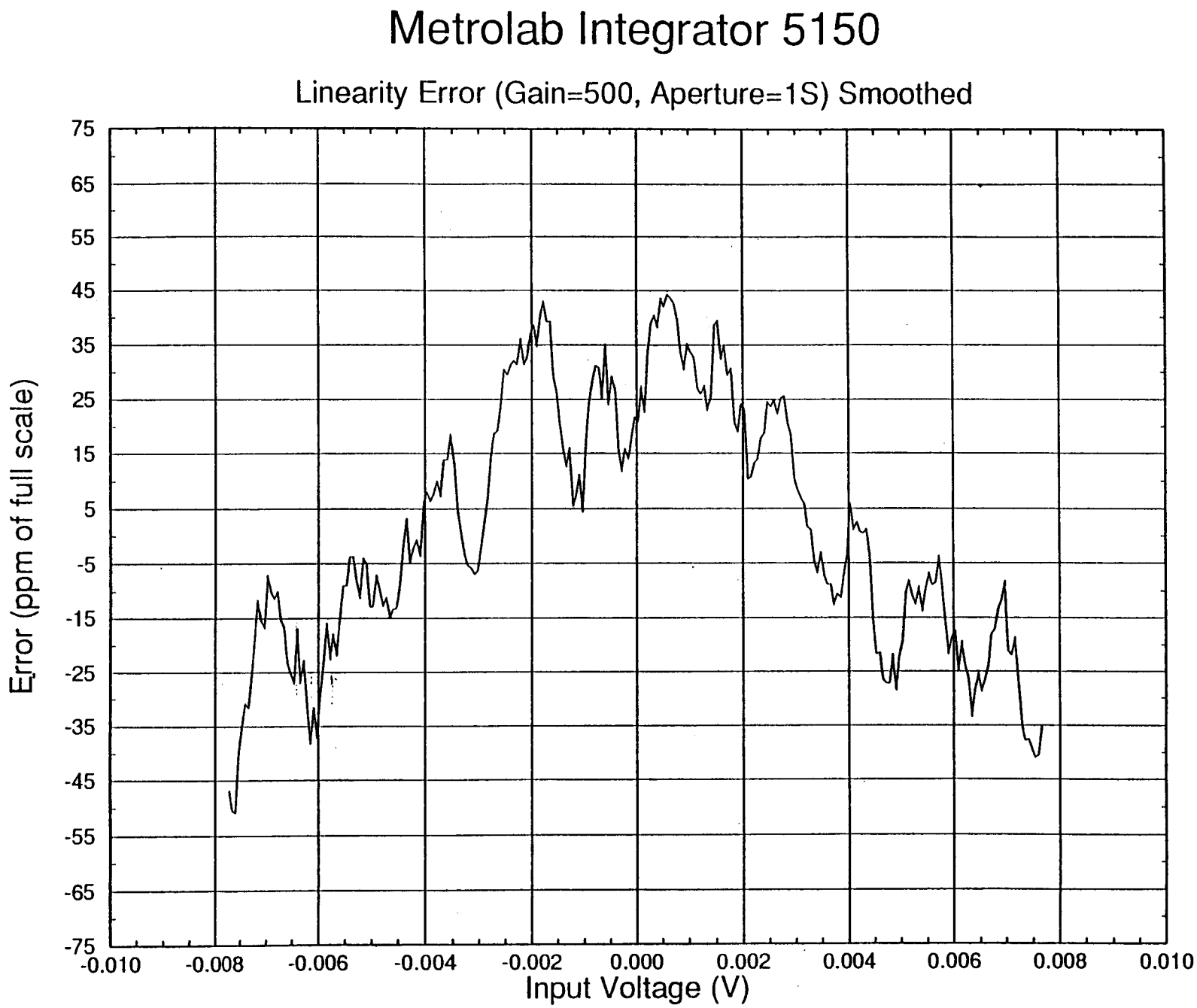

Metrolab Integrator 5150
Linearity Error (Gain=500, Aperture=1S) Smoothed
Error (ppm of full scale)
75
65
55
45
35
25
15
5
-5
-15
-25
-35
-45
-55
-65
-75
-0.010
-0.008
-0.006
-0.004
-0.002
0.000
0.002
0.004
0.006
0.008
0.010
Input Voltage (V)

Fig 8

8 hours 1025 points, U = 116 μV

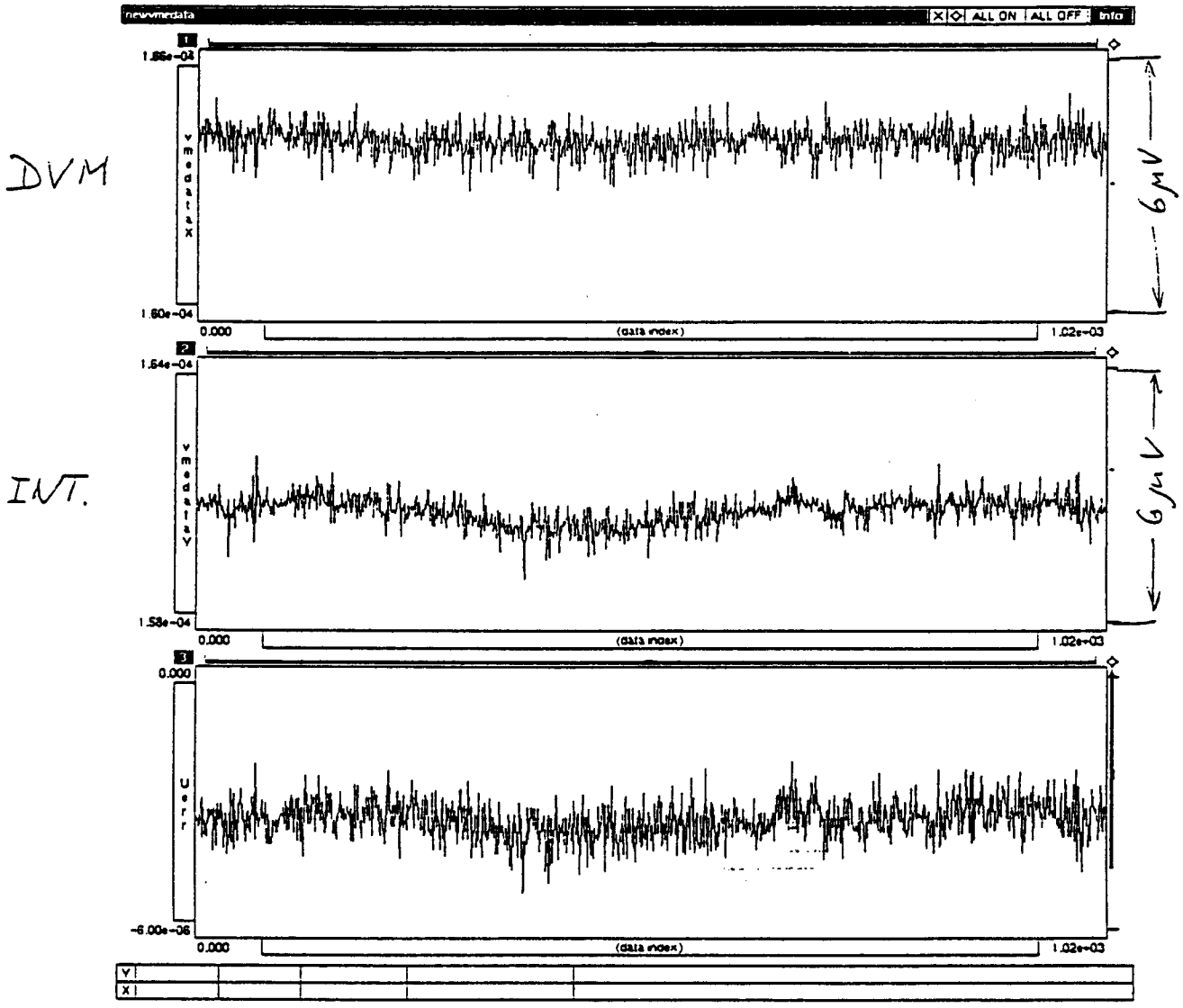


Fig 9

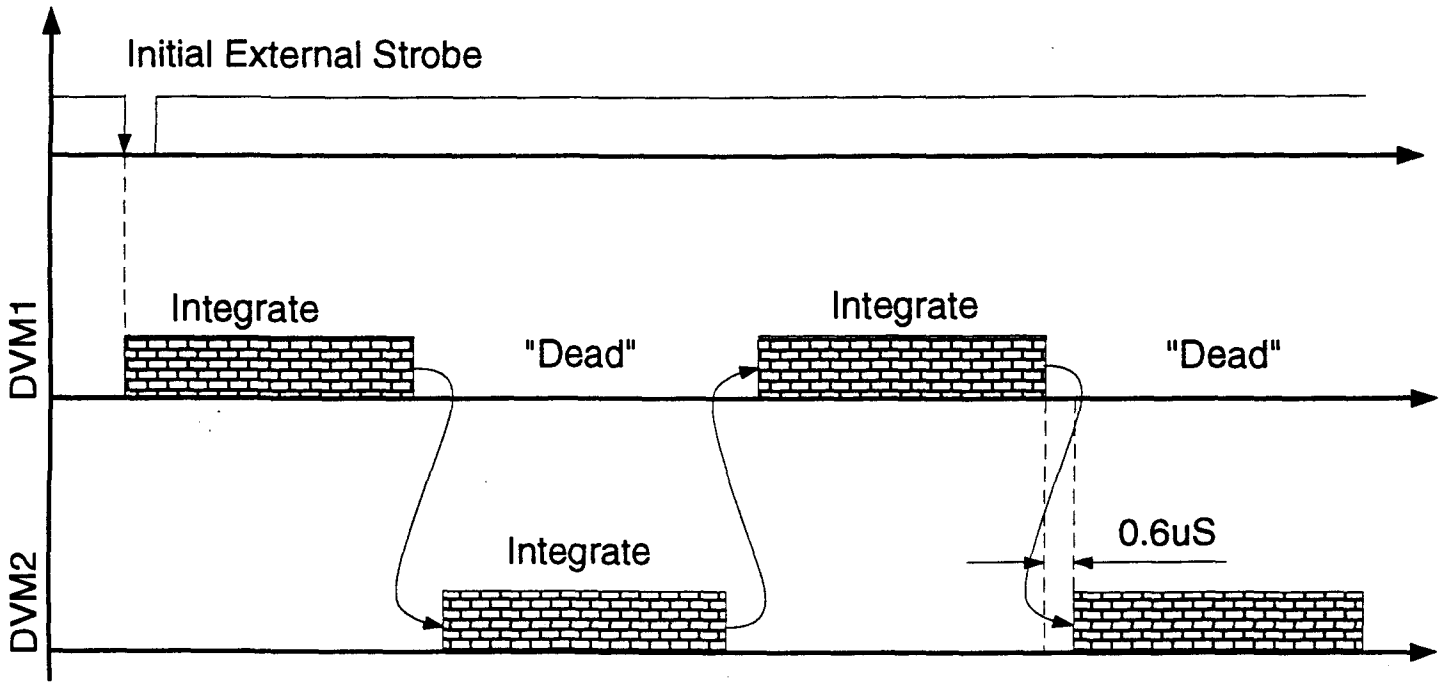

Initial External Strobe
DVM1
Integrate
"Dead"
Integrate
"Dead"
DVM2
Integrate
0.6uS

Fig 10

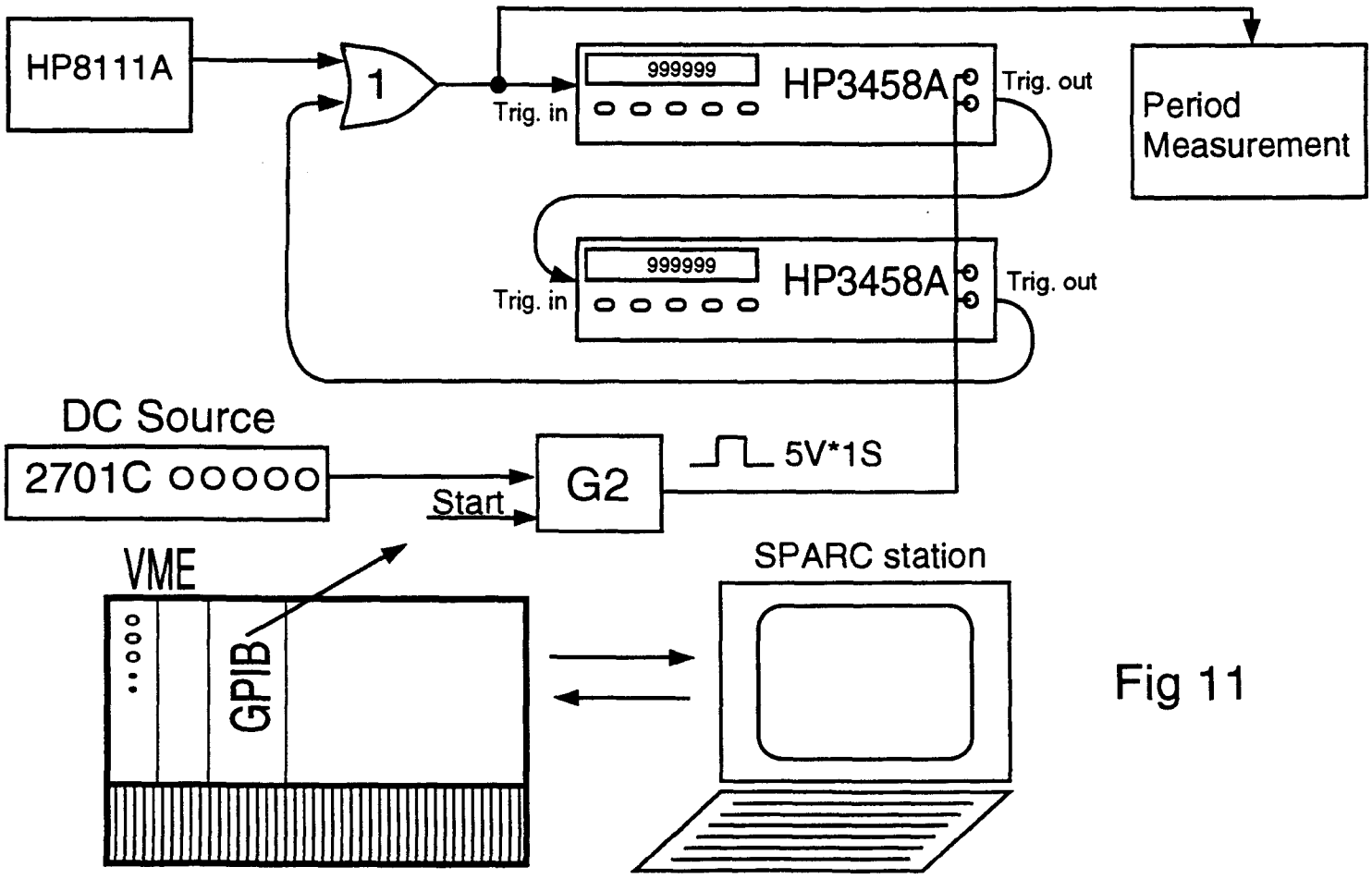

HP8111A
1
Trig. in
999999
HP3458A
Trig. out
Period Measurement
Trig. in
999999
HP3458A
Trig. out
DC Source
2701C
Start
G2
5V*1S
VME
GPIB
SPARC station

Fig 11

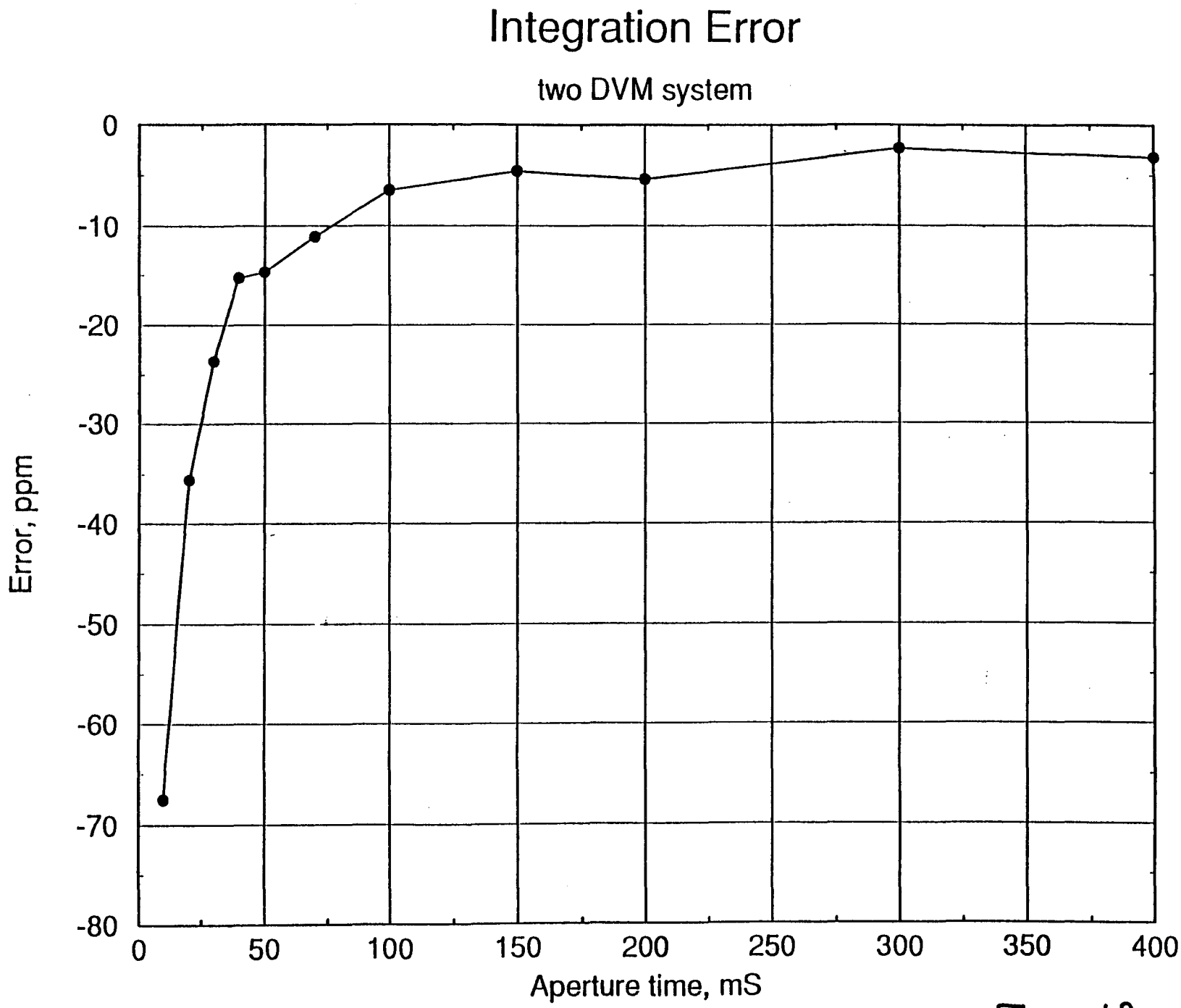

Integration Error
two DVM system
Error, ppm
0
-10
-20
-30
-40
-50
-60
-70
-80
0
50
100
150
200
250
300
350
400
Aperture time, mS

Fig 12

Third Draft
FINAL COPY

A NEW ROTATING-COIL TESLA-METER FOR DC MAGNETIC FIELDS UP TO 40 TESLAS

Morley J. Lush,
Rawson-Lush Instrument Co.,
Acton, Massachusetts

INTRODUCTION

I was very pleased to be invited to attend this Workshop. My company has been making magnetic field probes of the rotating-coil type for many years. I would like to describe for you some developments I have made which make possible an instrument which has already been tested up to 20 Teslas (200 kilogausses) at the MIT Magnet Laboratory and which I am confident ~~will reach~~ can be made for 40 Teslas if some laboratory ever makes a magnet which can reach this field strength. Another reason for my being here today is that I hope you will let me have your suggestions about what is needed by people working in magnetic fields. We have a lot of ability to make special equipment that larger companies do not want to bother with.

BACKGROUND

Coils of wire have been used for measuring magnetic fields since the earliest days of electrical measurements. By definition, they are perfectly linear with field strength. When you get twice as much voltage, you know that the field is exactly twice as strong. I hope that most of you are already familiar with Rotating-Coil Gaussmeters. I believe that my little company has made most of the many that have been used in the last forty years or so. Early models used the Rawson high sensitivity laboratory millivoltmeters as read-outs, without amplification of any kind. In more recent years, we have used the increased resolution and convenience of modern digital voltmeters.

One of our regular gaussmeters is shown in the first slide.

(Slide 1)

This particular instrument has a large coil, about two inches square. It will give a one digit indication for a field of only one microgauss! The coil is located in the bulb at the tip of the probe, and is rotated by a motor at the other end. A number of different sized coils are available. The one most often used is much smaller, only 3/16 inch diameter, rotating inside a tube, 1/4" (6.4 millimeters) outside diameter.

The coil must be rotated around one of its diameters, as shown in the next slide.

(Slide 2)

The voltage output of the coil is AC, at the rotation frequency, usually 25 or 30 Hertz. The coils are usually low in resistance and give a fairly high output voltage, so that thermal noise is rarely a problem. The magnetic field should be perpendicular to the axis of rotation, as field components along the axis do not produce any output. If you need to measure fields along the axis, we have a gear-driven coil arrangement.

(Slide 3)

The one shown here is an early one with two separate coils for the measurement of fields in three perpendicular directions. Notice that the axis of the coil driven by the gears is at right angles to the usual direction. This coil is sensitive to the field along the axis.

This brings me to the main subject of this presentation, the new TESLA-METER. I have been told that many people are working in high fields using cryogenic magnets, and a good reliable magnetometer is needed for use in the range of zero to 20 Teslas or higher. Although they can use Hall probes in the liquid helium, these need calibration at high field strengths. The magnets are usually solenoids with the field in the axial direction, and only the most expensive ones are uniform enough for NMR measurement. I have been working very hard to fill this need, and the new Type 788 is a result of this. Improvements over previous models have been made in a number of areas.

NEW AXIAL COIL DESIGN

In the previous design shown in the picture, it was difficult to get more than three digit stability in the output of the axial coil (the one driven by the gears). The outside diameter of the probe in this case was only a little more than one centimeter. The coil bearings were so close together that any loose fit in the bearings allowed the axis of rotation to shift, and this affected the output. In our new model, we have eliminated this by using spring-loaded conical bearings spaced further apart,as shown in this sketch.

(Slide 4)

We had to increase the outside diameter of the probe to 3/4 inch to do this, but we now get a stability of four or five digits in the readings, a truly remarkable increase. I have a sample of the improved coil structure, if you would like to see it after my talk.

DESIGN FOR LOW EDDY CURRENTS

Whenever you rotate a piece of conducting material in a strong magnetic field, eddy currents are produced which dissipate energy. I know most of you have people around who can calculate the amount of these currents, but I had to do it the hard way, myself! It took a while, with sketches of the probable current distributions followed by calculated current values. I checked the calculations by rotating a large copper tube in a convenient magnetic field and measuring the power losses. Knowing what the eddy currents would be made it possible to evaluate design changes until I could come up with a design which would work at very high fields and which we could build. It also makes it possible to calculate the torque required to rotate the design in the field. The new design has reduced eddy currents to very low values in two ways. First, insulating materials have been used wherever possible. Instead of rotating a metal shaft in a plastic bearing, it is now a plastic shaft rotating in a metal bearing. Our long shaft to the motor is now a fiberglass tube. The only rotating metal parts at the tip are the tiny tapered silver shafts and the coil itself.

VERY SLOW ROTATION RATE. Most important to the low eddy current losses is the use of a very low speed for the rotating coil. The present prototype has a rotation frequency of 5 Hertz and it reaches 20 Teslas without difficulty. At this very slow speed, the wear on the moving parts is very low. In addition, the probe outer tubing is filled with lubricating oil, so the rotating parts should last almost forever.

Here is a photograph of the prototype of our new type 788 Tesla-Meter.

(Slide 5).

This one has a speed of 5 Hertz, and it operated successfully in a field of 20 Teslas at the MIT Magnet Laboratory. I am now in the process of changing the rotation speed a further step down to 100 RPM or 1.666 Hz, at which speed I am confident that the instrument will have no difficulties going all the way to 40 Teslas. The magnet lab at MIT has already promised me a test at 30 Teslas. If any one of you knows of a 40 Tesla field I can borrow to test this new instrument, please let me know!

NEW ELECTRONIC CIRCUITS

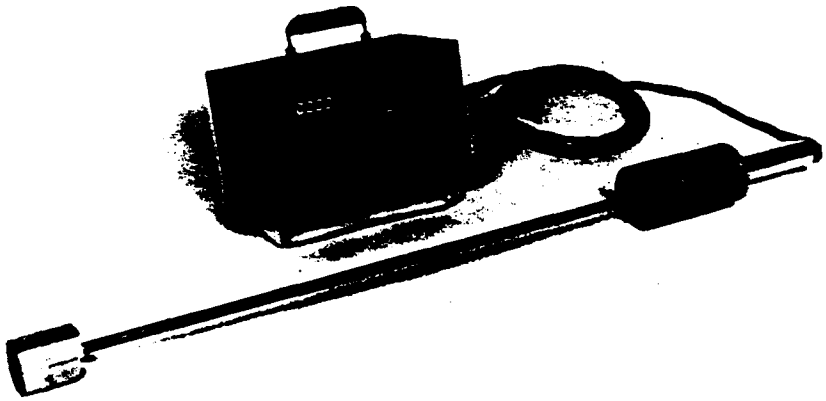
I have not yet said anything about the electronic circuits used with our rotating-coil magnetometers. Usually we can use a simple amplifier with a full-wave rectifier to provide DC for the digital voltmeter. This usually requires a low-pass filter to eliminate the ripple. A very long time-constant would be required at the new low frequency of 1.66 Hertz, so a different approach has been used here. I like to use an integrating amplifier with these rotating coils, because the amplifier output then is the waveform of the flux in the coil instead of the derivative of it. The 1/f frequency response of the amplifier makes the output independent of the rotation frequency, and high frequencies in the coil output due to the gears or bearing roughness are largely eliminated. When the integrating amplifier is used, the best way to get a DC output for the digital voltmeter is to measure the peak to peak value of the AC voltage. We accomplish this by two Sample and Hold amplifiers, one for the plus peak and the other for the negative. The sum of the two outputs is then applied to the DGVM. The SAH amplifiers are switched by pulses from two photochoppers controlled by a slotted disc on the motor shaft. The response to changes in the field is fast, because the amplifier outputs are being up-dated continuously with each revolution. A worm gear coil phase adjustment is provided to maximize the reading. Here is a simplified diagram of the electronic indicator circuit.

(Slide 6)

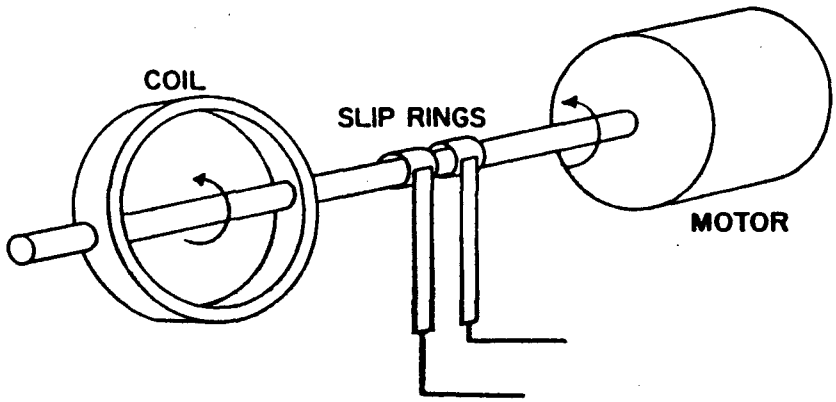
The circuit is actually a very narrow-band-width amplifier, with a correspondingly low noise level. Because of the low noise, three ranges can be provided, 0 -.39999 T, 0 - 3.9999 T, and 0 - 39.999 T, the ranges being obtained from high precision resistor dividers. With this circuit, you can get an indication from 0.1 gauss to 400,000 gausses, LINEAR ALL THE WAY. If the response is adjusted against an NMR standard at one convenient magnetic field, all readings will be inside .05% of full scale. Unlike NMR field meters, this one does not require uniformity of field over the coil volume, and it reads all the way down to zero. Try that on an NMR!

CONCLUSION. I have brought along with me bulletins showing many of the instruments my company can make, including the new one. ~~I also have printed copies of this talk.~~ I must say that my company is a very small one, but it has been making fine laboratory equipment since 1918. We have made thousands of rotating-coil gaussmeters in the last forty years or so. We can make special variations on any of these instruments, special probe lengths, ranges, dimensions, protective sleeves for very cold or very hot environments. Let us know what you need. I want very much to hear from you about other types of instruments we might be able to supply. I would like to have your names on our mailing list if you are interested. We have been advertising in the Review of Scientific Instruments for many years. I know I am enjoying this Workshop. I hope you are also. Thank you.

Rawson-Lush Type 905 Gaussmeter
One Microgauss to 20 Gausses

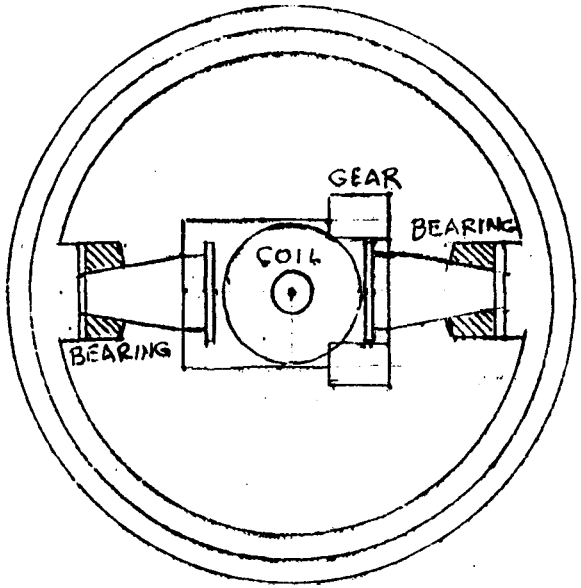


Operating Principle of the Rotating Coil Gaussmeter

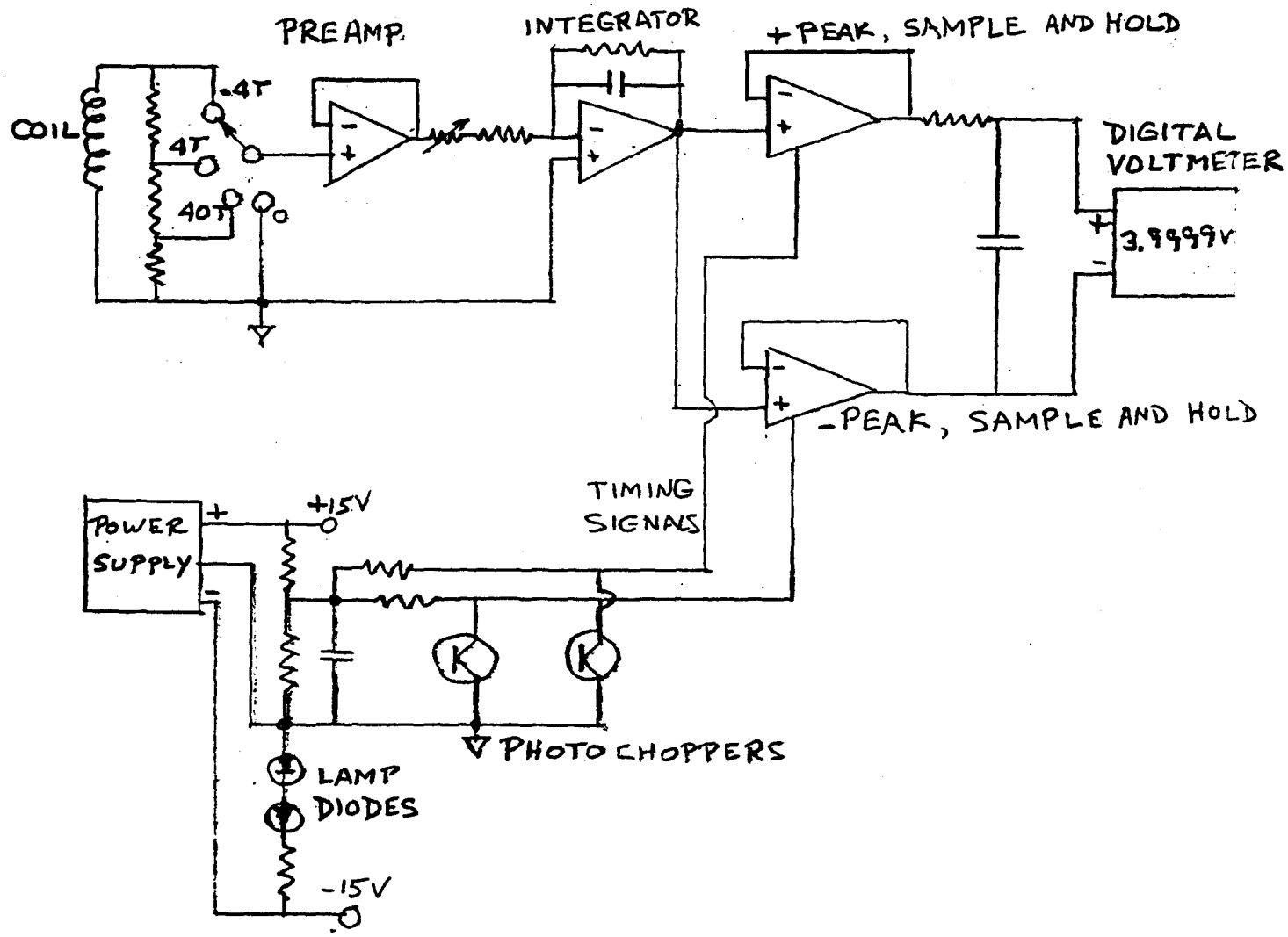


Gear-Driven Coil for Axial Field Measurement

Enlarged cut-away view: Probe tip


GEAR
BEARING
COIL
BEARING

T88 INDICATOR CIRCUIT



COMPARE DIGITAL, ANALOG BUCKING

Measuring coil:

1 m long, 2.5 cm diameter SSC mole (FA3)
Windings designed for analog bucking
Five windings: tangential, 2 dipole buck, 2 quad buck
Windings not connected on coil form (...digital bucking)
For analog bucking, connect coils in series temporarily,
beyond coil form
Also, take data with digital 3-winding program

"Air" magnet:

Eight precisely-placed, 2 m-long conductors (cf. A. Jain talk)
I = 1 kA, about ~~MM~~ dipole field 0.18 T
strong quadrupole (7%)
higher terms fall of quickly with increasing multipolarity

Harmonic coefficients:

Usual system -- $10^4/B_0$
Reference radius is 1 cm

Mean values:

Dipole amplitude -- from bucking windings, same for all
Dipole phases -- slightly different

Quad amplitude -- from bucking windings (except for the 3-winding digital data), same to within 1/1000 even for 3-winding data
Quad phases -- most of the difference from difference in dipole phase

Sextupole, octupole -- amplitudes very close for analog and 5-winding data, small phase difference; 3-winding data not quite as good

Decapole, Dodecapole -- differences not understood (this is work in progress)

14-pole, 16-pole -- similar to sextupole, octupole

R.M.S variation:

analog, 5-winding digital -- comparable, with 5-winding slightly better in some cases

3-winding digital -- much larger than the other two, presumably due to lack of quadrupole bucking

COMPARISON OF VARIOUS BUCKING SCHEMES -- MOLE FA3 IN AIR MAGNET (1000A)

Prog.	Run No.	b0	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12
MA1	FA3001.024	-3861.9	-612.5	-13.52	-14.17	0.39	3.00	0.17	-0.37	0.00	0.00	0.00	0.00	0.00
MOLE66	FA3001.025	-3820.3	-608.6	-14.48	-14.06	-0.06	5.97	0.27	-0.37	0.00	0.00	0.00	-0.01	0.00
MDQ6	FA3001.026	-3877.6	-612.0	-13.88	-14.10	0.31	5.94	0.18	-0.37	-0.01	0.00	0.00	0.00	0.00

Prog.	Run No.	a0	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12
MA1	FA3001.024	-9224.1	-285.8	35.68	-12.73	14.42	0.26	-1.56	-0.02	0.07	0.00	0.00	0.00	0.00
MOLE66	FA3001.025	-9241.4	-290.8	35.65	-13.00	14.45	0.79	-1.57	-0.02	0.06	0.01	0.00	0.02	0.01
MDQ6	FA3001.026	-9217.5	-285.7	35.58	-12.76	14.42	0.72	-1.56	-0.02	0.07	0.00	0.00	0.00	0.00

Prog.	Run No.	sig-b0	sig-b1	sig-b2	sig-b3	sig-b4	sig-b5	sig-b6	sig-b7	sig-b8	sig-b9	sig-b10	sig-b11	sig-b12
MA1	FA3001.024	24.2	2.4	0.18	0.09	0.03	0.03	0.01	0.02	0.01	0.01	0.01	0.00	0.01
MOLE66	FA3001.025	40.8	3.6	1.17	0.34	0.32	0.14	0.12	0.09	0.07	0.06	0.05	0.04	0.02
MDQ6	FA3001.026	39.4	2.0	0.11	0.04	0.02	0.04	0.01	0.01	0.01	0.00	0.00	0.00	0.00

Prog.	Run No.	sig-a0	sig-a1	sig-a2	sig-a3	sig-a4	sig-a5	sig-a6	sig-a7	sig-a8	sig-a9	sig-a10	sig-a11	sig-a12
MA1	FA3001.024	10.1	1.4	0.15	0.07	0.06	0.03	0.01	0.02	0.01	0.01	0.01	0.00	0.01
MOLE66	FA3001.025	16.8	4.6	0.83	0.22	0.27	0.29	0.08	0.09	0.07	0.05	0.05	0.03	0.03
MDQ6	FA3001.026	16.9	1.2	0.15	0.05	0.03	0.03	0.01	0.01	0.01	0.00	0.01	0.00	0.00

MA1: ANALOG BUCKING MOLE66: 3 WNDG. DIGITAL MDQ6: 5 WNDG. DIGITAL

RHIC DIPOLE INTEGRAL FIELD

MEASURED WITH A STATIONARY COIL

People:

G. Ganetis, J. Herrera, R. Hogue, A. Jain, R. Thomas,
P. Wanderer, E. Willen

Items affecting design of measurement system:

Accelerator requirement for reproducibility:
r.m.s fractional variation of integral $< 5 \times 10^{-4}$

$L_{iron} = 9.64$ m
Magnet coil inner diameter = 80 mm
Sagitta = 46 mm
size of sagitta, aperture => curved (flexible) coil

All magnets will be measured warm, not all cold
=> nice to have same hardware for warm, cold

warm: 30A => 0.02 T
cold: 5 kA => 3.45 T

Magnet diode => warm measurement is unipolar

Advantageous to be independent of angular orientation
=> two coils, orthogonal

RHIC STATIONARY INTEGRAL DIPOLE COIL

L = 9.8 m (= L_{Fe} + 2 x 4 x inner coil diameter)
radius = 25.4 mm
no. turns = 30 per coil (Litz wire...aggh!)
2 coils, orthogonal

CURRENT WAVEFORM

WARM MEASUREMENTS:

dI/dt = 60 A/sec (30A, 500 ms) => 0.6 V signal

HP3458, direct integration of voltage

COLD MEASUREMENTS:

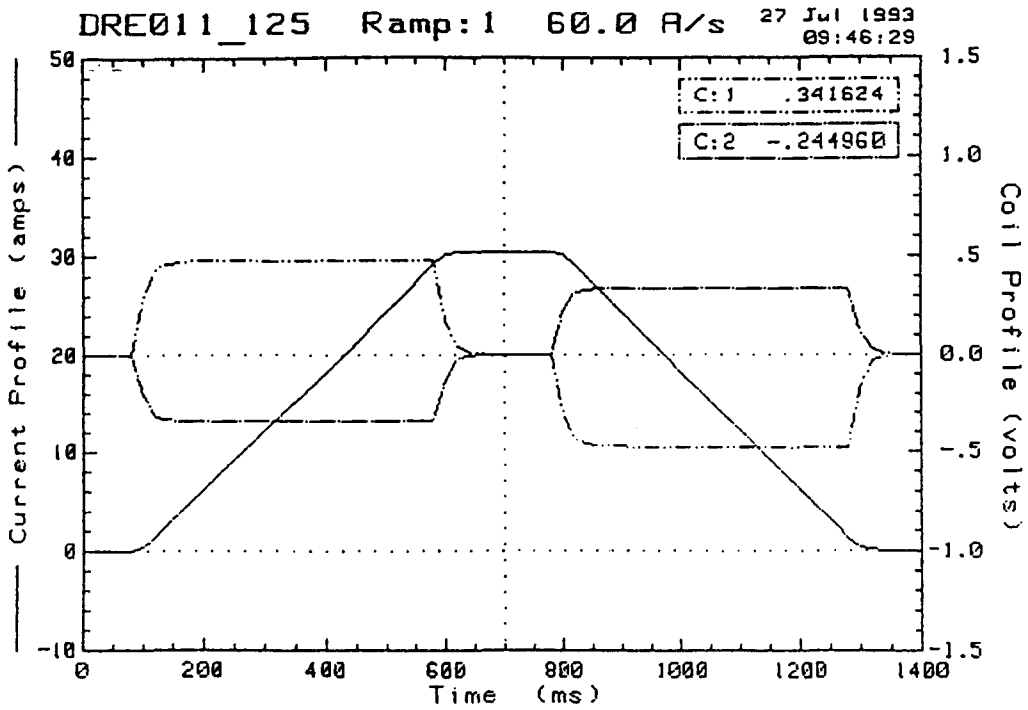
dI/dt = 83 A/sec (accelerator design - 60 sec, 5 kA)
=> 0.8 V signal

HP3458, integrate voltage for 10 power line cycles, with 2ms deadtime for readout =>

382 points/ramp (plus 40 more at beginning and end of ramp to establish endpoints) =>

can calculate integral field for many intervals of current

Room Temperature Measurement

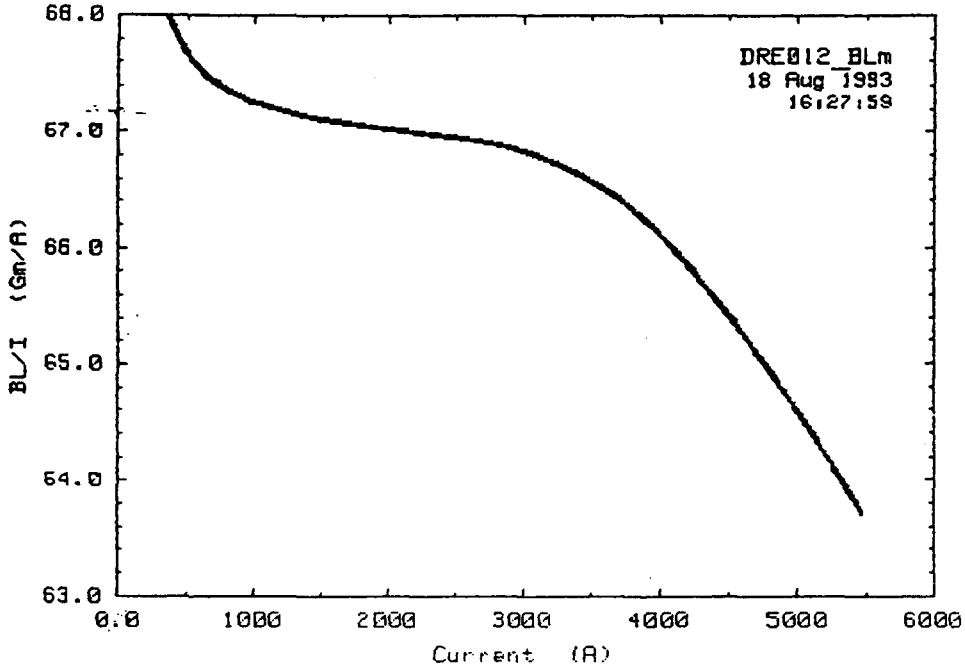


	09:46:29	Ramp:	60.0	.010	30.401	.201971	66.459275
	09:46:39	Ramp:	60.0	.010	30.400	.201975	66.459459
	09:46:48	Ramp:	60.0	.009	30.400	.201972	66.458277
	09:46:56	Ramp:	60.0	.008	30.400	.201967	66.454623
	09:47:05	Ramp:	60.0	.008	30.400	.201970	66.456284
	09:47:14	Ramp:	60.0	.008	30.399	.201978	66.458350
	09:47:23	Ramp:	60.0	.007	30.399	.201979	66.458336
	09:47:32	Ramp:	60.0	.007	30.399	.201970	66.456716
	09:47:41	Ramp:	60.0	.006	30.398	.201966	66.454764
	09:47:50	Ramp:	60.0	.006	30.398	.201972	66.456681
2	09:47:50	Ramp:	60.0	.008	30.399	.201972	66.457277 (2182)1643

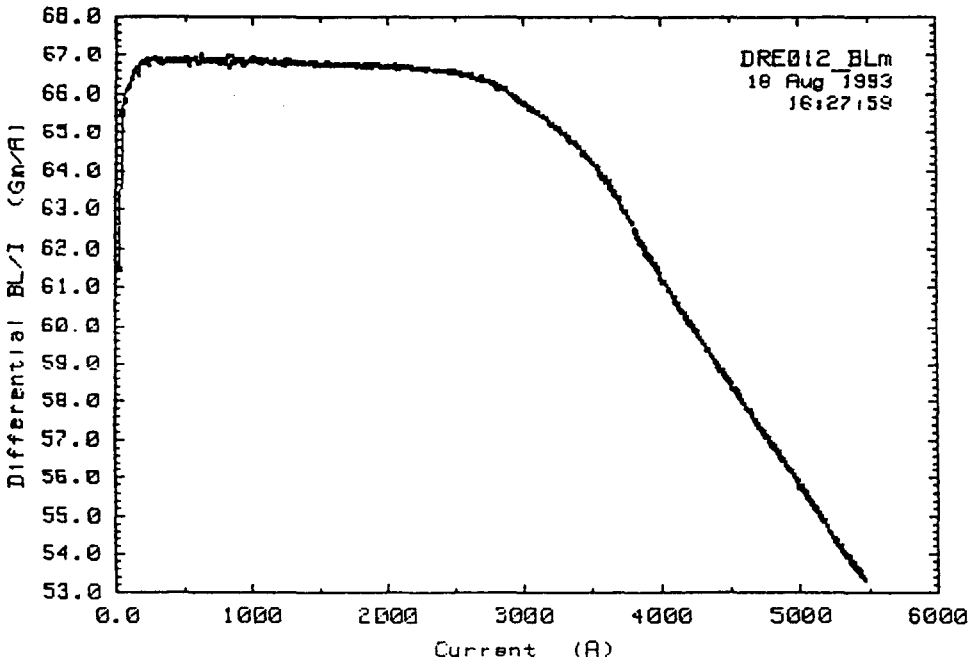
C1 +0.3416 C2 -0.2450 sqrt(C1^2+C2^2) +0.4204 ABS(C1)-ABS(C2) +0.0967

Fractional r.m.s. = 0.2×10^{-4}

BL/I vs. Current



Differential BL/I vs. Current



ACCURACY

Compare with integral from mole z-scan to bring out any major errors. (More work would be needed to make precise comparison.)

DRE012 Transfer Function		
Current	**Z-scan**	**Integral Coil**
660 A, 660 A	66.77	67.46
1450 A, 1447 A	66.80	67.11
2400 A, 2406 A	66.74	66.96
5000 A, 5010 A	64.48	64.56

SENSITIVITY TO ORIENTATION

Condition	Line Labels	Result (WARM)
C1 positive		
C1 ≈ 0.34, C2 ≈ 0.24	2, 3, 4	66.4565
C1 ≈ 0.24, C2 ≈ 0.34	6, 7, 8	66.4709
C1, C2 about equal	9, 10, 11	66.4621
C1 ≈ 0.11, C2 ≈ 0.41	12, 13, 14	66.4892

SHORT-TERM VARIATION (fractional r.m.s.)

Includes effect of setting coil angle to make coil amplitudes about equal, changing coil angle, then resetting for equal amplitudes --

warm: 0.2×10^{-4} cold: 0.1×10^{-4}

(more work is needed, but the magnet was taken away...)

Design of a Fluxgate Probe for Quadrupole Center Measurements

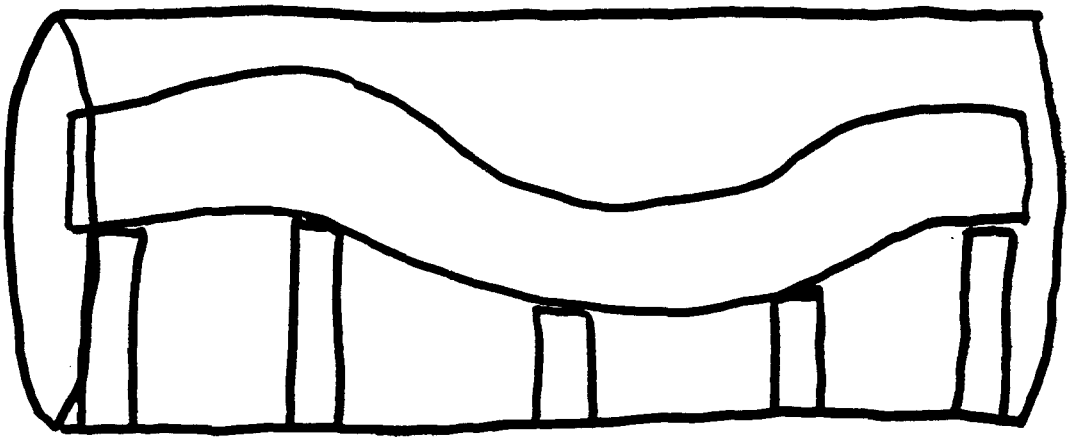
Zachary Wolf

SSC Laboratory

September 28, 1993

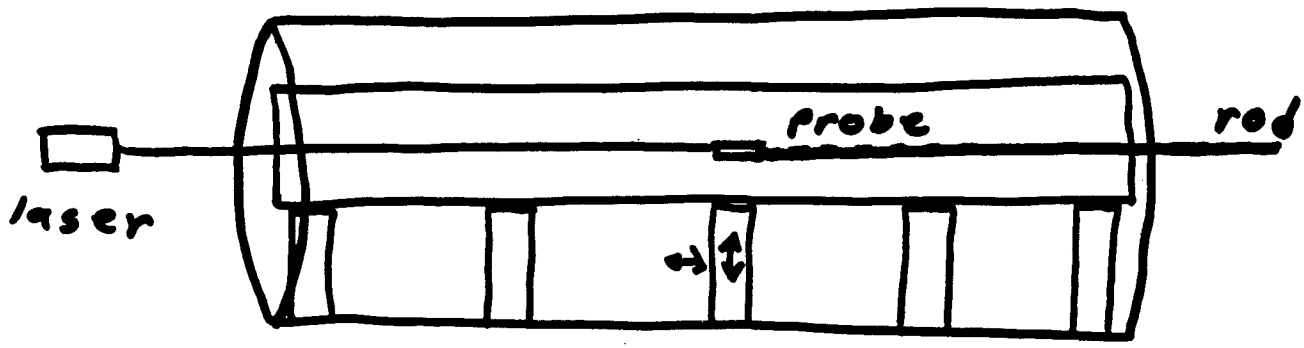
Measurement Problem

The interaction region quadrupoles are 15 m long and must remain straight to 0.2 mm.

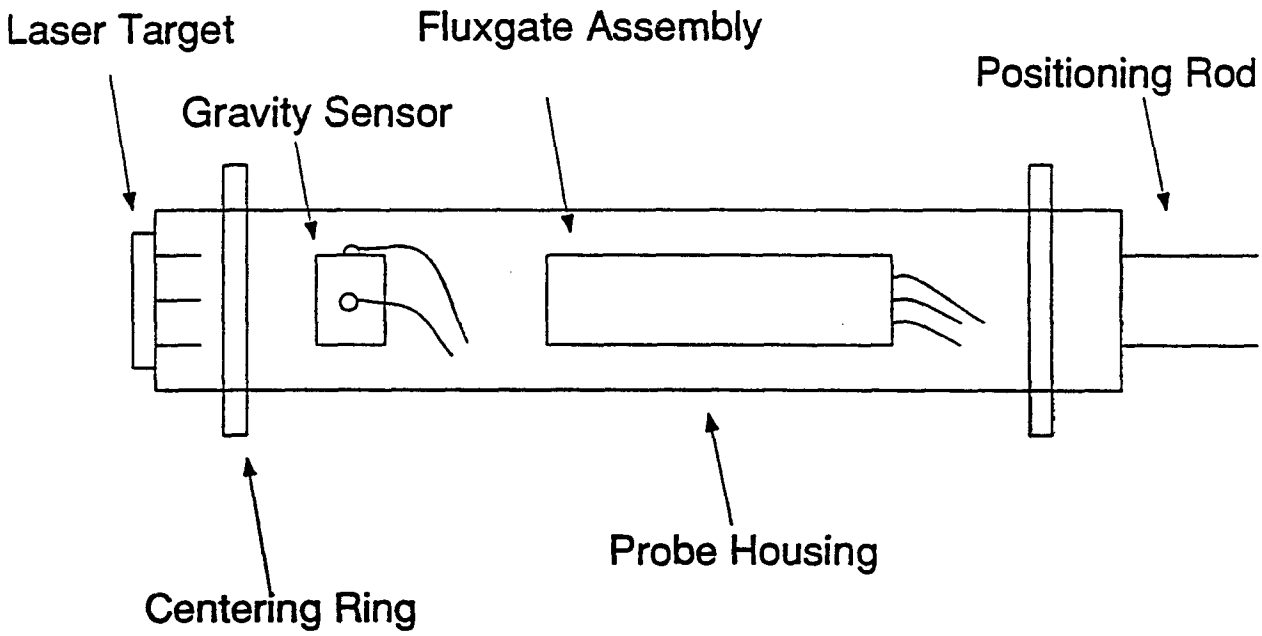


We need a device which allows us to adjust the support posts to the correct position.

Also "dipole center"



We use a reference laser beam and adjust the supports until the center of the field is on axis of the beam.



$$\bar{r}_{\ell c} = \bar{r}_{\ell t} + \bar{r}_{t f} + \bar{r}_{f c}$$

measure

calibration

measure

Figure 1

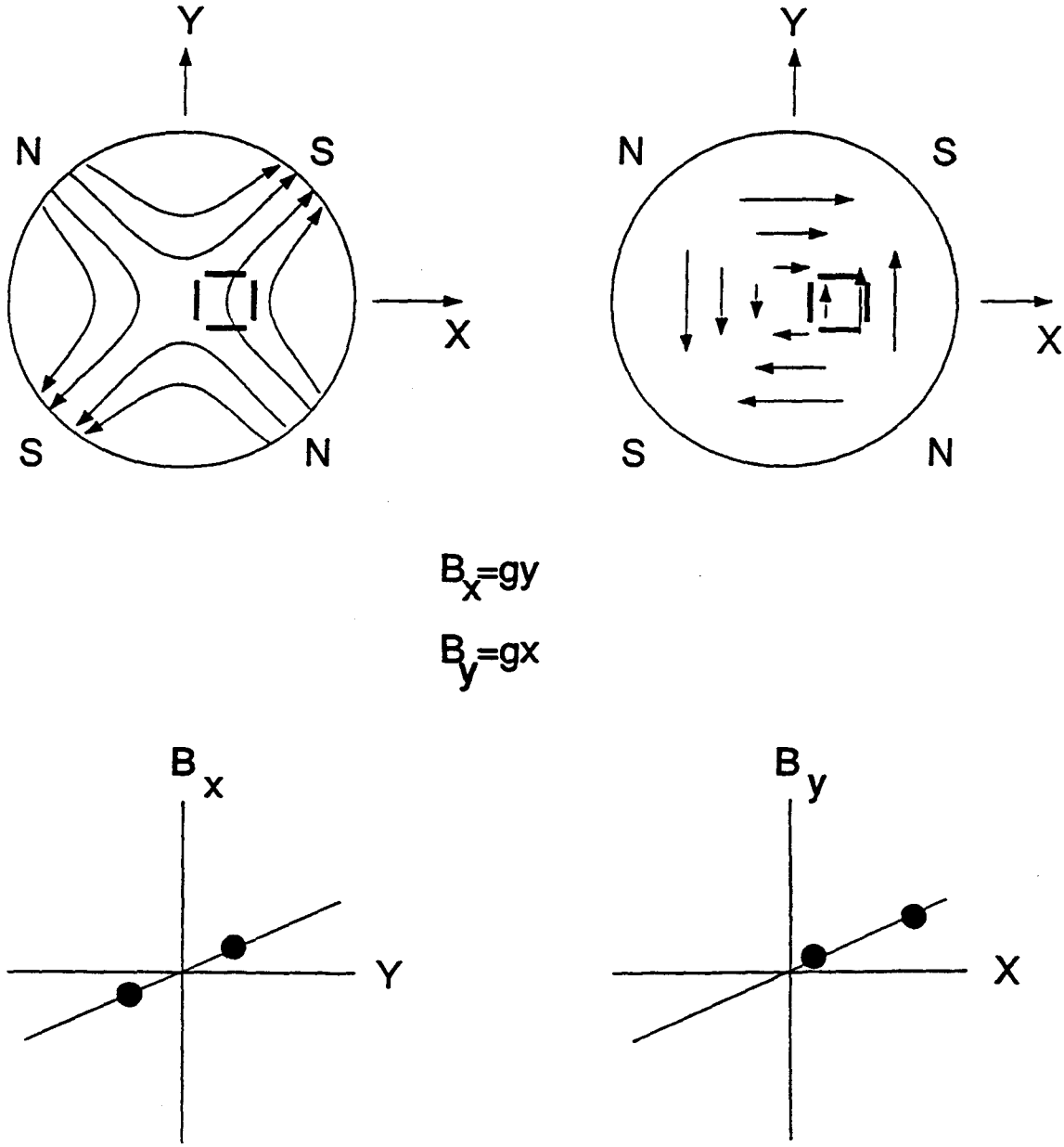


Figure 3

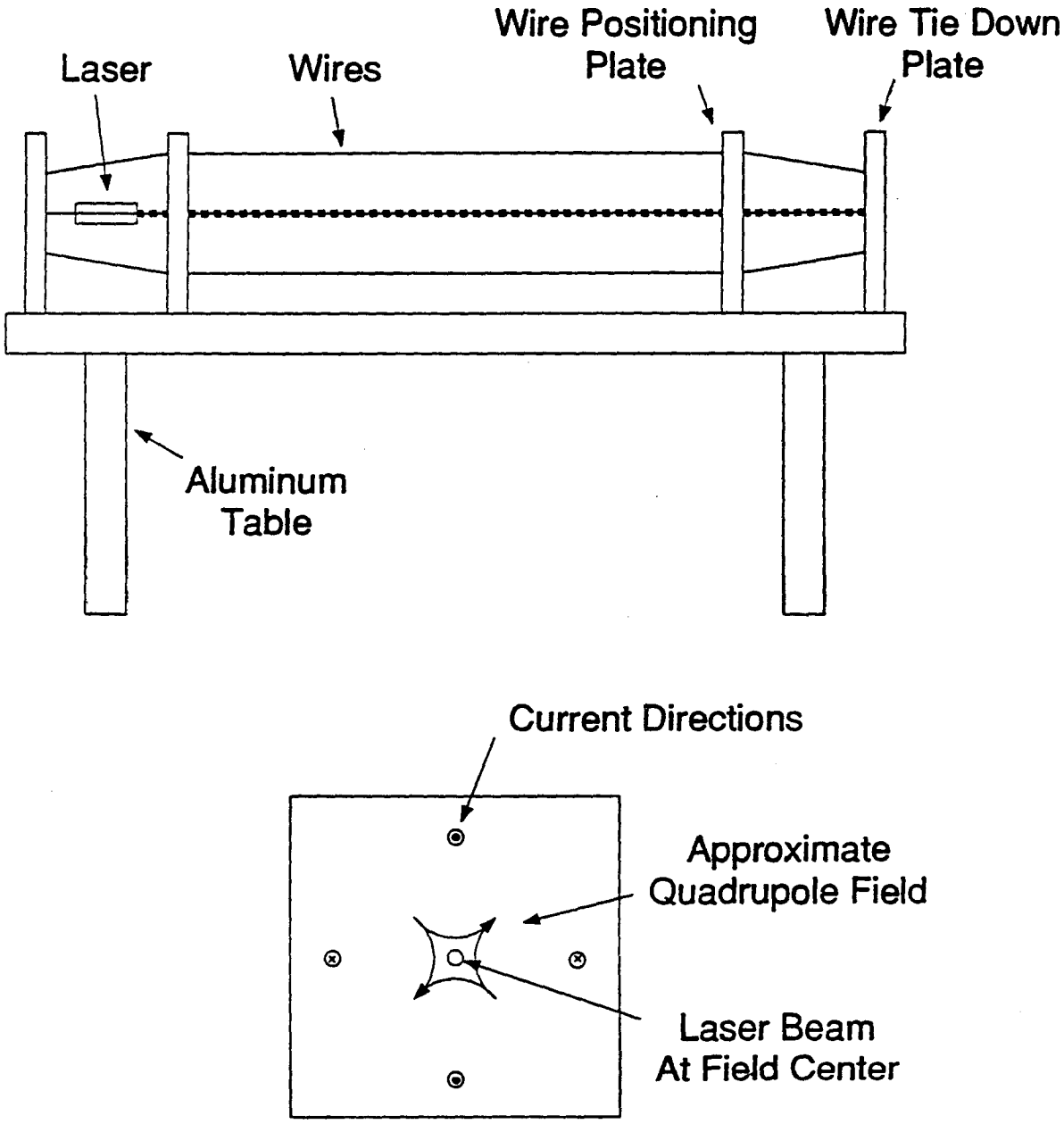

Laser
Wires
Wire Positioning Plate
Wire Tie Down Plate
Aluminum Table
Current Directions
Approximate Quadrupole Field
Laser Beam At Field Center

Figure 4

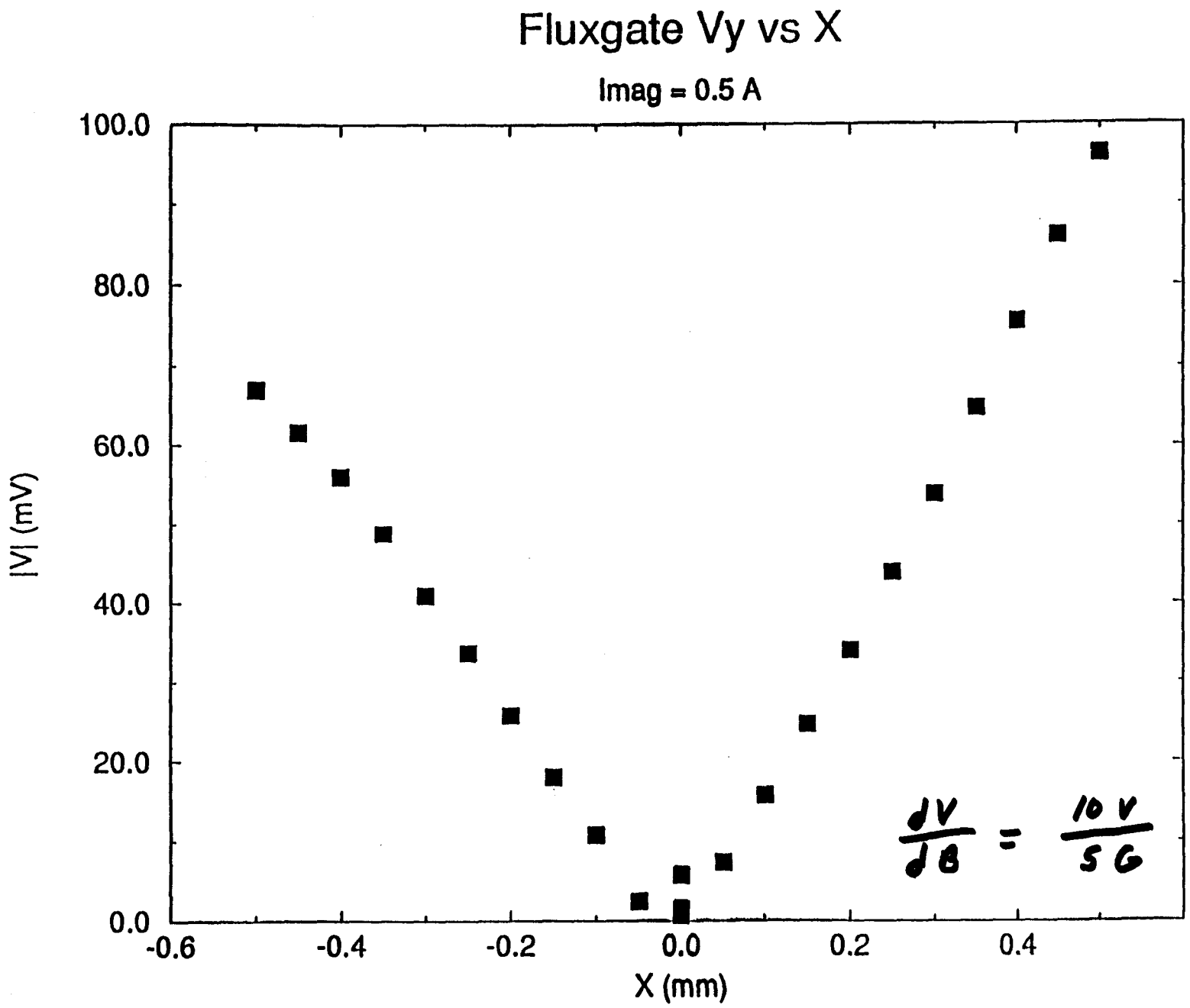

Fluxgate Vy vs X
Imag = 0.5 A
100.0
80.0
60.0
40.0
20.0
0.0
|V| (mV)
-0.6
-0.4
-0.2
0.0
0.2
0.4
X (mm)
dV/dB = 10 V / 5 G

Figure 4

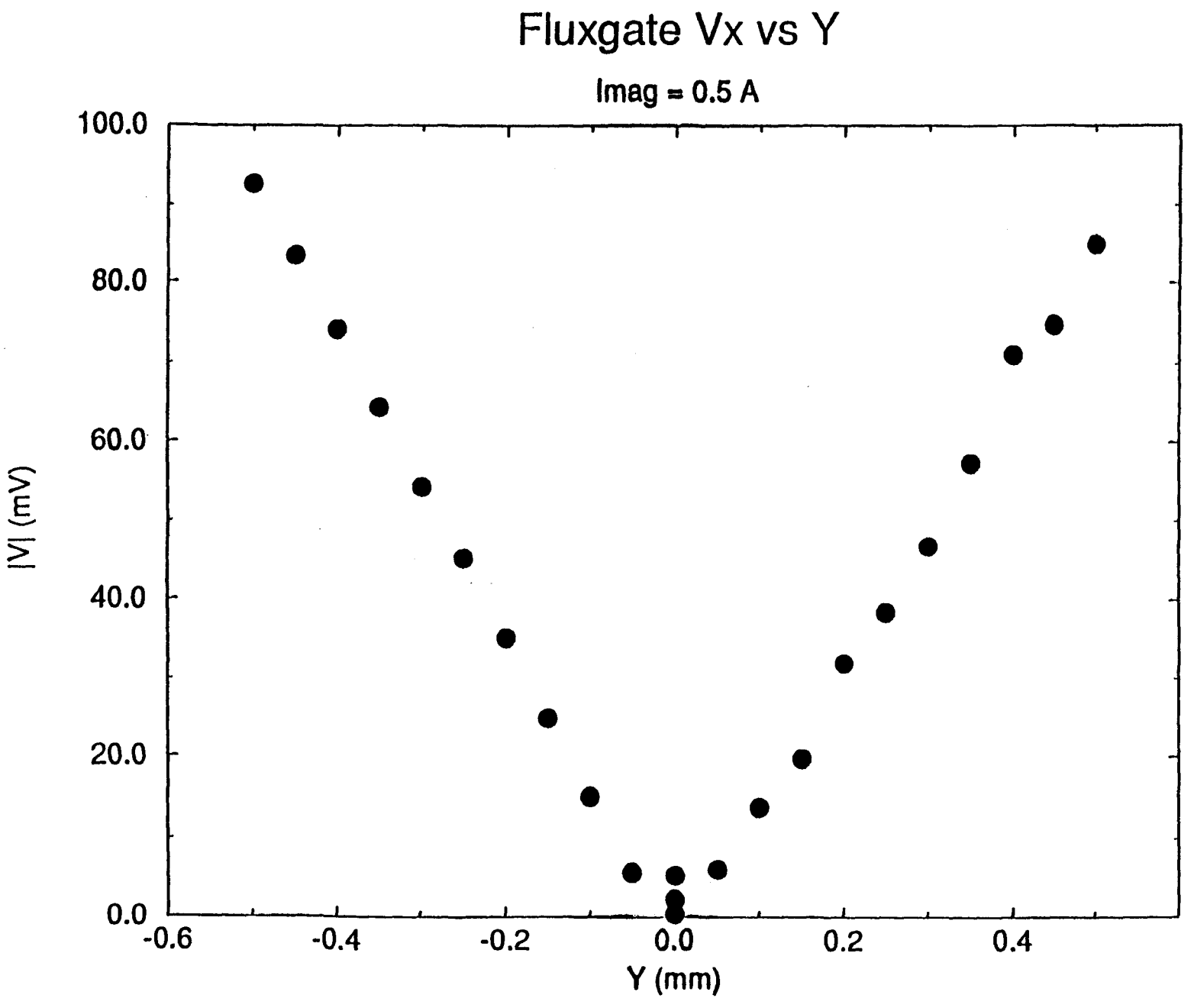

Fluxgate Vx vs Y
Imag = 0.5 A
100.0
80.0
60.0
40.0
20.0
0.0
|V| (mV)
-0.6
-0.4
-0.2
0.0
0.2
0.4
Y (mm)

Figure 3

Status

Our first probe is built. It uses a single flugate to measure B_x and another for B_y. The data acquisition system and software is complete. The calibration stand is almost complete. This probe requires calibration and will be ready to use.

The parts for our second probe using the custom fluxgate assembly are here. Assembly will begin soon.

Other uses: compare to stretched wi
"dipole center", other assembly use

C. REYMOND

METROLAB

NEW PRODUCTS

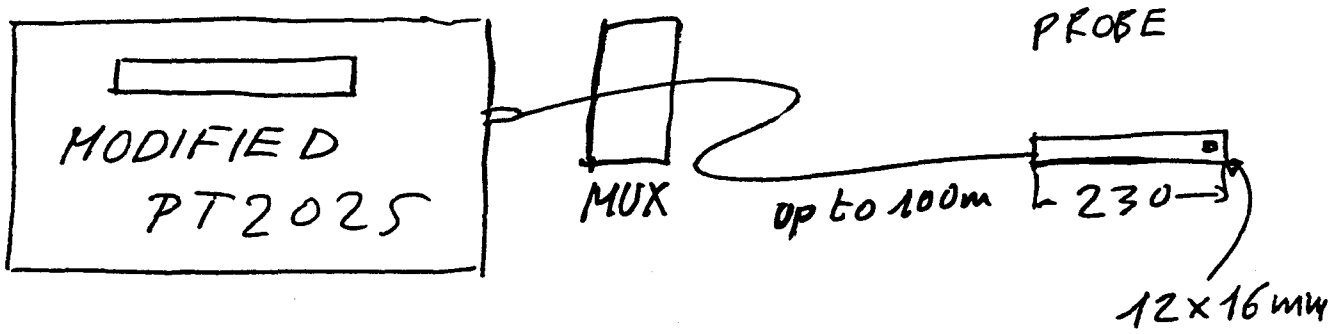
- EPR PROBE : 10 ~ 30 Gauss

- NMR MULT-PROBES SYSTEM FOR MAPPING

- FLIP-COIL : 1 → 100 Tesla

EPR / ESR / ? / PROBE

TYPE 1072-5



- RANGE: 30 - 90 MHz (10 - 30 Gauss)
- RESONANCE FREQUENCY: 2,8016(2) MHz/G
- ABSOLUTE PRECISION: ≈ 30 ppm
- STANDARD DEVIATION: ≈ 1 ppm

1062 INTEGRATED NMR PROBE

The 1062 Integrated Probe combines the function of the 1030 amplifier and the 1060 NMR Probe in the same housing that the 1060 Probe.

To be connected to Teslameters model : BENCH : PT 2025
RACK 19" : PT 4025

Main features :

- 0.043T to 2.1T sample (^1H)
- 1.5T to 13.7T D_2O sample (^2H)
- Rugged construction
- Automatic probe identification
- Axial and Transverse measurements
- 8 probes can be multiplexed through the multiplexer 2030.

Specifications

Active measuring volume: dia 4 x 4.5mm to dia 8 x 4.5mm

Temperature dependence of the probes less than 100 ppb/°C

The (^1H) probe is built with a solid sample containing a large amount of hydrogen.

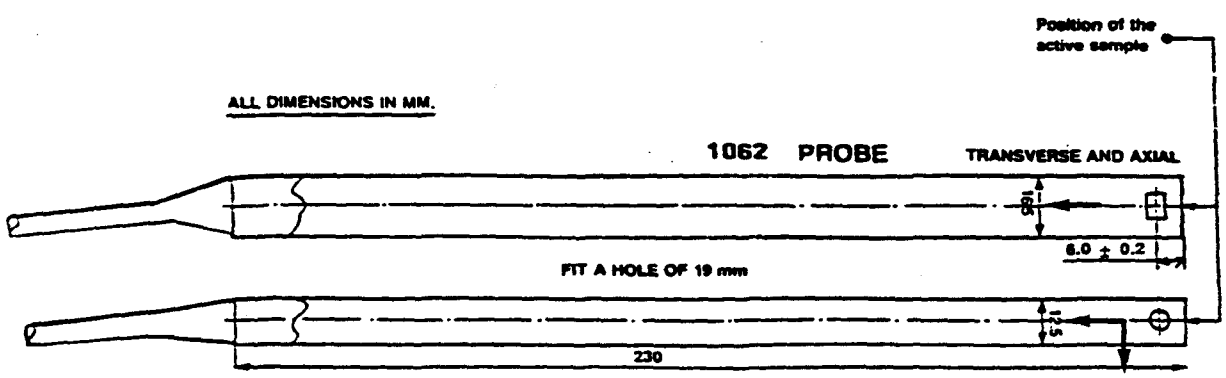
The (^2H) probe is built with a sample of D_2O (heavy water) and consequently cannot be exposed below freezing point.

External dimensions : 16.5 x 12.5 x 230mm; fit hole diameter of 19mm.

Housing : CuBe.

Integral 10m length standard cable. For special lengths, up to 100m, consult factory.

Special low profil cable can be supplied. RF COAX DIA 1.05mm + signal 5 wires shielded cable DIA about 3mm, length up to 18 meters.



110, ch. du Pont-du-Centenaire
CH-1228 Geneva/Plan-les-Ouates
Switzerland

Telephone 41 (22) 794 11 21
Telefax 41 (22) 794 11 20

Bank. Crédit Suisse Genève
No. 443 820-51

METROLAB

Instruments SA

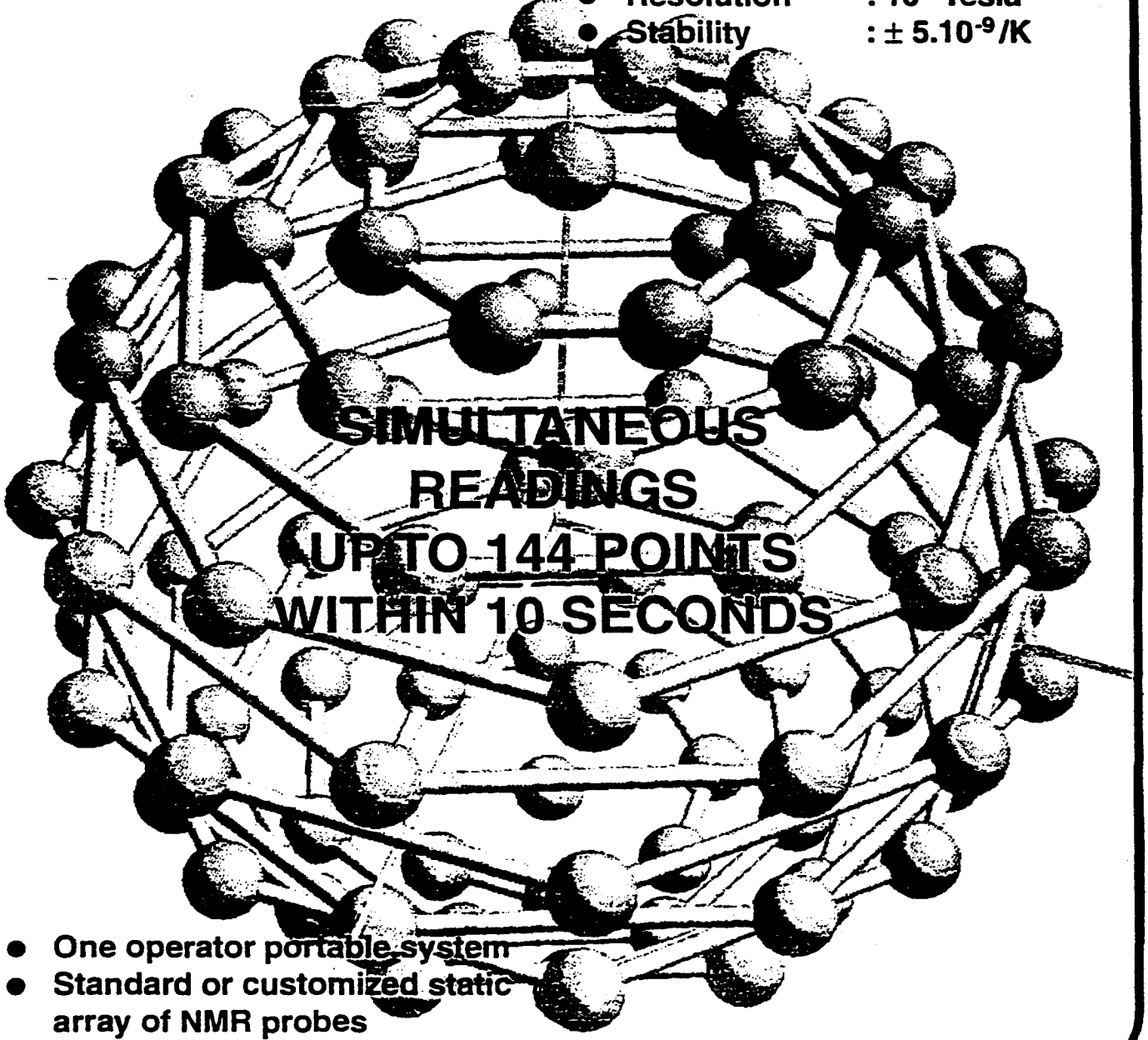
NMR MAGNETIC FIELD CAMERA

MFC 3035

3035/93/07

For magnet mapping

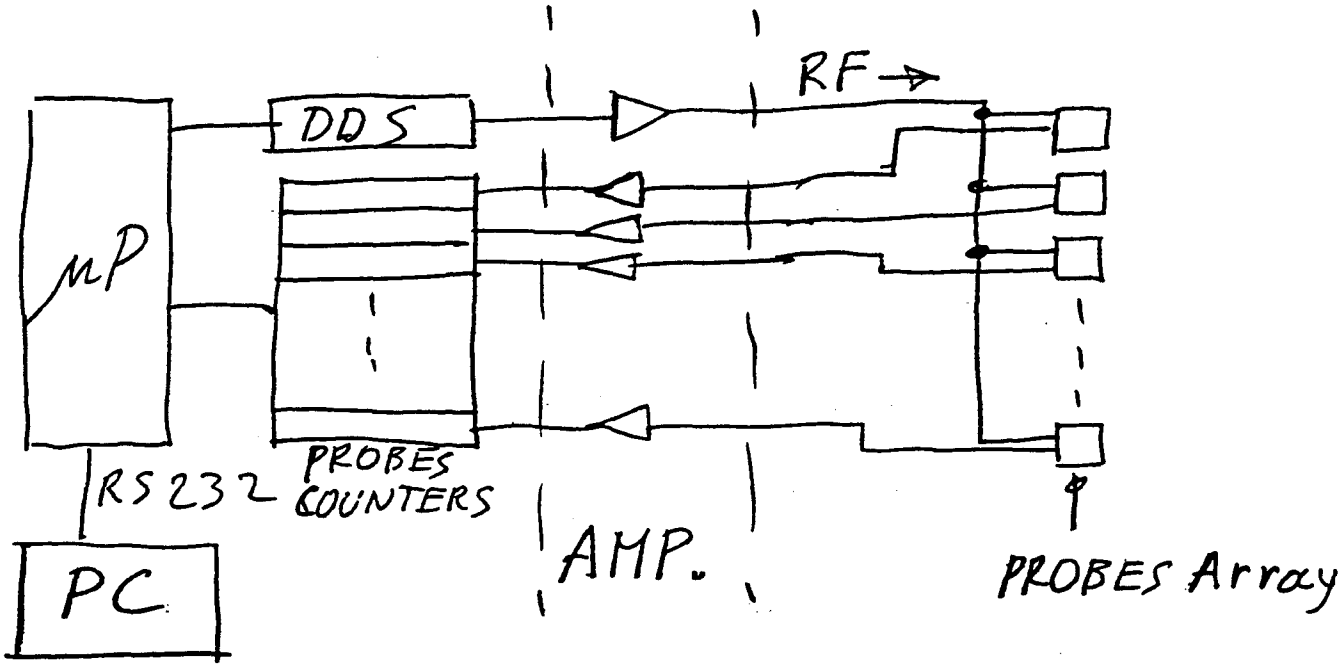
- Field range : 0.08 to 2.3 Tesla
- Resolution : 10^{-7} Tesla
- Stability : $\pm 5.10^{-9}$ /K

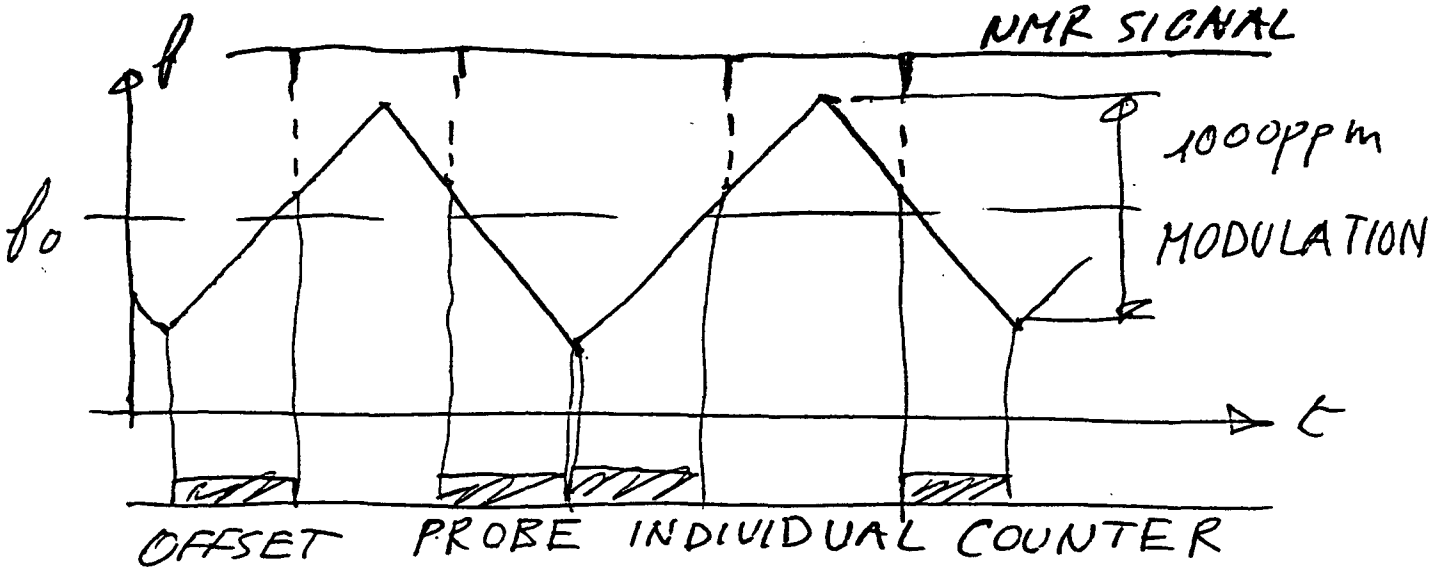


- One operator portable system
- Standard or customized static array of NMR probes
- Digital interface: RS-232C

110, CH. DU PONT-DU-CENTENAIRE CH-1228 GENEVA (SWITZERLAND) TEL (41 22) 794 11 21 FAX (41 22) 794 11 20

MULTI-PROBE NMR SYSTEM
MFC - 3035



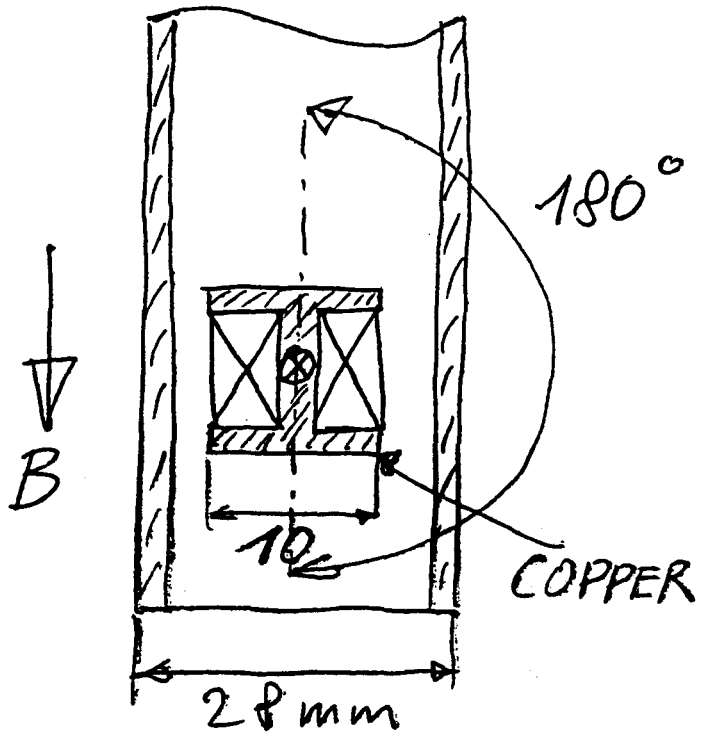


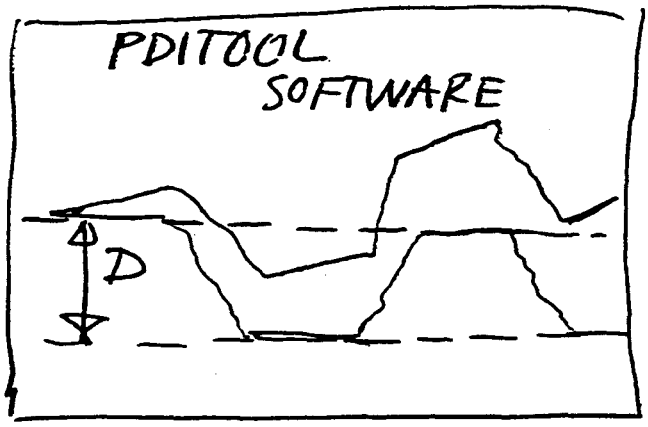
- MEASUREMENT TIME : 3 - 5 Sec.
- RESOLUTION : 1Hz (0,1ppm)
- STABILITY : $\approx 10^{-8}$ (OCXO)
- FOR MRI MAGNETS : SPHERICAL HARMONICS COEFFICIENTS CALCULATION IN THE P.C.

FLIP-COIL FOR 100 T.

- CRYOGENIC -

TO BE USED WITH THE PDI-5025 DIGITAL INTEGRATOR





MEASUREMENT

$$B_c = \frac{D[V \cdot s]}{2\,NA[m^2]}$$

OVERALL PRECISION : $\approx 10^{-4}$

COIL AREA " : 50 - 70 ppm (25°C)

TEMPERATURE COEFFICIENT : LIKE COPPER

NEW GENERATION OF HALL SENSORS

B. BERKES

30 SEPTEMBER 1993

IMMW - 8

NEW GENERATION OF HALL SENSORS

A. Differences of the VHS (Vertical Hall Sensor) with respect to the common Hall Generators:

- material
- geometrical configuration (terminals)
- size (thickness)

B. Advantages of the VHS:

- extremely small dimensions of the sensor chip (Hall element)
- linearity
- small temperature coefficient
- long-term stability and, in turn, only one calibration necessary
- single or multiple sensors
- custom tailored sensors
- high reliability
- high imunity to EM (electromagnetic) interference and mechanical vibration
- additional functions (current supply, Hall voltage amplifier etc.) can be easily integrated; up to 5 T no influence of the magnetic field on the electronics

C. Open questions:

- Hall-voltage leads configuration (induced voltages during flying-mode measurements)
- "planar" Hall-effect due to high internal resistance of the VHS [Advatage: Current lines symmetry under normal conditions (!)]
- "planar" Hall-effect at multiple field-component measurements
- thermal e.m.f.'s

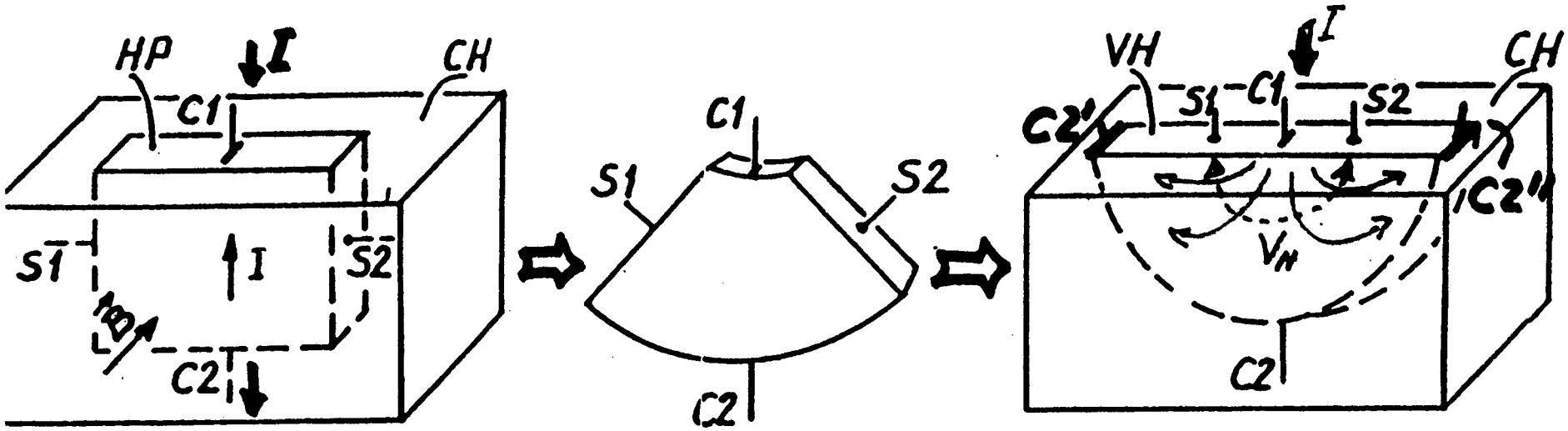
D. Applications:

- Research: magnetic field sensing (standard and high precision) for magnetic measurements on room-temperature as well as superconducting magnets, MRI-magnets etc.

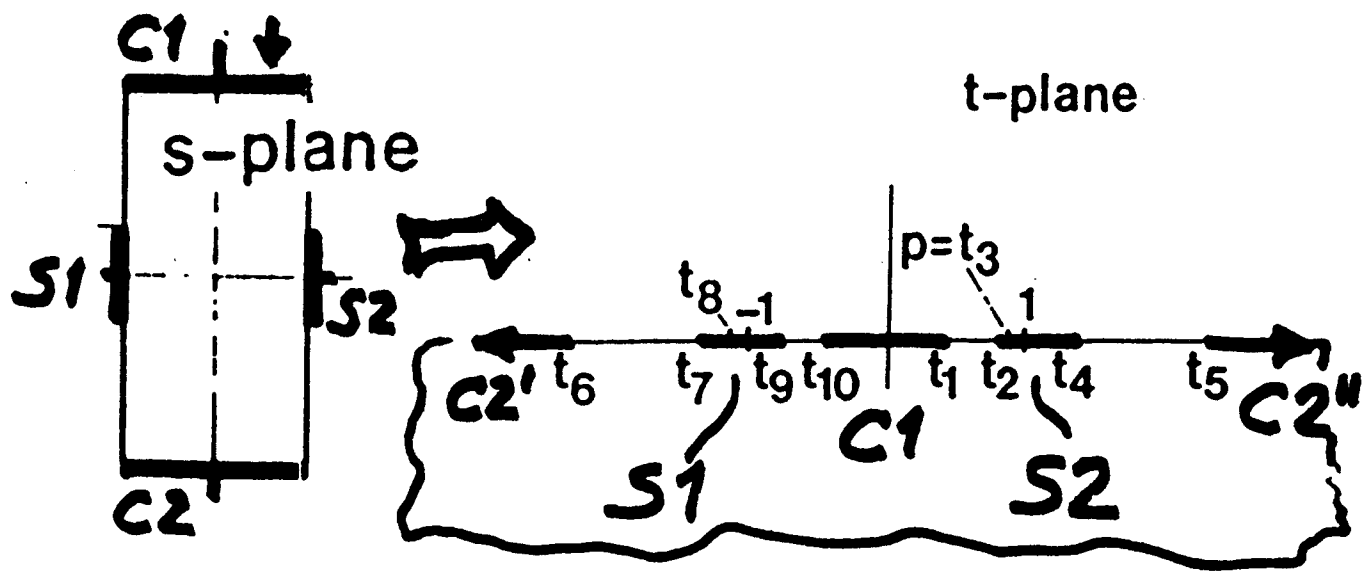
- Industry: General transducer element (Examples: Electric power meter, Position detection of moving parts)

GENESIS OF THE VERTICAL HALL DEVICE

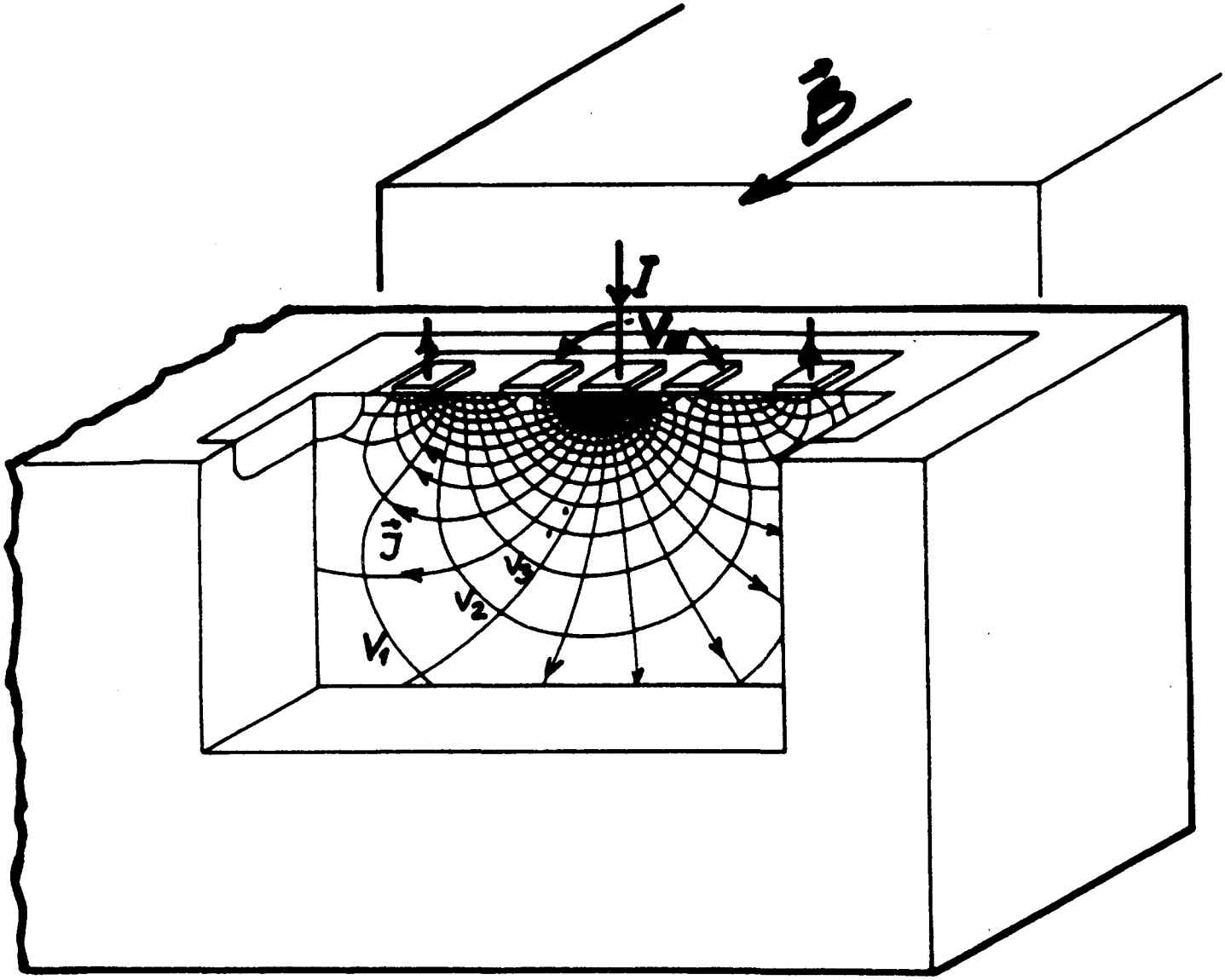
INTUITIVE:



BY CONFORMAL MAPPING:



The Vertical Hall Device



PRECISION HALL PROBES PHP

PHP are smart, self contained, high precision Hall probes with analog output. The probe contains a battery, bias circuit and output amplifier. To do a magnetic measurement, you need just a PHP and a good voltmeter. The probe features a very high long term stability: for a measurement with a 0.1 % precision, no calibration is needed.

Specifications (preliminary)

(If not otherwise specified, T = 22 °C +/- 5 °C)

Output signal (Sensitivity):	1 V / T (100 uV / G)
Long term instability of sensitivity:	< 0.1 % over 10 years
Influence of temperature variations:	
Output signal at zero field:	< 5 uV / °C (0.05 G / °C)
Temp. coefficient of Sensitivity:	< 0.3 10^{-4} / °C
Output noise and ripple, peak to peak: (integration time: 100 us)	< 30 uV (0.3 G)
Non-Linearity of output (at B < 1 T):	< 0.1 %
Frequency range:	DC to 10 KHz
Operating temperature range:	-25 °C to 75 °C
Sensitive volume:	2 x 0.5 x 0.2 mm^3
Dimensions of the sensor tip:	2 mm x 4 mm

Information and Distribution:

M C S - Magnet Consulting Services
Dipl.Ing. Branko Berkes
Weizenstrasse 12
CH-5430 Wettingen

Tamfax: +41 56 262 904

PRECISION HALL PROBES PHP

B. BERKES

30 SEPTEMBER 1993

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PHP are smart, self contained, high precision Hall probes with analog output. The probe contains a battery, bias circuit and output amplifier. To do a magnetic measurement, you need just a PHP and a good voltmeter. The probe features a very high long term stability: for a measurement with a 0.1 % precision, no calibration is needed.

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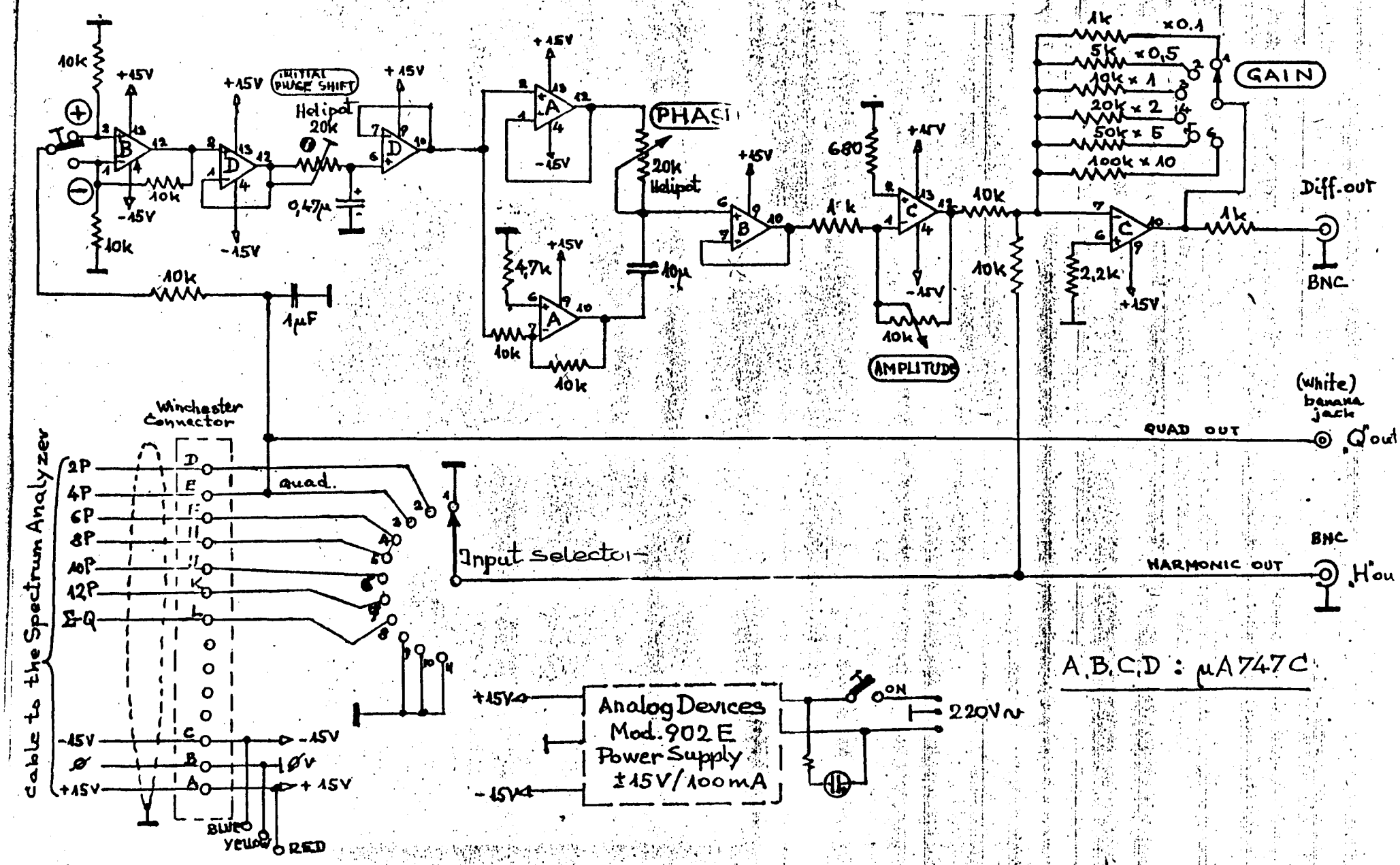
Weizenstrasse 12
CH-5430 Wettingen

Tamfax: +41 56 262 904

HARMONIC ANALYZER COMPENSATOR



A List of Magnet Measurement Publications

- more than 300 references with keywords
- ASCII-file for simple handling and retrieval
- can be used on HP-95 and similar pocket devices
- available by e-mail or on DOS diskette
- a list of manufacturers of magnet measurement equipment has also been compiled

example of entries:

[1853-1] W.Weber, "Ueber die Anwendung der magnetischen Induction auf Messung der Inclination mit dem Magnetometer", Ann. der Physik, 2 (1853) 209-247. /search coil

[1856-1] W.Thomson, "On the magnetization of the electric conductivity of metals", Philosoph. Trans., 146 (1856) 736-751. /magneto-resistivity

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[1993-4] A.Daël, H.Desportes, F.Kircher, C.Lesmond, R.Duthil, Y.Pabot, J.Thinel, "Construction and test of a superconducting high accuracy solenoid for the SMC polarized target" Int. J. Mod. Phys. A, 2B (HEACC'92) (1993) 650-652. /fluxmeter /magnetic resonance /search coil /solenoid

[1993-5] S.Kawabata, "Magnetic permeability of the iron yoke in high field superconducting magnets", Nucl. Instr. and Meth., A 329, (1993) 1-8. /low temperature /permeability /superconducting

- available from Knud N. Henrichsen, CERN

e-mail: KNH@CERNVM.CERN.CH

/ac measurement
/accelerator
/alignment
/analog integrator
/ballistic galvanometer
/compass magnetometer
/compensating coil
/conventional magnet
/cyclotron
/detector magnet
/digital integrator
/dipole
/dynamic measurement
/Faraday effect
/flip coil
/floating wire
/fluxgate
/fluxmeter
/Hall effect
/harmonic analysis
/harmonic coil
/Helmholz
/hybrid magnet
/insertion device
/integral coil
/integral measurement
/large volume
/lock-in amplifier
/low temperature
/magnetic resonance
/magneto-optical
/magneto-resistivity
/mapping
/multipole magnet
/null measurement
/on-the-fly
/permanent magnet
/permeability
/probe array
/quadrupole
/reference magnet
/rotating coil
/search coil
/sextupole magnet
/shielding
/shimming
/small aperture
/solenoid
/squid
/stretched wire
/superconducting
/undulator
/wiggler

MAGNETIZATION CURVE DATA FIT

G. MORITZ

30 SEPTEMBER 1993

Magnetization curve data fit

G. MORITZ, GSI

Work performed by F. Klos

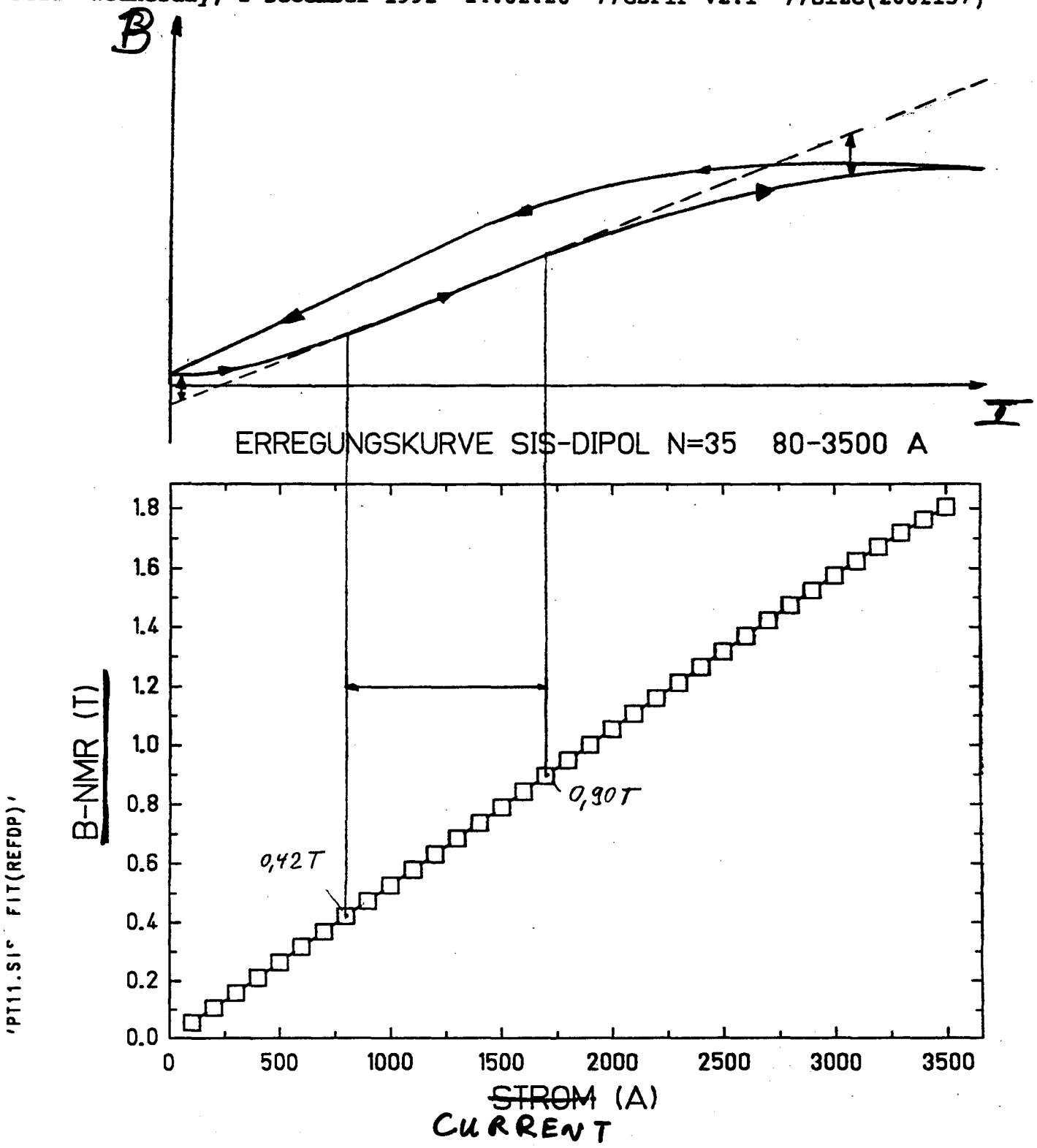
for every magnet we had to provide the operating team with the following data:

$$B(I), \quad B*L(I)$$

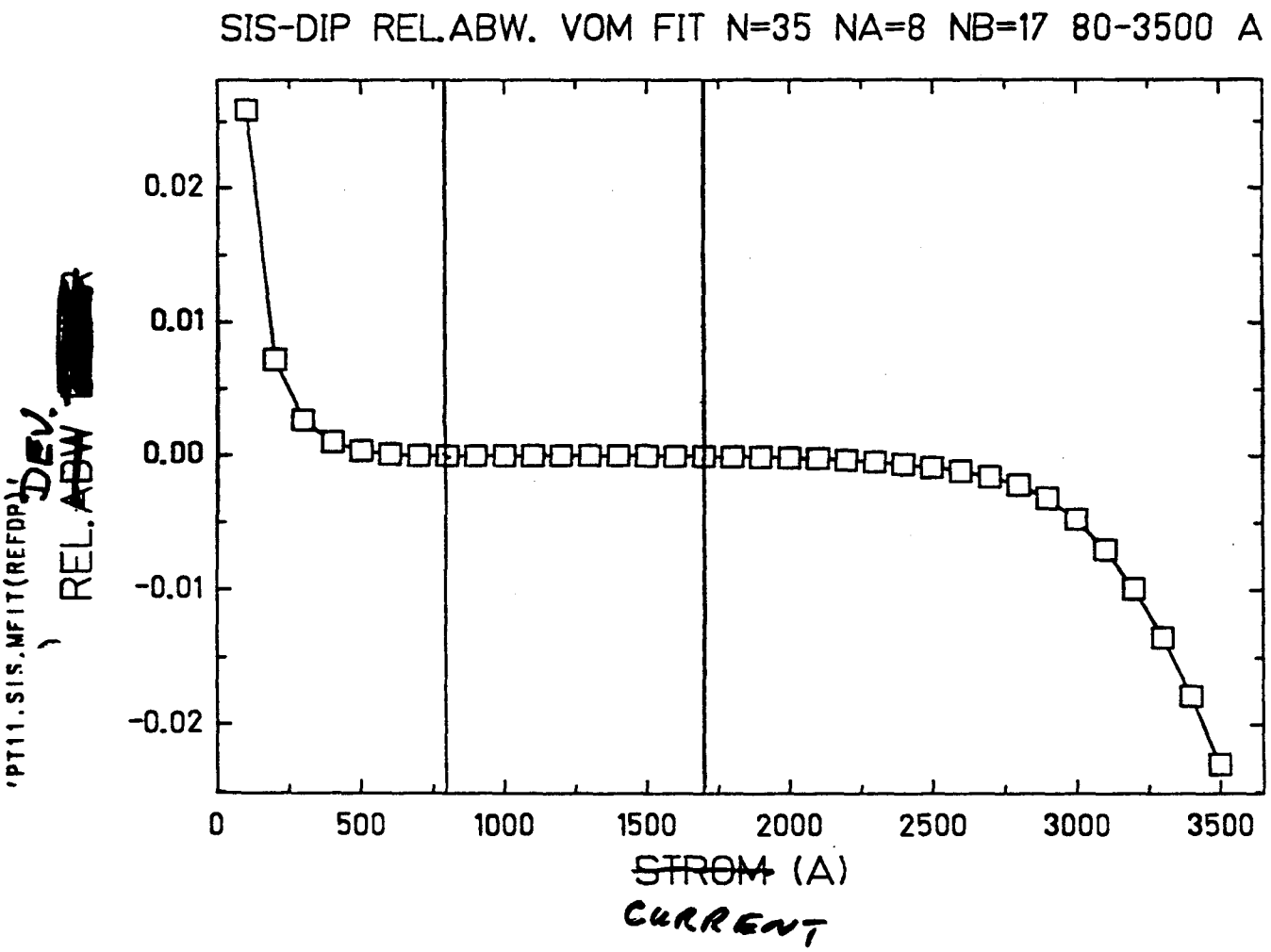
$$\left\{ \begin{array}{ll} G(I), & G*L(I) \\ S(I), & S*L(I) \end{array} \right\} \text{ respectively}$$

and the inverse functions.

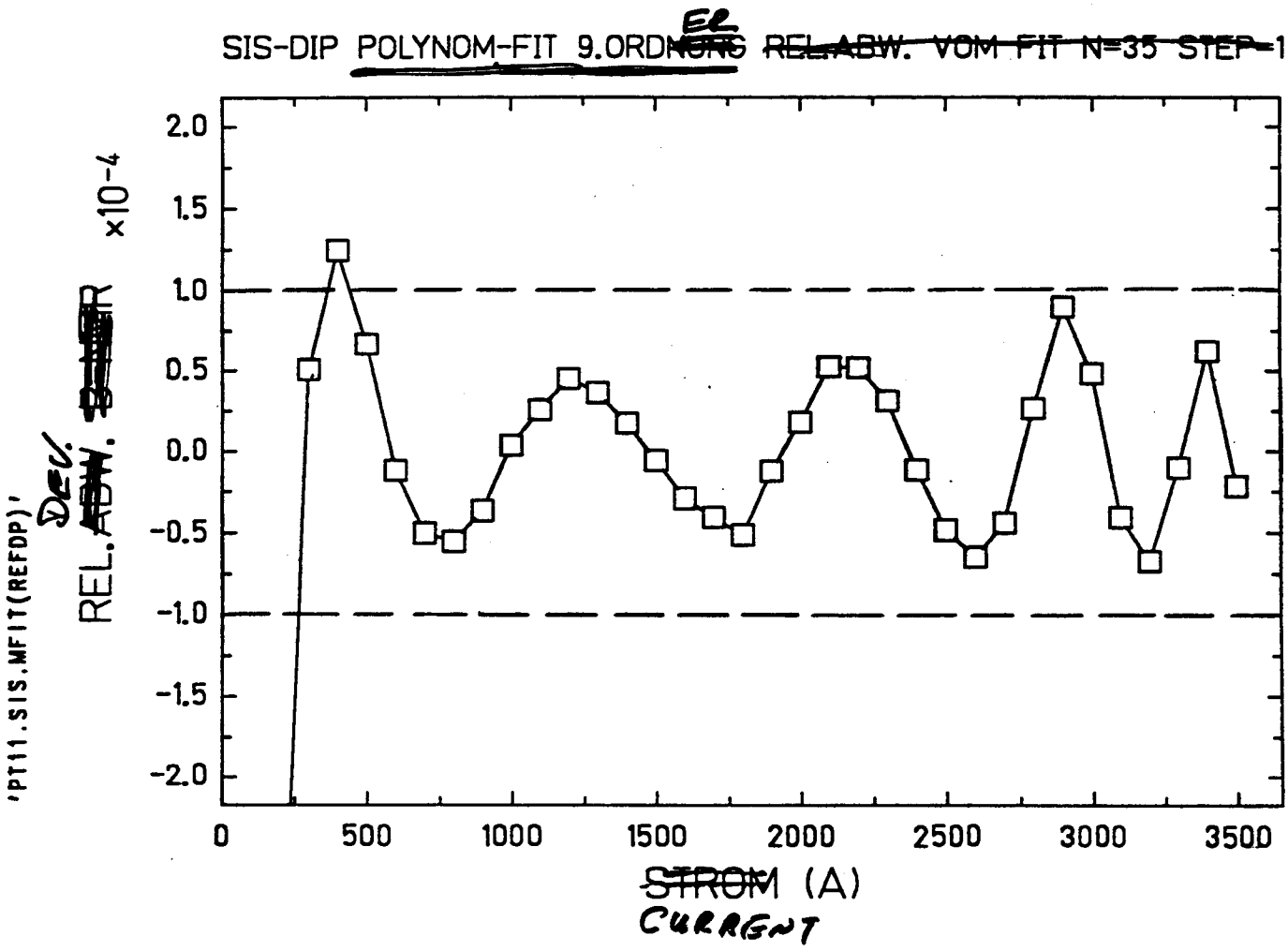
PT11 Wednesday, 2 December 1992 14:02:20 //GDFIP V2.1 //Size(200£157)



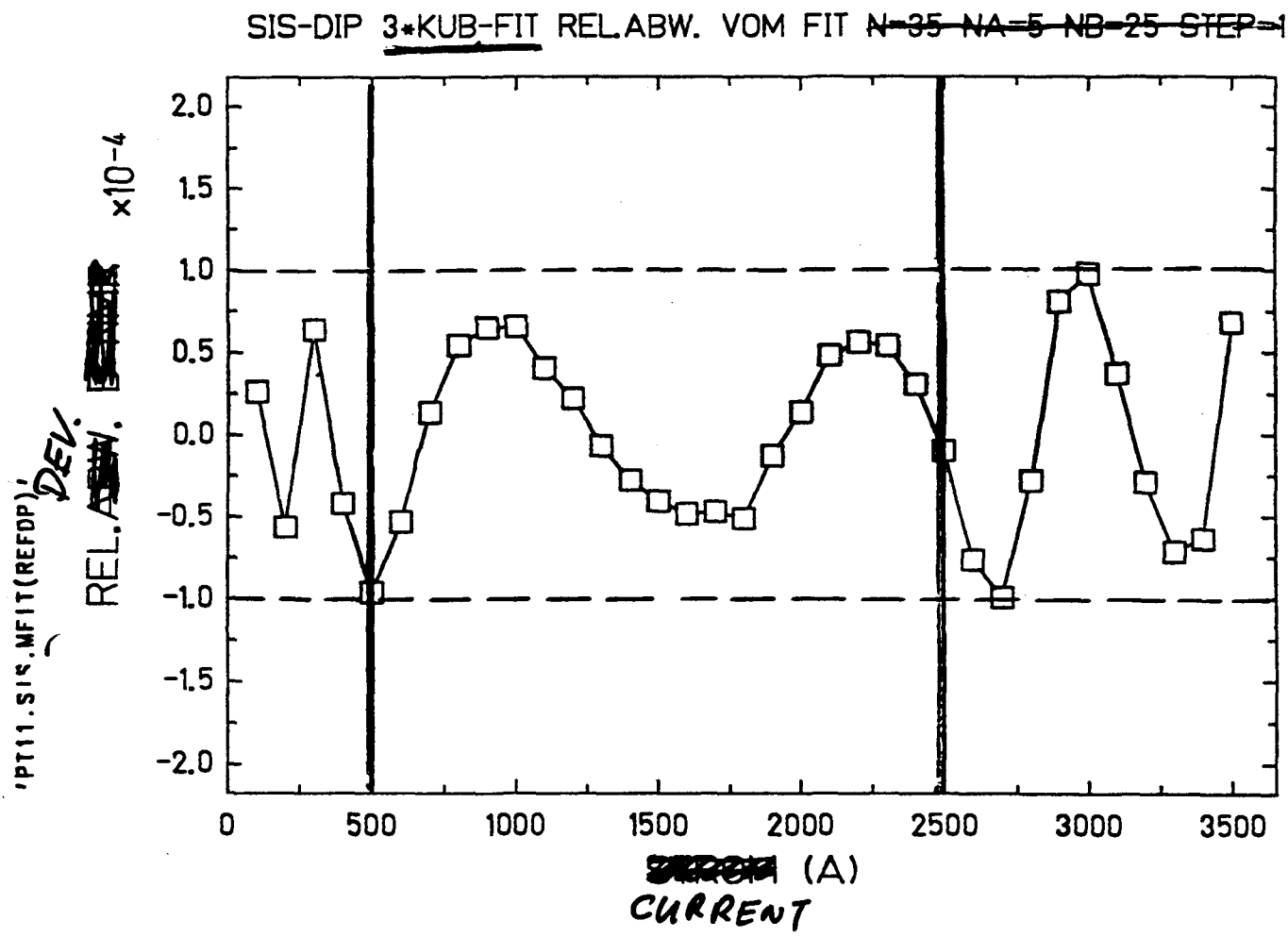
$$\frac{B(I) - \text{linear Fit}}{B(I)}$$



PT11 Thursday, 3 December 1992 9:47:55 //GDFIP V2.1 //Size(200£157)

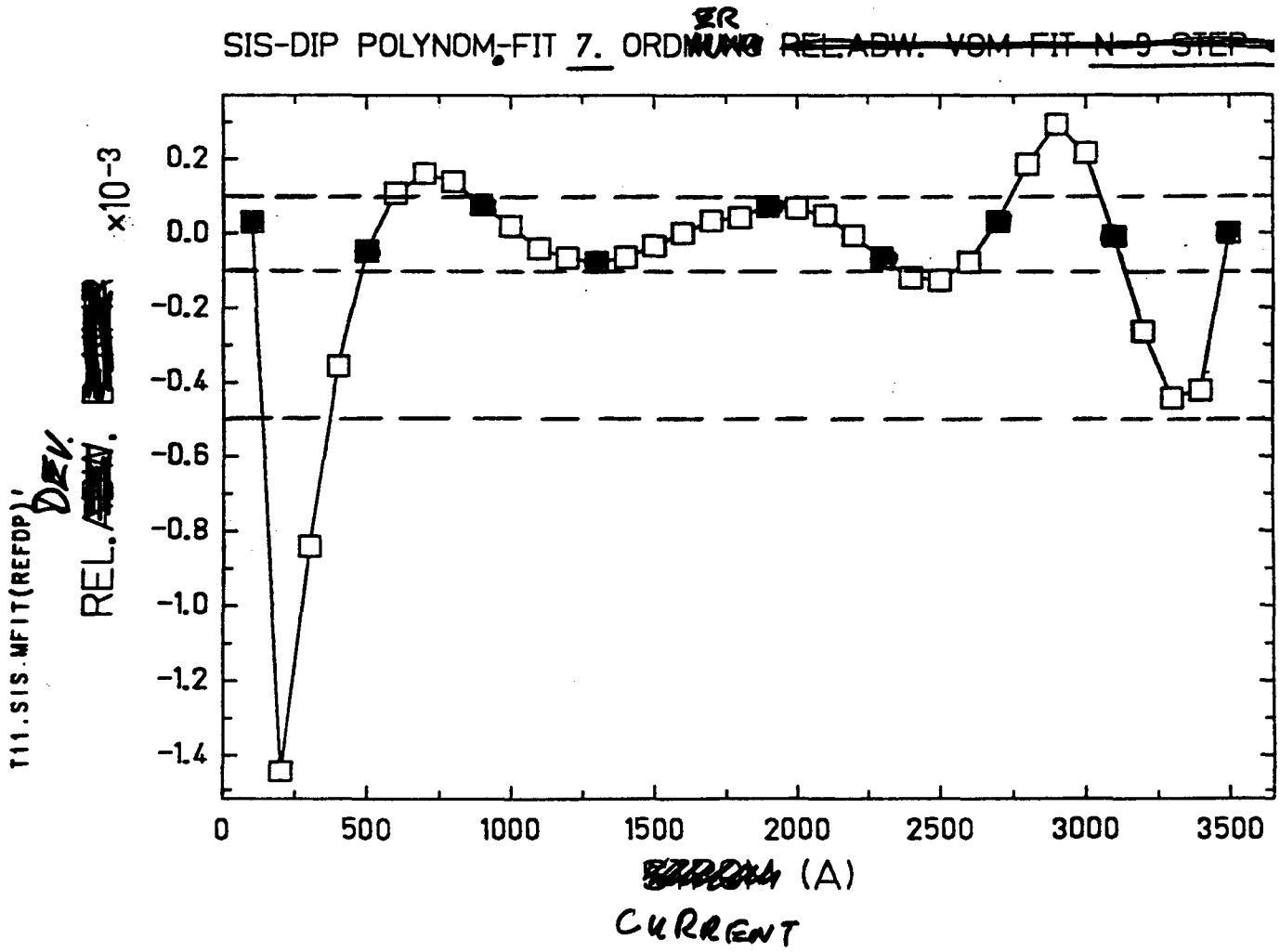


PT11 Thursday, 3 December 1992 13:01:22 //GDFIP V2.1 //Size(200£157)



Stored : 3 x 4 coefficients
+ 2 intersection points
14 single precision value

PT11 Thursday, 3 December 1992 10:10:46 //GDFIP V2.1 //Size(200£157)



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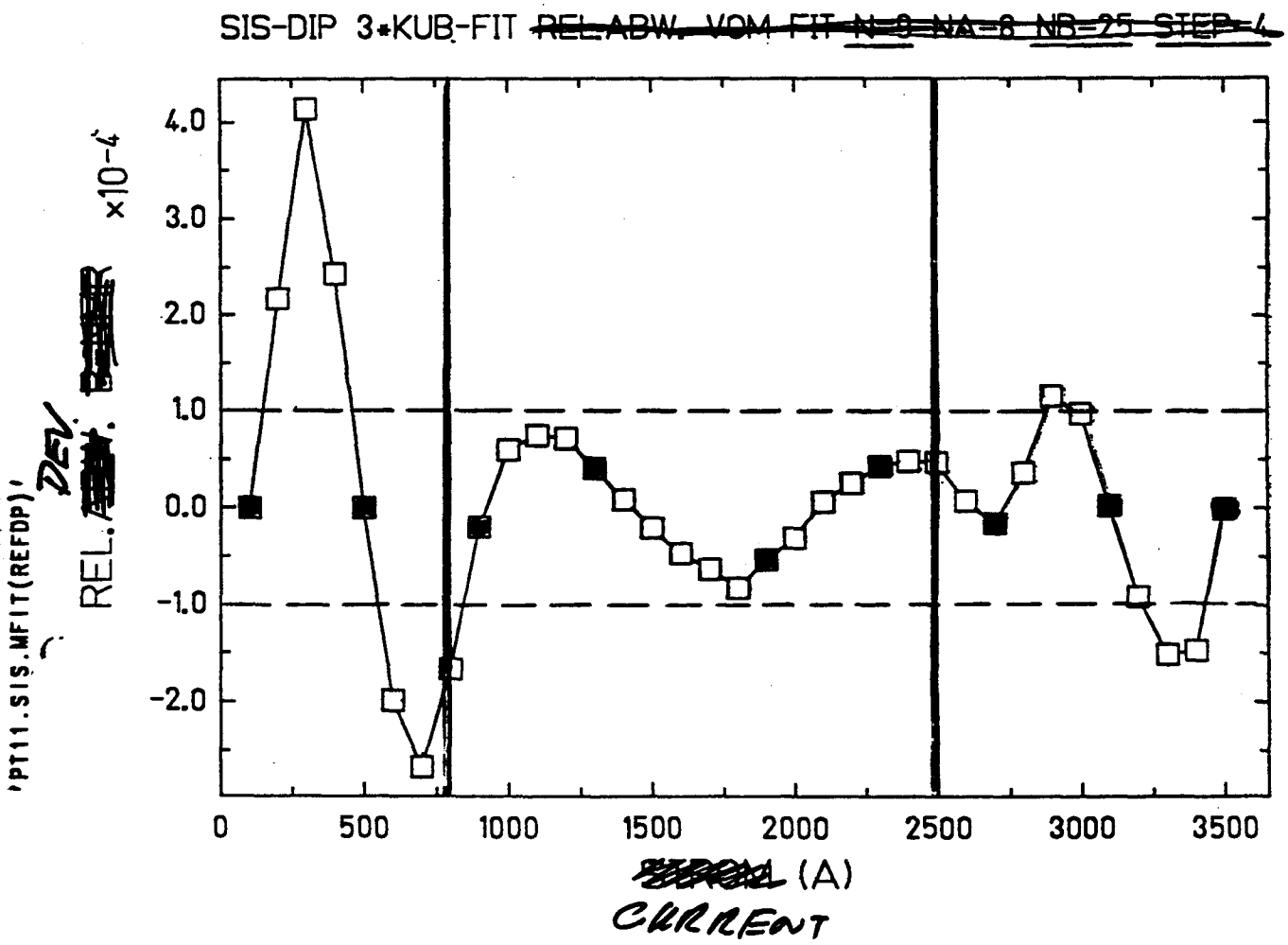


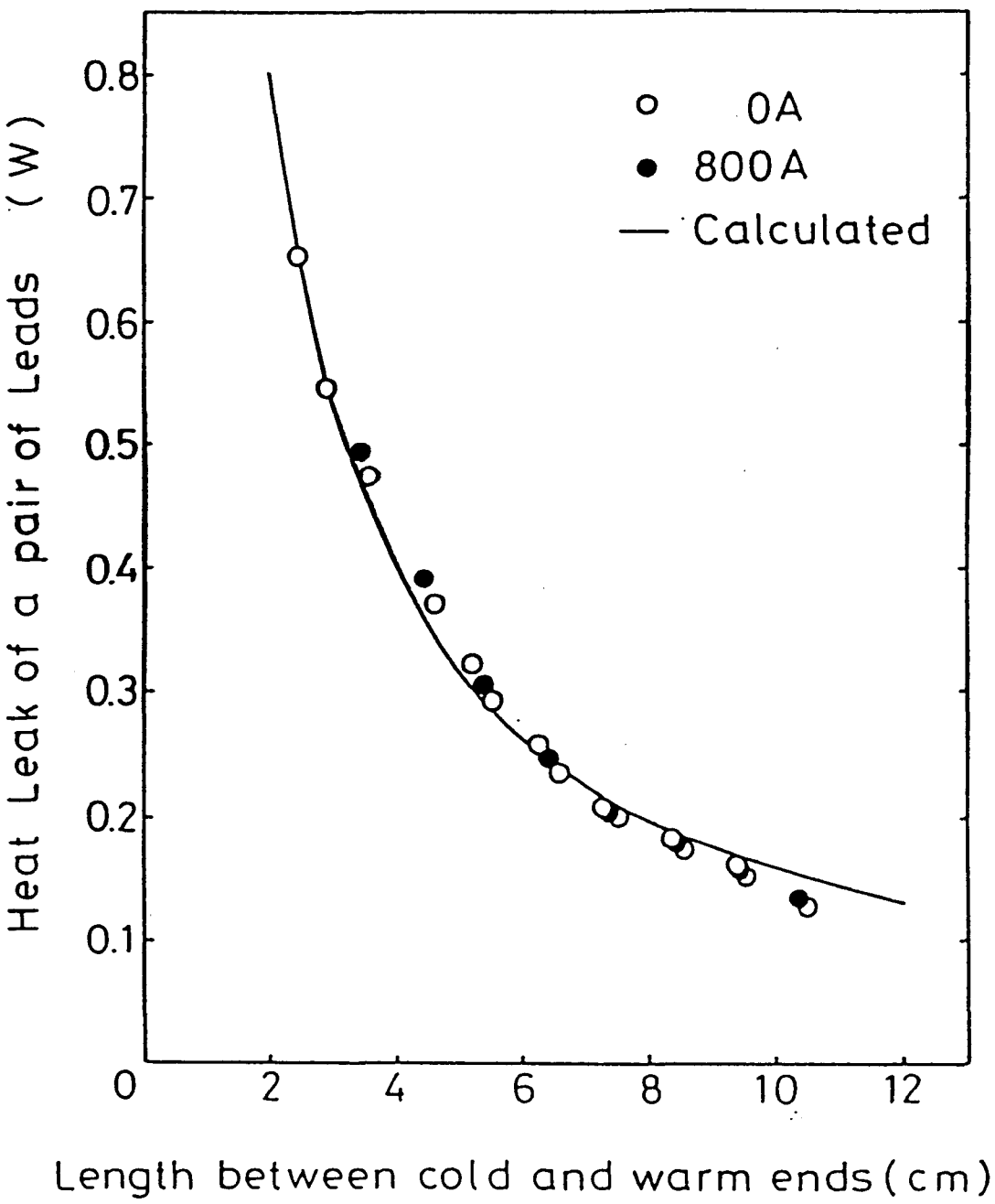
$(Nb, Ti)_3Sn$ Superconducting Magnet Operated at 11 K in Vacuum Using High-T_c $(Bi, Pb)_2Sr_2Ca_2Cu_3O_{10}$ Current Leads

Kazuo WATANABE

Institute for Materials Research, Tohoku University, Sendai 980, Japan

$$Q = \frac{S}{\ell} \int_{4.2}^{77} \lambda \, dT \qquad \int_{4.2}^{77} \lambda \, dT = 1.04 \ \mathrm{W/cm}$$

Bi (2223) Current Lead

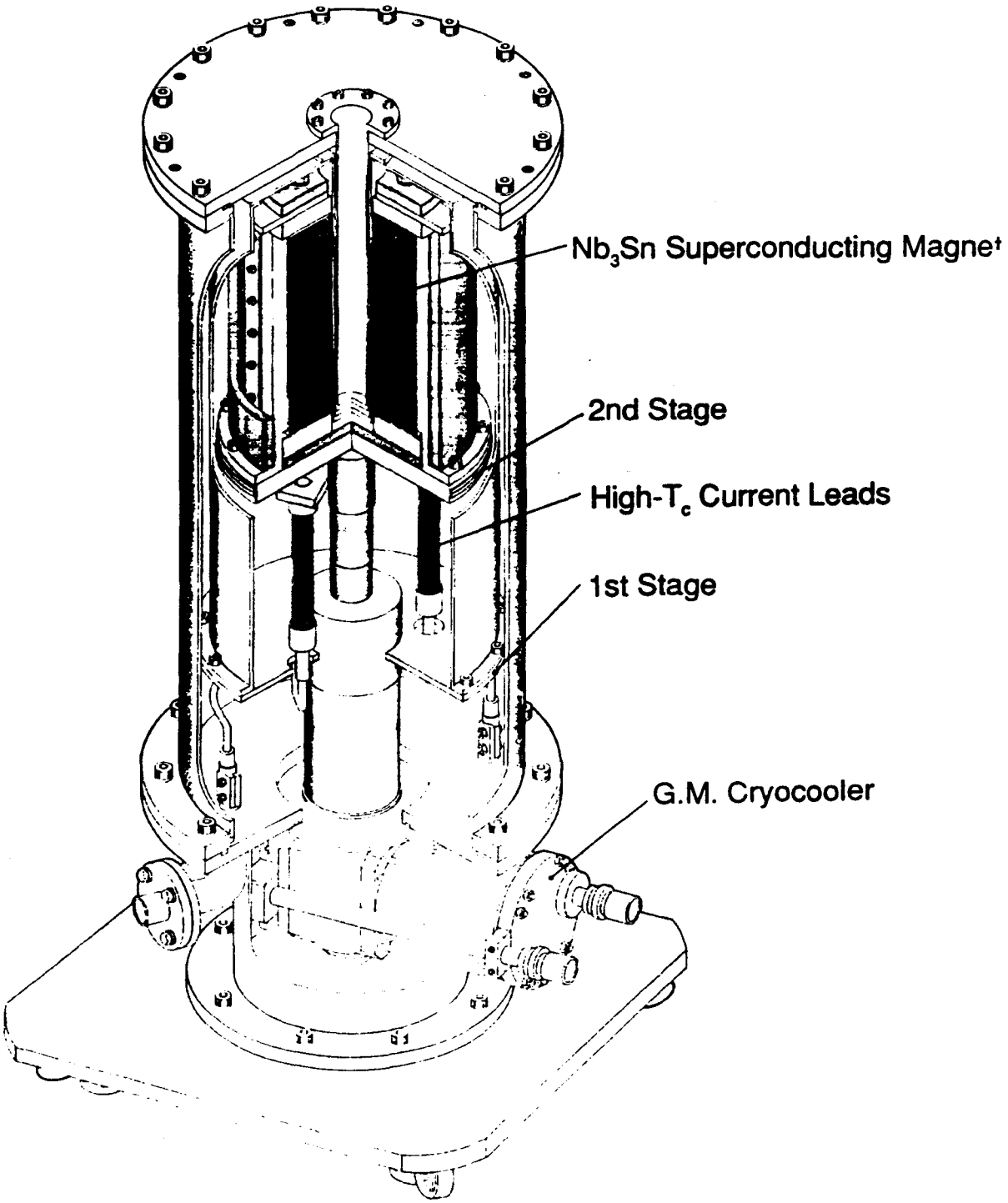


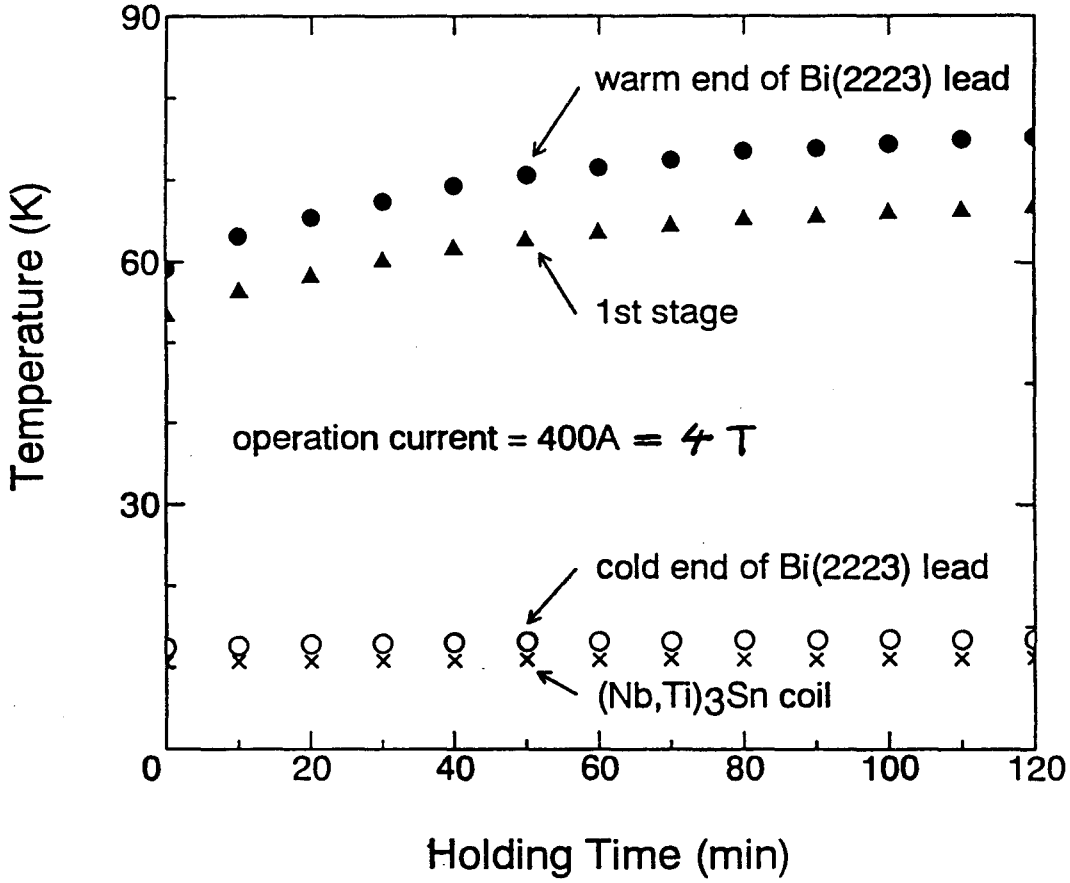
UP
SUPERIEURE
OBEN
ЗЕРХ

Parameters of Conduction Cooled $(Nb,Ti)_3Sn$ Superconducting Magnet System

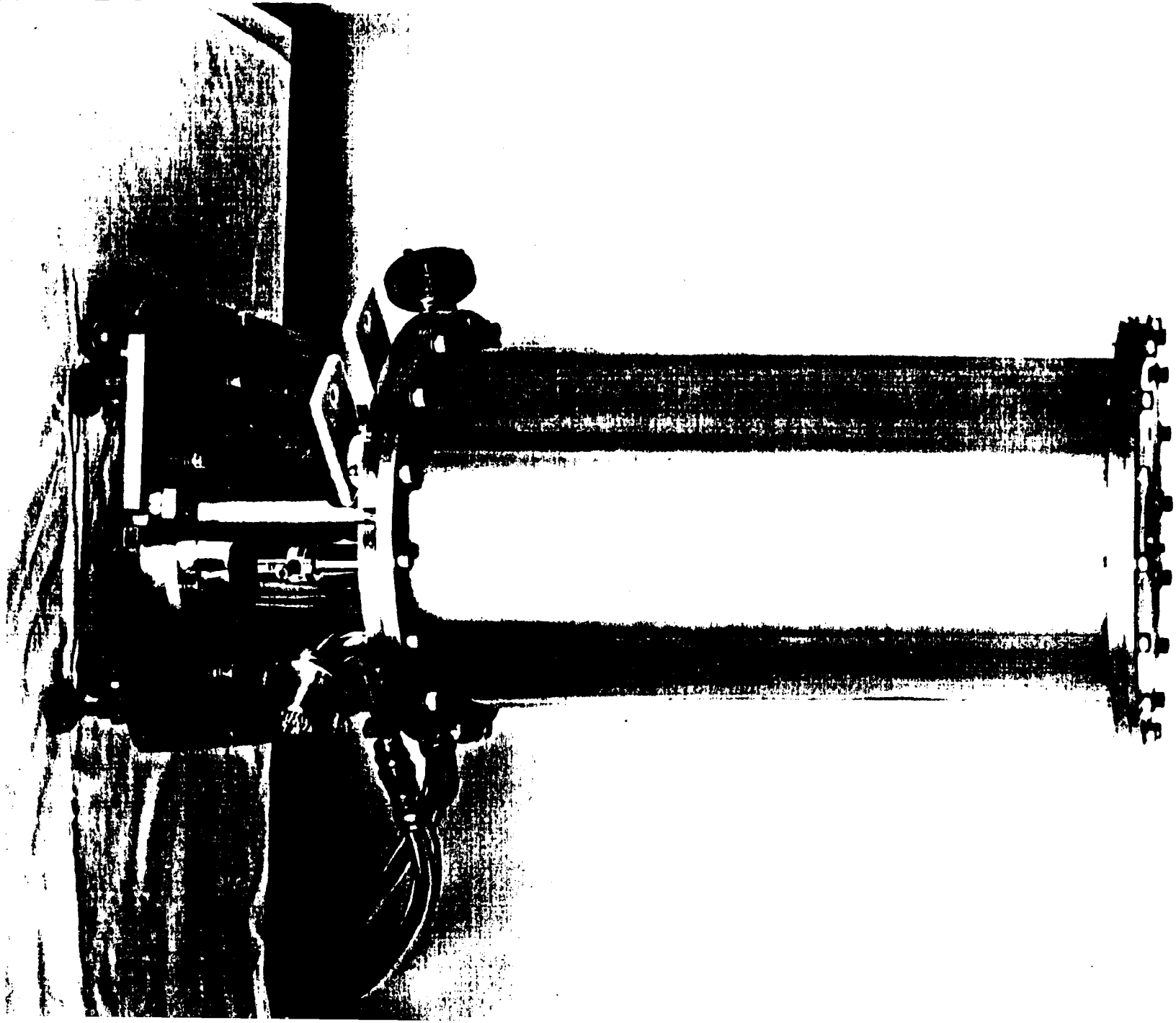
Items		Parameters
Magnet System	Central field	4.0 T at 400A
	Room temp. bore	φ38 mm
	Room temp. depth	270 mm
	Dimensions	Outer diameter 320 mm Hight 920 mm
	Weight	190 kg
	Cooling type	Conduction cooling by refrigerator
Superconductor for coil	Material	$(Nb,Ti)_3Sn$ (30 % Sn)
	Dimension	1.6 mm×2.4 mm×0.4 mmR (bare)
	Insulation	Quarts 250 μm
	Copper/superconductor ratio	1.2
	Diameter of filament	91 μm
	Number of filament	264
Superconducting coil	Type	Solenoid
	Cold bore	50 mm
	Inner diameter	59 mm
	Outer diameter	164 mm
	Coil hight	188 mm
	Number of turns	1659
Oxide superconducting current leads	Material	$(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$
	Dimensions	φ23mm×φ20mm×140mm
	Critical current	Over 1,000 A at 77.3 K, 0 T
Refrigerator	Type	SHI SRD208
	Refrigeration capacity	0.4 W/10 K、40 W/60 K
	Dimensions	180 mmW×318 mmD×512 mmH
	Maintenance cycle	10,000 hr

Conduction Cooled Superconducting Magnet System




90
60
30
0
20
40
60
80
100
120
Temperature (K)
Holding Time (min)
warm end of Bi(2223) lead
1st stage
operation current = 400A = 4 T
cold end of Bi(2223) lead
(Nb,Ti)3Sn coil

UP SUPERIÉURE OBEN おもて



Technical Advantages of a Cryogen-free Superconducting Magnet

1. Needlessness of troublesome handling in both initial cooldown and liquid helium supply for the magnet.

   50 mm room temp. bore 11 T SCM

2. Long time operation without interrupting for liquid helium supply.

   220 mm room temp. bore 6 T SCM

3. Very compact cryostat enough to be combined with a unique apparatus.

   50 mm bore, 50 mm gap 6 T SSCM X-ray, neutron diffraction

4. Operation of the superconducting magnet in vacuum.

   electron device, plasma heating, gyrotron