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INITIAL DESIGN CONSIDERATIONS OF A 35-MEV DEUTERON LINEAR ACCELERATOR

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1. Introduction

This report chronicles an aborted design effort carried out as a collaboration of the three organizations listed above. These organizations began the design of a 35-MeV deuteron linear accelerator that is to be the basis of the Fusion Materials Irradiation Test (FMIT) facility to be constructed at the Hanford Engineering Development Laboratories (HEDL) in Richland, Washington. The work discussed here concerns only the linear accelerator; the liquid-lithium target to be used for neutron production by stripping reactions is being developed separately by HEDL. Design work on the linear accelerator by this collaboration had just begun when it was superseded by a collaboration of HEDL and Los Alamos Scientific Laboratory. The purpose of this report is therefore to set down some design problems and possible solutions for consideration by the Los Alamos group.

2. Specifications of the Accelerator

The following specifications were developed by HEDL, with some additions by Fermilab, as the basis for design.

Table I. Accelerator Specifications

Particle	Deuterons
Peak Kinetic Energy	35 MeV (variable in 5 MeV steps)
Operation	CW, with pulsing capability
Current	100 mA

Initially, it was decided that nothing should be done in the design to preclude the possibility of later accelerating a peak current of 200 mA and all the design work described here was done with this requirement. Near the end of the effort, the requirement of eventual 200-mA capability was dropped, but this change is not reflected in this report.

There was initially also a requirement for completely debunched beam, but this requirement was later dropped. Some debunching of the final beam will occur naturally and, in addition, the transport system to the target will probably have space to install a cavity to provide a significant amount of debunching.

In view of the nature of the project and the completion date desired, we excluded from consideration any radical design innovations, no matter how attractive they looked for linacs of the next generation.

3. Choice of Frequency and Injection Energy

At the conceptual design stage, before there was any opportunity to do technical design work on the linear accelerator, the operating frequency had been chosen as 50 MHz and the injection energy as 750 keV.[1] In contrast, the Brookhaven[2] proposal had settled on 50 MHz and 500 keV, while the INGRID facility proposed by Oak Ridge,[3] for which the linac design work was done by Fermilab people, made use of 60 MHz and 350 keV.

If a given linac structure is scaled up in frequency, it goes down in lateral dimensions. The space-charge limit for a given injection energy decreases because the beam size is smaller. If the space-charge limit is inadequate at higher frequency, it can be increased by raising the injection energy. The choices of frequency and injection energy are therefore not independent.

As frequency is raised and lateral dimensions shrink, one would expect the tank-fabrication costs to decrease. But this economy is, at least to some extent, balanced out by the increased costs of fabricating more drift tubes, because the cell length $\beta\lambda$ has shrunk and the costs of fabricating the total structure do not decrease as the frequency is raised - in fact, they may even increase slightly. The lateral dimensions of the accelerator building also shrink and some economies in building construction should be expected.

Not only do the costs and difficulties of manufacture of the injector increase with increasing energy, but the cross sections for neutron production from D-D reactions between lost deuterons absorbed on walls and beam deuterons increases rapidly, so that shielding becomes more difficult in the injection area. For a given current, it is therefore desirable to go to as low an injection energy as possible. As the present work began, there was concern at HEDL about the total estimated cost of the FMIT facility as its scope became more clearly defined. The Fermilab people proposed at the outset that higher frequencies and lower injection energies should be investigated for possible economies. A frequency of 70 MHz and an injection energy of 500 keV were chosen for initial investigation. It is important to note that these were in no sense final choices, but rather parameters in an exploration of limits of the design. Because these choices made the first drift tube very short, most of the rest of our work was an investigation of the design of the first drift tube of a conventional Alvarez linear accelerator at 70 MHz and 500 keV.

It would be entirely possible to solve the problems arising from shortness of the first drift tube by designing a short 2 $\beta\lambda$ or Wideroe structure at the low-energy end or by changing from +-+= to +--+ focusing. Either of these changes would give a larger beam and it therefore appeared useful to try to solve the design problems of the conventional structure.

4. Beam Dynamics and Focusing Requirements

There are three forces affecting transverse particle motion, (i) rf defocusing, (ii) space-charge defocusing, and (iii) focusing by magnetic quadrupoles installed inside drift tubes to overcome the affects of (i) and (ii). Both rf defocusing and space-charge forces decrease as particles gain energy, so the requirements for quadrupole focusing are largest at the low-energy end of a linac, where the cell length and, consequently, the drift-tube length available for the quadrupole are shortest.

Ohnuma has given[4] a method by which to estimate the quadrupole strength needed. The envelope equations with quadrupole and space-charge forces are solved numerically, adding a δ-function force w at the gap center to represent the rf defocusing. Here w is the beam envelope (x or y) and

$$\Omega = - \frac{\pi e E_o T}{m_o c^2 \ s} \sin\phi_s .$$

The space-charge force is calculated assuming that the beam is a uniformly populated ellipsoid occupying $\pm 30°$ in phase. For the design under consideration, the curves given in Figs. 1 and 2 are derived. These curves are plotted for energies appropriate for injection, the most difficult place for the quadrupole. In these graphs, the current I is plotted as a function of Ω, or of E_oT for two values of ϕ_s. Here E_o is the average axial electric field and T is the transit-time factor. Curves are given for a number of focusing-quadrupole strengths, expressed as the pole-tip field B_p. In both graphs, the maximum beam diameter is taken to be 3 cm and the effective magnetic-gradient length of the quadrupole is taken to be 5 cm. In Fig. 1, drawn for an injection energy of 500 keV, the quadrupole diameter is taken to be 4 cm, while in Fig. 2, for an injection energy of 375 keV, the quadrupole diameter is taken to be 3.8 cm.

At the time these curves were developed, we were designing to the criterion that a current of 200 mA was not to be precluded. Currents of 200 mA at 375 keV require either pole-tip fields approaching 10 kG, which would be difficult to achieve, or give values of E_oT of 0.1 to 0.2 or V/m depending on the value of ϕ_s chosen. Such small values of E_oT would require a long, inefficient structure. We therefore concentrated our efforts on 500 keV. If, however, the criterion on current is changed to 100 mA with no further future capability, the designer should not neglect the possibility of injection energies lower than 500 keV.

For 8.5 kG on the poles, which is thought to be feasible, and for $\phi_s = -40°$, the curves given $E_oT = 0.75$ MV/m at 500 keV and 200 mA. For T = 0.61, corresponding to a 4-cm bore, this gives an average field $E_o = 1.23$ MV/m, while for T = 0.67, corresponding to a bore diameter of 3.4 cm, $E_o = 1.12$ MV/m. For 100 mA, $E_oT =$ 1.26 MW/m and $E_o = 2.07$ MV/m for T = 0.61 and $E_o = 1.88$ MV/m for T = 0.67.

The maximum current calculated by this method may be an overestimate because nonsynchronous particles can have considerably large values of Ω. On the other hand, the current may be an underestimate, because the beam may be more diffuse than the assumed ellipsoid. The current calculated here should be taken (as is almost always the case with space-charge calculations) as an indication rather than as a precise result.

5. Quadrupole Design

For purposes of exploration, the pole-tip field of the quadrupole in the first drift tube was fixed at 8.5 kG. Its physical length was fixed at 6 cm, its bore diameter at 4 cm and its outside diameter at 40 cm. The pole design resulting from the assumptions is shown in cross section in Fig. 3 and the magnet parameters are given in Table II below. There is some saturation in the narrow pole tips in this design and approximately 12% additional ampere turns are required as indicated by a LINDA run. One might also add this as an extra turn near the tip end of the pole. It is also possible to increase the pole length in the center of the pole, still leaving room at the sides for the radius of curvature of the coils.

TABLE II. Quadrupole Parameters

Field Gradient	10.8 kG/in. 4.25 kG/cm
Magnet Length	2.362 in. (6 cm)
Aperture	1.575 in. (4 cm)
Width of Good-Field Gradient	$\pm$0.787 in. (2 cm)
Gradient Quality ($\Delta B/xB_o'$ at 0.75 inch)	+0.04%
Coil Turns per Pole	32
Copper Conductor Cross Section	0.2294 in. x 0.2294 in.
Water-Cooling Hole Diameter	0.128 in.
Conductor Corner Radius	0.040 in.
Conductor Current	254 A
Magnet Inductance	
Coil Resistance	0.0395
Voltage Drop	10 V
Power	2.54 kW
Cooling-Water Pressure	85 psi
Number of Water Paths	4
Water Flow	1.24 GPM
Temperature Rise	7.8°C
Outside Dimensions	16 in. Diameter (40 cm.)
Iron Weight	69 lb
Copper Weight	25 lb

Note that the length of the yoke is 6 cm, but longitudinal space is required for the coils to wrap around the poles, so the poles themselves are 4 cm long and the effective gradient length of the magnet is approximately 5 cm.

This is a very large gradient for a conventional iron and copper quadrupole. It is in fact larger than the gradients of some superconducting quadrupoles that have been built. But computations indicate that it is feasible and can be built.

It should be noted that we have not attempted to solve the problem of coil insulation in the radiation environment of the first drift tube. It is certainly true that insulation containing or consisting partly of alumina can be used in the radiation environment expected, but we have not investigated any space-factor or fabrication problems that might arise with such insulation.

6. Electromagnetic Field Calculations

Initial exploration were carried out utilizing the SUPERFISH program developed by Halbach.[5] The program computes power losses on outer walls, drift tubes and end walls. It does not, in the form we used, take account of the perturbation of modes and frequencies by drift-tube stems nor does it compute the power lost in stems.

Almost 100 cases were treated, varying parameters of the linac cell at several energies. These initial cases were not integrated with the orbit-dynamics and magnet-design efforts described above; all cases had a 4-cm bore diameter rather than the 3.5 cm used in the orbit work. This discrepancy will affect mostly the transit-time factor T. We could achieve values of 0.61 for T at 4 cm and might expect from analytical estimates to reach a value of approximately 0.67, 10% higher, at 3.5 cm.

The computational results show that it is possible to keep the maximum electric field within reasonable (10 MV/m) limits at a gap to cell length ratio g/L = 0.2. It is also entirely possible to achieve an inner radius of curvature of 0.5 cm where the bore meets the face and an outer radius of curvature, where the curved face meets the cylindrical drift-tube body, of 2 cm, leaving maximum room inside for cooling and the quadrupole. It is possible to reduce the power loss on the drift tube by slanting back the face, in effect increasing the outer radius of curvature, or by reducing the outer diameter of the entire drift tube. But these changes make it more difficult to incorporate the cooling and quadrupole. In addition, the power saved in this way is small compared with the power lost on end walls and even smaller compared with power put into the beam. This beam power is fixed by the design criteria and one result of improving the efficiency of rf excitation by lowering the excitation power is to make the job of the compensating feedback systems more difficult. There is thus only a limited amount to be gained in a search for more efficient rf excitation.

The results show that with an average field E_o of 2.2 MV/m, the rf loss on the drift tube is close to 5.2 kW and we proceeded to investigate cooling of this heat loss. It should be noted that the value of E_o assumed here is not consistent with the values derived in the orbit-dynamics discussion of Sec. 4 above. We used a larger E_o here to explore how far we could go in cooling.

On the other hand, we have not included any cooling for particle losses on the drift tube in our estimates. Orbit-dynamics investigations to estimate the distribution of these losses would be required to attack this problem.

7. Drift Tube Cooling

In order to provide the dimensional stability needed in a high Q system like a linac cavity, it is necessary to keep temperature differences very small. We assume a ΔT of 1°C. The water flow required is then approximately 10 gallons per minute for each face of the drift tube, or 38 in.^{3}/sec.

It is intended to cool the drift-tube faces by cooling channels inside them, a method suggested to us by G. M. Lee of Fermilab. We assume 10 cooling paths for each drift-tube face. The space available between the ends of the quadrupole and the outer shell leave approximately 0.1 in. longitudinally for a cooling channel. We take the other dimension of the channel to be 0.4 in. The flow velocity needed is then 8.0 ft/sec in each channel.

We can calculate the average channel length by assuming that this average channel goes around the circumference at a radius halfway between the inner and outer diameters. Then the average length is 33.4 in.

The Reynolds number is calculated to be 1×10^4, at 25°C and ambient pressure, so the flow is turbulent. The pressure drop in a channel is calculated to be 1.33 psi, an easy pressure to produce. We have also calculated the case of 5 cooling paths and derive commensurate results ($R_e = 1.9 \times 10^4$, v = 15.2 ft/sec, pressure drop = 9.7 psig).

Thus our calculations show that it is possible to cool the first drift tube.

8. Drift Tube Design

The design that was developed is shown in Fig. 4. A slightly different design is shown in Fig. 5. The drift-tube stem is concentric to allow for supply and return water paths and quadrupole current leads. It is attached to a cylindrical drift-tube body, of variable length for different energies. The drift-tube faces are envisaged as curved copper surfaces (perhaps spun) approximately 0.1 in. thick.

Inside are the cooling channels, formed in one unit for each face (perhaps die-cast copper or brass) with all supply and return channels cast into the body. The cooling-channel units are to be brazed to the outer surfaces. If it is necessary to cool the drift-tube bore because of particle losses, those channels would be cast into the same cooling body and the bore sleeve inserted and welded.

9. Conclusions

We have shown that it is possible to design a $\beta\lambda$ Alvarez structure for deuterons at 500 keV and 70 MHz and to produce a feasible first drift tube. It may be noted in this connection that a first drift tube of 500 keV corresponds to a lower injection energy, because there is energy gain in the first gap between the half drift tube mounted on the end wall (which can, of course, be cooled easily) and this first drift tube.

It may well be that the optimal design is not at 70 MHz and 500 keV, but difficulties at the low-energy end cannot be cited as arguments against these parameters. Further investigation will be needed to determine an optimum design, including development of an entire systems design and modeling of components, including the drift tube discussed in this report.

Acknowledgements

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References

1. Initial Conceptual Design, Schedule, and Cost Estimate for the Accelerator System of the Fusion Materials Irradiation Test Facility; W. M. Brobeck and Associates, Inc., Report 4500-225-7-R1, September, 1977.

2. Proposal for an Accelerator-Based Neutron Generator, Brookhaven National Laboratory Report BNL 20159, P. Grand (ed.) July, 1975.

   Accelerator-Based Neutron Generator (Addendum), Brookhaven National Laboratory Report BNL 20840, P. Grand (ed.) January, 1976.

3. INGRID, A Proposal for an Intense Neutron Generator for Radiation-Induced Damage Studies in the CTR Materials Program, Oak Ridge National Laboratory Report ORNL-TM-5233, M. J. Saltmarsh and R. E. Worshams (eds.), January, 1976.

4. Shoroku Ohnuma and Joseph N. Vitale, Space-Charge Effects on the Quadrupole Focusing System in Low-Energy Proton Linear Accelerators; Proceedings of the U. S. National Particle Accelerator Conference, IEEE Transactions on Nuclear Science NS-14, June, 1967, p. 594.

5. K. Halbach and R. F. Holsinger, SUPERFISH - A Computer Program for Evaluation of RF Cavities with Cylindrical Symmetry. Particle Accelerators 7, 213 (1976).

Fig 1

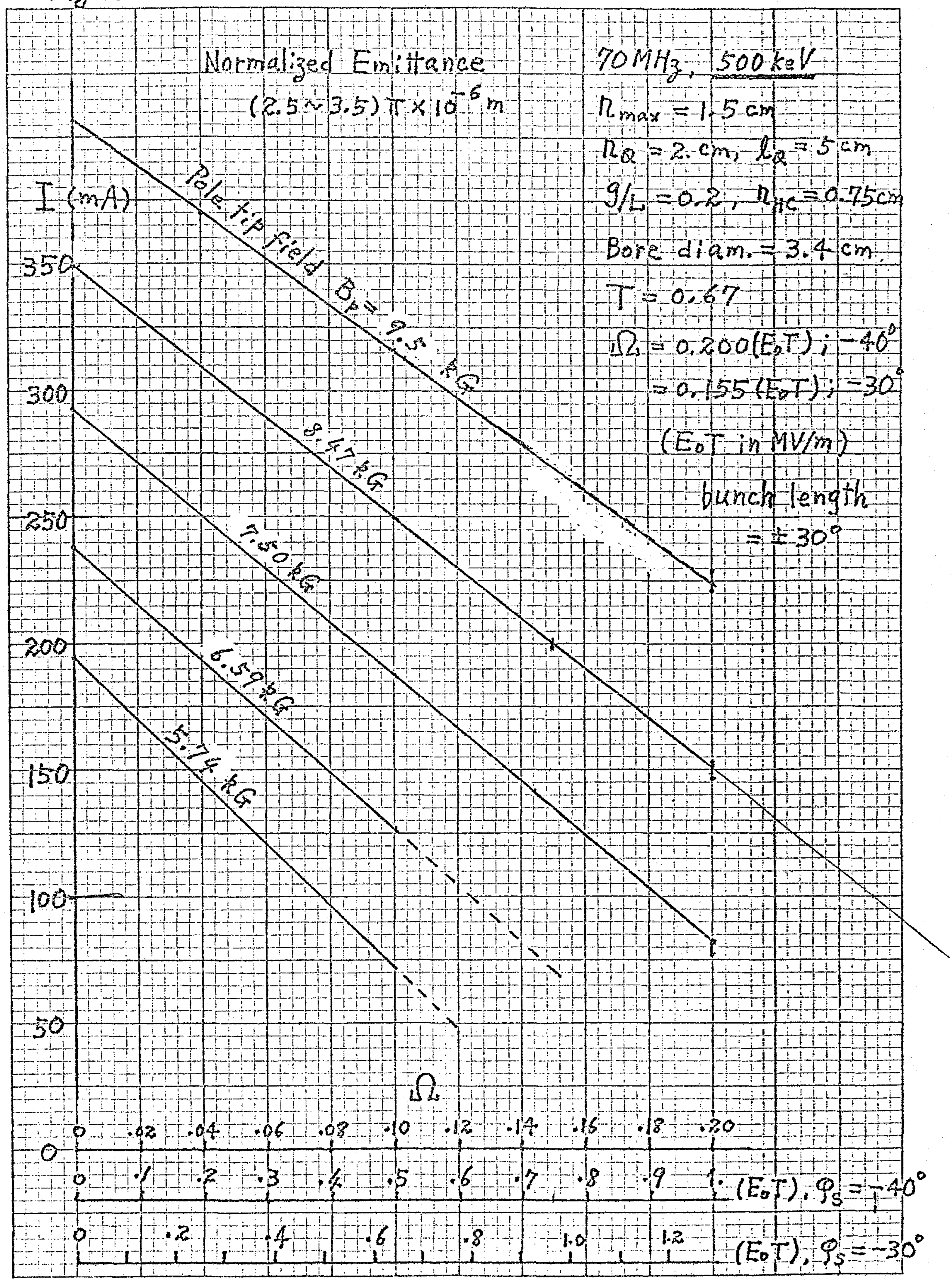

Normalized Emittance
(2.5~3.5) π × 10^-6 m
70 MHz, 500 keV
r_max = 1.5 cm
r_Q = 2. cm, l_Q = 5 cm
g/L = 0.2, r_HC = 0.75 cm
Bore diam. = 3.4 cm
T = 0.67
Ω = 0.200 (E₀T); −40°
= 0.155 (E₀T); −30°
(E₀T in MV/m)
bunch length
= ±30°
I (mA)
Pole tip field B_p = 9.5 kG
8.47 kG
7.50 kG
6.59 kG
5.74 kG
350
300
250
200
150
100
50
0
Ω
0 .02 .04 .06 .08 .10 .12 .14 .16 .18 .20
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.
(E₀T), φs = −40°
0 .2 .4 .6 .8 1.0 1.2
(E₀T), φs = −30°

Fig 1

Fig 2

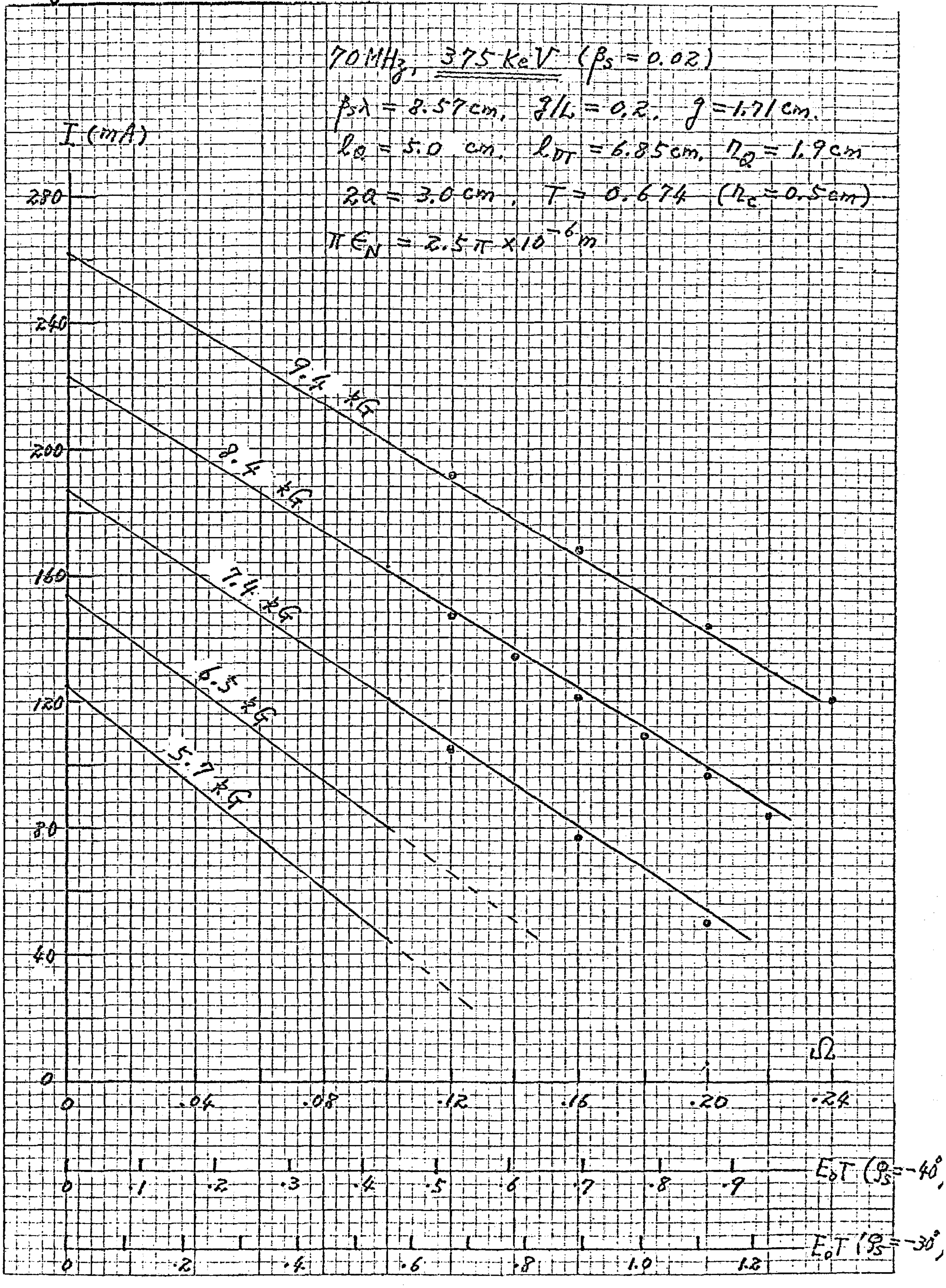

70 MHz, 375 KeV (β_s = 0.02)
$\beta_s\lambda$ = 8.57 cm, g/L = 0.2, g = 1.71 cm.
l_Q = 5.0 cm, l_{DT} = 6.85 cm, r_Q = 1.9 cm
2a = 3.0 cm, T = 0.674 (r_c = 0.5 cm)
$\pi\epsilon_N = 2.5\pi \times 10^{-6}$ m
I (mA)
280
240
200
160
120
80
40
0
9.4 kG
8.4 kG
7.4 kG
6.5 kG
5.7 kG
Ω
0
.04
.08
.12
.16
.20
.24
E_0T (φ_s = -40°)
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
E_0T (φ_s = -30°)
0
.2
.4
.6
.8
1.0
1.2

Fig. 2

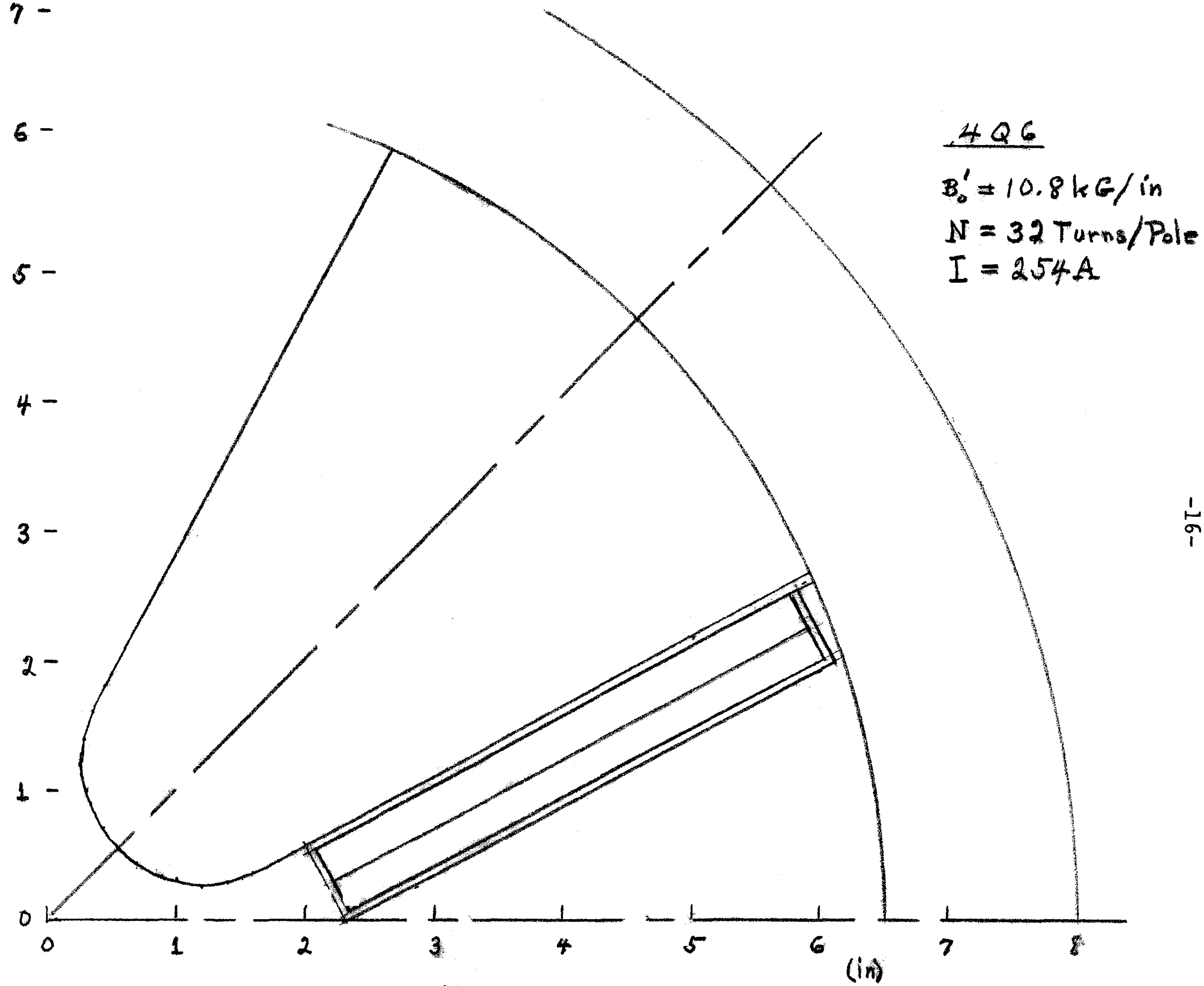


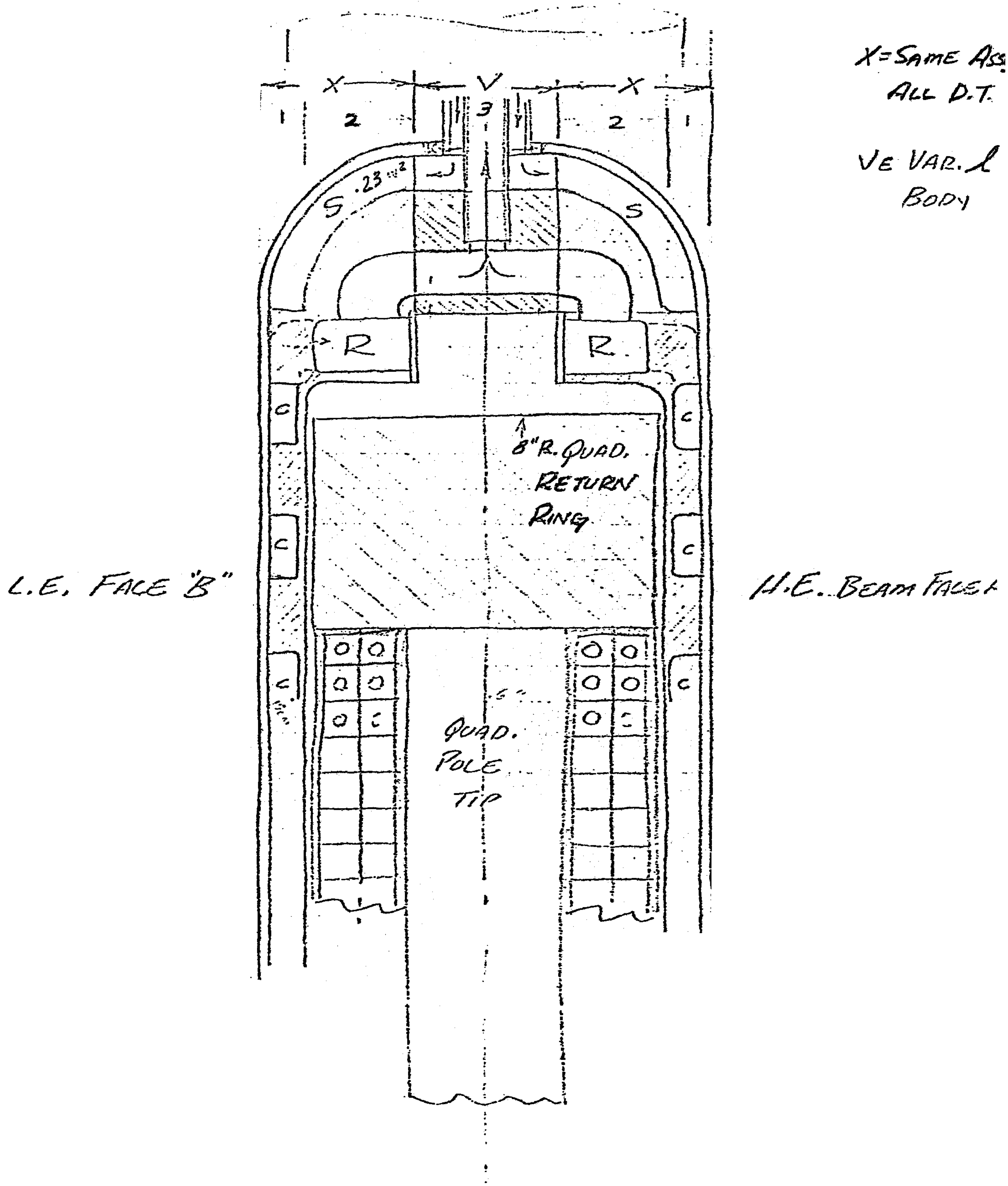
Fig. 3

HEDL-FMIT	JOB	PAGE 3 OF 3
	BY DEM (5) CHK	DATE 2-24-7

D.T CROSS SECTION

X=SAME ASS
ALL D.T.

VE VAR. ℓ
BODY



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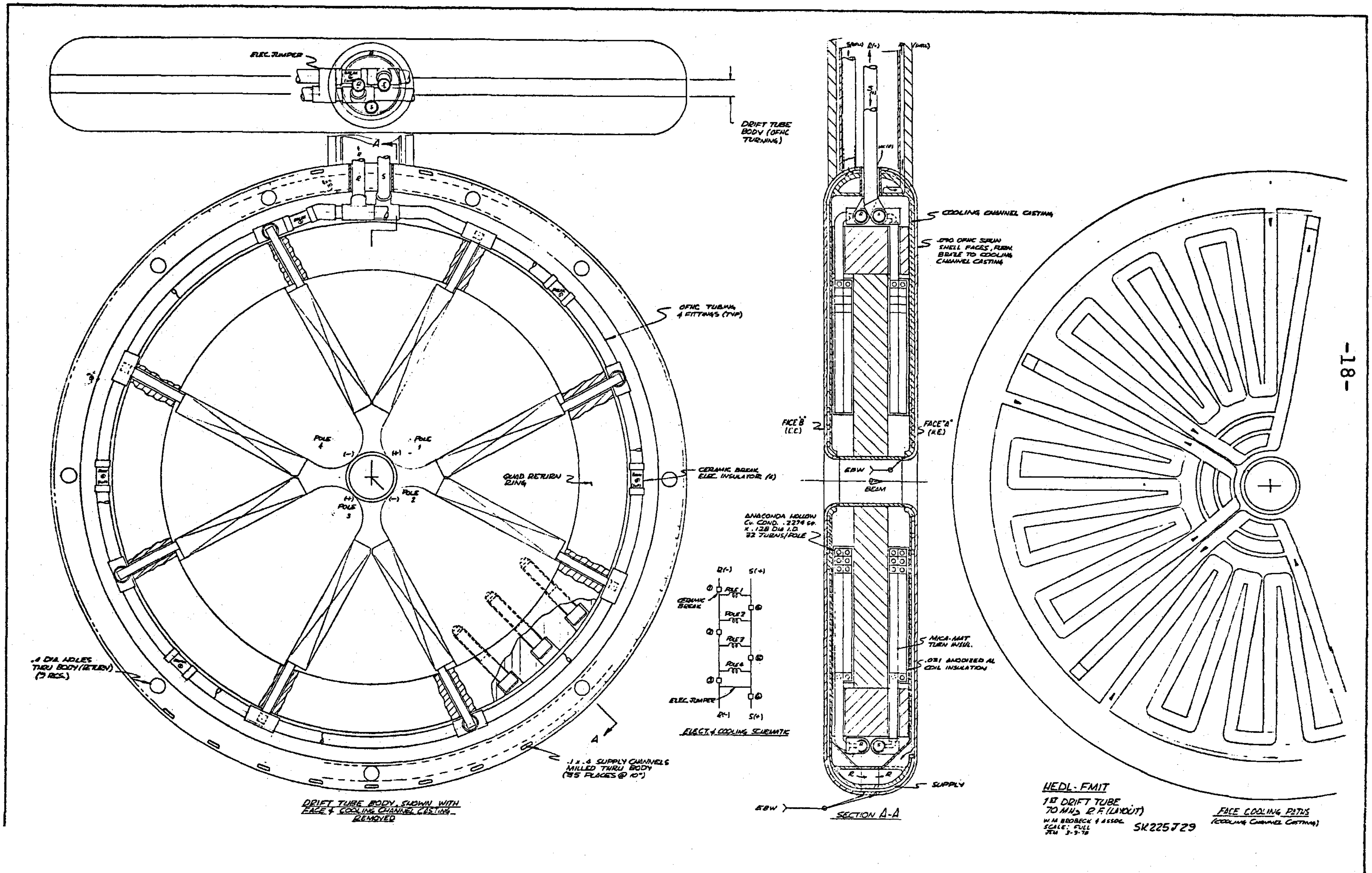
ELEC. JUMPER
DRIFT TUBE BODY (OFHC TURNING)
OFHC TUBING & FITTINGS (TYP)
POLE 1
POLE 2
POLE 3
POLE 4
QUAD RETURN RING
CERAMIC BREAK ELEC. INSULATOR (4)
.4 DIA. HOLES THRU BODY (RETURN) (3 PLCS.)
.1 x .4 SUPPLY CHANNELS MILLED THRU BODY (35 PLACES @ 10°)
A
DRIFT TUBE BODY, SHOWN WITH FACE & COOLING CHANNEL CASTING REMOVED
COOLING CHANNEL CASTING
.090 OFHC SPUN SHELL FACES, FURN. BRAZE TO COOLING CHANNEL CASTING
FACE "B" (L.E.)
FACE "A" (H.E.)
EBW
BEAM
ANACONDA HOLLOW Cu. COND. .2274 Sq. x .128 DIA I.D. 32 TURNS/POLE
MICA-MAT TURN INSUL.
.031 ANODIZED AL COIL INSULATION
SUPPLY
SECTION A-A
R(-)
S(+)
CERAMIC BREAK
ELEC. JUMPER
ELECT. & COOLING SCHEMATIC
HEDL-FMIT
1st DRIFT TUBE
70 MHz R.F. (LAYOUT)
W.M. BROBECK & ASSOC.
SCALE: FULL
SK225J29
FACE COOLING PATHS
(COOLING CHANNEL CASTING)