SSC DIPOLE MAGNETS

REVIEW ON "COLD" VERSUS "WARM"

MAGNETIC FIELD MEASUREMENT DATA COMPARISON *)

B. Berkes, SSC/CDG, Berkely

SUMMARY

Data from different SSC dipole model magnets and one full size magnet, measured in the "warm" as well as in the "cold" state, have been analyzed in order to obtain the correlation between the harmonics at room and cryogenic temperatures,respectively. Dealing with the normal geometrical sextupole only,one comes to the conclusion that this harmonics cannot be predicted with a precision ("sigma") better than 0.25 ... 0.5 "units" (1 "unit" being 1.0E(-4) of the main (dipole) harmonics).

A. FOREWORD

One has to say beforehand that the present report is less a scientific one, than the result of a large amount of detective work. The conclusions, based on the available magnetic field measurement data - presented in different forms by three laboratories - might therefore to some extent be influenced by the personal opinion of the reviewer.

B. INTRODUCTION

Because the "cold" magnetic field measurements on ALL 7680 SSC dipole magnets cannot be performed in due time, a special magnetic field measurement program - according to which only every 10th magnet would have to be measured in the "cold" state, has been established ([1], ch. 5.2.11). This has increased the importance of "warm" measurements, which shall - beyond the detection of manufacturing errors - serve now also to PREDICT the magnet behaviour (field harmonics due to the magnet geometry) in the "cold" state.

There exists a widely spread opinion that the mentioned prediction can be made with a PRECISION ([13],[14]) of 0.10 "units" (1 "unit" = 1.0*E(-4)). The purpose of this report is to investigate - on basis of existing data - the correctness of the above statement and to determine the degree of precision, which can be expected for the predicted field behaviour.

*) Talk given at the Magnet Systems Integration Meeting on May 5/6,1988 at the Industrial Center, Fermi National Accelerator Laboratory, Batavia, IL. This report represents the revised and modified version of the draft, attached to the minutes of the said MSIM (May 17, 1988).

C. ACCELERATOR REQUIREMENTS

For reasons of completeness, the tolerable errors of systematic and random multipole field components **) are presented in Table I. ([1], ch. 4.3.1; [11]). All the comparison results, determined below, will have to be judged against the tabulated data.

T A B L E I.

Systematic and Random Errors of the Multipole Field Components **)
[in "units" of dipole field at 1 cm radius]

Multipole Coeff.	Systematic Error	Random Error
b1	0.2	0.7
b2	1.0	2.0 (0.4;[12])
b3	0.1	0.3
b4	0.2	0.7
b5	0.04	0.1
b6	0.07	0.2
b7	0.1	0.2
b8	0.2	0.1

D. LIMITATIONS OF THE "COLD" - "WARM" COMPARISON STATEMENTS

Several effects, which could reduce the precision statements, are described in the subsequent paragrahs:

1. Because the magnets (models as well as the full size) are to a certain degree imperfect, it is difficult to separate the construction errors from those of the measuring system itself. A separate investigation of the latter ones, including the relevant instrumentation (electronics), appears to be neccessary. These internal checks have been done at BNL ([8],[9]) and LBL [2], but more extensively at LBL.

2. The magnetic axis as well as the axis of the measuring equipment are unlikely to be identical; if no correction (shift) of the measurement data has been made, additional "feed-down" higher harmonic errors will be incorporated in the particular harmonics looking into.

3. "Cold" fields depend on the direction of the current change (increasing or decreasing) due to the persistent current effects. Only if these are very small or can be mathematically cancelled with help of the current up-ramp and down-ramp field measurements [3], the geometric harmonics can be estimated.

4. After a particular "cold" magnet current is reached, an obvious time dependent effect of the amplitude of the harmonics,especially at low field levels, was observed [4]. It seems therefore reasonable, to compare only those data of "cold" magnets, measured after a certain (agreed) period of time after the requested current level has been reached.

**) In order to comply with the terminology used in the context below, the expressions "tolerance" and "multipole field error",used in [1],are replaced by terms "error" and "multipole field component".

5. Saturation in the yoke steel will show visible effects at higher field levels (beyond 5 T). One has to determine the magnitude of these effects very carefully in order to avoid false conclusions concerning the amplitude of the harmonics in the "cold" state.

6. The "history" of the yoke steel has an influence on the measurement results (up to 2 "units" in the sextupole harmonics were measured). In order to avoid this effect, magnet current cycling is necessary before making field measurements. By subtracting the amplitude of a particular harmonics at a negative current from that one at a positive current of the same magnitude, one can get the remanent field harmonics and so the correct geometrical field harmonics.

7. The same magnet can be measured with various equipment, distinguishable in design and instrumentation. Measurement data intercomparisons are therefore of importance in order to draw the final conclusion concerning the precision of the predicted harmonics [9].

E. FNAL MEASUREMENTS ON D0001

Measurements on full size magnet were made at 10 amp ("warm") and 2000 amp ("cold") with the BNL-"mole" (type B). For "cold" measurements, a warm finger was inserted into the magnet bore in order to prevent freezing of the measuring equipment. Measurements were taken at 28 positions along the magnet, 26 of them being in the homogenous field region.

The comparison results (integral field harmonics, transfer function and field angle) can be found in [5] and [6]. Furthermore, computer drawings of various harmonics and of the transfer function, showing the values at individual measurement points, have been made available to the reviewer [7].The FNAL results were shifted (see ch. D.2.), but not corrected for the persistent current effects at 2000 amp (see ch. D.3.).

All measurement results include errors due to the measuring equipment as well as those due to the magnet imperfections. However, assuming that the errors from the latter ones will remain the same regardless of the current level, the difference between "cold" and "warm" data will contain only the errors due to the "mole" itself. With the present data one will get then for the normal sextupole a "sigma" of approx. 0.25 "units" for the integral "cold" - "warm" comparison; according to [5], an average level "shift" of approx. +0.70 "units" could be attributed to the persistent current effect of the "cold" magnet (Fig. 1). Results for the normal decapole show a factor of two smaller "sigma" and level "shift".

One cannot expect that the above results are representative in the sense of statistics, because they have been obtained by measurements on ONLY one magnet. When at least 30 or more full size magnets ([15], p. 203) will be available, more information can be gained and a reasonable statistical analysis carried out.

In connection with the measurements on magnet D0001,one has to mention that 3 independent sets of magnetic field measurements on "warm" magnet D000X, performed at BNL, lead to a "sigma" of the sextupole integral (27 "point" measurements) of 0.50 "units", whereas the integral value itself repeats within 0.20 "units" ([8],[9]). [The latter value is the repeatability error ([13],[14]) of 3 averages (integrals), measured on the SAME magnet at only ONE state. It must not be not be mixed up with the above mentioned 0.50 (or 0.25) "units", which represents the statistical error of only ONE average, no matter whether it is a sextupole or a difference between two sextupole averages.]

F. LBL MODEL MAGNET MEASUREMENTS

A large number of LBL model magnets has been extensively measured in "warm" and "cold" state, respectively; since June 1988, the results of a variety of measurements can be found in the LBL "prompt reports" (for example [4]). An impressive amount of measurement log-books is existing at the LBL Supercon Group and has been made available to the reviewer.

All the model magnets use the same return yoke steel and only the coils, collars, assembly coil stress etc. were changed. For the purpose of this report only the data of the magnets D-15A-1 to D-15A-4F were used for "cold" - "warm" comparisons (before measurements, magnets were exposed to a "virgin" and 3 full excitation cycles). Furthermore, for reasons of simplicity, the comparisons were made only for the geometric normal sextupole (at "cold" currents from 1.0 kamp to 6.5 kamp, in some cases up to 8.5 kamp).In order to determine the "cold" geometric sextupole, data measured at up-ramp and down-ramp current changes were averaged [3]; this procedure appears at least for those magnet current levels reasonable, at which the persistent current effects are small. The remanent field part in the "warm" data was avoided by the method, described in ch. D.6. .

Fig. 2 shows clearly a plateau (measurement points within less than 0.25 "units") on all central and integral sextupole comparison curves for magnet currents between 3.0 and 5.0 kamp; in some cases the plateau is extended at its lower end to 2.0 or even 1.0 kamp. The integral plateau values (data were taken at 3.0 kamp) vary between -0.82 and -1.96 "units", from which figures one gets a "shift" of approx. -1.40 "units" and a precision "sigma" of the "cold"-"warm" geometric sextupole of approx. +-0.50 "units".However, this conclusion may be a wrong one, because the relatively large span between the precision limits can be also attributed to some other sources of errors ("cold" as well as "warm") besides the measurement ones.

The above errors must not be compared with the reproducibility data of the LBL measuring equipment ([2], Table I.), which show at least half an order of magnitude better results due to the following:

a) For the reproducibility measurements the coils were left at the same place within the magnet bore and only the field measurements were repeated, which excludes coil positioning and magnet current setting errors as well as possible errors from different persistent currents.

b) The measurement errors, refered to in [2], are estimated under the condition of the same magnet geometry. This is not the case for errors of the above "cold" - "warm" comparison,where - besides other possible sources of errors - the influence of constructional changes is to some extent still present.

T A B L E II.

LBL-SSC Model Magnets / Assembly Data *)

Magnet ID	D-15A-1	2	3	4	4F
Collar pole shims (in)					
inner	0.041	0.041	0.0305	0.027	0.030
outer	0.025	0.041	0.0335	0.038	0.035
Final assy. pressure (kpsi)					
inner	10.0	10.0	7.5	7.4	8.6
outer	3.5	3.5	7.5	6.7	5.0
Collar dia. after collaring (in)					
vert.	4.369	4.379	4.3710	4.3735	4.3733
horiz.	4.371	4.3705	4.7945	4.4905	4.7905
Collar/yoke shimming (in)					
shims used	0.012	0.012	0.012	0.014	0.014
interf. on dia.	0.008	0.008	0.008	0.008	0.008
Coil median radius (in)					
inner	0.985	0.9874	0.9854	0.985	0.985
outer	1.388	1.3904	1.3884	1.388	1.388
********************************					
Normal integral 6-pole ("units") (at 20 amps)	+2.74	+7.51	+1.93	+2.19	+5.14
Comparison "warm"-"cold" normal geom. 6-pole ("units") ("cold" ref.: 3 kamp)					
central region	-2.91	-2.47	-1.71	-2.77	-1.87
integral	-1.88	-1.96	-1.14	-0.82	-1.12

An interesting experiment was performed on D-14B-11 magnet some time ago. This magnet was measured at first in the "warm" state at LBL and then shipped to BNL,where both "warm" and "cold" measurements were made. Afterwards, the magnet was returned to LBL and remeasured both "warm" and "cold".

Based on first set of data, the comparison of the LBL vs. BNL "warm" values for the normal sextupole results in approx. +0.75 "units" for "point" measurements (LBL short coil length: 10 cm, BNL coil length: 60 cm) and approx. -0.45 "units" for the "warm" integral. According to other data [9], the "point" comparison ("warm" - "warm") at the magnet central plane amounts only approx. +0.25 "units". [Due to lack of time, "warm" - "cold" differences from the intercomparison measurements were not evaluated.]

*) Based on LBL "prompt reports".

The above figures would mean that ALONE due to the difference between two measuring systems the results may vary at least within +-0.25 "units" (normal sextupole harmonics). This IMPORTANT fact has to be taken care of at the time when final decisions concerning the measurement systems for "cold" and "warm" measurements would have to be made.

G. BNL MODEL MAGNET MEASUREMENTS

There exist numerous data on "warm" and "cold" measurements, performed on 1.8 m BNL model magnets [10], which need to be evaluated in detail *). A comparison between the BNL experience with that of the LBL (see ch. H.) regarding measurements on both magnet states and the prediction precision of the "cold" magnet will be of great interest.

H. CONCLUSIONS

Before drawing conclusions concerning the prediction accuracy of the "cold" dipole magnet behaviour based on "warm" measurements,one shall recapitulate the above comparison results (Table III.) .

The analysis of all relevant data for random errors (Tables I. and III.) leads to the conclusion that to the best of our present knowledge - even using SIMILAR type of equipment for "warm" and "cold" measurements and carrying out the measurements with great care (industrial measurements!?) - the INTEGRAL normal geometrical SEXTUPOLE harmonics

CANNOT BE PREDICTED WITH A PRECISION ("SIGMA") BETTER THAN
0.25 ... 0.50 "UNITS"

This precision must be compared with "sigma" requirement for the corresponding sextupole harmonics of 0.4 "units" (Table I. and [12]), which value is apparently inconsistent with 2.0 "units" (Table I.). However, after correction of the sextupole harmonics (up to 2.0 "units") with appropriate elements, the residual error shall not exceed a "sigma" of 0.4 "units", which explains the above difference.

The value for the prediction precision is rather a judgement than based on statistics and will, therefore, remain slightly QUESTIONABLE until several (30 or more) full size magnets of the finite design will be measured in both "warm" and "cold" state (ch. E., 4th para., and [15]). Only after the measurements on full size magnets have been evaluated and the correlation between particular harmonics in both operational states estimated, one will be able to obtain the necessary degree of CONFIDENCE in the prediction precision. However, the prediction of the field behaviour in the magnet "cold" state will still remain, as far as the reviewer is concerned, a CHANCY undertaking.

*) In the meantime, a report by P. Wanderer: "Comparison of Warm and Cold Multipoles in DSS Magnets" has been published (SSC-N-516, June 2, 1988).

T A B L E III.

A. Errors of the Integral Normal Sextupole Harmonics [in "units" of dipole field at 1 cm radius]

A.1 "Cold" Magnet

- Magnet Construction Imperfections		?
- Difference in Magnet Construction (LBL; rough estimate)		+-0.4
- Persistent Currents (at 3 T)	max.	+-0.3
- Time Decay (Center Region; 0.3 T; after 1 hr)	max.	3.0
- Saturation Effects (at 6.5 T)	max.	1.0
- Steel History		?

A.2 "Warm" Magnet

- Intercomparison LBL vs. BNL (Integral)	approx.	+-0.25
- Intercomparison LBL vs. BNL (Central Region)		+-(0.10 ... 0.40)
- Integral (Average) Error (D000X)	("sigma")	0.50
- Integral Repeatability (D000X)		+-0.10

B. Comparison Errors "Cold" vs. "Warm" for the Integral Normal Sextupole Harmonics [in "units" of the dipole field at 1 cm radius]

	"shift"	"sigma"
B.1 Full Size Magnet (D0001)	+0.70	0.25
B.2 LBL Model Magnets (D-15A-1 ... 4F)	-1.40	0.50
B.3 BNL Model Magnets (see p. 6, footnote)	-0.60	0.20

I. ACKNOWLEDGMENTS

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APPENDIX: METROLOGY DEFINITIONS ([13],[14])

ACCURACY	The degree of correctness with which a measured value agrees with the true value; customarily expressed in terms of an "error" (absolute, relative).
BIAS	A systematic error, due to equipment conditions (see ERROR (systemmatic)).
CONFIDENCE (measurement)	The chance (in percents) that a certain percentage of all future values generated by a measurement process will lie within bounds,determined by previous sets of measurements.
DRIFT	An undesired but relatively slow change in output of a measuring equipment over a period of time, with a fixed reference input.
ERROR (measurement)	Any discrepancy between a measured quantity and the true, specified, or theoretically correct value.
ERROR (random or accidental)	A component of error whose magnitude and direction vary in a random manner in a sequence of measurements made under nominally identical conditions. Also defined as the closeness with wich a series of readings of the same quantity repeats (see PRECISION and REPEATABILITY).
ERROR (systematic)	The inherent bias (offset) of a measurement process or of one of its components (see BIAS and OFFSET).
MEASURING EQUIPMENT	Devices or systems used to measure,test,or inspect in order to acquire research, development, or test data or to determine compliance with design, specifications,or other technical requirements.
OFFSET	The component of error that is constant and independent of the inputs, often used to denote bias (see BIAS).
PRECISION	The repeatability of measurement data, customarily expressed in terms of standard deviation ("imprecision").
REPEATABILITY (measurements)	The closeness of agreement among a number of consecutive measurements of the output for the same input value under the same operating conditions,approaching the measurement from the same direction; measured usually as "nonrepeatability" and does not include hysteresis.
REPRODUCIBILITY	The closeness of agreement among repeated measurements of the output for the same value of the input made under the same operating conditions over a long period of time, approaching from both directions (i.e. including hysteresis). May also be expressed as the ability of a system or element to maintain its output/input precision over a relatively long period of time.
RESOLUTION	The degree to which nearly equal values of a quantity can be discriminated.

REFERENCES

[1] SSC/CDG : Conceptual Design of the Superconducting Super Collider, SSC-SR-2020, Berkeley (March 1986)

[2] Green, M.I. et al. : Magnetic Measurement System for Harmonic Analysis of LBL-SSC Model Dipoles and Quadrupoles, LBL-23104, Berkeley (Sept. 1987)

[3] Gilbert, W.S. : Private Communication (Feb. 18, 1988)

[4] Gilbert, W.S. - Barale, P.J. : "Prompt Report" on LBL - SSC Model Magnet D-15A-4F, LBID - 1370 / SSC-MAG-186, Berkeley (Feb. 1988), ch. 3.5.2.1, p. 24

[5] Strait, J. et al. : Full Length Prototype SSC Dipole Test Results, IEEE Trans. on Magnetics, Vol. MAG - 23 (March 1987), p.1208

[6] Wanderer, P. : Expected Quench Plateau, Transfer Function and Multipoles of the First Two 17m SSC Dipoles, BNL Magnet Div. Note 196-11 (SSC-147), Brookhaven (Oct. 1986)

[7] Brown, B.C. : Private Communication (April 6, 1988)

[8] Wanderer, P. : Private Communication (Feb. 9, 1988)

[9] Wanderer, P. : Measurement Intercomparisons, MMW - 5 / Magnet Measurement Workshop, BNL (Sept. 1987) (not published)

[10] Wanderer, P. : Private Communication (Feb. 10, 1988)

[11] Chao, A. : Errors & Corrections, SSC-N-440, Berkeley (Jan. 8, 1988)

[12] Peterson, J. : Private Communication (May 2, 1988)

[13] Considine, D.M. : (Editor-in-Chief) Encyclopedia of Instrumentation and Control, McGraw-Hill Book Co., New York (1971)

[14] Jay, F. : (Editor-in-Chief) IEEE Standard Dictionary of Electrical and Electronics Terms, Third Edition, IEEE and J. Wiley & Sons, New York (1984)

[15] Freund, J.E. : Statistics, Prentice-Hall Inc., Englewood Cliffs (1970)

Fig. 1

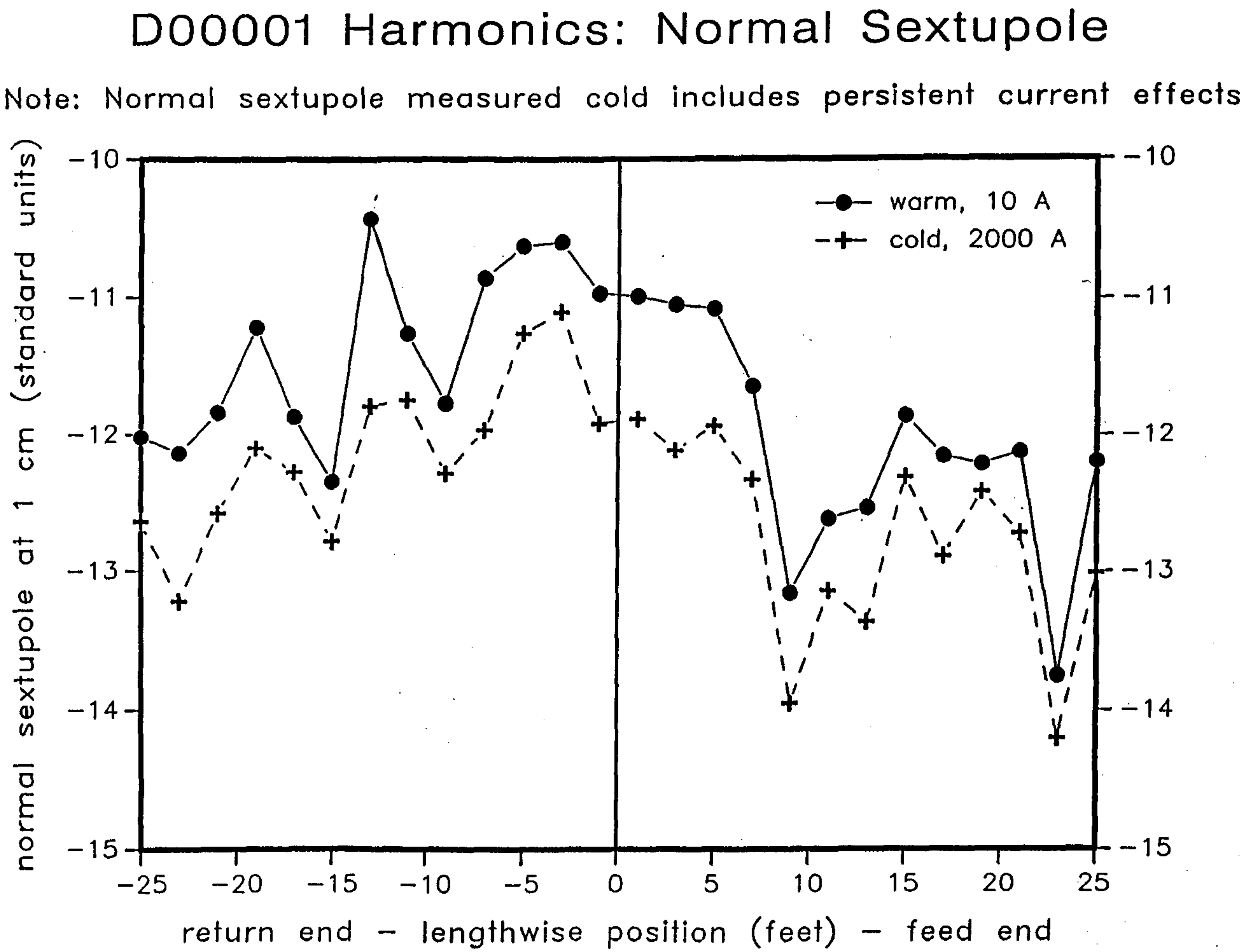
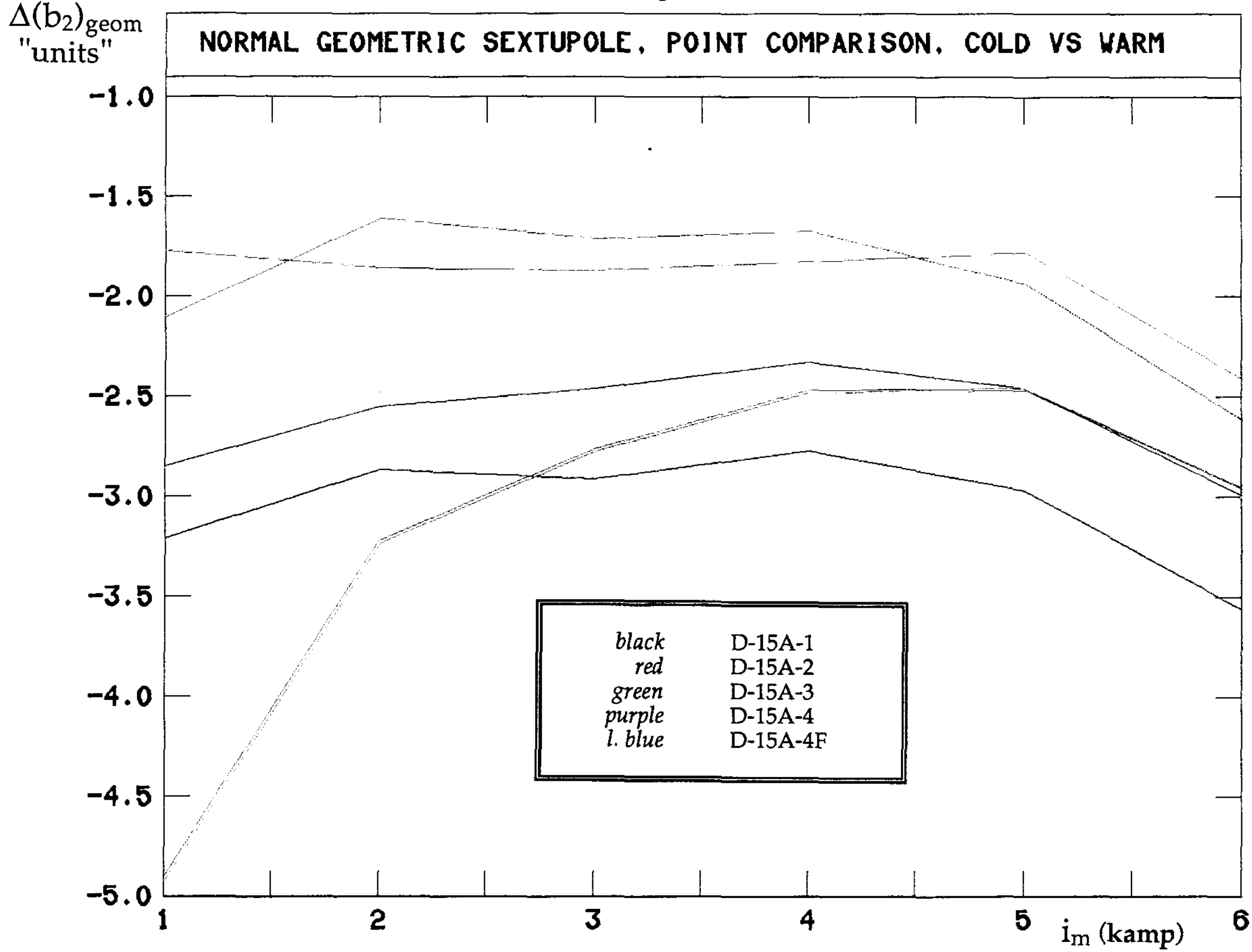
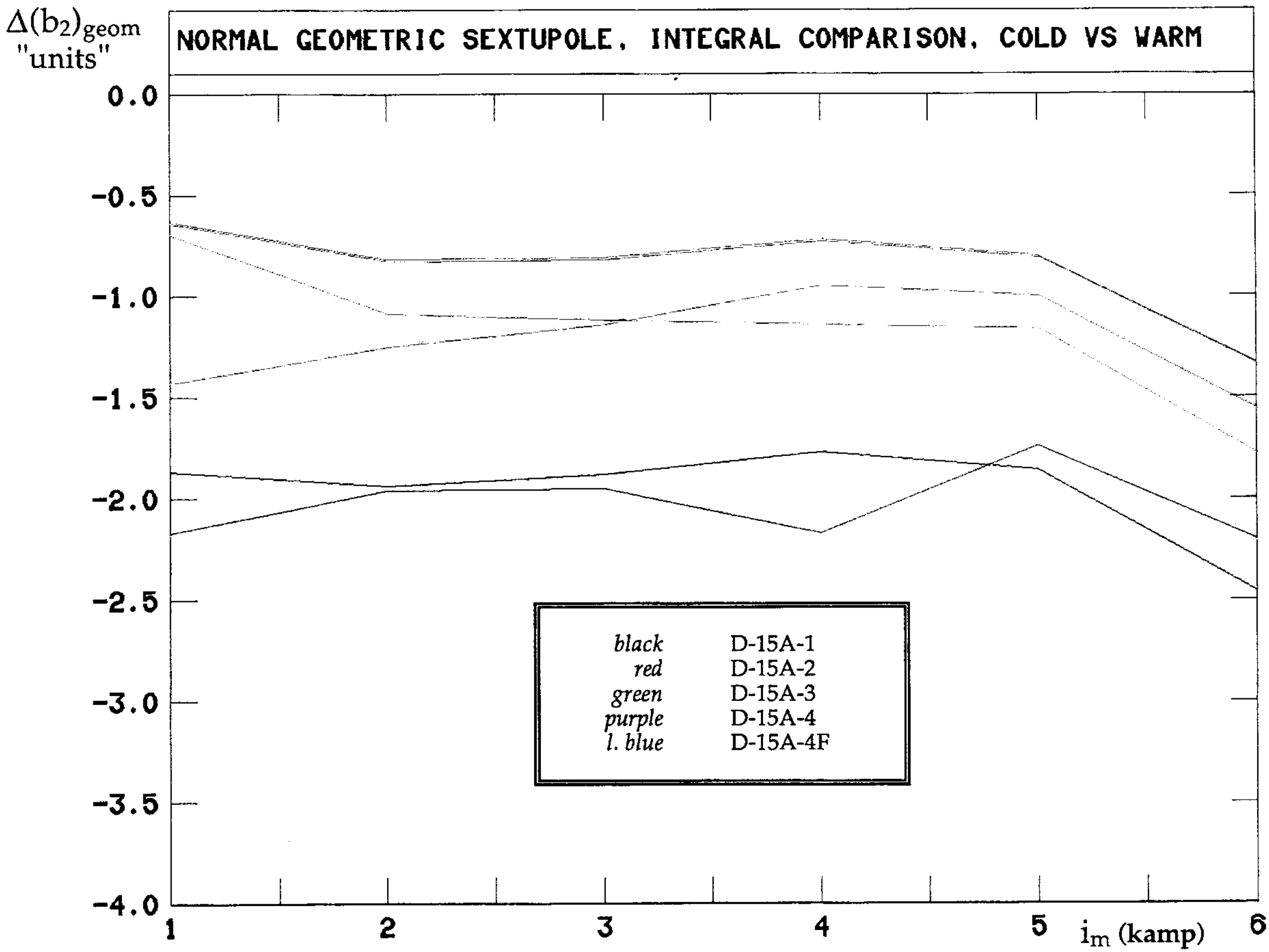

D00001 Harmonics: Normal Sextupole
Note: Normal sextupole measured cold includes persistent current effects
warm, 10 A
cold, 2000 A
normal sextupole at 1 cm (standard units)
−10
−11
−12
−13
−14
−15
−25
−20
−15
−10
−5
0
5
10
15
20
25
return end − lengthwise position (feet) − feed end

Fig. 2a



Δ(b2)geom
"units"
NORMAL GEOMETRIC SEXTUPOLE, POINT COMPARISON, COLD VS WARM
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
1
2
3
4
5
6
im (kamp)
black D-15A-1
red D-15A-2
green D-15A-3
purple D-15A-4
l. blue D-15A-4F

Fig. 2b



NORMAL GEOMETRIC SEXTUPOLE, INTEGRAL COMPARISON, COLD VS WARM
Δ(b2)geom "units"
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
1
2
3
4
5
6
im (kamp)
black D-15A-1
red D-15A-2
green D-15A-3
purple D-15A-4
l. blue D-15A-4F