Data Analysis and Quality Control of the Fermilab Main Injector Dipoles using the Flatcoil Measurements

C. S. Mishra
Fermi National Accelerator Laboratory*
Batavia, Illinois 60510

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I. INTRODUCTION

We have measured the magnetic properties of the Fermilab Main Injector (FMI) R&D and Production Dipoles at the Fermilab Magnet Test Facility (MTF). At MTF we measure each dipole by using four different kinds of probes Flatcoil, Harmonic Coil, Hall probe and NMR. In this paper we will present a short description of the FLATCOIL measurements. More detailed description of the Flatcoil Measurement system can be found elsewhere[1]. We have used the measurement data from the R&D and production dipoles to develop an analysis and QC criteria for the production dipole measurements. In this paper We will discuss the analysis of the data, and the QC for the Flatcoil excitation and scan measurements. The final MTF implementations of these analysis procedures and QC checks will be described elsewhere[2]. QC of the Flatcoil measurements are different and tighter than the dipole magnet acceptance criteria[3]. Tighter limits on the measurements are set to monitor any small variation in magnet production and measurements.

II. Flatcoil Measurements

Two different types of measurements are performed on the FMI dipoles using the 24 foot long Flatcoil Probe[1]. In one measurement, called excitation measurement, the Flatcoil is placed through the magnet at x=y=0.0 and the magnet excitation history is established. The current is ramped up from zero to the measurement value in 500 amps steps and than ramped

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down to zero in same steps. We are considering different step sizes for these measurements to characterize our magnet better. At each step during the ramp the total field integral ($\int B.dl$) of the magnet is measured at that current. In other measurement, called scan measurement, the X dependence of the field shape is measured with respect to the field at x=y=0. At each x location we measure the relative change in $\int B.dl$ (i.e. $(B - B_o)/B_o$), where B_o is the $\int B.dl$ at x=y=0 and B is the $\int B.dl$ at current x location). In this measurement the magnet current is raised from zero to certain current similar to excitation measurement than the Flatcoil probe is moved from one edge of the magnet (-1.8 inches) to the other edge (1.8 inches) and back in 0.100 inch steps . These limits in X are defined by how far the present probe can be moved in the magnet aperture. Magnet current is increased (in 500 Amps steps) further and this process is repeated till the maximum current of 9500 Amps. All these excitation and scan data are stored in SYBASE[4].

These data are collected using a checklist which was determined after series of reviews to determine what data are needed to fully characterized a dipole magnet using a Flatcoil probe. We require that all of the measurements specified in checklist[5] is completed successfully, within 2% of the specified current below 1500 Amps and less than 0.5% above.

III. Data Retrivial and Analysis for R&D Dipoles

We extract the data from SYBASE using reports[4] and analyses the extracted data by using Fortran programs, PAW and Xmgr. In this section we will describe this analysis procedure. All of these commands are run from a script file. Here we list the whole command for completeness.

a) SUMMARY OF MAGNET MEASUREMENTS:- First step in this procedure is to determine what data were take for a particular magnet (i.e IDA001, IDB001 ..). We run a report

% runrw mtfmsa.glass.fc_red_run_summary -V magnet IDA001 -V probe 12222 -o ida001.fcrun

where IDA001 is the name of the magnet under study. 12222 is the identification number for 24' long Flatcoil probe. For 80" long Flatcoil probe the identification number is 12207. The output of this report is written to a file magnet_name.fcrun (ida001.fcrun). A sample of the output file is in APPENDIX I.

We examine this file to find a list of SATISFACTORY excitation and scan runs. One can choose several excitations and scan runs.

b) EXTRACTION OF THE EXCITATION DATA:- After the selection of one or several excitation data, identified by red_run_sn we run the following report to extract the excitation data from the database.

%runrw mtfmsa.glass.fc_red_pnt_excite1 -V redrun red_run_sn -o fc_red_pnts.red_run_sn -P password

red_run_sn is the number from the summary file. This report generates an output file fc_red_pnts.red_run_sn. This file the integrated strength of the magnet in T-m. A Sample of the output file is in APPENDIX II. These excitation results will be saved in the results database.

c) EXTRACTION OF THE SCAN DATA:- The scan data is the representation of the x dependence of the magnetic field. It is normalized to the field at x=y=0.0. This normalization is done by scaling the field strength measured by an excitation run and setting the offset flux to zero at x=y=0.0. The scan measurement represents the change in the magnetic field strength as a function of x, (B(x)-B(0))/B(0), and is a direct measure of field uniformity.

The normalized scan data is extracted from the database by

%runrw mtfmsa.glass.fc_shape -V exrun exec# -V scanrun red_run_sn -V curwin 25. -o fc_shape.red_run_sn -P password

Where exec# is the excitation run red_run_sn number and red_run_sn is the serial number for this scan run. To select a magnetic field from the excitation run at a current close to this scan run, we use a current window of 25 Amps. This output file contains a normalized field shape of the magnet as a function of x. The shape is expressed in terms of relative units. A sample output file is on Appendix III.

IV. Data Analysis and QC of the FLATCOIL Measurements

Using the R&D and production dipole magnet data we have developed an analysis and QC of Flatcoil measurement procedure for the production dipole measurements. The production dipole measurements will be compared to the nominal value and sigma of strength variation or predetermined limits, calculated from the R&D and production dipole measurements. Each of the parameters describes above will be compared with two levels of limits called Level 1 and Level 2. These levels are intended to indicate different levels of severity of discrepancy between measured values and nominal values. Level 1 limits are set such that they indicate an off-normal condition in the magnet or measurement. Level 2 limits are set to indicate a serious out of tolerance condition. For a gaussian distributed data level 1 limits would be exceeded for about 10% of the magnet measurements. The Level 1 limits will be set at 2 sigma of the first 25 Production Dipole measurements distributions. Level 2 limits will be set at 1.5 times the sigma of the magnet acceptance criteria[3]. In most cases the FMI dipole magnet sigma are much smaller than what is used for the FMI tracking simulations[3]. If for some higher multipoles FMI dipole magnets sigma are larger than what have been used for simulations, we will set the level 2 limits for that multipole at 3 sigma of the production dipole measurements.

Each measurement will be tested against a low and a high bound according to the following scheme

$-Level2 < -Level1 <$ deviation from nominal value $< Level1 < Level2$

If a magnetic measurement, either excitation or scan, falls outside lower limit(Level 1) that measurement of the magnet should be repeated with the same probe under similar conditions. On the other hand if it also falls outside the higher limit(level 2) and remeasurement confirms earlier measurements the magnet should be labeled for further investigations. Further investigations will consists of measurements with other probes. This comparison and further investigations will be described elsewhere[6].

A. EXCITATION MEASUREMENT

The extracted data from database contains $\int B.dl$ as a function of current. The measurement current is always different from the nominal current. We calculate the $\int B.dl$ at nominal current by a method of spline interpolation. The corrected $\int B.dl$ and error in $\int B.dl$ as a function of current will be stored in the results database. We donot have plans to measure the effective length as a function of current for every dipole magnet. We have measured the effective length of a few dipole magnet and plan to use these as the nominal value of the dipole effective length as a function of current. We will calculate the magnet body strength and its error using $\int B.dl$ and effective length. These numbers will be stored in the results database.

The QC of the excitation measurements we will calculate the relative difference in the strength of the present magnet with respect to the nominal strength calculated from the production dipole magnets (i.e (MAGNET - NOMINAL)/NOMINAL). This difference will be compared to 2 and 3 sigma variations of the production magnets strength. If the present magnet strength is within ± 2 sigma bounds the Flatcoil excitations measurement will be considered satisfactory. If the current magnet strength will fall between ± 2 and ± 3 sigma bounds (more than 3 points) than the measurer will remeasure the Flatcoil excitations of this magnet. If a magnets excitation measurement (more than three points) falls outside the ± 3 sigma limits the magnet should be remeasured. If the remeasurement doesnot change the result, magnet excitation should be labeled for further investigation with Hall and Harmonics probes. Fig. 1 shows the comparison of a magnet excitation with QC limits.

The nominal value of magnet strength and ± 2 sigma and ± 3 sigma variation limits should be stored in Quality Control database. These values will be updated on a periodic basis as enough data is accumulated. There are different sets of nominal values and sigmas for the strength measurements of 6m and 4m dipoles.

As a QC check of the measurement system and probe every tenth magnet should be remeasured regardless of the QC criteria.

B. SCAN MEASUREMENTS

The scan data contains the relative difference in magnetic strength as a function of x. This scan data is fitted with a seven order polynomial using least square minimization routine MINUIT from CERNLIB. The coefficient of the polynomial are the higher order multipoles of the dipole magnet. In the analysis of the R&D and production dipole magnet data we have found that the x placement of the Flatcoil in the dipole magnet is better than 0.100". Any offset in x introduces an unphysical quadrupole component at high currents. This quadrupole is essentially due to feed down from large sextupole, which is present by design. This off set is calculated by doing a linear fit of the measured quadrupole(y) and sextupole(x) components as function of current. The intercept of this linear fit is the quadrupole strength of the magnet and the slope is the ΔX offset of the probe. This calculated Flatcoil offset ΔX will be stored in the results database. The Flatcoil probe will be required to be recentered and all the scan measurements repeated if the calculated ΔX is larger than 0.050". Using the calculated value of offset ΔX, measured and fitted quadrupole strength we correct the measured scan for the Flatcoil placement error. This correct value of scan as a function of x will be stored in the "results" database. We refit the corrected scan data with a seven order polynomial to calculate the normal higher order multipoles. These multipoles will be saved in the results database.

Using the scan data from the first 14 (R&D and production) dipoles we have calculated the nominal value of x scan and normal multipoles as a function of currents Fig 2-6. We are interested in the flatness of the field over a region of ± 1.25". Main Injector dipole magnet has large sextupole component at high currents. The nominal value of x scan at 7000 and 9500 Amps have been calculated by removing quadrupole and sextupole components.

The scan measurements QC will be done by calculating a difference between the present magnet x scan after the offset correction at a particular current to the nominal x scan. We will calculate the difference between measured scan and nominal scan at 500, 1500, 5000, 7000 and 9500 amps. The dipole magnets nominal x scan should be stored in the quality control database. The lower and upper limits of the scan difference is $\pm 1e-4$ and $\pm 2e-4$ respectively over ± 1.25" in x. The procedure for remeasurement or labeling the Flatcoil scan measurements for further investigation is similar to the excitation measurement. A magnet with questionable scan measurements should be compared with derived x dependence using Harmonics probe measurements[6]. Fig. 7 shows a QC example for a scan measurements.

The normal components of the magnetic multipoles calculated by the fit to the x offset corrected scan measurements should be compared with the nominal value of the dipoles multipoles by calculating the difference (b_n present magnet - nominal b_n dipoles). The nominal values has been calculated by using the data of first 14 R&D and production dipoles. The nominal b_n should be stored in the quality control database. The lower and upper limits of the multipole comparison is $\pm 0.5e-4$ and $\pm 1e-4$ respectively. If a magnet's multipole falls outside the lower limit than the magnet should be remeasured, if it also falls outside higher limit than it should also be labeled for normal multipoles check with the harmonics probe.

These intermediate data along with QC limits is plotted by using CERNLIB's PAW. Special care has been taken in writing these output files so that they can be read by these programs. We have developed standard format for these plots as detailed in PAW command files (excite.kumac and scan.kumac) so that plots from different magnets can be compared on the same scale.

V. Summary

This analysis and QC of Flatcoil measurement procedure has been verified for the R&D and production dipole measurements. Sample output from the excitation and scan analysis and QC programs are shown in APPENDIX IV and V.

VII. REFERENCES

1 H. D. Glass, MTF NOTE XXX, Flatcoil Measurement system for FMI Dipole (to be submitted).

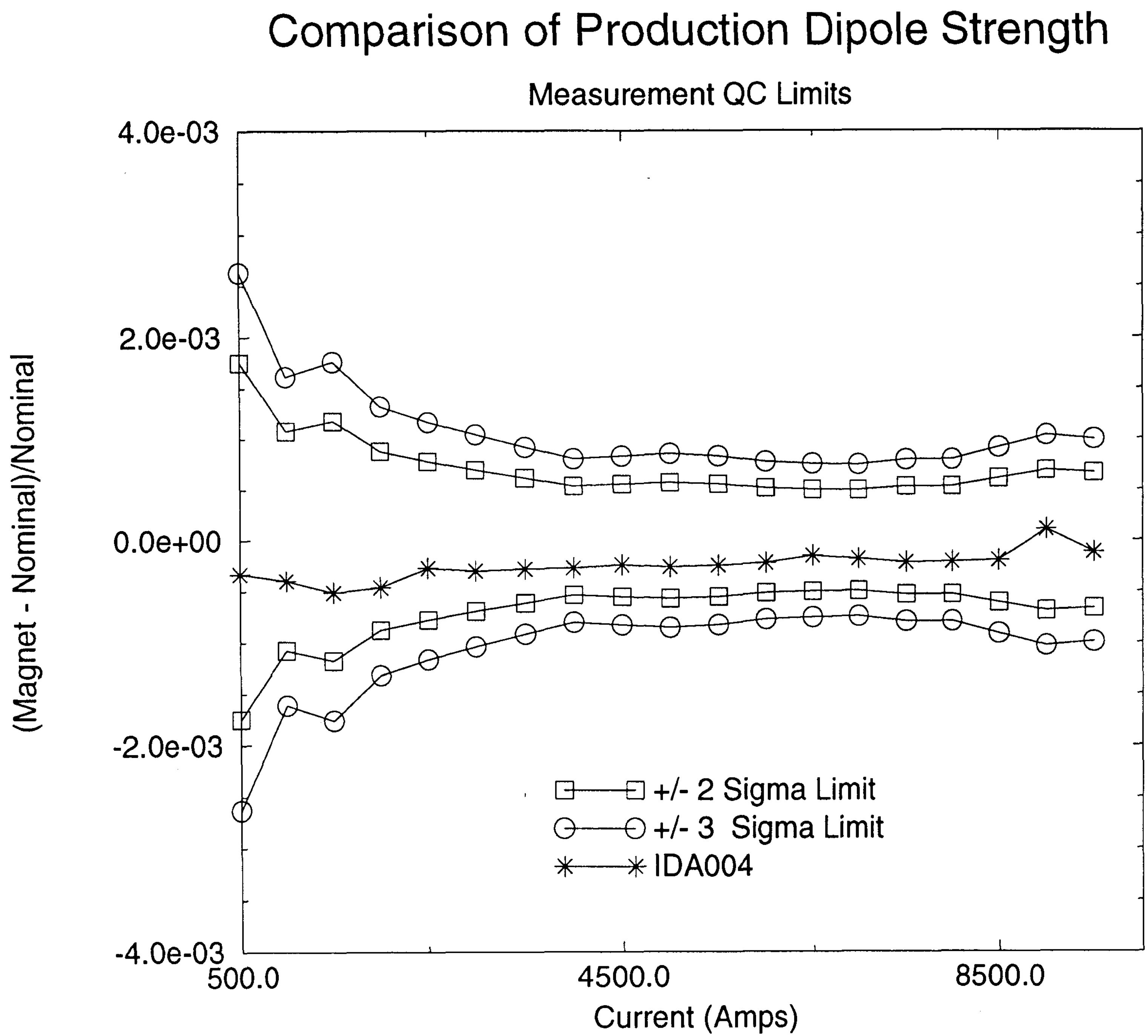
2 J. Nogiec, et al. MTF NOTE XXX MTF implimentation of Flatcoil Data Analysis and QC Control (to be submitted).

3 C. S. Mishra MI Note, Main Injector Dipole and Quadrupole acceptance criteria. (to be submitted)

4 MTF Note 92-0017, Design of the Flatcoil Virtual Database.

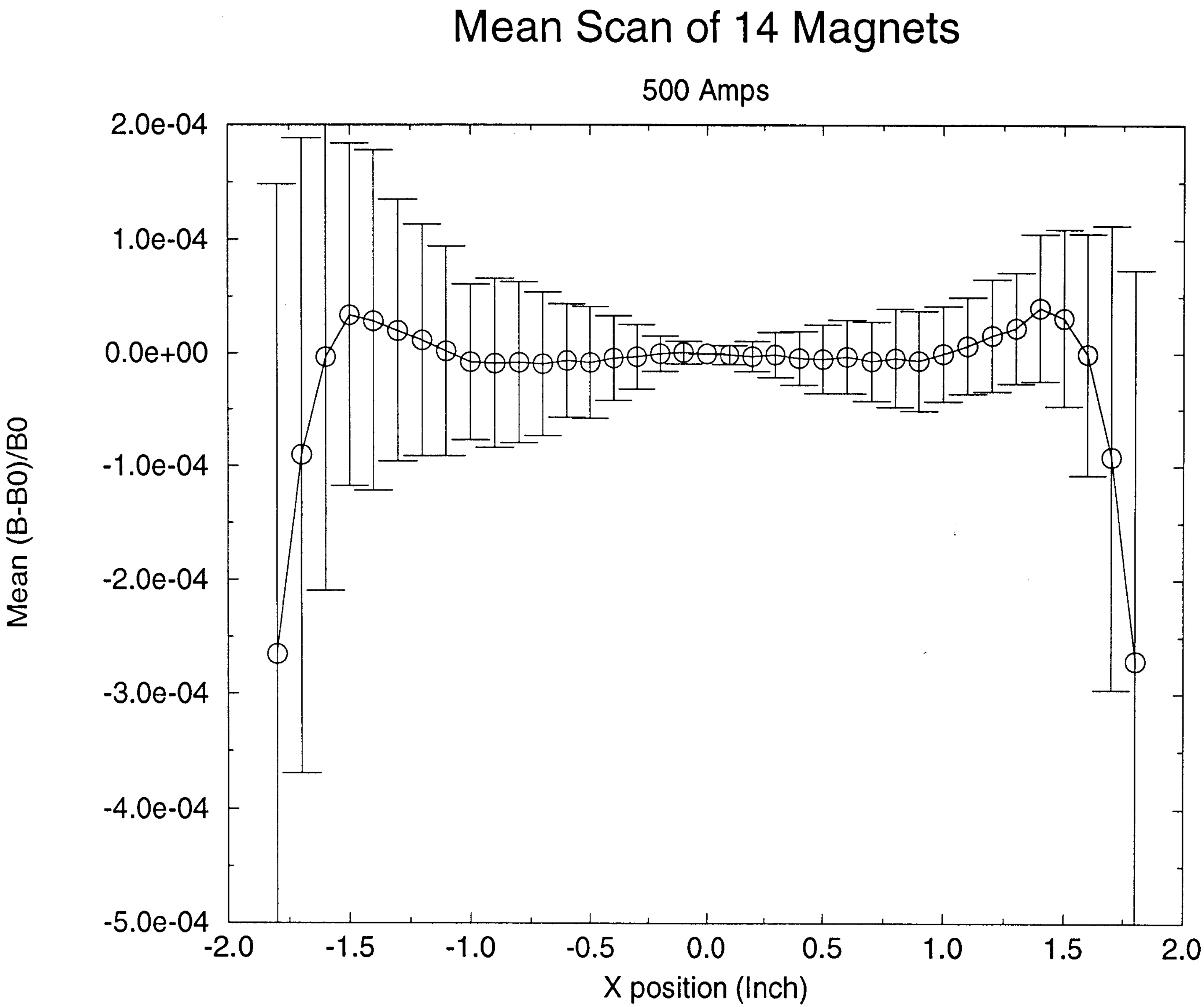
5 J. Sim, MTF Note, Checklist for Magnet Data Acquisition.

6 C. S. Mishra et al. (MI Note) Cross check of Dipole measurements with different probes.



Comparison of Production Dipole Strength
Measurement QC Limits
4.0e-03
2.0e-03
0.0e+00
-2.0e-03
-4.0e-03
(Magnet - Nominal)/Nominal
500.0
4500.0
8500.0
Current (Amps)
+/- 2 Sigma Limit
+/- 3 Sigma Limit
IDA004

Fig. 1



Mean Scan of 14 Magnets
500 Amps
Mean (B-B0)/B0
2.0e-04
1.0e-04
0.0e+00
-1.0e-04
-2.0e-04
-3.0e-04
-4.0e-04
-5.0e-04
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
X position (Inch)

Fig. 2

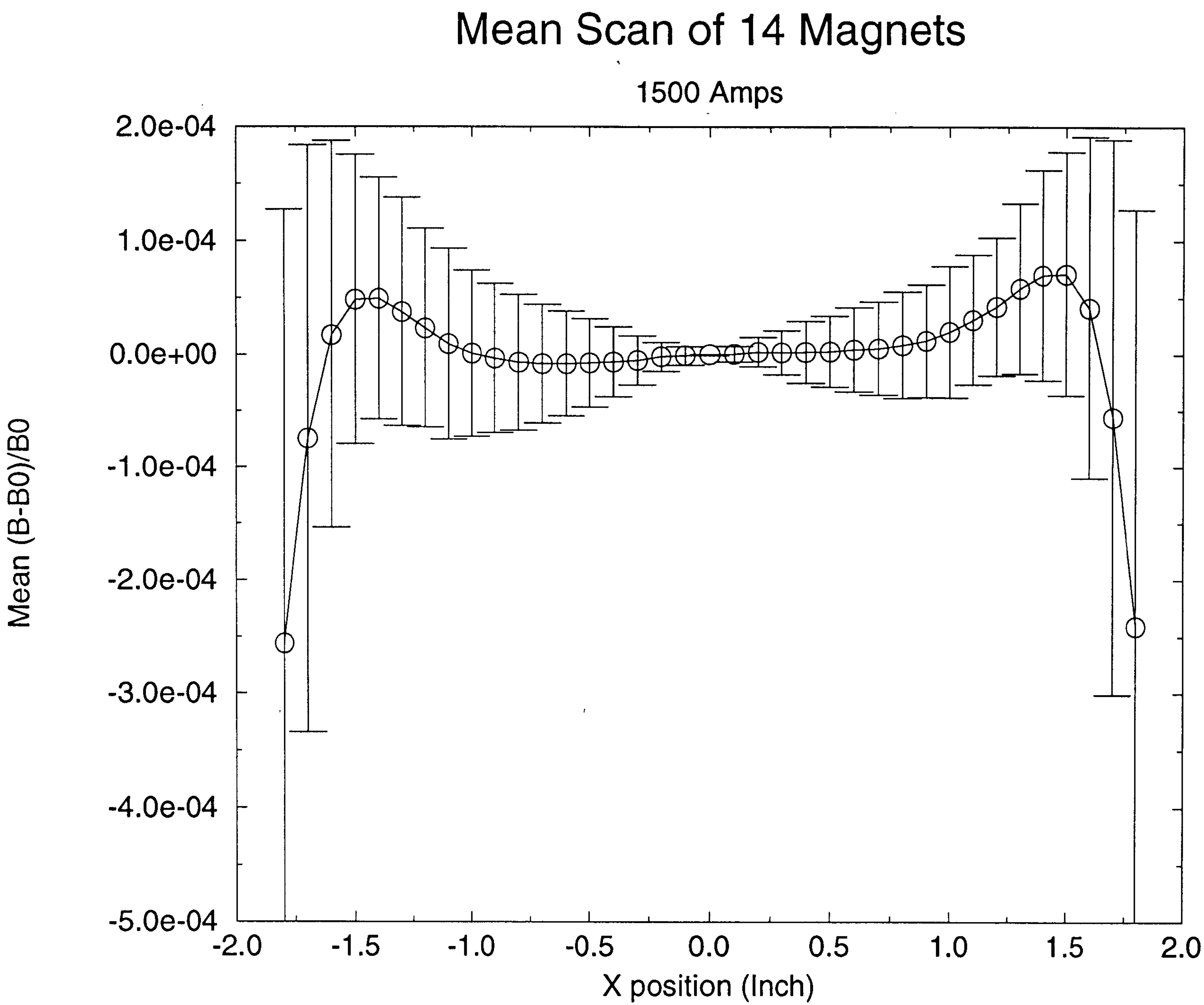
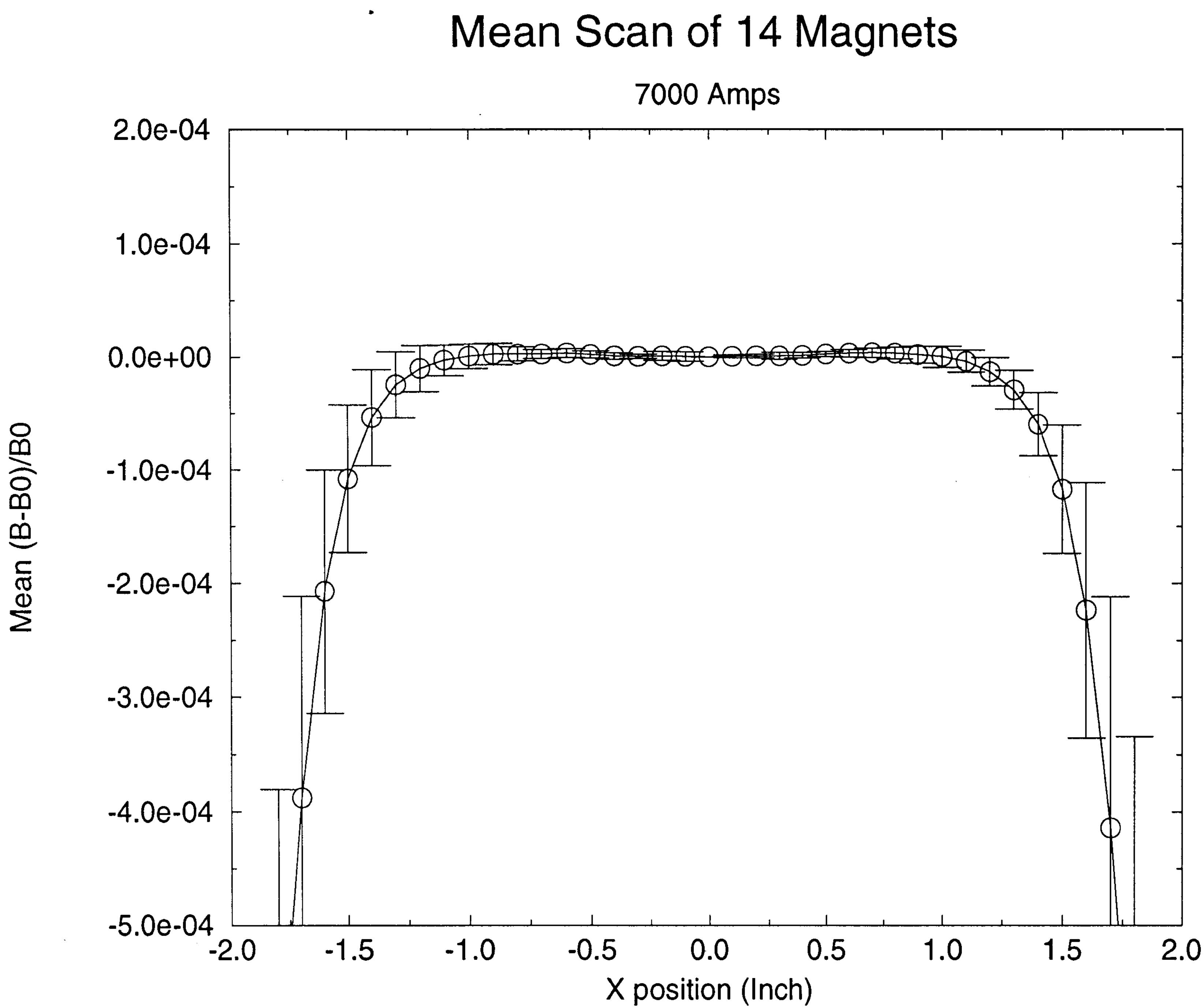

Mean Scan of 14 Magnets
1500 Amps
2.0e-04
1.0e-04
0.0e+00
-1.0e-04
-2.0e-04
-3.0e-04
-4.0e-04
-5.0e-04
Mean (B-B0)/B0
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
X position (Inch)

Fig. 3



Mean Scan of 14 Magnets
7000 Amps
2.0e-04
1.0e-04
0.0e+00
-1.0e-04
-2.0e-04
-3.0e-04
-4.0e-04
-5.0e-04
Mean (B-B0)/B0
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
X position (Inch)

Fig. 4

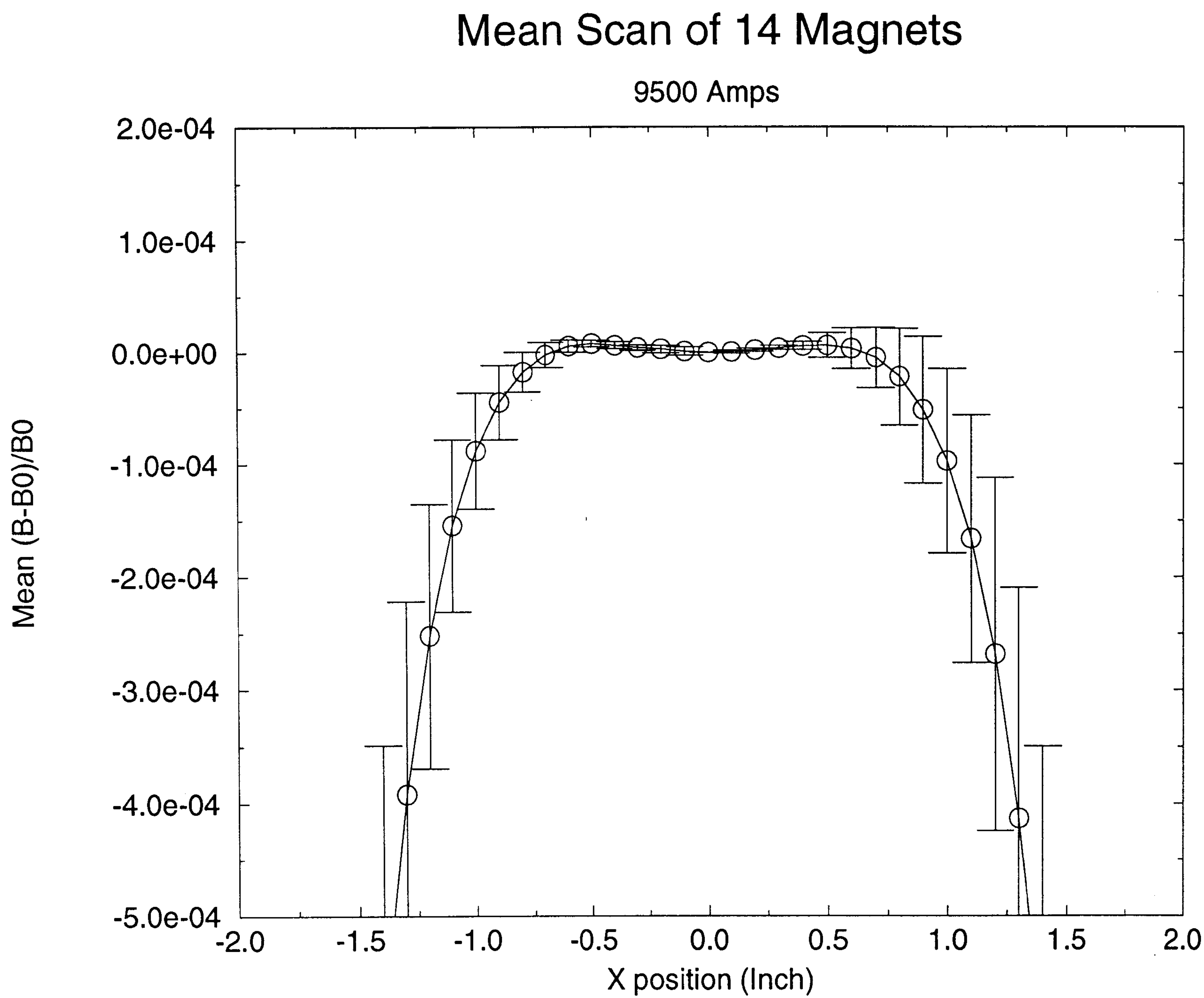

Mean Scan of 14 Magnets
9500 Amps
Mean (B-B0)/B0
2.0e-04
1.0e-04
0.0e+00
-1.0e-04
-2.0e-04
-3.0e-04
-4.0e-04
-5.0e-04
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
X position (Inch)

Fig. 5