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Measurements of the Longitudinal Shape and Center of the Magnetic Field of PDD Dipoles

Bruce C. Brown
Beams Division/Main Injector Department
*Fermi National Accelerator Laboratory**
P.O. Box 500
Batavia, Illinois 60510

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Abstract

Longitudinal shape measurements of PDD series dipoles for a new 8 GeV transfer line from the Fermilab Booster to the Main Injector are reported (the profile, the longitudinal center, and the field integral). Implications for beamline operation and future magnet construction are reviewed.

1 Introduction

A preliminary measurement of the longitudinal center of a PDD dipole was reported previously[1] along with implications for accelerator physics and measurement requirements. With the completion of the full set of PDD dipoles, we have chosen to measure the longitudinal profile on all of them. In this paper, we explore the gross structure of the longitudinal profile, calculate from the measurements the integrated bend strength and the bend center. We explore the data quality and record the initial installation information.

2 Measurement Hardware and Procedure

The results reported here are from a coarse longitudinal scan with a high resolution Hall probe which was positioned manually. The hardware and procedure for most of these measurements are described in note MTF-96-0008[2]. It consists of a Model MPT-231-7S Hall Probe manufactured by Group 3, read out by a Model DTM-141-DG Digital Teslameter. Transverse positioning is obtained with an aluminum holder with two fixed plastic buttons which are driven into contact with the edge of the magnet aperture by a spring loaded plastic button on the other face of the holder. The Hall probe is mounted in the manufacturers plastic mount which is, in turn, mounted in the aluminum bar. A 0.5″ dia. aluminum rod is used to push the block through the magnet and the position with respect to the "LABEL" end of the end of the magnet is noted by the measurer and recorded. The measurement procedure which was developed is recorded in MTF-96-0008, however, this procedure was under development when some data was taken, resulting in inferior data, as noted below. Further measurements with a holder which was positioned within the beam pipe were performed on a fraction of the magnets.

Raw data are recorded into 'pointscan' tables[3] of the MTF database. Data is reduced by converting the measured raw z position to a z position in inches from the 'OTHER' end (requiring only a shift in origin) as is standard for MTF Main Injector measurements. Reduced data is stored in files in the /usr/analysis/PDD/'visual_label'/special directory with a file name Hall_red_zscan.'run_sn' on the MTF Sun computers. Distances are given in inches from the 'OTHER' end of the magnet and fields are shown in Tesla.

2.1 Details of Measurement History

This effort began as an attempt to secure minimal information on the qualitative features of the longitudinal profile. The initial measurements revealed that the effect was large enough to have significance for the 8 GeV Line installation. However, the magnets were slated for almost immediate installation so the measurement effort proceeded while understanding of the correct procedure was developed. In particular, the interaction between keyboard commands, screen prompts and execution of the GPIB system reading of the Teslameter was misunderstood by this author and initial measurements frequently involved moving the probe immediately after a carriage return which was thought to have followed the measurement. Since, in fact, the measurement followed that carriage return, the reported field didn't necessarily reflect the field at the reported z position. All, or nearly all, of the faulty measurements were repeated, but some may have been missed. Measurements from this time period are labeled with the (Status = ?). In addition, small problems were encountered due to the aluminum positioning rod being too short. Kludged solutions were initially used with somewhat inferior results for the positions near the OTHER end (z near 0).

After the procedure was improved, measurements continued, with the best being taken by the staff at MTF using the same procedure. These various set are labeled with (Status = G). However, some additional magnets still required measurement after the beam pipe was installed, and for these a new way of obtaining the transverse positioning was required. Gerry Jackson provided a new 'sled' and measurements proceeded. For these measurements, (Status = N).

The procedure to zero the Group 3 Teslameter system is complex and might have been inadequately executed for some of the early measurements. The "N" measurements were executed after a careful probe zero and within a short period of time. Tables 1 and 2 list the measurements which have been use for this analysis. The measurement status described above is shown along with the database serial numbers for the selected runs.

Edited List of PDD Zscans per 26 Nov 1996					
visual label	raw seq_sn	raw run_sn	measurement dt		Status
PDD002-1	987092	987094	Oct 30 1996	9:37PM	?
PDD003-2	987034	987036	Oct 30 1996	8:15PM	?
PDD004-2	989146	989148	Oct 31 1996	2:08PM	G
PDD005-2	1008788	1008790	Nov 12 1996	1:41PM	G
PDD006-2	1037981	1037985	Nov 25 1996	9:49PM	N
PDD007-1	987099	987101	Oct 30 1996	9:49PM	?
PDD008-2	1037963	1037967	Nov 25 1996	9:29PM	N
PDD009-1	1037935	1037939	Nov 25 1996	8:39PM	N
PDD010-2	1023988	1023992	Nov 19 1996	10:07AM	G
PDD011-1	1037954	1037958	Nov 25 1996	9:18PM	N
PDD012-2	987075	987077	Oct 30 1996	9:15PM	?
PDD013-1	1010471	1010473	Nov 13 1996	2:08PM	G
PDD014-1	987027	987029	Oct 30 1996	8:08PM	?
PDD015-1	1023742	1023746	Nov 19 1996	9:27AM	G
PDD016-1	987082	987084	Oct 30 1996	9:22PM	?
PDD017-1	1038069	1038073	Nov 25 1996	11:32PM	N
PDD018-1	1038044	1038048	Nov 25 1996	11:04PM	N
PDD019-1	1037990	1037994	Nov 25 1996	9:59PM	N
PDD020-0	989158	989160	Oct 31 1996	2:35PM	G
PDD021-1	1008939	1008941	Nov 13 1996	9:16AM	G
PDD022-1	1008794	1008796	Nov 12 1996	2:56PM	G
PDD023-1	1010116	1010120	Nov 13 1996	1:36PM	G
PDD024-0	987048	987050	Oct 30 1996	8:29PM	?
PDD025-0	988521	988523	Oct 31 1996	11:44AM	?

Table 1: Production PDD Dipoles with POINTSCAN measurement sequence and run selected for final analysis. The Status column reflects the the procedure development status: ? for unrepeated measurements from the first set of measurements, which may be affected by moving probe too soon. G indicates measurements after the procedure was firmly established including by MTF Staff which are assumed good, N indicates new measurements at MP9 after system was more fully understood. Transverse positioning for these required the sled in the beampipe.

Edited List of PDD Zscans per 26 Nov 1996					
visual label	raw seq_sn	raw run_sn	measurement dt		Status
PDD026-0	1037917	1037921	Nov 25 1996	8:01PM	N
PDD027-0	1038060	1038064	Nov 25 1996	11:23PM	N
PDD028-1	989152	989154	Oct 31 1996	2:23PM	G
PDD029-0	1038008	1038012	Nov 25 1996	10:23PM	N
PDD030-0	1009131	1009161	Nov 13 1996	10:05AM	G
PDD031-0	1010481	1010483	Nov 13 1996	3:12PM	G
PDD032-0	1023849	1023857	Nov 19 1996	9:47AM	G
PDD033-0	1038035	1038039	Nov 25 1996	10:53PM	N
PDD034-0	1023117	1023121	Nov 18 1996	3:50PM	G
PDD035-1	1023760	1023772	Nov 19 1996	9:36AM	G
PDD036-0	1009570	1009572	Nov 13 1996	11:33AM	G
PDD037-0	1037944	1037948	Nov 25 1996	8:50PM	N
PDD038-0	987020	987022	Oct 30 1996	7:59PM	?
PDD039-0	987068	987070	Oct 30 1996	9:03PM	?
PDD040-0	1038026	1038030	Nov 25 1996	10:41PM	N
PDD041-0	1037926	1037930	Nov 25 1996	8:25PM	N
PDD042-0	1023724	1023728	Nov 19 1996	9:16AM	G
PDD043-0	1037999	1038003	Nov 25 1996	10:12PM	N
PDD044-0	1038053	1038055	Nov 25 1996	11:14PM	N
PDD045-0	1038017	1038021	Nov 25 1996	10:32PM	N
PDD046-0	987041	987043	Oct 30 1996	8:22PM	?
PDD047-0	1037972	1037976	Nov 25 1996	9:39PM	N

Table 2: Production PDD Dipoles with POINTSCAN measurement sequence and run selected for final analysis (continued). The Status column reflects the the procedure development status: ? for unrepeated measurements from the first set of measurements, which may be affected by moving probe too soon. G indicates measurements after the procedure was firmly established including by MTF Staff which are assumed good, N indicates new measurements at MP9 after system was more fully understood. Transverse positioning for these required the sled in the beampipe.

3 Results

The purpose of these measurements was to obtain longitudinal profiles and to obtain from them the position of the bend centers. We report these results in this section. However, we also measure the integrated bend field which we calculate and report, since it reflects on the quality of the other results. Readers are advised that the graphs were prepared in color (POSTSCRIPT). Colored copies will not be printed up, but online versions will will be available with color graphs.

3.1 Longitudinal Profiles

The preferred measurement of longitudinal profile for each dipole is plotted in Figures 5 - 9. Plots with higher resolution on the magnetic field are shown in Figures 10 - 14. We will examine several profiles to seek an explanation for the observed diversity of shapes. Note that magnets PDD033-PDD039 show quite symmetric profiles when examined on the high resolution view. However, PDD010-PDD019 have a profile which is high on the 'OTHER' end and falls monotonically toward the LABEL end (less so for 012,013,017 and 018). Meanwhile, PDD004 is high on the 'LABEL' end and falls toward the 'OTHER' end. These characteristicly different patterns are a result of the plan for stacking ferrite bricks behind the poles of the PDD magnets. It was planned that with the bricks available for early production, a magnet with all bricks installed would have a strength a few percent higher than the design strength. The design strength was to be achieved by removing bricks from the ends until the desired strength was measured. Except for magnet PDD004, this was accomplished by removing all bricks from the 'LABEL' end and additional bricks from the 'OTHER' end as required. As production proceeded, the strength of ferrite bricks available increased to the point that few bricks were required on the 'OTHER' end, resulting in the more symmetric profile observed for some later magnets.

This profile is achieved by transporting flux through the pole piece from sources in bricks nearer the center of the magnet toward the ends. Since a $\geq 4''$ long portion of the pole tip (LABEL end) is completely supplied with flux carried through a $0.965''$ thick pole piece, the flux creates a sufficiently high field[1] that a large $\int H dz$ is required to drive this flux, resulting in the $> 10\%$ non-uniformity observed (*i.e.* the poletip is not a good equipotential

[1] The observed B_y field is at least 0.16 T (Figure 2). This requires a field of at least .66 T to be carried through the pole tip at the edge of the region without bricks.

when examined as a function of z). These high field effects mask any subtle effects which might be present due to remanent magnetization of the poletip iron.

3.2 Bend Center (Zcenter, Zoffset)

Utilizing the files described previously, and the list of preferred measurements as shown in Tables 1 and 2, a script using the Perl language was developed which calculated the integrated field, the location of the bend center (in inches from the OTHER end), and the center offset (in cm from the nominal mechanical center) for each dipole. The integrations were performed simply with the end points for each interval. In Figure 4 we see the measured magnetic centers. Also shown are measurements[2] using the stretched wire technique suggested previously[1]. The correlation is excellent. After examining the plot, the author decided to confirm the assumed position of the hall probe within its package and observed that there was a systematic 3 mm error in the reported z position of all readings reported here.[3] In Table 3 and 4, the centers and center offsets are shown, along with installation locations for the initial 8 GeV Line installation of these magnets.

3.3 Data Quality Issues

Examination of the ends by graphing with higher resolution in x reveals a few additional insights. In Figures 1 and 2, we see the sharp edge of the field at the end of the magnets. In this reference system, the end of the poletip is at $2.5''$ and at $99.5''$. We see that the field has fallen to about half strength at this point. We would also expect the mechanical reproducibility to be very good and take the observed spread in the end position as a measure of the positioning resolution of these measurements.

[2] Private communication from Joe DiMarco

[3] By measurement, this was accomplished using the Compensator Test Dipole, which provided a suitable shape end with convenient geometry for a hand held measurement. Later, in discussing this with Ian Walker of GMW, Inc. which distributes the Group 3 systems, he informed me that the position is well marked. I discovered that the mark was hidden from view by our choice of installation polarity. The clue is that the active probe is buried in a white plastic holder. These measurements had assumed the detector was in the longitudinal center of this package, whereas it is marked to be and observed to be near the end.

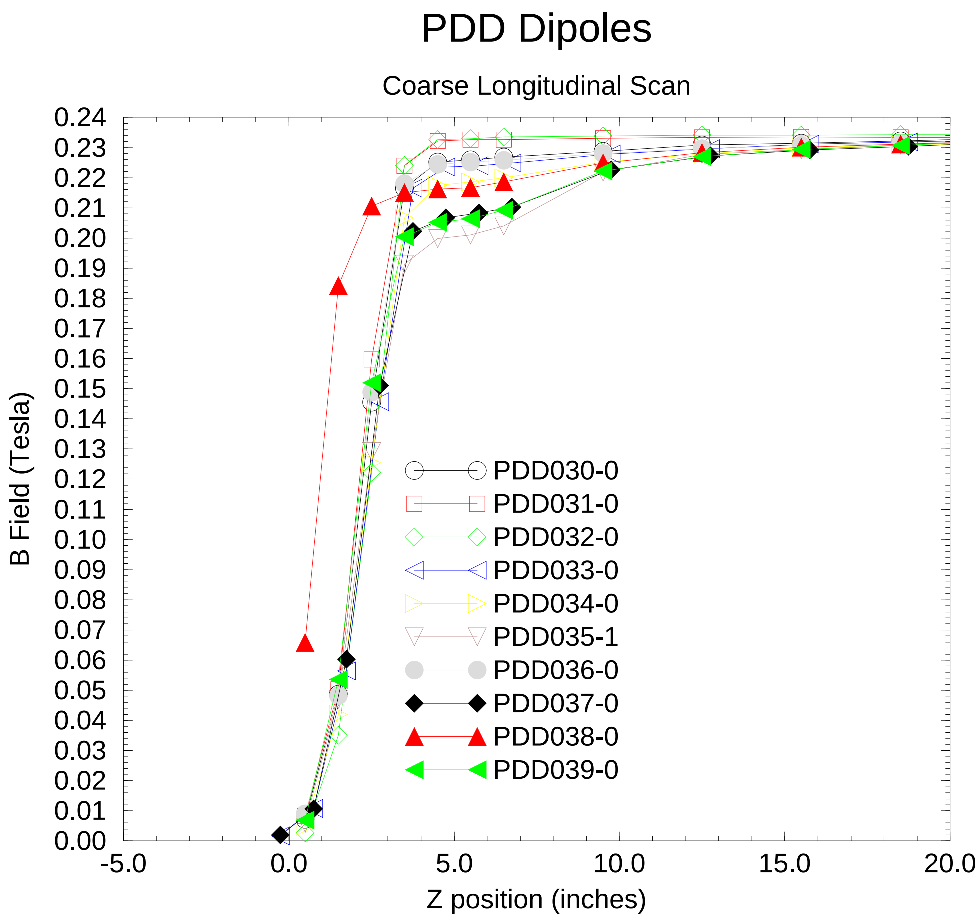

Figure 1: End Field Plots - OTHER End - PDD030-039

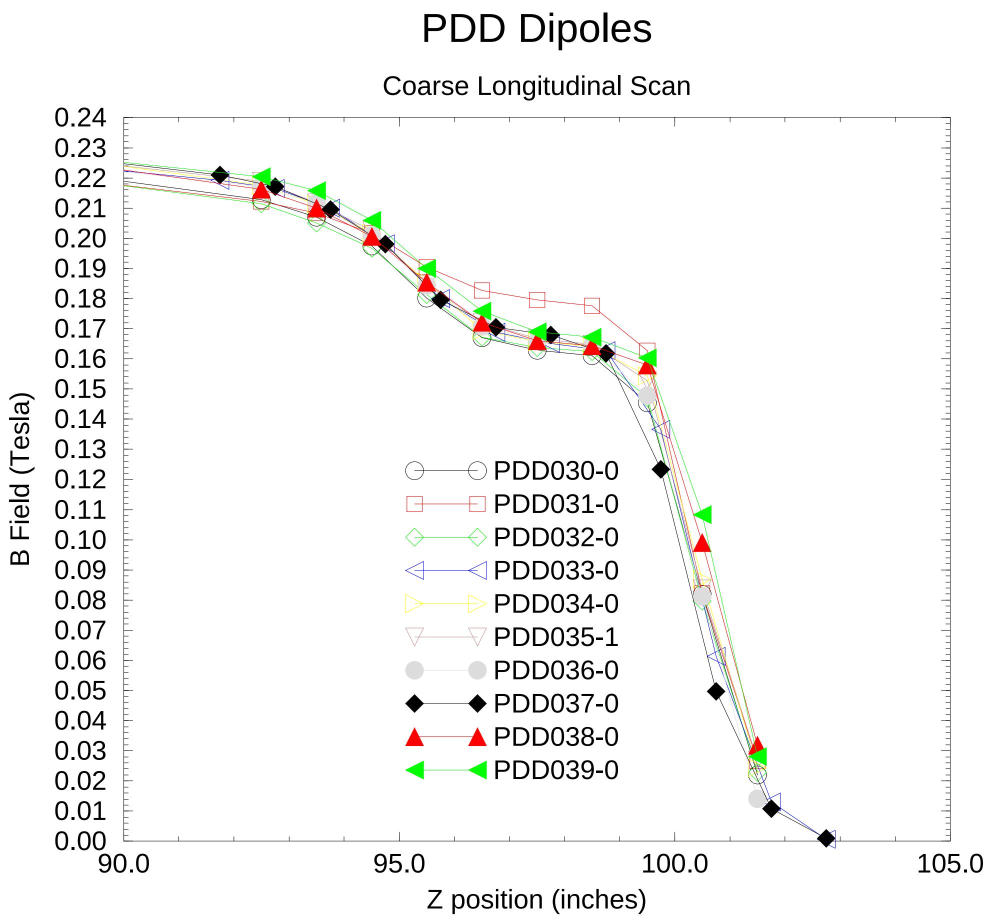

Figure 2: End Field Plots - LABEL End - PDD030-039

Results from PDD Zscans					
visual label	Status	Zscan $\int B\,dz$ T-m	Zcenter inches	Zoffset cm	Assigned Location
PDD002-1	?	0.57322	50.369	-1.602	Spare
PDD003-2	?	0.57281	50.120	-2.236	8133
PDD004-2	G	0.57082	52.122	2.850	8452
PDD005-2	G	0.56847	50.439	-1.425	8483
PDD006-2	N	0.56751	50.201	-2.029	8462
PDD007-1	?	0.57200	51.359	0.911	8467
PDD008-2	N	0.56790	50.762	-0.605	8503
PDD009-1	N	0.56886	50.027	-2.472	8484
PDD010-2	G	0.56700	50.137	-2.193	8312
PDD011-1	N	0.56819	50.070	-2.361	8473
PDD012-2	?	0.57185	50.131	-2.207	8203
PDD013-1	G	0.56900	50.146	-2.170	8352
PDD014-1	?	0.57130	49.822	-2.993	8323
PDD015-1	G	0.56809	50.201	-2.029	8303
PDD016-1	?	0.57211	50.062	-2.382	8183
PDD017-1	N	0.56815	50.147	-2.168	8494
PDD018-1	N	0.56835	50.002	-2.535	8343
PDD019-1	N	0.56780	50.101	-2.283	8443
PDD020-0	G	0.57139	50.114	-2.251	8192
PDD021-1	G	0.56853	50.400	-1.525	8124
PDD022-1	G	0.56843	50.403	-1.516	8213
PDD023-1	G	0.56828	50.149	-2.161	8182
PDD024-0	?	0.57127	50.090	-2.312	8113
PDD025-0	?	0.57081	50.133	-2.203	8322

Table 3: Production PDD Dipoles with POINTSCAN measurement results as described in the text. Zcenter is the position of the longitudinal bend center in a reference frame with zero at the OTHER (non-LABEL) end of the magnet. Zoffset is the bend center referenced to the mechanical center with positive away from the OTHER end. Installation locations in the Booster to Main Injector 8 GeV transfer line are shown in the last column.

We note that the apparent OTHER end of PDD038-0 is substantially displaced; the measurer (this author) is likely to have blundered.

Results from PDD Zscans					
visual label	Status	Zscan $\int B\,dz$ T-m	Zcenter inches	Zoffset cm	Assigned Location
PDD026-0	N	0.56677	49.959	-2.643	8463
PDD027-0	N	0.56933	50.560	-1.118	8475
PDD028-1	G	0.56987	50.577	-1.074	8302
PDD029-0	N	0.56836	50.339	-1.679	8476
PDD030-0	G	0.56808	50.298	-1.783	8193
PDD031-0	G	0.56869	50.261	-1.877	8103
PDD032-0	G	0.56677	50.168	-2.112	8332
PDD033-0	N	0.56861	50.568	-1.098	8212
PDD034-0	G	0.56878	50.709	-0.740	8114
PDD035-1	G	0.56983	50.886	-0.290	8333
PDD036-0	G	0.56864	50.434	-1.436	8134
PDD037-0	N	0.56833	50.785	-0.547	8342
PDD038-0	?	0.57713	50.168	-2.113	8104
PDD039-0	?	0.57239	50.899	-0.256	8313
PDD040-0	N	0.56739	50.163	-2.127	8504
PDD041-0	N	0.56818	50.744	-0.651	8442
PDD042-0	G	0.57000	50.868	-0.335	8202
PDD043-0	N	0.56919	50.820	-0.456	8353
PDD044-0	N	0.56880	50.122	-2.231	8493
PDD045-0	N	0.56792	50.535	-1.180	8123
PDD046-0	?	0.57129	50.799	-0.511	8478
PDD047-0	N	0.56711	50.465	-1.359	8453

Table 4: Production PDD Dipoles with POINTSCAN measurement results as described in the text. Installation locations in the Booster to Main Injector 8 GeV transfer line are shown in the last column. As discussed in the text, the results for PDD038 are shown to be unreliable. We note that this was the earliest unrepeated measurement with this system. The results reported privately for PDD034-0 involved a mis-recorded data point which has been corrected in this analysis. Zoffset changes were insignificant.

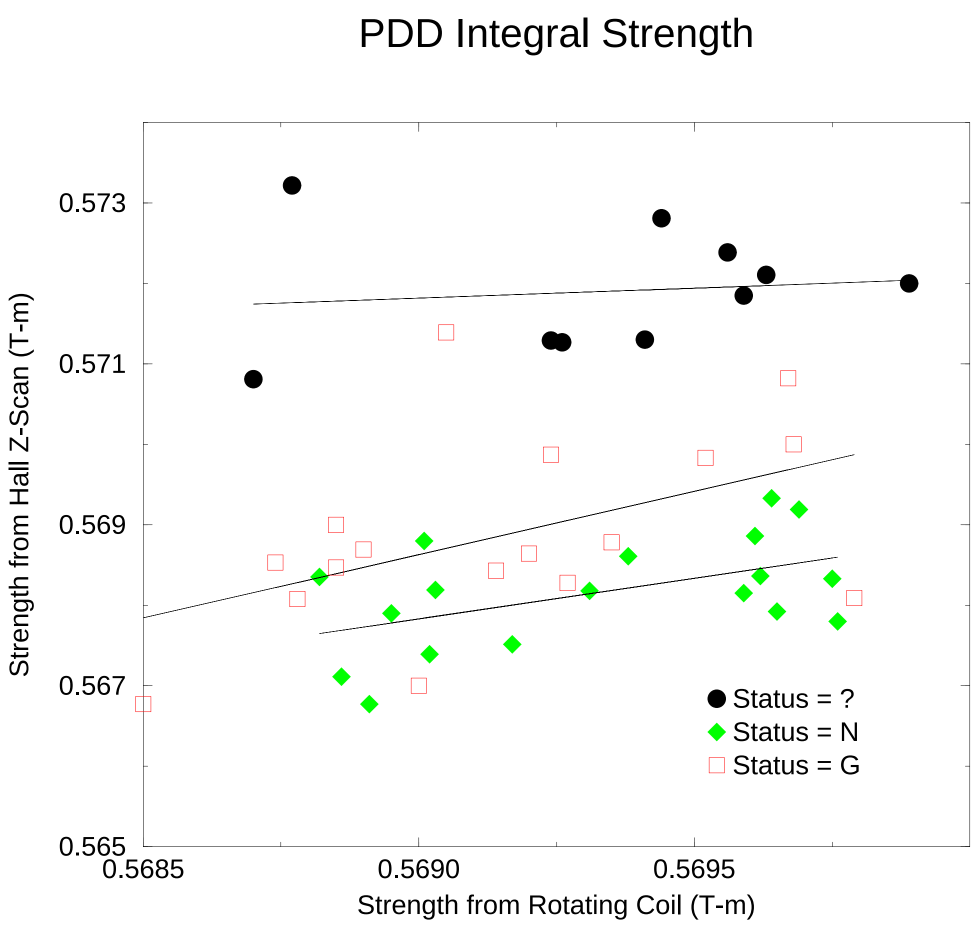

Figure 3: Strength measurements ($\int B \ dz$) are plotted against the measurements reported from the rotating coil harmonics. Measurements from different measurement eras are shown separately. PDD038-0 has been excluded. The correlation line for the separate data sets are shown.

3.4 Integrated Field

In the third column of Tables 3 and 4 are recorded the value of $\int B\ dz$ obtained from this Hall Probe measurement technique. This measurement was not designed to provide a reliable measure of the integrated magnet strength, $\int B\ dz$ but the center is calculated by dividing $\int zB\ dz$ by $\int B\ dz$ and we examine it in attempting to assure the data quality. It was apparent from the values of strength shown in Tables 1 and 2 that the variation in measured strength was excessive, since the magnets were known to have been trimmed to about 0.1%. In Figure 3 we explore the data divided into groups according to when it was measured (Status). We plot the zscan results against the rotating coil measurements (which correlate well with flip-coil measurements). We see that the discrepancy reveals some calibration problems (about 0.67%) with the magnetic field measurements. Regression analysis of each data set reveals that only the newest data (Status = N) correlates well. The resulting fit lines are shown for all three data sets. For the Status = N data, we find a SLOPE of 1.0083 and in INTERCEPT of -0.0059 T-m. Since it is apparent that the various sets have some inter-calibration problem with the Hall Probe data, we look at the RMS of each group separately. For (?,G,N) the value of RMS / Mean of $\int B\ dz$ is (13E-4, 21E-4, 12E-4) whereas for the rotating coil data these values are (6.6e-4, 6.5E-4, 6.1e-4). The inferior results from the zscan measurement is not unexpected. Since the bend center measurement normalizes out the Hall calibration, we are unworried that the problems shown for the integrated strength measurement (as revealed when viewed in sets by Status) will impact the bend centers measurement.

4 Summary and Conclusions

Measurements of the longitudinal profile of the dipole field have been performed on centerline of the PDD dipoles. These dipoles will be used for the Fermilab Booster to Main Injector 8 GeV transfer line. Although these magnets have been trimmed to provide very uniform integrated strength, the selected procedure has created longitudinal profiles which fall by $> 10\%$ near the ends of the installed bricks and an additional $> 15\%$ nearer to the ends. Initial planning had called for installing these dipoles in serial number order. Tracking simulations of the transverse position of the beam by J. Johnstone indicate assuming that the one and only error source is the PDD delta-z error:

- if the magnets were installed sequentially, with no flipping of alternate magnets to get partial delta-z error compensation: x(max)=5.3 mm x(rms)=1.8 mm
- installing the magnets sequentially, but flipping alternate magnets: x(max)=1.7 mm x(rms)=0.47 mm
- sorting of magnets PLUS flipping alternate magnets: x(max)=0.14 mm x(rms)=0.04 mm

Note that there are critical differences between the measurements reported here and in MI-0162[1]. Those measurements did not include the ends of the magnet at all. PDD002 has been rebuilt since then, trimming the field strength by removing ferrite bricks, creating the very different profile reported here.

In addition to the concerns about longitudinal displacement of the bend center which were addressed in MI-0162, this profile raises the possibility that other issues may be relevant to the accelerator design if such large longitudinal variation is experienced in gradient magnets for the Recycler. The sagitta of a dipole is a simple geometric effect when the field is uniform. Correctly evaluating the sagitta is significant for obtaining the correct bend (average field) in a gradient dipole. Having a straight magnet with gradient and a non-uniform longitudinal field involves a more complicated set of considerations. With a total variation of $> 25\%$, we must consider second order effects in determining the correct transverse placement of the magnet. The focusing effects in a strong focusing lattice depend upon the β functions and the local gradient. Initial designs for the Recycler have assumed uniform focusing (quadrupole field) along the length of the gradient magnet. For the present gradient magnet design, the assumption of a uniform normalized gradient is probably valid. However, the focusing is complicated by building a straight magnet which has both quadrupole and sextupole terms. Allowing large longitudinal variations will surely change the net focusing (since the β function falls significantly along the dipole length. This implies that the pole tip shape (normalized gradient) required may depend upon the longitudinal non-uniformity permitted. Considerations of the net effect of the sextupole may further require modification in the normalized gradient. These issues merit further discussion.

5 Acknowledgments

Thanks to all those who make this measurement possible. Clark Reid provided the rectangular probe holder design and Dan Snee shepherded it through the shops. Gerry Jackson created the sled probe holder. Jim Sim assisted in making the required database entries and software setups to permit CHISOX checklist measurements to be performed at MP9. Gerry Jackson, Bill Foster, the MP9 Magnet Assembly Staff and the MTF Measurement Staff all assisted with various of the measurements. I am grateful to Joe DiMarco for implementing the stretched wire bend center measurement and supplying me with this data. Henry Glass compiled the rotating coil strength measurements reported. John Johnstone made it worthwhile by using the data in magnet assignment. Helpful discussions with Jim Holt and Gerry Jackson on Recycler Ring implications are also gratefully acknowledged.

References

[1] Bruce C. Brown. Closed Orbit Effects Due to Longitudinal Bend Center Displacement. Main Injector Note MI-0162 Ver 1.1, Fermilab, April 1996.

[2] Bruce Brown. Procedure for Manual Z-Scan of PDD dipoles with a Hall Probe. Technical Report MTF-96-0008 1.1, Fermilab, November 1996.

[3] D. J. Harding, K. Trombly-Freytag, B. C. Brown, and H. D. Glass. Design of the **pointscan** Virtual Database. Technical Report MTF-93-0003 1.7, Fermilab, December 1993.

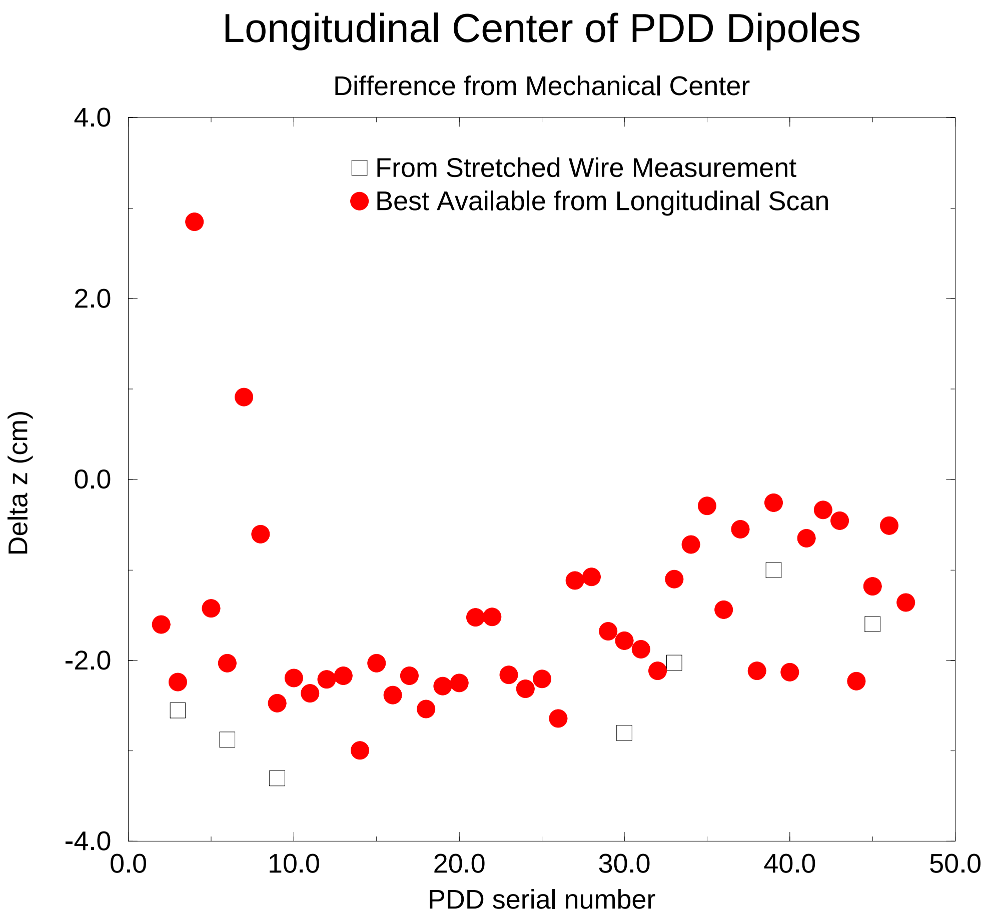

Figure 4: Best available measurement of Zoffset for the set of PDD dipoles. Zoffset is the position of the longitudinal bend center with respect to the mechanical center of the magnet. Positive numbers indicate a displacement away from the OTHER end.

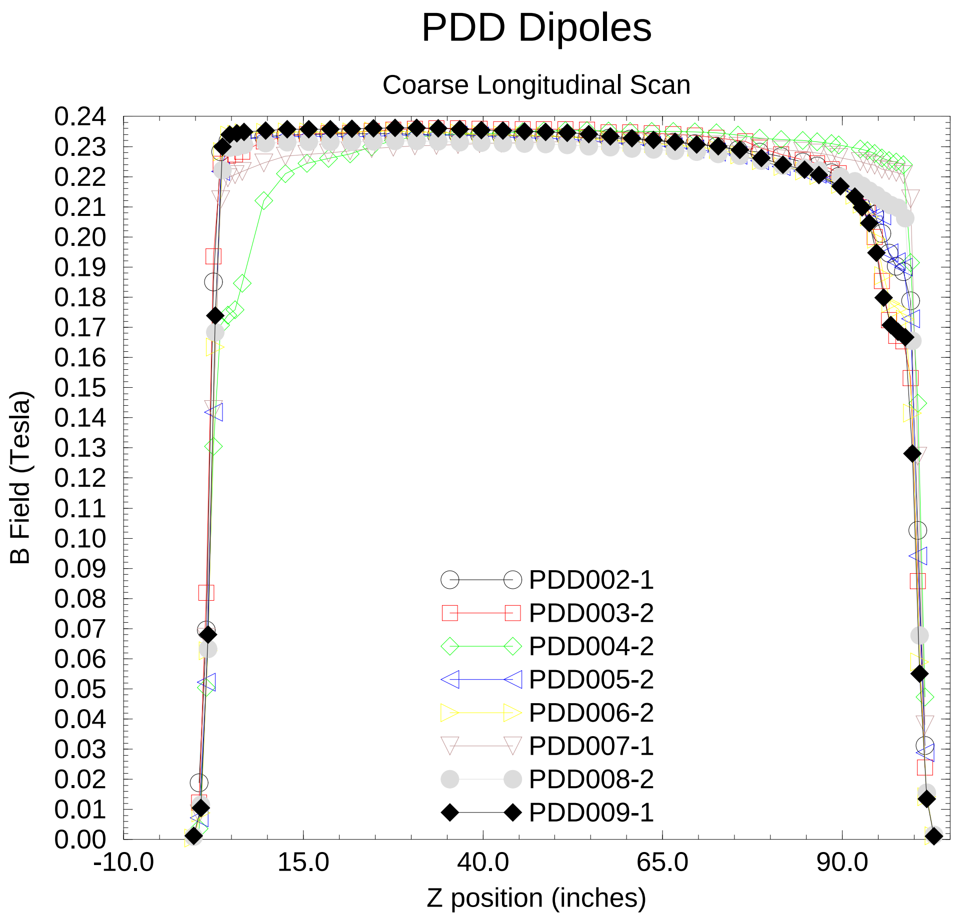

Figure 5: Low Resolution Plots - PDD002-009

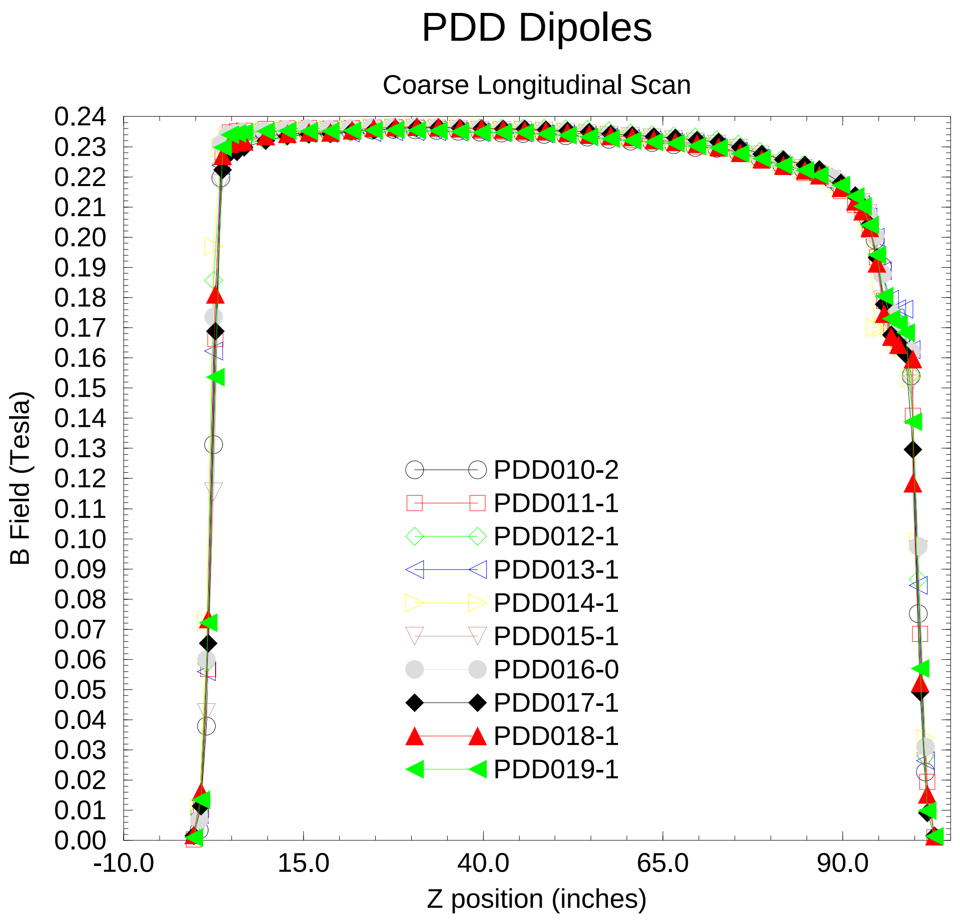

Figure 6: Low Resolution Plots - PDD010-019

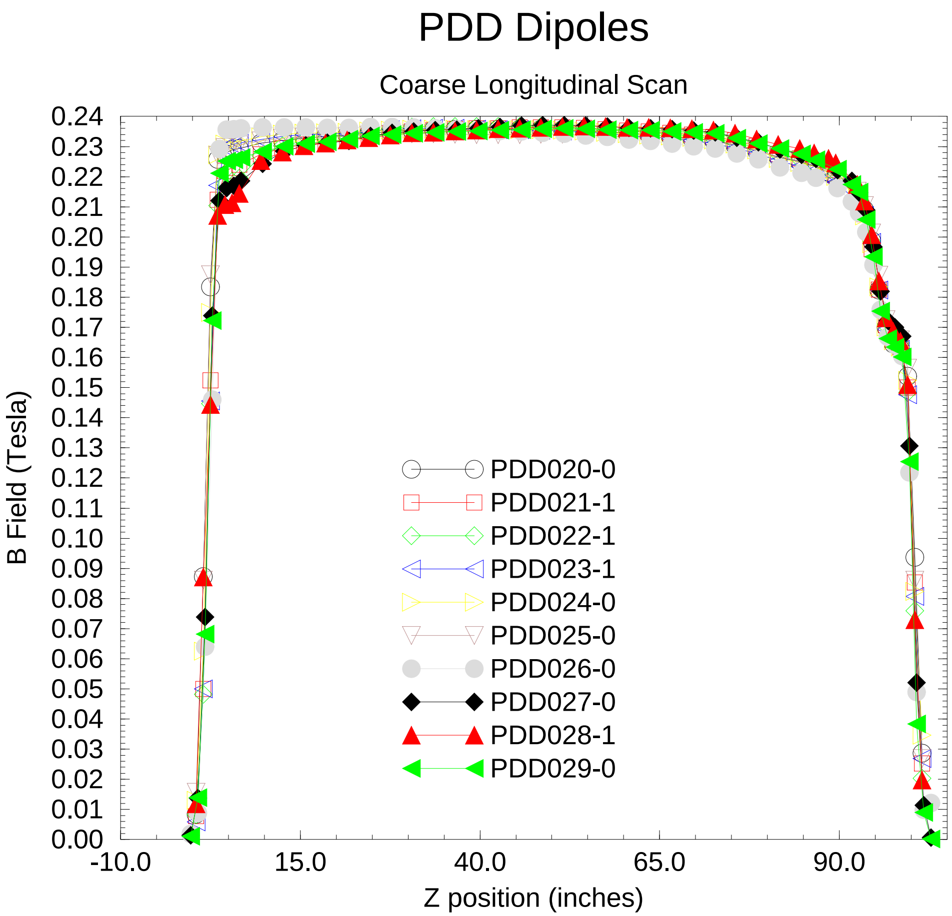

Figure 7: Low Resolution Plots - PDD020-029

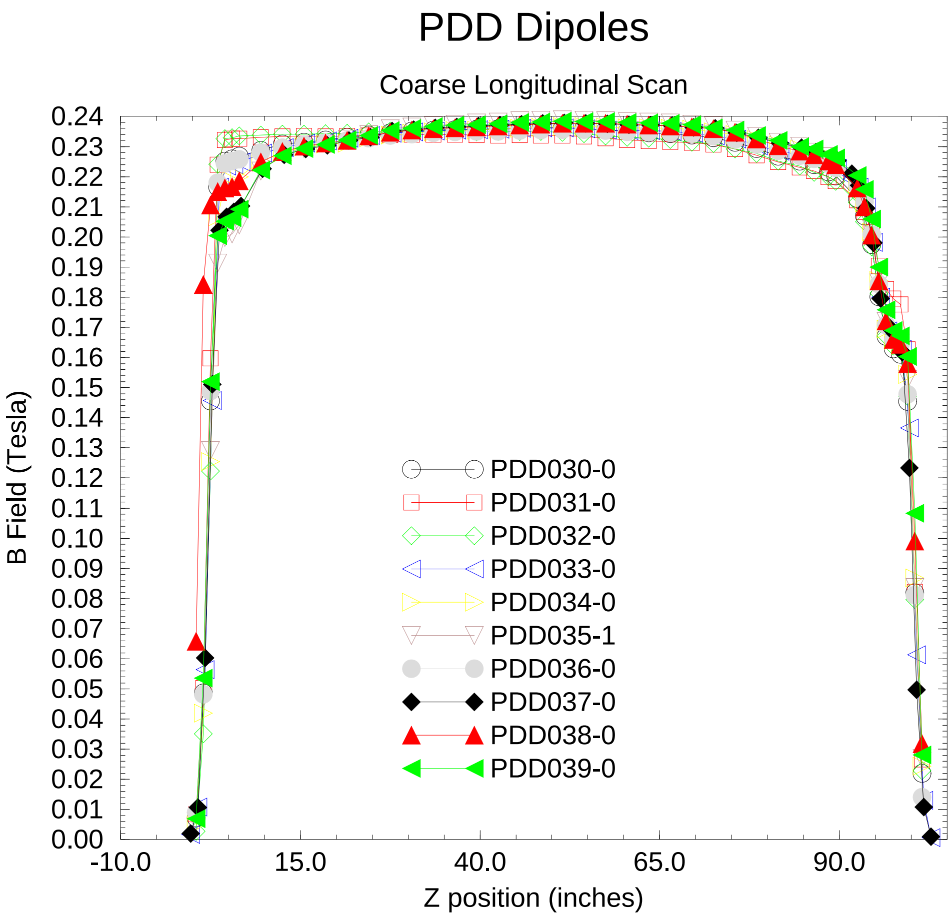

Figure 8: Low Resolution Plots - PDD030-039

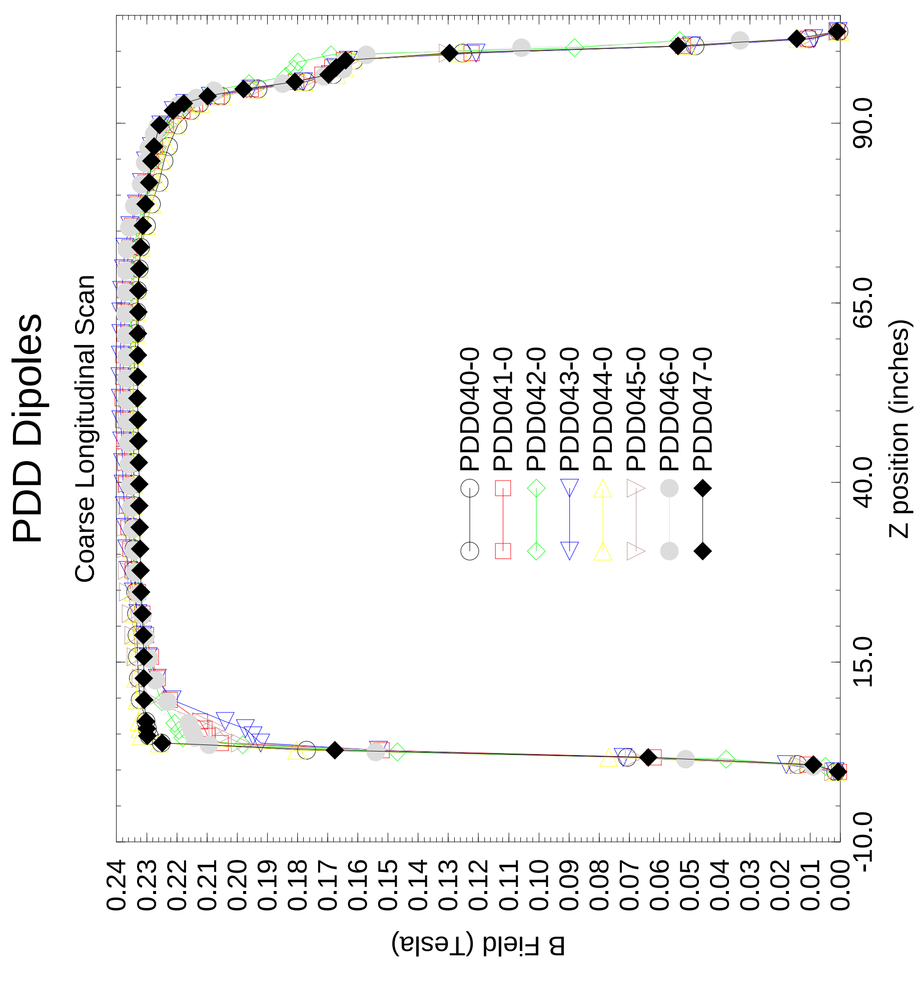

Figure 9: Low Resolution Plots - PDD040-047

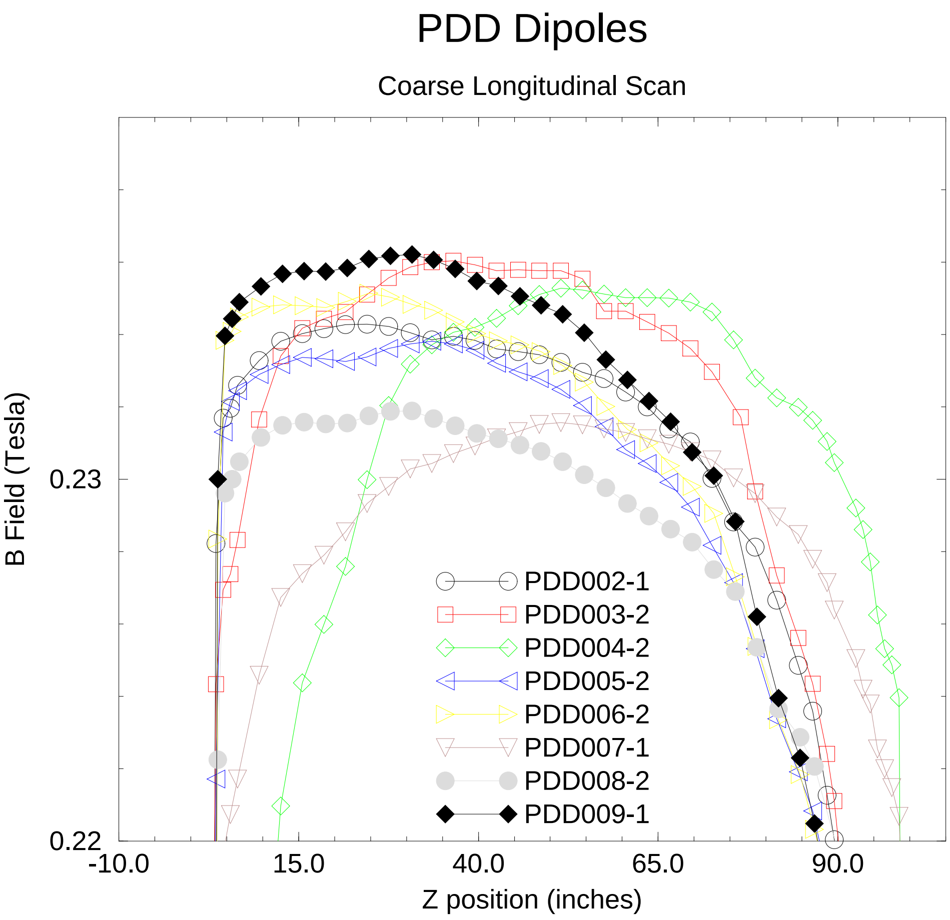

Figure 10: High Resolution Plots - PDD002-009

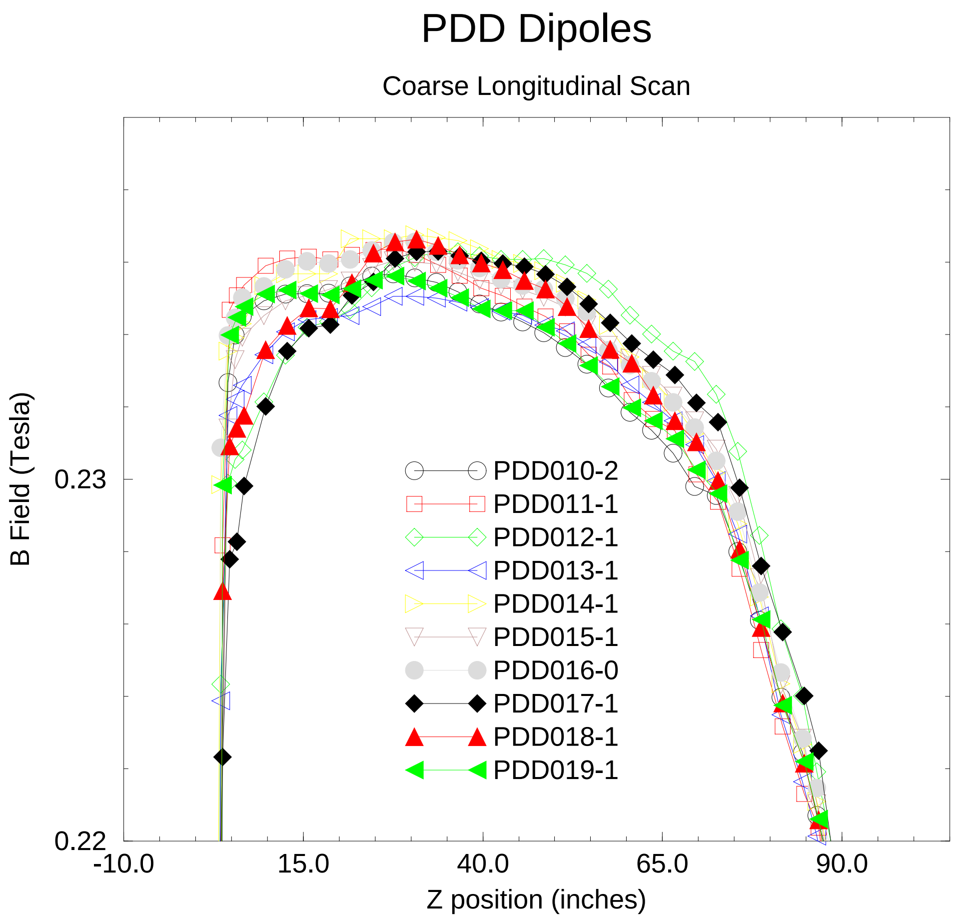

Figure 11: High Resolution Plots - PDD010-019

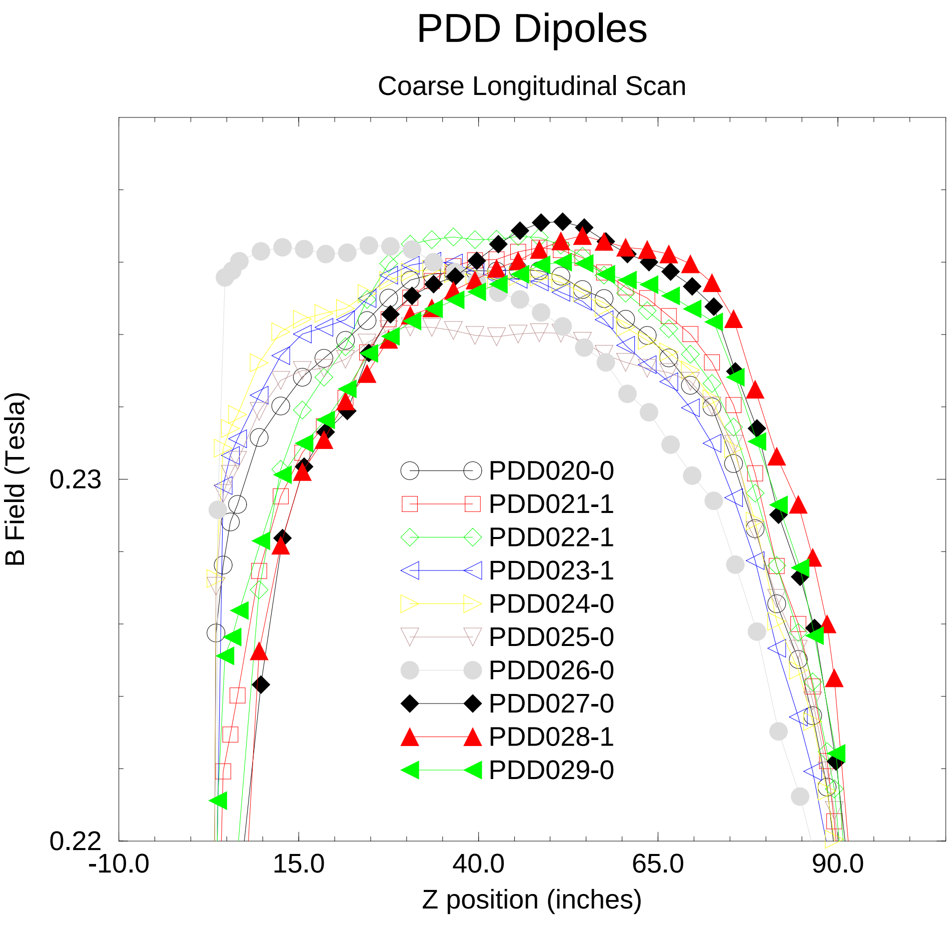

Figure 12: High Resolution Plots - PDD020-029

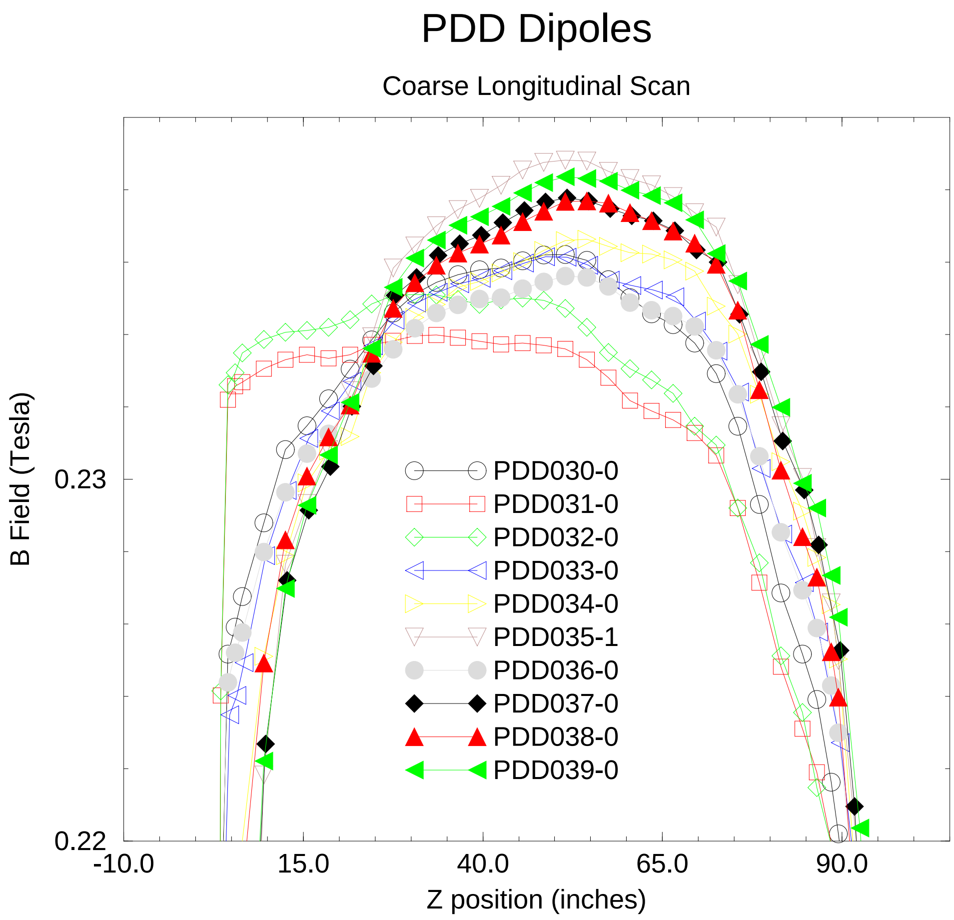

Figure 13: High Resolution Plots - PDD030-039

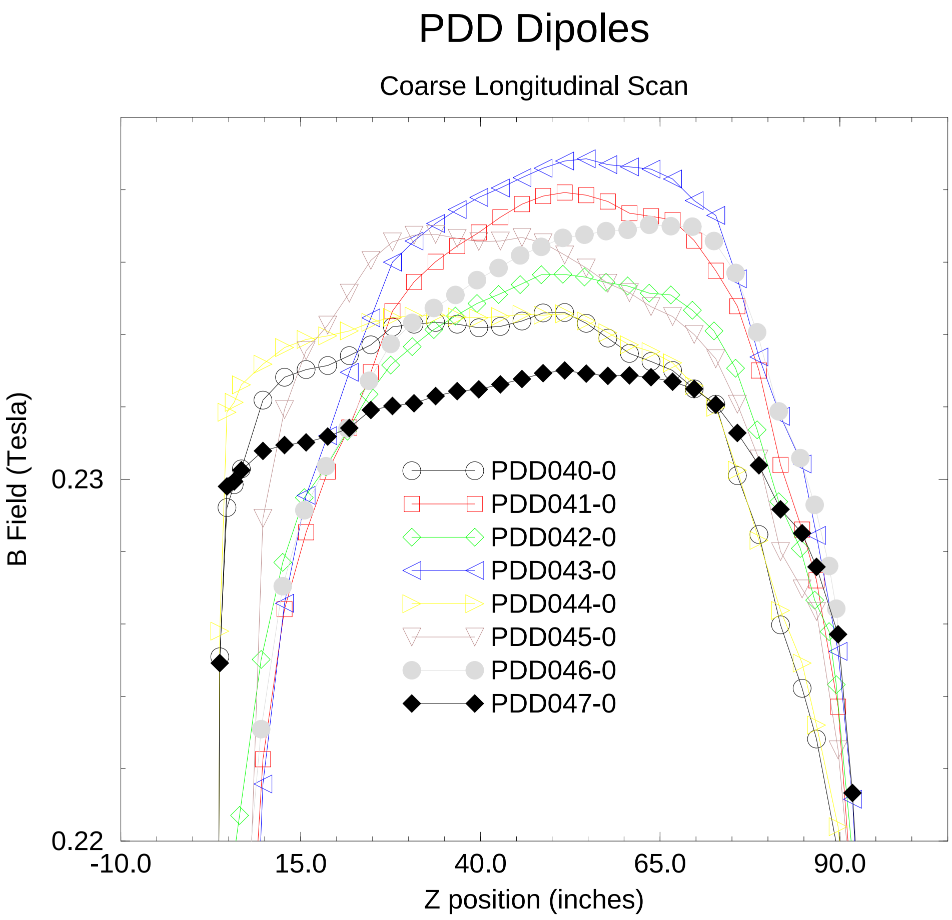

Figure 14: High Resolution Plots - PDD040-047