Field Quality Issues in Iron-dominated Dipoles at Low Fields

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ABSTRACT

In order to help assess the usable dynamic range of iron-dominated dipoles, field shape data at low field on several Fermilab accelerator dipole designs are presented. Emphasis is placed on the systematic and random values of the low field sexupole since it is the first "allowed" field error. The Main Injector dipoles provide four times smaller sextupole and more than 20 times less sextupole hysteresis than earlier designs for the Main Ring.

I. INTRODUCTION

The Fermilab Main Ring, when utilized at 400 GeV, explored a dynamic range of about 45 from its 400 gauss injection field (for 8.9 GeV/c) to 1.8 T at 400 GeV. The Fermilab Main Injector is designed to operate from 8.9 GeV/c to 150 GeV for a dynamic range of 17, using an injection field of 0.1 T and a field of 1.7 T for 150 GeV. When considering future accelerators, one must allocate an field error budget (lattice dependent) and choose a suitable dynamic range.

Magnet design requires an understanding of the sources of systematic and random errors which determine the field shape at low, intermediate, and high fields. The field shape errors due to hysteretic effects in iron at low fields are not well understood. We will explore here some data available from the measurement of several series of magnet designs for the Main Ring and one series from the Main Injector to illustrate the large differences which are experienced in existing designs. At this time, calculations which include hysteretic effects have not been available for these magnet designs.

A. Design Perspectives and Fermilab Experience

For accelerator design, one must answer the question: For a specified normalized field error budget, what dynamic range can be used for a given magnet technology? For magnet design one must answer the questions: For specified magnet technology, what design features control the systematic and random errors in the field shape? Which tools permit one to design such features? Frequently, the answer given for both superconducting (coil dominated) and iron dominated magnets has been that a field range of 20:1 was a nominal upper limit.

The Fermilab Main Ring, when injecting 8.9 GeV protons into a 400 Gauss field experiences poor storage lifetimes during injection and significant losses at the beginning of acceleration. This is due in large part to the field shape at low fields in the Main Ring dipoles. The Fermilab Main Injector will replace the Main Ring as a Tevatron injector (at 150 GeV) and also provide beams (at 120 GeV) for anti-proton production and external beam experiments. The injection field was raised for this accelerator to 0.1 T so that effects due to remanent fields would be smaller. Fields at extraction will be 1.35 T and 1.7 T, so the maximum dynamic range is only 17. But the design of the Main Injector dipoles has achieved fields which are very good even at 400 gauss.

What controls the field shape? For most high quality magnets, there is an intermediate field range where effects due to finite permeability of iron are negligible and the observed field shape is due to the mechanical shape of the iron. At high fields, iron saturation may affect both magnet strength and shape. At low fields, the hysteretic contribution of the iron to the field may affect both strength and shape of the magnetic fields. The strength (dipole field) change due to iron hysteresis is related simply to $\int H\,dl$ along the relevant flux lines which pass through the beam aperture of the dipole. The quality of the iron is the significant parameter which can be controlled to impact this magnet property. The field shape changes due to iron hysteresis (differences from the intermediate field shape) are governed by both iron quality and geometry. Neither design strategies nor analytic tools are widely known which guide this design problem. Computer codes for magnet design have provided good descriptions of the fields at intermediate and high fields. Currently, no code *conveniently* describes the hysteretic field contributions.

Magnet	Accel	Aperture H $\times$ V	Remanent Sextupole	Remanent Dipole
B1(ADM)	MR	$1.5'' \times 5''$	-.0196	17 G
B2(BDM)	MR	$2'' \times 4''$	-.0188	13 G
B3(ODM)	MR	$3'' \times 5''$	-.0122	20 G
IDC	MI	$2'' \times 6''$	-.00069	20 G

Table I: Summary of apertures and fields of dipoles considered in the report. For Main Ring dipoles, there are coils on the mid-plane which define an aperture edge. For the Main Injector dipoles, no copper is placed on the mid-plane, and the aperture reported is the nominal pole width. Transverse cross sections are the same for all four MI Dipoles (IDA, IDB, IDC, and IDD). Sextupole is the normalized sextupole harmonic with a reference radius of $1''$. ODM Dipoles are made with a variety of steel types and exhibit a wide variation in remanent dipole.

II. DATA

We will present data from several fairly comparable accelerator dipoles. Table I lists the names and nominal transverse apertures of the magnets which we will consider. The important field errors of the respective accelerators are dominated by these mag-

*Operated by the Universities Research Association under contract with the U. S. Department of Energy

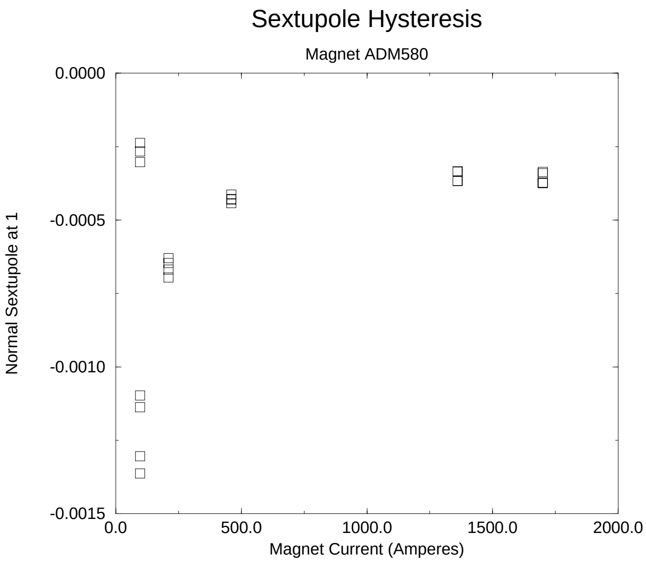

Figure 1: Normalized sextupole harmonics for a portion of the body of a Main Ring B1 dipole at transverse center. Injection field is about 400 Gauss at a current of about 97 A. All measurements are on an up ramp except for the more positive values shown at 97 A which are measured on a down ramp after a ramp to full field.

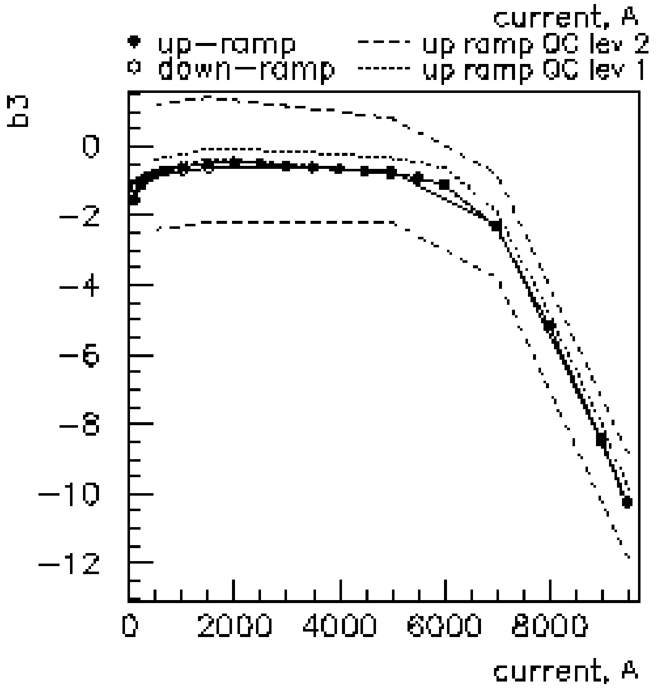

Figure 2: Normalized sextupole harmonics $\times 10^4$ at $1''$ reference radius integrated through Main Injector dipole IDC028-0. Injection is at 1000 Gauss at a current of 500 A. Measurements with a full length probe are taken at the fixed currents plotted with both up ramp and down ramp measurements shown. At most currents, the hysteretic fields produce a slightly more positive sextupole on the down ramp. Solid and dashed line are limits on the magnet-to-magnet variability expected based on previously measured dipoles.

nets. We will present the sextupole fields for these magnets since they are the first field error which respects the dipole symmetry of the design. Since we are examining errors which come from the design rather than from fabrication errors, sextupole will raise the issue which is of interest.

Figures 1 and 2 plot the normalized sextupole fields as a function of current for some representative dipoles.[1] Characteristically, beginning with no excitation current and some sextupole, the sextupole *vs.* current traces out a hysteretic curve with lower values when the current is increasing and higher values when the current is decreasing. Only a minimal set of measurements is available for an example Main Ring dipole, whereas, with a full length probe and more automated data acquisition, we have acquired more complete data on Main Injector dipoles[3][4]. The Main Ring magnets were measured only up to a field of about 0.7 T, so saturation effects were not explored. The full 1.7 T is explored in the Main Injector measurements so the high field saturation sextupole is shown.

The hysteretic sextupole (down ramp minus up ramp) is quite large for Main Ring dipoles. Routine measurements were only made, however, at a few currents including 97 A on the up ramp and 0 A on the down ramp. From the variability of these as well as the difference in average value, we will demonstrate the magnitude of these fields. Figure 3 provides histograms of the normalized sextupole harmonics at 400 Gauss on the up ramp for a sample of Main Ring dipoles. Figure 4 provides histograms of the same quantity at a current of 0 A (remanent field). The reference dipole field for these measurements are given in Table I. Both sets of histograms are for fields averaged over the full length (including end fields) of the magnets.

The more extensive data on the Main Injector dipoles provides a direct measurement of the magnitude and variability of the (very small) sextupole hysteresis in those magnet. Figures 5, 6 and 7 histogram the sextupole on the up ramp, on the down ramp, and the magnet by magnet difference for the IDC series dipoles of the Main Injector but not at the Main Injector injection field of 0.1 T but at 0.04 T (400 Gauss) to be directly comparable to the Main Ring data. Figure 8 is a histogram of the distribution of integrated remanent sextupole for these magnets.

Summaries of the magnitudes of these sextupole field at 0.04 T are provided in Table II. The dipole and sextupole remanent

[1] Measurements of Main Ring dipoles with harmonic coils were carried out since 1986 using a VAX-CAMAC-based measurement system derived from the one used for measurements of anti-proton source magnets[1]. A bucked tangential coil[2] of radius selected for each magnet series (ADM, BDM, ODM), was used for all of these measurements. Either three or four longitudinal positions were required to measured the full length of these 6 m dipoles. Results of these measurement are available in permanent databases, but no formal reports of this measurement effort are available.

Magnet	Sext	Sext	Sext
Series	Up	Down	diff
	400 g	400 g	400 g
ADM (B1)	-7.5E-4		
BDM (B2)	-4.6E-4		
ODM (B3)	-1.0e-4		
IDC	-1.15E-4	-1.15e-4	0.8E-6

Table II: Summary of mean values of the normalized sextupole harmonics at 0.04 T for a various series of accelerator dipole designs.

are summarized with the apertures in Table I.

III. DISCUSSION AND CONCLUSIONS

Accelerator magnets require high field quality to allow high intensity, high quality beams to be injected, accelerated and stored. While it is possible to provide correction magnet systems which reduce the need for precise fields in the main magnets, such systems add complexity and cost, so one seeks clean designs which minimize the need for correction. Since field errors due to hysteretic iron properties usually change with excitation level, their correction is particularly cumbersome. This makes the discovery that their magnitude is greatly reduced in the Main Injector Dipole design of some general interest.

The data above provides a remarkable contrast between the Main Injector dipoles and the Main Ring dipoles. When comparing the B2 dipoles with the Main Injector dipoles, we find that the normalized sextupole at 0.04 T is improved by $\times 4$ in the newer design (comparing magnets of comparable aperture). The hysteretic component of the sextupole is $\times 20$ smaller. Comparing the variability of these quantities (*e.g.* RMS values) confirms the improved rejection of hysteretic iron influences in the Main Injector design. Other hysteretic non-uniformities are also significantly improved, providing a very uniform dipole field at all excitation levels until iron saturation begins to influence the field at about 1.3 T. To reduce the overall iron cost, the Main Injector dipoles were designed with a large saturation sextupole at high fields. The pole shape was optimized to minimize the field errors due to saturation and a sextupole correction system was built to control the beam effects of the high field sextupole. A comparable magnet was designed for the SSC Medium Energy Booster. It utilized more steel to carry the flux at high fields and the saturation sextupole was about $\times 3$ smaller than for the Main Injector. Examining the field quality achieved in these magnets suggests that a dynamic range of greater than 40 is demonstrably achievable. Further examination of the low field properties of the Main Injector dipoles would be a worthwhile way to learn more about the low field possibilities for iron dominated magnets for accelerators.

We have not understood what effects permit the low hysteretic field errors in the Main Injector dipole design. The larger horizontal aperture will have some effect. We suspect that the overall transverse profile of the pole may have a significant impact. That shape is quite similar to the end shape which has been designed so that the field in the iron will be vertical at all excitations[5]. Such a pole shape may assist in reducing variable field errors by controlling the effects of iron magnetization. Contemplation of very large accelerators with iron dominated magnets makes such considerations quite important in the optimization of such magnets.

IV. ACKNOWLEDGMENTS

I would like to thank Peter Mazur for his leadership in the effort which remeasured the Main Ring dipoles with harmonic coils. My colleagues who assisted in the Main Injector measurements are gratefully acknowledged. Discussions with François Ostiguy were the source of the suggestion that the improved hysteretic behavior was due to the pole shape.

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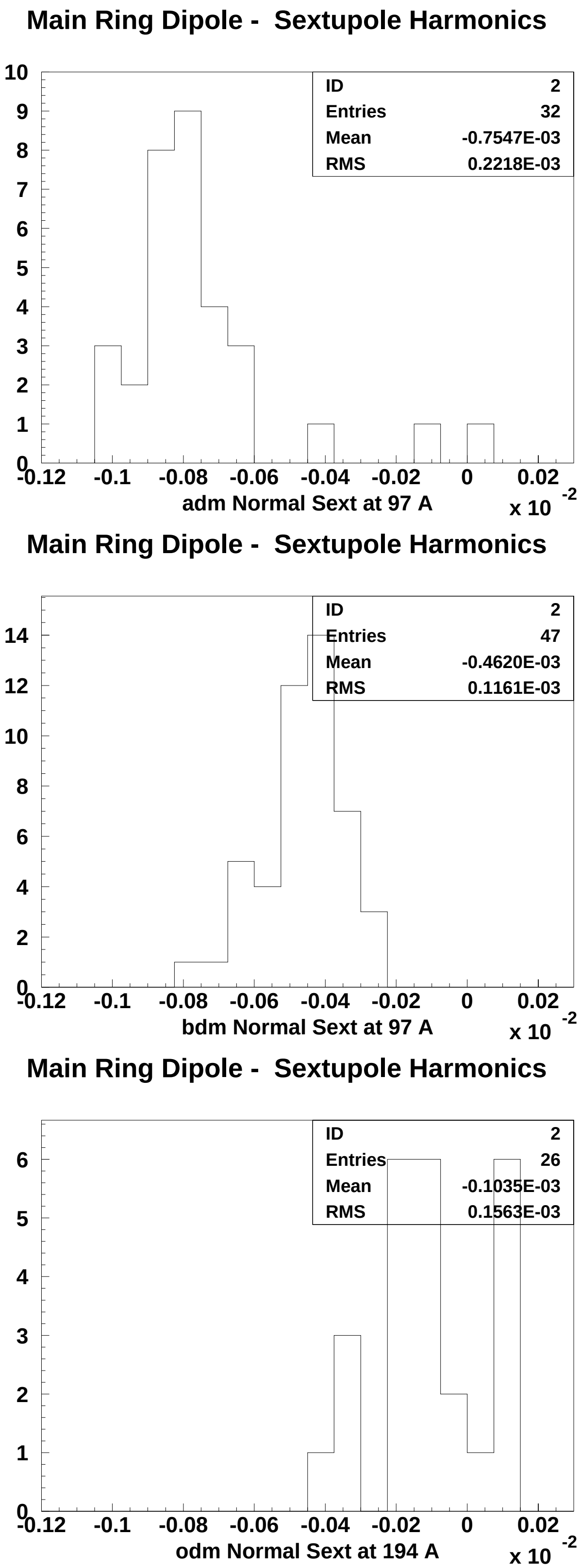

Figure 3: Histogram of normalized sextupole field at 400 Gauss for Main Ring B1, B2, and B3 (ADM, BDM, and ODM) dipoles. Magnets prepared with 3 ramps to full field followed by a reset at 0 A before ramp to 97 A (194 A for ODM) for this measurement.

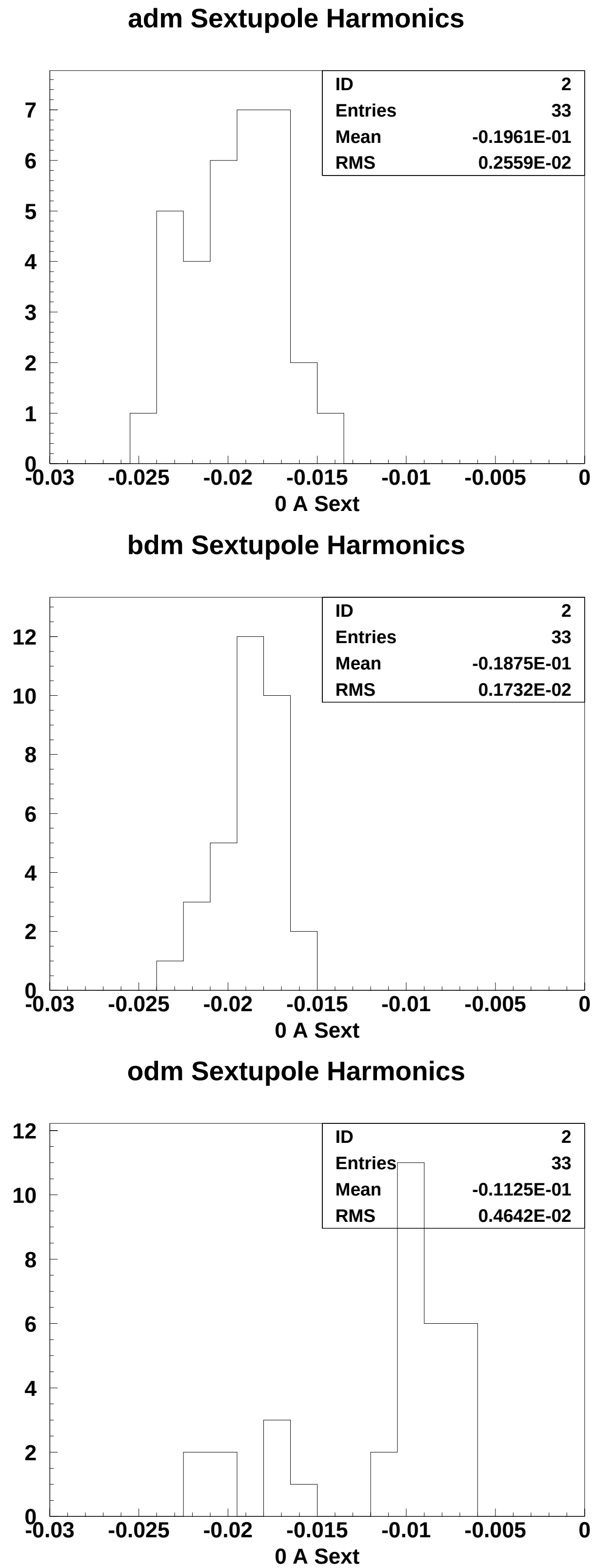

Figure 4: Histogram of normalized sextupole field at 0 A excitation for Main Ring B1, B2, and B3 dipoles. Magnets prepared with 3 ramps to full field before down ramp to 0 A for this measurement.

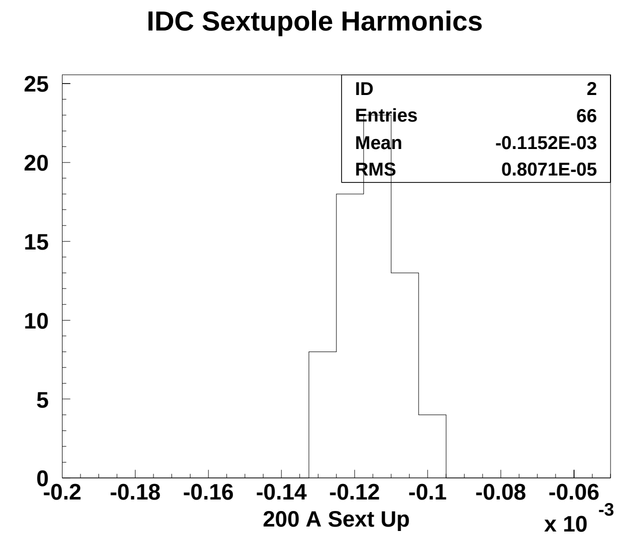

Figure 5: Histogram of normalized sextupole field at 200 A excitation for Main Injector IDC dipoles. Magnets prepared with 3 ramps to full field with resets to 0 A before ramp to 200 A for this measurement.

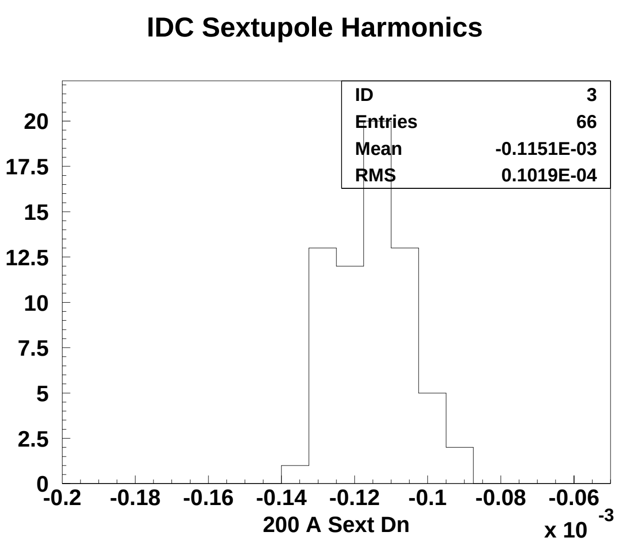

Figure 6: Histogram of normalized sextupole field at 200 A excitation for Main Injector IDC dipoles. Following 200 A up ramp measurement, magnets ramped to full field before down ramp to 200 A for this measurement.

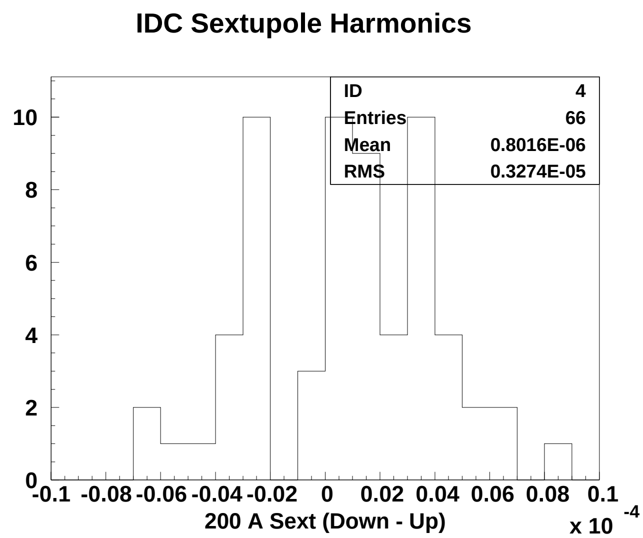

Figure 7: Histogram of normalized sextupole field difference of down ramp value minus up ramp value at 200 A excitation for Main Injector IDC dipoles.

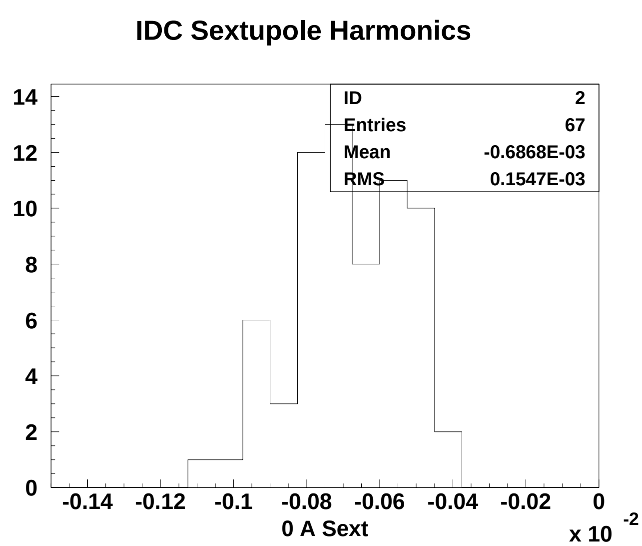

Figure 8: Histogram of normalized sextupole field at 0 A excitation for Main Injector IDC dipoles. Magnets prepared with 3 ramps to full field before down ramp to 0 A for this measurement.