QA Quadrupole Field Quality

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Summary

A subset of the QA quadrupoles had multipole data taken upon receipt during the construction of CEBAF. These results are available on paper and obsolete format digital tapes in Document Control. One QA has recently been measured up to 17A. Multipoles obtained from a large subset of the former and the one recent measurement are presented and compared with Mike Borland's implementation of Klaus Halbach's manufacturing tolerance models.

Quadrupole measurement

Quadrupoles are measured with a rotating single wire apparatus. Voltage from the wire is recorded and Fourier- transformed to yield multipole amplitude and phase. Allowed and skew multipoles are not calculated. Two probes are used. In one a probe about twice as long as the quad is used to measure integrated gradient (primary) and multipoles (secondary). When this long probe was used, a reference quadrupole was chosen. The quadrupole under test was mounted about one length from it. The two were powered in series with opposing orientations so the quadrupole fields would cancel. A long rotating wire probe was placed through the bore of both quadrupoles and the output voltage Fourier-transformed. This was intended to improve signal to noise for the multipoles but cancels harmonics in the reference quad. This method would have been better if the reference quad could have had much larger bore and thus smaller high harmonics. Most of the harmonic data is believed to have been taken with the short probe in the same way, sans bucking quad, but many of the summary sheets are unmarked. There is a systematic difference between long and presumed/marked short probe data. Most of the plots in this document have the long probe data plotted with larger squares than the short.

Quadrupole field quality requirements are derived in TN 89-175. The higher multipoles allowed by geometry in a quadrupole, those with 12 and 20 poles, are specified at the pole radius. All other multipoles, allowed and skew, are specified at half radius. Jeff Karn used a spreadsheet to summarize the short and long probe multipole data at the specified radii for each multipole. I have not seen this spreadsheet, only the printed output. Those quadrupoles with full multipole measurements have five pages in the Document Control files. Most quadrupoles have measured multipoles only at 1, 5 and 10A.

All summary sheets with 1A current steps were photocopied and give to Tom Oren to digitize and run through OCR software. All but six of the sheets were usable, resulting in 126 measurements on 103 magnets. One recent measurement extending to 17A was added to the large set of old measurements. This measurement is the one from which K's were derived by L. Harwood and given to CASA. Of the 126 measurements, 16 are labeled “long probe”. The others are labeled “short probe” or unlabeled. QA079, the reference magnet for the east test stand, was measured five times with long probe; the sixth data set for this magnet is unlabeled. Figure 1 on the next page plots sextupole and octupole for this magnet. The unknown probe data set is highlighted. Ordinate is multipole/quadrupole at the pole tip. Current in Amps.

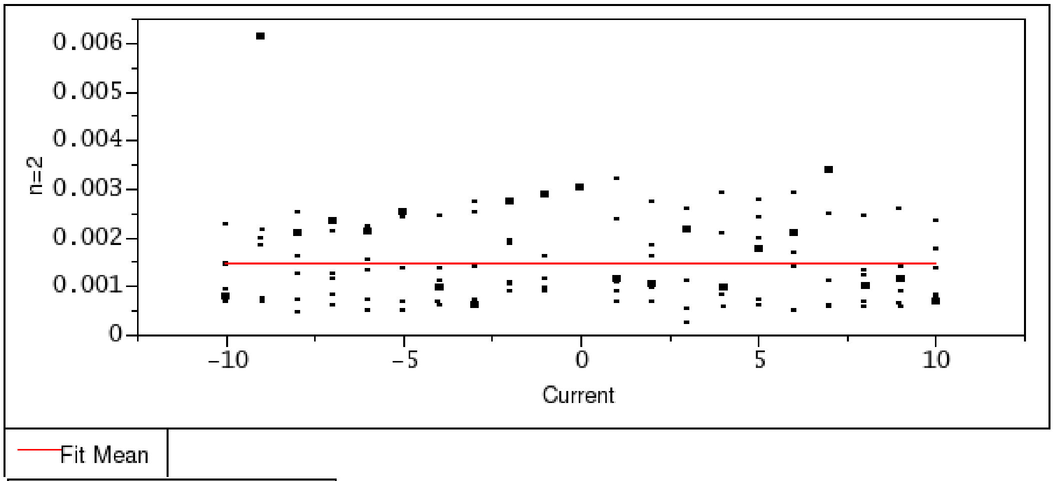
Also available in Document Control are the QA drawings. The top assembly drawing is 22232-

E-0001. Some of the design choices seem strange to me. The pole tip was contoured to minimize the allowed multipoles (12 and 20) and is specified with 66 (x,y) points along its curve. Then a 0.380-0.390” hole for a stainless steel threaded rod was placed with center 0.495” from the tip. 0.250”+-0.0003” drill rod was used for alignment in a groove of depth 0.252-0.256” and width 0.247-0.248”. I would have used a depth of 0.250-0.252” and width of 0.249-0.250, minimizing lamination distortion due to intentional interference in width while preserving the alignment needed. Other tolerances in the stack-up allow for all the distortions considered in Halbach's analsis at the 0.005” (125 microns) level.

Analysis

I began by analyzing the raw voltage (unbucked) data, comparing it to various runs of Borland's sddsrandmult. I found a combination of errors supportable by tolerance stackups, most of magnitude ~125 microns. I did not think CEBAF could not be matched to the degree it is (TN 05-074) with multipoles of this magnitude, so I moved on to the summary data sheets even though there is no record of the processing used to arrive at them. Long probe measurements of QA079 may provide a means for systematic error correction. The 15 long probe measurements of ten magnets are consistently larger for n=2 and n=3 than the short probe measurements. The two data sets are closer if the means of QA079 long probe measurements are added to short probe values. Since the long probe data have possible systematic errors the short probe data doesn't, I don't do the addition.

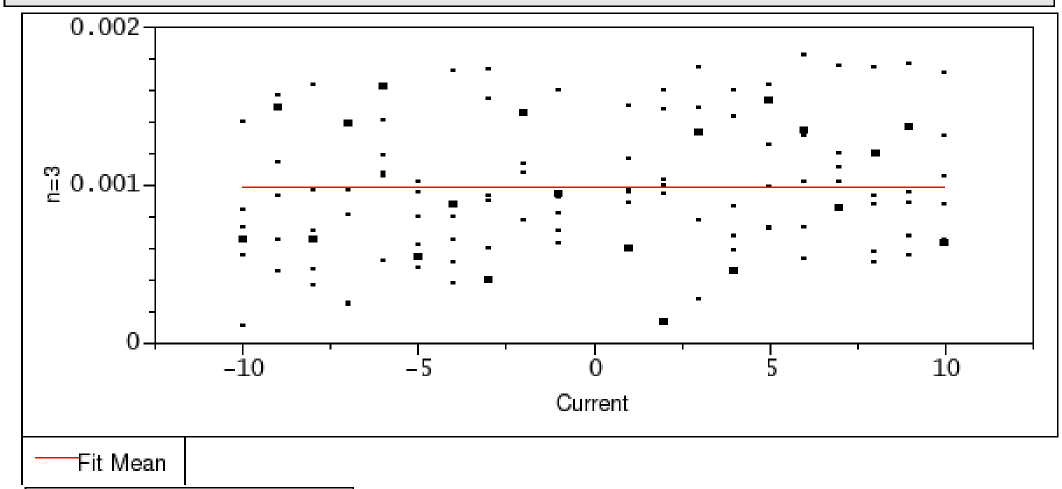
Bivariate Fit of n=2 By Current



Fit Mean

Mean	0.001504
Std Dev [RMSE]	0.000879
Std Error	0.00008
SSE	0.000092

Bivariate Fit of n=3 By Current



Fit Mean

Mean	0.000991
Std Dev [RMSE]	0.000416
Std Error	0.000038
SSE	0.000021

Figure 1. Sextupole/quadruple and octupole/quadrupole at pole tip radius for QA079. Five long probe measurements and one unmarked (highlighted) measurement. Standard deviation is large, giving an estimate of the uncertainty of all the measurements. Compare this with figure 5 which includes all the data.

For the data set derived from the summary sheets I found that manufacturing errors of order 25 microns sufficed to produce multipole amplitudes comparable to the measurements. This is about a fifth the range allowable by the mechanical drawings. Output of sddsrandmult is given below.

```
SDDS1
&parameter name=MagnetType, type=string, fixed_value=quadrupole &end
&parameter name=BoreRadius, type=double, fixed_value=1.429000e-02, units=m &end
&parameter name=EffectiveLength, type=double, fixed_value=3.048000e-01, units=m &end
&parameter name=SxPole, type=double, units=m, fixed_value=2.500000e-05 &end
&parameter name=SyPole, type=double, units=m, fixed_value=2.500000e-05 &end
&parameter name=SxSplit, type=double, units=m, fixed_value=1.250000e-05 &end
&parameter name=SySplit, type=double, units=m, fixed_value=1.250000e-05 &end
&parameter name=SphiHalves, type=double, fixed_value=7.000000e-05 &end
&parameter name=SrPole, type=double, units=m, fixed_value=1.500000e-05 &end
&parameter name=referenceRadius, type=double, fixed_value=1.429000e-02, units=m &end
&column name=order, type=long &end
&column name=an, type=double &end
&column name=bn, type=double &end
&data mode=ascii no_row_counts=1 &end
1 2.823336e-03 8.002922e-04
2 8.640408e-04 8.664369e-04
3 9.002017e-04 2.552154e-04
4 3.237371e-04 3.249138e-04
5 2.439582e-04 1.073289e-04
6 3.125636e-05 3.128800e-05
7 6.079284e-05 4.832482e-05
8 3.742877e-05 3.760577e-05
9 3.492165e-05 2.172756e-05
```

The normal components are in the second column and the skew in the third column above. n=1 values are quadrupole error terms versus ideal quad.

On the following pages I plot the multipole data for each magnet normalized to the amplitude of each from SDDS, neglecting phase information since that is very noisy in the measurements. Data at 0A is discarded. Only the portion of the hysteresis curve used in CEBAF is plotted. A spreadsheet with all the digitized data and the modest processing done on it is available by request. I then plot the ratios of multipoles to quadrupoles directly, for those who prefer units. (Pun intended - for many accelerator designers, a unit is a part per thousand of the base multipole.)

The SDDS output is a reasonable fit to the data for the lower harmonics. Above the allowed 12-pole harmonic the measurements appear non-physical given Halbach's analysis and Mike Borland's implementation of it. Through an email colloquy with Mike Borland I recognized that the mean values for the two allowed multipoles were larger than those for the unallowed. This difference is not statistically significant because the standard deviations are so large compared to the means. Nevertheless it provides a way to get a rough estimate of the systematic normal component of these two multipoles by attributing all of the “excess” to them.

The first table below gives the means and sigmas for the ratios of short probe data to the amplitudes of the SDDS output. For unallowed multipoles I then multiplies these ratios by the normal and skew components to give the best estimates available from the data on hand. For allowed multipoles the manipulation is a bit more complicated, to implement the impution of systematic component discussed in the preceeding paragraph. The spreadsheet in which the work is done is available from the author. The results of this processing are given in the second table below.

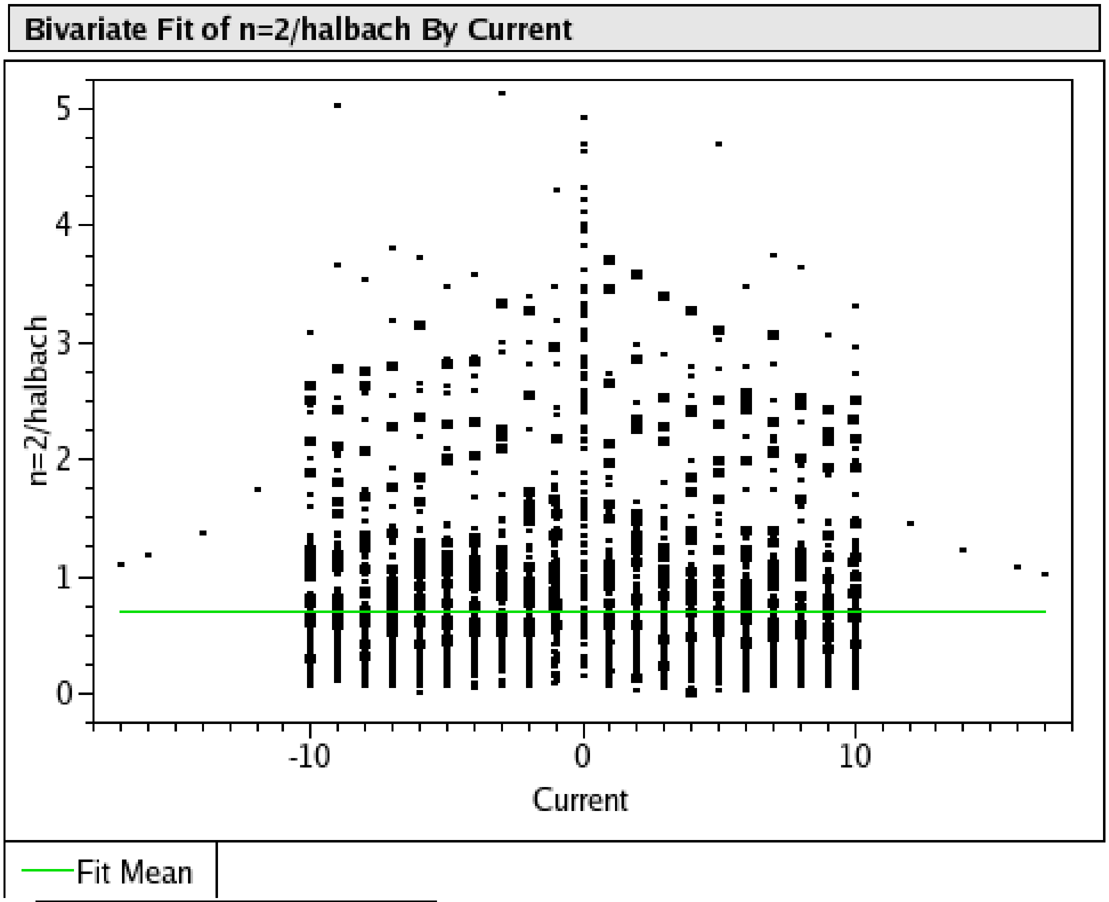
multipole	sddsrandmult normal/quad	sddsrandmult skew/quad	data/sdds ratio mean	data/sdds ratio sigma
2	8.640E-04	8.664E-04	0.61	0.54
3	9.002E-04	2.552E-04	1.03	0.94
4	3.237E-04	3.249E-04	1.13	0.97
5	2.440E-04	1.073E-04	2.5	1.59
6	3.126E-05	3.129E-05	18.9	16.6
7	6.079E-05	4.832E-05	15.3	13.7
8	3.743E-05	3.761E-05	31.9	28.8
9	3.492E-05	2.173E-05	37.7	25.1

It is recommended that the estimates below be used in future simulations, including the ones which appear non-physical. The latter are still smaller than the values Edward Pozdeyev used in his specification for accelerator dipoles and quads. TN06-018 discusses recent changes to the measurement system reflected in the one +- 17A data set shown in the following figures. It suggests reasons for the non-physical values in multipoles 6-8. One might reduce these three multipole values above and below by an order of magnitude to get more realistic values; I don't.

multipole	systematic norm/quad	rand normal mean/quad	rand normal sigma/quad	rand skew mean/quad	rand skew sigma/quad
2		5.3E-04	4.7E-04	5.3E-04	4.7E-04
3		9.3E-04	8.5E-04	2.6E-04	2.4E-04
4		3.7E-04	3.1E-04	3.7E-04	3.2E-04
5	1.8E-04	4.5E-04	3.94E-04	1.86E-04	1.65E-04
6		5.9E-04	5.2E-04	5.9E-04	5.2E-04
7		9.3E-04	8.3E-04	7.4E-04	6.6E-04
8		1.2E-03	1.1E-03	1.2E-03	1.1E-03
9	4.2E-04	9.6E-04	8.50E-04	5.02E-04	4.45E-04

Acknowledgements

Useful comments were received from T. Hiatt and M. Borland.

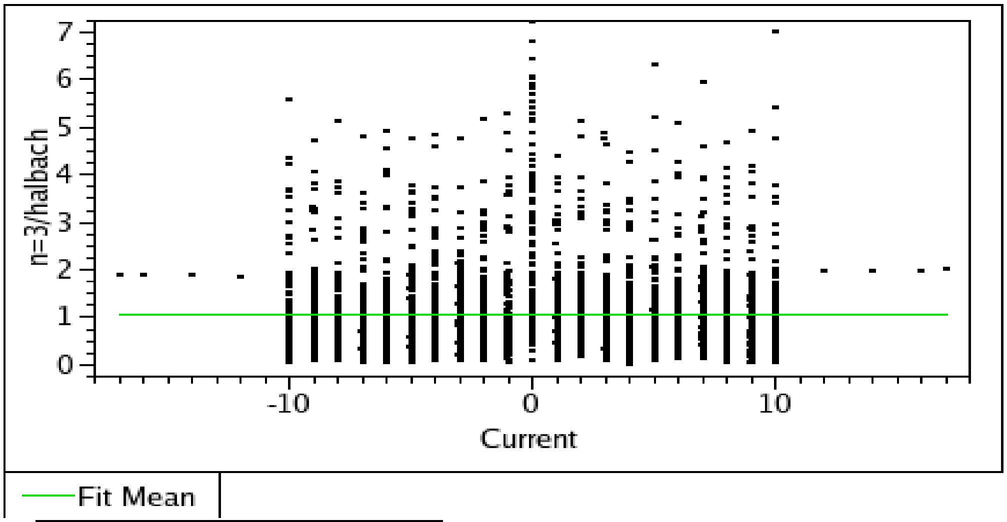


Fit Mean

Mean	0.697454
Std Dev [RMSE]	0.618825
Std Error	0.012296
SSE	969.6165

Figure 2. Measured sextupole divided by SDDSRANDMULT as a function of current. Highlighted points are the long probe measuremens. These values may have been taken with a bucking quadrupole to null the fundamental term. Note that they are higher than the bulk of the data; their mean is 1.27. The others plotted were likely taken without the bucking quad; their mean is 0.61. SDDSRANDMULT inputs are ~20% of the values supportable by tolerance stackup of the engineering drawings. Only the points on the portion of the hysteresis curve used in the machine are plotted. Zero current values are plotted but not included in the means.

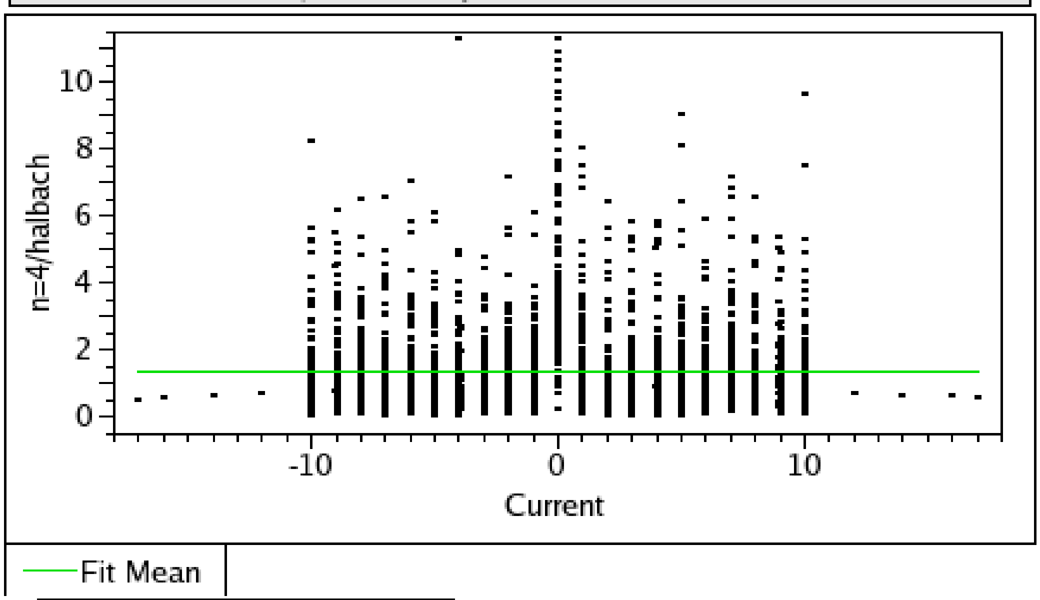
Bivariate Fit of n=3/halbach By Current



Fit Mean

Mean	1.072673
Std Dev [RMSE]	0.905188
Std Error	0.017985
SSE	2074.635

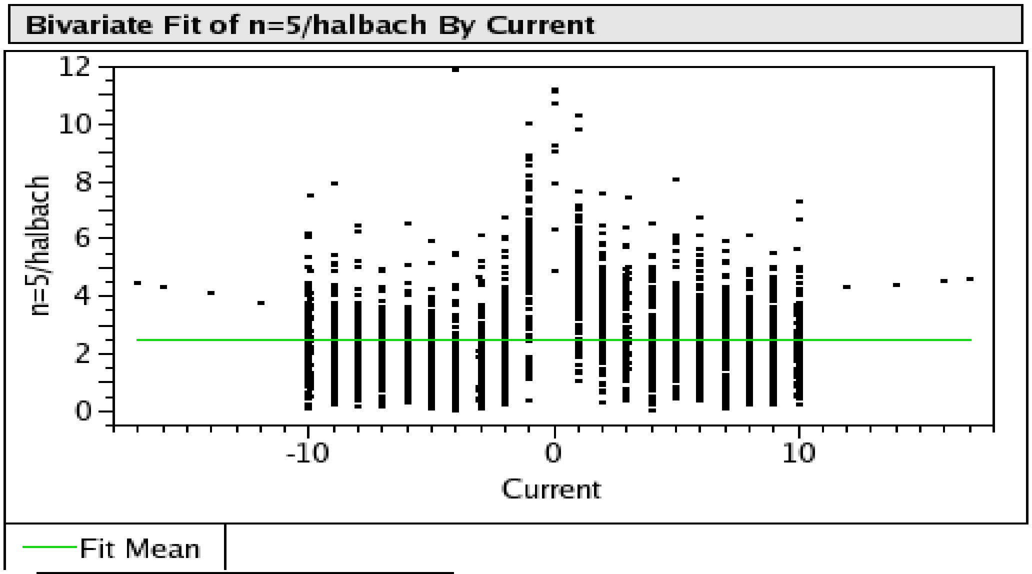
Bivariate Fit of n=4/halbach By Current



Fit Mean

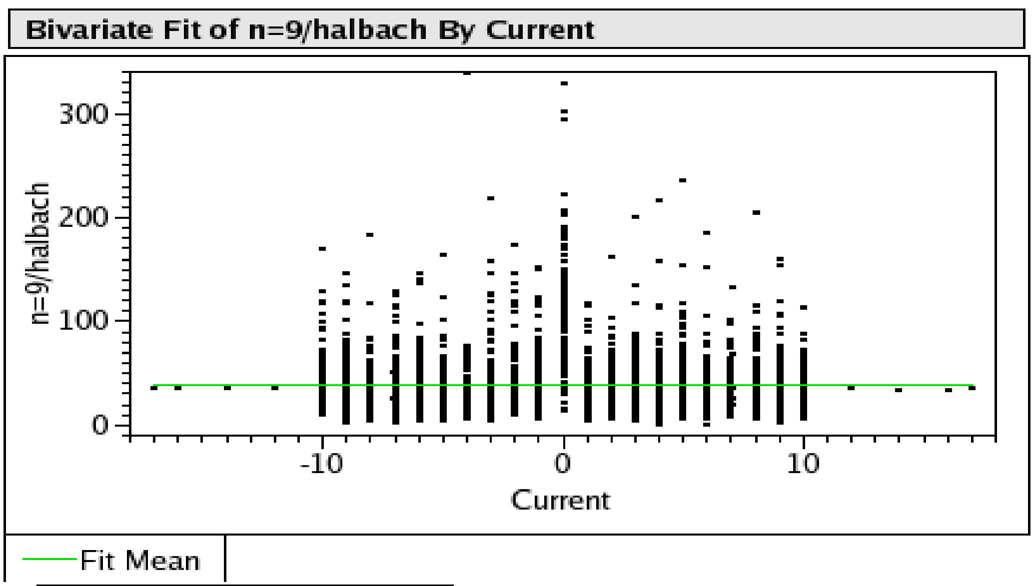
Mean	1.353332
Std Dev [RMSE]	1.20239
Std Error	0.023891
SSE	3660.617

Figure 3. Octupole and decapole content relative to SDDSRANDMULT. Note recent 17A measurement.



Fit Mean

Mean	2.520572
Std Dev [RMSE]	1.565797
Std Error	0.031111
SSE	6207.755

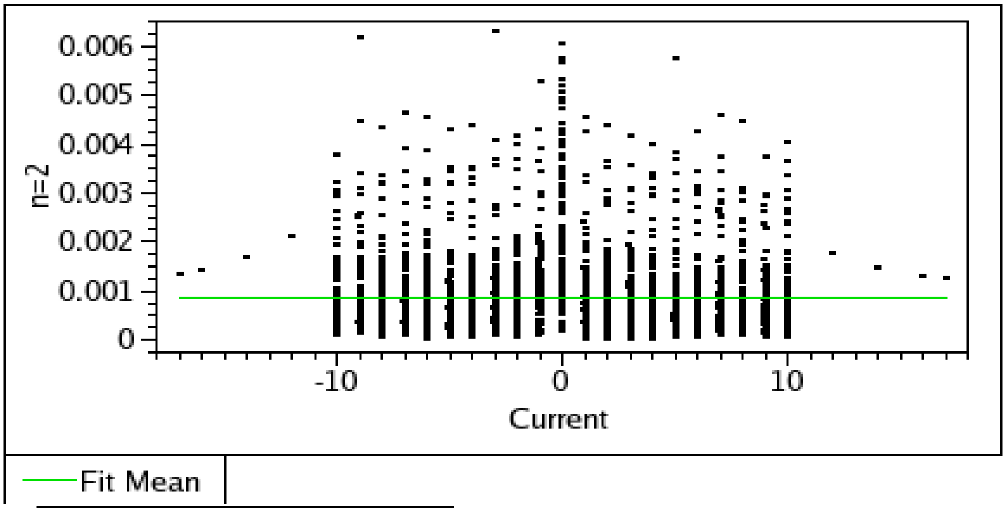


Fit Mean

Mean	38.26717
Std Dev [RMSE]	26.13502
Std Error	0.519284
SSE	1729456

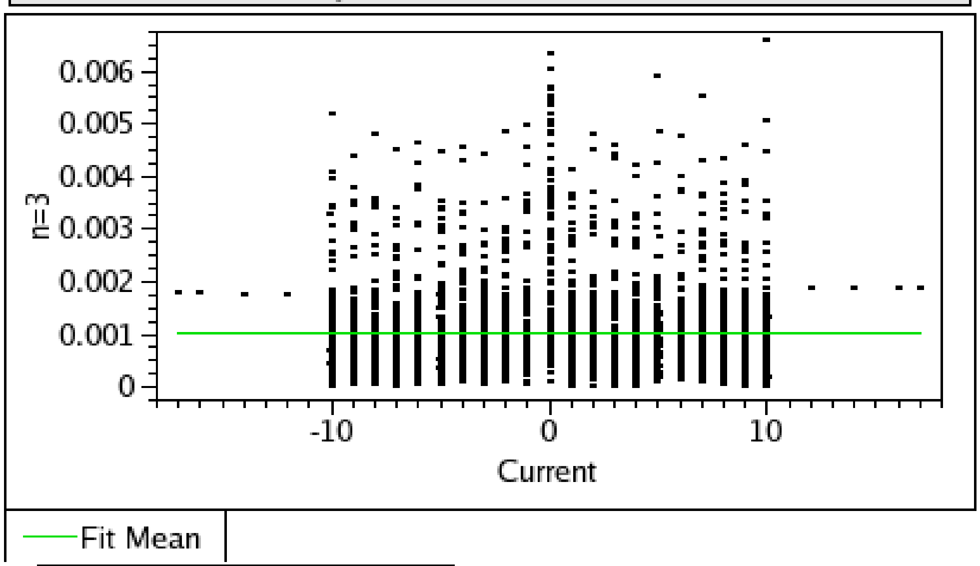
Figure 4. Dodecapole and icosapole (allowed multipoles) content relative to SDDSRANDMULT output. Measurements seem physically unrealistic for multipoles 6-8. Icosapole is high relative to simulation yet old and new measurements agree.

Bivariate Fit of n=2 By Current



Fit Mean	
Mean	0.000852
Std Dev [RMSE]	0.000757
Std Error	0.000015
SSE	0.001454

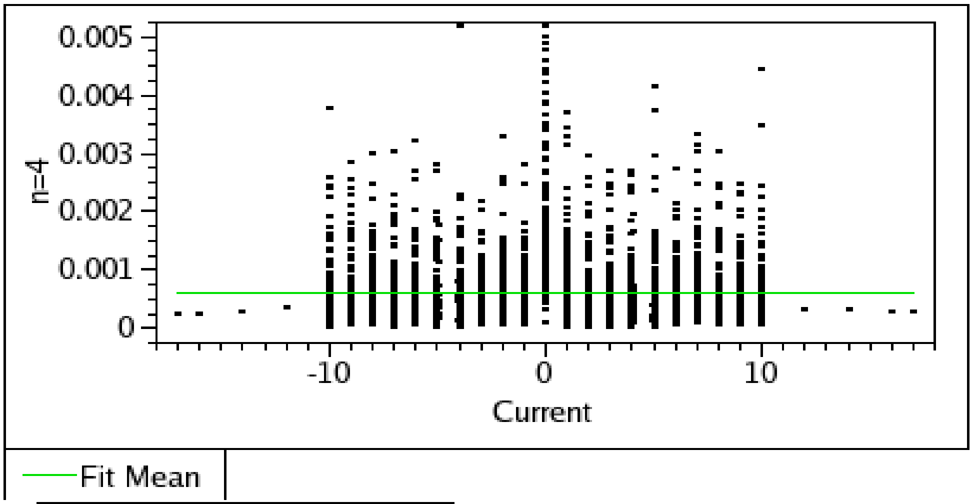
Bivariate Fit of n=3 By Current



Fit Mean	
Mean	0.001002
Std Dev [RMSE]	0.000847
Std Error	1.682e-5
SSE	0.001819

Figure 5. Sextupole/quadrupole and octupole/quadrupole at pole tip radius.

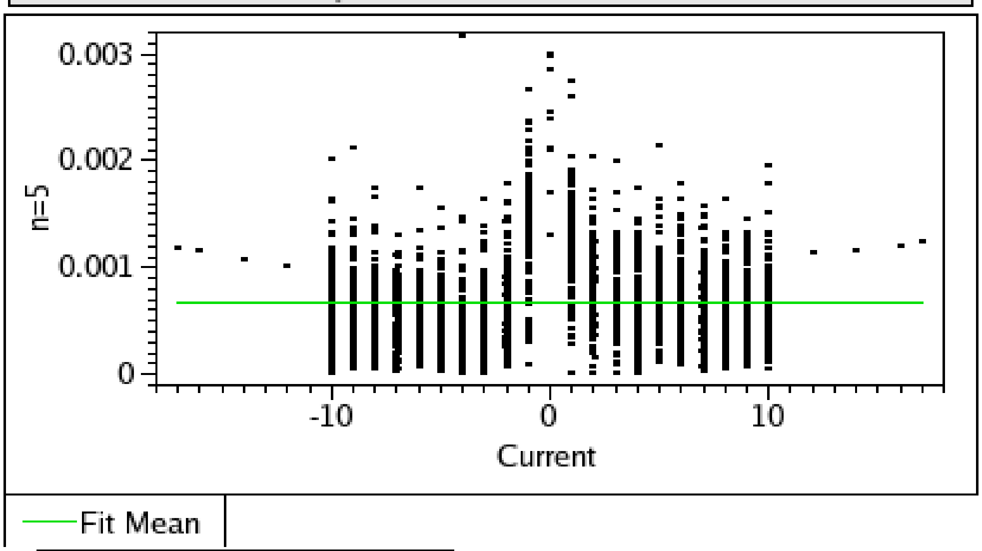
Bivariate Fit of n=4 By Current



Fit Mean

Mean	0.00062
Std Dev [RMSE]	0.000552
Std Error	0.000011
SSE	0.000771

Bivariate Fit of n=5 By Current

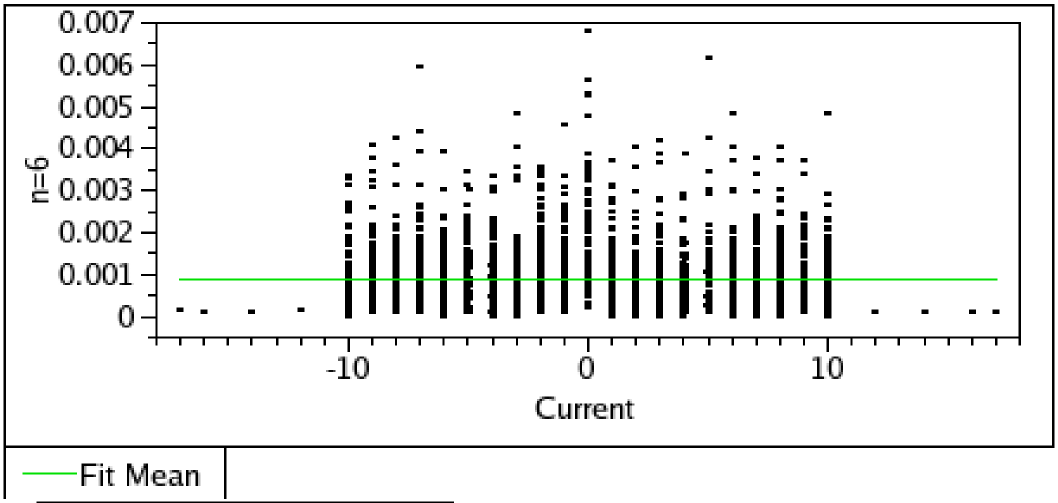


Fit Mean

Mean	0.000671
Std Dev [RMSE]	0.000418
Std Error	8.296e-6
SSE	0.000442

Figure 6. Decapole/quadupole and dodecapole/quadrupole at pole tip radius

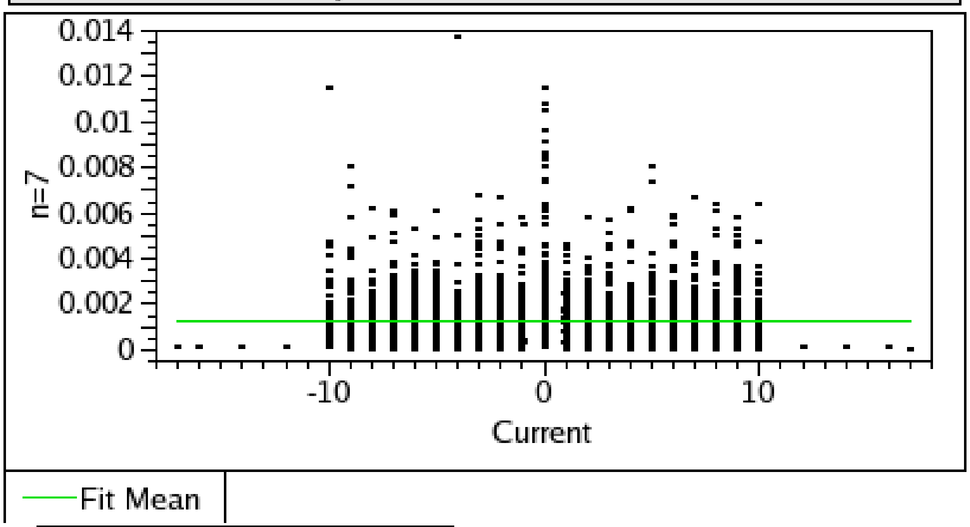
Bivariate Fit of n=6 By Current



Fit Mean

Mean	0.000904
Std Dev [RMSE]	0.000771
Std Error	1.532e-5
SSE	0.001509

Bivariate Fit of n=7 By Current

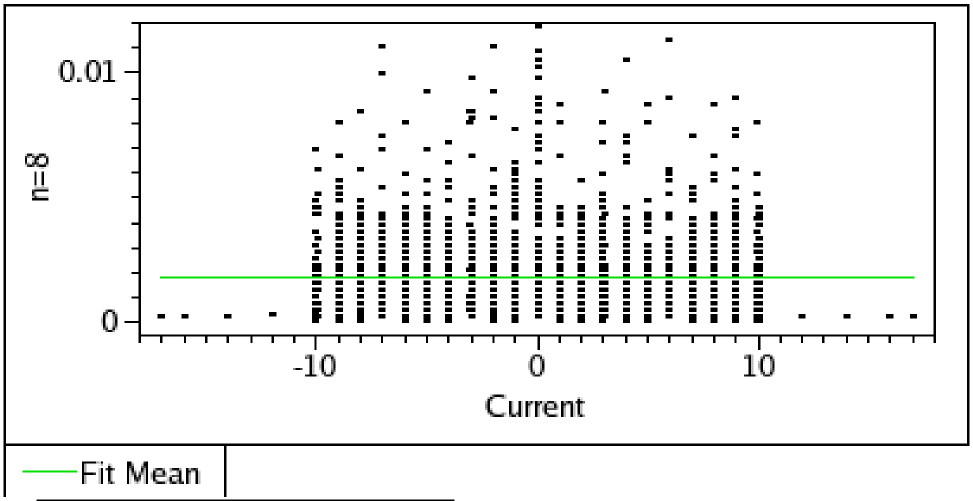


Fit Mean

Mean	0.001276
Std Dev [RMSE]	0.001131
Std Error	2.246e-5
SSE	0.003244

Figure 7. 14pole/quadrupole and 16pole/quadrupole at pole tip radius. Note that the recent 17A measurement is much lower than the old, suggesting the old values are poor.

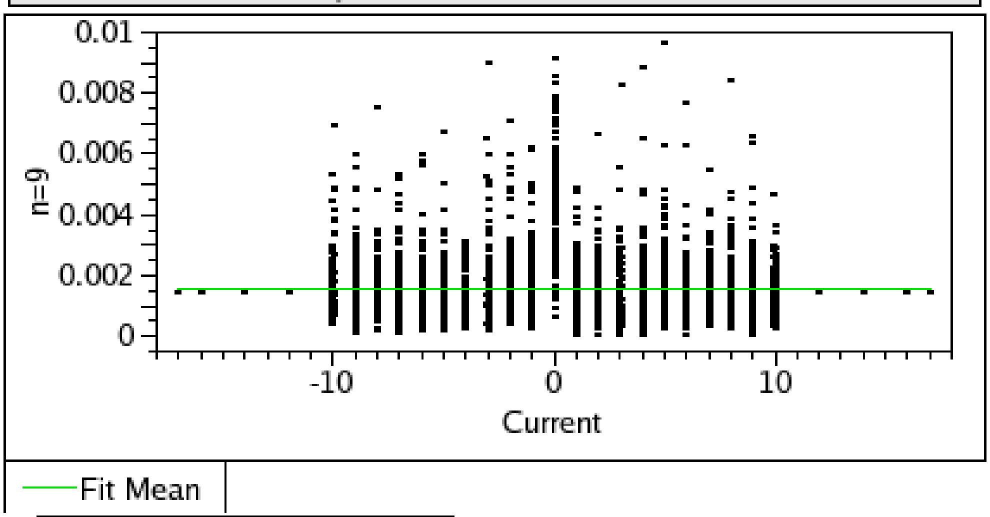
Bivariate Fit of n=8 By Current



Fit Mean

Mean	0.00178
Std Dev [RMSE]	0.001615
Std Error	0.000032
SSE	0.006615

Bivariate Fit of n=9 By Current



Fit Mean

Mean	0.001572
Std Dev [RMSE]	0.001076
Std Error	2.136e-5
SSE	0.002933

Figure 8. 18pole/quadrupole and icosapole/quadrupole at pole tip radius. Note that recent and old measurements for icosapole agree, unlike those for 14, 16 and 18 poles.