JLAB-TN-08-078

Multipoles as a function of central magnetic field

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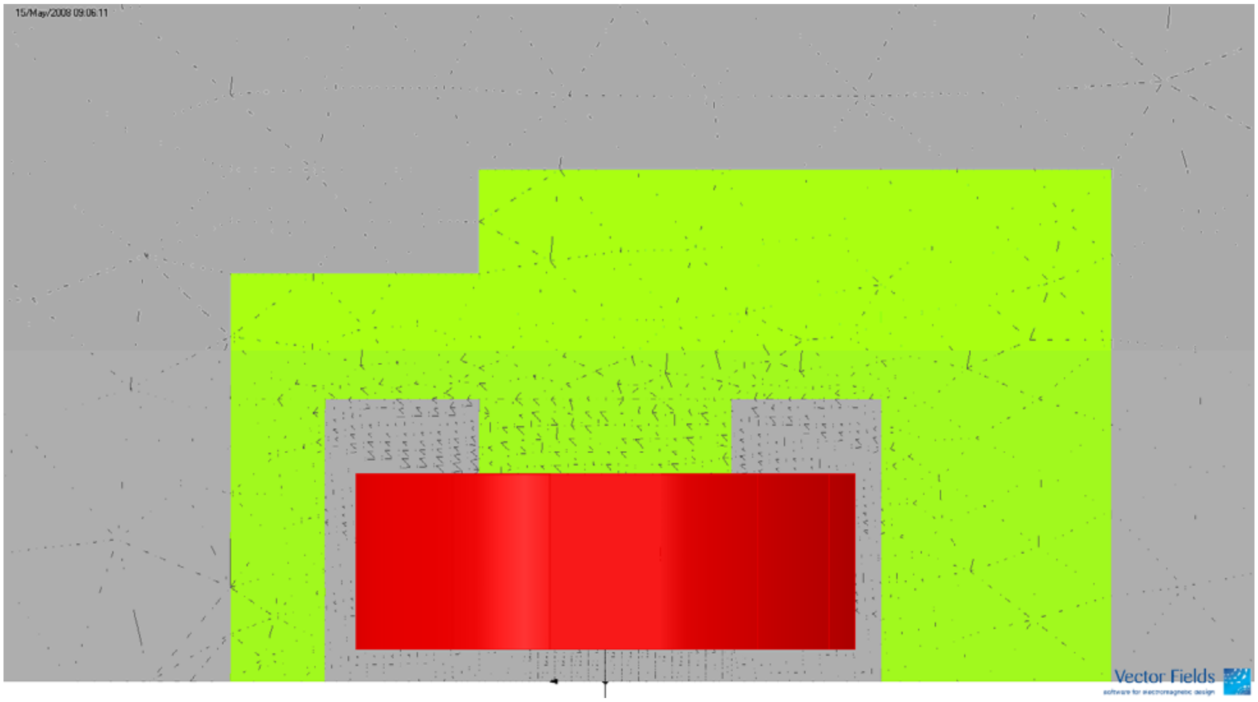
Abstract

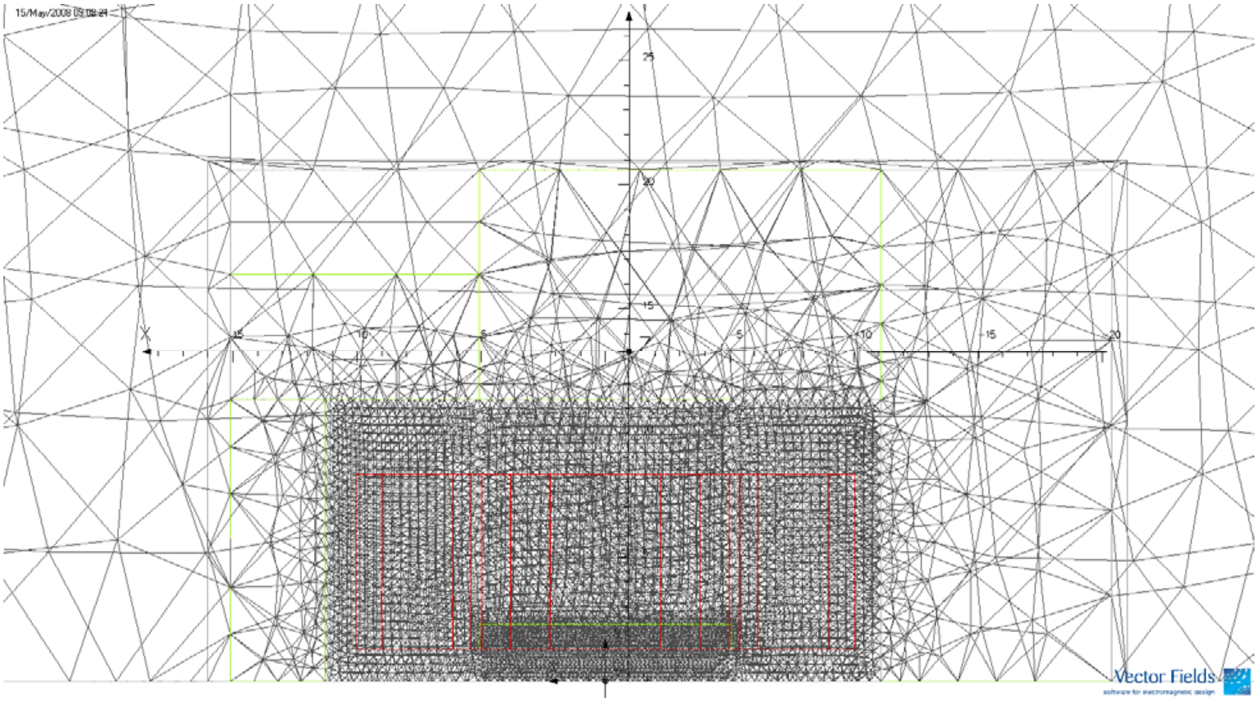
In TN-08-022 I showed that the coil size did not significantly affect nodal interpolation calculation of central field and line integrals. Multipoles are derived from calculations of 60 points on a circle and so also should not be affected by coil size. I have therefore modeled the one meter dipole used in the spreaders and recombiners in arcs 3-8 with a single, typical coil pack. I have ten models assuming symmetry across the bend midplane and five models without this assumption. The latter are needed to evaluate skew multipoles. Sagittas range from 3 to 12 mm. Pole is 10 cm wide. I show select multipoles as a function of field for the largest sagitta orbit and for the design orbit of the highest field dipole, MAB6R. Incidental to this work I developed a saturation curve for the magnet. I suggest that dipole fields be kept below 12 kG.

This TN was sent to the 12 GeV Project team for review May 16, 2008. Comments were received Nov. 13, 2008. These comments are included as an appendix.

The model

The basic model is shown below. Green is steel. The coils are red. Air is grey. In the next figure I turn off surfaces so you can see the mesh. The original C magnet is on the right and the added "H-return" steel on the left. Geometry of the original C magnet and typical coil pack taken from engineering drawings. Geometry of the H return steel taken from ME group magnet models.





Mesh is densest in the first cm of the pole steel and in the air under the pole. Next densest in the remainder of the pole proper and the air occupied by the coils. The coils are outlined in red. The steel is outlined in green but difficult to see on a display, much less here. Mesh in the return steel is coarse because saturation there is not of interest to me - the MEs have already checked it is OK. The boundary is relatively close in this model, which was created before the work discussed in TN-08-022. As discussed there, this doesn't have a significant effect on nodal interpolation results and therefore the multipole values.

Symmetric model field (kG)	reflected model?	Magnet	sagitta (cm)	mesh under steel	mesh at end background 8cm
5				2.5mm	5mm for 12cm
7.07		MAC7	0.342	2.5mm	5mm for 12cm
8.94		MAC5	0.601	2.5mm	5mm for 12cm
10.6	yes	MAA3	**1.171**	2.5mm	5mm for 12cm
11				2.5mm	5mm for 12cm
11.5	yes			2.5mm	10mm for 10cm
12	yes			2.5mm	10mm for 10cm
12.41	yes	MAE8	0.526	2.5mm	5mm for 12cm
12.43	yes	MAF4	1.040	2.5mm	5mm for 12cm
12.8				2.5mm	8cm
13.81		MAB6S	0.777	2.5mm	5mm for 12cm
13.96	yes	MAB6R	**0.785**	2.5mm	5mm for 12cm

Five of the ten symmetric models are for actual magnets as shown in the table. The same model is used for MAF/MAE and MAB6R/MAB6S. The other five were used to fill in the B(I) curve so a 0.3% accurate polynomial fit could be obtained for shunt current calculation. Fields for which reflected models are available are indicated in the second column. All of the models will be post-processed to provide multipoles at 300 locations along an arc corresponding to the 1.17cm sagitta beam path. Sagitta is split with half on either side of the pole mid-line. Selected models will also be post-processed along the arc corresponding to the 0.785cm sagitta. Finally, some old results with lower resolution will be plotted for six of the magnets along their individual orbits. Spreadsheets with the numerical results will be made available to those interested.

The arc 3-9 dipoles have poles 1.75cm wider than this dipole. Sagittas are either 1.3cm (arcs 4-6) or 1.5cm (arcs 7-9) wider than the 1.17cm used here. Multipole behavior in these arcs will therefore be similar to those shown here at/below 11 kG, the maximum arc 3-9 dipole field. End effects will be proportionally smaller since this dipole is 96cm long and those are 200 cm or 300 cm long.

The following graphs show some odd behavior outside the steel. This is due to my learning curve on mesh necessities for accurate results. For 12.8 kG, the earliest model below, I meshed the region outside the steel as background, at 8cm, rather than putting a finer mesh around the coil. This is reflected in the periodicity in the blue triangles from 50 to 60 cm below. I document mesh size under the steel and in the end region in the table above to explain the ragged behavior in all the models outside the steel. Figures 3 through 11 are along the orbit with 1.17cm sagitta. Steel ends at 48cm. Most of the models are well meshed to 60cm.

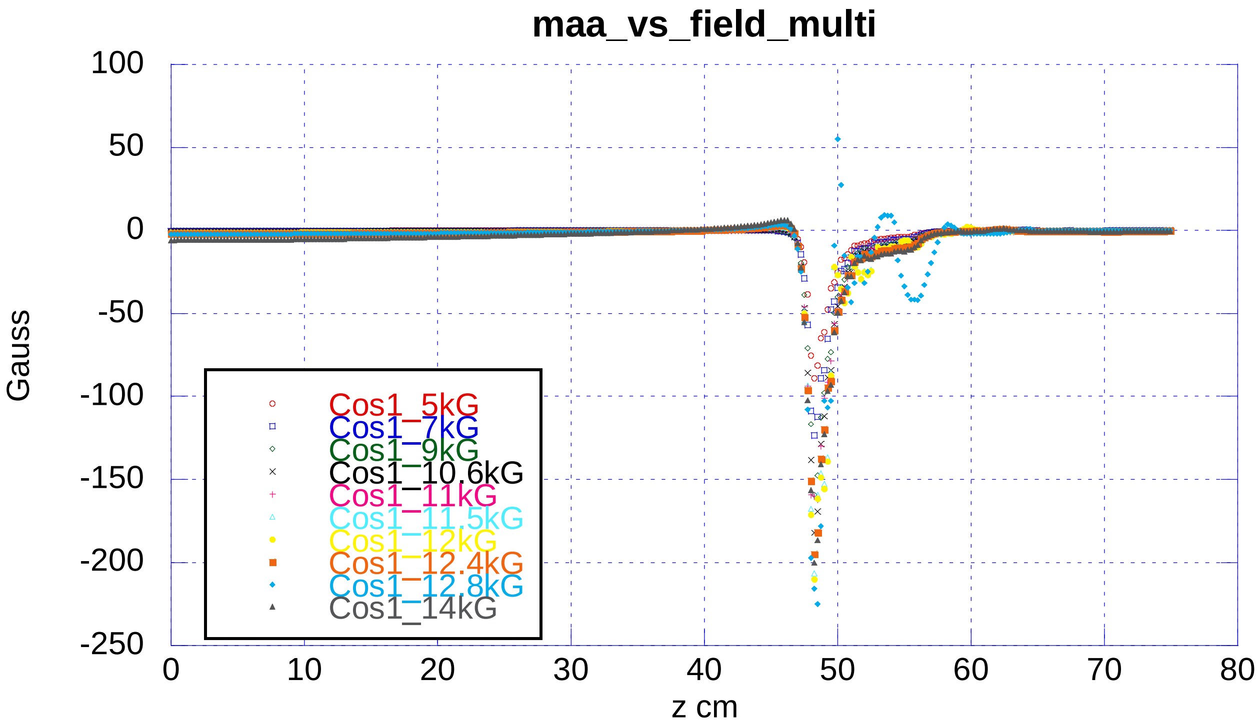


Figure 3. Quadrupole term for ten symmetric models at different fields.

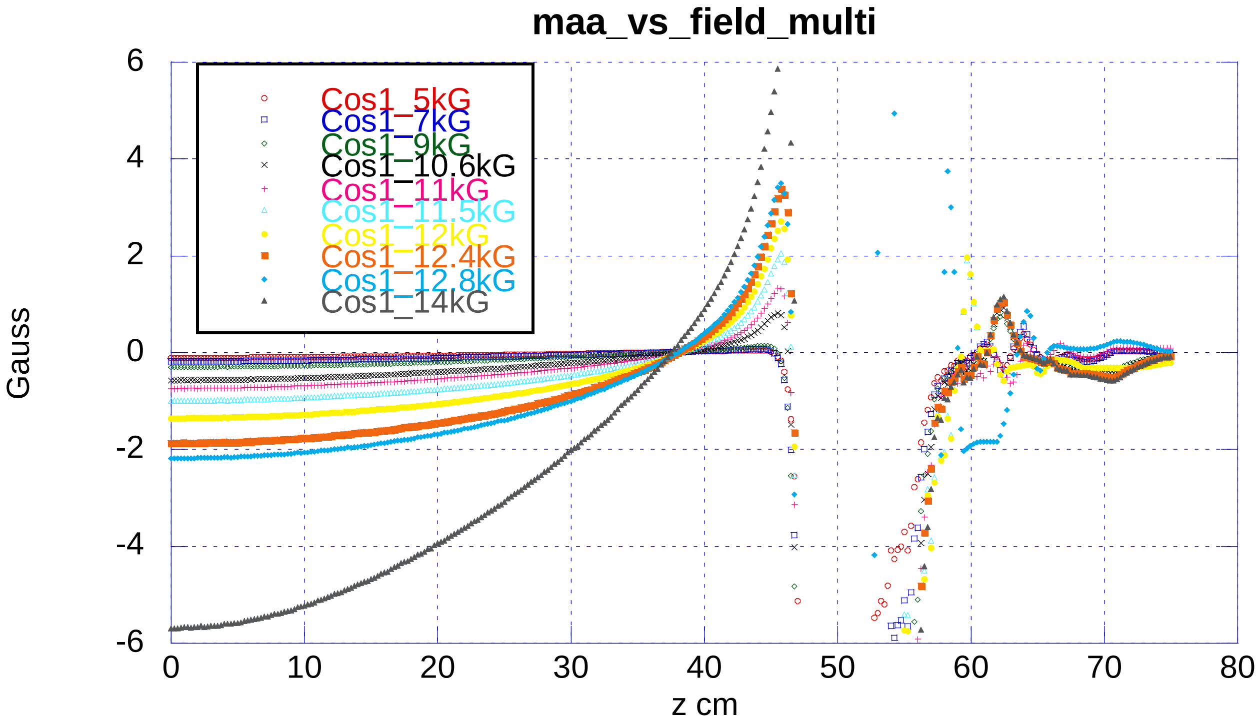


Figure 4. Same as figure 3 except vertical scale so field dependence in the body of the magnet is clearer.

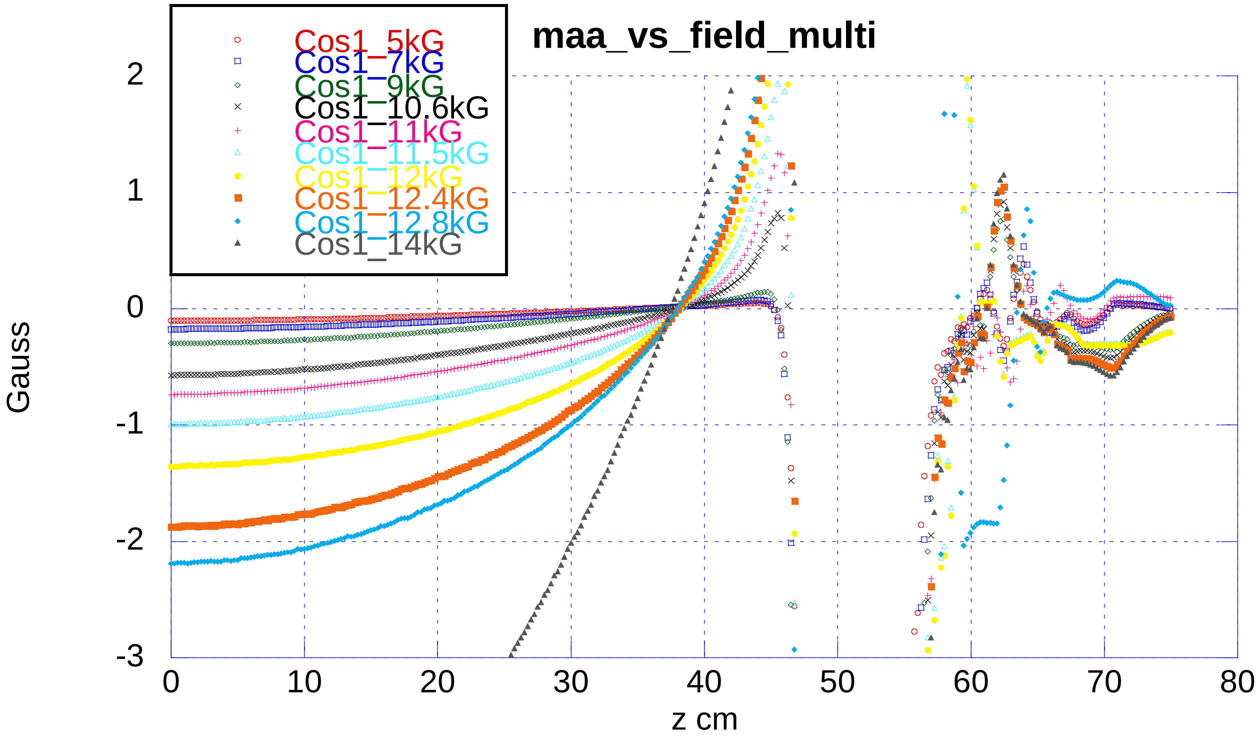


Figure 5. As above with still finer vertical scale

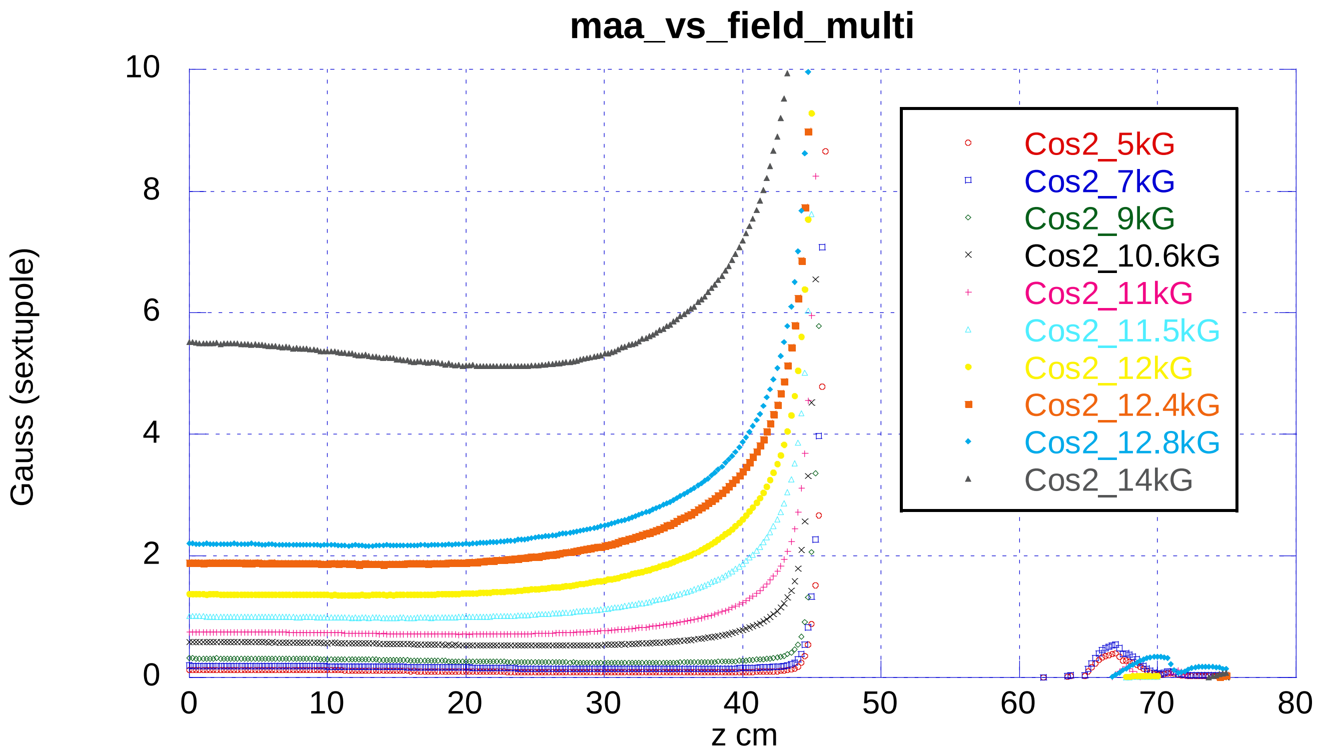


Figure 6. Sextupole in body of dipole as a function of field.

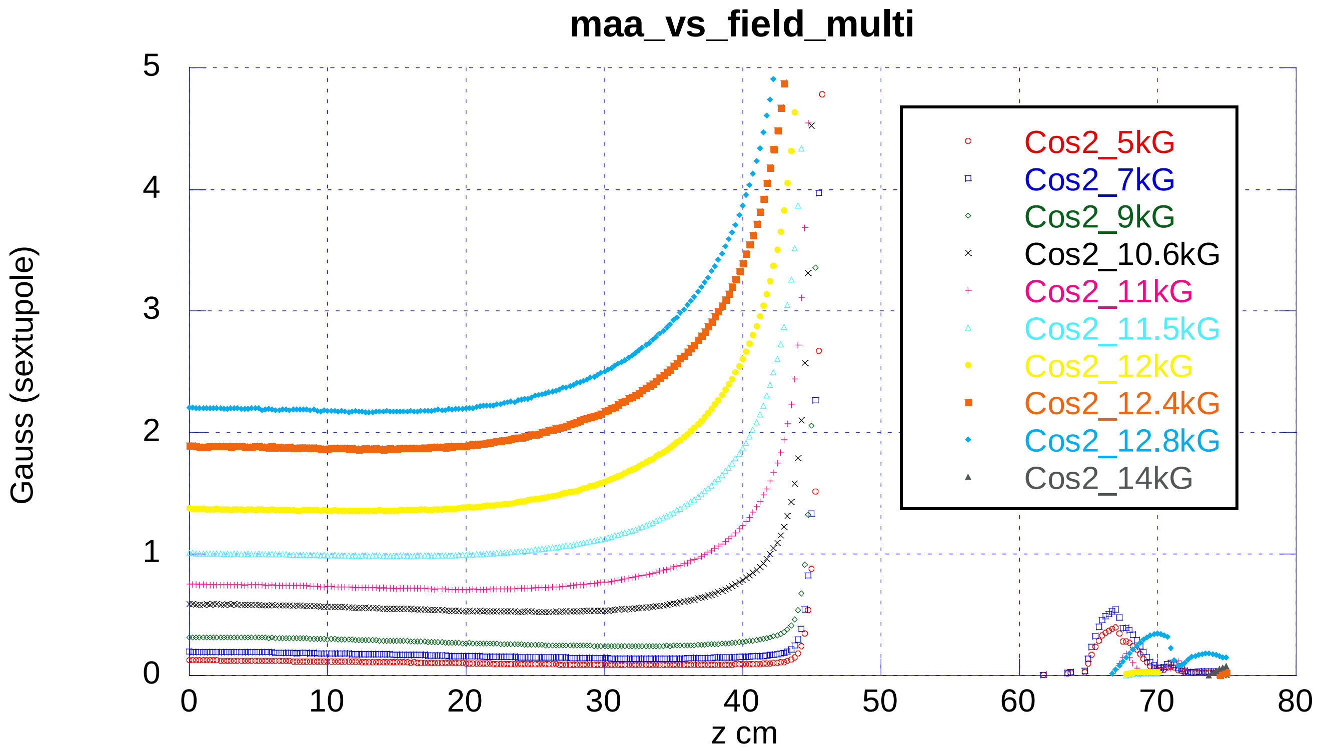


Figure 7. As above, different scale.

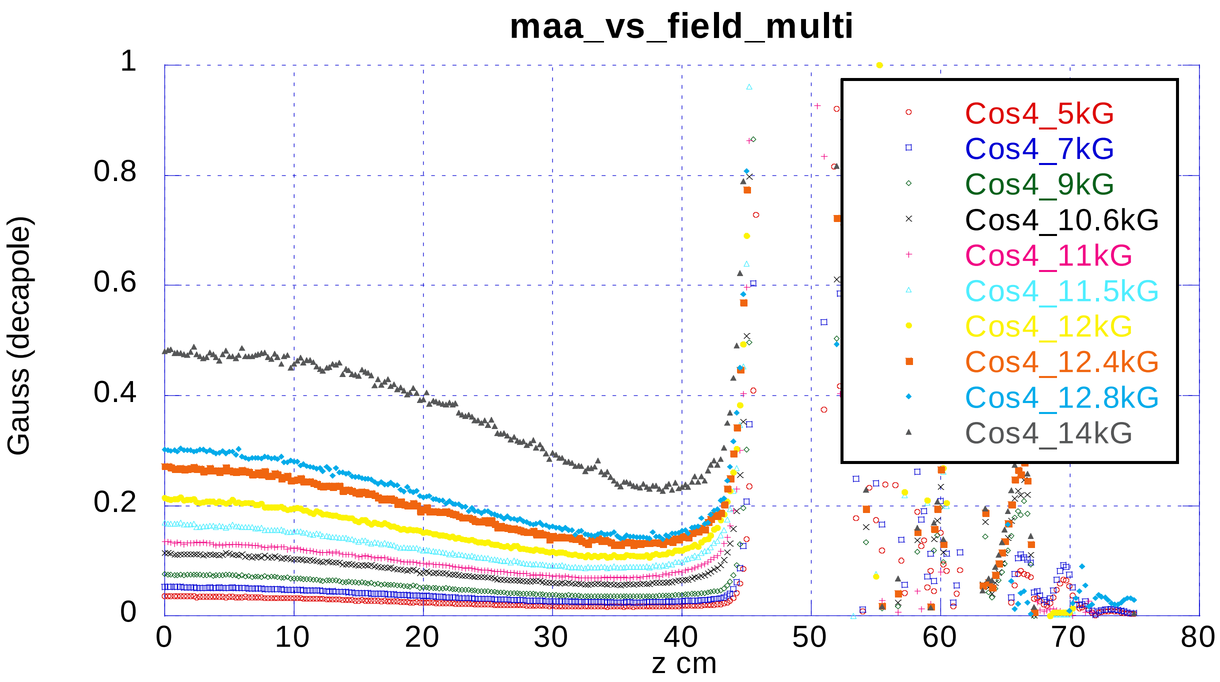


Figure 8. Decapole in dipole body as a function of field

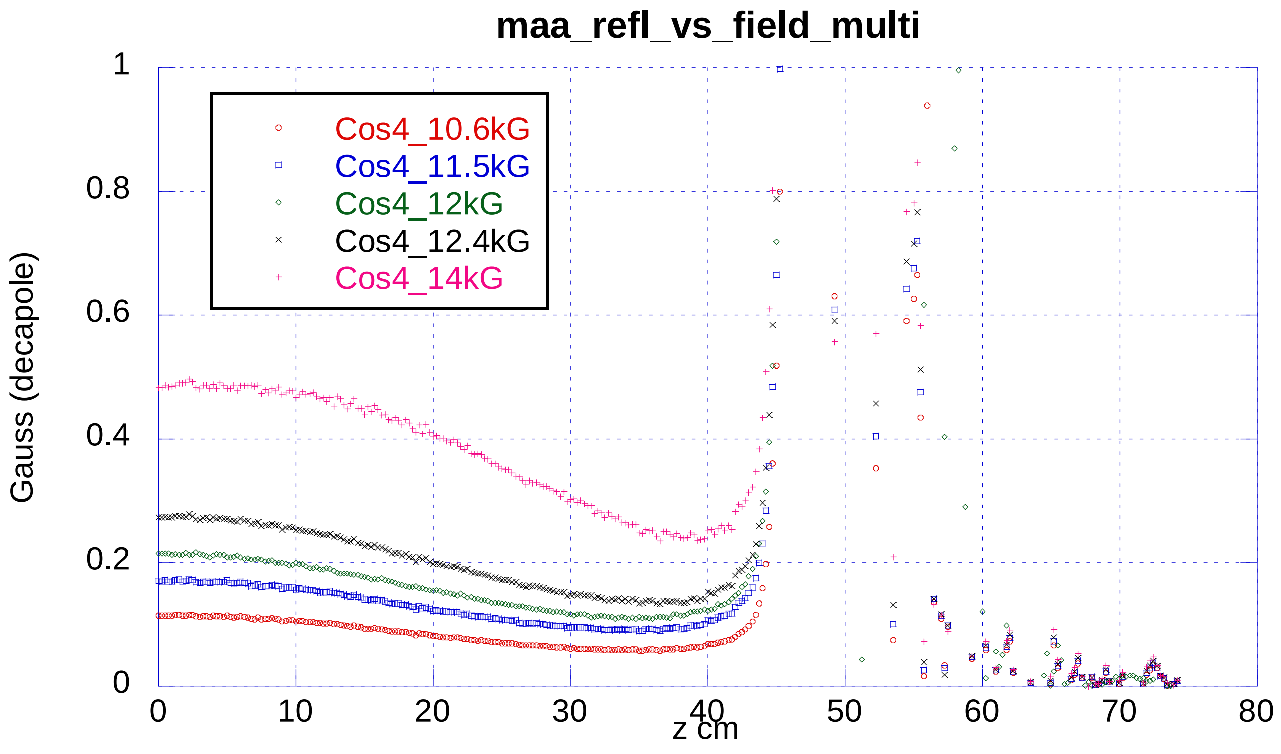


Figure 9. Decapole in dipole body as a function of field in models which do not have symmetry imposed across the bend midplane. I call them reflected because I construct them by reflecting all the elements I created in one half of the magnet into the mirror half and then remove the symmetry constraint.

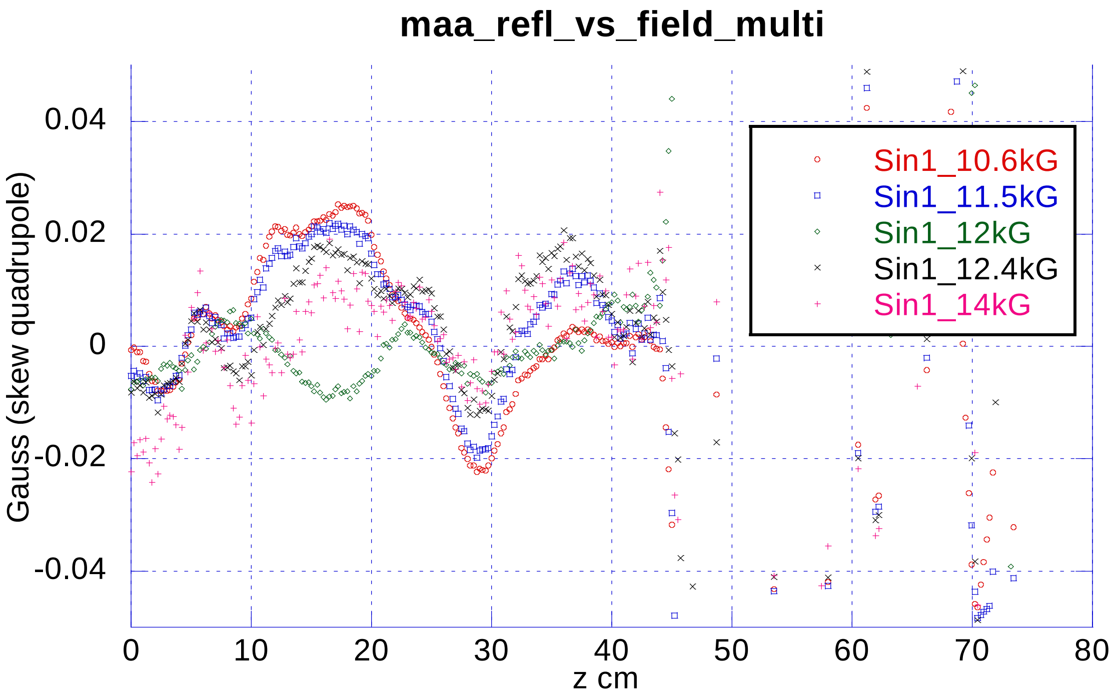


Figure 10. Skew quadrupole field from "reflected" model. Variation along the length is non-physical so I regard this ±20mG as numerical noise likely resulting from the mesh. I have a cutting plane at 25cm in these models to restart the mesh generator. This may be why the values are zero there.

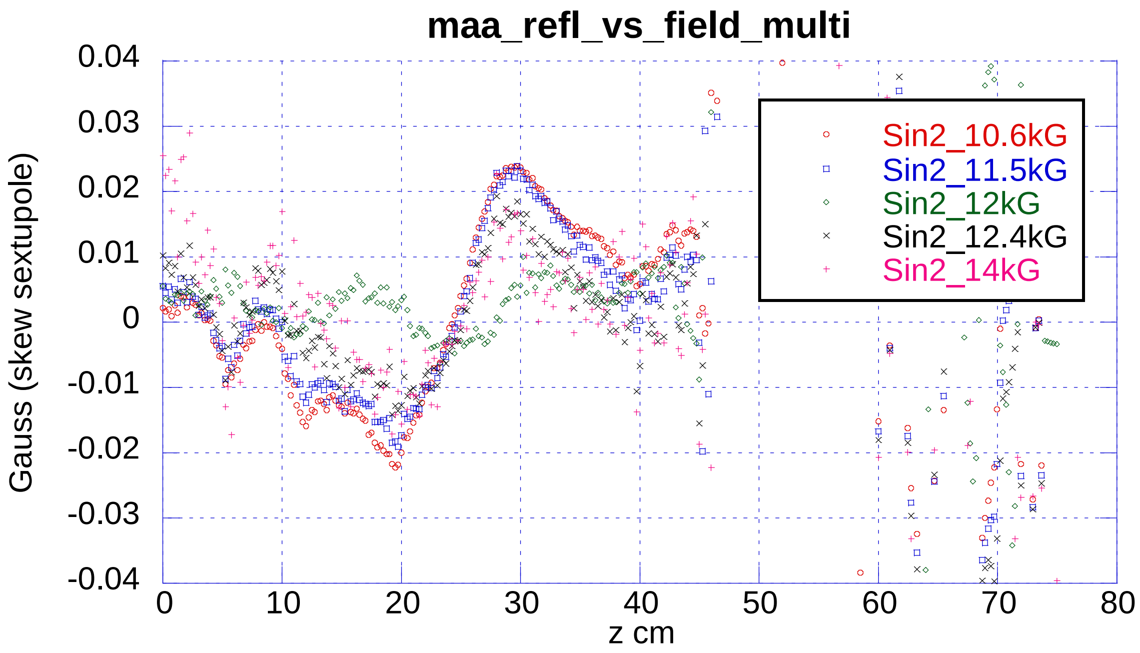


Figure 11. Skew sextupole. Again, I regard this as mesh-derived numerical noise rather than true skew field.

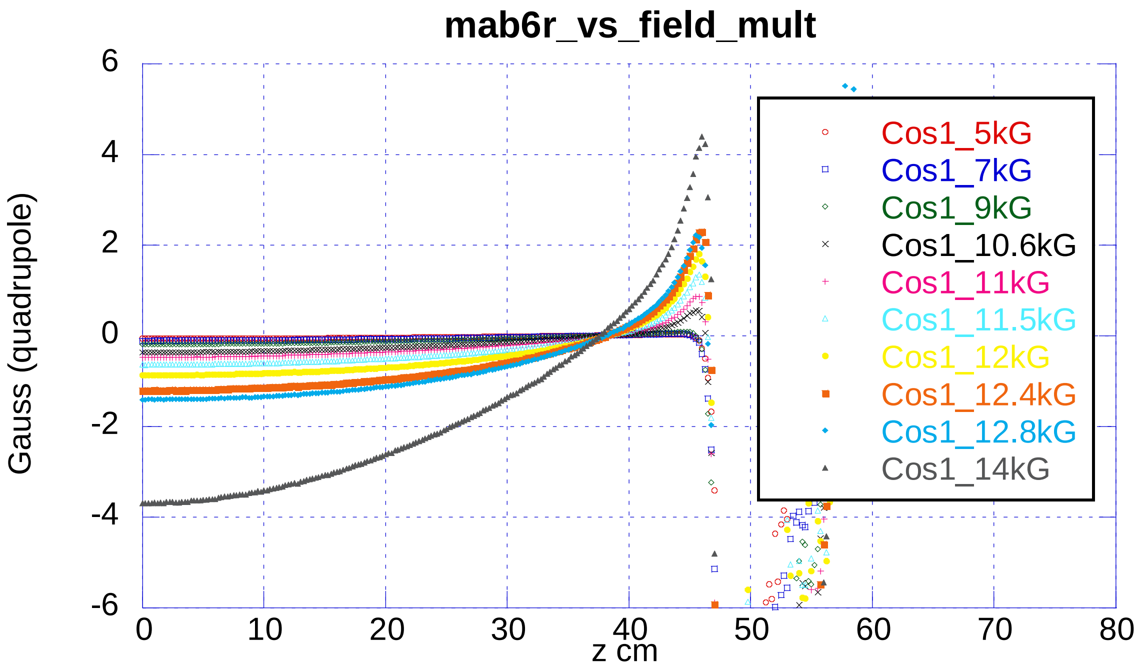


Figure 12. Same as figure 4 except along arc with 0.785cm sagitta.

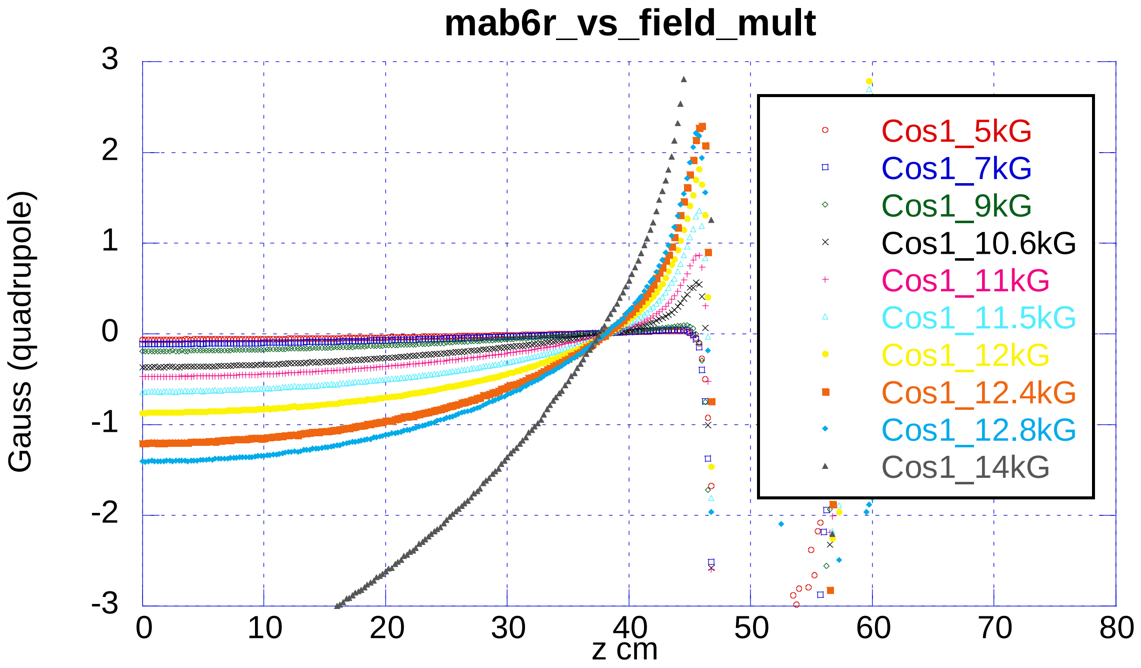


Figure 13. Same as figure 5 except along arc with 0.785cm sagitta.

These simply show the scaling with sagitta of the field dependence of the quadrupole term. It's roughly linear in sagitta, suggesting (per M. Tiefenback) feeddown from sextupole.

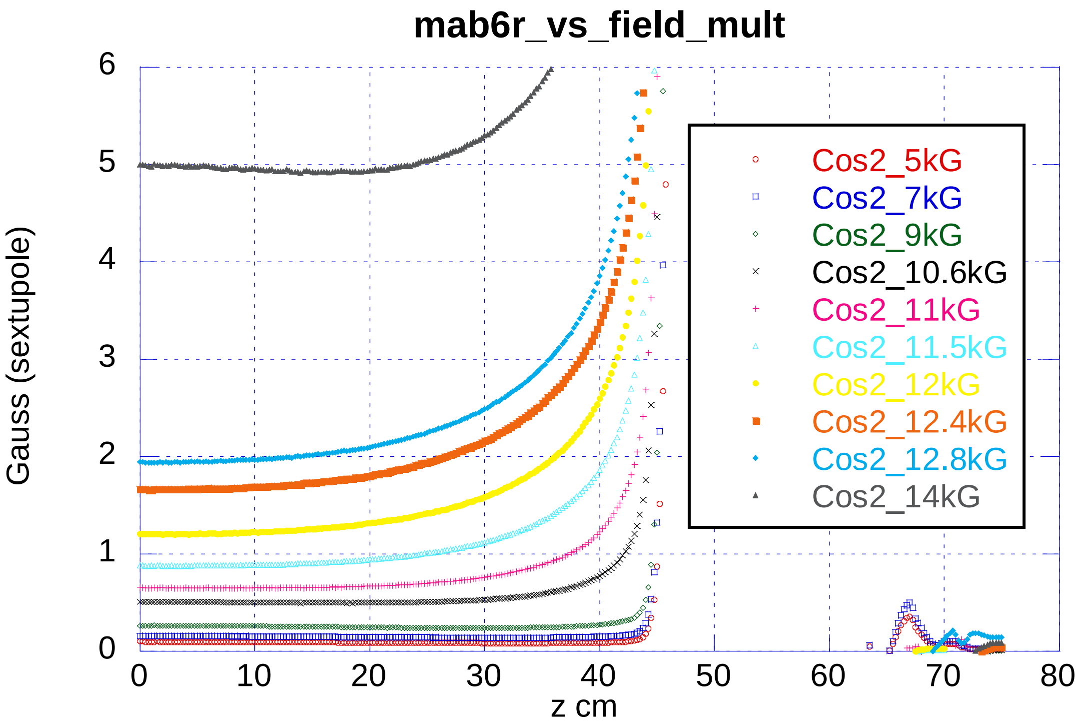


Figure 14. Compare with figures 6 and 7. Sagitta 0.785cm versus 1.17cm there.

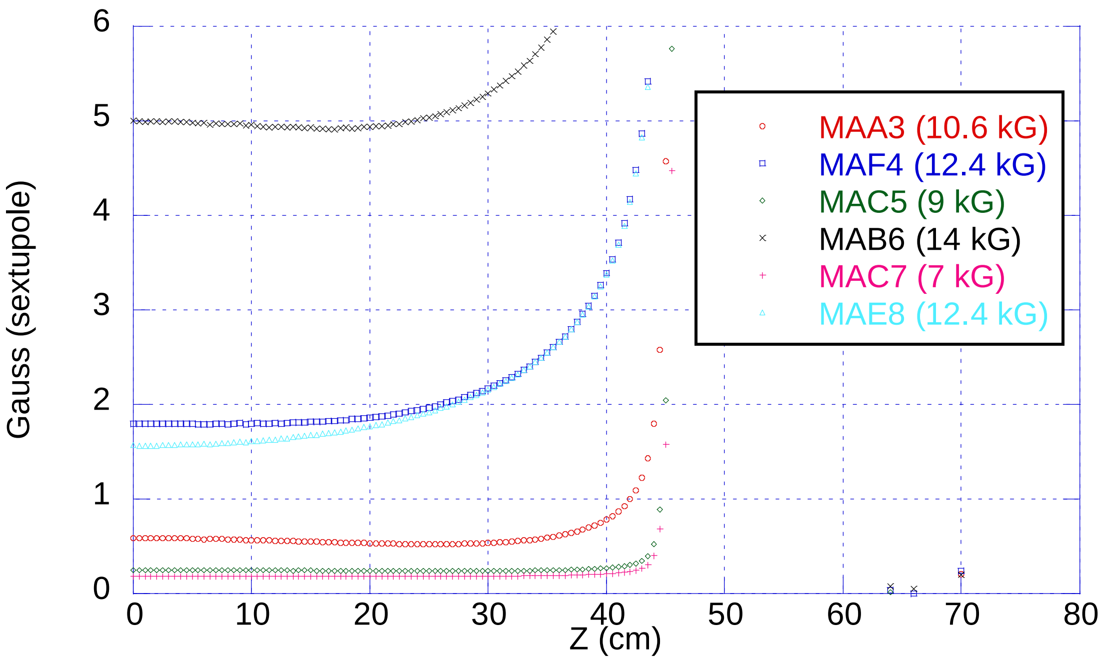


Figure 15. Body sextupole along the actual orbits for the indicated magnets. Compare with figures 6, 7 and 14. The difference in sagittas for MAE/MAF is 5mm (see table on page 2)

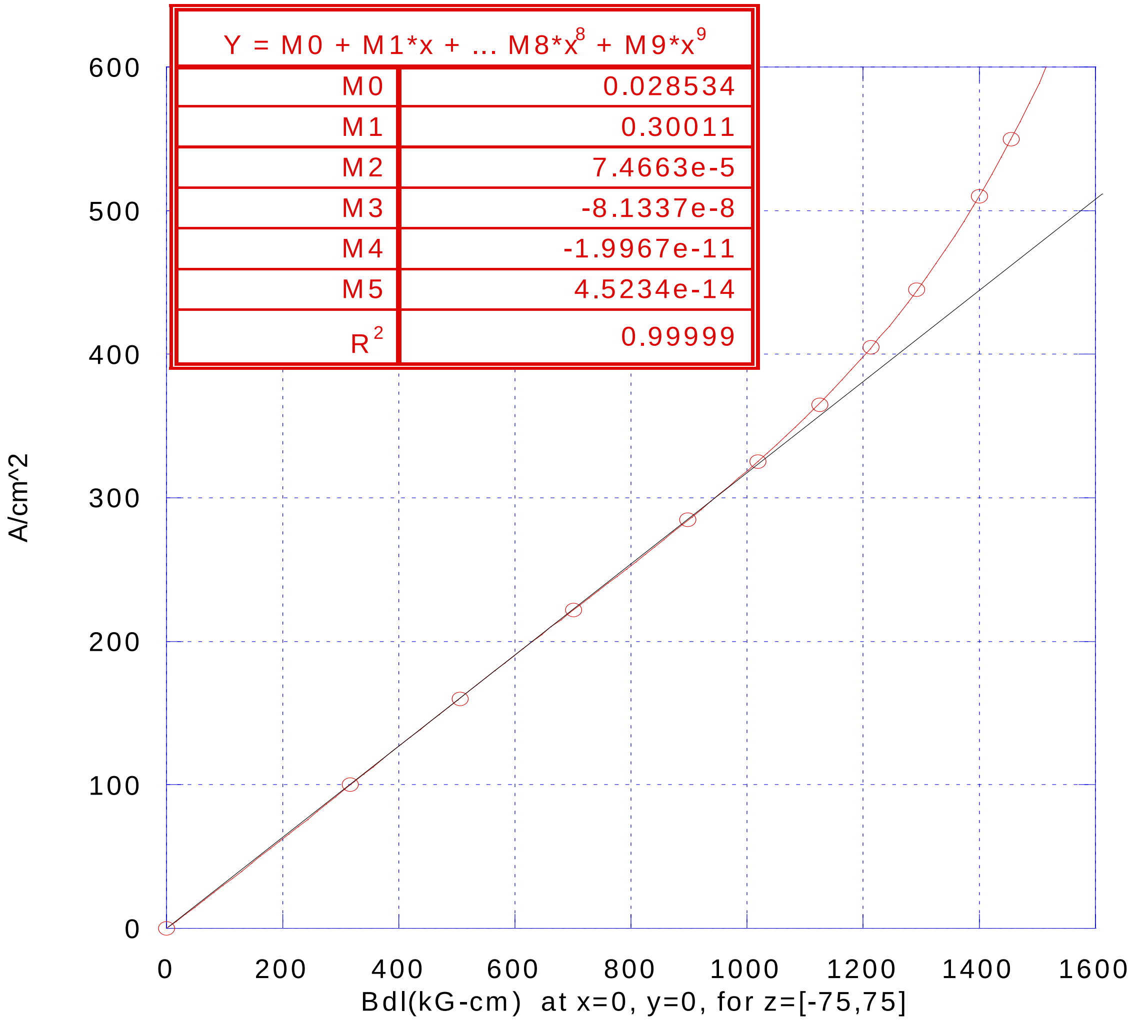


Figure 16. J(A/cm^2) vs. BdL plot for new one meter dipole models with air meshed at 5mm out to z=70cm instead of ~60cm as shown in table on page 2. The steel is the same as in the earlier models - only the air mesh at the end of the steel is changed. The straight line was laid in by hand. The linear fit to the first six points is J=0.31783*BdL. The fifth order polynomial fit reproduces the J values used in the models within +-1 A/cm^2 . Fit fractional departure is maximum for the 160 (A/cm^2) point, 0.34% . This magnet has a steel length of 96cm and an Optim/DIMAD/elegant length of 100cm. Divergence from the straight line begins after 10 kG and is significant by 12 kG. Magnet center is (0,0,0). The coil pack modeled is 4.655cm x 7.05cm = 32.81775cm^2. Convert to amps or amp-turns as you wish.

(Similar plots and polynomial fits were used to calculate current needed as a function of energy at 5% intervals from 50-100% for many of the dipoles in the 12 GeV baseline. The resulting spreadsheet was transmitted to Mechanical Engineering for review March 25, 2008. The magnets at/above 12.4kG exceed 20A shunt capacity.)

As figure 16 indicates, I have solved new models with larger background and 5mm mesh out to Z=70cm for 3, 5, 7, 9, 10, 11, 12, 13, 14 and 14.6 kG fields. Below I plot quadrupole term along the MAA orbit for six of these new models.

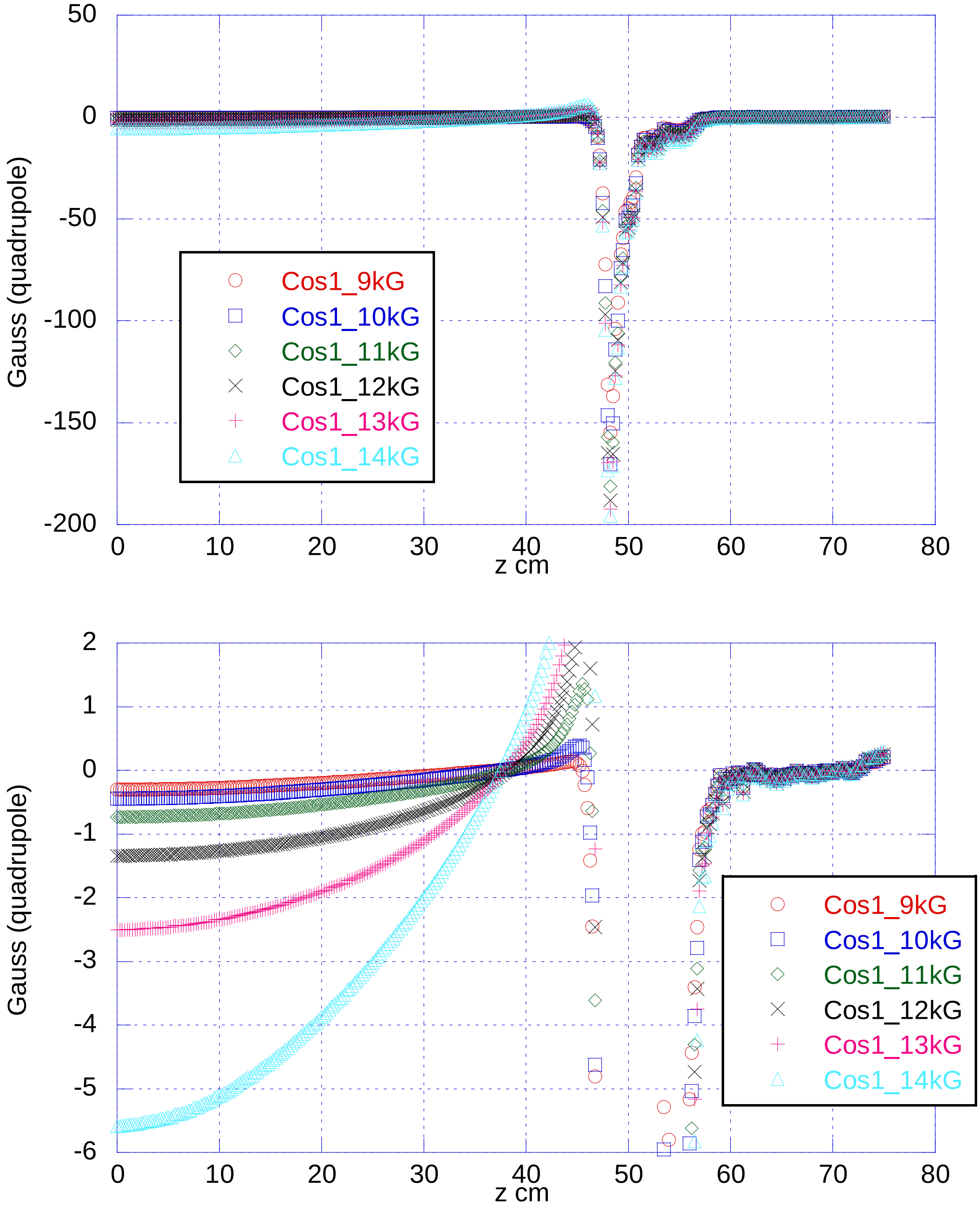


Figure 17. Quadrupole term for model with better end mesh at two vertical scales. The variations from 50-58cm in the upper plot are due to the coils.

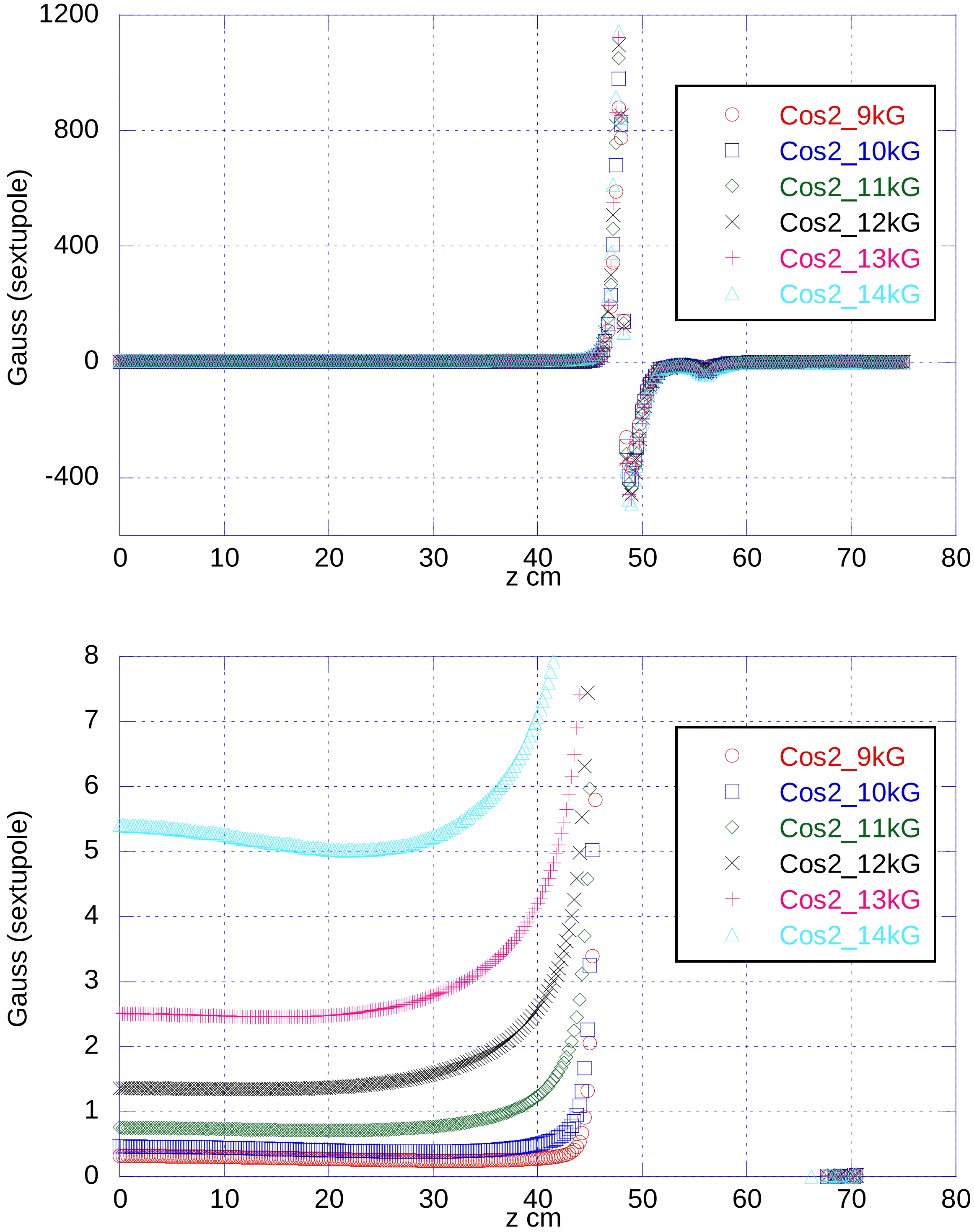


Figure 18. Sextupole term for the new models on two vertical scales. Again one sees the effect of the coils in the upper plot.

	dipole	quadrupole	sextupole	octupole	decapole	12-pole	14-pole	16-pole	18-pole	icosapole
9kG(body)	-812165	-12.99	27.46	-4.61	5.19	-1.27	0.89	-0.17	0.07	-0.01
9kG(total)	-900015	-659.91	227.01	49.23	1.32	10.68	38.48	21.27	24.49	10.31
10kG(body)	-921770	-19.69	43.66	-5.75	6.71	-1.56	1.09	-0.21	0.07	-0.02
10kG(total)	-1021041	-733.82	283.64	57.14	5.19	11.11	42.19	24.31	27.82	11.02
11kG(body)	-1019168	-33.43	85.51	-7.98	9.59	-2.03	1.36	-0.24	0.07	0.00
11kG(total)	-1128066	-793.26	369.95	62.93	10.10	10.47	45.08	27.24	30.59	11.72
12kG(body)	-1100981	-63.32	164.85	-13.53	14.59	-2.65	1.64	-0.26	0.04	0.00
12kG(total)	-1217526	-853.50	489.31	63.70	16.57	10.59	47.62	28.27	32.19	13.00
13kG(body)	-1172618	-116.85	281.93	-23.60	21.82	-2.98	1.73	-0.25	-0.04	-0.01
13kG(total)	-1295665	-927.68	645.16	59.30	25.08	11.05	49.66	28.98	33.62	14.17
14kG(body)	-1271859	-249.33	531.27	-41.11	33.08	-2.19	1.74	-0.50	-0.16	0.01
14kG(total)	-1403649	-1076.16	957.60	49.80	38.40	12.62	52.12	29.42	35.59	15.76

Summary of multipoles from new models, MAA orbit. I define body as the inner 90cm of the 96cm steel region. Total is the full 150cm of the orbits I used. All are in "G-cm" in that my calculation interval is 2.5mm and I divided the sums of the columns in my spreadsheet by 4 to get cm and then multiplied by 2 to account for both Z halves of the magnet. The "kG" labels in the first column are rounded from the total dipole BdL/100. *Note that this numerical integration is* ***wrong*** *in that it does not include the effect of the curvilinear coordinate system. For a rectangular dipole (horizontal bend) the horizontal focusing of the ends and body should cancel due to geometric effects, leaving only vertical focusing. This doesn't occur here because I'm adding locally rectangular elements. This is shown clearly on the next page where the sector magnets (shimmed for normal incidence) shown zero integral rather than the* $1/r^2$ *focusing. Higher order multipoles which are due to finite pole size effects are not affected, only the quadurpole term.*

One sees that the summed quadrupole term is totally dominated by the ends below 13 kG. Ends dominate in sextupole, but not to the same extent. For decapole the body dominates. For octupole, 12-pole and 16-pole, there's modest cancellation between ends and body. For 14, 18 and 20 pole, the ends dominate at all fields.

The sextupole value for 14 kG is comparable to the value specified in TN07-018 for S/R dipoles in arc 6. For the MAB6R orbit, the value is 843G while the spec is 871G. The 12kG sextupole value, extrapolated linearly to the BdL for MAE8, is well above the TN specification. All the models assume perfect manufacturing. The reader will make his/her own judgment as to the prudent engineering fudge factor to introduce to account for manufacturing tolerances. Given shunt capacity and the data above, I'd put the field limit under 12 kG.

Since the sextupole value for 12.2 kG (~MAE8) is above specification I ran a case with the proper MAE orbit and dipole field. I also ran a case in which I shimmed the dipole so the beam enters at normal incidence. BdL is higher since I kept J the same. The shim is 2.14mm tapering to 0 across the 10.16cm width of the pole, 3cm high. *Quadrupole is reduced almost to zero due to the way I'm doing the sum.* Sextupole and octupole are reduced, sextupole by about 10%. Decapole increased a bit but is still well below spec. *The weak focusing of a sector dipole is not reflected in the quadrupole value shown for the shimmed cases.*

Since these results were quite interesting I solved the shimmed model at three lower current densities. I solved a new basic model as close to 12 kG as I could judge. I ran the post-processor script for MAE orbit on three lower current density basic models for comparison with the shimmed models. The sextupole specs given in parentheses on these table lines assume use in arc 8 spreader, i.e. are also 310ppm of the dipole field.

model	dipole kG-cm	quadrupole G(1cm)	sextupole G(1cm)	octupole G(1cm)	decapole G(1cm)
specification (baseline optics)	1241.30		**383** (310ppm of dipole)		236
basic model, 12.4 kG	1241.95	-384	**503**	53	43
12.4 kG, shimmed for normal incidence beam	1243.19	-14	**468**	27	52
12 kG basic model	1202.76	-370	**441** (spec 372)	53	39
12 kG, shimmed for normal incidence beam	1204.06	-6	**406**	28	48
11.3 kG basic model	1128.0	-348	**350** (spec 349)	51	34
11.3 kG, shimmed for normal incidence beam	1129.44	4	**317**	27	41
10.2 kG basic model	1020.98	-321	**268** (spec 316)	46	27
10.2 kG shimmed for normal incidence beam	1022.61	8	**238**	25	34

These results suggest that the 12 kG upper bound previously suggested is too high, even with shimming. 11.5 kG, with shimming?

There exists a CASA spreader/recombiner design which can be made to meet ME requirements, keeps shunt currents at or below 20A through the 50-100% energy range for all but three magnets, and has fields at or below 12 kG in all but two common dipole magnet types. Whether the orbit and field change together suffice to keep within specification has not yet been evaluated.

I looked at the question of normal versus angle incidence, sector versus rectangular magnets, in another fashion. I took my reflected model at 12.4 kG and ran 1 cm radius circles down the middle of the magnet from 10cm outside the steel to 10cm inside the steel. I did this with the circles inclined at 5 degrees to the line, as if they were entering a rectangular magnet, and perpendicular to the line, as if they were entering a sector magnet. I chose 5 degrees because this is typical of the entry angle for the banana magnets. These are being replaced and the 12 GeV project is discussing end configuration. The table below shows the results:

magnet	quadrupole	skew quadrupole	sextupole	skew sextupole	octupole	skew octupole	decapole	skew decapole
rectangular	-1079	11	167	-4	-7	0	4	3
sector	6	14	171	-6	-11	-2	3	2

There is again a large gain in quadrupole from the end without much detriment for other harmonics, normal and skew. These values are in Gauss at 1 cm radius and cover only the 20cm. They are not doubled to cover both ends.

Shimming is a dilemma for accelerator magnets due to available measurement techniques. CEBAF used a single rotating wire to measure multipoles in quadrupoles. For dipoles it has recently used a Hall probe on a carriage which moves along the beam path to measure bending field. High energy physics labs use assemblies of rotating coils, typically quadrupole and sextupole and a rotating wire, to measure multipoles. The assembly, called a mole in the superconducting magnet game, is straight. The sagitta of the beam in these magnets is of order a mm so straight versus curved doesn't matter. For our magnets it does.

One can imagine an array of Hall probes on a circle or two adjacent circles, perhaps ten on each circle and the two circles offset by 18 degrees. An NMR probe should be added to the assembly to calibrate the Hall probes with respect to each other in the body of the magnet where the field is uniform. The gradients at the end are too high for an NMR probe to lock. Temperature compensation is required for the Hall probes. The one known vendor of quiet, ion-implanted, integrated-amplifier Hall sensors was purchased a couple of years ago and no longer makes them. The ones available now are much noisier. Still, one can conceive of such an array providing data on multipoles through decapole, normal and skew, as it is moved along the curved beam path. This would allow one to shim the ends for normal beam incidence and still measure the magnet properly.

On the other hand, if one is measuring with straight rotating coils normal to a rectangular magnet entrance, the table above suggests one will get acceptable accuracy for everything except the normal quadrupole. A straight rotating coil parallel to the long axis of a sector magnet will give bad normal quadrupole too. With CNC machines one can think about fabricating the linear superposition of a shim calculated to handle other orders and the simple wedge needed to null normal quadrupole. Whether the project can afford the time involved is a matter beyond the scope of this note, as are the implications for commissioning and operations if such measurements aren't made.

Comment incidental to this work: Accuracy of skew terms at the ends of magnets is enhanced with smaller mesh where the field has high gradient, within 3cm of the end of the steel. It is also much enhanced by switching to the "integration" mode of calculation ~2cm inside the steel and using that for the rest of the chosen path outside the steel. (personal communication, N. Ruiz) Accuracy of normal terms is fine with 5mm mesh as discussed above. Where the steel exists, the 2.5mm mesh in the steel governs and steel itself keeps gradients down except close to the end of the pole. Outside the steel the mesh on the coils governs field irregularities and they are non-physically oscillatory in the skew terms. Meshing the coil volumes at 2.5mm outside the steel appears to suffice, based on examination of nine models. Outside the steel the integration method of field evaluation may be quieter than the nodal method, as skew terms are smaller and much less noisy with the former as expected physically, but the hundred-fold time penalty remains an issue.

Conclusions

1. If one wants to keep sextupole below the emittance blowup specification of TN-07-018, these calculations indicate one must keep the field under 11.3 kG. This limit also allows 20A shunts in the 50-100% energy range with judicious turn count choice, except for the common dipoles. How close to 11.3 kG to design given manufacturing tolerances in real magnets is a good topic for discussion. Close to may be from above. There exists a S/R design which keeps fields below 12 kG, limits shunt currents on these 1m dipoles to 20A, and may meet multipole specification given the orbit differences. It will not be evaluated since the 12 GeV project has chosen another path.
2. Focusing term from dipoles must be taken into account in setting the lattice quadrupoles for all dipole fields. It is necessary even at the low fields in 6 GeV CEBAF.
3. Accurate evaluation of skew multipoles due to end effects and saturation requires meshing air at 2.5mm in high gradient regions and 5mm thereafter, to at least 22cm beyond the steel. For normal multipoles, 5mm mesh outside the steel suffices. The models shown through figure 15 are among my earliest, created before the studies documented in TN-08-022.

Acknowledgments

Emails and conversations with Mike Tiefenback, Yves Roblin and Nicolas Ruiz improved this work significantly.

Appendix - comments from Leigh Harwood for 12 GeV Project team received 11/13/08

- Need to include in the abstract that the analysis pertains to preliminary designs from March 2008 that are no longer part of the Project plan
- First two comments above about “SR bucking coils” also apply to this document even though some of the later tables do use the integral values.
- The report includes results from cases that vary both the excitation and the trajectory (sagitta), although the graphs and tables use only the energy to identify a case. This makes it rather confusing for drawing conclusions.
- A description of how the multipoles are calculated is needed.
- Comments at bottom of pg 10 about shunts being outside 20A shunt range pertain to a different set of magnets than are presently in the 12 GeV plan. The comments need to be removed or at least qualified with “for the geometries evaluated in this report” to avoid confusion.
- The comment at the bottom of pg 14 needs to be more specific about the shimming used in the analysis, i.e. that it was linear/flat shimming. Or, again, a “for the shapes evaluated in this report” qualifier needs to be added.
- Skew multipoles are mentioned at several points in the document. All the models had median-plane symmetry of the iron and copper. If that was indeed the case, then Maxwell’s equations preclude all non-median-plane symmetric (skew) components in the field. Thus any skew term derived from the model is purely a numerical artifact. So, the inclusion of them in any of the discussion is inappropriate, other than to comment on the noise level of the calculations.
- There seems to be some kind of English problem with the last sentence on pg 14. Would like to re-read it after the author checks the text for typos.
- For the last paragraph on pg 15, it needs to describe how information in the table leads to the stated conclusion.
- Pg 16 conclusion 1:
  - The first sentence needs to have the phrase “for the geometries evaluated here” added to it.
  - There seems to be an English problem with the sentence that starts with “Close to....”
- Pg 16 conclusion 2: The quadrupole term mentioned is the source of the edge focusing in dipoles and is accounted for automatically by the codes. The accuracy is improved when a realistic field roll-off is used in the optics codes. (For the original DIMAD-based optics analysis for CEBAF, Dave and Leigh agreed what values to use for the roll-off equation.)
- Pg 16 conclusion 3: See earlier comment about skew terms only providing information on the noise level of calculations.