A Panofsky quad with corrector coils

Jay Benesch

Abstract

Bob Legg modeled the addition of correction coils to Panofsky quads before the first solenoid in the new FEL layout with Poisson, a 2D FEM program. These models suggested that the stray field of the dipole component would extend to the cathode. A 3D Opera model of a Panofsky quad with corrector windings has been developed. This has a square aperture of 12cm, sufficient to pass a 4.625" vacuum flange. The 3D model confirms the large extent of the stray dipole field, still 1.7% of peak at 30cm from the magnet center. The magnet aperture could be reduced by 20%, to 9.6 cm, if assembled over the beam pipe or bellows before the flanges are welded on, lowering stray field extent. The use of a magnetic material boundary 7.35-7.5 cm from the magnet centerline is being solved as this is being written. This might require moving the solenoid out 5cm in Z.

Subsequent to the initial work there were a total of four more iterations. Bore was set at 2.5" for all of these. Lengths were 10cm, 8cm and 4cm, with round and square holes for the last two. Results for all are discussed.

Background

The beam coming out of the FEL gun is not radially symmetric because the electrons cannot be sourced from the center of the wafer as ion back-bombardment kills the quantum efficiency there. It is desirable to have a round spot on axis before the beam gets to the emittance compensation solenoid as the solenoid would otherwise mix x and y beam parameters, complicating enormously the downstream optics. The FEL group planned to use a pair of picture-frame correctors upstream of the solenoid to center the beam. These were described in meetings as Panofsky magnets. Fay Hannon and I independently realized that Panofsky quad windings (ref 1) could be added as in (ref 2) to adjust beam parameters as well as steer upstream of the solenoid. Bob Legg used Poisson to make 2D models of the magnets, figures 1 and 2 .

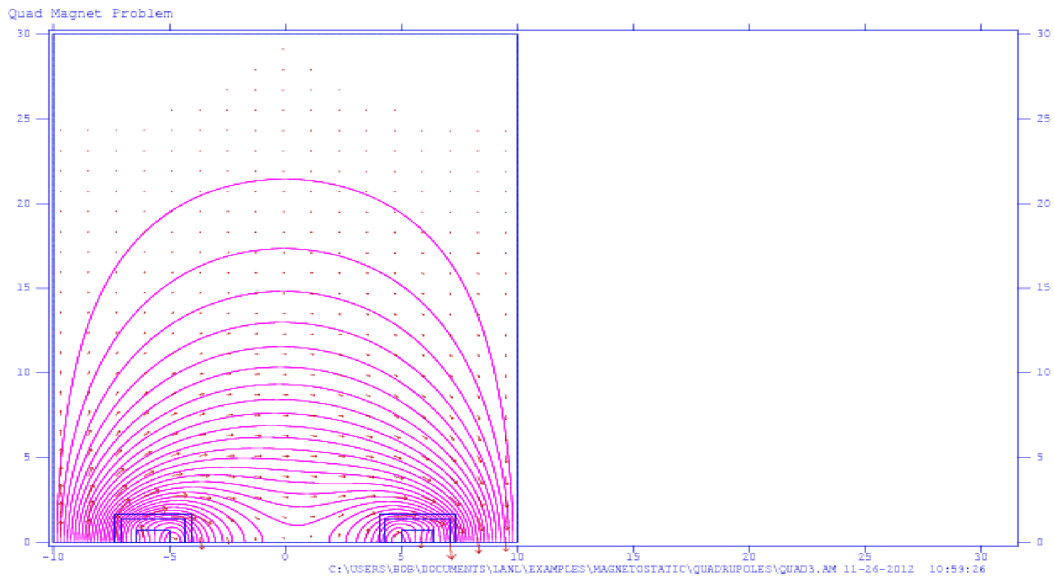


Figure 1. XZ? RZ? plot from Poisson

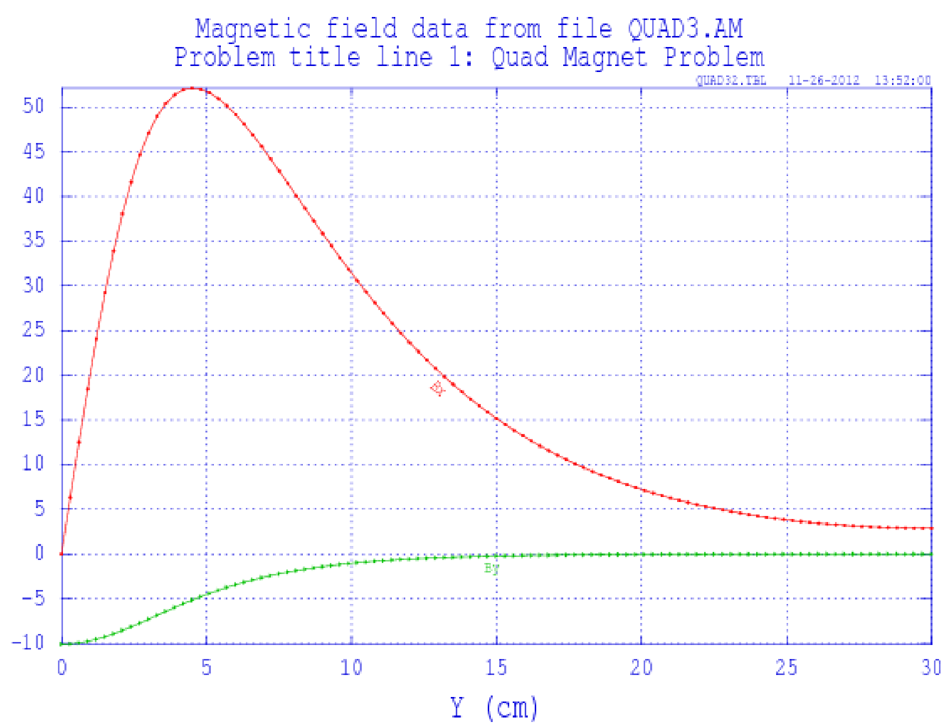


Figure 2. Magnitudes from Poisson.

The large, lingering stray field caused some consternation because the intent was to have the first of these magnets about 20cm from the cathode and the second only 15 cm (center to center) from the first. I was asked to create and solve a 3D model.

Conclusion: It's not as bad as the 2D suggests, but it's not good. Details follow.

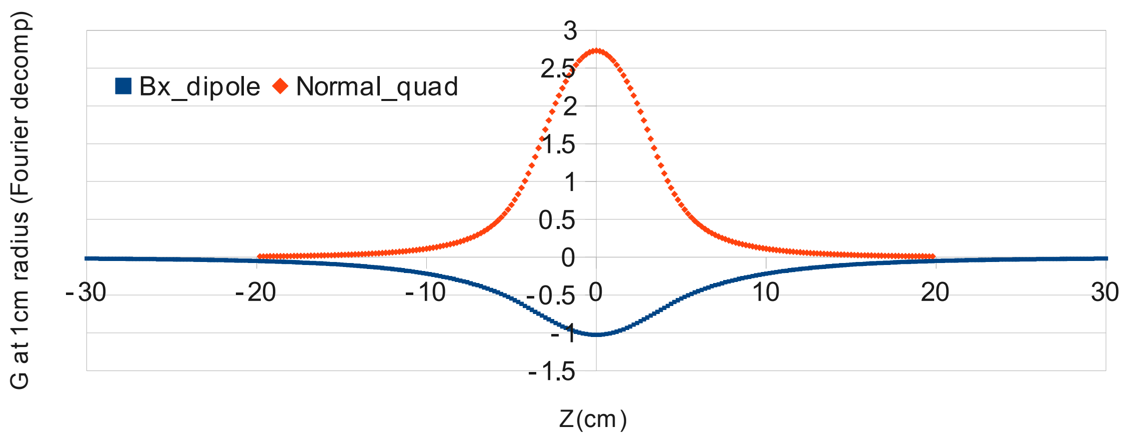


Figure 3. Fourier components of model in figure 4 with 460 AT in quad and 15 AT in dipole. 1 cm radius

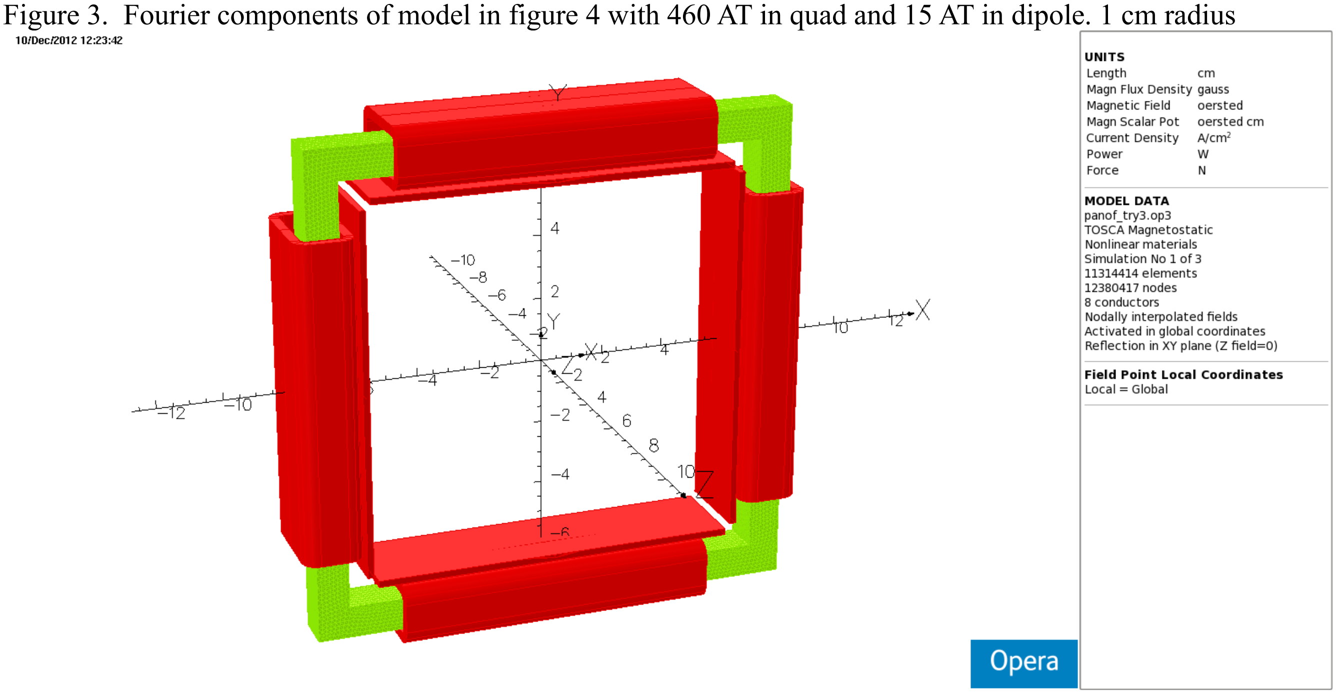


Figure 4. 3D model. The green core is 2.54 cm long; only the positive Z half is shown because I specified symmetry in solving the model. The full Z extent of the coils is shown due to an Opera peculiarity. The long coils wrapped around the core excite the dipole field. In this model only the top and bottom coils are energized providing a horizontal field which, when crossed with the beam, yields a vertical kick. Since they are wrapped around the core, only 15 AT are required in each to get the 1G peak field shown in figure 3. The red bars are the current sheets for the Panofsky quad. Since the quadrupole field is produced by the interaction of the current sheets with image currents in the core, much higher excitation is required: 460 AT per sheet to get the 2.7G peak shown in figure 3. I don't show the complicated corners needed to connect the right vertical bar with the bottom horizontal bar as a continuous winding, one of two needed.

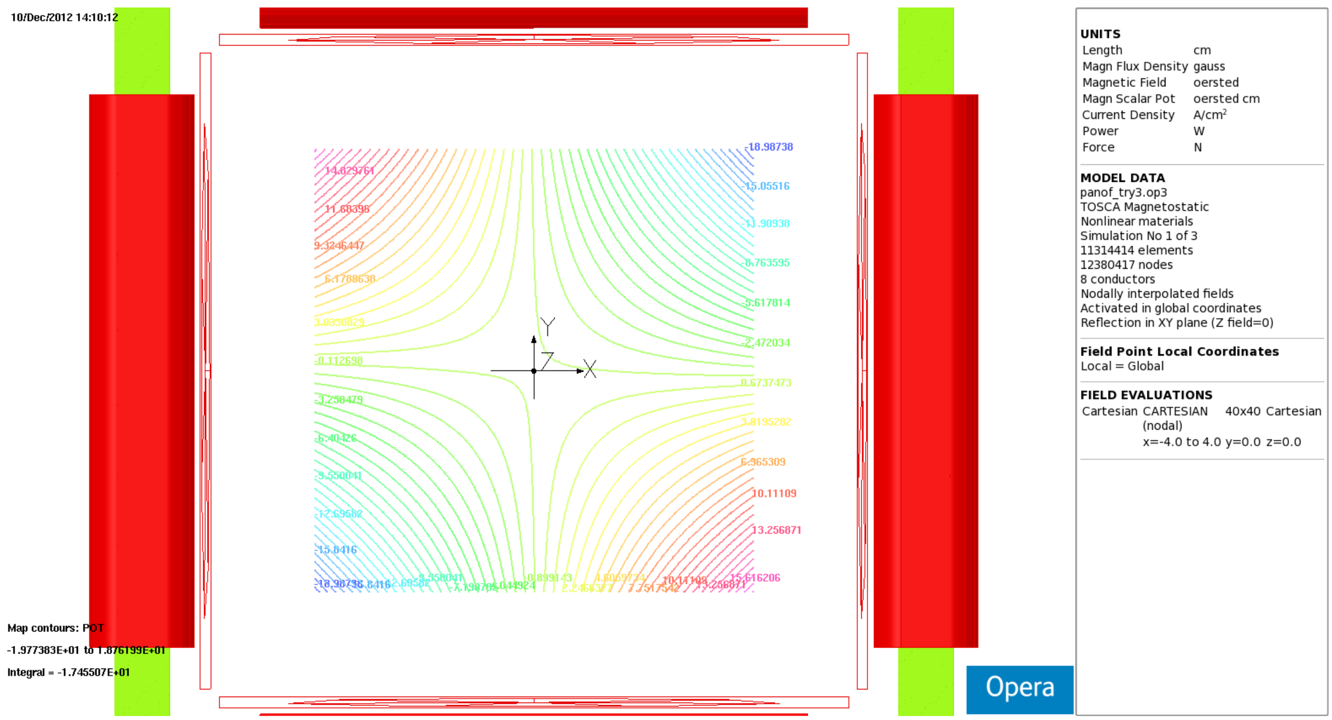


Figure 5. Potential lines with current bars energized, at Z=0.

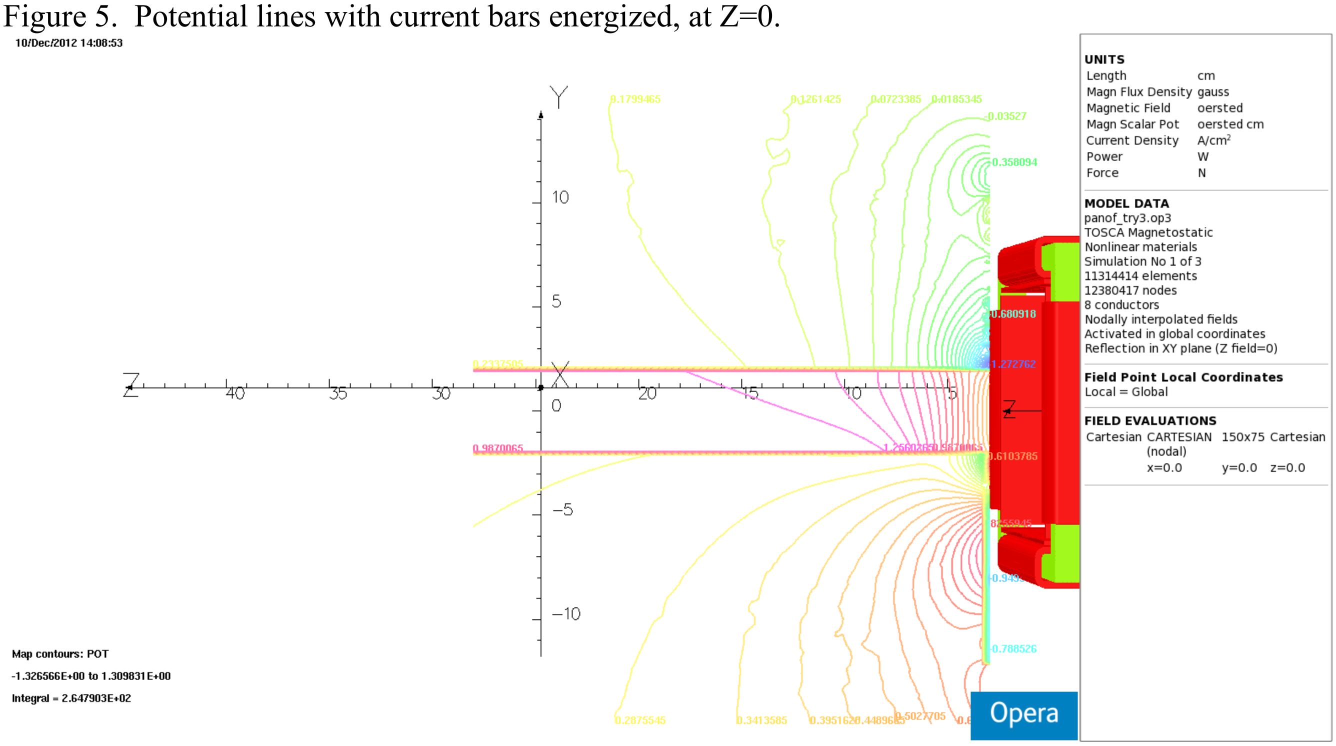


Figure 6. Potential in yz plane showing a discontinuity between a reduced potential region, 4cm square by 30 cm long, and the rest of the air. I am re-running the model with different potential definitions in an attempt to fix this. The values in figure 3 and in the spreadsheets I sent under separate cover were obtained using the “integration” field evaluation option which should reduce the impact of the discontinuity.

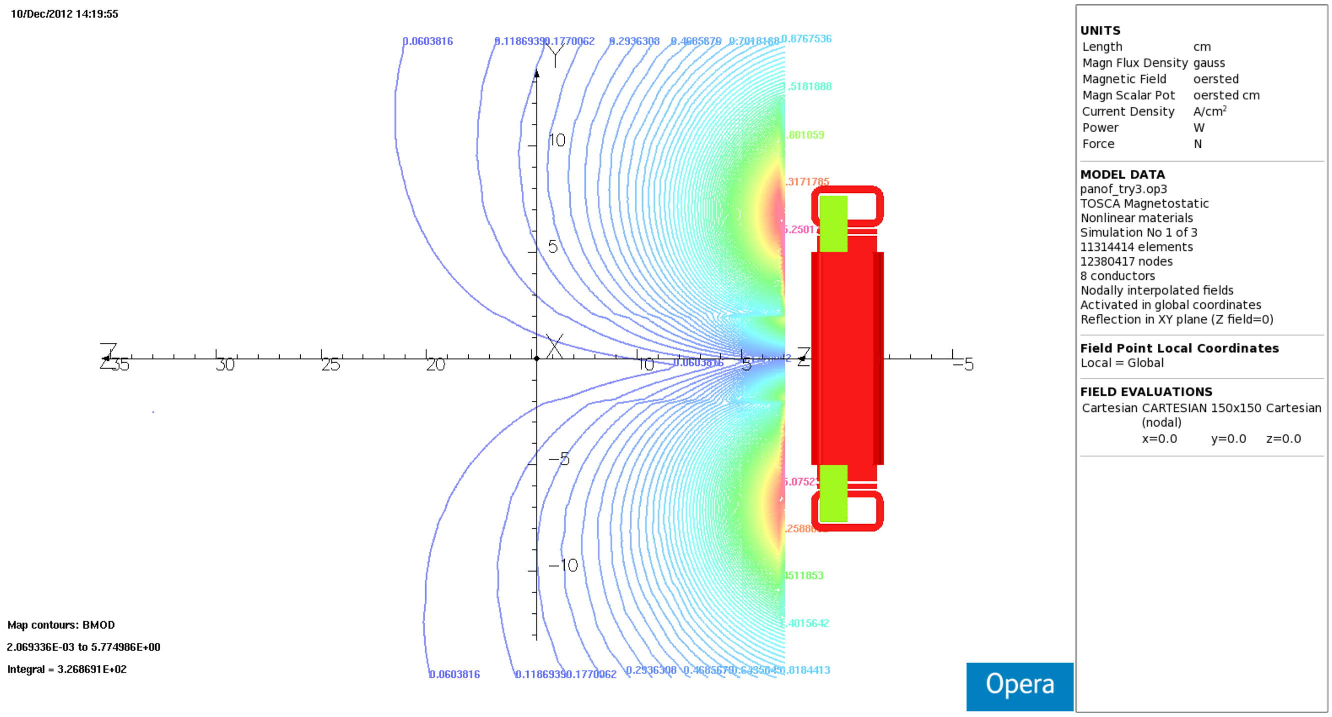


Figure 7. BMODulus in YZ plane at X=0. Discontinuity is still apparent but shape is OK. We'll see what try5 looks like late today.

In an attempt to reduce the stray field I added an annulus of the same magnetic material spanning z=[7.35,7.5] (aka 0.06”) with IR 4cm and OR 16 cm. Looking at the plots which follow, I probably should have used 7.62 cm ID and 20 cm OD for the magnetic barrier. SRF has dies to stamp out the latter from 3mm niobium so they ought to be able to make four out of magnetic material of half the thickness. That will be model try6 if anyone is interested.

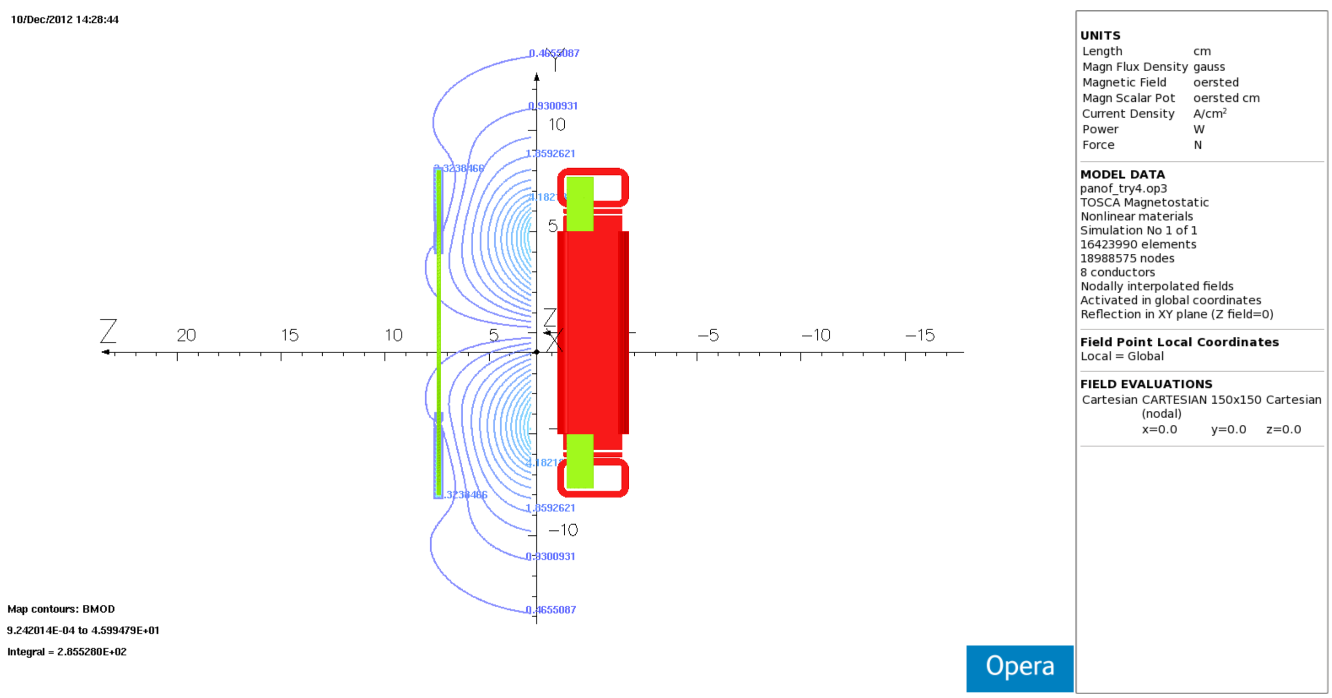


Figure 8. Same BMOD plot as figure 7. Most of the 100 field lines wrap around the magnetic material near z=7.4.

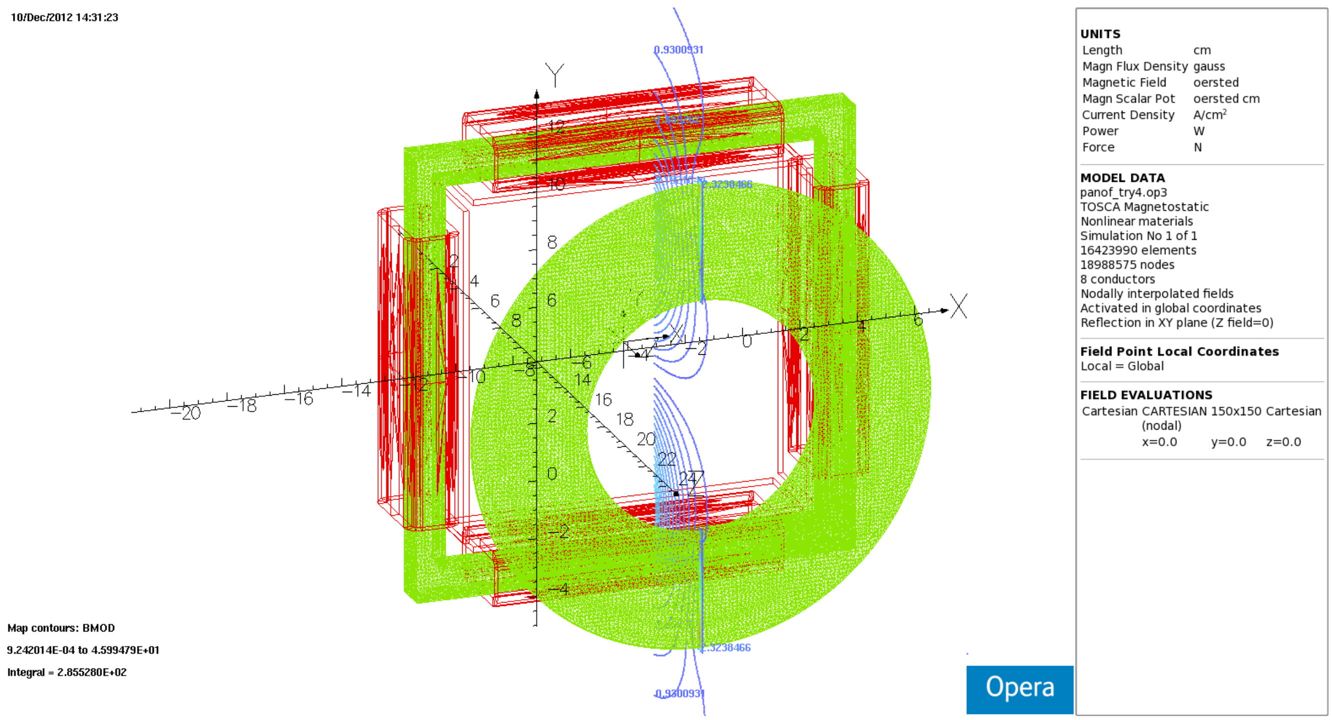


Figure 9. Perspective view of figure 8 with surfaces removed so only the mesh in the magnetic material and the coil outlines are seen.

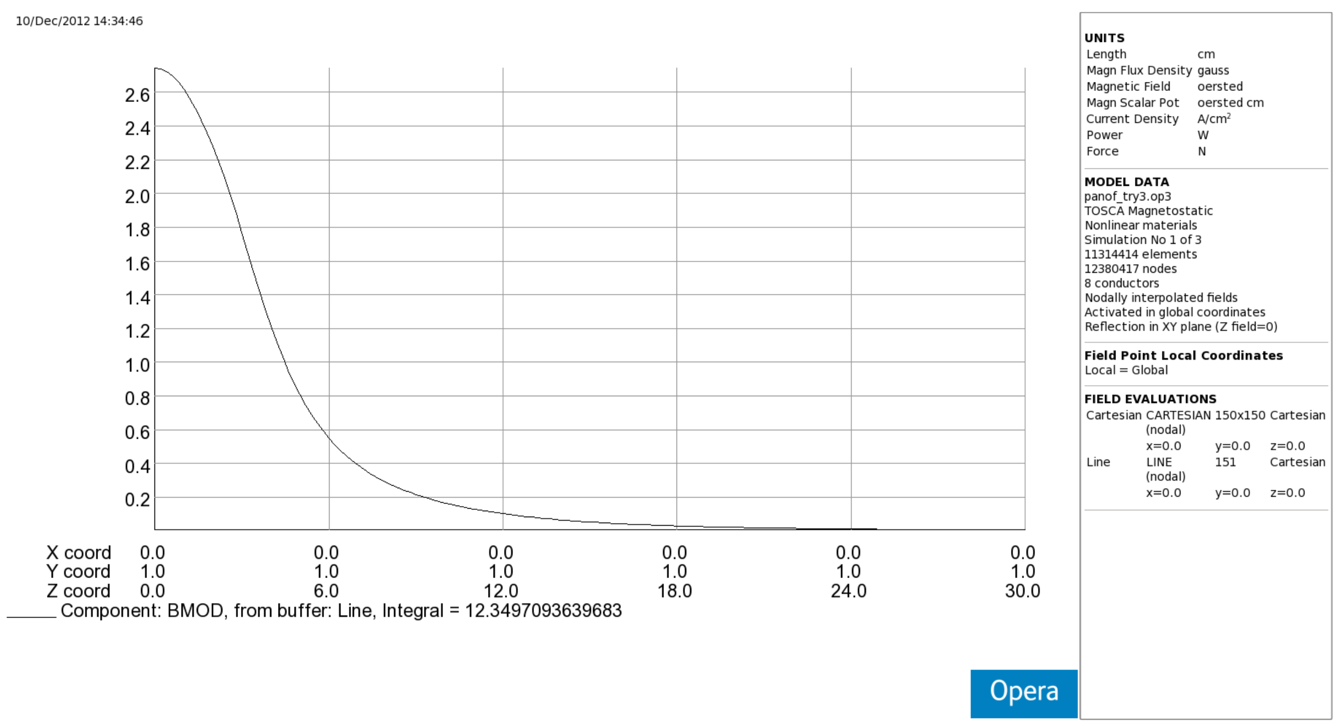


Figure 10. BMOD vs Z for model without annulus. Field is about 0.1G at 12cm.

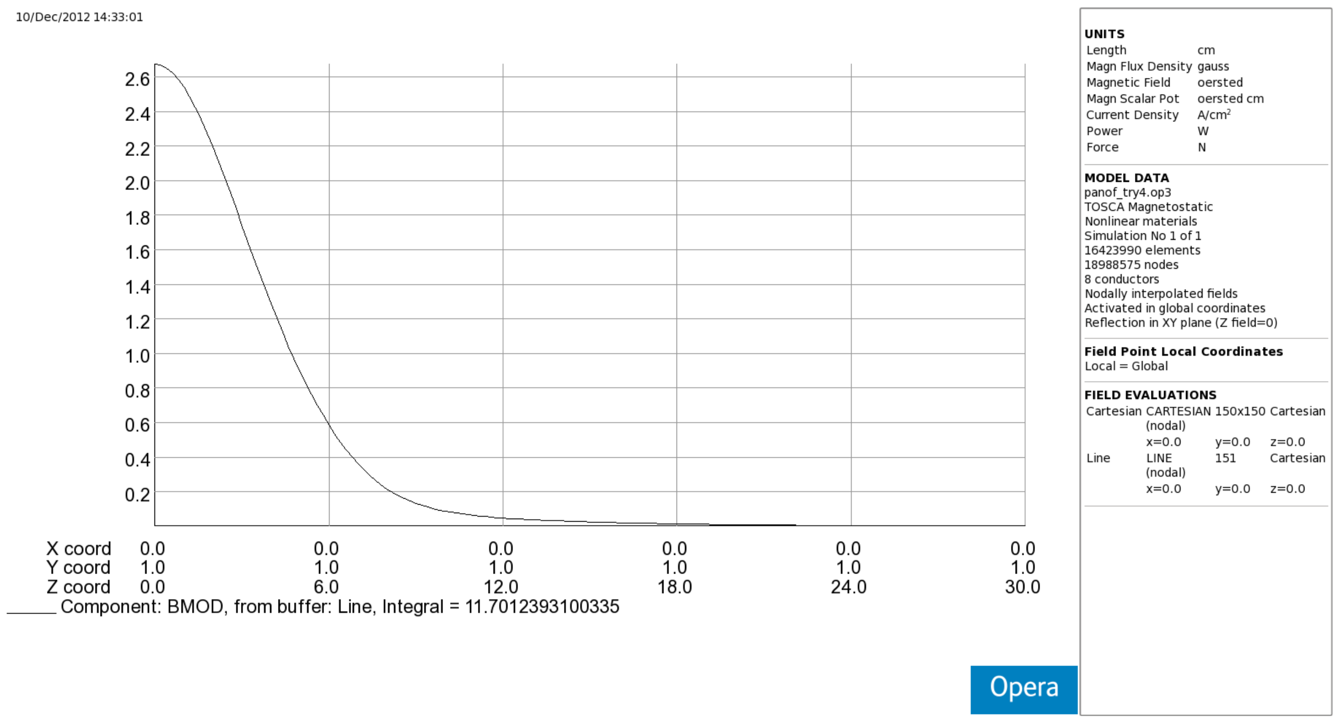


Figure 11. BMOD vs Z for model with annulus. Field at 12 cm about half of that above. Integral is 95% of that in figure 10.

Second iteration

It was decided at a meeting with FEL injector folks Dec. 11, 2012 that the stray field extent of this large aperture magnet was too great. I was asked to model a similar unit with aperture just over 2.5”, the beam pipe diameter. Approximately 22cm is available between the gun vacuum wall and the desired location of the compensation solenoid, starting 40cm from the cathode. The items to be placed in this region are:

- 2.3cm bolt insertion allowance which will also be used for a corrector set wound around mu-metal with beamline length 1.9 cm. One may have to use studs, not bolts.
- 1.3cm flange allowance.
- 8.6cm gate valve with blind tapped holes on both sides.
- 1.3cm flange allowance.
- 0.5cm bolt head allowance as the magnet described hereafter is to be assembled onto the pipe after the vacuum joint is made, flush against the bolts.
- 10 cm long multiple function picture frame magnet with field clamp
- Total 24cm, 2cm over the allowance. Since the solenoid was recently moved upstream 7.5cm in the optics model and the improvement wasn't spectacular, I assume this is acceptable. If not, the gate valve will have to move downstream of the solenoid.
- If the first corrector were a version of figure 4 with coils wound around a 1/2” rod and aperture sufficient to contain the flange, about a cm of beam pipe could be recovered. Stray field wouldn't be an issue at the cathode because it's transverse and in the desired direction. The stray field from the first corrector at the second could be bucked by the second as needed.

Setup concept as outlined by Dave Douglas:

1. turn off all the magnets upstream of the first viewer
2. use the first corrector to center the beam in the multiple function magnet by looking at how the

beam is steered via cycling of the quad in the latter.

3. Use the correctors in the multiple function unit to get the angle right in the solenoid by watching how the beam is steered when the solenoid is cycled.
4. Iterate as needed.

Shielded multiple function magnet

The core of the new model is formed of four sets of three 1/2” mu-metal rods with one or two sides flattened so their centers are 1cm apart. George Biallas suggested the mu-metal rods. I decided to flatten the sides so the flux wouldn't see abrupt restrictions. The assembly is 3.27cm long. The rod ends may be machined so the four pieces may be joined tongue-and-groove and bolted through the Z direction or may be mitered and bolted in the X direction. The model has one layer of 1mm conductor for the corrector (dipole) windings and four layers of 1mm for the quadrupole. The currents are low enough that only two layers are needed for the quad which means two can be used for the dipole as well. This is for elegance: coils are wound in spirals and therefore have one net “turn” in the direction of the length of the spiral as well as the circumferential turns that one actually wants. By winding two layers the two transfers along the length of the spirals cancel leaving only the effect of the circumferential turns. Field quality is better as a result. This is in the real world; the model doesn't have the leads or the subtle spirals.

The new model is shown in Figure 12. The full core and coils are shown. Only half the magnetic return is shown. The model is calculated with Z symmetry so only half is needed. The four corners of the cores were radiussed by trimming the overlap with a cylinder of 6.9cm inner radius. Chamfering would do as well but would have required more Boolean operations and I am lazy. The outer shell is assumed to be 1.5mm mu-metal wrapped on a 6” tube of non-magnetic material: stainless, G-10, acrylic, whatever. End plate the same.

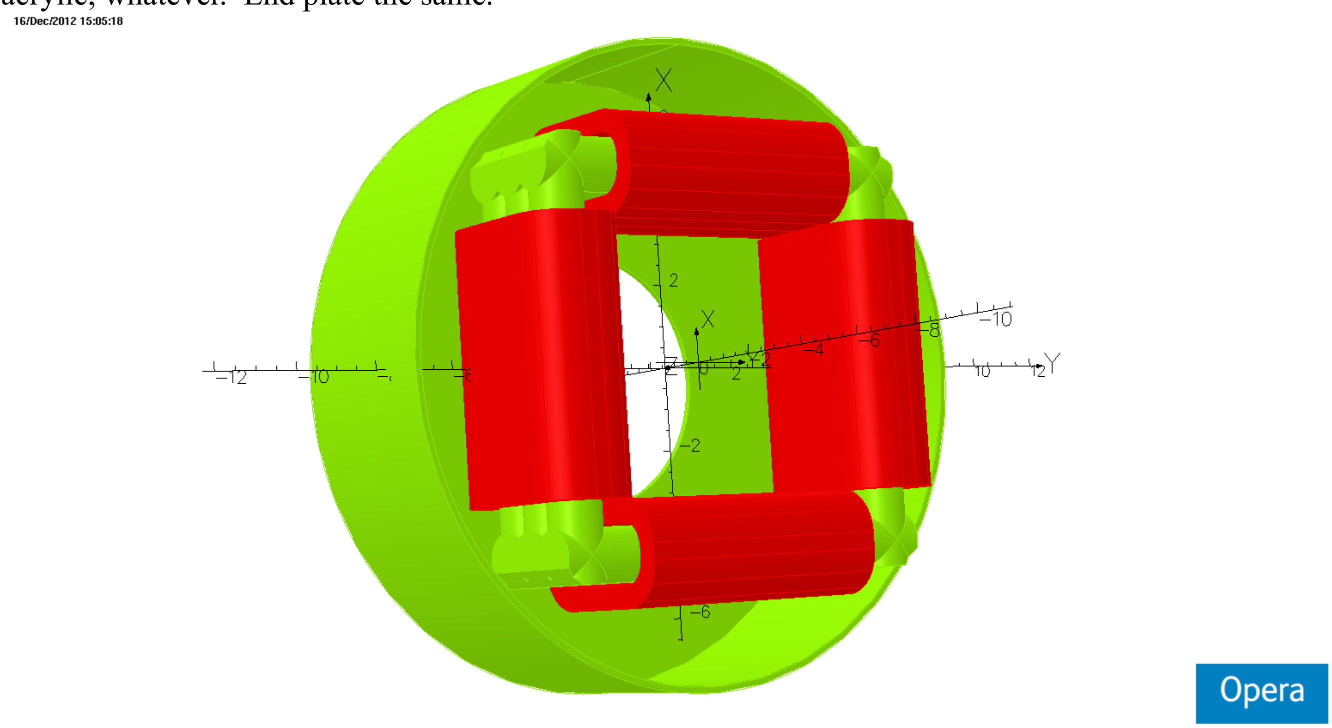


Figure 12. Inside of the smaller multiple-function magnet. Only Z+ half of the magnetic return aka field clamp is shown. 6.4 cm round clear bore in the model, mu-metal and coils.

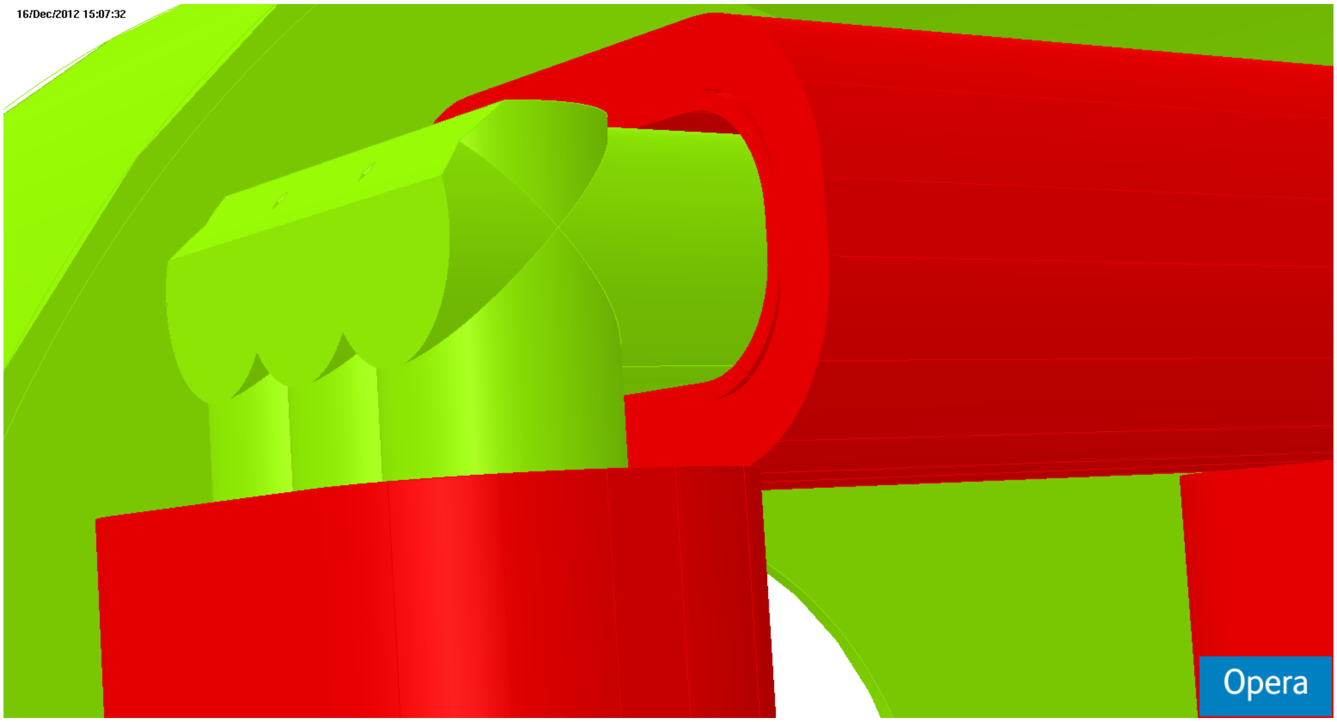
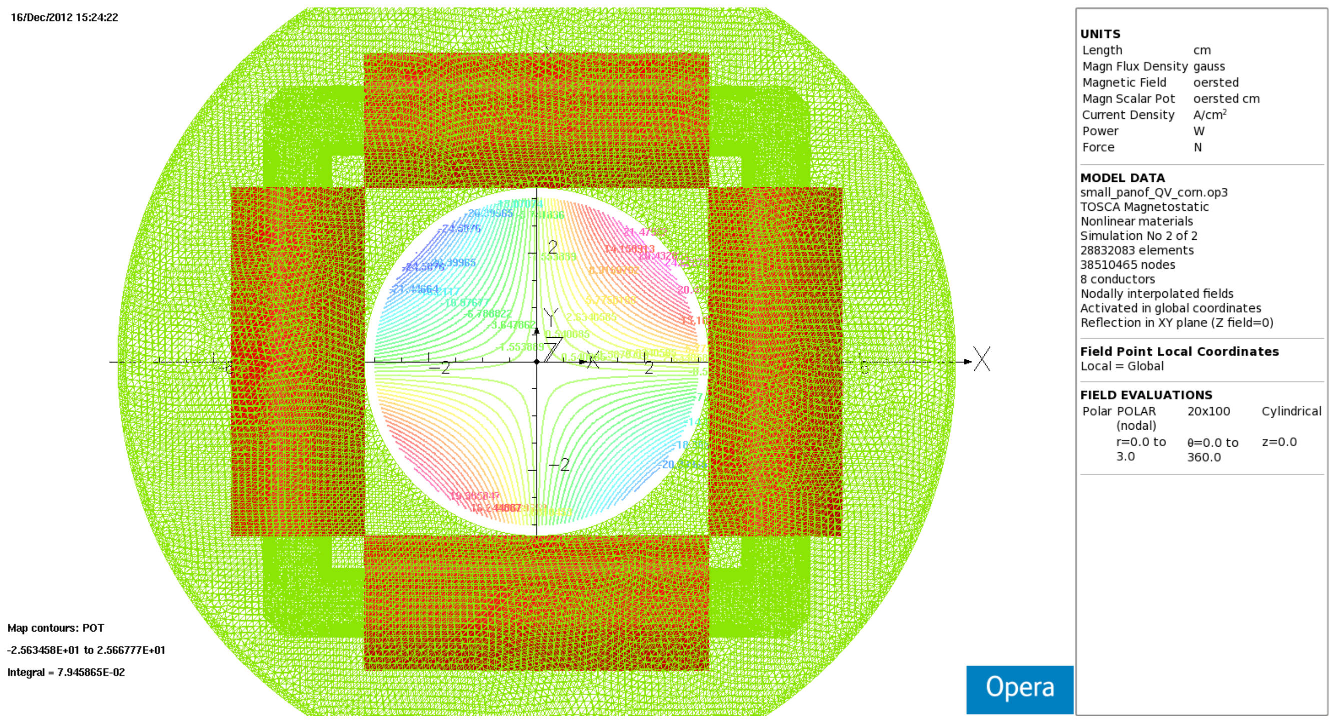


Figure 13. Close-up of the conductors. There's a 1mm air gap between the coil and inner conductor because Opera gets very unhappy if there isn't at least one voxel of air between coil and magnetic material. One can just see that there are two coils, dipole and quad, via shading in the top and middle center of the image. As mentioned on the bottom of the previous page, final configuration is likely to have two double layers with the inner one (dipole) wound directly on the core. This would put the inside edge of the coils at 3.4 cm radius versus 3.2 cm in the model, providing clearance at the corners of coil array.



Fiugre 14. Potential lines. The quadrupole pattern is not centered because both quad (35G integral) and dipole (7 G-cm integral) coils are excited. One sees the 1mm mesh used throughout the magnetic material and the air containing the coils too.

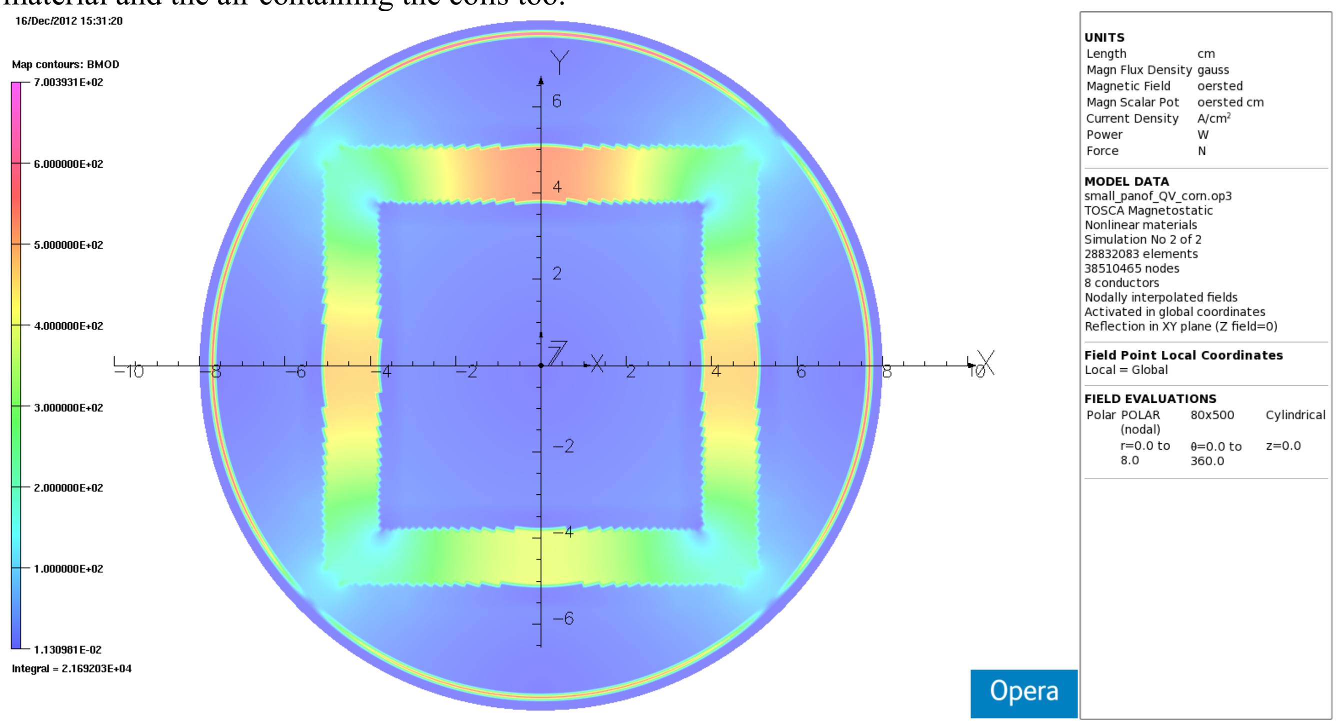


Figure 15. BMOD in the midplane. One sees peak field about 700G in the mu-metal shell and perhaps 500G in the core rods. It follows that one can get a lot more deflection and focusing out of this unit than the FEL gun requires. I over-design. Core is only 7.83mm wide at the flats on the 1/2" rods but peak flux is similar.

Multipoles were evaluated by having Opera Post Processor calculate Bx at 60 points on a 2cm radius circle at 2mm intervals over the span Z=[-30,30]. "Fit Fourier" was applied to the 60 values on each circle. The results were summed in Z, divided by 5 given 2mm interval, and then normalized by dividing by 2^n or 2^{n-1}, depending on the convention you prefer. Opera uses n=0 for dipole so 2^n was used in calculating the values below.

dipole (cos0)	-7.06 G-cm
quadrupole (sin1)	-36.6 G
sextupole (cos2)	0.04 (0.6% of dipole)
octupole (sin3)	-0.002 (5E-5 of quadrupole)
decapole (cos4)	-0.004 (0.06% of dipole)

Intended amplitudes were 7G-cm for dipole and 35 G for quadrupole, so current density in the quad should be reduced 4%. Not that this is relevant for evaluating the utility of the coil design. If someone is interested in the 12-pole and 20-pole terms, the allowed multipoles due to errors in a quadrupole, ask. With 2 mm mesh I can use 60 points on a 2cm radius circle and exceed the sampling theorem a little up to 20-pole. It's unlikely to be relevant in anything other than a light source storage ring, so I generally don't bother. Were it not for the fine features in the model the minimum mesh size would be 2.5mm and I'd have only 48 points on the circle – not so good for 20-pole but okay for 12-pole, aka n=5 in Opera-speak.

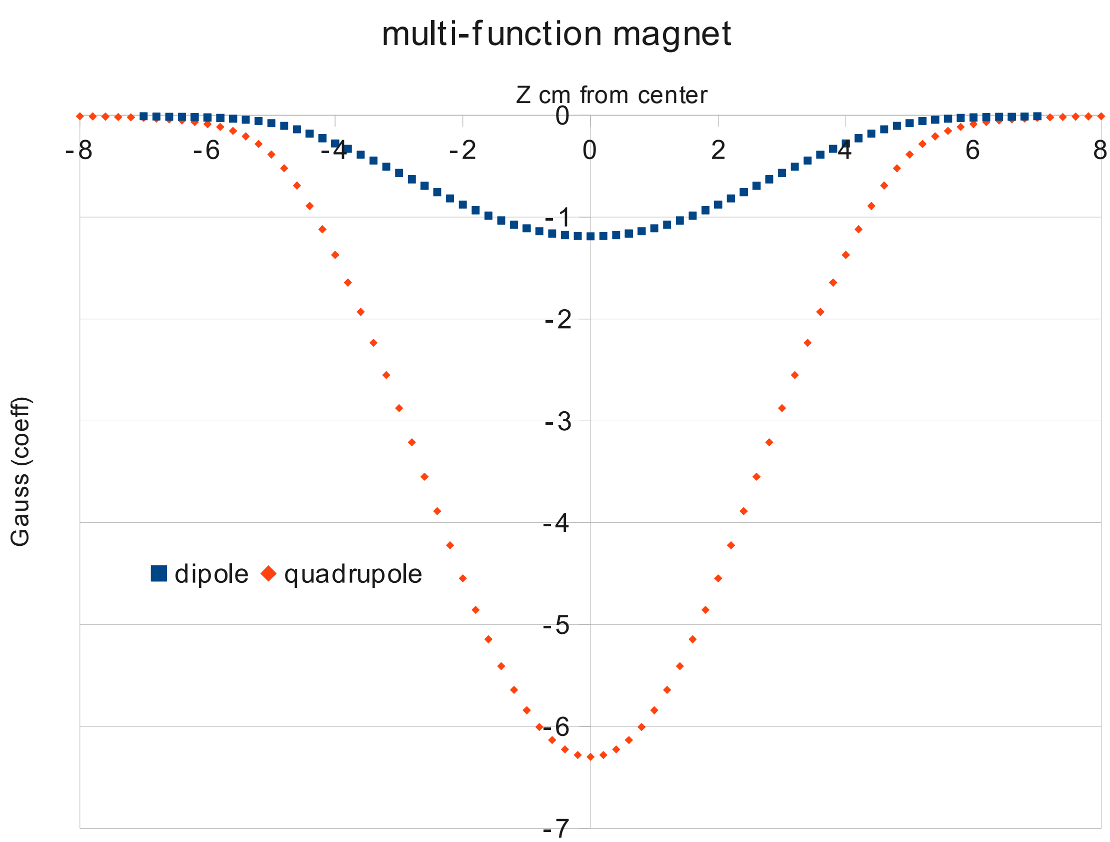


Figure 16. Multipole coefficients as a function of Z for the model. Integrals at top of page. Field clamp annular plate extends z=[4.85,5] cm and has a hole radius of 3.2 cm. Nothing to be seen on this scale at 1.6 cm beyond the plate. There would be if the dipole field were higher.

Unshielded corrector

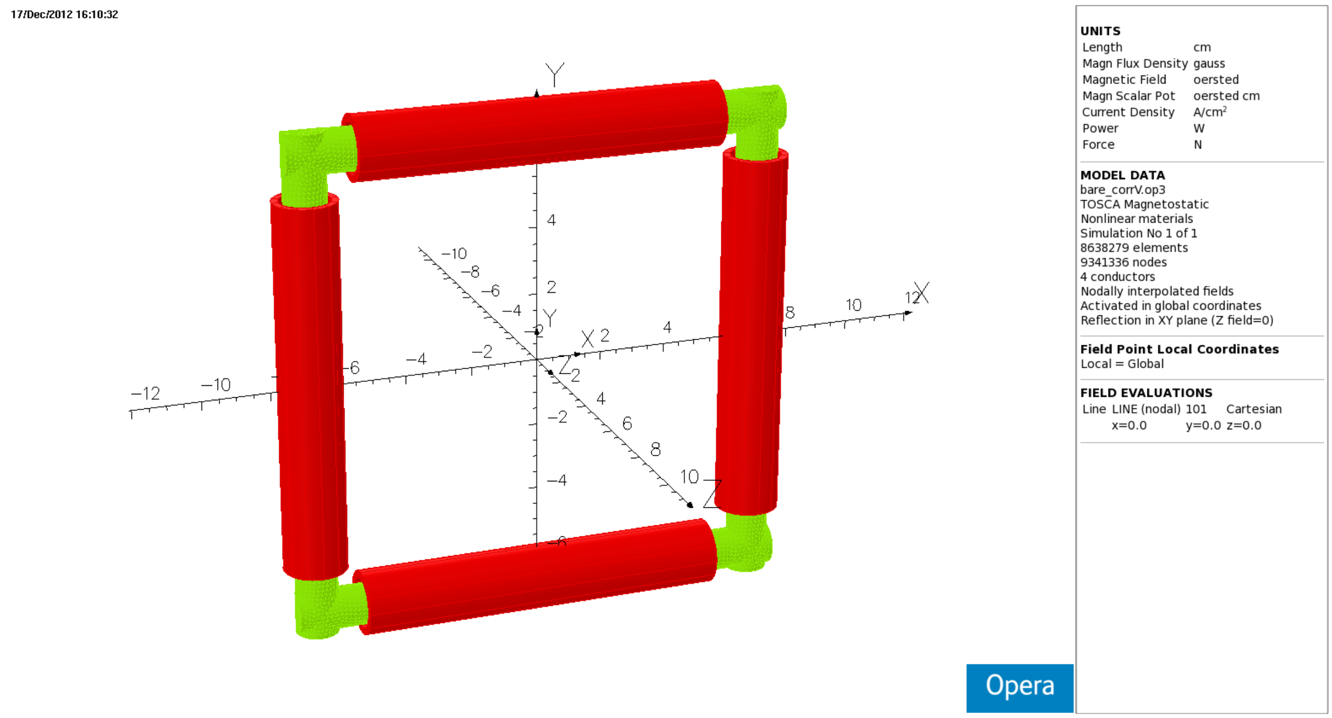


Figure 17. Bare corrector set: 2mm thick coils wound on 1/2" rod mounted up against the anode tank wall. 1.9cm in Z as modeled, about 1.7cm in the real world. 15 cm rods, 11 cm coils.

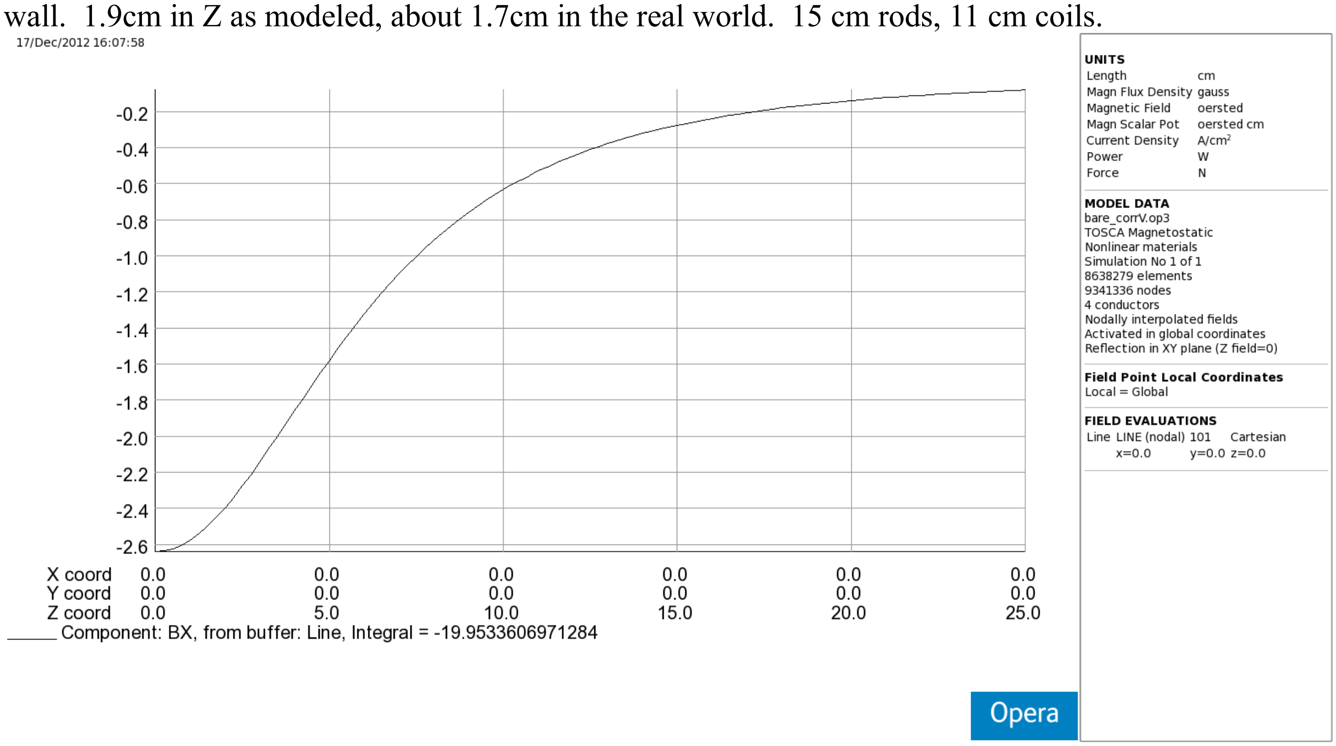


Figure 18. Bx vs Z. This will produce vertical beam motion (cross product). Per Fay, this corrector must provide 35 G-cm vs 40 G-cm modeled. 44 AT in 220 turns of #20 wire, aka 0.2A. Depending on exactly where the gate valve is located, the multi-function magnet will start at Z=13 to 14 cm on this plot. Sextupole is 0.1% of the dipole at 1cm radius.

Iteration Three

At a meeting Jan. 7 the stack-up on page 7 was reviewed. The list of dimensions arrived at there is NOT the one below. I cut 0.5cm from the hardware allowance and increased resolution to two decimal places in the list below so I could increase the combined function magnet from 7.5cm to 8cm.

1.5	corrector on 2.5” tube.
1.0	hardware (7 threads of 5/16-18, nut takes 0.52cm)
1.27	flange
8.6	valve
1.27	flange
0.59	bolt head+washer
0.27	float, use where you choose
8.0	combined function magnet

22.5 total vs 22.519 quoted by Keith, so there's really 2.9mm of float in this scheme. Enough for a carpenter!

At George's request I cut the core down in the combined function magnet to just one 1/2” mu-metal rod. Thus the core is shortened by 2cm and the shield moved in 1cm on each end, to 8cm total. Rather than build a separate model for the corrector without shield I changed the shield to air in the combined model and remeshed. This gives me an aperture ~2.8” inside the coils, a bit larger than needed, but saves a lot of work (and therefore my labor cost to FEL). The model with shield is shown in figure 19 below.

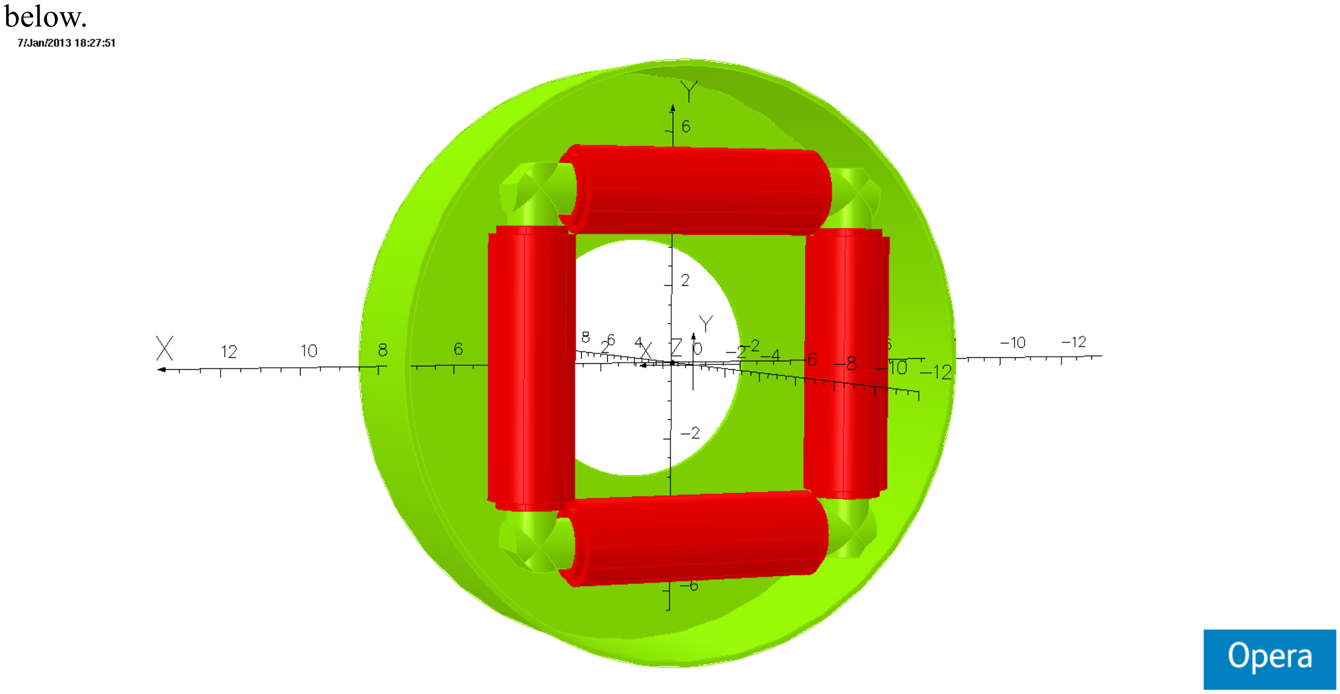


Figure 19. 8cm long combined function magnet. There are two coil layers at 2mm each. The slightly longer one is the dipole set and the other the quad set. 7 cm and 6.6 cm long respectively. I've chamfered the corners with a cylinder again because it's easy. 6.8cm radius vs 7.62cm IR for mu-metal. Clear radius 3.335 cm. Hole in steel 3.2 cm radius. Again, for the corrector all I'm doing is turning the steel shell to air and deleting the quad coils.

Small unshielded corrector

As stated above I used the core and dipole coils from the model shown in figure 19 for the small unshielded corrector which is to be butted up against the gun vacuum tank. Results are shown in the next two figures.

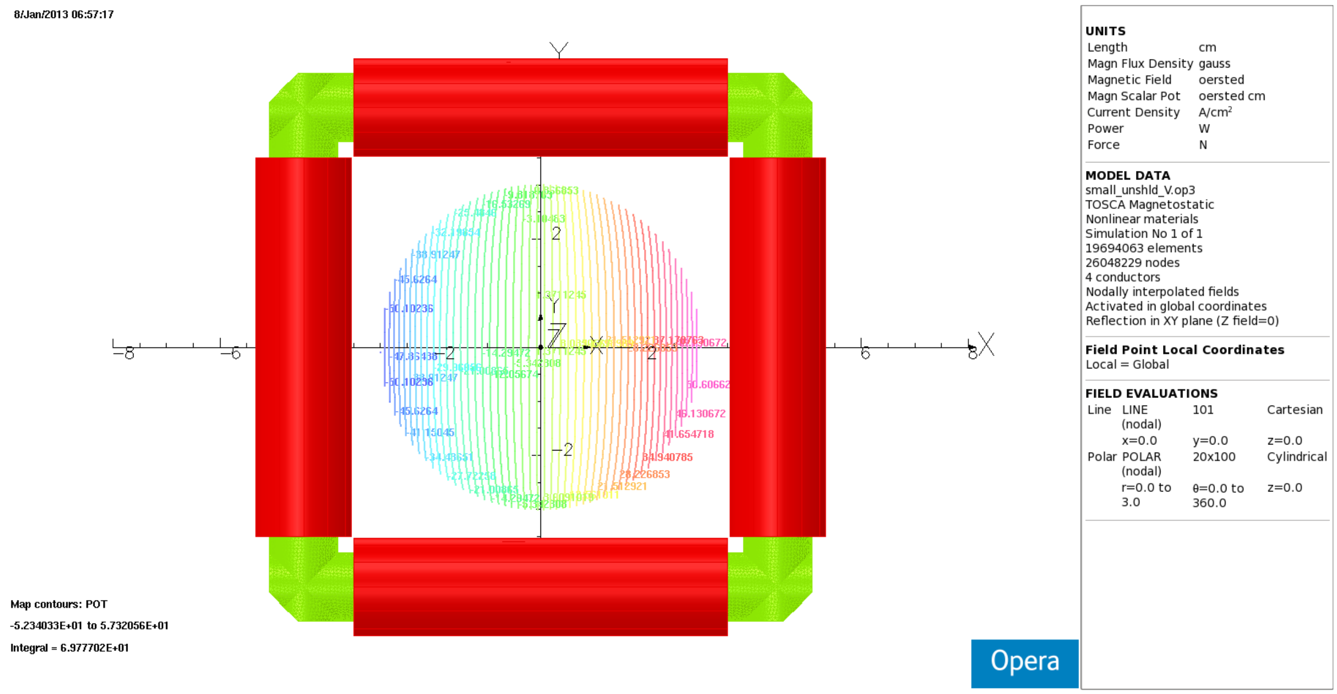


Figure 20. Small corrector model with potential lines suggesting field quality isn't too bad. Field in the mu-metal is ~1.5 kG for this excitation, so higher fields are possible.

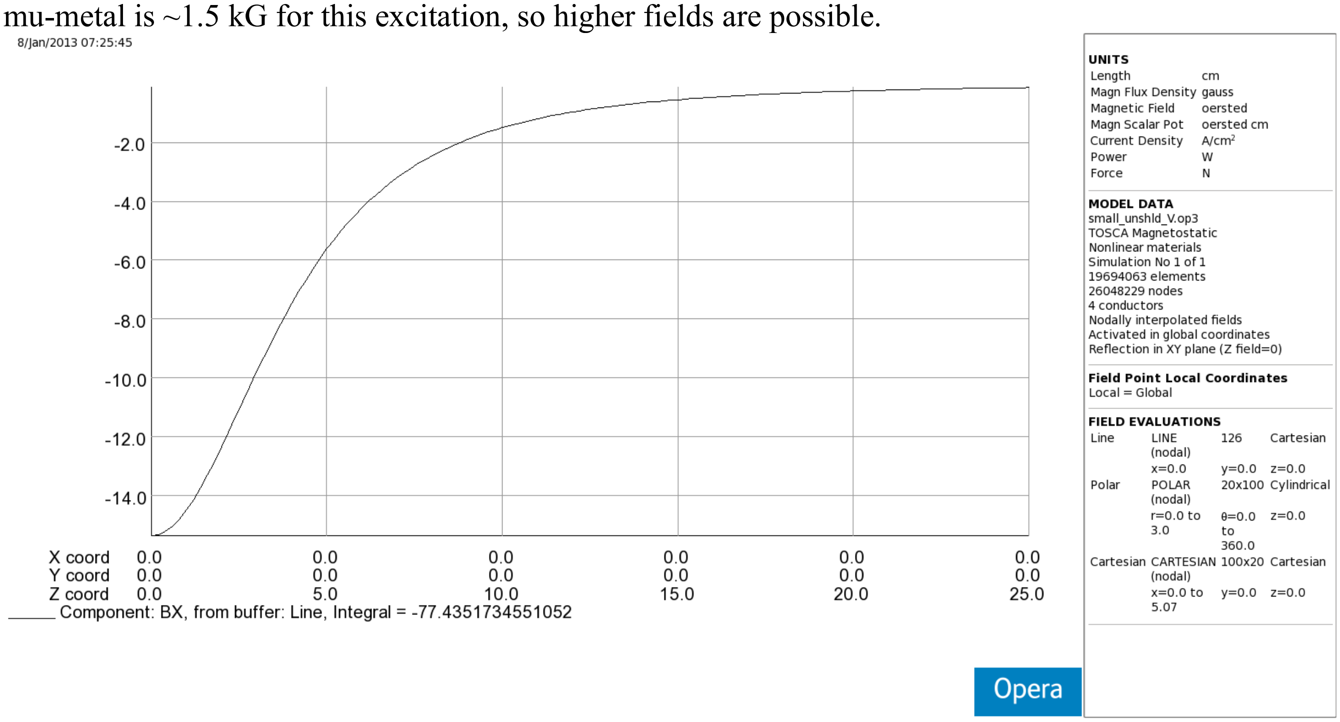


Figure 21. Horizontal field for 140 AT vs Z. Compare to figure 18, the larger unshielded corrector. Cathode and the combined function magnet are both around 15cm from the center of this magnet. Excitation will be about a fifth of that shown in the FEL gun, 0.4A in 70 turns.

8cm combined function model, round hole

The results from the quad-only solution and the unshielded corrector solution were used to set current densities for a simulation with both quad and vertical corrector energized in the combined function magnet. Four iterations were needed as the shield had more effect on the corrector than expected and I got the quad scaling wrong once. The multipoles below are calculated as discussed beginning at the bottom of page 10.

Multipole	**coefficient at 1cm radius**	**coefficient at 2cm radius**
dipole (cos0)	-6.99 G-cm	-6.99 G-cm
quadrupole (sin1)	-34.9 G	-69.8 G
sextupole (cos2)	0.003 (0.04% of dipole)	0.012 (0.17% of dipole)
octupole (sin3)	-0.002 (6E-5 of quadrupole)	-0.017 (2.4E-4 of quad)
decapole (cos4)	-0.005 (0.06% of dipole)	-0.07 (1% of dipole)

Intended amplitudes were 7G-cm for dipole and 35 G for quadrupole at 1 cm. Excitation for dipole 13.16 AT in 140 turns, so just under 0.1A. One could use one layer of wire but that would increase field error as discussed above. Excitation for quadrupole 1.75A in 132 turns, 231 AT.

Fields in the mu-metal are shown in figure 22 below. At least a factor of seven increase is available. Field in the 1.5mm end plate is similar to that in the cylinder below, ~0.7 kG, so the rods are limiting with respect to steel. The quad wire will limit the overall field as no cooling is provided. It might be better to have a single layer dipole winding and use #18 for the double quad winding.

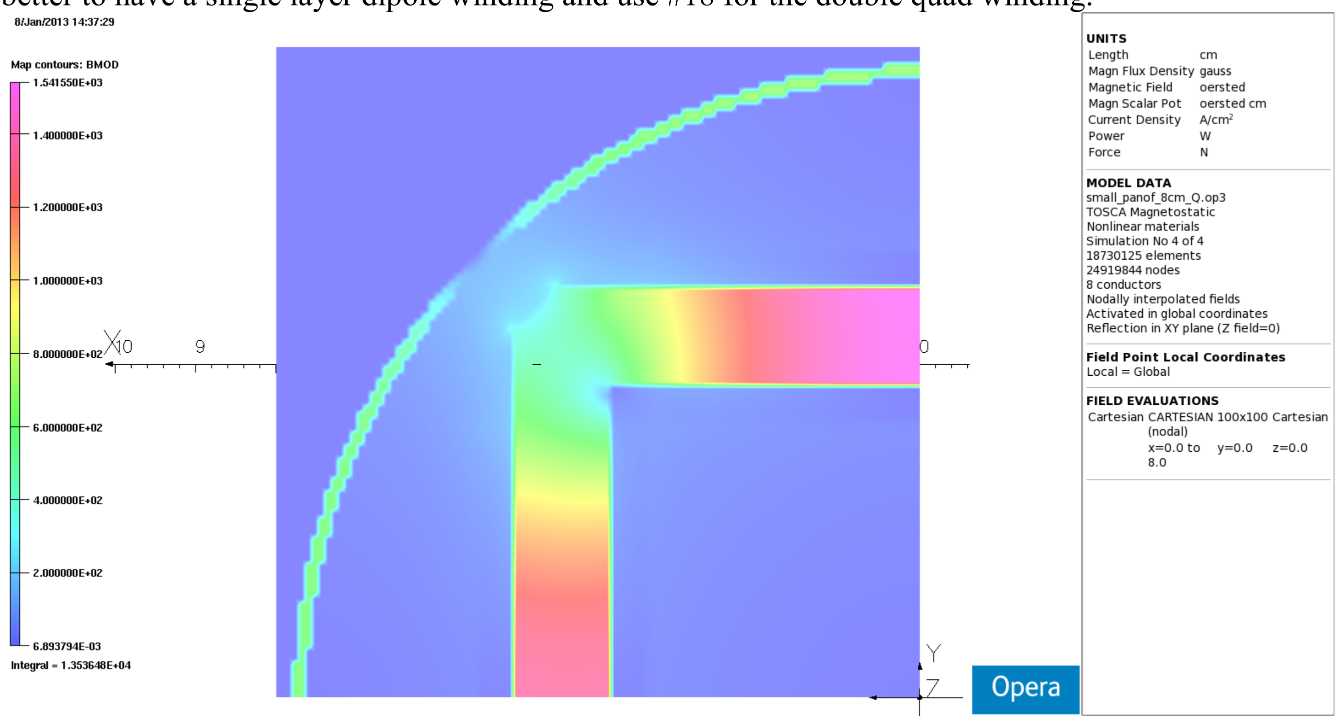


Figure 22. BMOD in midplane of model with both quad and dipole coils energized for fields above. Mesh is so dense that it is hidden here, allowing the colors to be seen. **THE SHELL AND END PLATE SHOULD BE SPLIT ALONG THE DIAGONAL, NOT ALONG THE MIDPLANE WHERE THE FIELD IS HIGHEST, FOR ASSEMBLY AROUND THE BEAM LINE.**

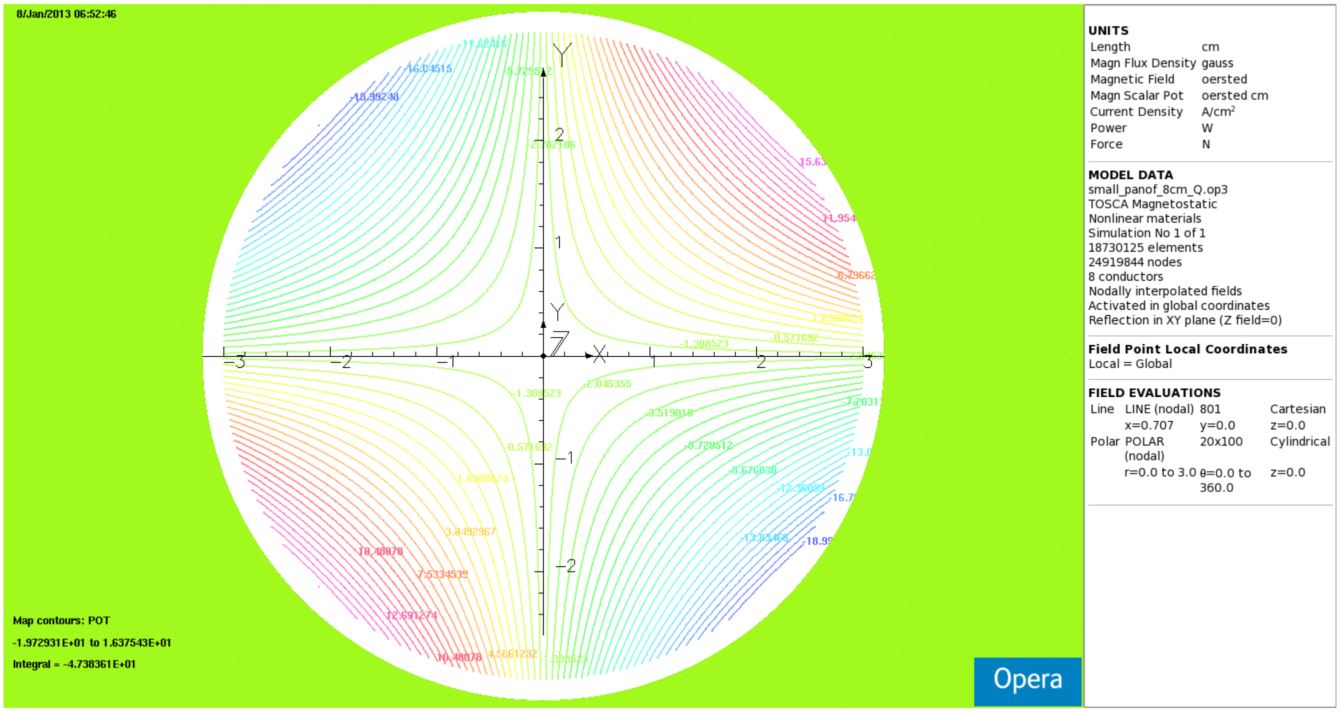


Figure 23. Potential lines of pure quad in 8cm combined function unit.

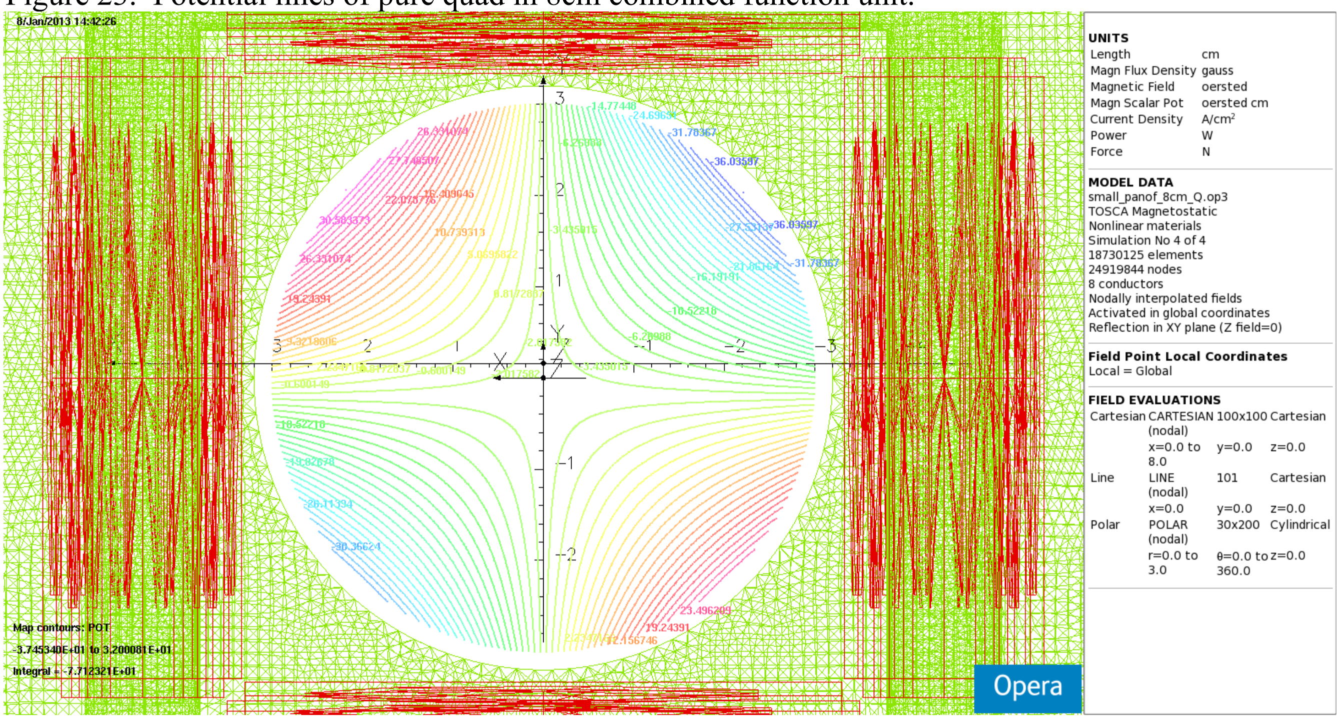


Figure 24. Potential lines for combined quad and dipole. The pattern moves down uniformly.

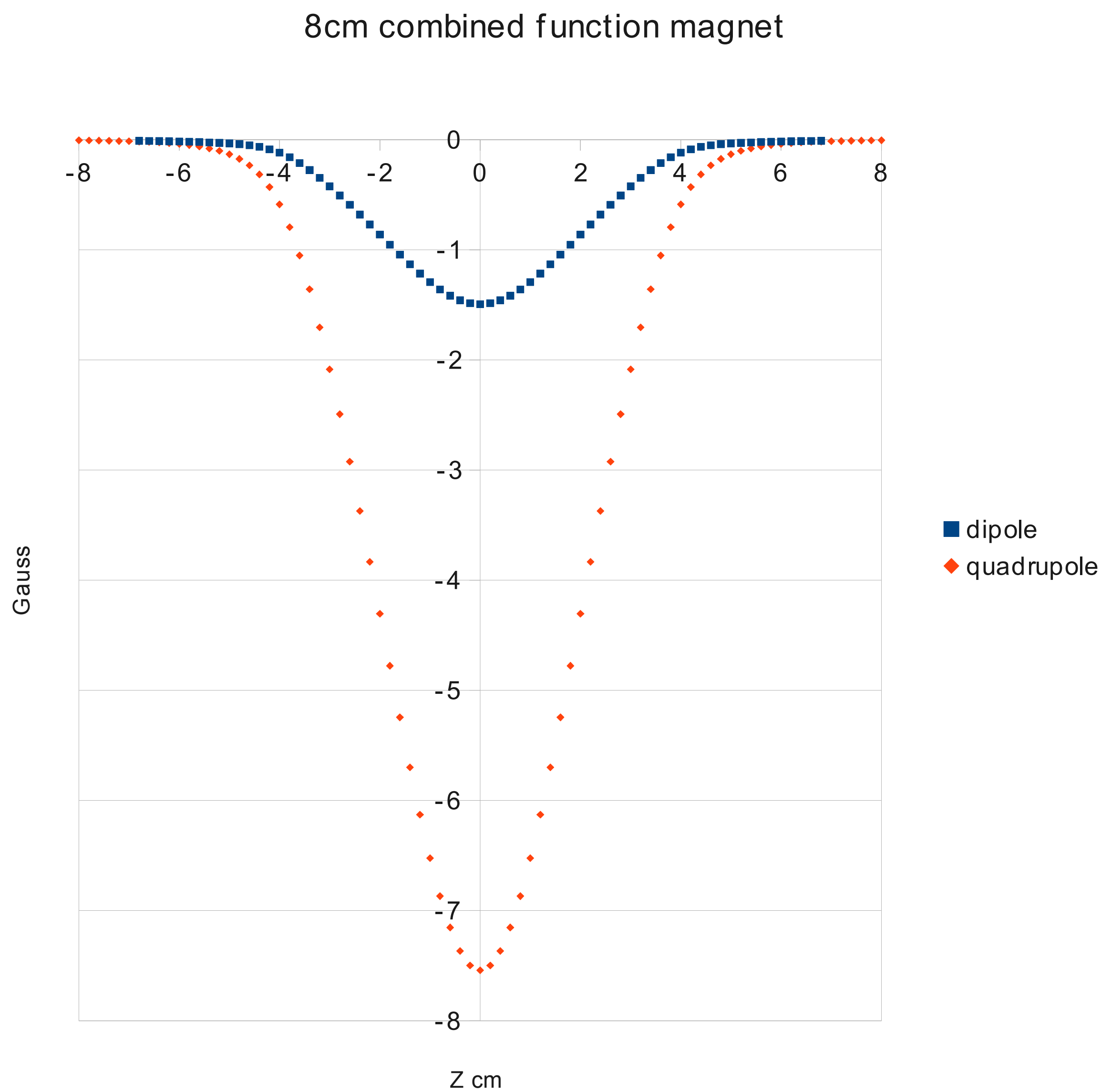


Figure 25. Plot of dipole and quadrupole components for the 8cm long combined function magnet. Compare with figure 16 on page 10, the same plot for the 10cm long unit.

Iteration four

The 8cm concept works only if a bellows and transition to 3" beam pipe are placed inside the compensation solenoid. That solenoid is wound on at 6" copper water pipe, schedule 80, so it has lots of radial space inside it. Steel end plate hole diameter was set for stray field by FEL folks, altering the original design which set it for field uniformity. The end plate is segmented so the solenoid can be assembled over 4.625" CF flanges.

There was an objection within the FEL group to this idea. I was asked to shorten the field shell to 4cm overall length from 8cm in the third iteration. Lots more flux gets sucked into the steel rather than remaining in the bore to influence electrons, so this choice is a lot less efficient. This can be seen with a lot of perspective plots of LOG10(POT) but I haven't come up with one that really helps in visualizing the issue. Since I already have too many figures in this paper I'm going to present a table with the results of all the models which fit around a 2.5" beam pipe. AT= amp-turns.

model	dipole AT	quad AT	Dipole (1cm)	quad (1cm)	sext(1cm)	oct(1cm)	dec(1cm)
goal			7	35	0	0	0
10cm combo long core	8	140.6	-7.06	-36.59	0.0395	-0.0018	-0.0036
8cm combo, round hole	13.16	231	-6.99	-34.92	0.0029	-0.0021	-0.0045
8cm combo, square hole	12.46	219.78	-6.99	-35.01	0.0344	-0.0025	-0.0027
4cm combo, square hole	22.4	382.8	-7.02	-35.18	0.0258	-0.0028	-0.0008
4cm combo, round hole	28	492.36	-7.07	-35.04	-0.1148	-0.0023	-0.0161

One sees that at 8cm length the round hole has an order of magnitude less sextupole and about twice the decapole than the square hole. Amp-turns needed for fixed field are about 5% higher than the square hole. For the 4cm length the square hole is much better for efficiency and multipoles. In both lengths the square hole is 6.6 cm on a side and the round hole is 6.4 cm diameter. Beam pipe is 6.35 cm.

It is my understanding that discussions January 16 resulted in a decision to use the 8cm design.

Conclusions

Many multi-function picture frame magnets with field clamp have been designed and modeled. They have ample focusing and steering strength for the intended use in the FEL gun. The same is true of the unshielded correctors shown on pages 12 and 14. A detailed layout of the line is required to determine the length of the beam pipe coming out of the gun tank so the location of the compensation solenoid may be determined. The list on page 13 will provide guidance. The magnets may be built from sketches since only one of each will be prepared. This TN would then serve as the only documentation of the units not bolted to the beam line. And the 190 GB of Opera models I generated, of course.

Postscript
Several decades ago, faced with a need to torque bolts in quarters too tight for a conventional torque wrench, I ordered a box end torque wrench with size and torque pre-set. McMaster-Carr will still sell you one. This might help in mounting the gate valve to the gun tank.

References

1. L.N. Hand and W.K.H Panofsky, Rev.Sci.Instr. V30 n10 pp 927-930 October 1959, "Magnetic Quadrupole with Rectangular Aperture"
2. Combined Panofsky Quadrupole & Corrector Dipole [Adobe PDF]
   Two styles of Panofsky Quadrupoles with integral corrector dipole windings are in use in the electron beam line of the Free Electron Laser at Jefferson Lab. We combined steering and focusing functions into single magnets, adding hundreds of Gauss-cm dipole corrector capability to existing quadrupoles.
   Authors: G. H. Biallas; N. T. Belcher (W&M); D. Douglas, T. Hiatt, K. Jordan

Ideas on mechanical design

1. Use 4” mu-metal rods.
2. Machine a 1mm groove down the length of each. Designate this the outside.
3. Chamfer the outside corners of the rod 2.5mm on each end. Or not – see #9.
4. Machine a 3mm groove 13mm deep centered in one end. Machine the other end into a central tongue 3mm thick by 13mm long.
5. Drill a 2mm hole 9mm in from the end through the tongue on one end and through both sides of the groove on the other.
6. Tap one of the groove holes for #3-UNF. Clear drill the other groove hole and the tongue hole 2.5mm for #3.
7. Wind one or two layers of turns 7cm long. If you are winding only one layer for the dipole, put the starting lead in the groove first, cover with Kapton tape, and then wind the layer back up the rod so the leads are at the same end. Wind two more layers 6.6 cm long if the piece is being used for the combined function magnet.
8. Screw the four rods together on a jig which keeps them squared up, using socket head machine screws. Remove two screws so one of the rods may be removed to allow the assembly to be mounted on the beam pipe. After mounting, re-assemble. Check that it's square.
9. For the shielded unit, consider mounting the thing in a thick walled G10, CE or TBD tube, 6” OD with at least 0.25” wall. Put grooves inside it to locate the coil assembly. Put survey marks outside. Wind mu-metal around it. Screw mu-metal ring with 6.4cm ID hole to both ends. **THE SHELL AND END PLATE SHOULD BE SPLIT ALONG THE DIAGONAL, NOT ALONG THE MIDPLANE WHERE THE FIELD IS HIGHEST, FOR ASSEMBLY AROUND THE BEAM LINE.**