Solid XL - last look with CLEO steel and first without it

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Abstract

A revised magnetic model of the SoLID system with the ME-specified layout at the magnet-endcap interface has been created. This model still uses the CLEO steel even though it may be replaced. It uses a 1010 BH curve rather than the Opera default “good magnet steel” as in previous documents. This increases stray field outside the iron from 5G to 10G where PMTs and detector readouts are to be placed. It also increase the field at PMT locations inside the endcap from ~60 G to ~80 G. Appendix D shows that holes covering 2% of the surface area of the end cap don't have a large effect. The effect of the nose taper required to maintain acceptance to the end of the PVDIS target on the field in these regions is also shown to be small (~2%), contrary to my expectations.

Discussion

As a result of my discovery, detailed in TN17-032 on the HRS resistive quads, that moving from 2 cm to 1 cm mesh maximum made a 0.25% change in quadrupole term and caused the dipole term to go from strange to making sense, I decided to create two volumes of “detector air” with finer mesh than the steel and remainder of the interior. This resulted in a model with ~300M non-zeroes in the matrices with eight-fold symmetry. I could not later break the symmetry with the turret cut-out within Opera's limit of 2147M non-zeroes so I had to cut back on elements. From Whit Seay I got inner radii of the new support systems in the solenoid and end cap. From Xiaochao Zheng I got the length of the region behind the shashliks. These changes, and some I made to the air surrounding the steel, got the model down to 246M non-zeroes. “Detector_air1” is now R132 Z [-188,188]. “Detector_air2” is now OR 258, dR 173 Z [224.79,508.79]. The mesh is shown in figure 1.

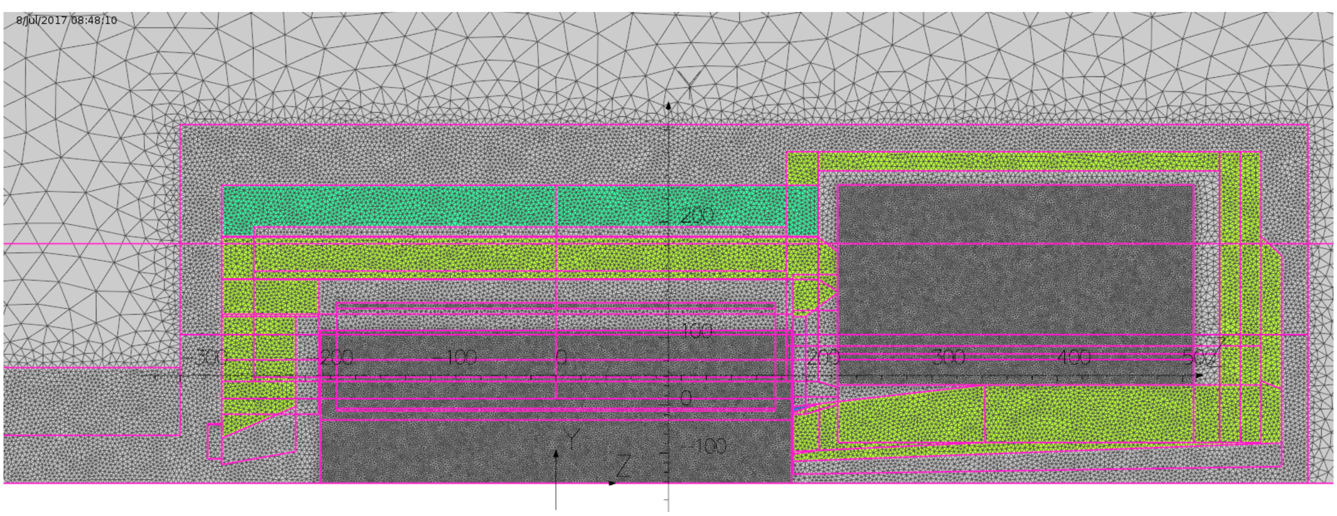


Figure 1. Mesh of markV_try3 models. The two large dark rectangles are “detector air”. The thin R dark block above the left one contains the solenoid. Dark mesh has 2 cm maximum elements. Medium grey and green steel has 4 cm maximum mesh. Light grey scales from 4 cm to 32 cm maximum.

Question for collaboration: May I reduce the OR of “detector_air2” from 258 cm to 250 cm? The latter is the OR of the volume I was given for the LGC and HGC PMTs. **Or even smaller?** **See page 19 for an update.**

Try1

There were four try1 models solved with varying upstream plug thicknesses. The first three had plug thicknesses of 76, 66 and 61 cm. Opera calculated forces on the solenoid for each. I plotted, added a quadratic fit line, and solved the quadratic. The fourth model used the solution, 58.8 cm. The four-point plot and fit are shown below. The solution for this fit is 58.95 cm thick aka -207.75 cm.

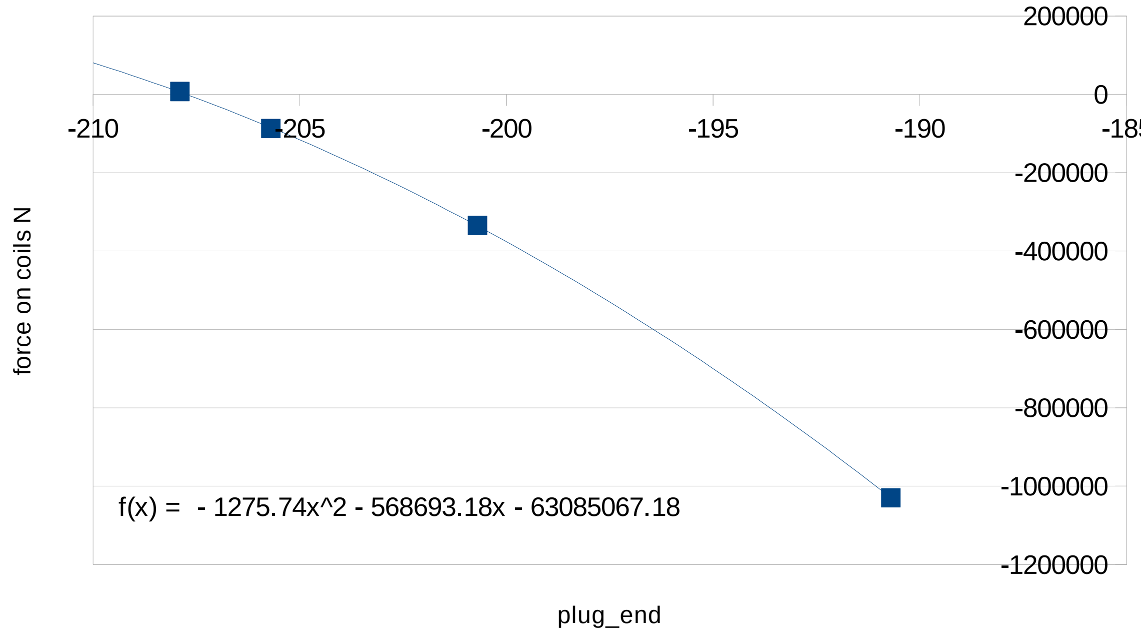


Figure 2. Force on the solenoid coils (Newtons) as a function of the downstream end of the upstream plug. The upstream end is at Z=-266.7. One zero of the fit equation is -207.75. The four axial load cells can handle 5000 kgf each, aka ~200 kN total. The pair of points at upper left yield 43 kN/cm.

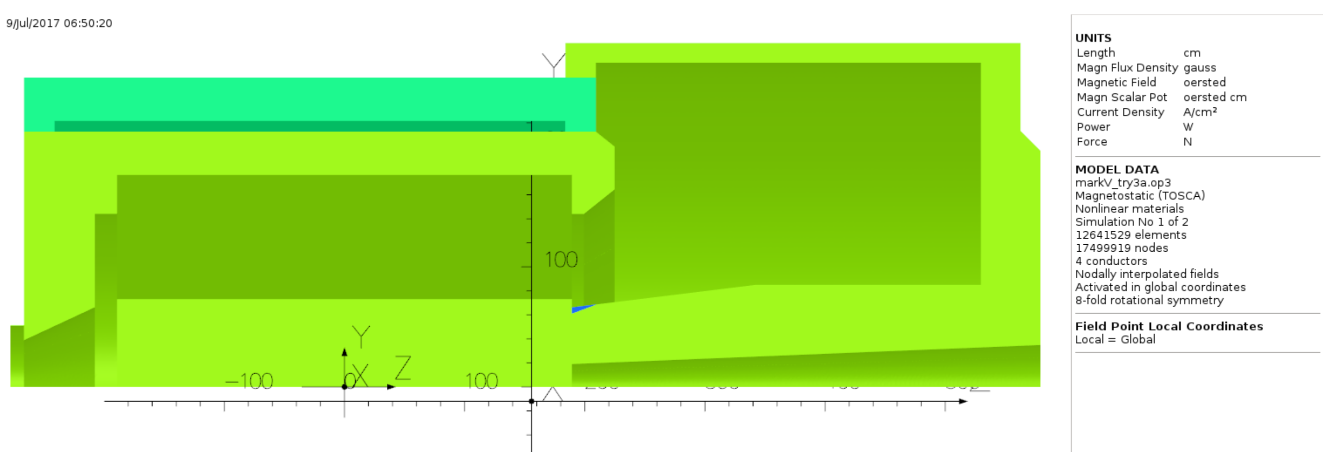


Figure 3. This is a quarter-section of the try3a model. The small blue region on the nose cone is the region Zhiwen wishes to remove to provide acceptance of the full length of the PVDIS target. Solving the model with that region having BH curves of 1010 steel (sim 1) and air (sim 2) yields a change in the coil force from +827 N to -19.5 kN, 20.3 kN total. About the same as 5 mm of thickness change in the upstream plug.

Contrary to my expectation, the field in the region where the LGC and HGC PMTs reside dropped by 2% when the BH curve for the blue region was changed from 1010 to air. The field in the region just above the cone increased a similar fraction. Peak field on the surface of the model dropped 3% because the peak was at the edge that was removed. It follows that we can cut that volume out of the nose and gain the desired acceptance without significant detriment. Location of the upstream plug end should therefore be -207.25.

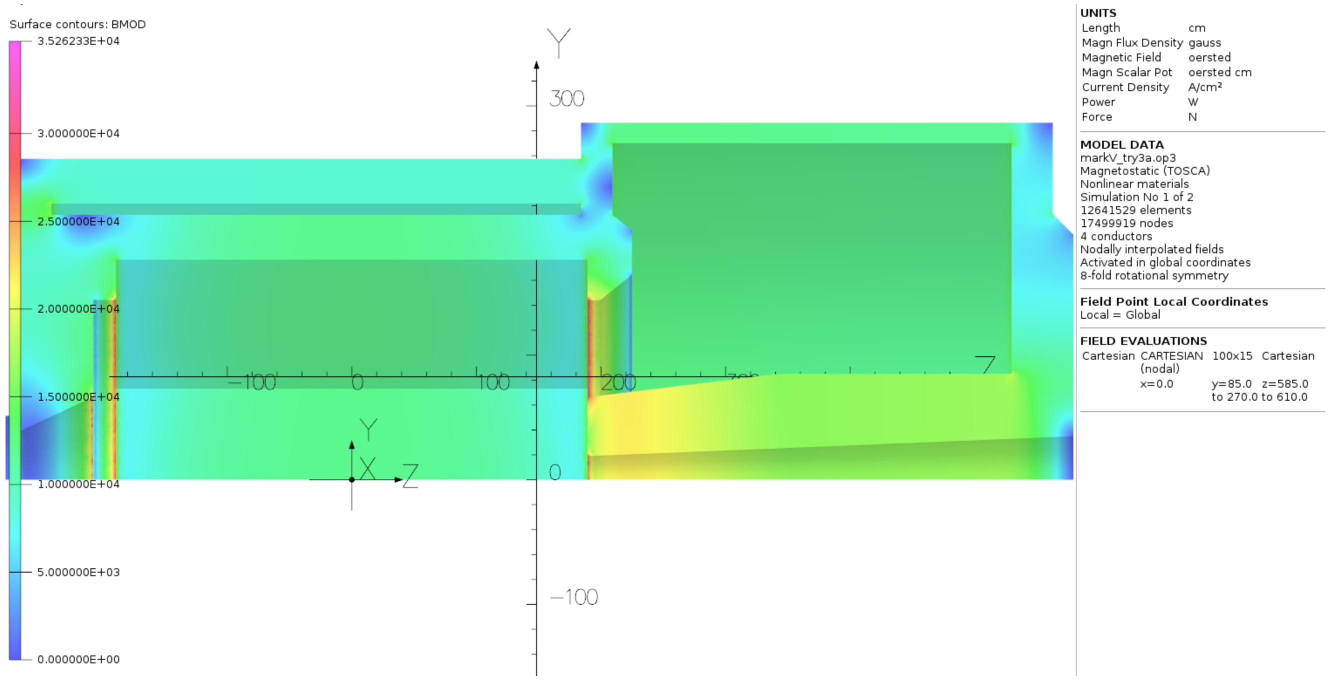


Figure 4. Bmodulus on surface with single nose taper (aka blue in figure 3 = steel). Peak 3.526 T

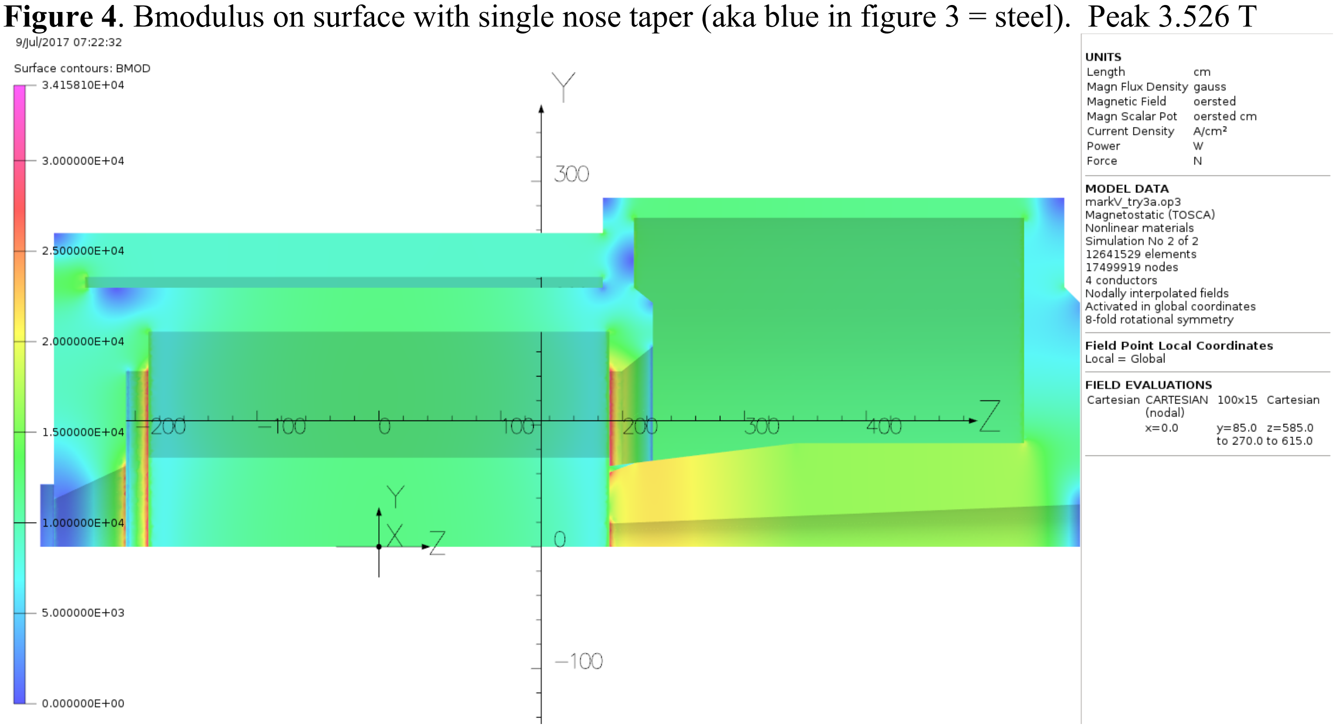


Figure 5. Bmodulus on surface with double nose taper (aka blue in figure 3 = air). Peak 3.415 T

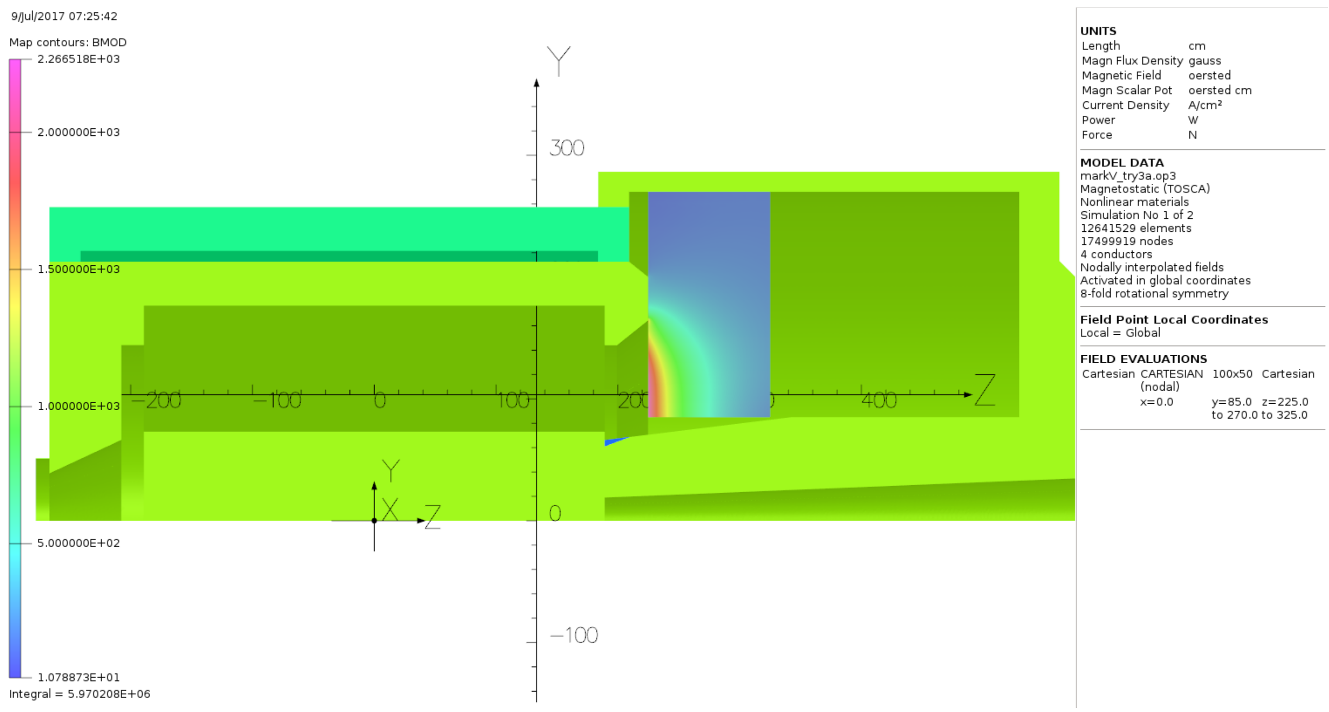


Figure 6. Bmodulus in endcap over the cone, single taper on nose (blue=steel) . Peak 0.227 T

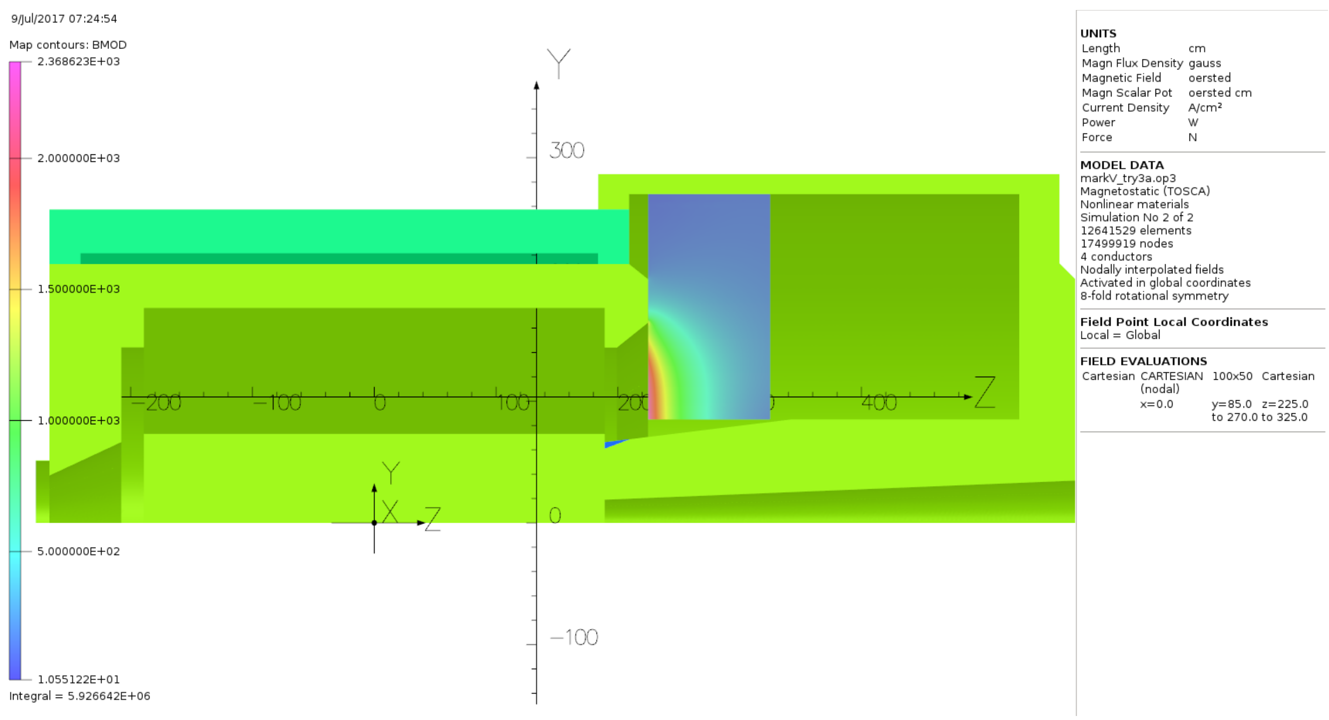


Figure 7. Bmodulus in endcap over the cone, double taper on nose (blue=air) . Peak 0.237 T. Some flux which would have been conducted through the nose and around the entire endcap now jumps directly to the downstream coil collar. This is what I didn't consider at the collaboration meeting.

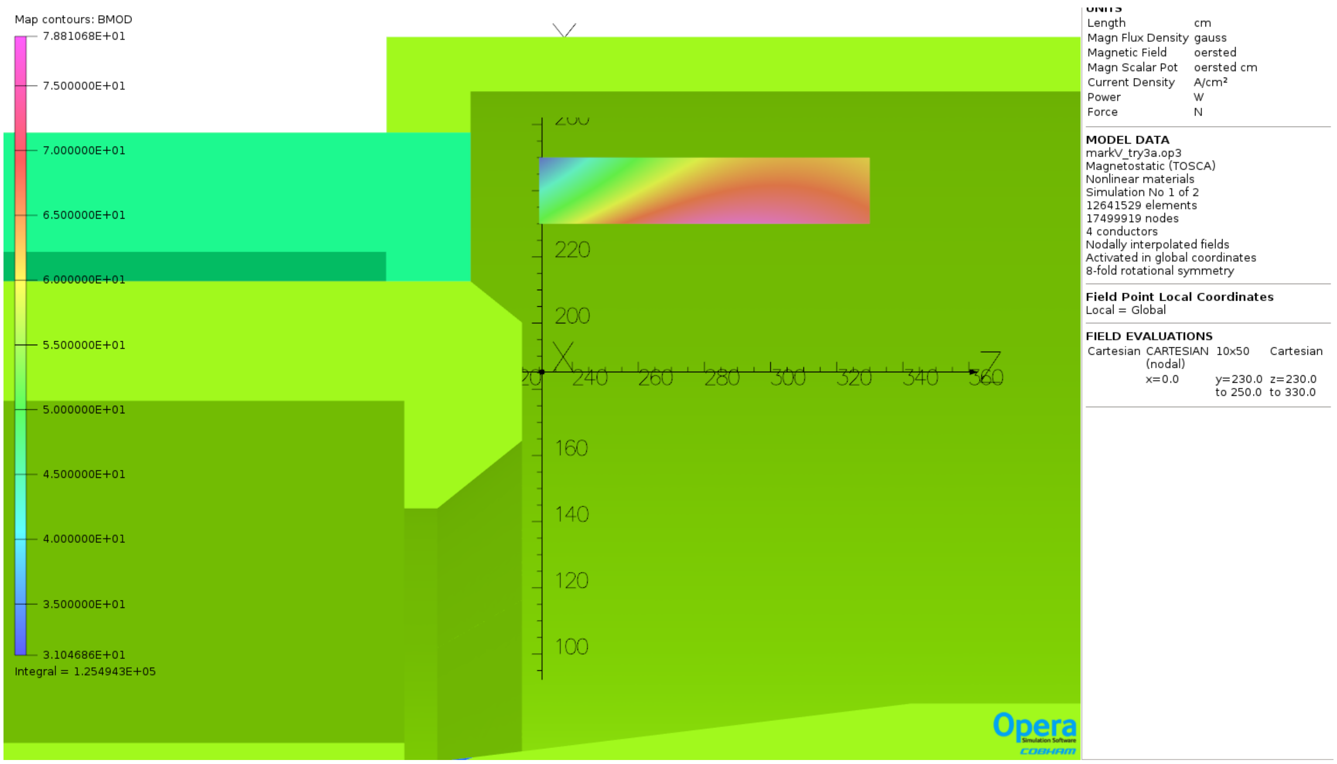


Figure 8. Bmodulus in vicinity of LGC and HGC PMTs. 1010 BH curve used here. Single taper on nose.

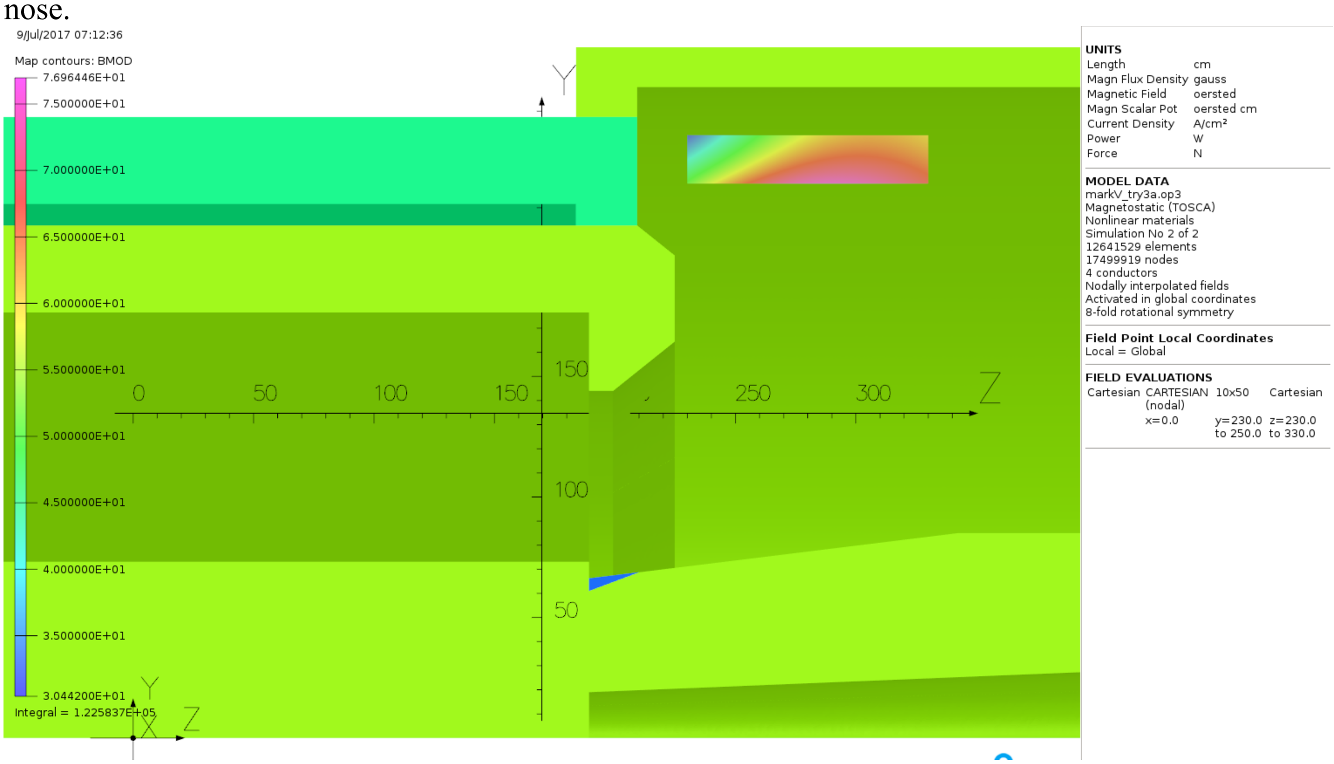


Figure 9. Bmodulus in vicinity of LGC and HGC PMTs. 1010 BH curve used here. Double taper on nose. Peak 77 G here vs 79 G in figure 8. With Default BH curve, 71.5 G peak. With JLabSR, 74.4 G.

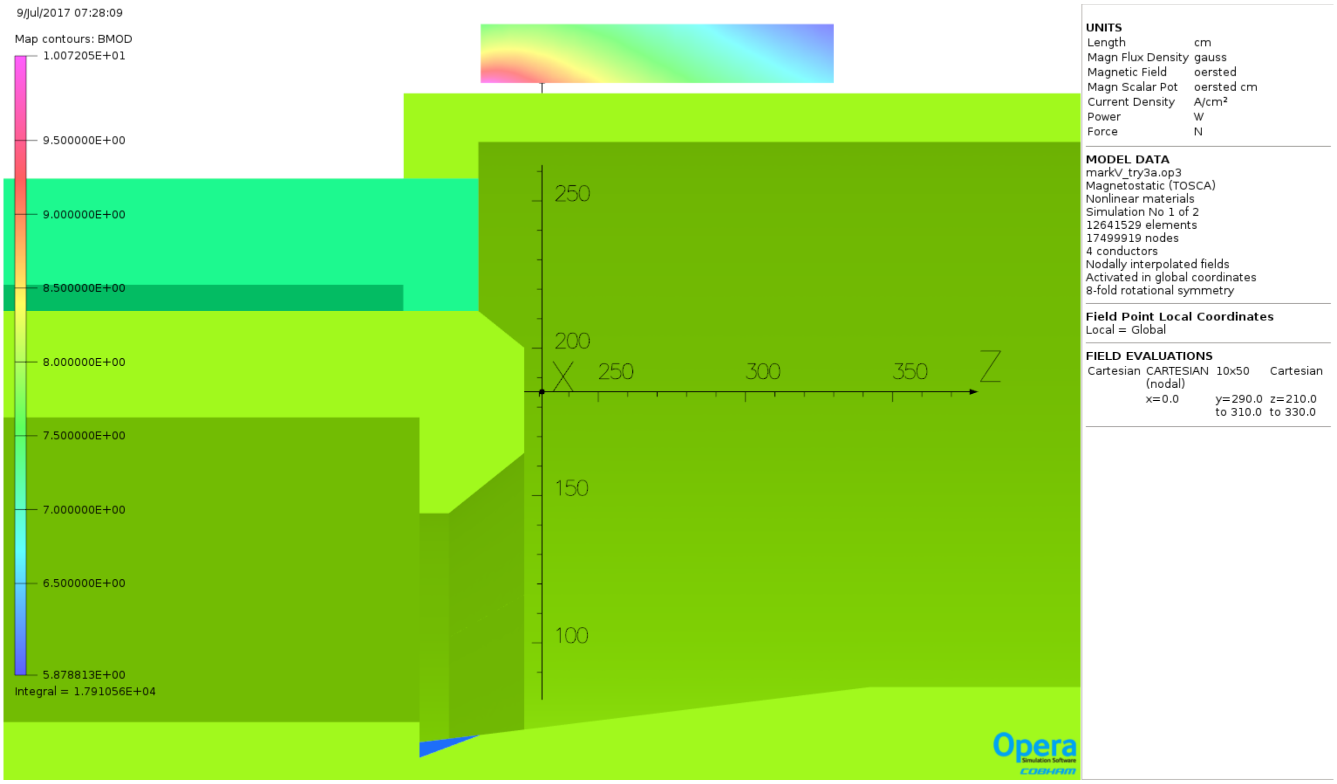


Figure 10. Bmodulus in vicinity of GEM electronics. Single taper on nose. Peak 10 G. 1010 BH curve used here.

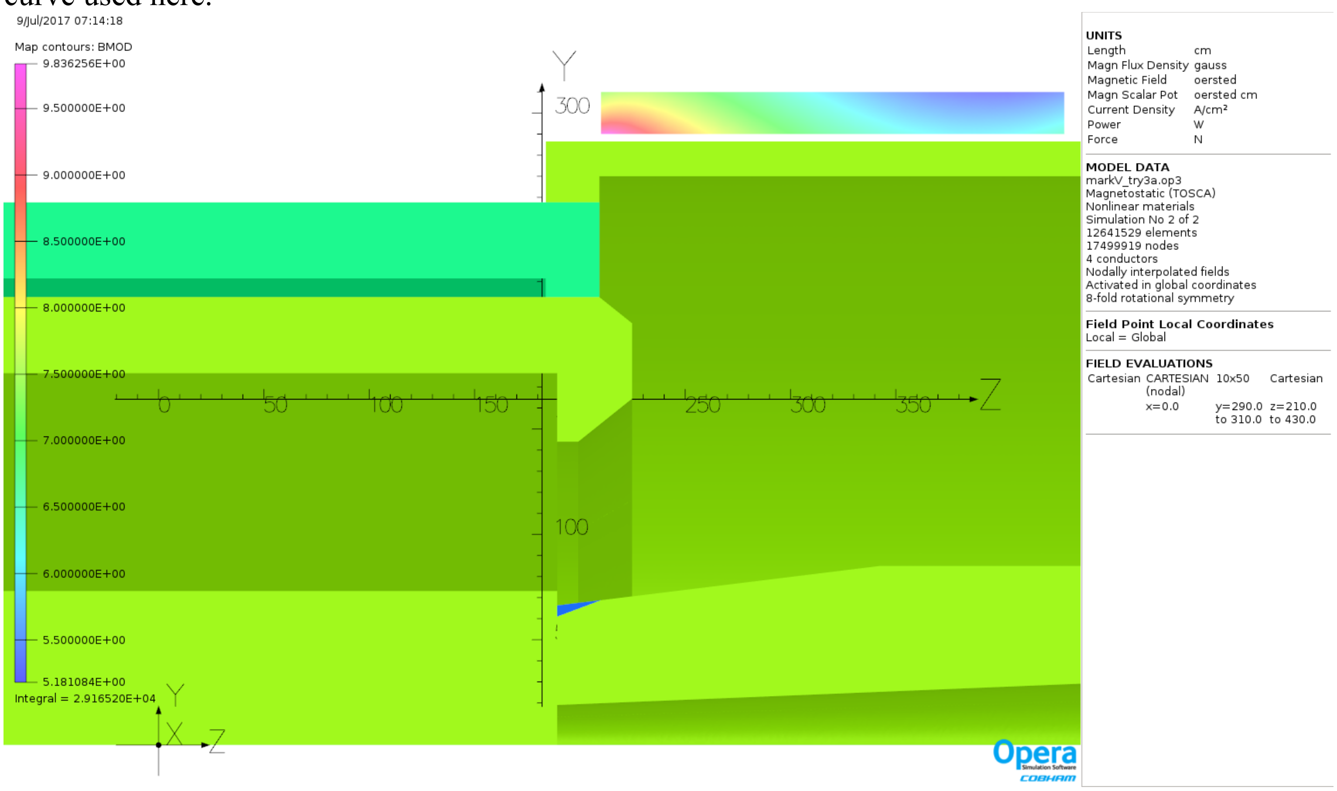


Figure 11. Bmodulus in vicinity of GEM electronics. Double taper on nose. Peak 9.8 G, slightly less than figure 10. 1010 BH curve used here. With Default BH curve, 7.1 G peak. With JLabSR, 8 G.

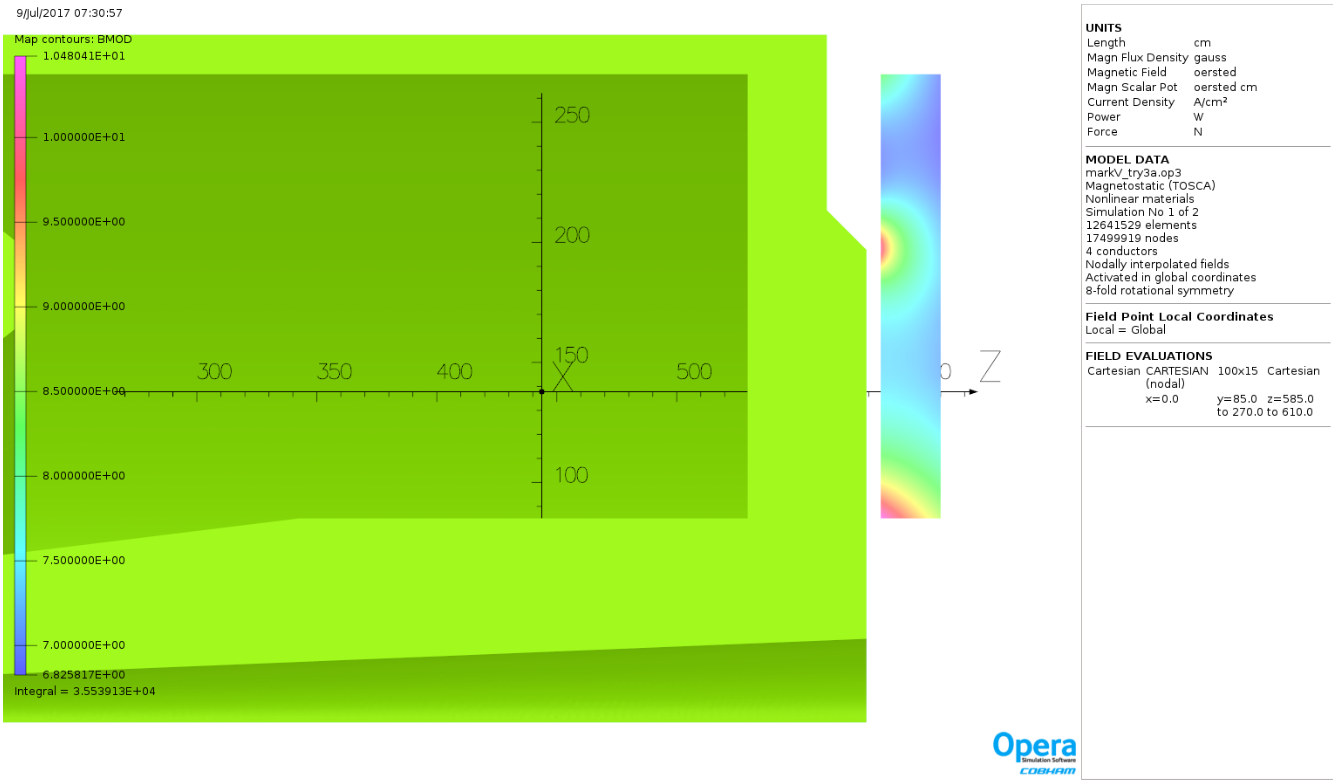


Figure 12. Bmodulus in vicinity of ECAL PMTs. Single taper on nose. Peak 10.5 G. 1010 BH curve used here.

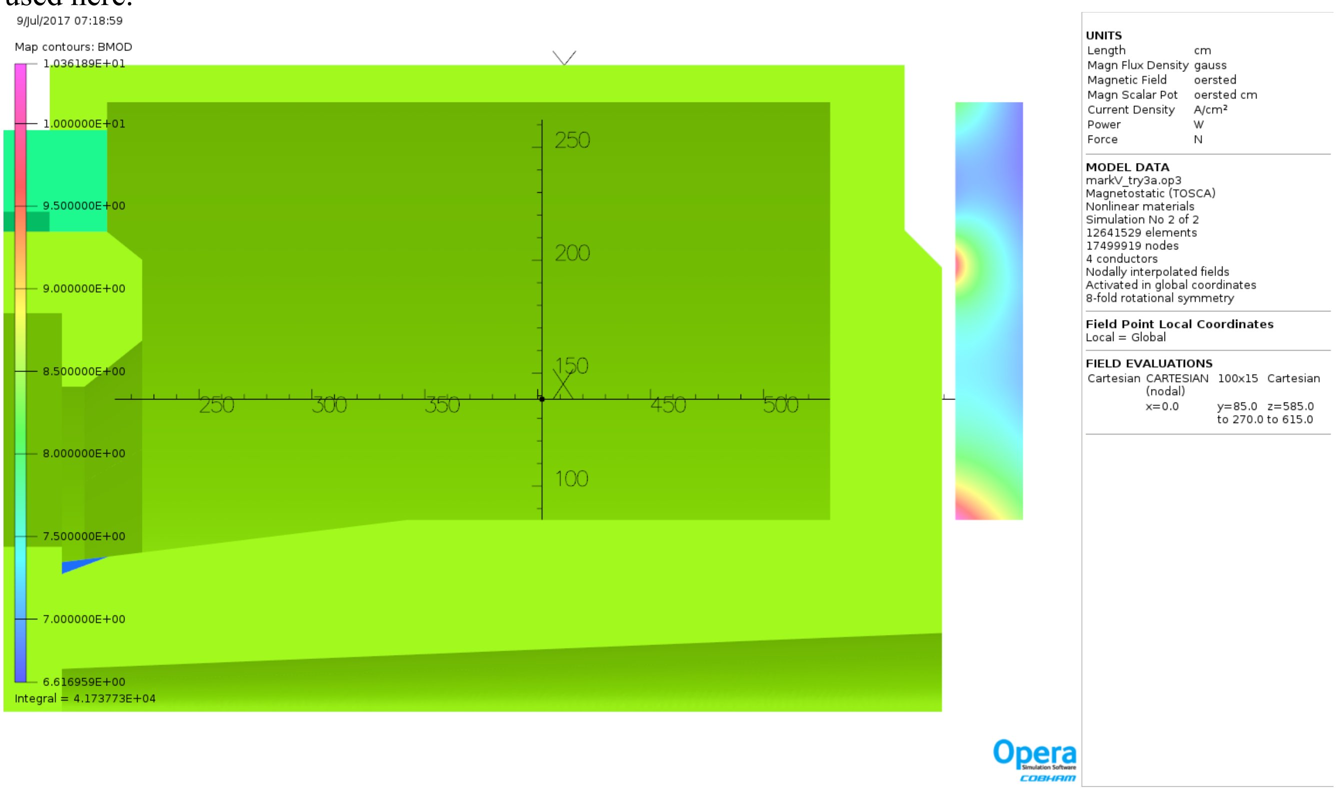


Figure 13. Bmodulus in vicinity of ECAL PMTs. Double taper on nose. Peak 10.4 G. 1010 BH curve used here. With Default BH curve, 4.5 G peak. With JLabSR: 6.9 G peak.

Three B-H curves

The model with double taper and upstream plug ending at Z -207.75 cm was run with three different B-H curves. With the Opera Default "good magnet steel", force on the coil is 11.4 N, With 1010 B-H, -19.5 kN. With the B-H curve discussed in TN-09-47, which includes a chemistry specification, +3.9 kN. The last was scaled from one provided by Robin Wines to match the measured properties of accelerator magnets used to 1.4T bore field, the topic of the TN. The chemistry spec and one figure from the TN follow in Appendix B.

Conclusions

1. It is OK to make a double taper on the nose to get acceptance of particles from the downstream end of the PVDIS target
2. Three B-H curves spanning the likely range of steel quality produce a force range of +11.4 kN to -19.5 kN. This is well within the +-196 kN range of the four load cells. It's equivalent to a range of plug thickness of 0.7 cm out of 58.95 cm, 1.2%.
3. Measuring the BH curves for the upstream plug and the cone steel when fabricated and re-running the calculations would be helpful in defining final thickness of the upstream plug. Buying steel to the CEBAF spec in Appendix B should also work.
4. Given the change in stray field inside the end cap with BH curve, the model should be rebuilt with the endcap cylinder and end plates assigned yet another BH curve, one in which B is multiplied by 0.98 to account for 2% area reduction for cable holes.
5. The field in the inner octagon peaks at 1.18T at (x,z)=(0,0). In the outer octagon, 0.87T. It follows that three layers of the same 6.5" steel used in the model for the end cap and end plates would do as well as the two layers of 14.2" CLEO steel shown here.

Appendix A: Modeller primitives used to build Opera models revised 7/9/2017

Inner octagon steel1 level 92 4cm

inside Y 69.5” = 176.53 cm * (1/cos 22.5)= 191.075 IR
outside Y 83.71” =212.62 cm * (1/cos 22.5) = 230.142 OR
radial thickness 39.069 cm.
Z -266.7 to 224.79

Opera has a operation: make n-sided polygon. Using 230.142 OR and thickness 39.069 one arrives at an octagon with the inside and outside heights on the Cornell drawing 6052-303 sheet 3.

Chamfer at Z 224.79 OR 15.56 in Z by 12.45 in R

Notch construction air at end of inner octagon

Whit has a 1.5” notch running Z=189.23 to 224.79 which is 1.5” deep to match hexagonal OD of new coil collar. But coil collar has round ID. So I have to make a hexagonal notch in inner octagon and then trim overlap. As above, the OR 71” = 180.34*(1/cos 22.5) = 195.2,
IR 69.5” =176.53*(1/cos 22.5) = 191.075 but use deltaR 4.25 and Z 225 max to grab it.

Outer octagon steel2 level 91 4cm (so I can make it air BH later)

outside Y 101.42” = 257.61*(1/cos 22.5) = 278.832 OR
radial thickness 39.069 cm
Z -266.7 to 209.23
Again, make n=8 polygon of this Opera “tube”

Spacer bars steel2 level 91 4cm (so I can make them air BH later)
Between octagons: I figured out the volume of the bars and determined that cutting the Z extent to 25.5 cm would maintain the steel volume. Z extent: -266.7 to -241.2, 183.73 to 209.23. This simplifies the model a lot. These end annuli are merged with the outer octagons in the model and trimmed by inner - no air gaps.

Coils used cold dimensions from OMT manual, including Z shrinkage, and warm Z lengths of outer segment from winding drawing.

IR 151.7 OR 154.9
Z1 -173.75 to -85.45 3814.273 A/cm^2
Z2 -85.45 to 85.45 3708.32 A/cm^2
Z3 85.35 to 173.75 3814.273 A/cm^2

Current densities were derived by looking at total turns, 1281, and conductor sizes from IEEE paper and estimating winding pattern. Only later did I see the winding drawing. I can't find turns count on it. I did learn that the 4.9 mm conductor is used only on the outer winding outer layer, not both layers. More recently I've multiplied the current densities above by -1.0072 (ends) and -0.9961 (center) to get the ratio closer to 1.04 quoted in the paper. Correction solenoid 9 cm square, -1.2

Upstream coil collar steel1 93 4cm
OR 194.145 cm, 113.50” ID => 144.145 cm IR, deltaR 50, Z -266.7 to -189.23 cm (30.5” extent). Trim overlap with inner octagon.

Coil air: level 100 2cm
OR 156 cm, thickness 5 cm, Z -175 to 175 cm

Upstream plug steel1 93 4cm
Z -266.7 to **-207.25** cm with Zhiwen taper steel set to air. **-207.75** if set to steel. OR 144.145 cm. Solid to start. Create a cone with 1 mm R tip at Z=-350 and base 74.61 cm R at Z=-190, aka 25 degree angle. Trim overlap of steel with air, then delete air leaving conical hole. *Bold value will be varied to null force on coils.*

Downstream collar steel1 94 4cm
Z 189.23 to 224.79
tube OR 195.20 deltaR 51.2
at IR 144, Z 224.79 chamfer R 20.447 Z 25.56
trim overlap to inner octagon notch made on previous page

Cone steel1 95 4cm
R66.25 at Z 189.23 from 7 degree constraint
R85 at Z 342.27 from 7 degree constraint and 85 cm OR maximum

Zhiwen_taper steel3 96 4cm
R61 Z189.23
R68.759 Z210
trim overlap with cone above. Check for errors before and after.

CylinderA steel1 95 4cm
OR 85 Z 342.27 to 579.12

Endcap_cyl steel1 90 4cm
OR 286.51delta R 16.51 (6.5") Z 209.23 to 529.59

End_plate1 steel1 90 4cm
OR 286.51 delta R 201.51 (leaving 85 cm for CylinderA), Z 529.59 to 546.1

End_plate2 steel1 90 4cm
OR 286.51 delta R 201.51 (leaving 85 cm for CylinderA), Z 546.1 to 562.61

Cone_plate steel1 95 4cm
OR 213.36 delta R 128.36 (leaving 85 cm for CylinderA), Z 562.61 to579.12.
chamfer at OR 16.51 by 16.51

Hole in cone: IR 19 cm at Z 189.23, IR 35 at Z 581.85 from 2 and 3.5 degree constraints

Interface_endcap steel1 90 4cm
OR 286.51 delta R 32 Z 183.83 to 209.23 aka 10": interface octagons to end cap cylinder. Trim overap with outer octagon.

Inner_air level 80 4cm
R310 Z -300 to 600. R100 Z -450 to -300
And in gap between octagons: Z -240 to 184 overlaps bars a bit OR 240 deltaR 10 should cover gap. Use cut plane at Z=0 to see gap and trim overlap sequentially.

Detector air, level 82 2cm
part 1: R132 Z [-188,188] *part 2*: OR 258, dR 173 Z [224.79,508.79] shorter OK per Xiaochao

Outer air 70 32cm
R500 Z -500 to 800. level 70.

Background cylinder has multipliers applied to stuff I defined. Z 9 R 8 320 cm max mesh. Meshes out to 5000 cm both directions.

corrector_ring steel1 97 2cm
OR 51.435 deltaR 0.635 so IR 50.8 (20")
Z -266.7 to -278

correction_coil IR 40 cm vs end plug hole 38.84 IR. Cross section 9 cm square. J 100 A/cm^2 Offset -277 cm so downstream end is at -268, 1.3 cm from plug face. #8 square conductor is 0.1298+0.005 = 0.1348 maximum dimension. 0.3424 cm. Assume conductor is butted within layers and there is 0.010" glass between layers to wick epoxy. 25 turns/layer +1 for transition, 24 layers, 600 turns total.

Service turret steel removal. I built a rectangular parallelopiped of air inclined at 22.5 degrees with 13.2" X width and 14" Z width. I made it substantially longer than the chord of the paired octagons. I moved it to 30.75" from -Z end at the edge of the top plate. I trimmed the overlap of the steel and air, then deleted the air. "Inner air" above fills the gap created.

Appendix B: CEBAF steel statement of work (from TN-09-047)

The steel for CEBAF magnets was purchased to a statement of work, 22161-S-002/Rev. C, which specifies the steel chemistry, not the BH curve. The relevant portion of section 3.1 is:

The chemistry of the hot rolled steel shall be as described below. Mill certification is required. The steel shall meet the specifications for AISI 1006 in all other respects.

Impurity	*Allowable %*
C	*greater than or equal to 0.04, less than or equal to 0.08*
Si	*less than or equal to 0.1*
Mn+Ni+Cr+Cu	*less than or equal to 0.5*
Al+Mo+S+P	*less than or equal to 0.1*
N	*less than or equal to 0.004*
O	*less than or equal to 0.002*
B	*traces*

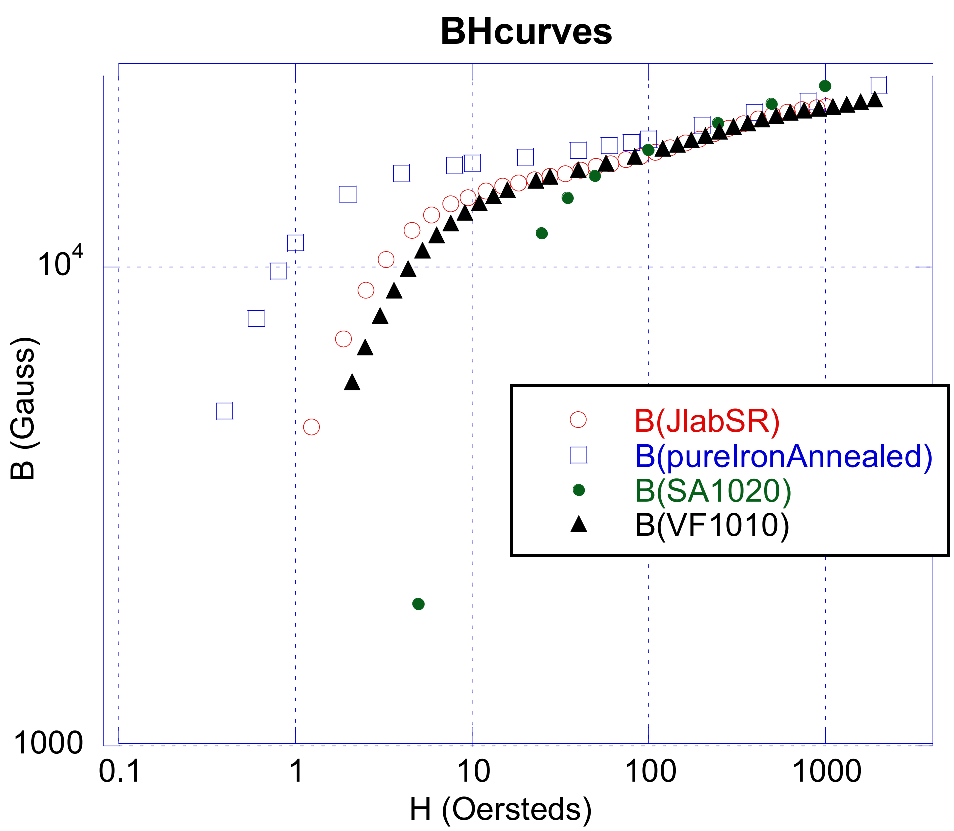


Figure 9 of TN-09-047. JlabSR, two reference BH curves from ANSYS (pure iron and SA1020) and one BH curve from Vector Fields (VF1010) which encompass the required steel chemistry (see below). VF1010 and SA1020 should be harder magnetic materials than JLabSR due to higher carbon content. The multipliers used in this work, maximum 1.03, will not appear on this log-log plot so only the unmodified curve is shown. .

Appendix C - One layer of CLEO steel

I removed the outer octagon and spacer bars. I built an octagon with OR 248.5, deltaR 18.4, Z -266.7 to 209.23. I trimmed-overlap with inner octagon. The nominal thickness of the new layer is 17 cm, about what is needed as starting material for the endcap before rolling. I increased the thickness of the interface between endcap and octagons to 14” (should have been 34 cm, not 35.56, using 17 cm stock). DeltaR needed for overlap (trimmed) with octagon 60 cm. See figure C1. Octagonal steel extends along Y axis from 69.5” (176.53 cm) to 229.584 cm , 53.054 cm thick. Three layers of 17 cm stock instead of one layer of CLEO and one new would increase the field in the steel 4%.

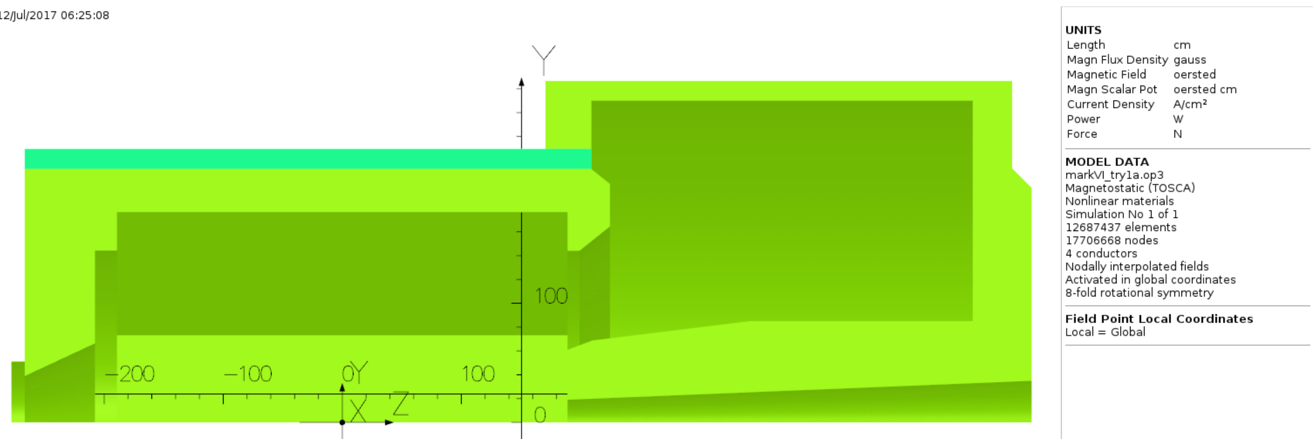


Figure C1. Darker green is new steel replacing outer octagon.

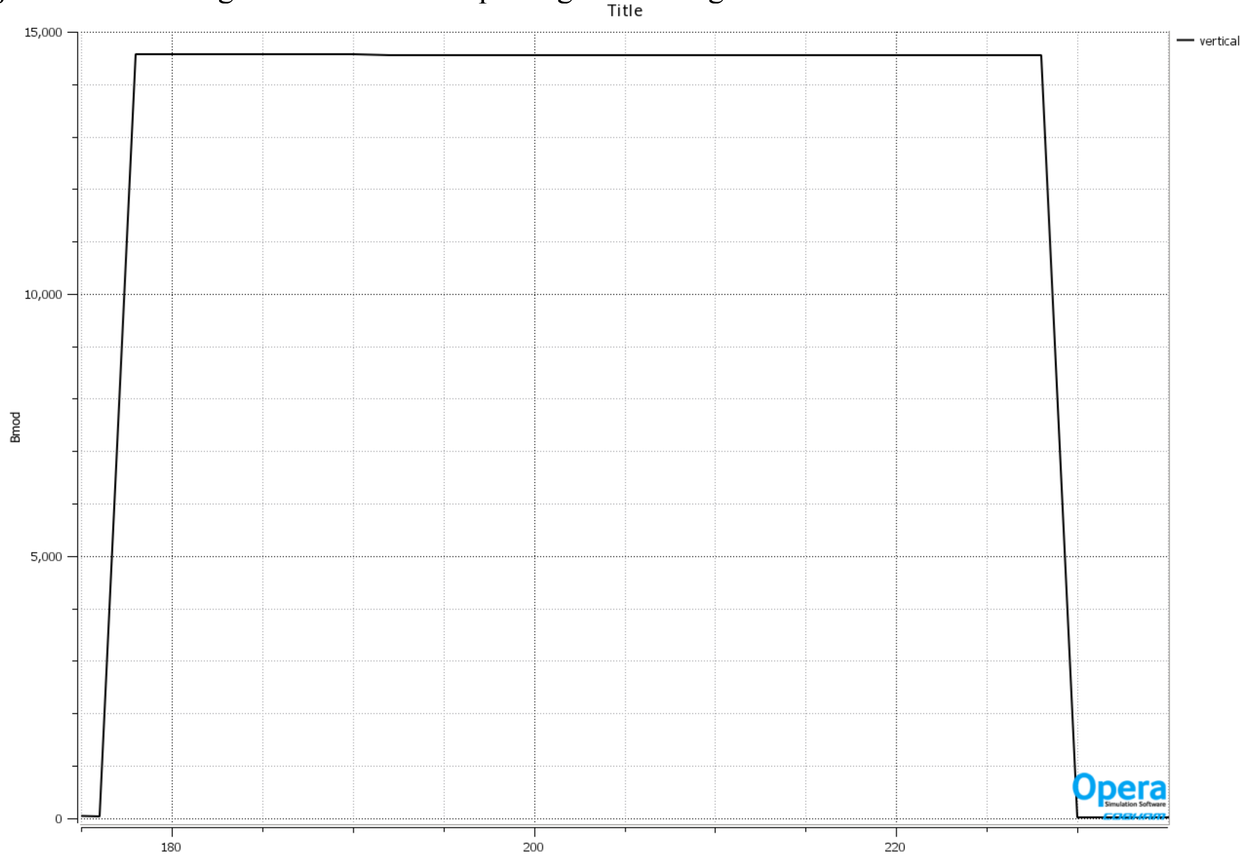


Figure C2. Bmod along vertical line at (x,z) = (0,0). With peak ~1.46T, a 4% increase would not be an issue.

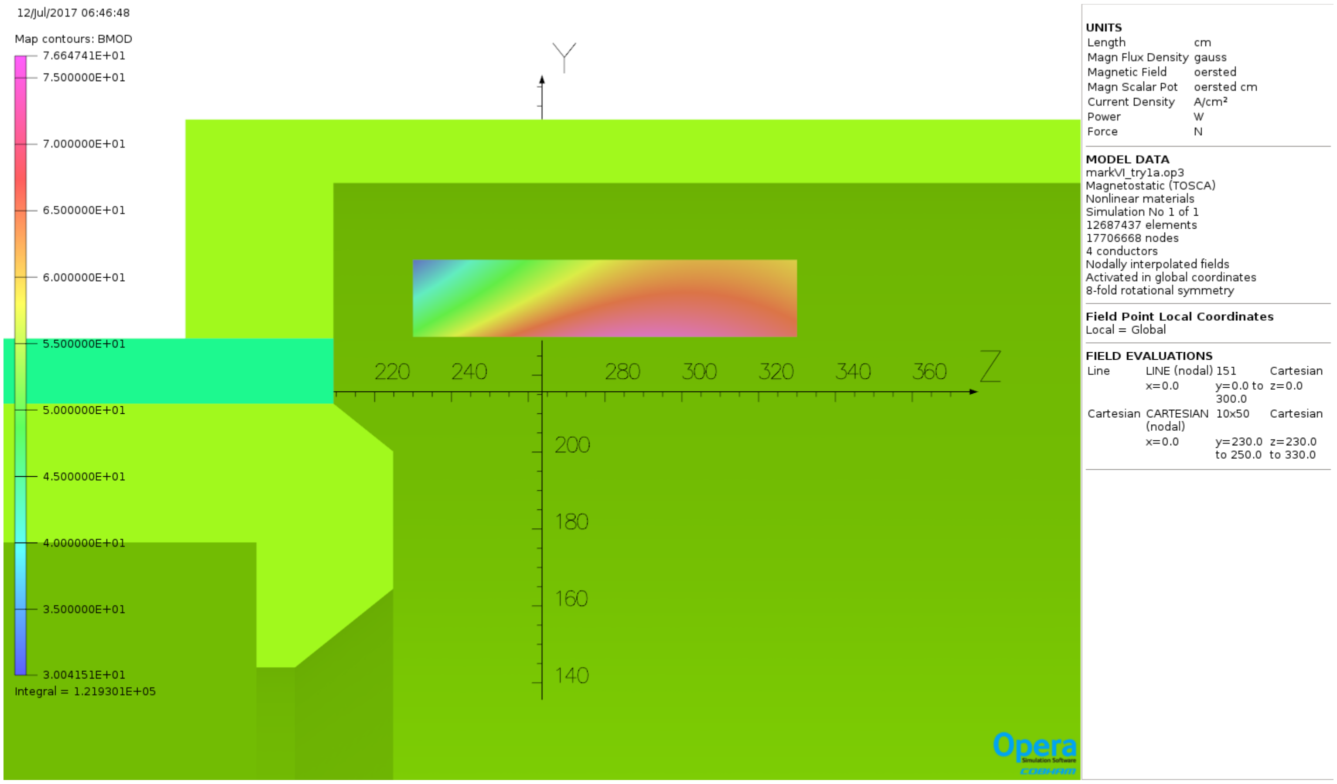


Figure C3. Field in vicinity of gas Cherenkov PMTs. Compare with Figure 9 as this model has double taper on the nose. The volumes in figures 11 and 13 were also checked. Figure 11 volume differed little in this model. Figure 13 differed more: 13.5 G peak in this model vs 10.4 G there. I should have made the back plates out of 17 cm stock instead of 16.51 cm stock. 1010 BH curve.

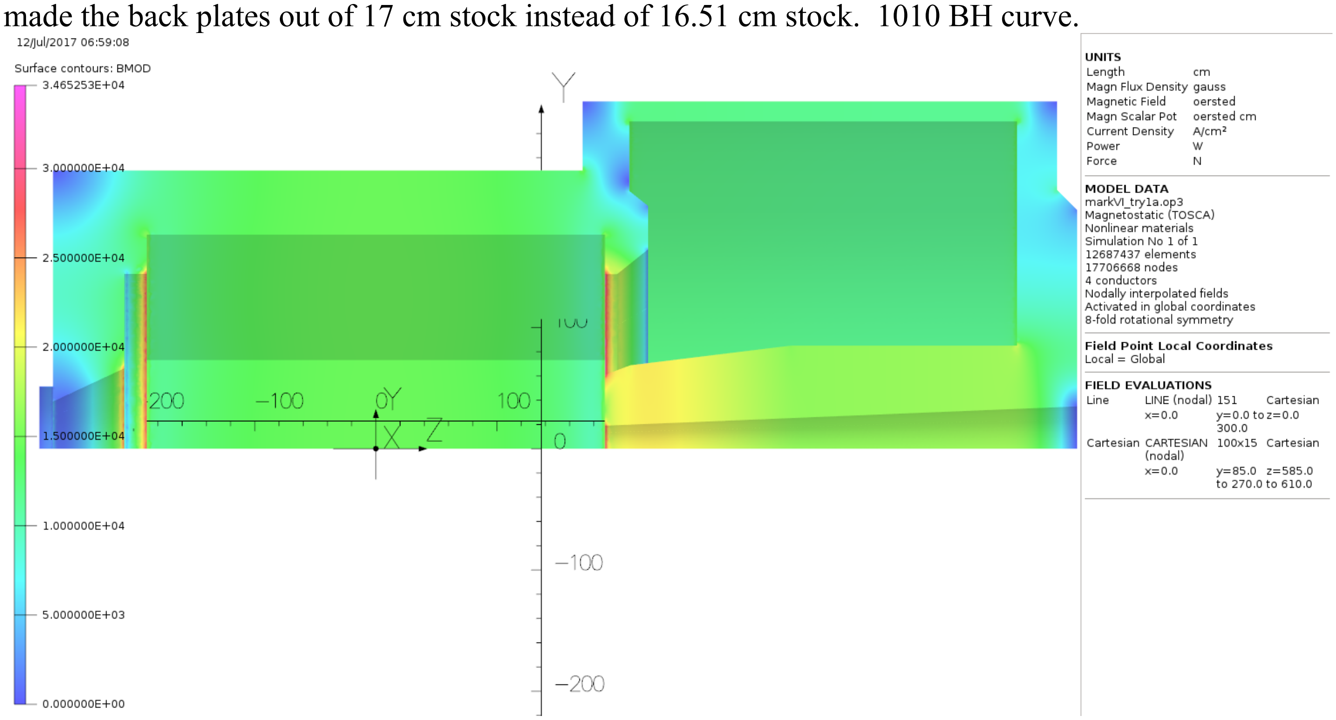


Figure 4. Bmod on surface of model.

Total force on the coils in this model is -17.7 kN, similar to the -19.5 kN determined for the model in the main body with double taper and 1010 steel.

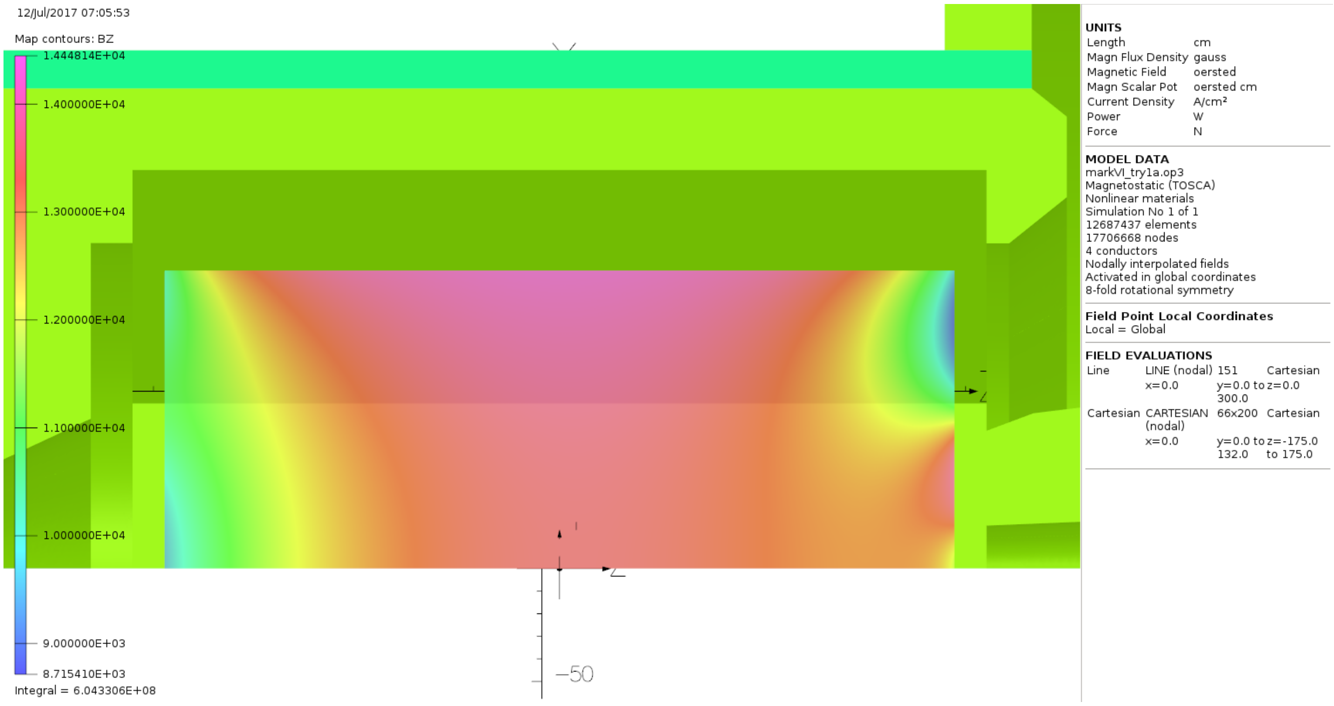


Figure C5. Bz under coil on YZ plane. Double taper on nose is seen clearly here at right.

Appendix C Conclusions

1. Layer one of CLEO steel may be supplemented with eight new 17 cm slabs without affecting the experiment.
2. The $98K of Cornell's latest demand equals the scrap value of 500 tons of steel.
3. SoLID magnet steel may be fabricated from 17 cm thick slabs except for cone (cast in halves) and downstream coil collar (single forging preferred for strength).
4. Buying steel to specification in Appendix B would reduce external stray fields where electronics and PMTs are to be located.

Appendix D - simulating holes in end cap and end plates

I created a new BH curve by multiplying the B in the one in Appendix B by 0.98 and making slight adjustments at the high end to insure B/H >= 1. I assigned the Appendix B curve to most of the steel and the new curve to the end cap and plates where cable holes will be drilled.

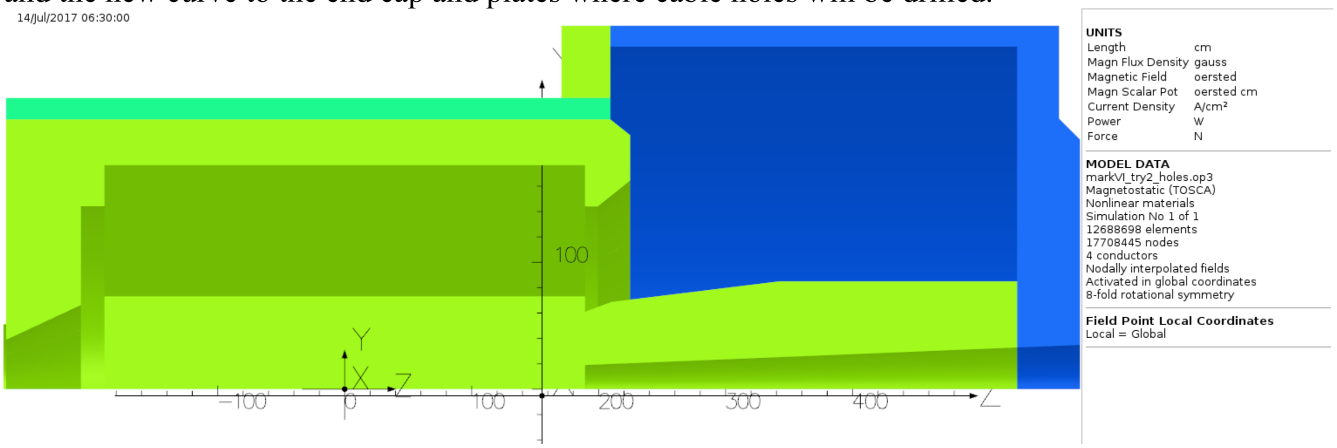


Figure D1. Green steel has SR BH curve of Appendix B. Blue is the curve with 0.98B-H.

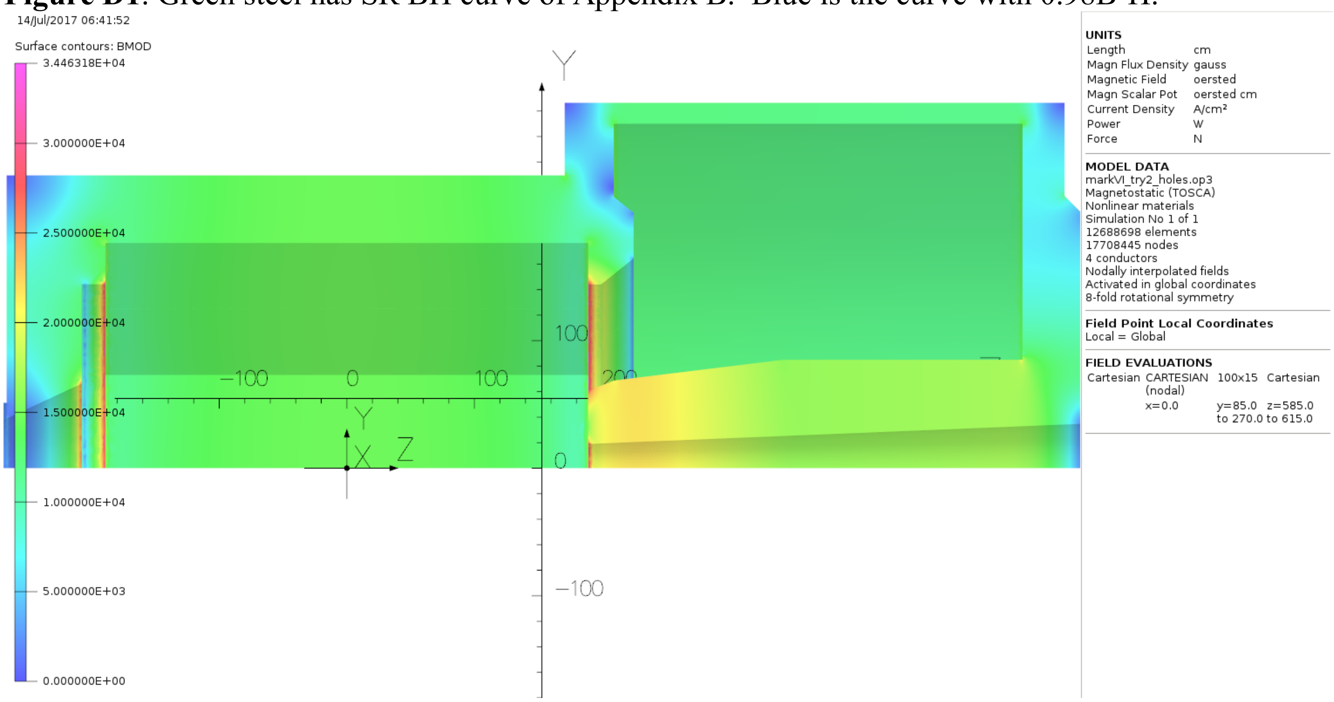


Figure D2. Bmod on surface of model.

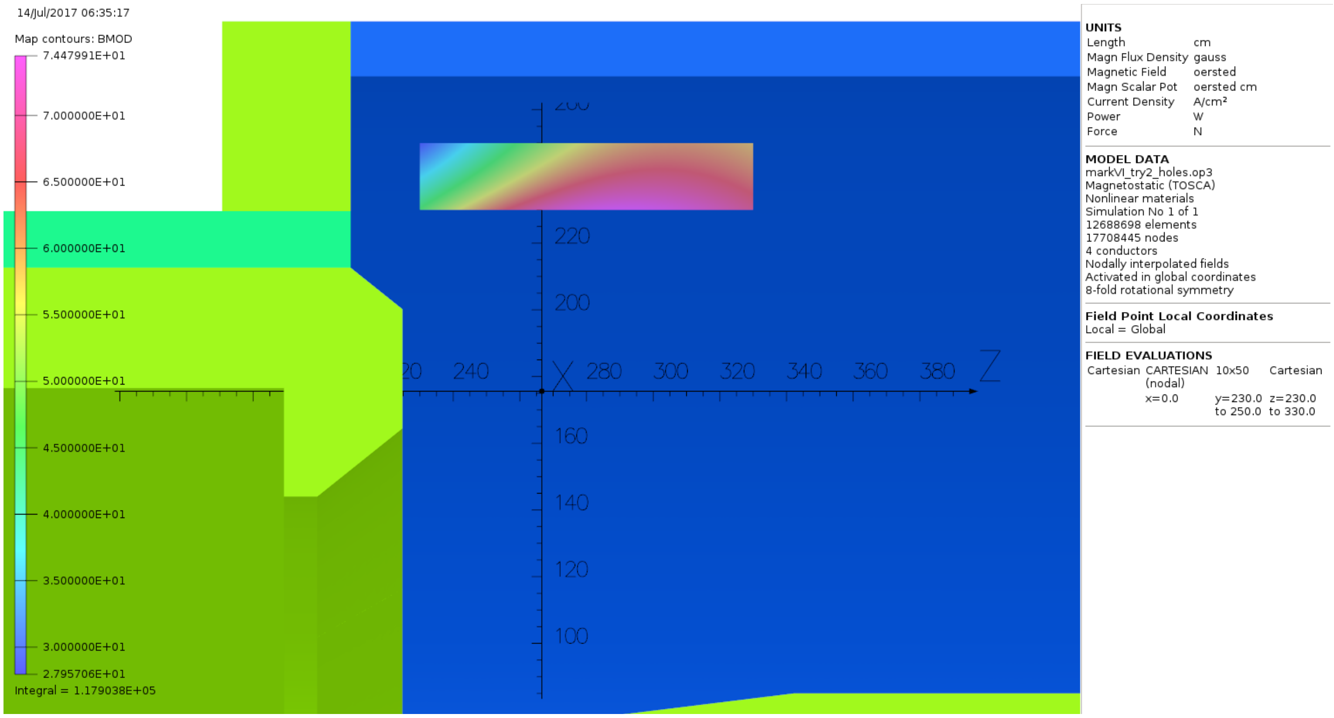


Figure D3. Bmod in vicinity of PMTs for LGC and HGC.

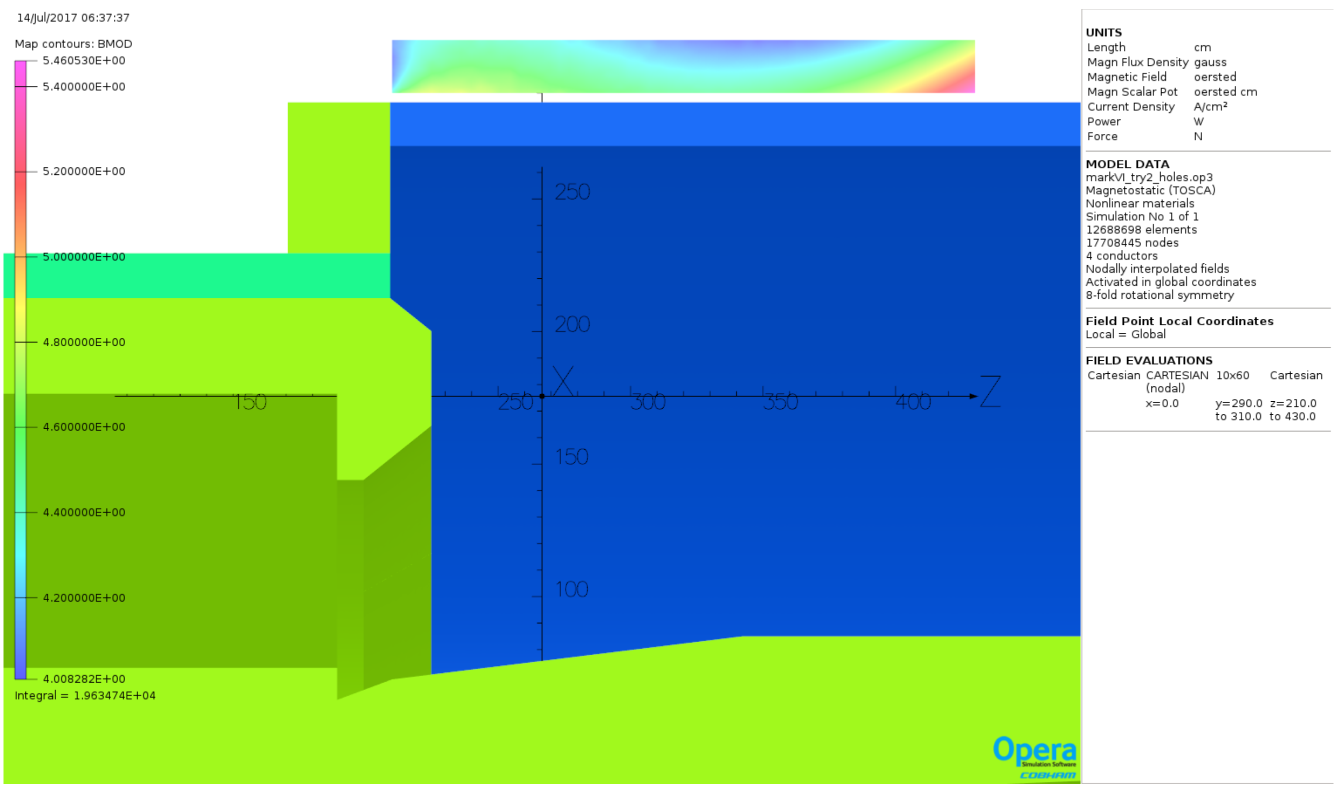


Figure D4. Bmod in vicinity of GEM electronics

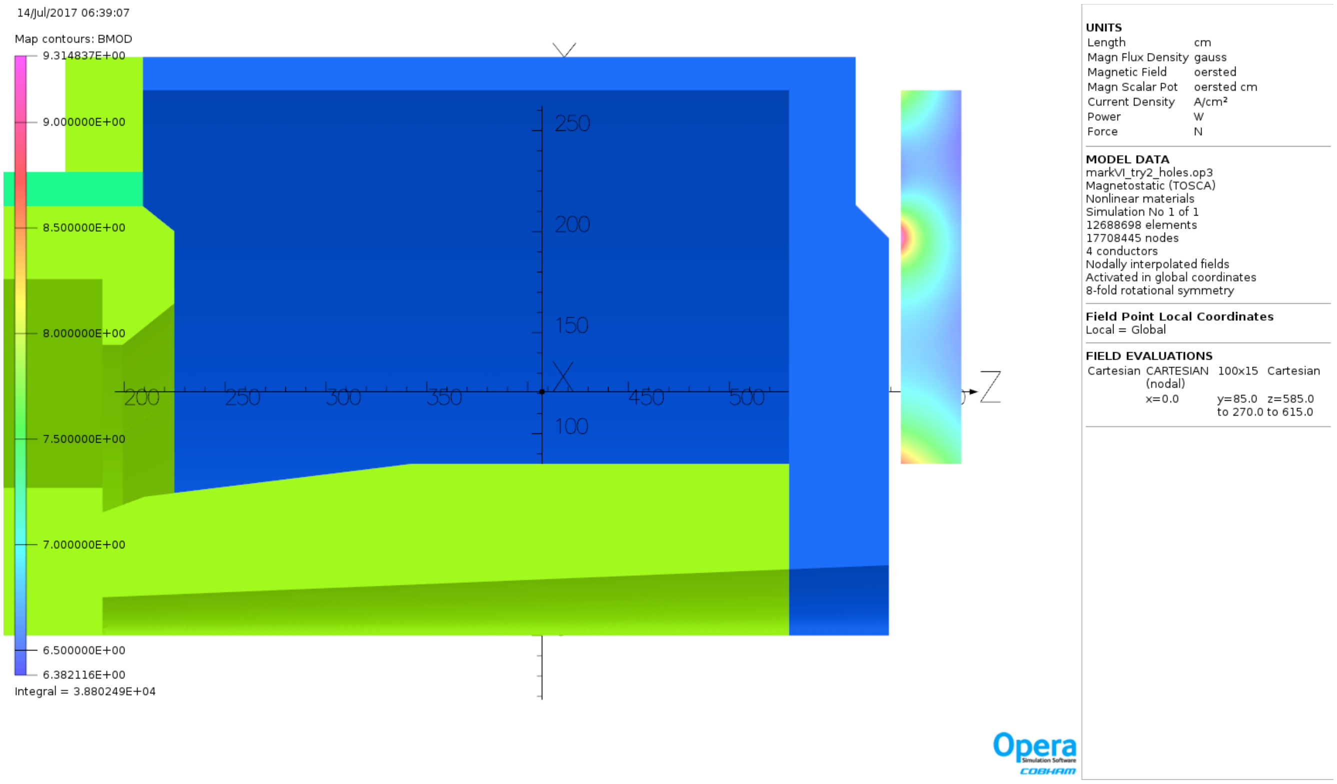


Figure D5. Bmod in vicinity of ECAL PMTs.

Appendix D Conclusion

With steel as specified in Appendix B, a little shielding will be required on PMTs and probably none on the GEM electronics with cable holes comprising 2% of the volume of the end cap.

Appendix E. Alternative meshes

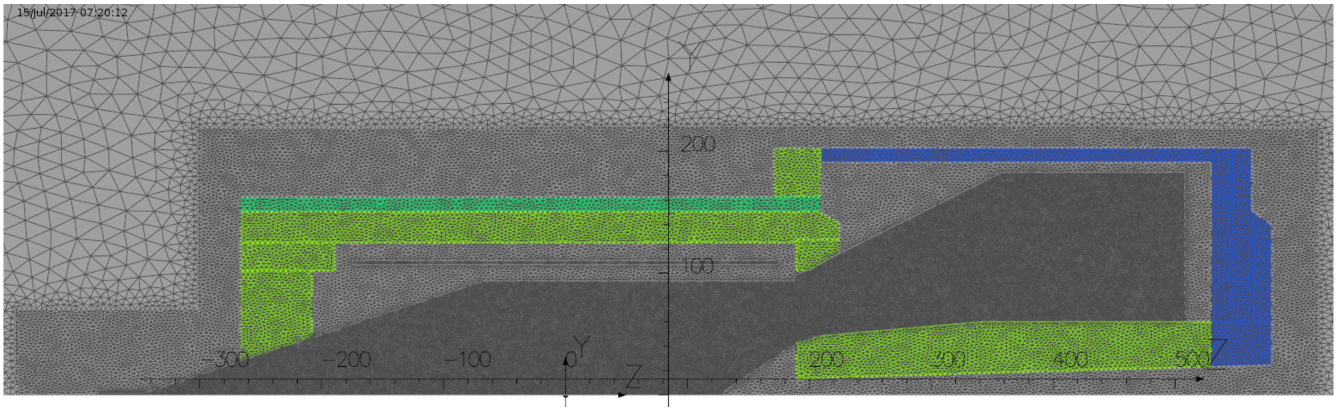


Figure E1. Since I haven't gotten any response to the question on page one I rolled my own.

The dark volume above starts at Z=-350 and expands in a 25º cone until it hits R 132, at which point it turns into a cylinder until Z 188. Starting there I created a 35º cone which continues until it hits R 258. Cylinder thereafter. I trimmed overlap between this “detector air”, the steel nose and the air inside the nose. I created another cone in front of the nose, Z130 R4 to Z189.23 R61 and subtracted it from the finer mesh volume as well. I added a R2 cylinder Z -380 to -320 to encompass the long He3 target.

This volume assumes that tracking neutrons or muons going through the steel needs less precision than the particles which hit the detectors directly from either target. This mesh has 236M non-zeroes, 10M fewer than the one on page 1. Every little bit helps. The image is viewed from -X and the plane shown is at a 45º angle so the Y axis values need to be multiplied by √2. Z values are correct. The 100 cm radius cylinder in medium grey at left is provision for future insertion of the three Helmholtz pairs around the He3 target. When I break the eight-fold symmetry this model will require about 100 GB of RAM and take perhaps two weeks to solve. It will reach about seven-eighths of Opera's theoretical maximum; I'm not sure anyone has ever gotten that close. Even a modest reduction in the outer radius, R258, would help.

Is any of the dark volume with 2 cm mesh in figures E1 or E2 unnecessary for tracking/simulation?

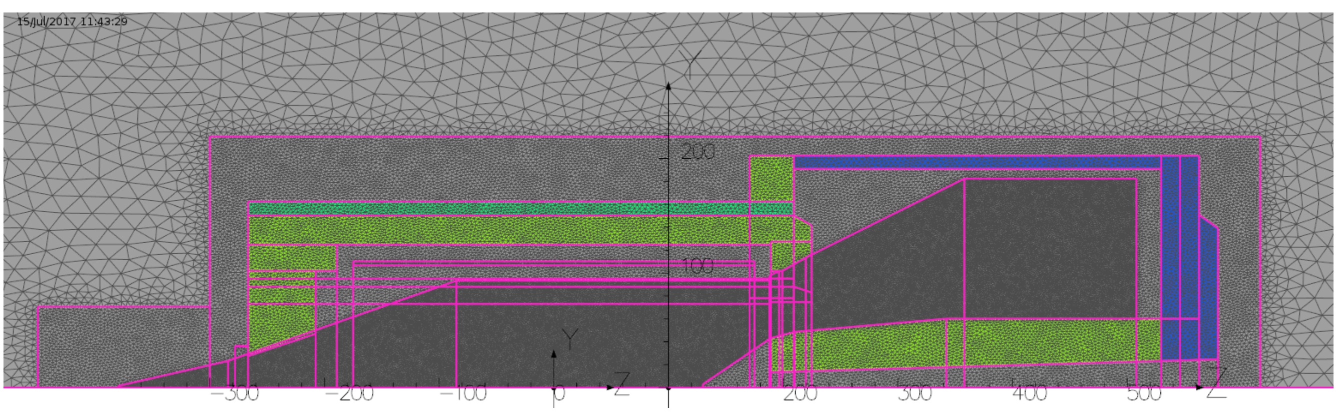


Figure E2. Cones were added to extend acceptance to a 60 cm long upstream target 2 cm in radius and a 40 cm target centered at Z=10. This model has 237M non-zeroes in the matrices, only 9M less than figure 1. 77.2% of Opera nominal maximum when symmetry is broken.

Appendix F : Static potential plots for model shown in figure E2; more on alternate meshes

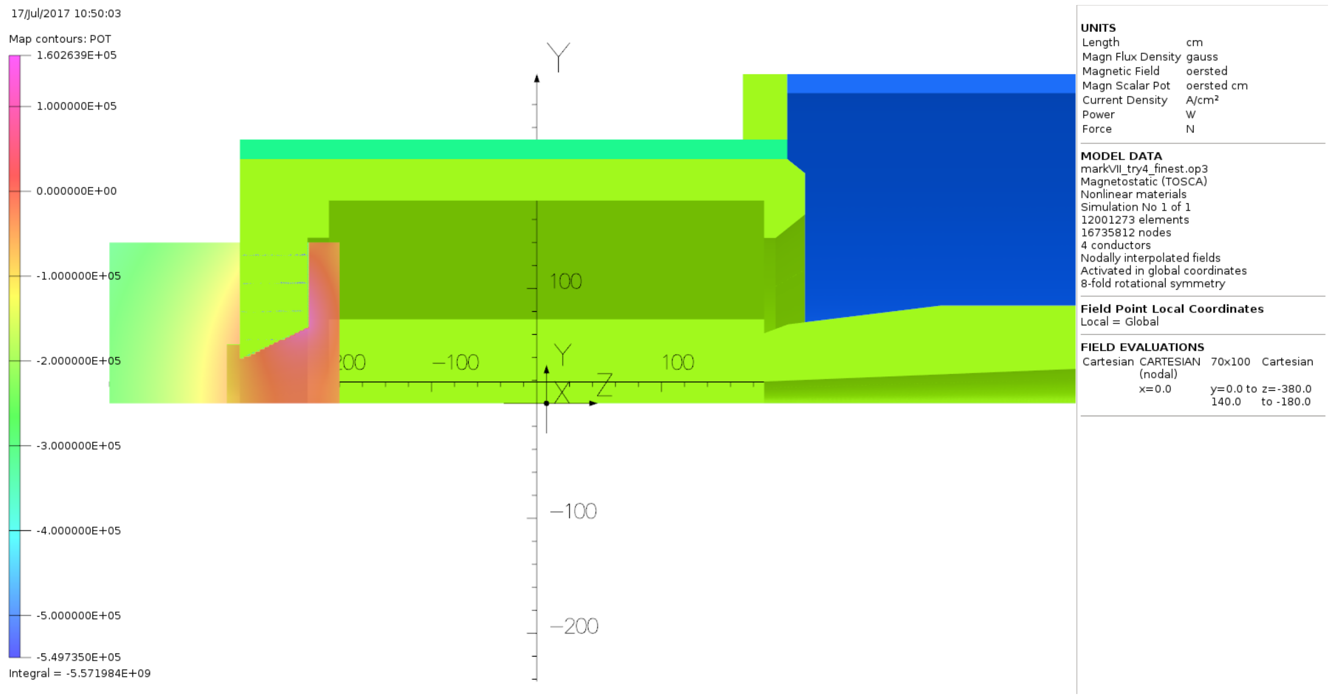


Figure F1. Magnetic scalar potential in oersted-cm from target upstream end to just before solenoid. See Field Evaluation block at right of figure for location of plane.

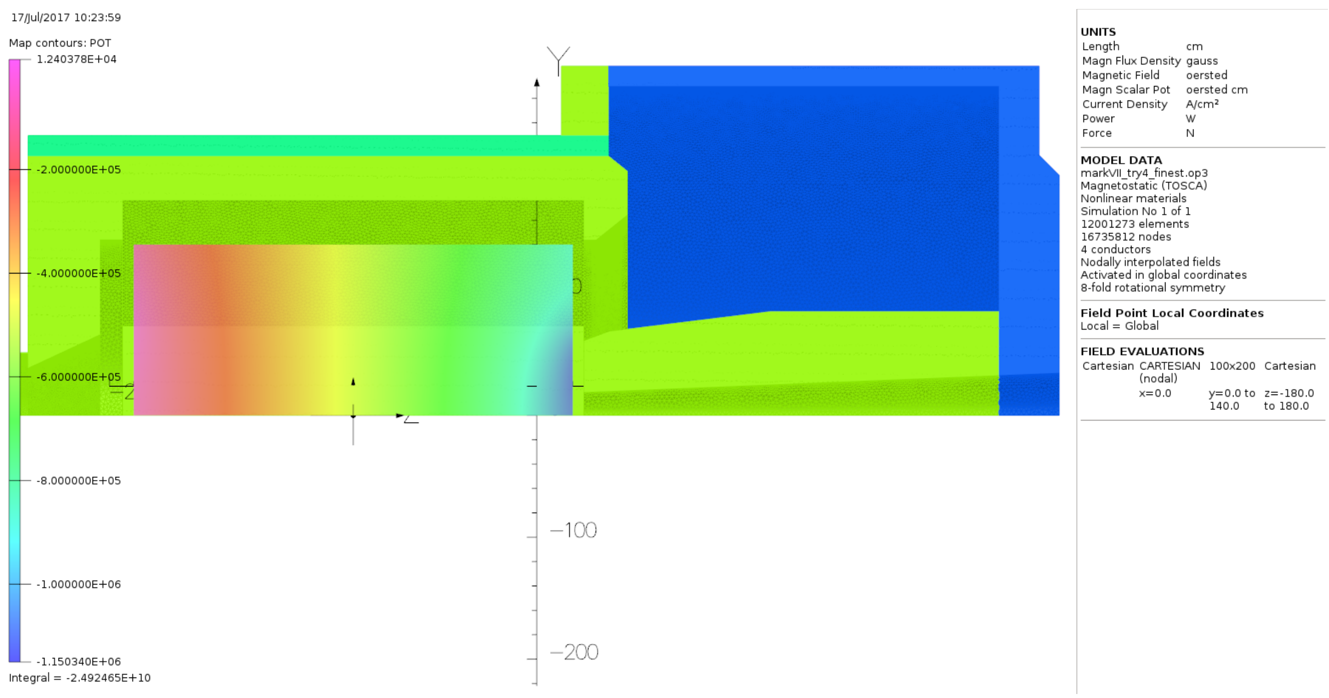


Figure F2. Next segment of potential.

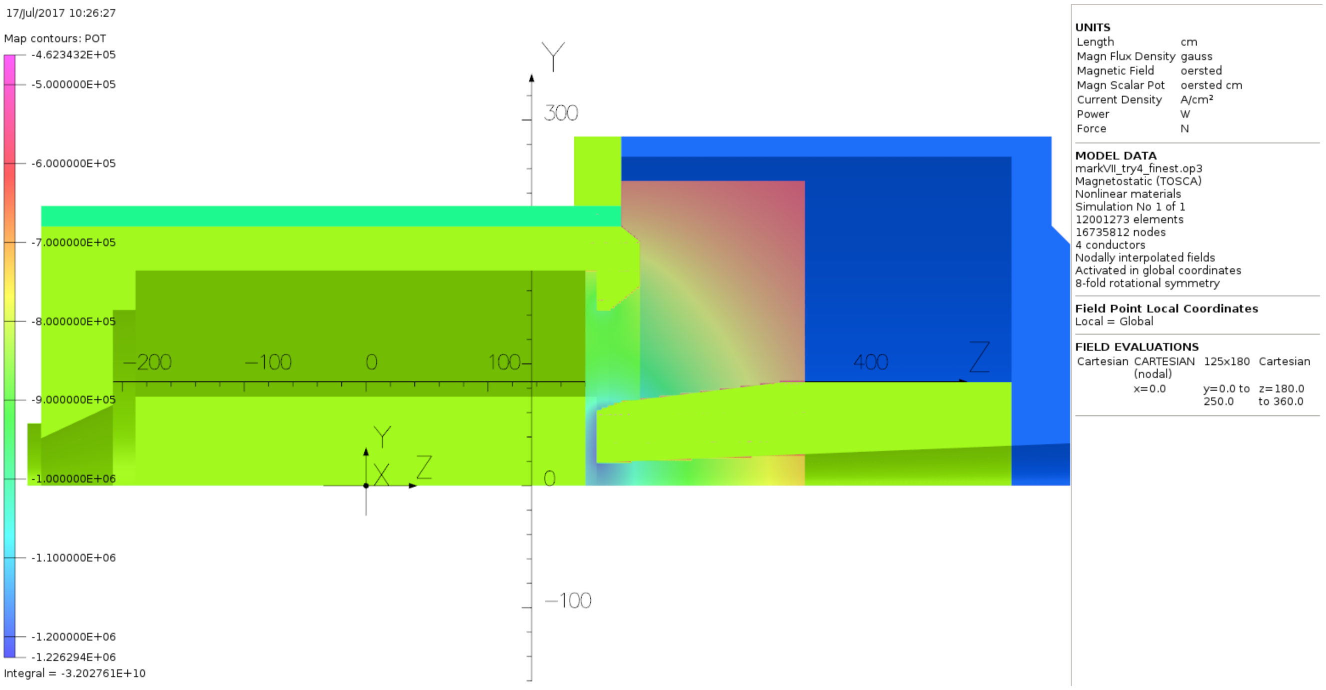


Figure F3. This one covers the span between figures 2 and 5 with no overlap.

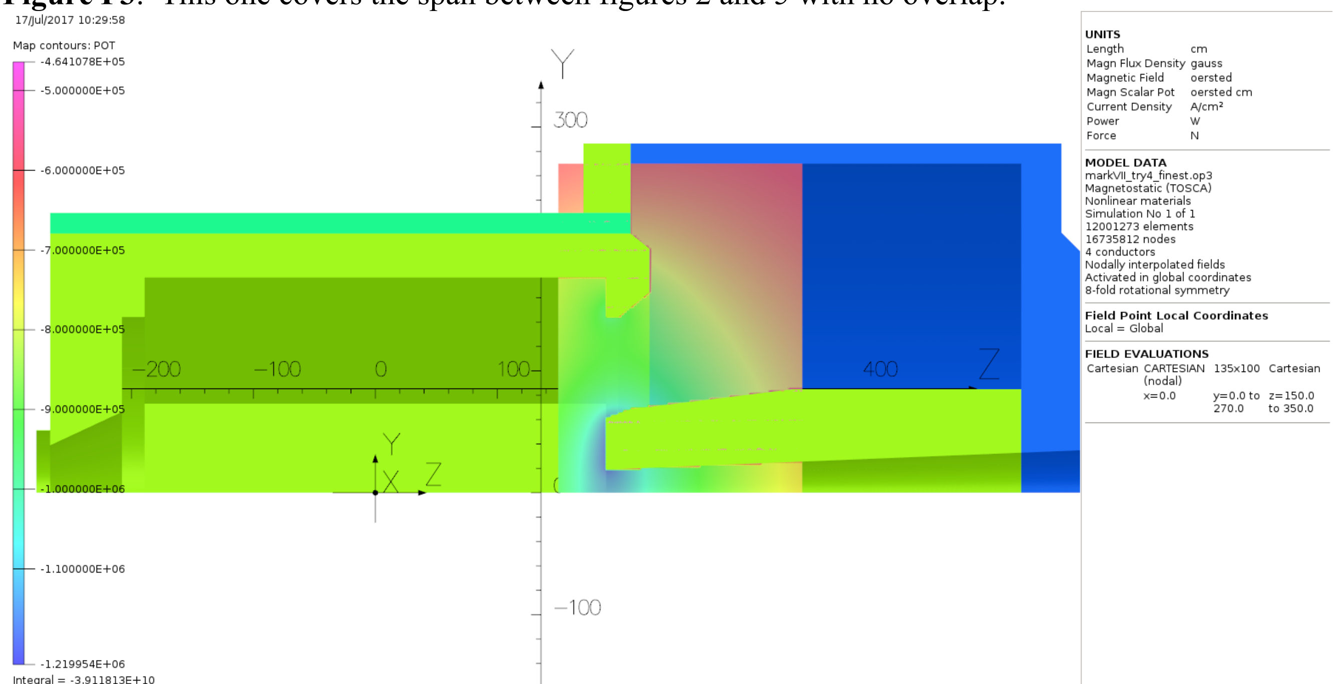


Figure F4. This covers Z=[150,350] vs [180,380] above and so better shows the variation around the nose.

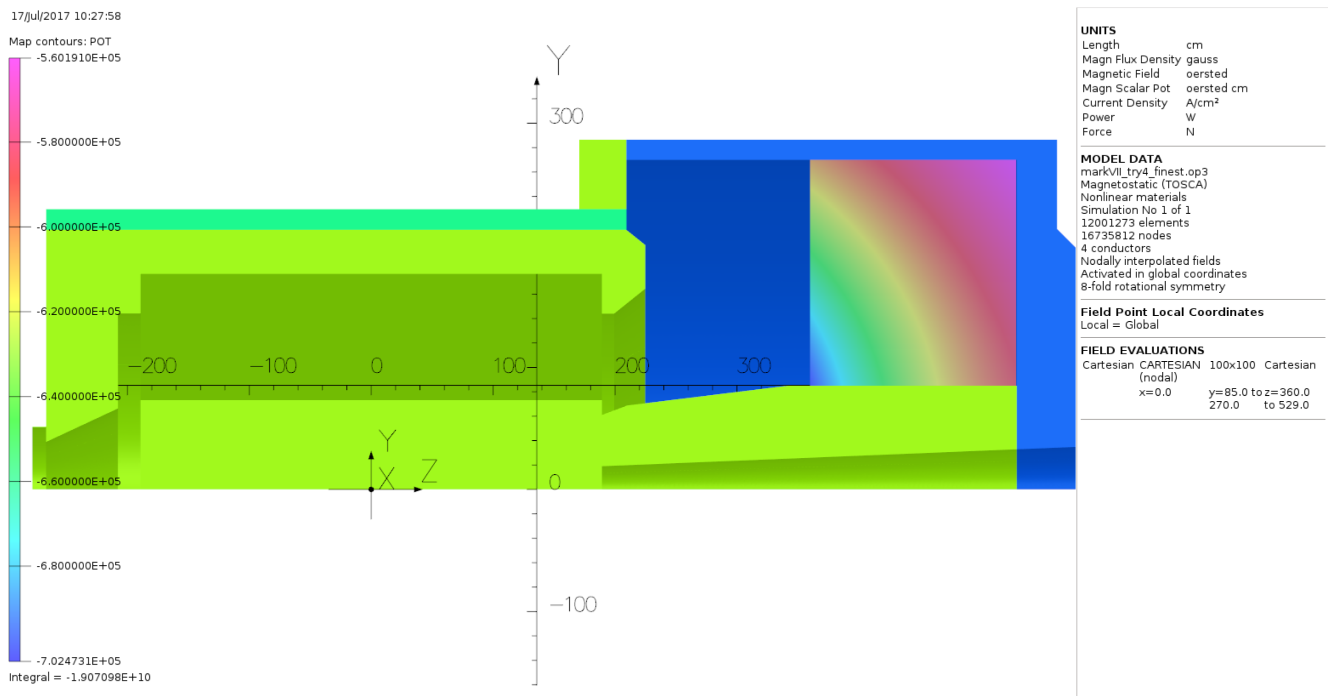


Figure F5. This covers the last of the end cap.

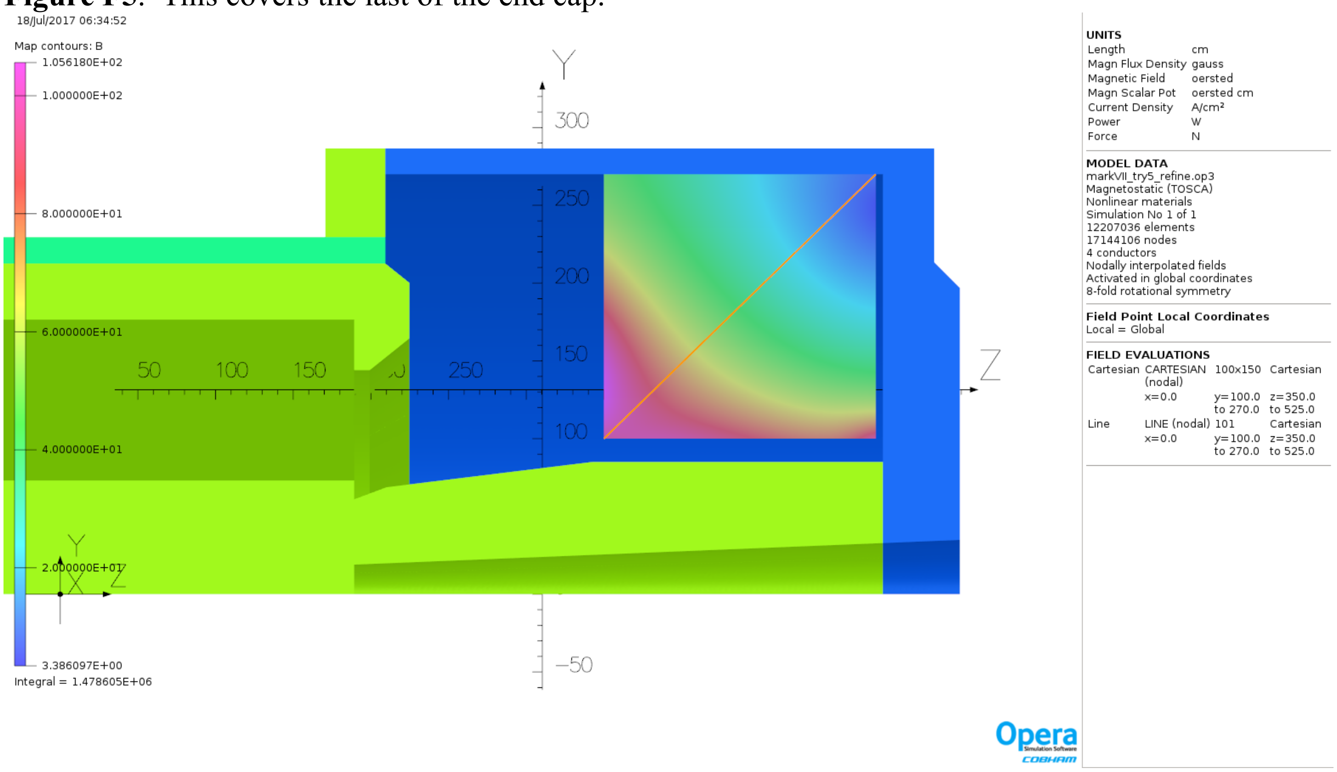


Figure F6. B in region slightly smaller than that above, with orange line along which I plotted B in the next figure. Since the field gradients shown are under 0.5 G/cm I will set this region back to 4 cm mesh from 2 cm mesh in figure E2. R=[100,270] Z=[350,525].

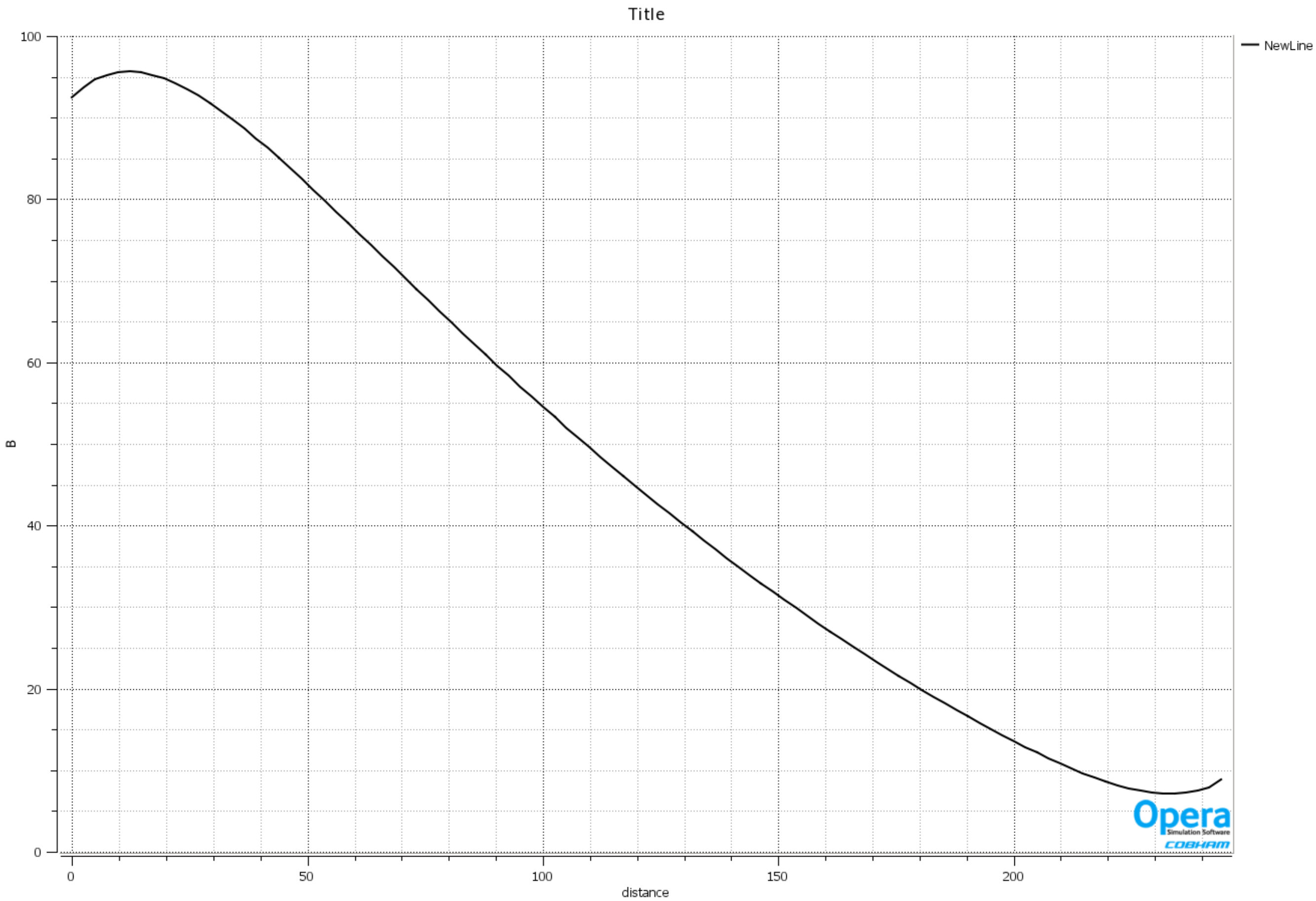


Figure F7. Field magnitude B along the orange line in figure F6.

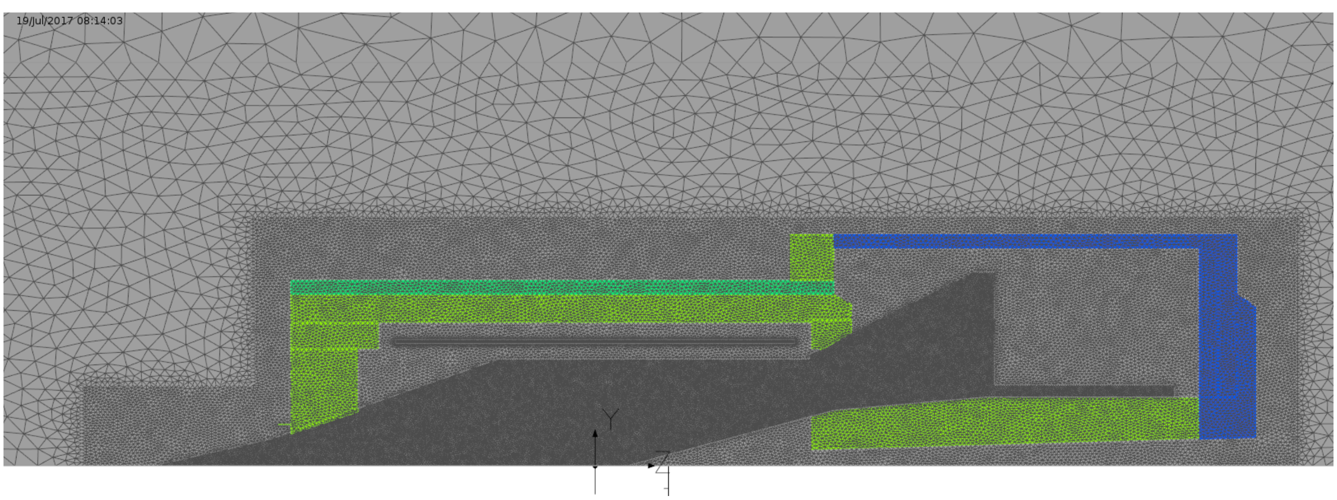


Figure F8. Mesh resulting when area explored in figures F6 and F7 is set back to 4 cm. Again, this is looking at an eighth of the model so the vertical dimensions must be mutiplied by √2. Compare with figure E2. The thin dark band just under the thick steel encapsulates the solenoid coil. A model with 2 cm maximum mesh there has 1.18E9 non-zeroes in its matrices, 55% of Opera's capability. I have also prepared models with 1.67 cm, 1.35 cm, 1 cm and 0.8 cm maximum mesh for solenoid. They took 5-10 days each to run. 1.67 cm: 1.22E9 non-zeroes. 1.34 cm: 1.3E9 non-zeroes. 1 cm: 1.5E9 non-zeroes. 0.8 cm: 1.81E9 non-zeroes, 84% of Opera's capability.

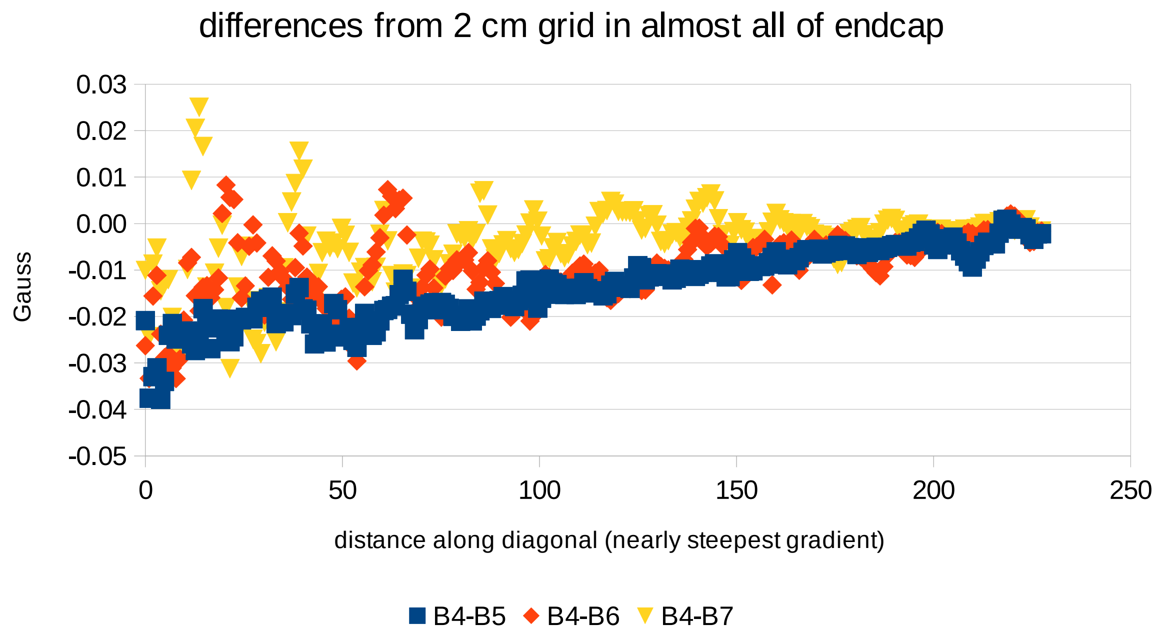


Figure F9. I made four rotationally symmetric models with successively larger volumes of 4 cm mesh and no other changes, labeled try4 to try7. Here I show the pairwise difference in Gauss along the line of figures F6 and F7 in the region in which detectors will be placed.

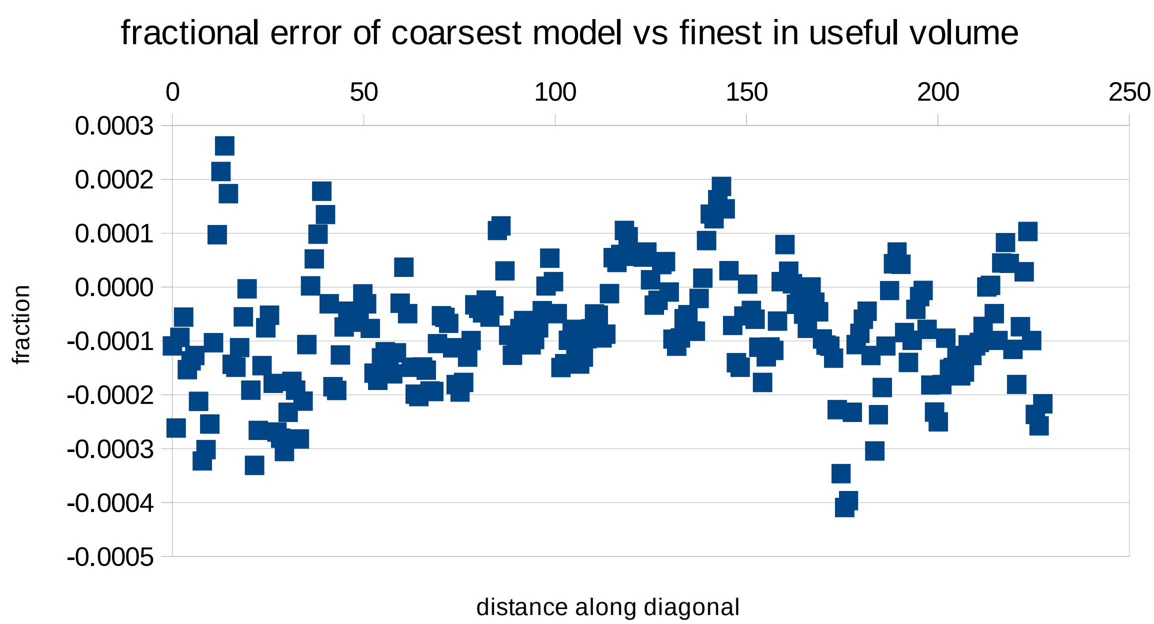


Figure F10. Here is the fractional error for B4-B7. The error is small enough in both absolute and fractional terms to be well worth the reduction in model size and computation time.

Appendix G: mesh size around solenoid coil

As shown in Appendix A, the coils are surrounded by air, OR 156 cm, thickness 5 cm, Z -175 to 175 cm. In Appendix A mesh maximum is given as 2 cm. In 4Q16 I ran a number of models with symmetric steel/coils but without imposing the eight-fold symmetry. I learned that 2 cm mesh around the coil was not sufficient for 10% confidence in forces/torques on the coil when the symmetry was broken by the turret cut-out. I created five models with the mesh of figure F8 varying the mesh maximum in the air around the solenoid coil: 2 cm, 1.67 cm, 1.34 cm, 1 cm and 0.8 cm. These take 1.5 to 3.5 days to prepare and 3.5 to 6.3 days each to solve. X and Y forces and torques should be zero from symmetry. They are not because the mesh is not symmetric. An attempt last fall by Vector Fields support to divide the volume into eight segments was halted after two days of model preparation by a disk failure at their facility. I tried it and didn't have sufficient RAM. Thus the route described. Coil 4 is the upstream stray field suppression solenoid. Coils 1 and 3 are end segments of the solenoid with higher current density than the center.

2 cm mesh model	X	Y	Z	
Total force on coil 1 =	452	131	2964803	N
Total torque on coil 1 =	19769	-68773	0	N-cm
Total force on coil 2 =	905	-586	71222	N
Total torque on coil 2 =	-34853	17857	0	N-cm
Total force on coil 3 =	383	-234	-3031180	N
Total torque on coil 3 =	30333	48235	0	N-cm
Total force on coil 4 =	0	0	56	N
Total torque on coil 4 =	79	20	0	N-cm
Total force on all coils =	1740	-689	4900	N
Total torque on all coils =	15328	-2661	0	N-cm

NB: upstream plug thickness was not adjusted by 1 mm to minimize the Z force when the BH curve was changed so ~5000 N Z net is expected.

1.67 cm mesh model	x	y	z	
Total force on coil 1 =	103	-37	2965454	N
Total torque on coil 1 =	-15079	-12859	0	N-cm
Total force on coil 2 =	-357	511	71235	N
Total torque on coil 2 =	-10330	-13460	0	N-cm
Total force on coil 3 =	-176	-56	-3031065	N
Total torque on coil 3 =	5937	-33589	0	N-cm
Total force on coil 4 =	0	0	56	N
Total torque on coil 4 =	-61	-27	0	N-cm
Total force on all coils =	-430	418	5680	N
Total torque on all coils =	-19533	-59934	0	N-cm

If mesh were sufficient, there wouldn't be such wide swings in transverse torques.

1.34 cm mesh model, nodal 32,4,32				
Total force on coil 1 =	239	-59	2965881	N
Total torque on coil 1 =	-9783	-35421	0	N-cm
Total force on coil 2 =	-673	408	71216	N
Total torque on coil 2 =	-29496	-13106	0	N-cm
Total force on coil 3 =	-59	-18	-3031650	N
Total torque on coil 3 =	1308	-9300	0	N-cm
Total force on coil 4 =	0	0	56	N
Total torque on coil 4 =	-22	14	0	N-cm
Total force on all coils =	-494	331	5503	N
Total torque on all coils =	-37993	-57814	0	N-cm

1 cm mesh, nodal 32,4,32			
Total force on coil 1 =	-187	-23	2965879
Total torque on coil 1 =	-7773	25032	0
Total force on coil 2 =	-89	-303	71227
Total torque on coil 2 =	18906	-7347	0
Total force on coil 3 =	35	38	-3031966
Total torque on coil 3 =	401	115	0
Total force on coil 4 =	0	0	56
Total torque on coil 4 =	-74	-40	0
Total force on all coils =	-240	-288	5196
Total torque on all coils =	11460	17760	0

1 cm mesh, nodal 32,4,32, faces 2 cm mesh			
Total force on coil 1 =	233	-380	2960959
Total torque on coil 1 =	-21908	-32091	0
Total force on coil 2 =	162	-214	70790
Total torque on coil 2 =	7815	16998	0
Total force on coil 3 =	-96	17	-3030756
Total torque on coil 3 =	-8900	-11446	0
Total force on coil 4 =	0	0	56
Total torque on coil 4 =	-11	74	0
Total force on all coils =	299	-577	1048
Total torque on all coils =	-23004	-26465	0

Note the sign changes in the two tables above with same mesh except on steel faces.

0.8 cm mesh, nodal 32,4,32			
Total force on coil 1 =	109	27	2965875
Total torque on coil 1 =	1870	-14344	0
Total force on coil 2 =	53	218	71220
Total torque on coil 2 =	-1087	-12141	0
Total force on coil 3 =	138	180	-3031893
Total torque on coil 3 =	-28356	16230	0
Total force on coil 4 =	0	0	55
Total torque on coil 4 =	70	117	0
Total force on all coils =	299	425	5257
Total torque on all coils =	-27504	-10138	0

While the transverse forces are low in all but the coarsest mesh model, the torques are still larger than I'd like. Recall that transverse forces and torques are all supposed to be zero because the model has eightfold symmetry about the Z axis, coils and steel. The point of this exercise is to determine how fine a mesh is required to obtain reasonable B fields when I break the symmetry with the service turret. Last December the difference in torques between a symmetric and asymmetric model was 180 kN-cm so the numbers above imply 20% accuracy in torque; I'd really like to do better.

mesh	transverse torque sum in quadrature N-cm
2	99503
1.67	42942
1.34	49803
1	33145
0.8	37754

Units: 1 lbf-ft=135.58 N-cm

There's an irritating non-monotonicity in torque. I therefore explored the “integration” method of calculating fields/forces. I normally use nodal interpolation because integration takes about a thousand times as long. The values above took 4-18 minutes to calculate after a model was loaded in an interactive session. Those below, while closer to zero, took 5-10 hours in a session initiated via CLI and used 1/64 the number of points, the documentation recommendation. I don't think integration is a viable method for producing simulation field maps with cm steps because I'm not sure my Linux box would remain up for the months required. I have enough RAM to let it perk away in the background so I may try it anyway. Since the license server gets interrupted by the monthly CC maintenance this may crash - I've had this happen thrice in 2017 with large models.

2 cm mesh model, integ 8,1,8	**X**	**Y**	**Z**	
Total force on coil 1 =	-7	23	2973437	N
Total torque on coil 1 =	6961	2034	0	N-cm
Total force on coil 2 =	5	43	70909	N
Total torque on coil 2 =	-3493	-2397	0	N-cm
Total force on coil 3 =	23	26	-3040508	N
Total torque on coil 3 =	-7430	1890	0	N-cm
Total force on coil 4 =	0	0	119	N
Total torque on coil 4 =	38	23	0	N-cm
Total force on all coils =	22	93	3957	N
Total torque on all coils =	-3925	1550	0	N-cm
add in quadrature torques	10764	3668		
all transverse torques	11372			

1.67 cm mesh model, integ 8,1,8		*nice*		
Total force on coil 1 =	30	34	2974236	N
Total torque on coil 1 =	6763	-4783	0	N-cm
Total force on coil 2 =	33	34	70999	N
Total torque on coil 2 =	2720	-1346	0	N-cm
Total force on coil 3 =	43	-3	-3040647	N
Total torque on coil 3 =	-1829	3549	0	N-cm
Total force on coil 4 =	0	0	118	N
Total torque on coil 4 =	-106	30	0	N-cm
Total force on all coils =	106	63	4706	N
Total torque on all coils =	7548	-2551	0	N-cm
add in quadrature torques	7516	6106		
all transverse torques	9683			

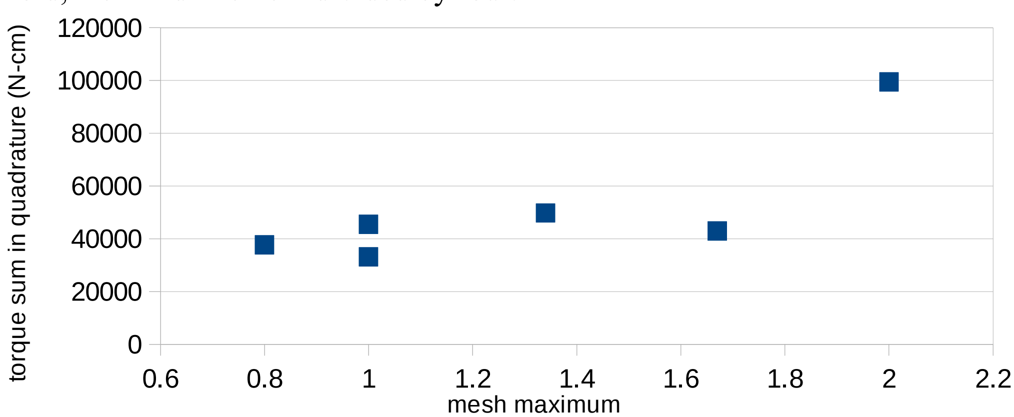
1.34 cm mesh model, integ 8,1,8				
Total force on coil 1 =	-39	-3	2973349	N
Total torque on coil 1 =	1494	3495	0	N-cm
Total force on coil 2 =	-24	-1	70899	N
Total torque on coil 2 =	-1251	-3501	0	N-cm
Total force on coil 3 =	2	0	-3040470	N
Total torque on coil 3 =	-514	-3013	0	N-cm
Total force on coil 4 =	0	0	119	N
Total torque on coil 4 =	-110	4	0	N-cm
Total force on all coils =	-61	-5	3896	N
Total torque on all coils =	-381	-3015	0	N-cm
add in quadrature torques	2018	5792		
all transverse torques	6134			

1 cm mesh model, integ 8,1,8			
Total force on coil 1 =	-24	-20	2973333 N
Total torque on coil 1 =	-7162	6404	0 N-cm
Total force on coil 2 =	-40	-29	70884 N
Total torque on coil 2 =	1423	-510	0 N-cm
Total force on coil 3 =	1	9	-3040473 N
Total torque on coil 3 =	3583	-3001	0 N-cm
Total force on coil 4 =	0	0	119 N
Total torque on coil 4 =	-19	-109	0 N-cm
Total force on all coils =	-63	-40	3862 N
Total torque on all coils =	-2175	2785	0 N-cm
add in quadrature torques	8134	7092	
all transverse	10791		

0.8 cm mesh model, integ 8,1,8			
Total force on coil 1 =	-17	-7	2973279 N
Total torque on coil 1 =	-1099	949	0 N-cm
Total force on coil 2 =	-32	-23	70870 N
Total torque on coil 2 =	1878	-4680	0 N-cm
Total force on coil 3 =	-12	-26	3040484 N
Total torque on coil 3 =	5982	-7496	0 N-cm
Total force on coil 4 =	0	0	118 N
Total torque on coil 4 =	0	-8	0 N-cm
Total force on all coils =	-62	-57	3784 N
Total torque on all coils =	6760	-11235	0 N-cm
add in quadrature torques	6366	8888	
all transverse	10932		

With integration, all of the meshes except 1.34 cm maximum give roughly the same results. The model with 1 cm maximum mesh around the coil has 1.5E9 non-zeroes in its matrices, 70% of the maximum allowed by Opera. It peaked at 86 GB of RAM. The 0.8 cm maximum mesh around the coil took a sixth of a day to mesh; model database creation 3.25 days, and the solution 6.33 days. Peak RAM 106 GB; 84% of Opera maximum non-zeroes. It is no better than the 1 cm model. For the results excluding 1.34 cm, mean transverse torque sum in quadrature 10700 N-cm (79 lbf-ft), std dev 718 N-cm. Units: 1 lbf-ft=135.58 N-cm. For all six integration results, Z force mean 3740 N, std dev 650 N.

When the nodal interpolation results for the six models are plotted one sees something similar: all the meshes except 2 cm give about the same transverse torque sum in quadrature. I may try 1.25 cm around solenoid, 5 cm radial extent divided by four.



Appendix H - New octagonal steel

The model below was solved with eight-fold symmetry. The octagonal steel is 51 cm thick, 3*17. It is solid in the model rather than having the air gaps which will occur with real fabrication. JLab will not get CLEO steel beyond the coil collars. Unfortunately, as demonstrated by drawing AJE060 in http://hallaweb.jlab.org/12GeV/SoLID/download/cleo_manual/20120314%20Accelerator%20SCANS/Box%203%20-%20Oxford%20Instruments%20Limited/ , the cryostat is adapted to an octagonal mounting shell so it is likely that we must continue to make an octagonal piece rather than, say, casting 12 30° segments incorporating both coil collars.

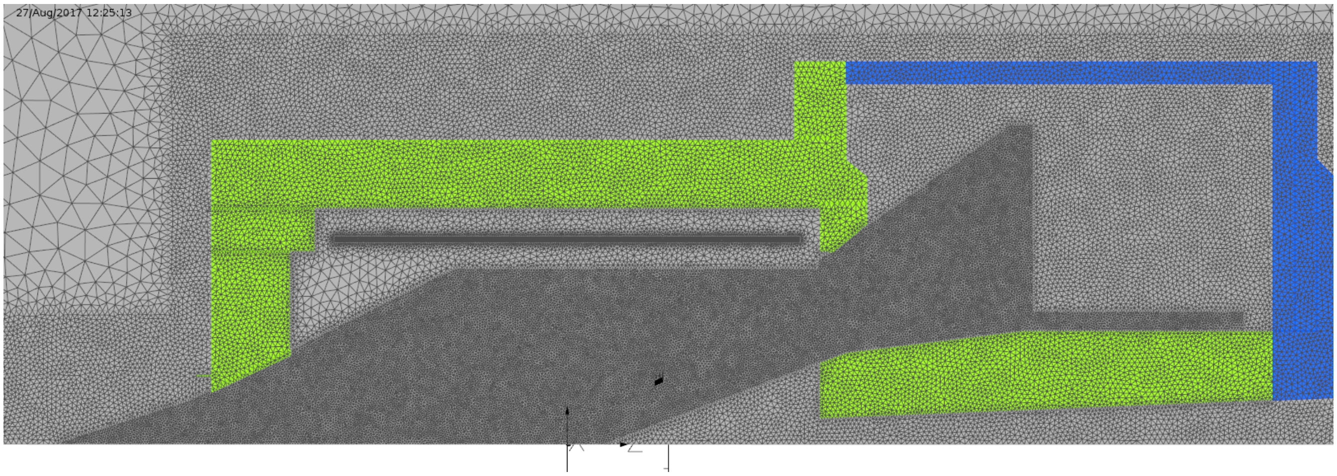


Figure H1. MarkVII_try8 mesh. 2 cm mesh imposed on all inside faces of the steel in the solenoid "compartment" is the only difference with that of Figure F8. Air around the solenoid is meshed at 1 cm maximum given results of Appendix G.

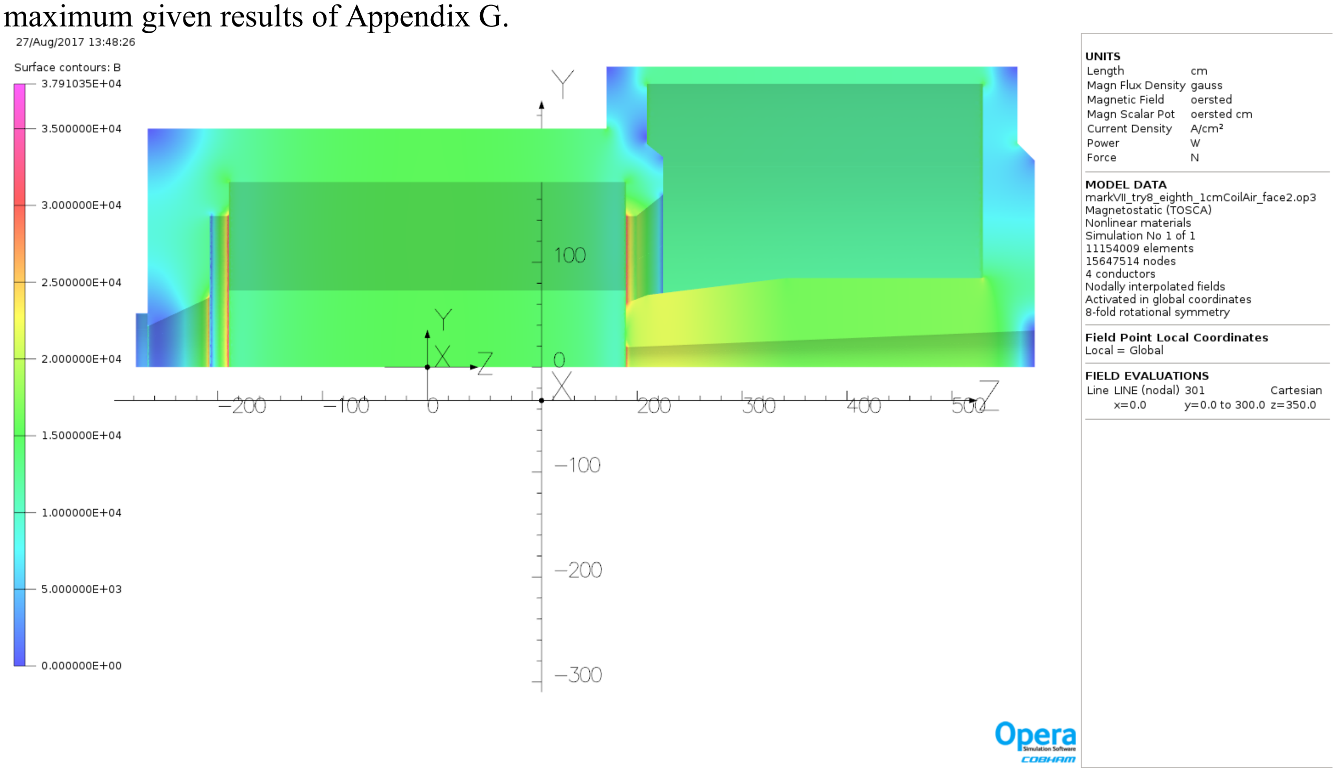


Figure H2. B modulus on surface of model. The annulus which interfaces solenoid octagon to end cap cylinder is thicker than it needs to be magnetically. Magnetic force is large, 1.5E6 N. I chose to leave chamfer and details of bracing/attachment to Hall A engineering and simply model a big ring.

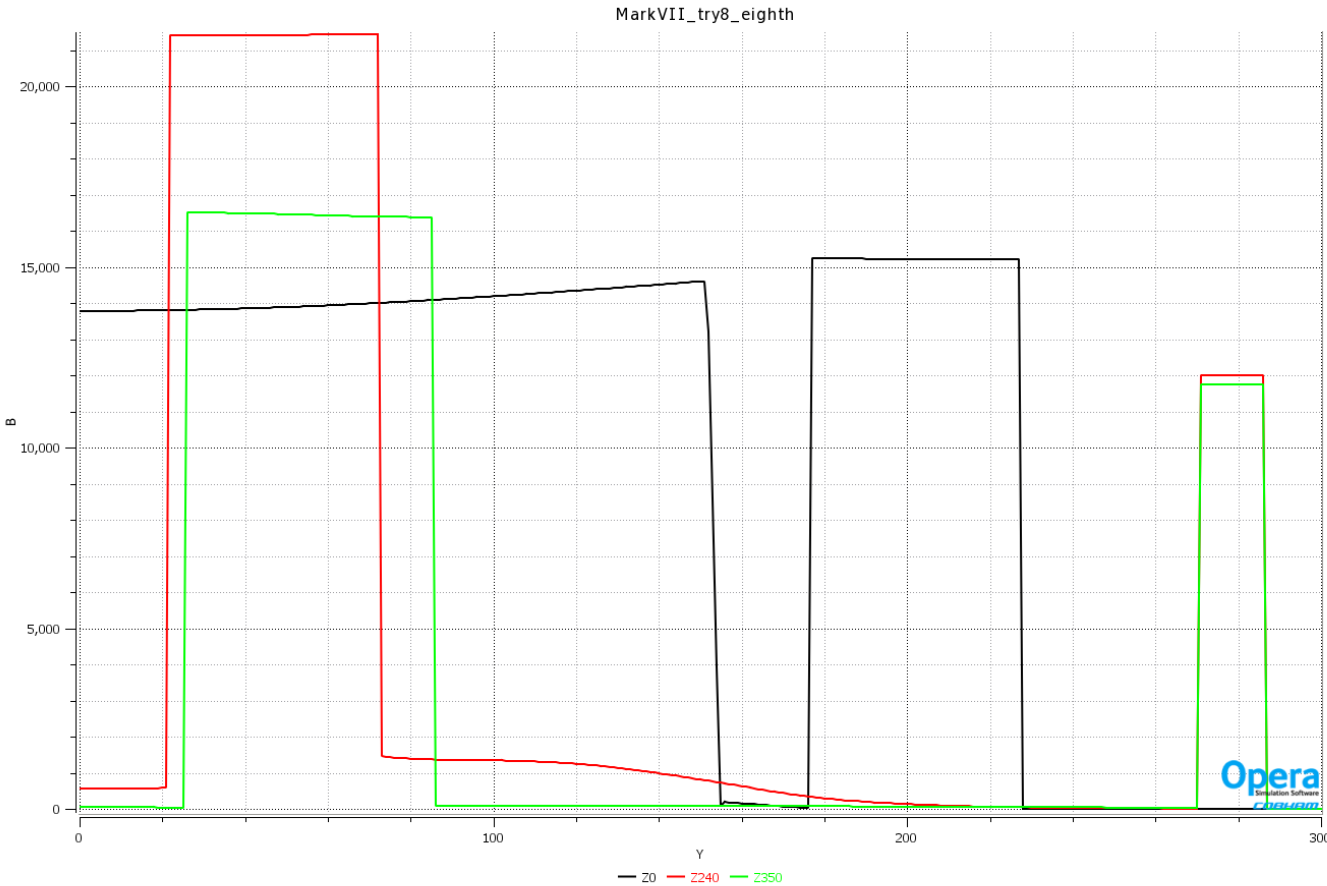


Figure H3. Plots of |B| on lines parallel to the Y axis at three Z locations. X=0 for all three. The black line is at Z=0 cm, the center of the solenoid. Field is a bit under 14 kG for much of the central volume and is just over 15 kG in the 51 cm thick return steel. The red line is at Z=240 cm, through the nose piece which conducts much of the flux. It peaks around 21250 G, well into saturation. The field is above 1 kG until the line is about 60% of the way to the ID of the end cap cylinder and is just 12 kG in the end cap cylinder. The green line is at Z=350 cm, where the coarser mesh in figure H1 starts. The field in the nose piece is about 16.5 kG here as radius is 85 cm, while the field in the end cap cylinder is a little below 12 kG. Field just outside the octagonal steel ~20 G while that outside the endcap cylinder varies from 5 to 11 G as Z increases.

Looking back at figure H1, one sees that my method to account for the cable holes in the end cap was too quick and dirty. The green cone should have continued through the three back plates as it won't have any holes. Instead I simply cut the last 51 cm of the cone off and converted it to a steel with BH curve reflecting 2% holes (blue). This will be fixed in the final model. I will adjust the upstream plug thickness to get the Z force on the solenoid below 1 kN as well since the BH curve in Appendix B will govern all but the upstream coil collar.

Appendix I: Full models with 17 cm steel

My first two non-CLEO models without imposing eight-fold symmetry were built before the graph at the bottom of page 28 was generated. They have 1 cm mesh on the coil. It appears from that graph that 1.25 cm would do as well, saving time. The two models now in solution also have 2 cm mesh maximum imposed on all the interior steel faces which have line-of-sight to the solenoid. One model has symmetric steel and the second has the cut-out for the service turret.

When the two models are complete I will use the post-processor to create field maps covering 90° at half-degree intervals [22°,112°], r=[100,140] and z=[-205,-105]. These maps will have about 900K points and will cover the volume where the turret cut-out will have the largest effect on the field. Someone competent can take the two files and create histograms of the ratios and differences. I'll do this first with the nodal interpolation method (an hour each) and then with the integration method (six weeks each?). Maps with cm spacing over the entire volume of interest have about 9E8 points which is why I really want a model where nodal interpolation is accurate enough.

Results from the model with symmetric steel are shown below. The Z force on the three main coils sums to 2923 N in the integration result. It follows that I may need to increase the plug thickness from 58.95 to 59.00 cm, reducing this value below 1 kN. *59.055 cm (23.25") thick upstream plug should yield -1400 N.* I await results of the model with turret cut-out. Forces in N, torques in N-cm.
Recall 1 lbf-ft=135.58 N-cm.

1 cm mesh, nodal 32,4,32, faces 2 cm mesh			
Total force on coil 1 =	-112	3	2959747
Total torque on coil 1 =	-15205	15211	0
Total force on coil 2 =	-226	152	70812
Total torque on coil 2 =	-747	13532	0
Total force on coil 3 =	136	-93	-3029335
Total torque on coil 3 =	9796	26558	0
Total force on coil 4 =	0	0	58
Total torque on coil 4 =	-56	-3	0
Total force on all coils =	-202	61	1284
Total torque on all coils =	-6214	55299	0
add in quadrature torques	18103	33464	
x+y torques in quadrature	38047		
torque stdev	12551	7086	

1 cm mesh model, integ 8,1,8, steel faces 2 cm			
Total force on coil 1 =	-14	42	2969004
Total torque on coil 1 =	8446	286	0
Total force on coil 2 =	-45	36	70603
Total torque on coil 2 =	5429	-4334	0
Total force on coil 3 =	-31	8	-3036684
Total torque on coil 3 =	-1860	-7075	0
Total force on coil 4 =	0	0	121
Total torque on coil 4 =	-46	21	0
Total force on all coils =	-90	85	3044
Total torque on all coils =	11969	-11103	0
add in quadrature torques	10212	8303	
x+y torques in quadrature	13161		
torque stdev	5299	3720	

The table below shows the forces and torques on the solenoid for the model with turret cut-out in the steel. The differences in the nodal values are only suggestive due to the variation shown in the past several pages.

1 cm mesh, nodal 32,4,32, faces 2 cm mesh, TURRET				
Total force on coil 1 =	-66	-262	2963878	N
Total torque on coil 1 =	-67040	21183	0	N-cm
Total force on coil 2 =	184	138	71400	N
Total torque on coil 2 =	15886	-25616	0	N-cm
Total force on coil 3 =	9	-12	-3029995	N
Total torque on coil 3 =	40	-1271	0	N-cm
Total force on coil 4 =	0	0	59	N
Total torque on coil 4 =	5	-86	0	N-cm
Total force on all coils =	126	-135	5342	N
Total torque on all coils =	-51109	-5789	0	N-cm
add in quadrature torques	68897	33264		N-cm
x+y torques in quadrature	76506			N-cm
torque stdev	44022	23406		N-cm

1 cm mesh model, integ 8,1,8, steel faces 2 cm, TURRET				
Total force on coil 1 =	-150	-448	2972418	N
Total torque on coil 1 =	-91085	32024	0	N-cm
Total force on coil 2 =	15	57	71207	N
Total torque on coil 2 =	20362	-1551	0	N-cm
Total force on coil 3 =	-13	-25	-3038684	N
Total torque on coil 3 =	8194	25	0	N-cm
Total force on coil 4 =	0	0	121	N
Total torque on coil 4 =	0	-44	0	N-cm
Total force on all coils =	-148	-417	5062	N
Total torque on all coils =	-62529	30454	0	N-cm
add in quadrature torques	93692	32062		N-cm
x+y torques in quadrature	99026			N-cm
torque stdev	61135	18946		N-cm

Turret-symmetric integration mode

	x	y	z	
Total force on coil 1 =	-136	-490	3413	N
Total torque on coil 1 =	-99531	31739	0	N-cm
Total force on coil 2 =	60	21	604	N
Total torque on coil 2 =	14933	2783	0	N-cm
Total force on coil 3 =	18	-33	-1999	N
Total torque on coil 3 =	10054	7100	0	N-cm
Total force on coil 4 =	0	0	0	N
Total torque on coil 4 =	46	-65	0	N-cm
Total force on all coils =	-58	-502	2018	N
Total torque on all coils =	-74497	41557	0	N-cm

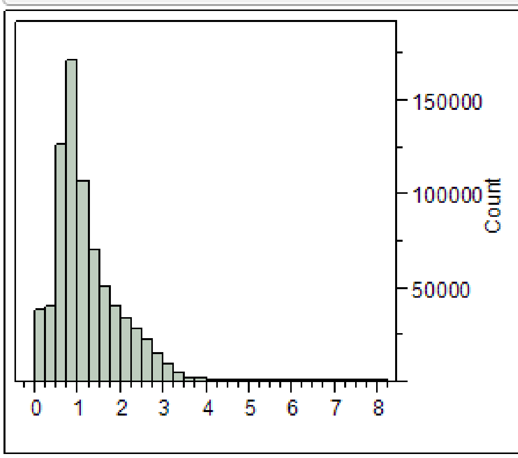
In the table immediately above I've subtracted the values from the "integ" table on the previous page from the "integ, TURRET" values immediately above. These differences are significant because the "integ" forces and torques varied at the 100N and 1000 N-cm level among the models with maximum coil mesh under 2 cm. The biggest difference is in coil 1 torque where the twist is towards the side which didn't lose steel. Since the coils are joined by solid aluminum the total torques are what matter. In US units, x -549 lbf-ft, y 307 lbf-ft. Upstream plug thickness 59.055 cm (23.25") looks good.

If I wanted to be really rigorous I would go back to the original Z-symmetric CLEO steel and model the torques similarly to compare with the ones derived above. Before I spend a month doing that Hall A Engineering should examine the Oxford documentation to determine what torques the cryostat internals were likely designed for.

I generated three tables of field values using a script which turns (r,theta,z) ranges into (x,y,z) points. All three covered theta [45,135] as the cut-out is in this quadrant. The two tables with larger radius used half-degree steps. The one with smaller radius used one degree steps.

first: r=[100,140] z=[-205,-105] *just about all of this is outside acceptance*
useful: r=[100,140] z=[-100,0] *all of this is within acceptance*
front: r=[0,100] z=[-205,-100]
25 degree cone starts at z=-350 so points inside r=67.6 cm are OK at z=-205 and r=100 is reached at z=-135.

absBdiffTS

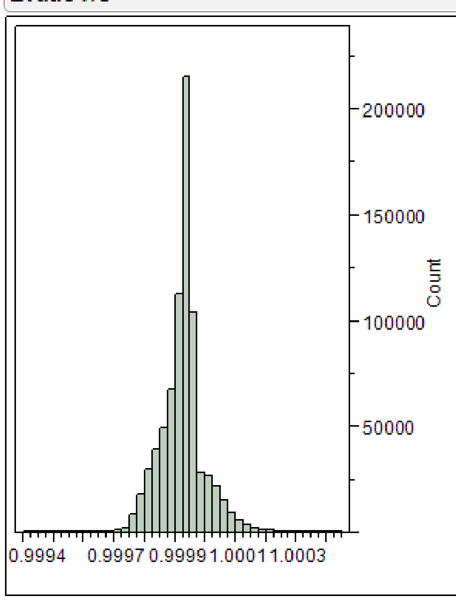


Quantiles		
100.0%	maximum	8.20494
99.5%		3.46429
97.5%		2.94164
90.0%		2.2885
75.0%	quartile	1.56431
50.0%	median	1.00355
25.0%	quartile	0.72989
10.0%		0.49296
2.5%		0.12451
0.5%		0.0248
0.0%	minimum	1.1e-5

Moments	
Mean	1.2051823
Std Dev	0.7203139
Std Err Mean	0.000832
Upper 95% Mean	1.206813
Lower 95% Mean	1.2035516
N	749521

Figure I1. For the useful volume, absolute value of the differences of the B values at 749521 points for the two models is shown.

BratioT/S

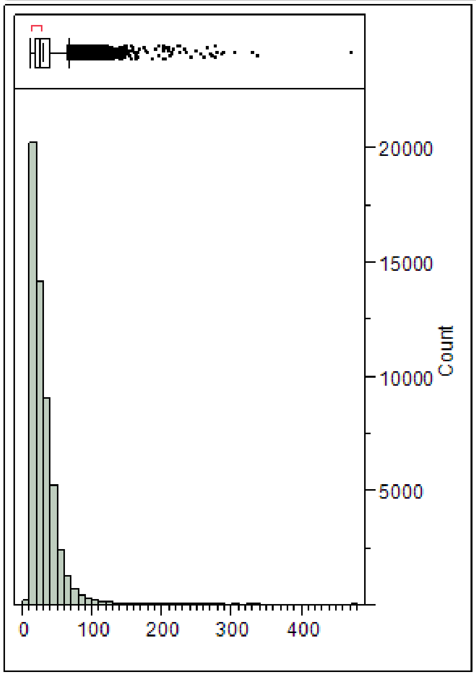


Quantiles		
100.0%	maximum	1.00045
99.5%		1.00015
97.5%		1.00008
90.0%		1.00001
75.0%	quartile	0.99995
50.0%	median	0.99993
25.0%	quartile	0.99989
10.0%		0.99984
2.5%		0.99979
0.5%		0.99975
0.0%	minimum	0.99942

Moments	
Mean	0.9999261
Std Dev	6.7643e-5
Std Err Mean	7.8133e-8
Upper 95% Mean	0.9999262
Lower 95% Mean	0.9999259
N	749521

Figure I2. Ratios of fields in “useful” volume two models are shown. Symmetric model looks good

absBdiffTS



Quantiles		
100.0%	maximum	470.433
99.5%		106.957
97.5%		72.3861
90.0%		49.2652
75.0%	quartile	35.9496
50.0%	median	24.0314
25.0%	quartile	16.2959
10.0%		12.7455
2.5%		11.1159
0.5%		10.2417
0.0%	minimum	8.8089

Moments	
Mean	28.68456
Std Dev	17.861587
Std Err Mean	0.0770971
Upper 95% Mean	28.835671
Lower 95% Mean	28.533449
N	53674

Figure I3. For the “front” volume, absolute values of the B differences between the two models are shown for points with greater than 0.1% differences, 5.5% of the 974246 points calculated.

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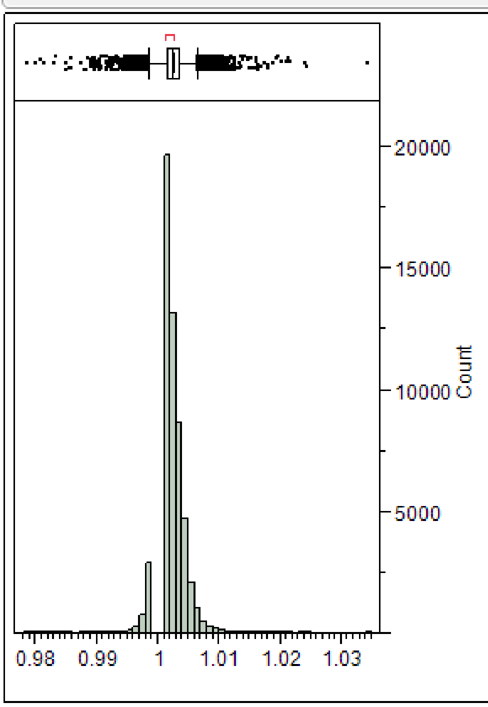

Quantiles		
100.0%	maximum	1.03422
99.5%		1.00865
97.5%		1.00642
90.0%		1.00459
75.0%	quartile	1.00338
50.0%	median	1.00222
25.0%	quartile	1.00142
10.0%		1.00106
2.5%		0.99821
0.5%		0.99662
0.0%	minimum	0.97855

Moments	
Mean	1.0023949
Std Dev	0.0019461
Std Err Mean	0.0000084
Upper 95% Mean	1.0024114
Lower 95% Mean	1.0023784
N	53674

Figure I4. Ratio of the field at the points in the “front” volume which are outside the range [0.999,1.001] Inspecting the table by eye, at least some of these points are inside the acceptance. Someone competent at coding will have to retrieve the raw files from docdb-53 and figure out what the real percentage is and wether it will matter to tracking in general and parity experiments in particular.

docdb-52 has the data for the “useful” volume. docdb-53 has the data for the “front” volume.

Conclusions

1. The mesh shown in figure F8 is sufficient for the collaboration's purposes if 1 cm mesh is used around the solenoid coil. 1.25 cm mesh maximum may suffice, based on the figure at the end of appendix G, page 28.
2. Someone competent will have to use the data in docdb53 to determine if a symmetric model which assumes eight-fold symmetry is sufficient or if a full model with turret cut-out is needed. Figures I3 and I4 suggest the latter, but some of the points graphed are outside the acceptance.