Solid XL - last look with CLEO steel?
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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.

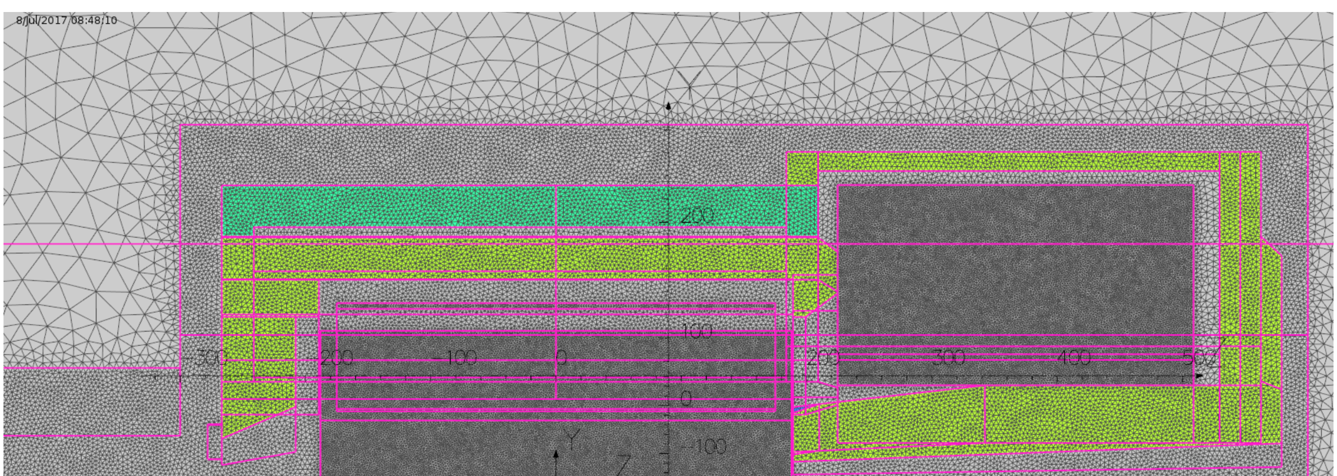

Figure 1. Mesh of markV_try3 models. The two large dark rectangles are "detector air". The thin R dark block above the left one contains the solenoid. Dark mesh has 2 cm maximum elements. Medium grey and green steel has 4 cm maximum mesh. Light grey scales from 4 cm to 32 cm maximum.

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.

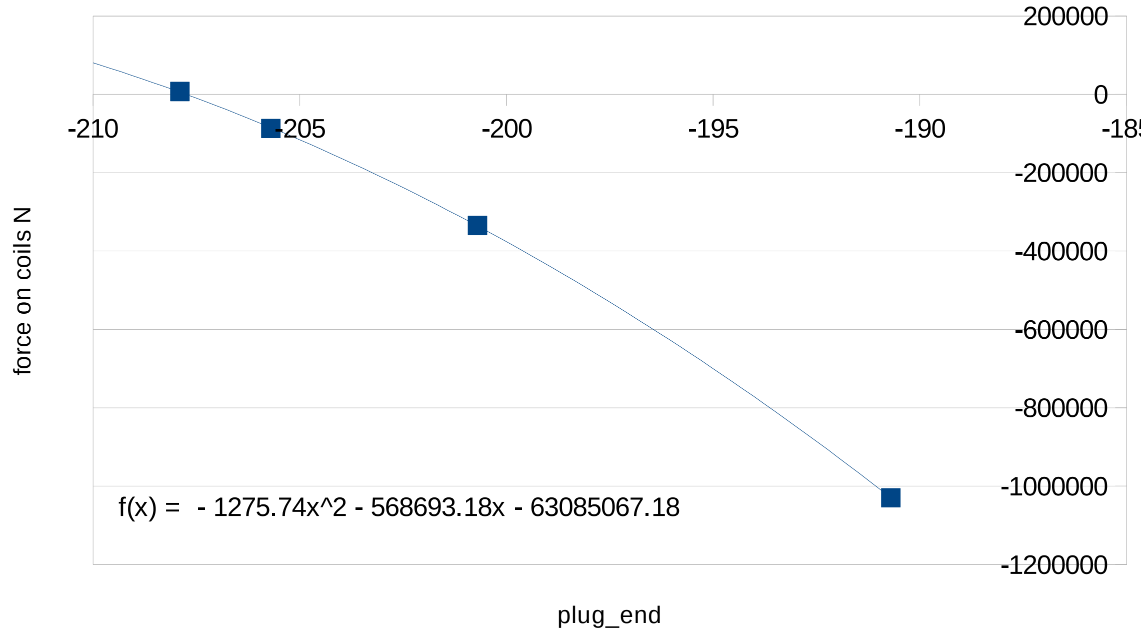

Figure 2. Force on the solenoid coils (Newtons) as a function of the downstream end of the upstream plug. The upstream end is at Z=-266.7. One zero of the fit equation is -207.75. The four axial load cells can handle 5000 kgf each, aka ~200 kN total. The pair of points at upper left yield 43 kN/cm.

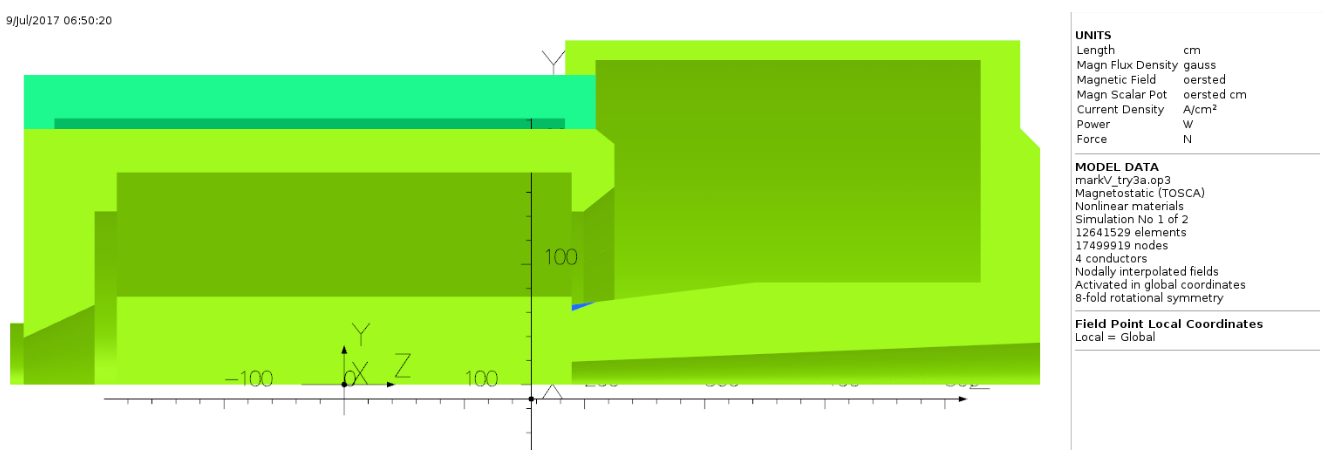

Figure 3. This is a quarter-section of the try3a model. The small blue region on the nose cone is the region Zhiwen wishes to remove to provide acceptance of the full length of the PVDIS target. Solving the model with that region having BH curves of 1010 steel (sim 1) and air (sim 2) yields a change 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.

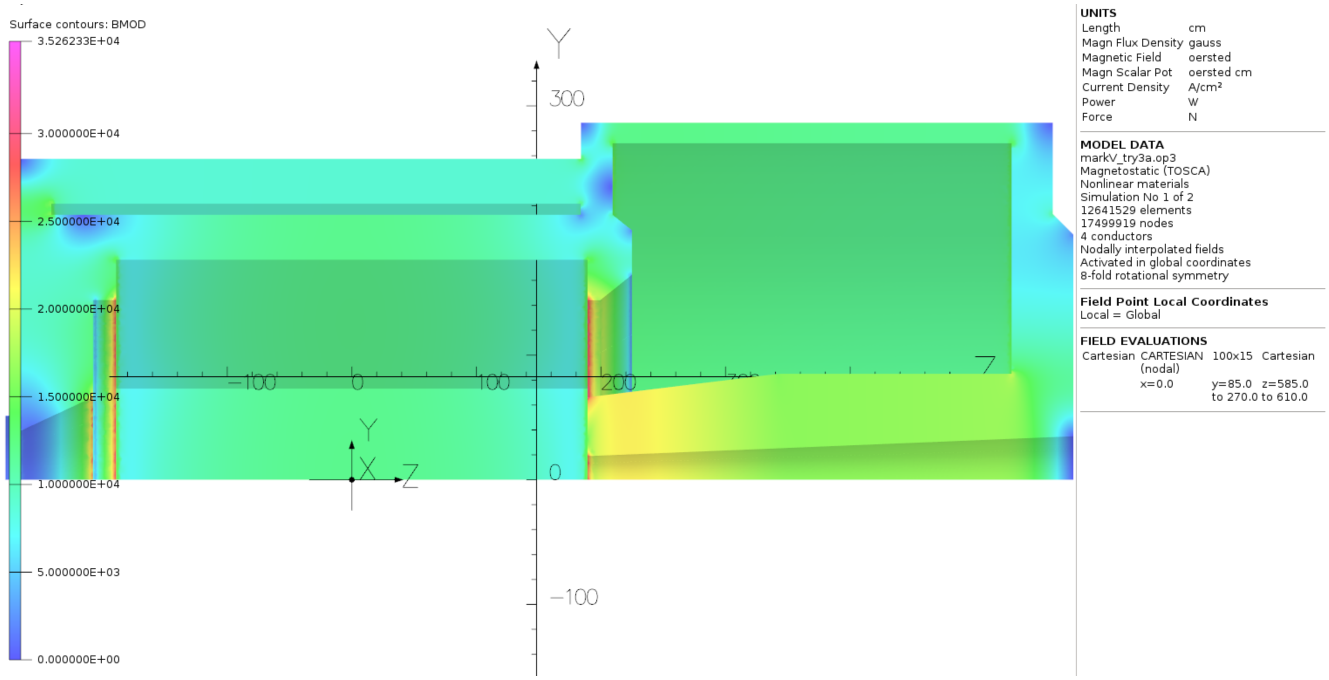

Figure 4. Bmodulus on surface with single nose taper (aka blue in figure 3 = steel). Peak 3.526 T

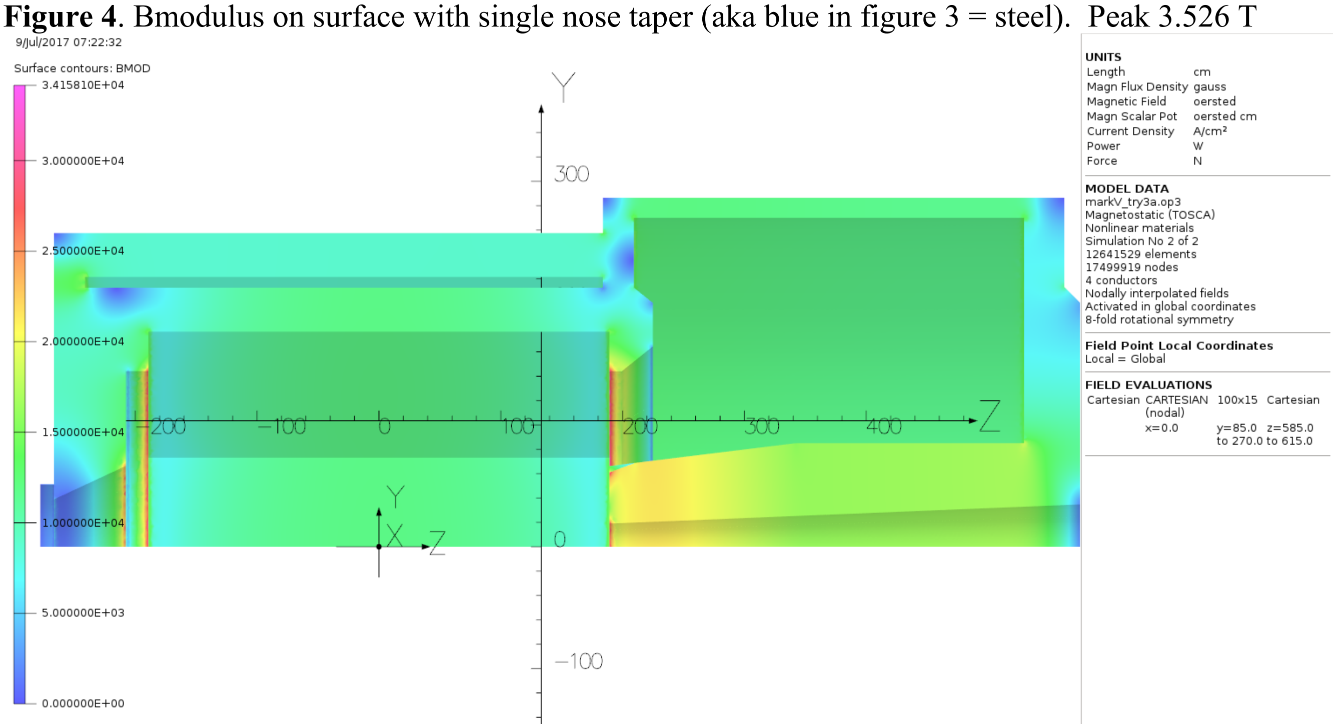

Figure 5. Bmodulus on surface with double nose taper (aka blue in figure 3 = air). Peak 3.415 T

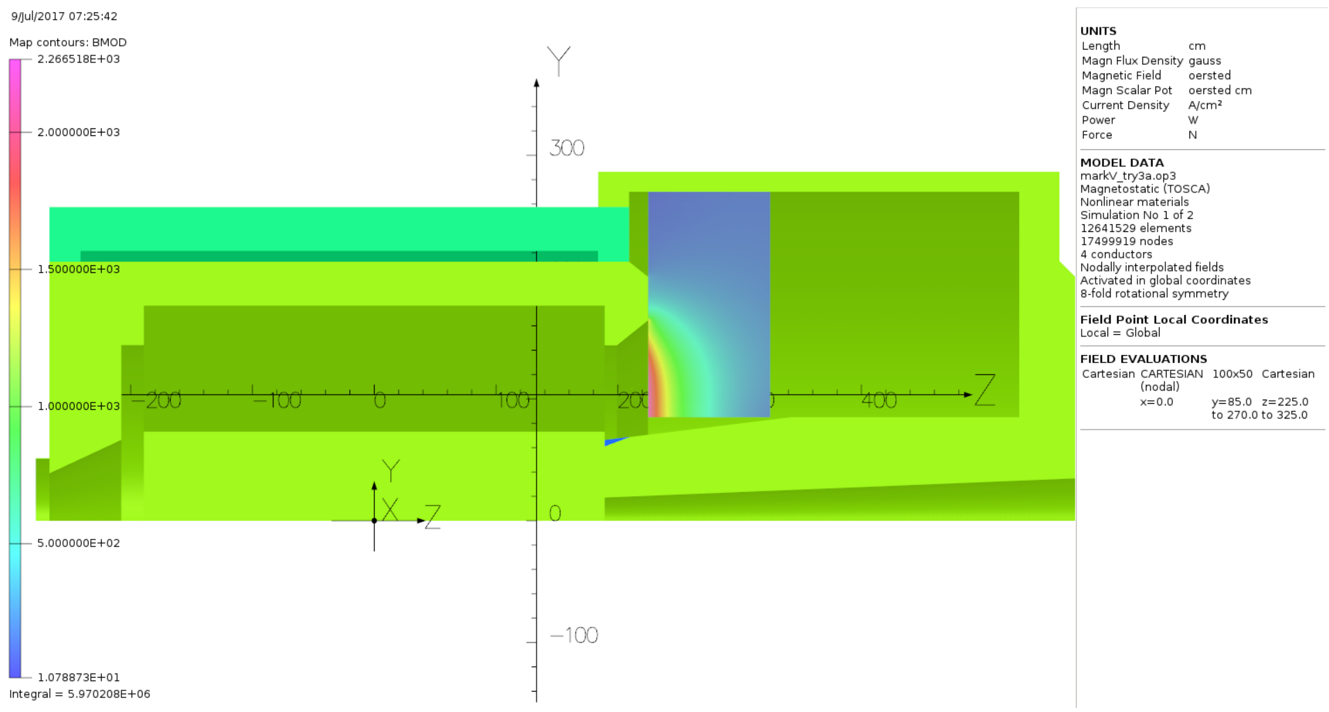

Figure 6. Bmodulus in endcap over the cone, single taper on nose (blue=steel) . Peak 0.227 T

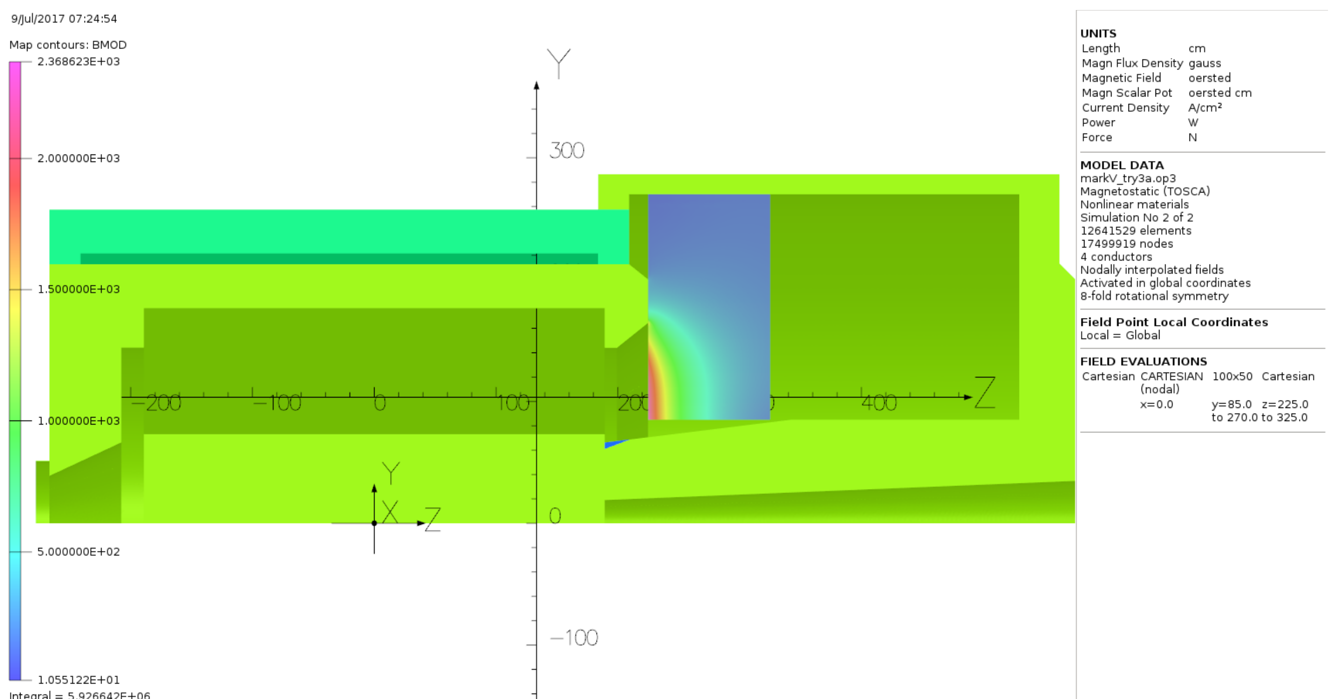

Figure 7. Bmodulus in endcap over the cone, double taper on nose (blue=air) . Peak 0.237 T. Some flux which would have been conducted through the nose and around the entire endcap now jumps directly to the downstream coil collar. This is what I didn't consider at the collaboration meeting.

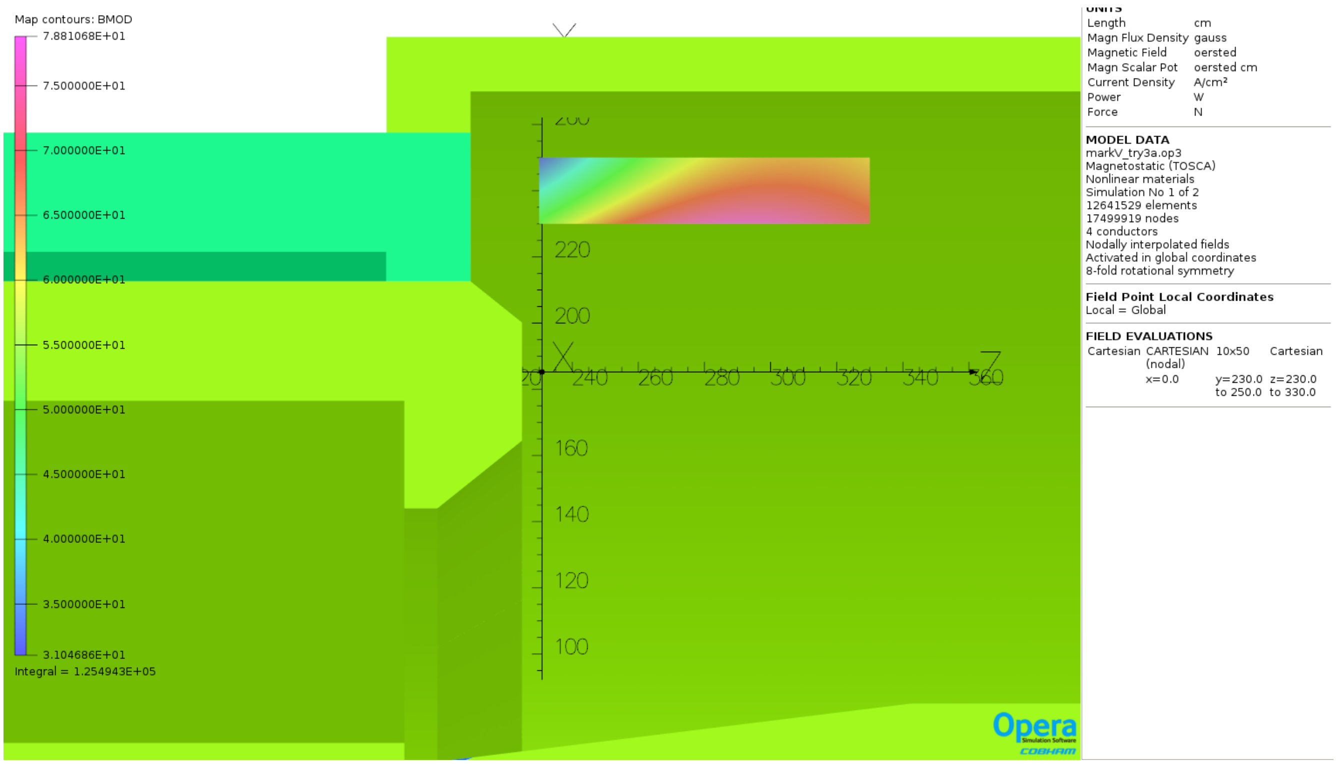

Figure 8. Bmodulus in vicinity of LGC and HGC PMTs. 1010 BH curve used here. Single taper on nose.

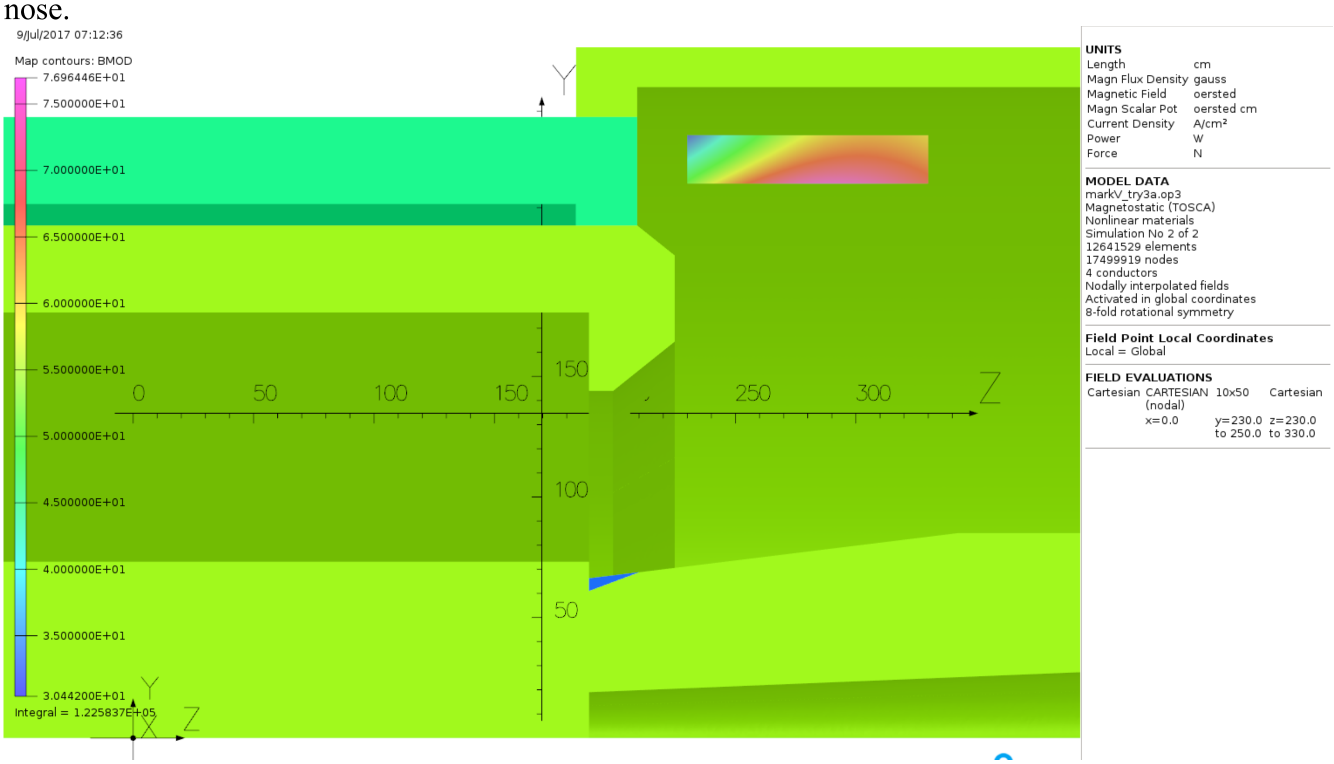

Figure 9. Bmodulus in vicinity of LGC and HGC PMTs. 1010 BH curve used here. Double taper on nose. Peak 77 G here vs 79 G in figure 8. With Default BH curve, 71.5 G peak. With JLabSR, 74.4 G.

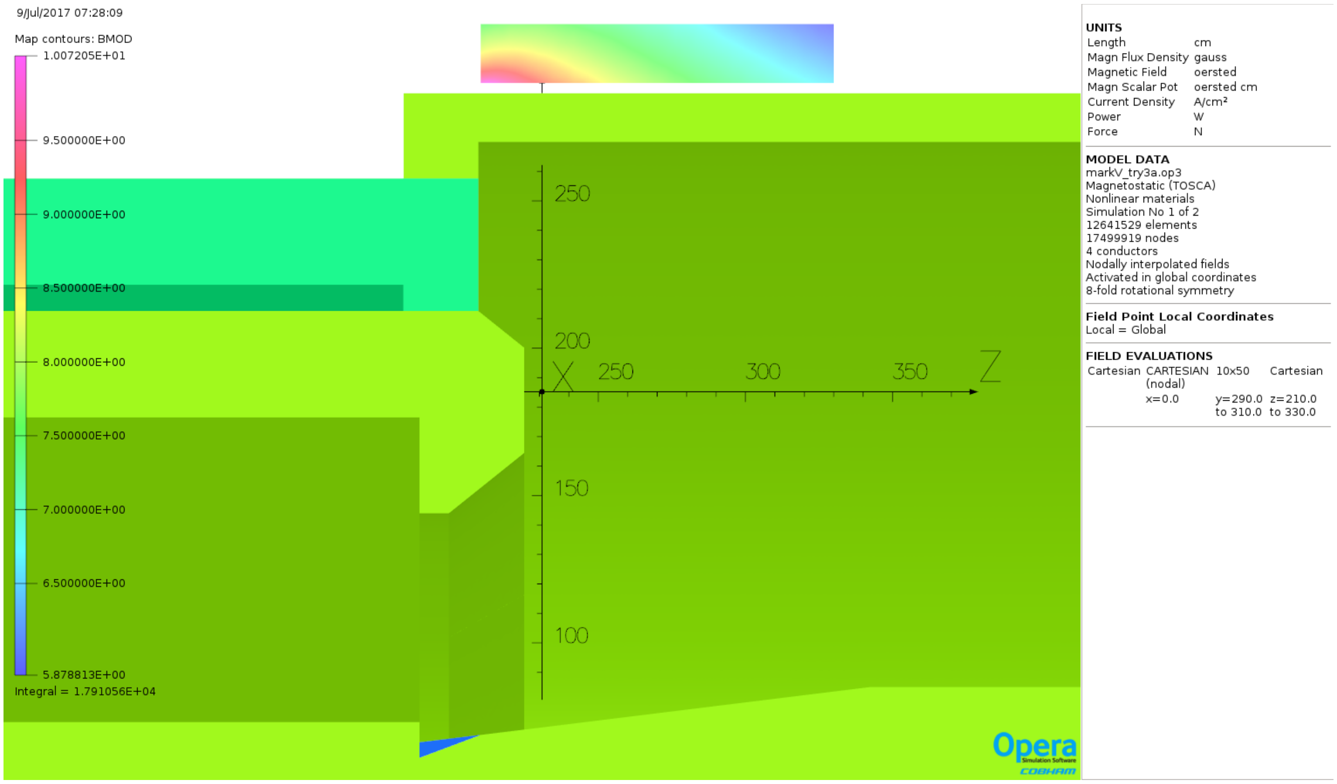

Figure 10. Bmodulus in vicinity of GEM electronics. Single taper on nose. Peak 10 G. 1010 BH curve used here.

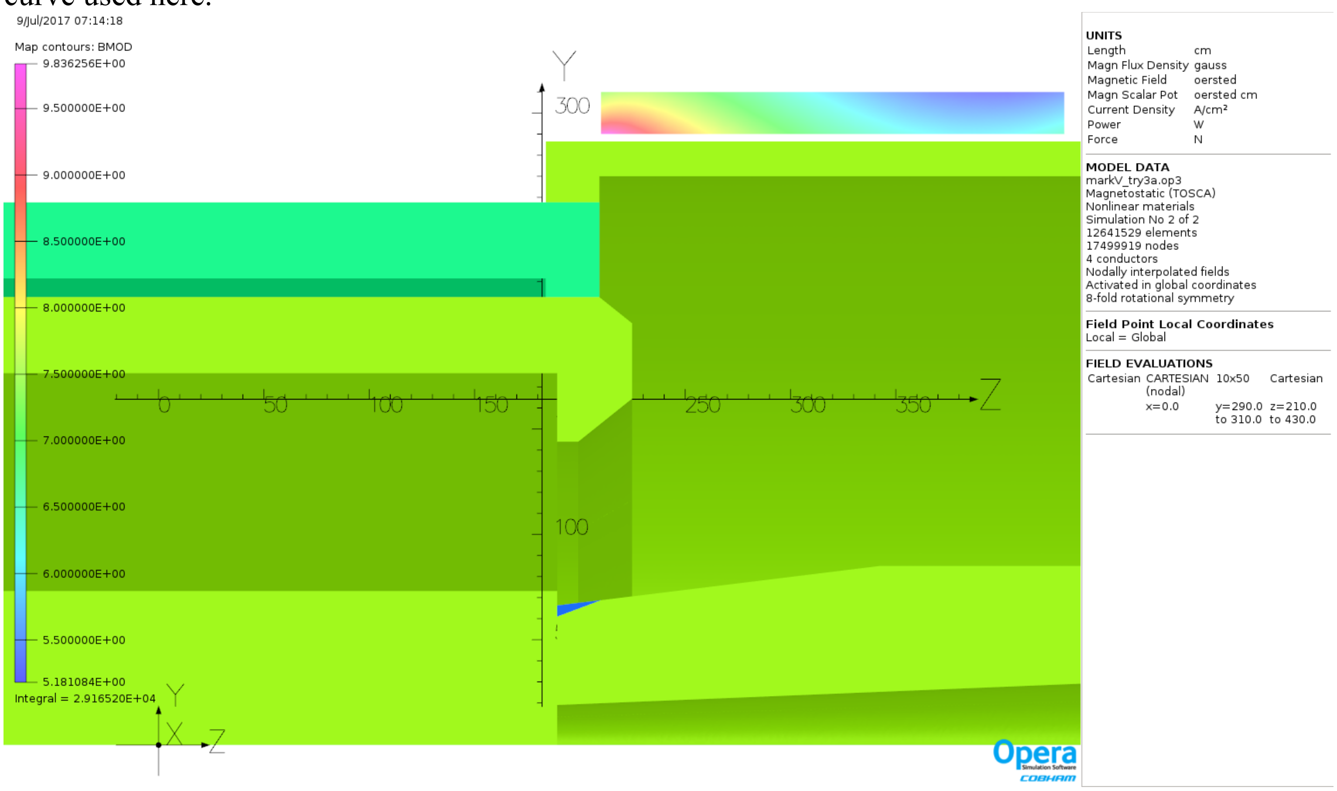

Figure 11. Bmodulus in vicinity of GEM electronics. Double taper on nose. Peak 9.8 G, slightly less than figure 10. 1010 BH curve used here. With Default BH curve, 7.1 G peak. With JLabSR, 8 G.

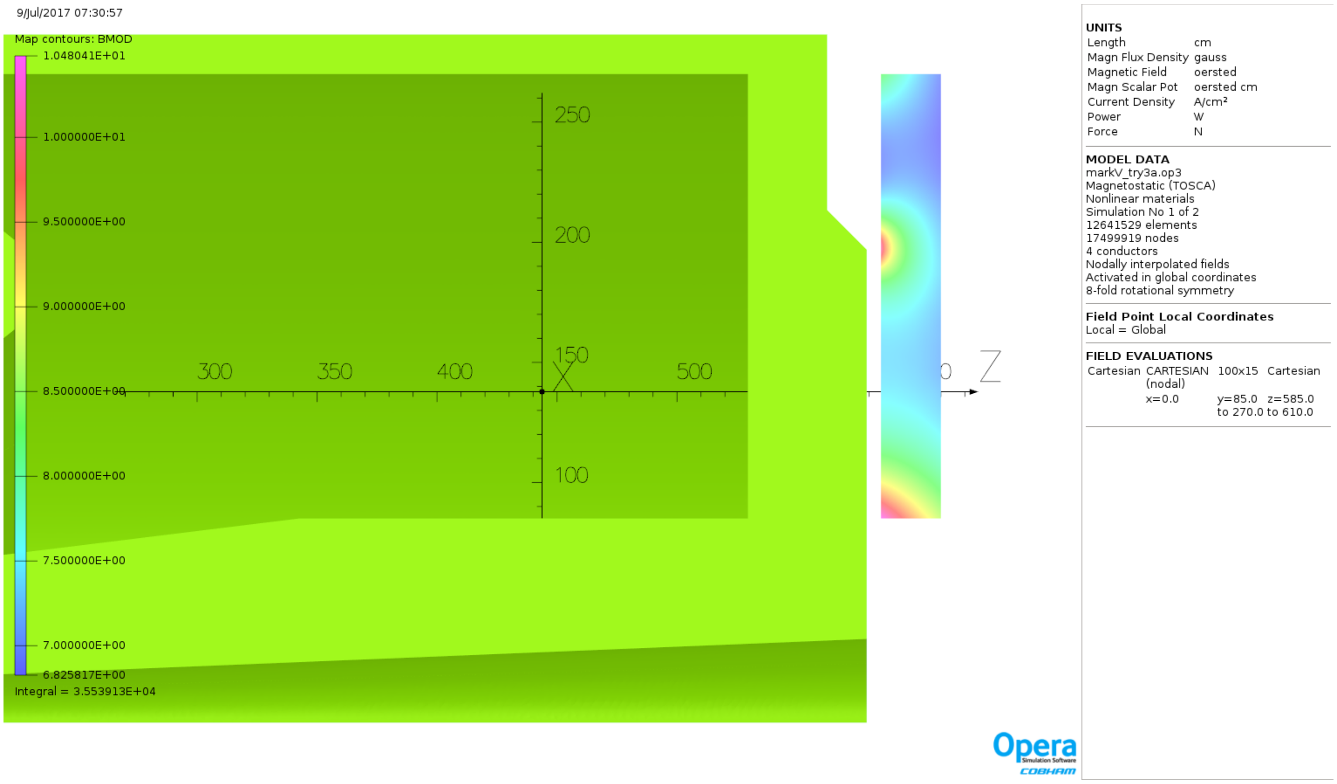

Figure 12. Bmodulus in vicinity of ECAL PMTs. Single taper on nose. Peak 10.5 G. 1010 BH curve used here.

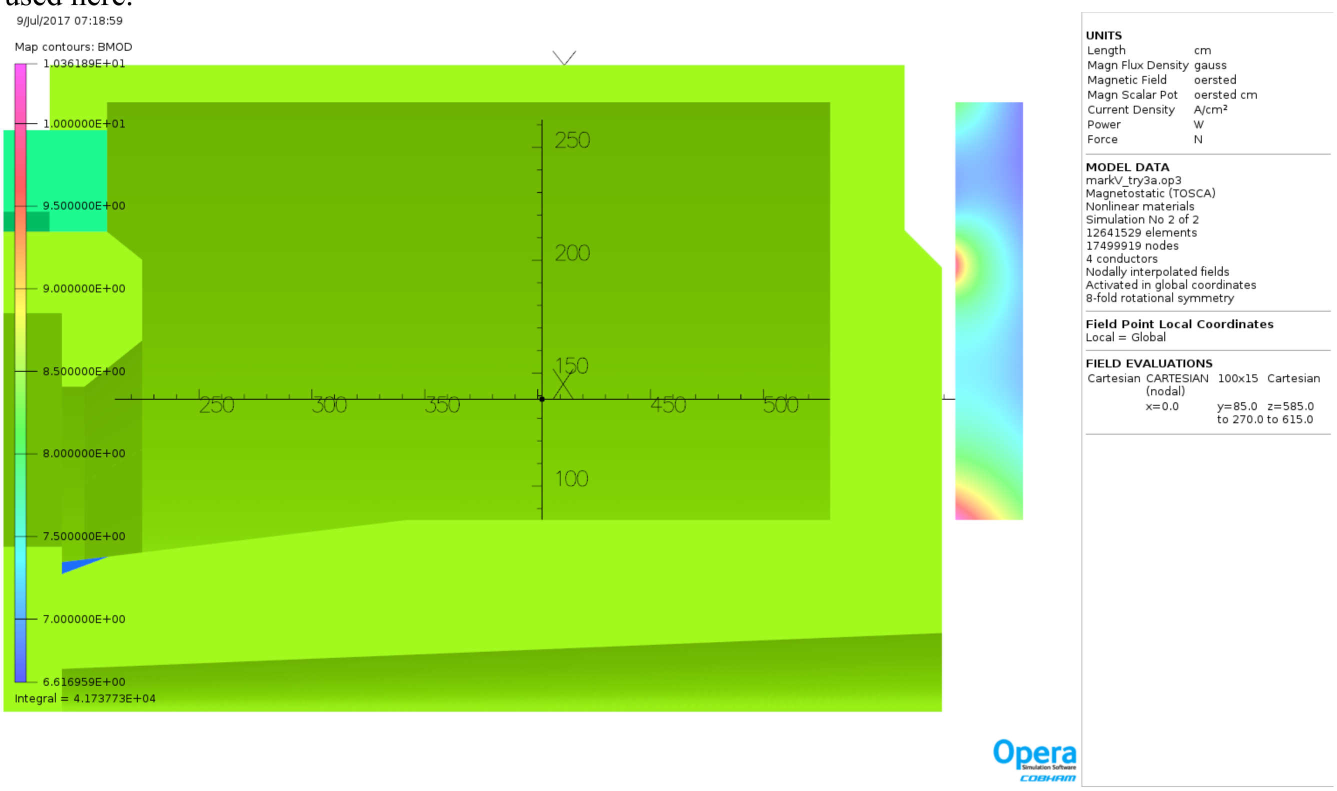

Figure 13. Bmodulus in vicinity of ECAL PMTs. Double taper on nose. Peak 10.4 G. 1010 BH curve used here. With Default BH curve, 4.5 G peak. With JLabSR: 6.9 G peak.

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

<u>Upstream plug</u> 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.*

<u>Downstream collar</u> 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

<u>Cone</u> 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

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

<u>CylinderA</u> steel1 95 4cm
OR 85 Z 342.27 to 579.12

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

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

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

<u>Cone_plate</u> 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

<u>Interface_endcap</u> 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.

<u>Inner_air</u> 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*

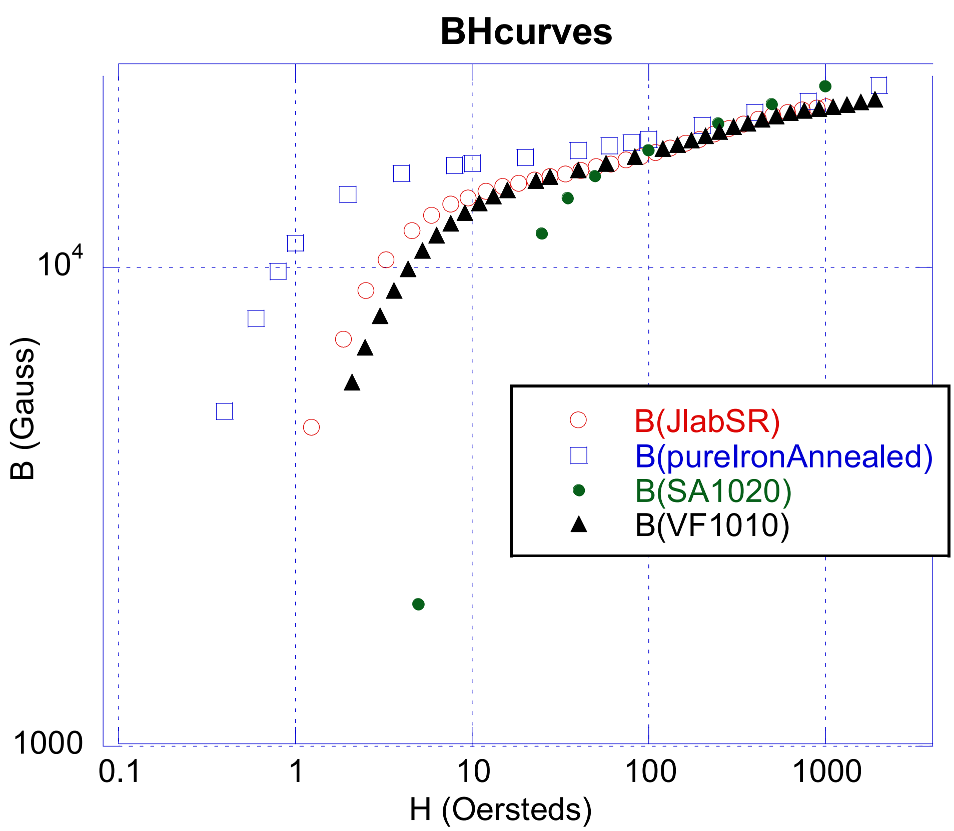

Figure 9 of TN-09-047. JlabSR, two reference BH curves from ANSYS (pure iron and SA1020) and one BH curve from Vector Fields (VF1010) which encompass the required steel chemistry (see below). VF1010 and SA1020 should be harder magnetic materials than JLabSR due to higher carbon content. The multipliers 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%.

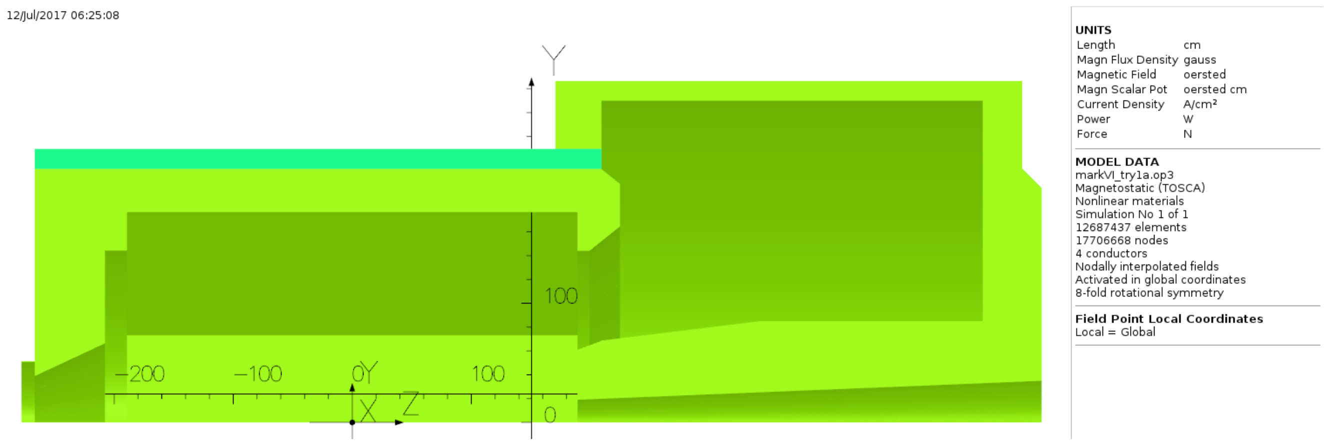

Figure C1. Darker green is new steel replacing outer octagon.

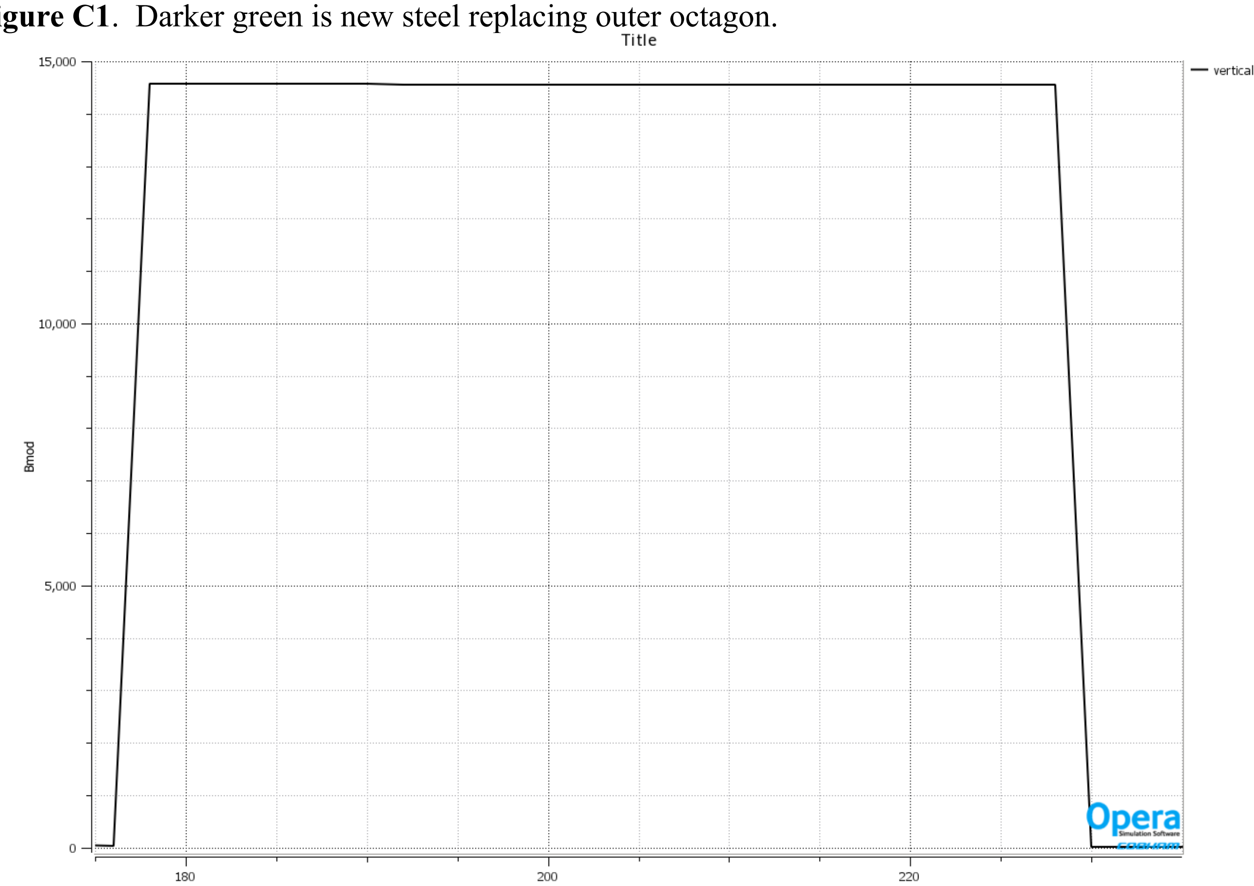

Figure C2. Bmod along vertical line at (x,z) = (0,0). With peak ~1.46T, a 4% increase would not be an issue.

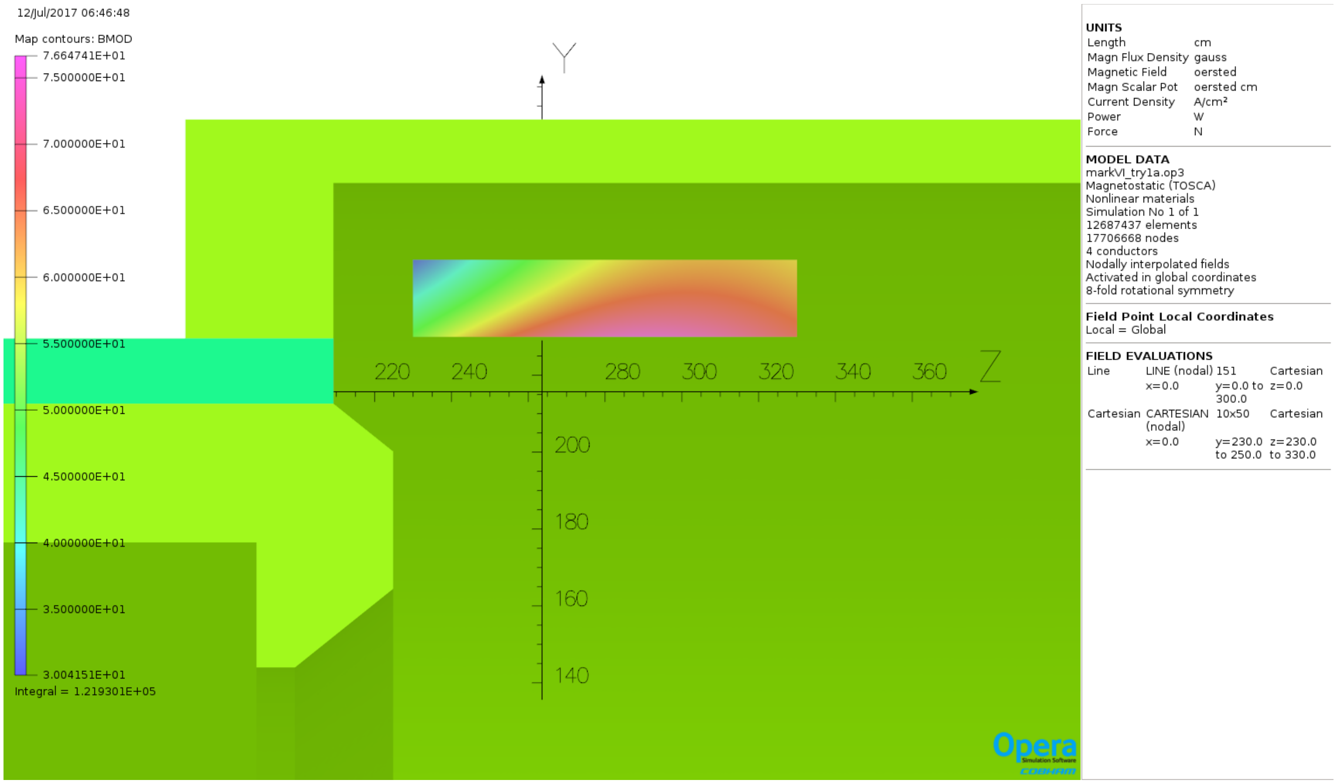

Figure C3. Field in vicinity of gas Cherenkov PMTs. Compare with Figure 9 as this model has double taper on the nose. The volumes in figures 11 and 13 were also checked. Figure 11 volume differed little in this model. Figure 13 differed more: 13.5 G peak in this model vs 10.4 G there. I should have made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

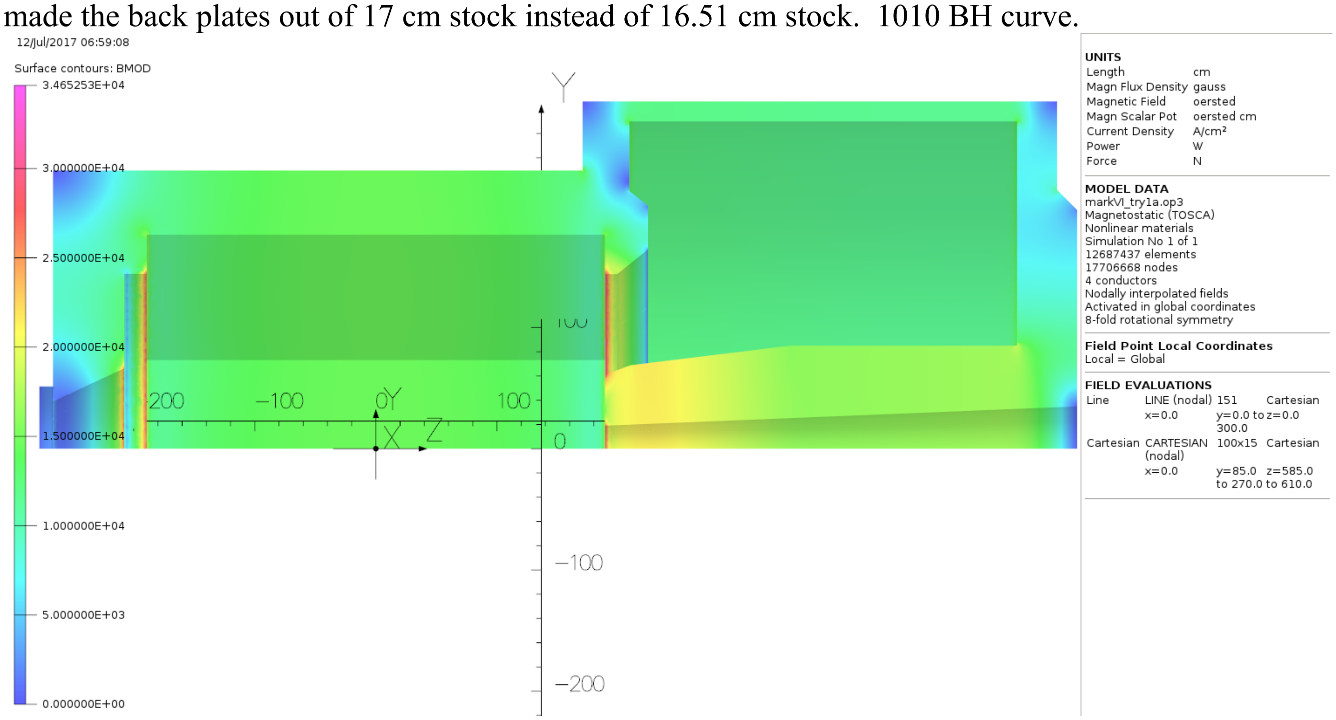

Figure 4. Bmod on surface of model.

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.

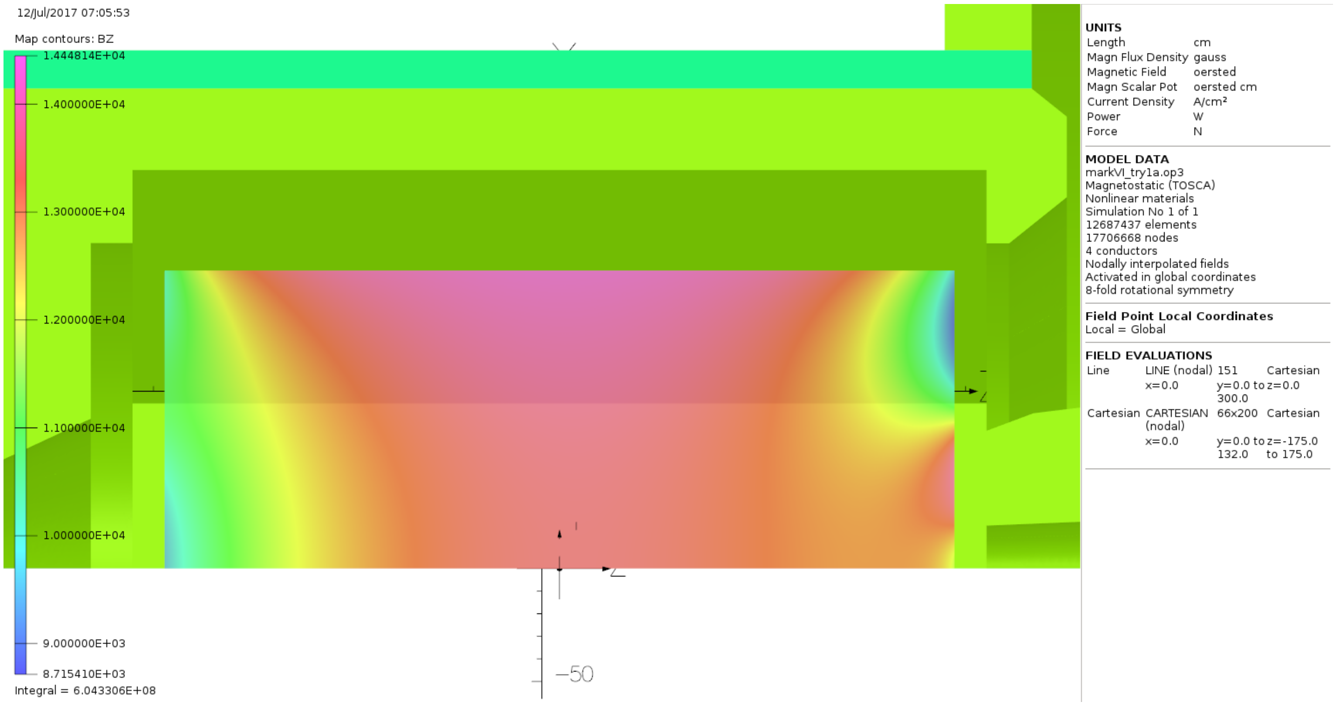

Figure C5. Bz under coil on YZ plane. Double taper on nose is seen clearly here at right.

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.

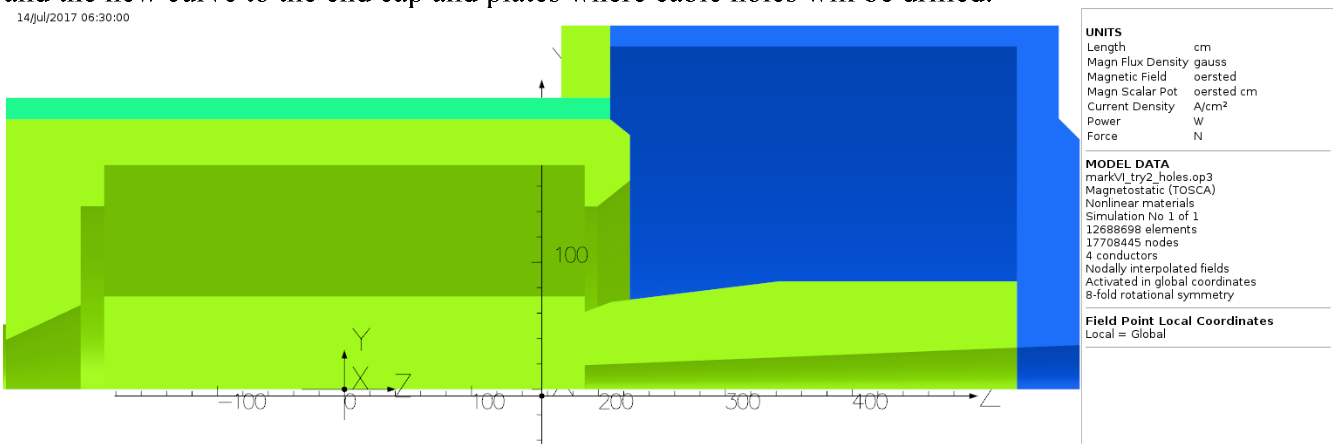

Figure D1. Green steel has SR BH curve of Appendix B. Blue is the curve with 0.98B-H.

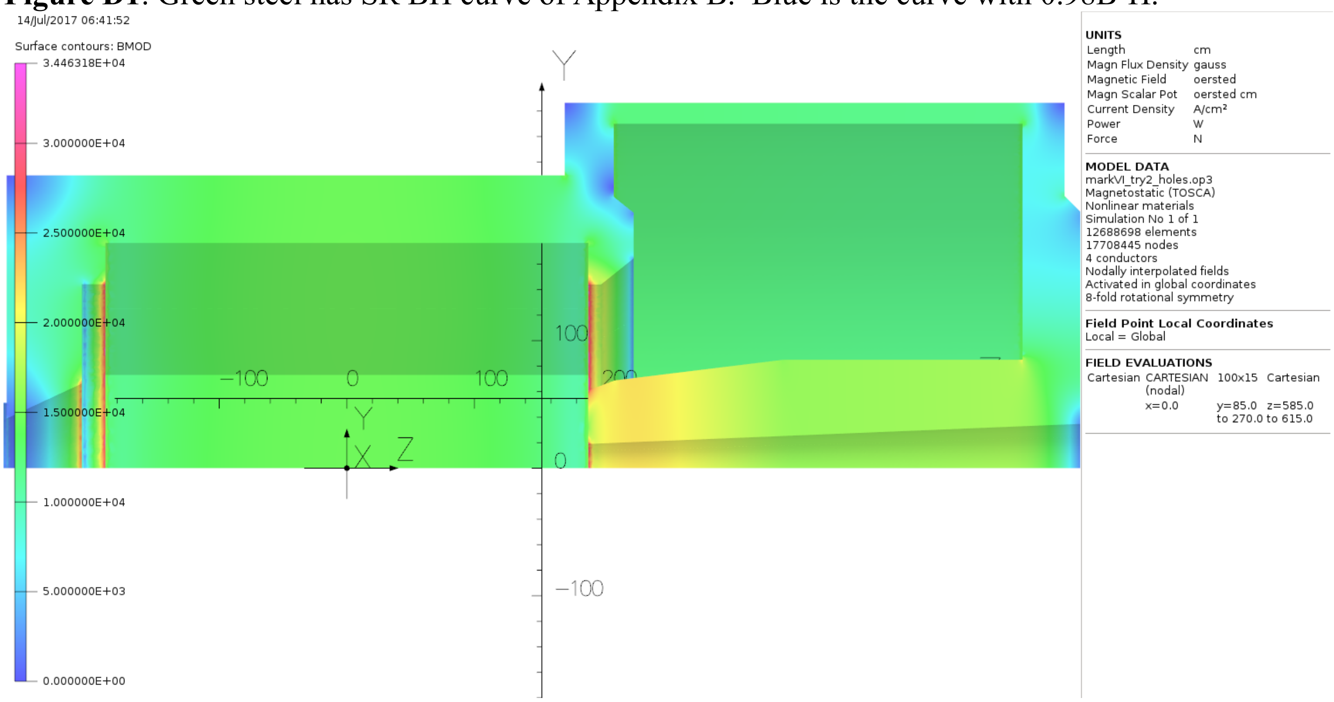

Figure D2. Bmod on surface of model.

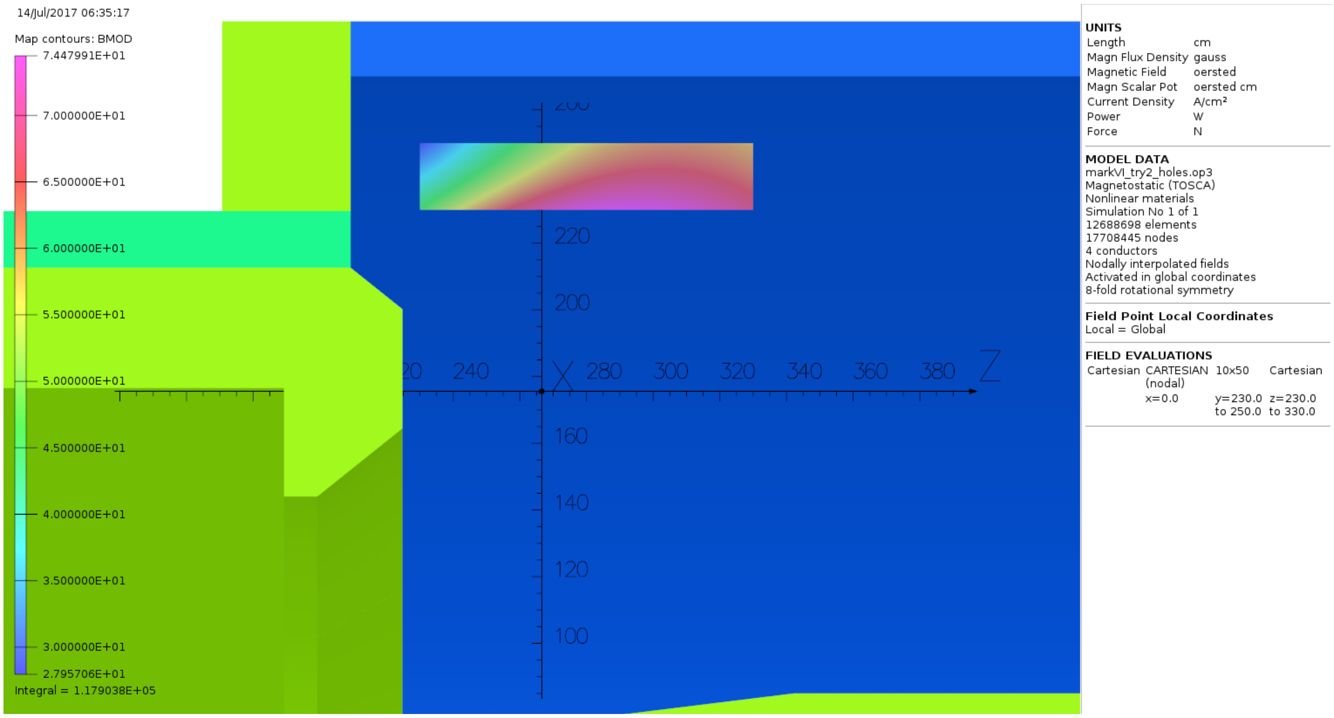

Figure D3. Bmod in vicinity of PMTs for LGC and HGC.

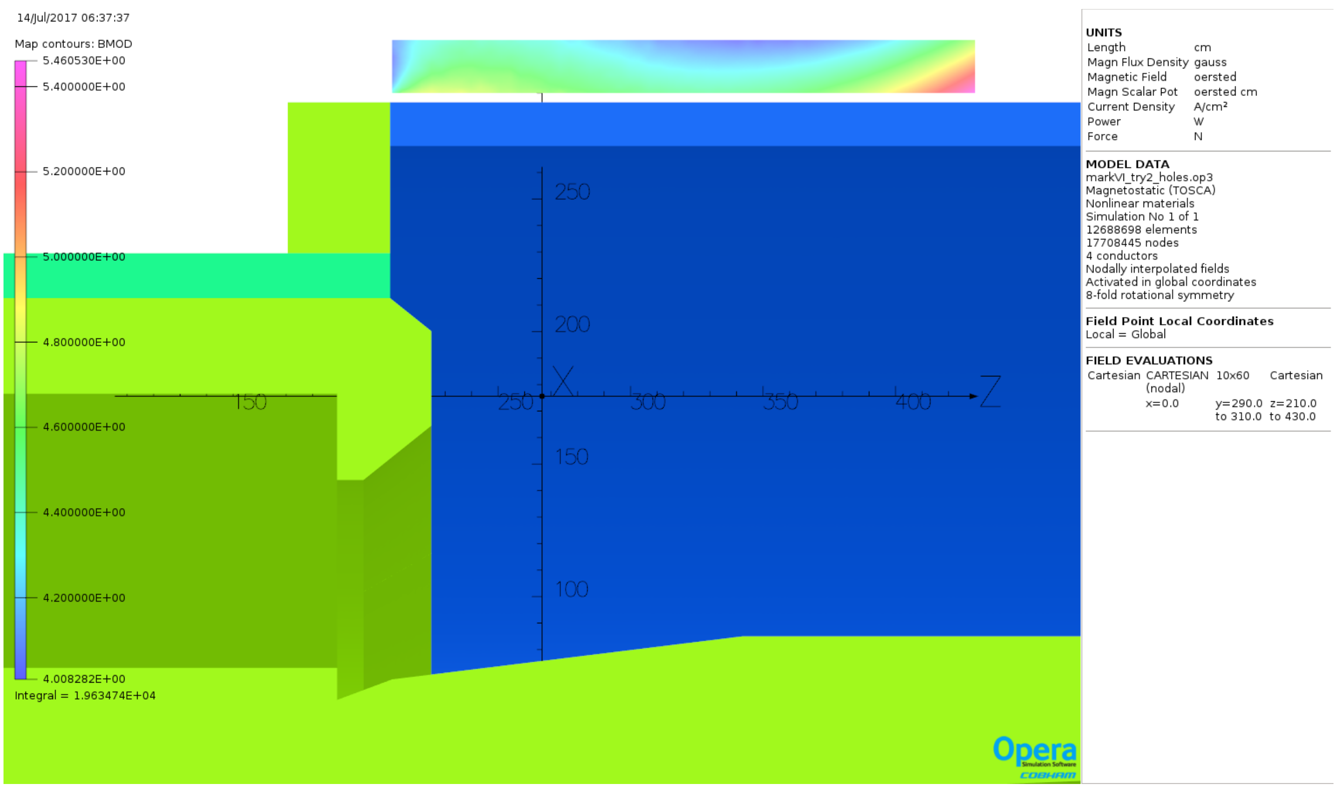

Figure D4. Bmod in vicinity of GEM electronics

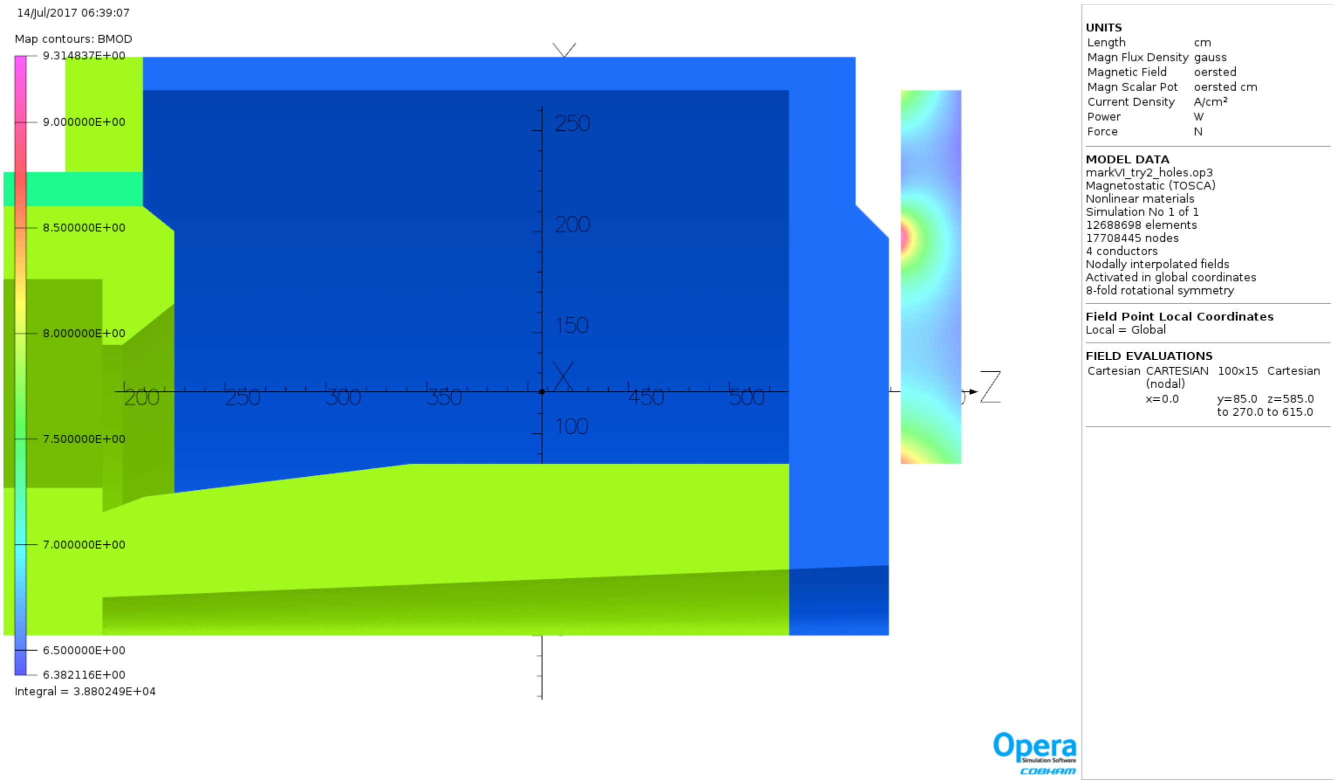

Figure D5. Bmod in vicinity of ECAL PMTs.

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

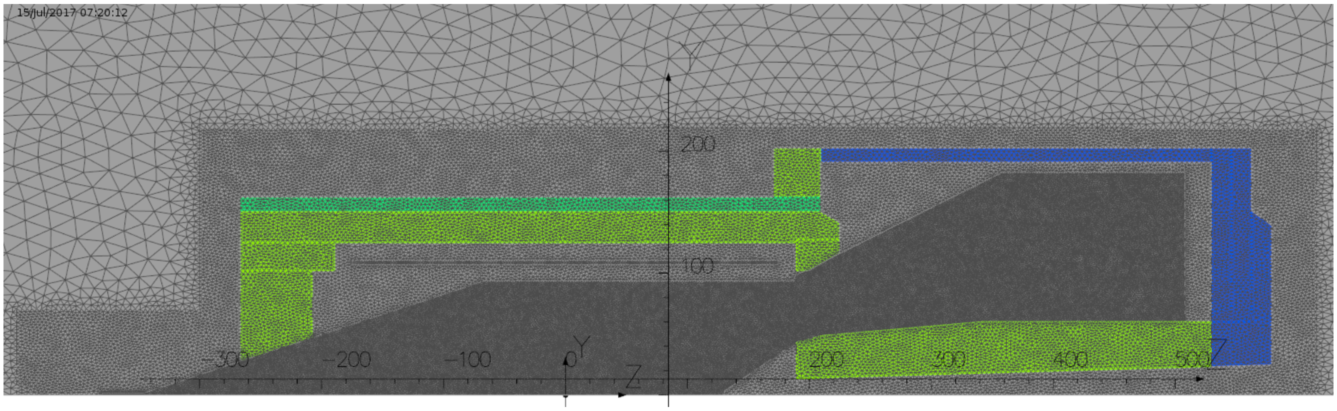

Figure E1. Since I haven't gotten any response to the question on page one I rolled my own.

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?

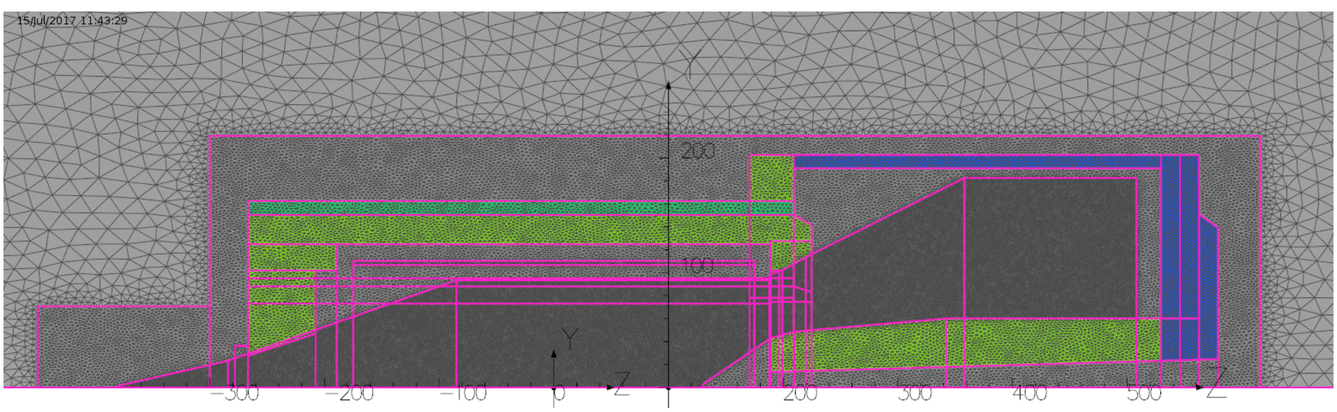

Figure E2. Cones were added to extend acceptance to a 60 cm long upstream target 2 cm in radius and a 40 cm target centered at Z=10. This model has 237M non-zeroes in the matrices, only 9M less than figure 1. 77.2% of Opera nominal maximum when symmetry is broken.

Appendix F : Static potential plots for model shown in figure E2

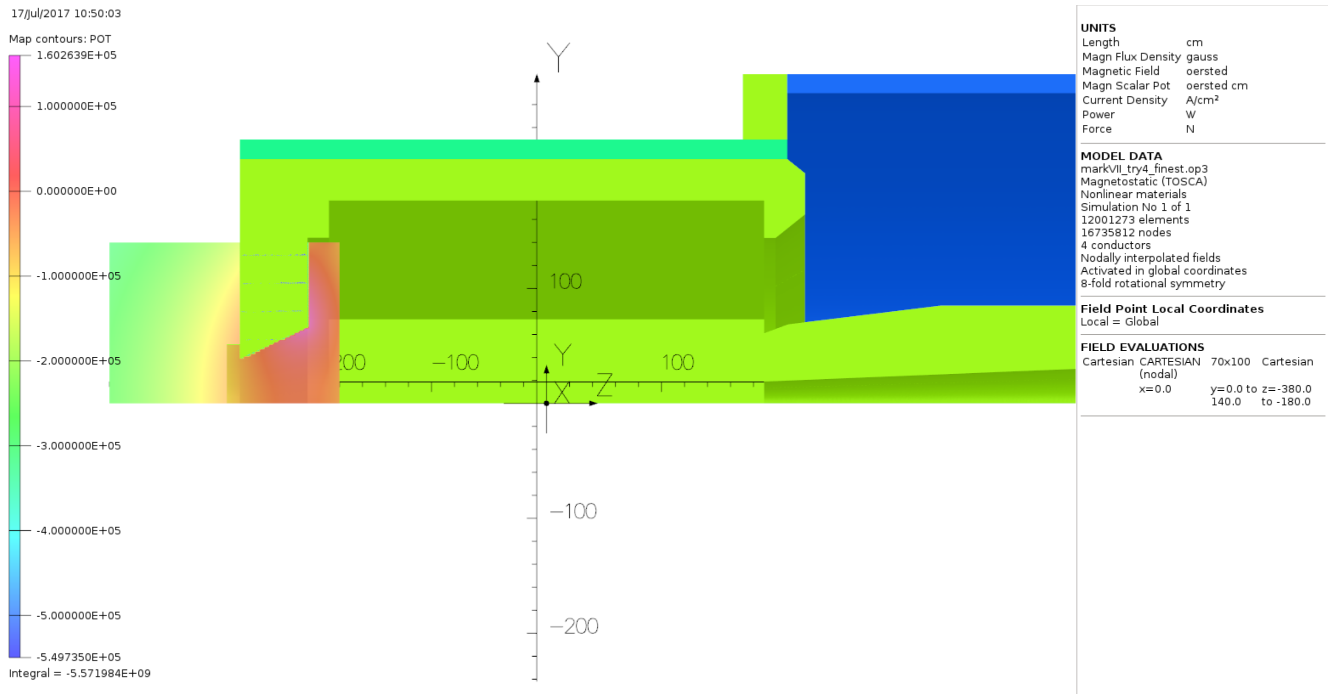

Figure F1. Magnetic scalar potential in oersted-cm from target upstream end to just before solenoid. See Field Evaluation block at right of figure for location of plane.

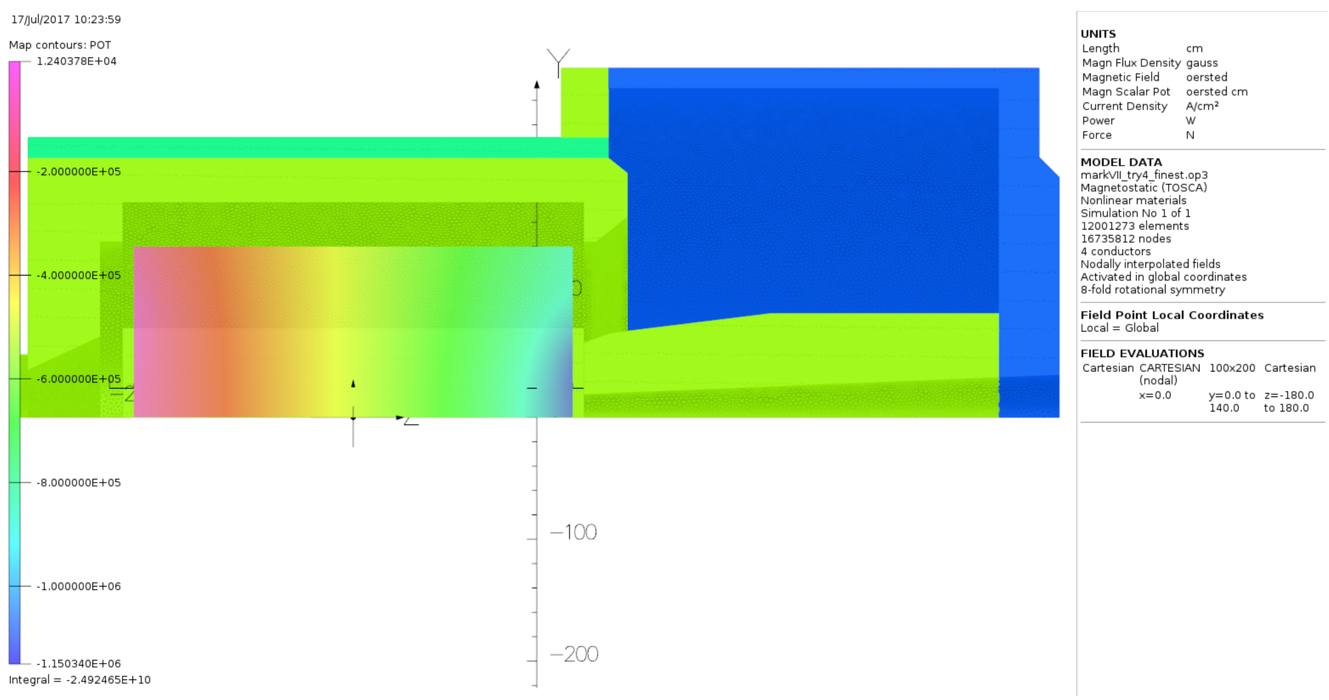

Figure F2. Next segment of potential.

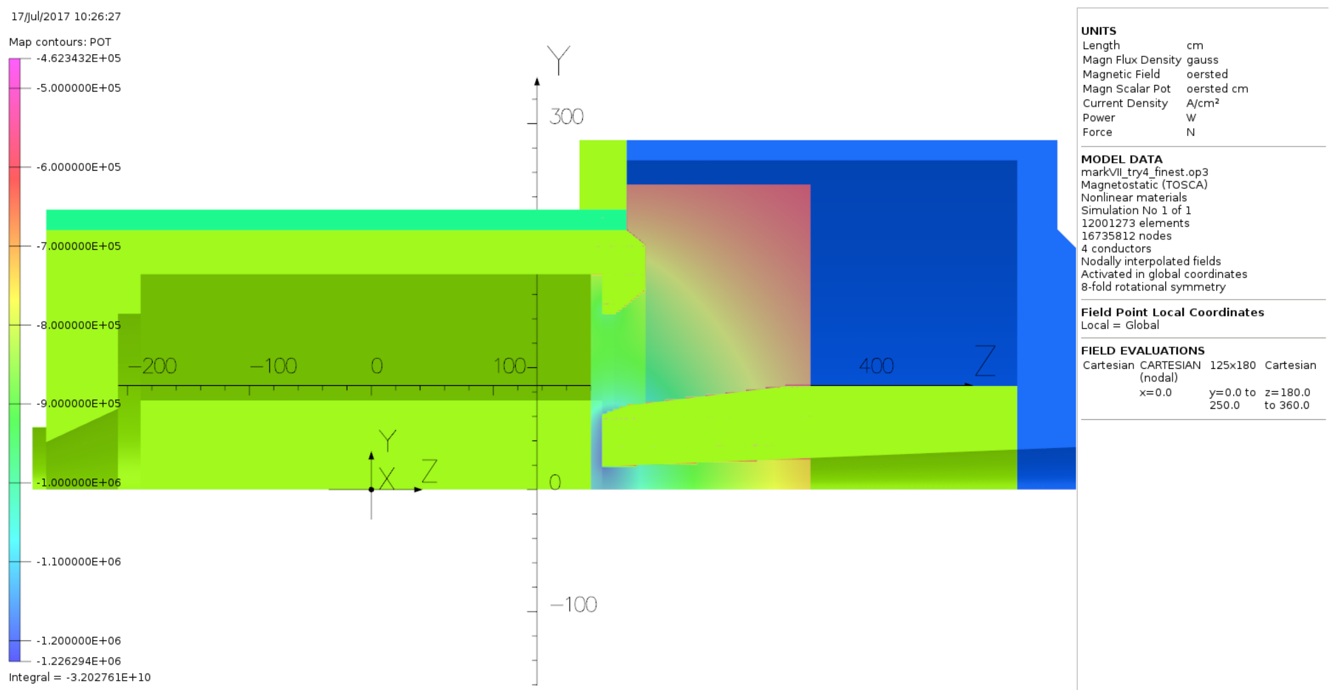

Figure F3. This one covers the span between figures 2 and 5 with no overlap.

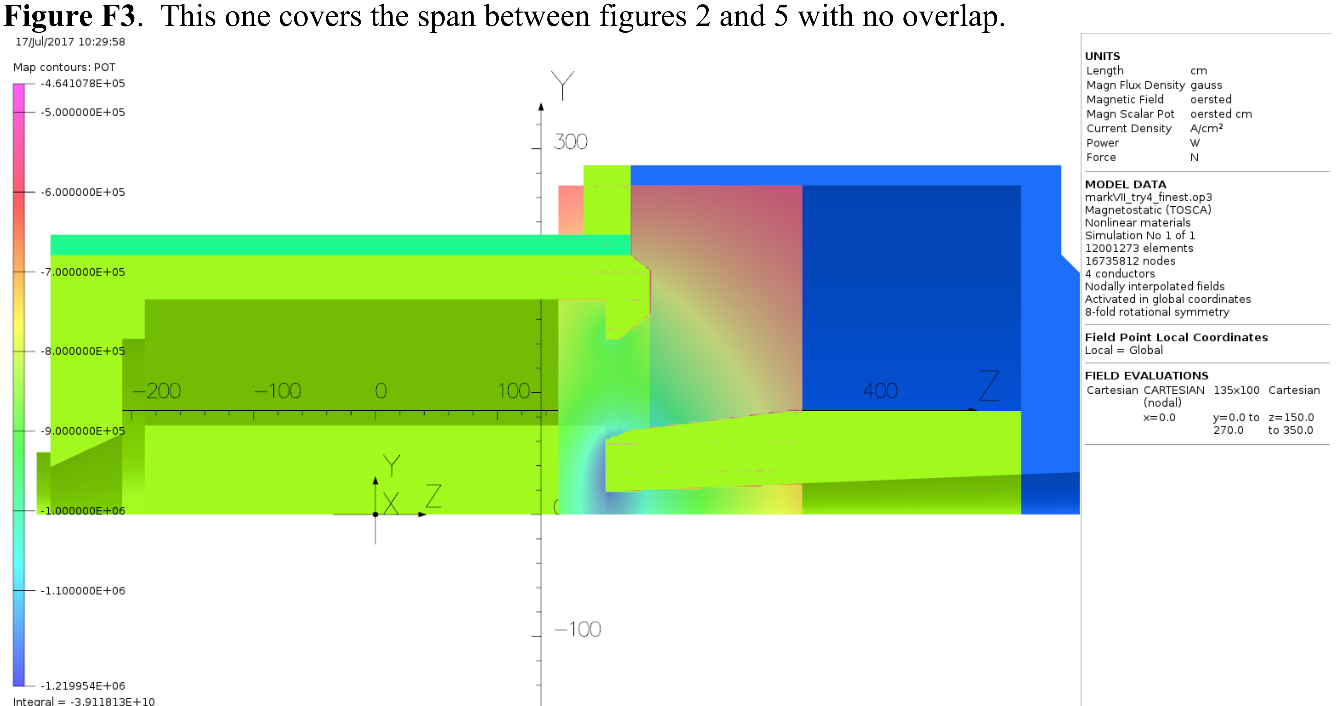

Figure F4. This covers Z=[150,350] vs [180,380] above and so better shows the variation around the nose.

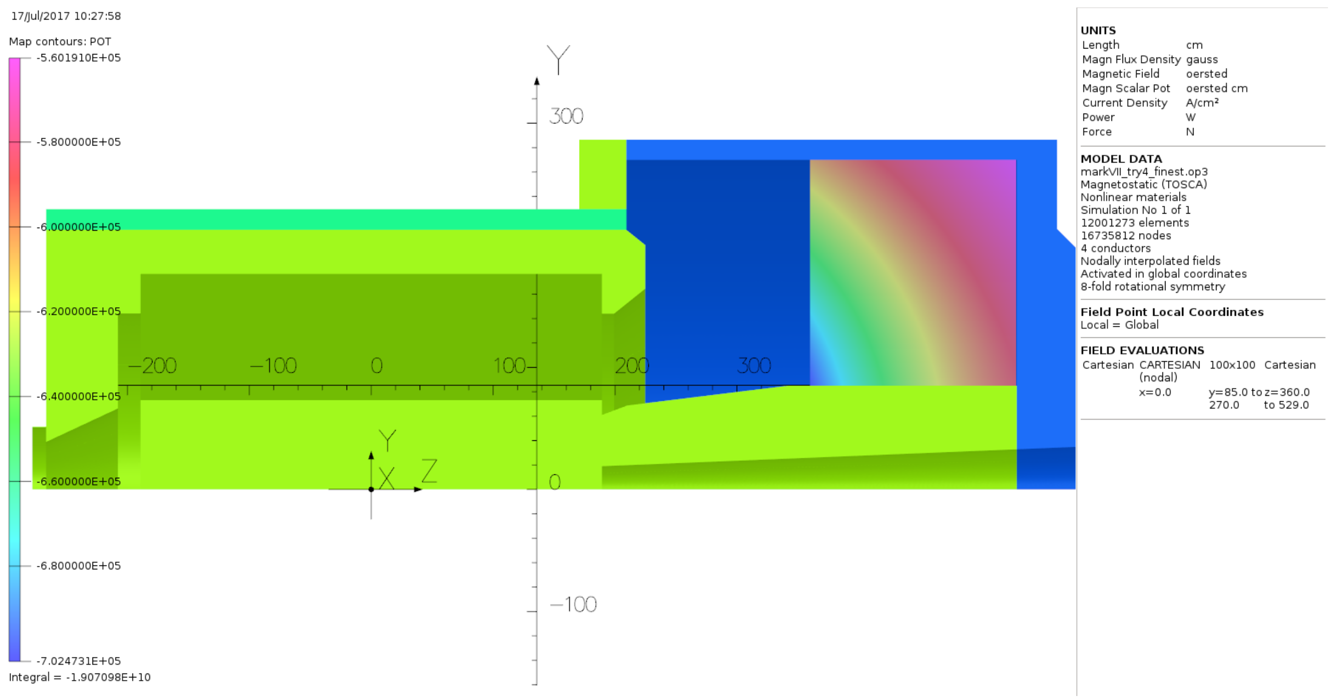

Figure F5. This covers the last of the end cap.

Where are the gradients small enough to coarsen the mesh in Figure E2?