JLAB-TN-08-081

"Banana" magnets for 6 and 12 GeV CEBAF

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Abstract

The "banana" magnets are two types, the MAV and MAU, now in use in arcs 4 and 6. They are called this because the poles were curved to reduce their width given large sagitta. These are the first magnets after the common dipoles and restore the beam to parallel to the floor, so they must provide the sum of the BdL of the preceeding common dipoles. The east end magnets with the same function, the MAN and MAM, already are far enough into saturation that they need "shunt adders" and so need replacement for the upgrade as well.

In the MAV and MAU magnets, coils stick out the top and bottom of the "C" so the coils could be straight like the return legs. It is shown below with a model cross-section that this configuration works OK to 7.2 kG, the field needed for 6 GeV CEBAF, but is problematic above that field. Single and paired C magnets were modeled to investigate their interactions in this tight region, where beams are roughly 30cm apart versus the 50cm in the arcs. Single and paired H magnets are also modeled.

It is concluded that an H magnet 252 cm long with 21m radius of curvature is the best solution for both east and west ends. The arc 3 and 5 magnets have the same BdL requirement within 1%, as do the arc 4 and 6 bananas, so these magnets can be powered from the arc 3 or 4 bus, using the same number of turns, with a modest shim on one arc's set to keep within the 20A shunt range. The same magnets can also be used in three other locations where new purchases are required. Reuse of the MAV and MAU cores on the east end of the machine with new, curved coils and H steel is an acceptable and lower cost alternative to complete replacement with new H magnets.

This TN was submitted to the 12 GeV Project team for review July 25, 2008. Comments received Nov. 13, 2008 are included as the appendix.

Banana magnet for use in arcs 4 and 6

ME designed separate cores, 235cm and 250cm long, to replace the MAV and MAU magnets for the upgrade CD2 design, labeling the replacements MXV and MXU. The existing MAV and MAU magnets were to be moved to the east end and run at 12.5 kG. The BdLs of the east end magnets are equal within a percent in the April 2008 design, as are those of the west end. I altered the ME cross-section slightly, modeling a 252cm straight dipole with 10cm pole and 10.5cm return steel. **Coil cross-section 4x7.5cm^2.** I envision this being built with a 21m radius of curvature, matching arc 6 needs. The 1.5cm sagitta caused by the mismatch between arc 4 and arc 6 beam radii will not affect the ultimate beam quality given subsequent synchrotron radiation emittance driven growth.

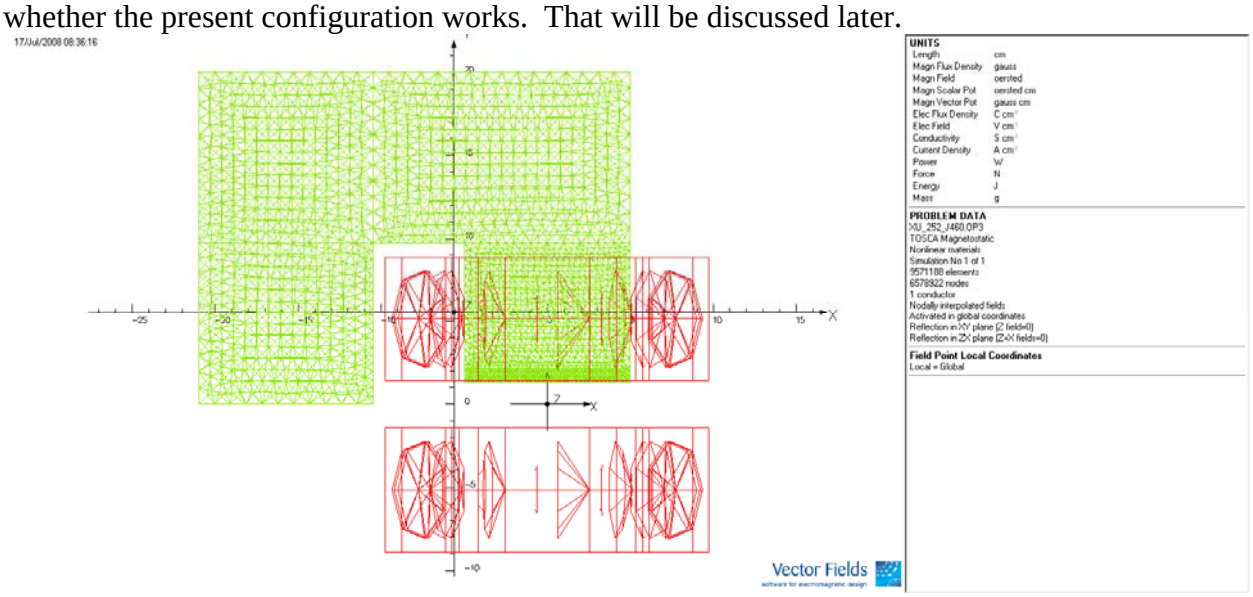
This magnet might also be applied in the hall D line instead of the arc 10 dipoles, saving 6m of steel and copper. In that case the radius of curvature might be increased to ~28m. It could even be profitably used in lieu of the XH magnet in the arc 10 S/R. It cannot be used in the fifth pass transport recombiner due to the relatively narrow pole and the offsets of A and C beams. If the

last choice is made the "XH" dipole needed for the AT line could be fabricated by taking the spare BR core and adding return steel.

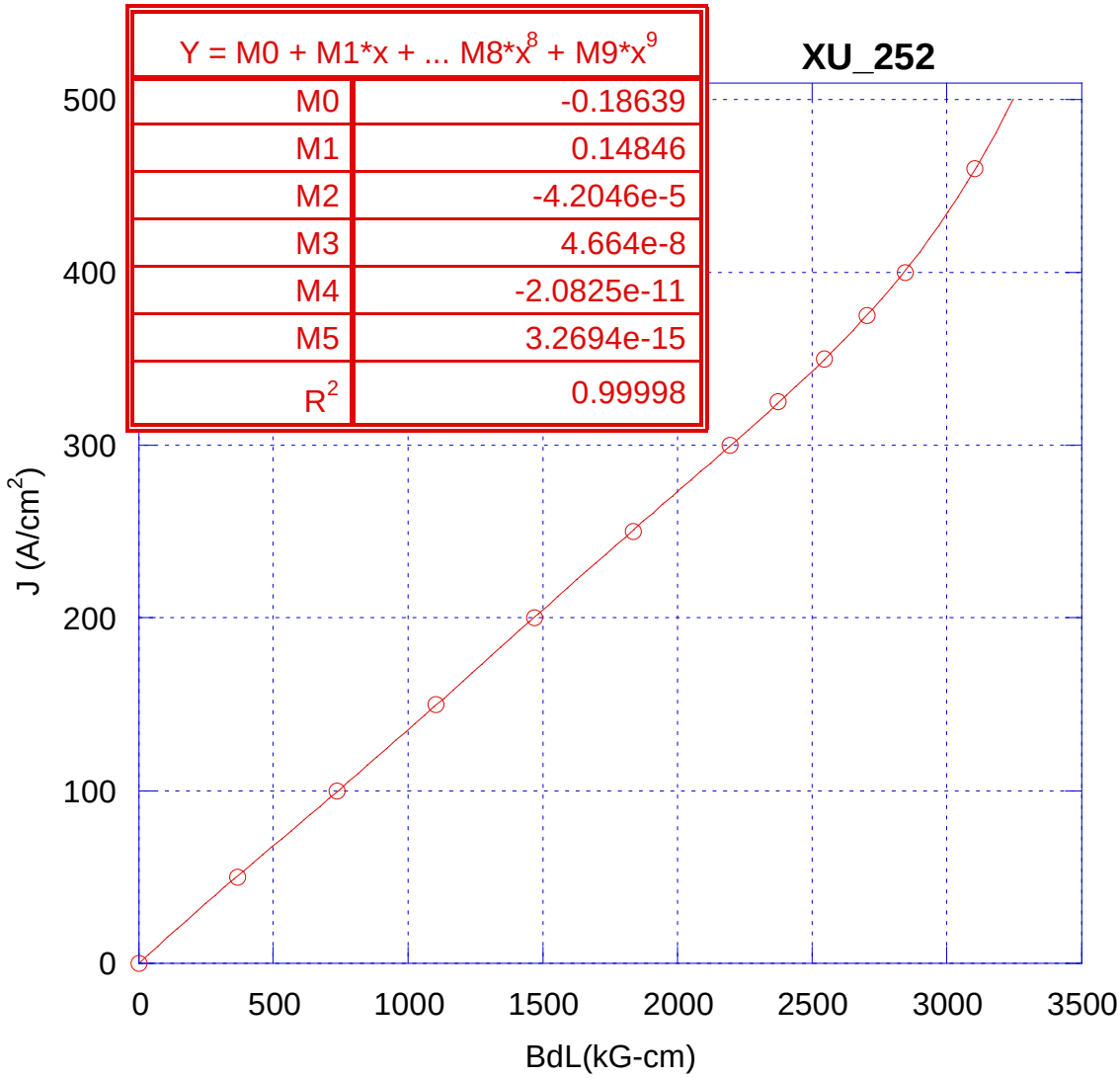
This page and the next have the coils wrapped around the poles as in our usual C magnets. The pages which follow these have the coils wrapped around the top and bottom of the C so when mounted for vertical bending there is less vertical extent.

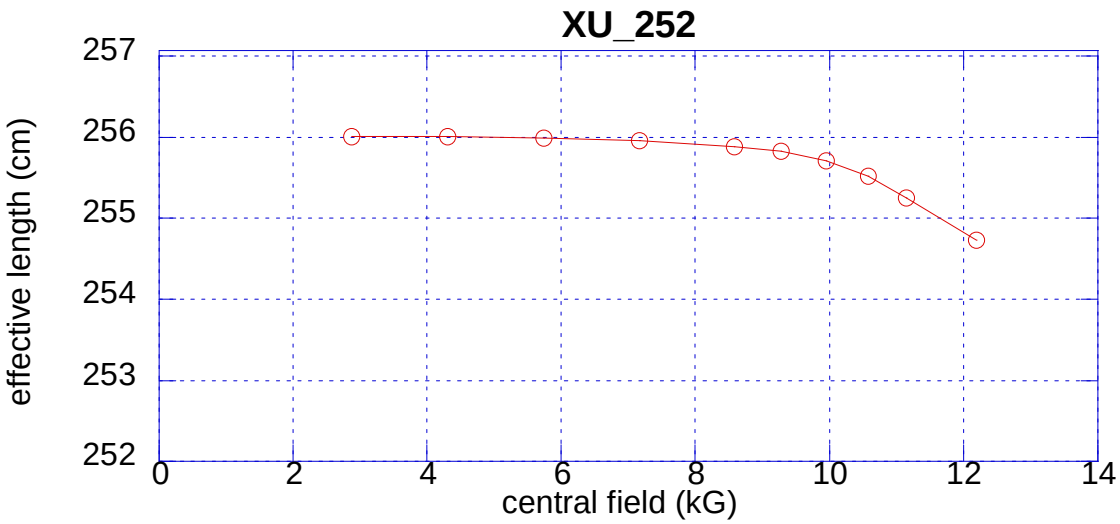
BdL(kG-cm)_	J (A/cm2)	formula	formula/actual	central field (kG)	effective length (cm)
0.000	0				
367.711	50	50.679	1.0136		
735.421	100	99.417	0.9942	2.873	256.009
1102.959	150	149.507	0.9967	4.308	256.005
1469.885	200	200.529	1.0026	5.742	255.990
1835.035	250	250.750	1.0030	7.169	255.953
2196.007	300	299.655	0.9988	8.582	255.886
2373.126	325	324.255	0.9977	9.276	255.826
2544.856	350	349.523	0.9986	9.952	255.714
2704.826	375	375.377	1.0010	10.586	255.517
2844.946	400	400.908	1.0023	11.146	255.252
3105.526	460	459.643	0.9992	12.191	254.734

The last row was added as a rough check on the existing MAV and MAU magnets, which are to be moved to the east end from the west. They are 200cm long and need to produce ~2500 G-cm. The last line has about 1% lower BdL than the equivalent needed for MAV3 and MAU5. I multiply by 200/252 because the effective length will change similarly on both. On the second page following I show field in the steel and stray field for this magnet. Note that the MAV and MAU magnets have coils wrapped around the top and bottom of the C, not the poles proper as here. I am checking whether the steel is usable with new coils wrapped around the poles, not whether the present configuration works. That will be discussed later.

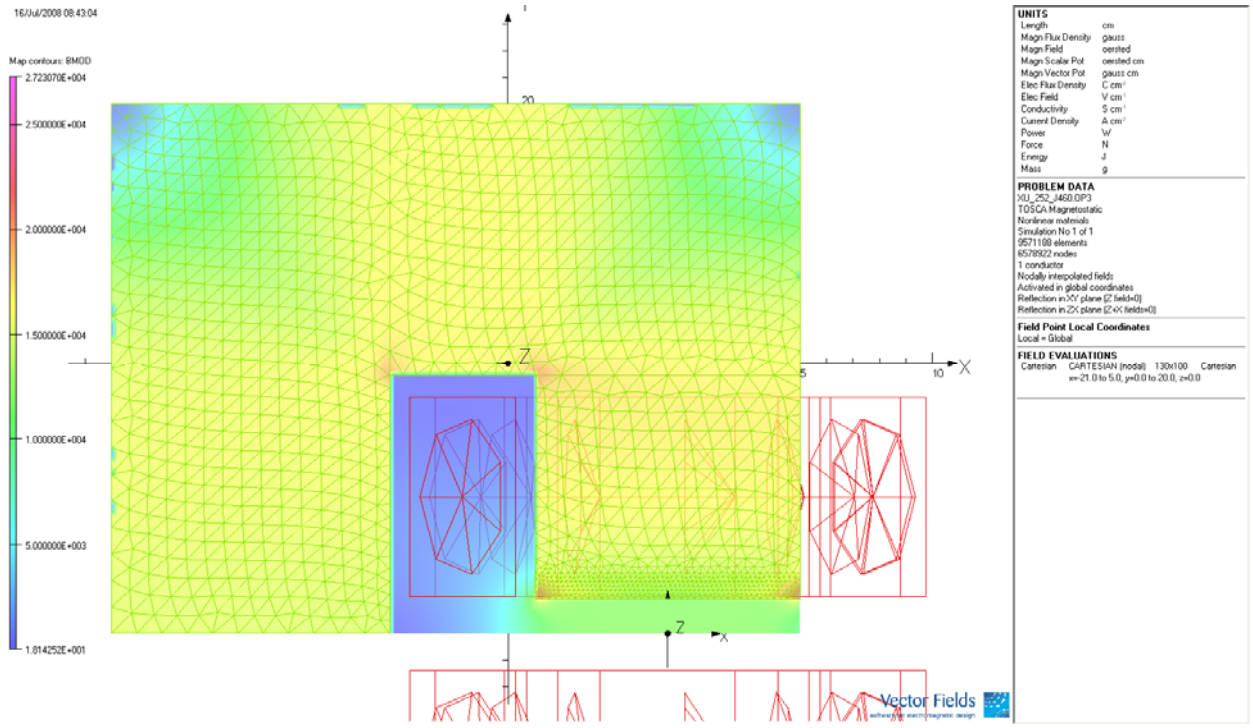


Cross section of C model with coil wrapped around pole.

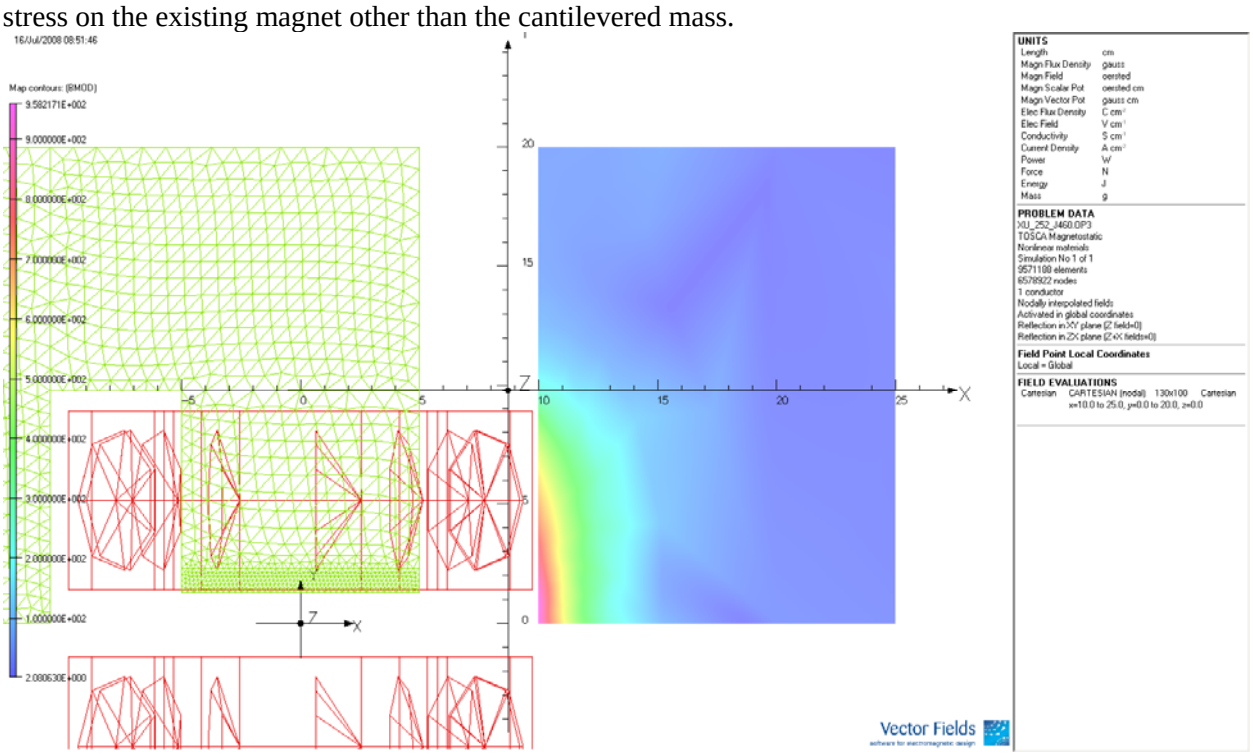




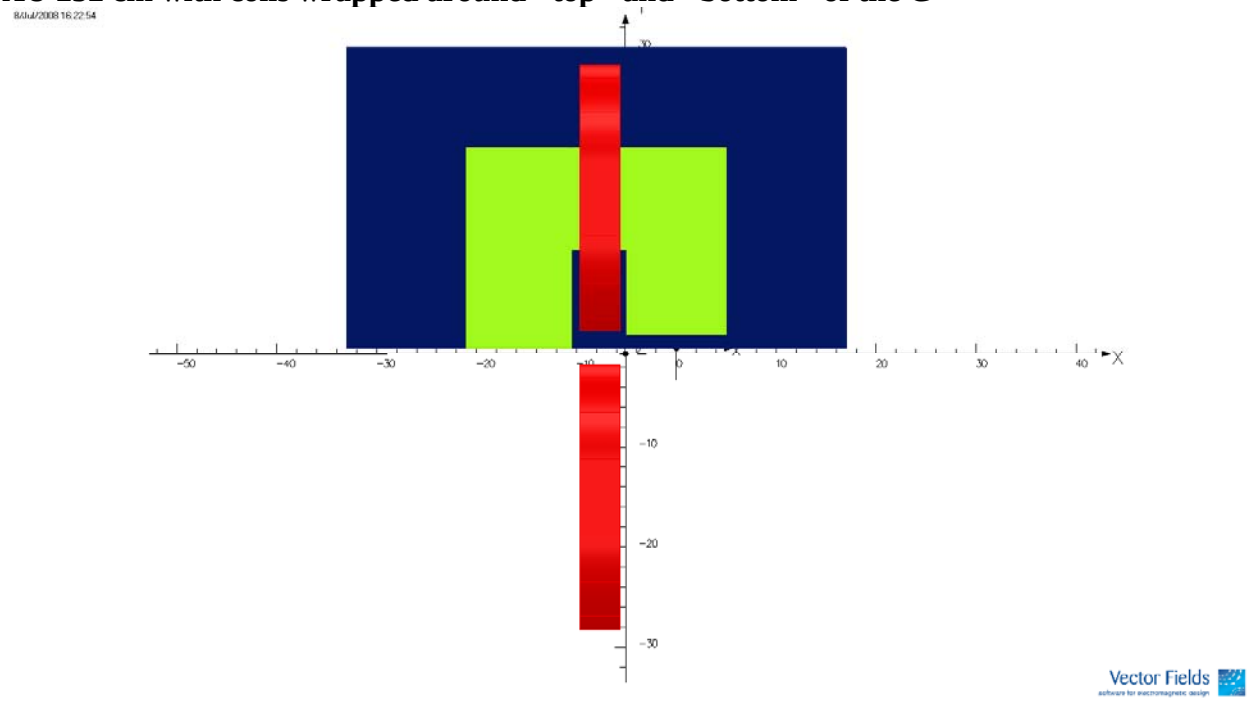
Effective length. Steel is 252 cm long, the lower Y limit of the graph.



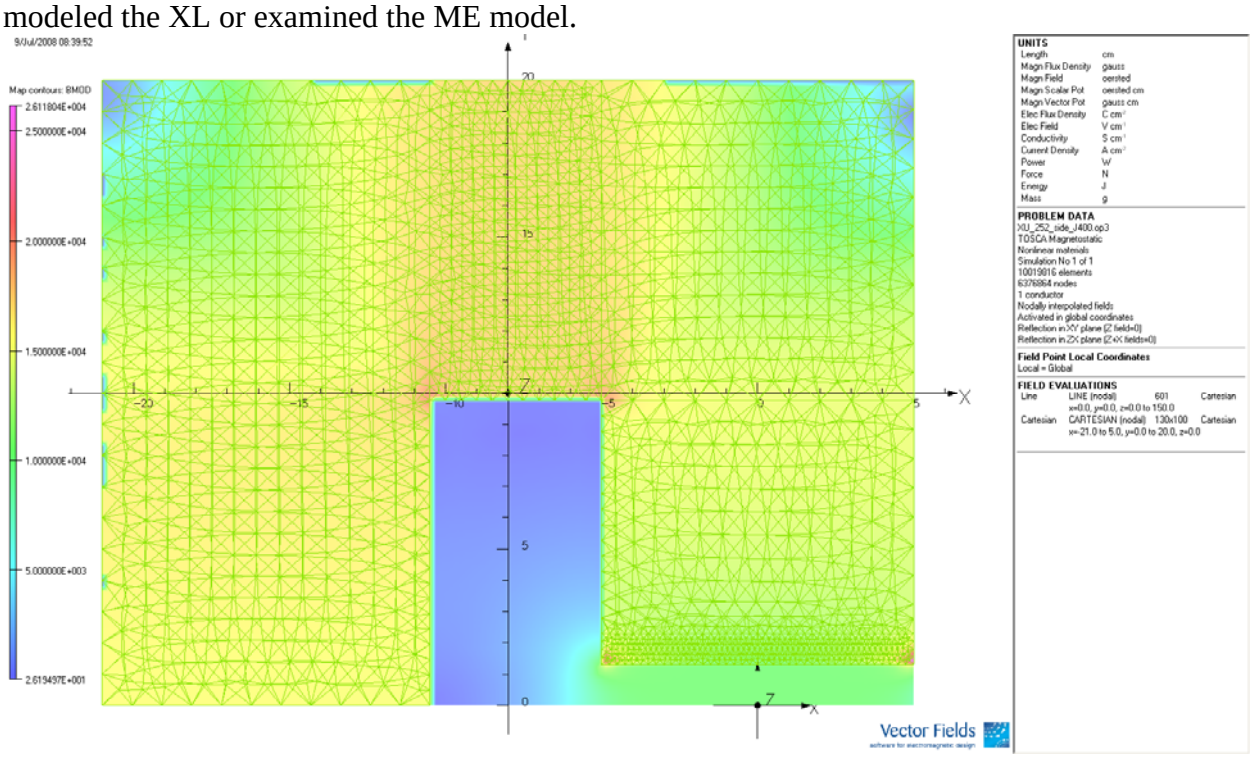
Field in steel of my XU model at east end field (12.5 kG). The real MAU steel has a 8.9cm wide pole and only 7.62cm return. The return will have to be increased. The MAU pole is curved and the return straight, unlike the concept for this magnet in which everything is curved. New curved coils would be required. This model assumes 2.5cm is added to the return at the back of the steel, the lowest cost option. Adding 3cm of curved H steel instead would improve the stray field situation (below) considerably. The curved H steel need not be finish-machined. If the horizontal extension is fabricated a bit "long" and the rolled H steel mounted between the horizontal extensions, they could be match-drilled so there was no stress on the existing magnet other than the cantilevered mass.



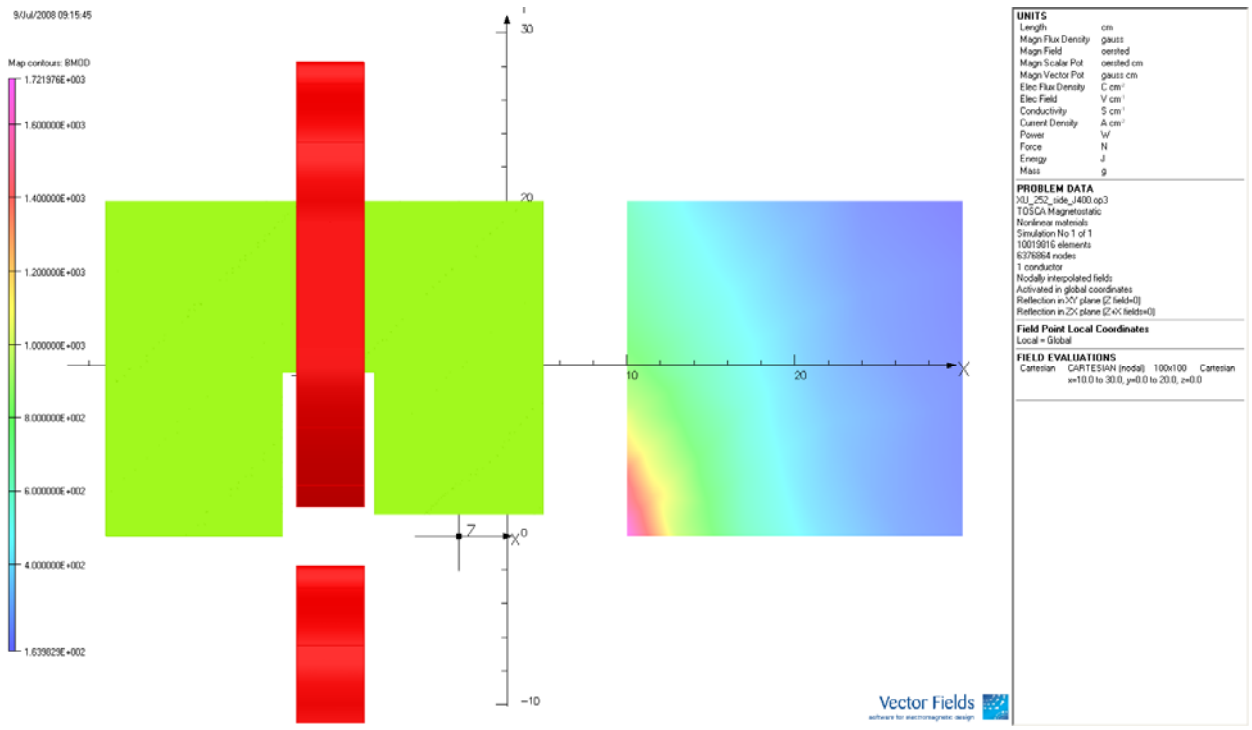
XU 252 cm with coils wrapped around "top" and "bottom" of the C



Top half of this C magnet variation is shown above. Green is steel and red conductor. The blue background is the extent of the air modeled at 0.5-1 cm mesh maximum. A background element extending a factor of 10 in X, 8 in Y and 2 in Z with 50 cm mesh maximum is added just before meshing. Tangential fields are set to zero on the boundary of this large rectangular volume.
This is the coil orientation used by ME (R. Michaud) for his XL. XV and XU designs. I have not modeled the XL or examined the ME model.



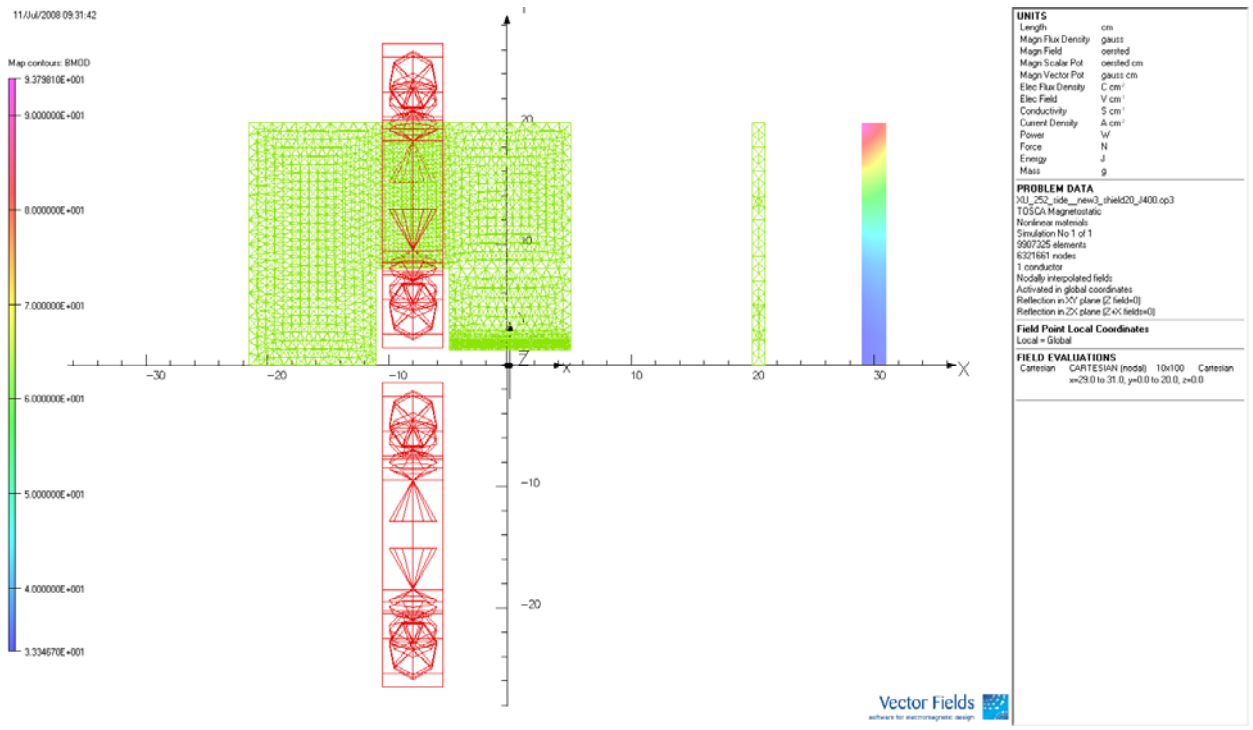
Field in the steel for current giving 102% of needed BdL at full energy, west end.



This design, with the same coil "pocket" as that done by ME, is likely unacceptable due to stray field. Z=0 field magnitude in the X-Y plane is shown. At the location of the adjacent beam, x=~30cm, field is ~200 G. (The gap between coil and steel can be reduced to improve coupling and the coil cross-section changed from 4x7.5 to 5x6 cm^2.) I solved the model shown with the usual J values and present the table below. I don't bother to plot. I include comparisons of central field and BdL with the data in the table on page 2.

BDL/2	BdL(kG-cm)_	J (A/cm2)	central field (kG)	effective length (cm)	BdL/2 side/pole	Bcenter side/pole
0	0	0				
184.28	368.56	50				
368.56	737.11	100	2.869	256.888	1.002	0.999
552.65	1105.31	150	4.303	256.876	1.002	0.999
736.10	1472.20	200	5.732	256.836	1.002	0.998
917.64	1835.27	250	7.148	256.749	1.000	0.997
1093.00	2186.01	300	8.520	256.562	0.995	0.993
1172.17	2344.35	325	9.143	256.407	0.988	0.986
1239.01	2478.02	350	9.671	256.244	0.974	0.972
1293.85	2587.70	375	10.105	256.073	0.957	0.955
1340.38	2680.76	400	10.477	255.881	0.942	0.940

At 7.15 kG, almost exactly the field in the MAU and MAV magnets at 6 GeV, the return flux is still well contained by the steel as shown in the last two columns of the table. (What is shown is a better condition than the MAU and MAV because their return legs are only 75% of that shown here and poles are 89%.) By 9 kG, about 1% leaks into the air. By 10.5 kG, almost 6%. Hence the large stray fields plotted above.

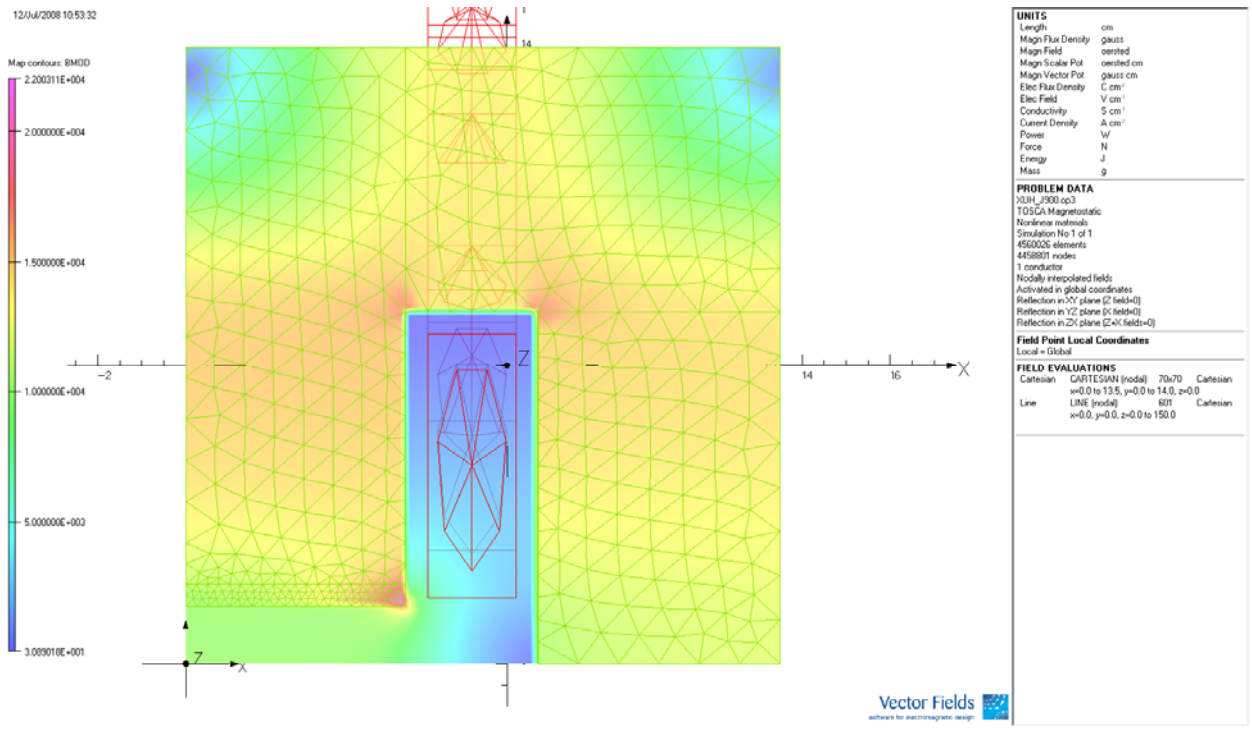


I have examined several cases with 1cm shield plates at various heights and offsets. In the case above, the best of the lot, stray field is cut about a factor of five at the location of the other beam, shown by the slice around x=30cm. This magnet has the altered coil with 5x6 cm^2 cross-section. 5mm gap to steel all around the coil. The plot is non-physical since the second beam is 5 cm into its pole, of course. This assumes the openings of the C face each other as shown on the song sheets.

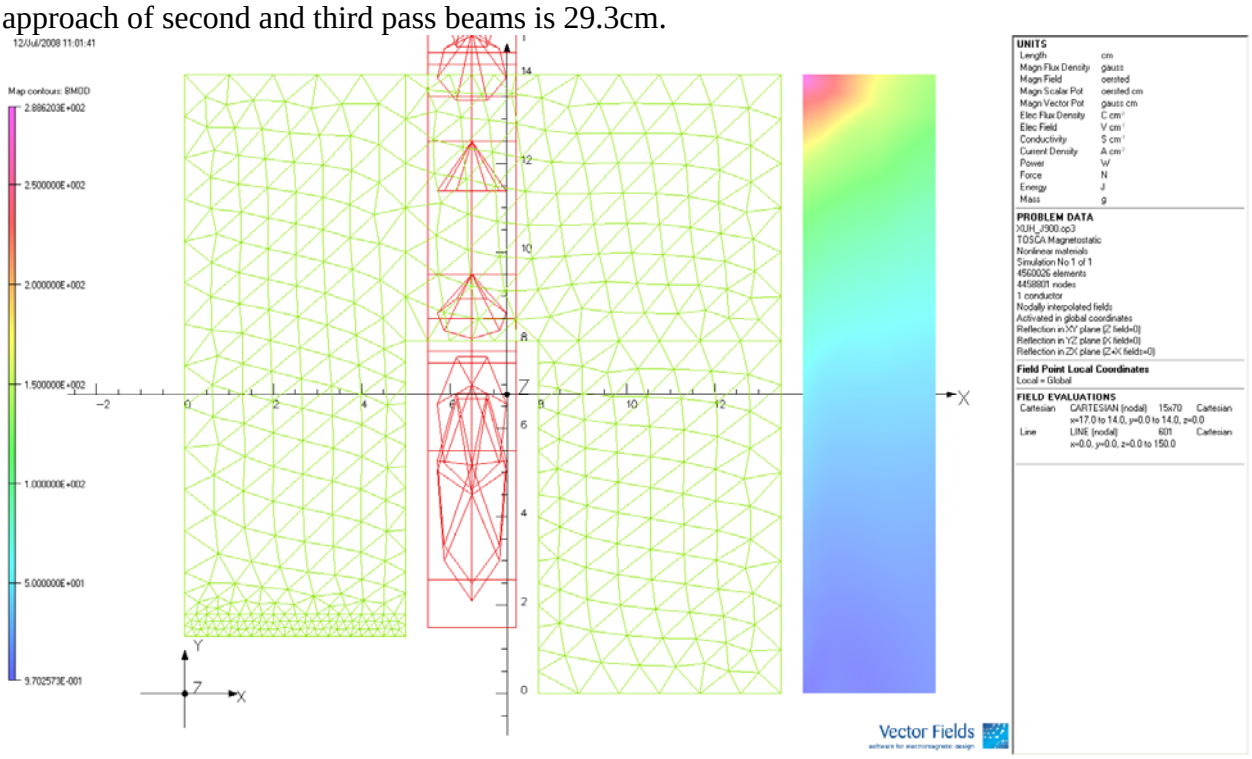
The distance between the beams in these two magnets ranges from 29.3-36.6 cm. There are three ways one might handle the problem. One would "stack" the three roll-over magnets of the C type shown above with return steel up. The return steel for each magnet will intercept flux from the next, reducing saturation in the return leg. The second option has the open Cs of second and third pass facing each other. The third option is H magnets. I modeled all of these.

I will contruct a model with two coil-steel assemblies shown above offset by 30cm as an approximation of the real geometry and solve. I will compromise multipole accuracy by increasing the element size in the gap from 0.25 to 0.325 cm, cutting the number of elements there in half. Since I use quadratic elements, this will still provide adequate resolution for terms up to decapole.

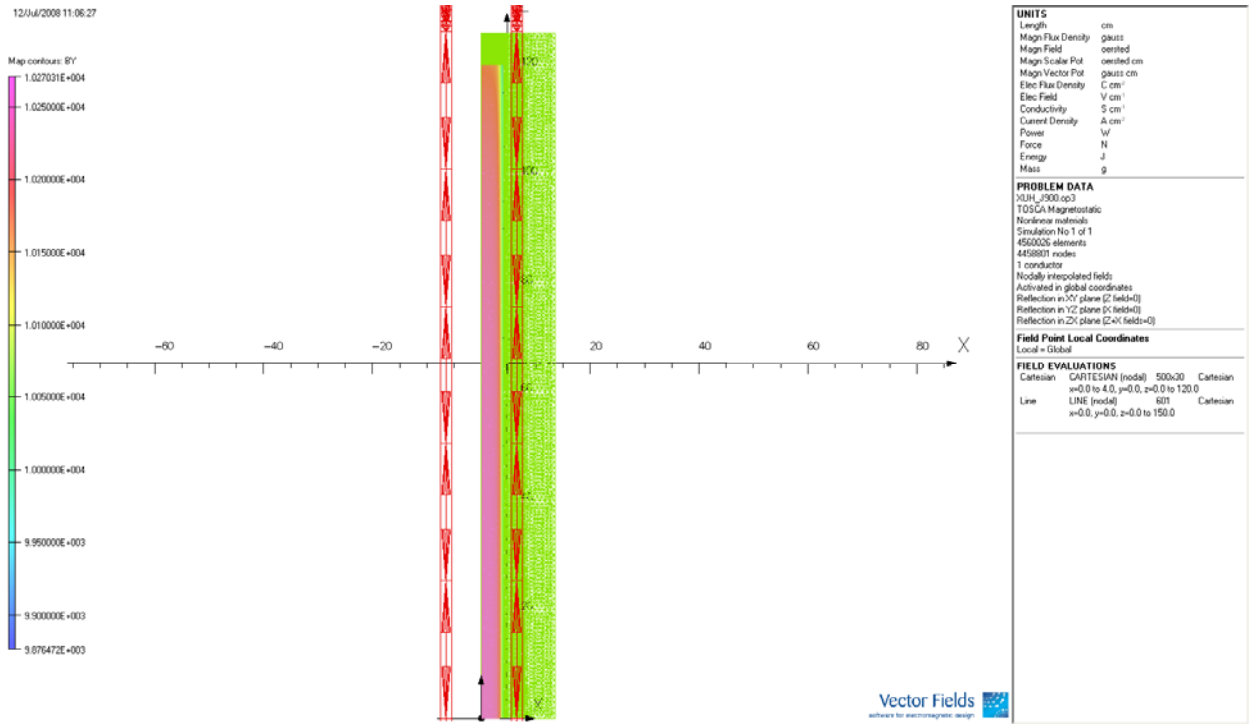
The H model is smallest due to symmetry. It solved fast and will be presented first. BdL of this model is 0.3% above requirement of the April 2008 design.



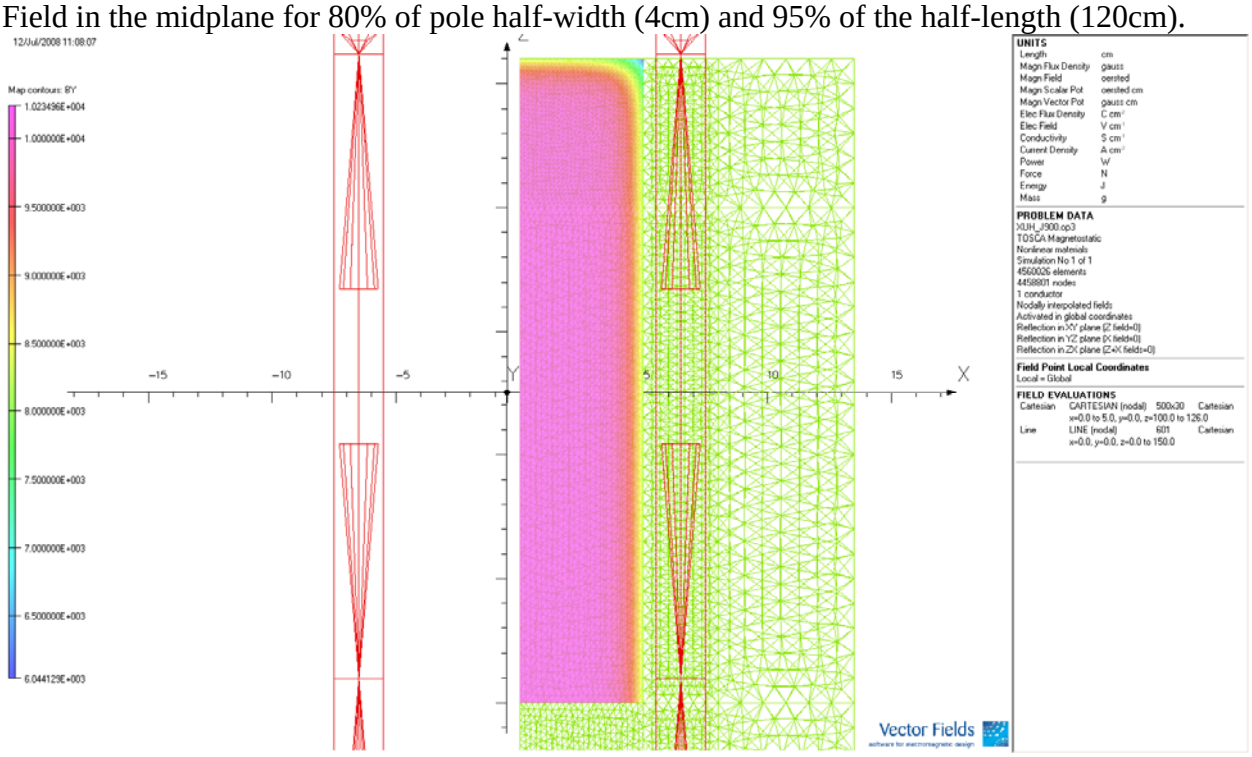
Field in the steel and gap of a peculiar H magnet. This is one fourth of the cross-section. Symmetry conditions allow this to suffice for calculation. This magnet is 27cm wide (vertical as installed) versus 26.5cm for the C magnets previously shown. ME's design is 26.6cm. Closest approach of second and third pass beams is 29.3cm.



Stray field is much lower than in the C magnet. The steel of the adjacent magnet will be just inside the right edge of the colored band in the figure. Coils are 2x6 cm^2. J=900 A/cm^2, quite high. Coil pocket is 3x6.7 cm^2, assuming bottom of coil is parallel to the pole face.



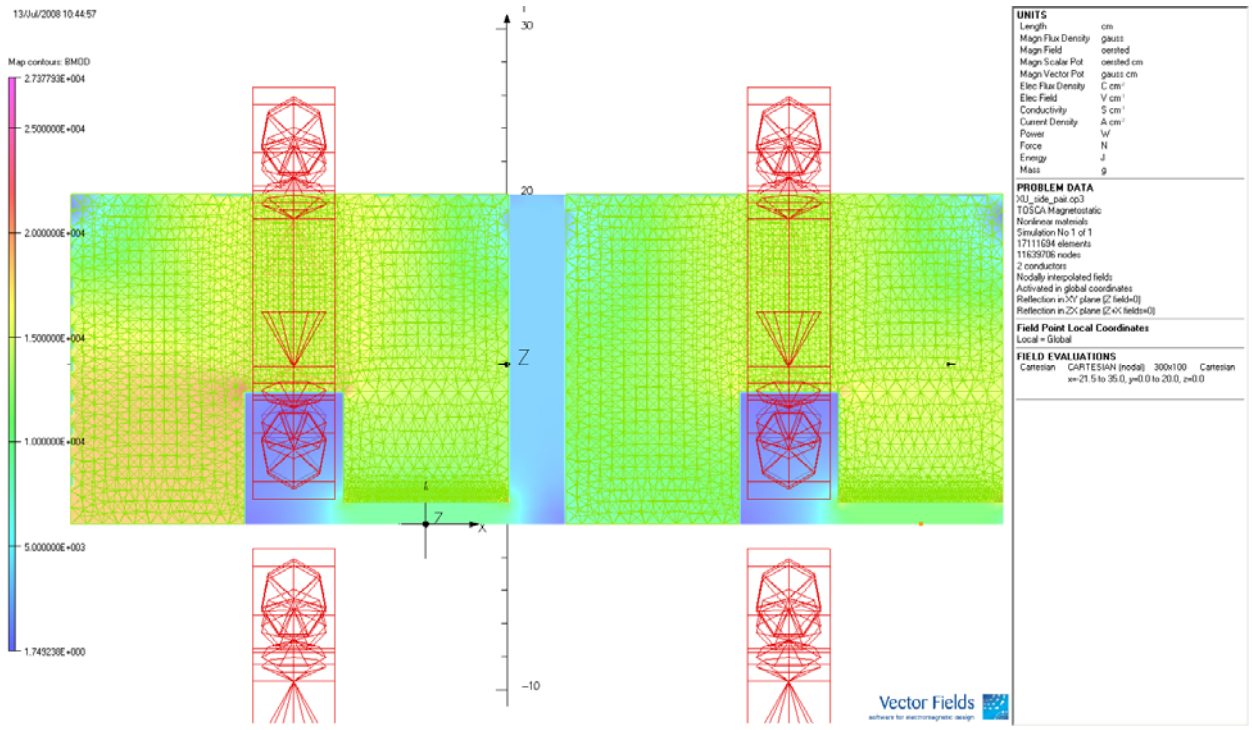
Field in the midplane for 80% of pole half-width (4cm) and 95% of the half-length (120cm).



Field in the midplane for the last 26cm of the steel, full pole half-width of 5 cm. Since the magnet is curved, pole width might be reduced to 4.5cm to increase the coil pocket width to 3.5cm and decrease the current density in the real coil pack to ~600 A/cm^2. With insulation, epoxy and water cooling hole, this is about the limit for copper without chilled water cooling. Detailed thermal analysis would be required, of course, as would a check on multipoles for the arc 4 orbit with radius smaller than that of the magnet. Sagitta of that orbit is ~1.5cm if the

magnet has 21m radius of curvature. At 10.3 kG a pole half-width six times the half-sagitta, 4.5cm, should have multipoles well under the specification in TN-07-018. See TN-08-TBD for calculations of multipoles as a function of field on orbits with similar sagitta.

The model with two C magnets took 36 hours to solve. Fields in the XY plane at Z=0 are shown below.

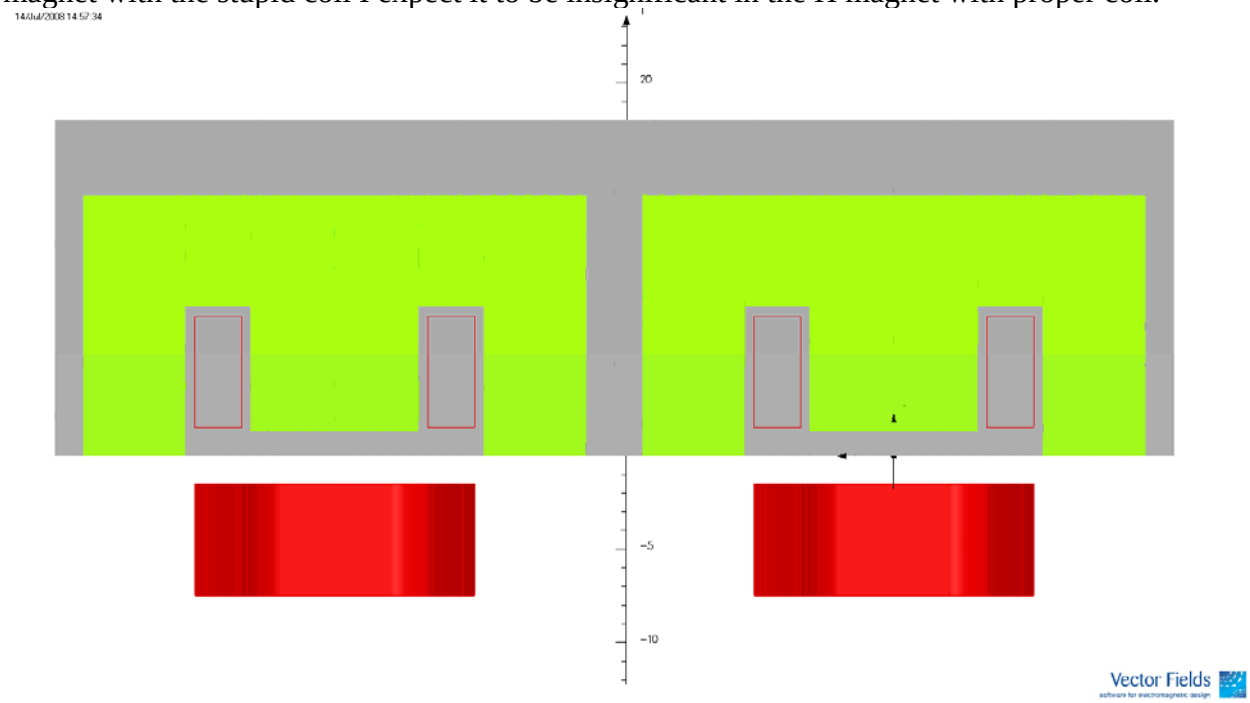


The pairing of two C's with coils of this orientation has large effects on both magnets. One can easily see that there is much less field in the return leg of the right hand magnet than the left. What one can't see with this color scale is that the central field of the left hand magnet is reduced by 14% from that of a single magnet and the field of the right hand magnet is enhanced by 3%. I used the same current densities in the coils. Given the field in the steel in the return leg of the left magnet (18.4 kG) it is likely that one cannot increase the current enough in the left magnet to obtain the needed BdL. It follows that C magnets of this type cannot be used in close proximity in this orientation.

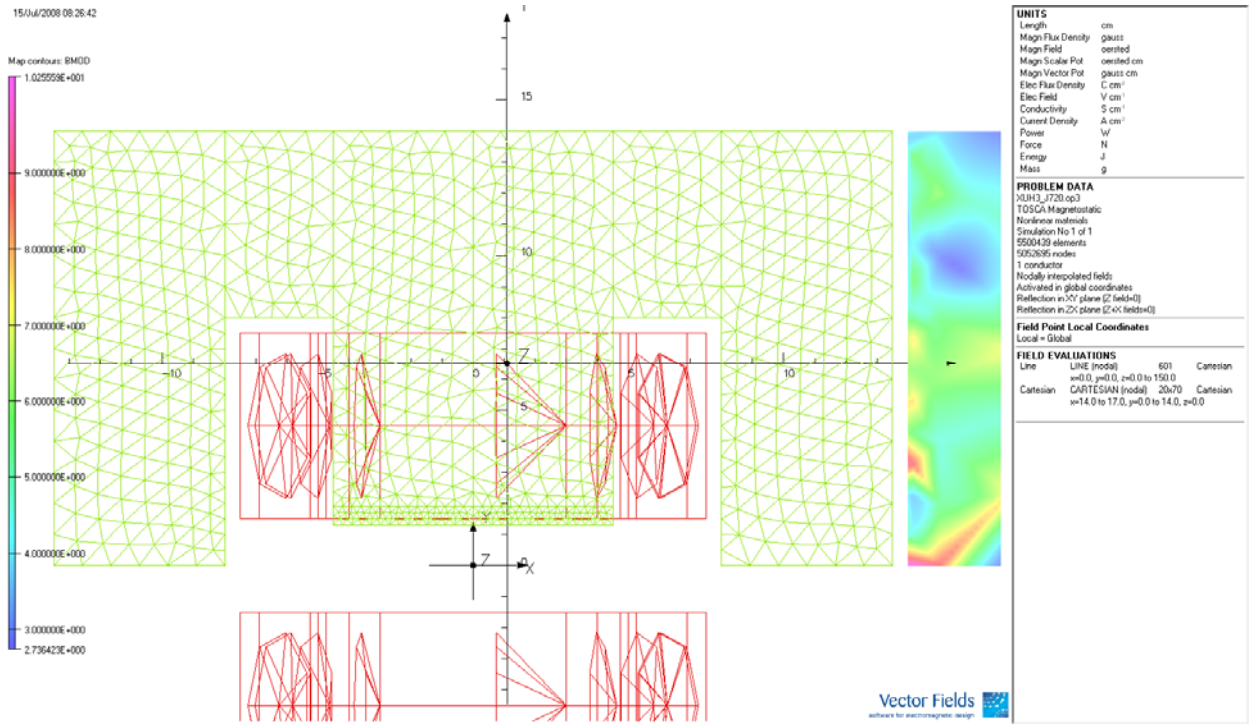
This leaves two options, the H magnet and the Cs with pole gaps in the middle. Coil orientation on the Cs must be explored. Mike Tiefenback pointed out that the coils in the H should wrap the poles rather than the return leg as modeled above. While current density is high, the steel area is lower than that in the C's above.

With the coil wrapped directly around the C pole, the coupling between magnets shown above would be reduced. Since magnets like these would require perhaps twice the steel of the H magnets, the H magnet seems the better choice. I'll build a model with two of them to check on coupling but I expect it to be much lower. Better yet, I'll build another model of one of them with the 9cm wide pole and 11 cm total return steel (5.5 cm per side). I will start this model towards solution and then duplicate it as I did the C pair above to create a second model. A third

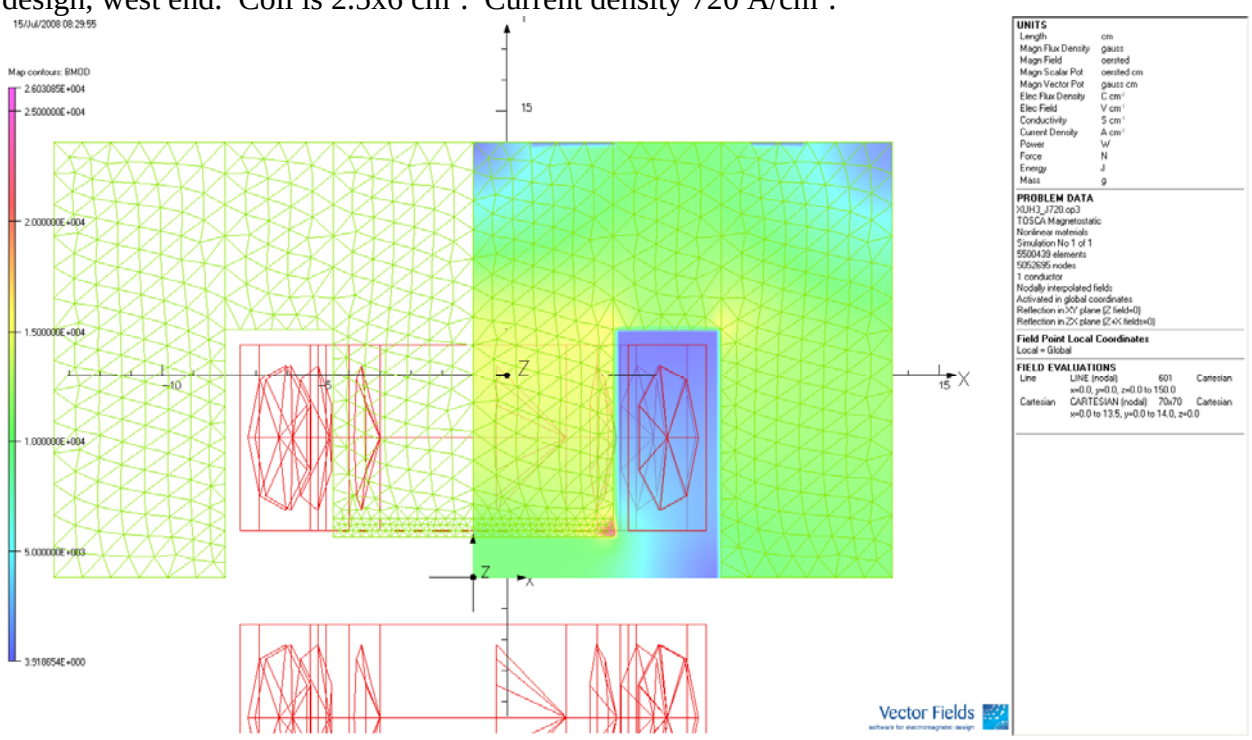
model, using symmetry around the X=0 (yz) plane, would allow a stack of three of these to be evaluated. The MAL magnet is 150cm long, not 252 cm like these, so such a model would again be an approximation - but it would be a useful glimpse at the situation. I will allow the models with one and two magnets to solve before building the third. Since stray field was small in the H magnet with the stupid coil I expect it to be insignificant in the H magnet with proper coil.



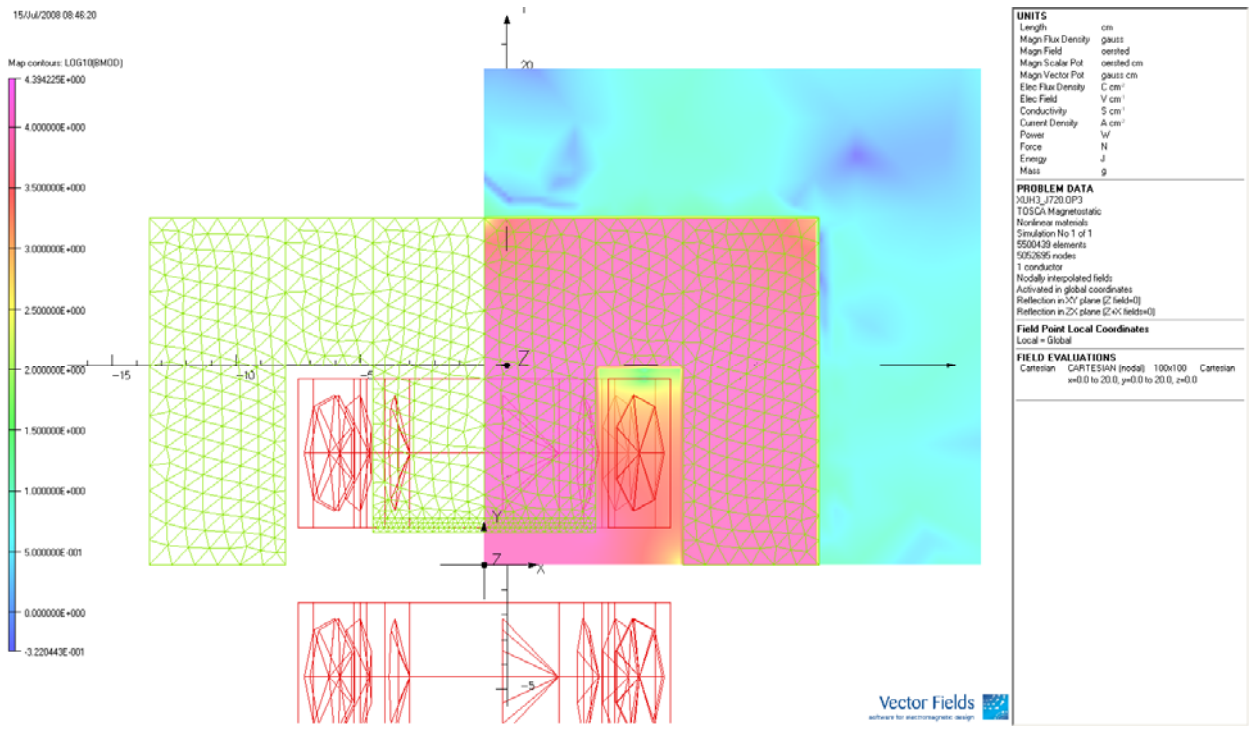
The two H magnet model is shown above. The red boxes show the coils which wrap around the pole. The magnet can be divided horizontally into three 9cm segments. One could manufacture one magnet by procuring six 9.5cm x 14.3 cm x 253 cm bars, rolling them to 21m radius, and machine the coil pockets and all sides of the pole. For better magnetic properties, figure out what radius to roll the piece to so it relaxes to 21m radius after heat treatment to restore magnetic properties degraded by the rolling stress. By procuring near-net bars and rolling one will save substantially on machining costs. The three pieces which comprise each half would be bolted together. The coils would be inserted and the two halves bolted together. The magnets could be supported by bolts threaded into the (Z) ends. The relatively low field in the steel allow for through bolts and end bolts.



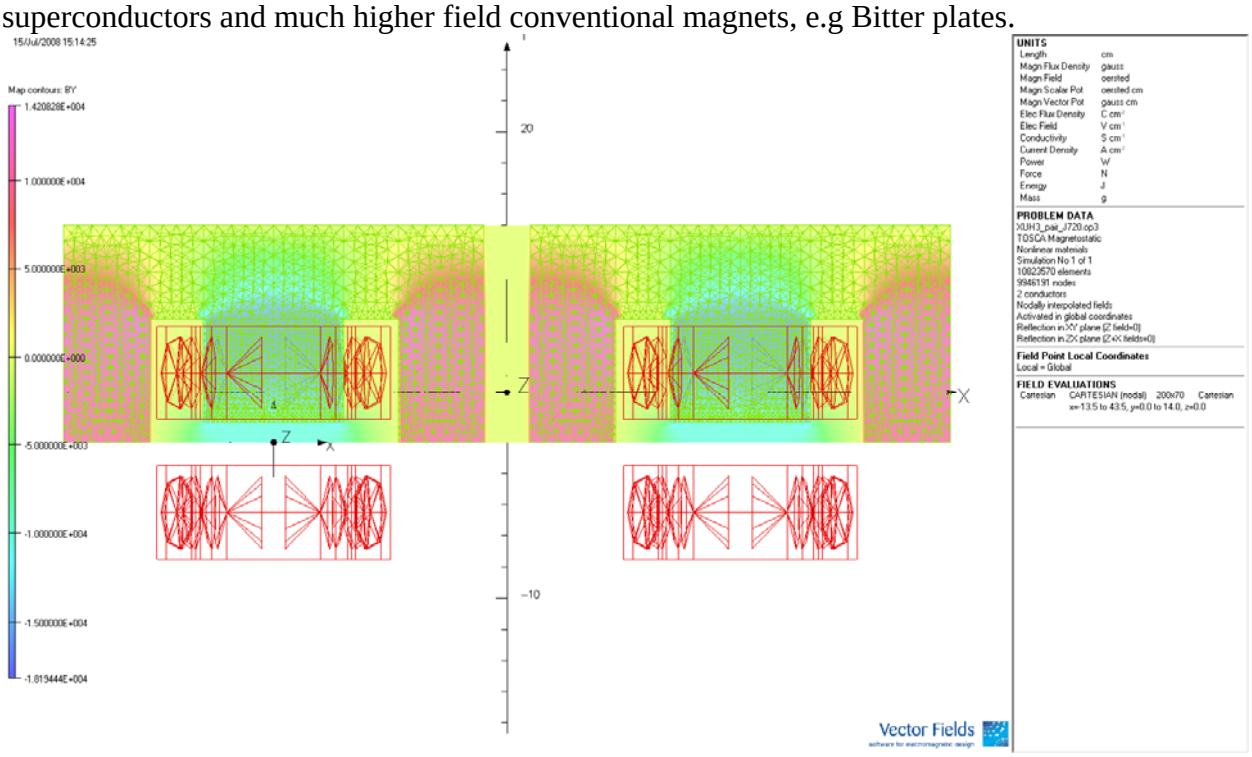
With the coil wrapped around the pole, field adjacent to the return is no more than 10.3G starting 5mm from the return. It follows that such magnets can be stacked in close proximity without influencing each other. The BdL of this magnet is 0.3% above the requirement of the April 2008 design, west end. Coil is 2.5x6 cm^2. Current density 720 A/cm^2.



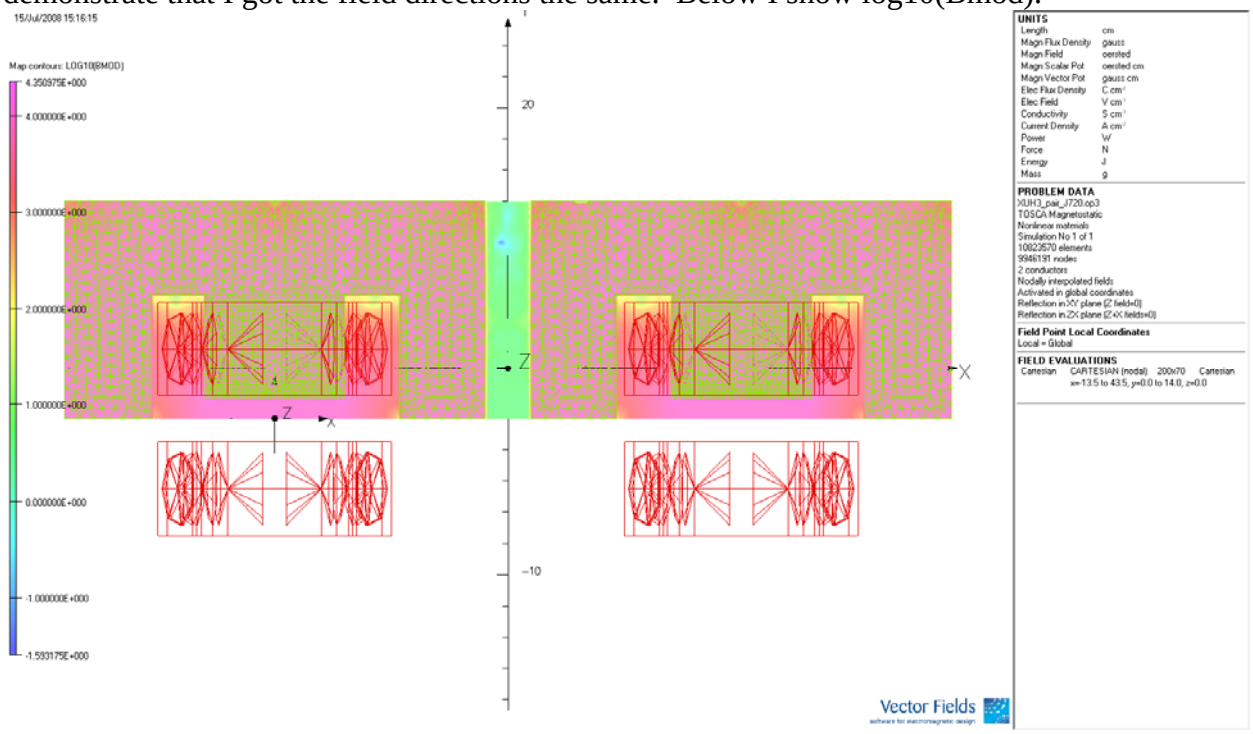
Fields in the pole steel are acceptable. If the three segments of the magnet were increased to 9.5 cm, total 28.5cm, current density would drop to 600 A/cm^2 if one maintains the 5mm gap around the coil used in all these models.



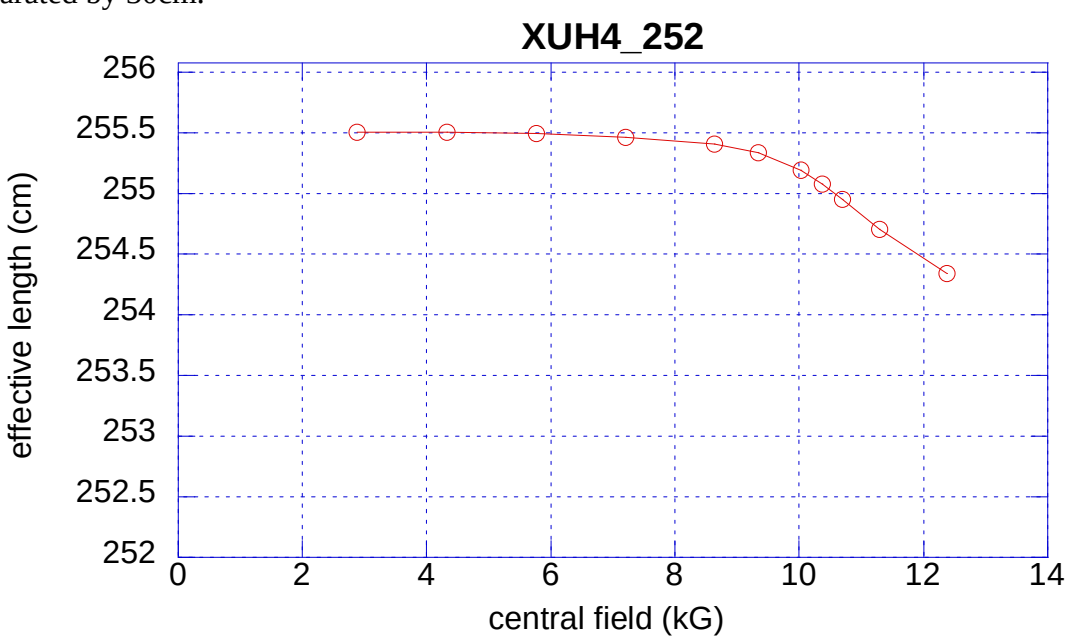
I just got an email from Vector Fields support responding to a request for log scales instead of linear ones on such plots. A hidden feature of Opera is the ability to apply a function to a field component before plotting. Here I've plotted log10(Bmod) using this new datum. One can't see fields as well as on the previous two plots, but at least one can see everything. The field in the coil pocket is low because I have chosen the default, which doesn't compute the field in the coil. This is true for all previous plots too. It's the default because field in the coil matters only for superconductors and much higher field conventional magnets, e.g Bitter plates.



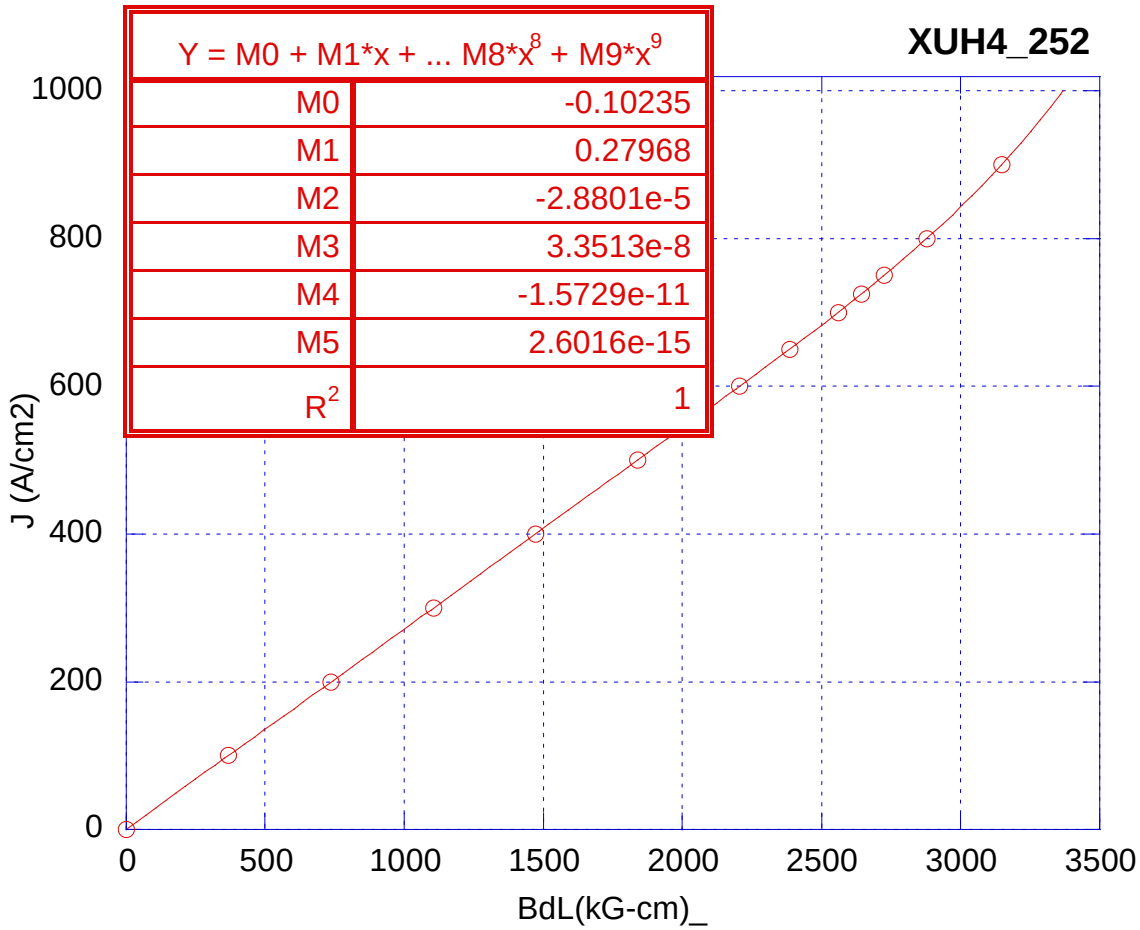
In the figure at the bottom of the last page I show B_y for the pair of H magnets. I show this to demonstrate that I got the field directions the same. Below I show log10(Bmod).



The field in the gap between the magnets can now be seen to be ~10G as for the single magnet. Field at the center of the left magnet = 10303.4976 G. For the right magnet, 10303.4963G. The difference is just over 1 mG. BdL left 1314221.4 G-cm right 1314224.3 G-cm. 3 G-cm difference, again insignificant. One can stack such H magnets three deep on both sides of the machine without worrying about cross-talk. This contrasts with the C magnets stacked front to back as shown earlier. Here, as in all other models of paired magnets, the two beams are separated by 30cm.



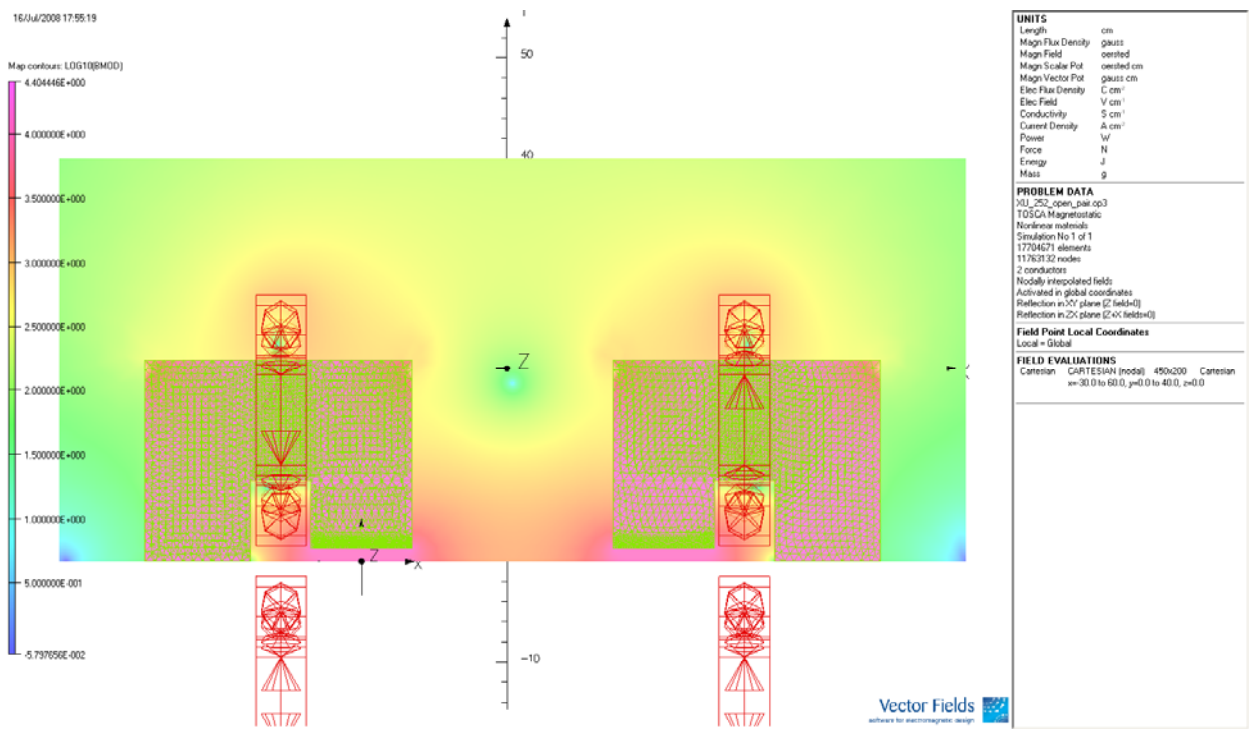
Effective length of single H magnet with 252 cm steel as a function of central field.



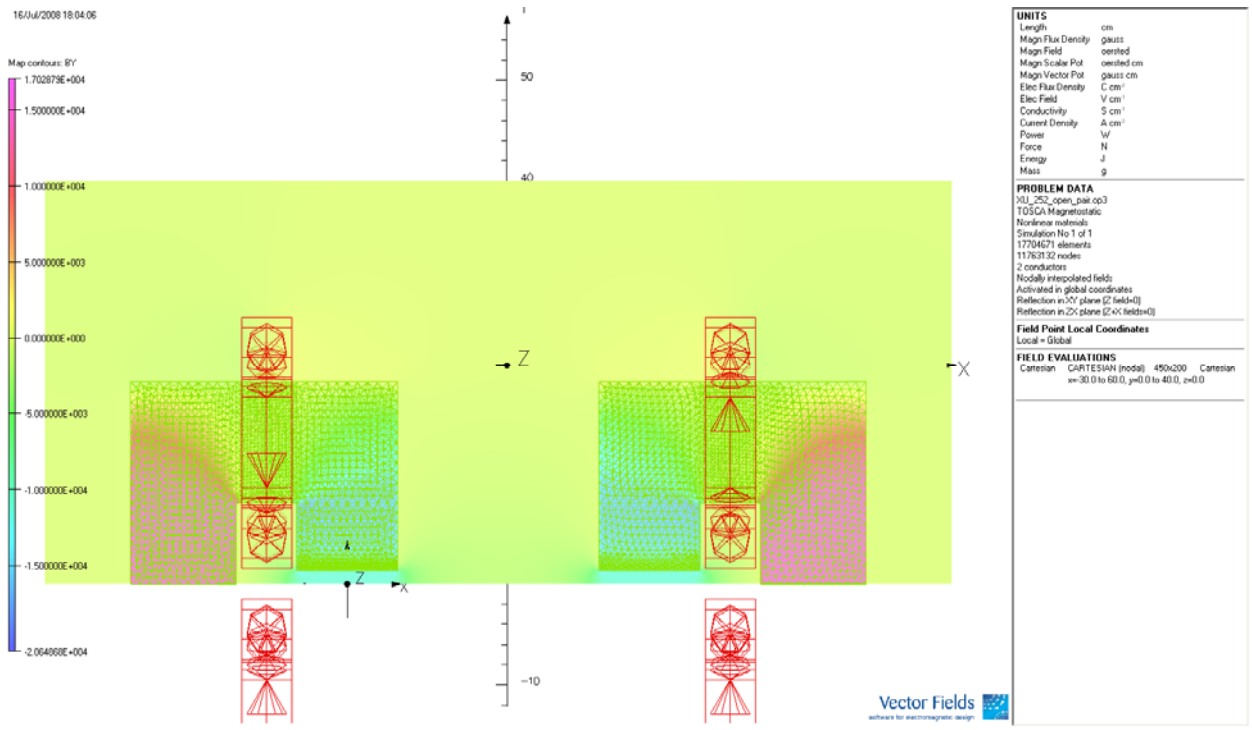
J(BdL) curve for single H magnet of cross-section shown in preceeding section.

H dipoles are clearly the preferred choice for operational ease due to the complete lack of cross-talk. Cost is a consideration, so re-use of the existing MAV and MAU steel, moved from the west end to the east, must continue to be examined. I therefore model a pair of C magnets with coils at the top and bottom of the C, as in the existing MAV and MAU. Results are shown on the next three pages.

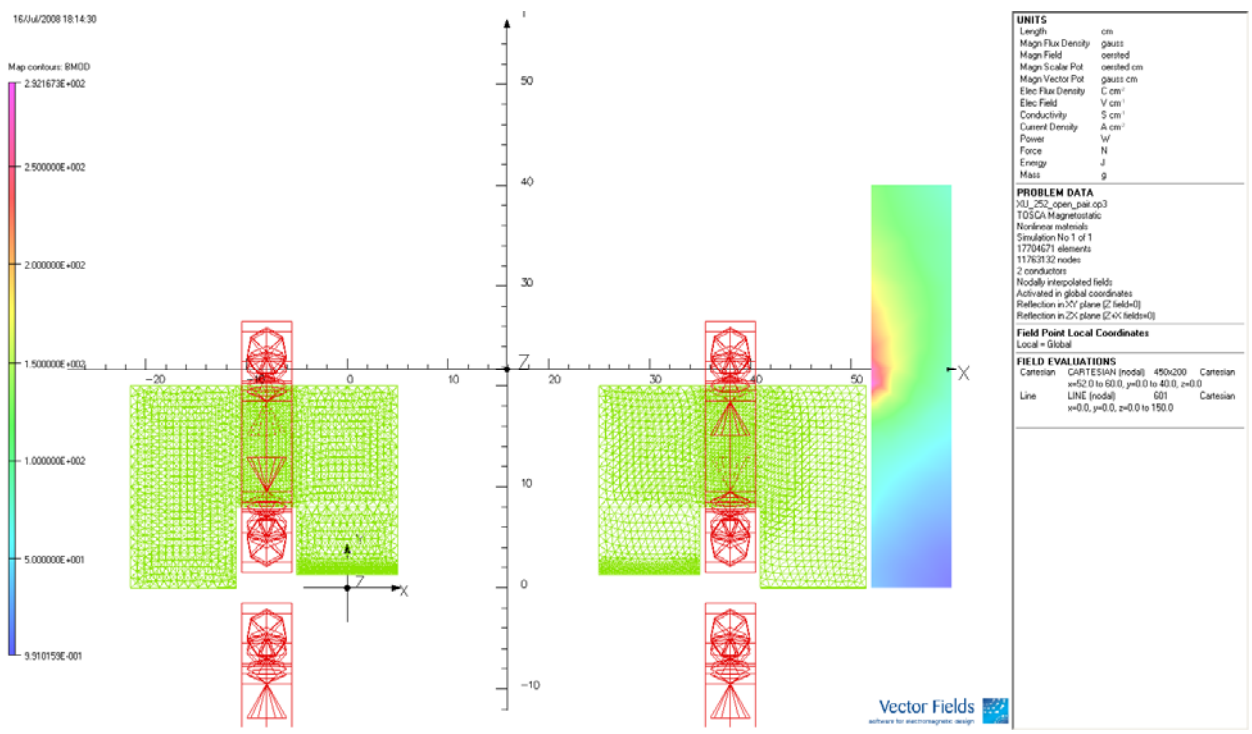
The field at the center of the left magnet below is 11.07726 kG. It is 11.07741 kG in the right. This is much better than the result when the return leg of one was near the pole of the other (page 10). Halfway between them, 1.415 kG. For a single magnet with the same amp-turns, 10.86844 kG. (This is not the same value as the table of page 6 because the coil profile and the steel under the coil differ - this design is better than that one.) Since the two magnets augment each other by ~1.9%, one will have to shunt a bit more than 2% of the current (saturation effects) from each beyond what one would calculate for a single, isolated magnet. Current density used is 400 A/cm^2. Field magnitude in the steel is ~17 kG. For the MAV and MAU magnets on the east end, required gap field is 12.5 kG. Can this be reached in that magnet? A model with 550 A/cm2, 16500 A total in each coil, approaches the BdL needed with stray fields at the adjacent beam of a few hundred Gauss on the return steel side and one kG on the open side. Again, this model has more return and pole steel than the AU. Return steel can be added easily to the straight return leg of the AU.



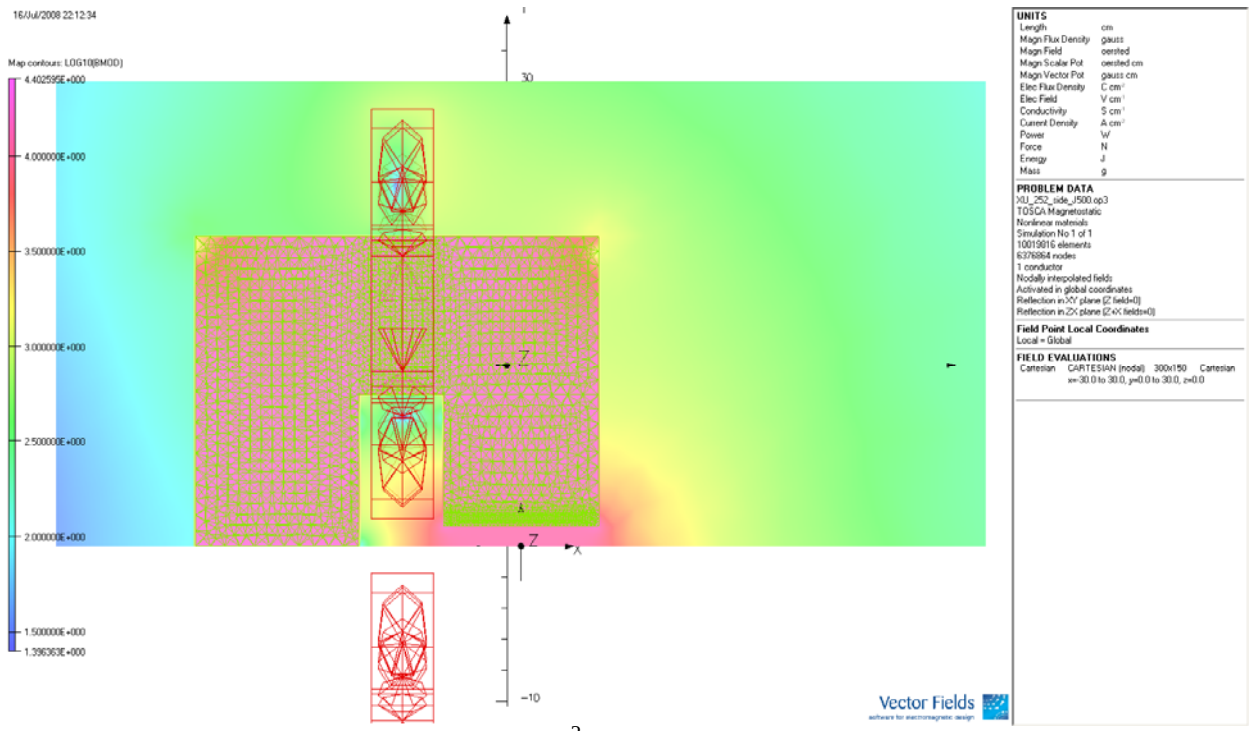
Log10(Bmod) for the pair of dipoles facing each other.



B_y for the pair, showing they are bending in the same direction.

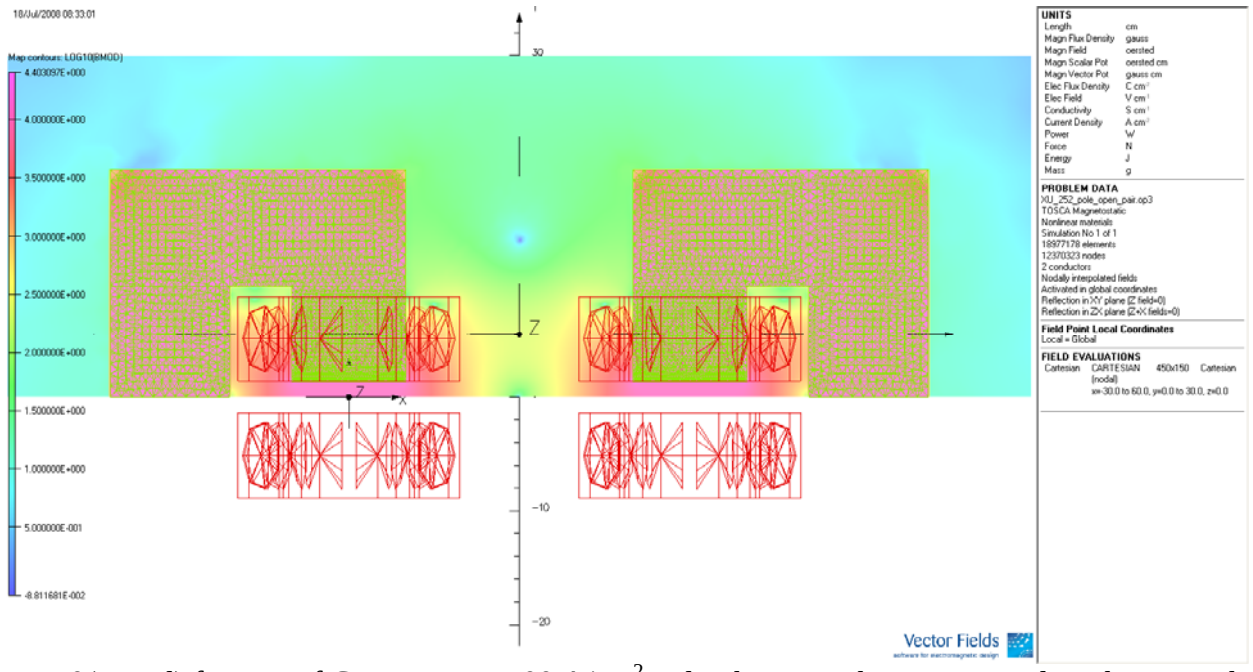


Finer resolution on stray field on "top" of the pair - remember these are actually vertical bends even though oriented in the model for horizontal bend. I extend the evaluation beyond the steel because the adjacent dipole may be wider. The return leg of dipoles for the adjacent dipole will be in the colored band, with fields ~100G. This will certainly affect both the dipoles modeled and the adjacent, unmodeled dipole.



Log10(Bmod) for the case with J=500 A/cm^2. Central field 11.616 kG, less than half the increase generated by the change from 300 to 400 A/cm^2 . The stray field is up to ~1 kG at the adjacent magnet. Field in the steel under the coil is ~19 kG so it's not surprising that lots of flux is leaking. It does not appear that it will be possible to reach a central field of 12.5 kG with this coil configuration.

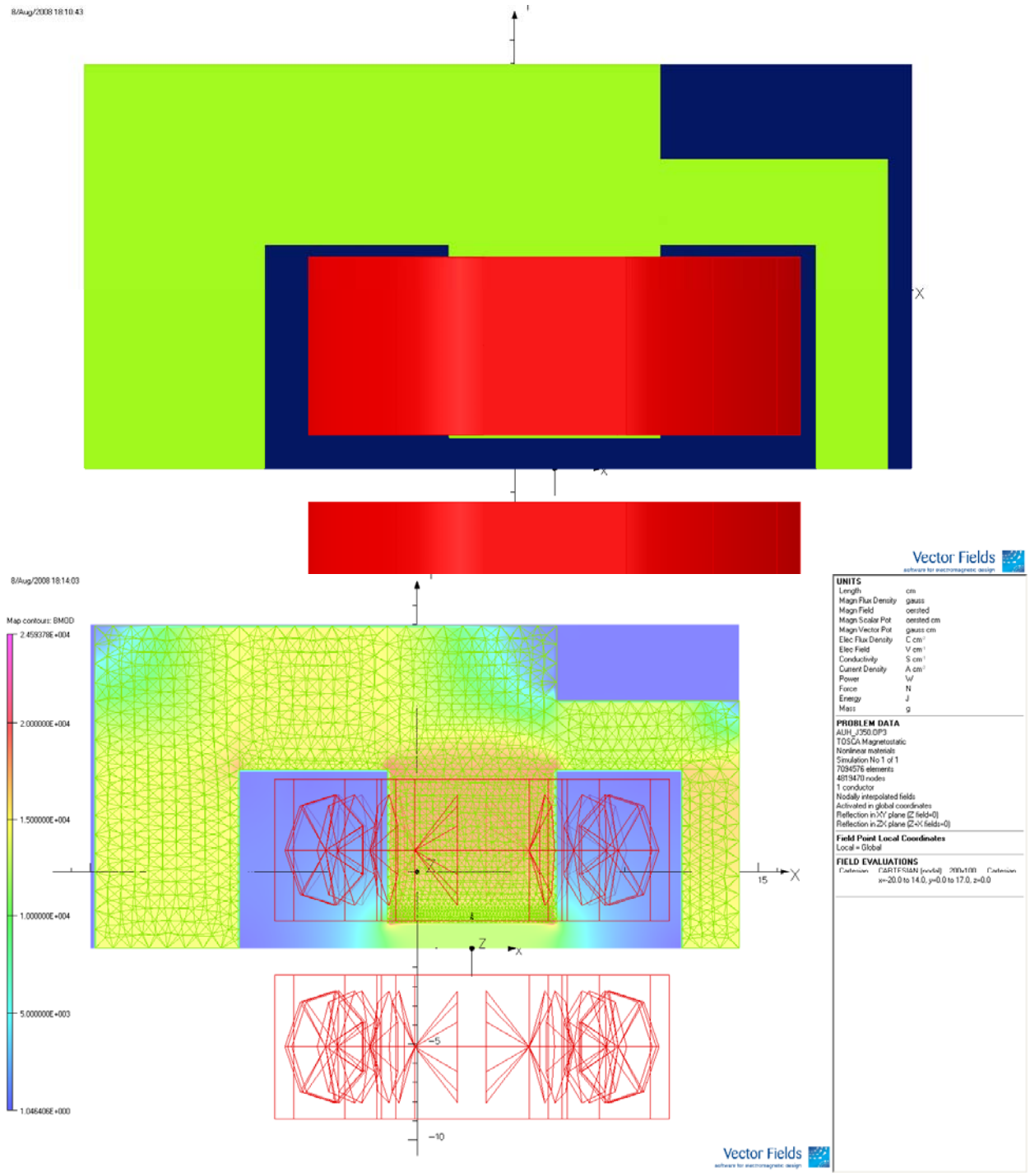
The stray field is better contained if the coils are wrapped around the poles. Sufficient space appears to exist. The existing MAV and MAU have the coil orientation shown above to reduce 1990 coil cost. As discussed on page 6, for the gap fields reached at 4-6 GeV stray field isn't a big problem. The fields in the steel and the adjacent air at 12.5 kG in a similar steel cross-section with coil wrapped around the pole are shown on page 4. It appears likely that the addition of return steel and new, curved coils will allow the existing MAV and MAU magnets to be used on the east end. Since space it tighter on the return leg sides of these magnets than on the gap side, adding the return steel as curved H steel appears preferable. Detailed layout and modeling will be required to confirm this.



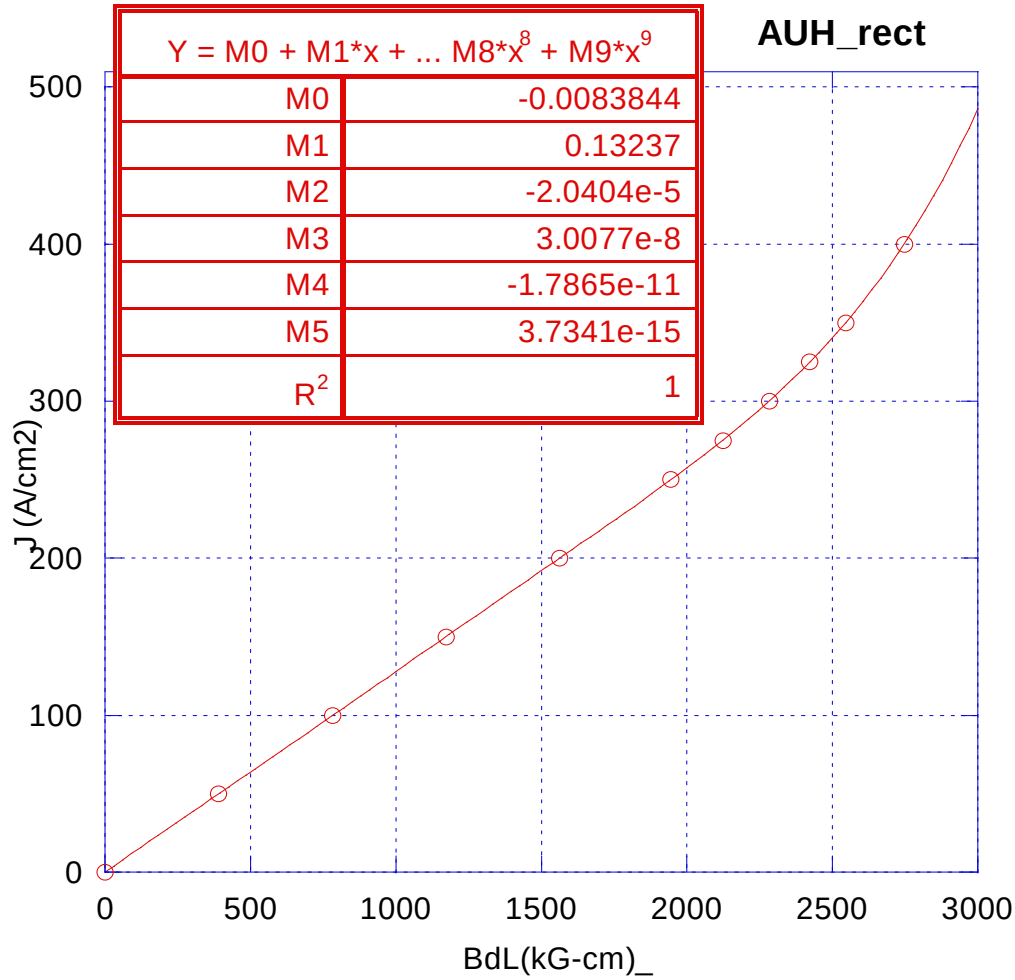
Log10(Bmod) for pair of C magnets at 400 A/cm^2. Flux between the magnets is less than a tenth of that for the same steel with coils "vertical" rather than wrapped around the pole as here. Field at the center of each pole is equal to that of the single magnet in the table on page 2. Closest approach of the two beams is 7mm less than the 30cm shown, so there's room for H steel between them - especially since the poles shown here are 1.1 cm wider than in the actual MAV/MAU magnets. While this was solved at lower current density than would be needed on the east end, there does not appear to be any major problem with this magnet modification. It took 31 hours to solve at this current density. Perhaps 36 hours at the higher current density.

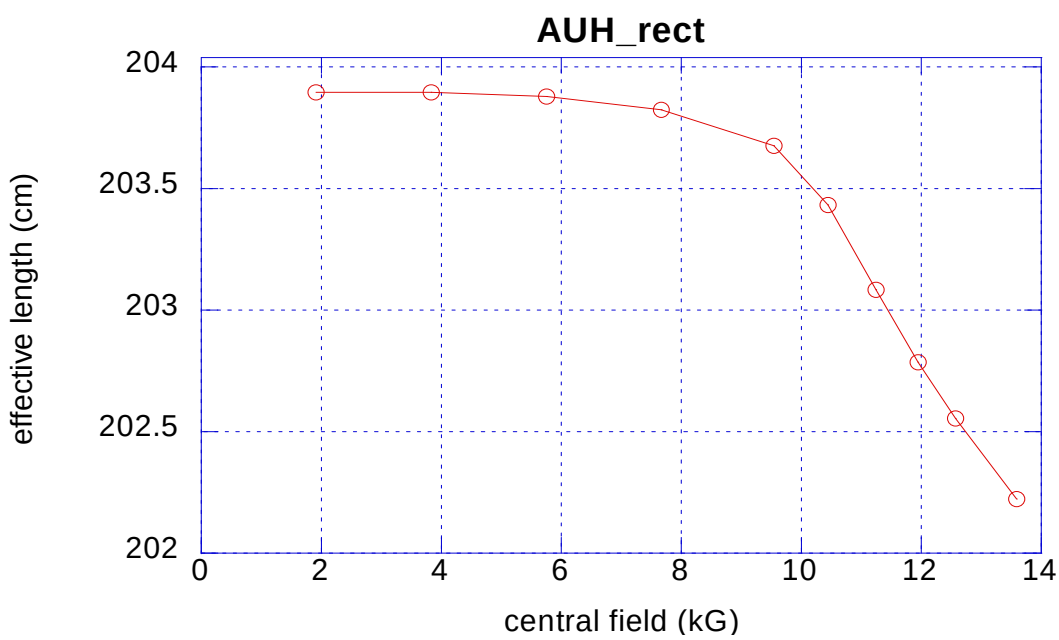
One concept for the H steel: Take a 3-4 cm thick plate ~15 cm wide, 200cm long and machine it to the curve of the pole on both of long sides, creating a curved plate with 9cm span. Repeat to create a second piece for the other half of the magnet. Roll a piece of steel 3 cm thick to approximately match the curve of the pole. The width of this piece should span the gap between the two 3-5cm plates. Heat treat after rolling for magnetic property restoration if you wish. Clamp the rolled plate between the two others and match drill. This removes the need for precision rolling or machining of the rolled plate. Alternatively, one might simply weld the rolled plate to the other two. Bolt the assembly to the existing magnet, match drilling if tapped holes don't exist.

A rectangular version of the MAU/MAV with the H steel and with proper pole width is shown below. This does not have the proper change in length of the original top and bottom of the C to reflect the curved pole, but since the steel isn't too saturated this is OK as a preliminary approximation. It's all one can do in 2D, of course. I am trying to figure out how to morph this model into the exact one in parallel with running cases on the simple model.



Field magnitude is graphed in the lower plot. BdL for this model is 2% above that needed in 3S/5S. Changing some of the air (blue) in the upper right corner to steel may be desirable. The vertical piece on the right is 3cm thick. Stray field to the right of the H steel is 10-20G, comparable to the stray field shown between the two symmetric H magnets. If additional return steel can be accommodated without interference, it should be.





Steel length 200 cm for AUH. Operating point ~12kG.

Conclusions

1. It is possible to use the steel from the existing MAV and MAU magnets on the east end of the machine with new coils and 3cm of additional return steel. Both the CASA and 12 GeV project team layouts have sufficient distance between 3S and 5S to allow the modified configuration. This eliminates one new magnet design, that planned for 3 S/R.
2. On the west end new magnets have always been planned. These should be H magnets rather than C. A compact design with no cross-talk has been presented. Each can be inexpensively fabricated from six rolled bars, machining only mating and survey reference surfaces.
3. The H magnet (2) can also be used in the east end if the MAV and MAU magnets cannot be salvaged. It can be further applied in the hall D line, saving 6m of steel and copper and increasing quantity on the procurement, likely lowering costs.
4. The same H cross-section may be usefully applied to the "MAL2S" 1.5m dipole, which has not been detailed.

Banana magnets

- The Project has no plans to use magnets of the "return-leg coil" design that is the focus of most of the document. The abstract should inform the reader that the analysis is of a preliminary design approach that has subsequently been abandoned.
- (In this comment, "cross-talk" means that the presence of one magnet changes the behavior of another.) At several points there seems to be a confusion between cross-talk and fringe fields. The two are not equivalent. The presence of fringe field does not mean that there is cross-talk. The text seems to imply that it does. This needs to be corrected. (The presence of fringe field at significant levels is certainly a necessary condition for cross-talk, but it's not sufficient.)
- Pg 1
    - Abstract: The last paragraph says that the AV and AU can be used for the east end of the machine. The sentence should be changed to "....a potentially acceptable..." since the document does not address the field quality in a quantitative manner.
    - "banana magnets for arcs 4 & 6": The rationale given for why using the same magnet in 4S/R and 6S/R is potentially valid when high energy beams (when synch radiation emittance growth is occurring) are going to the end stations. However,the users also want lower energies, i.e. 6 GeV in 5 passes and 2-3 pass beam , when 12 GeV is going to Hall D. A simple fix is to add "for high energy beams" to the last sentence of the present first paragraph and then to add a new sentence that says "further study for lower energies would be required."
- At the bottom of pg 10 the discussion shifts from the "return-leg coil" design to using a "pole coil" design or an "H" magnet.
    - The text says "Since magnets like these ("pole coil") would require perhaps twice the steel of the H magnets, the H magnet seems the better choice." Granted that the word "perhaps" is in the statement, but as written it leaves the impression that the difference is 2x, which is not the case. Further, the statement ignored machining costs, which are higher for "H" than for "C" because the former has more surface area. The section needs a re-work to soften the firmness of the suggested cost advantage of an H.
- Pg 19
    - Conclusion 1: This conclusion ignores the field quality issue identified above (beam quality at lower energies) and should acknowledge the open question.
    - Conclusion 2: The document makes a clear case for why "return-leg coil" C magnets shouldn't be used. It does not make a case for why H magnets are a "should" vs "pole coil" C magnets. Without making that case, the conclusion needs to be modified.
    - Conclusion 3: Same comment as about the abstract. "Potentially" should be added.