Second attempt at a conductively-cooled superconducting septum magnet for the FFA upgrade
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16 August 2022

Abstract

As discussed in TN-22-033, it is impossible to scale the existing, water-cooled copper septum magnet design to higher beam energies. In that TN a six meter magnet with ~200 A/mm^2 superconducting coil, expected to be conductively cooled, was examined as a possible solution. In this TN the concept is taken further. Two three-meter magnets with wider poles, separated by 1.5 m for cryocoolers, instrumentation and perhaps correctors, have been modeled. The second magnet is offset 6 cm from the first so the fourth pass beam passes beside it while the six destined for the FFA are bent by the second magnet. The beam orbits do not exactly match those from Ryan Bodenstein's Optim decks because the fields are more realistic; J = 205.5 A/mm^2 was chosen to get all the orbits within a few mm of Ryan's numbers at the exit of the pair.

Background

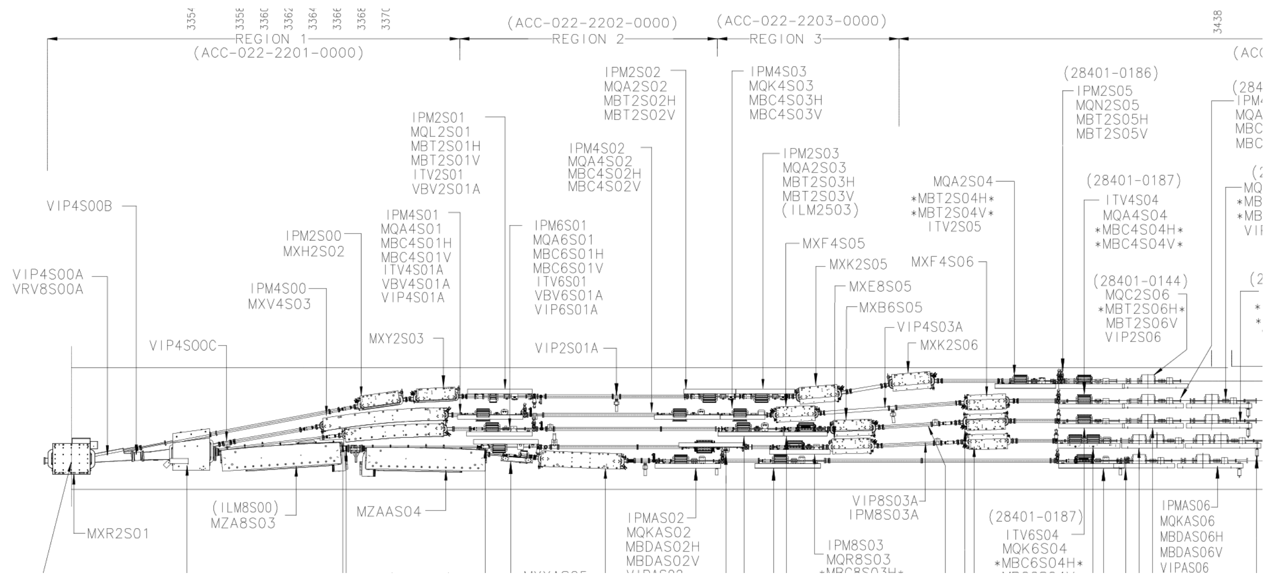

Figure 1. Part of the SW spreader song sheet. The SW spreader is shown even though the first set of orbits to be shown are in the NE spreader. The present NE spreader has provision for extracting Hall D beam which will move downstream to the horizontal splitters of the FFA, so this is more representative of the expected configuration. The two three-meter ZA magnets at the lower left are to be replaced with superconducting counterparts with wider poles. Most of the other magnets are to be replaced or rearranged. Detailed layout is a very iterative process involving Optics and ME; close to a hundred iterations were required for the 12 GeV upgrade to remove all interferences while retaining an acceptable optics. This will not be done until there is a real project.

The ZA core is defined in MAG0030011-0002, Revision: D. On sheet 2, radius of the top of the steel is shown at 40.981 m. The septum coils are also curved with this radius. This iteration of the new concept does NOT have curved steel or coils. That's more effort than is appropriate at this stage of the FFA effort.

NE spreader

The NE and SW spreaders may have different offsets of the second magnet to accommodate the reduced beam spacing in the latter due to higher fourth pass energy. The images in this section pertain to the NE spreader as defined by Ryan Bodenstein's Optim decks.

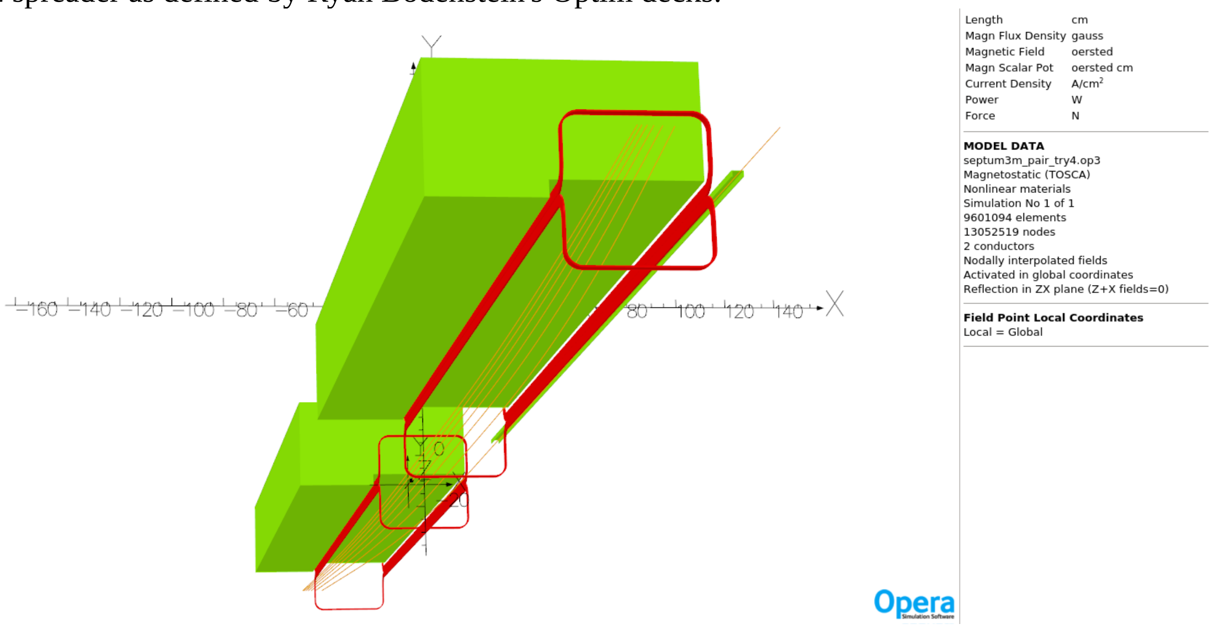

Figure 2. Perspective view of two-magnet system. Beams enter at the back and move towards the viewer. The forward magnet is offset 6 cm to the left so the fourth pass beam passes through the steel tube at right, reducing the stray field it sees. The other six passes see both magnets.

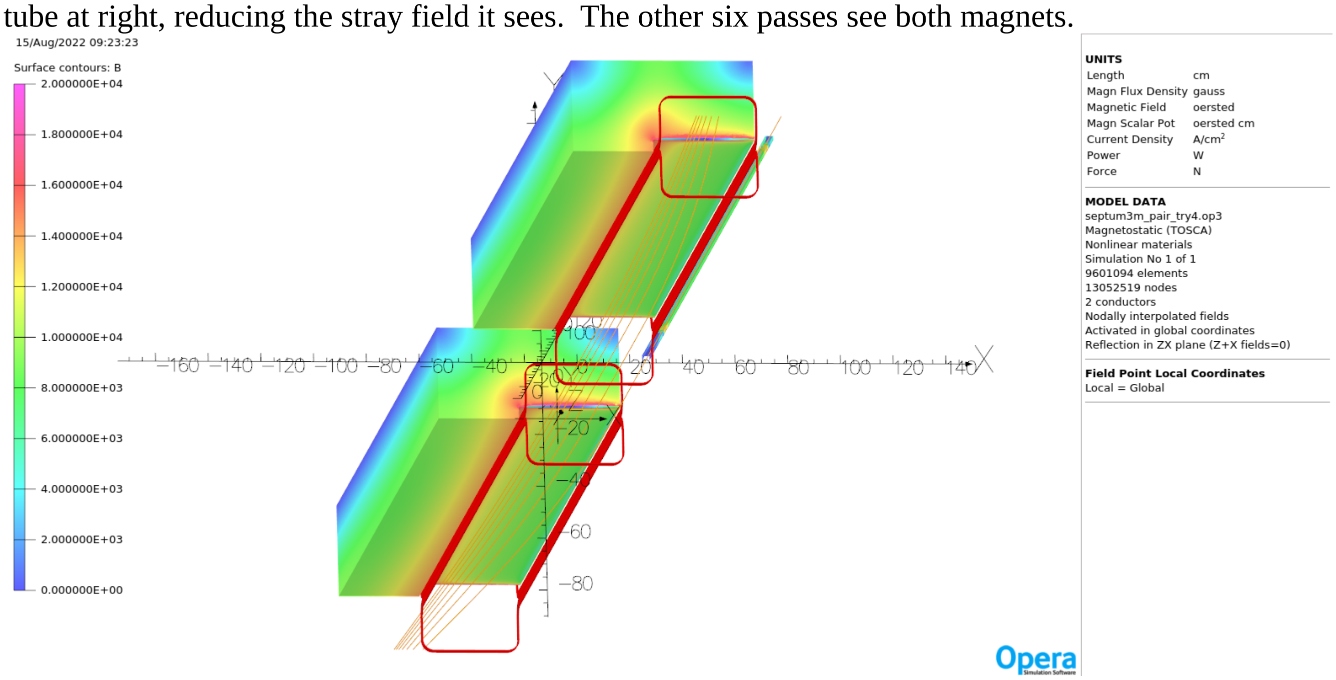

Figure 3. Similar view with fields on the surface displayed with color codes at left. Not perspective.

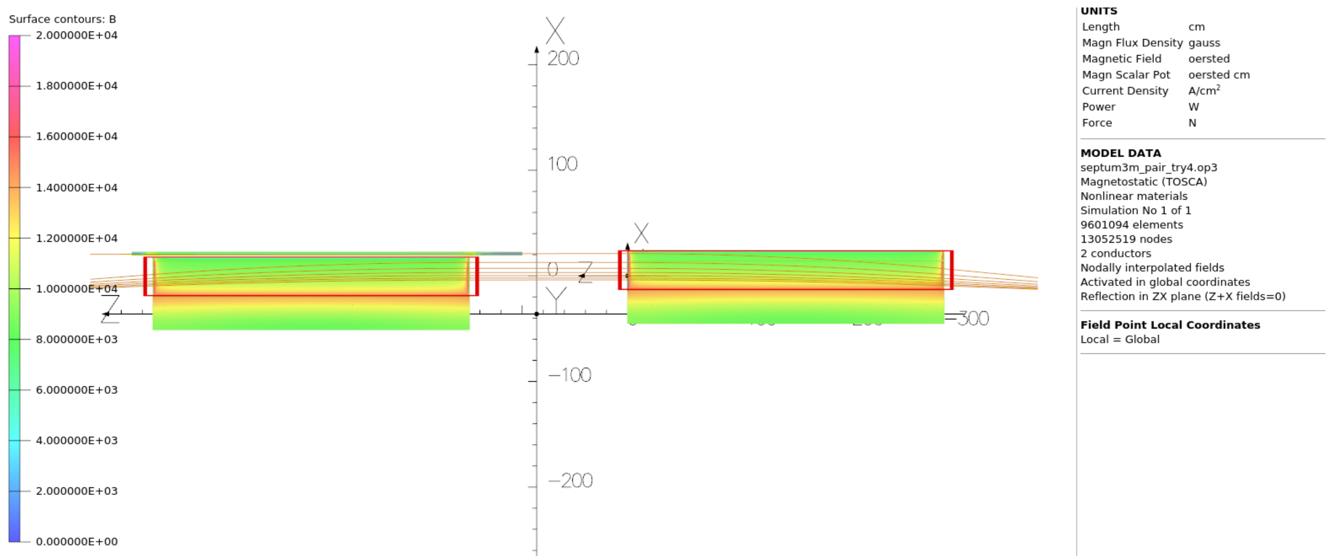

Figure 4. Bottom view, surface fields displayed, not perspective

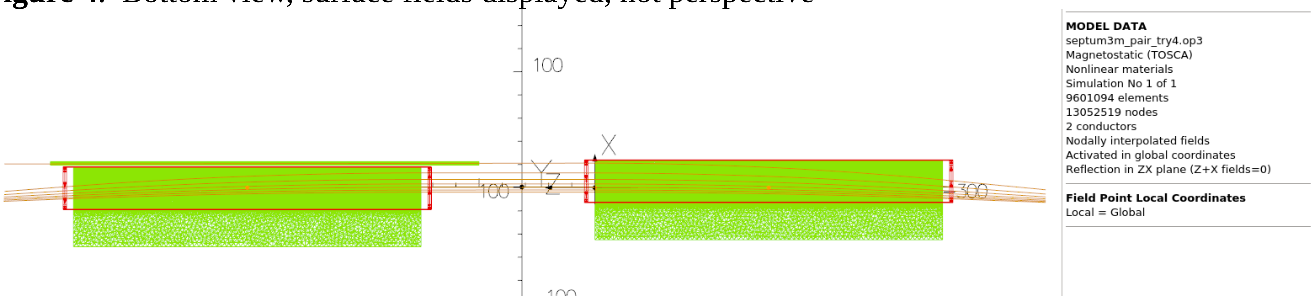

Figure 5. Seven orbits through the pair, beams move right to left.

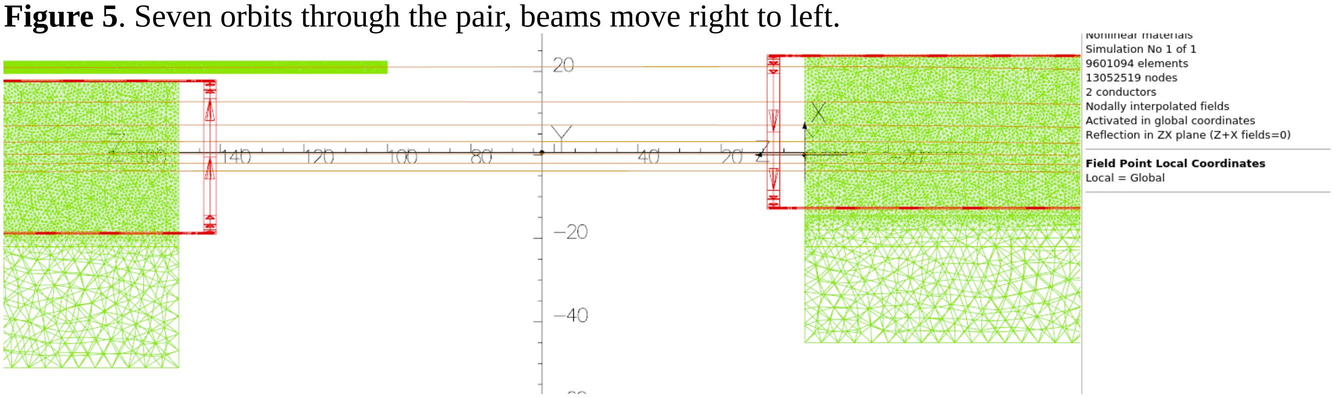

Figure 6. Closer view of the middle of the model.

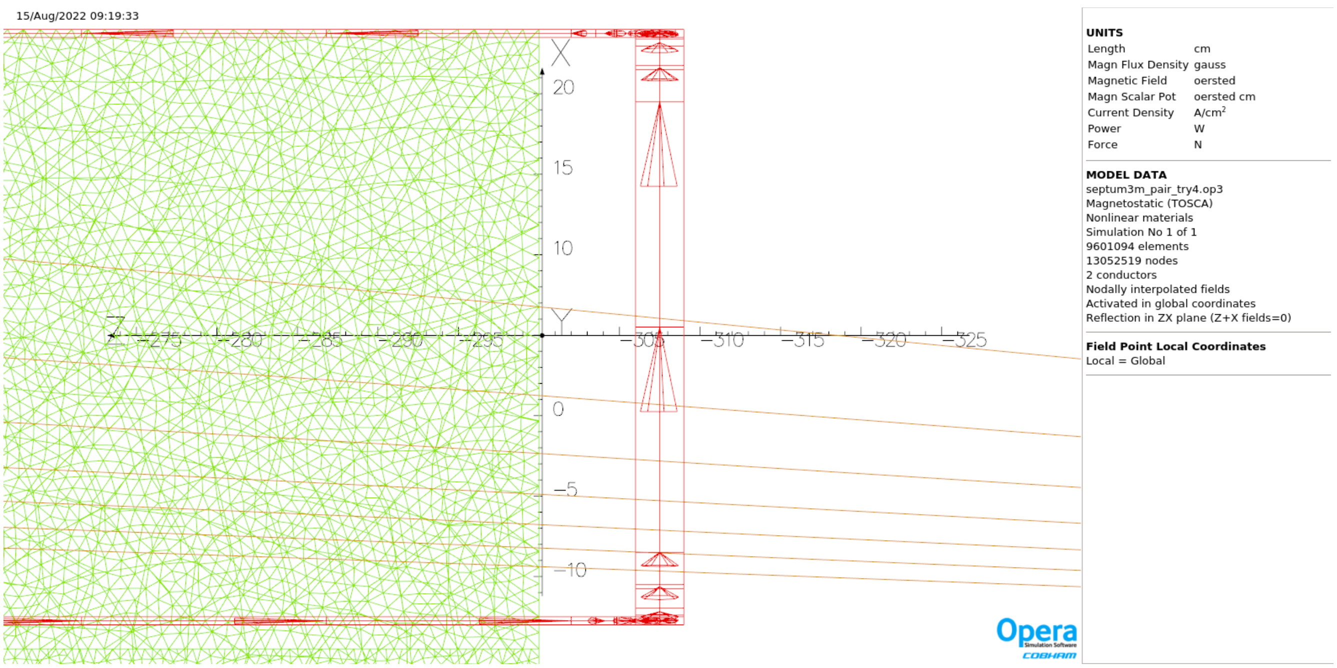

Figure 7 Seven beams entering the upstream magnet. Launch point 89 cm upstream of this magnet.

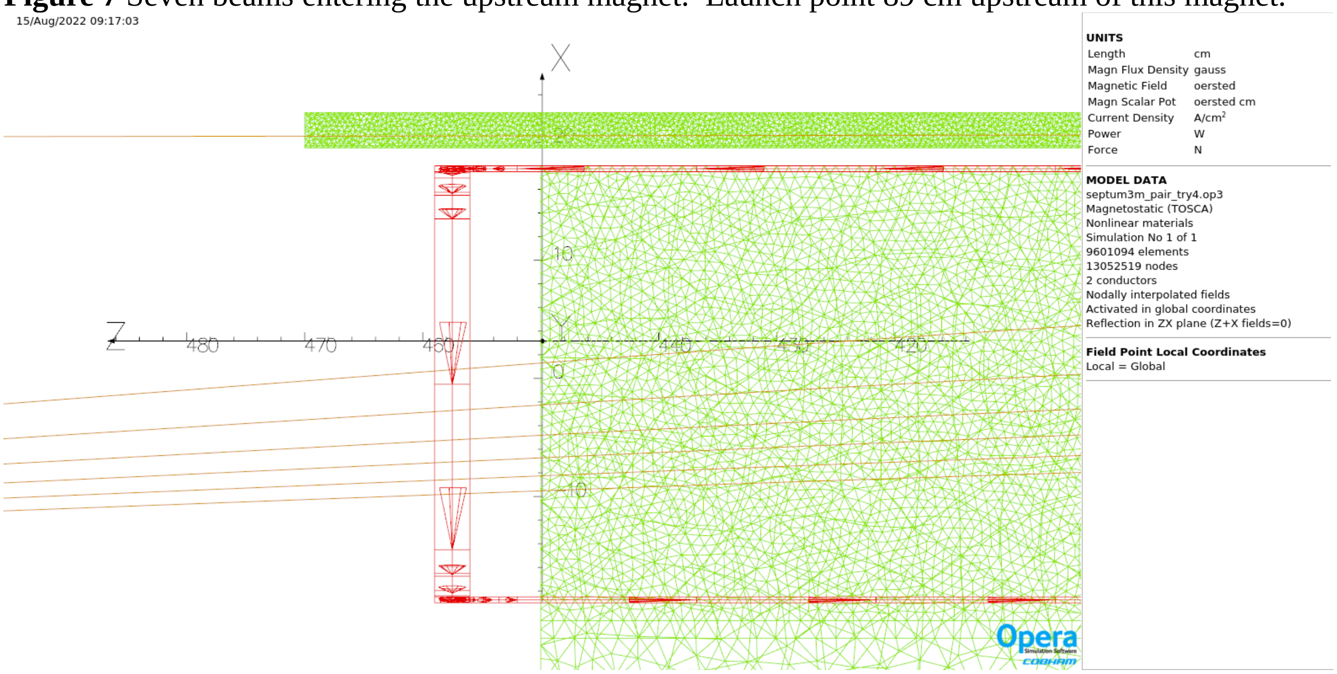

Figure 8 Seven beams exiting the downstream magnet, with fourth pass up top. It's about 5 mm lower here than in **Fig. 6**. The other beams are within 3 mm of their heights in **Fig. 7**. Current density was adjusted in small steps in four simulations over two days to minimize the differences in the lower group of six. Little change could be made in the fourth pass; corrector likely needed.

These models were built with maximum voxel size in the beam region 0.5 cm. This is insufficient to get good values for Fourier harmonics along these orbits. This model took about six hours to solve. A new model with 0.25 cm maximum voxels is being preparted. It will likely take two days to solve. Harmonics can be calculated along the orbits in that model. They will be better than the harmonics from a model with curved steel and coil as the beams will be closer to the interface in that case. Table 3 of TN-22-010 https://jlabdoc.jlab.org/docushare/dsweb/Get/Document-254194/22-010.pdf has harmonics of the YR model with added steel to approximate the required FFA septum.

Coil and Conductor

There are 61650 AT in the two bedsteads. It is expected that the coil will be fabricated as a single bedstead but modeling that would require eliminating a symmetry which reduces the solution time and was not done. Coil block is 5 mm wide by 60 mm high in the model. My thought was to have a thin aluminum channel extruded and bent to the required shape, 1 mm section with 5.5 mm side lips. Six layers of 1 mm conductor, 60 turns per layer, hexagonal close pack, would be wound into the channel, 360 turns total. Perhaps another aluminum plate to close the box, 0.5 or 1 mm, for better conductive cooling. Current is then 171.25 A. Field at conductor 1.05 T. MgB2 is suggested based on Akira Yamamoto and Amalia Ballarino, Advances in MgB2 Superconductor Applications for Particle Accelerators, https://arxiv.org/abs/2201.09501 MgB2 can sustain this load at 20 K so the task of the cryostat and cryocoolers is less. NbTi is also possible but dealing with the heat load including the leads will be more difficult. Nb3Sn wind and react is also an option with copper channel (closer to Nb3Sn thermal expansion during reaction cycle than aluminum). It may be desirable to use a coil of eight layers, 480 turns, 128.44 A; I haven't looked at beam clearances for 7 mm or 9 mm coil pack width. The concept allows at least 15 mm clearance on all sides of the 5 mm coil for the cryostat. There's only 30 mm from the outside of the 5 mm wide coil to the fourth pass beam centroid at the entrance to the second dipole in this model. That dipole can be shifted a few mm more than it has been here, at least for the NE spreader. This model has 90 mm pole gap, 10 mm more than the gap used in TN-22-033. J increased from 180 to 205.5 A/mm^2 14.2% versus 12.5% on geometry. I am reluctant to increase the gap further to accommodate a larger cryostat section at this stage in the design. Turns per layer can be decreased to get more space if eight layers are used and the coil is expanded towards the six-beam grouping. (Yes, I recognize this paragraph does not proceed in the most readable fashion, but that's the way my mind worked when I was writing it. Deal with it.)

SW Spreader

The plots which follow for the SW spreader use the same basic model. Current density was increased by 3.25% as a first approximation based on the ratio of B values in Ryan's models. Another 0.25% increase is likely needed and I'm running that case but I want to get this out for review and no one can see the difference without the magnification available only with the actual model in Opera. There is only a 21.3 cm drift between BCOM2 and the first of these magnets in the files Ryan provided. He is reworking them to provide about 90 cm drift, as in the NE spreader, to provide room for the needed cryocooler and cryostat interface. I'll likely revise the images once I have those values. Since the model, including the 6 cm offset of the second magnet, is the same as above some images will not be duplicated.

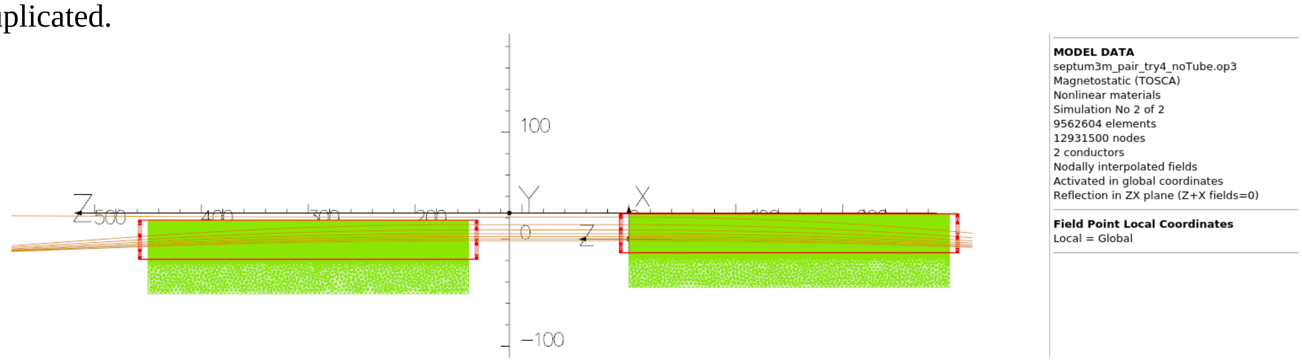

Figure 9. Seven orbits through the model, J 212.16 A/mm^2

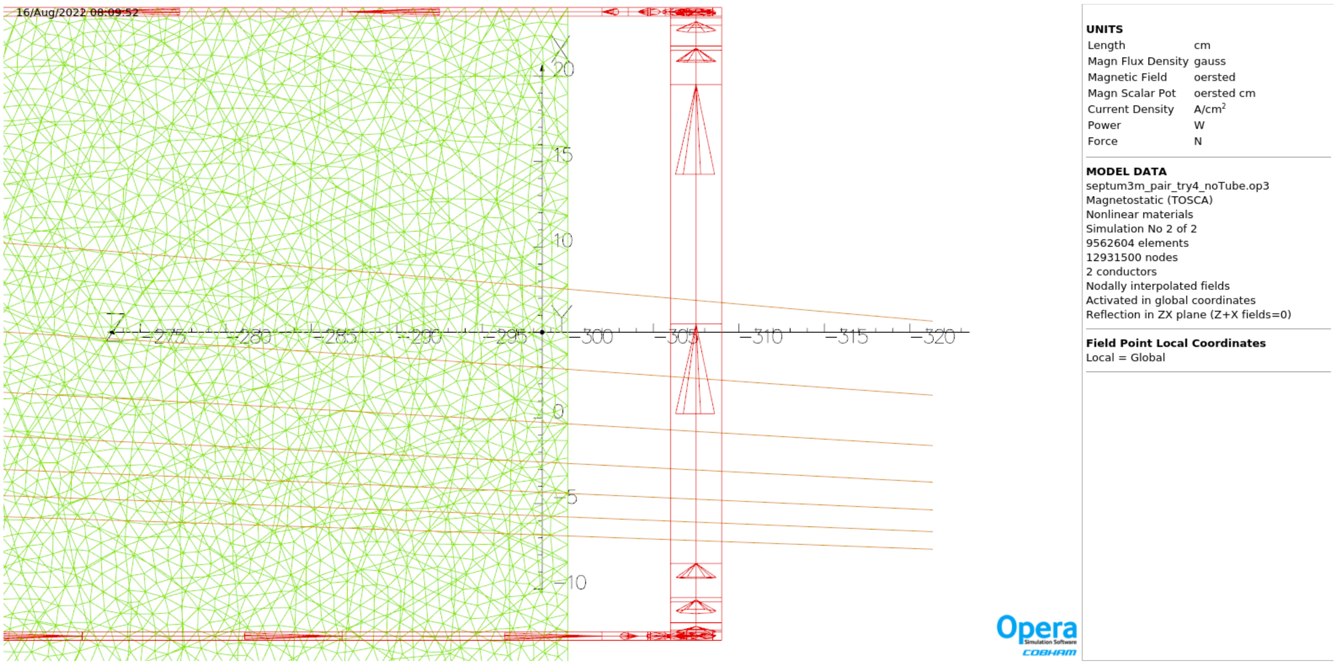

Figure 10. Seven orbits at entrance of model

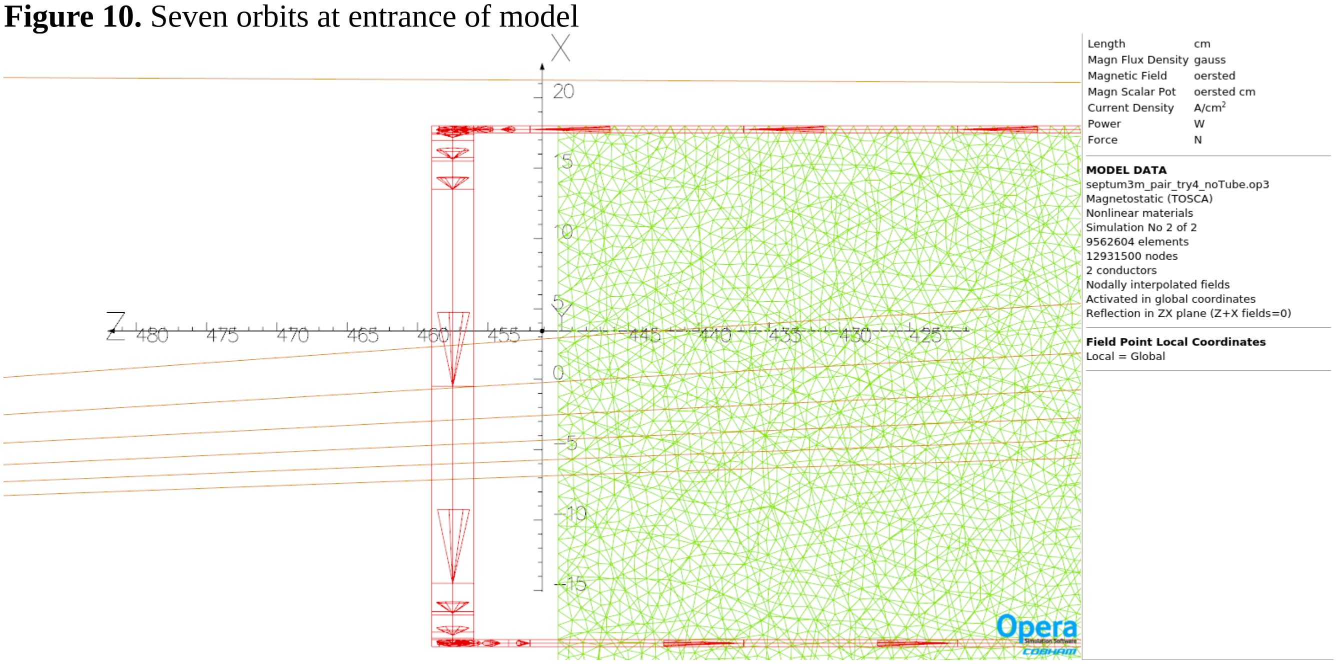

Figure 11. Seven orbits at exit of model

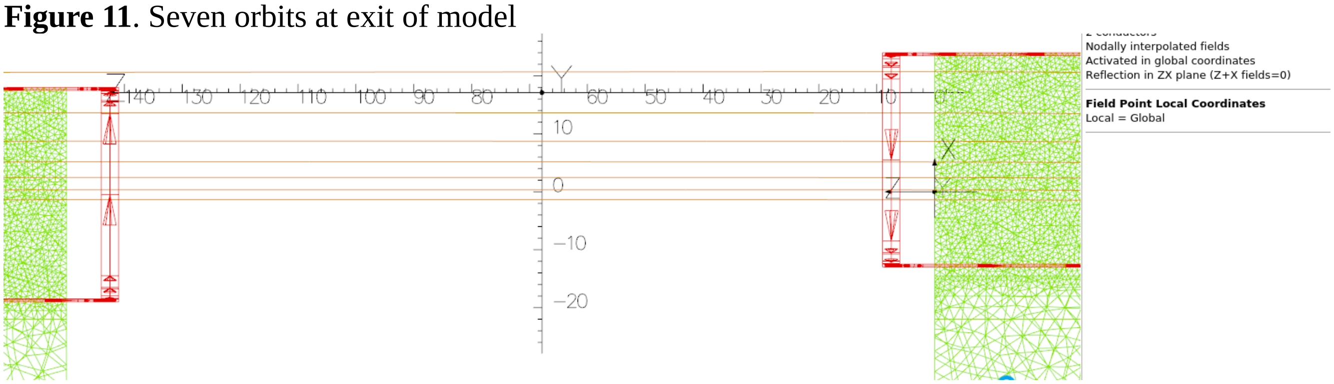

Figure 12. Seven orbits at center of model. 2.7 cm of beam clearance between the inside of the 5mm coil on the right and 2.7 cm of clearance between outside of the 5 mm coil and the beam on the left.

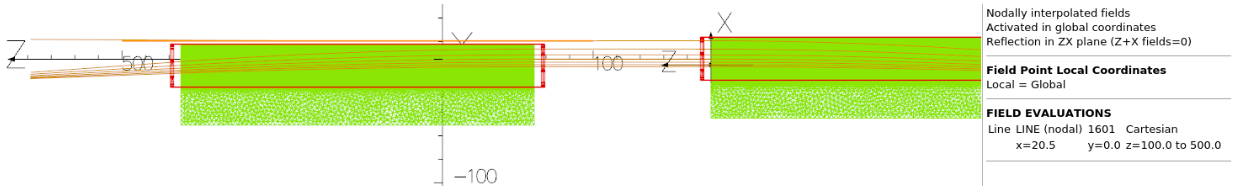

Figure 13. If one looks carefully, one can see a wider orange line at the top left, Z=[100,500]

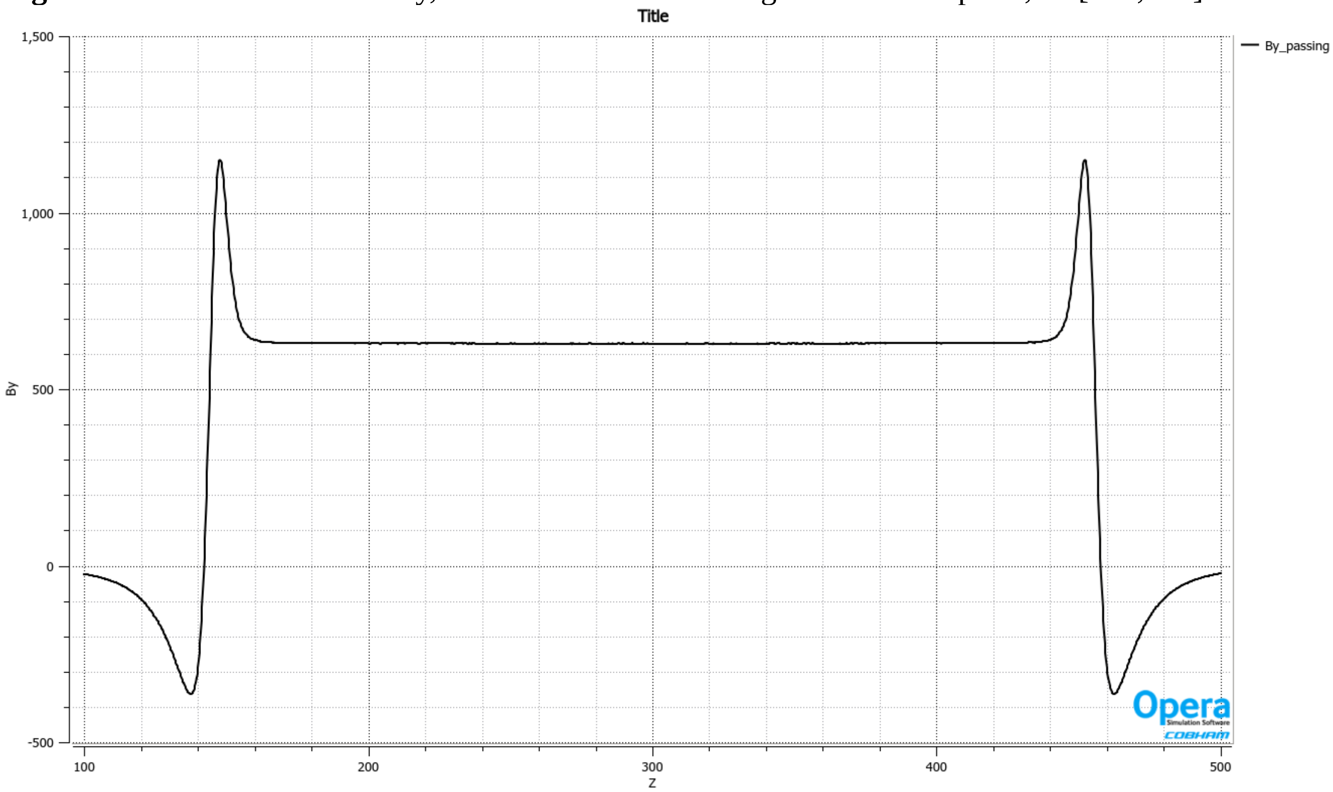

Figure 14. Field along the line in Figure 13, or rather x=20.6 vs x=20.5 there. BdL 192 kG-cm. BdL along x=20.5 cm 202 kG-cm; the gradient is steep. Clearly the steel tube shown in the NE spreader section is necessary. Orbit information was needed to determine if relocation of the second magnet was necessary (it wasn't) so I deleted it from the model.

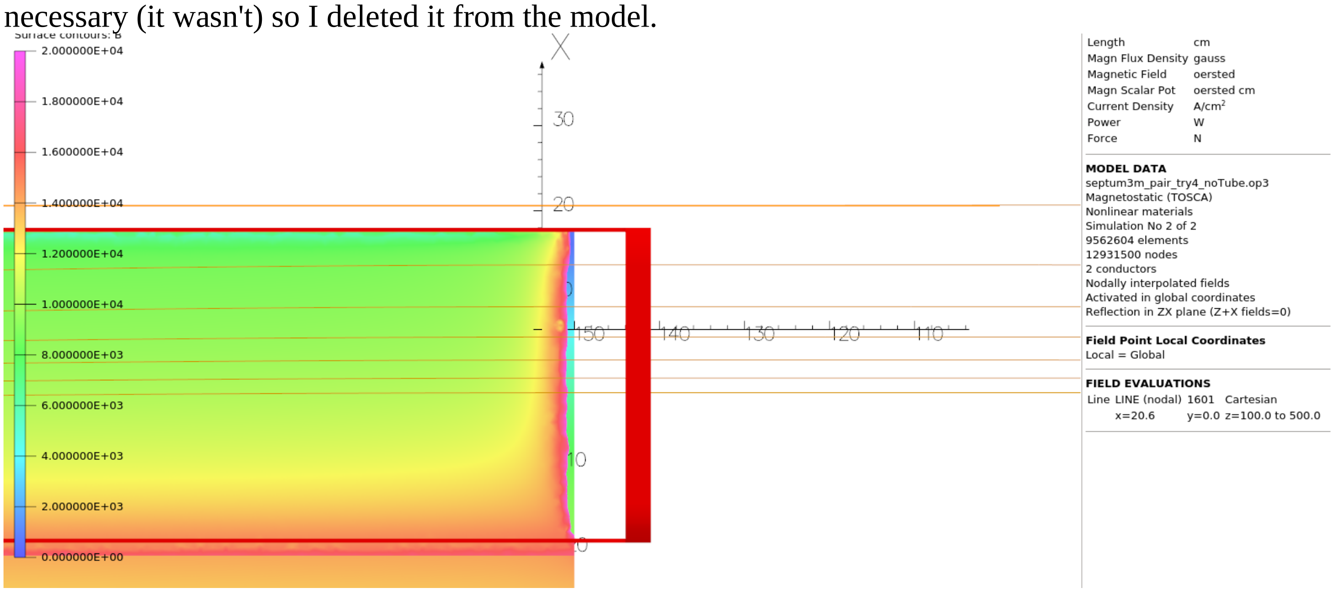

Figure 15. Here one sees the start of the wider orange line at Z = 100 and the pole end saturation. The thin orange line at top right is the passing beam orbit centroid.

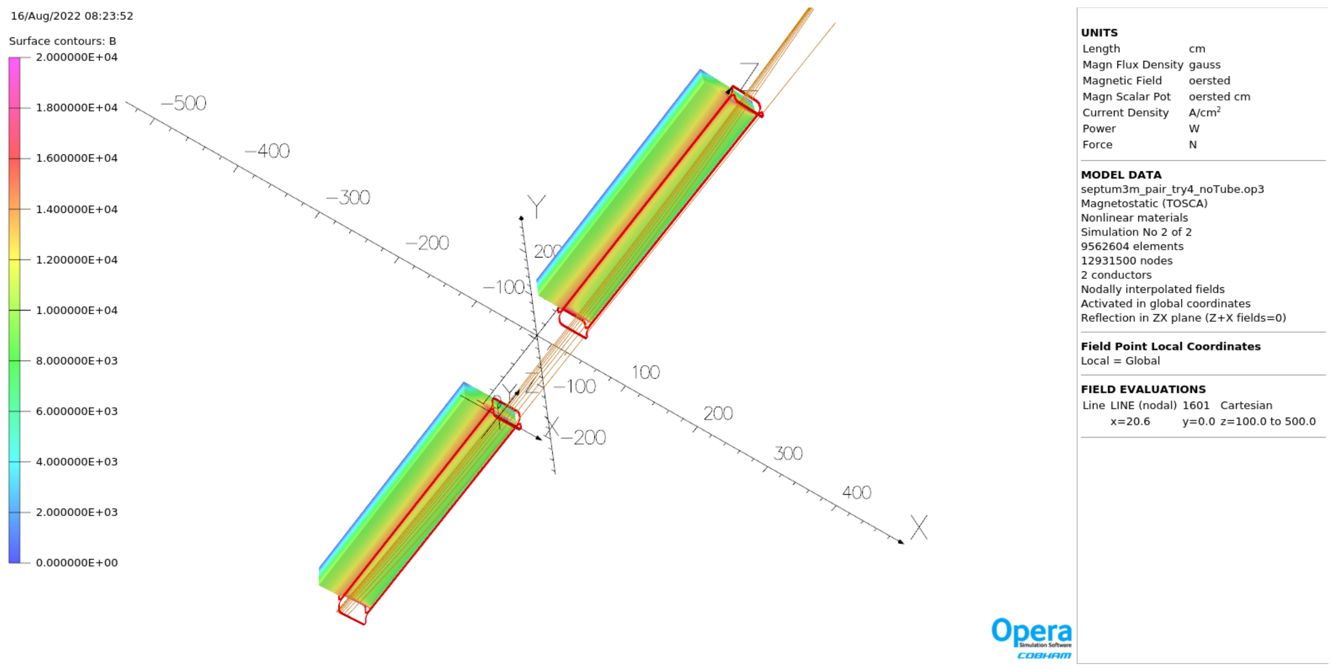

Figure 16 Perspective view of the model with seven orbits, |B| on the surface.

Next steps

1. Check whether the steel tube location for the passing beam is compatible with both spreaders. If it is, run it with the SW spreader J and duplicate Fig. 14 for both spreaders. If it isn't, modify model and run both cases with best guess J's.
2. Decrease the voxel size in the volume which will see beam from 5 mm to 2.5 mm. This will allow accurate calculation of Fourier harmonics on 10 mm radius circle up to 20-pole. Solution time about two days; the models above took six hours.
3. When launch points with beam energies including SR radiation losses are available, calculate harmonics. Or perhaps on the orbits shown above, since the latter will take some time to generate.
4. Think about chamfering the entry at the first magnet and exit of the second by perhaps 10 cm, returning to steel shown 100 cm from the end. This would help engineering layout. It will make the magnetic modeling much more painful because the conductors will have to be made of bricks and arcs and the ends matched to microns. This will not be started until there is a first engineering layout. This will increase harmonic content, as in the YR, and so should be done only if necessary.

Conclusions

A more realistic septum arrangement for the NE and SW spreaders has been modeled. Next steps have been outlined. Others need to start thinking about the cryostat design including current lead heat stationing and cryocooler interface.