First attempt at a conductively-cooled superconducting septum magnet for the FFA upgrade

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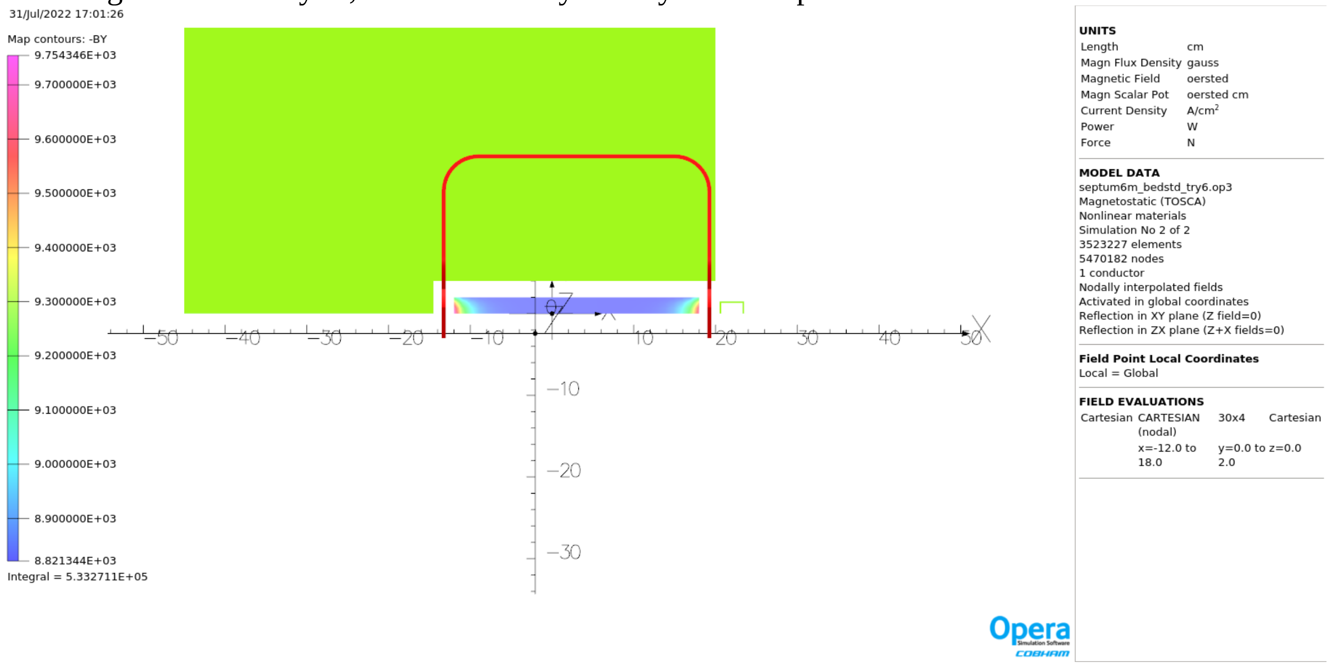
5 August 2022, additions 12 August

Abstract

The water-cooled copper technology used in the existing CEBAF septum magnets cannot be extended to higher energy. (1) MgB2 conductor is commercially available and can do 200 A/mm$^{2.}$ at 2T/20 K. (2) At the FFA working group meeting 29 July Ryan Bodenstein showed a concept for the NE spreader which included two 3 m dipoles at 8.83 kG nominal field, separated by 5 m. Scott Berg, in the subsequent discussion, suggested making one 6 m dipole. Only after I built the model described below did I realize that there have to be two 3 m dipoles with TBD drift between them because the lowest energy beam has to pass by the second dipole to continue in its purely electromagnetic magnet pass. The other six beams end up in the FFA after being brought back down to linac height. Nevertheless, the exercise was instructive. Current density of 180 A/mm$^{2.}$ is required. Field at the conductor is 1.1T. The pole has to be widened about 3 cm from that shown below to accommodate the cryostat. Conductive cooling via copper sheet on either side of the SC has not been evaluated; that will be done after the next iteration since the distance to cryocoolers will be halved. Pole gap of 8 cm may be insufficient given 17 turns of 3.5 mm cable = 5.95 cm stack. It's worth documenting this work before the next iteration. Magnet modeled as horizontal bend, vertical is actually required.

Discussion

Five variations on septum design, including hybrid ones with both iron and current sheets, were tried before the one shown here was settled on for deeper exploration. Figure 1 shows an end view of the model with the field at the midplane displayed; this model has 185 A/mm$^{2.}$ Two bedstead coils are used in the model, reflected about the horizontal axis. It is expected that only one will be fabricated, extending ±3 cm about y=0, but the use of symmetry cuts computation time.



UNITS

Length	cm
Magn Flux Density	gauss
Magnetic Field	oersted
Magn Scalar Pot	oersted cm
Current Density	A/cm^2
Power	W
Force	N

MODEL DATA

septum6m_bedstd_try6.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 2 of 2
3523227 elements
5470182 nodes
1 conductor
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in ZX plane (Z+X fields=0)

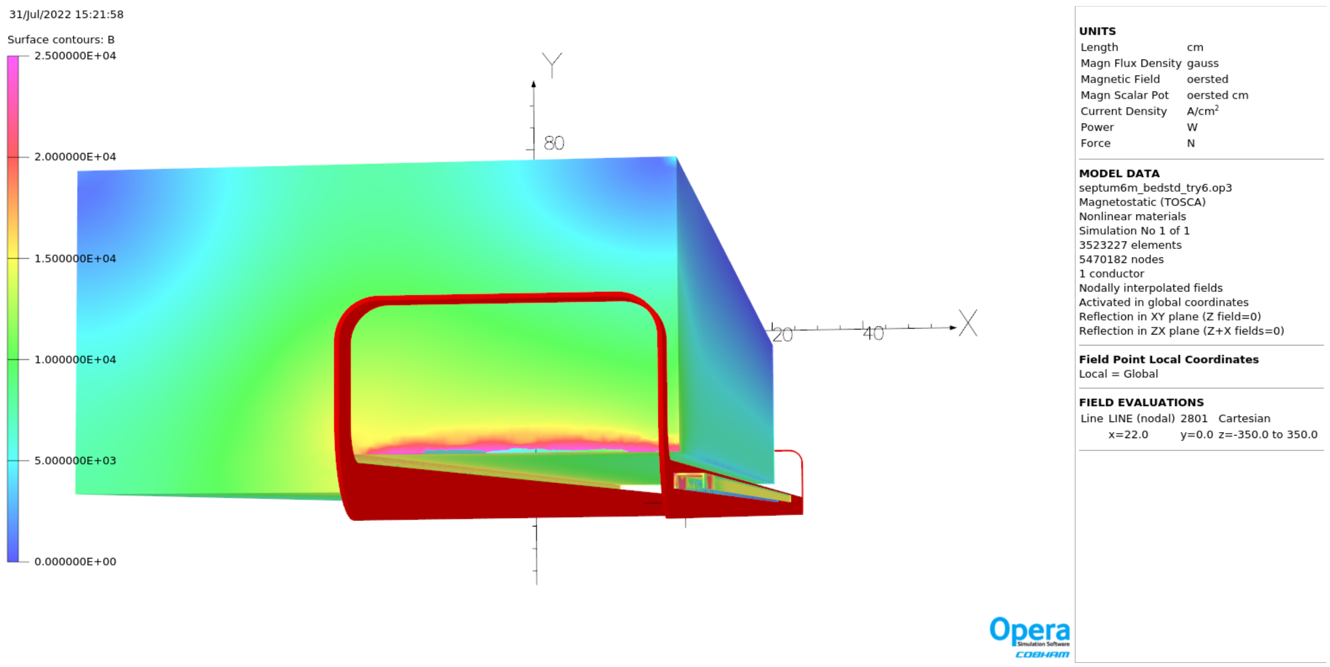
Field Point Local Coordinates

Local = Global

FIELD EVALUATIONS

Cartesian	CARTESIAN (nodal)	30x4	Cartesian
	x=-12.0 to 18.0	y=0.0 to 2.0	z=0.0

Figure 1. End view of model. Note the small green feature just to the right of x=20. This is a rectangular carbon steel beam tube for the “passing” beam.



UNITS

Length	cm
Magn Flux Density	gauss
Magnetic Field	oersted
Magn Scalar Pot	oersted cm
Current Density	A/cm^2
Power	W
Force	N

MODEL DATA
septum6m_bedstd_try6.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
3523227 elements
5470182 nodes
1 conductor
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in ZX plane (Z+X fields=0)

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS
Line LINE (nodal) 2801 Cartesian
x=22.0 y=0.0 z=-350.0 to 350.0

Figure 2. |B| on the surface of the steel. Again, 185 A/mm$^{2.}$ The field on the tube at the right indicates that most of the stray flux is blocked except at the ends.

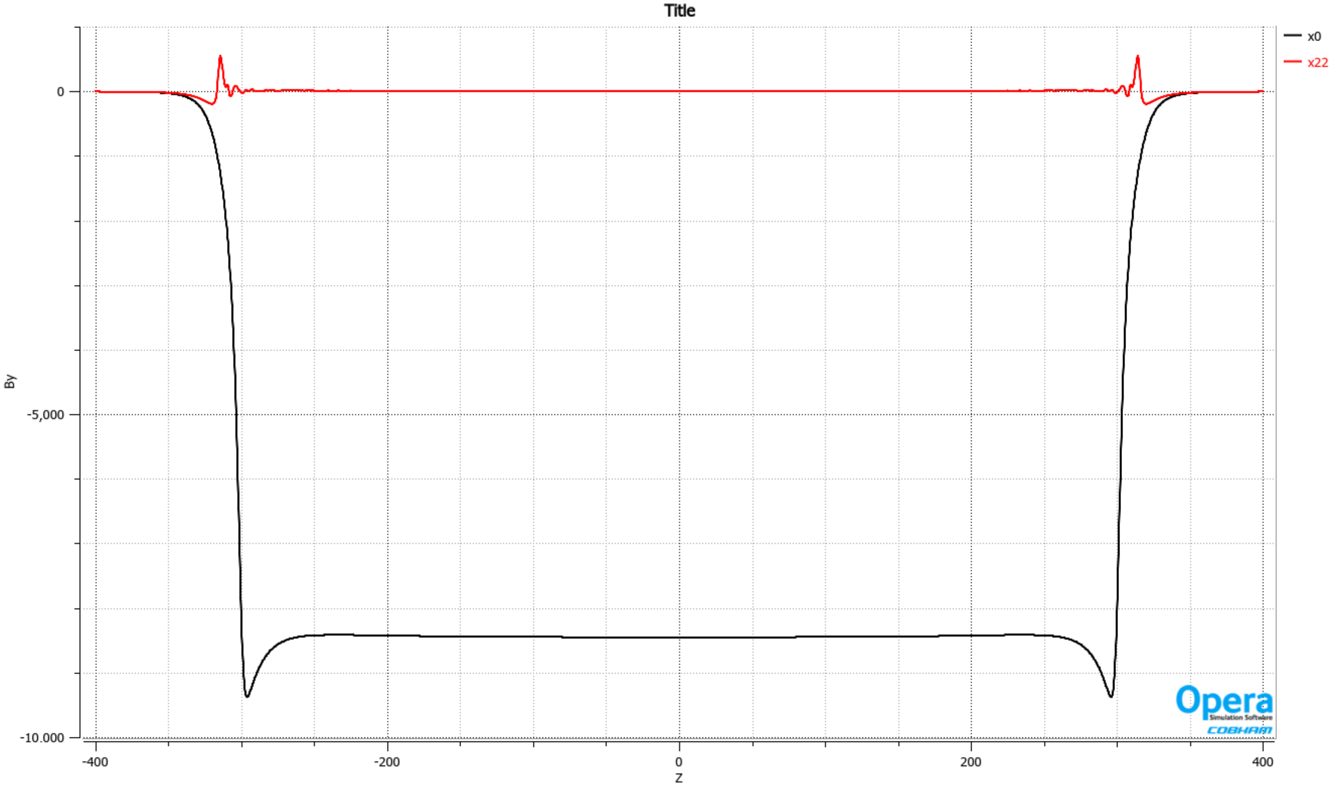


Figure 3. By(z) at X=0 (x0, black) and X=22 (x22, red) cm; the latter is within the steel beam tube noted above. This plot was done in the simulation with 180 A/mm$^{2.}$ Field integral along the black line -5.213E6 G-cm. Field integral along the red line 1312 G-cm.

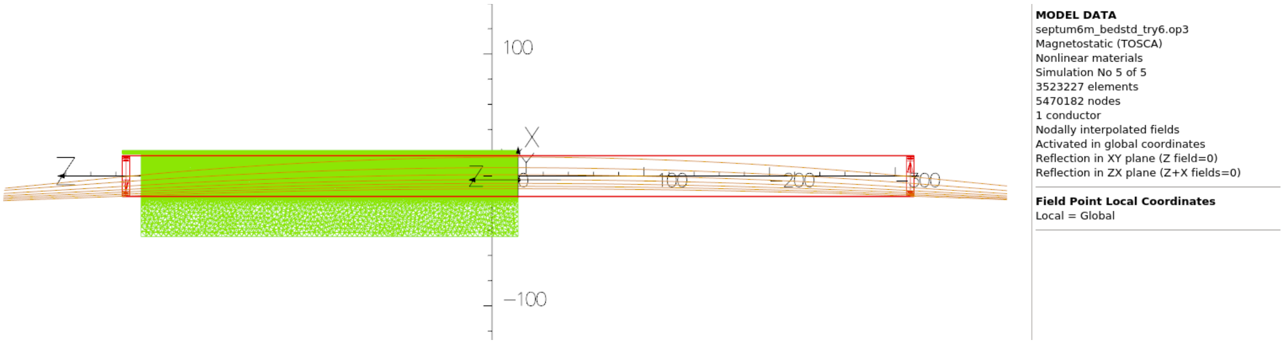


Figure 4. Seven orbits, energies 8350 -21550 MeV at 2200 MeV intervals with starting locations and angles taken from Ryan's NE spreader design.

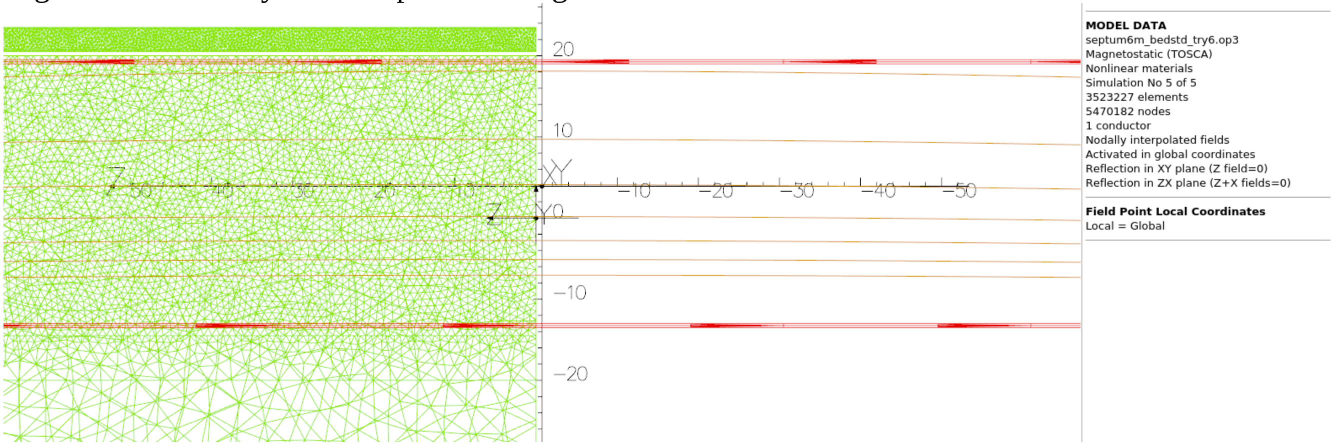


Figure 5. Central region of Figure 4. The lowest energy beam (topmost) is too close to the conductor for a functional cryostat so the pole will have to be widened and the conductors separated by ~3 cm.

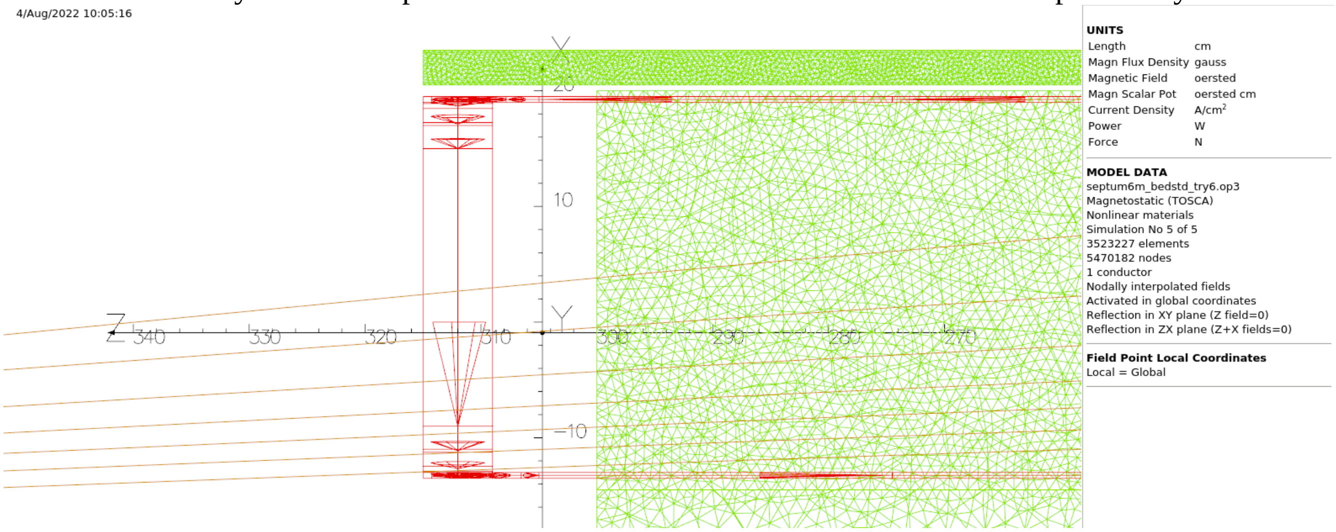
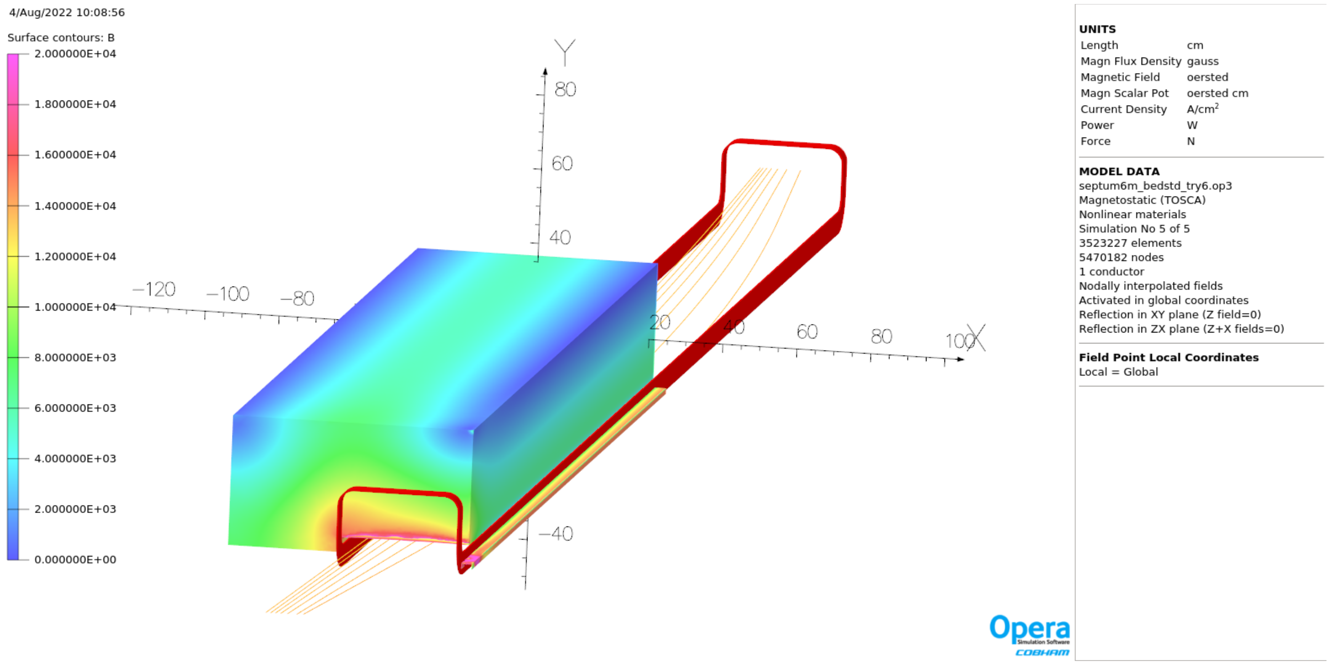


Figure 6. Seven orbits at left end of figure 4, exiting the magnet. Again the beam is too close to the conductor for a functional cryostat.



UNITS

Length	cm
Magn Flux Density	gauss
Magnetic Field	oersted
Magn Scalar Pot	oersted cm
Current Density	A/cm^2
Power	W
Force	N

MODEL DATA
septum6m_bedstd_try6.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 5 of 5
3523227 elements
5470182 nodes
1 conductor
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in ZX plane (Z+X fields=0)

Field Point Local Coordinates
Local = Global

Figure 7. Perspective view of the model with the seven orbits. 180 A/mm$^{2.}$

Conclusions

This first look at a septum magnet for the CEBAF energy upgrade demonstrates:

1. Two three-meter magnets will be required so the fourth pass beam can be conveyed to its arc, drift at least one meter for cryocoolers, rather than one six-meter unit as shown above.
2. Superconductor is absolutely required: the existing ZA at 50 A/mm^2 in the copper already pushes conventional technology farther than any other DC septum magnet. Highest current pulsed septum the author has located is 80 A/mm^2 ; not relevant for CEBAF.
3. Clear width between the conductors in the next model should be 35 cm as compared to 32 cm here to allow 1.5 cm on either side of the conductor for the cryostat and ~1 cm beam halo allowance. There is only a 1 cm gap between the conductor and the pole top and bottom; I'm assuming we can live with greater heat leak there. If not, pole gap will have to increase to 9 cm. I will solicit input from out cryo group before starting the next iteration. [1.3 cm gap is roughly what the MRI magnets I worked on had between the OD of the helium vessel and the OD of the “patient” cylinder. This gap included a thermal shield connected to a cryocooler and superinsulation. In other words, I've seen an existence proof. Of course those were cylinders, not flat-sided, so deflection due to air pressure was less of a consideration.]
4. With the additional pole width this magnet will be 68 cm high. Bottom is getting close to the floor. Overall width 70 cm.
5. The author can provide Fourier components along the seven orbits if requested. Allow a few days for response.
6. 17 turns of LHC-developed cable at 3530 A in the coil will be difficult to supply from the surface. 240 turns of 1 mm strand, hexagonal pack, fits in same space. 125 A.

References
1. https://jlabdoc.jlab.org/docushare/dsweb/Get/Document-254194/22-010.pdf
2. https://arxiv.org/abs/2201.09501 Advances in MgB2 Superconductor Applications for Particle Accelerators, Akira Yamamoto

Will Oren sent the draft to Probir Ghoshal. Probir sent me questions which I answered in email, below.

On 8/5/22 15:04, Probir Ghoshal wrote:
> Dear Jay and team,
>
> I had a quick look at the document shared by Will O on the "First attempt at a conduction cooled SC septum magnet for FFA upgrade" dated Aug 4th, 2022 authored by you (Jay B).
> I will need a few answers (that i am sure you will have), even for me to attempt provide any details regarding the estimate.
>
> Q1. As suggested 6 m long is not the option to start with and hence 2X3m is good starting. Any idea of the gap between them (3m long magnets)?

Estimate is 1.5 m, figuring 0.5 m each for termination, GM, dealing with vertical offset and 0.5 m for contingency. Next model.

> Q2. With the field required ~0.9T (nominal), why SC magnet?

It's a septum magnet. The beams are too close together to use copper. The existing ZA septum uses the 3 mm square hollow conductor at 47 A/mm^2 in the copper to get half this field. Each conductor is a separate water circuit. Next maintenance day stop by and I'll take you down to look at one. Seven bar LCW. We've had one fire, albeit due to chips left in the conductor slot.

> Q3. Why MgB2 and why not a proven technology using NbTi conductors conduction cooled? Who the vendor is for MgB2 (is is Hypertech?)

LHC developed three MgB2 vendors - see Akira's paper. My thought was warm iron. Given limited real estate in all three dimensions, a conductor functional at 20 K seemed better than 5 K. More lift is available at 20 K.

> Q4. The Iron in there, is it warm or cold? and what are the gaps you have or intend to have (A schematic hand sketch will be helpful) between warm and cold (CCM).

As mentioned in draft, ~15 mm for the cryostat in all directions from the coil pack, 35 mm total width by 90 mm height. Plus 5 mm steering allowance on each side to beam centroid. Iron will likely be curved as in YR and ZA but for a first cut I went rectangular.

> Q5. The heat load you expect to the CCM (approx - TOTAL) in order to have cryo-cooler(s) along with the operating current (say the worst case eg 100A, 1000A, etc?)

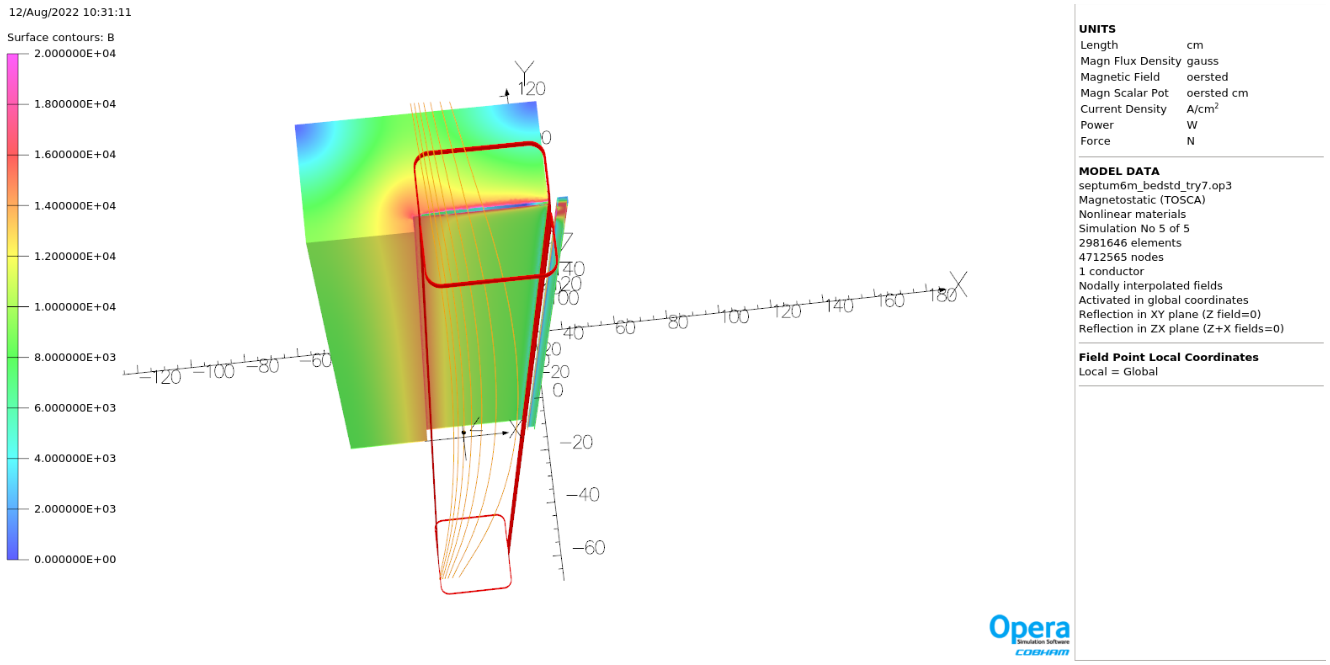
I haven't a clue as to heat load, which is why I asked Jonathan to have someone look at it. Coil pack 3.75 mm by 60 mm so 1 mm strand hexagonal close pack 240 turns for 30000 AT aka 125 A.

> Q6. the intent of have correctors or shims will be warm or cold (if any)?

No shims or correctors. There's no way to get decent field quality from a septum magnet. CERN loses about a third of each bunch from Linac 4 to LHC, mostly in the extraction/injection septa. CEBAF loses less because we (now) have much more margin. Margin will shrink a lot at 20 GeV.

Addititionn 12 August

I decided to widen the pole and increase the pole gap in the six meter model before cutting it in half and offsetting the second half to form the septum pair. Engineering current density increased a bit more than the ratio of pole gap, 9/8, to 207.5 A/mm^2 from 180A/mm^2. I also realized that the odd behavior at the magnet ends in Figure 3 was due to the way I had implemented the bedstead coils and fixed that. This design accommodates a cryostat which extends 15 mm beyond the conductor on all sides and perhaps a bit more laterally. The last won't be settled until the septum pair is modeled.



UNITS

Length	cm
Magn Flux Density	gauss
Magnetic Field	oersted
Magn Scalar Pot	oersted cm
Current Density	A/cm^2
Power	W
Force	N

MODEL DATA
septum6m_bedstd_try7.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 5 of 5
2981646 elements
4712565 nodes
1 conductor
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in ZX plane (Z+X fields=0)

Field Point Local Coordinates
Local = Global

Figure 8. Perspective view of the model with the seven orbits. 207.5 A/mm$^{2.}$ |B| on surface shown.

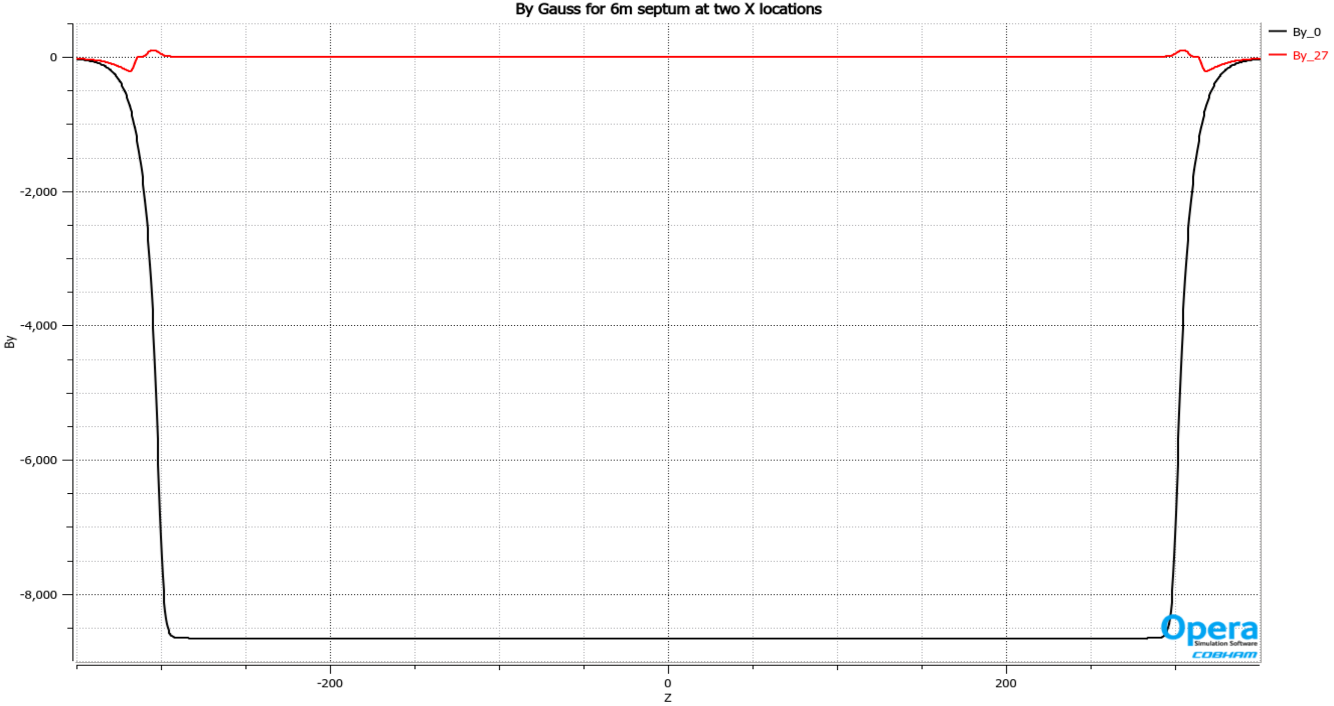


Figure 9. By along x=0 and x=27. The latter is within the shield tube seen on the right of the figure above. BdL -5.30653E6 G-cm along x=0 and -4108 G-cm along x=27, shield saturated at ends

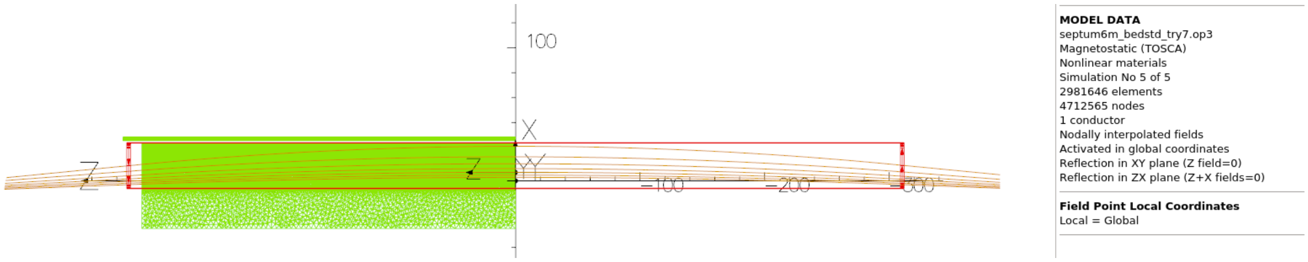


Figure 10. Seven orbits through the model

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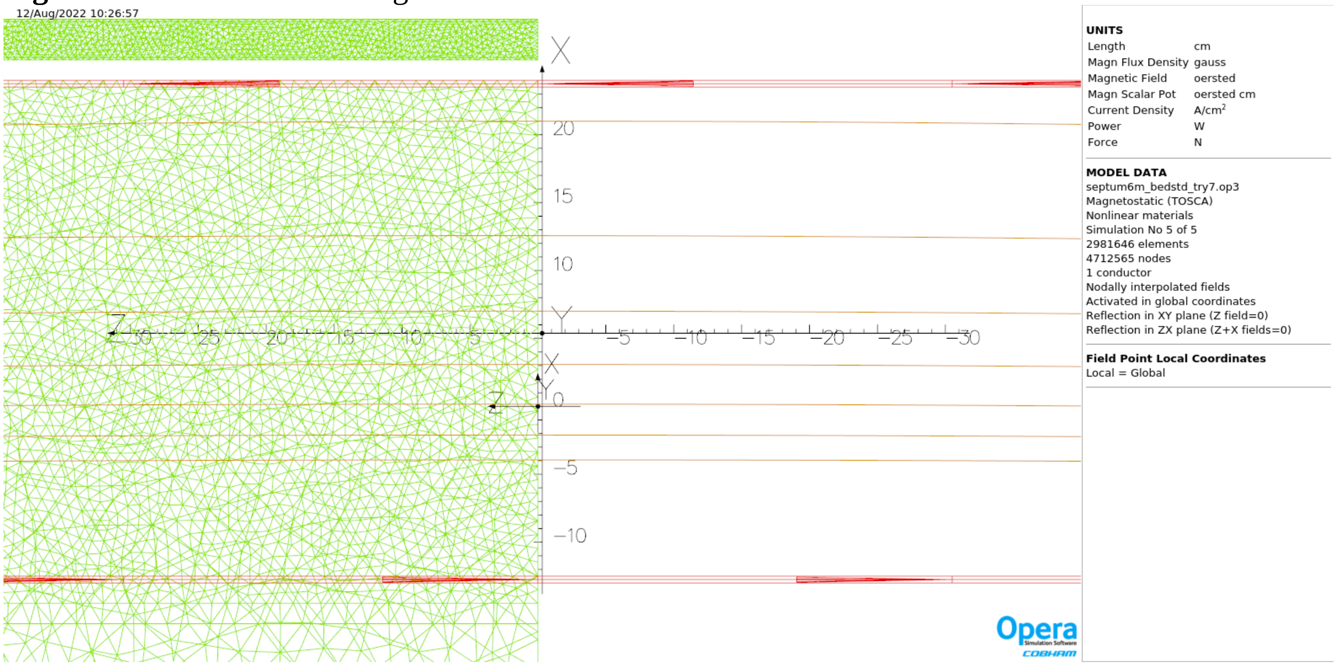

Figure 11. Seven orbits at the center of the model

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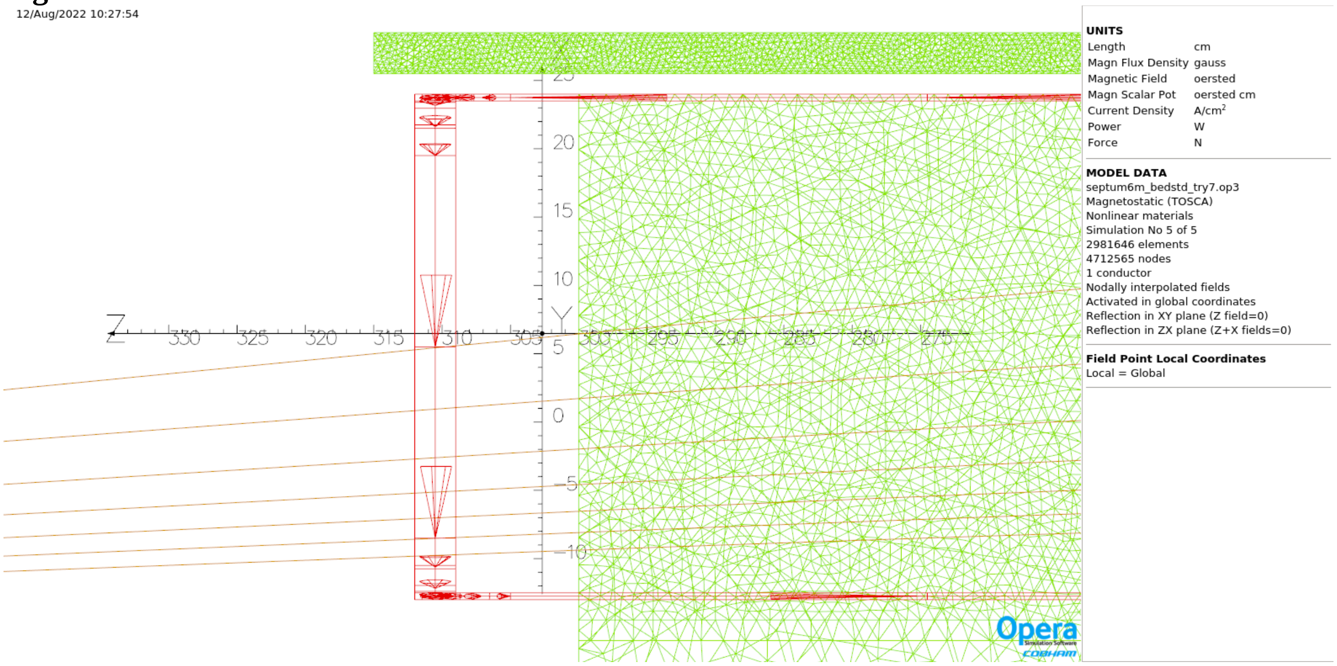

Figure 12. Seven orbits exiting the model.

Figures 11 and 12 show much improved clearance between beam and coil, hence increased space for cryostat versus model shown in the first part of this tech note.