Rough conceptual design for positron capture solenoid

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15 October 2023

Summary

At the Ce+BAF meeting 11 October, Andriy Ushakov presented an update on his work on shielding the capture solenoid for charged particles after a 120 MeV 1 mA electron beam strikes a 4 mm tungsten target. https://jeffersonlab.sharepoint.com/:p:/r/sites/PositronSource/_layouts/15/Doc.aspx?sourcedoc=%7BD39C1791-A223-476E-BBE2-CFFF2790A3AF%7D&file=Ushakov-TrackingInSolenoid-20231011.pptx&action=edit&mobileredirect=true Alternate link if that doesn't work https://jeffersonlab.sharepoint.com/sites/PositronSource/SitePages/2023-10-11-Ce+BAF-Meeting.aspx

The image below is from one of his slides. The blue is W10Cu or TZM. The target is at the left and a copper re-accelerating cavity is the grey at the right. The field at the rotating target in his model is 7.5 kG, problematic due to the currents that will be driven in the disk.

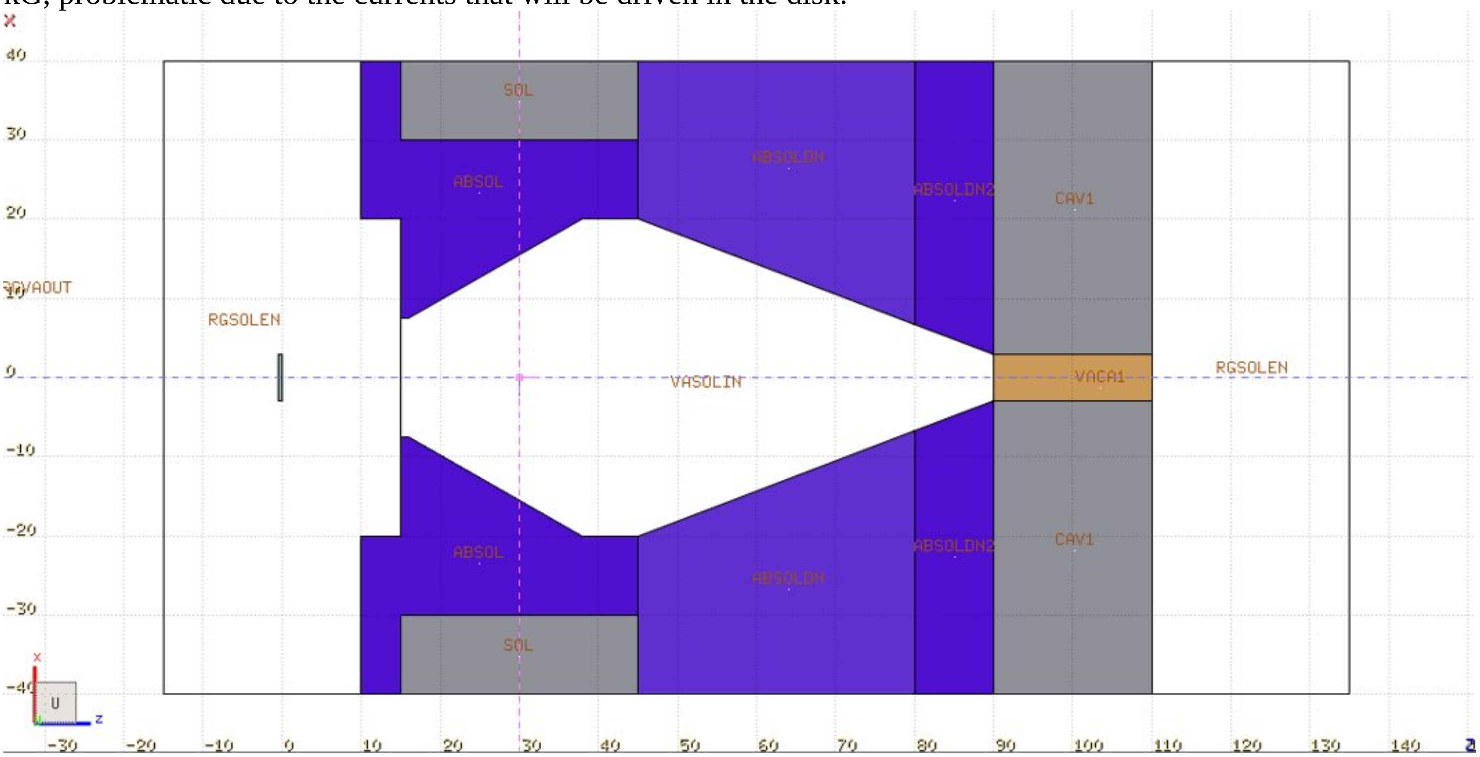

Figure 1. Andriy's FLUKA layout

I describe below an “engineering” concept for the magnet, aka one with more reasonable current density and an iron return to reduce the field at the target. In the design immediately below the field at [0,0,-30] is 4560 G, a 40% reduction over the magnet without return steel shown in the PowerPoint linked above. The steel occupies much of the volume shown in blue and has lower radiation length so energy deposition and radiation escape will change, necessitating change in the shielding design. Still, something that can be built is better than an ideal.

I started with Andriy's dimensions, wrapping it in 5 cm steel with IR 20 cm aka the step shown at left in the W10Cu. I found that 2400 A/cm^2 was required and the steel was fully saturated with 1.7T bore field. I successively increased steel and coil size to arrive at the model below: 15 cm steel, 1 cm air gap to coil, coil 30 cm long with 30 cm IR and 54 cm OR so current density 1000 A/cm^2 suffices as that is generally an acceptable J for water-cooled copper.

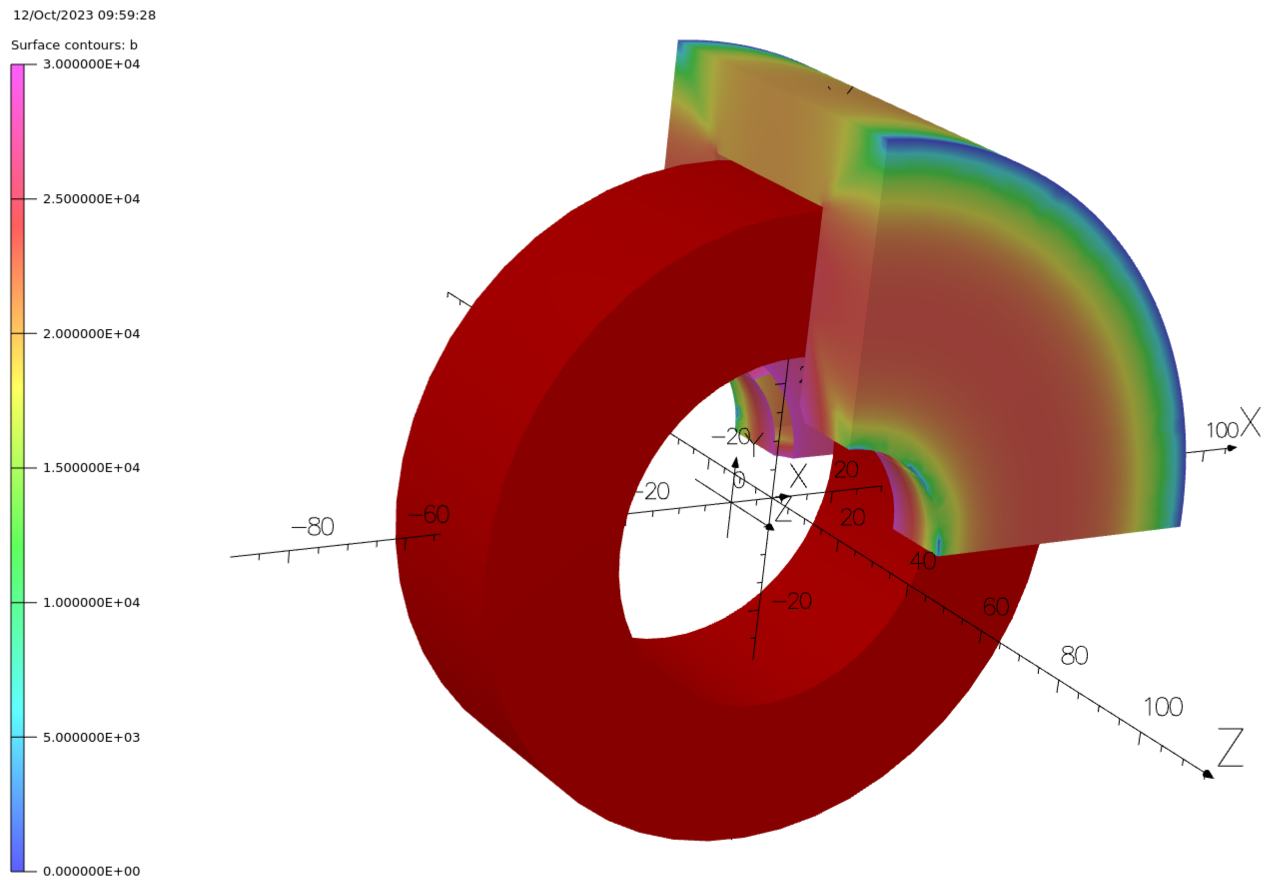

Figure 2. Magnet model showing field in steel, truncated at 30 kG aka well into saturation. The steel is scalloped at the IR in the image because that volume is above 30 kG. Default “good magnet steel” BH curve was used. If one uses 6” common cold-rolled steel, lower field in the bore. Cylindrical symmetry assumed and only one fourth of steel shown.

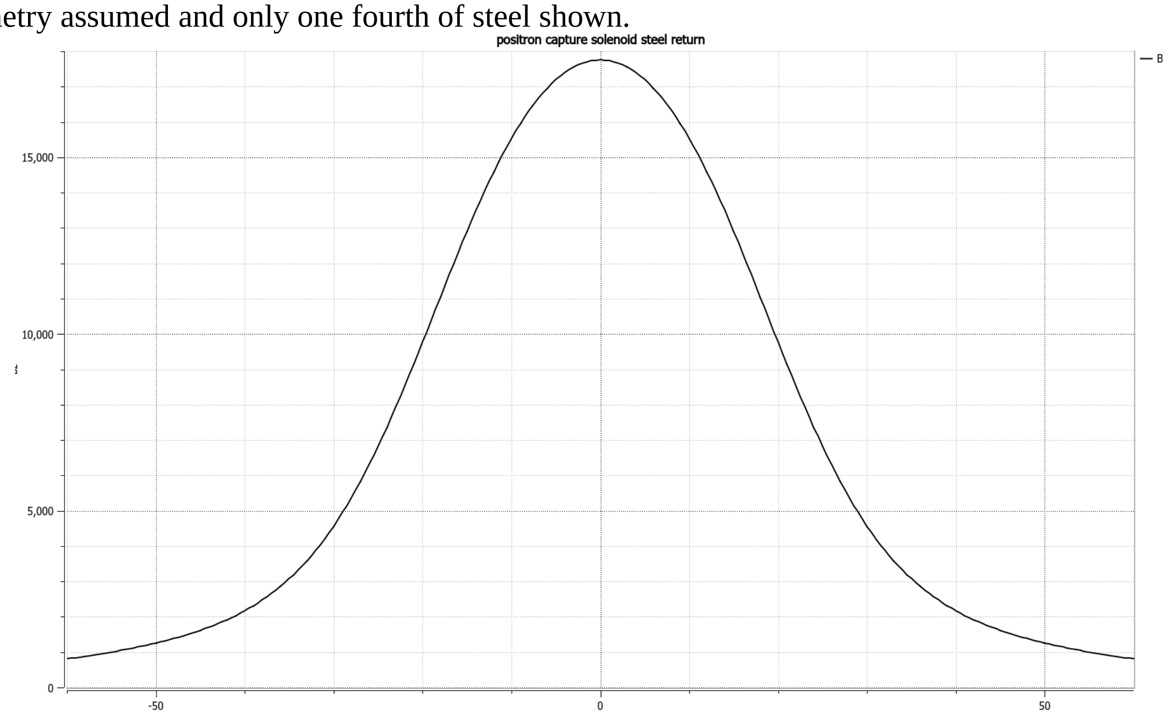

Figure 3. Field along the Z axis. Rotating target is at -30 cm, Bz= 4560 G. Field at z=90, entrance to the cavity in first figure, is 300 G. Maximum 17.75 kG

If I assume Luvata 8154, 14 mm square with 8 mm hole and 1 mm corner radii, 100 cc/sec through a 16 turn per side double pancake, aka 32 turns, requires 6 bar water. Copper about 205 mm^2. Assume that with insulation the conductor occupies 15 mm square so 2250 A given J. Resistance of double pancake 8.5 mΩ so power 43 kW which is far more than 100 cc/sec can deal with. Even with an 11 mm hole the water pressure over 85 m of the double pancake has to be 80 bar for 1 l/s which is not feasible. So the conductor and its hole and therefore current from the power supply has to be larger. If I assume 19 mm square with 12 mm hole, 68 kW and 32 bar needed for 1 l/s. A rectangular conductor with larger water flow area like that used for the MOLLER spectrometer coils with 20 bar water is required. A longer solenoid with lower peak field is clearly indicated. So let's play with that.

If I assume instead that each layer of the 30 cm solenoid is a separate water circuit, the outer layer is 68 m long with 15 mm square insulated conductor. If the 14 mm square conductor with 11 mm hole is used, 500 cc/sec requires 18 bar water. Resistance of the outer layer is 8.5 mΩ so power 43 kW and 500 cc/sec water would rise 86 C with perfect heat transfer. Inner layers are shorter and so would have lower temperature rise. A chiller providing 4 C inlet water at 20 bar would suffice, barely.

Increase solenoid length to 50 cm. This requires that that solenoid center be farther from the target because the steel would extend to 40 cm from the center of the solenoid and the target is 30 cm from the solenoid center now. I assume the target will be 50 cm from the center of the solenoid, with a 10 cm gap as shown in Figure 1. This magnet provides the same B^2 with 600 A/cm^2 as the 30 cm version that can't be cooled does at 1000 A/cm^2 . Using the same 14 mm square conductor, the outer layer dissipates 26 kW so the cooling requirement is less than that in the previous paragraph.

As Sergei Nagaitsev wrote in an email exchange I started with Figures 2 and 3, this would be much easier with a HTC material like MgB_2 which can do 200 A/mm^2 at ~2T and 20 K. A cryostat with total radial thickness 10 cm is doable, albeit with more heat leak than one might like. The 30 cm overall length could then be maintained with coil 20 cm. Steel would have to be cut back to 10 cm thickness on the upstream side to allow the target to remain in the same location, with steel edge at z=5 cm in Figure 1. This would prevent interference with the mechanism rotating the target while reducing the field at the target and eddy currents therein somewhat. GM or pulse tube refrigerator(s) would be mounted on the OD of the cryostat through holes in the steel. A SWAG based on my analysis of the CLEO solenoid for SoLID including the 14” square hole through the return steel for the cryo and lead tower is that the field would change by under one percent in the quadrant under the holes in the return steel. The effect was reduced when the CLEO return steel was obtained, increasing return from 51 cm to 71 cm thickness, so it would be more pronounced with 10 cm return than 15 cm. The end plates can be 10 cm and the outer cylinder 15 cm to reduce the effect on the bore field.

Information on HTC superconductors for accelerators is available in https://arxiv.org/abs/2201.09501 and https://arxiv.org/abs/2208.12379 A useful superconductor reference is https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

The magnet shown in the next figures provides about 14% more focusing ($\int B^2$) than the one Andriy showed in his presentation with J = 200 A/mm^2. Field at the target (0,0,-30) 5115 G, about a third less than one without the steel.

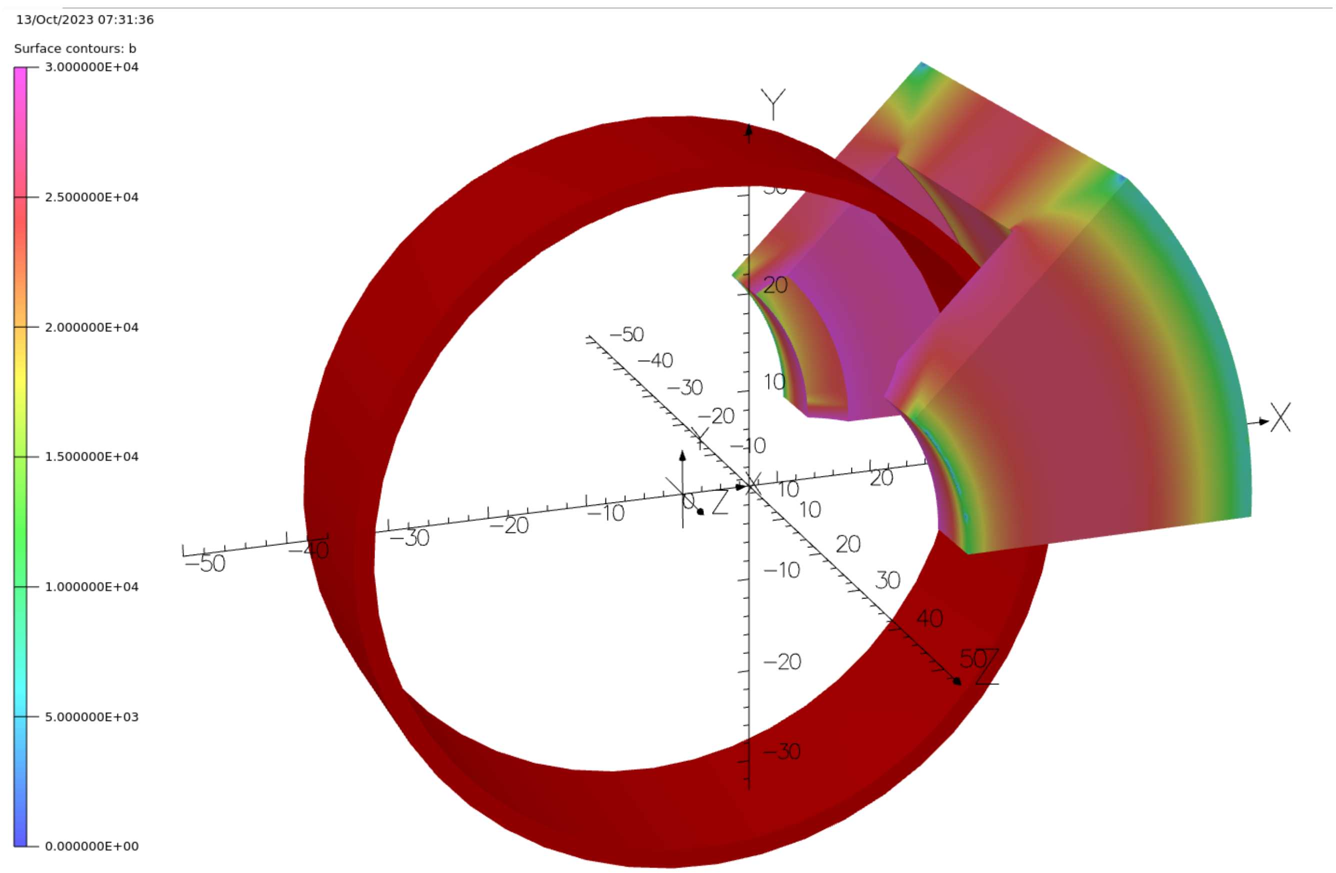

Figure 4. Solenoid with HTSC coil and 10 cm steel. Color scale to 30 kG

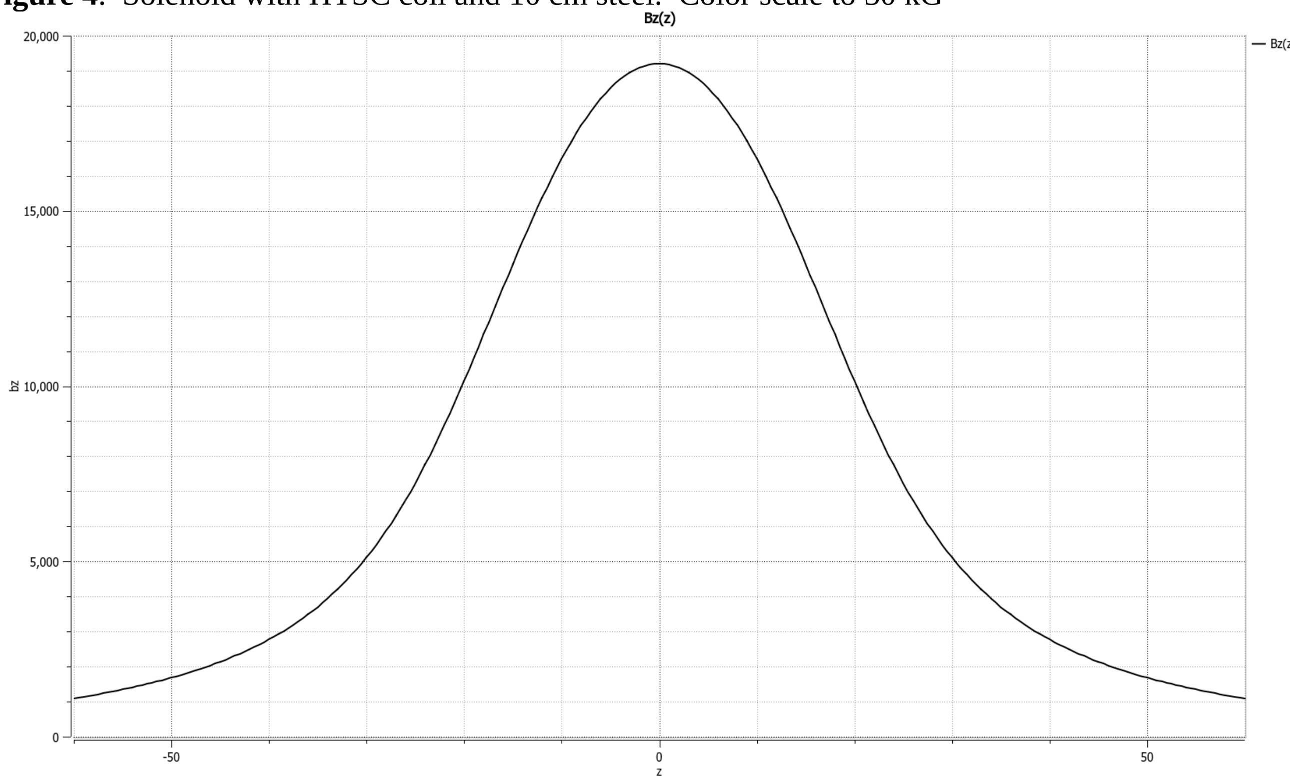

Figure 5. Bz(z) for coil above

Since Andriy indicated in email that he would try the 50 cm solenoid with steel mentioned on page 3, I provide figures here.

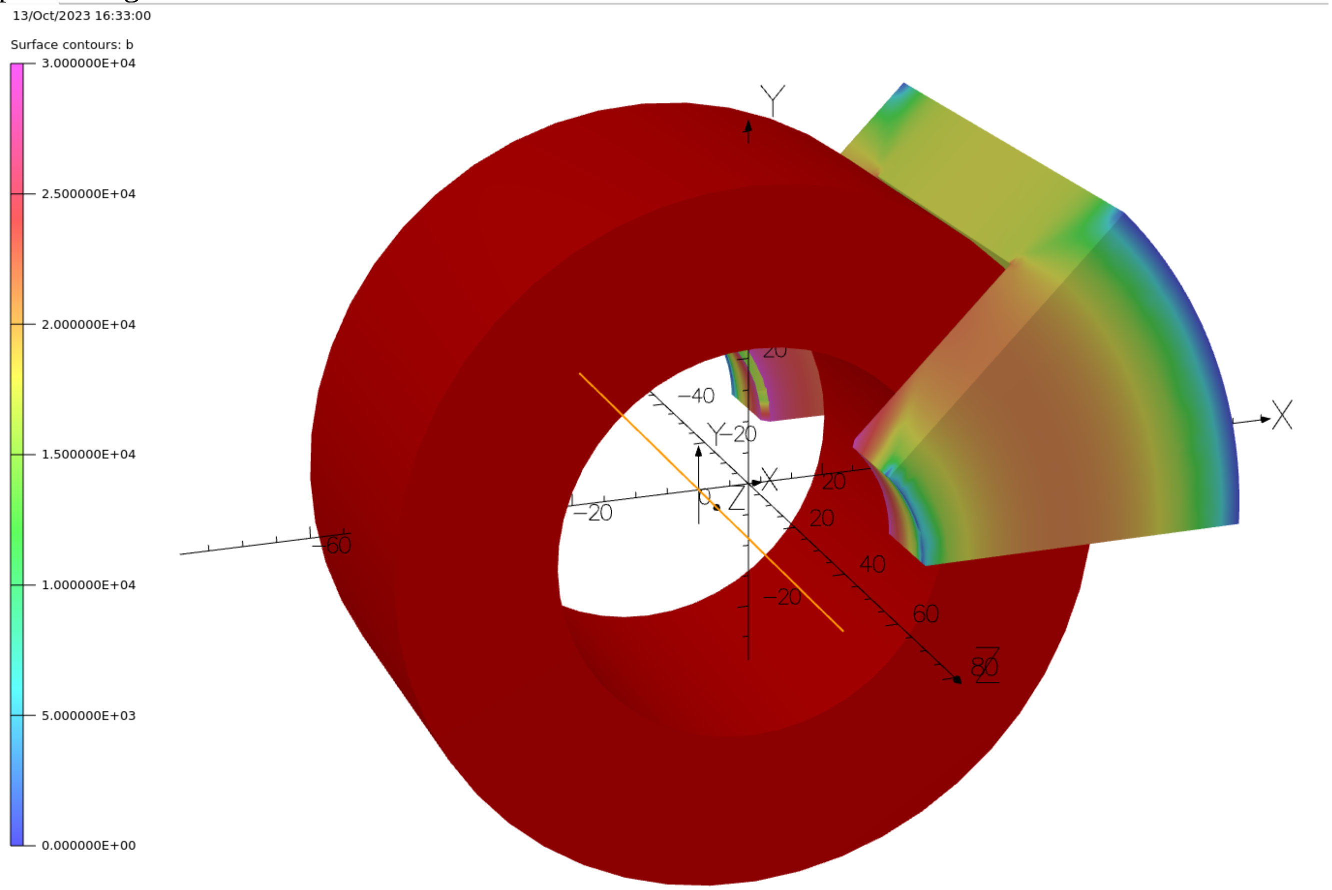

Figure 6. 50 cm long by 24 cm radial depth coil with 15 cm thick steel return

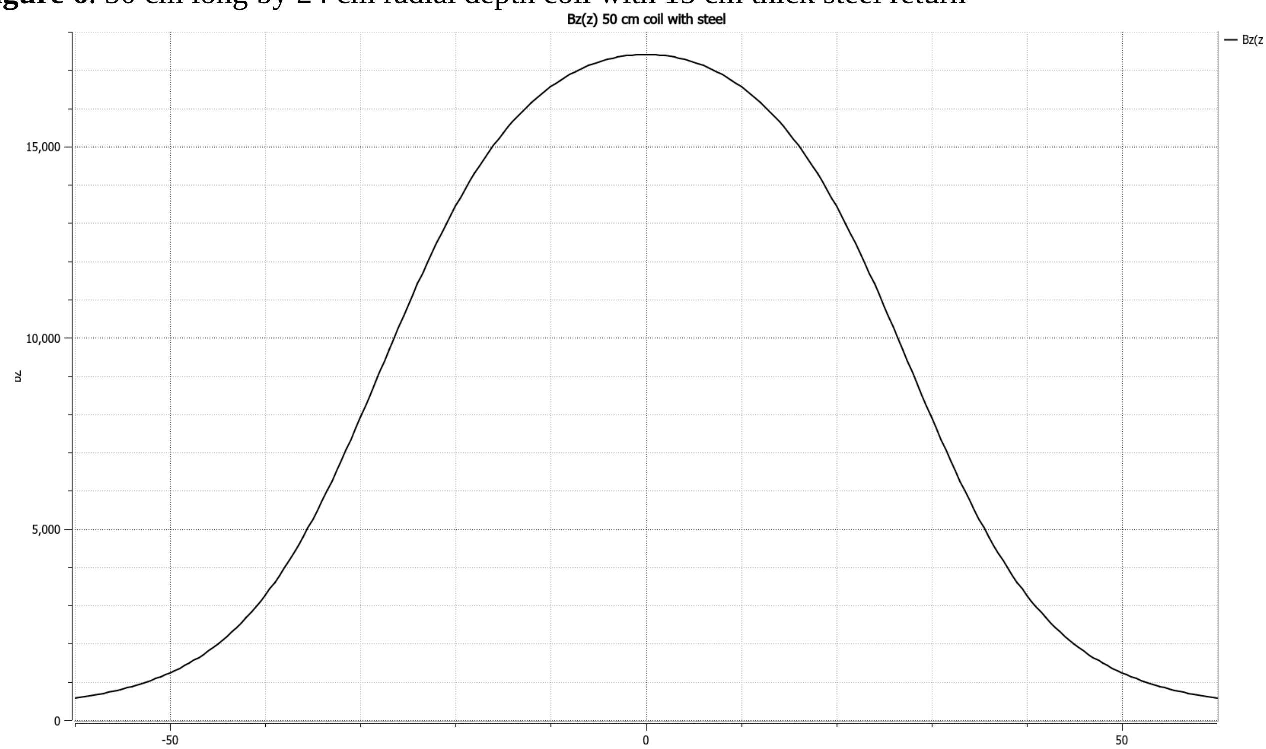

Figure 7. Bz(z) for the coil above

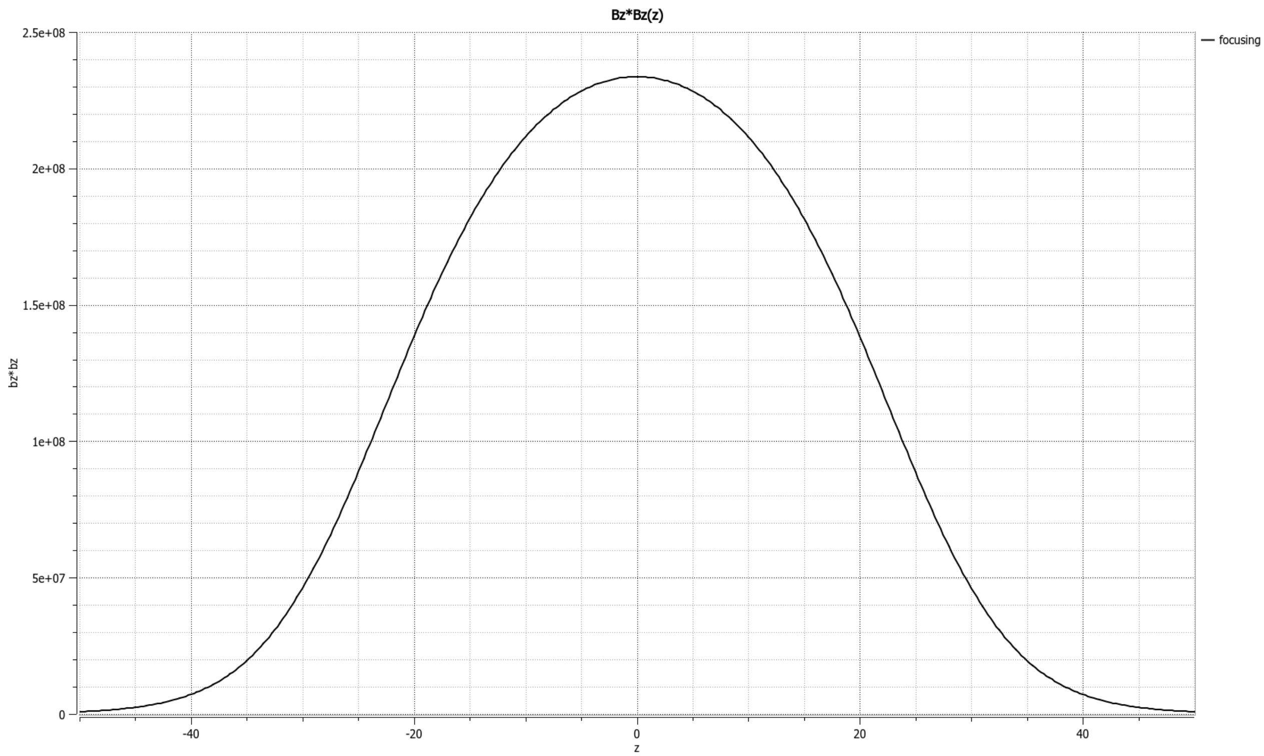

Figure 8. Square of figure 7

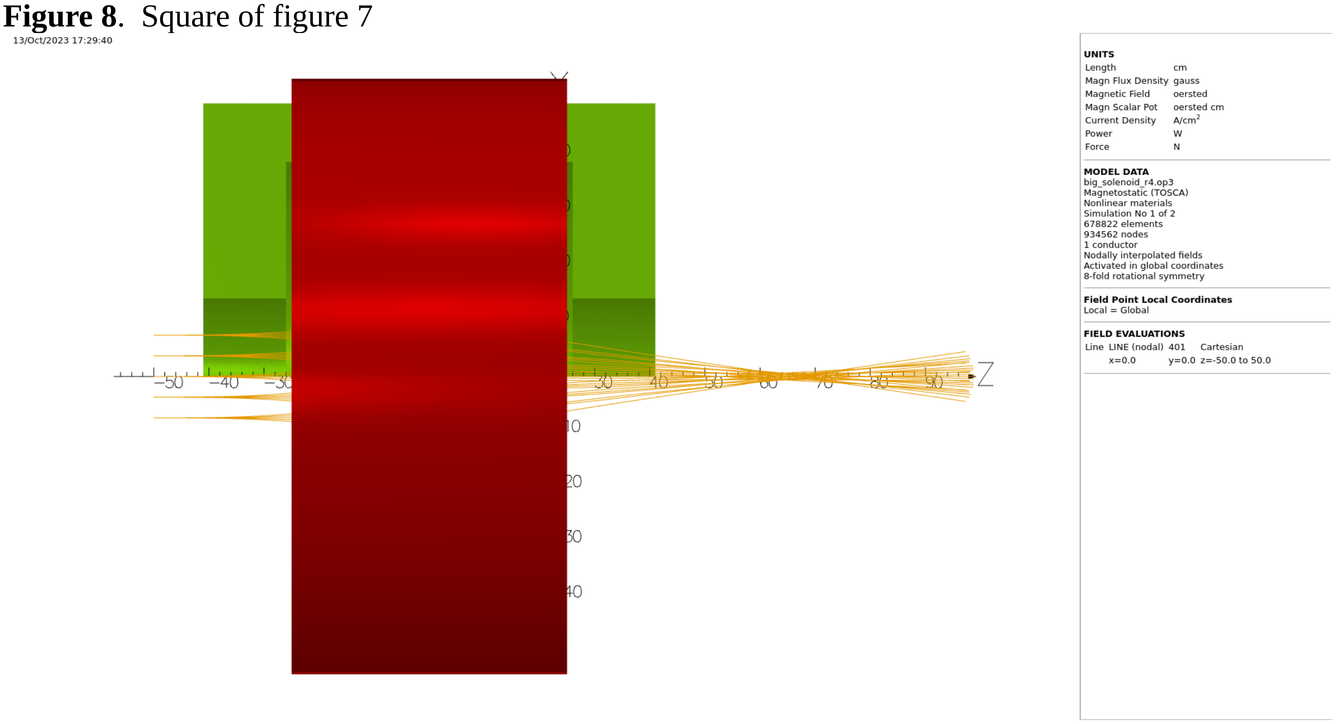

Figure 9. 15 cm square array of 120 MeV electrons focused by solenoid.

Figure 10. Bz(0,0,z) of 50 cm long, 60 cm ID, 108 cm OD coil, with (red) and without (black) steel.

A field map 60 cm square extending z=[-70,130] with respect to coil center has been provided to Andriy Ushakov for simulations. 1 cm grid.

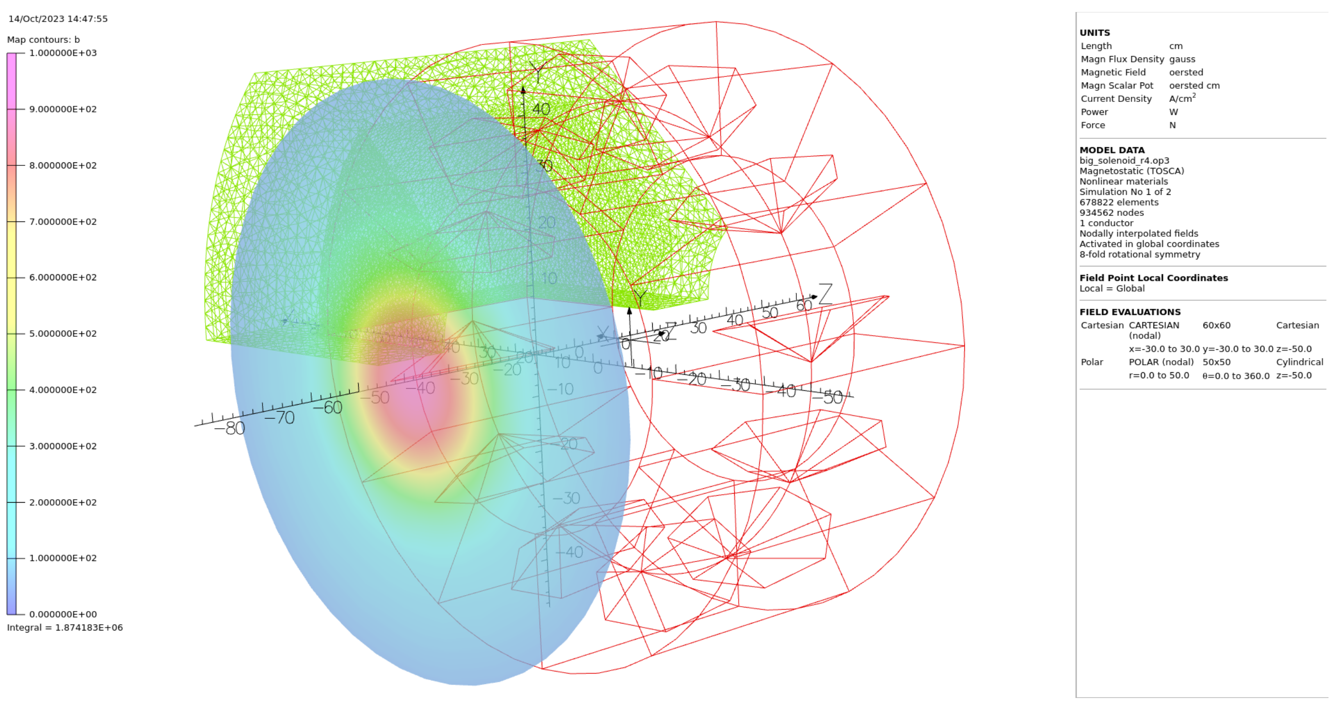

Figure 11. |B| on a one meter diameter disk 50 cm upstream of the center of the coil, possible spinning target Z location.

Conclusions

A 50 cm long conventional solenoid with 30 cm IR and 10-15 cm steel return can be built to create the focusing used by Andriy Ushakov in his presentation. Gap between coil and steel on each end will likely be 2-3 cm, not the 1 cm used above, to allow for water lines and layer to layer current connections. This work simply scoped out the problem.

A conductively cooled solenoid using high temperature superconductor, e.g. MgB_2, would fit in Figure 1 layout and provide more focusing but requires substantial development.

Side Note

The SoLID end-cap requires about 40 square meters of 15 cm magnet steel. aka 400 sq ft of 6" plate. If that project goes ahead in a timely manner the steel required for this magnet should be rolled into that purchase. It will be almost impossible to roll 15 cm plate on a central radius of 37.5 cm (40% strain!) so the outer shell should be made octagonal with end plates to match, as in the CLEO magnet. Better yet, cast/forged as a cylinder. There's a large casting that's also part of SoLID; Whit Seay has a vendor. The two needs total about 60 tonnes which is the minimum size for ladle chemistry specification. Some steel vendors want 80-100 tonnes for a special chemistry order. If the positron work moves ahead well before SoLID, common 6" low carbon steel plate is the way to go.