# A quick and dirty magnet design for the magnetized beam LDRD proposal

Jay Benesch 10/16/2015

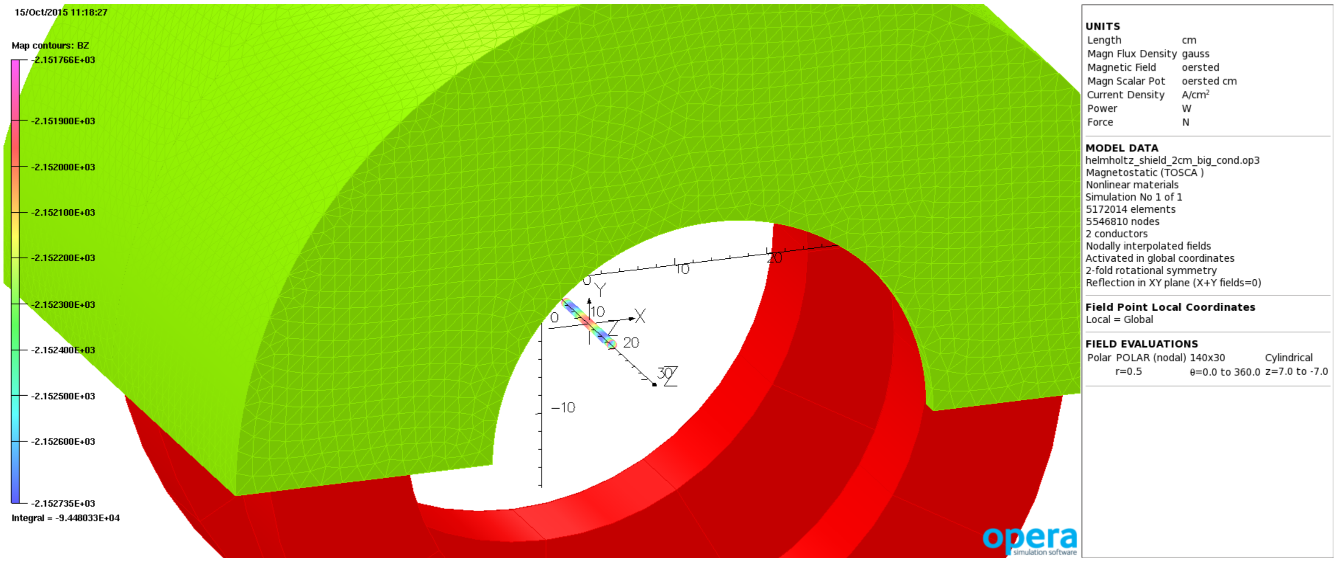
## Abstract

I describe a realizable Helmholtz pair design which provides 500 ppm Bz uniformity over a 1 cm cylinder 14 cm long for possible use in the LDRD magnetized beam experiment. The assembly has a 2 cm steel return to partially contain stray field and enhance the bore field about 20%. Other options suggested include a Halbach cylinder and an “open” MRI magnet. Both would require much less facility modification than would an electromagnet.

## Electromagnet

Coils are Z-symmetrically placed extending from Z=13-23 cm and R = 28.5 – 43.5 cm, 10 cm Z by 15 cm R cross-section. A 9 mm square conductor with 6 mm hole is assumed, half-lapped with 0.002” mylar and then single-lapped with 0.01” B-staged S or E glass. The mylar provides insulation and the fiberglass-epoxy structural strength. With tolerances, the insulated conductor is 1 cm square. Coil will be fabricated of five double pancakes, each with 30 turns, for a total of 150 turns. Water pathlength 68m per double pancake, use 70 m for convenience. Copper cross-section 0.496 cm$^2$, use 0.5 for convenience. If I assume a 40C temperature rise, copper resistivity 2.09 µohm – cm. Resistance about 30 milli-ohm per double pancake or 0.3 ohm per pair of coils. At 420A, yielding ~2 kG, ~5300 W/double pancake aka water circuit. Water volume in 68 m of 6 mm hole is 1920 cc, so 2.76 W/cc. Since I don't know what the heat transfer efficiency is from the copper to water, I'm going to assume 1 calorie/s (4.2W) per cc. Round the 1920 cc to 2 liters. At 2 l/s, 1C conductor rise. At 2 l/min, 60C rise (too much given 35C entry), but only 2.8 bar pressure drop per http://www.pressure-drop.com/Online-Calculator/ for straight 70 m of 6mm tube with 0.005 mm internal roughness. For 3 l/min, 40C rise (so 75C exit), 5.8 bar. Unfortunately, building 18 (LERF) has only 80 psi (~5.5 bar) LCW pressure per G. Biallas. Power supply: 450A, 150V would be nice, but 425A by 140V would probably do, including lead losses. 60 kW. Ten double pancakes each requiring 3 l/min is 30 l/min, plus power supply coiling. Say 10 gpm at 35C and 8 bar at entry to be comfortable. But since I equated 2.76 to 4.2 above, this is a crude estimate. Tommy Hiatt confirmed that ~7 bar differential pressure is needed.

http://www.luvata.com/en/Products/Special-Products/Hollow-Conductors/Tool-List/Square-with-round-hole/



**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**
helmholtz_shield_2cm_big_cond.op3
Magnetostatic (TOSCA )
Nonlinear materials
Simulation No 1 of 1
5172014 elements
5546810 nodes
2 conductors
Nodally interpolated fields
Activated in global coordinates
2-fold rotational symmetry
Reflection in XY plane (X+Y fields=0)

**Field Point Local Coordinates**
Local = Global

**FIELD EVALUATIONS**

| | | | |
|---|---|---|---|
| Polar | POLAR (nodal) | 140x30 | Cylindrical |
| | r=0.5 | θ=0.0 to 360.0 | z=7.0 to -7.0 |

Figure 1.  Coil pair with a 1 cm diameter, 14 cm long cylinder at the center showing field uniformity.

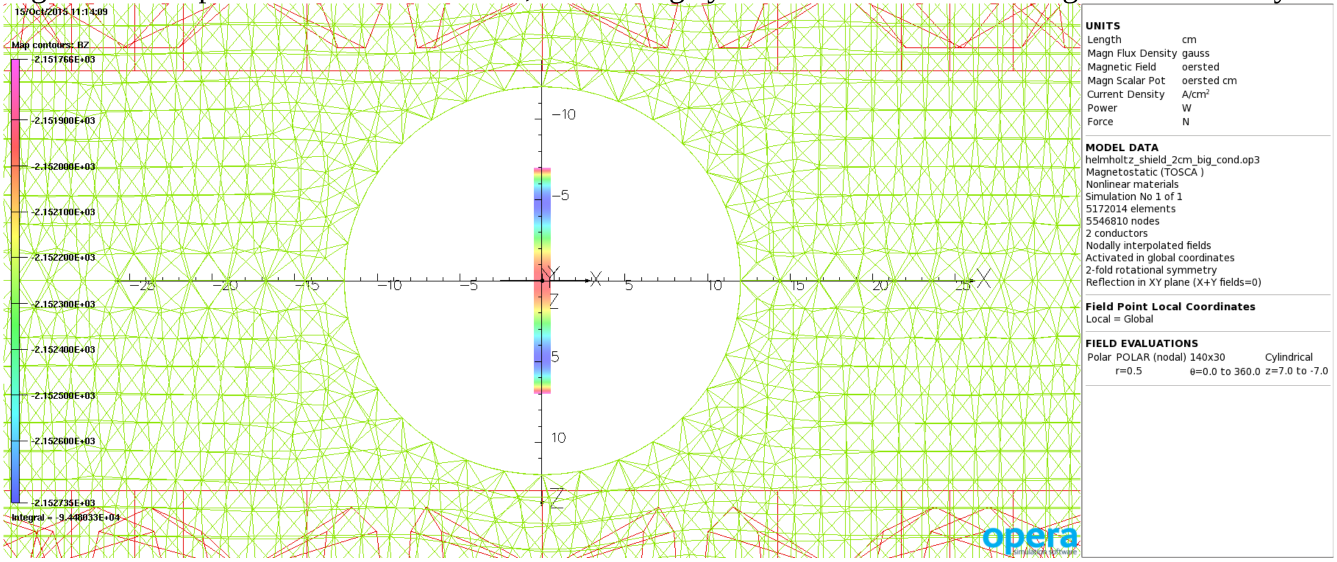


Figure 2.  Top view of assembly showing the 24 cm diameter hole in the shield, the green steel mesh, the edges of the red coils, and the same 1 cm diameter by 14 cm long cylinder with Bz evaluated on its surface.  Field homogeneity needed was not specified in the LDRD proposal.  Laser spot was to be up to 6 mm in diameter, so a 1 cm cylinder ought to encompass the beam.

The steel shield is 2 cm thick.  The cylinder has an IR of 50 cm and an inside half-length of 35 cm, so it's 12 cm from the coils.  Each end has a 24 cm radius hole.  Top and bottom have 12 cm radius holes.  Homogeneity would improve modestly if steel collars were put around the top and bottom holes to replace the steel lost to the holes.  Peak field in the 2 cm steel is 1.58 T with 420A, 2013 G Bz.  I haven't modeled 0.75” (1.9 cm) or 1” (2.54 cm) plate.  Either would work; thinner is easier to roll.  Steel is about half a tonne net of holes at 2 cm.  Conductor brings it to about 0.8 tonne.  Can the floor in the gun test stand take the load?  150 #/sq.ft. before the gun's weight and all support structures.  200#/sq.ft. indicated.

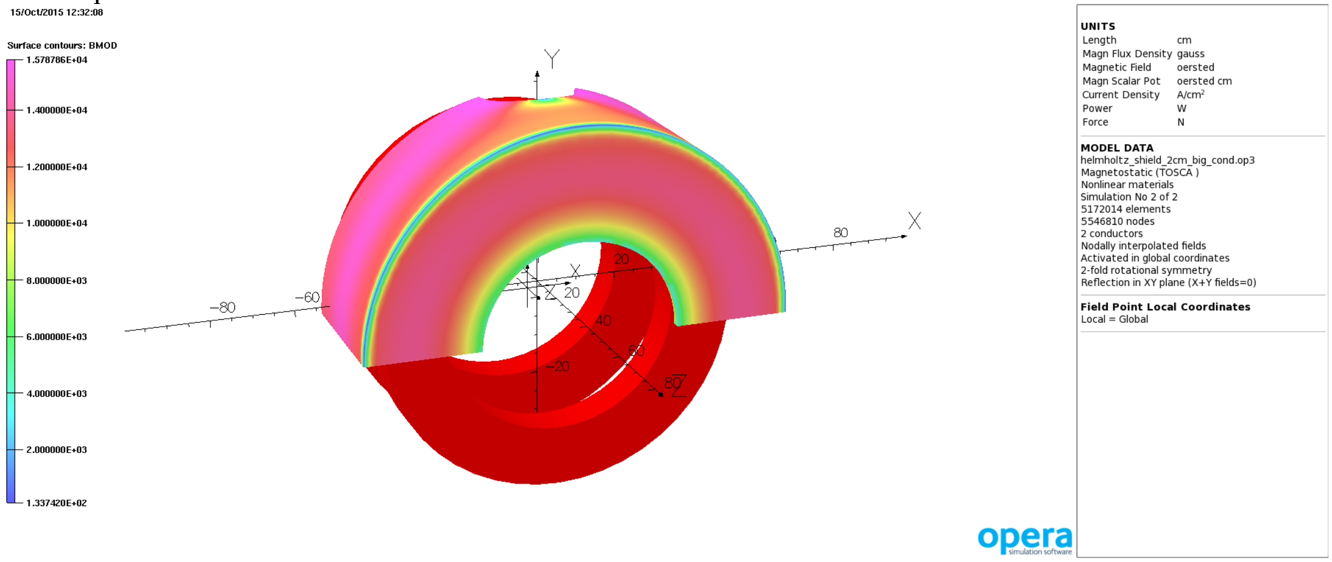


Figure 3.  Field in steel with 420 A in coil.

The sizes shown here were my eyeball estimates of what would work if the shield were fabricated in pieces and the magnet assembled around the gun less cable.  Cable plugged into top hole later.  If it has to be larger – much more weight.

## Alternatives

Halbach cylinder of permanent magnets. http://arxiv.org/abs/1510.02772 discusses the possibility of these for MRI systems in less developed countries and has references indicating some of the required size have been built.

Adapting an MRI magnet. http://paramedmedicalsystems.com/ is an Italian firm which makes “open” 0.3T MRI systems using MgB2 wire and a closed-cycle refrigerator. The big names (GE, Phillips, Siemens) won't sell magnets, just full MRI systems. This smaller firm might, perhaps with intervention by one of JLab's Italian collaborators. This could cost less than the electromagnet when the changes necessary in facilities (LCW, power, HVAC, floor capacity) are properly accounted for.

## Conclusion

A conventional electromagnet of the required size and access can be built. If better homogeneity is required, the 1968 paper by Milan Wayne Garrett has four and six coil solutions for the adapting. If an MRI magnet of appropriate size can be purchased off the shelf, that is likely the best solution.

---

## Addendum 12/27/2015

Riad Suleiman asked yesterday if I could design a coil set which would fit closely around the gun vacuum vessel and provide 2 kG at the cathode located 3” from the center of the vessel. I did not take into account that the cathode was offset in the original design. The Bz field at (x,y,z)= (0,0,7.5-13.5) for the design above is shown in figure 4. It spans 30G or 1.5% of 2 kG. 63 kAT required.

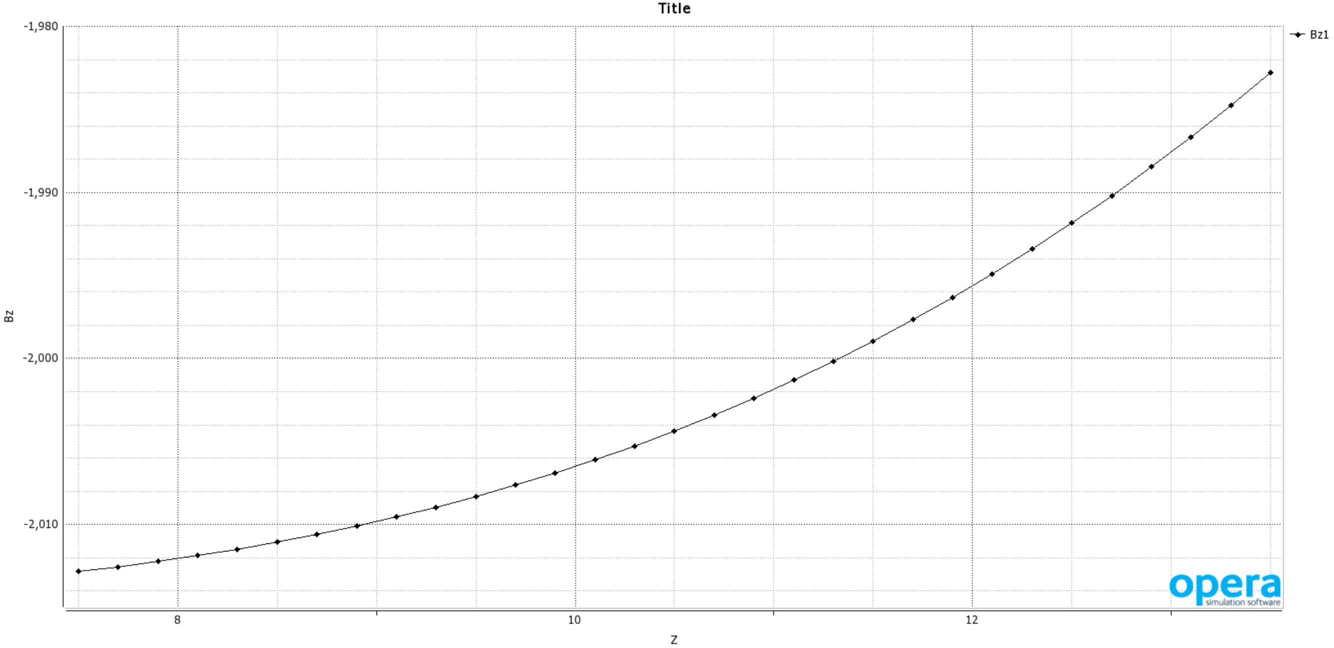
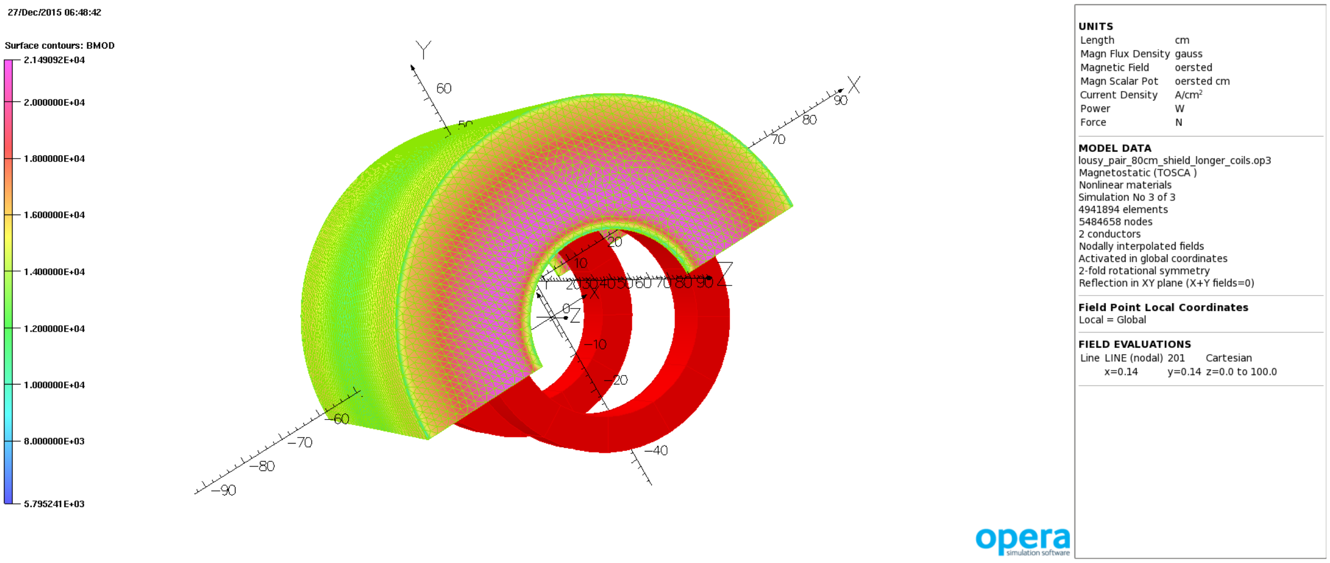


Figure 4. Bz along Z axis for design shown in figures 1-3. Z axis 7.5 to 13.5 cm, roughly from cathode to anode.

The next four figures show a design with coils closer to the vacuum vessel and therefore using a little less copper. The coil is only 8 cm radially by 12 cm Z, 96 $cm^2$ cross-section vs 150 $cm^2$ in the original design, so the required 102 kAT for 2 kG at the cathode would demand a much higher current power supply. The coil cross-section might be increased to 15 cm R by 12 cm Z to lower the current. Note that the original design is much more efficient in achieving the 2 kG at the cathode, requiring 63 kAT vs 102 kAT, because there isn't a much higher field volume under the coils. The amp-turns required reflect $B^2$ integrated over the full volume so the high field volumes require more AT.



**UNITS**

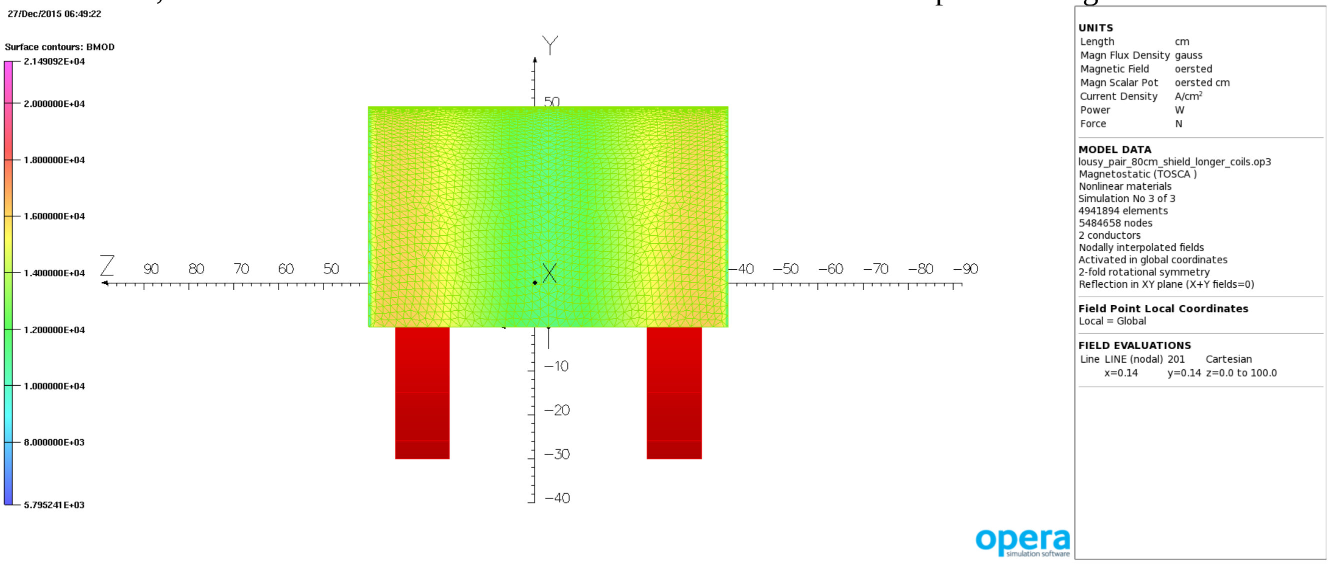
| | |
|---|---|
| Length | cm |
| Magn Flux Density | gauss |
| Magnetic Field | oersted |
| Magn Scalar Pot | oersted cm |
| Current Density | A/cm$^2$ |
| Power | W |
| Force | N |

**MODEL DATA**
lousy_pair_80cm_shield_longer_coils.op3
Magnetostatic (TOSCA )
Nonlinear materials
Simulation No 3 of 3
4941894 elements
5484658 nodes
2 conductors
Nodally interpolated fields
Activated in global coordinates
2-fold rotational symmetry
Reflection in XY plane (X+Y fields=0)

**Field Point Local Coordinates**
Local = Global

**FIELD EVALUATIONS**
Line LINE (nodal) 201 Cartesian
x=0.14 y=0.14 z=0.0 to 100.0

Figure 5. Less efficient coil pair, 44 cm Z spacing and 44 cm ID. Coils shown are 12 cm long by 8 cm radial extent, but will have to increase to ~15 cm radial extent to lower input current given AT.



**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**
lousy_pair_80cm_shield_longer_coils.op3
Magnetostatic (TOSCA )
Nonlinear materials
Simulation No 3 of 3
4941894 elements
5484658 nodes
2 conductors
Nodally interpolated fields
Activated in global coordinates
2-fold rotational symmetry
Reflection in XY plane (X+Y fields=0)

**Field Point Local Coordinates**
Local = Global

**FIELD EVALUATIONS**
Line LINE (nodal) 201 Cartesian
x=0.14 y=0.14 z=0.0 to 100.0

Figure 6. Side view of model. I have not cut holes top and bottom in this model as above, but one can see that the field in the center of the steel is low enough, 1.2T, to allow them to be cut.

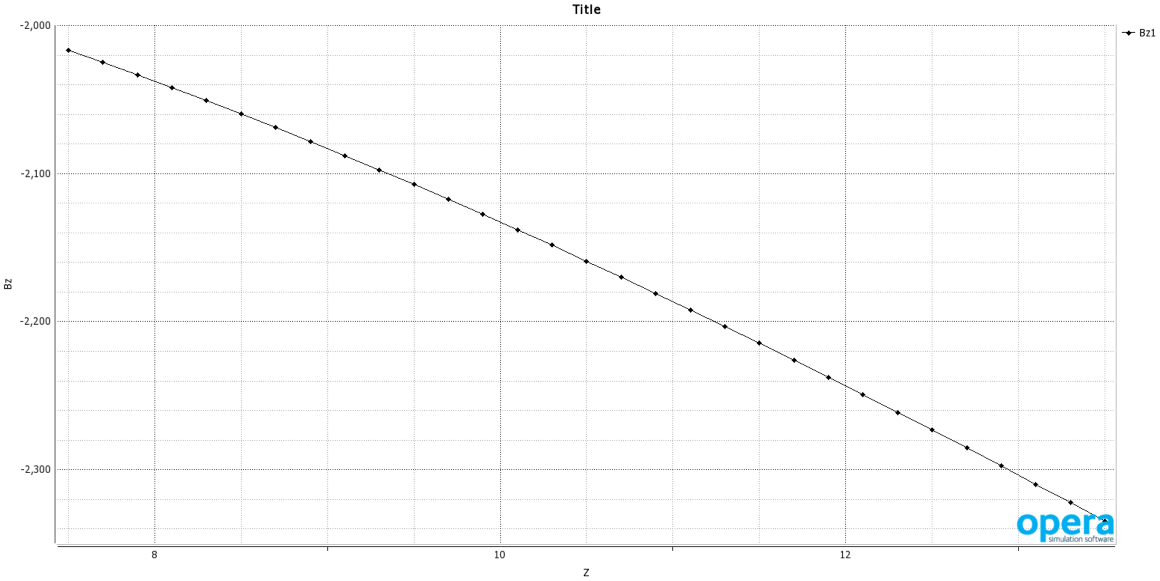


Figure 7.  Bz(z) over same 7.5 to 13.5 cm range.  The span is now over 300 G, not 30 G as in the original design, figure 4.

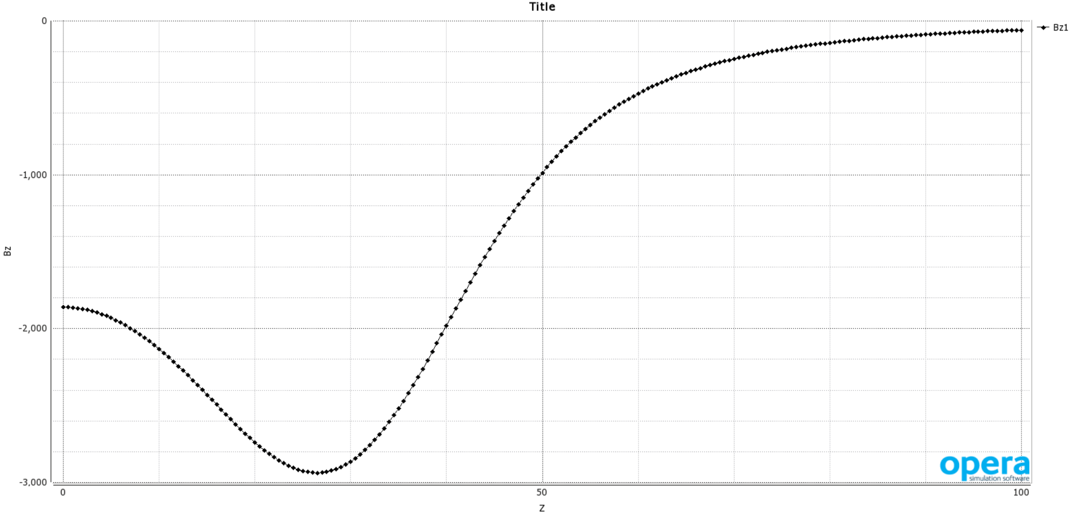


Figure 8.  Bz(z) over 1 m along Z axis, showing that field peaks ~3 kG under the coils.

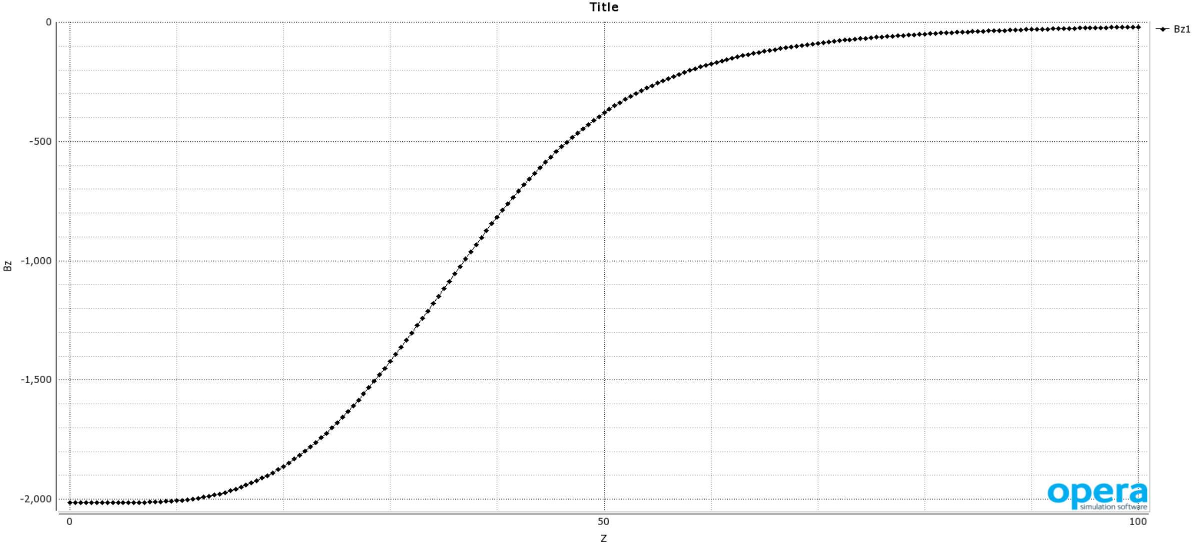


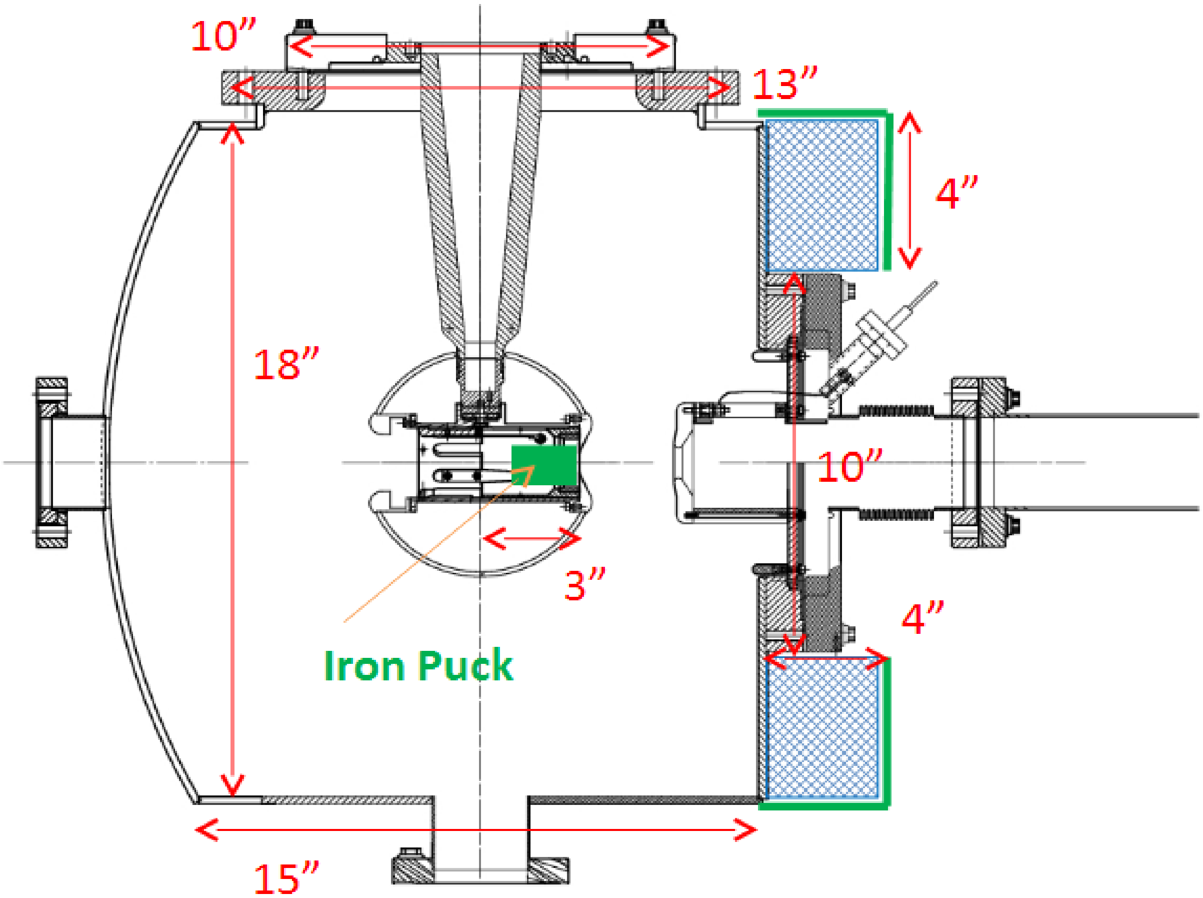
Figure 9.  Bz(z) over 1 m along Z axis for original design.  No visible bump.

## Conclusions

The conclusions on page 3 were affirmed by the alternate design. The design on pages 1-3 is best if a conventional electromagnet is to be built. Given the engineering and infrastructure cost of any such design, if a bare MRI magnet can be purchased from Paramed, that would be a lower cost and superior performance solution. If the floor won't support an electromagnet and the MRI magnet can't be purchased, a Halbach cylinder might be the way to go. DOE FES (fusion) labs might have 30-40 year old magnet coils of about the right size in storage, but finding them, especially coils which can run CW rather than pulsed, would be a challenge. Finally, the LDRD money might be returned to the Director, stating that the project cannot be completed for the estimated cost.

---

## Second addendum 12/27/2015



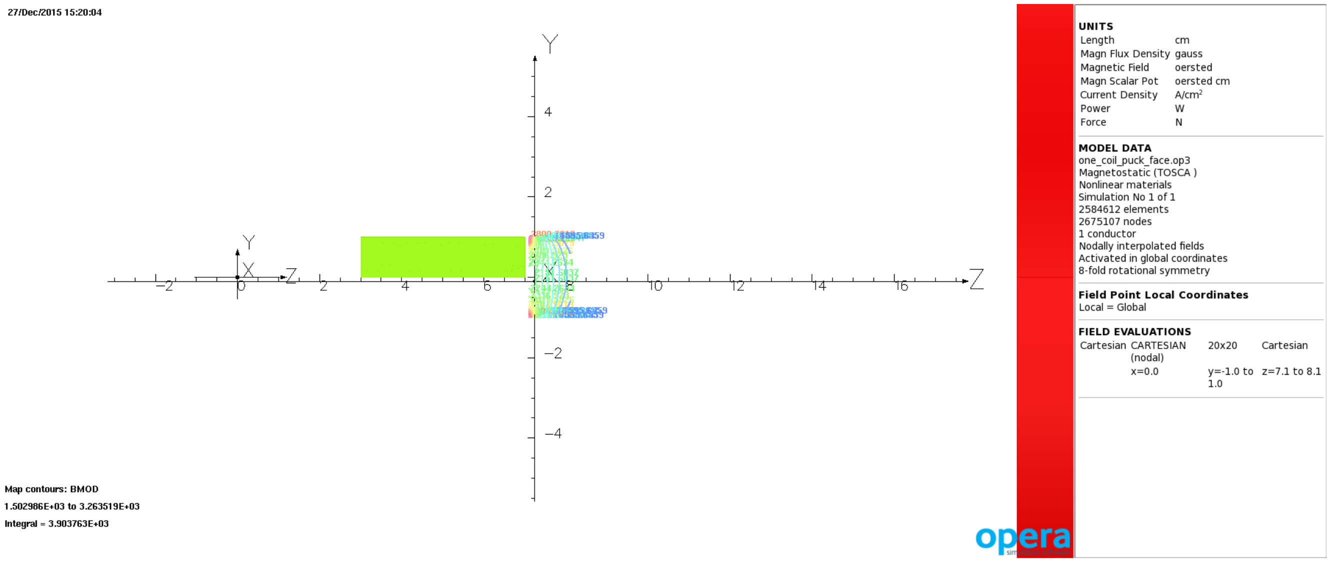
In response to the first addendum, Riad sent the sketch above, denoted figure 10, and asked that I model it. I assumed a conductor with insulation totalling 7.5 mm square, 14 turns and 14 layers, hence 10.5 cm square. Luvata has tooling for 7.0 mm square conductor with 3.5, 3.7, 4, 4.3, 4.5 and 5 mm round holes. It also has tooling for 7.1 mm square with either 4 mm or 4.5 mm round holes. One of these should work for cooling even through the double pancakes would be about 32 m in length.

The design shown above will not work. The fields at the surface of the steel will have too large a gradient. Based on experience, I used a 5 mm gap between steel and cathode location. The steel puck I modeled is 2 cm in diameter and 4 cm long, extending over Z=[3,7] cm. Cathode is taken as Z=7.5 cm.

I first meshed the steel with tetrahedra with 5 mm maximum size. I also meshed a 4 cm diameter by 120 cm long air volume along the Z axis with the same mesh. Outside that, including the coil, 2 cm for the first meter and 25 cm for the next five meters, to get down to a low field at the boundary given no iron shielding for the coil. Boundary field ~ 40 mG, so low enough not to affect the region I care about when it's forced to zero by Opera. This first model allowed me to adjust the amp-turns to get ~ 1 kG at the cathode without the steel and ~2 kG with it. 74970 AT, or 382.5A in 196 turns. Had I used a larger conductor, as in the model on pages 1-3, the current would have been much higher. Water cooling connections have to be on the OD of the coil since the flange is on the ID, so one has to have one water circuit per double pancake. A duplicate of the new dogleg supply would suffice and could become the spare which wasn't purchased by Ops.

After finding the proper AT, I used the face meshing option in Opera. I meshed the face of the steel at Z=7 with 1 mm triangles and had Opera copy this five times outside the face at 2 mm intervals. This provided 1 cm of fine mesh without a lot of effort on my part or too many extra elements. The figures below come from models with this refined mesh.

For the request to model with and without the steel puck, I used the same mesh but set the magnetic characteristics of the puck to those of air. It still shows green in the models so the cathode can be located, but has no effect on the field.



**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**
one_coil_puck_face.op3
Magnetostatic (TOSCA )
Nonlinear materials
Simulation No 1 of 1
2584612 elements
2675107 nodes
1 conductor
Nodally interpolated fields
Activated in global coordinates
8-fold rotational symmetry

**Field Point Local Coordinates**
Local = Global

**FIELD EVALUATIONS**

| | | | |
|---|---|---|---|
| Cartesian | CARTESIAN (nodal) | 20x20 | Cartesian |
| | x=0.0 | y=-1.0 to 1.0 | z=7.1 to 8.1 |

Figure 11 shows field lines in the vicinity of the puck (rotational symmetry used, not all the iron shows), and its location with respect to the 10.5 cm square coil.

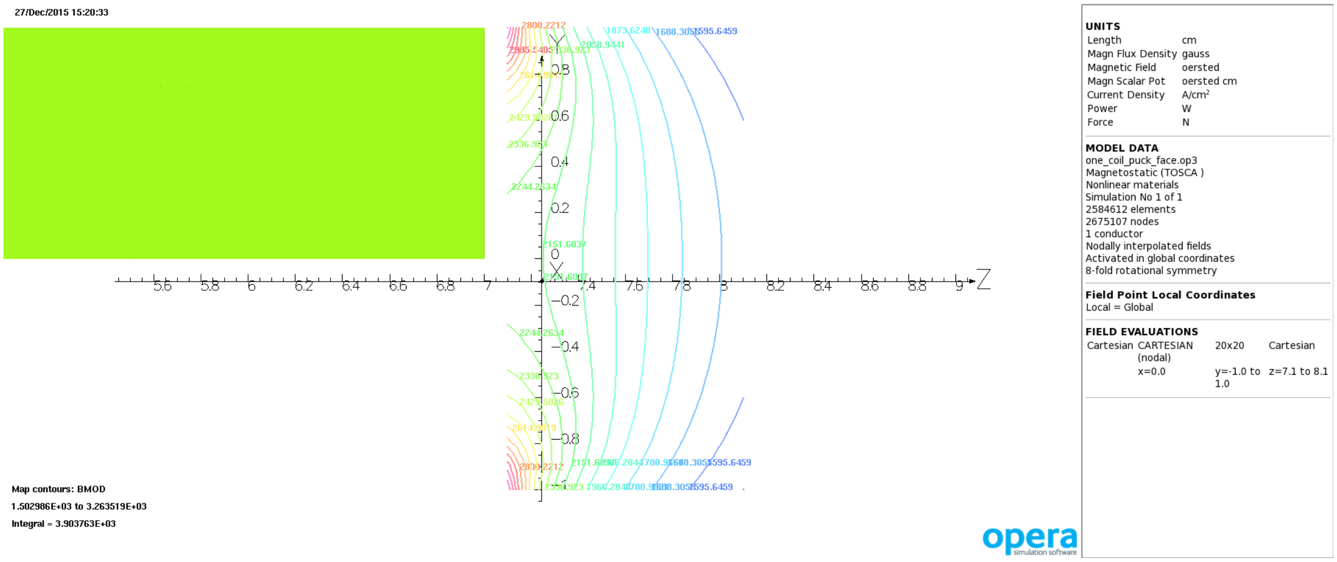


Figure 12 shows the field lines near the puck in close-up

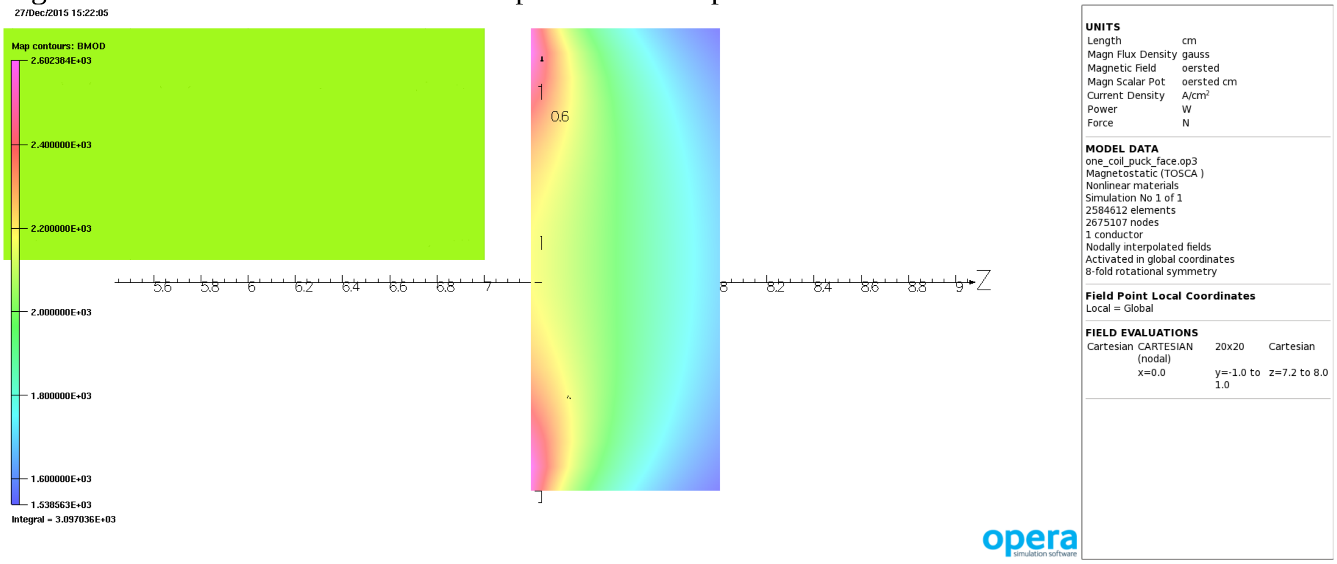


Figure 13 shows a zone map of the field with color scale that's easier to read than the labels on the lines

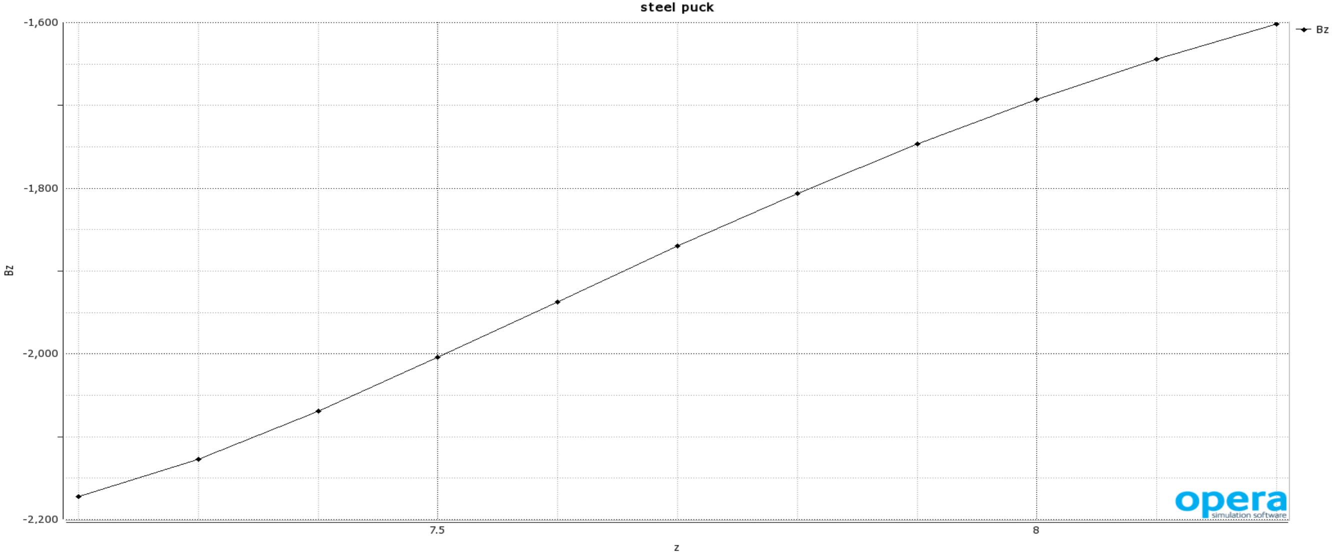
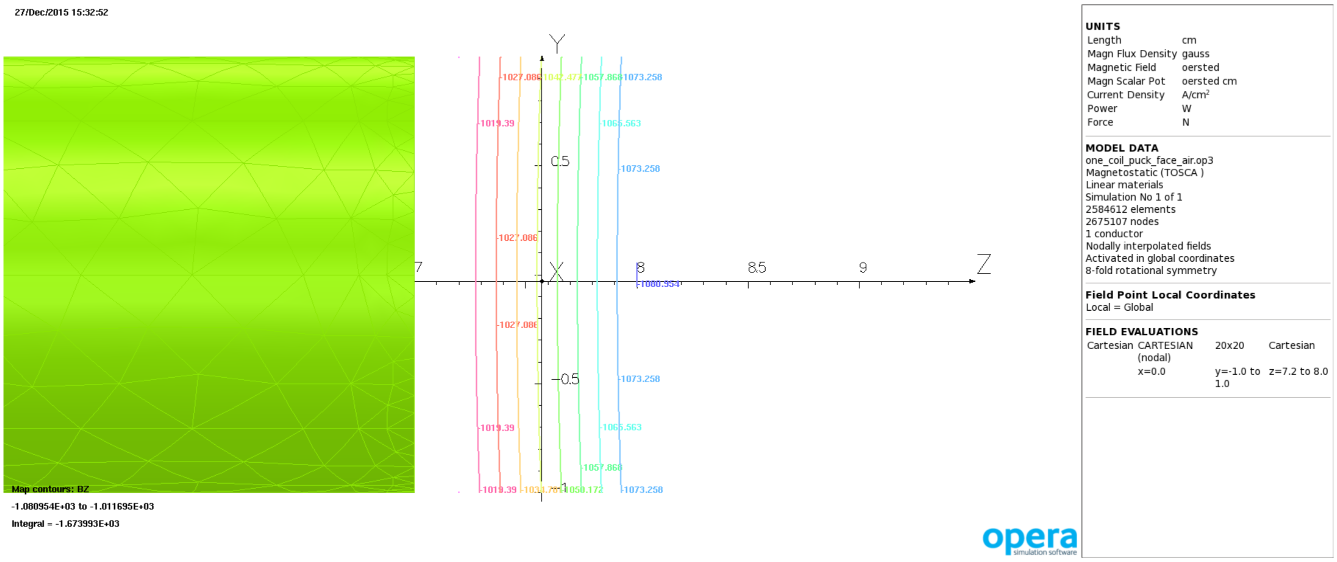


Figure 14 gives Bz(Z) over z=[7.2,8.2] cm on axis. Vertical axis span 600 G over the cm in Z. Just over 2 kG at z=7.5, my assumed cathode location.



**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**
one_coil_puck_face_air.op3
Magnetostatic (TOSCA )
Linear materials
Simulation No 1 of 1
2584612 elements
2675107 nodes
1 conductor
Nodally interpolated fields
Activated in global coordinates
8-fold rotational symmetry

**Field Point Local Coordinates**
Local = Global

**FIELD EVALUATIONS**

| | | | |
|---|---|---|---|
| Cartesian | CARTESIAN (nodal) | 20x20 | Cartesian |
| | x=0.0 | y=-1.0 to 1.0 | z=7.2 to 8.0 |

Figure 15 is a line map of field with the puck non-magnetic. About 1 kG with same current as above. I had Opera plot without assuming cylindrical symmetry here so one sees the full puck, unlike figures above.

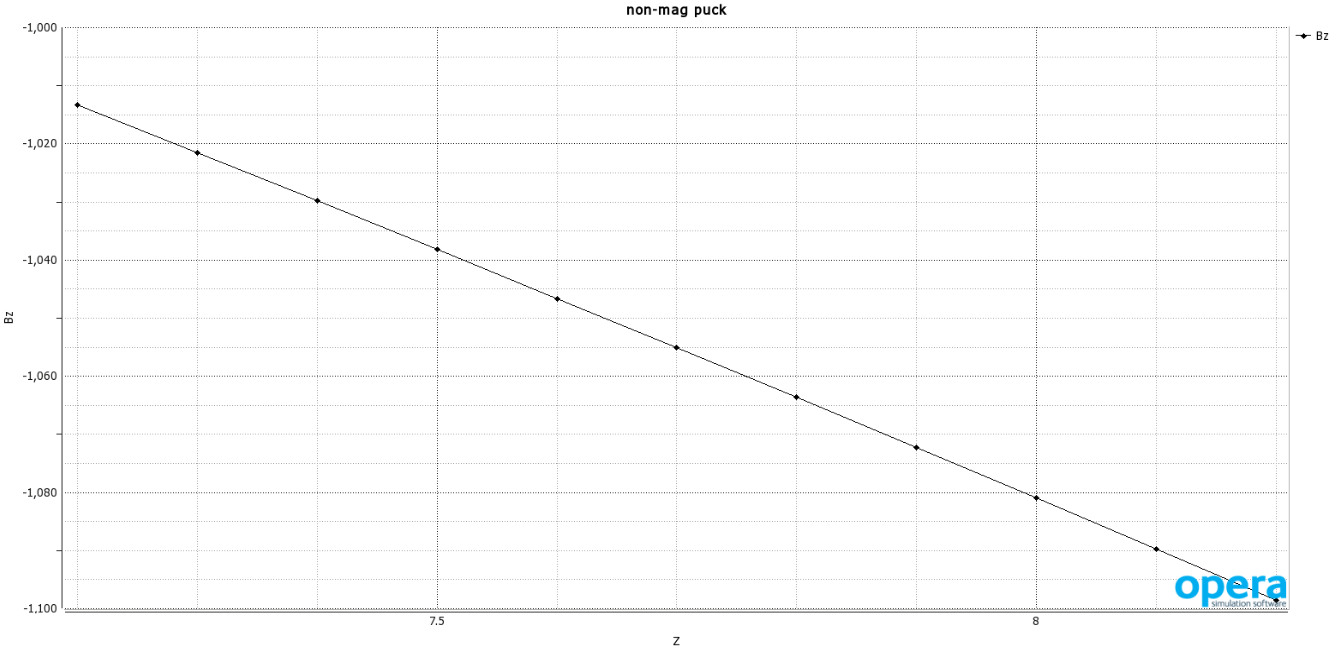


Figure 16. Bz(z) over z=[7.2, 8.2] for non-magnetic puck. Vertical axis span now 100 G. ~1038 G at z=7.5 cm with the same current density as in figures 11-14.

## Conclusions the third

If field uniformity and stray field matter, go with the design on pages 1-3. If field uniformity and stray field don't matter, go with the single coil approach, with or without the magnetic puck. In the last case, figure 12 shows the field is flattest at z=7.55 cm, 0.55 cm from the steel, so one must have a non-magnetic interface between steel puck and cathode crystal.