TRIUMF Experiment E614
Technical Note
3-D Magnetic Field Calculations of the E614 Magnet - Part II

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Abstract

Additional questions about the effect of design changes on the E614 magnet are addressed by magnetic field calculations using OPERA-3D. It was found that there is little difference between 1010 steel and 1020 steel. Body forces on the coils were calculated and found to be within the manufacturer's limits provided the coils can be positioned to ± 0.2 cm. However the coils must be positioned to ± 0.05 cm to keep field asymmetries small. Cutting a hole in the bottom of the yoke to balance the cryogenic port at the top balances the y force on the coils and increases field symmetry. Reinforcing rods in the floor of M13 affect the field in the region of the beam holes but not in the region of the drift chambers. Reducing the radius of the beam entry hole from 20 to 10 cm reduces the width of the radial field distribution in that region by half. Optical positioning holes in the yoke doors do not affect either the central field or the radial feild around the beam entry hole.

1 Introduction

Calculations of the magnetic field in the E614 detector have been performed in three dimensions using OPERA-3D [1]. Details of the magnet/yoke design and the resulting fields are given in Technical Note 40 [2]. Additional design questions are addressed here and include:

- is there a difference between 1010 and 1020 steel?

- what are the forces on the coils ?

- should another hole be cut in the yoke to balance the coil forces ?

- do reinforcing rods in the floor affect the field ?

- will a smaller beam entry hole narrow the radial field distribution ?

- do optical positioning holes in the doors of the yoke affect the field ?

Coil pair	z (cm)	F_y (N)	F_z (N)
1	-76.695	-1704	2009789
2	-33.230	-436	351222
3	-10.315	-330	968
4	10.315	-330	-968
5	33.230	-436	-351222
6	76.695	-1704	-2009789
Net force		-4940	0

Table 1: Force in Newtons on the six coil pairs situated in the E614 yoke with a cryogenic services opening in the top. F_x is 0 (within $\pm$ 1 N) in all cases. z values give the location of the coil centers relative to the center of the yoke.

2 1010 Steel vs. 1020 Steel

Previous field calculations were performed with a B-H curve for 1020 steel, however the yoke will be now be constructed of 1010 steel. Using the same finite element mesh, field calculations were performed with both B-H curves with the result that no significant differences, either in field uniformity or magnitude, were observed between the two. All subsequent calculations in this report were carried out assuming 1010 steel.

3 Forces on Coils

The cryogenics opening at the top of the yoke introduces an asymmetry in the field which in turn produces a net force on the coil assembly. According to the manufacturer [3] net forces in any direction should not exceed one ton. In order to check this the net forces on the 6 coil-pairs in the E614 magnet were calculated and are shown in Table 1.

As expected the net sideways force (F_x) is zero. The net downward force (F_y) is 4940 N or 1113 lbs. which is well within the one-ton limit. The net force along the beam axis (F_z) is zero, although the compressive forces on four of the six coil-pairs are very large. As a check the coil forces were also calculated without a yoke. In this case the compressive forces were unchanged and the downward forces disappeared.

While coil forces in a slightly asymmetric field may be acceptable if the coils are exactly centered in the yoke, a small displacement may cause such forces to increase. The forces were re-calculated for coil displacements of -0.5, 0, +0.1, and 0.5 cm in y. The net downward force on the coils is shown for each case in Table 2. The force is linear in the y displacement and exceeds the one-ton limit for a downward displacement of 0.5 cm. Hence the coils must be placed to within $\pm$ 0.2 cm to safely avoid high forces.

The results of similar calculations, performed for displacements in x and z, are shown in Tables 3 and 4, respectively. The forces F_x are linear in the x displacement of the coils but because there is no field asymmetry in the x direction, the forces do not approach the

Coil displacement (y) (cm)	F_y (N)
-0.5	-9443
0.0	-4941
0.1	-4046
0.5	-438

Table 2: Net downward force in Newtons on full coil assembly as a function of coil displacement in y.

Coil displacement (x) (cm)	F_x (N)
-0.1	-908
0.0	0
0.5	4578

Table 3: Net sideways force in Newtons on full coil assembly as a function of coil displacement in x.

one-ton limit for any of the calculated displacements. Similarly, the forces F_z are linear in the z displacement of the coils and, while larger for a given displacement, do not approach the one-ton limit.

Another consideration is the effect of coil displacements on the field quality. For all of the above displacements in x and y the field uniformity in the region of the drift chambers is unaffected to any significant degree. This is not true for the radial field in the beam entry/exit holes. Fig. 1 shows the radial field 1 cm from the z axis when the coil assembly has been displaced 0.5 cm upward. The effect is large, especially in the region $70 < z < 130$ cm. For a 1 mm displacement Fig. 2 shows a smaller, but still significant, effect. In order to reduce the size of this asymmetry to 5 gauss or less, it will be necessary to position the coils to $\pm$ 0.5 mm.

When the coils are displaced in z the radial field in the region of either beam hole is unaffected. When the coils are displaced 1 mm there is a small upstream-downstream asymmetry in the B_z field in the drift chamber region as shown in Fig. 3. The maximum size of the asymmetry is 1 gauss which is at or below the precision of a possible field measurement. The error in coil position in the z direction should therefore be kept to 1 mm or less.

Coil displacement (z) (cm)	F_z (N)
-0.5	-7529
0.0	0
0.1	1505

Table 4: Net force along z in Newtons on full coil assembly as a function of coil displacement in z.

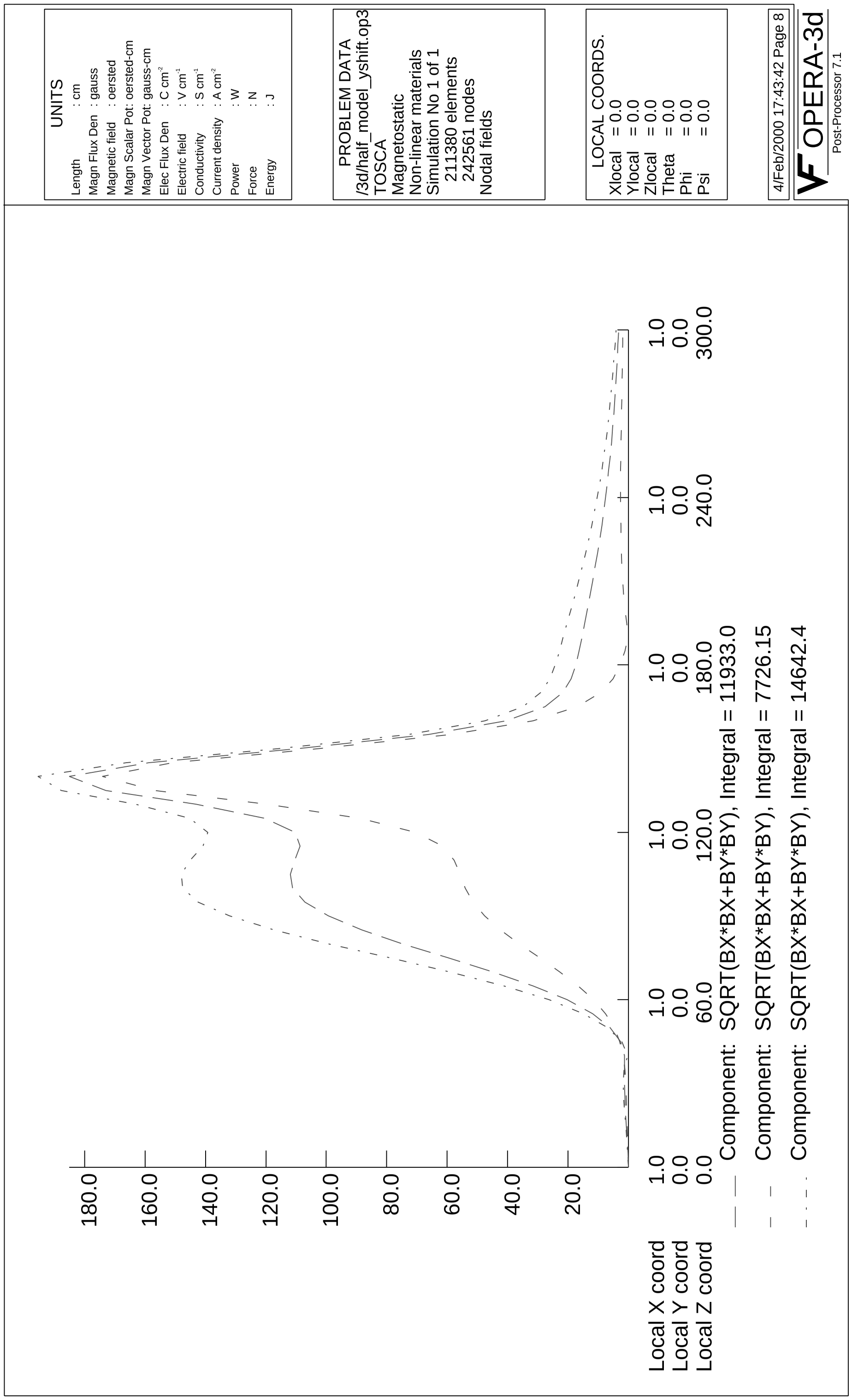

Figure 1: Effect of coil assembly shifted +0.5 cm in y. B_r is calculated on a line parallel to and 1 cm from the z axis. Top curve: $y = -1, x = 0$ cm. Middle curve: $y = 0, x = +1$ cm. Bottom curve: $y = +1, x = 0$ cm.

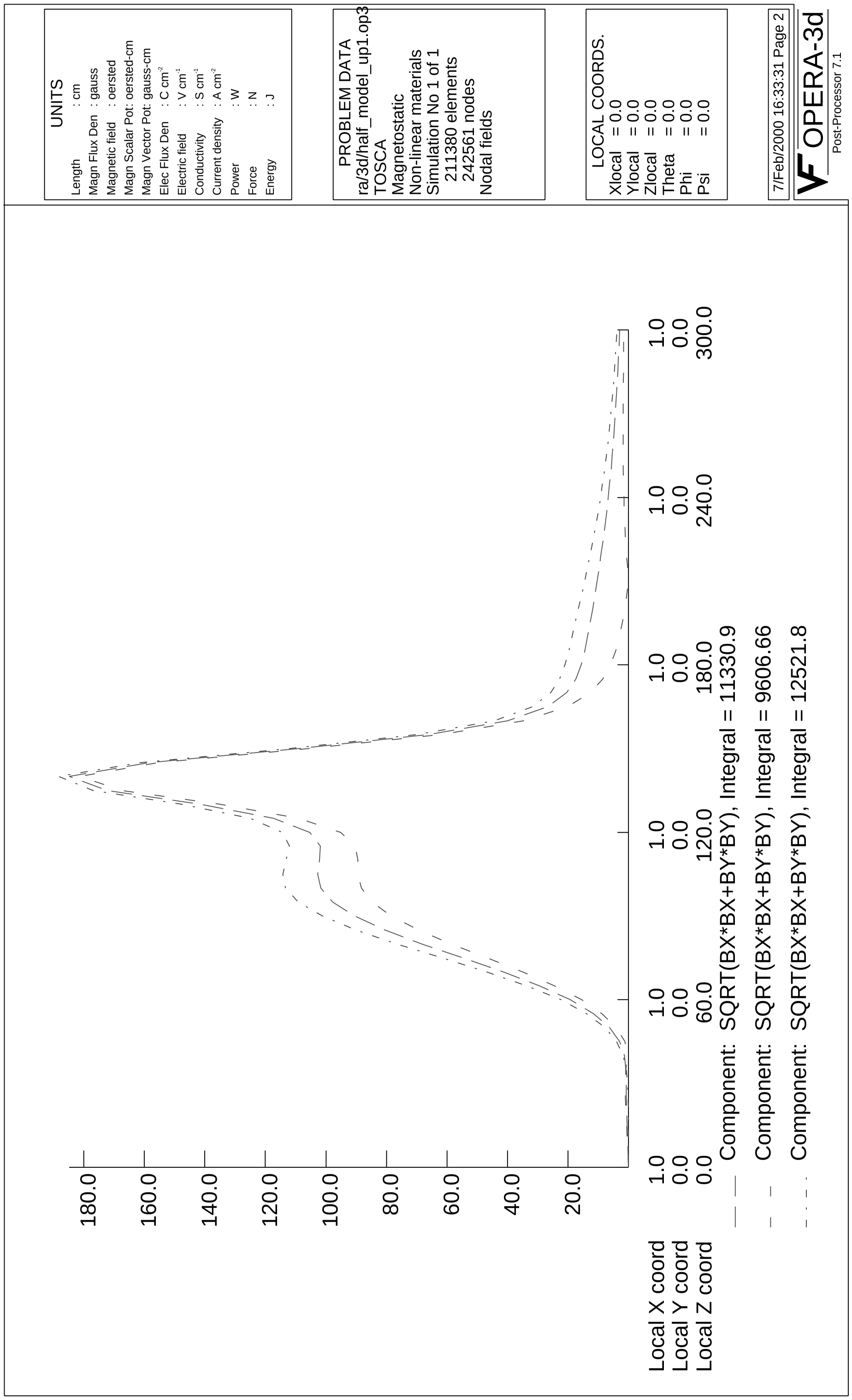

Figure 2: Effect of coil assembly shifted +0.1 cm in y. B_r is calculated on a line parallel to and 1 cm from the z axis. Top curve: $y = -1, x = 0$ cm. Middle curve: $y = 0, x = +1$ cm. Bottom curve: $y = +1, x = 0$ cm.

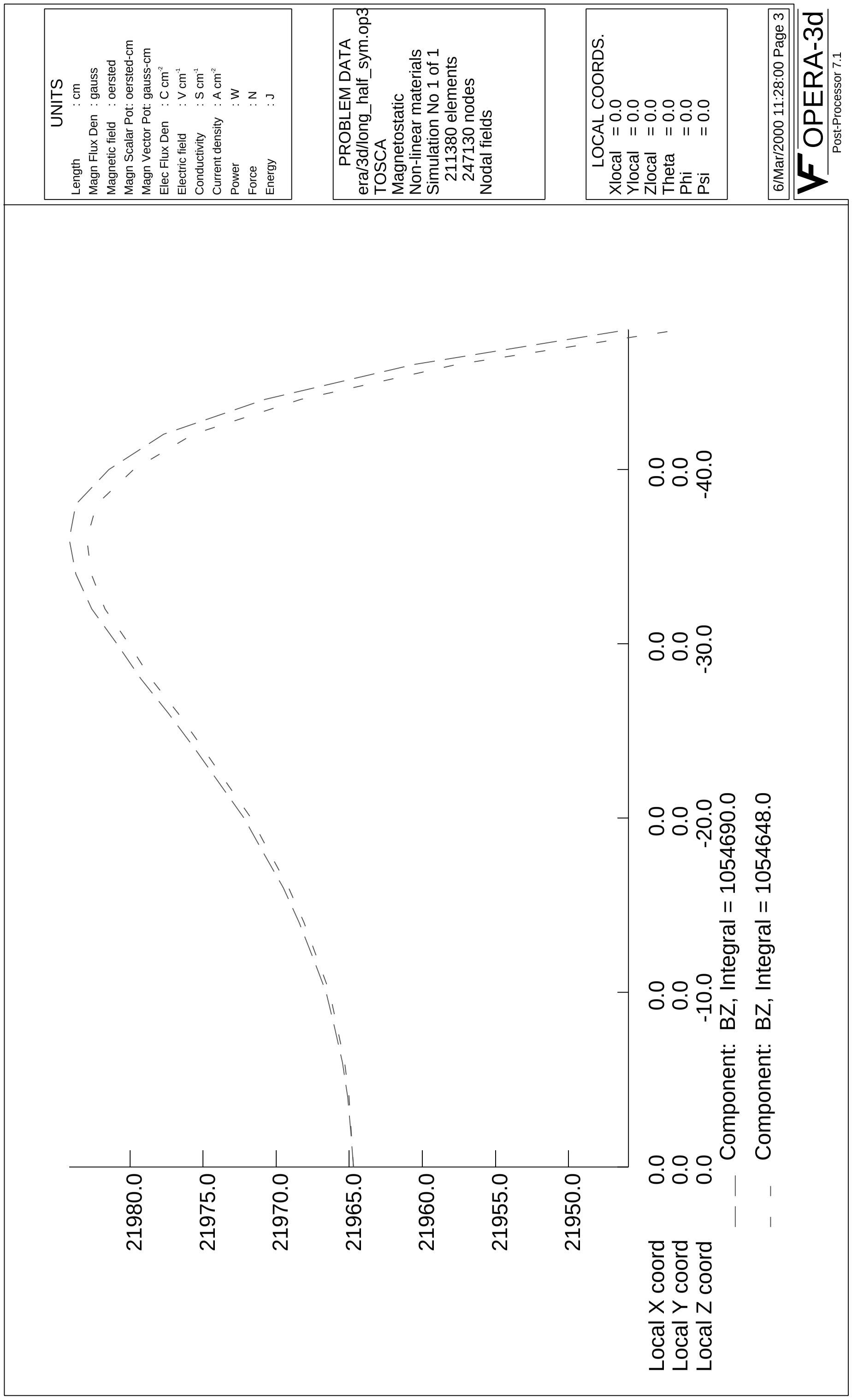

Figure 3: Effect on B_z of -1 mm shift in z of coil assembly. Top curve: B_z along z axis for $-48 < z < 0$ cm. Bottom curve: B_z along z axis for $0 < z < 48$ cm.

4 Effect of a Hole in the Bottom of the Yoke

As indicated in the previous section, the coil forces do not exceed the manufacturer's limit, provided the coils are well positioned. However the net downward force can be eliminated if a hole identical to the cryogenics port is cut in the bottom of the yoke. This would increase the safety margin with respect to unknown position shifts of the coil.

In order to study the effect on the field, the model was changed by placing a hole in the bottom of the yoke at the same position as the one in the top. The extra steel bars, placed around the top hole to take up flux, were removed. The resulting field in the detector region was very symmetric and was sampled over a circular path of radius 16 cm in the $x-y$ plane, centered on the z axis at $z = 15$ cm. The B_z field varied by only a fraction of a gauss over the entire path. There is no up-down asymmetry in B_r in the region of the beam holes as long as the coils are well-positioned. When the coils are shifted by 0.1 cm in y an asymmetry appears as shown in Fig. 4. Comparing Figs. 2 and 4, it is clear that the asymmetry for a given coil displacement is smaller when there is a balancing hole in the bottom of the yoke.

5 Steel Reinforcing Rod in M13 Floor

Blueprints of the floor in the M13 area indicate a large amount of steel in the form of reinforcing rods beginning 1.9 cm beneath the surface of the concrete and extending to a depth of 27.4 cm. The rods are 1.79 cm and 1.61 cm in radius and are spaced at 6 inch (15.24 cm) and 9 inch (22.86 cm) intervals. This amount of steel may be sufficient to affect the field in and around the magnet. The effect of buried steel was studied by adding reinforcing rods in approximately the correct amount and distribution to the model, but only down to a depth of 15.5 cm. Limitations in the Opera software make it very difficult to model the rods exactly, and the small cross section of the rods compared to the size of all other facets in the model reduce the precision of the calculated field. Hence it is best to view the resulting field outside the magnet yoke as an underestimate.

The distribution of reinforcing rods in the model is shown in Fig. 5. The resulting field in the region of the drift chambers shows no effect whatsoever due to the rods. This is true whether or not an additional hole is cut in the bottom of the yoke to balance the cryogenic port. However the radial field in the beam hole region is affected. Fig. 6 shows an up-down asymmetry of about 20 gauss outside the yoke. In the beam hole itself and further inside the yoke this asymmetry vanishes. The magnitude of the asymmetry at any point along the beamline outside the yoke is not large but it is nearly constant out to at least 4 meters. It may therefore pose a significant problem for the incoming muon beam and its polarization. A good prediction of the field at the 20 gauss level will require that all other steel masses in the vicinity be modeled. However, irregular shapes and orientations will make modeling even more difficult. In this case the best approach may be to measure the fields directly and correct them by adding steel in various places.

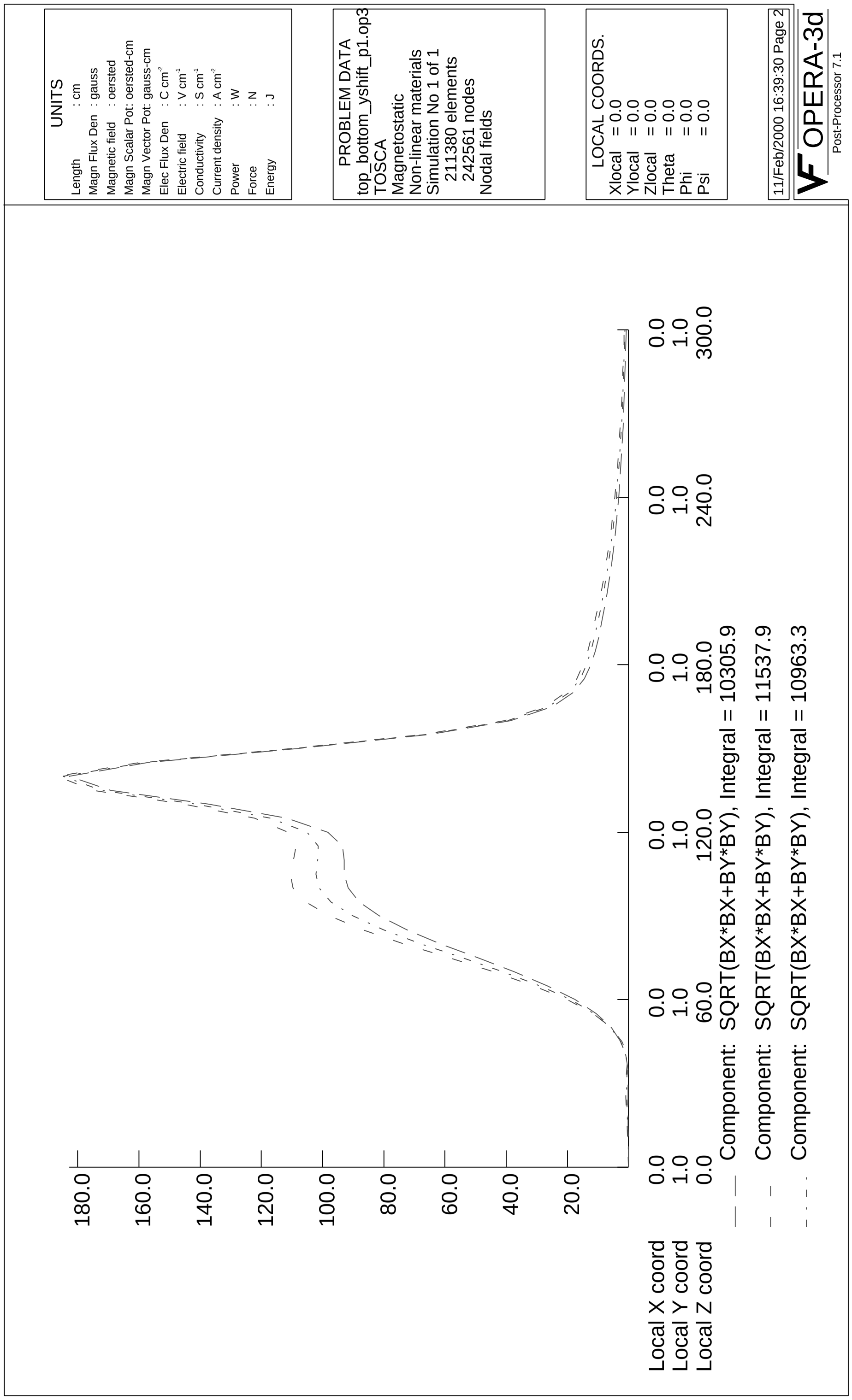

Figure 4: B_r field from yoke with cryogenic port at the top and a mirror image of the port at the bottom. The coil assembly has been shifted +0.1 cm in y. B_r is calculated on a line parallel to and 1 cm from the z axis. Top curve: $y = -1, x = 0$ cm. Middle curve: $y = 0, x = +1$ cm. Bottom curve: $y = +1, x = 0$ cm.

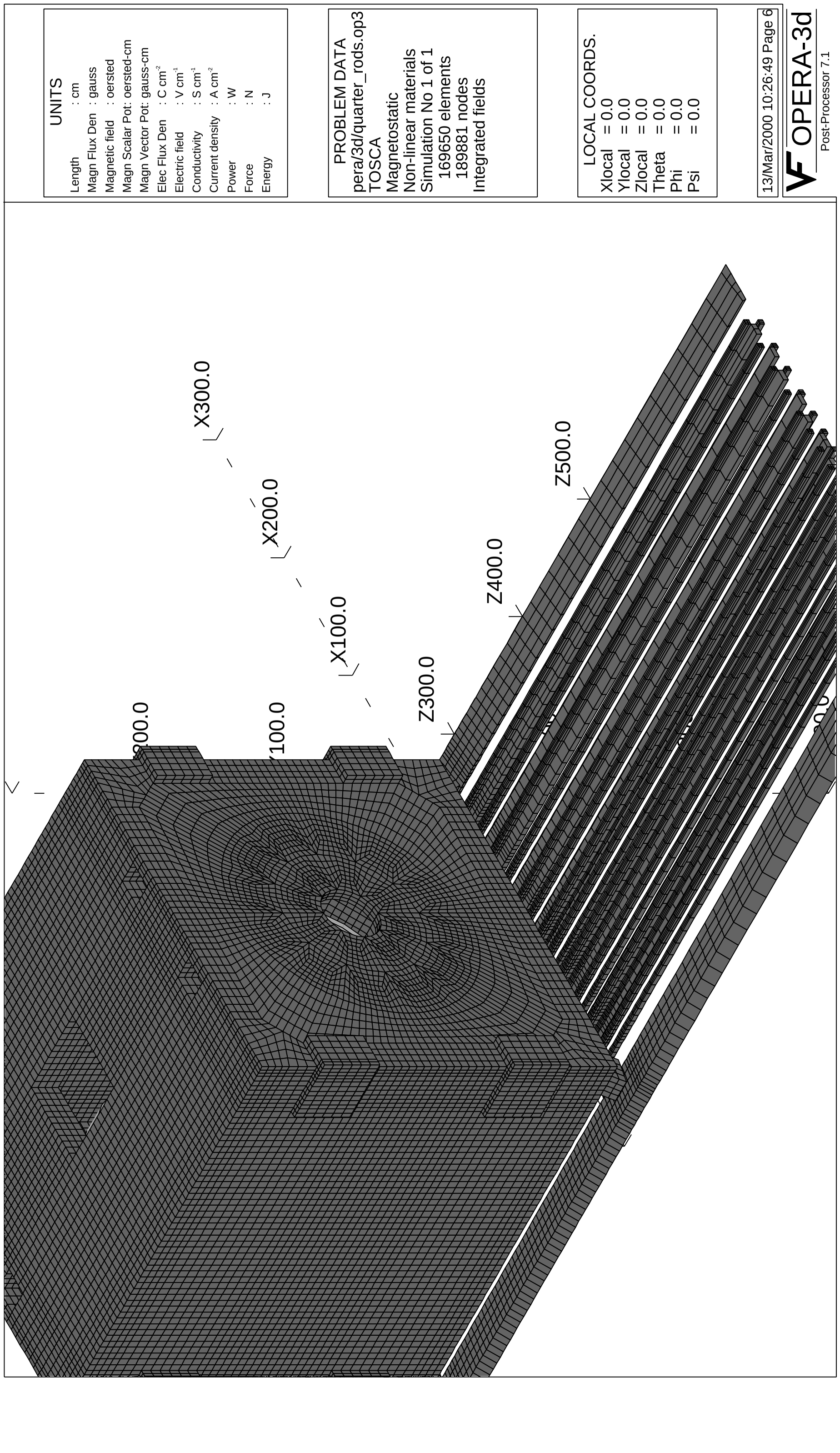

Figure 5: Steel distribution in the model used to calculate the effect of reinforcing rods in the M13 floor.

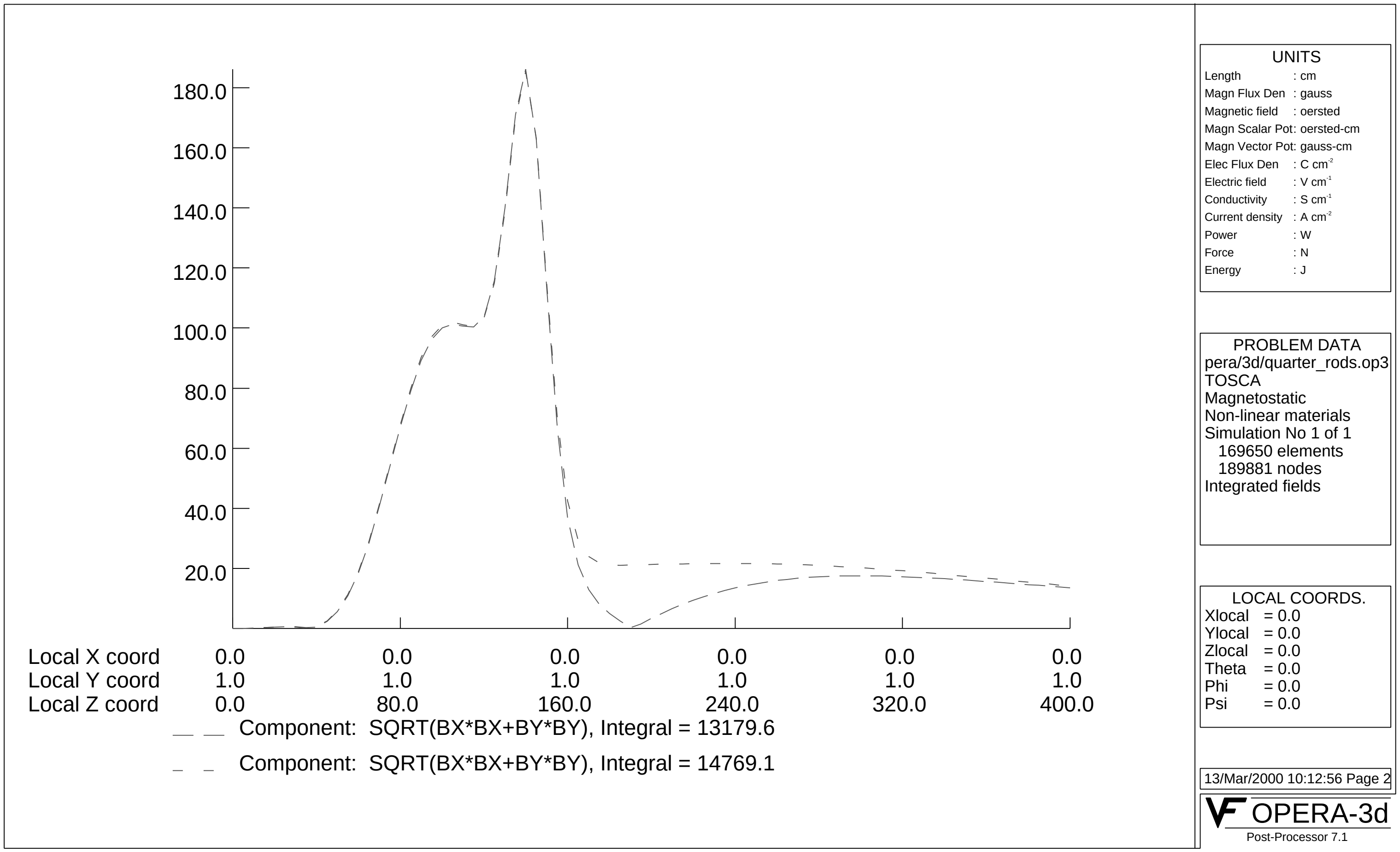

Figure 6: B_r field due to yoke and reinforcing rod in M13 floor. B_r was calculated on lines parallel to and 1 cm from the z axis. Bottom curve: $y = 1, x = 0$ cm. Top curve: $y = -1, x = 0$ cm.

6 Effect of 10 cm radius Beam Entry Hole

The standard yoke design of Ref. [2] had a beam entry hole of radius 20 cm. Reducing this radius may reduce the extent of the fringe field which in turn could reduce the muon depolarization. The new field was calculated with a hole radius of 10 cm and compared to the 20 cm case. The radial field B_r is shown for both cases in Fig. 7. With a radius of 10 cm the field in the beam hole (large peak) is twice as intense and roughly half the width of the field obtained with a 20 cm radius. The lower and broader peak, centered at $z = 100$ cm is due to radial field lines which pass between the end of the last coil and the inner face of the yoke. The size and shape of this peak is the same for both radii. The field uniformity in the detector region is unaffected by this change. Fig. 8 shows that B_z in the region $0 < z < 50$ cm is nearly identical for both radii except that the field from a 10 cm radius hole is 5 gauss larger at all points.

7 Effect of Optical Positioning Holes

The laser-pinhole-CCD system [4] used to position the detector package within the magnet yoke requires six holes of radius 2.54 cm in both the upstream and downstream faces of the yoke box. These holes will be placed at 60 degree intervals with their centers located between 40 and 50 cm from the beam axis, depending on the final detector cradle design. In order to simulate the effect of the holes on the field, the magnet model referred to in Ref. [2] was modified by replacing six facets in the steel endplate with air. The facets were not circular but nearly rectangular with cross sections of 5 cm $\times$ 6.2 cm, or about 53% larger than the desired circular holes. The air facets were placed at 60 degree intervals at a radius of 47.5 cm from the beam axis.

The resulting field calculations were compared to those made with no holes in the endplate (other than the beam hole) with primary attention given to the field in the drift chamber volume and in the region surrounding the beam hole. In the drift chamber region the azimuthal dependences in B_z were indentical showing no effect from the extra holes. The holes did however reduce the magnitude of B_z by about 4 gauss out of 22014. In the region of the beam hole there was no difference between the two models in the azimuthal dependence of B_z or B_r. The extra holes caused a 0.7% increase in B_z for $(r, z) = (5, 147)$ cm and a 1.4% decrease in B_r at the same point. At points further from the beam hole the effect was smaller and in some cases the sign of the effect was reversed.

8 Conclusions

Additional Opera-3D calculations showed that the magnet coils must be positioned as a unit to within $\pm$ 0.5 mm in x and y and to $\pm$ 1 mm in z to maintain field symmetry. Within these limits forces on the coils are small. A hole should be cut in the bottom of the yoke which is a mirror image of the cryogenics port at the top of the yoke. This improves field

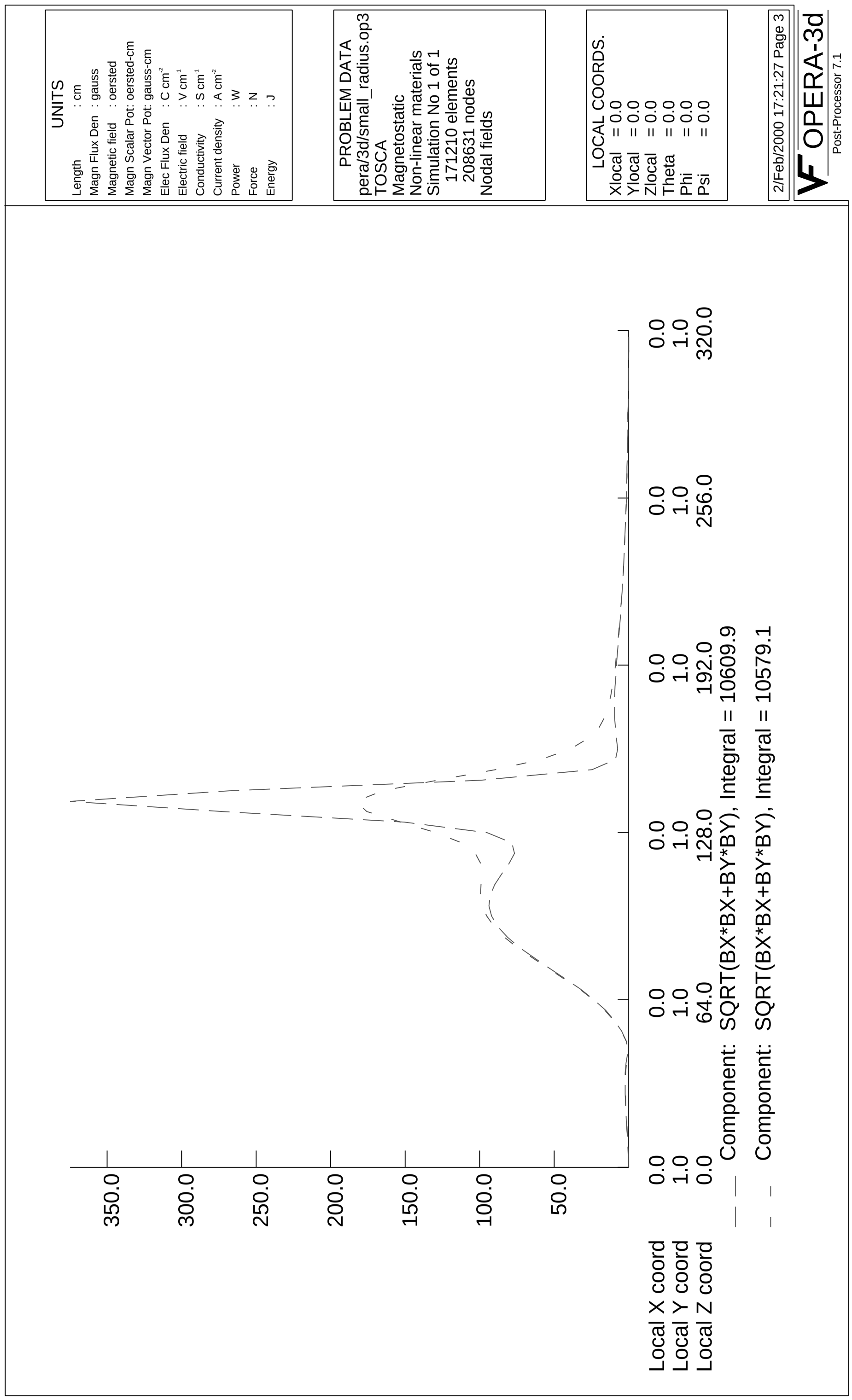

Figure 7: B_r on a line 1 cm above and parallel to the z-axis. The long-dashed curve is the field due to a 10 cm radius beam hole. The short-dashed curve is the field due to a 20 cm radius beam hole.

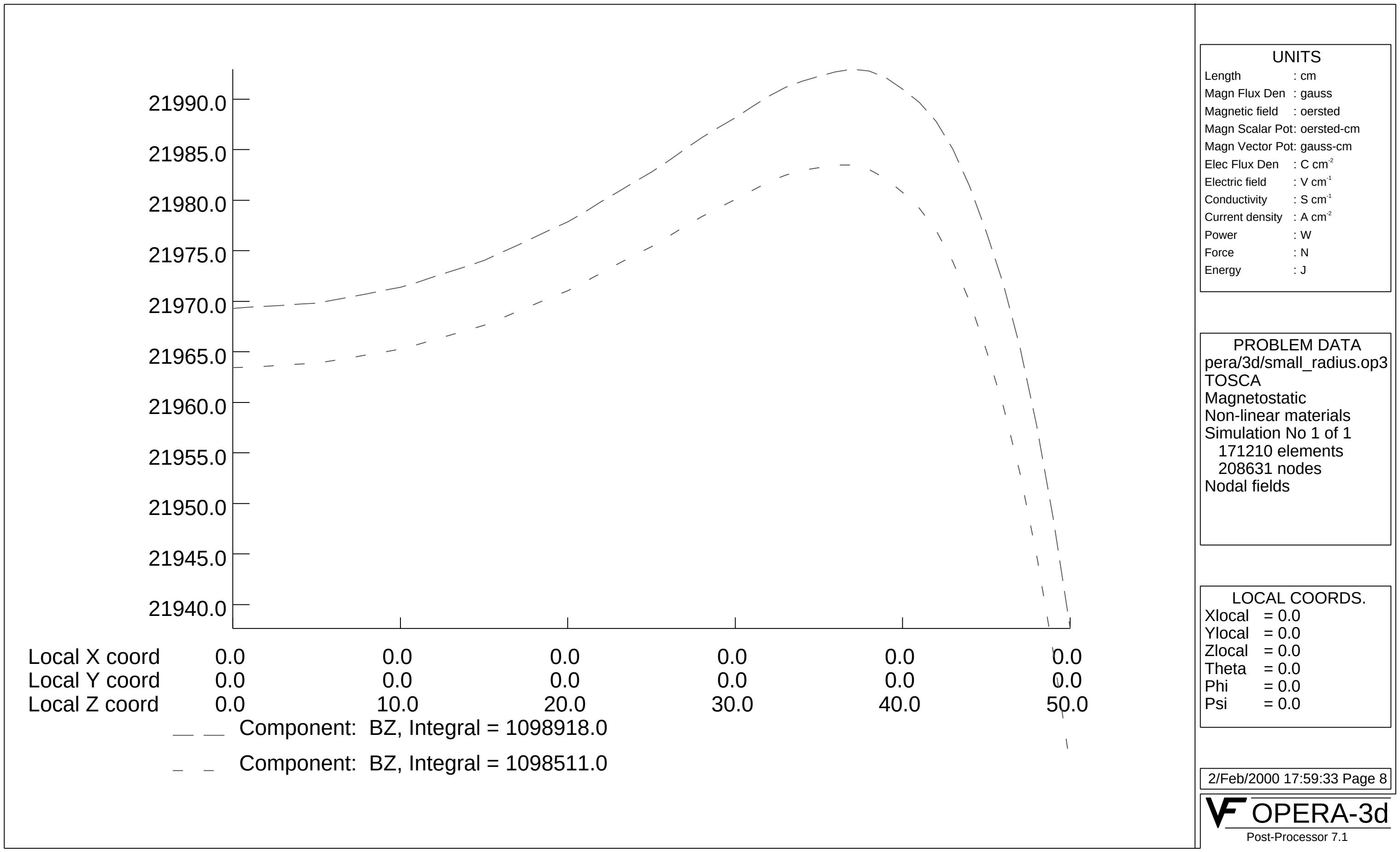

Figure 8: B_z calculated along the z axis. Top curve: 10 cm beam hole radius. Bottom curve: 20 cm beam hole radius.

uniformity and more importantly reduces downward forces on the coils. Reinforcing rods in the M13 floor have no effect on the field inside the yoke but the radial field outside the yoke and along the beam line shows a significant asymmetry which is difficult to calculate. Ultimately this field should be measured directly and corrected by adding steel at various places along the beam line. The radius of the beam hole should be decreased from 20 cm to 10 cm. This narrows the radial field distribution in the region of the beam hole and will decrease beam depolarization. Finally it was found that placing six optical positioning holes in the upstream and downstream faces of the yoke will not affect the field either in the drift chamber region or in the beam hole region.

References

[1] OPERA-3D, V7.1, Vector Fields Co., 2000.

[2] D.H. Wright, E614 Technical Note 40, 2000.

[3] F. Davies, Oxford Magnet Technology Ltd., private communication to D. Gill, 2000.

[4] P. Kitching, E614 Technical Note 27, 1999.