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

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Abstract

The three dimensional magnetic field for the downstream half of the E614 magnet coils and yoke was calculated using OPERA-3D. Earlier results indicating that a square cross section yoke produced a cylindrically symmetric field near the drift chambers were confirmed. Construction details such as access ports, hinges and braces were added to the model and their effects studied. The addition of a steel shim at the beam entrance to the yoke was found to narrow the radial field distribution in that region at the expense of greater non-uniformity in the drift chamber region. Recommendations are made for the placement of ports and extra steel which will remove some asymmetries in the field.

1 Introduction

Calculations of the magnetic field in the E614 detector have already been performed in two and three dimensions. A summary of these studies and the design decisions derived from them are given in E614 Technical Note 37 [1]. In the 2-D case the return yoke was assumed to be cylindrical and in the 3-D case only 1/8 of the total volume was solved. Because access ports or steel attachments to the yoke may potentially disrupt the symmetry of the field and because it is not always be wise to cut holes or add steel solely for the sake of symmetry, 3-D calculations are required for the entire downstream half of the detector. Questions which must be answered before construction begins are:

- does a square cross section yoke introduce azimuthal asymmetries in the beam entry hole and the chamber region of the detector which would be absent in a cylindrical yoke?

- do the cryogenic port and electronics cable access ports in the top of the yoke introduce up-down asymmetries, and if so, can they be reduced or removed ?

- do the magnet door hinges or blocks of iron near the cryogenic services port have an effect?

- can the radial field distribution at the beam entry hole be made narrower by the addition of a steel shim around the hole?

These questions were answered using the OPERA-3D finite element code [2].

2 Details of the Model

The downstream half of the magnet was modeled, assuming symmetry about the plane $z = 0$. The details included in the finite element mesh are listed here. The magnet yoke consists of 1020 steel and has the following outside dimensions: half-length(along z axis) = 148.0 cm, width = height = 261.0 cm. The walls (top, bottom ($\pm y$) and sides ($\pm x$) are 20 cm thick with solid triangular steel braces running along each of the four corners. The magnet door is 8 cm thick with a 20 cm radius beam hole centered on the z axis. The door occupies the space between $z = 140$ and $z = 148$ cm. In the center of the top face of the yoke is a cryogenic services port with a half-length (along z) of 30.48 cm and a width of 61 cm. On either side of this port is a solid block of steel which is intended to take up some of the return flux which was expelled by the hole. Immediately upstream of the magnet door, in the top face of the yoke is an access hole for electronics cables. The hole extends from 130 to 140 cm in z and from -30.5 to 30.5 cm in x. Near each of the four corners of the magnet door is placed a steel hinge. The hinges on the right-hand side of the door are functional while those on the left are merely pieces of steel added to maintain field symmetry. More details of the steel yoke can be found in TN37 [1] .

Inside the yoke is a set of six current-carrying coils, three upstream and three downstream. The current density has been adjusted to give approximately 2.2T at the center of the detector. The yoke and coils are displayed in Fig. 1 along with the external facets of the finite element mesh.

Not shown in the figure is the volume of air that must also be meshed and assigned boundary conditions in order to obtain a solution for the fields. It extends from $z = 0$ to $z = 550$cm, $x = -250$ to $x = 250$ cm, and $y = -250$ to $y = 250$ cm.

3 Field Symmetry

Using the above model the first of the above questions was addressed. A contour plot of B_z in the plane $z = 0$ (Fig.2) shows a positive flux along the z-axis near the center of the magnet and a negative flux returning through the yoke. The flux avoids the hole of the cryogenic services port, as expected, but it does not enter the steel bars on either side of the port. This may indicate that the bars do not improve field symmetry. Fig. 3 shows a contour plot of B_z in the $y - z$ plane in the region of the drift chambers. The field in this region is very uniform and symmetric despite the obvious asymmetry observed near the cryogenics port in the yoke. A more complete view of the field asymmetry is given in Fig. 4 where B_z is plotted along a circle in the $x - y$ plane with radius 16 cm, centered at $x = 0, y = 0, z = 15$ cm. The maximum up-down asymmetry in the chamber region is seen to be about 1.3 gauss or 0.006%. This is compared to an expected error on the field mapping measurements of 1 gauss.

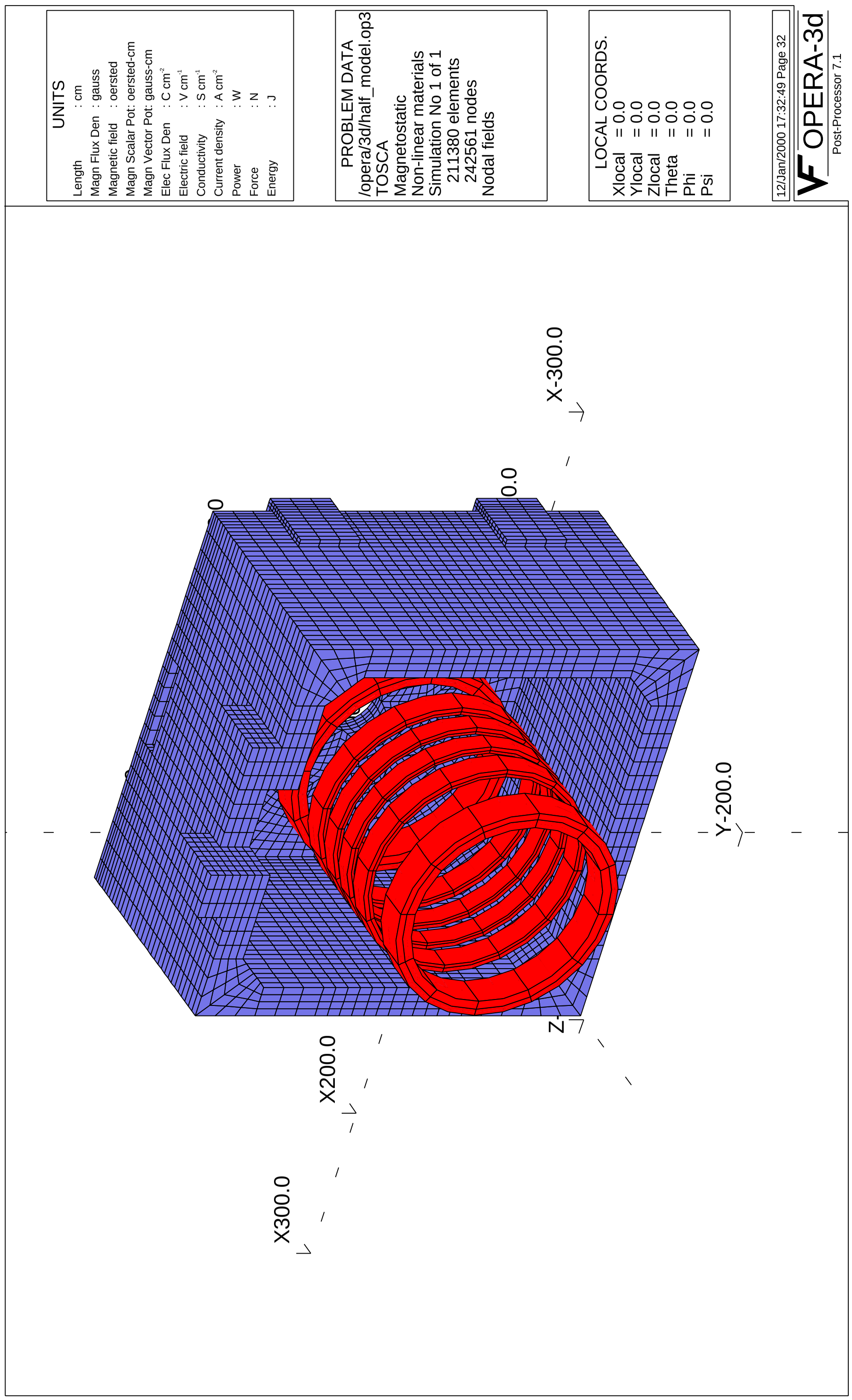

Figure 1: View of the downstream half of the E614 steel yoke and coils. Lines on the surface of the steel show exterior facets of the finite element mesh.

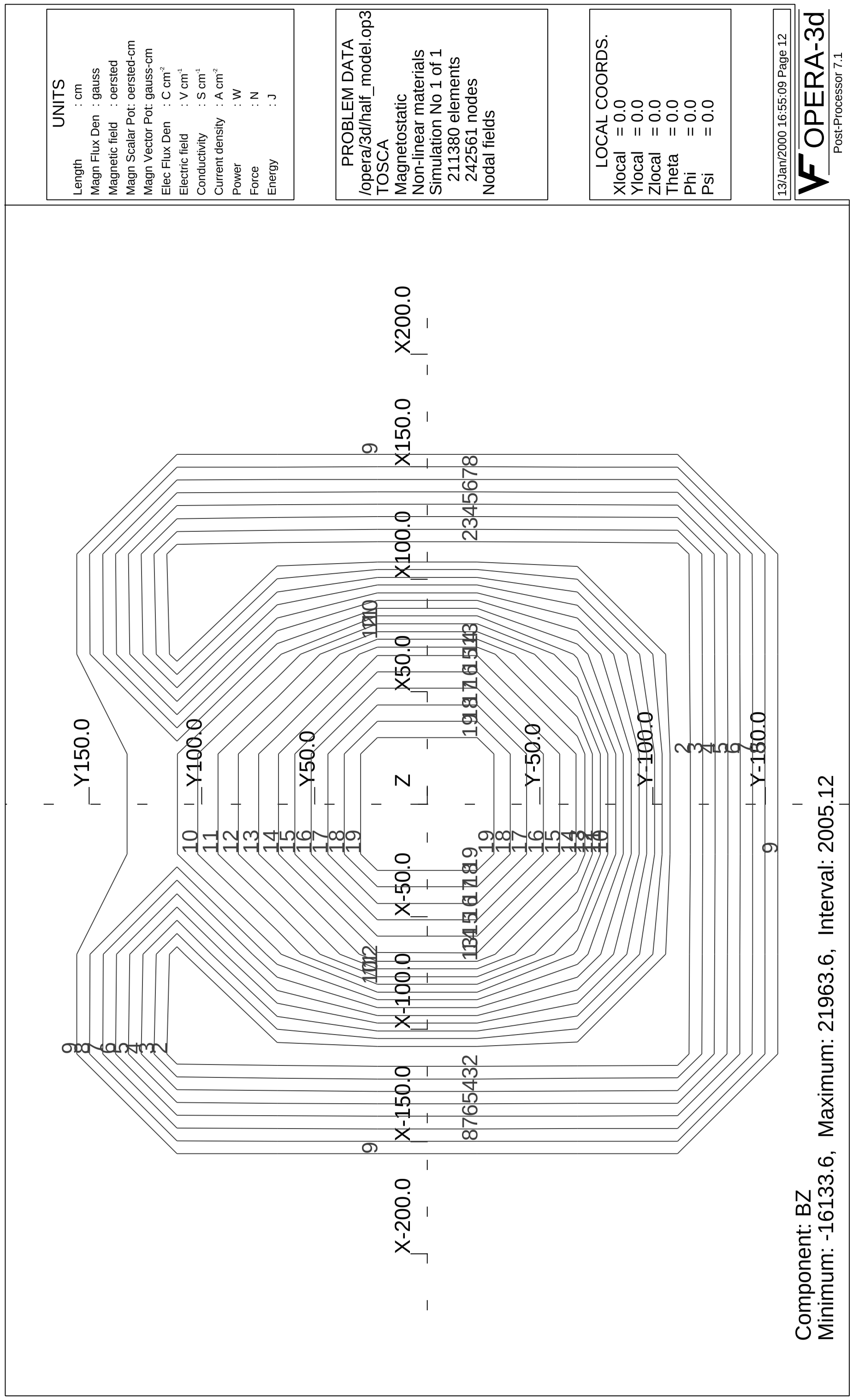

Figure 2: Contours of B_z in the plane $z = 0$. Contour 19 represents the largest flux coming out of the page (along $+z$) and contour 2 represents the largest flux going into the page (along $-z$). Contour 9 represents a B_z flux of nearly zero.

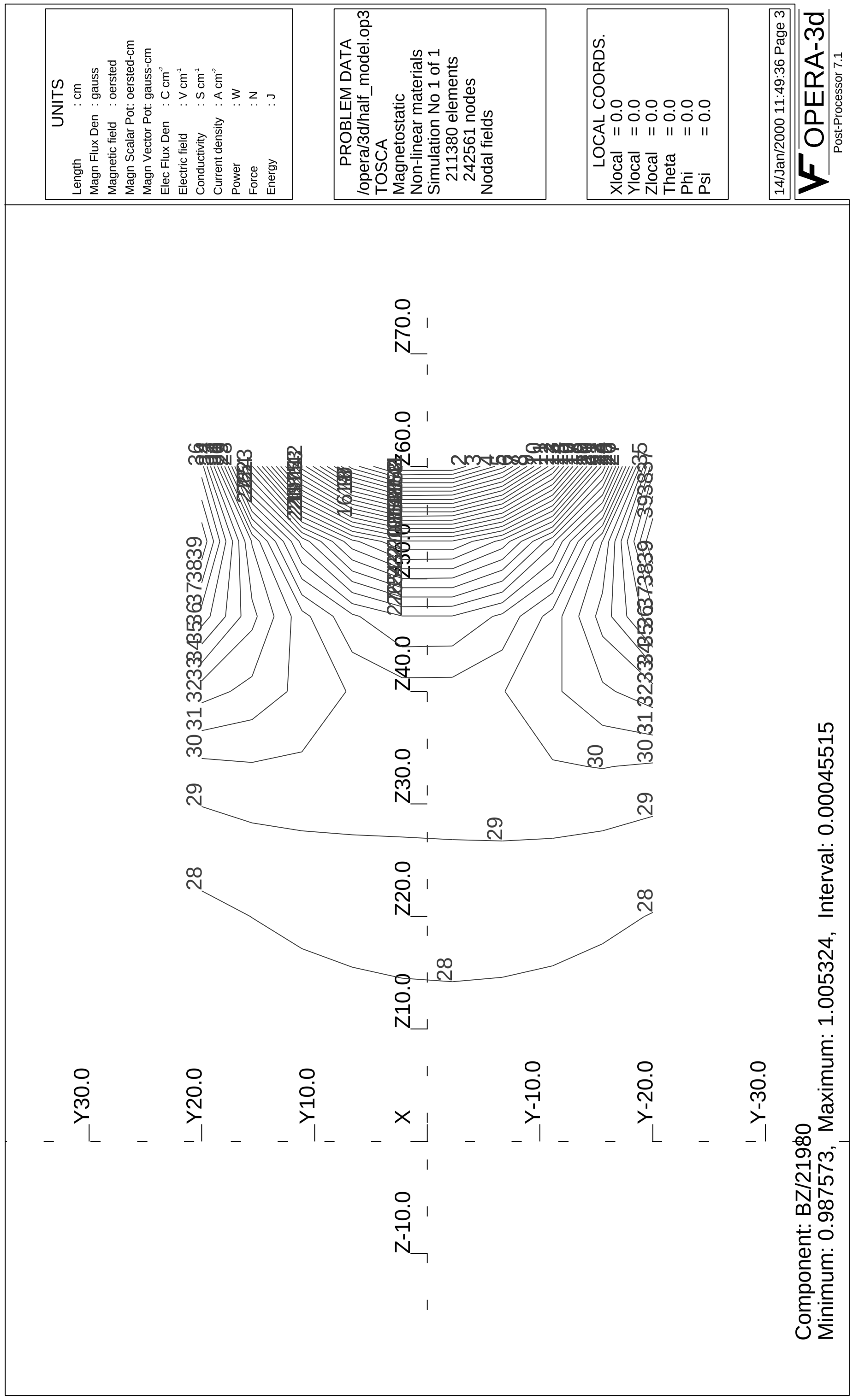

Figure 3: Contours of B_z in the $y-z$ plane in the region of the drift chambers. Each contour represents an increment of 10 gauss.

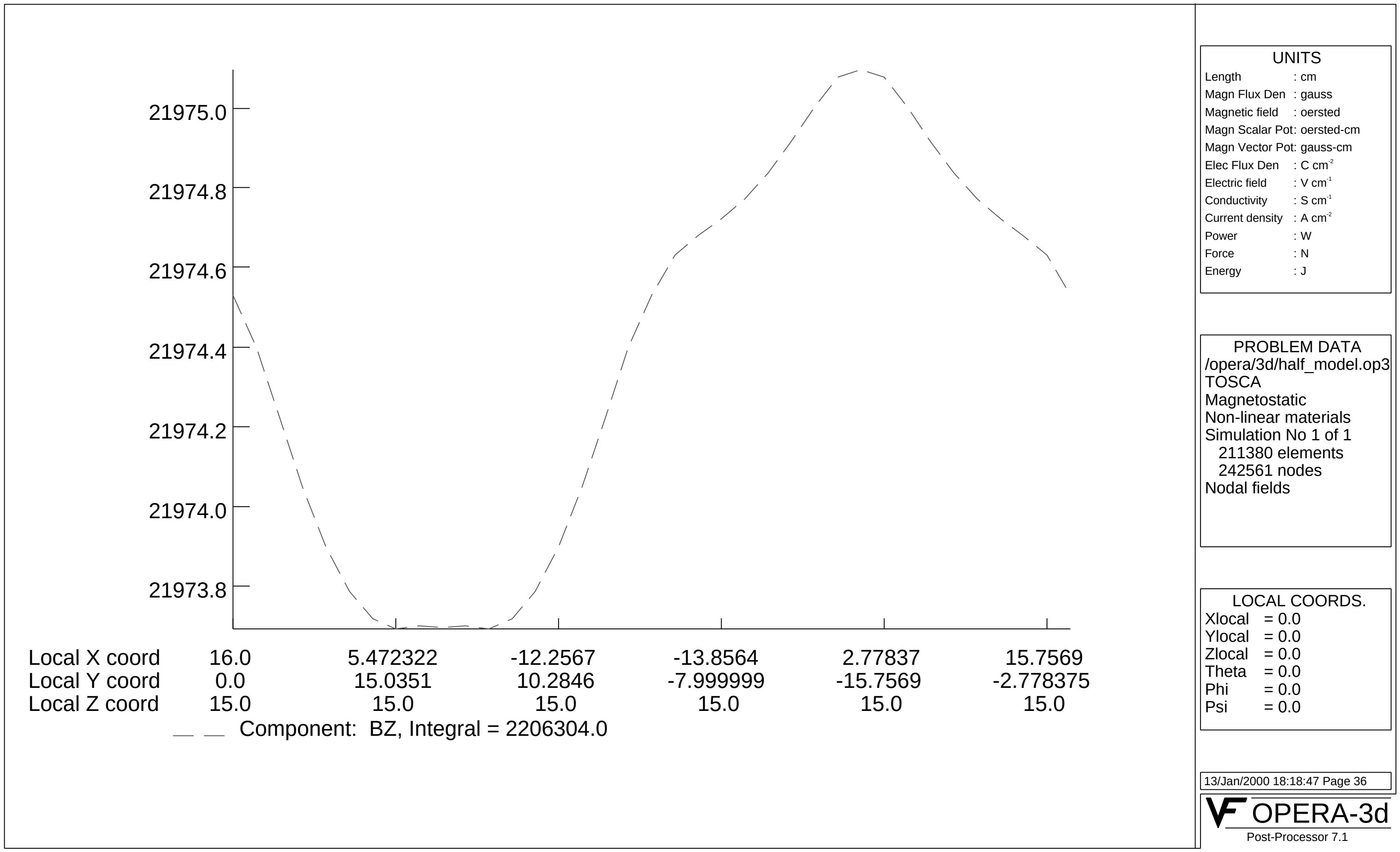

Figure 4: B_z on a circle (0 to 360 degrees) in the $x-y$ plane of radius 16 cm, centered on $x=y=0, z=15$ cm.

The radial field in the beam entrance hole is also of interest because it imparts an off-axis kick to the momentum and spin of the incoming muon. Asymmetries here can seriously distort the spin distribution at the stopping target. The radial field for the above model is shown in Fig. 5 along four lines, each parallel to and 1 cm away from the z-axis and located at ($x = 0$,$y = 1$), ($x = 0$,$y = -1$), ($x = 1$,$y = 0$) and ($x = -1$,$y = 0$). While there is exact symmetry along the ($\pm x$) lines, the asymmetry along the $\pm y$ lines is well outside the expected measurement error. The difference is due to the electronics cable access port which is almost directly above the beam hole. Another model calculation shows that when the cable port is removed the radial fields along all four lines are identical within errors. Not shown in Fig. 5 is the radial field on the z-axis. It is non-zero with a maximum value of 7.5 gauss. As the field is sampled further and further from the z axis, the % asymmetry decreases. Removal of the cable port causes the field along the z axis to go to zero (within errors), as expected for a solenoid.

4 Repairing Field Asymmetries

The largest asymmetry in the above model to which the experiment is sensitive is in the radial field in and around the beam access hole. As stated above this is due to the 10 cm x 61 cm cable access hole in the top plate of the yoke. With respect to electronics cabling it would be easier to split the hole into two 10 cm x 30.5 cm holes and move the two halves as far as possible away from each other in x. The model yoke was modified accordingly and the fields recalculated. The results are shown in Fig. 6. Here the radial field is calculated over the same four lines as in Fig. 5 but now they all nearly overlap. In fact they are identical within the estimated error of the calculation. A comparison of the fields in the drift chamber region shows that splitting the cable port does not significantly disturb the cylindrical symmetry. Because the radial field due to the split cable port is so nearly symmetrical in both the beam entrance region and the drift chamber region, these ports need only be placed on the downstream end of the yoke and not on the upstream end where the beam enters.

It has been suggested [3] that a thick steel cover over the cryogenics port would take up enough of the return flux to increase the azimuthal symmetry in the drift chamber region. Fig. 7 shows such a cover added to the model of the yoke. Fig. 8 shows that indeed some flux is taken up by the steel cover, however it is not enough to symmetrize the central flux region. In fact the flux distribution is very little different from the original model as shown in Fig. 2. Another look at Fig. 2 shows that no flux enters the steel bars placed on either side of the cryogenics port. This suggests that the bars are not necessary for improving symmetry and may be removed.

As stated above two of the steel hinges are used to hold the downstream yoke door and the other two are used for symmetry (see Fig. 7). When the two non-functional hinges were removed, a 10 - 15% left-right asymmetry in the radial field was observed for $z > 180$ cm, as shown in Fig. 9. However, no left-right asymmetry was observed in the drift chamber region (see Fig. 10). As long as there is no interest in the beam profile as it leaves the yoke it is unnecessary to add fake hinges to the downstream door. Because the asymmetry at the

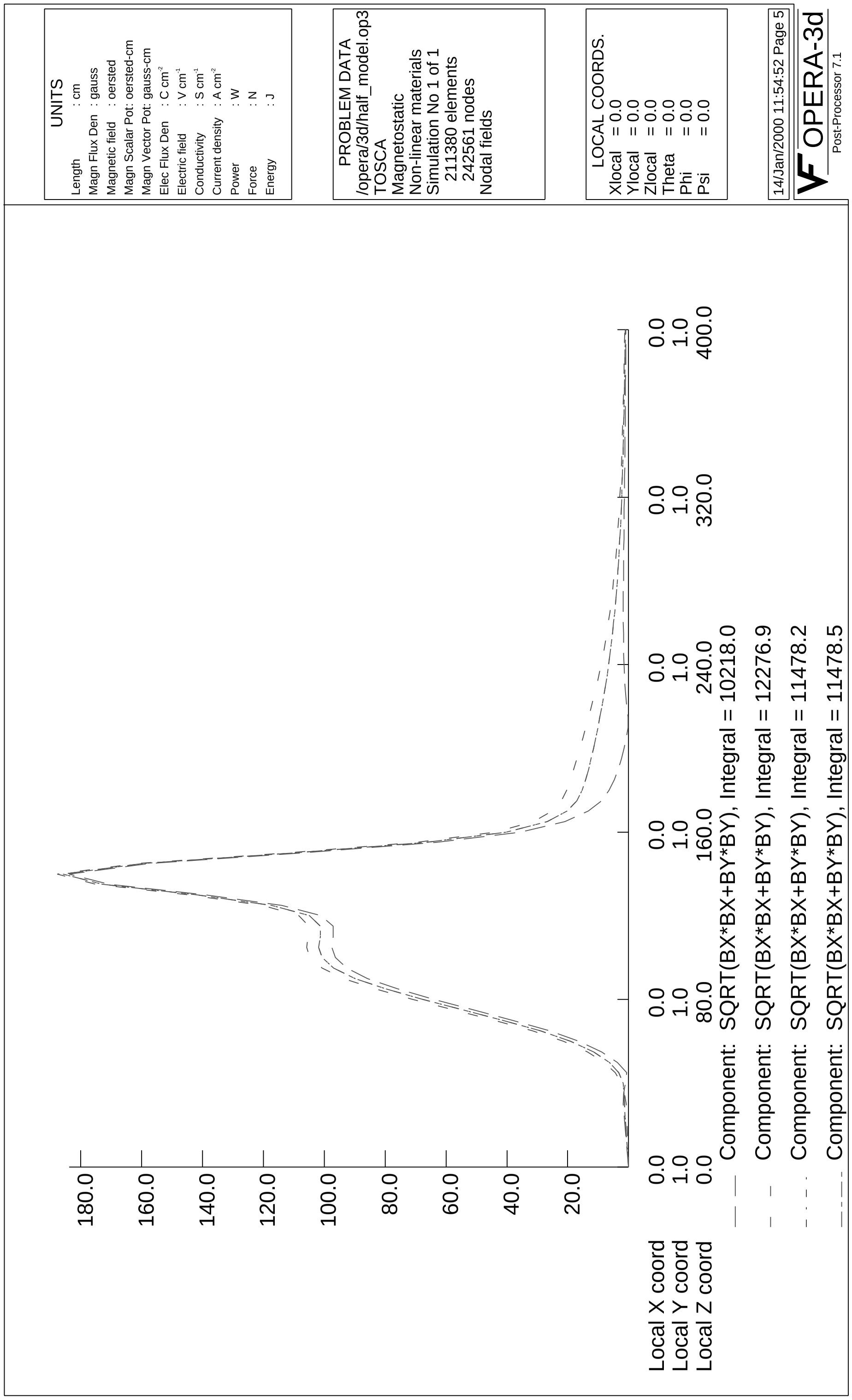

Figure 5: B_r on lines 1 cm from and parallel to z-axis. Top curve: $x = 0$, $y = -1$. Bottom curve: $x = 0$, $y = 1$. Middle curves (overlapping): $x = 1$, $y = 0$ and $x = -1$, $y = 0$.

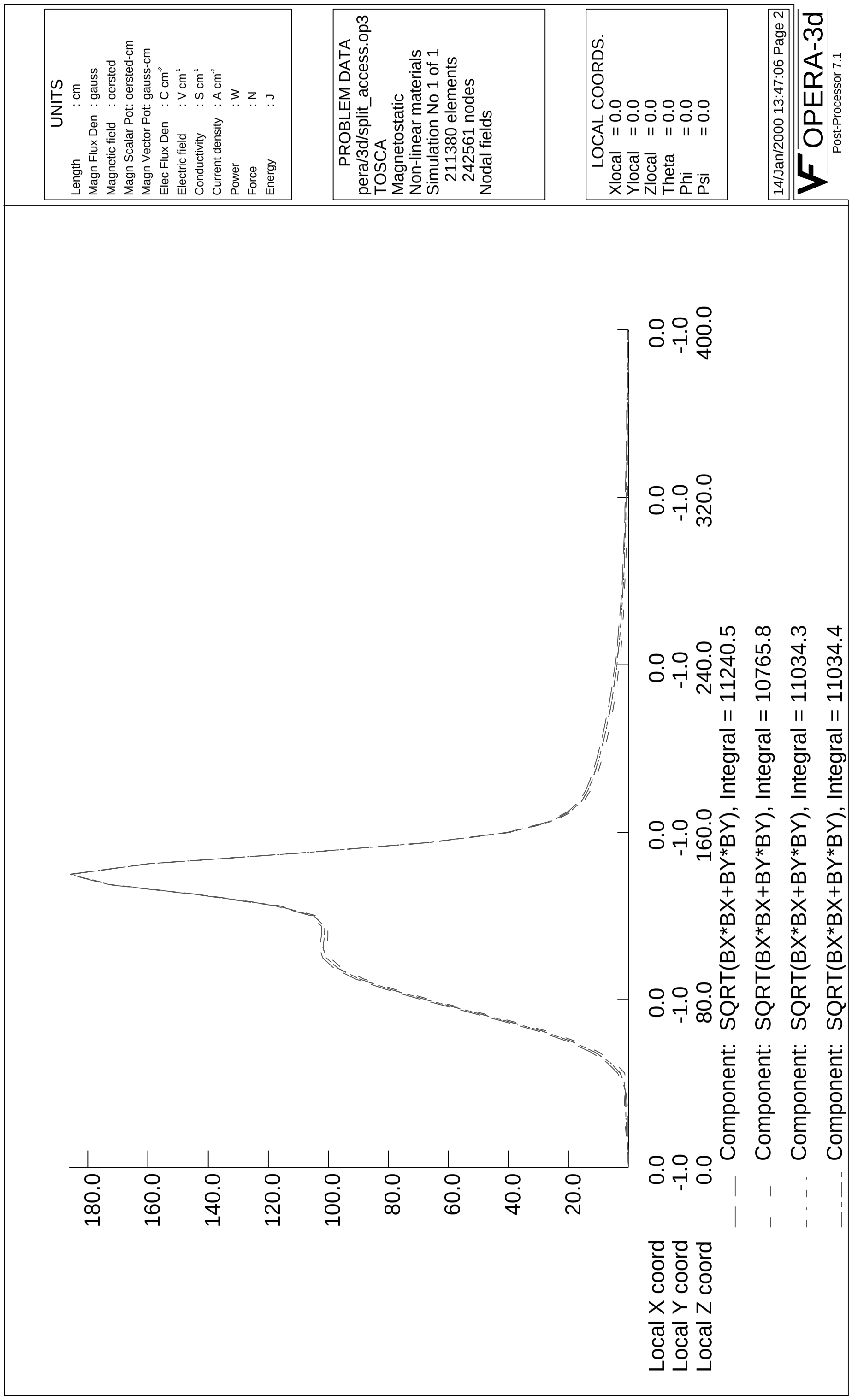

Figure 6: Cable access port split in two. B_r on lines 1 cm from and parallel to z-axis. Top curve: $x = 0$, $y = -1$. Bottom curve: $x = 0$, $y = 1$. Middle curves (overlapping): $x = 1$, $y = 0$ and $x = -1$, $y = 0$.

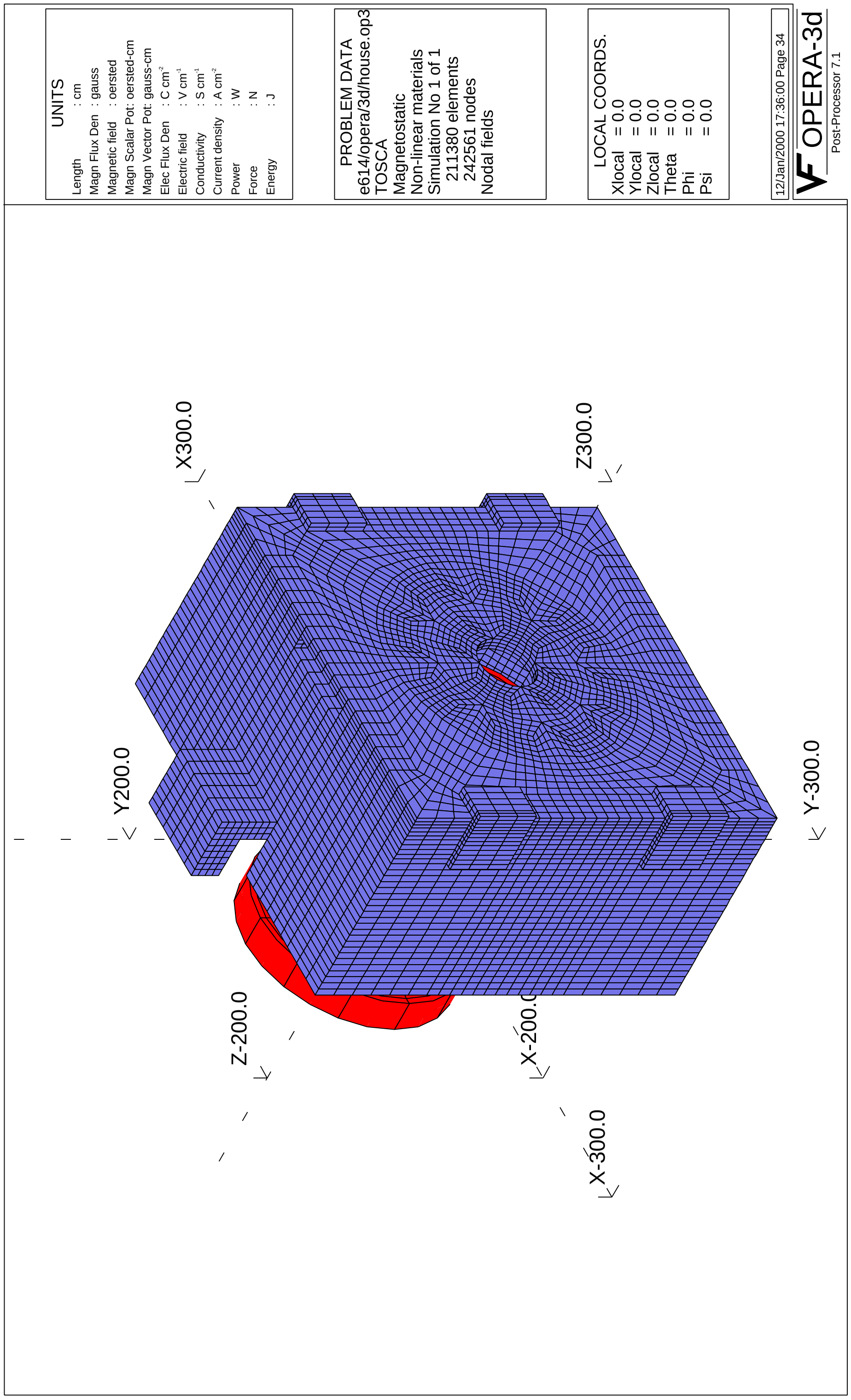

Figure 7: View of the downstream half of the E614 steel yoke and coils with a 20 cm thick steel cover placed over the cryogenic services port.

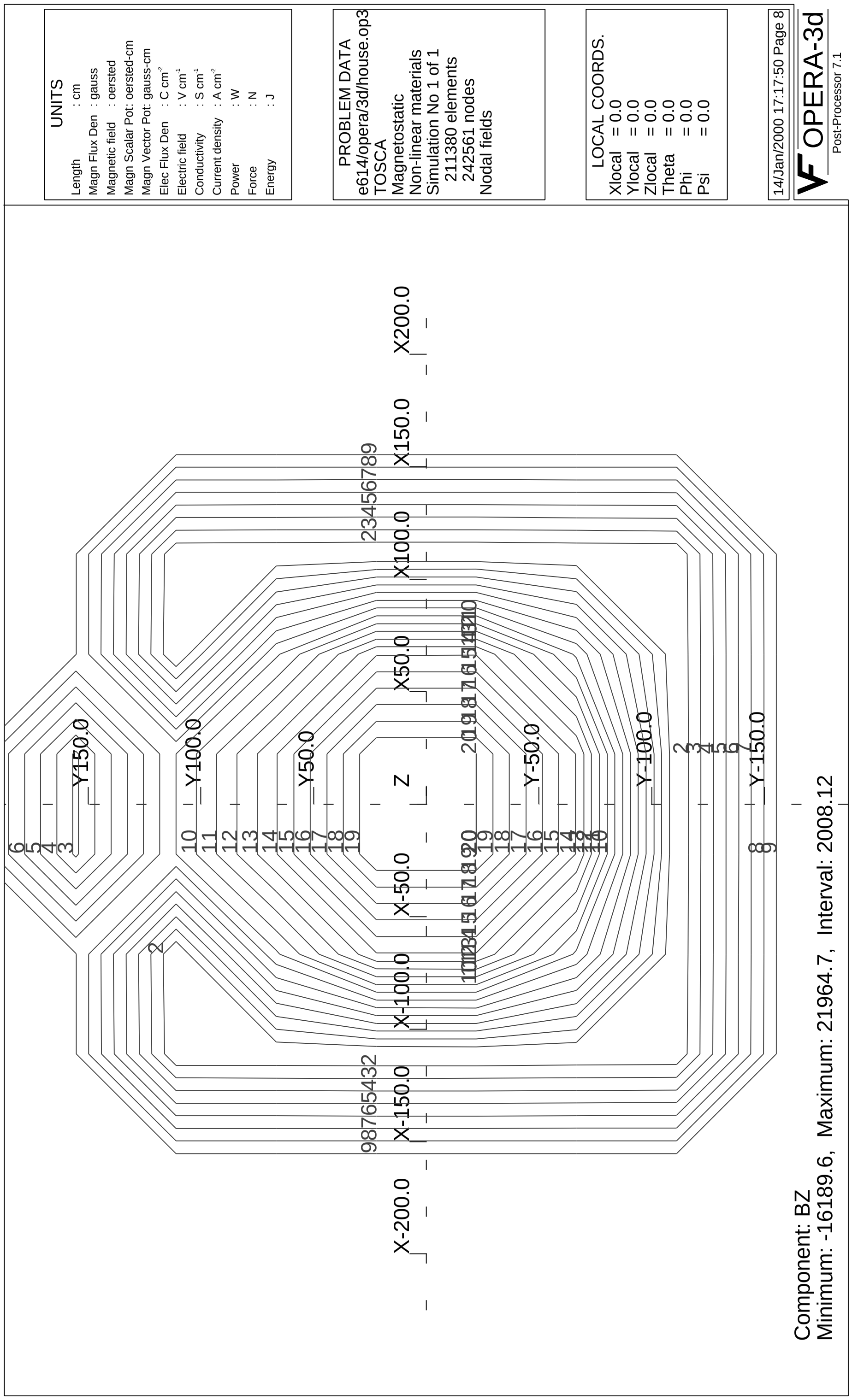

Figure 8: Cover over cryogenics port. Contours of B_z in the plane $z = 0$. Contour 19 represents the largest flux coming out of the page (along $+z$) and contour 2 represents the largest flux going into the page (along $-z$). Contour 9 represents a B_z flux of nearly zero.

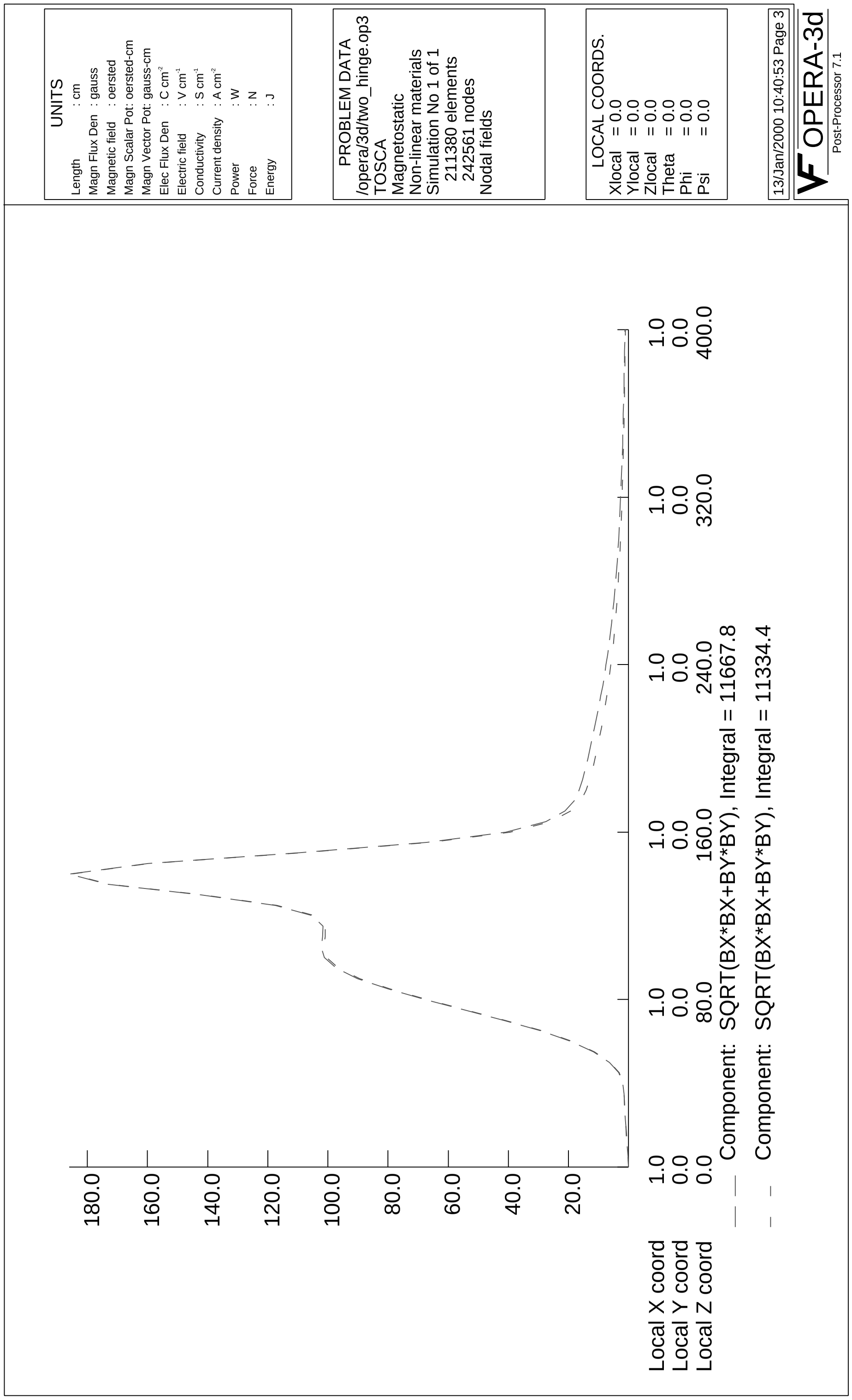

Figure 9: Left-right asymmetry in radial field when fake hinges are removed from downstream yoke door. Upper curve ($x = 1, y = 0$ cm), lower curve ($x = -1, y = 0$ cm).

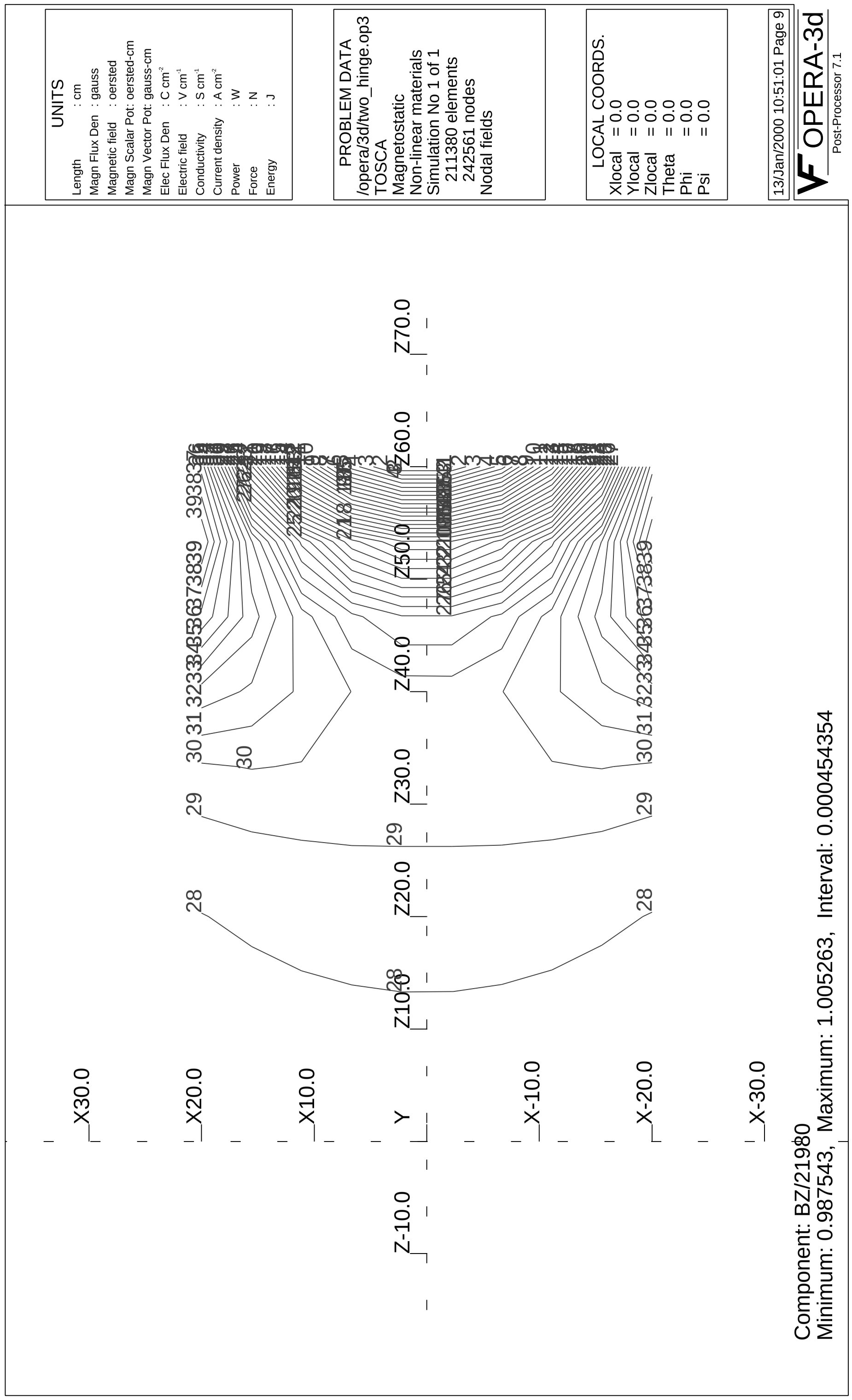

Figure 10: Contour plot of B_z in $x-z$ plane when fake hinges are removed from downstream yoke door.

beam exit does not propagate to the chamber region fake hinges on the upstream face of the yoke are also unnecesary.

5 Modifying the Radial Field with Shims

It has been suggested that the addition of a steel shim around the beam entrance to the yoke could narrow the radial field distribution, thereby reducing the overall transverse kick imparted to the incoming muon [4]. The shim would have the same effect as a coil placed at the beam entrance. To test this proposal, a cylinder of steel 10 cm thick with inner and outer radii of 20 and 50 cm, respectively, was centered on the z axis and placed immediately downstream of the beam entrance to the yoke. The resulting radial field is shown in Fig. 11 where it is compared to the field obtained without the shim. The radial field with the shim is about 10% narrower than without it, while the integral varies by less than 1%. However the addition of the steel at the beam entrance disturbs the field uniformity at the center of the magnet. Fig. 12 shows that B_z along the z axis now increases by about 70 gauss over 40 cm, compared to 20 gauss over 40 cm for the model without the shim (see Fig. 3).

6 Conclusions

A square cross section yoke is sufficient to produce a magnetic field which is cylindrically symmetric to within 2-3 gauss in the drift chamber region of the detector ($r < 20$ cm). This confirms the calculation by Don Lobb of a 1/8 model magnet [1]. The addition of solid triangular braces along the corners of the yoke, access holes in the top for cryogenics and cables, and hinges on the magnet door did not affect the symmetry in this region.

A single electronics cable hole in the top face of the yoke at its downstream end and centered over the beam exit hole causes an up-down asymmetry in the radial field in the region of the beam exit. This asymmetry can be almost totally removed by splitting the hole in two. The holes cut in the yoke will extend from +130 to +140 cm in z, with one between +60.5 and +90.18 cm in x and the other between -60.5 and -90.18 in x. These need only be placed at the downstream end of the yoke.

The opening in the yoke for the cryogenic services creates an up-down asymmetry near the yoke which propagates only slightly into the drift chamber region. Placing a thick steel cover over the cryogenics port does not draw sufficient flux to reduce the asymmetry in the field near the yoke, nor does the addition of steel bars on either side of the opening. However the asymmetry in the drift chamber region is at most 2-3 gauss without any additional steel, so it may safely be omitted.

Adding two fake hinges to the downstream yoke door helps to symmetrize the radial field where the beam leaves the yoke, but the beam in this region is probably of no interest so the extra hinges may be omitted.

Placing a cylindrical shim at the beam entrance to the yoke decreases the width of the

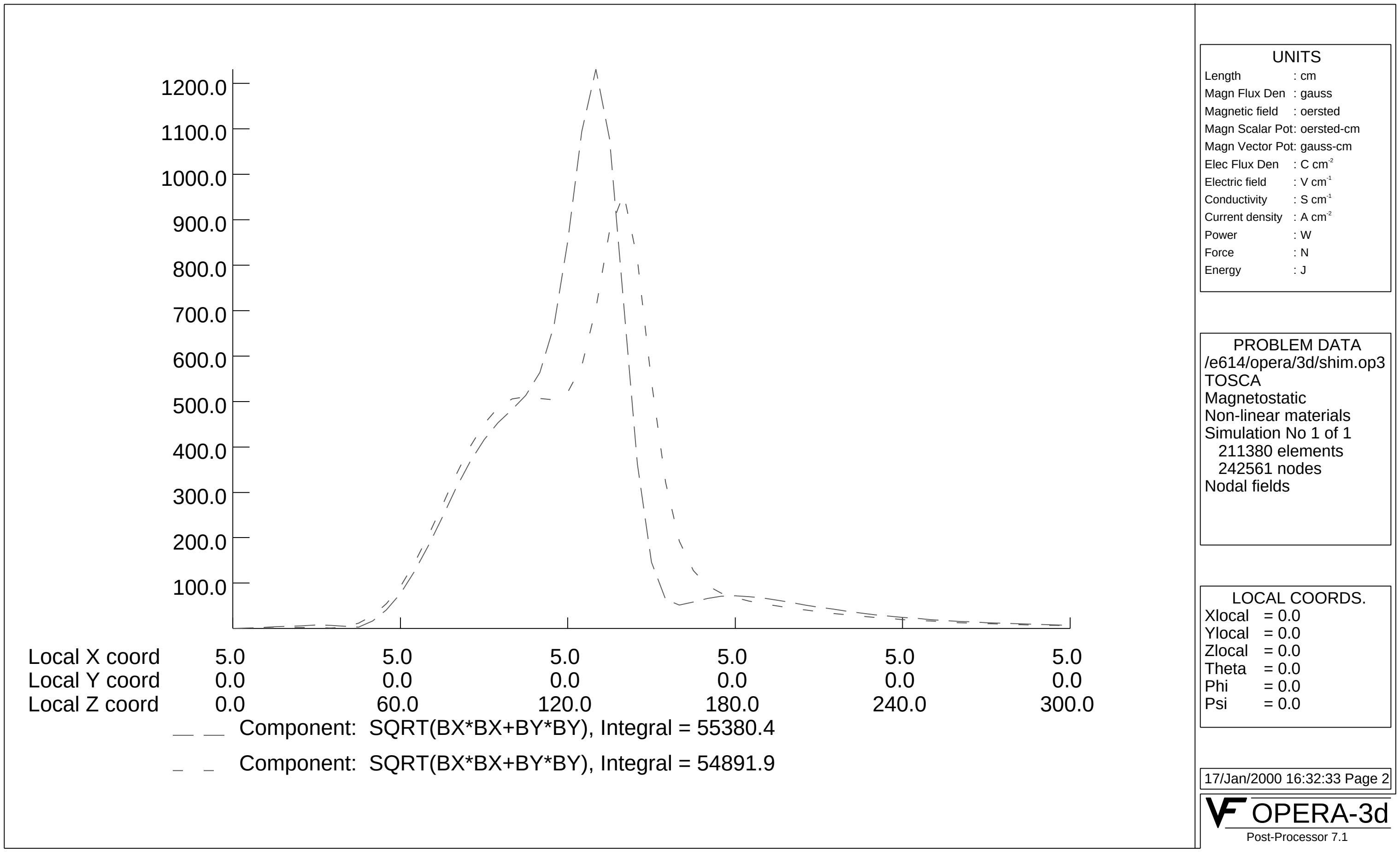

Figure 11: Radial field on a line parallel to the z axis with $x = 5$ cm and $y = 0$. Long-dashed curve: radial field with shim at beam entrance. Short-dashed curve: no shim.

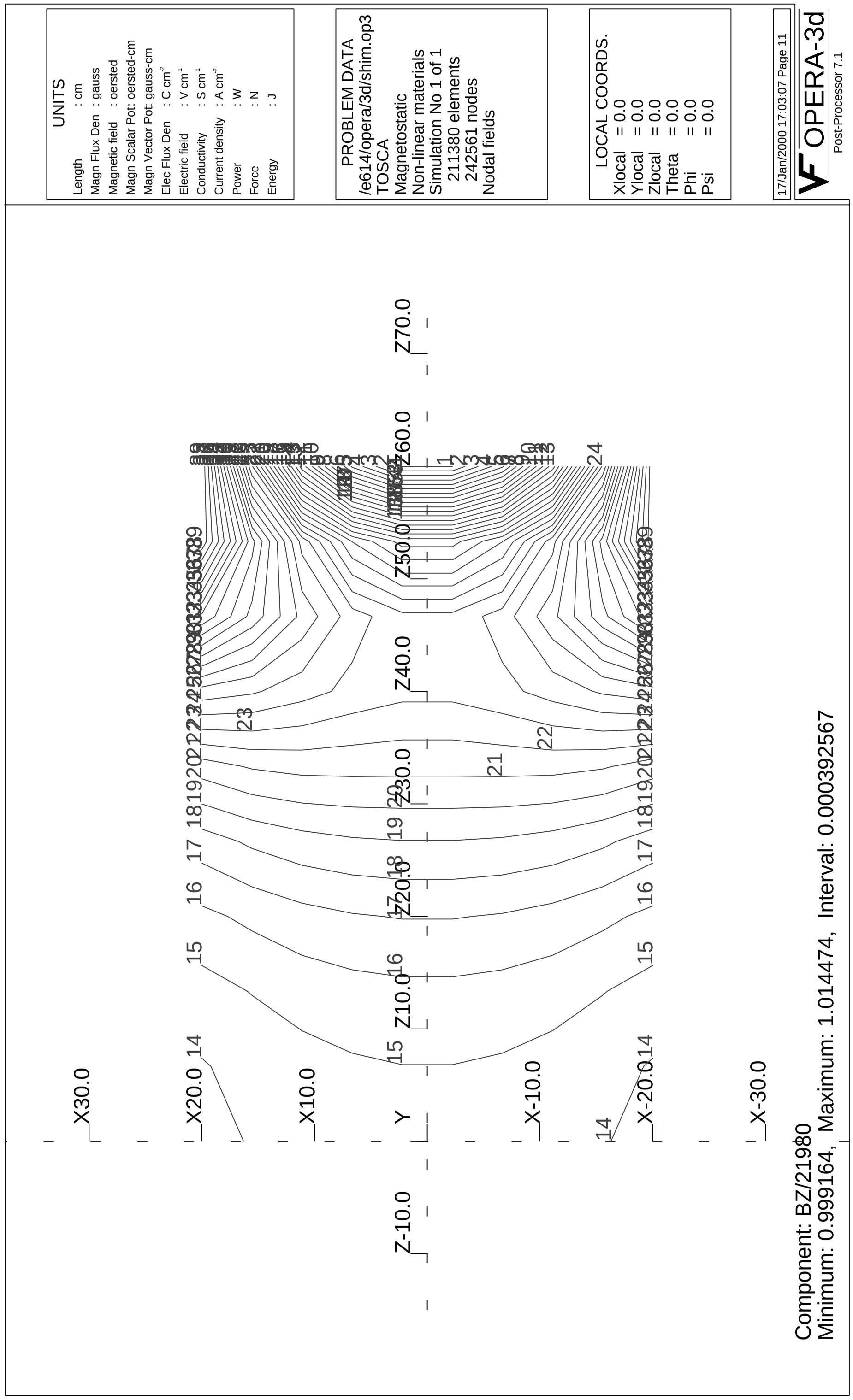

Figure 12: Contour plot of B_z in the $x - z$ plane with the shim at the beam entrance. Each contour increment represents 8.6 gauss.

radial field distribution by about 10% which may be useful in reducing muon depolarization at the target. However it also causes greater non-uniformity (by a factor of 3.5) near the center of the magnet where the drift chambers are located.

References

[1] J.A. Macdonald, E614 Technical Note 37, 1999.

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

[3] J.A. Macdonald, E614 Meeting, 1999.

[4] D. Lobb, private communication, 1997.