1. Introduction

1.1 What is *TWIST* ?

TWIST stands for TRIUMF Weak Interaction Symmetry Test. As its name indicates, *TWIST* is a study of the weak interaction. Its goal is to precisely measure the parameters involved in this interaction in order to compare these measurements with the standard model predictions. To do so, we observe a muon decay into a positron and neutrinos inside a detector. We then track the muon and positron to extract each parameter.

1.2 Why do we need to know the magnetic field precisely?

The detector is located inside of a 2 Tesla superconducting solenoid magnet. We need to know precisely the field it produces for many reasons.

First, in the central region, we need precise tracking. The magnetic field is related to the momentum and trajectory of a particle:

$$q\vec{v} \times \vec{B} = \frac{\mathrm{d}\vec{\mathrm{p}}}{\mathrm{dt}}$$

Secondly, upstream (before the muon gets in the detector), we need to know the muon polarization. One of the parameters (ξ) is coupled with the polarization ($P\mu$) and cannot be measured independently. Because of the way the muon is produced, it enters the magnetic field with its spin opposite to its momentum. However, the spin then precesses, trying to align itself with the field. Knowing the radial component of the field gives one the importance of the depolarization.

1.3 TWIST magnetic field study history

Glen Marshall and John A. Macdonald took measurements in the central region in 2002. An OPERA model was then created by Michael Barnes and later improved by Roberto Armenta in order get a better match between simulation and measured data [1]. In 2003, measurements were taken upstream and the discrepancies between the model and this new data were studied by Mathieu Simard [2].

2. Measuring the Field

2.1 Using Hall probes

Hall probes were used measure the field. These devices measure the Hall voltage which is the voltage that the Lorentz force creates in a conductor subjected to a current. The Hall probe accuracy is usually around 0.01 %.

2.2 Calibrating with NMR probes

The NMR (nuclear magnetic resonance) probe is based on the nuclei precession caused by the nuclei trying to align their magnetic moments with the magnetic field. Its accuracy is usually around 10 ppm, but it needs a rather homogeneous field to work properly. Here, NMR probes were used to calibrate the Hall probes.

2.3 Taking measurements

We measured the z component of the field at five different radii for different positions in z and phi as shown below.

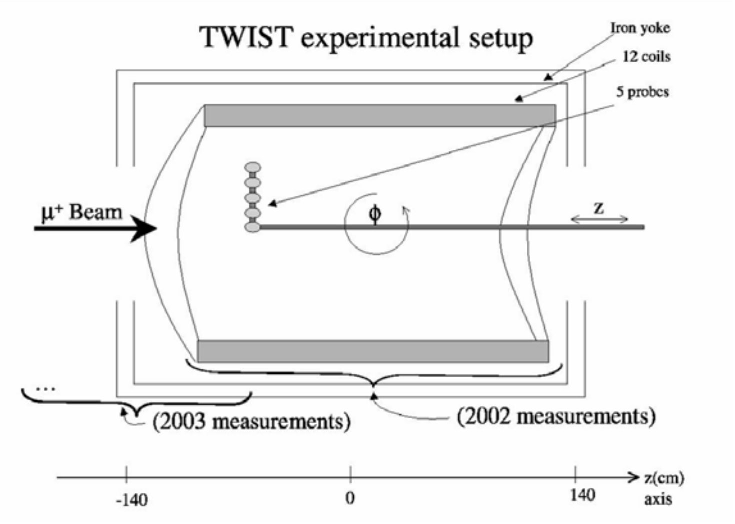

Figure 1: Experimental setup and the Hall probes; figure from Mathieu's report [2]

As previously mentioned, we took measurements in the central region in 2002 and in the upstream region in 2003.

3. Modeling the Field with OPERA

3.1 Why do we need to model the B-field?

We need to model the field because we only measured the z component of the field and we need to know the x and y components also. We chose OPERA because it is a well respected and widely used software package used for mapping magnetic fields.

3.2 How does it work?

Roughly: one enters the experimental setup geometry; OPERA processes it and gives a map of the magnetic field (more details in appendix). Here is a picture of the model we are using now:

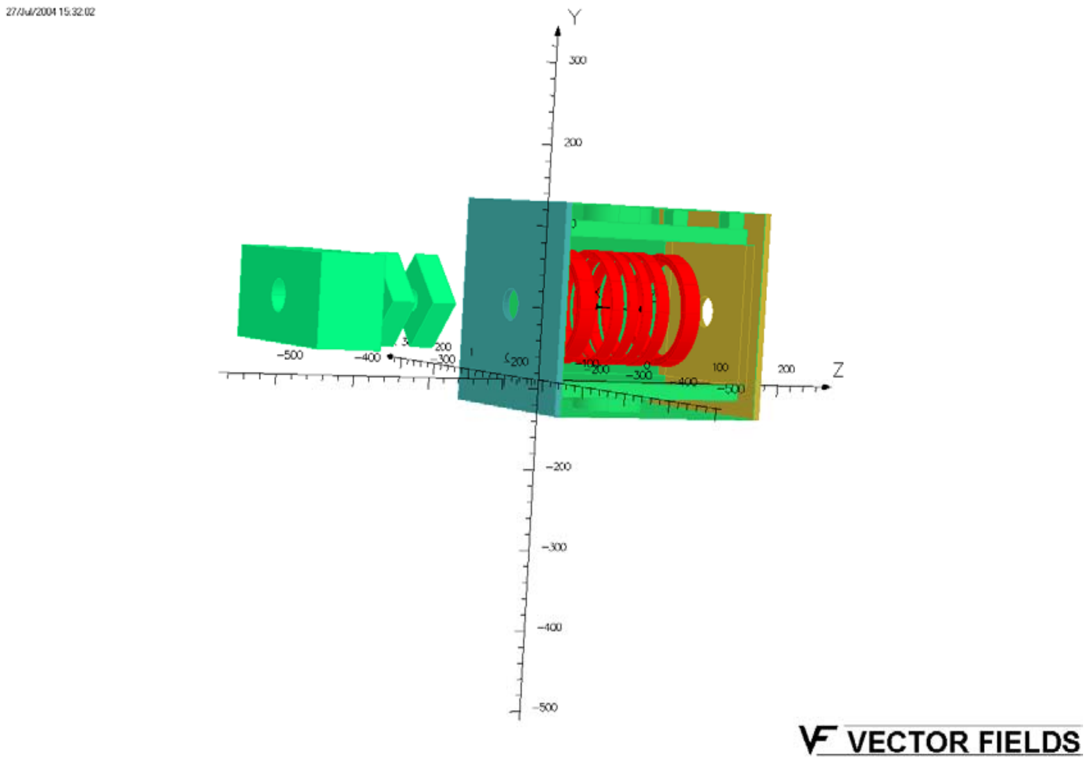

Figure 2: OPERA model of the *TWIST* experimental setup

This model was first created by Michael Barnes. It was then modified by two summer students: Roberto Armenta and Mathieu Simard. On the left, you can see a dipole and two quadrupoles that come from the beam line. The coils, in red, are inside of a steel yoke (in green). The presented scale is in centimeters. The origin of our coordinate system is located in the center of the yoke, which extends from z = -140 cm to z = 140 cm. The z-axis increases in the direction of the beam.

4. Improving the Model

4.1 How it was before I started

To see how well we are matching the field, we compare the B_z values from OPERA with the measured B_z values. The z component of the field along the z-axis in the upstream region can be seen in figure 3 (top). On the bottom, you can see the difference between the OPERA values and the data values as it was before I began (old model).

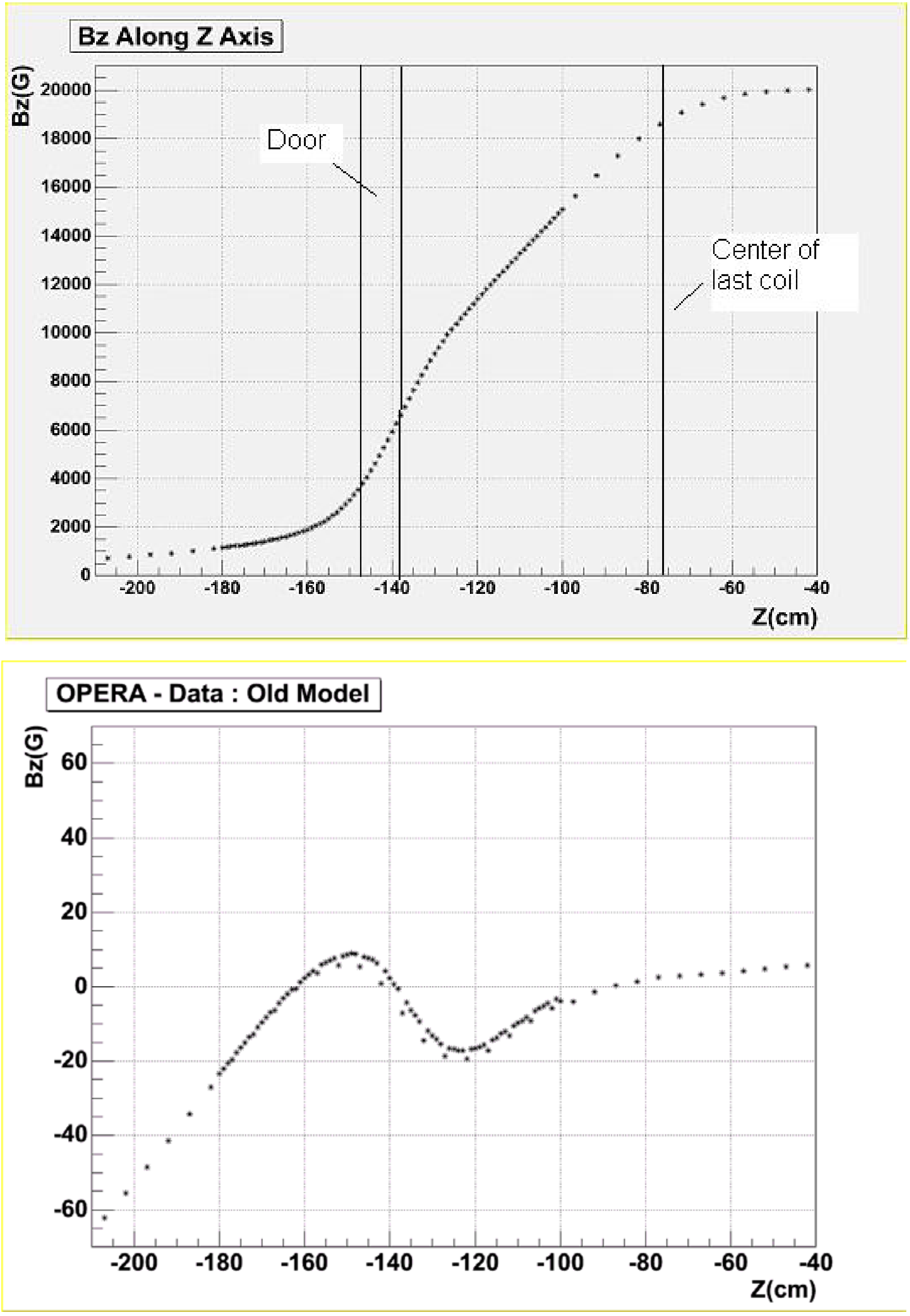

Figure 3: B_z along the z-axis and the difference between OPERA and data before I began (database 9 in appendix)

If one were to plot both the measured and OPERA data on the top plot, the curves would overlap perfectly since our deviance is less than 60 G in a 20 000 G field. On the bottom plot, we show the main discrepancies that we are trying to fix. Two features are worth noticing. First, we have a tail around -200 cm where OPERA is missing some field. Second, there is a kink in the door area (-140 cm).

4.2 Adding the quadrupoles and dipoles

The first thing we did to improve the agreement in the tail area was to add the quadrupoles and dipole to the model as Mathieu Simard recommended (database 4 in appendix). The last quadrupole is located from -253 cm to -283 cm which is near the upstream region we are studying.

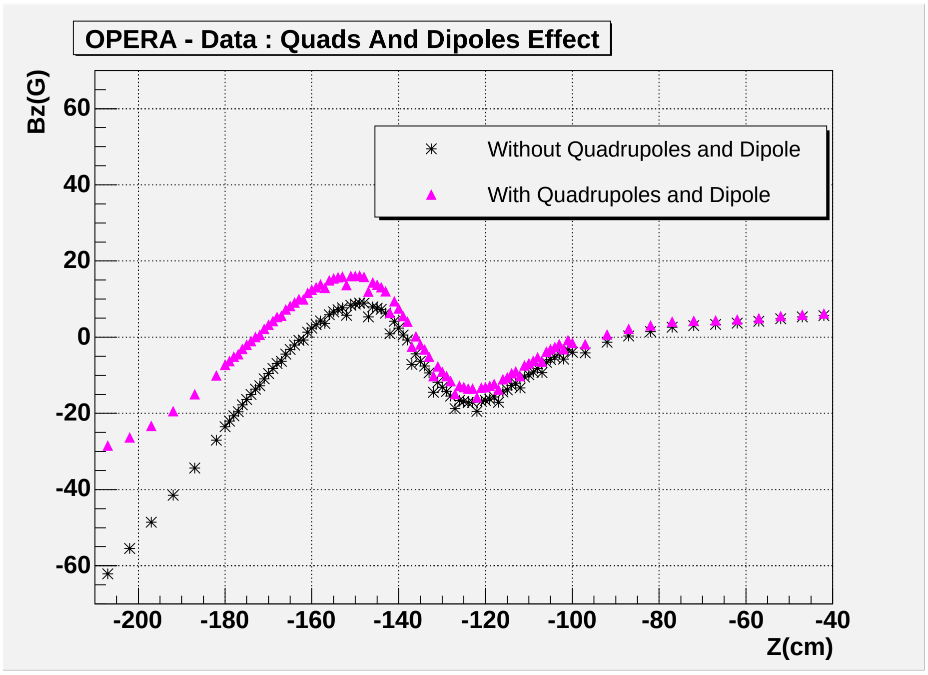

Figure 4: Plot of the difference between OPERA and measurements showing the effect of adding the quadrupoles and dipole

Since adding the quads and dipole improved the agreement, they will remain in the model from now on. However, there are other issues related to these magnets. First, the dipole is at a 19^{o} angle to the z axis, but we are using a quarter model in OPERA (symmetric around the YZ and XZ planes) for technical reasons. A full model takes much longer to process and we are having trouble with the meshing of this full model (more details later). Fortunately, no differences were noticed between the effects produced by a dipole at no angle and by a dipole rotated by 19^o [3], thus allowing us to leave the dipole at no angle. Also, we realized that during measurements, the quads and dipole were sometimes on and sometimes off. In OPERA, they are always off: the magnetization of their steel is responsible for the changes in the field. Fortunately, we again saw no difference between the maps that were taken with the quads and dipoles on and off. This can be explained by the fact that those magnets are creating a localized radial field.

4.3 Changing the BH curve

The BH curve is a measure of a permanent magnet magnetization. Its slope corresponds to the permeability of the material. The larger the slope; the more the magnetic field will go through the material. In OPERA, we have to put in the BH curves of our steel (yoke, doors, dipole and quadrupoles). A Tenten steel BH curve from TRIUMF was used for all the steel in the old model.

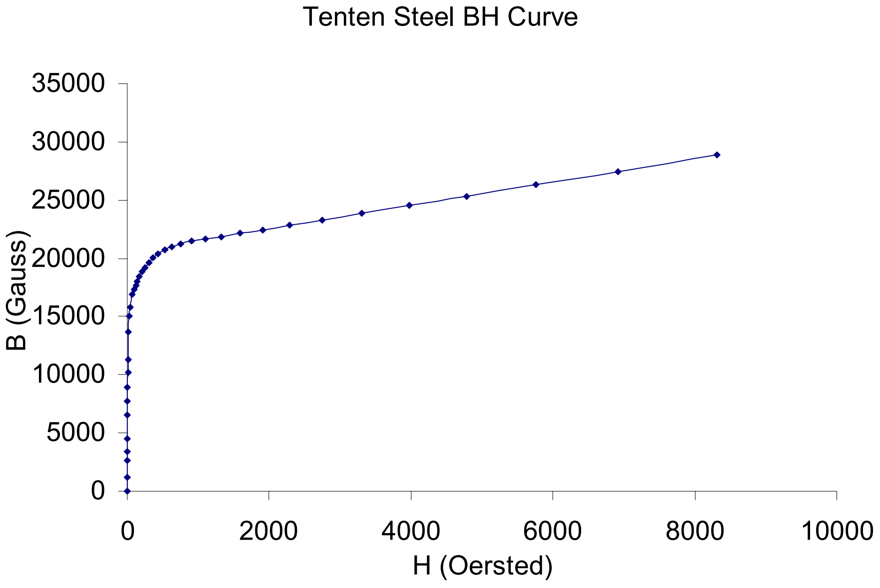

Figure 5: Tenten Steel BH curve from TRIUMF that was used everywhere in the old model

However, we do not know exactly how the steel was manufactured so we tried to improve our model by scaling this curve. First of all, we realized that the BH curve of the doors was the only BH curve that had a noticeable effect on the field when scaled by a factor of 1 or 2 percent (no effect of the yoke, quads and dipole BH curves). The effects of this scaling along the z axis are shown on figure 6. We started with the old model containing the quads and dipole (blue curve scaled by 100 % (BH 100), database 4).

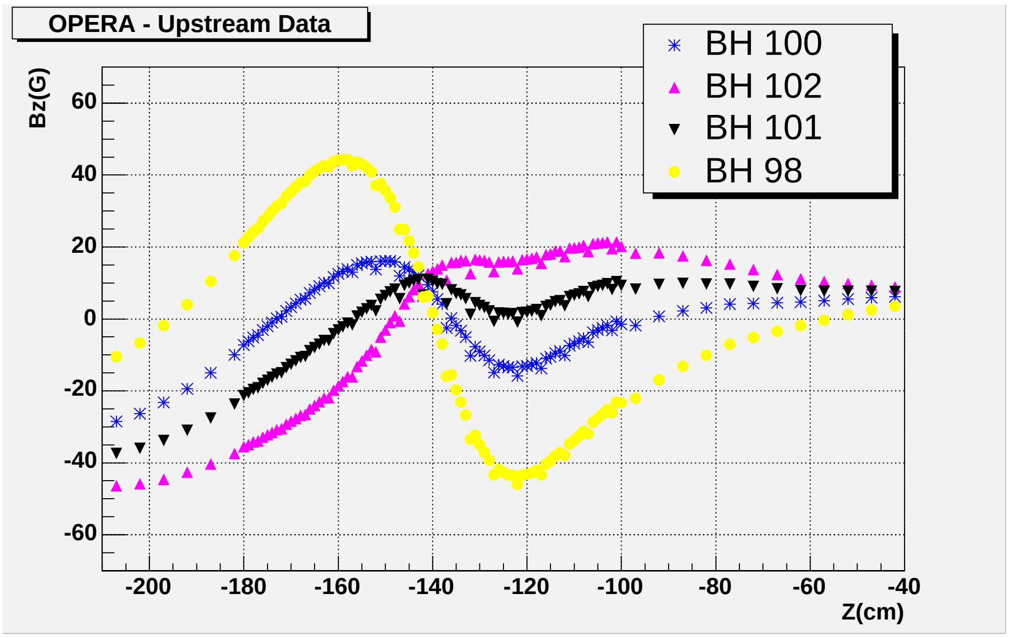

Figure 6: Effect of scaling the doors BH curves along the z axis (databases 4 (BH100), 10 (BH 102), 11 (BH 101) and 3 (BH 98))

As you can be seen, scaling the BH curve down has an undesired effect. Even though it brings the difference closer to 0 in the -200 cm area, it increases the kink by a large amount. Scaling the curve up seems to flatten the kink, despite making the tail worse.

Until now, we have focused on the field along the z axis since it is the most important region (this is where the beam is mostly located) and it is where we have the most reliable data. Now, we are going to look at the field off-axis at x = 16.51 cm (almost at the end of the hole) since it can give ideas on how to improve the model.

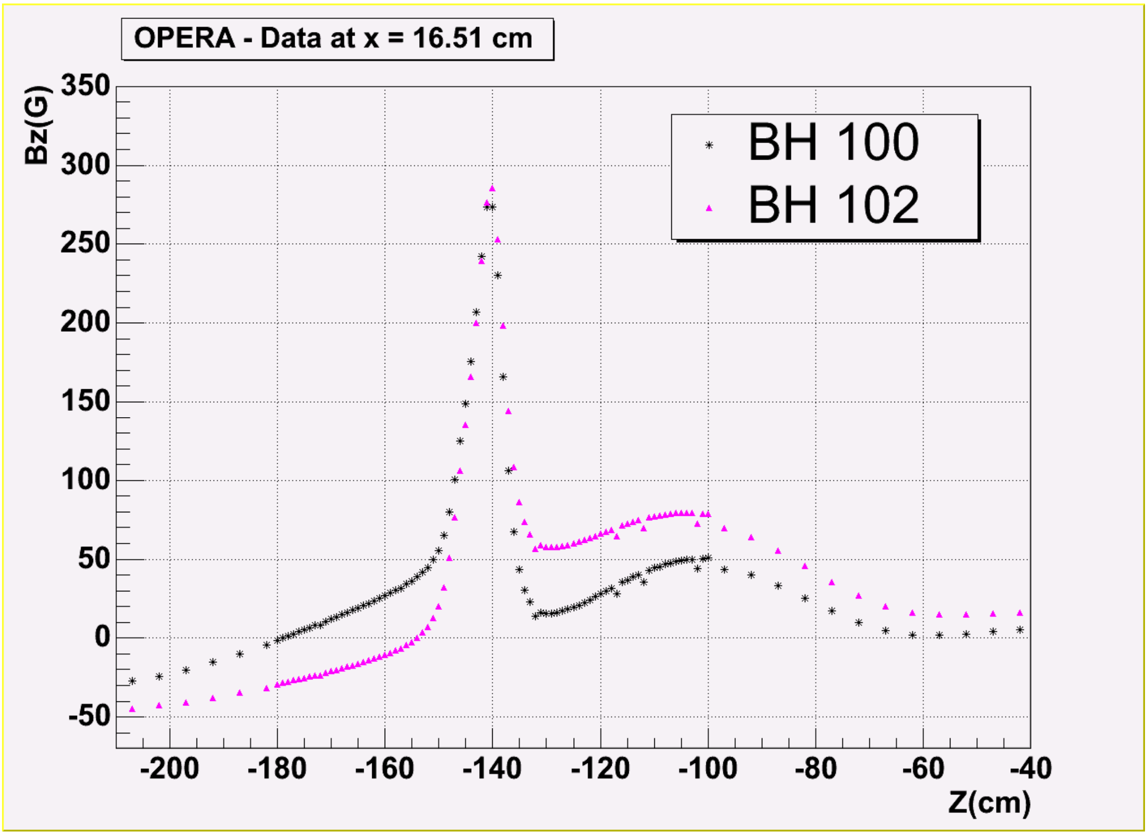

Figure 7: Difference between OPERA and data for two different BH curves at x = 16.51cm.

As can be seen, both BH 100 and BH 102 have a large peak in the door area. Increasing the permeability does not flatten the kink. So, we are going to keep BH 100 (not scaled).

Also, we thought that the quads and dipole might have some remnant field that could explain the tail. In fact, the magnetization of a material is influenced by its history and this can be modeled by a hysteresis loop. However, it is very hard to include that in software like OPERA. To compensate, we tried to simulate a 50 G remnant field by adding 50 G to all B values in the quads and dipole BH curves, however it seemed to have no effect on the field. We are still not sure that OPERA is using the remnant field properly (putting it in the right direction, etc.).

4.4 Scaling the Dimensions of the Yoke Box

We thought that the doors might be distorted by the large force coming from the 2T magnetic field. We considered bringing the doors in by a few millimeters on each side in OPERA. However, for technical reasons, we scaled the box in z instead of translating the doors. Since the yoke is around 280cm long and we wanted to remove a few millimeters, the scaling factor due to this change was very close to one. Thus, this did not affect significantly the thickness of the doors. On the next figure one can see the effects of this scaling on the field along the z axis. We are starting with the old model with quads and dipole, BH 100.

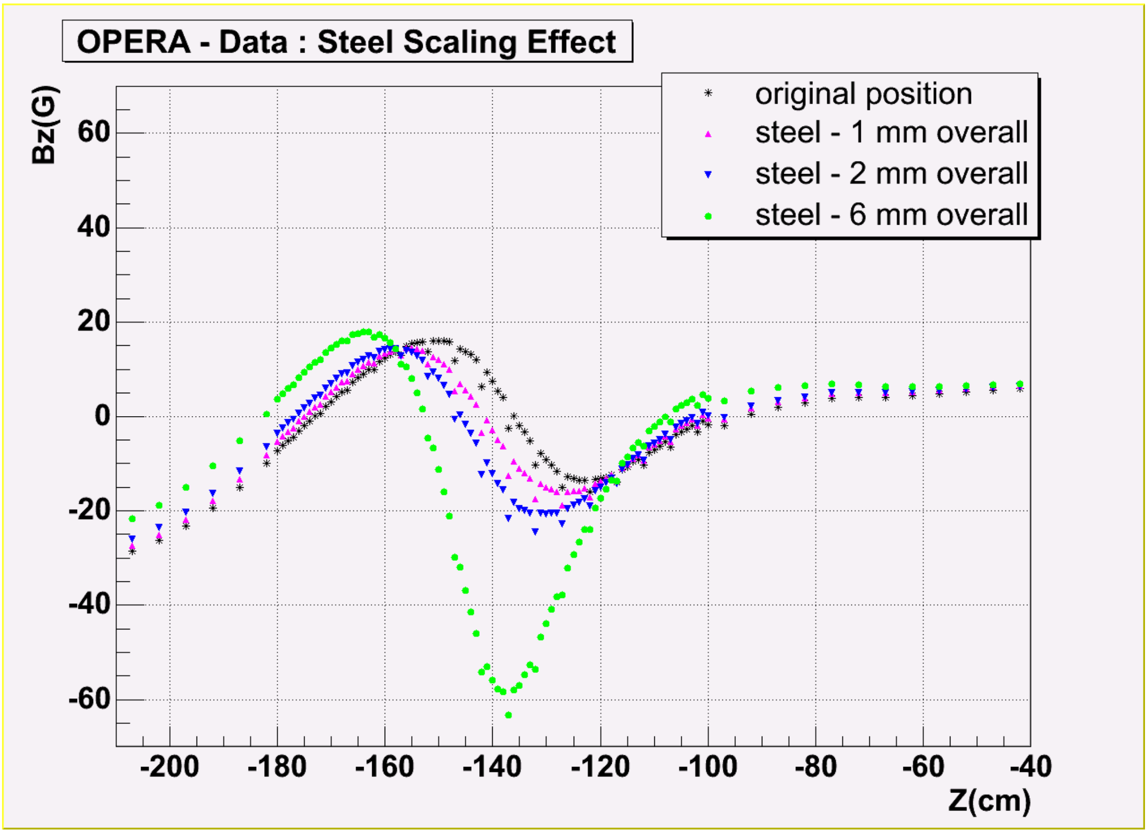

Figure 8: Steel scaling effect along the z axis. (databases 12 (steel -1 mm), 7 (steel – 2 mm) and 8 (steel – 6 mm) are shown)

As shown in figure 8, scaling the steel box by a few millimeters overall (0.5 mm or 1 mm at each end) has a neutral effect. It mainly displaced the kink without flattening it.

However, scaling the dimensions of the yoke by 6 mm overall increases the kink dramatically. Figure 9 shows the effect of this parameter away from the axis.

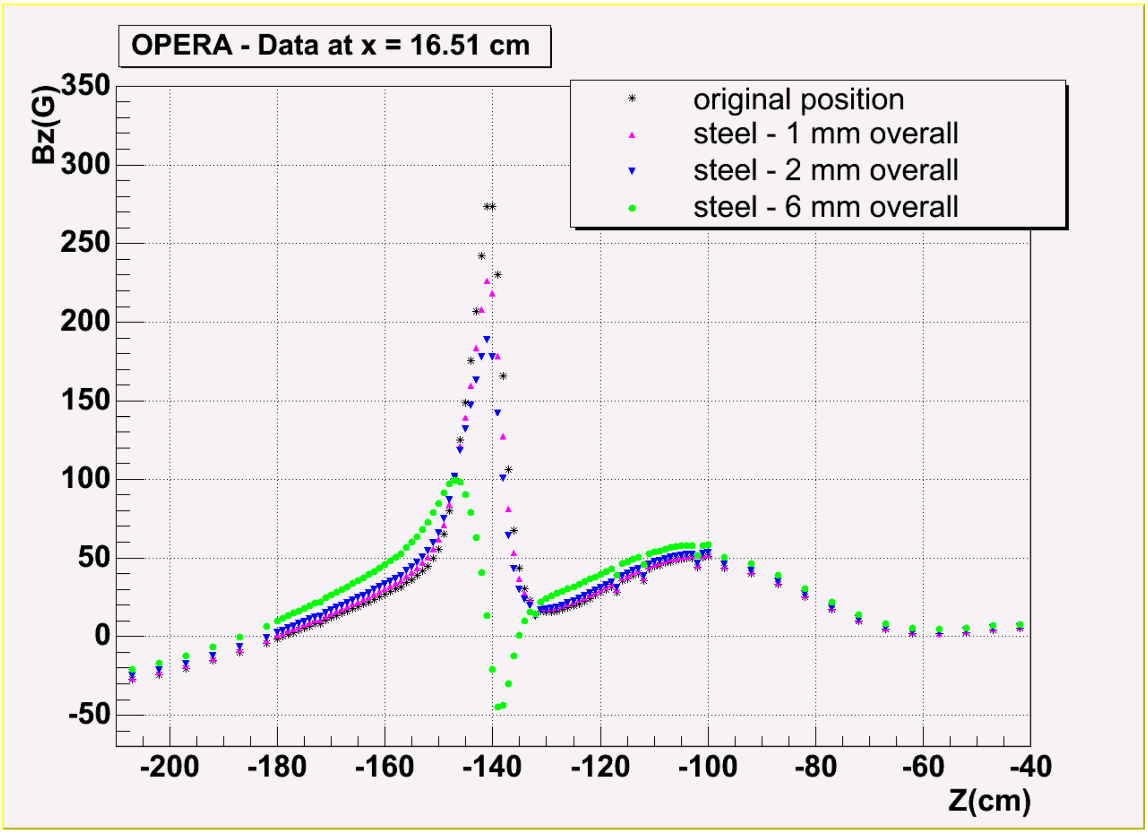

Figure 9: Steel scaling effect at x = 16.51 cm

Moving the doors closer together brings the peak down. The 6 mm overall factor reduces the difference to 0 at -140 cm, but creates a kink shape around it. Since, as previously mentioned, the field on the z axis for the 6 mm model is unacceptable, we are going to keep the steel in its original position.

4.5 Moving the outer coils

According to the magnet geometry data, the outer coils are located at z = ± 76.695 cm. However, they could be moving by a few millimeters because they are immerged in liquid helium. In fact, in his attempts to match the central field, Roberto found that the outer coils are probably located at z = ± 76.515 cm. When scaling the BH curve we realized that the models with the same outer coil positions, have the same B_z around z = -145 cm independent of the BH curve used (see figure 10). Thus, we tried to bring the difference to zero at that point by moving the outer coils to z = ± 76.443 cm. We chose to give this model a BH curve scaled by 102 %, because it is the one that was expected to look the best when translated down (OPERA generated data was too large everywhere after -145 cm).

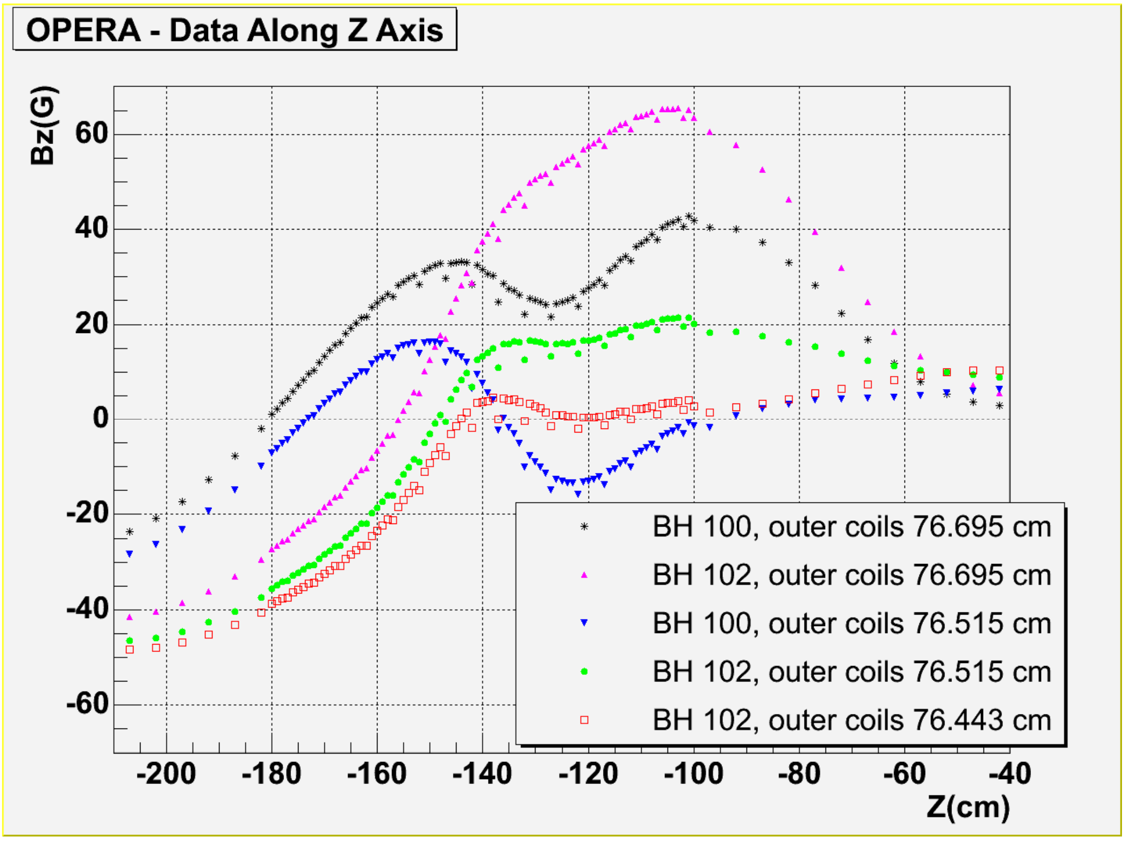

Figure 10: Effect of moving the outer coils (databases 13, 14, 4, 10 and 15 are shown)

As one can see, BH 102 with the coils moved to z = ± 76.443 cm makes things worse around z = -40 cm. And, the closer to the origin, the better the agreement needs to be since the detector is in the middle. Also, as previously noticed, BH 102 has the same peak as BH 100 off axis (no real flattening). So we are going to keep the coils in the old model position (z = ±76.515 cm).

4.6 Changing the radius of the coils

There is also some uncertainty on the radius of the coils. So, we tried adding 0.5 mm and 1 mm to the radius of all the coils (starting with the model containing BH 100 and quads and dipoles). As shown in figure 11, there is no noticeable effect in the upstream region. However there is an interesting effect on the central field. So if we want more accuracy in the central region (already within 5 G in a field of 20 000 G) after the upstream field is under control, the radius would be something to consider.

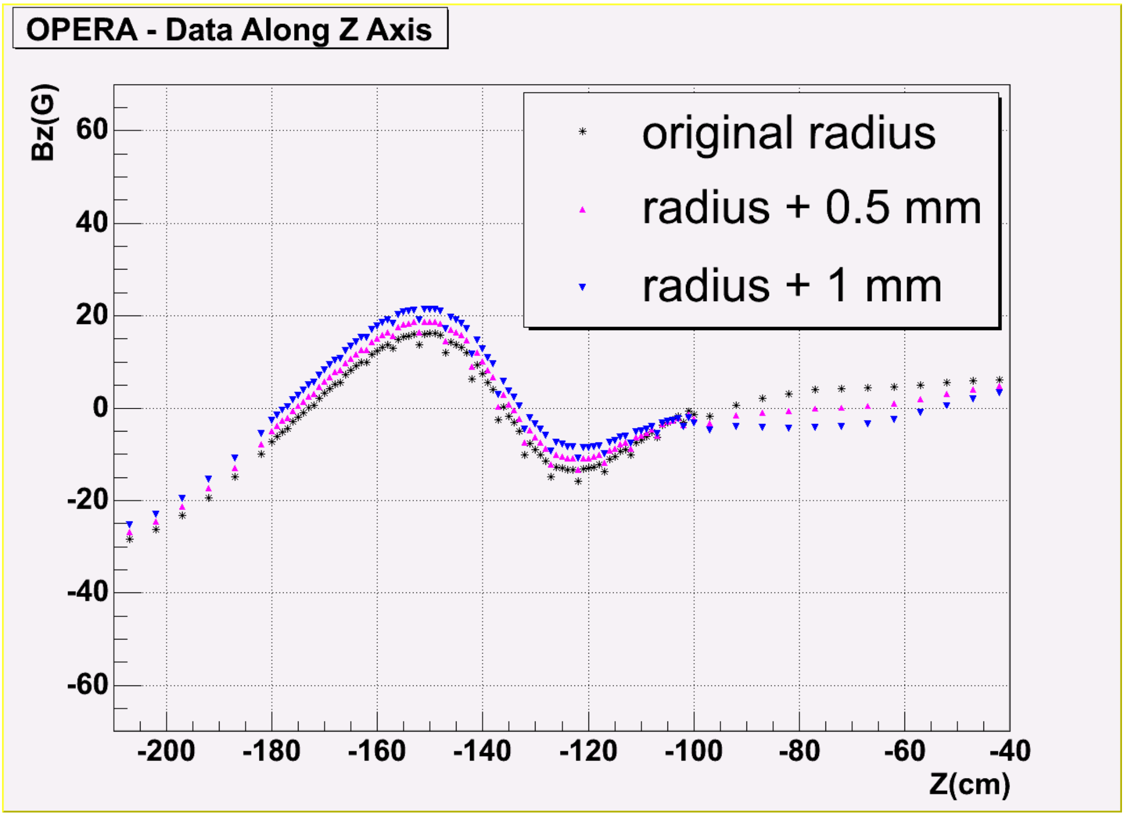

Figure 11: Effect of changing the radius upstream (databases 4, 16 (radius + 0.5mm) and 17 (radius + 1 mm))

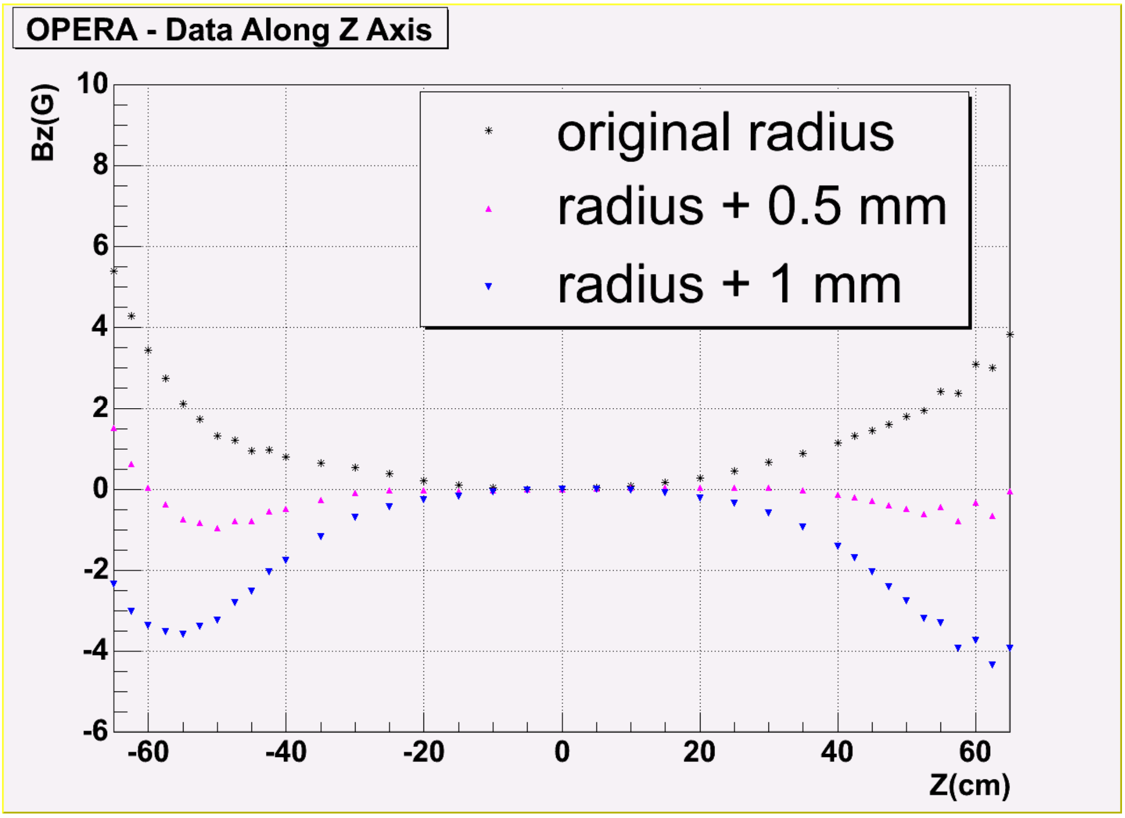

Figure 12: Effect of changing the radius on the central field

5. Measurements Issues

5.1 Is the probe off axis?

After some unsuccessful attempts to modify the model in order to improve the agreement between OPERA and data, we considered the fact that there might be something wrong with the measurements. First, the probe might be off axis. We might have, for example, measured the field at a coordinate shifted by ~1mm in the x-direction from the z-axis instead of along the z-axis. So we compared the data we thought was taken along the z-axis with the OPERA data along an axis parallel to the z-axis, but shifted in the positive x-direction by 1mm, 10 mm, 20 mm, etc. We used the OPERA model with BH 100 and quadrupoles and dipoles. As shown in figure 13, a shift of one millimeter has no effect (the curves are overlapping). In fact, we only notice an effect for shifts of 10 mm or more.

The discrepancies along the z axis are not caused by the measurements having been taken off the axis since a shift of 10 mm is unrealistic. It would be highly unlikely to have taken measurements more than a centimeter away from where they were supposed to be taken without noticing it.

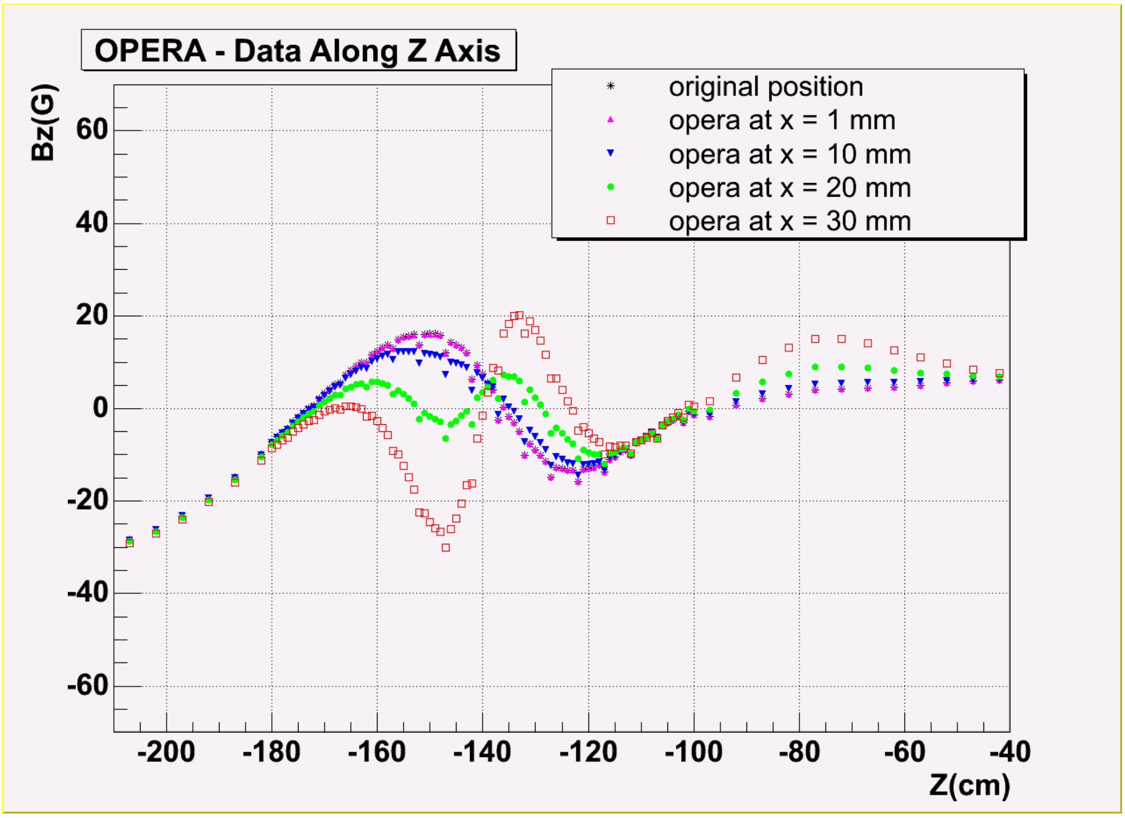

Figure 13: OPERA data along different axis minus the data along the z-axis (all with database 4)

5.2 Is the probe tilted?

In order to explain the discrepancies between OPERA and data in the off axis field, we thought that the probe might be tilted. If the probe is not perpendicular to the z axis, it will not measure B_z, but a combination of B_x, B_y and B_z. However, this could not explain the discrepancies along the z-axis since there is no radial field there. So we tested this idea along an axis parallel to the z-axis and located at x=0 and y=16.51cm. Along this

$$B_{measured} = B_z \cos\theta + B_y \sin\theta$$

axis, there is no x component to the field so a probe titled by an angle θ would measure a field of:

On figure 14, one can see the difference between the $B_{measured}$ for various angles (B_z and B_y coming from the OPERA model with quads and dipoles, BH 100) and the data.

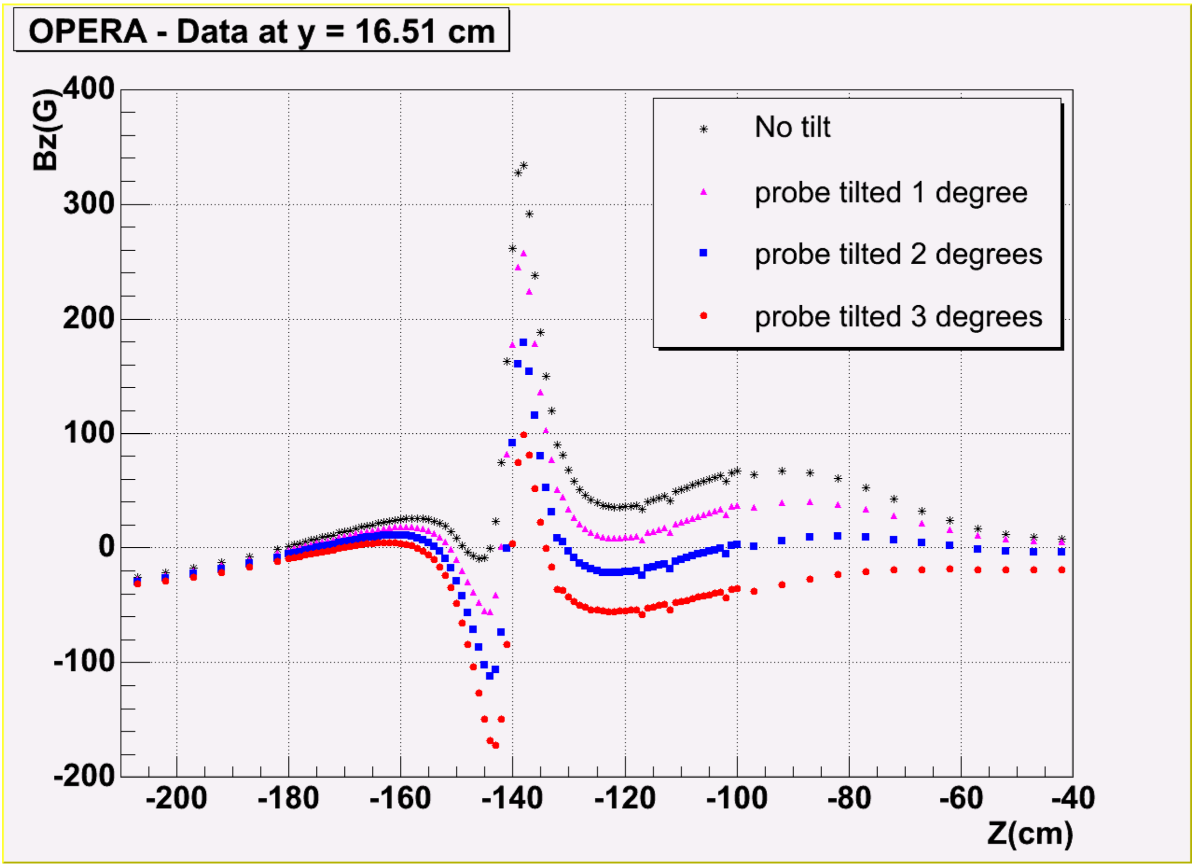

Figure 14: Difference between OPERA and data for various tilts of the Hall probe (database 4 was used)

As expected, the bigger changes occurred in the door area (z=-140cm), since it is where the radial field is the largest (see figure 15). Also, we simulated a tilt in a way that would bring the OPERA generated field down to hopefully decrease the large peak. A small tilt effectively brings the peak down, but it also makes the field too low around z=-145cm.

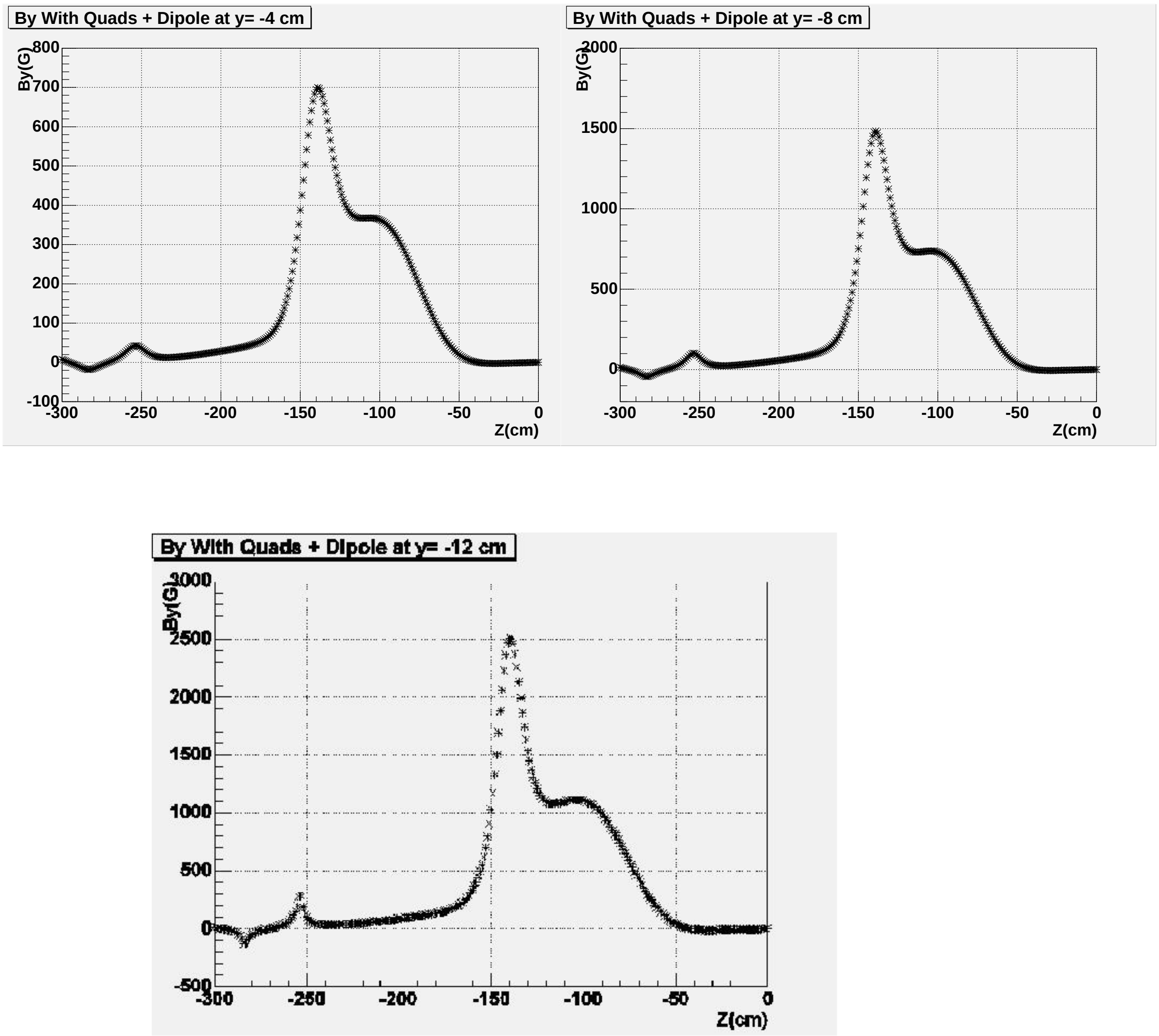

Figure 15: Plot of B_y vs z at various y positions: the radial component of the field is the largest in the door area (data from database 4)

5.3 Field asymmetry study

The magnetic field is created by a solenoid which is located in a rectangular yoke. In principle the measured field should be symmetric around the XZ and YZ planes. Yet, as shown on figures 16 and 17, that does not appear to be the case.

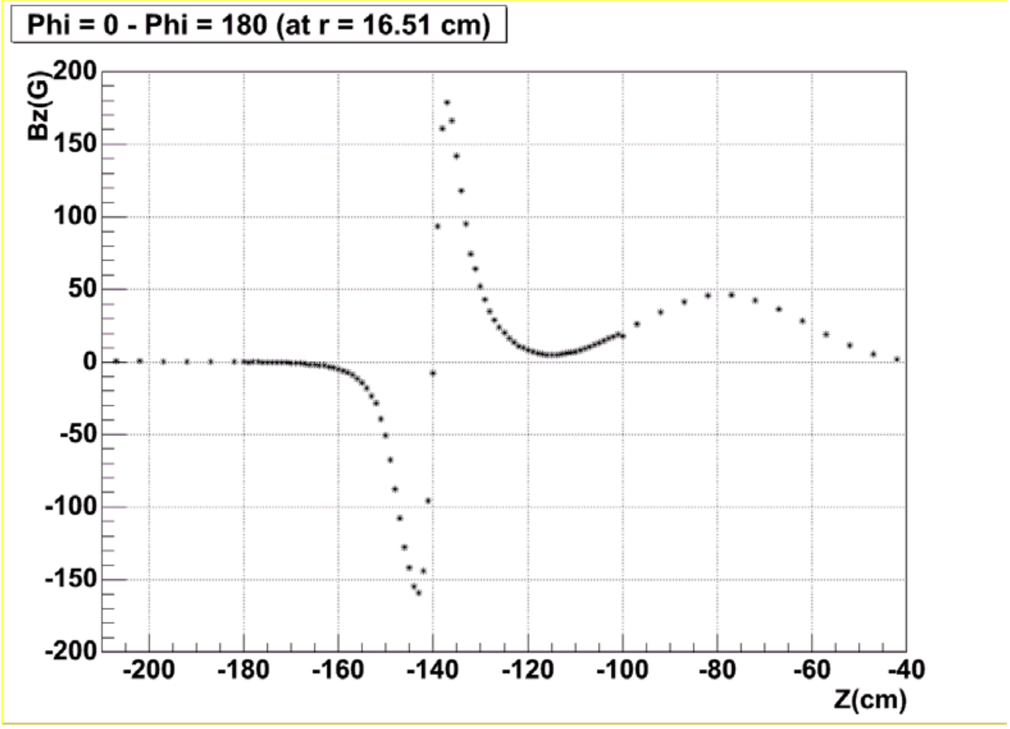

Figure 16: Difference between the B_z measured at x = +16.51cm (phi = 0°) and the one measured at x = -16.51cm (phi = 180°)

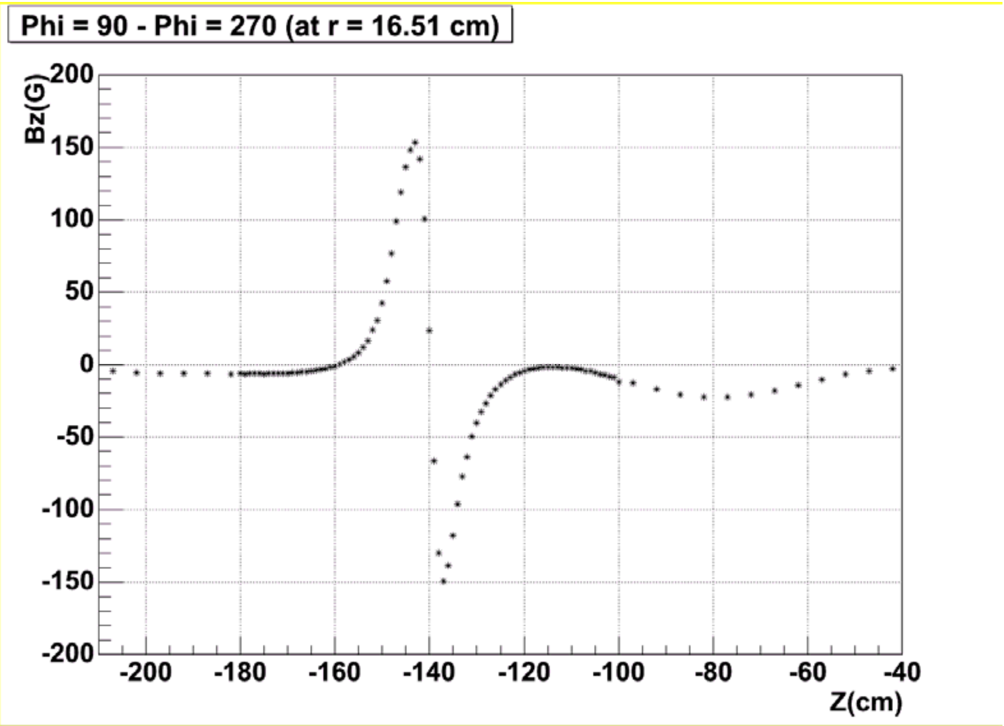

Figure 17: Difference between the B_z measured at y = +16.51cm (phi = 90°) and the one measured at y = -16.51cm (phi = 270°)

First we hypothesized that this asymmetry could be explained by a large gradient in B_z around this area (see figure 18). The slope at z = -140 cm is around 1200 G/cm, so a z position uncertainty of 1 mm would result in a 120 G uncertainty on B_z. This is before considering $\frac{\partial B_z}{\partial x}, \frac{\partial B_z}{\partial y}$ and the uncertainty of the probe itself!

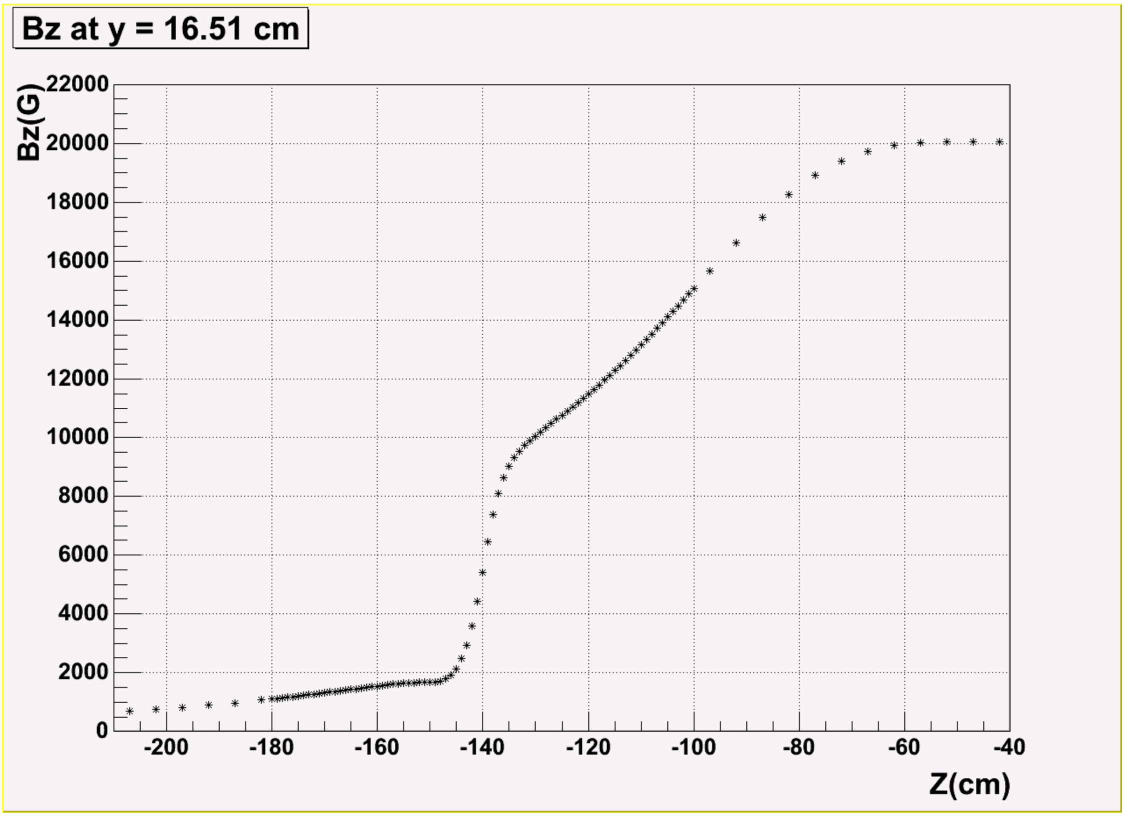

Figure 18: B_Z at y = 16.51cm; the slope is huge in the door area

However, we later realized that the arm center was not located at (x, y) = (0, 0), but at (x, y) = (+0.3753cm + 0.0001926*z cm, -0.14 cm) [2]. As expected from the study reported in section 5.1, this has no effect on the field along the z-axis. Yet, the displaced arm center could explain the asymmetry off the axis. To simulate its effect in OPERA, we extracted from the software the field along two axes. The first axis went from z (cm) = -210 to z = -40 (as usual), but with x (cm) = 0.3753 + 0.0001926*z and y = 16.37cm. The second axis had the same z and x coordinates as the first one, but was located at y = -16.65cm. We then subtracted the field values along the second axis from the field values along the first axis. As you can see, figure 19 is similar to figure 17. The agreement indicates that the apparent asymmetries in the measured field were caused by the off axis arm center.

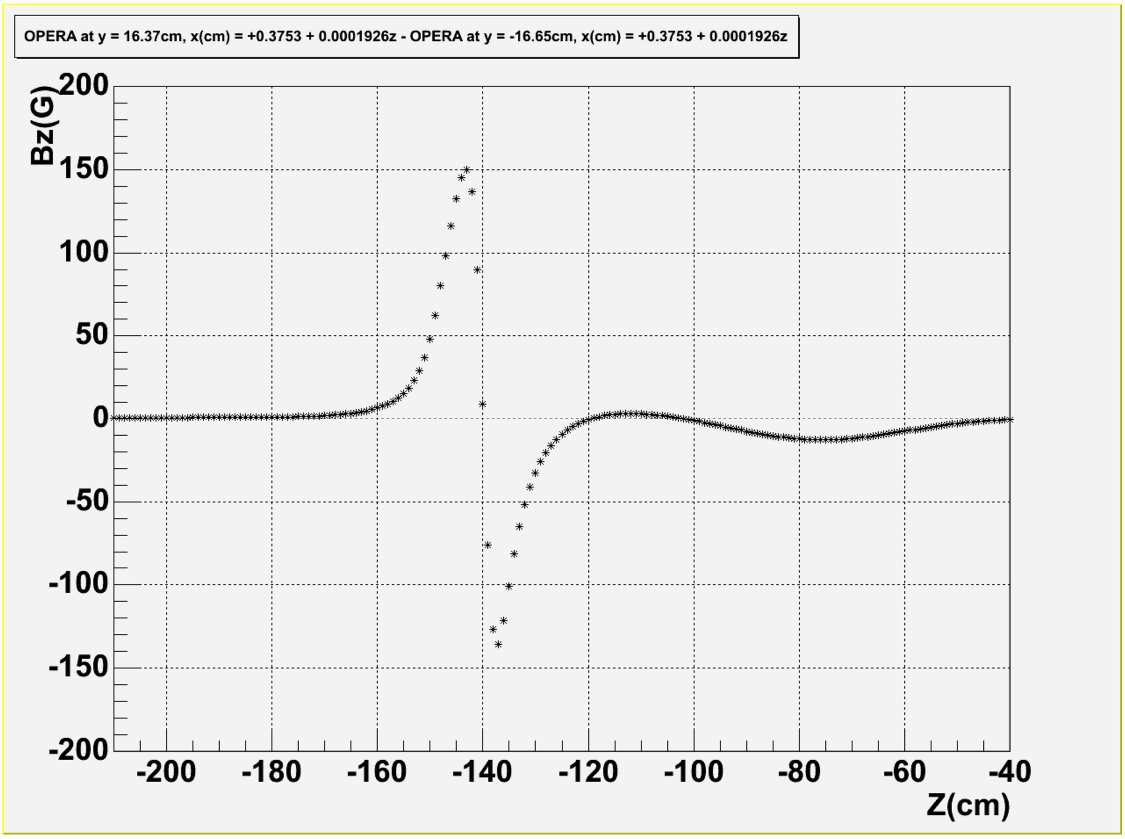

Figure 19: The asymmetry reproduced in OPERA

Encouraged by this success, we plotted again the difference between OPERA and data using the OPERA B-field values along the shifted axis. Unfortunately, as can be seen on figure 19, this study did not solve the discrepancies by itself.

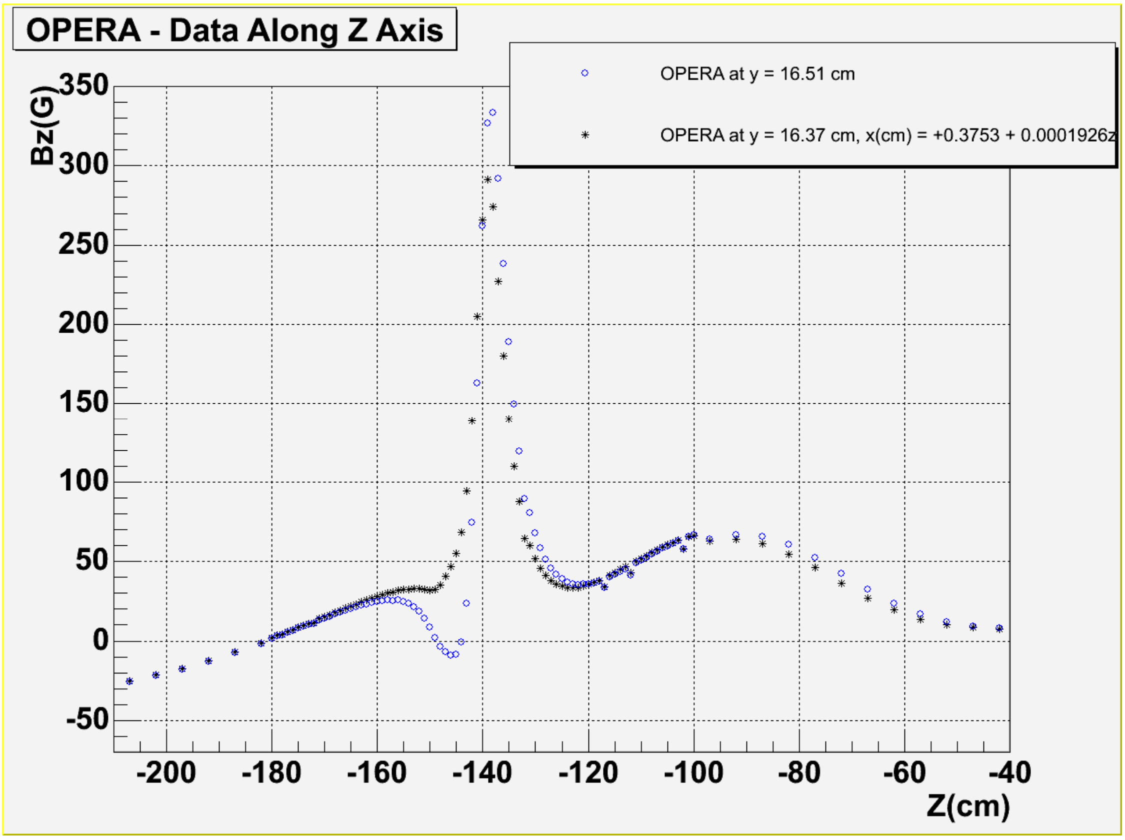

Figure 20: The off centered probe does not explain the discrepancies by itself (database 4 was used)

6. Effect of the Magnetic Field on the Muons Polarization

In order to investigate how closely the agreement between OPERA and measured data needs to be in order to reach a precision on the polarization of a few 10^{-4}, we ran GEANT simulations (see instructions in appendix) with different field maps. Due to time restrictions, we used OPERA to calculate a field on a plane (x = 0, y (cm) = - 30 to 0, z (cm) = -300 to 150) and assumed radial symmetries in the GEANT simulations here. Calculating a plane takes 15 hours, while the full map takes 30 days. Yet, to make sure that this would give realistic results, we made a phi-symmetric version of the current default map (bfld_map.00012 which is the same as field_map.0007 [1]) and compared the polarization with that of a full field map (map 1 vs map 2 in table 1 and 2). The mean polarization values are listed below for post October 2002 and 2003 beam tunes. We also took the mean over two different region (the muon polarization from 0.75 to 1 and from 0.9 to 1) in order to make sure that a few events far from the mean were not responsible for the change.

Map	h71 (from 0.75 to 1)	h70 (from 0.9 to 1)
Without quads and dipole, BH 100 (full map)	0.98797	0.98800
Without quads and dipole, BH 100 (phi-symmetric map)	0.98791	0.98795
With quads and dipole, BH 100 (phi-symmetric map)	0.98815	0.98819
With quads and dipole, BH 98 (phi-symmetric map)	0.98834	0.98802
With quads and dipole, BH 102 (phi-symmetric map)	0.98798	0.98802
With quads and dipole, steel – 6 mm (phi-symmetric map)	0.98808	0.98811
Maximum difference	$4.3 * 10^{-4}$	$2.4 * 10^{-4}$

Table 1: Mean polarization for post October 2002 beam tune

Map	h71 (from 0.75 to 1)	h70 (from 0.9 to 1)
Without quads and dipole, BH 100 (full map)	0.99759	0.99758
Without quads and dipole, BH 100 (phi-symmetric map)	0.99757	0.99758
With quads and dipole, BH 100 (phi-symmetric map)	0.99763	0.99764
With quads and dipole, BH 98 (phi-symmetric map)	0.99765	0.99767
With quads and dipole, BH 102 (phi-symmetric map)	0.99761	0.99763
With quads and dipole, steel – 6 mm (phi-symmetric map)	0.99764	0.99766
Maximum difference	$0.8 * 10^{-4}$	$0.8 * 10^{-4}$

Table 2: Mean polarization for 2003 beam tune

The statistical error was calculated by dividing the RMS by the square root of the number of events. It is on the order of $0.5*10^{-4}$ for the post October 2002 beam tune and about $0.1*10^{-4}$ for the 2003 beam tune. Also, the 2003 beam tune is the one that is going to be used for Pμξ calculations since the beam was better controlled in this tune. One can see on table 2 that the polarization values agree to the 10^{-4} level for all maps. Even though further studies will be needed, it seems that our map is already good enough upstream for the second phase of the *TWIST* experiment (10^{-4}).

7. Full Model

As previously mentioned, we are presently using a quarter model in OPERA. However, Roberto found that the coils may be centered at (x, y) = (-0.154cm, -0.183cm) instead of (x, y) = (0, 0) [1]. It is, of course, impossible to include those shifts in our present model. Also, we have tried every symmetric parameter changes we could think of. For those reason, it is time to move on to working with a full model. Unfortunately we are having many problems with this model, such as meshing and memory allocation issues. We are presently working with OPERA technical support on solving them.

6. Conclusion

In order to improve the agreement between OPERA and measured data, we studied the effect of many model parameters such as:

- The quadrupoles and dipoles
- The BH curve
- The steel door positions
- The outer coil positions
- The coil radii

We also considered the effects of a tilted probe and of an off centered probe (arm). However, none of these changes solved the discrepancies by itself.

Presently, our best quarter symmetric model is BH 100 with quads and dipoles. As one can see below, this model matches the measured field to 30 G (or 4 %) at z = -200 cm.

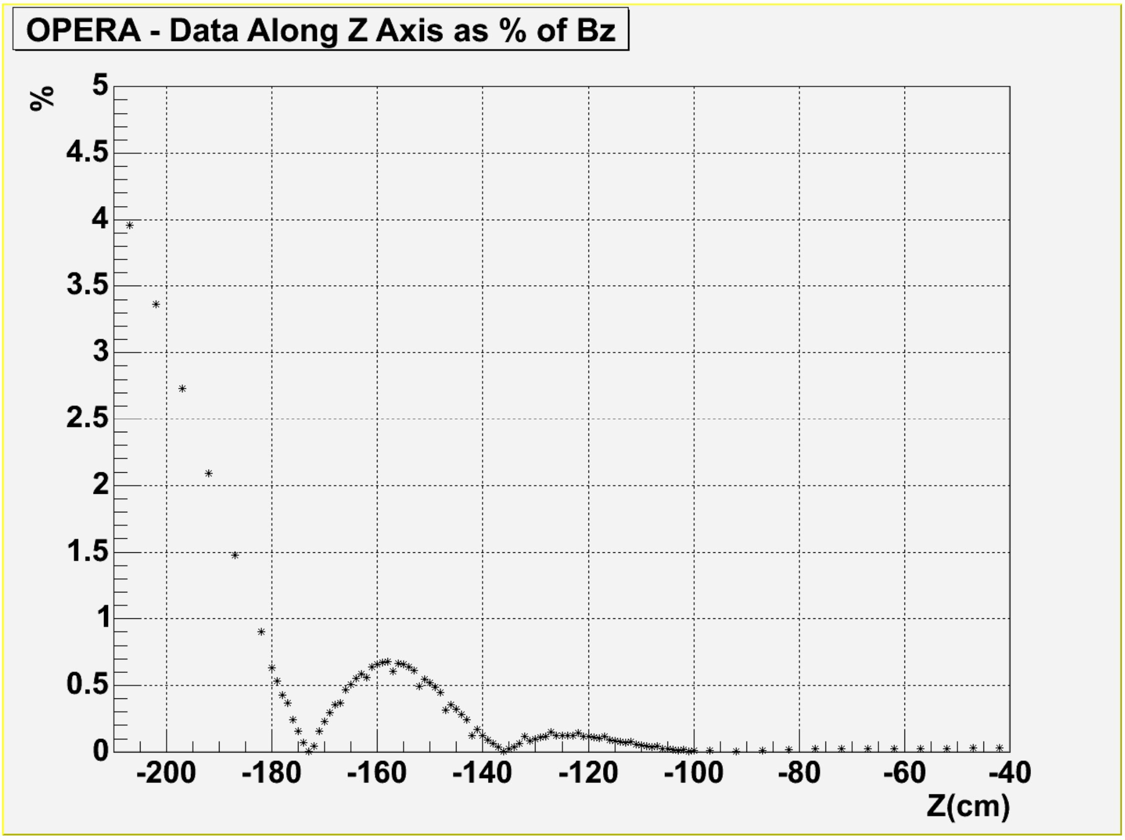

Figure 21: The OPERA simulation agrees with data to a factor of 4 %

We also found that the effect of the magnetic field on the muon polarization seems to be small at the level of our discrepancies.

7. Recommendations

In light of this summer upstream magnetic field study, the following suggestions can be made:

- Conduct further Monte Carlo studies and decide whether the agreement is good enough upstream for the second part of the experiment.
- Study the effect of shifts in x and y with the full model.
- Take measurements downstream and compare the discrepancies with the upstream tail.

References:

[1] Roberto Armenta, “TWIST Magnet: Field Map Study Final Report”, TRIUMF, August 2002.

[2] Mathieu Simard, “Study of Magnetic field map for TWIST experiment at TRIUMF”, TRIUMF, August 2003.

[3] M. Barnes, M. Fujiwara, D. Gill, G. Marshall, K. Olchanski, private communication, 2004.

[4] R. H. Henrichson, “Magnetic field imaging”, CERN, 8pp.

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[6] OPERA 3D Reference Manual, Vector Fields Ltd., 2002.