TRIUMF E614

TWIST Magnet: Field Map Study Final Report

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Abstract

The purpose of this study was to determine how accurately the magnetic field inside the spectometer is known. To do this, the Hall probe mapper was used to take a series of maps at different field strength settings. The comparison between the OPERA ($field\_map$.0003) and the measured maps that were taken in April of 2002 has been completed and three main discrepancies were found: the measured maps have an upstream-downstream asymmetry of $7Gauss$ that is not predicted by OPERA; the measured field falls faster than $field\_map$.0003 as we move away from the center of the yoke (i.e. field gradient is different as we move away from the center); and the axis of the coils seems to be shifted in x and y by one to two millimeters.

To introduce modifications to correct and study these discrepancies the following new OPERA maps were produced:

Map	Comment on modification
$field\_map$.0004	BH curve
$field\_map$.0005	BH curve + asymmetry + gradient corrections
$field\_map$.0006	BH curve + coil shift of $\Delta x = -1.54cm$ and $\Delta y = -1.83cm$
$field\_map$.0006a	BH curve + coil shift of $\Delta x = -0.154cm$ and $\Delta y = -0.183cm$
$field\_map$.0007	BH curve + coil shift of $\Delta x = -0.154cm$ and $\Delta y = -0.183cm$ + asymmetry + gradient corrections

$field\_map$.0005 is meant to be the new official CFM map to be used by GEANT and MOFIA. Agreement between OPERA ($field\_map$.0005) and the measured field was achieved to within $\pm 5Gauss$ for the region $-600mm \leq z \leq 600mm$ (which covers all the PC and DC chambers) and within $\pm 2Gauss$ for the region $-500mm \leq z \leq 500mm$ (which only covers the DC chambers and the target PC chambers). These uncertainties are representative of the accuracy with which the field is known inside the tracking volume.

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The purpose of this study was to determine how accurately the magnetic field inside the spectometer is known. To do this, the Hall probe mapper was used to take a series of maps at different field strength settings. The analysis of the maps has been completed. This report summarises the work done, the obtained results, and provides some recommendations for future studies.

1 Data Taken

1.1 Combined Maps

All the available mapper files were combined to obtain four maps: one at $19.6kGauss$, two at $20.0kGauss$ and one at $20.4kGauss$. Each map contains the average values of all the measurements that were taken under the same conditions. The mapper files were merged in the following way:

1.1.1 19.6 kGauss Map

File	z	ϕ	Comment
2002-04-25-16-24-22.dat	-650,650,50	0,345,15	19.600 kG, phi misses 200, -7 at 500
2002-04-26-15-52-59.dat	-650,650,50	0,345,15	19.600 kG
2002-04-27-15-23-15.dat	-650,-400,25	0,345,15	19.600 kG
2002-04-28-15-41-16.dat	400,625,25	0,345,15	19.600 kG
2002-05-01-17-19-01.dat	-450,600,50	0,90,15	19.600 kG, NMR(0) and Lock
2002-05-02-10-14-11.dat	-450,700,50	0,180,90	19.600 kG, NMR(0) and Lock
2002-05-02-11-41-00.dat	-450,700,50	0,180,90	19.600 kG, NMR(0) and Lock

1.1.2 20.0 kGauss Map (map without NMR measurements)

File	z	ϕ	Comment
2002-04-17-16-08-51.dat	-650,650,50	0,345,15	120.6 G
2002-04-19-16-56-15.dat	-650,650,50	0,345,15	20.000 kG, phi limit -10.6
2002-04-20-11-48-54.dat	-650,650,50	0,345,15	20.000 kG, phi misses 500,550
2002-04-21-13-00-59.dat	-650,500,50	0,345,15	20.000 kG, phi misses 500, quits
2002-04-22-16-29-03.dat	-650,500,50	0,345,15	20.000 kG, phi limit -6.3, misses 550
2002-04-23-09-27-25.dat	-650,-400,25	0,345,15	20.000 kG
2002-04-23-12-38-21.dat	400,625,25	0,345,15	20.000 kG, phi misses 500

1.1.3 20.0 kGauss Map (map with NMR measurements)

File	z	ϕ	Comment
2002-05-02-15-36-56.dat	-450,700,50	0,180,15	20.000 kG, NMR(0) and Lock
2002-05-03-11-54-28.dat	-450,700,50	0,180,15	20.000 kG, NMR(3.25) and Lock
2002-05-04-10-58-40.dat	-450,700,50	0,180,15	20.000 kG, NMR(3.25) and Lock
2002-05-05-12-51-48.dat	-450,700,50	0,180,15	20.000 kG, NMR(3.25) and Lock
2002-05-05-21-15-34.dat	-450,700,50	0,180,15	20.000 kG, NMR(6.5) and Lock
2002-05-06-09-54-22.dat	-450,700,50	0,180,15	20.000 kG, NMR(6.5) and Lock
2002-05-06-15-19-08.dat	-450,700,50	0,180,15	20.000 kG, NMR(6.5) and Lock

1.1.4 20.4 kGauss Map

File	z	ϕ	Comment
2002-04-23-17-22-59.dat	-650,650,50	0,345,15	20.400 kG, phi misses 500
2002-04-24-09-56-34.dat	-650,-400,25	0,345,15	20.400 kG
2002-04-24-13-36-05.dat	400,625,25	0,345,15	20.400 kG, phi wanders
2002-04-24-17-39-16.dat	-650,650,50	0,345,15	20.400 kG

1.2 Volume of Interest

The maps cover the cylindrical region defined by

$$\begin{array}{rcccl} -650mm & \leq & z & \leq & 650mm \\ 0\,\text{deg} & \leq & \phi & < & 360\,\text{deg} \\ 0mm & \leq & r & \leq & 247.56mm \end{array} \tag{1}$$

in standard TWIST coordinate system (with ϕ measured from the positive x-axis).

The data is spaced at intervals of $50mm$ in z, $15\,\text{deg}$ in ϕ and $41.3mm$ in r (the r figure corresponds to the spacing between Hall probes in the arm of the mapper). At least two measurements were taken at each point at different times. As a reminder, PC plane #1 is located at $z = -59.73mm$ and PC plane #12 is located at $z = 59.79mm$.

1.3 Calibration

Since the calibration of the Hall probes varies drastically every time the power is turned off, the probes were calibrated using a NMR probe; the calibration values were obtained at $z = 0mm$. The reproducibility of the Hall Probes is within $\pm 0.25 Gauss$ while the reproducibility of the NMR probe is within $\pm 0.05 Gauss$.

Since NMR probes measure the total magnitude of the field, and Hall probes measure only the z component of the field, a study was made to determine the impact of this difference on the calibration. The study was carried out in OPERA, and it demonstrated that

$$|B| - |B_z| \;\leq\; 10^{-6} kGauss \tag{2}$$

within the volume

$$\begin{array}{rcccl} -200mm & \leq & z & \leq & 200mm \\ 0\,\text{deg} & \leq & \phi & < & 360\,\text{deg} \\ 0mm & \leq & r & \leq & 247.56mm \end{array}\;, \tag{3}$$

where the calibration was taken.

1.4 Error Analysis

Since at least two points were available at each point covered by all four maps, standard deviations [1] were obtained at each point for each of the four maps. For most points, the values turned out to be in the order of $0.25Gauss$. The standard deviation in the measurements has probe dependence, and to show this, an average value of the standard deviation per probe was obtained by averaging the standard deviation of all the available measurements. The results are

$$\begin{array}{lcccl} \text{Probe 1} & : & \sigma_1 & = & 0.1925Gauss \\ \text{Probe 2} & : & \sigma_2 & = & 0.1974Gauss \\ \text{Probe 3} & : & \sigma_3 & = & 0.2265Gauss \\ \text{Probe 4} & : & \sigma_4 & = & 0.2073Gauss \;, \\ \text{Probe 5} & : & \sigma_5 & = & 0.2015Gauss \\ \text{Probe 6} & : & \sigma_6 & = & 0.2334Gauss \\ \text{Probe 7} & : & \sigma_7 & = & 0.2827Gauss \end{array} \tag{4}$$

where Probe 1 is the probe at the center of the mapper and Probe 7 is the outermost probe in the arm. Note that the highest value corresponds to Probe 7 and the smallest one corresponds to Probe 1.

As stated in the previous subsection, all probes were calibrated using a NMR probe; however, for reasons not fully understood, a poor calibration for Probe 2 was obtained. The rest of the probes have relatively good calibrations. Probe 2 had to be calibrated from an interpolation of the measurements in the remaining probes.

These standard deviations represent only the constraint in the reproducibility of the measurements. To obtain the final uncertainties, the error in the calibration (plus the error in the interpolation if applicable) has to be considered. It was concluded that in order to obtain consistent results, a criteria of at least plus-minus four average standard deviations (i.e. $\pm 4\sigma_i$ for $i = 1, 2, ..., 7$) must be used to give a final uncertainty for each probe. Using this criteria, it can be said that **most values in the measured maps can be trusted to** $\pm 1Gauss$. As will be shown later, if a criteria that produces smaller uncertainties is used, the measured maps present features that are unlikely to be real.

2 Shape of Measured Field Maps

Before discussing any features of interest produced by the analysis, a review of the measured field shape is presented to familiarize the reader with some features of the field that play a relevant role in the discussion ahead. For simplicity, only the $20.0kGauss$ field is presented, but the fields at $19.6kGauss$ and $20.4kGauss$ present the same general shape.

2.1 Field Variation as a Function of z

The various plots in Figure 1 show the measured B_z component of the $20.0kGauss$ field map as a function of z for different (x, y) points moving up in the positive y direction; all the

[1] Standard deviations were calculated in the following way:
For each (x, y, z) point, $\sigma^2_{(x,y,z)} = \frac{1}{n-1}\sum_{i=1}^{n}(B_i - \overline{B})^2$, where i represents each of the n available measurements at each (x, y, z) point.

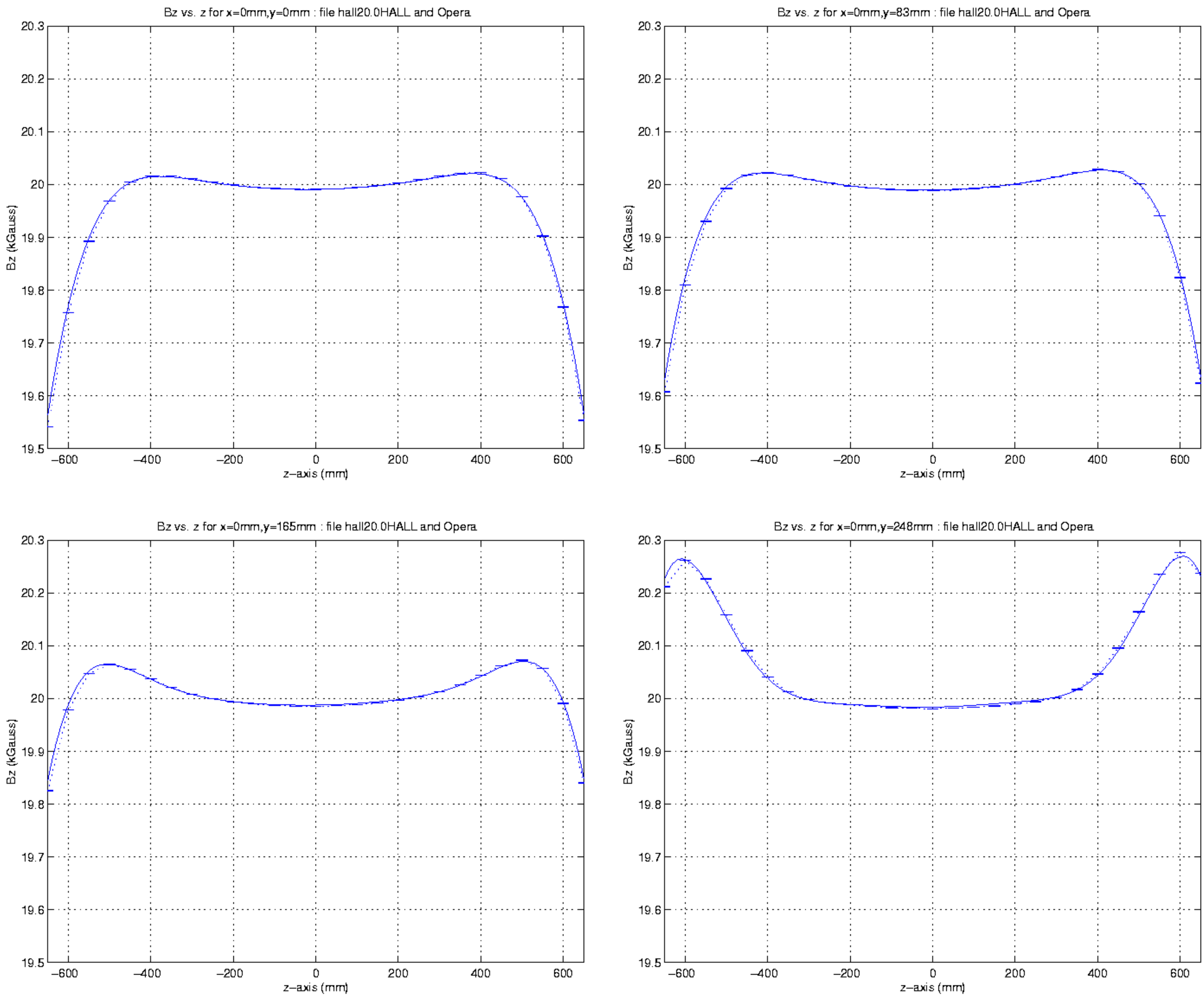


Figure 1: B_z vs. z plots for measured 20.0kGauss map (without NMR measurements) for various positions along the y-axis. All plots are in the same scale.

plots have the same scale and correspond to positions of the first, third, fifth and seventh probes respectively. The dashes represent the location of the measurements and the solid line represents a polynomial fit of the function $f(x) = ax^4 + bx^3 + cx^2 + dx + e$ to the measurements. This shape with "lobes" at $z = \pm 400mm$ is characteristic of all (x, y) points; note that the height of the lobes with respect to the field value at $z = 0mm$ increases as we move outwards in r.

2.2 Field Variation in the Radial Direction

To analyze the field variation as a function of r, the field map can be divided into three main regions:

$$\begin{array}{lclcccl} \text{Region 1} & : & -650mm & \leq & z & < & -325mm \\ \text{Region 2} & : & -325mm & \leq & z & \leq & +325mm\ . \\ \text{Region 3} & : & +325mm & < & z & \leq & +650mm \end{array} \tag{5}$$

The reason for dividing the map into three regions is that the field has inflection points at roughly $z = \pm 325mm$, and the pattern of the field as a function of r changes drastically in these three regions. Figure 2 shows five two-dimensional plots that show how the field varies as a function r (and ϕ) in each of the three different regions. The plot at the top of the figure shows a typical plot of the field in Region 2; the two plots at the center show the field at the inflection points; and the two plots at the bottom show the field in regions 1 and 3 respectively. The five plots have the same scale for all the three dimensions and the B_z-axis covers a range of $70Gauss$.

The plot at the top of Figure 2 shows the field in the center of Region 2 (i.e. $z = 0mm$). At $z = 0mm$, the field is roughly flat and smooth with a difference between its maximum and minimum value of roughly $11Gauss$. As we move away from the center of Region 2 towards Region 1 or 3, the overall field increases and the center values of the field increase faster than the values at the edge forming a central plateau at $z = \pm 325mm$ (see the two plots at the center of Figure 2). At $z = \pm 325mm$ the difference between the maximum and minimum value is roughly $20Gauss$.

As we move away from the boundaries at $z = \pm 325mm$ into regions 1 and 3, the values at the edge of the mesh plots tend to be higher than the values at the center forming a cone (see the two plots at the bottom of Figure 2). The difference between the maximum and minimum value in the two plots at the bottom of Figure 2 is roughly $35Gauss$. As we move in z towards the outer edges of regions 1 and 3, the field preserves the same conical shape shown in the two plots at the bottom of Figure 2, but the difference between the maximum and minimum value of the field can be as large as $250Gauss$.

3 Current OPERA Model

The CFM field map that is for use in GEANT and MOFIA is $field\_map$.0003. This map is based on the as built geometry of the spectrometer and corresponds to the OPERA map generated by Mike Barnes in May of 2002. The OPERA model used to generate this map is:

E614_iron_cube5b_YZ_noreg_X+0_Y+0_Z+0_221A_BH106_BHus106_BHds106.op3.

This model has been presented in previous reports and assumes a coil current of $221A$, which generates a field perfectly symmetric about z with center B_z value of $20.039kGauss$.

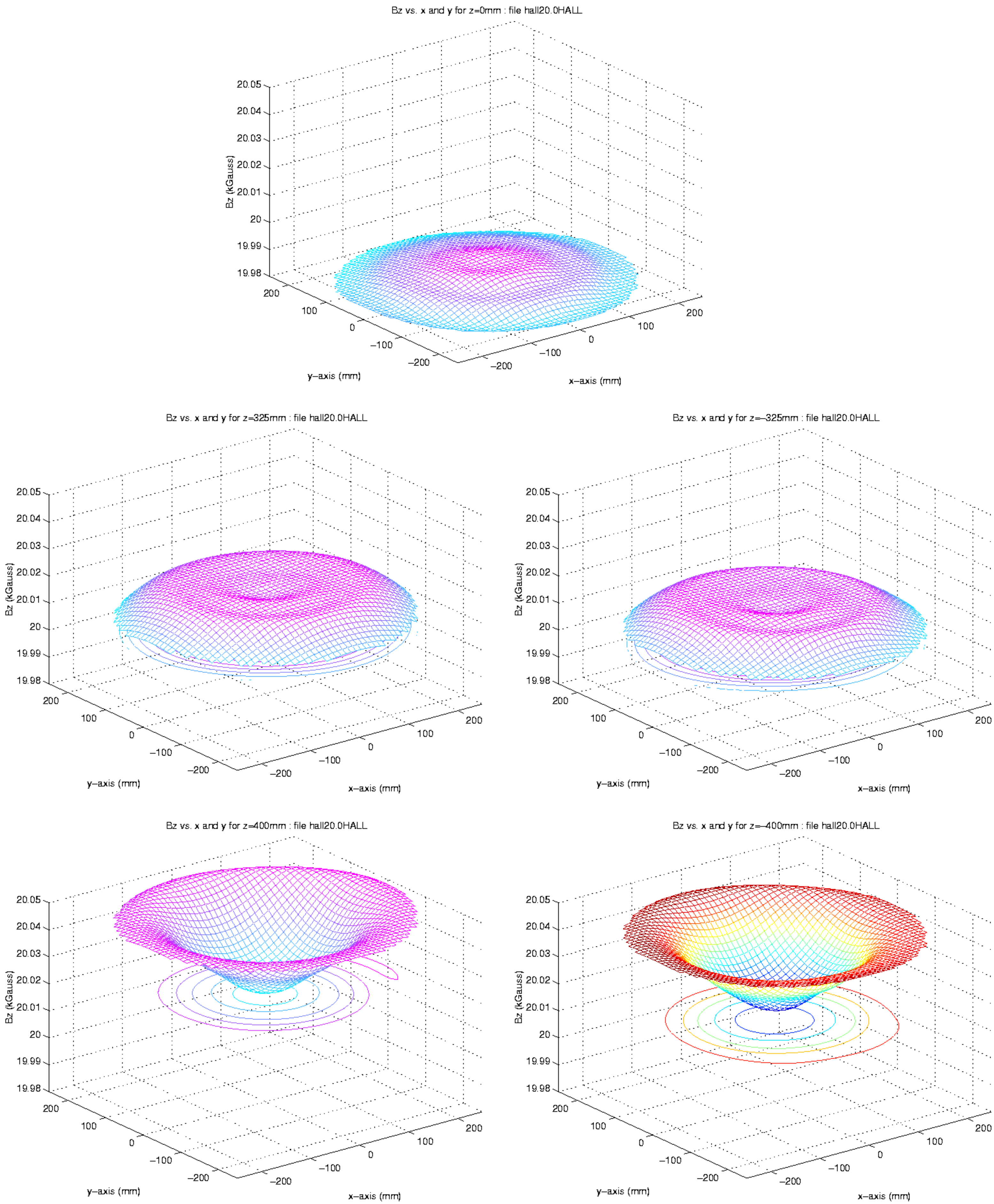


Figure 2: Mesh plots for measured $20.0kGauss$ map (without NMR measurements). All plots are in the same scale.

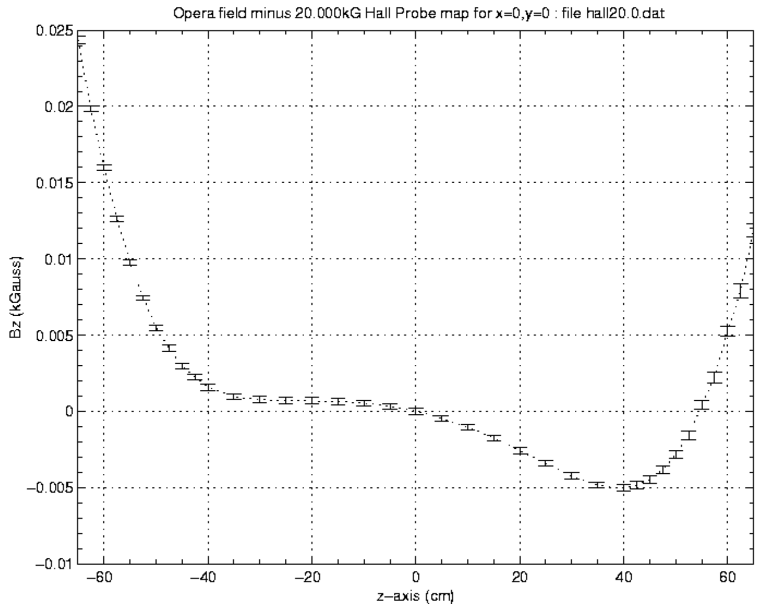


Figure 3: B_z vs. z for OPERA $field\_map$.0003 minus measured $20.0kGauss$ (map without NMR measurements) at $x = 0mm, y = 0mm$.

The same model that was used to generate $field\_map$.0003 was used to generate maps at $20.4kGauss$ and $19.6kGauss$ for comparison purposes. All four measured maps at the three different field strength values were compared with OPERA maps. In the next section, results are presented only for the comparison between $field\_map$.0003 and one of the $20.0kGauss$ maps. Similar results hold for the $20.4kGauss$ and $19.6kGauss$ maps and the extra relevant information is included in section 5.

Out of the two $20.0kGauss$ maps, only one covers the entire tracking volume (the map that was taken without NMR measurements). The comparison at $20.0kGauss$ was based mainly on this map; the other $20.0kGauss$ map (the one with NMR measurements) was used only to do a consistency check.

4 Comparison between current OPERA model and 20.0kGauss Measured Map

4.1 Comparison along the z-axis

Figure 3 presents a difference plot for $field\_map$.0003 and the measured field map as a function of z for the point $x = y = 0mm$. The error bars in the plot represent plus-minus one standard deviation in the values obtained for a given point; the plot is normalised at $z = 0$. There are three features of this plot that deserve highlights. First, note that the measured field has an **upstream-downstream asymmetry** of about $7Gauss$. Second, note that as we move away from the center towards $z = \pm 600mm$, the **measured field falls much faster than predicted by OPERA**; an OPERA study demonstrated that two main variables dominate this effect: the BH curve of the yoke and the position of the two sets of outer coils with respect to the z-axis. Third, note that the error bars in the measurements increase for values close to $z = 600mm$; this is due to a mechanical problem in the positioning of the mapper which was significant enough to slightly increase the standard deviation of the measurements.

Now, for completeness, Figure 4 presents how the difference between $field\_map$.0003 and the measured field for different (x, y) points moving radially outwards. The figure is composed of four plots, all on the same scale. The upper-left plot in Figure 4 corresponds to the plot shown in Figure 3. The upper-right, lower-left and lower-right plots present difference plots for positions corresponding to the third, fifth and seventh probes respectively. Note how the measured field map is quite irregular as we move outwards in the radial direction.

4.2 Comparison in the Radial Direction

Figure 5 shows three plots of B_z vs. r at $z = 0, +400$ and $-400mm$ respectively. The plots have two solid lines, one represents the OPERA map (the perfectly symmetric one) and the other represents a fit of $f(x) = ax^4 + bx^3 + cx^2 + dx + e$. Note that the apparent irregularity in the measured field shown in the upper plot of Figure 5 is just a calibration artifact. Considering the smoothness of the calibration independent measurements (i.e. measurements along the z-axis), it is very unlikely that this irregularity is a true feature of the field.

4.3 Map Scaling

As a remark, to be able to compare $field\_map$.0003 with the measured map, $field\_map$.0003 was scaled to match the value of the measured map at the center value. This scaling assumes that for a factor very close to one, OPERA generated fields scale linearly. This is a safe assumption that was demonstrated in OPERA and that was made because it is not practical to generate an OPERA field that exactly matches the center value of each of the measured fields. OPERA demonstrated that within a rage of $\pm 100 Gauss$ is safe to scale the field up or down without failing to predict the correct shape of the field.

5 19.6 kGauss and 20.4kGauss Maps

As far as the comparisons of the $19.6kGauss$ and $20.4kGauss$ maps are concerned, the only significant result is that the upstream-downstream asymmetry mentioned earlier increases with increasing field.

6 Axis of Symmetry

In theory, the field produced by the solenoid should be perfectly symmetric about z (i.e. no ϕ dependence), and a study was made to determine to what extent the measured maps have this property. For the purpose of this investigation, an axis of symmetry is defined as the (x, y) point where the center of the field lies for every available x-y plane in the measured maps. With this in mind, the results for one of the $20.0kGauss$ maps are now presented. Similar results hold for the $19.6kGauss$ and $20.4kGauss$ maps without any significant differences.

6.1 Axis Profile

To obtain a quantitative approximation of the axis of symmetry, the following technique was used: a polynomial of the type $f(x) = ax^4 + bx^3 + cx^2 + dx + e$ was fit to points corresponding

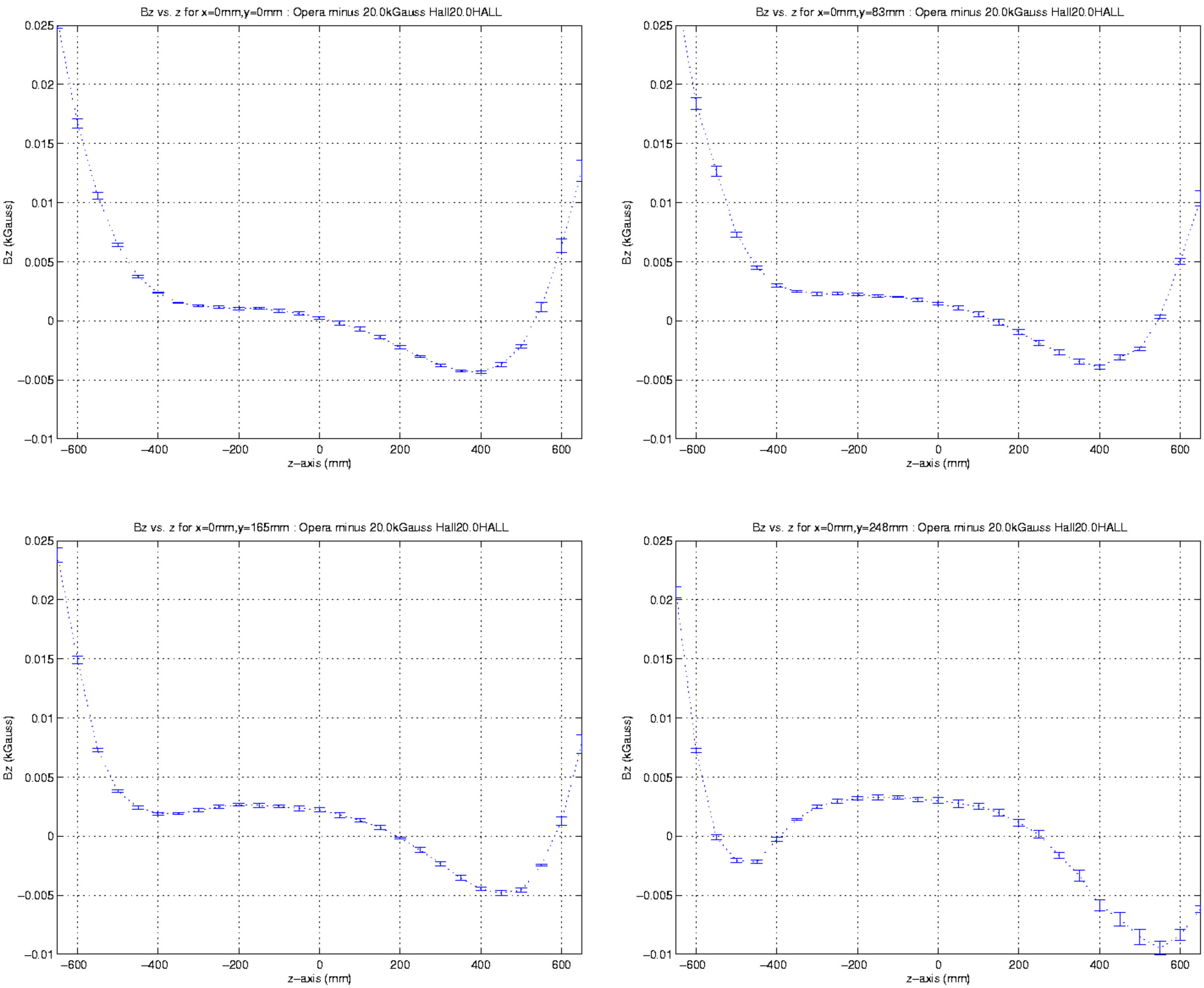


Figure 4: B_z vs. z plots for $field\_map$.0003 minus measured 20.0$kGauss$ map (without NMR measurements). All plots are in the same scale.

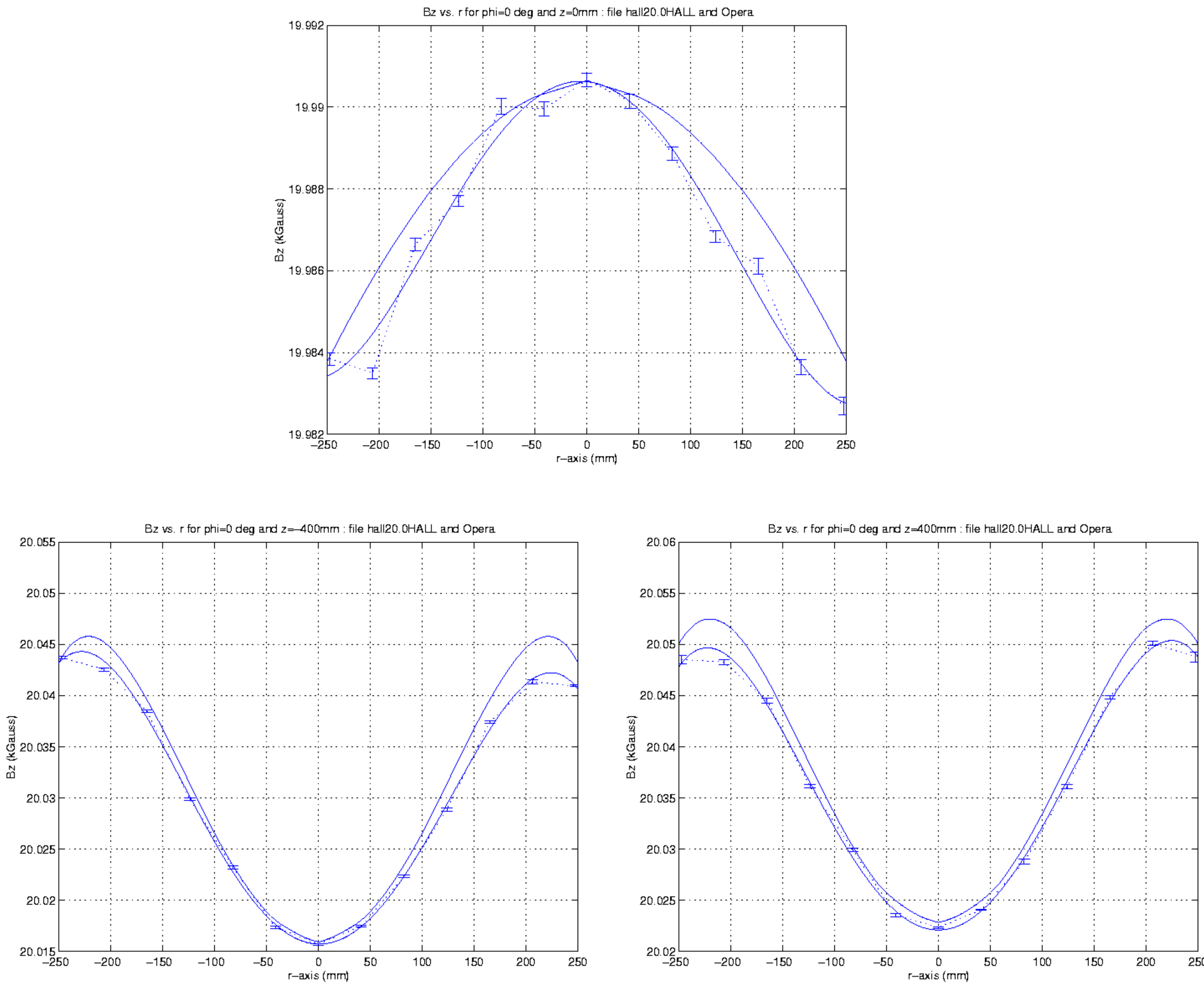


Figure 5: Plots of B_z vs. r at $\phi = 0\,\text{deg}$ and $z = 0, -400$ and $400mm$ respectively. The scale in the upper plot is $2Gauss$ per grid square and the scale in the lower plots is $5Gauss$ per grid square.

to probes 3 to 7 along the x and y axis. Then, the location of the minimum in the fitted polynomial that is closest to $x = y = 0$ was calculated. This was done for each available x-y plane in the measurements. Ideally, this fit should produce a polynomial that is perfectly symmetric about $x = y = 0$, and the shift of the minimum with respect to the center of each x-y plane is a measure of the overall shift in x and y.

The profile for the axis of symmetry obtained this way for the $20.0kGauss$ map is shown in Figure 6. The calculated x and y components of the field center are plotted as a function of z; the plot at the top shows the profile for the x-axis and the plot at the bottom shows the same for the y-axis.

Figure 6 needs some explanation to be interpreted. In the region defined by

$$-325mm \leq z \leq 325mm, \tag{6}$$

where the field shape is dominated by the coils (this has been confirmed in OPERA), the center of the field is shifted in x and y by approximately $\Delta x = -1.54cm$ and $\Delta y = -1.83cm$. Note that both profiles go to very large values at about $z = \pm 350mm$; this does not mean that the center of the axis goes to infinity, it just means that, at the field inflection points ($z = \pm 325mm$), the field center is ill-defined. Figure 6 seems to suggests that physically the coils are shifted in x and y by an amount that is in the order of $\Delta x = -1.54cm$ and $\Delta y = -1.83cm$ [2].

As a remark, better methods have been suggested and can be used to define and calculate an axis of symmetry; however, for the given resolution, the method used was found sufficiently accurate. Other methods (some of which might be more accurate) were used, but the overall conclusion did not change. Because fitting simple polynomials is computationally very easy, the presented technique was used.

6.2 Axis Profile OPERA Study

To determine whether or not the method used to obtain the profile of the axis of symmetry has a real physical meaning regarding the position of the coils, the following OPERA study was made: the coils in the model were shifted in x and y by $\Delta x = -1.54cm$ and $\Delta y = -1.83cm$ as suggested by Figure 6, and the profile of the axis of symmetry was calculated for this model using the same routine that was used for the measured map. This study was carried out only at the $20.0kGauss$ field strength value, and the results are now presented.

The OPERA models used for this study are:

- E614_iron_cube5b_YZ_X+0_Y+0_Z+0_221A_BH10_BHus10_BHds10.op3
- E614_iron_cube5b_XY_X-154_Y-183_Z+0_221A_BH10_BHus10_BHds10.op3
- E614_iron_cube5b_XY_X-015_Y-018_Z+0_221A_BH10_BHus10_BHds10.op3

The three models are fully based on the as built geometry and use the nominal ten-ten steel BH curve. The first model was used to produce a new map named $field\_map$.0004 and it is fully based on the as built geometry; the only difference between the current OPERA model (used to produce $field\_map$.0003) and $field\_map$.0004 is that in the current OPERA model the nominal ten-ten steel BH curve was scaled by a factor of 1.06.

[2] The exact numbers are $\Delta x = -1.54129cm$ and $\Delta y = -1.83495cm$

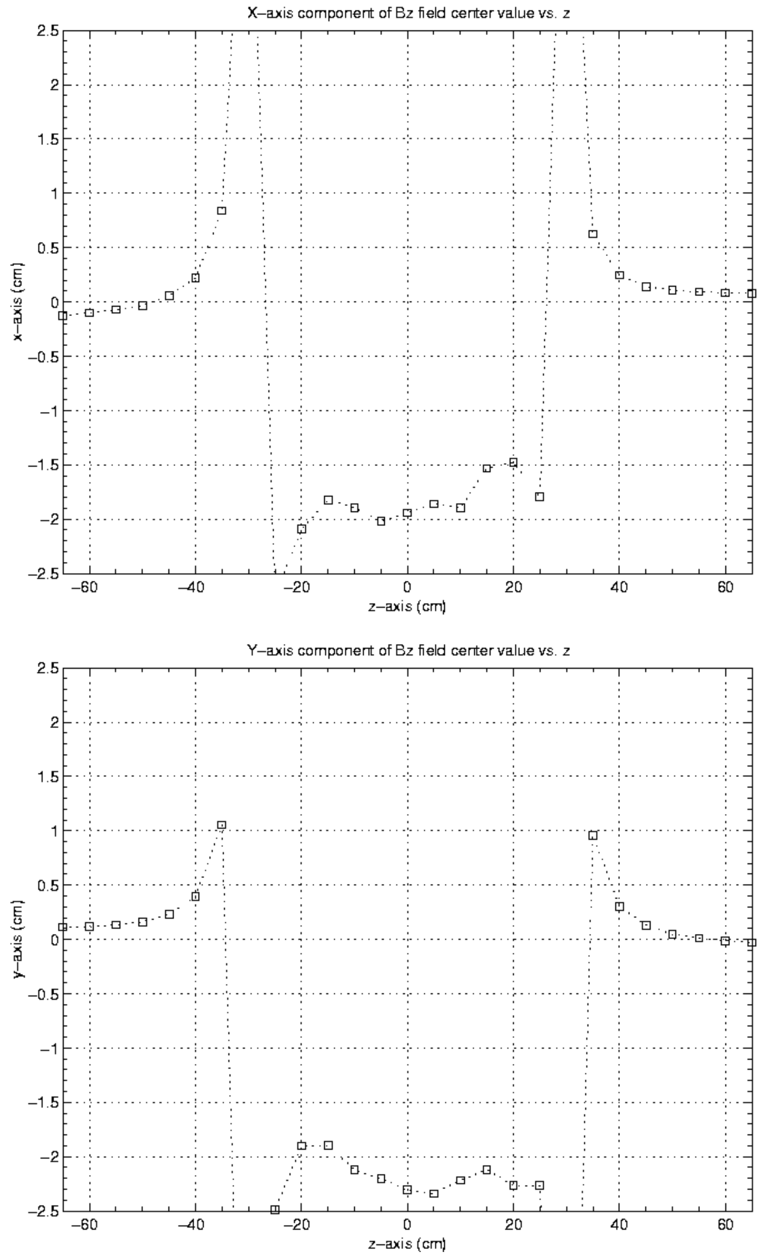


Figure 6: 20.0$kGauss$ Map Axis Profile. Upper plot shows the x-axis profile. Lower plot shows y-axis profile.

The second model was used to produce $field\_map.0006$. The only difference between the first model and second model is that in the second model all the coils were shifted by $\Delta x = -1.54cm$ and $\Delta y = -1.83cm$.

The third model was used to produce $field\_map.0006a$. The only difference between the first and the third model is that in $field\_map.0006a$ all the coils were shifted by $\Delta x = -0.154cm$ and $\Delta y = -0.183cm$. That is, in the third model the coils were shifted by an order of magnitude less than in the second model.

Figure 7 shows the calculated axis of symmetry profile for $field\_map.0006$. The outstanding result shown by Figure 7 is that the routine used to calculate the axis of symmetry **overestimates the coil shift by roughly one order of magnitude**. When the real shift in the coils is $\Delta x = -1.54cm$ and $\Delta y = -1.83cm$, the routine used to calculate the axis of symmetry suggests that the shift is in the order of 15cm to 18cm. This means that it is not possible that the coils in the magnet are out of place by more than two millimeters.

To actually reproduce in OPERA the output of the measured field as shown in Figure 6, the coils had to be shifted by $\Delta x = -0.154cm$ and $\Delta y = -0.183cm$. Figure 8 shows the axis profile produced by $field\_map.0006a$, where the coils were shifted by this amount. Figure 8 is the closest resemblance of Figure 6 that was obtained and confirms that **the actual shift in the coils is not greater than two millimeters**. Due to the uncertainty in the calibration, its not possible to do better than a one digit estimate of the actual shift, but two millimeters offers a good bound. It is therefore safe to say that **the coils are aligned with the z-axis of the yoke to within at least two millimeters**.

Finally, to show that the method used to calculate the axis of symmetry is representative of the position of the coils and does not introduce a constant bias, the axis of symmetry was calculated for $field\_map.0004$ where there is no coil shift. The resulting profile turned out perfectly flat, just as expected.

In summary, the routine used to calculate the axis of symmetry is helpful visualizing where the coils are in x and y; however, when there is a shift, it has an amplification effect of roughly one order of magnitude. The real magnitude of the shift is something in the order of one to two millimeters.

7 New OPERA Models

Thus far, the comparison between the current OPERA model (used for $field\_map.0003$) and the measured map yielded three features of interest: the measured map has an upstream-downstream asymmetry of $7Gauss$ that is not predicted by OPERA; the measured field falls faster than OPERA predicted as we move away from the center of the yoke (i.e. field gradient is different as we move away from the center); and the axis of the coils seems to be shifted in x and y by one to two millimeters. Since the ultimate goal of this study is to produce an OPERA model that is as close as possible to the real field, new OPERA models were produced that introduce modifications to correct these discrepancies or to study them in GEANT.

The new OPERA models produced as a result of this study are shown in Table 1. The BH curve for all the models in Table 1 is for nominal ten-ten steel. The main reason for a change in BH curve is that the nominal curve seems to produce field gradients that are closer to the measured fields than those produced by the current model, which had the nominal ten-ten

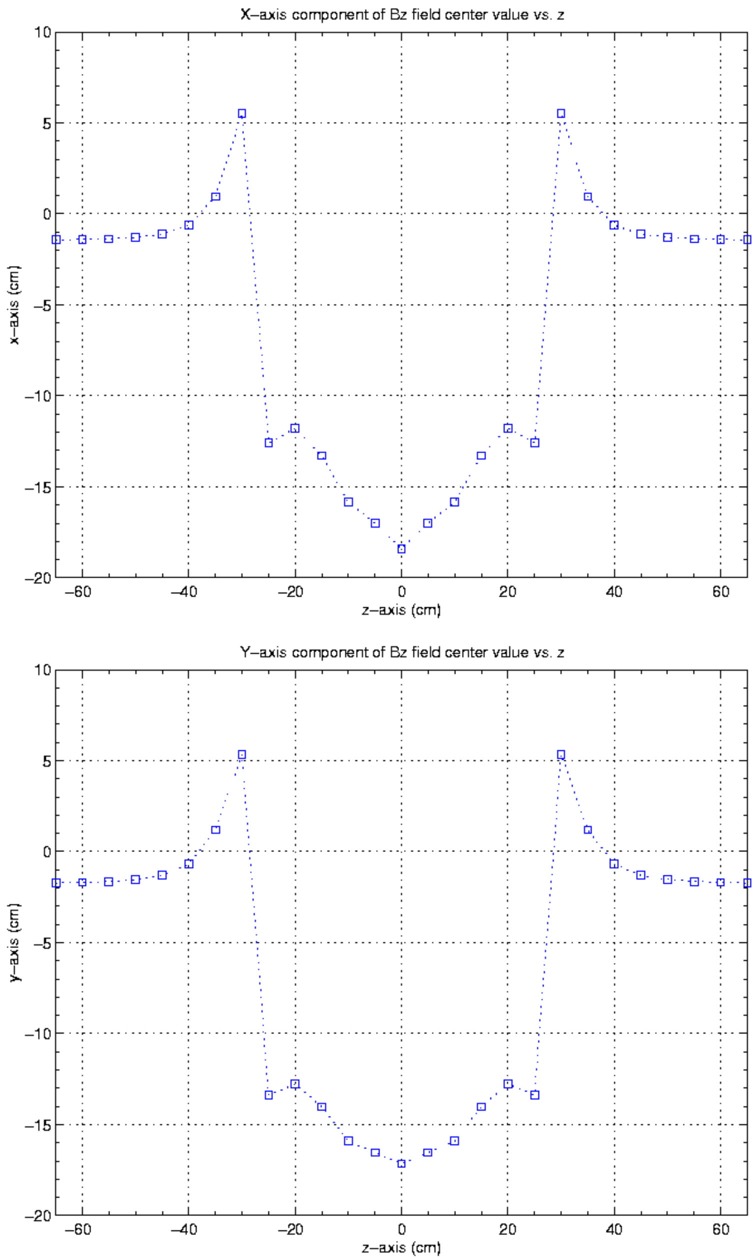
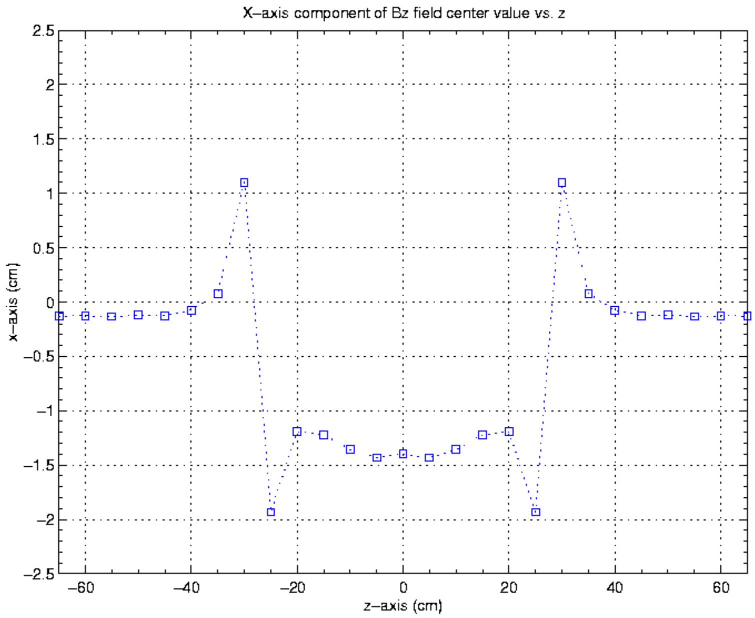


Figure 7: $field\_map$.0006 Axis Profile. Upper plot shows the y-axis profile. Lower plot shows x-axis profile. Coil shift corresponds to $\Delta x = -1.54cm$ and $\Delta y = -1.83cm$.



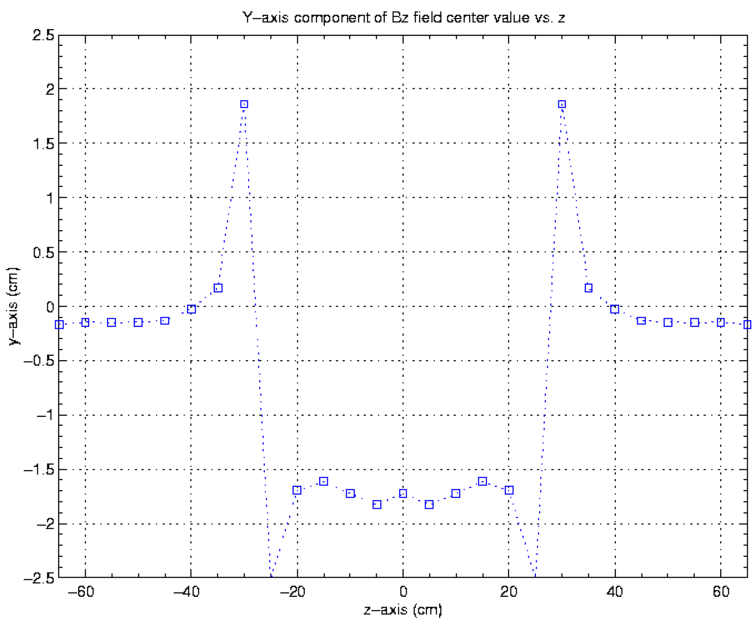


Figure 8: $field\_map.0006a$ Axis Profile. Upper plot shows the y-axis profile. Lower plot shows x-axis profile. Coil shift corresponds to $\Delta x = -0.154cm$ and $\Delta y = -0.183cm$.

File name: E614_iron_cube5b_YZ_X+0_Y+0_Z+0_221A_BH10_BHus10_BHds10.op3 Modification: New BH curve Map file: $field\_map$.0004
File name: E614_iron_cube5b_XY_X-154_Y-183_Z+0_221A_BH10_BHus10_BHds10.op3 Modifications: $\left\{\begin{array}{c}\text{New BH curve}\\ \text{Coil shift}\end{array}\right.$ Map file: $field\_map$.0006
File name: E614_iron_cube5b_XY_X-015_Y-018_Z+0_221A_BH10_BHus10_BHds10.op3 Modifications: $\left\{\begin{array}{c}\text{New BH curve}\\ \text{Coil shift}\end{array}\right.$ Map file: $field\_map$.0006a
File name: E614_iron_cube5b_YZ_X+0_Y+0_Z+0_221A_BH10_BHus10_BHds10_Z_shift_0018.op3 Modifications: $\left\{\begin{array}{c}\text{New BH curve}\\ \text{Field gradient}\\ \text{Upstream-downstream asymmetry}\end{array}\right.$ Map file: $field\_map$.0005
File name: E614_iron_cube5b_XY_X-015_Y-018_Z+0_221A_BH10_BHus10_BHds10_Z_shift_0018.op3 Modifications: $\left\{\begin{array}{c}\text{New BH curve}\\ \text{Coil shift}\\ \text{Field gradient}\\ \text{Upstream-downstream asymmetry}\end{array}\right.$ Map file: $field\_map$.0007

Table 1: New OPERA models.

steel BH curve scaled by 1.06.

The first three models in Table 1 have already been discussed. The last two models were used to produce $field\_map$.0005 and $field\_map$.0007; these are the models that offer the closest match to the measured field. $field\_map$.0005 is intended to replace $field\_map$.0003 and $field\_map$.0007 was produced to study what is the effect of a misalignment in the position of the coils with respect to x and y. Maps $field\_map$.0005 and $field\_map$.0007 are now discussed.

7.1 field_map.0005

In section 4.1, Figure 3 was presented and two discrepancies were highlighted: an upstream-downstream asymmetry and a difference in the field gradient. To correct for these two discrepancies, two modifications were introduced to the as built geometry to produce $field\_map$.0005. First, the two sets of outer coils were moved towards the center of the yoke by 0.18cm; this shift together with the change in BH curve corrected the gradient of the model to match the gradient of the measured map. Second, to correct for the upstream-downstream asymmetry, the current density in three of the inner coils was scaled; Figure 9 shows the scaling factors that were used.

Back in section 4.1, Figure 4 presented difference plots for $field\_map$.0003 and the 20.0$kGauss$ measured map that documented the upstream-downstream asymmetry and the gradient difference. The exact same set of difference plots were made for $field\_map$.0005 and are presented in Figure 10. Note that the gradient of the field has been significantly corrected and

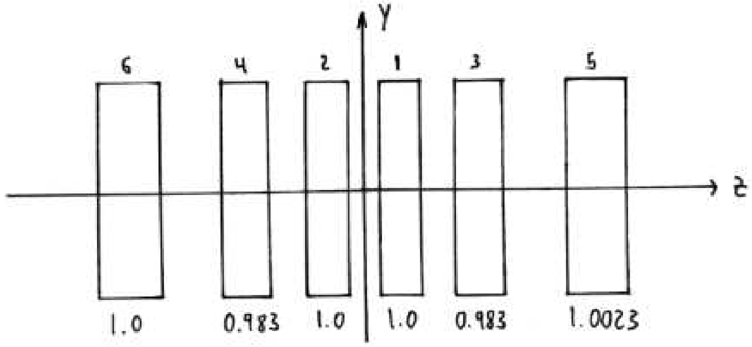


Figure 9: Coil scaling factors used to produce $field\_map.0005$. The current densities in the inner coils were scaled by the factors shown at the bottom of the coils; the OPERA coil numbers are shown at the top of the coils.

the maximum difference is now in the order of $\pm 5 Gauss$. Inside the volume defined by

$$\begin{array}{lcccl} -600mm & \leq & z & \leq & 600mm \\ 0\deg & \leq & \phi & < & 360\deg \\ 0mm & \leq & r & \leq & 170mm \end{array} , \quad (7)$$

which includes the PC and the DC chambers, the maximum difference (in absolute value) was found to be $4.84 Gauss$. However, inside the volume defined by

$$\begin{array}{lcccl} -500mm & \leq & z & \leq & 500mm \\ 0\deg & \leq & \phi & < & 360\deg \\ 0mm & \leq & r & \leq & 170mm \end{array} , \quad (8)$$

which includes only the DC chambers, agreement was achieved to within $\pm 2 Gauss$.

It is important to keep in mind that the changes introduced in $field\_map.0005$ to the as built geometry (i.e. change in current densities and coil position) are not necessarily real. The model used to generate $field\_map.0005$ is a black box (whose contents are known) that produces an output similar to the black box in the field (whose contents are ignored). With the currently available tools, it is not possible to make a study that will discriminate among all possible solutions.

7.2 field_map.0007

To study the effect of a coil shift in all the calculations that assume knowledge of the magnetic field, $field\_map.0007$ was produced. This map has all the changes that were introduced in $field\_map.0005$ and, in addition, all the coils were shifted by $\Delta x = -0.154cm$ and $\Delta y = -0.183cm$.

8 OPERA Systematics

It is worth mentioning that many precautions were taken to ensure that OPERA did not introduce any bias in the solution of the model. Different models were used to make sure that

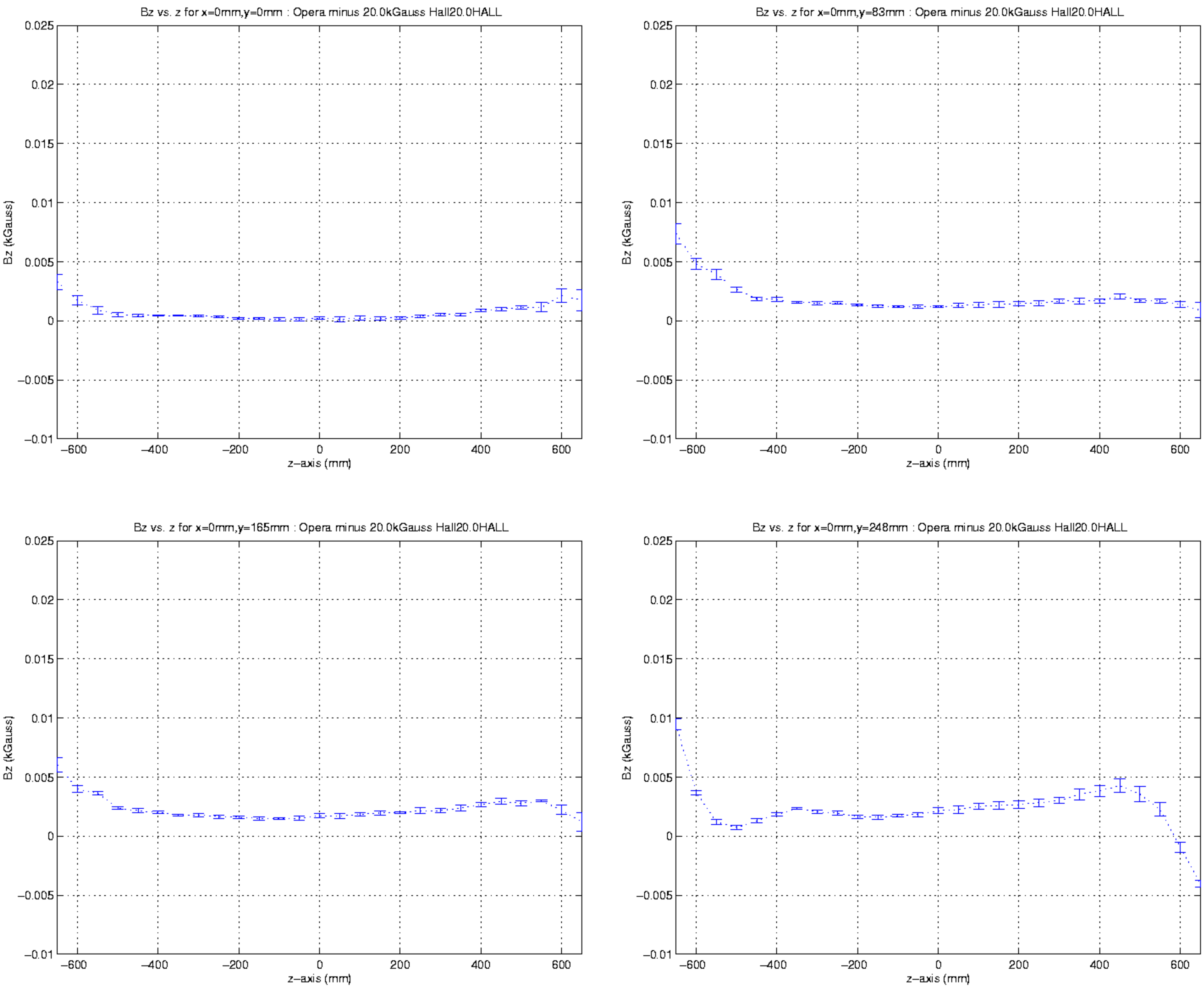


Figure 10: B_z vs. z plots for $field\_map.0005$ minus measured $20.0kGauss$ map (without NMR measurements). All plots are in the same scale.

the solution was independent of finite element mesh size, regularisation of the air and material volumes and the type of potentials used. It should also been mentioned that OPERA has been upgraded from the version that was used to make $field\_map.0003$. Maps $field\_map.0004$ to $field\_map.0007$ were made in OPERA V8.53 and this allowed for a better assessment of the software systematics.

9 Conclusions

In summary, the comparison between the current OPERA model (used to generate $field\_map.0003$) and the measured maps that were taken in April of 2002 has been completed and the main discrepancies found are: the measured maps have an upstream-downstream asymmetry of $7Gauss$ that is not predicted by OPERA; the measured field falls faster than $field\_map.0003$ predicted as we move away from the center of the yoke (i.e. field gradient is different as we move away from the center); and the axis of the coils seems to be shifted in x and y by one to two millimeters.

To introduce modifications to correct and study these discrepancies the following new OPERA maps were produced:

Map	Comment on modification
$field\_map.0004$	BH curve
$field\_map.0005$	BH curve + asymmetry + gradient corrections
$field\_map.0006$	BH curve + coil shift of $\Delta x = -1.54cm$ and $\Delta y = -1.83cm$
$field\_map.0006a$	BH curve + coil shift of $\Delta x = -0.154cm$ and $\Delta y = -0.183cm$
$field\_map.0007$	BH curve + coil shift of $\Delta x = -0.154cm$ and $\Delta y = -0.183cm$ + asymmetry + gradient corrections

Based on the results of the OPERA and measured map comparisons, the following conclusions were made:

- Agreement between OPERA ($field\_map.0005$) and the measured field was achieved to within $\pm 5Gauss$ for all the chambers in $-600mm \leq z \leq 600mm$ and within $\pm 2Gauss$ for all the chambers in $-500mm \leq z \leq 500mm$. These uncertainties are representative of the accuracy with which field predictions can be made inside their respective volumes.
- If a measured field map with final uncertainties of less than $\pm 1Gauss$ and in agreement with OPERA is needed, a denser map with better calibrations will have to be taken.
- The coils are aligned in x and y to within at least $\pm 2mm$. A misalignment in z has not been observed.

10 Recomendations

Based on the results of the OPERA and measured map comparisons, the following recommendations are made:

- The current OPERA map in CFM ($field\_map.0003$) must be replaced by $field\_map.0005$ since this map is the closest approximation available to the measured map.
- A study in GEANT must be made to determine if the achieved agreement between OPERA and the measured maps is good enough for all calculations and assumptions that rely on knowledge of the magnetic field.
- $field\_map.0007$ should not be used as the official CFM version; it was only created to document the observed misalignment. A better estimation in the coil shifts will have to be made if this feature needs to be incorporated into the model.
- When another set of maps is taken again, some measurements should be taken nearby the yoke doors ($z = \pm 139cm$) and as far upstream as possible ($-300cm \leq z \leq -150cm$); this would allow a better determination of the BH curve and asses the accuracy of the upstream extrapolations made for beam studies.

References

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