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Study of Magnetic field map for TWIST experiment at TRIUMF

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ABSTRACT

This is a study of the magnetic field in the upstream area of the TWIST detector and in the beam package. The two main reasons we studied this part are that we want to know the magnetic field precisely because we use it to measure the momentum of the muon beam and because we want to know how well the magnetic field holds the muon beam polarisation beam by the coupling of the muon spin with the magnetic field.

We want to model the magnetic field with the software called OPERA because we can only measure the z component of the field, in a limited number of space points. OPERA can tell us the three components of the field at any position that we want. So we compare the common component of each field and modify the OPERA simulation to have the best model that describe the field measurements.

We first compared the common measurements taken this year and in the previous one, to make sure that the two maps were compatible. After that we substracted measurements from the OPERA field and tried to get a flat difference in function of position by changing some parameters in order to match OPERA with the real field.

We still have to understand both why there is a kink in the middle part of the difference curve and why this one is increasing in the far upstream area. However we determined that 2002 and 2003 maps appear to be consistent with each other. We eliminated position shifts, BH curve changes and presence of extern field outside the yoke as an explanation of the problems in the difference between OPERA and the upstream measurements. Finally we will have to verify where is the error in our OPERA model of the setup and make sure that our model can be run by OPERA latest version.

1 INTRODUCTION

1.1 Fundamentals

The Standard Model of Fundamental Particles and Interactions in particle physics (that we will shortly call Standard Model) describes nature at its smallest level. This model describes the world as being made up of two different kinds of bricks (the fundamental particles) : the *quarks* and the *leptons*. The mortar between these bricks (the forces) are four distinct kinds of interactions between those particles.

The most widely recognized interaction is *Gravity*. At the same time it is the least understood at the fundamental level (not quantized), or at the particle level for it is very weak at this scale. Another recognized interaction is the *Electromagnetic* one (combination of *Electricity* and *Magnetism*), which is the best known physically, as the theory that describes it is quite complete! The remaining two interactions are recent discoveries, because they do not interact on a large scale; we cannot see their effects in our daily life, only at scale of the size of nuclei or atom. These two interactions are the *Weak* and the *Strong* interactions.

Each of the fundamental interactions are propagated by particles (bosons) called "Force carriers". For the Electromagnetic force, there is only one propagator : the *photon*. For Gravity, there is only force carrier predicted theoritically known as the *graviton*. For the Strong interaction, there are eight different force carriers, all called *gluons*, and they are all a linear combination of the differents ways matter couples through this interaction (or for colours to be intersected; from the three basic colour that quarks can have, in analogy with the light colour theory). Finally, the Weak interaction has three different propagators, called *vector bosons* (the Z^0, W^+ and W^- bosons).

Every objects that has mass (and which obviously is made from elementary particles) interact by Gravitational interaction, particles that have electric charge interact by the Electromagnetic interaction and all particles interact by the Weak interaction. The main difference between quarks and leptons is that only quarks interact by the Strong interaction. There are six different quarks, which we put in groups of two (called generations) following their mass level. The quarks are *up* (u) and *down* (d), *charm* (c) and *strange* (s) and *top* (t) and *bottom* (b). There are also six leptons, also classified in three generation. The leptons are : the *electron* (e^-) and its *neutrino* (ν_e), the *muon* (μ^-) and its *neutrino* (ν_μ), and lastly the *tau* (τ^-) and its *neutrino* (ν_τ). Finally, each of this fundamental particles has an associated antiparticle which has the same mass but opposite values in every other quantum number. Antiparticles are represented with the same symbol as their associated particle, but with the opposite charge, or with a bar over the particle symbol (when there is no charge in the symbol).

1.2 Theoritical motivations

The study of particle physics involves many different symmetries regarding the interactions and particles. Those symmetries are related to particles or spacetime quantum number. By reversing quantum number we study if the situation is the same (which would be the case if every quantum number would be symmetric) or if it is different (non-symmetric situation) and determine conservation laws this way.

There are many different possible symmetries that has been found, but for our study, only two are important : the charge conjugation (C) and the parity (P). Charge conjugation means that we change only a particle to its antiparticle, so with the opposite charge (*i.e.* $q = +1 \quad \rightarrow \quad q = -1$). Parity refers to a change in the orientation of every spatial axis ($\vec{r} \quad \rightarrow \quad -\vec{r}$). There is also time reversal (T) which is similar to parity in a relativistic situation; time reversal looks at the inverse reaction, like if the final state would be the initial one and vice versa ($t \quad \rightarrow \quad -t$). The Weak interaction is non symmetric under charge conjugation and parity change, which is known as CP violation, meaning that charge-parity symmetry does not exist in a Weak reaction.

CP violation in Weak interaction means the vector bosons couple only with particles that are left-handed in their helicity. Helicity is defined by the sign of the dot product between the spin and the momentum following the equation 1.

$$\begin{aligned} helicity \equiv +1 \quad &\Leftrightarrow \vec{S} \bullet \vec{p} \; > 0 \quad \text{and} \\ helicity \equiv -1 \quad &\Leftrightarrow \vec{S} \bullet \vec{p} \; < 0 \end{aligned} \tag{1}$$

However, there is a possibility that a vector boson would couple to a right-handed particle, but since this reaction does not occur very often, this boson would have to have a much greater mass than the one that is coupling with left-handed particles.

Every time a particle interaction occur, there is an exchange of force carrier between those particles. The mass of the force carrier is used to define the coupling constant of this force carrier. If there are more than one possible reaction for the same initial and final particles, the coupling constant of each force carrier is playing the role of statistical ponderation. In a more general Weak interaction theory than the one described by the Standard Model, there are many coupling constants for the Weak interaction. In the Standard Model, all these constants are zero coefficient exept the one that couples left handed to left handed particles, which has a value of one.

The TWIST experiment is looking to find wether or not the right-handed coupling bosons exits. It is done by measuring the Michel parameters and comparing them with the Standard Model prediction. The Michel parameters (η, ρ, δ and ξ) are numbers that characterise the probability distribution of the positron after an anti-muon (μ^+) decay (see equation 3). They appear in the equation 2 which describe the variation of the probability distribution in function of the angle $cos(\theta)$ and the ratio of energy $x = E/E_{max}$; sign + in $\pm$ is for anti-muon (μ^+)and sign $-$ is for muon (μ^-). The Standard Model values of the Michel parameters are contained in table 1.

$$\frac{1}{x^2}\frac{d^2\Gamma}{\mathrm{d}x\,\mathrm{d}(cos\theta)} \propto 3(1-x) + \frac{2\rho}{3}(4x-3) + 3\eta x_0\frac{(1-x)}{x} \pm P_\mu \xi \frac{p}{E}\Big(1 - x + \frac{2\delta}{3}(4x-3)\Big) cos\theta \tag{2}$$

In particular, if the right-haded coupling W^+ boson exists, it would have it is own coupling constant that we would have to consider in the probability calculation. Each one of the

Table 1: Standard Model values of the Michel parameters

Parameter	**Numerical value**
η	0
ρ	3/4
δ	3/4
ξ	1

Michel parameters is a different combination of these several coupling constants. If different values for the Michel parameters are found experimentally, it will mean that there are other coupling constants in the Weak interaction. This would mean some physics beyond the Standard Model and maybe that this boson exists. But if the values of Michel parameters are the same as predicted by the Standard Model, this would mean that the right-handed coupling $W^{\pm}$ boson does not exit!

1.3 TWIST experiment

TWIST experiment studies Weak interaction. To avoid any complications or confusion in the measurements and analysis, the experiment uses the decay of leptons which do not interact with Strong interaction. More specifically, the study is about the decay of the anti-muon (μ^+) in a positron (anti-electron) following to the muon decay reaction (see equation 3 and figure 1).

$$\boxed{\mu^+ \rightarrow \mathbf{e}^+ + \nu_{\mathbf{e}} + \bar{\nu}_\mu} \tag{3}$$

The reasons of choosing the anti-muon (μ^+) instead of any other leptons, are : it is the lightest non-relativistic lepton with the values of our field, which gives easier calculations. With this decay, we avoid most of the regular interactions and restrict the interactions to the one we want to study. Also, we study reaction with the anti-muon (positively charged) instead of the muon itself (negatively charged) because muon interacts with atoms similarly to a “heavy electron”, and get captured by nuclei while anti-muon does not. There is so much caution taken to produce muons that we do not want them to be captured in an atom. Now that the distinction has been made, we will just call the anti-muon (μ^+) a muon in the rest of this report and avoid any reference to the real muon (μ^-), to facilitate the writing .

The purpose of studying the muon decay is to measure, with a greater precision than ever before, three of the Michel parameters (δ, ρ and $P_\mu\xi$ which is the ξ parameters times the muon polarisation that we assume $P_\mu = -1$), when before, only one was measured at the time!

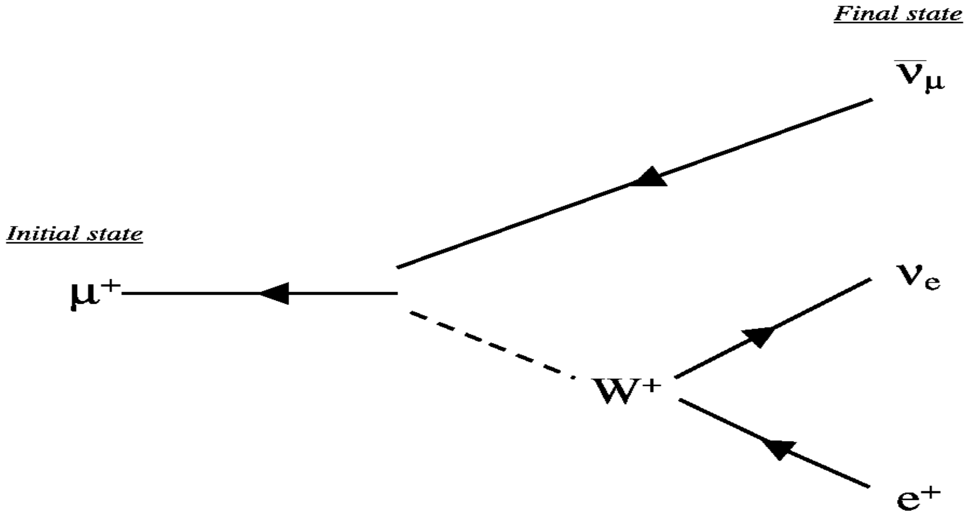

Figure 1: Feynman diagram of the muon decay, showing the W^+ boson as the propagator.

1.4 History of the TWIST manget map

The study of the TWIST magnetic field was begun by Michael Barnes who created the three dimensionnal OPERA model of the TWIST magnet [1]. Measurements were done by Glen Marshall and the late John A. MacDonald. Last summer (2002), Roberto Armenta, a summer student, studied the field inside the magnet, and compared it succesfully to the OPERA field. Modifications were made in the OPERA model to take account of small differences [2].

1.5 Purpose of this study

The purpose of this research is to study the magnetic field in the upstream area of the TWIST detector and in the beam package (see figure 2). New measurements were taken during the previous year in this particular area that we cover in this report. The two main reasons we studied this part are the following :

- we want to know the magnetic field $\vec{B}$ precisely because we use it to measure the momentum $\vec{p}$ of the positron inside the magnet, after the muon decay :

$$\sum_i^N \vec{F} = \vec{0} \qquad \Rightarrow \qquad qvB = \frac{mv^2}{r} \qquad \Rightarrow \qquad r = \frac{mv}{qB} = \frac{p}{qB}$$
$$\Rightarrow \qquad p = eBr \tag{4}$$

- we want to know how well the magnetic field holds the muon (μ^+) beam polarisation by the coupling of the muon spin with the magnetic field $\vec{S} \bullet \vec{B}$.

2 TWIST MAGNETIC FIELD MAP

2.1 Experimental setup and measurements

The muon beam is coming from the uptream part, which corresponds to the negative part of z axis, and so this is the location of the studied magnetic field. The magnetic field is created by a solenoidal superconductor. A magnet, made of twelve coils that are two concentric coils (placed at different radii) at every of six different positions along z axis, shapes the field at the beam entrance. Measurements were taken with the *Magnet Mapper*, which is a long aluminum tube called *Hall mapper* that was moving along z axis. On this tube was a small arm bearing five Hall probes, located at five distinct radii, and that could rotate in the plan. So this way, we could measure the magnetic field for five different values of the radius (r) at the same time. The probes could then be moved to any value of z and of the angle ϕ as we wished.

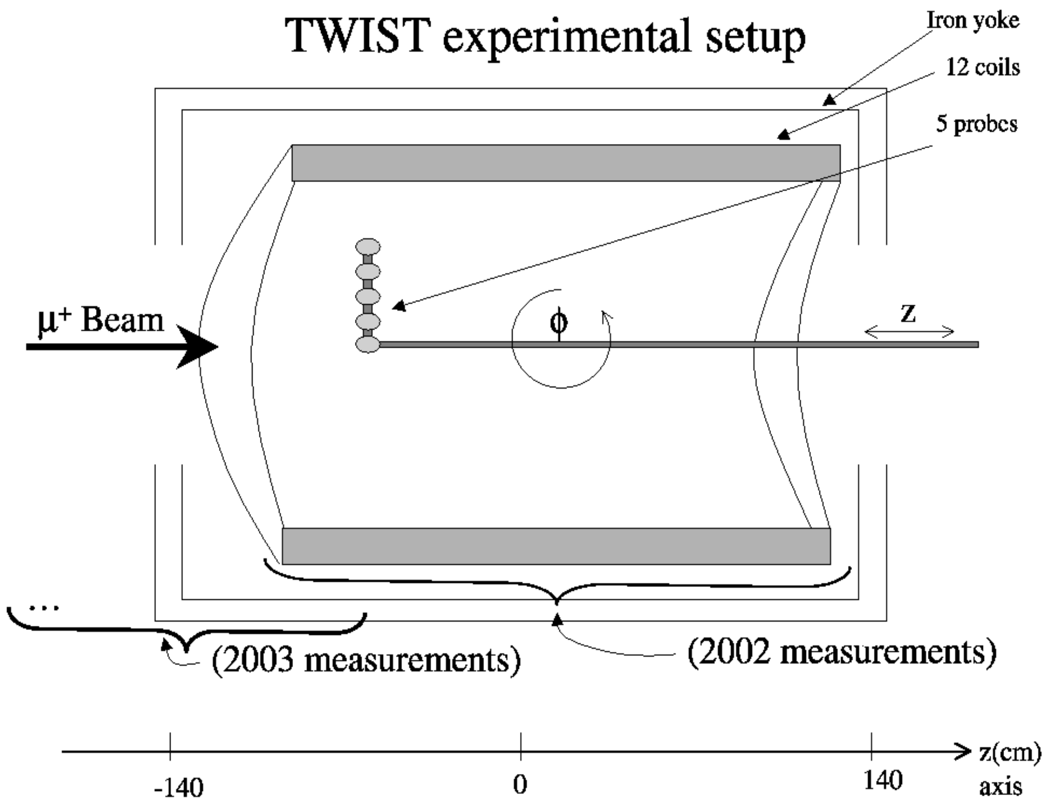

Figure 2: Drawing of the experimental setup; the area studied in this report is the upstream region, where the beam is coming from.

One restriction on the measurements was that we could only measure the z component of the field B_z, instead of the whole field (B_x, B_y, B_z). Many data acquisitons were made, so we did a statistic sum on each on all the measurements, and manipulated the average value of the field for our comparison, and used the root-mean-square (see equation 5) for the calculation of the uncertainties of each point. Finally, to simplify the calculations, we restricted ourselves to the first probe only to avoid any ϕ dependance at $r = 0$.

$$\bar{B}_z = \frac{\sum_{i=1}^{N} B_{z,i}}{N} \qquad \text{and} \qquad RMS_{B_z} = \sqrt{\sum_{i=1}^{N} \left(\bar{B}_z - B_{z,i}\right)^2} \tag{5}$$

2.1.1 Calibration

Calibration was done with a more sensitive probe (NMR probe) to verify the values and accuracy of the Hall probe measurements. The calibrations were taken at $z = -40$ *centimeter* for six different values of the field [3]. The problem with this calibration is that the NMR probe is measuring the total field $B = \sqrt{B_x^2 + B_y^2 + B_z^2}$ instead of only the component B_z. Another problem with calibration was that Hall probes were repowered during measurements, hence some points were taken on ramp up and some on ramp down : since magnetic field is sensitive to current variation, this might have changed slightly our measurements. Finally, we could not place the two probes at the exact same position in x, y and z, which gives a little modification in B_z itself following equation 6.

$$\Delta B_{z,pos} = \sqrt{\left(\frac{\partial B_z}{\partial x}\Delta x\right)^2 + \left(\frac{\partial B_z}{\partial y}\Delta y\right)^2 + \left(\frac{\partial B_z}{\partial z}\Delta z\right)^2} \tag{6}$$

The correction to the Hall probe measurements was calculated this way : $Corr \equiv Hall_{meas} - NMR_{meas}$, and we tryed to find the best polynomial fit to have an algebraic correction for every value of B_z. For most of the probes, the correction seems to be quadratic as figure (3) shows, for the fifth Hall probe (that we will call *Probe 5*), which has the best quadratic fit of all the probes. The first Hall probe (that we will call *Probe 1*) is the one that fits the most badly with a second level polynome, as shown on figure (4), but since it was as good as the other polynomial level, we kept this one for more uniformity in our analysis. On every calibration plot, χ^2 is low because errorbars are big.

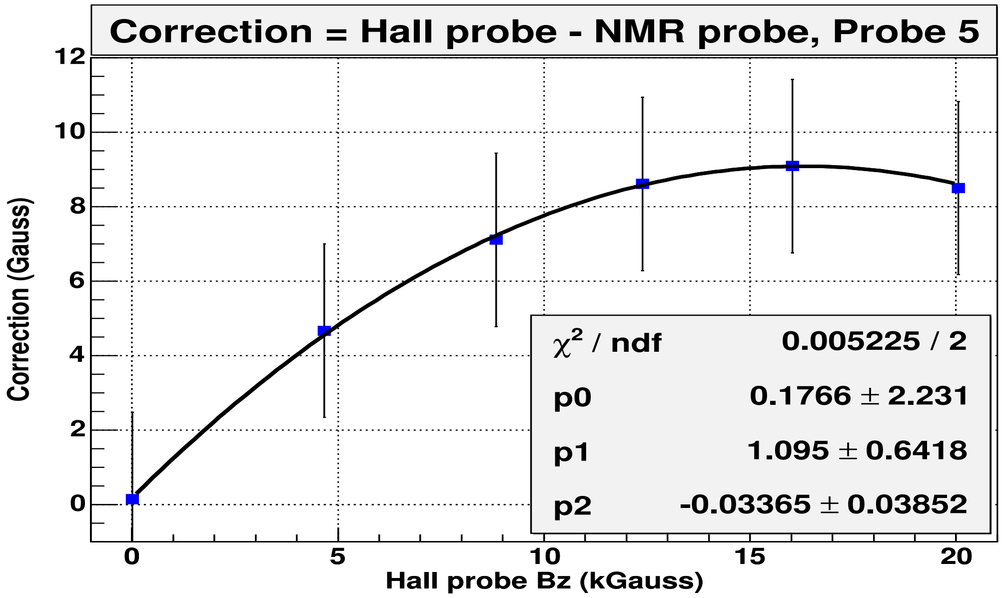

Figure 3: Best second level polynomial fit for Probe 5.

But we studied more in detail the way that the calibration were done, and realized that errorbars (which weight points in the maximization calculation) are not really the same for the field at every values of field. So we corrected the uncertainty calculation by adding :

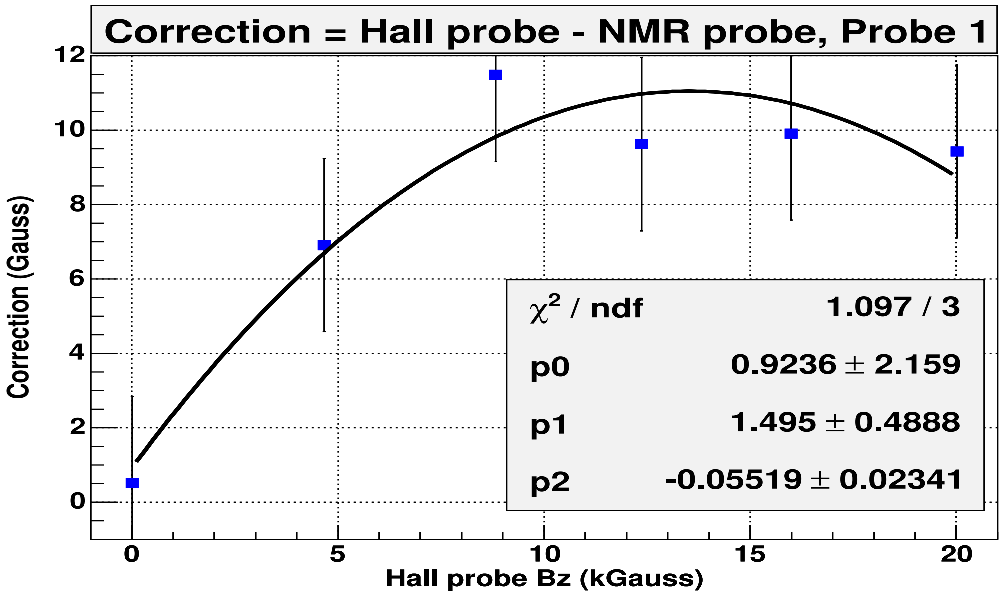

Figure 4: Best second level polynomial fit for Probe 1.

- A maximal radial part $B_r \sim 500\ Gauss$ of uncertainty in our field which would gives :

$$\Delta B_{z,rad} = B_z - B_z^{'} = B_z - \sqrt{B^2 - B_r^2} \sim 6.25 Gauss.$$

- Aknoledging that the NMR field varies of 0.5 $Gauss$ when $\Delta z = \pm 1\ cm$ so $\Delta B_{z,\Delta z} \simeq 1$ $Gauss$.
- Field is not constant with current interruption $\Rightarrow \Delta B_{z,current} = 0.25\ Gauss$.
- Finally we discounted the two first points for they were not taken at the same time (and the third one because it does not fit well with the other *Probe 1* measurements).

Results of those corrections are shown in figures (5) and (6) and in table 2. Those results are more interesting for they are fairly linear, which means that we do not have to use them, since the corrections are the same for every values of the field.

Table 2: Polynomial fit for the calibration

Probe	2^{nd} **level polynomial** B_z correction ($Gauss$)	0^{th} **level polynomial** B_z correction ($Gauss$)
1	$1 + 1.5B_z - 0.06B_z^2$	9.7
2	$0 + 0.8B_z - 0.03B_z^2$	4.9
3	$1 + 1.1B_z - 0.04B_z^2$	7.7
4	$1 + 0.9B_z - 0.04B_z^2$	4.6
5	$0 + 1.1B_z - 0.03B_z^2$	8.9

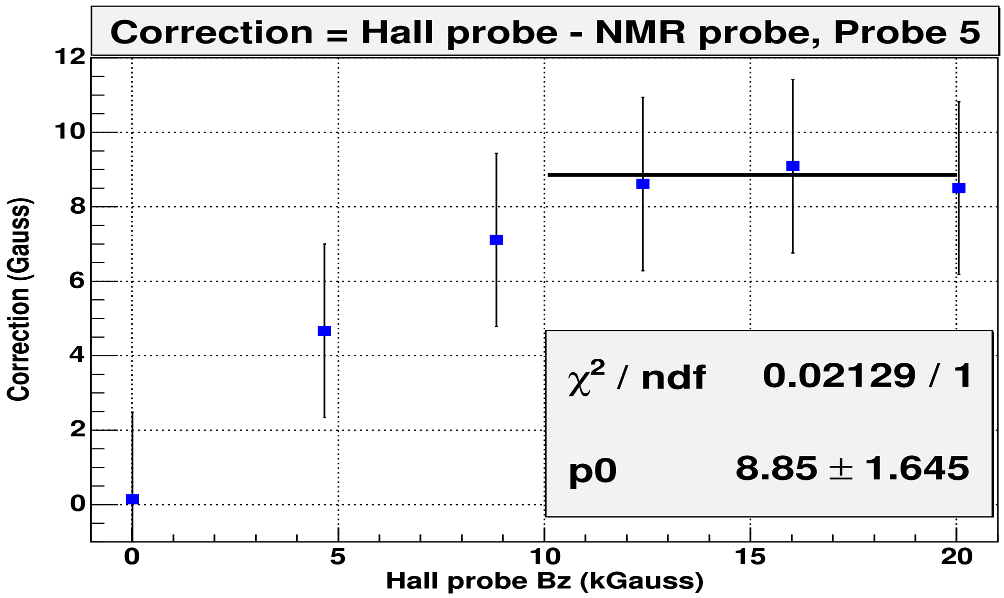

Figure 5: Best zeroth level polynomial fit for Probe 5.

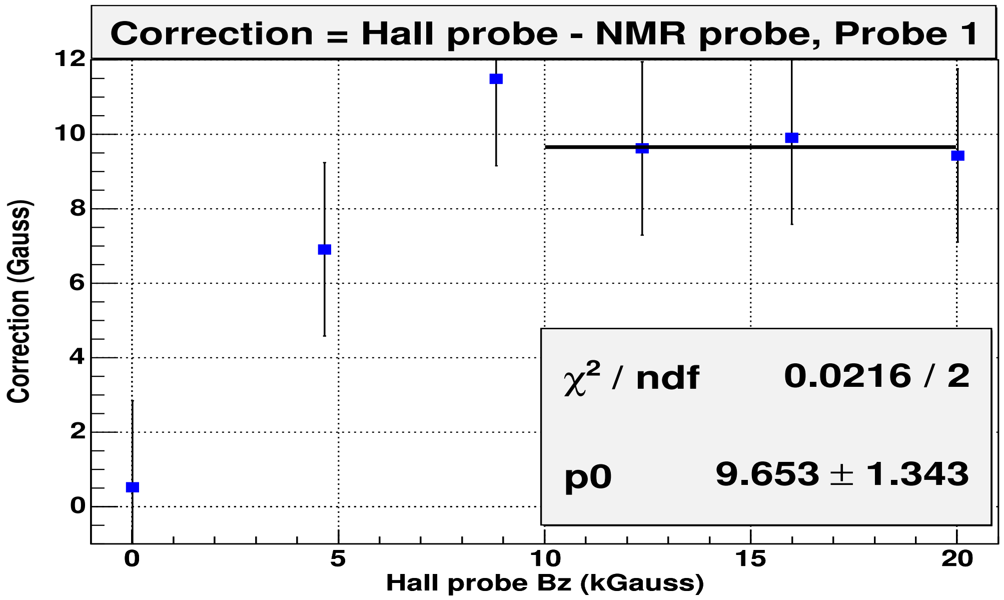

Figure 6: Best zeroth level polynomial fit for Probe 1.

2.2 Modelling with OPERA

2.2.1 "What?" and "Why?"

OPERA is a software package that simulates electric and magnetic fields. The user is free to choose the geometry, the dimension, the material and the physical properties of every of every part of his setup, so the model could be as close as possible to the real system. As an example, the OPERA model of TWIST magnet is shown at figure (7).

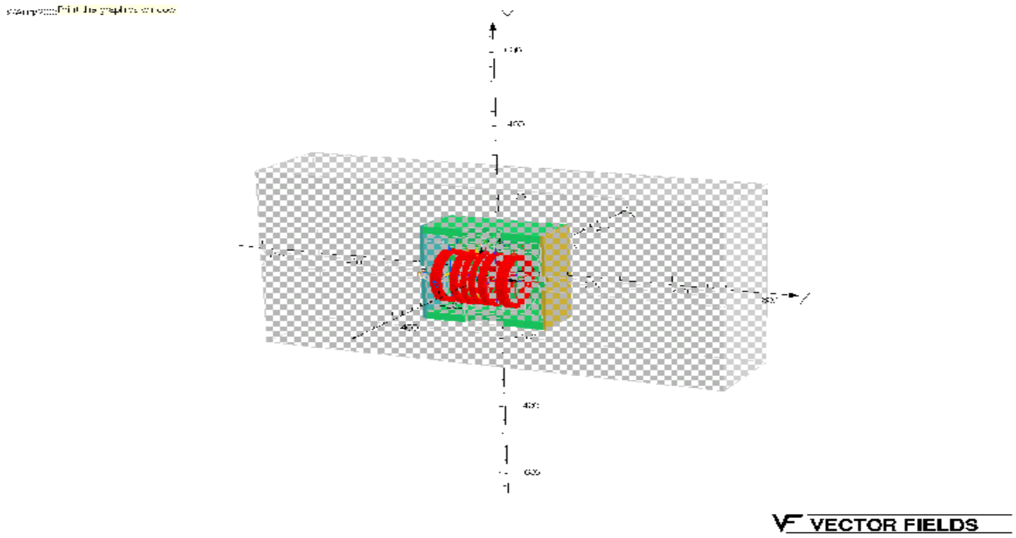

Figure 7: OPERA model of TWIST magnet : in green is the yoke, in red the coil, and transluency is the air in the room.

We want to model the magnetic field with OPERA because we can only measure one component of the field (B_z), in a limited number of space points. OPERA can tell us the three components of the field at any position that we want. So we compare the B_z component of each field and modify the OPERA simulation to have the best model that describe the field measurements.

2.2.2 "How to use?"

To run OPERA, one would need an account on the server *alph10*. Here are the general steps for a user who already have a file created. The one used for this study is **E614_iron_cube5b_YZ_noreg_X+0_Y+0_Z+0_221A_BH106_BHus106_BHds106.opc** and is found in the following directory : **/home2/barnes/e614/modeller** on *alph10*. There are three different applications to run :

- Modeller
  - Open the *.opc file and change some parameters (as the user wishes).
  - Generate one after the other surface mesh and volume mesh (under label *"Model"*).
  - Create the database (in *"Model"* again), which is a *.op3 file.
- TOSCA
  - It is the simplest and the longest part of the simulation.
  - Need database to be created first.
  - Only have to give the name of the file without any extension.
  - Quicker if mesh is done with larger value of *"Maximum element size"*, but less precise.
- Post-processor
  - Accessible only from PC X03 on the second floor of ISAC-II.
  - Open a *.op3 file (must be analysed previously by TOSCA) and choose the good reflexion (XY, YZ, ZX), the good one is often inserted in the filename; to see something, click on *"Default and refresh"* in *"View"* after.
  - Option ⇒ Field calculation method; (integration of the field only, not the coils).
  - Field ⇒ Field on a straight line (give the desired positions).
  - Table ⇒ Table of field value on a grid; (make sure to select field component and not only position).

2.3 Analysing with ROOT

ROOT is a software package based on C++ language which main purpose is to plot data. Because it is a programmation language, we have to compile the program every time we want to plot something, but an advantage is that we can save the code and repeat it many times. With ROOT, one can write almost everything related to the plot in command line, and also, change almost everything by hand on the plot itself : the two ways are possible. Moreover, ROOT is very handy with strings of characters : it can add two different string in one by the simple addition operation. Attached at the end of this report is an example of ROOT code, to help a new beginner that should work if the input file are provided. ROOT was very easy to use, and also well documented!

- Download the ROOT software at the following link :
  /twist/local/root.gcc32.new .
- Type *root* in the linux or unix shell.
- The compiler command is **.x file_name.C**; the name of the function on the first command line must be the same as the file name.

- Finally for every other details, the web site is very handy : **http://root.cern.ch/root/html304/ClassIndex.html.**

3 FIRST STEP : COMPARING MAPS INSIDE AND OUTSIDE THE MAGNET

Plot (8) shows the three sets of data that we are going to use in that study. One important remark to do is that both range are very big : the position (z) varies from -300 *centimeters* to 80 *centimeters* which represent about four *meters*, and the magnetic field varies from zero *kiloGauss* to approximately twenty *kiloGauss*. In contrast, we will keep our attention on very small variations of this field.

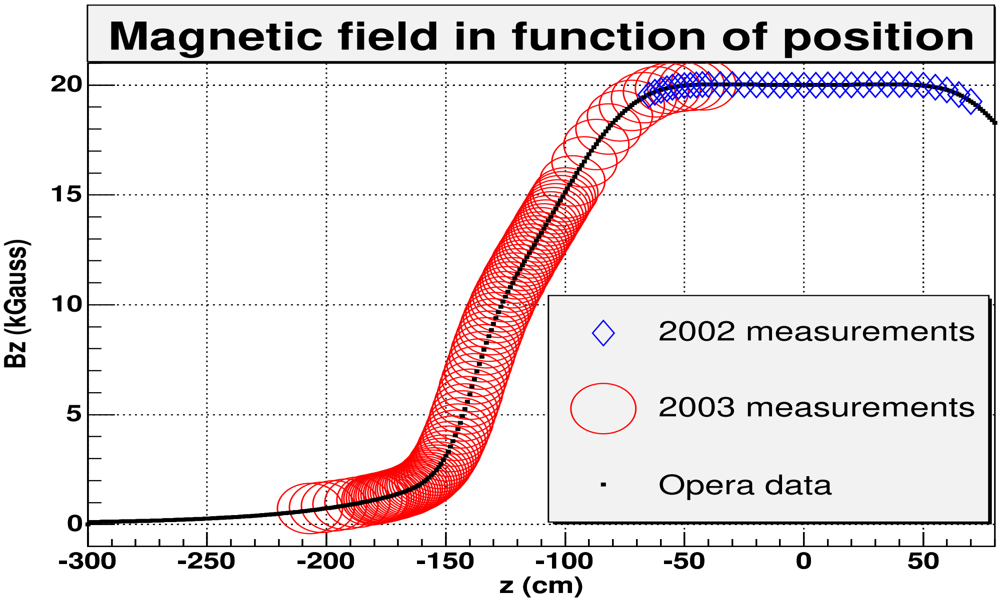

Figure 8: Comparison at large scale of the three sets of data.

3.1 Polynomial fit

The first verification to do was to make sure that the new measurements (in 2003) field map was compatible with the 2002 measurements field map. Then, we restricted ourselves to the only section between $z = -65$ *centimeters* and $z = -40$ *centimeters* (where the red circles and the blue lozanges overlap) which is a very small area compared to the whole region we studied.

One problem with comparing those two maps was that the position in z was not the same for both, so we could not just substract the field for each point and plot the result. We had to take a polynomial fit first, and the same level of polynomial function for a reasonable comparison. Third level was the best fit possible since the 2003 map has only five points, so we could not use a higher level than fourth but this one would not have allowed us any freedom level in this case. Figures (9) and (10) are showing values obtained for the best fit for each of these maps. By looking how the χ^2 values are far from one, we can easily see that polynomial fits are not the good way to interpolate results from those measurements. However, the curves are still fitting very well the points, so we can justify this method for our developpement because all we needed was the magnetic field values between the experimental points.

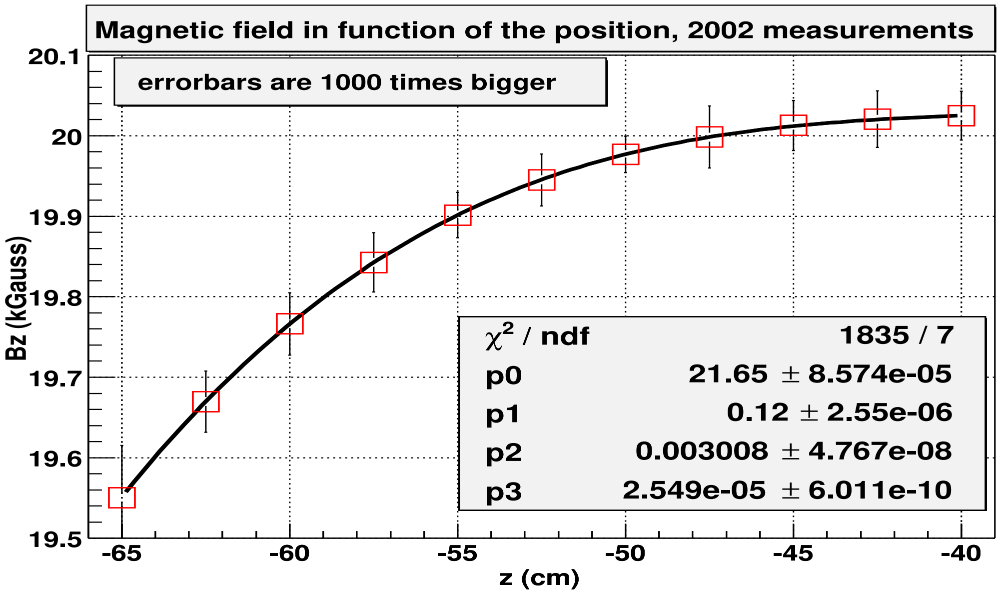

Figure 9: Interpolation of third level polynomial fit for the 2002 measurements.

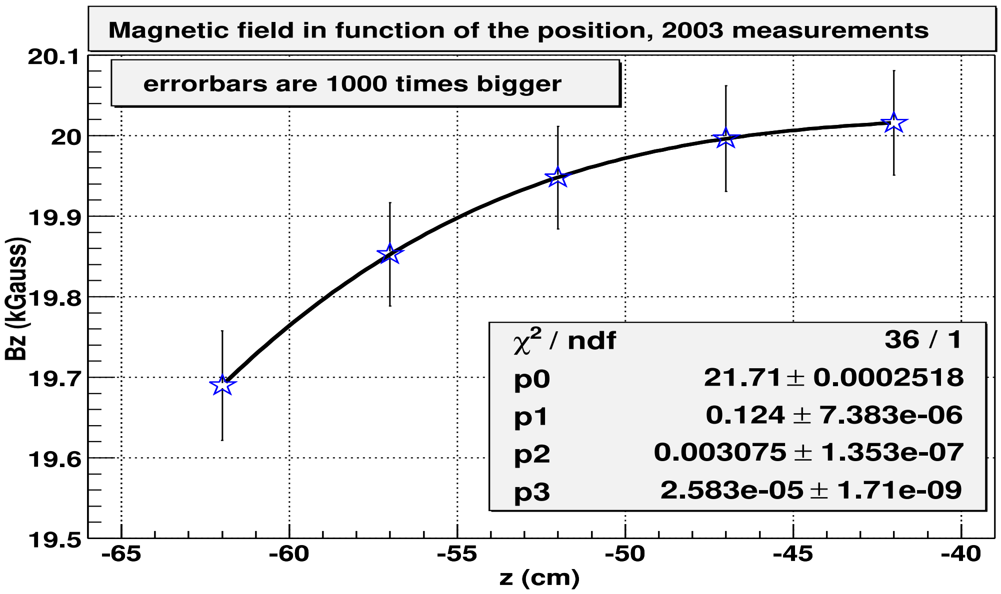

Figure 10: Interpolation of third level polynomial fit for the 2003 measurements.

Once we had the two polynomial fits, we could substract the one from the other following the equation 7. Field setpoint is not the same in both set of measurements, and also Hall probe calibration is different for the two sets, and those two facts give us one degree of freedom in our analysis. Since we have this degree of freedom, we choose to set one of the coefficient equals to one, and to place the zero point of the difference at $z = -55$ *centimeters* to facilitate the comparison.

$$\Delta B_{z,true} = \alpha_{2002} B_{2002} - \alpha_{2003} B_{2003} \tag{7}$$

$$\text{Where} \qquad \alpha_{2002} \equiv 1 \qquad \text{and} \qquad \alpha_{2003} \equiv \left.\frac{B_{2002}}{B_{2003}}\right|_{z=-55 \quad cm}$$

3.2 Shifting along z axis

Green crosses on figure (11) shows that difference between the maps is not really flat, though it is very small : about six *Gauss* for a field of $20,000$ *Gauss*. But we wanted to have a flat difference because both measurements describe the same field, so difference between them should be flat. Hence, we tried to shift 2003 measurements along z axis to see if the difference curve was not getting flat. A little shift can be understood by the fact that the origin has not been set exactly at the same place in the two measurements. A shift of about one millimiter could easily be allowed and is consistent with expected precision in positionning of the measuring apparatus. Finally, after trying several shifts, the difference curve looks very flat for a shift of $z - 0.14$ *centimeter* (represented by red stars) which confirms that the two sets of measurements are compatible together.

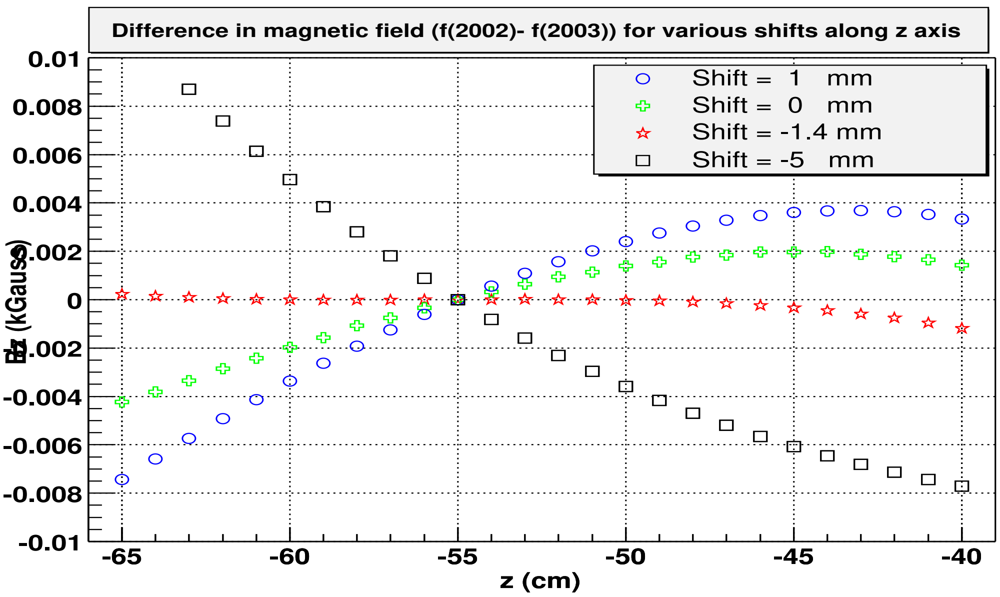

Figure 11: Difference between 2002 and 2003 measurements, in the overlaping area, for various shifting along z axis for 2003 measurements.

4 SECOND STEP : COMPARING OPERA SIMULATION WITH MEASUREMENTS

4.1 Nominal OPERA field

The *Nominal* OPERA field is the one produced from the TWIST-magnet model on OPERA, before modifications made last year from the comparison between OPERA and measurements in the coil area.

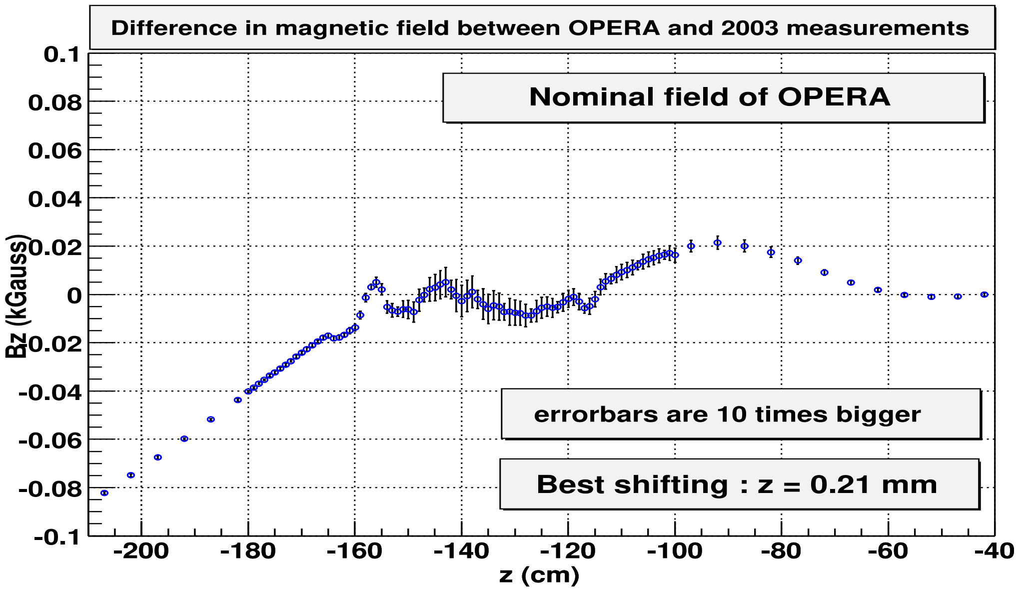

Figure 12: Difference between Nominal OPERA field and the measurements.

We can see a few problems on figure (12), the main one is probably the tail of the difference in the area of $z \rightarrow -210$ *centimeters* : the two fields are diverging one from the other till a significative number, 80 *Gauss*. Since it is OPERA minus the measurements, it means that the measured field is bigger, so maybe a remnant field outside the yoke is responsible of such a tail.

Another problem which is obvious on this plot is the wiggles in the middle part of the z axis. Those wiggles occurs exactly at the iron location (where the yoke is closing), and so lead to the interpretation that it could be the result of induced field in the iron. Finally in the area, the errorbars are also bigger than anywhere else, probably because the field gradient is so big in that area (see figure 8), so that maybe just a slightly variation in z position can produce huge errorbars, according to equation 5.

4.1.1 Z-shifting again

Once again, we looked if problems were not due to a position difference between the measurements and OPERA, which would explain both the wiggles and the tail. Since we did not have to do polynomial fit this time, we shifted OPERA of various displacements (ϵ) in z direction. We kept only the flatest curve, according to the following definition of flatness in equation 8 : the minimum of the quadratic difference between the original and shifted value of B_z.

$$\frac{d}{d\epsilon}\left(\sqrt{\sum_{i=1}^{N}\left(\Delta B_z\right)^2}\right) = \frac{d}{d\epsilon}\left(\sqrt{\sum_{i=1}^{N}\left(B_{z+\epsilon,OPERA} - B_{z,meas}\right)^2}\right) = 0 \quad (8)$$

The results of many shifts is shown on figure (13), let us just mention that the best shift is $\Delta z = -0.013$ *centimeter* which is quite small. Unfortunately no shifting in z fixed the mismatches.

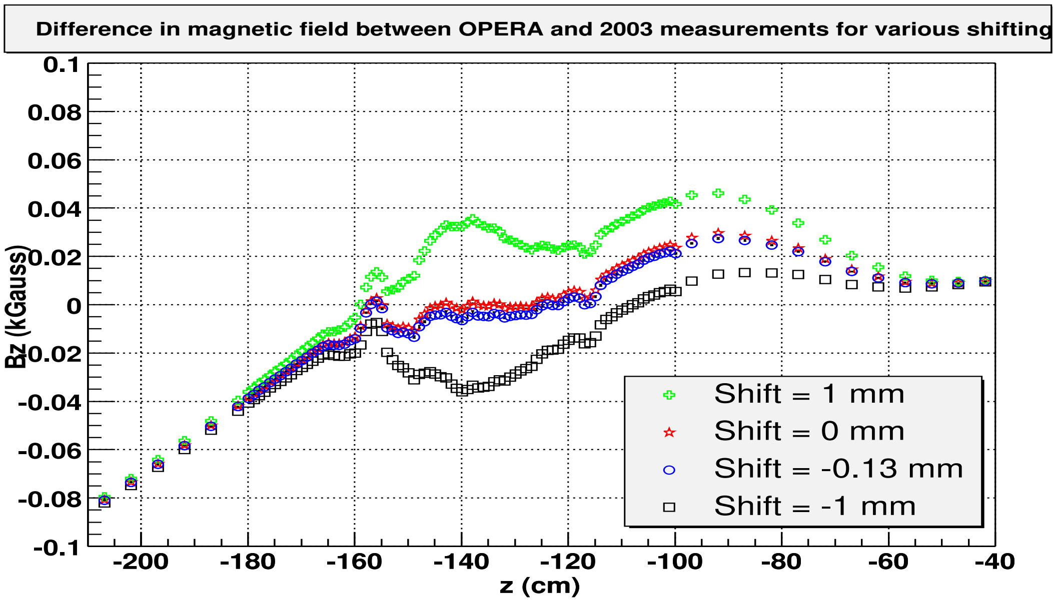

Figure 13: Difference in magnetic field for various shifting in z axis.

4.1.2 Various attempts

We tried by many ways to get rid of the tail and the wiggles; all of them are shown on figure (14). Each of these modification are described below.

- The first curve is the regular one, without any modification.

- It had been also experimentally determined that there was a small deviation in the position alignement [3], which means that $y = -0.14\ cm$ and $x(cm) = 0.3753 + 0.0001926 \times z$ instead of $x = y = 0$. So the first modification, was to include the experimental alignement in our calculation of OPERA field. The best shifting becomes for $z - 0.013\ centimeter$ with alignement.

- Have a more accurate value of the field by correcting it with the second level polynomial calibration correction (see table 2).

- Finally, we tried both alignement and calibration in the same curve.

But as shown on figure (14), changes are so tiny that both the tail and the wiggles are still there. Finally, we changed our approach and used the *Improved* OPERA field rather than the *Nominal* one.

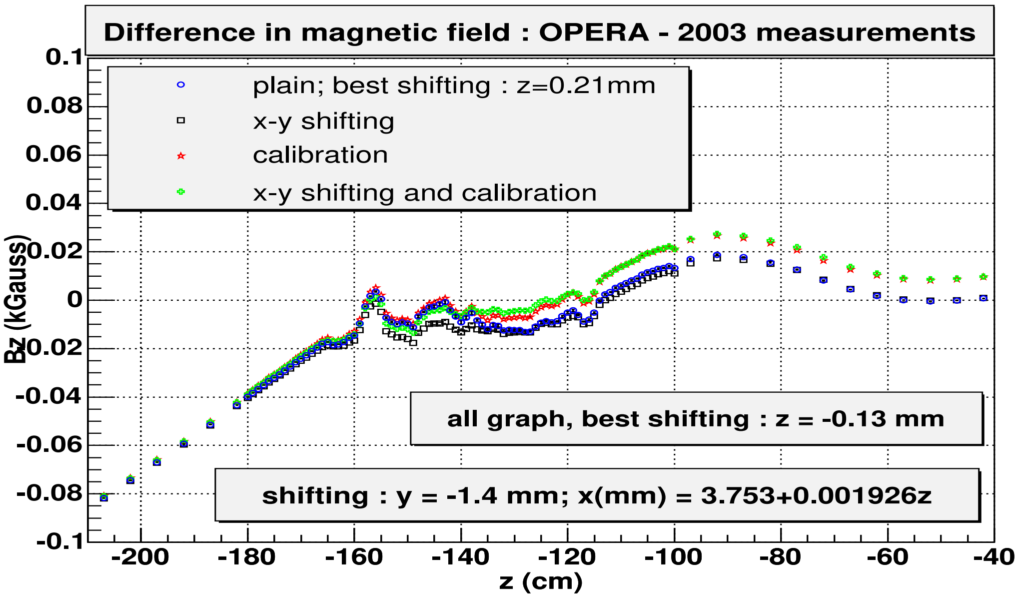

Figure 14: Unfruitful attempts to have a flat difference.

4.2 Improved OPERA field

The *Improved* field is based on the same model as the *Nominal* one, but with little changes in some properties of the field to fit better the 2002 measurements, which were taken inside the coil, instead of the upstream area. The major change is a slight asymetry between the upstream and the downstream part of the magnet. Figure (15) shows difference between this OPERA field and measurements. It is obvious that the wiggles had disappeared but gave place to a big kink in the area of the iron. Still the greatest problem remains : the tail did not vanish, but is the same in this version.

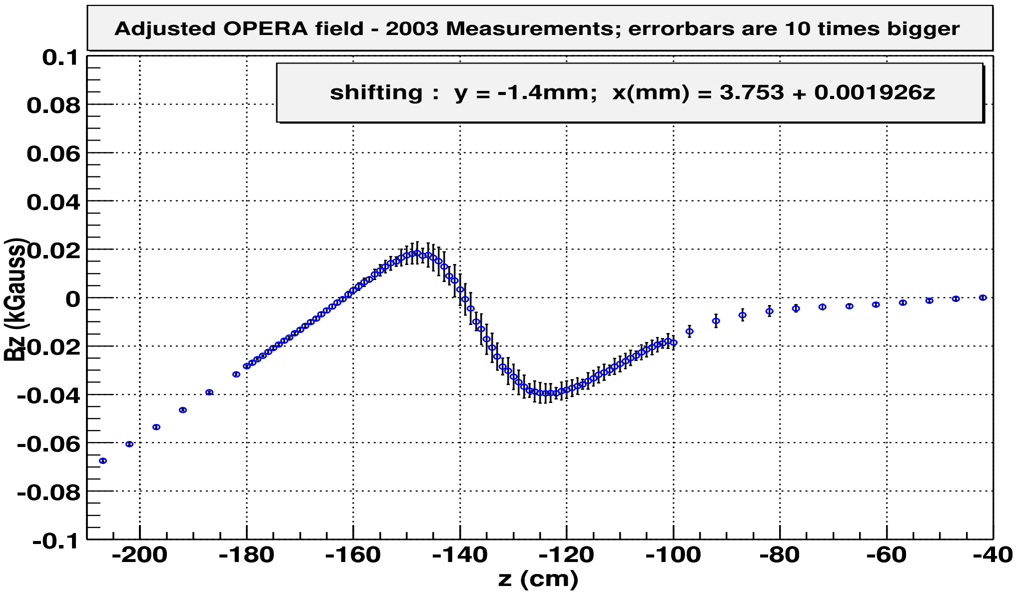

Figure 15: Difference between the Improved OPERA field and measurements, wiggles were traded for a kink, the tail is still present.

4.2.1 Position variation

Again we tried to move OPERA field in three directions to find if the difference curve could be flat. A very slight change in x and y position makes no change to the difference, we can easily see it from figure (17) which shows shifting in x (the result is exactly the same for identical shift in y), and all three curves overlap one another perfectly! On the other hand, a huge shift in y does not solve the problem but makes it worst, the kink is not getting smaller but bigger and with more oscillations, as displayed in figure (18). Finally, figure (16) shows that shifting in z does not give anything good neither, since the amplitude of the kink is getting bigger with a very small shift, and the tail does not disappear. So we conclude from this that position change is not a solution to our tail and kink problems.

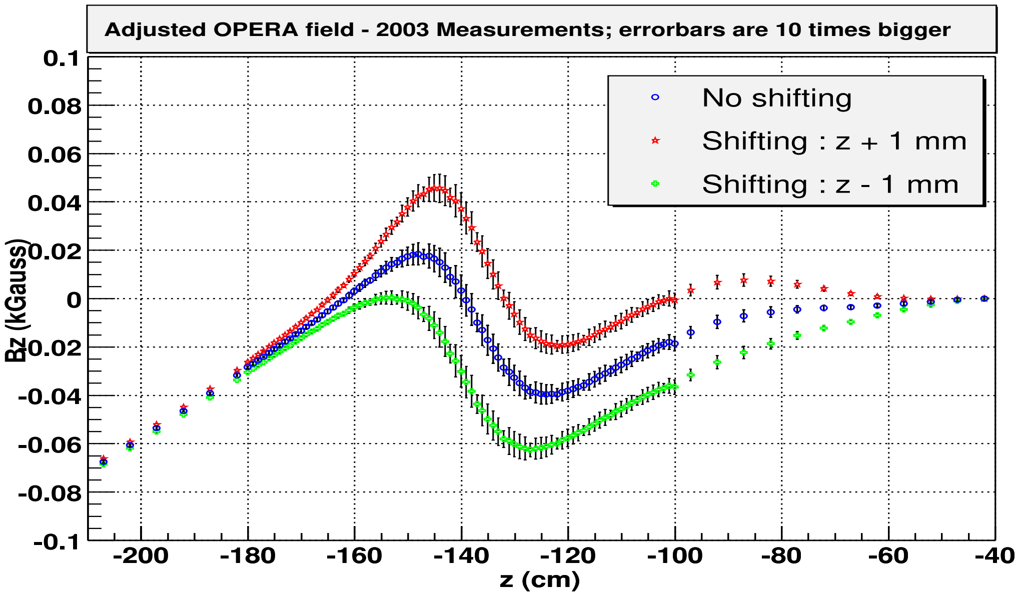

Figure 16: Slight shifts in z in OPERA : results are getting worse.

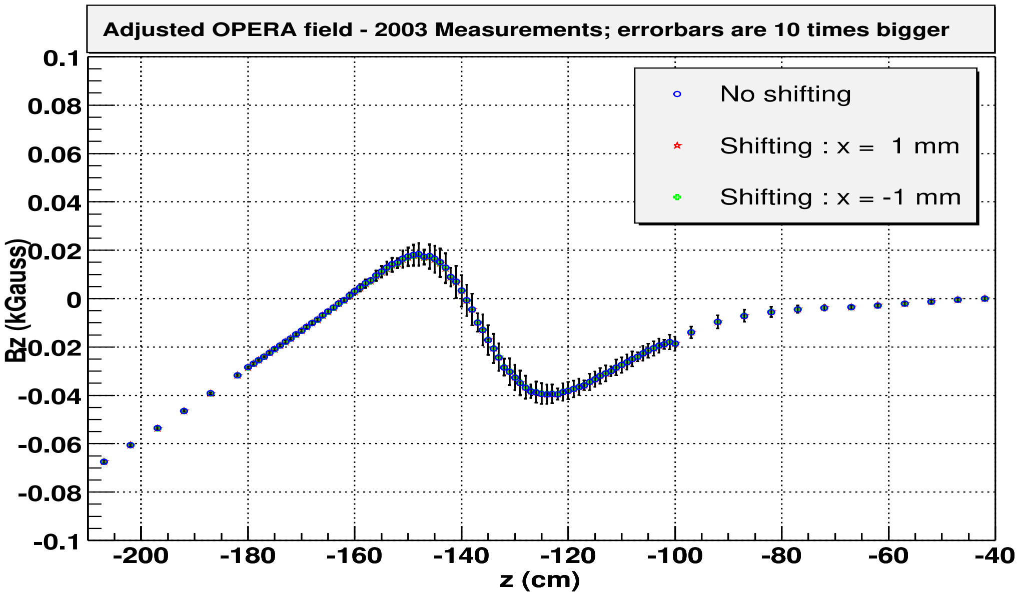

Figure 17: Slight shifts in x in OPERA, perfect overlap of three curves : change is inefficient.

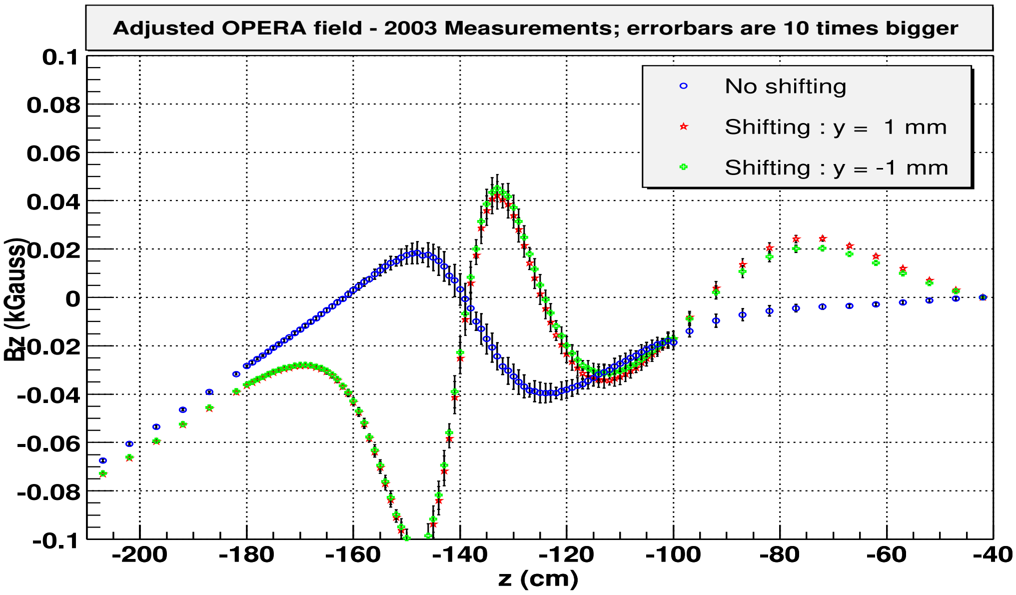

Figure 18: Shifts in y in OPERA (shifts are 50 times bigger than previously).

4.2.2 Position precision

Then we calculated which displacement would OPERA need to reproduce measured error-bars. The technique we used was to move OPERA slightly in each direction on z axis, to calculate averages and errors (see equation 9) of those three field values. This error was compared with the measurements statistical one and the code calculated the difference minimum (see equation 10). We used shifting (ϵ) varying from a magnitude of one millionth of a *centimeter* to five *centimeters*. The result is quite interesting : coincidence between theoritical and experimental data is at its best when the shifting is $\epsilon = 21 \times 10^{-3}$ *centimeter* (or 21 microns) which is very small. Figure (19) shows comparison between theoritical and experimental error for this best shift and figure (20) shows the difference between them. We see an excellent agreement between the measured and predicted error and RMS of field measurements.

$$\overline{B_z} = \frac{B_{z-\epsilon} + B_z + B_{z+\epsilon}}{3} \qquad \text{and} \qquad \Delta\overline{B_z} = \sqrt{\frac{(\overline{B_z} - B_{z-\epsilon})^2 + (\overline{B_z} - B_z)^2 + (\overline{B_z} - B_{z+\epsilon})^2}{3}} \tag{9}$$

$$\frac{d}{d(\epsilon)}\left(\sqrt{\sum_{i=1}^{N}(\Delta\bar{B}_{z,theo} - \Delta\bar{B}_{z,exp})^2}\right) = 0 \tag{10}$$

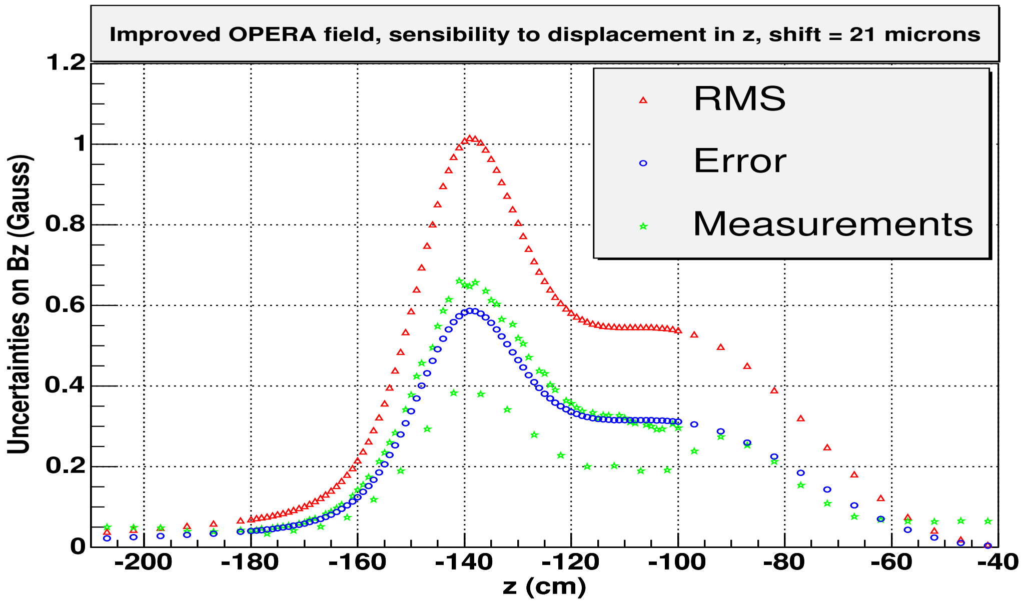

Figure 19: Comparison of theoretical RMS, error and experimental error in function of z.

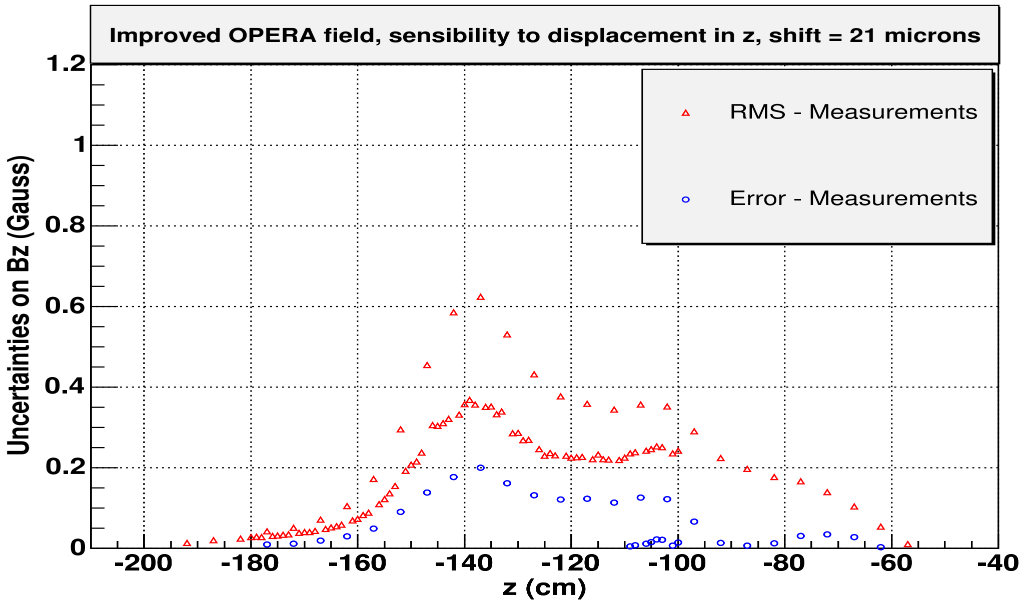

Figure 20: Difference between theoretical error (or RMS) and experimental error.

4.3 New field simulation : changing the BH curve

A BH curve is the path that would follow a material in the plane $B \times H$, where B is the magnetic flux density and H is the magnetic field. These two quantities are related by the following equation : $\vec{H} \equiv \frac{\vec{B}}{\mu_0} - \vec{M}$ where M is the magnetization of the material. We expected that changing the value of $\vec{B}$ for a given $\vec{H}$ by a few percents could give a new field that matches the measurements. In our graphics, term *"BH"* refers in fact to this multiplicative coefficient (a few percents) to $\vec{B}$ values in the regular BH curve data file.

Because of technical problems with OPERA version 9.0, we went back to version 8.7, and in order to save time, we run the simulation with one eighth ($\frac{1}{8}^{th}$) of the model, and used symmetry conditions, which are wrong (last year study shown us that the magnet was slightly asymetric [2]) but a good approximation, to complete the model from this eighth part. This file is found in this directory : **/home2/barnes/e614/modeller/** and named :

E614_iron_cube5b_eighth_noreg_X+0_Y+0_Z+0_221A_BH106_BHus106_BHds106.opc
.

Since the kink slope varies with the BH curve, we used a binary research to find the BH curve that would give the flatest difference. A binary research is used to find zeros (x_0) of a function $f(x)$, by spliting the domain $[a, b]$ (where obligatory $f(a)$ and $f(b)$ are of opposite sign) of this function in two and evaluating the value of the function at this point $f(c)$. The function domain is limited to the good half part where the domain passes from a negative value to a positive one, and we repeat the operation : dividing the domain in two, evaluating the function value and keeping the good half part. We repeat this operation until we have a good enough precision of our zero $x'_0 \simeq x_0$ where $f(x'_0) \approx 0$. In our case, we were not manipulating numbers, but slopes to find one that would give a flat difference (the zero we are searching). Precision is given by $\Delta x_0 = \frac{1}{2^n}$ where n is the number of iterations.

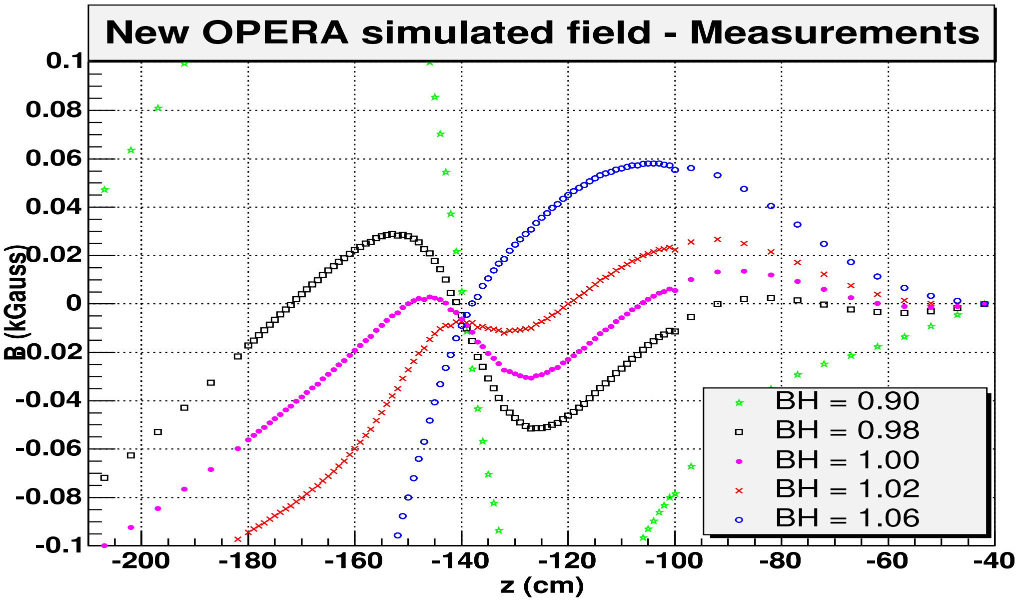

Figure 21: New simulations with different BH curve.

Figure (21) shows differences between many new simulated fields and our measurements. On each of the curve, the tail has the same slope, so the only criteria to define which curve is the best would be the amplitude of the kink. According to this criteria, it is obvious that the best simulation is for the regular BH curve, since there is a 1.00 multiplicative factor. This gives more credibility to our OPERA model because it means that our material model is good. However, the BH curve study does not fix upstream mismatch : it is still a mystery.

4.4 About OPERA : later and further developpements

Because we had a lot of problems running OPERA, this section can be a great support for the understanding of OPERA, and for solving problems later. All results from new simulations were produced by the 8.7 version of OPERA. First we tried to do all our simulations with version 9.0, but we faced the following problems.

- We were not able to generate a volume mesh from the **.opc file*. Hopefully we also had an **.opcb*, on which volume mesh was already generated, so we moved away from this problem with this **.opcb* file.
- Our first results also shown that the field was not of two $Tesla$ ($1Tesla = 10^4 Gauss$) at origin like it should be, the value was indeed $B_z = 18.609kGauss \neq 20\ kGauss$.
- The field produced was independant of the BH curve; we were trying to change the BH curve to study the field dependancy on this parameter, but since the field was exactly the same whatever BH curve we used it did not help our study.
- The most important problem was that TOSCA needed one whole day to run, so we waisted a lot of time just waiting for results that finally were not good. And to make TOSCA run faster, we had to change some parameter (*"Maximum Element Size"* and *"Data Storage Level"*) in volume mesh, which was always stopping and yielding error.

To solve them, we ran the 8.7 version, and with the one-eighth of the magnet model only. The problem is that we have not been able to reproduce those results with the 9.0 version, even with the one-eighth model. At least with this eighth model, magnetic field changes with the BH curve and we can generate the volume mesh with this model. The origin field remains to be a problem, for we still have the value we had for the full model. We tried to change current in the coil, but changes were very small, and they did not reproduce the one we had with 8.7 version. The way to change current is this one :

- select *Pick conductor* $\Rightarrow$ select the coil current is to be changed.
- Operation $\Rightarrow$ Modify conductor $\Rightarrow$ Solenoid $\Rightarrow$ Source drive.

Regular current values are -4729.6 for inside coils, and -6696.8 for outside coils. We first change separately each one of them, and after changed both together; finally we changed both to a higher value. Figure (22) seems to reveal another problem in this OPERA version : the field variation in function of the current is not monotonic.

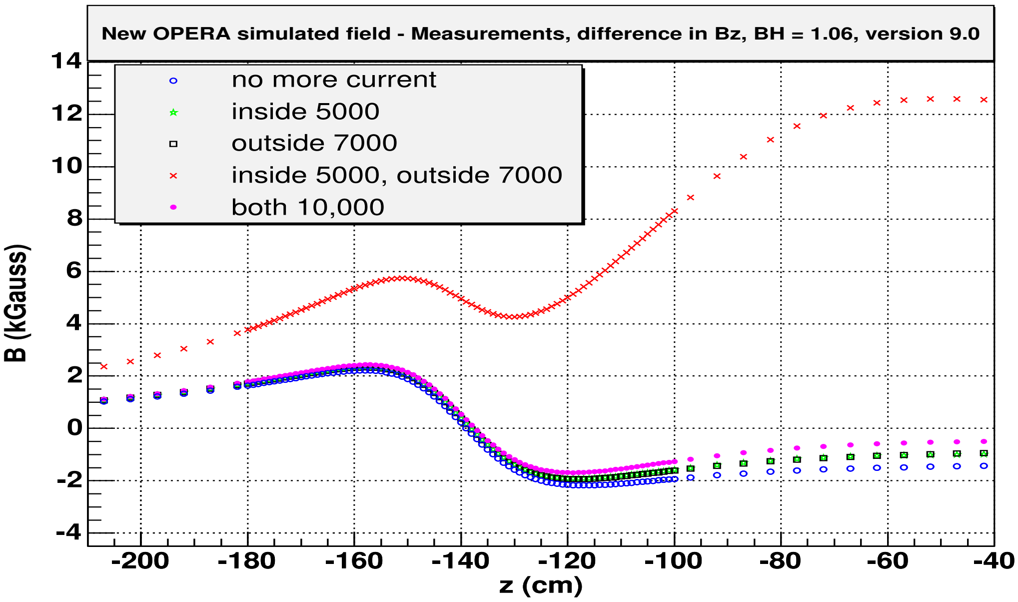

Figure 22: Simulations with various current values.

5 STUDY OF EXTERNAL FIELD OUTSIDE THE YOKE

For now, we only tried to change OPERA to explain every mismatches between OPERA and measurements, but another way to explain them would be to look if there would be another field that we measure beside the magnet one. Hence, we compared two different measurement sets, one that was done with the beam line on, and the other one with beam line off. In order to find if there was a remnant field, we substracted the magnet field off (or beam line off) data from the magnet field on data. Once again, both sets of measurements were not taken at the same group of positions and they have different number of points as we can see on figure (23). First we tried to fit data sets with polynomial function, but none of the fit matched well enough the measurements, so we just compared the few common points to both sets, which give a smaller statistic weight on the analysis.

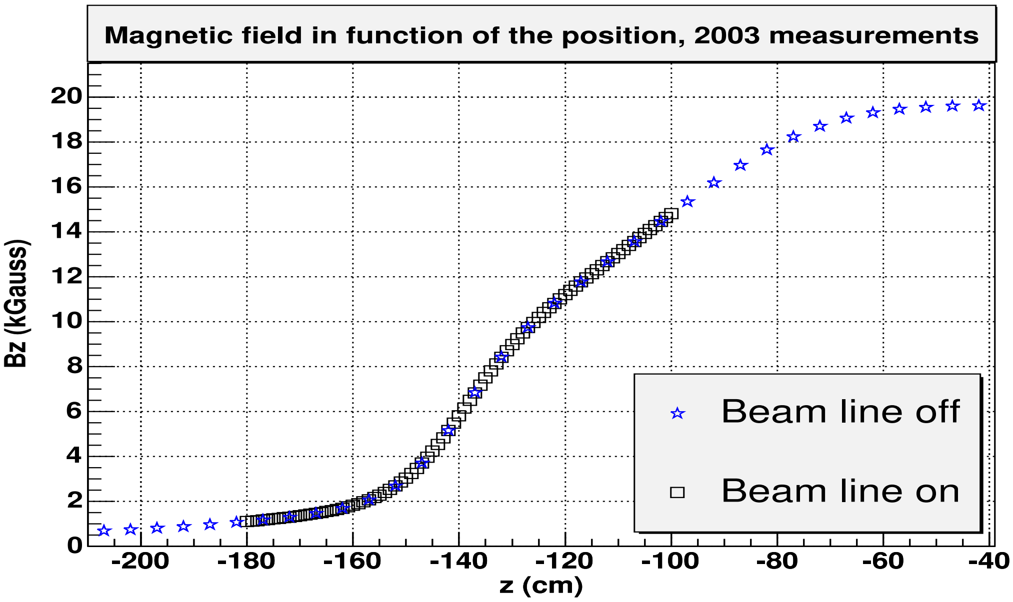

Figure 23: Two sets of data are not covering exact same positions.

Figure (24) shows two important results :

- First, if there is a remnant field, it is probably vectorially opposite to the magnet field, since every point is under zero. This contradicts our first purpose in that study, to find another field source that could explain why measured field was bigger than OPERA field.
- Second, the difference between two sets of data is statistically consistent with zero. This makes us wondering if both files would not have the same contents, and only different name. Doing again those measurements, and many times to have a better statistical error would be a great thing to do.

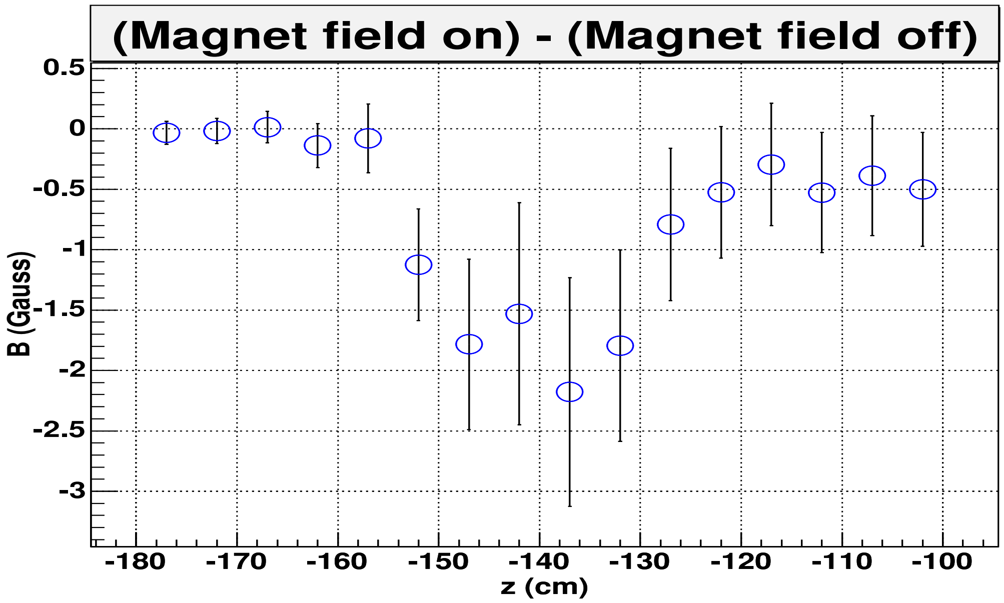

Figure 24: Difference between magnet field on and magnet field off is statistically zero.

Also, when we look at the experimental setup, we realize that for $z = -200$ *centimeters*, we are only 35 *centimeters* away from the quadrupole magnets ($Q6$ and $Q7$), which are surround by a large amount of steel. The magnetic field produced by quadrupole magnets at this point would not be large enough to make a difference in our calculations. However, the steel magnetization could be important enough to change the difference curve. Another source that we should consider is the cyclotron magnet itself, but the field is supposed vertical (along y axis instead of z axis, which is the component that was measured), so without any impact on our measurements.

Something is wrong about those measurements because we would expect a bigger difference between magnet on field and magnet off field, but they are too close to each other.

6 CONCLUSIONS

- **Problems**
  - Understand why there is a kink in the middle part of the difference curve ($z \approx -150\ cm$).
  - Understand why the tail of the difference curve is increasing when $z \to -200\ cm$.
- **Results summary**
  - Calibration of the Hall probes is fairly linear.
  - 2002 and 2003 maps appear to be consistent.
  - Best BH curve is for a 1.00 multiplicative factor, implying that our material model is good.
  - We eliminated position shifts, BH curve changes, and presence of extern field outside the yoke as an explanation of the problems.
- **Suggest for future directions**
  - Take new measurements of the field with beam line on and off to make sure there is no external field.
  - Find where is the error in our OPERA model of the setup.
  - Use a whole magnet model to be more accurate than with the one eighth model that we have used.
  - Make sure that our model can be run by OPERA version 9.0 .
  - Compare OPERA model with measurements for different radii (for different probes).

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Finally absolutely no thanks to Maher Quraan, because he did kid me all summer long with his 5 wifes and 33 children story, which both have no name but only number. Nevertheless, thanks for introducing me to number five. Knoc knoc! .... No, sincerely, thanks to Maher for his beautiful convertible copper mustang and for his leadership in the organisation of sushi lunch ... for Jim's 13 new fish instead of my birthday.

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BIBLIOGRAPHY

Armenta, R., summer work report : TWIST Magnet : Field Map Study Final Report, TRIUMF, (August 2002)

Marshall, G., Field Mapping status, TRIUMF, (May 10, 2002)

Barnes, M.J., "OPERA-3D Magnetic Field Calculation for the "as built" TWIST Magnet", Draft 4a, (January 8, 2002)

OPERA-3D Reference Manual, Vector Fields Ltd., 2002

Rodning, N.L., TWIST Physics Motivation, University of Alberta, (March 14, 2002)

TRIUMF web site : http://www.triumf.ca/

TWIST web site : http://twist.triumf.ca/

OPERA web site : http://www.vectorfields.com/files/html/products/products-frame.html

ROOT web site : http://root.cern.ch/

References

[1] M.J.Barnes, "OPERA-3D Magnetic Field Calculation for the "as built" TWIST Magnet", Draft 4a, (January 8, 2002)

[2] Roberto Armenta, summer work report : TWIST Magnet : Field Map Study Final Report, TRIUMF, (August 27, 2002)

[3] Glen Marshall, personnal notes and discussions on calibration and alignement, TRIUMF, pp

```
void shifting3_fast()
{
  const Int_t m = 99, max = 10000, nmb = 2000;
  Int_t i, j, J;
  Double_t b[3], x1[m], y1[m], x2[m], y2[m], yfirst = -0.1, ylast = 0.1, xfirst
= -210, xlast = -40;
  Double_t z1[m], z2[m], Bz1[m], Bz2[m], erBz2[m], diff[m], diff1[m], diff2[m],
rms, npt, shift,cons, erz[m], erz2 = 0.0021;

//********** ROOT particularity for string **********//
  TString name, name_file = "Statistic3-probe1.dat";







//********** Calling opera and reading file **********//


  gSystem.Load("OperaFld.so");
  OperaFld map;
  map.Load("/home/e614/e614soft/caldb_ascii/bfld_map.00012");

  name = "/home/msimard/Magnet/Files_all/Statistical_arrangement/" + name_file;

  ifstream in (name);
  for (i = 0; i < m; i++)
    {
      in >> z2[i] >> npt >> Bz2[i] >> rms >> erBz2[i];
      z2[i] = z2[i]/double(10);
      erz[i] = erz2;
      y2[i] = -0.14;
      x2[i] = 0.3753 + 0.0001926*z1[i];
      //printf("%5d %14.9f %14.9f\n",z2[i],Bz2[i],erBz2[i]);
    }









//********** 3 set of data **********//


  for (i = 0; i < m; i++)
    {
      x1[i] = x2[i];
      y1[i] = y2[i];
      z1[i] = z2[i];
      map.GetField(x1[i],y1[i],z1[i],20000,b);
      Bz1[i] = b[2]/double(1000);
      diff[i] = Bz1[i] - Bz2[i];
      erBz2[i] *= 10;
    }
  printf("Scaling in Bz = %15.12f\n",diff[m-1]);
  for (i = 0; i < m; i++)
    {
      diff[i] = diff[i] - diff[m-1];
      //printf("%5d %14.9f %14.9f\n",z1[i],Bz1[i],diff[i]);
    }
```



```


  cons = 5;
  for (i = 0; i < m; i++)
    {
      x1[i] = x2[i];
      y1[i] = y2[i] + cons;
      z1[i] = z2[i];
      map.GetField(x1[i],y1[i],z1[i],20000,b);
      Bz1[i] = b[2]/double(1000);
      diff1[i] = Bz1[i] - Bz2[i];
    }
  printf("Scaling in Bz = %15.12f\n",diff1[m-1]);
  for (i = 0; i < m; i++)
    {
      diff1[i] = diff1[i] - diff1[m-1];
      //printf("%5d %14.9f %14.9f\n",z1[i],Bz1[i],diff1[i]);
    }



  //map.Load("/home/e614/e614soft/caldb_ascii/bfld_map.00005"); //possibility of
 changing map
  shift = -cons;
  for (i = 0; i < m; i++)
    {
      x1[i] = x2[i];
      y1[i] = y2[i] + shift;
      z1[i] = z2[i];
      map.GetField(x1[i],y1[i],z1[i],20000,b);
      Bz1[i] = b[2]/double(1000);
      diff2[i] = Bz1[i] - Bz2[i];
    }
  printf("Scaling in Bz = %15.12f\n",diff2[m-1]);
  for (i = 0; i < m; i++)
    {
      diff2[i] = diff2[i] - diff2[m-1];
      //printf("%5d %14.9f %14.9f\n",z1[i],Bz1[i],diff3[i]);
    }




//********** Define canvas **********//

  gStyle->SetCanvasColor(10);
  c1 = new TCanvas("Plot/OPERA-2003many4","OPERA-2003",800,0,700,500);
  c1->SetGrid();
  c1->GetFrame()->SetBorderSize(12);


//********** Define 3 graph : name, variables, color, shape **********//

  gr = new TGraphErrors(m, z1, diff, erz, erBz2);
  gr->SetTitle("Improved OPERA field - 2003 Measurements; errorbars are 10 times
 bigger");
  gr->SetMarkerColor(4);
  gr->SetMarkerStyle(4);
  gr->SetMarkerSize(0.5);
  gr->Draw("AP");

  gr1 = new TGraphErrors(m, z1, diff1, erz, erBz2);
  gr1->SetMarkerColor(2);
  gr1->SetMarkerStyle(30);
  gr1->SetMarkerSize(0.5);
  gr1->Draw("P");

  gr2 = new TGraphErrors(m, z1, diff2, erz, erBz2);
  gr2->SetMarkerColor(3);
```

```
  gr2->SetMarkerStyle(28);
  gr2->SetMarkerSize(0.5);
  gr2->Draw("P");


//********** Set the scale and title of the axis **********//

  gr->GetXaxis()->SetTitle("z (cm)");
  gr->GetXaxis()->CenterTitle();
  gr->GetYaxis()->SetTitle("Bz (kGauss)");
  gr->GetYaxis()->CenterTitle();
  gr->SetMaximum(ylast);
  gr->SetMinimum(yfirst);
  gr->GetXaxis()->SetLimits(xfirst, xlast);
  gr->Draw("P");


//********** Define legend : a title according to each set of points **********/
/

  leg = new TLegend(0.6, 0.2, 0.85, 0.3);  // (x1, y1, x2, y2);
  leg->AddEntry(gr, "No shifting", "p");
  leg->AddEntry(gr1, "Shifting : y =  1 mm", "p");
  leg->AddEntry(gr2, "Shifting : y = -1 mm", "p");
  leg->Draw();

  c1->Update();
}
```