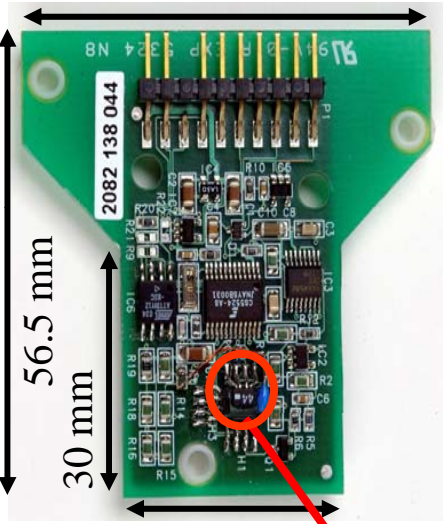


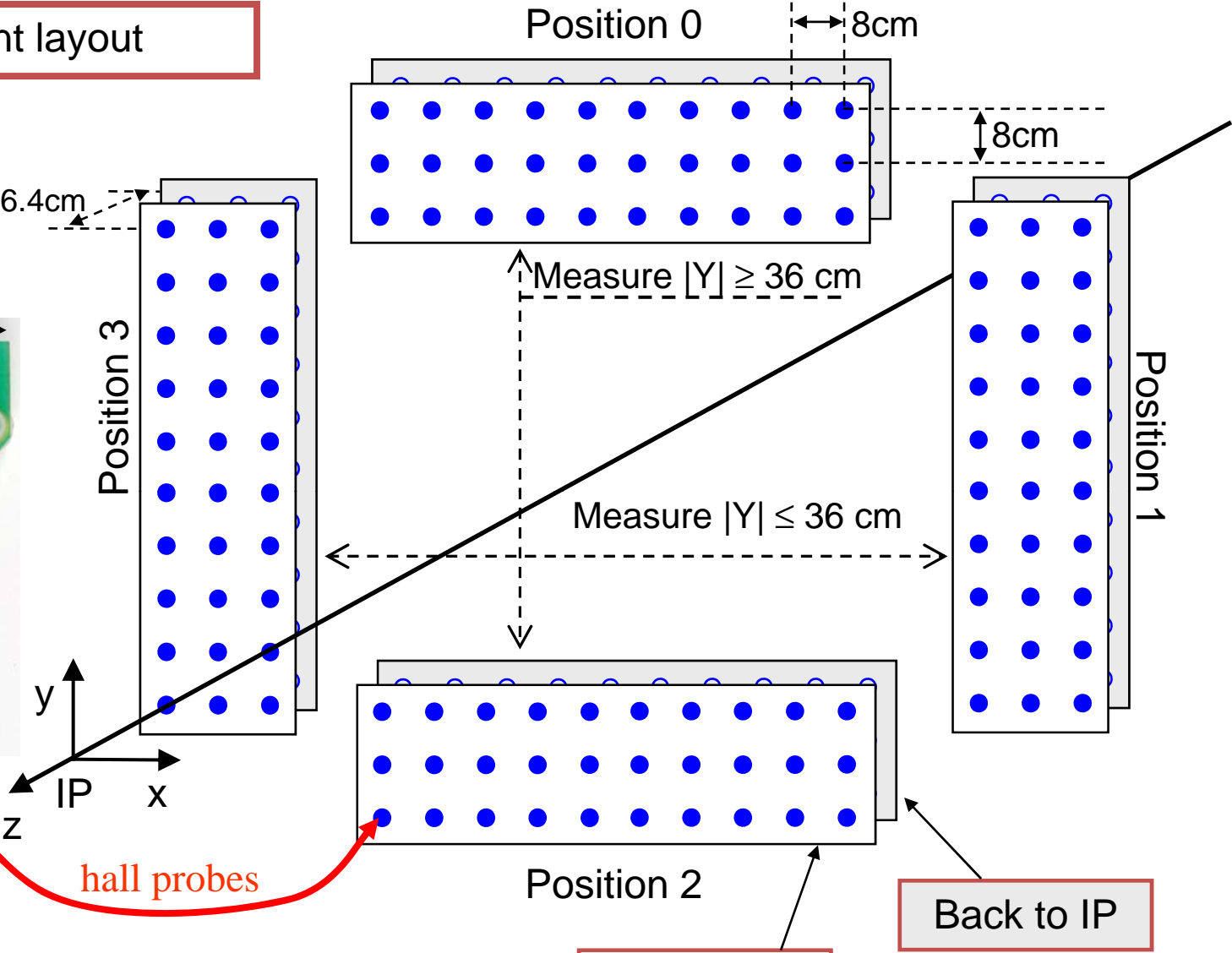
Status of the magnetic field map

Measurement layout



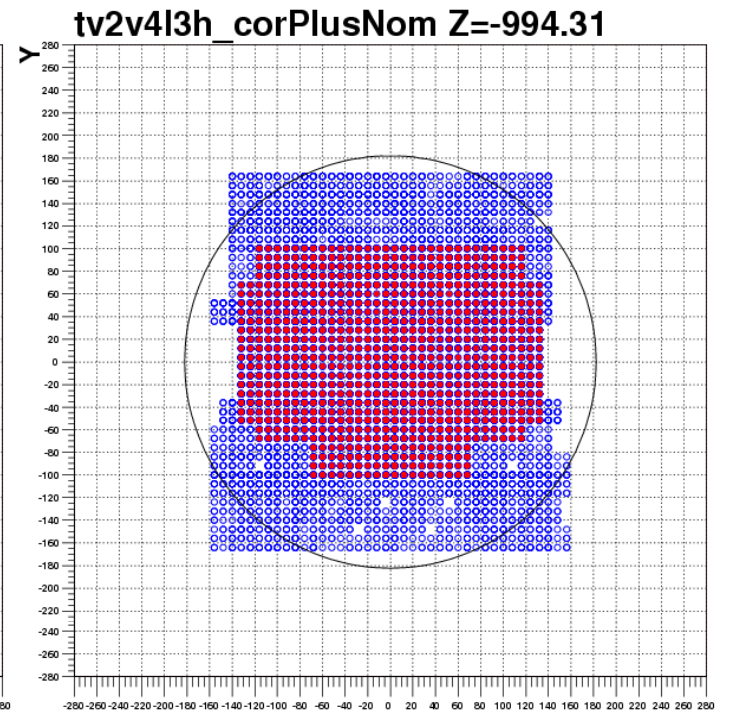
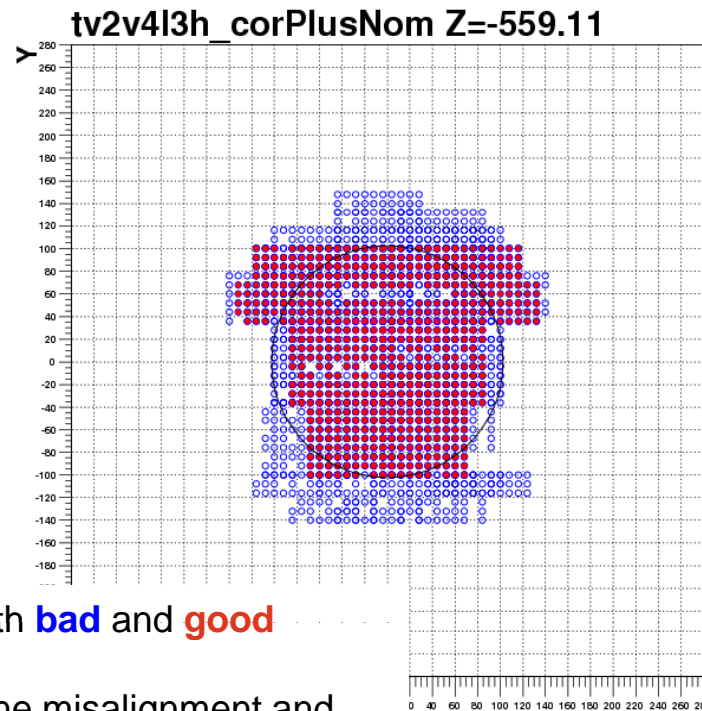
(F.Bergsma)

hall probes



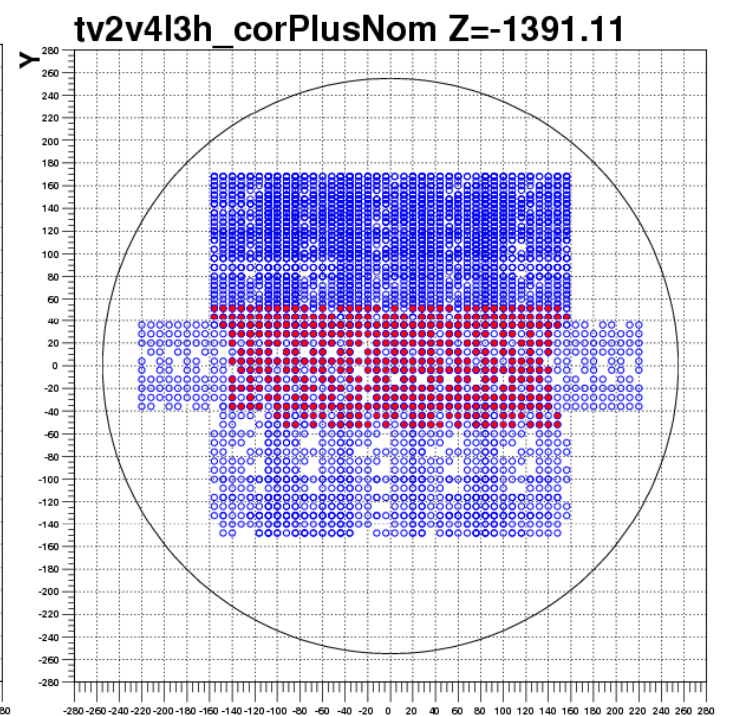
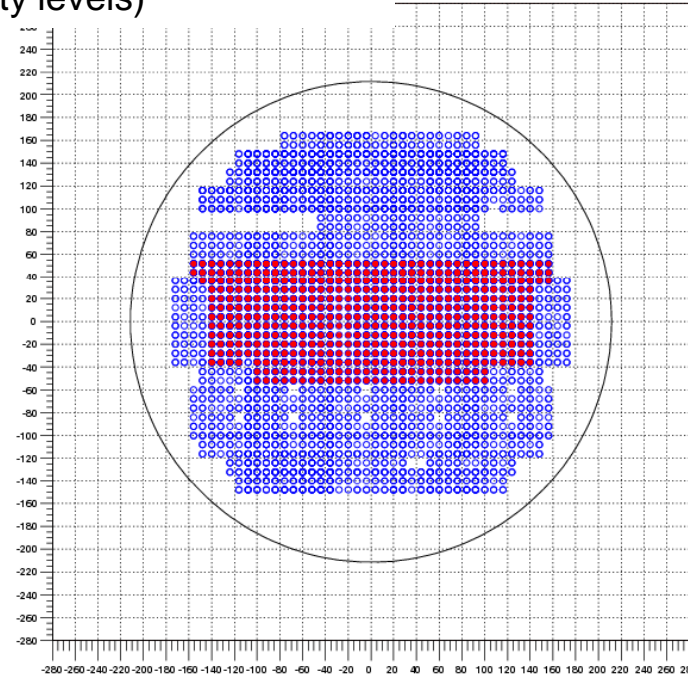
Z-steps of 6.4 or 8 cm

$$-1392.8 < Z < -1047.2$$
$$-1058.3 < Z < -555.9$$



Two data taking periods with **bad** and **good** hardware setups
(large differences in machine misalignment and measurements reproducibility levels)

n Z=-1154.31



Model to fit the field distortions

Field \vec{B}^m seen by the 3D probe in its local frame (\equiv lab.frame for FIP probes in position 0):

$$\vec{B}^m(\vec{r}) = R_{\vec{\theta}} R_p \vec{\hat{B}}(\vec{r} + R_p^{-1} \vec{\delta}) + \vec{\epsilon} \approx R_{\vec{\theta}} R_p \vec{\hat{B}}(\vec{r}) + R_p \frac{\partial \vec{\hat{B}}}{\partial \vec{r}} R_p^{-1} \vec{\delta} + \vec{\epsilon} \quad (1)$$

$\vec{\epsilon}$ - vector of residual miscalibration

$\vec{\delta}$ - vector of probe's displacements wrt its ideal position

R_p - rotation matrix bringing vector from lab to local frame

$\vec{\hat{B}}$ true field in lab frame

$$\frac{\partial \vec{\hat{B}}}{\partial \vec{r}} = \begin{pmatrix} \frac{\partial B_X}{\partial x} & \frac{\partial B_X}{\partial y} & \frac{\partial B_X}{\partial z} \\ \frac{\partial B_Y}{\partial x} & \frac{\partial B_Y}{\partial y} & \frac{\partial B_Y}{\partial z} \\ \frac{\partial B_Z}{\partial x} & \frac{\partial B_Z}{\partial y} & \frac{\partial B_Z}{\partial z} \end{pmatrix}$$

- gradients of field components in lab. frame
(calculated numerically from the difference of neighboring measurements for the dominant components and exploring $\vec{\nabla} \times \vec{B} = 0$ and $\vec{\nabla} \cdot \vec{B} = 0$ for minor ones)

$$R_{\vec{\theta}} = I + Q_{\vec{\theta}} = I + \begin{pmatrix} 0 & \theta_z & -\theta_y \\ -\theta_z & 0 & \theta_x \\ \theta_y & -\theta_x & 0 \end{pmatrix}$$

- rotation matrix accounting the probe's inclinations $\vec{\theta} = \{\theta_x, \theta_y, \theta_z\}$: its ideal position on the plate

Each component is measured by separate Hall probe and 3D assembly is not point-like ($\sim 4 \times 4 \times 4$ mm³)



Difference between the local measurement and the true field:

$$\begin{bmatrix} \Delta B_X \\ \Delta B_Y \\ \Delta B_Z \end{bmatrix} = Q_{\vec{\theta}} R_p \vec{\hat{B}} + R_p \frac{\partial \vec{\hat{B}}}{\partial \vec{r}} R_p^{-1} \begin{bmatrix} \delta_X \\ \delta_Y \\ \delta_Z \end{bmatrix} + \vec{\epsilon} \quad (2)$$

Initial method: reconstruction of scalar potential

(worked for L3 and to some extent for dipole “good setup” data)

- i. Assume that the “main” component (B_x) is almost not affected by distortions
- ii. Fit it to solution of Laplace equation and by integration (in x) obtain potential Ψ

$$\Psi(x, y, z) = \sum_{m,k} C_{mk} \begin{bmatrix} \sin\left(m \frac{\pi x}{X}\right) \\ \cos\left(m \frac{\pi x}{X}\right) \end{bmatrix} \begin{bmatrix} \sin\left(k \frac{\pi y}{Y}\right) \\ \cos\left(k \frac{\pi y}{Y}\right) \end{bmatrix} \begin{bmatrix} \sinh\left(z\pi / \sqrt{\left(\frac{mx}{X}\right)^2 + \left(\frac{ky}{Y}\right)^2}\right) \\ \cosh\left(z\pi / \sqrt{\left(\frac{mx}{X}\right)^2 + \left(\frac{ky}{Y}\right)^2}\right) \end{bmatrix} \quad (3)$$

- iii. Compute minor field components as $\vec{\nabla} \Psi$ and fit their difference with measured values to assumed distortions model (2) + extra field subject of 2D Laplace equation (an “integration constant” from step ii)

$$\begin{bmatrix} B_Y \\ B_Z \end{bmatrix} = \begin{bmatrix} \partial/\partial x \\ \partial/\partial y \end{bmatrix} \sum_m D_m \begin{bmatrix} \sin\left(m \frac{\pi y}{Y}\right) \\ \cos\left(m \frac{\pi y}{Y}\right) \end{bmatrix} \begin{bmatrix} \sinh(z\pi Y / my) \\ \cosh(z\pi Y / my) \end{bmatrix}$$

- iv. Correct all components to account for the extracted distortion parameters
- v. If needed, repeat same procedure few times.

Problems

- In Cartesian frame this method is very slow to converge (due to the lack of the periodicity condition, contrary to cylindrical frame of L3) and the measured grid density is not enough for needed precision.
- Point (i) is not fulfilled in most of the volume:
 - ♦ B_z and B_y can be as large as B_x ,
 - ♦ Due to the field gradients of up to 300 Gauss/cm in coils and yoke region and significant shifts even the dominant component can be wrong by ~100 Gauss.

New method: fit to splines

One can describe data by cubic splines and require their derivatives to respect the Maxwell equations. All field components are treated (varied) on the same footing.

Since the number of parameters to fit may reach a few 1000s, the model has to be linear.

Derivative of the spline passing through the points f_i can be presented as a linear form of the measurements

Spline describing the segment $[x_j, x_{j+1}]$ for measurements f_i on equidistant grid ($x_{j+1} - x_j \equiv \Delta_x$)

$$f(x) = Af_j + Bf_{j+1} + \frac{\Delta_x^2}{6}(A^3 - A)f_j'' + \frac{\Delta_x^2}{6}(B^3 - B)f_{j+1}'' \quad \text{with} \quad A \equiv \frac{x_{j+1} - x}{\Delta_x} \quad B \equiv 1 - A$$

The second derivatives f'' can be obtained from condition of their being continuous at the knots and an extra convention for the behavior at the endpoints, leading to tri-diagonal set of linear equations:

$$\frac{\Delta_x}{6} (f_{j-1}'' + 4f_j'' + f_{j+1}'') = \frac{1}{\Delta_x} (f_{j+1} - 2f_j + f_{j-1})$$

$$f_1'' = f_n'' = 0 \quad (\text{natural})$$

checks show that “not-a-knot” condition (continuous f''' at last but one endpoints) is best to fit the data

$$f_3'' - 2f_2'' + f_1'' = f_n'' - 2f_{n-1}'' + f_{n-2}'' = 0 \quad (\text{not-a-knot})$$

\Rightarrow the 2nd derivatives f'' can be obtained as a linear combination of the measurement $f_j'' = \frac{6}{\Delta_x^2} \sum_{i=1}^n M_{i,j} f_i$ where matrix M depends only on the number of measured points

\Rightarrow one can directly build the derivatives of the “splined field”: $f_j' = \frac{1}{\Delta_x} \sum_{i=1}^n f_i (-\alpha M_{i,j} + \beta M_{i,j+1} + \delta_{i,j+1} - \delta_{i,j})$ where $\alpha \equiv 3A^2 - 1 = -1$ and $\beta \equiv 3B^2 - 1 = 2$ for all points except 1st one where they are swapped and $\delta_{i,j} = 1$ for $i=j$, 0 otherwise.

Hence one can impose the Maxwell equations on the model (1) as a set of linear equations.

Example of $\text{div } \vec{B} = 0$

$$\Rightarrow + \frac{1}{\Delta_x} \sum_{p=1}^{n_x} B_x(p, j, k) \left(-\alpha M_{p,i}^{n_x} + \beta M_{p,i+1}^{n_x} + \delta_{p,i+1} - \delta_{p,i} \right)$$

$$+ \frac{1}{\Delta_y} \sum_{p=1}^{n_y} B_y(i, p, k) \left(-\alpha M_{p,j}^{n_y} + \beta M_{p,j+1}^{n_y} + \delta_{p,j+1} - \delta_{p,j} \right)$$

$$+ \frac{1}{\Delta_z} \sum_{p=1}^{n_z} B_z(i, j, p) \left(-\alpha M_{p,k}^{n_z} + \beta M_{p,k+1}^{n_z} + \delta_{p,k+1} - \delta_{p,k} \right) = 0$$

Global Fit

Corrections parameters are obtained from the global fit over large volume of data. For each {x,y,z} point with n measurements one obtains a set of linear equation (very schematically) :

$$\begin{aligned}
 & C_{Maxwell} \times \begin{cases} \vec{\nabla} \cdot \vec{B}(\vec{\delta}, \vec{\theta}) = 0 \\ \vec{\nabla} \times \vec{B}(\vec{\delta}, \vec{\theta}) = 0 \end{cases} && \text{Constraints from Maxwell equations} \\
 & + \\
 & C_{min} \times \begin{cases} \vec{\delta}_{X,Y,Z}^{(i)} = 0 \\ \theta_{X,Y,Z}^{(i)} = 0 \end{cases} && \text{Constraints to apply a "minimal possible" correction (model (1) is linearized, e.g. } \sin \theta \rightarrow \theta \\
 & + \\
 & C_{glob} \times \begin{cases} \sum \vec{\delta}_{X,Y,Z} = 0 \\ \sum \theta_{X,Y,Z} = 0 \end{cases} && \text{Constraints to prevent global shift and rotations of the setup} \\
 & + \\
 & C_{rep} \times \begin{cases} \vec{B}^i(\vec{\delta}, \vec{\theta}) - \vec{B}^j(\vec{\delta}, \vec{\theta}) = 0 \\ i \neq j; i, j = 1, n \end{cases} && \text{Constraints imposing the compatibility of } n \text{ repetitive measurements at the same point}
 \end{aligned}$$

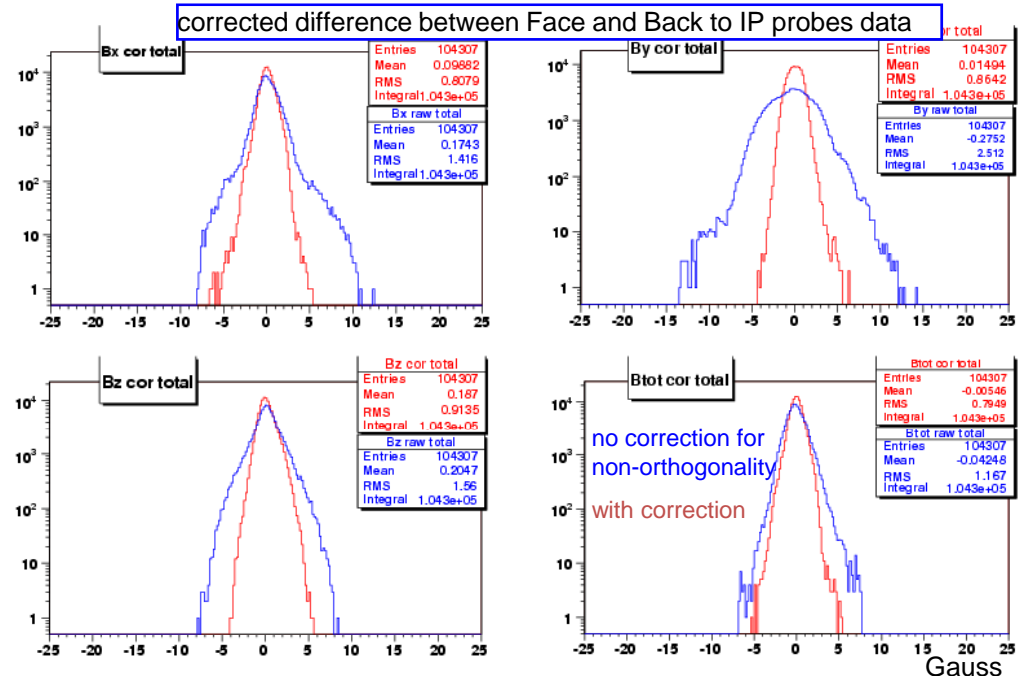
Coefficients C_x are relative weights for different constraints: equivalents of Lagrange multipliers but have to be tuned by hand (otherwise the model would be non-linear).

Once the correction parameters are found, the corrected field components (averaged over multiple measurements at each points) are fitted to (3) and parameterized by Chebyshev polynomials.

Some details

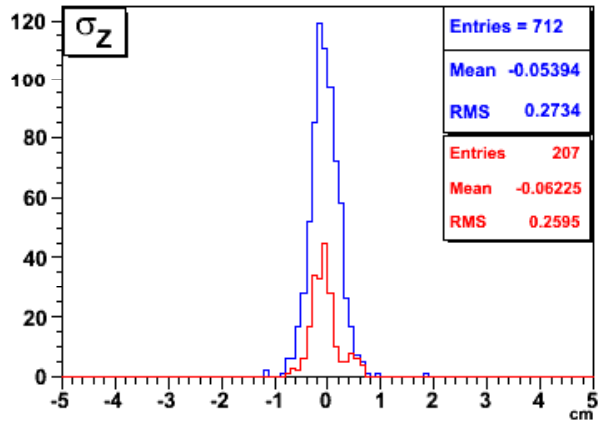
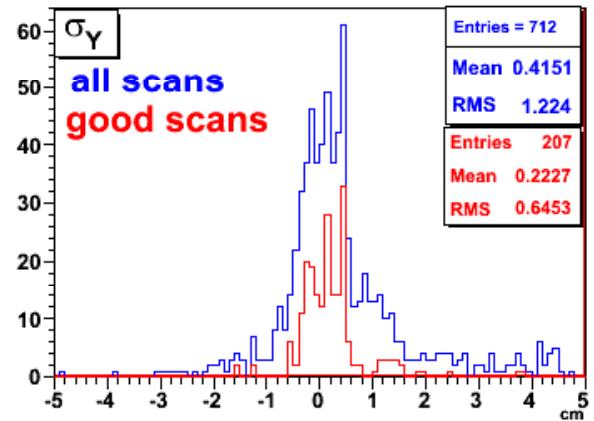
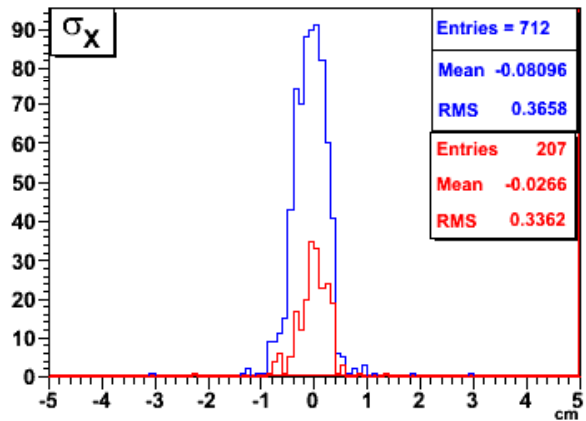
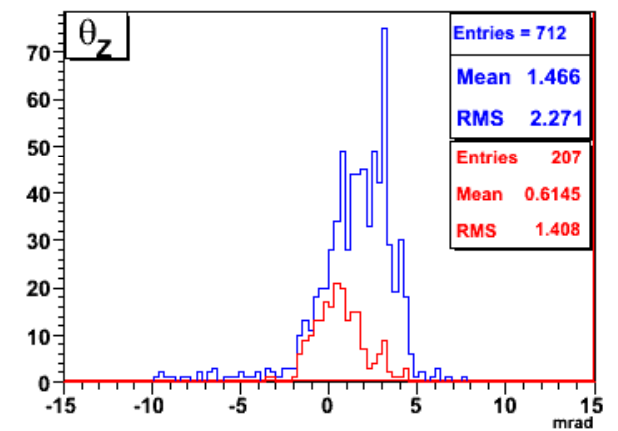
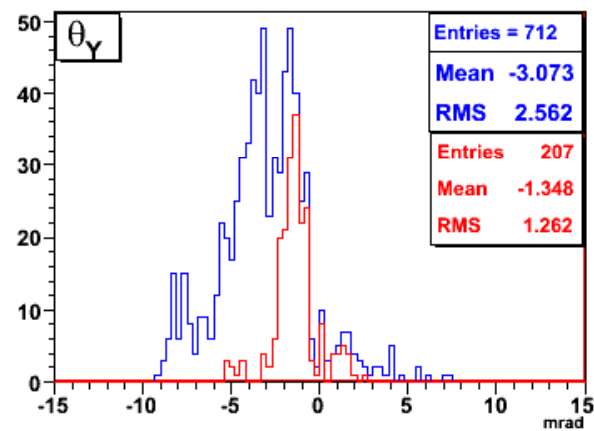
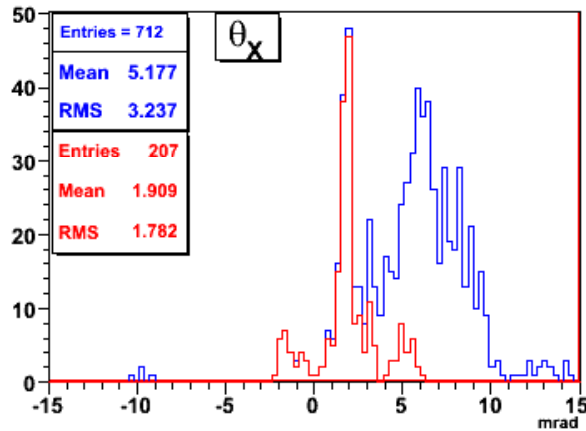
- ~350 scans for each current setting (12 and 30 kA in L3) were used for the fit.
- For 12kA in L3 only data at $|Y| < 116$ cm could be used: large $|Y|$ scans (all taken with “bad” setup) have either no overlap or were taken with shift of 4 cm (instead of 8cm) wrt. the rest of the data.
- 10 probe alignment sets were identified in 3 hardware setups (probe maps)

- Some 1D probes showed non-orthogonality up to 1mrad (supposed to be < 0.2 mrad). Only partial correction is possible by comparing probes on the opposite sides of the machine (special step before performing a global fit).



- At different periods 8, 16 or 6.4 cm steps in Z were used. They all were interpolated to 6.4 cm steps to have a data on the equidistant grid.

Extracted scan-wise corrections



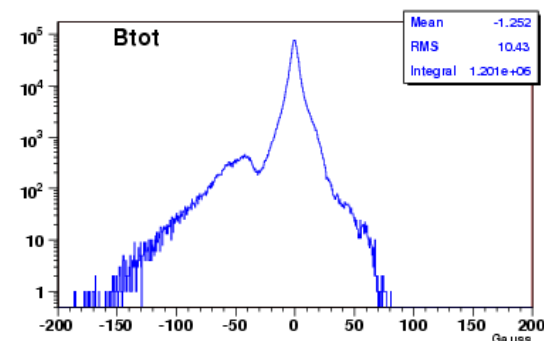
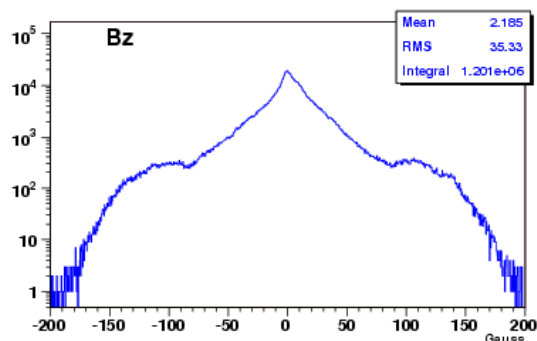
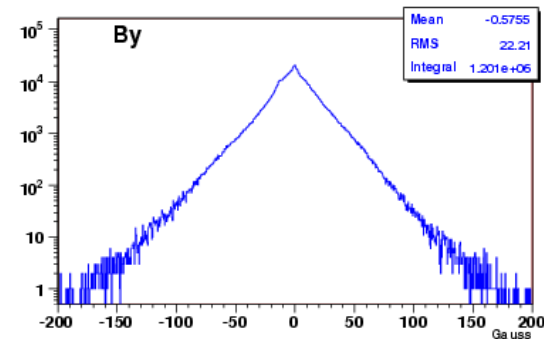
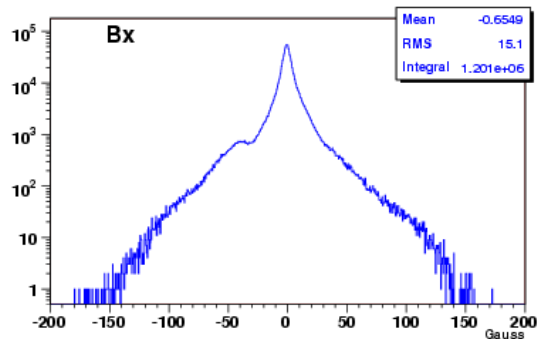
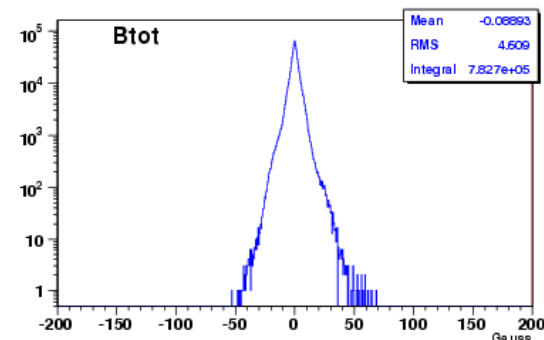
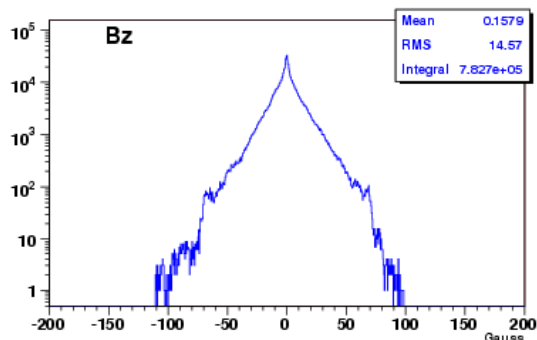
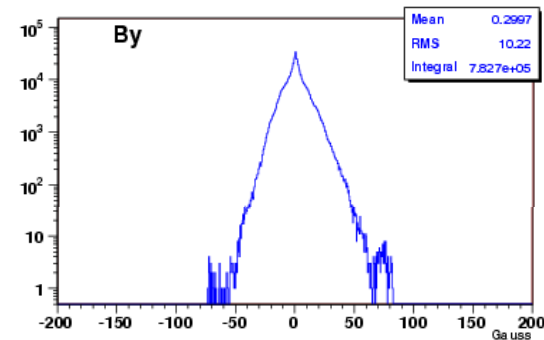
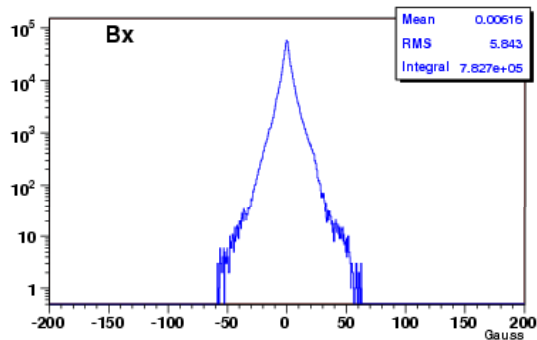
Results

Difference between the individual
measurements at each point
and their average
(L3 = 30kA data)

Data from “fine setups” (9-23/10/2005)

Before correction

Data from “fine+bad setups”



Results

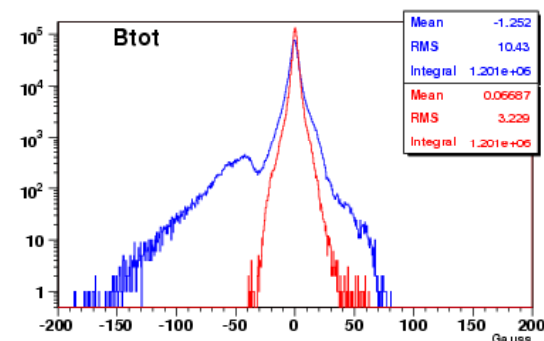
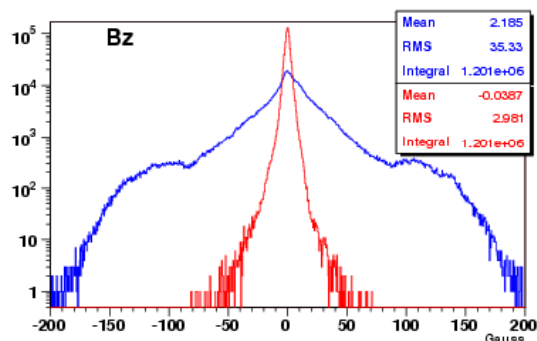
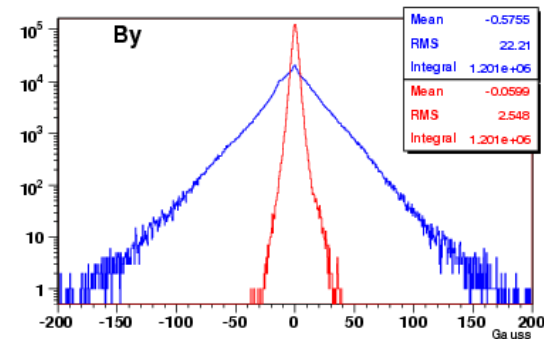
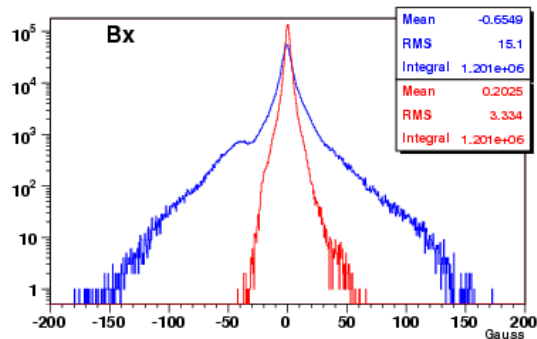
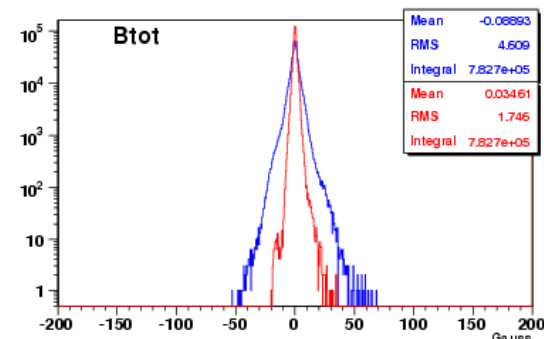
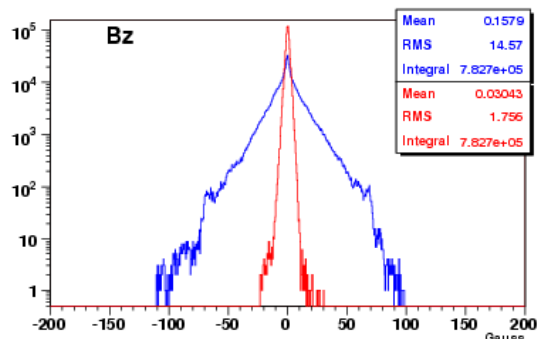
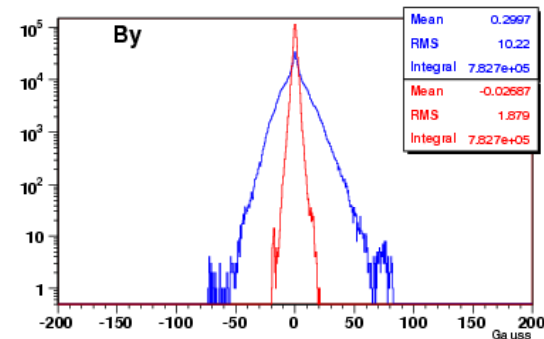
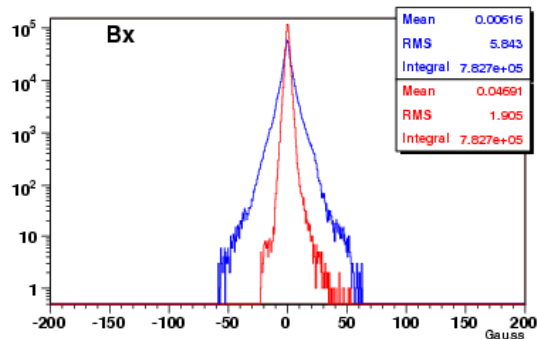
Difference between the individual
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Data from “fine setups” (9-23/10/2005)

Before correction

After correction

Data from “fine+bad setups”



Results

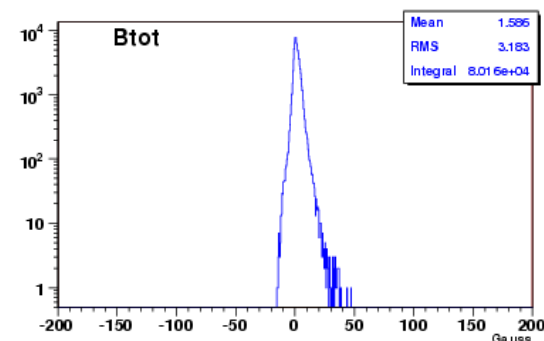
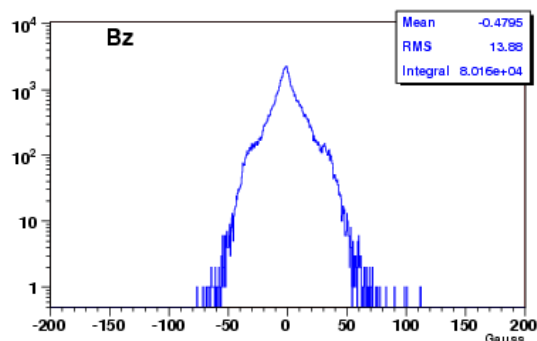
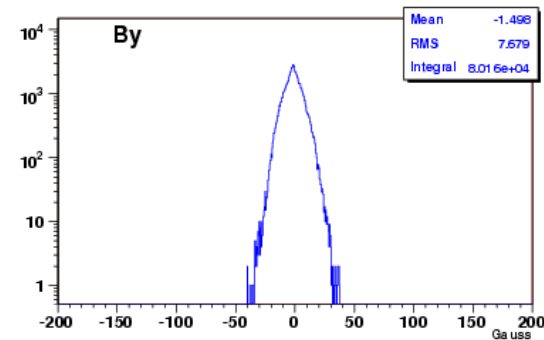
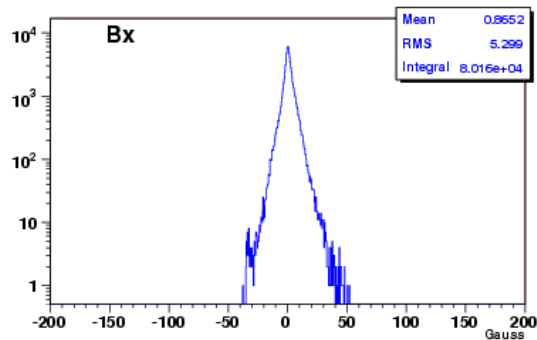
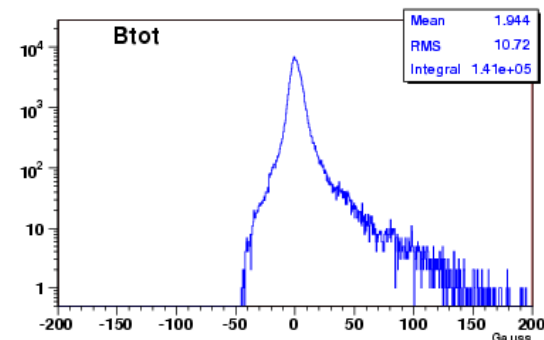
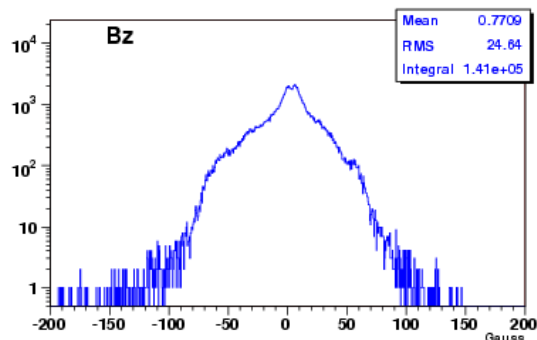
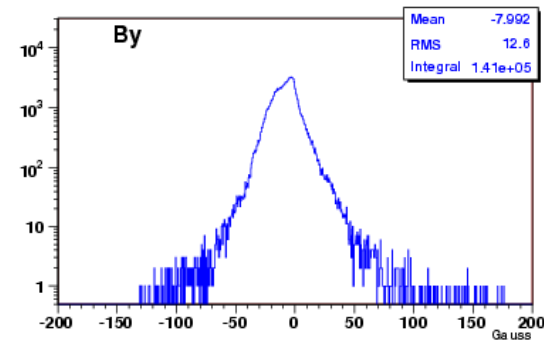
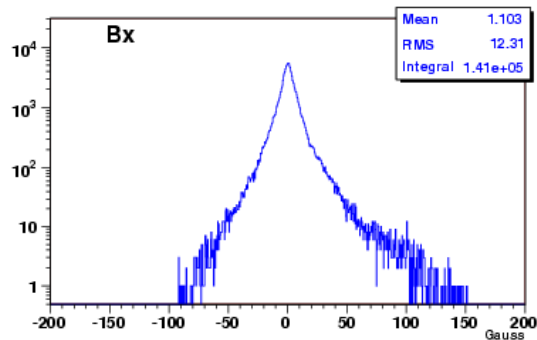
Difference between the average of the measurements each point and final parameterization

(L3 = 30kA data)

Data from “fine setups” (9-23/10/2005)

Before correction

Data from “fine+bad setups”



Results

Difference between the average of the measurements each point and final parameterization

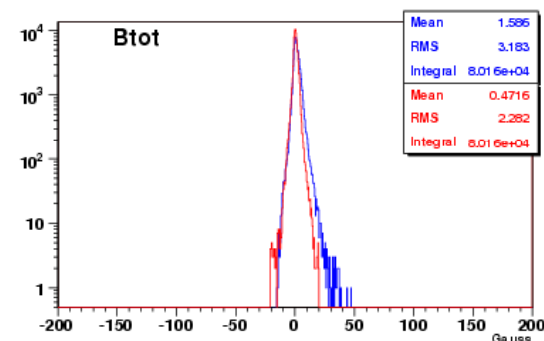
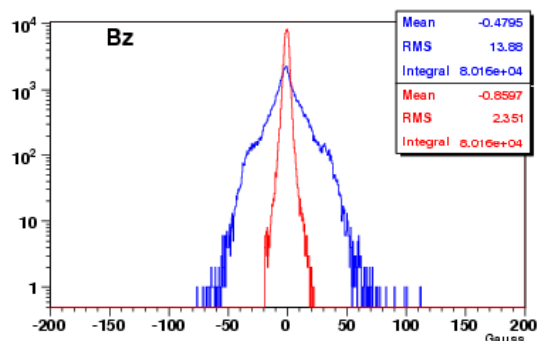
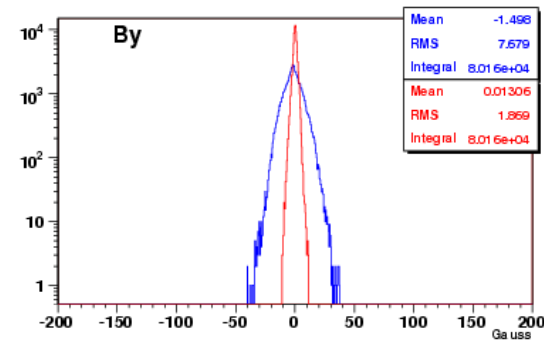
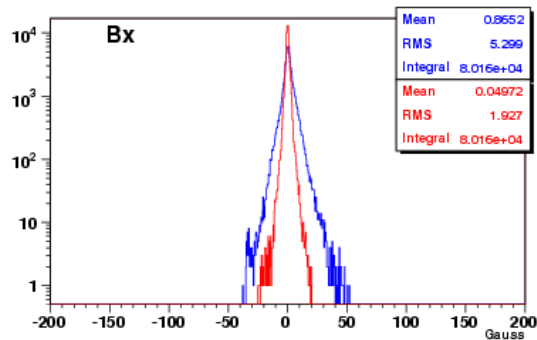
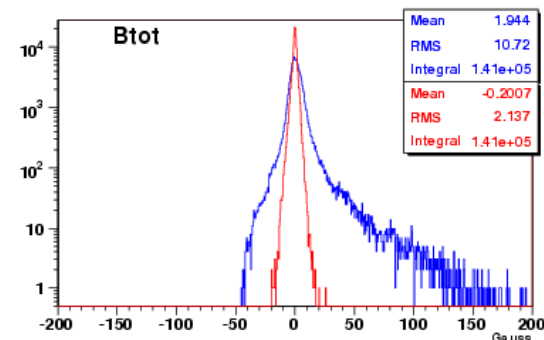
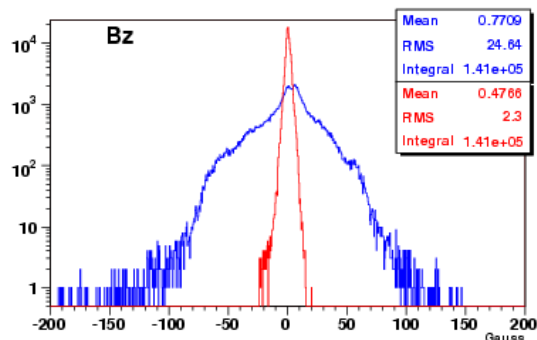
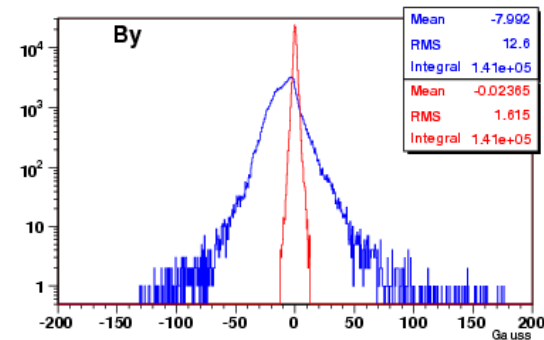
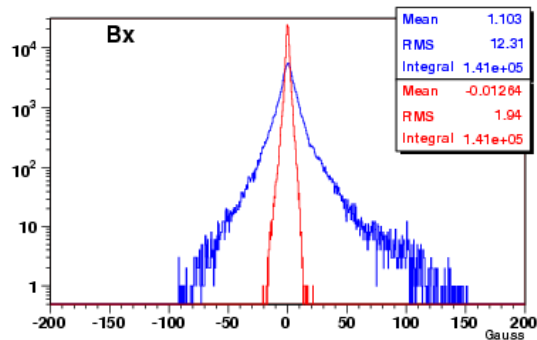
(L3 = 30kA data)

Data from “fine setups” (9-23/10/2005)

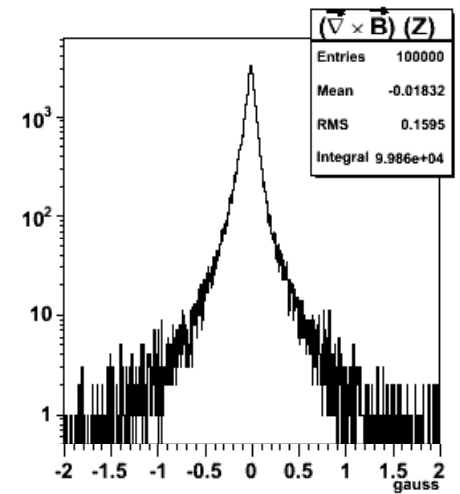
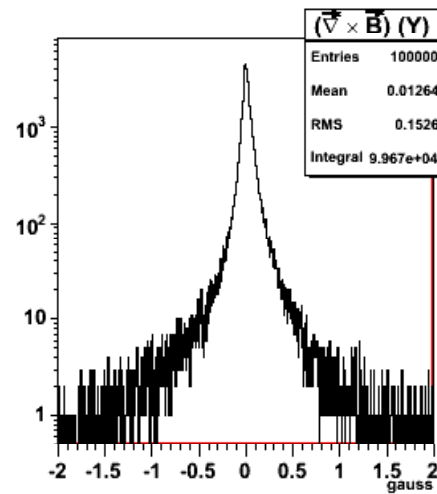
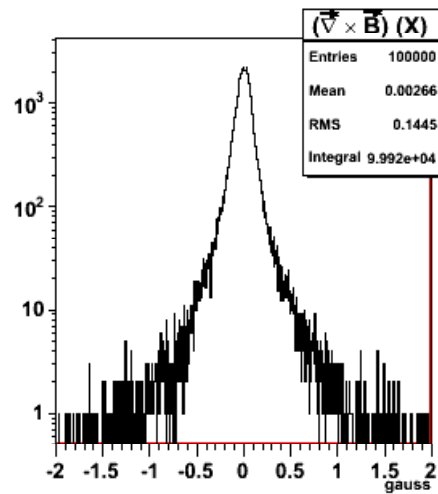
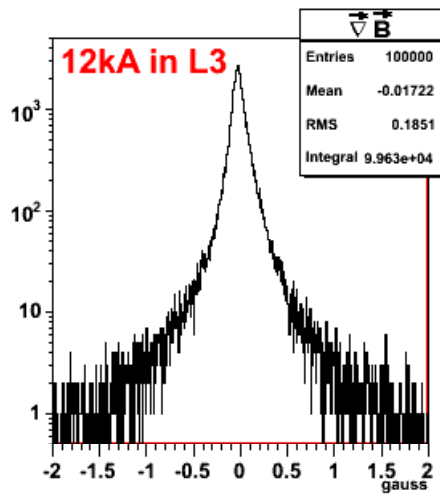
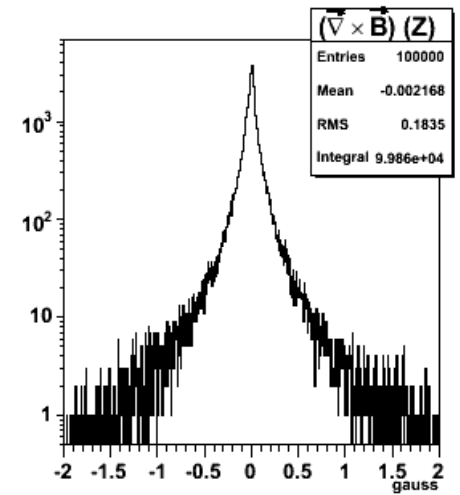
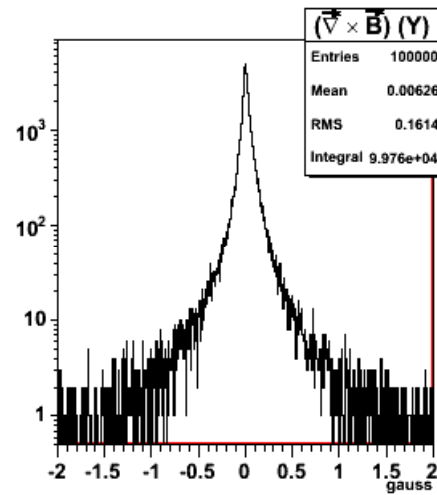
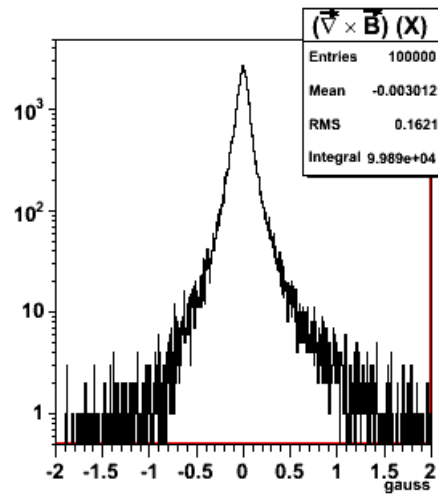
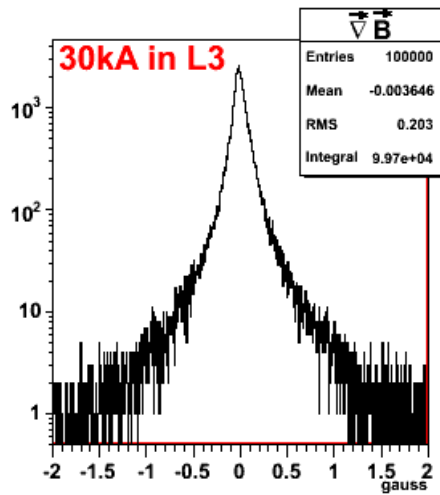
Before correction

After correction

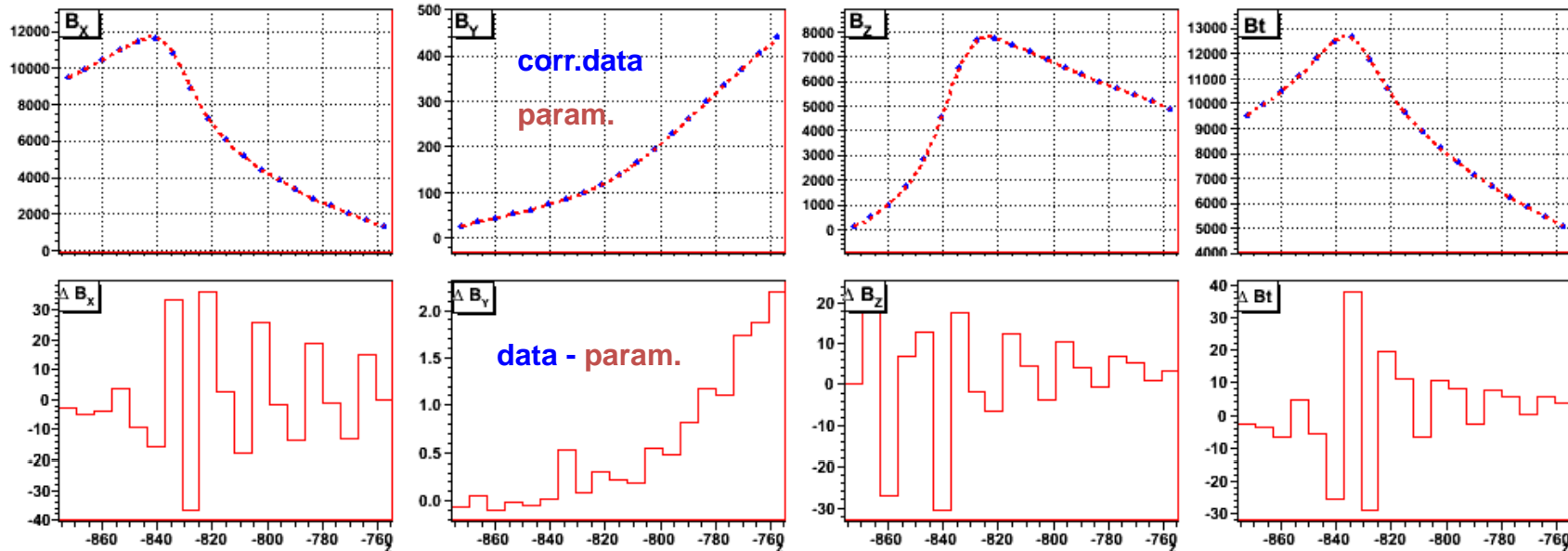
Data from “fine+bad setups”



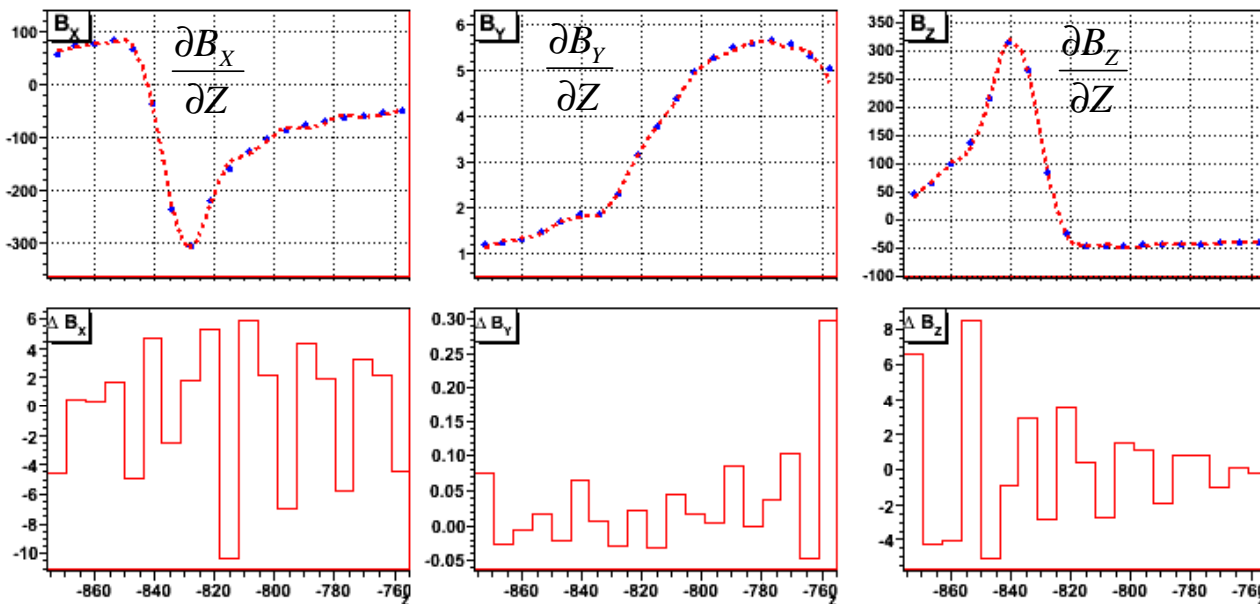
Deviation from $\nabla \cdot \mathbf{B}=0$ and $\nabla \times \mathbf{B}=0$ for corrected data parameterization



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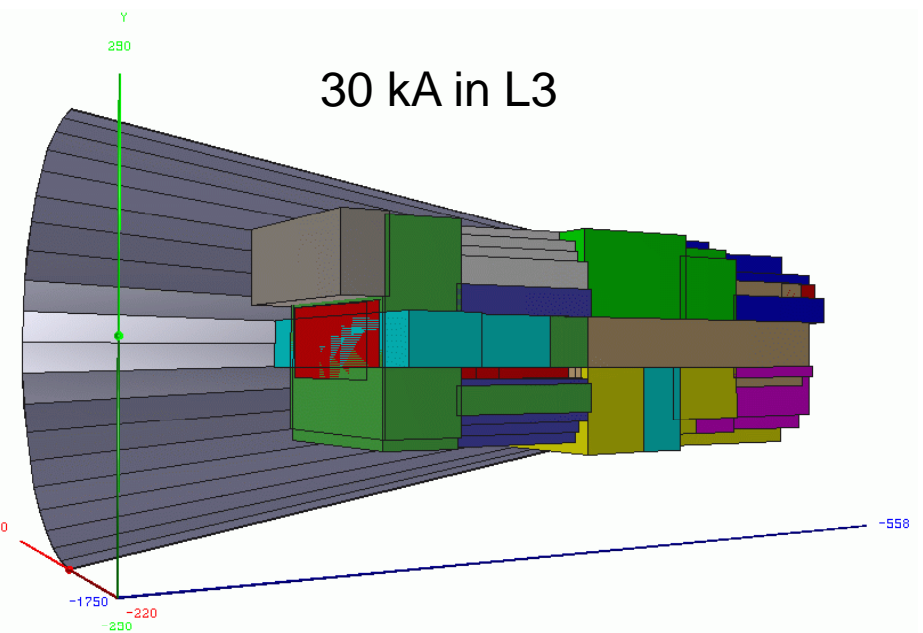
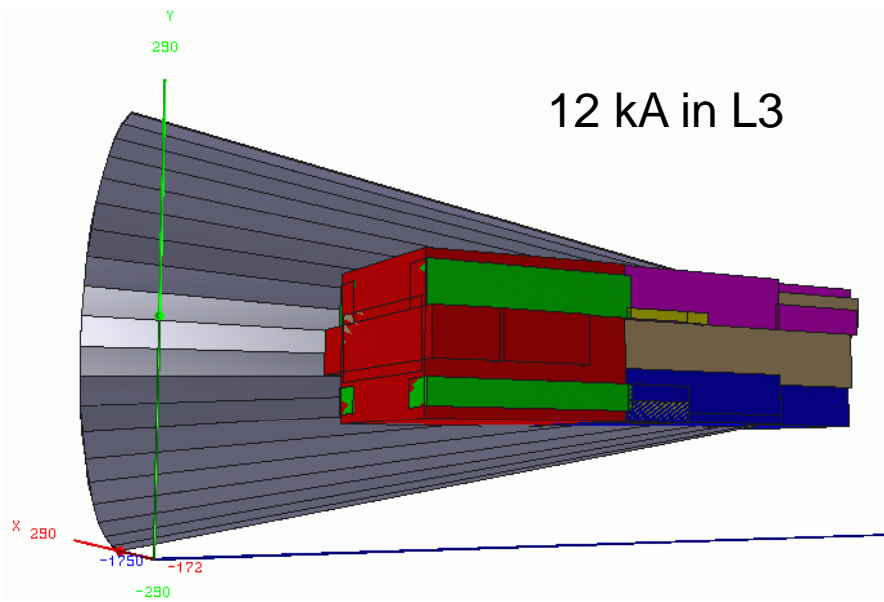


dip_L3H_X_m140_p124_Y_p36_p132_Z_m873_m758_r : X[0]=-140.000 Y[1]=+44.000 | Gauss

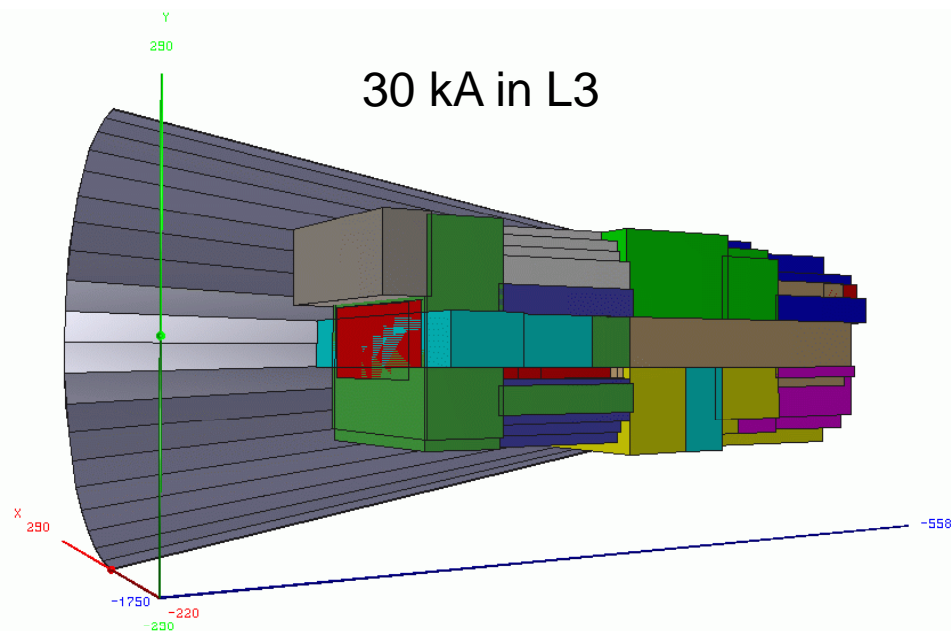
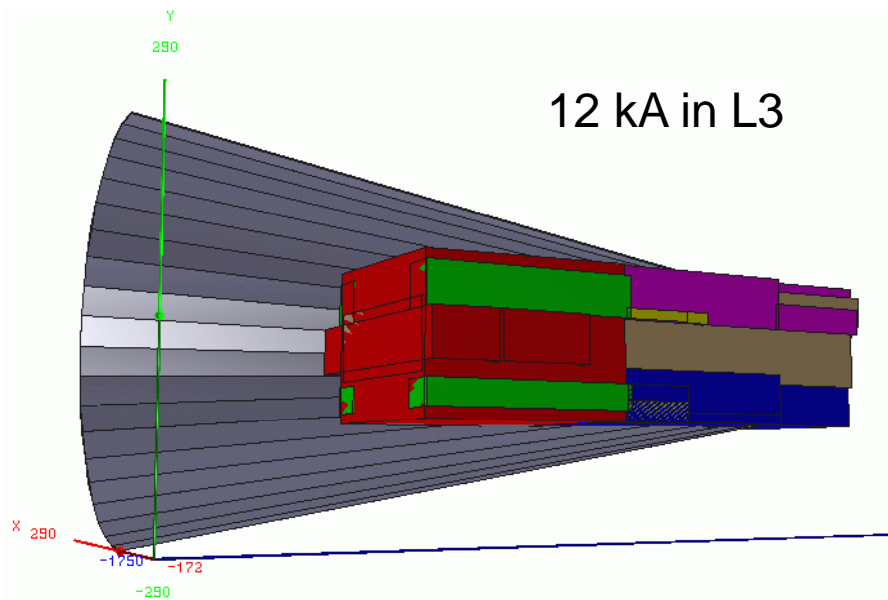


Measurements very close to coils/yoke region are difficult to improve to better than 20-30 Gauss precision:

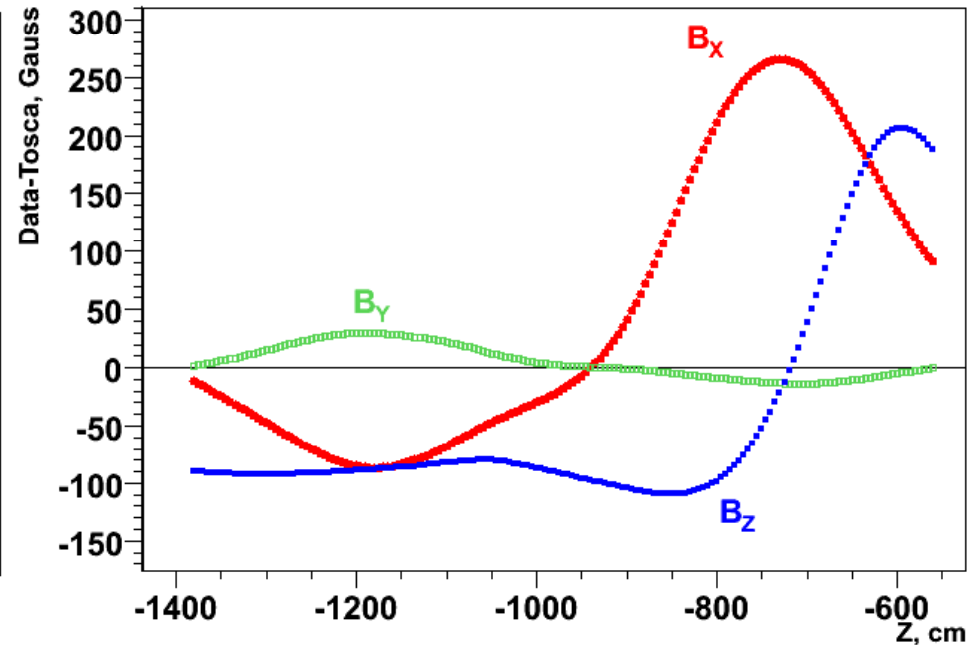
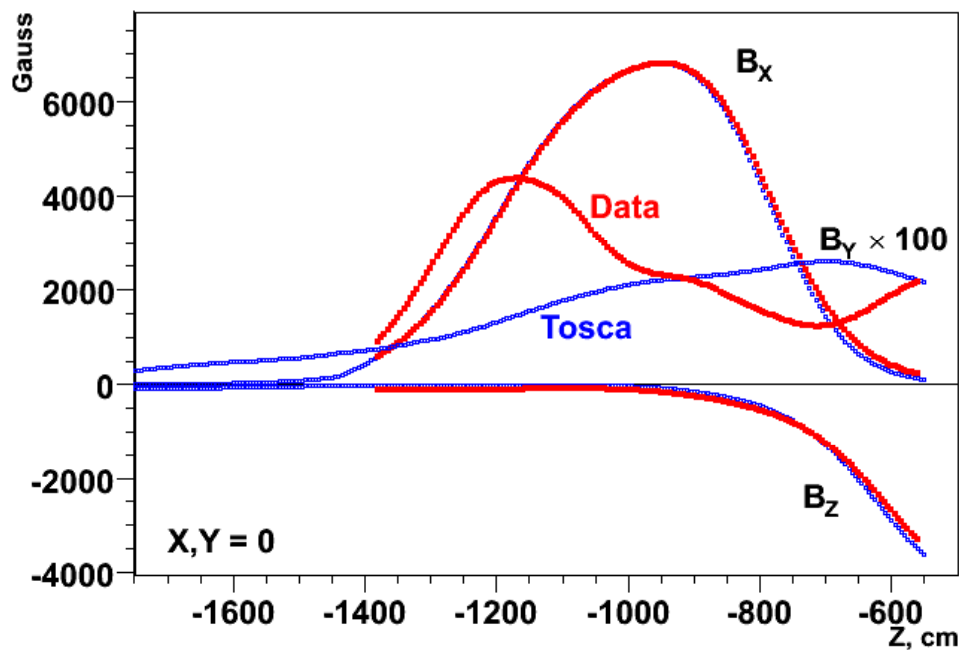
the gradients are too strong and a few 100 mm misalignment in machine/probe position leads to large errors.



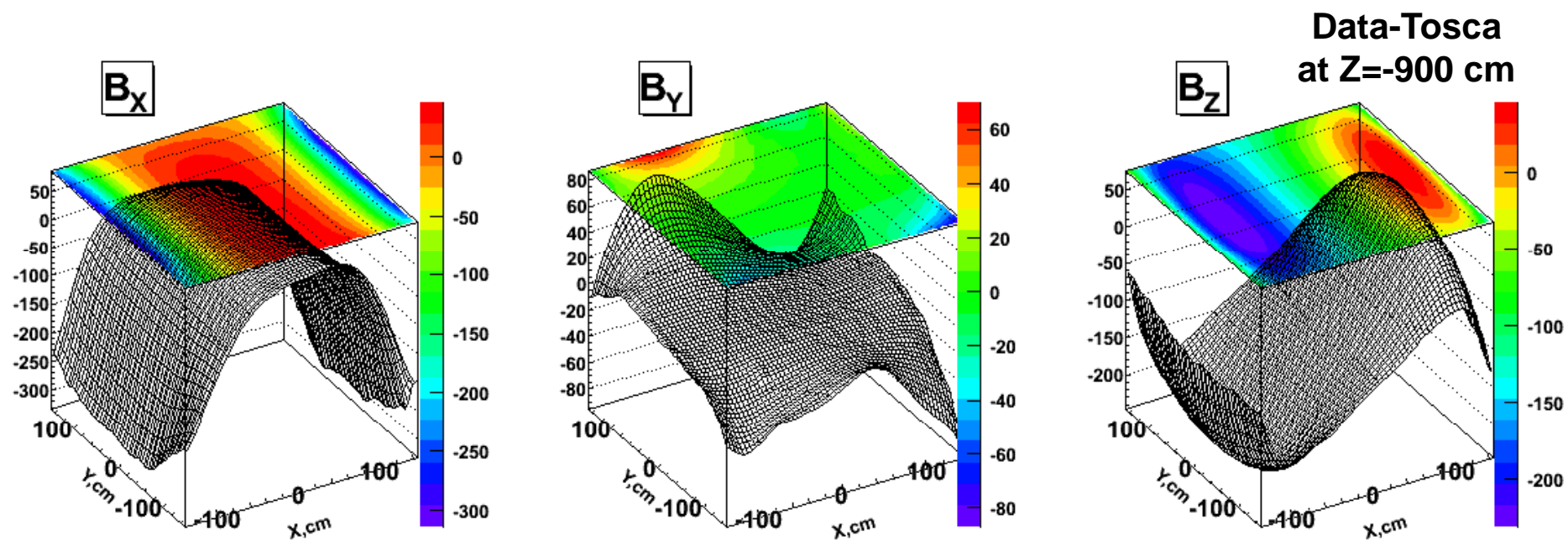
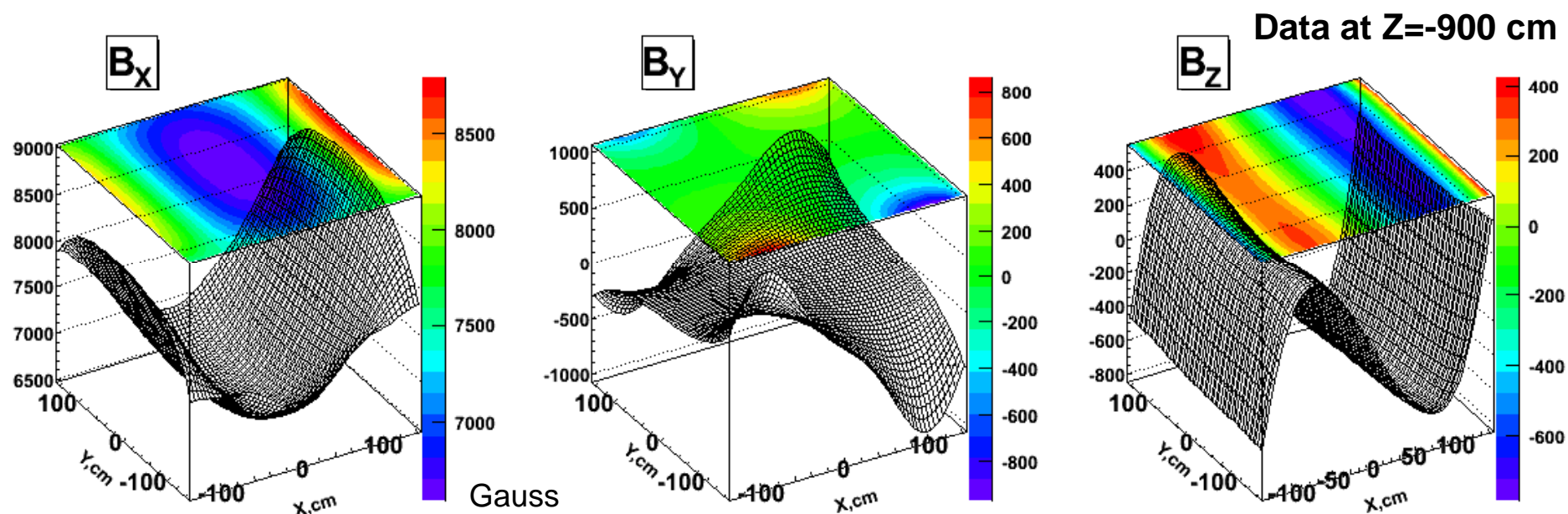
Measured data covers only part of the acceptance: $\sim -1380 < Z < \sim -550$ (need up to $Z \sim -1750$ cm)
 and even in this range does not fill the 9.5° acceptance cone
 \Rightarrow need to extrapolate measured field using Tosca calculation



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 and even in this range does not fill the 9.5° acceptance cone
 \Rightarrow need to extrapolate measured field using Tosca calculation



Merging measured and Tosca fields



Discrepancy between the Tosca and the data seems to be similar in case of LHCb dipole

Tests and Field Map of LHCb Dipole Magnet
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, 1051-8223

M. Losasso, F. Bersgma, W. Flegel, P. A. Giudici, J. A. Hernando,
O. Jamet, R. Lindner, J. Renaud, and F. Teubert

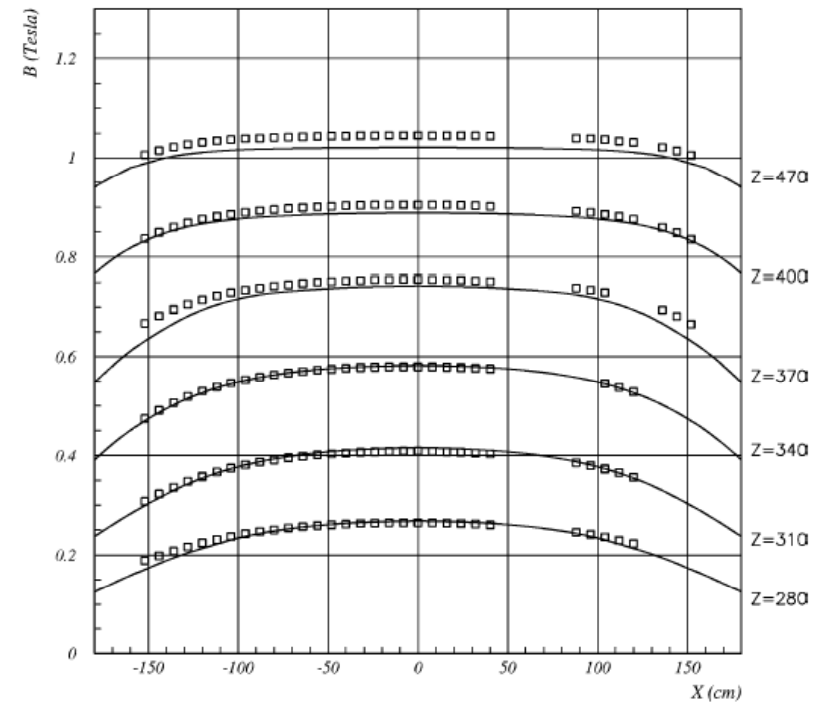
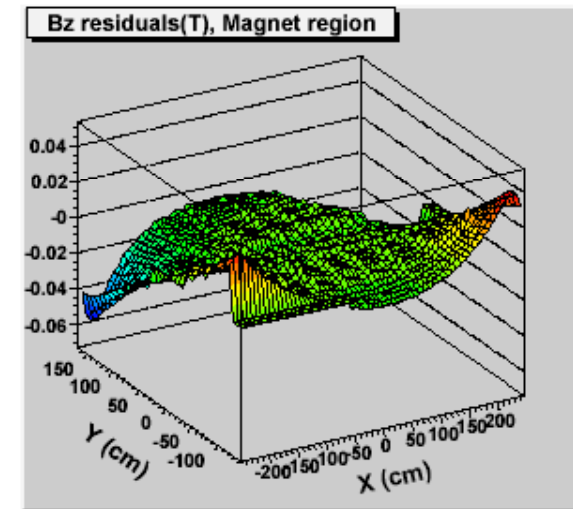
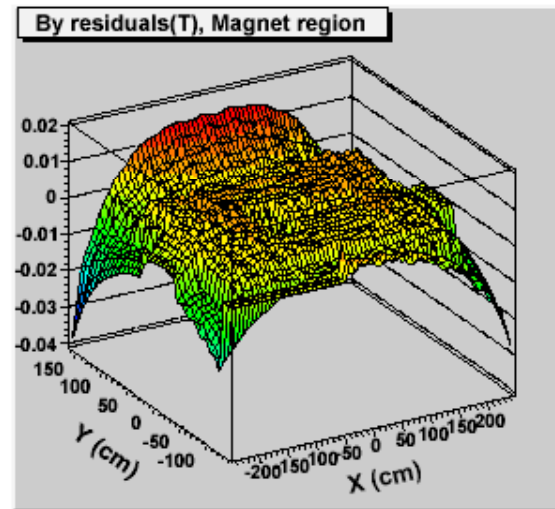
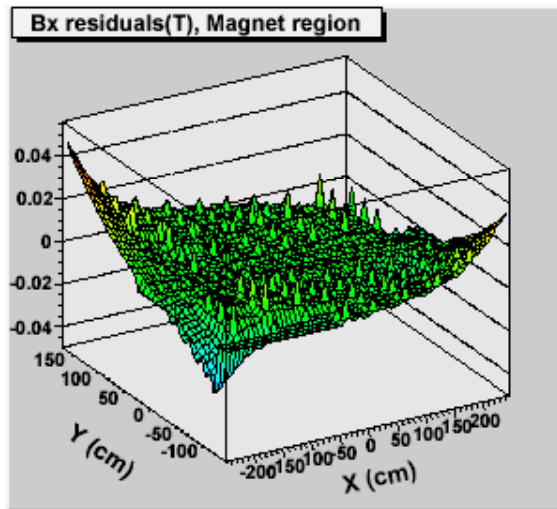


Fig. 6. Measured and computed field strength versus x, at several z positions.

Data – Tosca for LHCb magnet



Parameterization of the LHCb magnetic field map // A.Hicheur, G.Conti, CHEP07

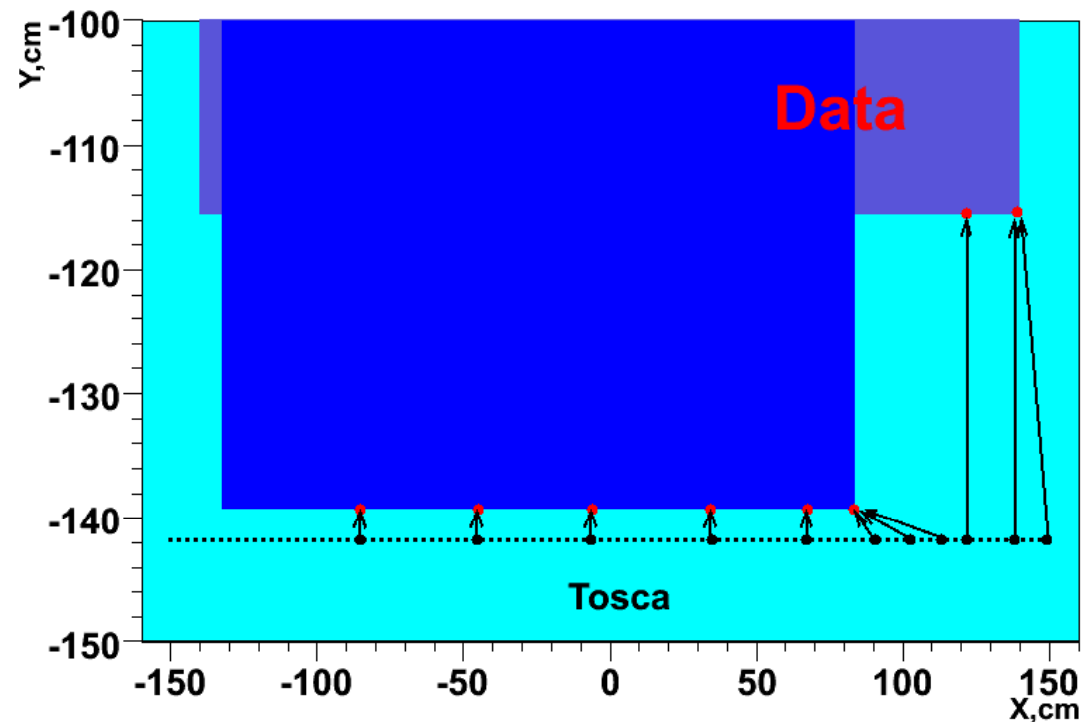
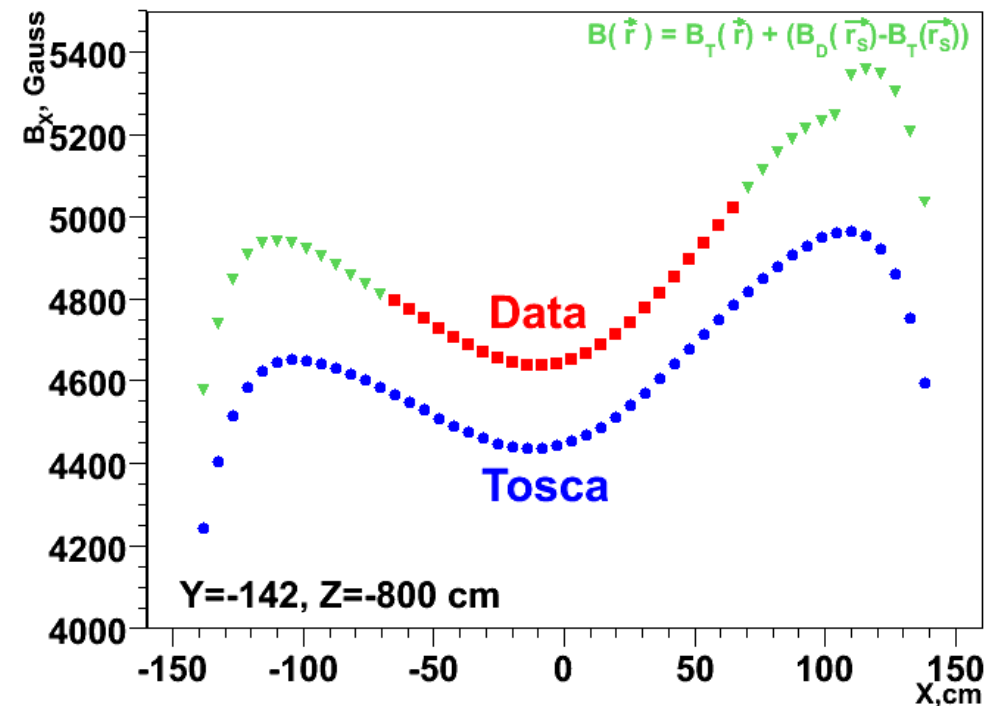
Most simple approach:

add to Tosca field outside of the measured volume the difference between the Data and Tosca at the closest point on the measured surface:

$$B(\vec{r}) = B^T(\vec{r}) + \Delta B^{DT}(\vec{r}_s)$$

(will work ideally if the Tosca and data gradients are the same).

⇒ Leads to strong jumps in the extrapolated field:
the measured surface is not smooth, so the
“closest point on surface” is not continuous.



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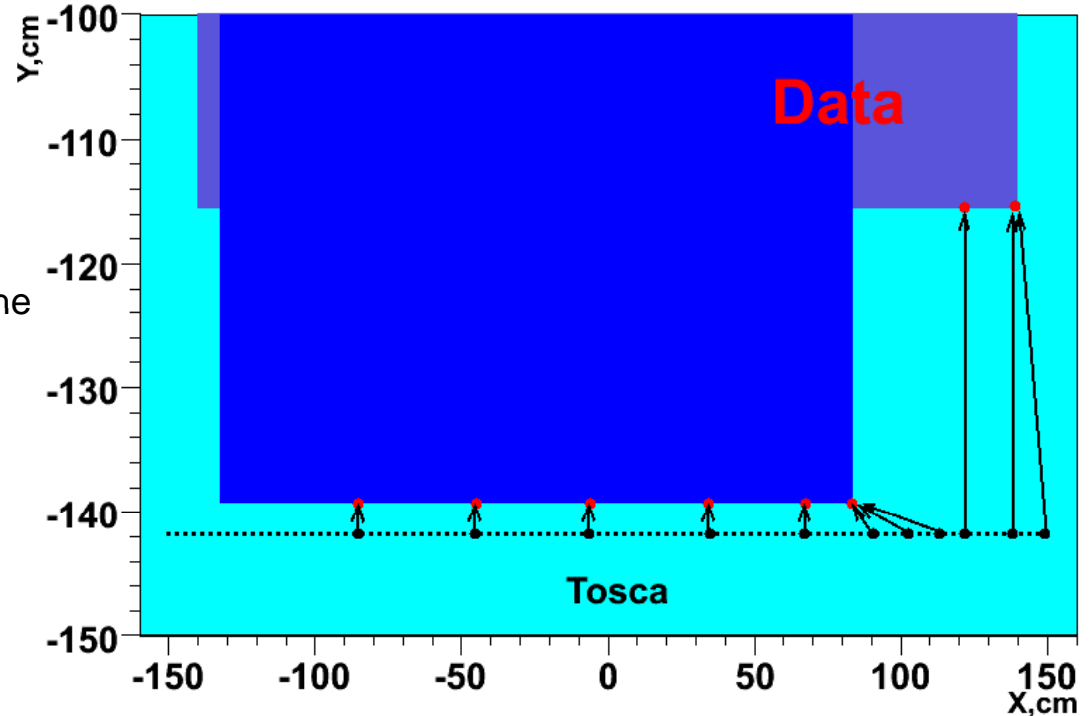
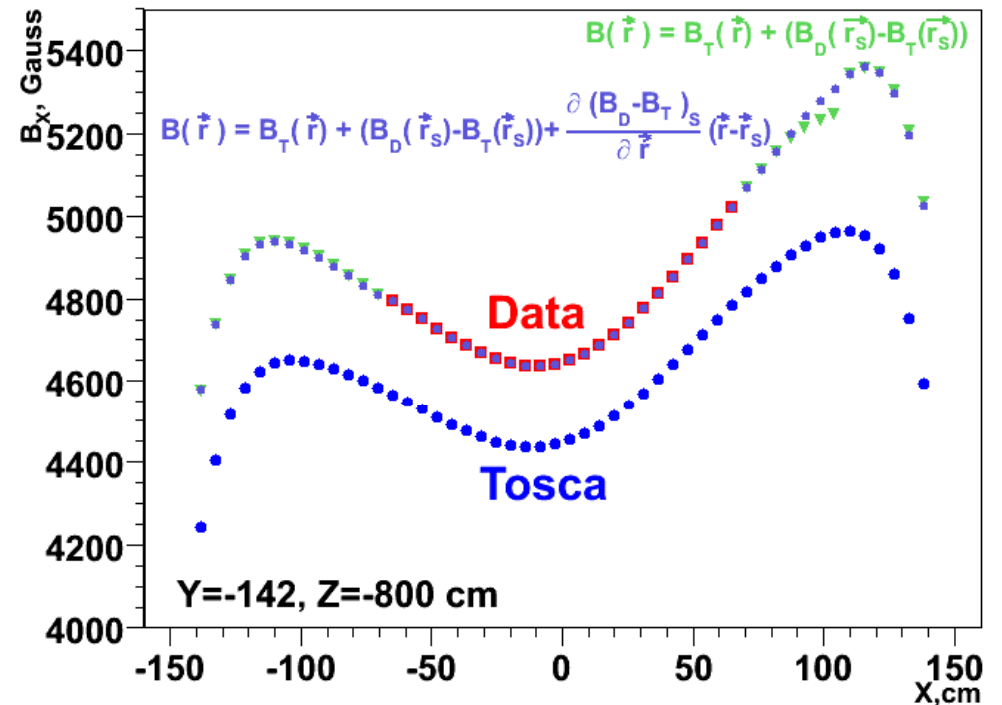
⇒ Leads to strong jumps in the extrapolated field: the measured surface is not smooth, so the “closest point on surface” is not continuous.

Next step:

account for the difference in gradients on the surface:

$$B(\vec{r}) = B^T(\vec{r}) + \Delta B^{DT}(\vec{r}_s) + \frac{\partial \Delta \vec{B}^{DT}(\vec{r}_s)}{\partial \vec{r}} (\vec{r} - \vec{r}_s)$$

Leads to smoother extrapolation but if the gradients are significantly different the field on the large distance from the measured surface diverges.



Currently used approach:

1. connect the point where the extrapolation is need with 7 fixed points in the measured volume by the straight lines
2. find their intersection with the measured surface
3. for each of them compute the extrapolated field as

$$B(\vec{r}) = B^T(\vec{r}) + \Delta B^{DT}(\vec{r}_s) \exp(-\Delta r / a) + \frac{\partial \Delta \vec{B}^{DT}(\vec{r}_s)}{\partial \vec{r}} \Delta \vec{r}_s \exp(-\Delta r / b) \quad (a=80\text{cm}, b=40\text{cm})$$

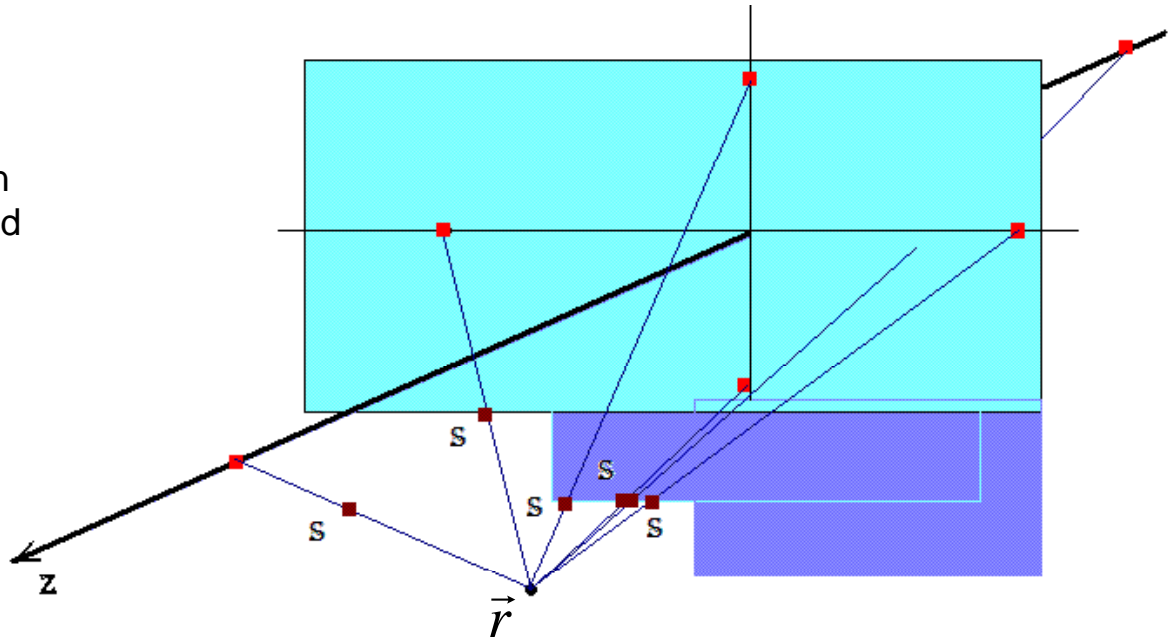
4. average over all 7 extrapolated values

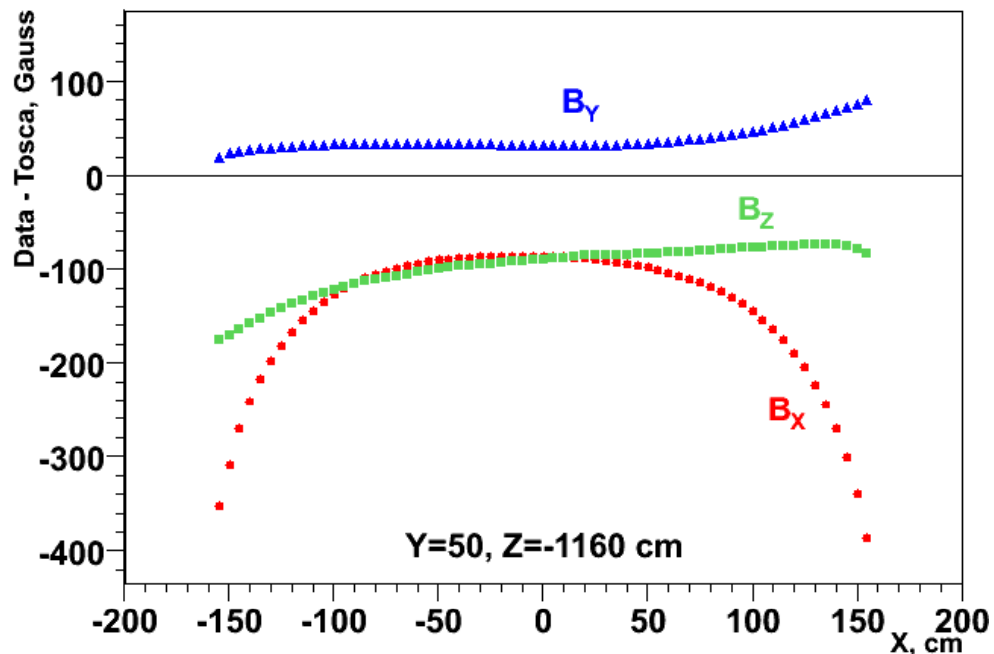
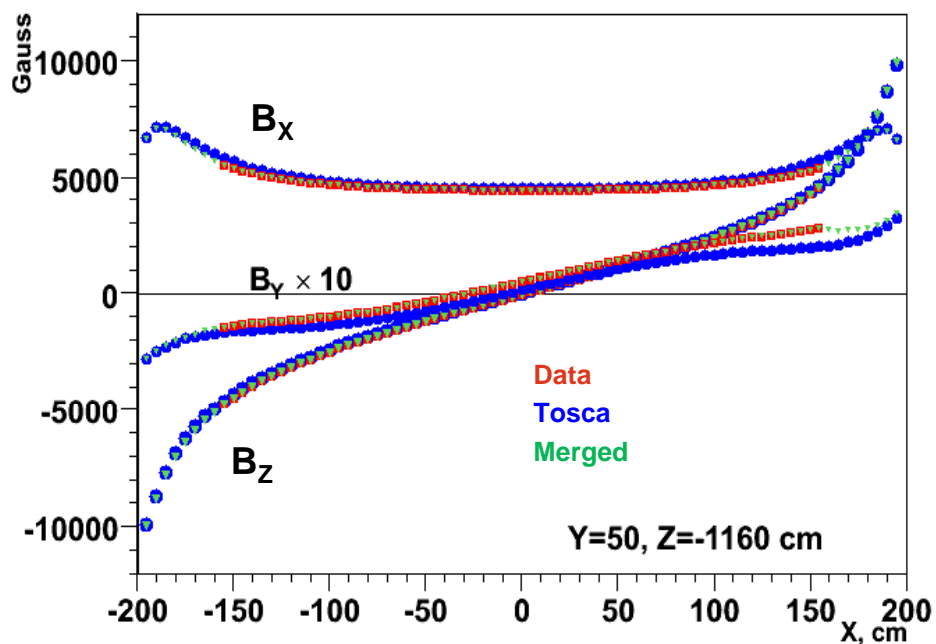
In this approach the field at large distances asymptotically tends to Tosca values

Still leads to unphysical kinks.

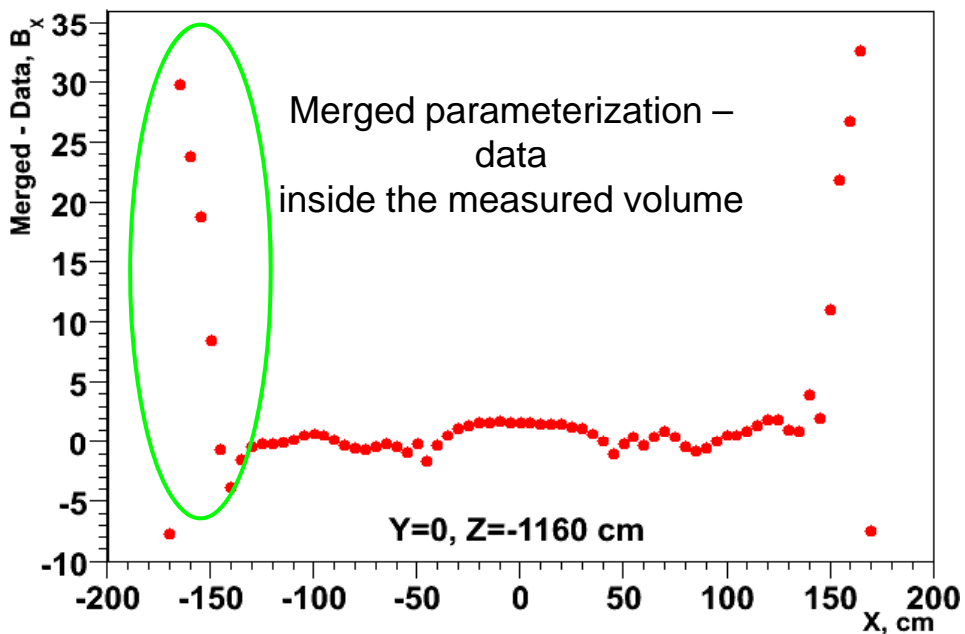
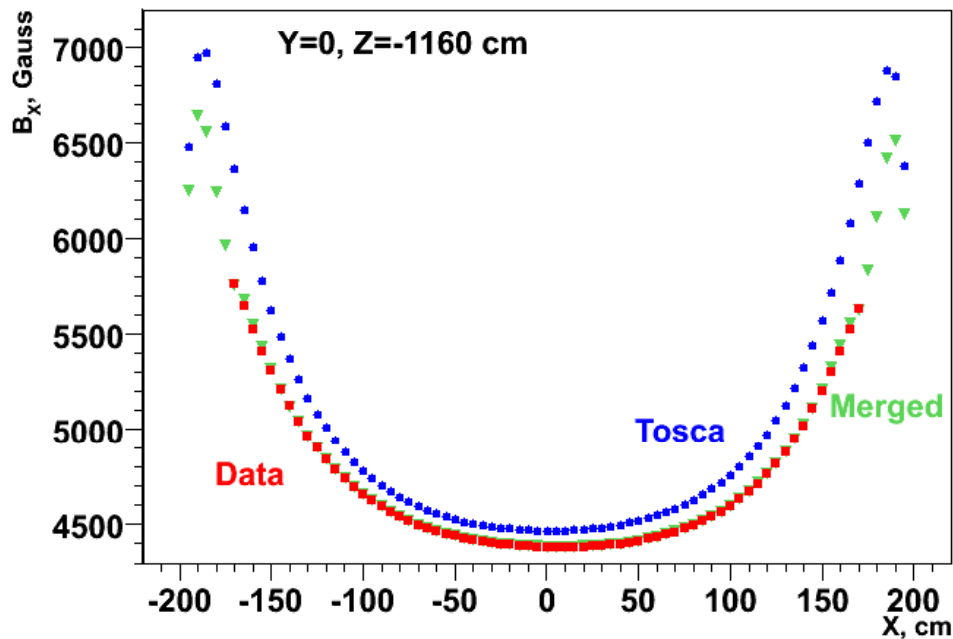
Currently working on the extrapolation accounting for the difference in second derivatives:

$$B(\vec{r}) = B^T(\vec{r}) + \Delta B^{DT}(\vec{r}_s) \exp(-\Delta r / a) + \frac{\partial \Delta \vec{B}^{DT}(\vec{r}_s)}{\partial \vec{r}} \Delta \vec{r}_s \exp(-\Delta r / b) + \frac{1}{2} \frac{\partial^2 \Delta \vec{B}^{DT}(\vec{r}_s)}{\partial \vec{r}^2} \Delta \vec{r}_s^2 \exp(-\Delta r / c)$$





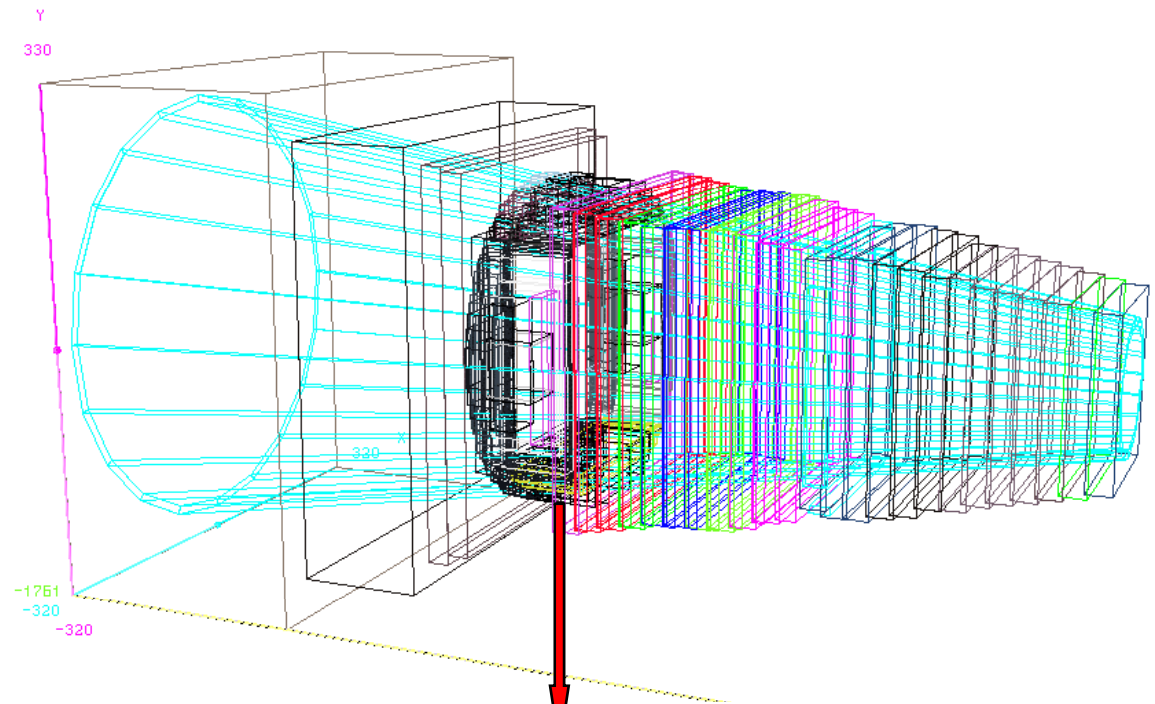
Bad extrapolation by Tosca also affects the final parameterization of the field in the measured volume close to the surface (when fitted with Chebyshev polynomials up to the reasonably low order)



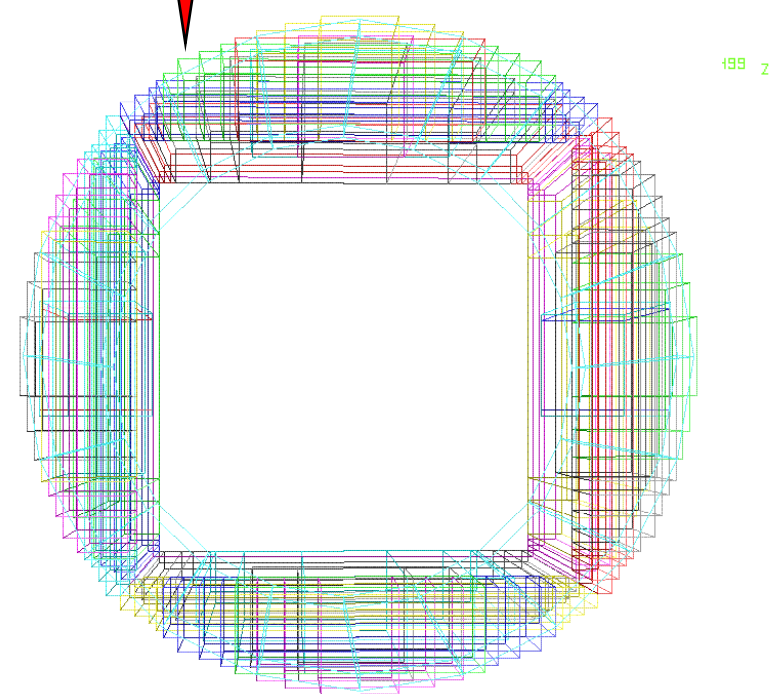
Currently existing parameterization: full coverage of the acceptance (at least 9.5°)

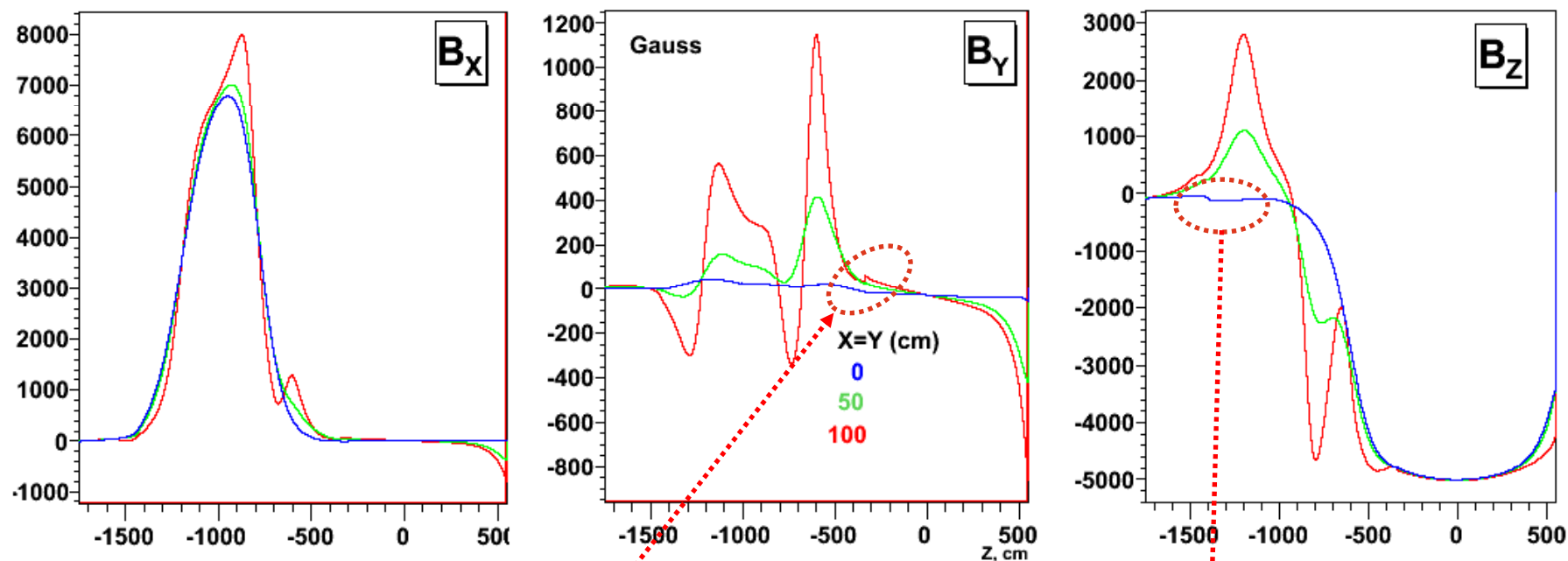
Build of ~150 separate boxes to fit the topology of the magnet with minimal overlap between each other (most of them for the coils region).

The merged field (with all drawbacks of the existing extrapolation scheme) is parameterized by Chebyshev series requiring max. 3 Gauss difference between the input value and final parameterization.



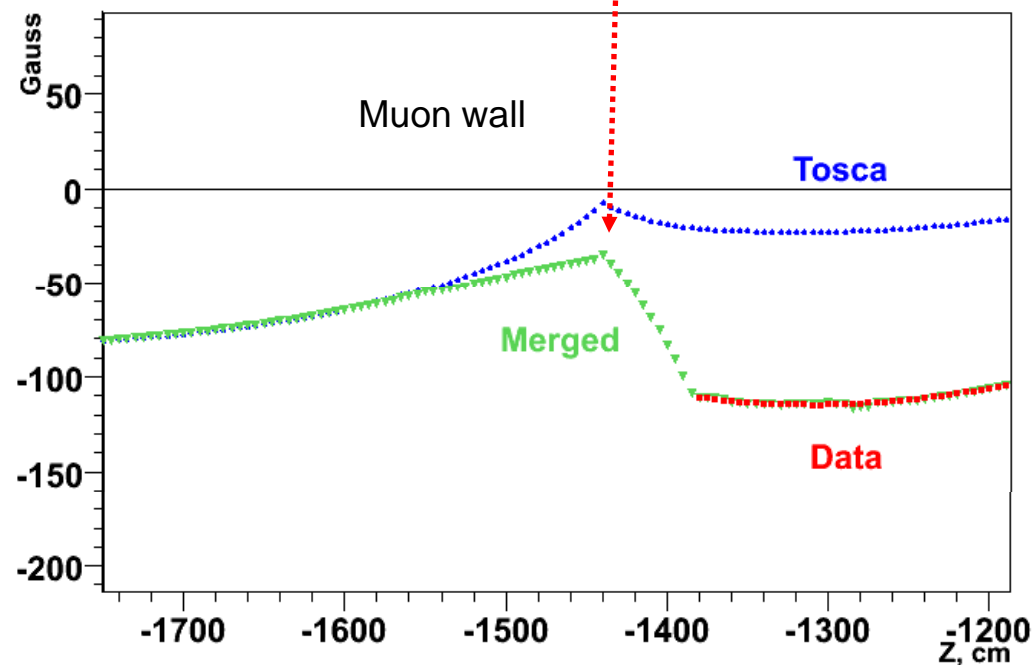
The connection with L3 field is done using the measured data only:
the $X, Y = \pm 100$ cm surface of the gap $-550 < Z < -340$ cm is filled by splines from L3 and Dipole measured data then fitted to solution of Laplace equations (3).





10-30 Gauss jump at the end-points of L3 / Dipole link. Problem is understood (too long in Z envelope was taken to calculate the input field for the parameterization).

The jumps will be corrected in next version, but this should be characteristic precision of the extrapolation to link region...



What exists in Aliroot:

Standalone classes (don't require Aliroot):

`AliCheb3D`, `AliCheb3DCalc` : classes for internal Chebyshev parameterizations
`AliMagFCheb` : container for the set of L3 and Dipole parameterizations
(TObjArray with fast search of need parameterization piece)

Methods:

to get the field in given point:

```
virtual void Field(Float_t *xyz, Float_t *b) const;  
virtual void FieldCyl(Float_t *rphiz, Float_t *brphiz) const; // for L3 only
```

to get the parameterized field integral from the point in TPC to closest cathode plane

```
virtual void GetTPCInt(Float_t *xyz, Float_t *b) const;  
virtual void GetTPCIntCyl(Float_t *rphiz, Float_t *brphiz) const;
```

Derived from AliMagF:

`AliMagWrapCheb` : wrapper class for the `AliMagFCheb`

Methods:

```
AliMagWrapCheb(const char *name, const char *title, Int_t integ,  
                Float_t factor=1, Float_t fmax=15, Int_t map = k2kG,  
                Bool_t dipoleON = kTRUE,  
                const char* path="$(ALICE_ROOT)/data/maps/mfchebKGI.root");  
virtual void Field(Float_t *xyz, Float_t *b) const;  
virtual void GetTPCInt(Float_t *xyz, Float_t *b) const;  
virtual void GetTPCIntCyl(Float_t *rphiz, Float_t *brphiz) const;  
AliMagFCheb* GetMeasuredMap();
```

When compiled with `#define _BRING_TO_BOUNDARY_` in the `AliCheb3DCalc.h` for the points outside the parameterized regions the field in the closest valid point will be returned. Otherwise the field is set to 0.

What exists on Aliroot:

`mfchebKGI.root` : file with current parameterizations

Sol30_Dip6_Hole

Sol12_Dip6_Hole

Sol30_Dip0_Hole (dipole off, valid for $Z > -550$)

Sol12_Dip0_Hole (dipole off, valid for $Z > -550$)

Same but w/o accounting for the hole in L3 door:

Sol30_Dip6_NoHole

Sol12_Dip6_NoHole

Sol30_Dip0_NoHole

Sol12_Dip0_NoHole

The typical field query time: 3-6 μ s depending on the dipole region.

Size of single parameterization set: 1.9 MB on disk, 2.8 MB in memory.

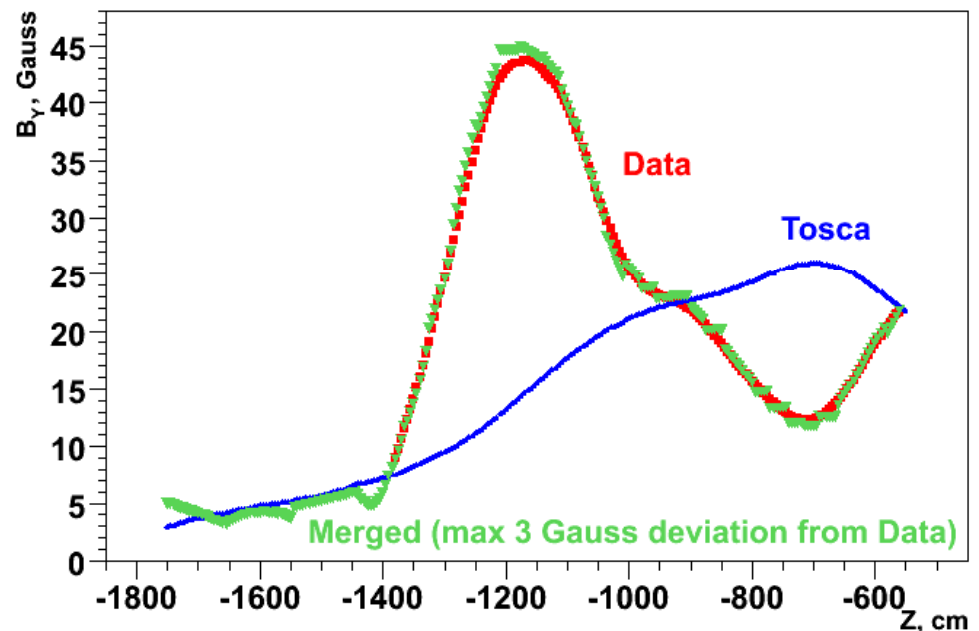
Note: current 3 Gauss tolerance on the

“input”-“final parameterization”

leads to ~3 Gauss discontinuities in the latter.

Should not affect the tracking since fluctuations go in both directions.

If needed they can be eliminated on the expense of CPUtime/memory



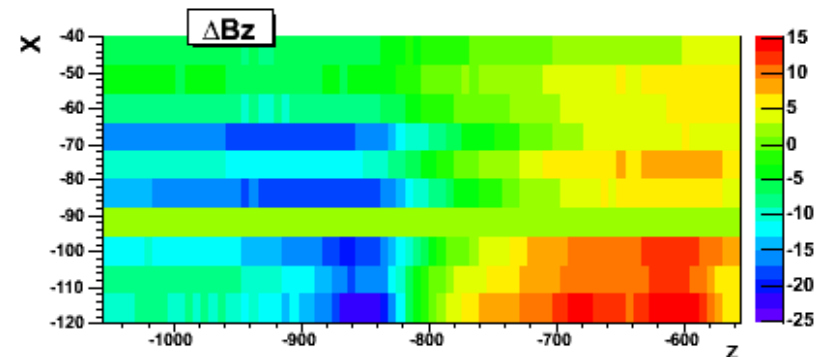
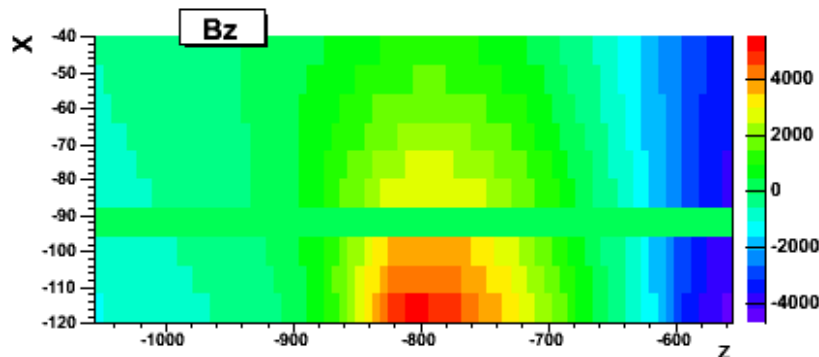
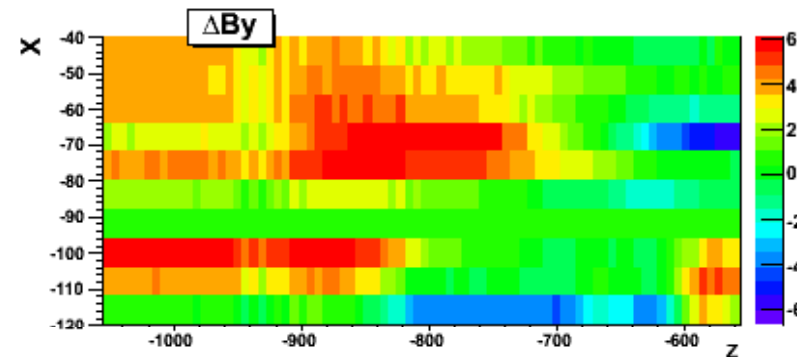
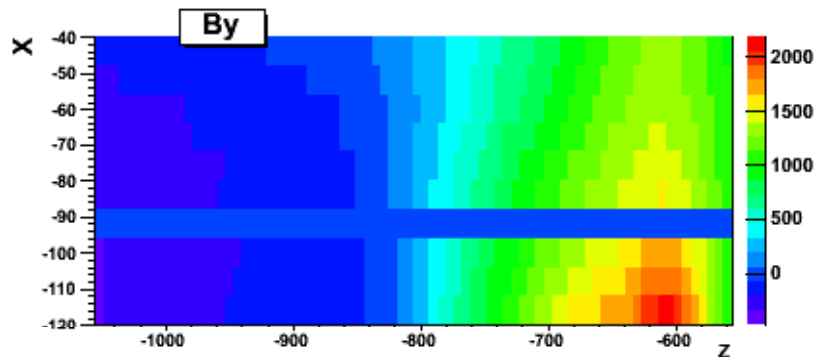
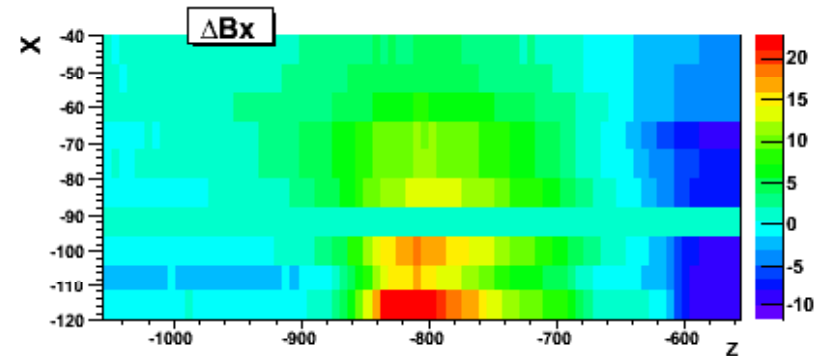
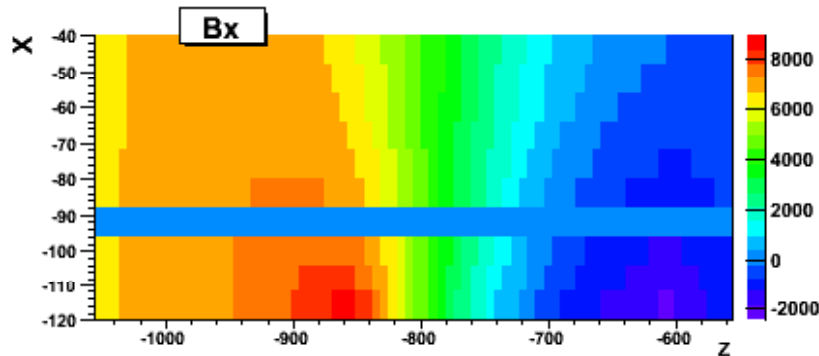
backup

Scan to scan variations

Check for reproducibility of the measurements by the same probes: the only fully overlapping scans with the same setup are done with opposite field polarities (possible hysteresis effect): compare after field inversion.

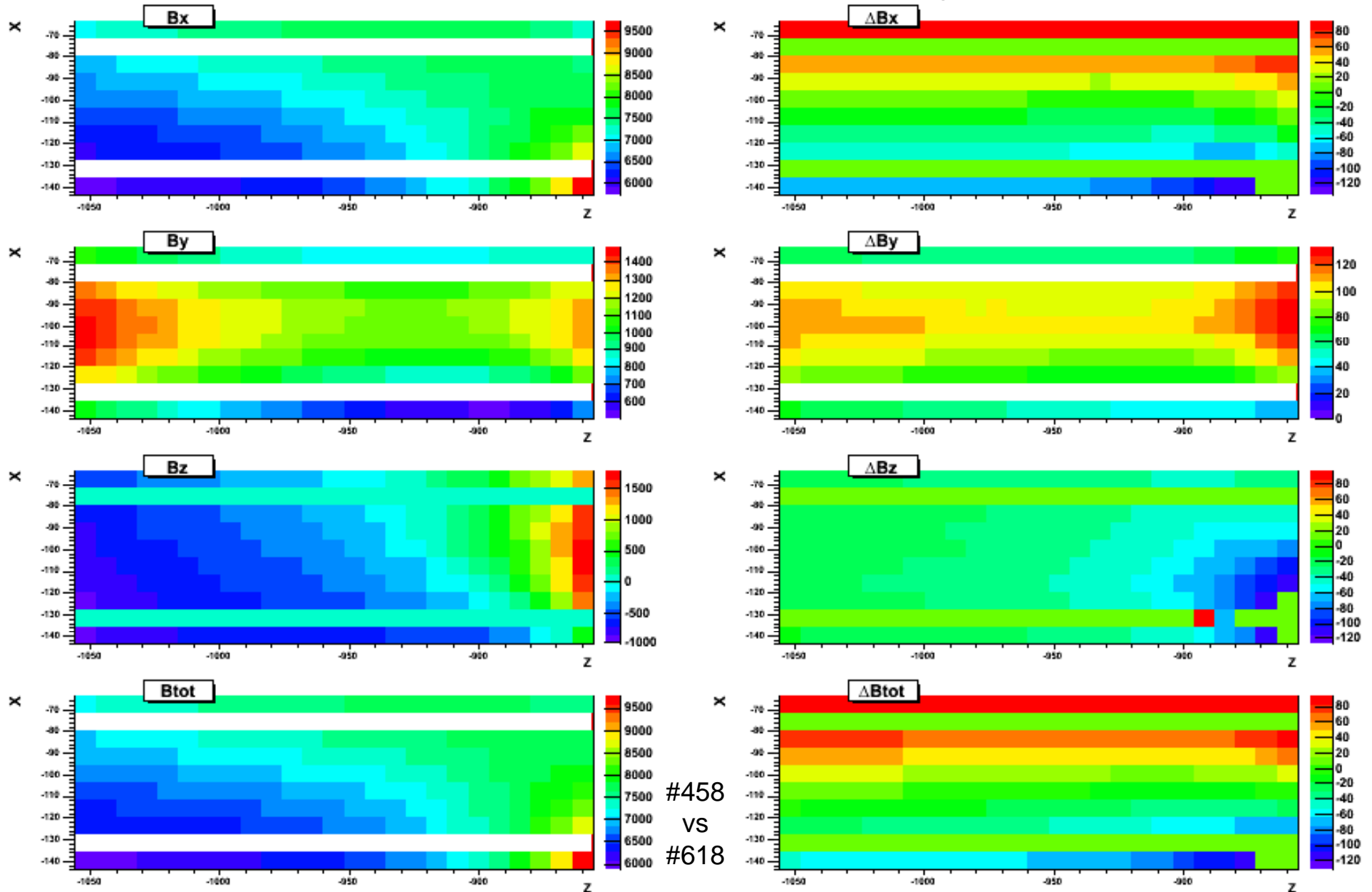
Worst case seen for “improved setup”, usually the differences are within ~10 Gauss.

Scan 968
vs
Scan 1011
Y=96 cm



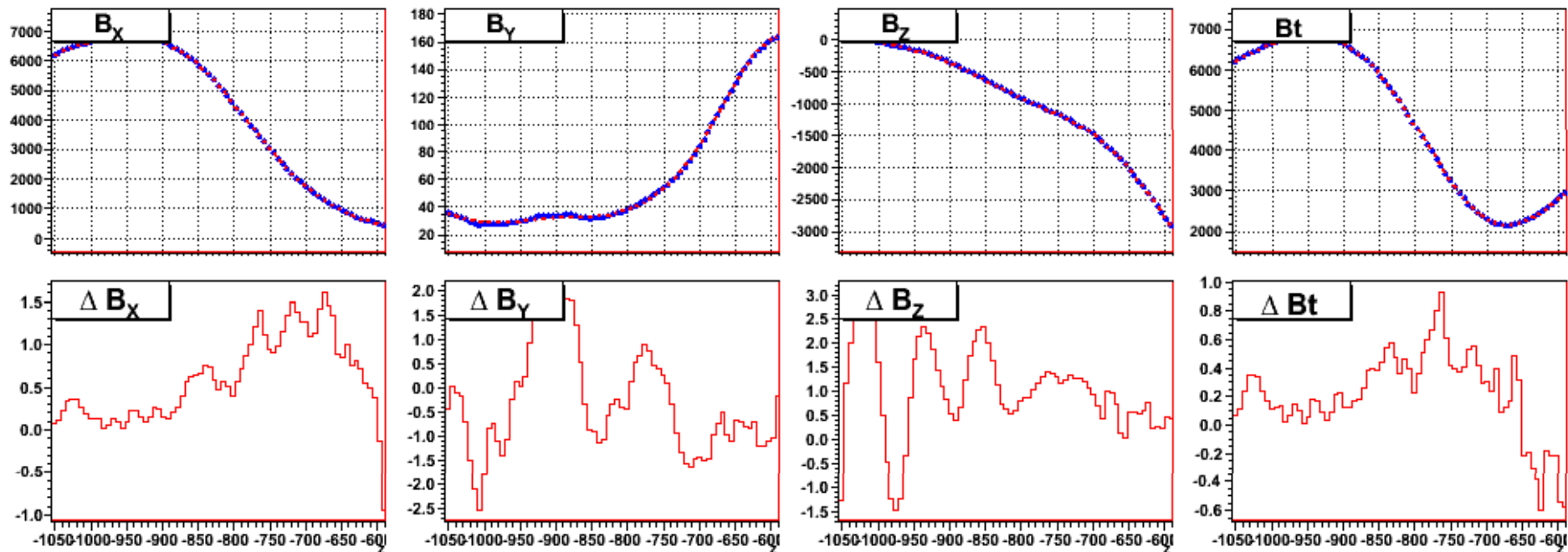
Scan to scan variations

Discrepancies are much worse for the 1st data taking period

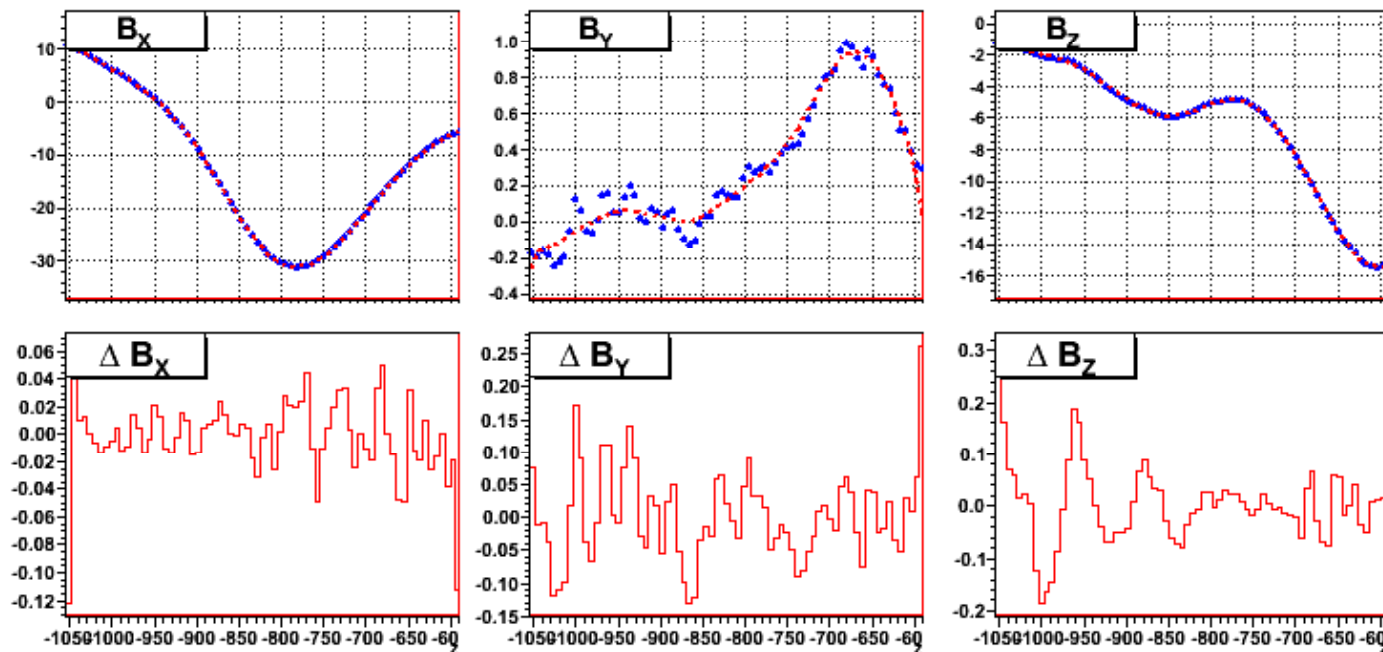


Y = -160 cm

dipf : X[3]=+12.000 Y[7]=+4.000 | Gauss



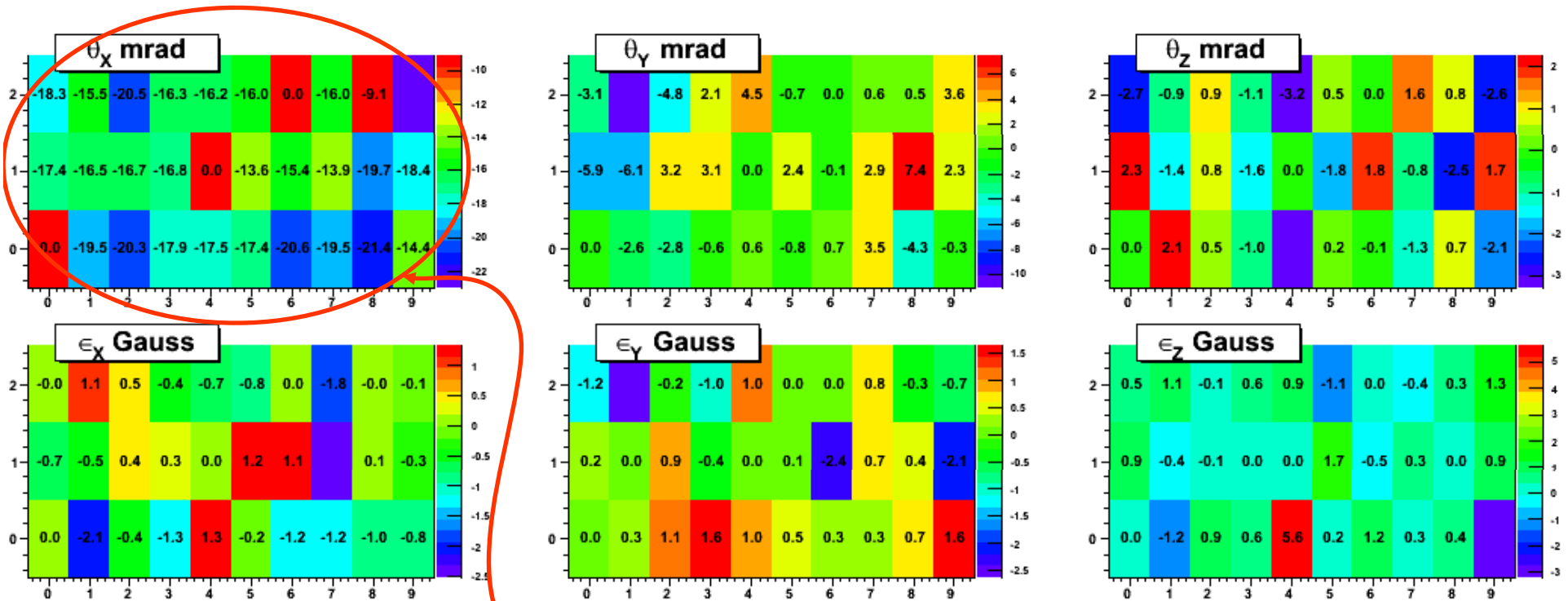
dipfCor : X[3]=+12.000 Y[7]=+4.000 | Gauss



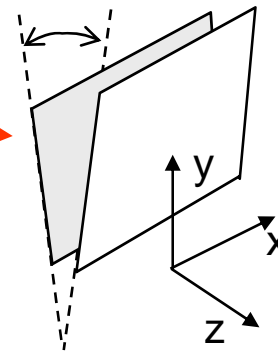
dB_i/dz

Correcting distortions

Example of obtained rotations and miscalibrations probe-map valid for the majority of scans: 19 Aug–10 Sep
(0 means that one of the FIP/BIP probes is missing)



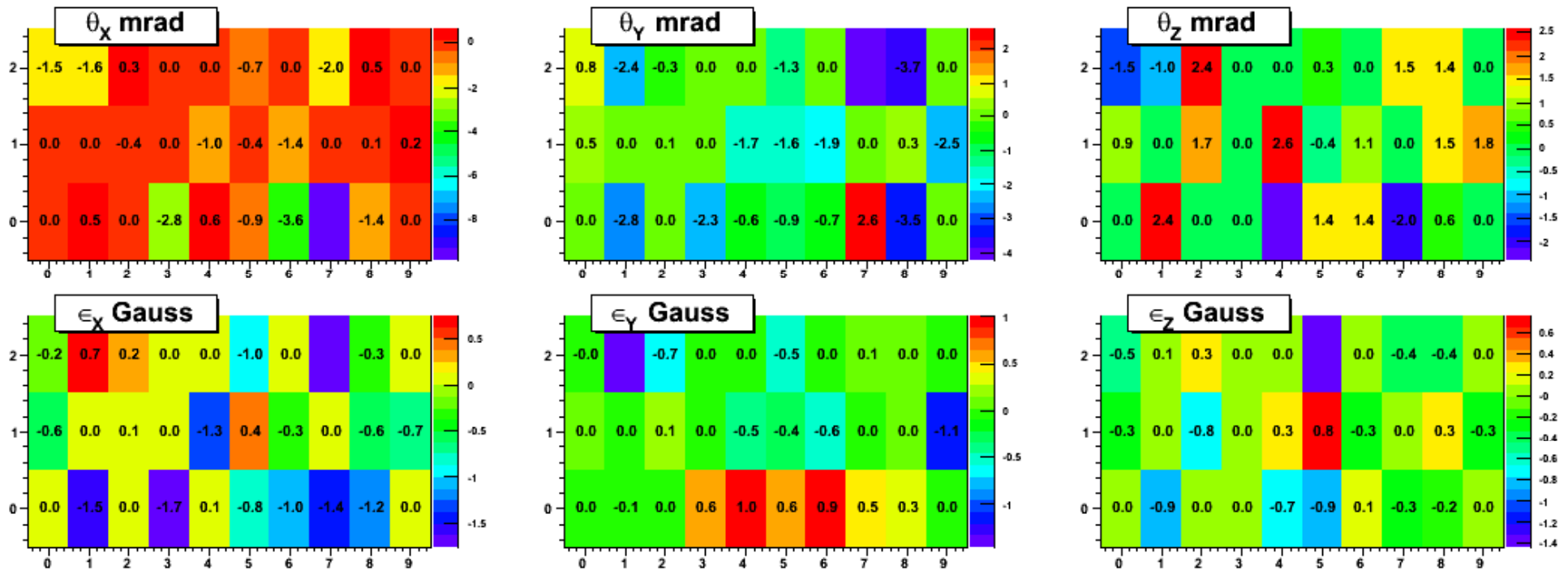
~17 mrad relative tilt between FIP and BIP plates



NOTE: these fits show only the relative alignment between the pairs of FIP and BIP probes

Correcting distortions

Example of obtained rotations and miscalibrations (last probe-map: 9-23 Oct. : probes were readjusted)



Tilt between plates has been removed

Correcting distortions

Example of obtained offsets for each 1D probe (last probe-map: 9-23 Oct)

