MNP33 Field Map

Ferrara September 2014

John Fry and Giuseppe Ruggiero

- Introduction and summary of tasks
- Orientation: shape of the magnetic fields
- Determination of sensor and panel angles
- Residual fields before and after corrections
- Obtaining the field map
- Systematic uncertainties
- Remaining work

- Appendices
  - Geometry
  - Magnetic-field transformations

Last presentation to a collaboration meeting

Physics note NA62-14-xx

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December 2014

Introduction

- MNP33 was mapped [FH et al] in September 2013.
- 60 3-D Hall probes were used [courtesy of Felix Bergsma] mounted on two rigidly connected panels.
- About 240,000 data points [+ calibration; special data] were measured over the entire X-Y area of diameter 2 m out to $\Delta Z = \pm 4$ m on either side of the centre of the magnet with a grid spacing of 80 mm in X, Y and Z
- The aim is to produce a well-behaved field map with well-understood systematics for NA62 physics analysis.

Precision requirement

Requirements:

- ➢Momentum resolution $\frac{\sigma_p}{p} < 0.5\%$ [TD in 2007]
- ➢$\frac{\sigma_p}{p} = -\frac{\sigma_{BL}}{B*L}$ => $\frac{\sigma_{BL}}{B*L} < 0.5\%$;

Note: our spectrometer can probably reach $\frac{\sigma_p}{p} \approx 0.1\%$

$\boxed{\text{Target: } \Delta \int B.dl \approx 0.1\,\% = 10^{-3}\ \text{T m} = 10\ \text{G m}}$

Magnet parameters:

$B_{centre} = 0.4$ T

$\int B.dl = 0.86$ T.m

$L_{eff} = 2.3$ m

$\Delta p_T = 260$ MeV/c

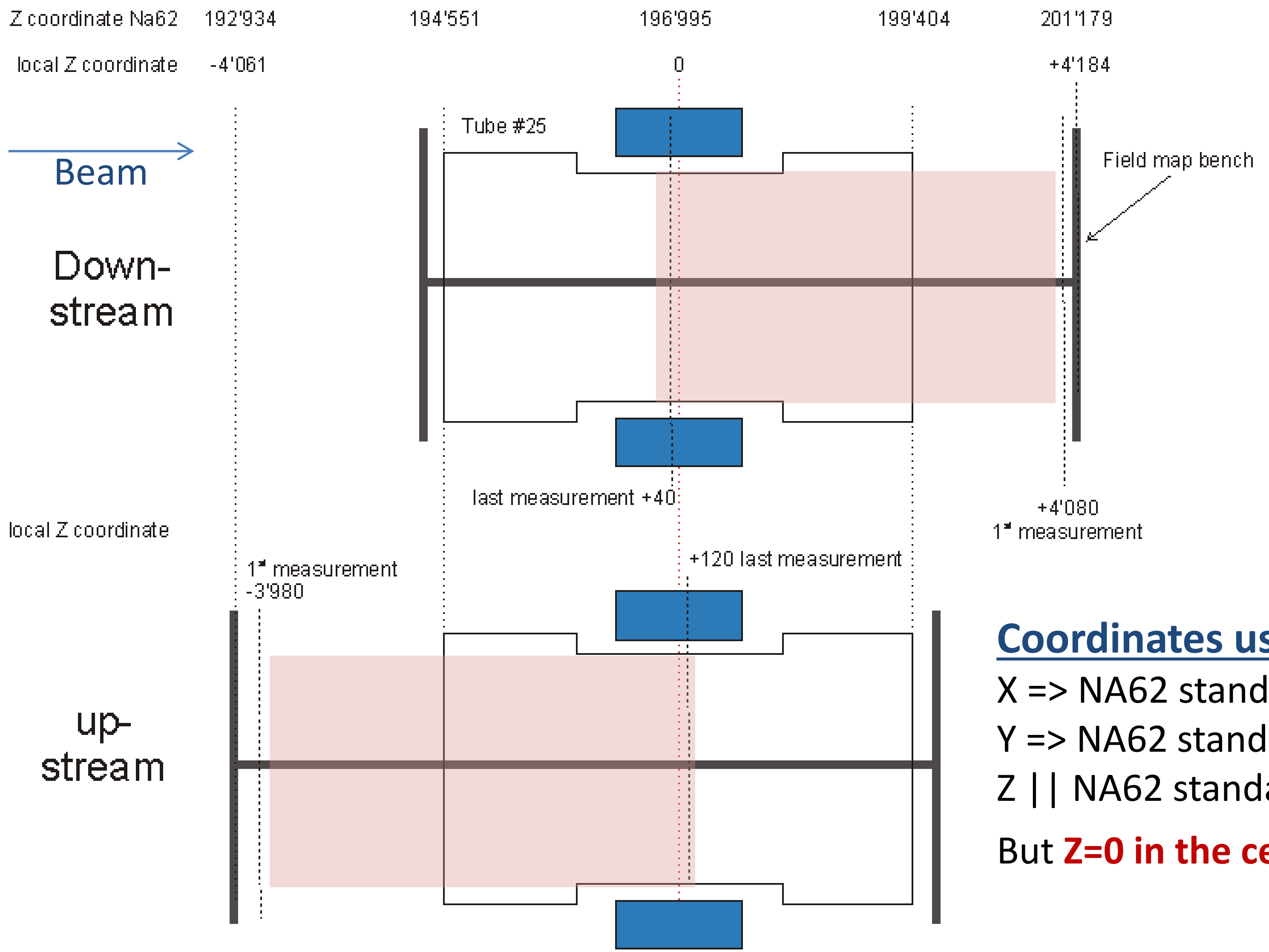
Physics insensitive to B_Z, since

i) Tracks parallel to Z

ii) $\int B_Z.dl = 0$

ΔB_X and ΔB_Y must each be controlled to better than 5 G.

Upstream/Downstream Installation



Coordinates used :

X => NA62 standard

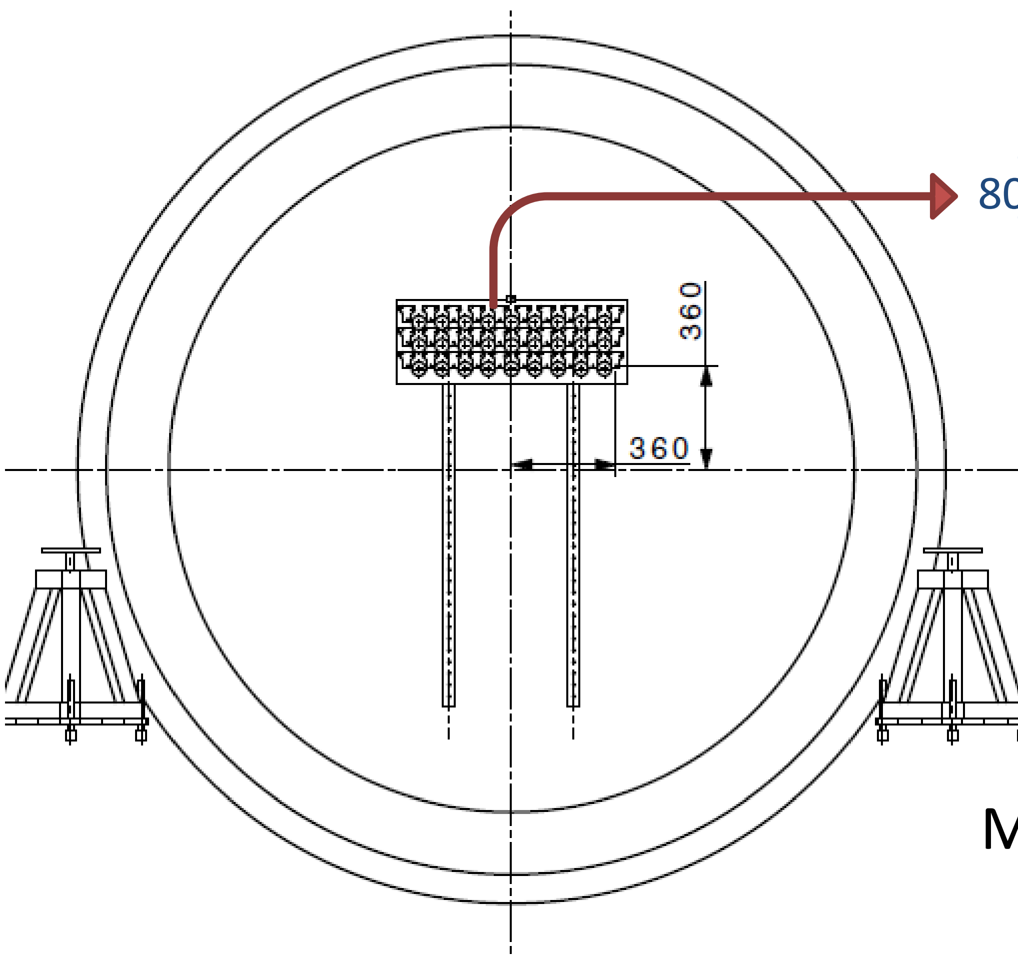
Y => NA62 standard

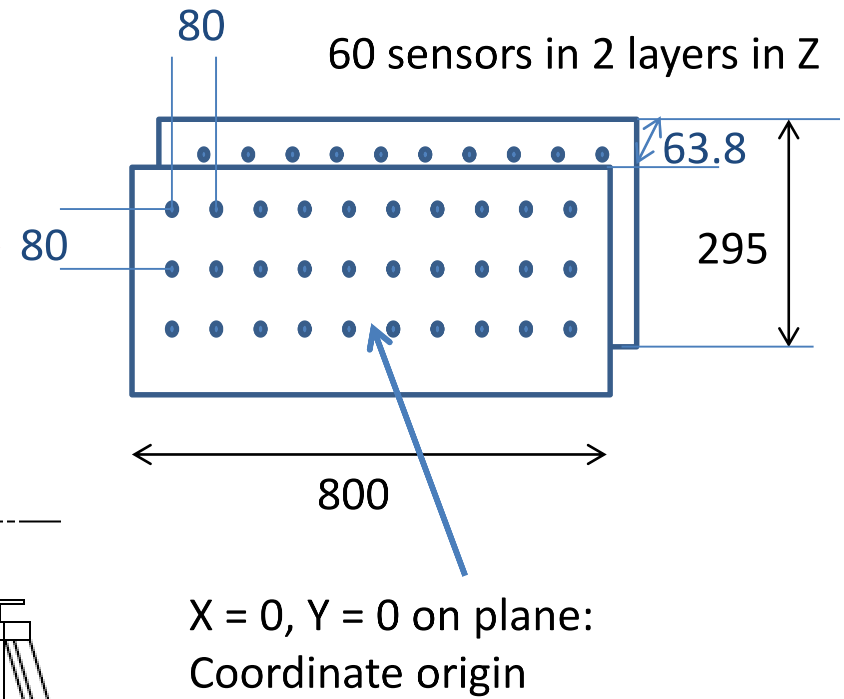
Z || NA62 standard

But **Z=0 in the center of MNP33**

Sensor Frame with 60 3D-Hall Probes

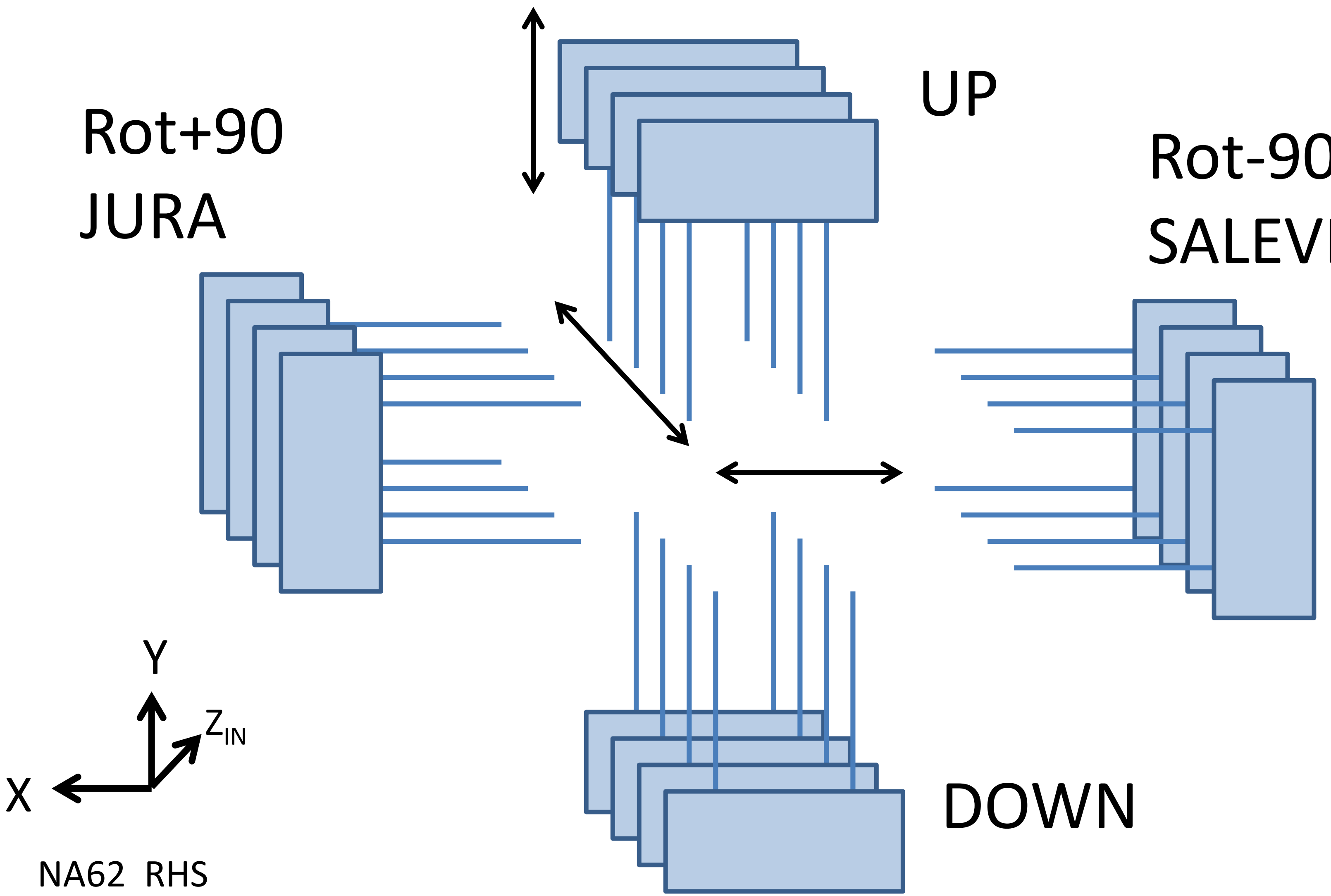
Position UP_X0_Y1_POS_1





MNP33 aperture 2 m diameter

Panel Positions viewed from Upstream



Measurement and Fitting Procedure

- The dangers in fitting several hundred parameters and constraining the boundary conditions to respect Maxwell's equations are that:
  - Precise symmetry may be enforced that is not present in the data;
  - Significant correlations may occur making the fit unstable;
  - It is hard to control the procedure and incorporate essential common-sense checks.
- The approach being taken instead is:

i. Measure the Hall Probe and sensor angular corrections, as well as the relative orientation of the two sensor planes, for a reference frame;

ii. Vary the 3 angles of the sensor frame for each data set to improve the smoothness of the data across the X-Y plane and as a function of Z.

iii. Examine the behaviour of the corrected B-field components as a function of X, Y and Z to assess the uncertainties on them and search for any "rogue" points;

iv. Average the corrected B_field measurements at each X, Y, Z position, with due regard to the uncertainties, and obtain a final data set.

v. Assess the expected symmetries of the field;

vi. Assess systematic uncertainties in ∫B.dl and the degree of interpolation between data points that is required.

A summary of the tasks

- Sensors are fixed to each panel with those on the front and back panels facing in opposite directions. Measurements are made with 8 different panel orientations, 4 for "upstream" data and 4 for "downstream".
- The location of each panel (X_0, Y_0) needs to be checked and the X-Y-Z coordinates of all 60 sensors precisely determined for each data point.
- The B-field components measured by the Hall probes must be translated into the NA62 coordinate system.
- The Hall-probe axes, sensor axes, and panel axes, are all approximately parallel to the NA62 axes. Because of mixing of the magnetic-field components all angles need to be precisely determined:

  eg: For $\Delta\phi = 1$ mrad, $\Delta B_x = B_y \Delta\phi = 4$ G
- Small irregularities in the data require smoothing out in a well-controlled manner, while maintaining $\Delta B_X < 5$ G, $\Delta B_Y < 5$ G and $\Delta\int B.dL \approx 0.1$ %
- Systematics need understanding and evaluating.
- The final field map should be capable of simple interpolation to determine accurate field values.

Orientation

- A reminder of the symmetry conditions for a dipole field:

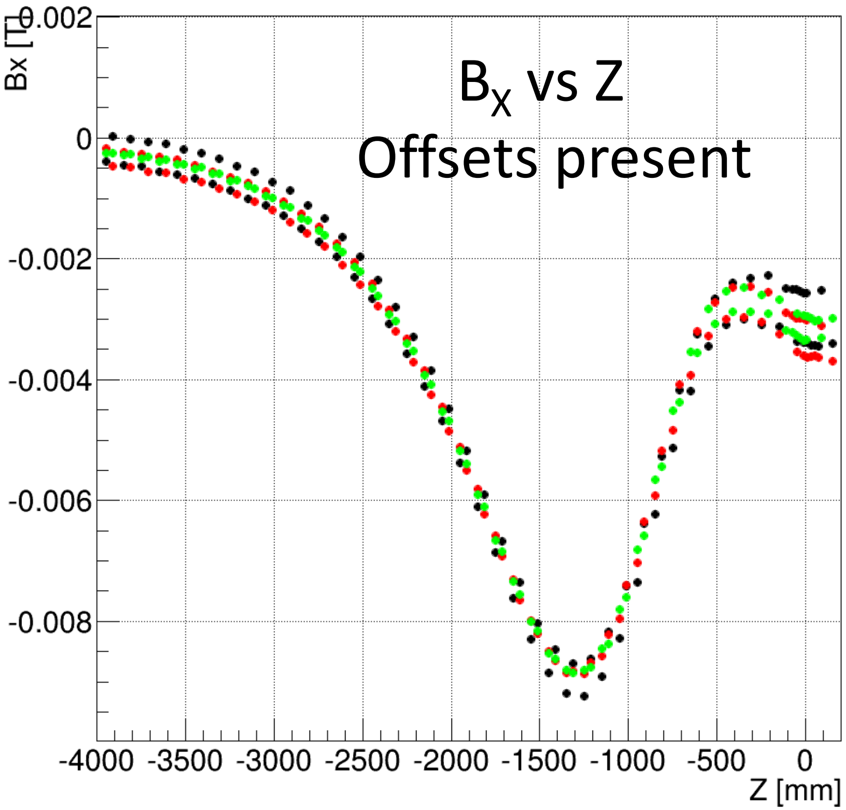
$$B_X (X, Y, Z) = -B_X (-X, Y, Z) = -B_X (X, -Y, Z) = B_X (X, Y, -Z)$$

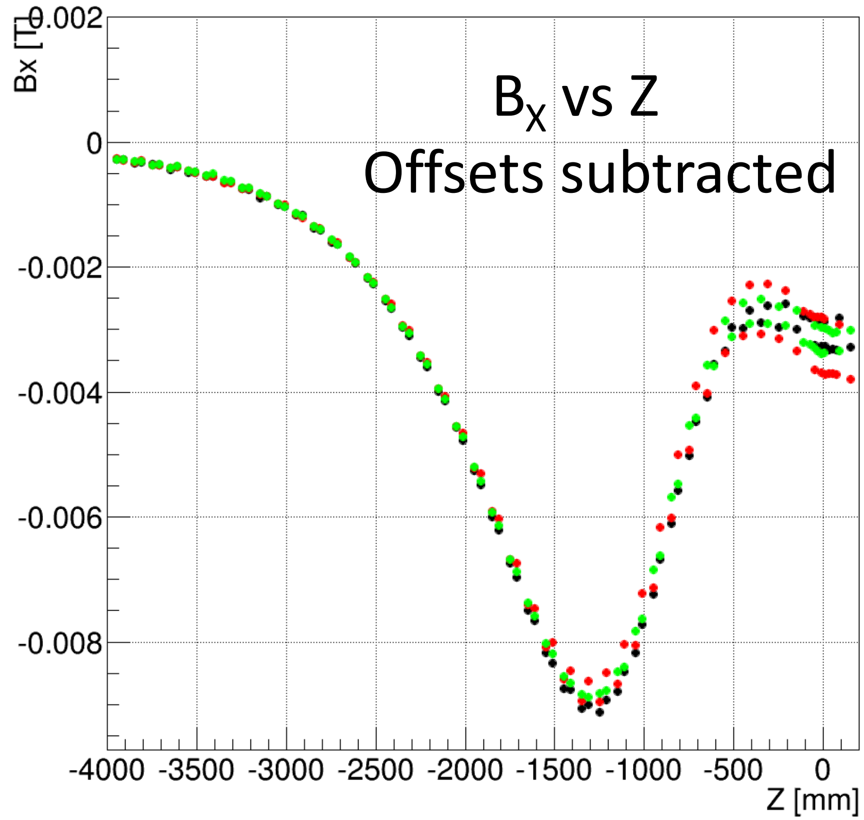
$$B_Y (X, Y, Z) = B_Y (-X, Y, Z) = B_Y (X, -Y, Z) = B_Y (X, Y, -Z)$$

$$B_Z (X, Y, Z) = B_Z (-X, Y, Z) = -B_Z (X, -Y, Z) = -B_Z (X, Y, -Z)$$

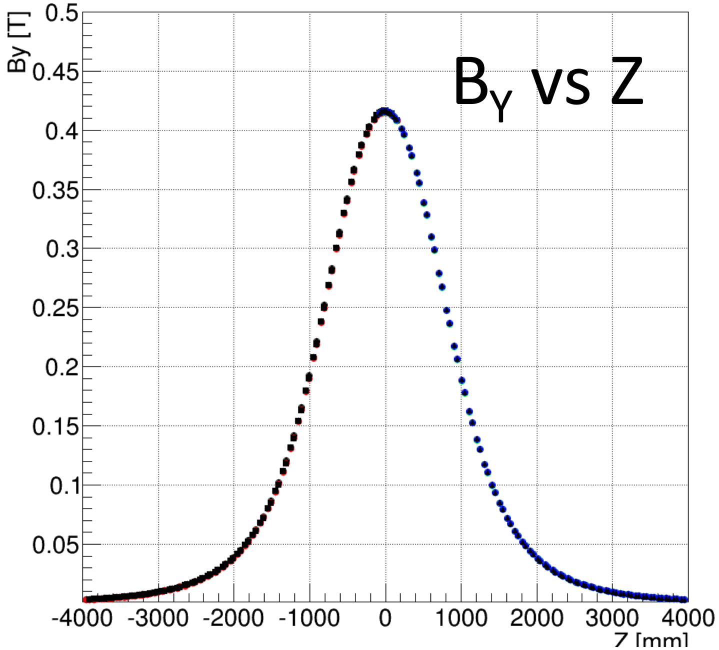
- Illustrative plots:
  - Offsets in zero magnetic field
  - B_X, B_Y and B_Z vs Z at X = Y = 0 — No further interest in B_Z.
  - Variation of B_X with X and Y — Shape of field
  - Variation of B_Y with X and Y — Shape of field

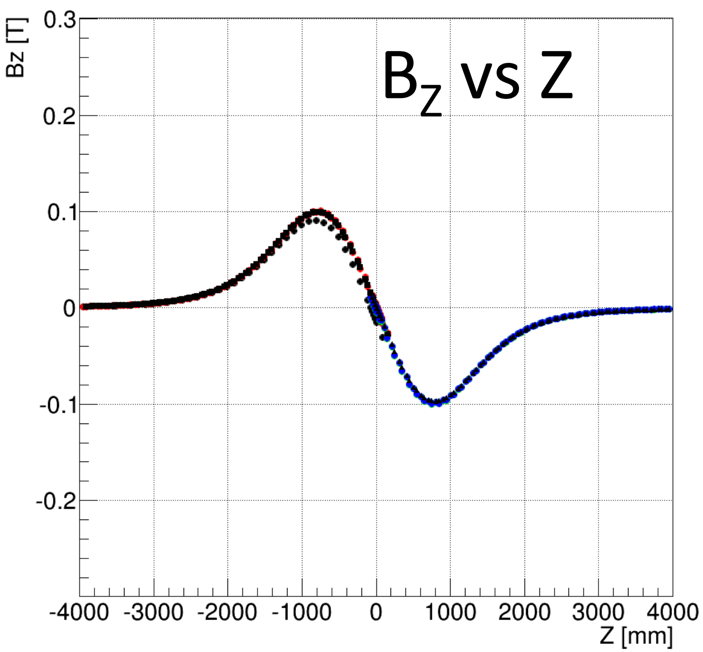
Subtracting HP_Offsets in zero field

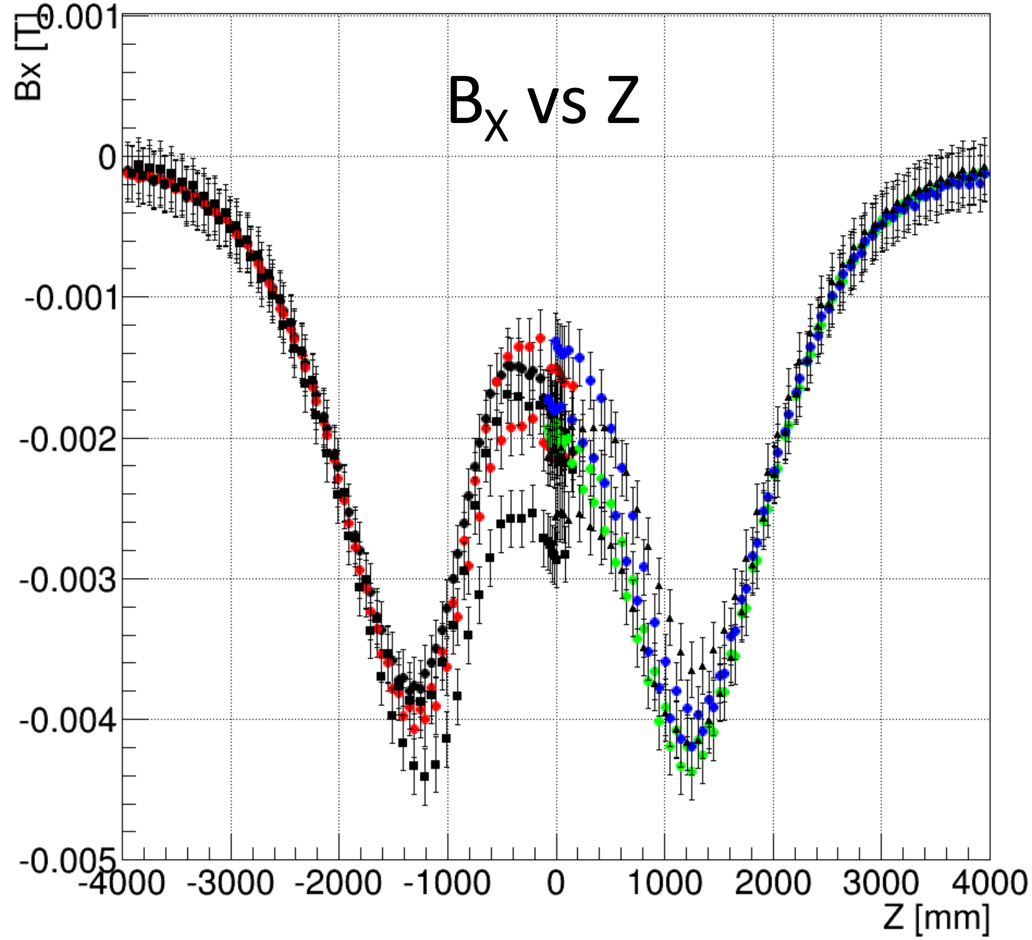




Effect of offsets only visible when |B| very small (Fringe Field)

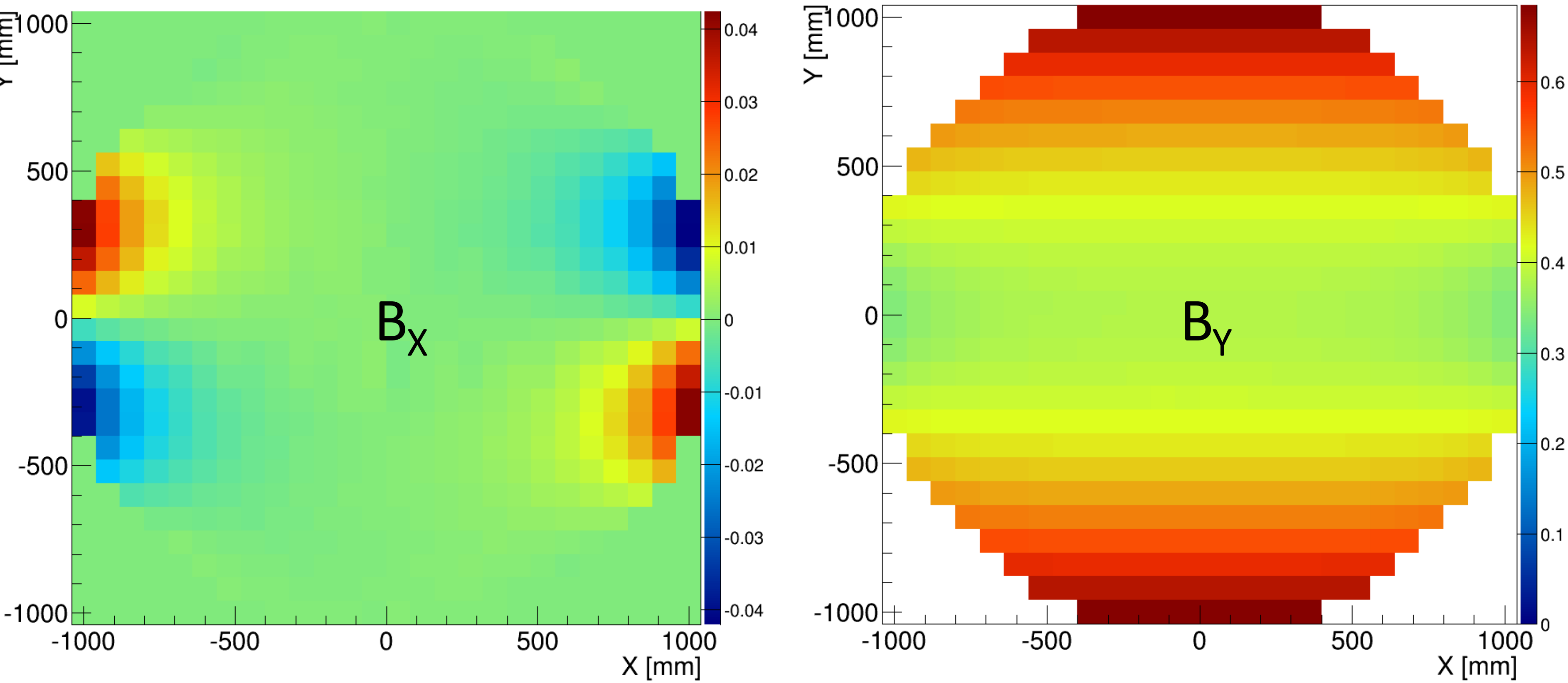






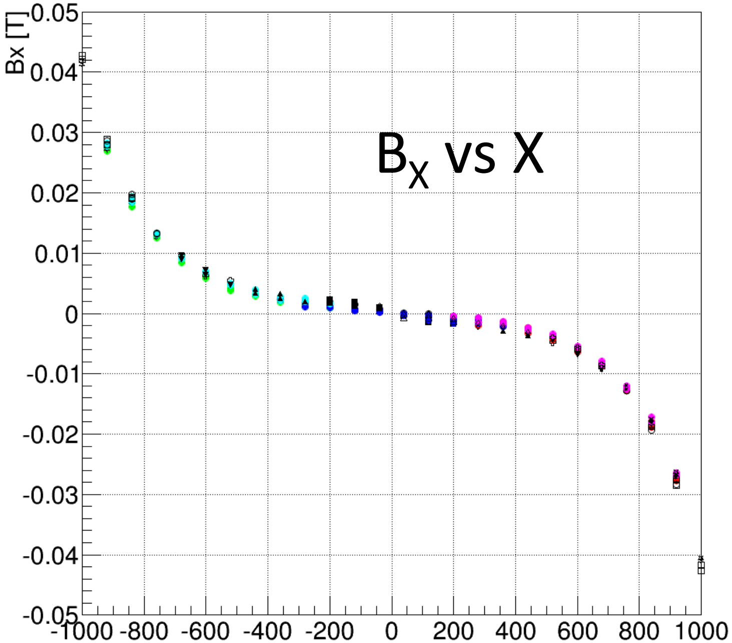
Spread of ~ 20 G before corrections

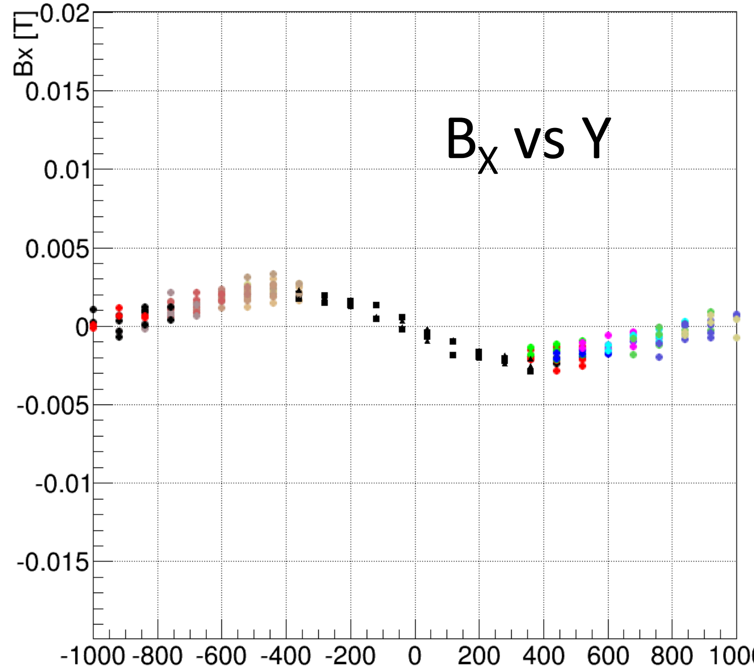
$\int B_Z\, dL = 0$

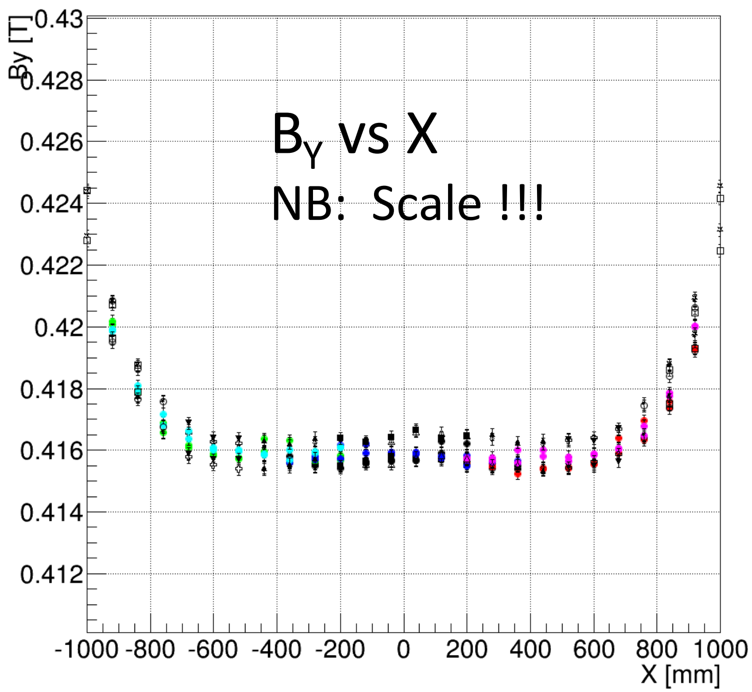


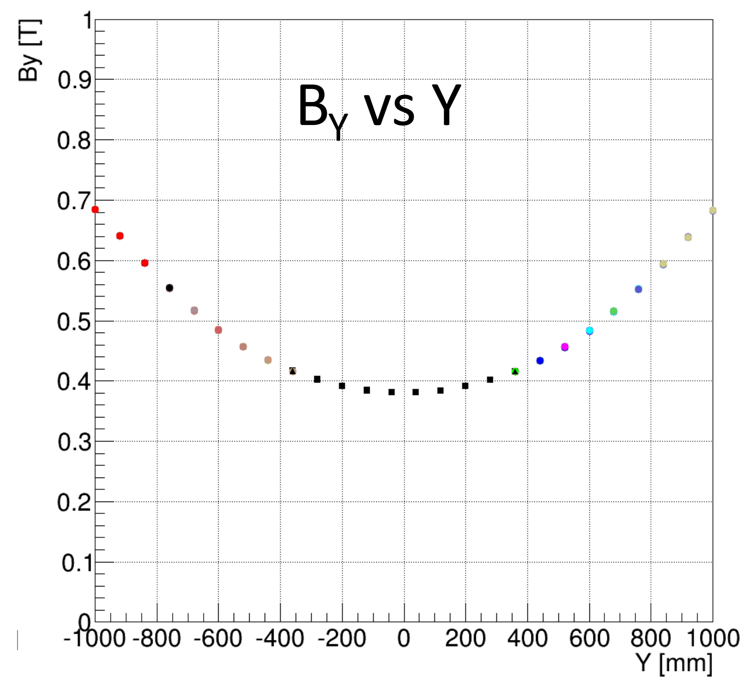
B_X has crossing symmetry: $B_X(X, Y, Z) = B_X(-X, -Y, Z)$ [Different scales !!]

B_Y is very uniform in X, but large increase with Y outside central region


Bx [T]
B_X vs X


Bx [T]
B_X vs Y


By [T]
B_Y vs X
NB: Scale !!!
X [mm]


By [T]
B_Y vs Y
Y [mm]

Angular Corrections to the field components

Upstream data: Up-Down orientation of the sensor panel

$$B_X^T = B_X^M + (\beta_2 + \phi_S + \phi_P)\, B_Y^M + (\gamma_2 + \theta_S + \theta_P)\, B_Z^M \qquad (1)$$

$$B_Y^T = B_Y^M + (\gamma_3 + \psi_S + \psi_P)\, B_Z^M \qquad (2)$$

Upstream data: Rot±90 orientation of the sensor panel

$$B_X^T = B_X^M + (\beta_3 + \phi_S + \phi_P)\, B_Y^M + (\gamma_3 + \psi_S + \psi_P)\, B_Z^M \qquad (3)$$

$$B_Y^T = B_Y^M + (\gamma_2 + \theta_S + \theta_P)\, B_Z^M \qquad (4)$$

Key: T true value; M measured;

β_2, β_3 and γ_2, γ_3 : Hall-probe angles relative to sensor-card axes;

ϕ_S, θ_S and ψ_S : angles of sensor cards relative to sensor panels;

ϕ_P, θ_P and ψ_P : angles of sensor panels relative to NA62 axes. They vary from data set to data set and may depend on Z.

Methodology for angular measurements

- Choose reference data sets close to X=Y=0: for each sensor in U_data set at a given X, the same sensor in the D_data is located at -X.

$$B_X^T (X, Y, 0) = B_X^{U, Up} (X, Y, 0) + (\beta + \phi) B_Y (X, Y, 0)$$

$$B_X^T (-X, Y, 0) = B_X^{D, Up} (-X, Y, 0) - (\beta + \phi) B_Y (-X, Y, 0)$$

- Take the average of the 4 values at a particular value of (X, Y, 0):

$$B_X^T = B_X^{AV} + ¼ [(\beta_j^{U,F} + \beta_k^{U,B} - \beta_m^{D,F} - \beta_n^{D,B}) + (\phi^{U,F} + \phi^{U,B} - \phi^{D,F} - \phi^{D,B})] B_Y$$

- average over all 30 sensors on each sensor panel for the upstream and downstream data – 120 measurements – $< B_X^T > = 0$:

$$<B_X^{AV} (X, Y, 0) / B_Y (X, Y, 0)> = -¼ (\phi^{U,F} + \phi^{U,B} - \phi^{D,F} - \phi^{D,B})$$

- cancellation within the β-term for B_X^T is good to < 0.5 mrad:

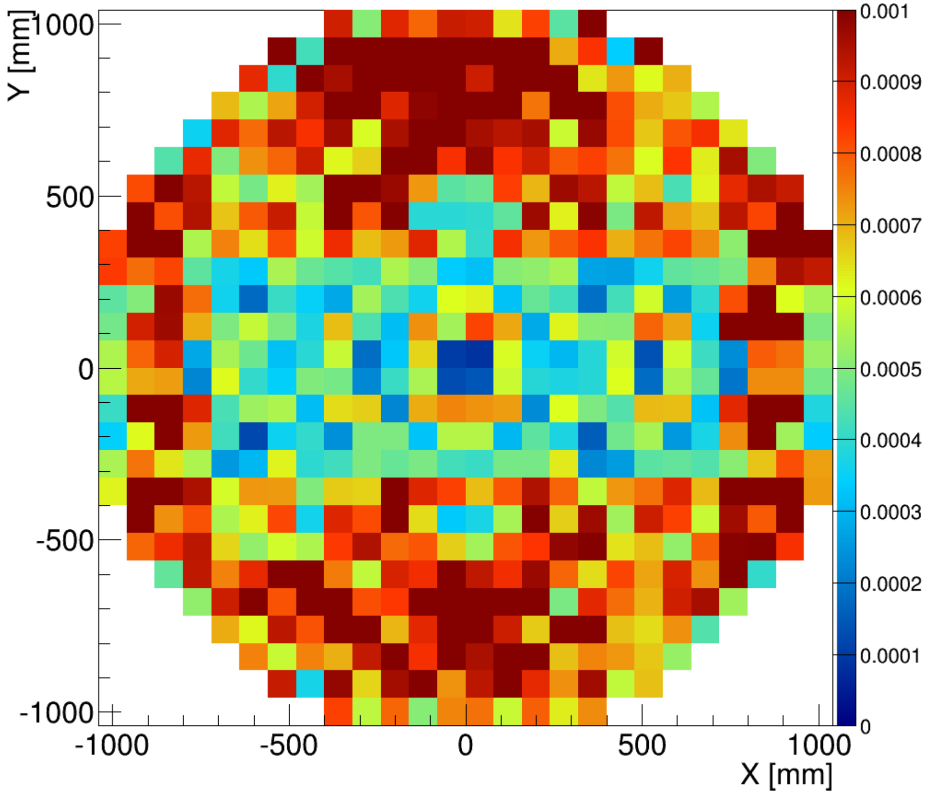
$$(\beta_j^{U,F} + \phi^{U,F}) = + [B_X^T (X, Y, 0) - B_{X,j}^{U,F} (X, Y, 0)] / B_Y (X, Y, 0)$$

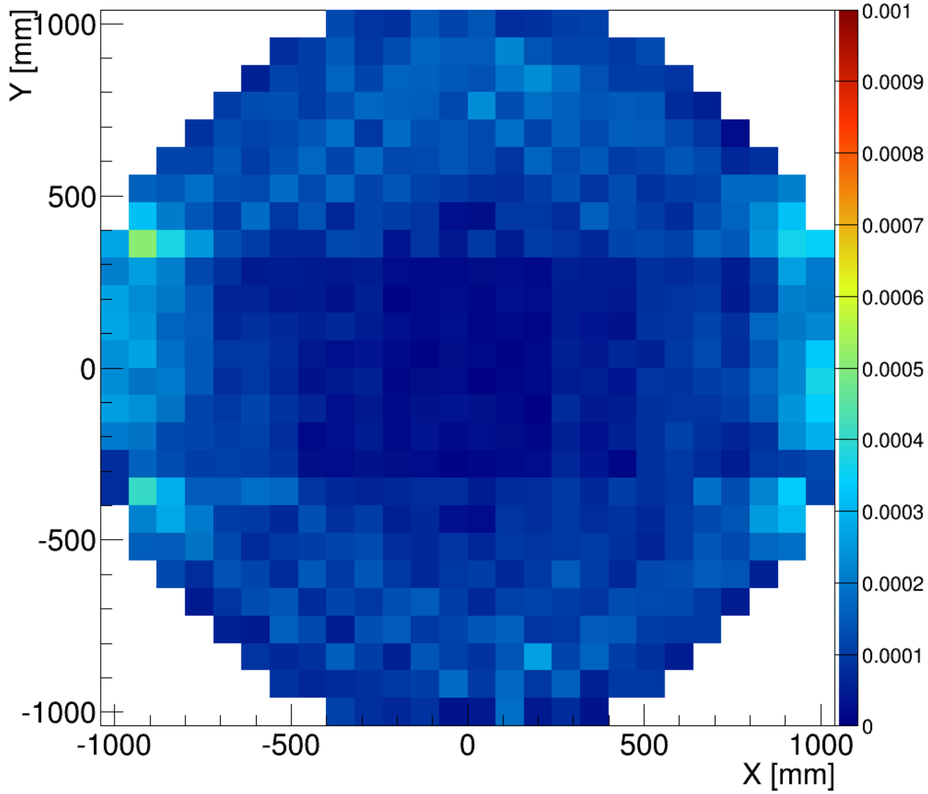
$$(\beta_n^{D,B} + \phi^{D,B}) = - [B_X^T (X, Y, 0) - B_{X,n}^{D,B} (X, Y, 0)] / B_Y (X, Y, 0) ....$$

Matching different data sets

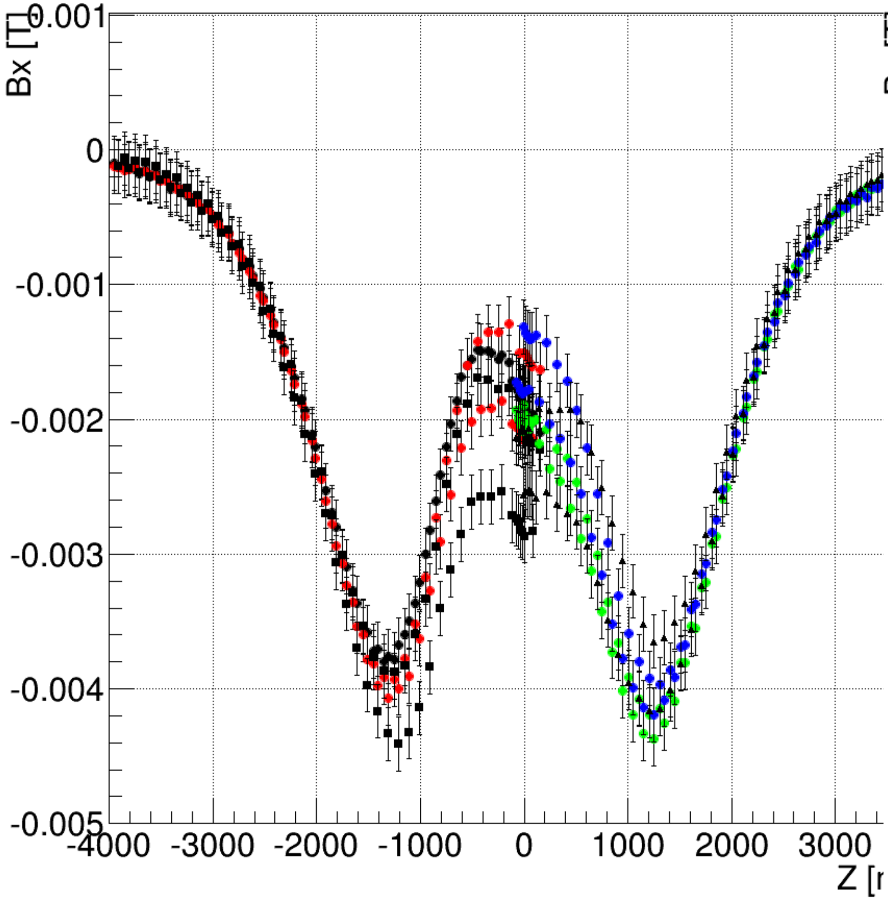
- Best value of B_X (X, Y, 0) is the average of all sensor measurements corrected for mixing, and the RMS residual is then calculated.
- ϕ_P varies with data set due to movement of the measurement frame:
- For those data sets where measurements of B_X occur at the same location in X, Y as for the reference data sets, the panel angles are varied to produce the minimum residuals.
- With these panel angles fixed, the residuals are examined for the data sets overlapping with the ones for which the panel angles have just been determined until all panel angles are fixed.
- The resulting residual distributions typically show a reduction from 10 G to < 2 G.
- The same technique is used for B_Y

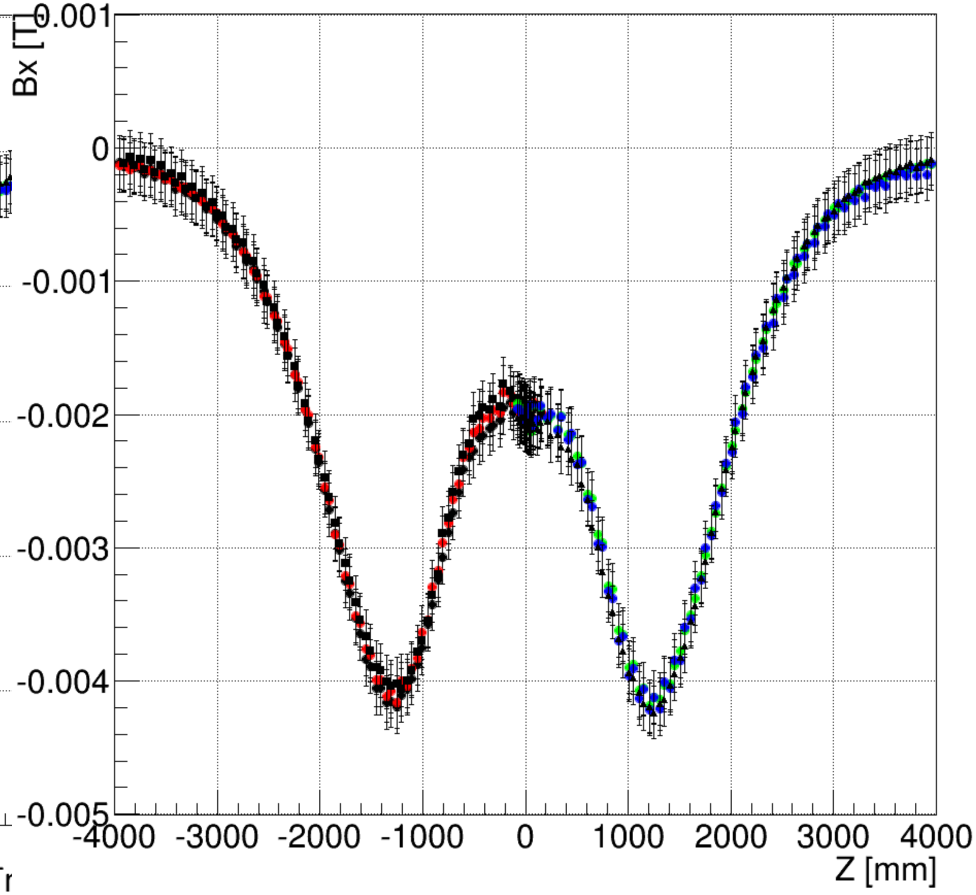
ΔB_X variation over the X-Y plane
a) Before ± 10 G; b) After corrections ± 2 G



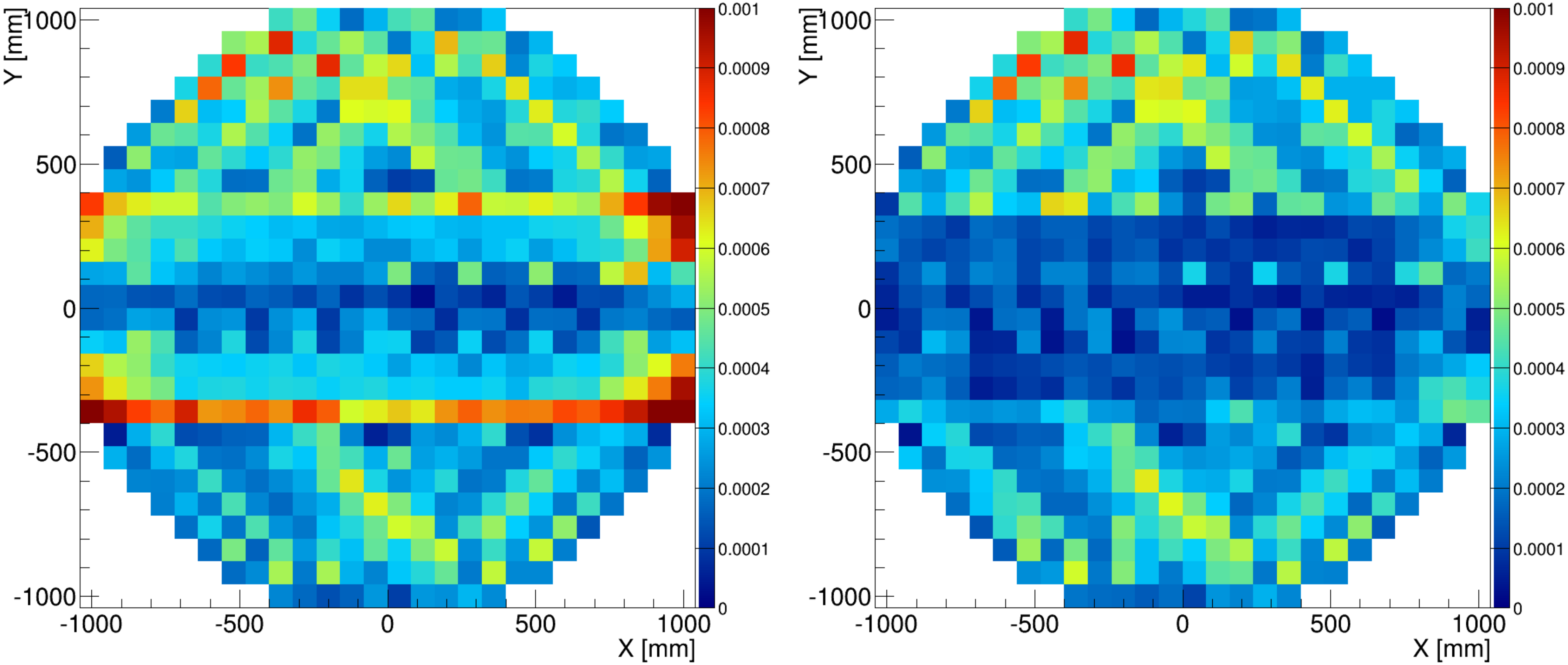


B_X variation with Z
a) Before ± 10 G; b) After corrections ± 2 G





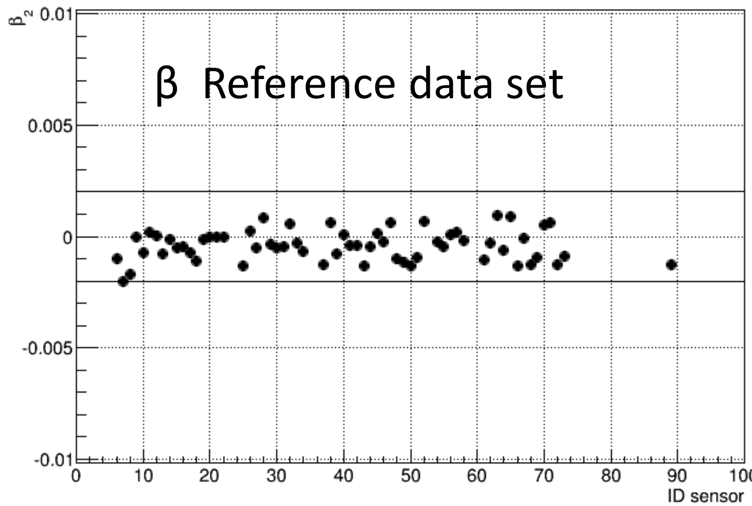
ΔB_Y variation over the X-Y plane
Main effect from relative data-set rotation
a) Before b) After

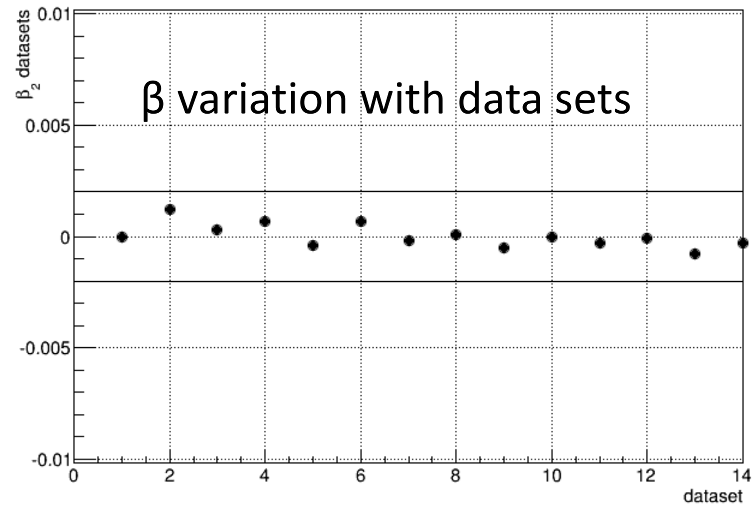


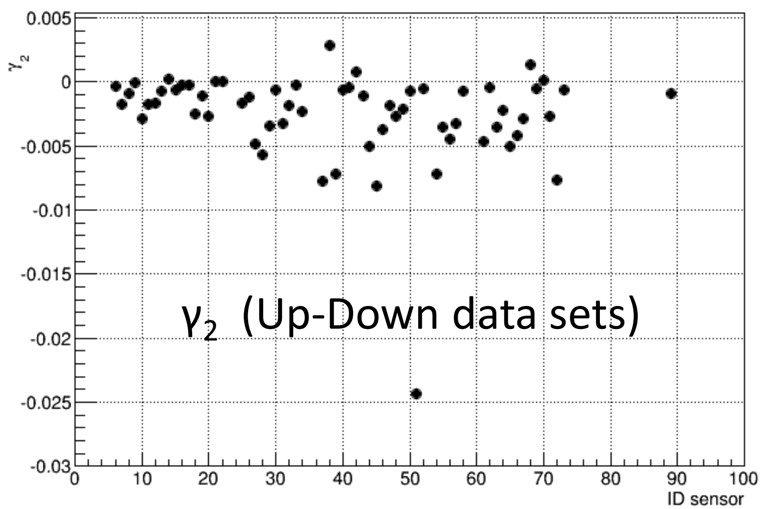
Sanity checks on β and γ angles

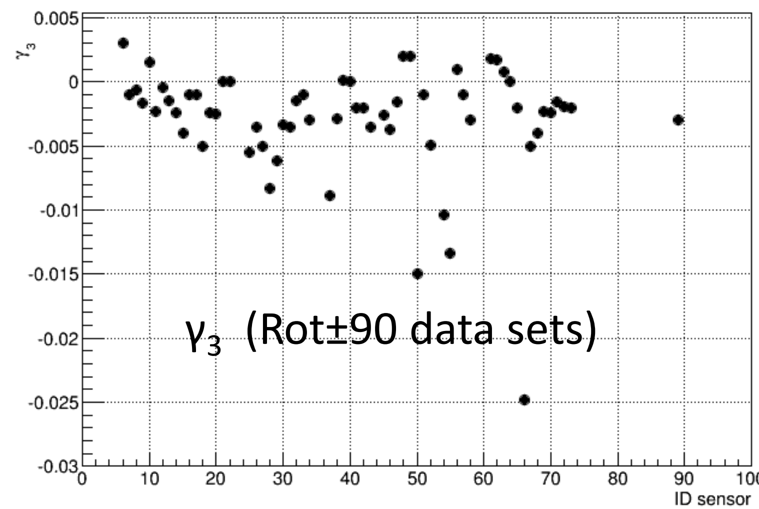
- Except for ≈ 6 misaligned sensors, mainly resulting in large angles for γ, we expect:
  - β angles to be 1-2 mrad, equivalent to $\Delta B_X < 10$ G;
  - γ angles to be 1-5 mrad, equivalent to $\Delta B_X < 5$ G;
- These expectations are met.

Values of β and γ for all sensors





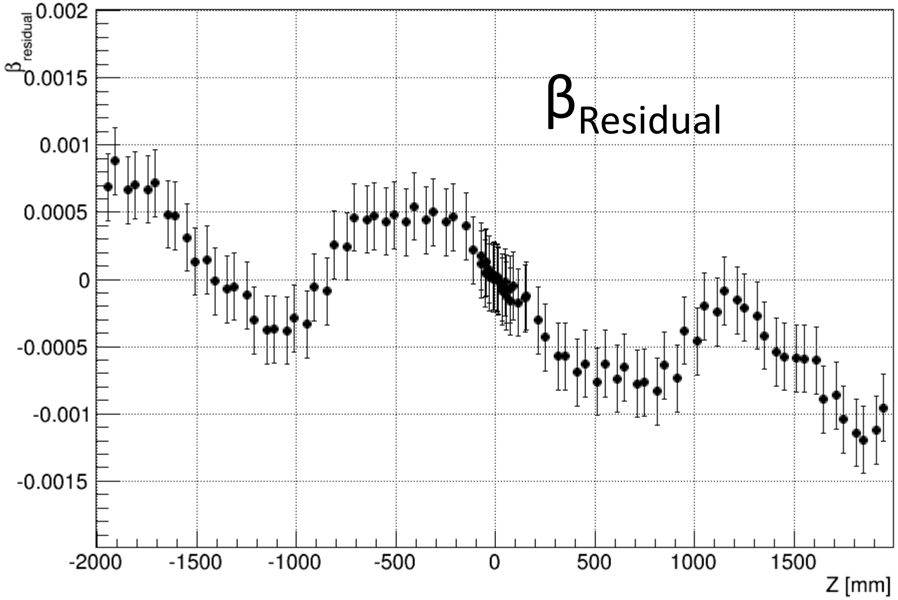


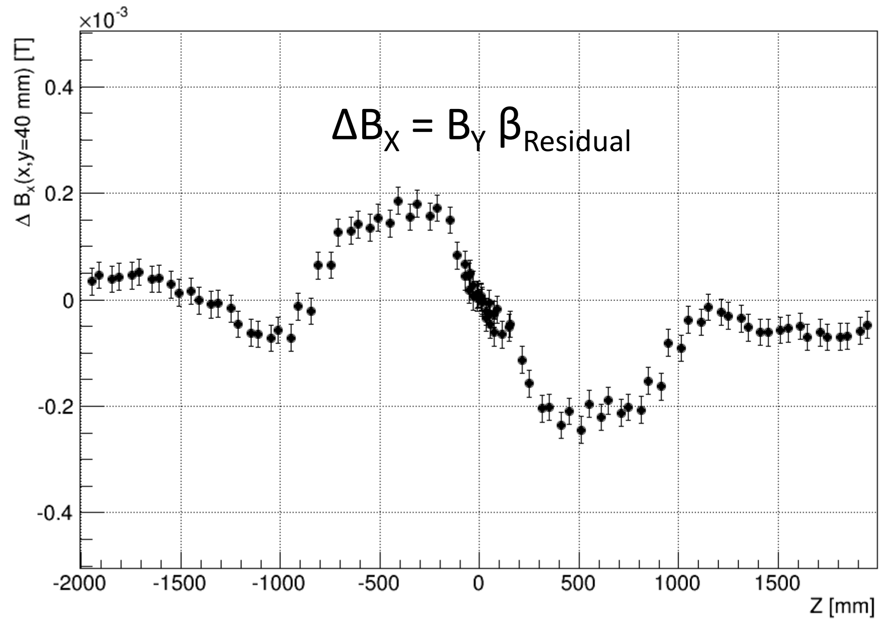


Possible Z-dependence of sensor angles

- Within the limit of the survey measurements there is a possibility of a small twist or wobble in the measurement carriage and also small variations in the (X, Y) positions of the sensors with Z.
- We see the effects of a small twist (< 0.5 mrad) and are investigating the potential effects of small (X, Y) movements.

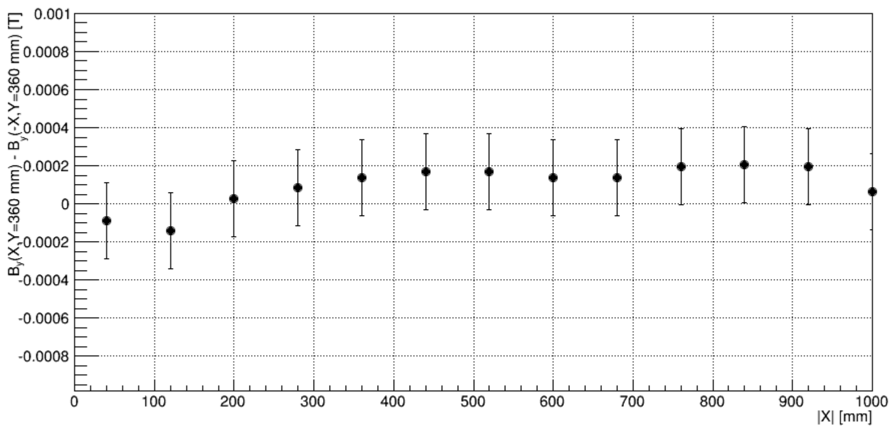
Residual β and ΔB_X





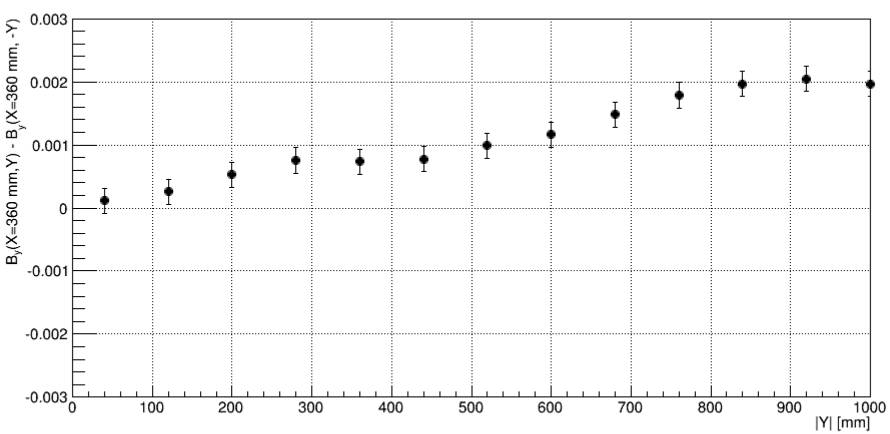
After all angular corrections, there is a systematic variation in β as a function of Z at the level of 0.5 mrad, and hence $B_X < 2$ G. It is common to all sensors and all data sets and could arise from a small wobble in the measurement carriage, consistent with survey measurements.

Asymmetry in B_Y vs X and Y



B_Y vs X shows little evidence – asymmetry < 2 G.

Magnet centre is good.



B_Y vs Y shows clear evidence – asymmetry ≈ 20 G.

Is the asymmetry real?

Is the Magnet centre offset?

Obtaining the Field Map

- The field map is obtained via the following stages:
  - Calculate the X, Y, Z coordinate of each Hall probe
  - Transform the HP measurements to NA62 coordinates
  - Calculate the angular corrections to Hall probes, sensors and sensor planes
  - Apply well-understood β(Z) corrections
  - Average the values of B_X, B_Y and B_Z at each grid location
  - Calculate the RMS residual for each field component at (X, Y, Z)

Preliminary Systematics on B_X and B_Y

- The overall calibration of the sensors [Felix Bergsma] is good to <2 G at 1 T. This gives a systematic uncertainty common to all measurements of ~ 1 G over the range of our measurements.
- Typically, $\Delta B_Y^{Meas} = B_Y^U - B_Y^D \approx 2$ Gauss at Z = 0. This cannot arise from mixing the B_Z component, which is zero at Z = 0, and gives rise to a systematic uncertainty on B_Y of ~ 2 G for all measurements.
- Measurements of β are good to ± 0.5 mrad, or ΔB_X of ~ 2 G. The adjustments from matching data sets are correlated, so this corresponds to a systematic uncertainty on B_X of ~ 2 G for all measurements.
- Measurements of γ are everywhere good to ± 1 mrad, corresponding to ΔB_X and ΔB_Y of ~ 1 G. Since the adjustments from data set to data set are correlated, this corresponds to a systematic uncertainty on B_X and B_Y of ~ 1 G for all measurements.
- All the above systematics are uncorrelated and may be added in quadrature to give an overall systematic uncertainty of ±3 G on both B_X and B_Y , corresponding to $\Delta\int B\, dL$ of less than one per mille.
- The systematics due to the asymmetry in B_Y is under investigation.

Remaining work

- Finalise understanding of systematic errors on B_X and B_Y.
  - Understand the variation of β with Z
  - Understand the origin of the asymmetry in B_Y vs Y
- Study the effects on ∫B.dl of the statistical and systematic errors on B_X and B_Y and determine Δ ∫B.dl
- Complete the write-up of the NA62 note with all details of the calculations and analysis of systematics –December.

Summary

- We understand the structure of the magnetic field;
- We have calculated all the angular corrections [HP, sensor cards, sensor panels] and identified and corrected "rogue" measurements from our analysis;
- We have a corrected field map covering ± 4 m in Z and the entire aperture in X-Y with 80 mm spacing in X, Y and Z;
- Systematic errors on B_X and B_Y are less than 5 G;
- To Do:
  - Further investigate $\beta(Z)$ variation and B_Y asymmetry wrt Y;
  - Complete write-up of work in NA62 Note by December 2014.

Appendix
Geometry and Field Transformations

For details of angular corrections and methods to check data and calculate systematics – see NA62 Note

Geometry

Decoding the data header

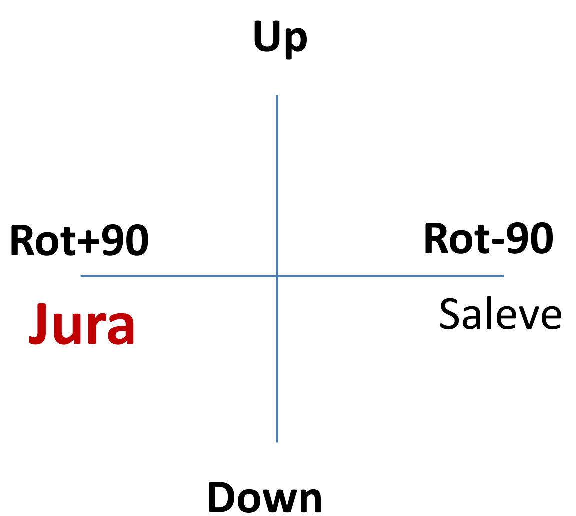
A typical data-file header looks like: U_I1240_name_Xm_Yn_PosK_1

where the current in the main coil is 1240 A and U specifies the UPSTREAM measurement configuration; there is also D for the DOWNSTREAM configuration.

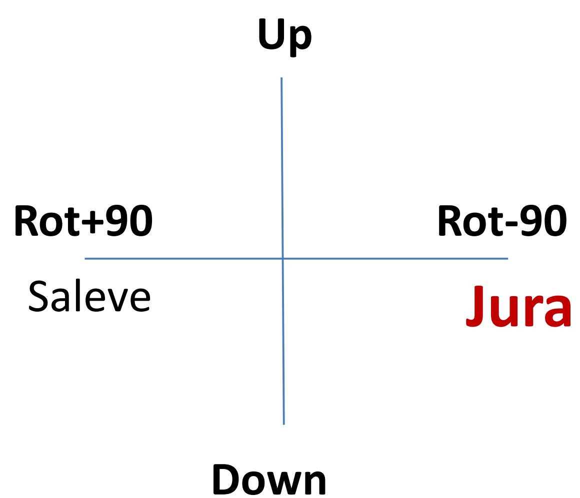
name:	Up (Down)	The panel is in the Up (Down) position – see slides 4 and 5
	Rot-90	The panel is rotated clockwise by 90 degrees [RHS]
	Rot+90	The panel is rotated counter clockwise by 90 degrees [LHS]

NB: The coordinate system is local to the panel and rotates with it

Upstream Data



Downstream Data



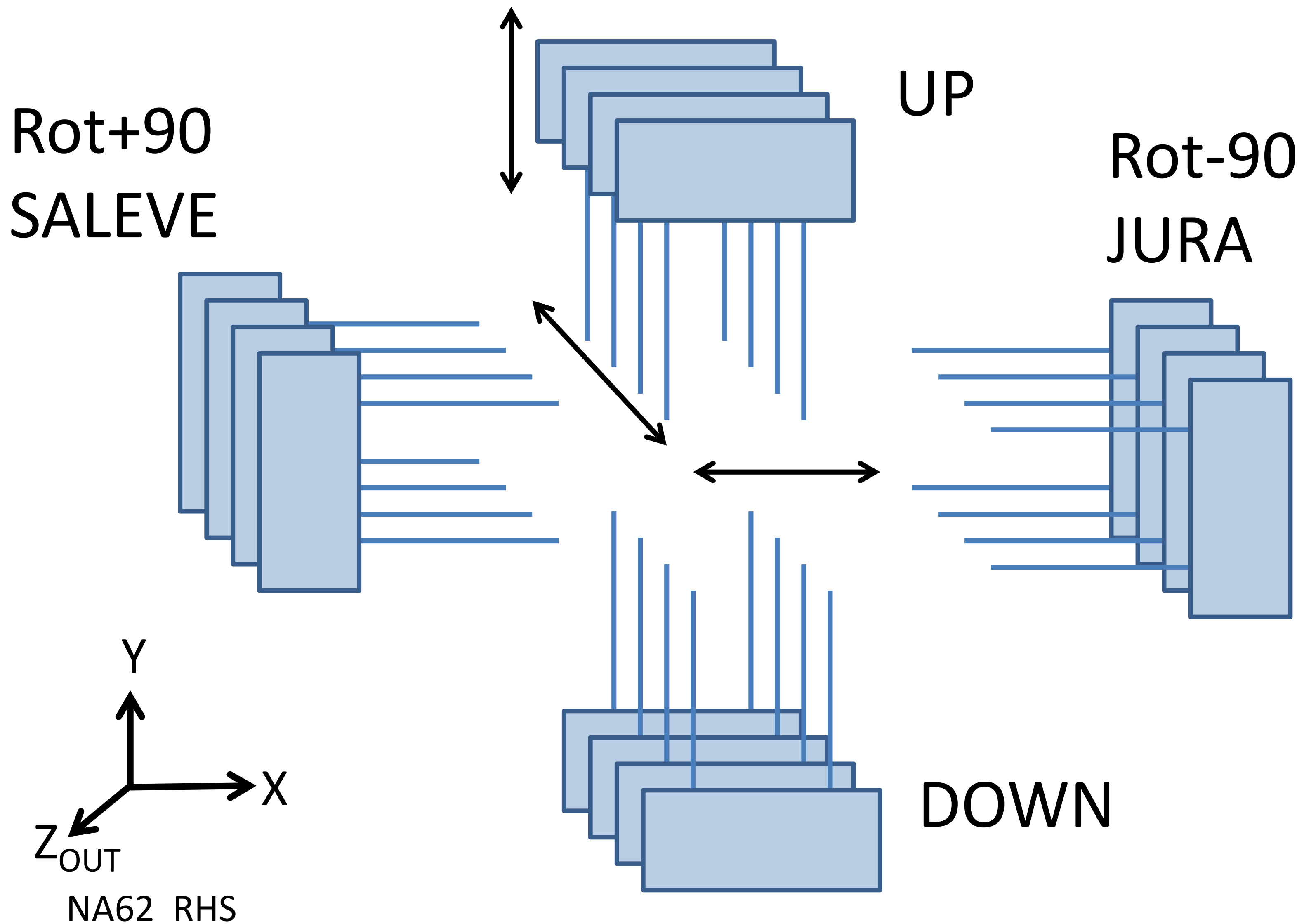
Calculating (X_0 Y_0) from Xm, Yn and PosK

In the header, m and n are always +ve. However, in the following calculations m must be replaced by –m for K = 3, 5, 7, 9, 11, 13, 15, 16, 20; this only affects Xm.

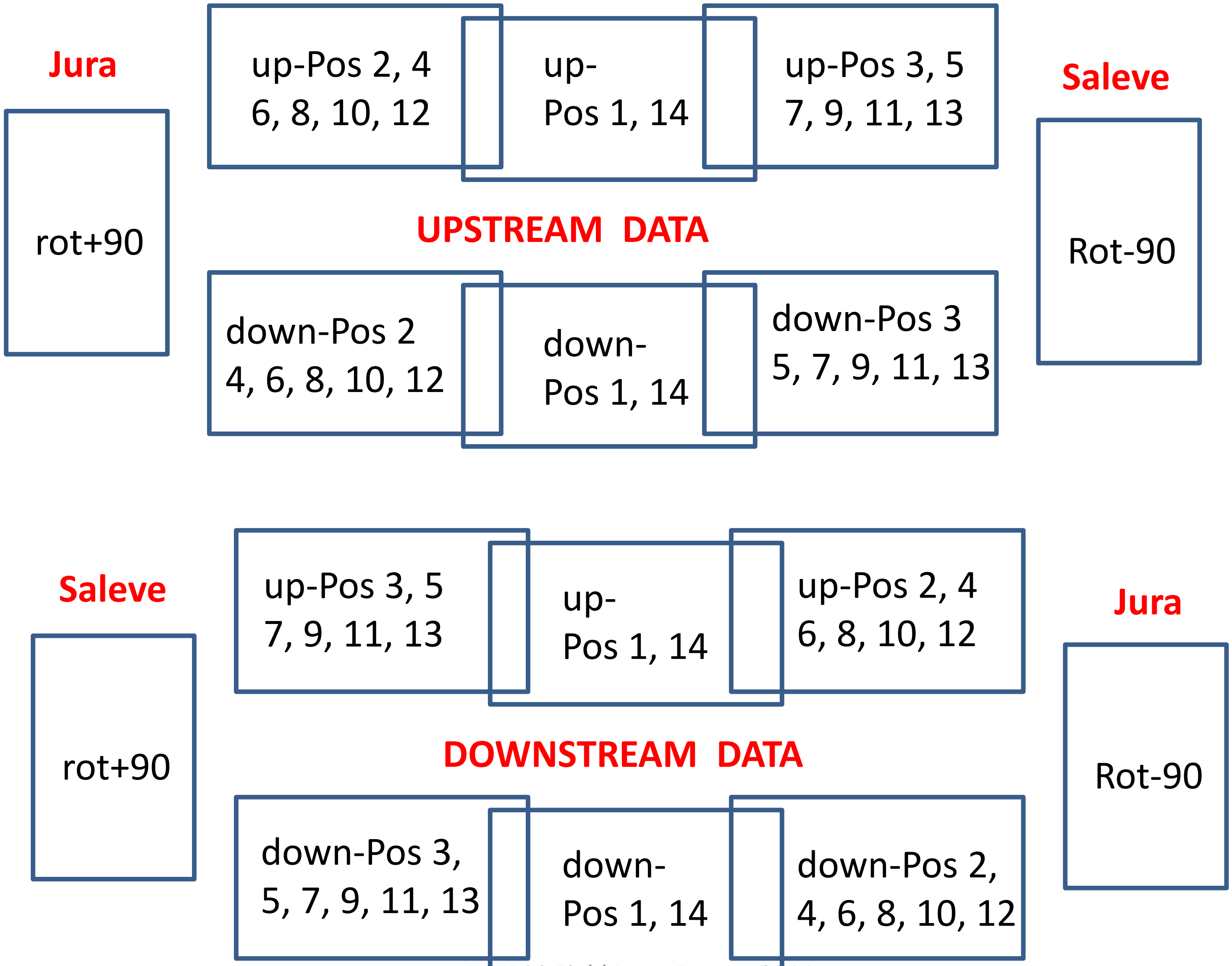
	UPSTREAM	**DOWNSTREAM**
Up:	X_0 = - 80*m	X_0 = 80*m
	Y_0 = 360 + 80*(n-1)	Y_0 = 360 + 80*(n-1)
Down:	X_0 = 80*m	X_0 = - 80*m
	Y_0 = - [360 + 80*(n-1)]	Y_0 = - [360 + 80*(n-1)]
Rot±90:	Y_0 = 0	Y_0 = 0
Rot+90:	X_0 = (m + 4.5)*80	X_0 = - (m + 4.5)*80
Rot-90:	X_0 = - (m + 4.5)*80	X_0 = (m + 4.5)*80

Examples:	U_I1240_up_X2_Y6_Pos12_1	X_0 = - 160; Y_0 = + 760
	U_I1240_up_X2_Y6_Pos13_1	X_0 = + 160; Y_0 = + 760
	U_I1240_down_X2_Y6_Pos13_1	X_0 = - 160; Y_0 = - 760
	U_I1240_rot+90_X2_Y1_Pos17_1	X_0 = + 520; Y_0 = 0
	U_I1240_rot+90_X1_Y1_Pos16_1	X_0 = + 280; Y_0 = 0
	U_I1240_rot-90_X6_Y1_Pos19_1	X_0 = - 840; Y_0 = 0

Panel Positions viewed from Downstream



Actual Panel Positions



Sensor Numbering on Panels

55	54	52	51	50	68	69	70	71	72
45	46	47	48	49	67	66	65	64	63
44	43	42	41	40	56	57	58	61	62

Position of sensors on **Front Panel**
viewed from the measuring bench
for **both** Upstream **and** Downstream data

X_0 mid-way between (6, 73) or (56, 40)
Y_0 coordinate of bottom row of sensors
Z_0 mid-way between planes ±31.9 mm

Viewed from: **Upstream** **Downstream**

39	38	37	34	33	16	17	18	19	20
28	29	30	31	32	15	14	13	12	11
27	26	25	89	73	6	7	8	9	10

Position of sensors on **Rear Panel**
- **for those people with X-ray eyes** -
viewed from the measuring bench
for **both** Upstream **and** Downstream data

X, Y and Z sensor Coordinates

Columns (j) $1 \rightarrow 10$

Rows (i) $1 \rightarrow 3$

1,1	1,2	1,3	…	1,10
2,1	2,2	2,3	…	2,10
3,1	3,2	3,3	…	3,10

$X_{Rel} = 0$ at position (3,5 + 3,6) / 2
$Y_{Rel} = 0$ for positions 3,1 to 3,10

NB: NA62 Coordinate System
$X_{Rel}(i, j) = (5.5 - j)*80$
$Y_{Rel}(i, j) = (3 - i)*80$

Sensors are on a square grid of side length 80 mm

NB: Within a data file Zpos is always negative: The Z-coordinate (**relative to the magnet centre**) is given for the front and back panels by:

UPSTREAM Data $Z_{Front} = Zpos - 31.9$; $Z_{Back} = Zpos + 31.9$
DOWNSTREAM Data $Z_{Front} = -[Zpos - 31.9]$; $Z_{Back} = -[Zpos + 31.9]$

The Z coordinate of the magnet centre is at $Z_{NA62} = 196.995$ m

UPSTREAM coordinates within a panel

1,1	1,2	1,3	…	1,8	1,9	1,10
2,1	2,2	2,3	…	2,8	2,9	2,10
3,1	3,2	3,3	…	3,8	3,9	3,10

1,10	2,10	3,10
1,9	2,9	3,9
………	………	………
1,2	2,2	3, 2
1,1	2,1	3,1

X_{UP} (i, j) = (5.5 - j)*80 Y_{UP} (i, j) = (3 - i)*80

X_{Right} (i, j) = (i - 3)*80 Y_{Right} (i, j) = (5.5 - j)*80

X_{Left} (i, j) = (3 - i)*80 Y_{Left} (i, j) = (j – 5.5)*80

X_{Down} (i, j) = (j - 5.5)*80 Y_{Down} (i, j) = (i - 3)*80

3,1	2,1	1,1
3,2	2,2	1,2
………	………	………
3,9	2,9	1,9
3,10	2,10	1,10

3,10	3,9	3,8	…	3,3	3,2	3,1
2,10	2,9	2,8	…	2,3	2,2	2,1
1,10	1,9	1,8	…	1,3	1,2	1,1

Subtlety

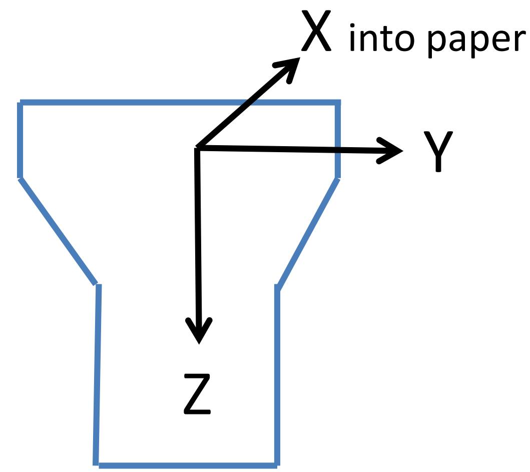
- The coordinates as calculated are those of the centre of the cube on which the Hall probes are mounted.
- Since the cube has side dimension of 4 mm, an offset of ±2 mm has been incorporated into the true position of the respective Hall probes

Magnetic-field Transformations

Hall-probe to NA62 coordinates

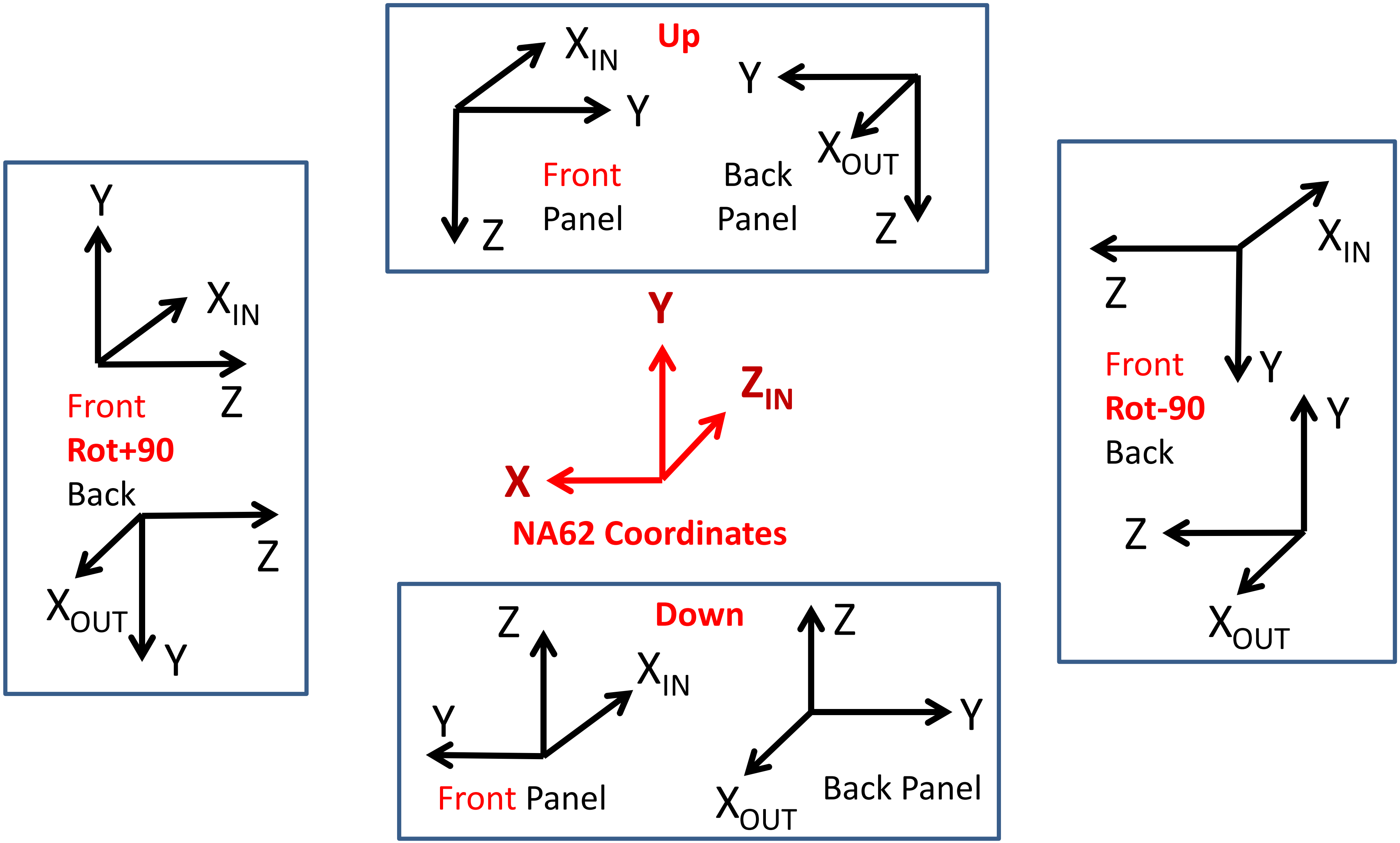
Sensor Mounting Geometry
Hall-probe axes

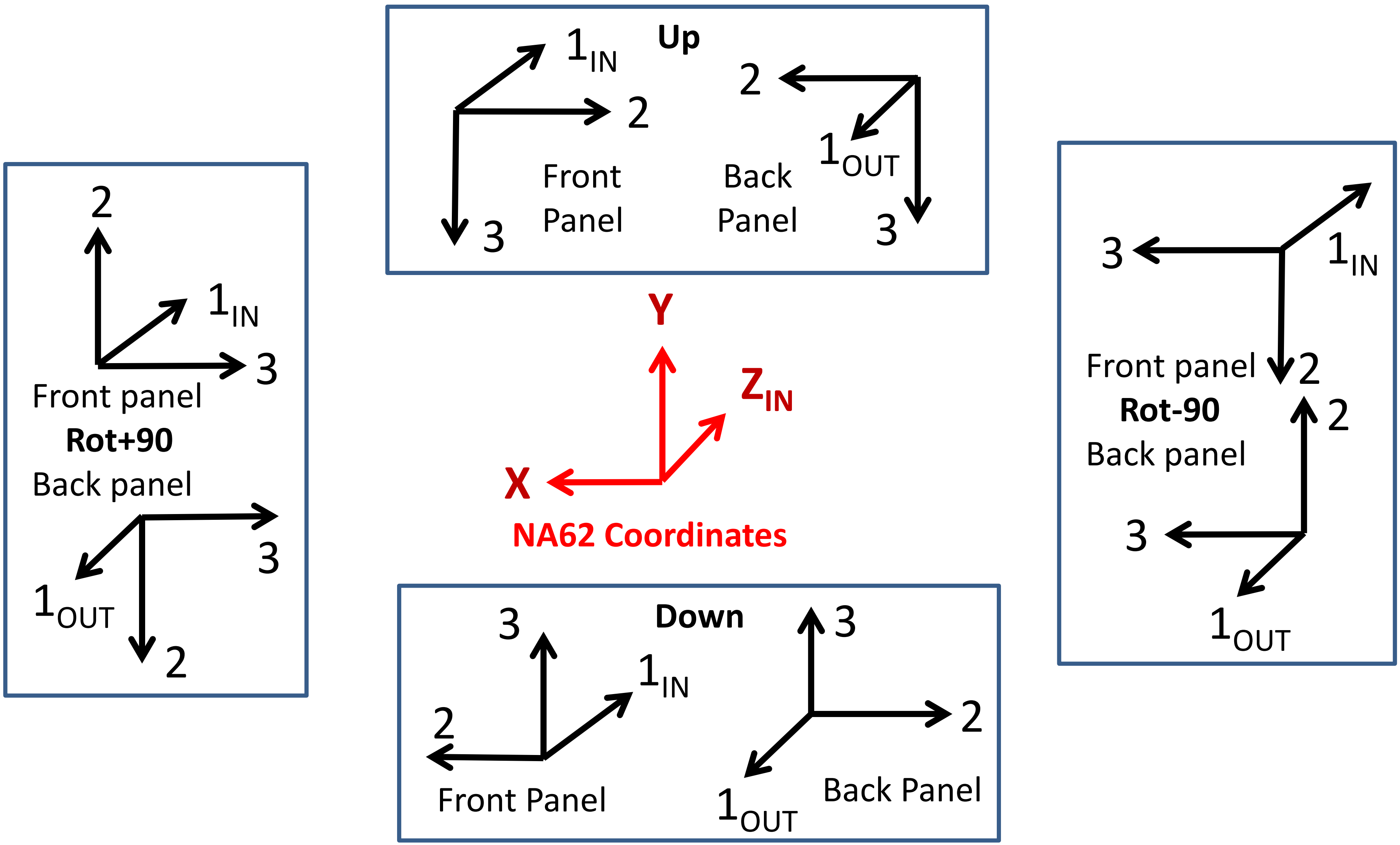
20	19	18	17	16	33	34	37	38	39
11	12	13	14	15	32	31	30	29	28
10	9	8	7	6	73	89	25	26	27



Back panel (LHS) showing the location of all sensors, and the orientation of a single sensor (RHS) together with the local coordinate system of the 3 Hall probes.

Sensor and NA62 coordinates: UPSTREAM




Up
1_{IN}
2
3
Front
Panel
Back
Panel
2
1_{OUT}
3
2
1_{IN}
3
Front panel
Rot+90
Back panel
3
1_{OUT}
2
Y
Z_{IN}
X
NA62 Coordinates
3
1_{IN}
Front panel
2
Rot-90
2
Back panel
3
1_{OUT}
Down
3
1_{IN}
2
Front Panel
3
2
1_{OUT}
Back Panel

Transforming B_i from sensor to NA62 coordinates UPSTREAM Data

NA62	U_F	U_B	R_F	R_B	D_F	D_B	L_F	L_B
B_X	$-B_Y$	B_Y	B_Z	B_Z	B_Y	$-B_Y$	$-B_Z$	$-B_Z$
B_Y	$-B_Z$	$-B_Z$	$-B_Y$	B_Y	B_Z	B_Z	B_Y	$-B_Y$
B_Z	B_X	$-B_X$	B_X	$-B_X$	B_X	$-B_X$	B_X	$-B_X$

U_F:	Up position:	Front sensor panel
U_B:	Up position:	Back sensor panel
R_F:	Rot-90 (Right):	Front sensor panel
R_B:	Rot-90 (Right):	Back sensor panel
D_F:	Down position:	Front sensor panel
D_B:	Down position:	Back sensor panel
L_F:	Rot+90 (Left):	Front sensor panel
L_B:	Rot+90 (Left):	Back sensor panel