Field Mapping: Magnetic axis of FC2, SSU & SSD

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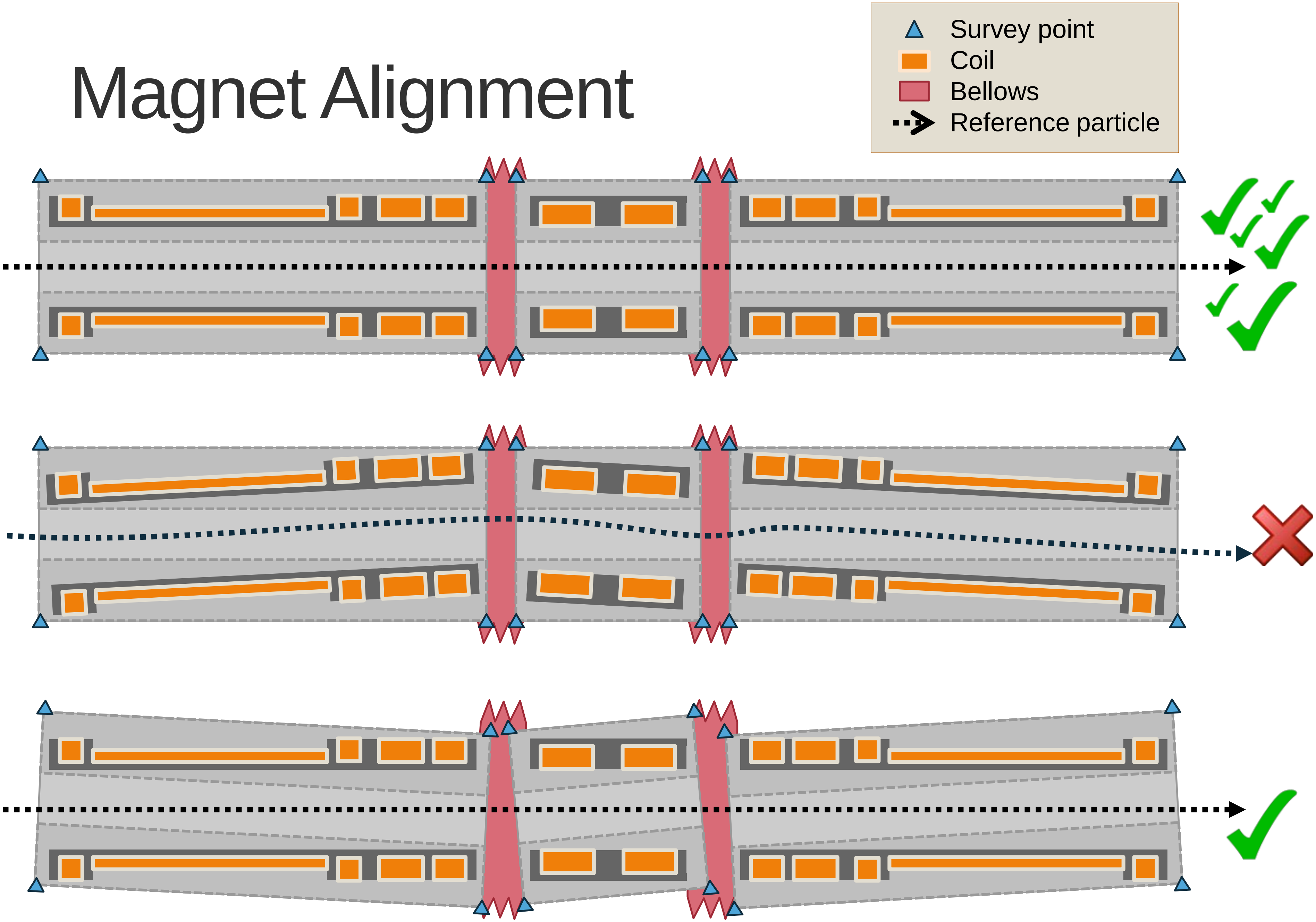
CM41

9th February, 2015

THE PROBLEM

- Alignment
- Geometric, magnetic and mapper axes

Magnet Alignment

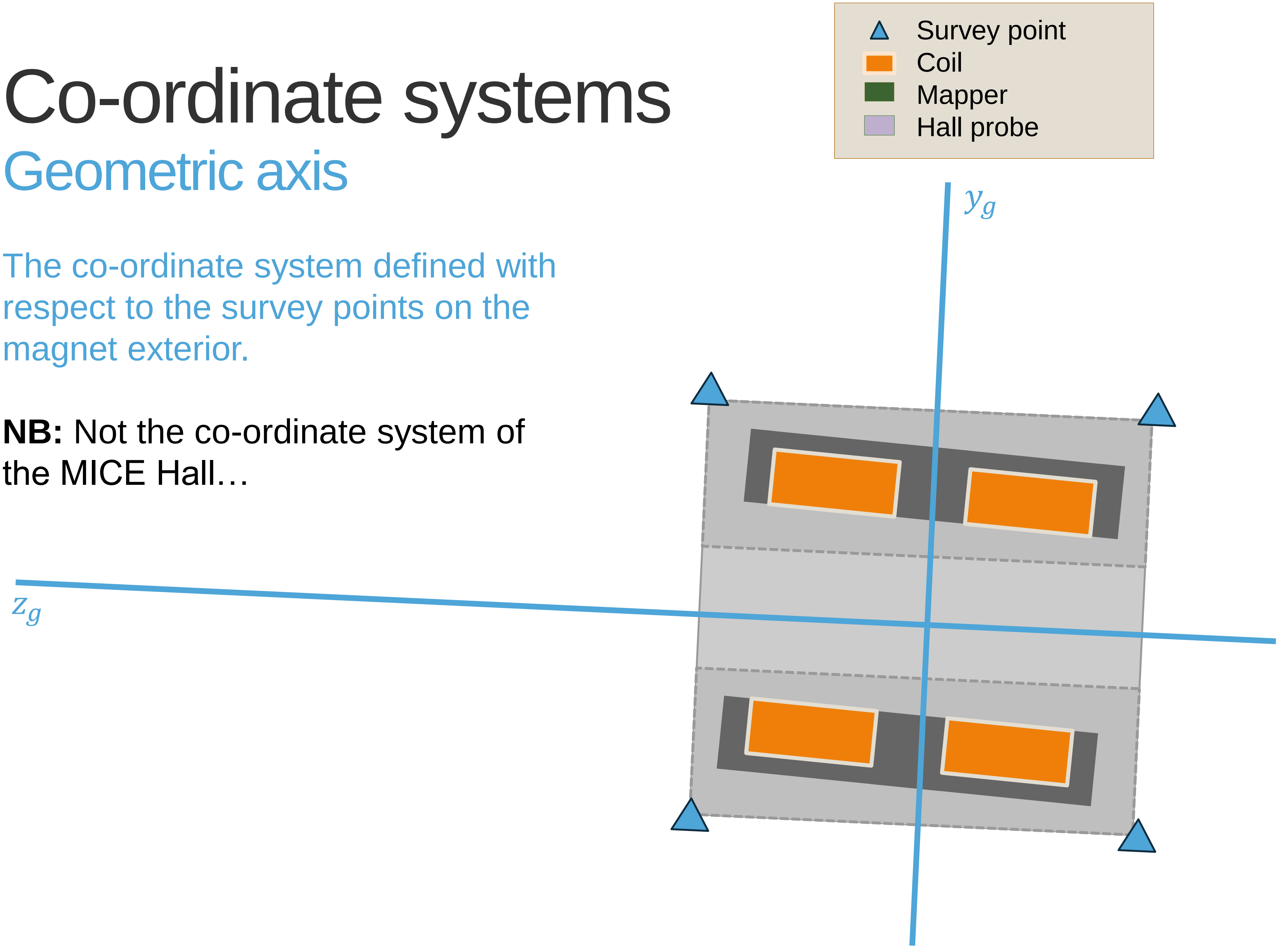


Co-ordinate systems

Geometric axis

The co-ordinate system defined with respect to the survey points on the magnet exterior.

NB: Not the co-ordinate system of the MICE Hall…

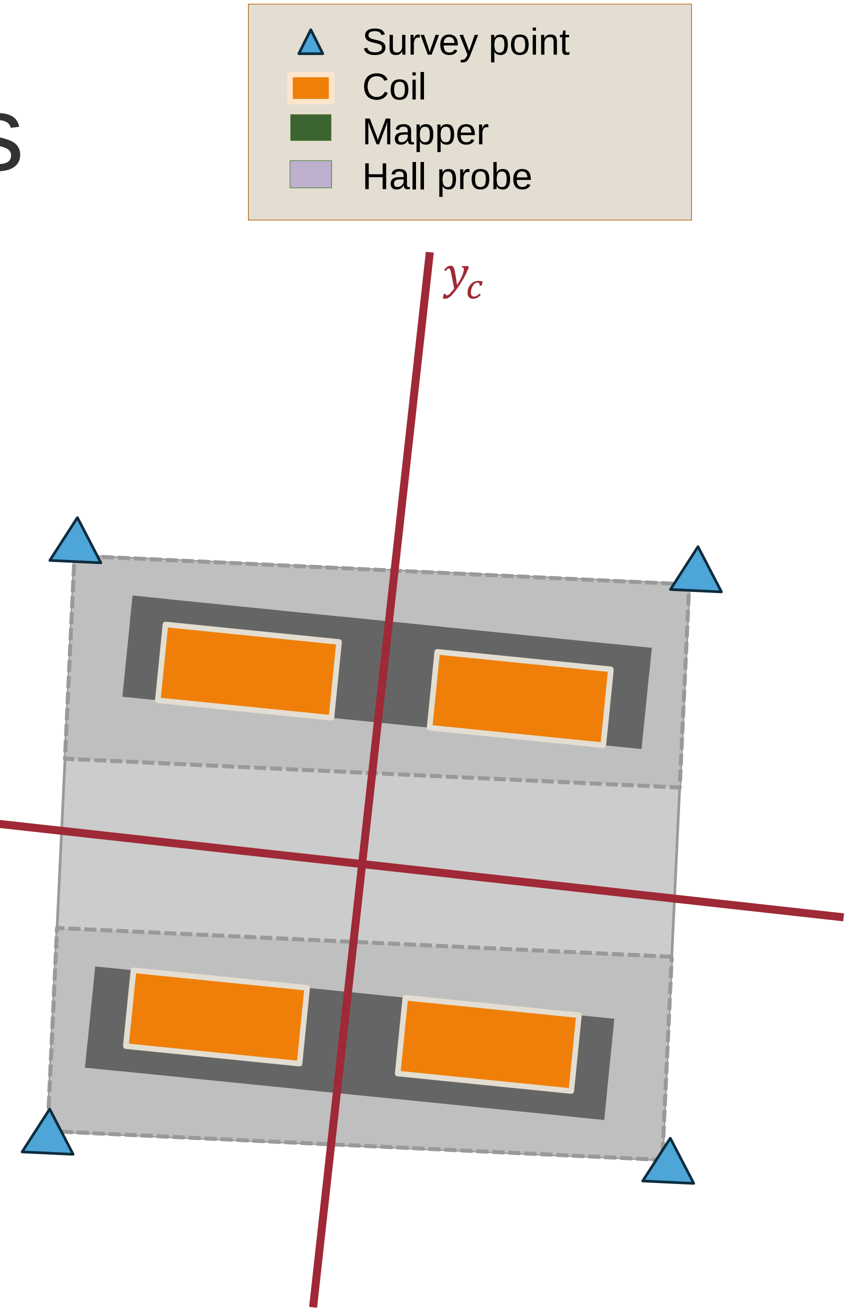


Co-ordinate systems

Magnetic axis

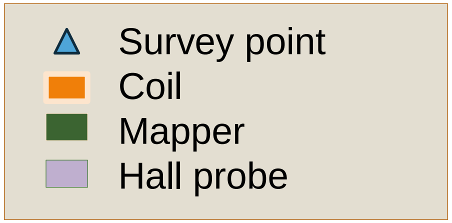
The co-ordinate system defined with respect to the coils on the magnet bobbin.

Also the line along which $B_x = B_y = 0$.

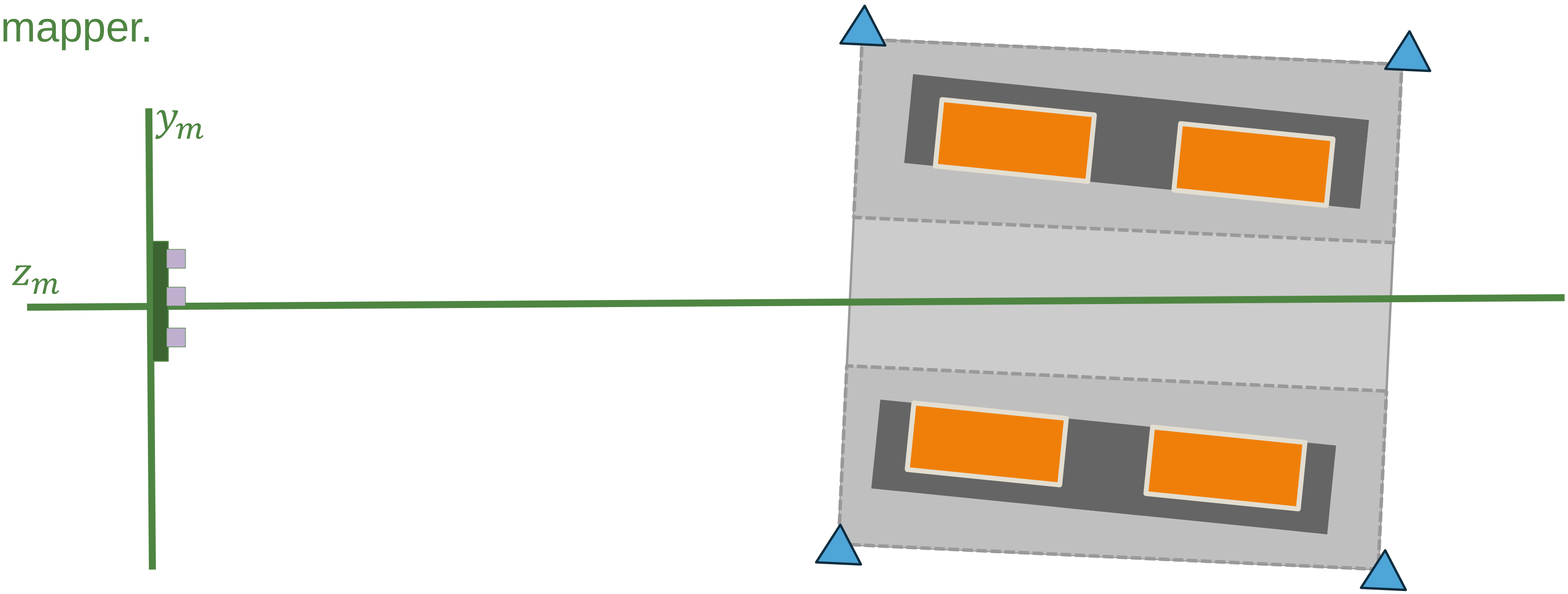


Co-ordinate systems

Mapper axis

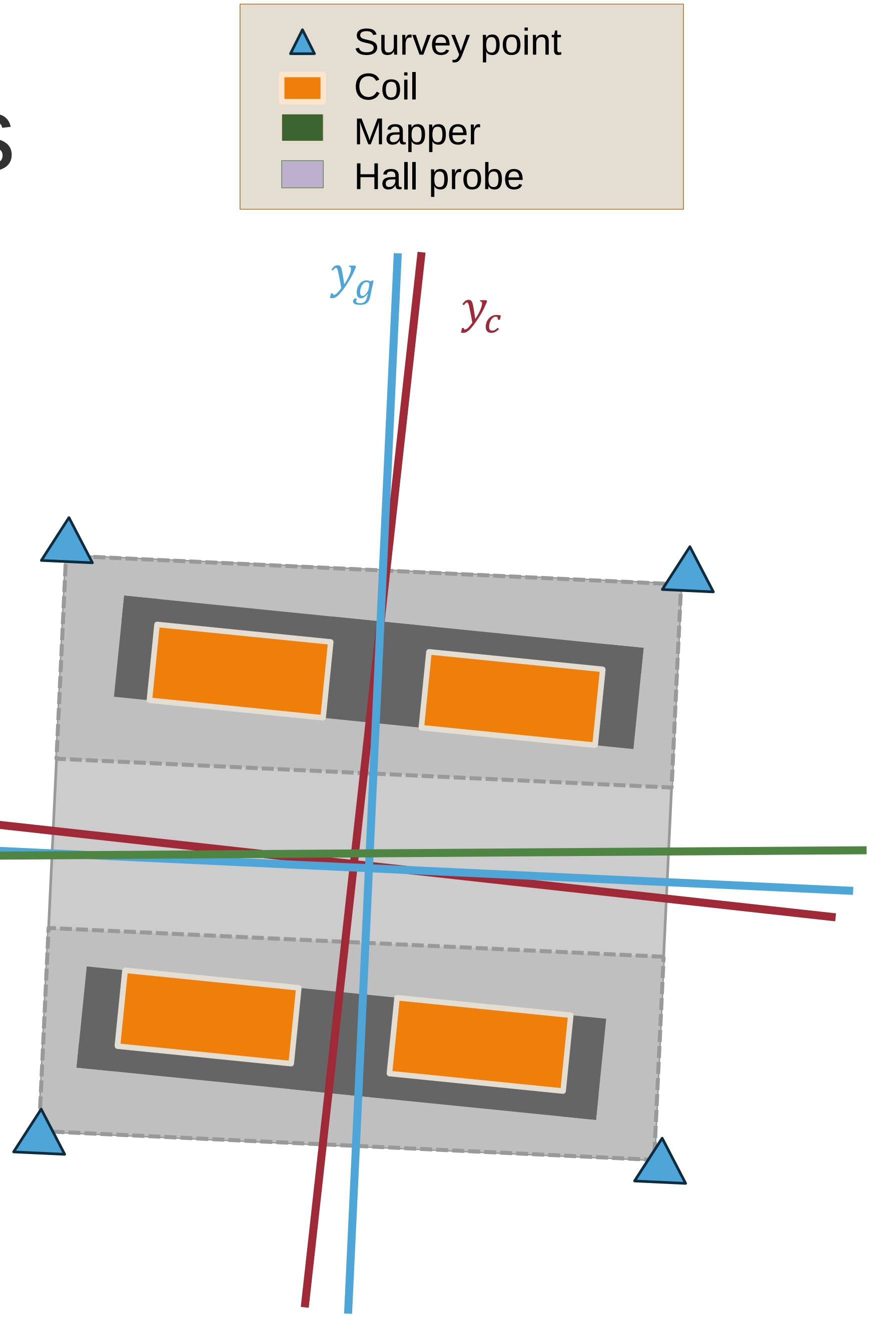


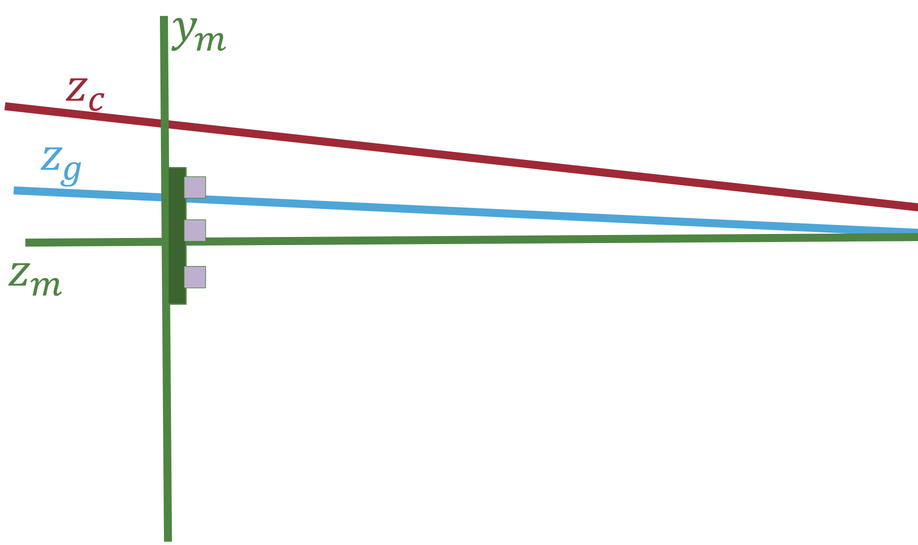
The co-ordinate system defined with respect to the centre of the measurement disc on the CERN field mapper.



Co-ordinate systems

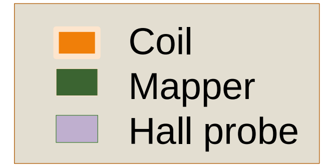
- Measure the magnetic axis with the mapper
- Transform from mapper to geometric co-ordinates





Sounds easy!

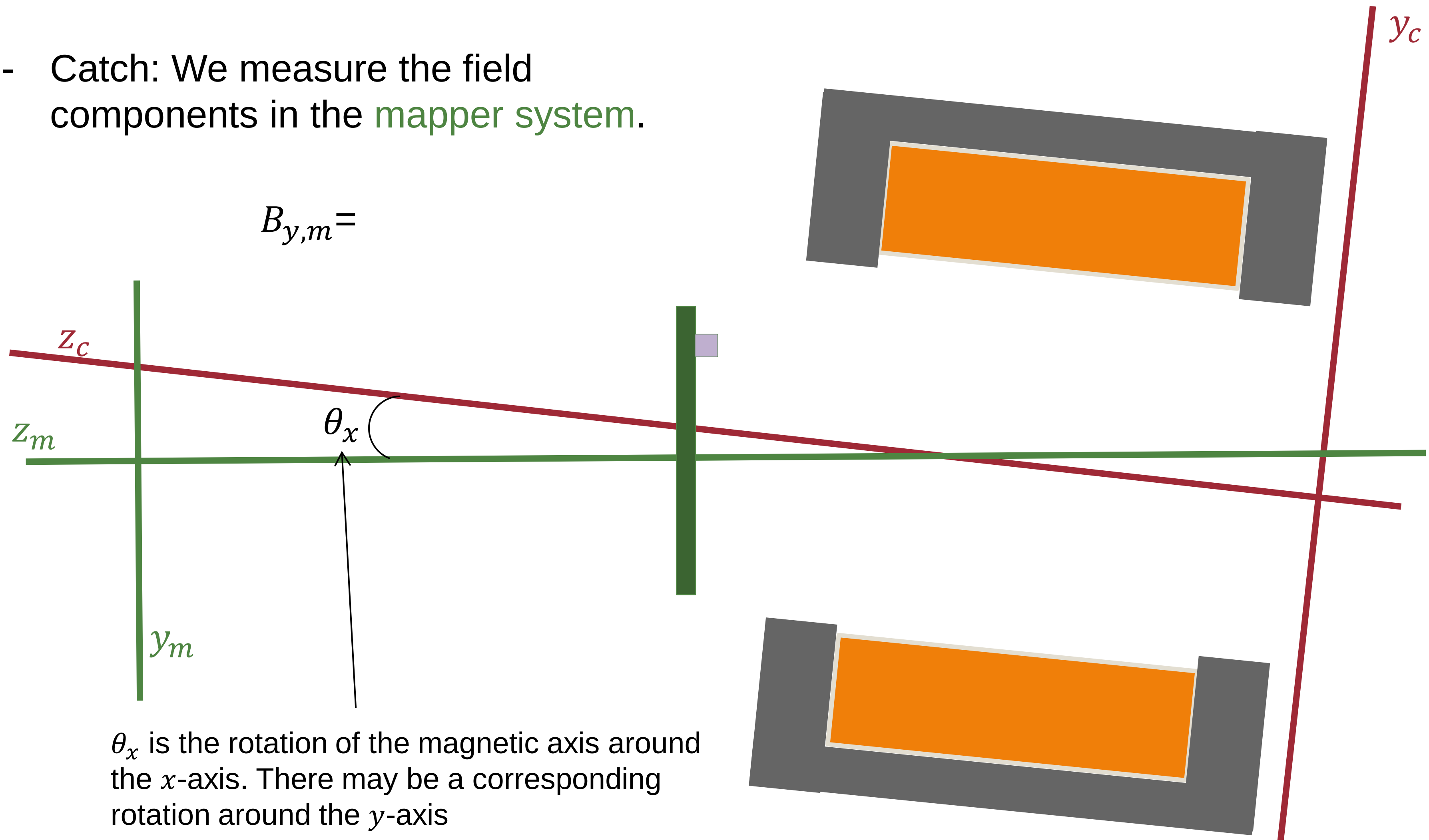
… right?



Co-ordinate systems

- Catch: We measure the field components in the mapper system.

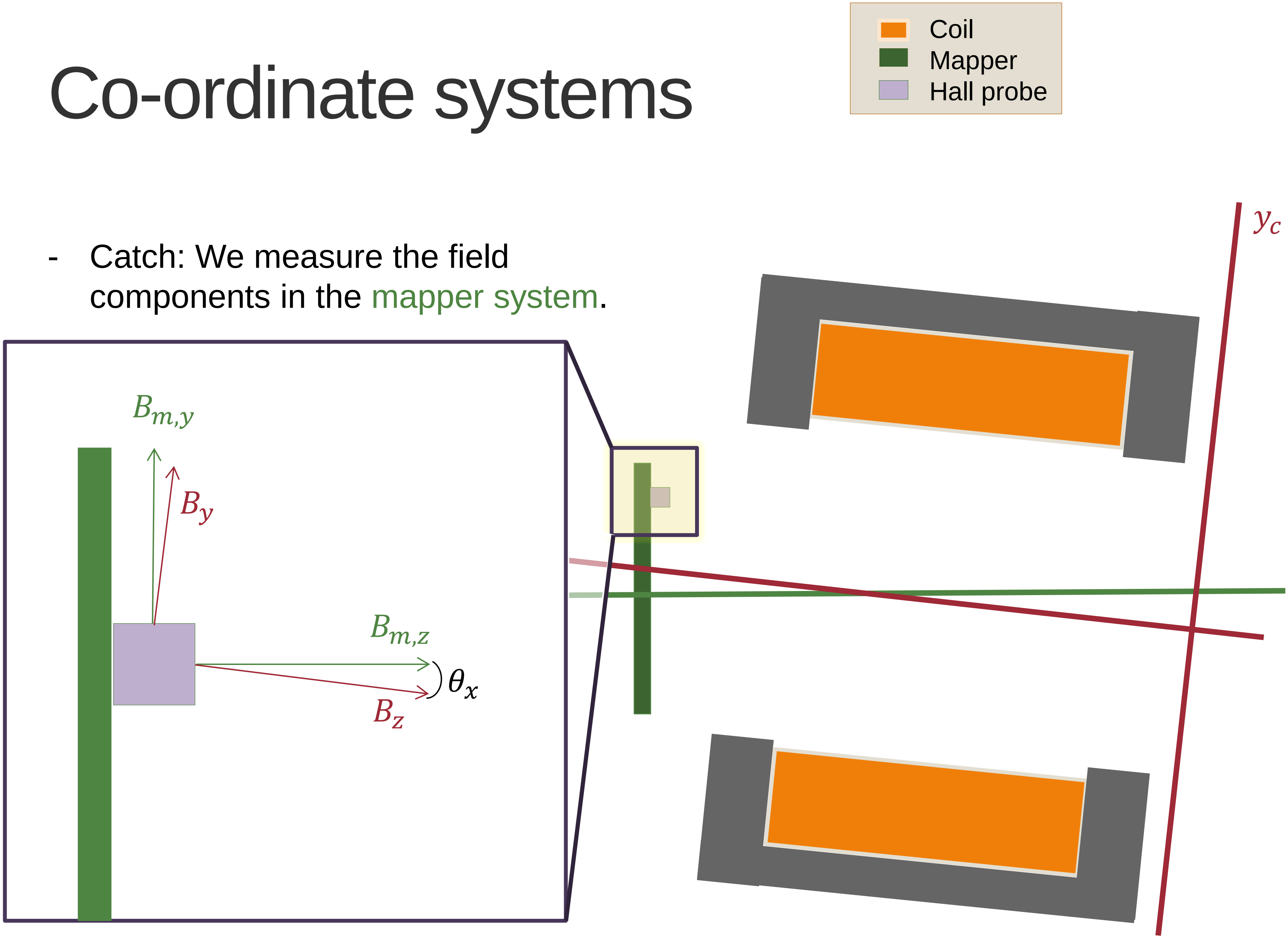
$B_{y,m}$=



θ_x is the rotation of the magnetic axis around the x-axis. There may be a corresponding rotation around the y-axis

Co-ordinate systems

- Catch: We measure the field components in the mapper system.



Test field maps*

1. Define a measurement grid in the mapper system: (x_m, y_m, z_m).
2. Transform measurement grid to coil system:

$$\begin{pmatrix} x_c \\ y_c \\ z_c \end{pmatrix} = R_z R_y R_x \begin{pmatrix} x_m \\ y_m \\ z_m \end{pmatrix}$$

3. Calculate field in coil system: $(B_{x,c}, B_{y,c}, B_{z,c})$
4. Transform fields back to mapper system:

$$\begin{pmatrix} B_{x,m} \\ B_{y,m} \\ B_{z,m} \end{pmatrix} = (R_z R_y R_x)^T \begin{pmatrix} B_{x,c} \\ B_{y,c} \\ B_{z,c} \end{pmatrix}$$

5. Now have 'measurements' of a tilted coil (or coils) in mapper system.

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x \\ 0 & \sin\theta_x & \cos\theta_x \end{pmatrix}$$

$$R_{xT} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & \sin\theta_x \\ 0 & -\sin\theta_x & \cos\theta_x \end{pmatrix}$$

$$R_y = \begin{pmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{pmatrix}$$

$$R_{yT} = \begin{pmatrix} \cos\theta_y & 0 & -\sin\theta_y \\ 0 & 1 & 0 \\ \sin\theta_y & 0 & \cos\theta_y \end{pmatrix}$$

$$R_z = \begin{pmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$R_{zT} = \begin{pmatrix} \cos\theta_z & \sin\theta_z & 0 \\ -\sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

** Here just look at rotations, offset in (x, y, z) would be a constant shift.*

Test field maps

$$
\begin{aligned}
B_{x,m} &= B_{x,c}\cos\theta_y - B_{z,c}\sin\theta_y \\
B_{y,m} &= B_{x,c}\sin\theta_x\sin\theta_y + B_{y,c}\cos\theta_x + B_{z,c}\sin\theta_x\cos\theta_y \\
B_{z,m} &= B_{x,c}\sin\theta_x\sin\theta_y - B_{y,c}\sin\theta_x + B_{z,c}\cos\theta_x\cos\theta_y
\end{aligned}
$$

To first approximation, at a particular z, $B_{x,c}$ should be linear with x and similarly for y,

$$B_{x,c} = m_x x_c + C$$

If we were offset from the axis, C would represent that offset. In the perfectly aligned magnet system, $C = 0$.

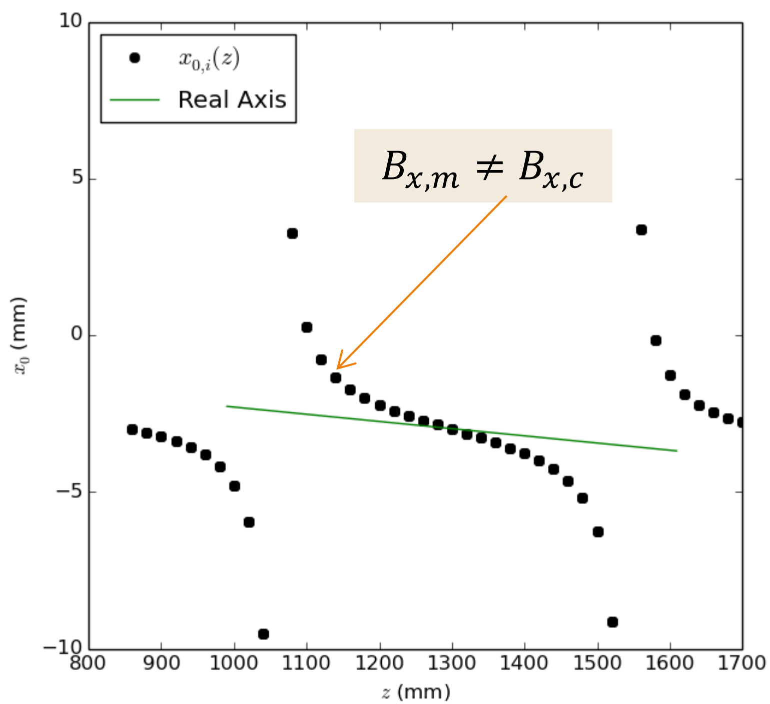
On the axis in the magnet system, $B_{x,c}(x_c = 0) = 0$. So in the mapper system, on the axis we would see,

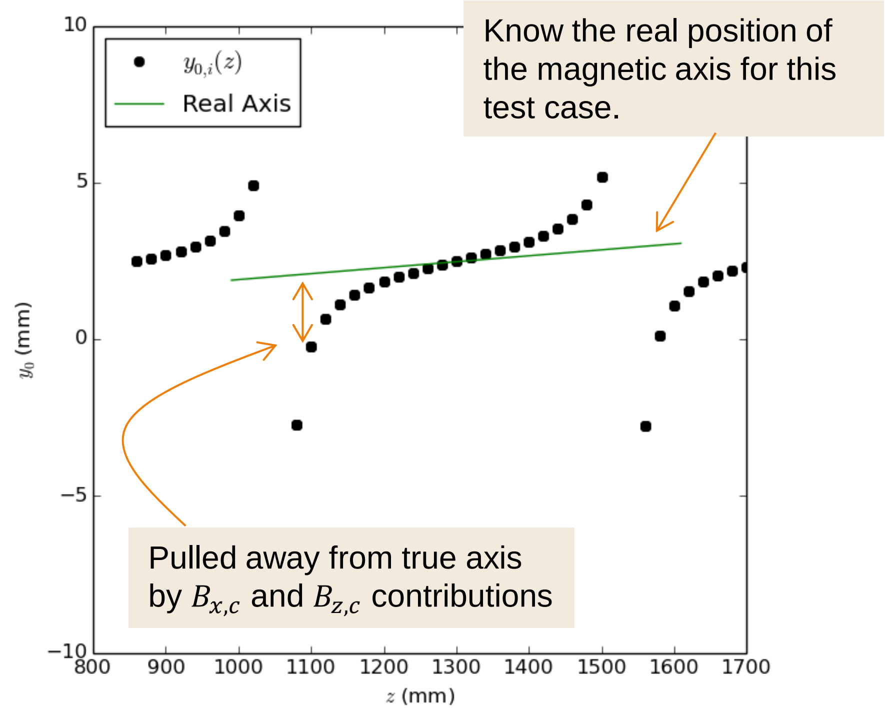
$$
\begin{aligned}
B_{x,m} &= -B_{z,c}\sin\theta_y \\
B_{y,m} &= B_{z,c}\sin\theta_x\cos\theta_y \\
B_{z,m} &= B_{z,c}\cos\theta_x\cos\theta_y
\end{aligned}
$$

Anyone who remembers this talk at CM40 might recognise this “feature”!

Test Magnet: “FC-like”

- Assume that there is no rotation and that the mapper and magnetic axes are aligned.
  - At each z, fit $B_{x,c} = m_x x_c + C$
  - Then $x_{0,m} = -\frac{C}{m_x}$ is the position of the axis at that z. (Similar for y)





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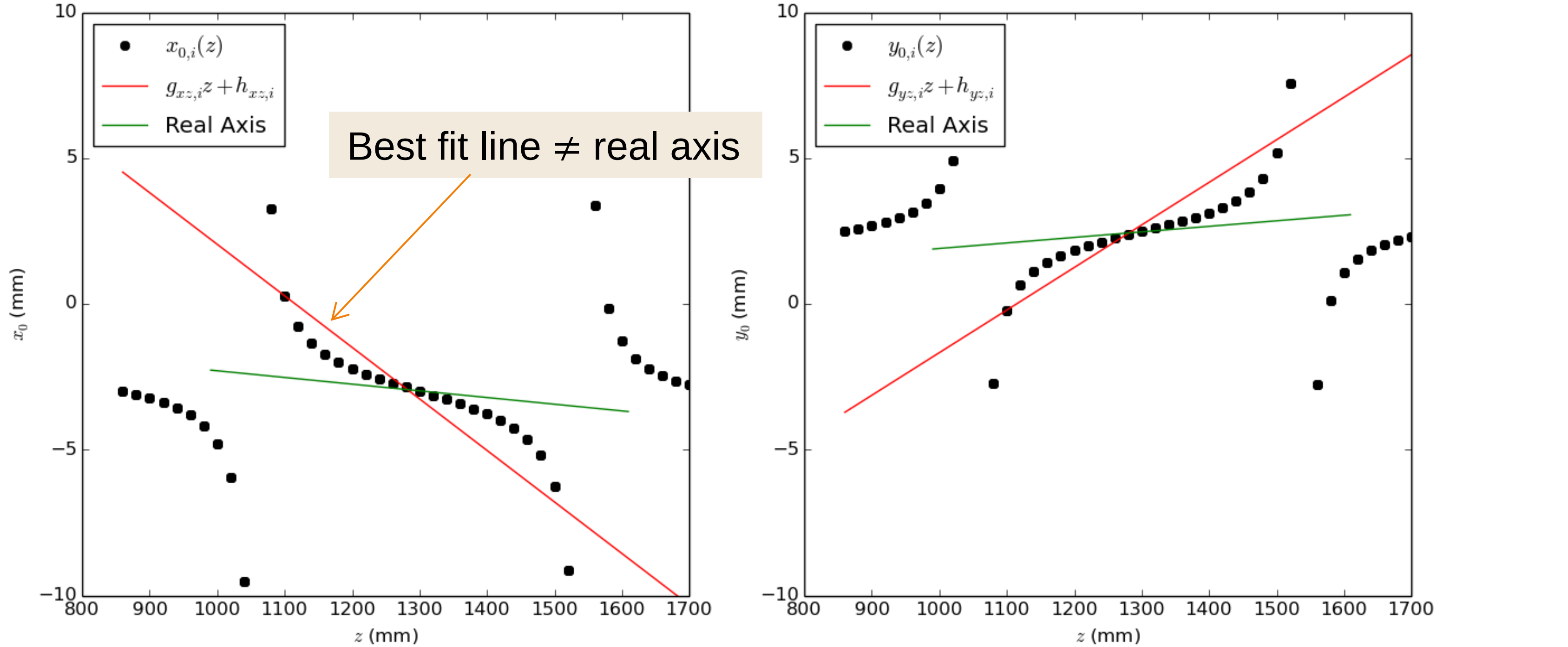


Test Magnet: “FC-like”

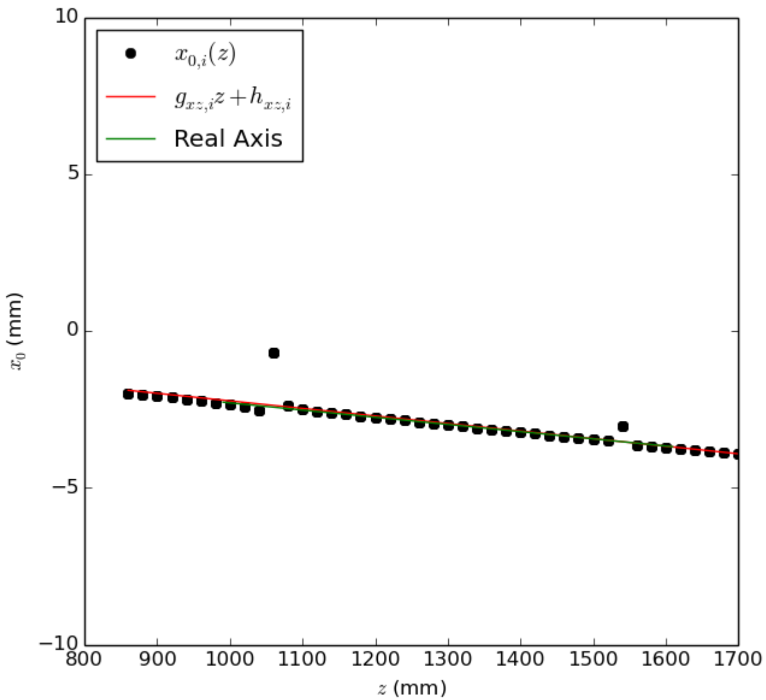
NB: This slide blatantly cheats at the fit to prove a point. We need to *find* θ_x and θ_x still!

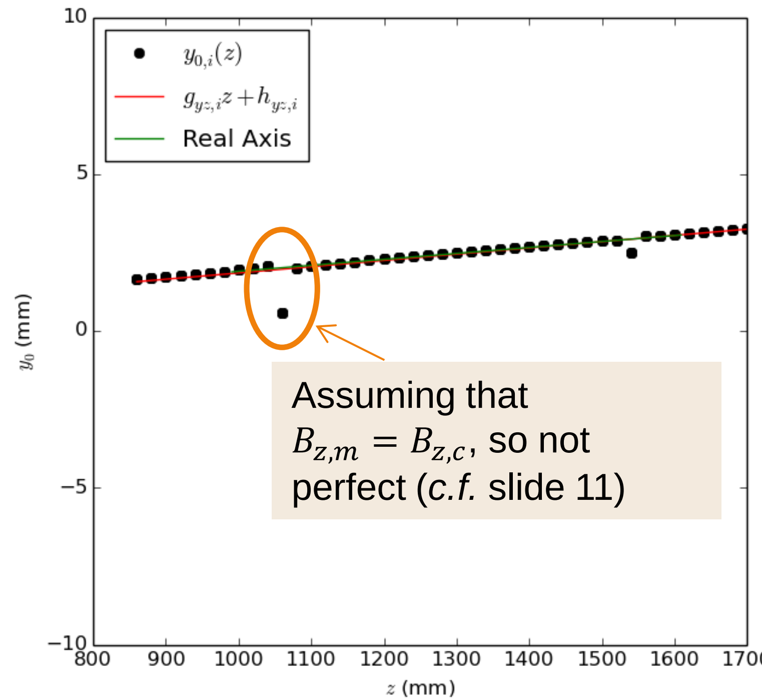
- B_z is large, so axis tilts gain a non-negligible contribution

$$B_{x,m} = B_{x,c}\cos\theta_y - B_{z,c}\sin\theta_y = (m_x + C)\cos\theta_y - B_{z,c}\sin\theta_y$$

Can't ignore this

- Fit again, but with *true* θ_x and θ_y:



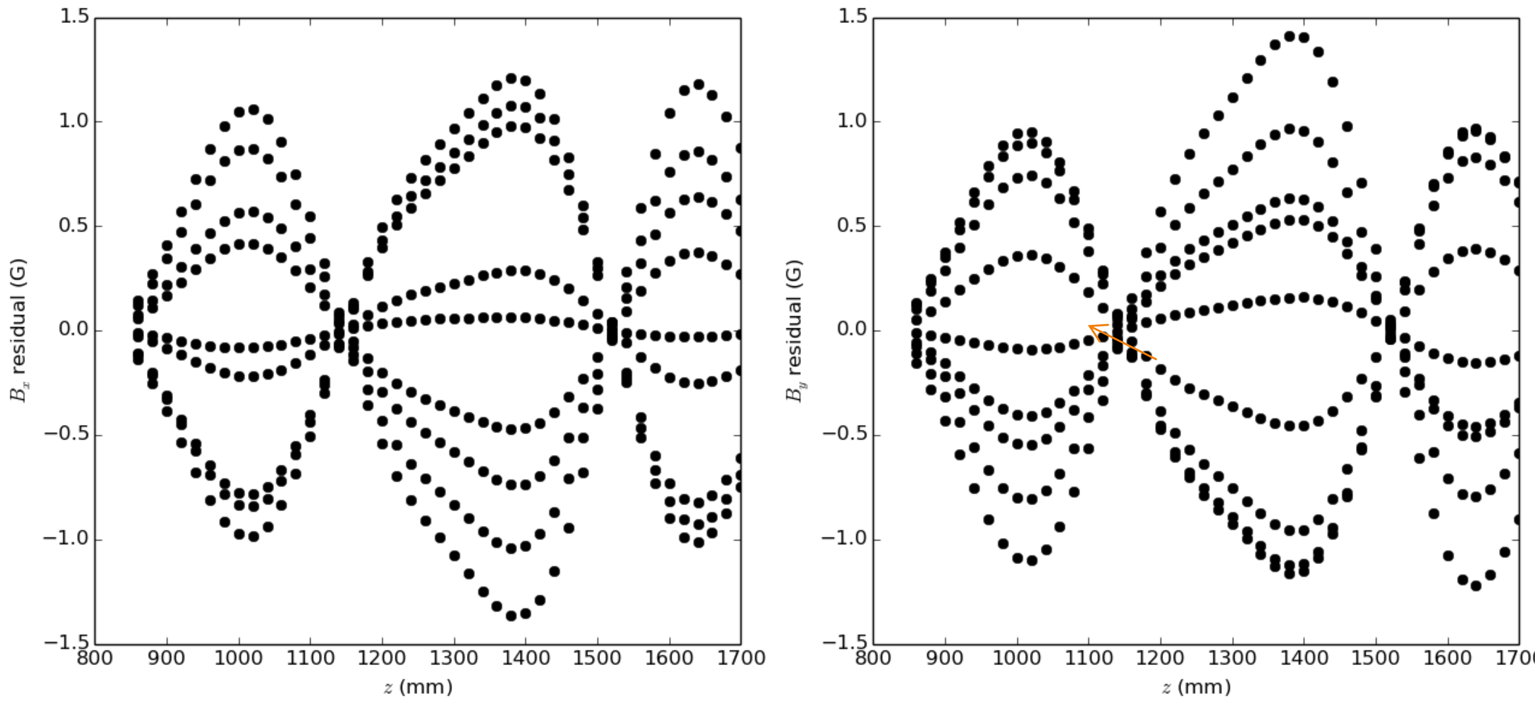


Assuming that $B_{z,m} = B_{z,c}$, so not perfect (*c.f.* slide 11)

NB: This slide blatantly cheats at the fit to prove a point. We need to *find* θ_x and θ_x still!

Test Magnet: "FC-like"

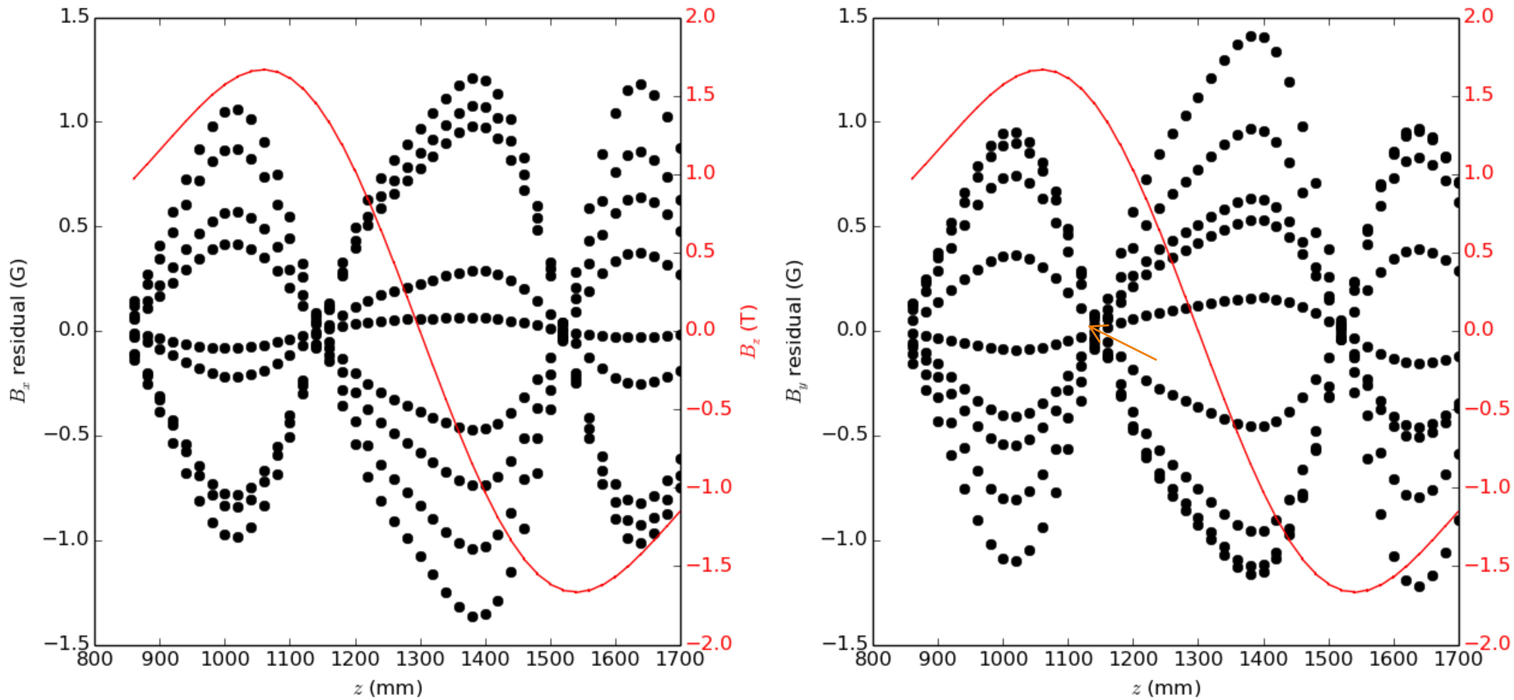
- Using fitted values of $m_x, C, \theta_x, \theta_y$, estimate $\langle B_{x,m} \rangle$ (and similarly for y) and plot the residual
- Getting θ_x and θ_y perfectly, still limited by knowledge of $B_{z,c}$ at the level of 1G ($\sim$ error on Hall probe)



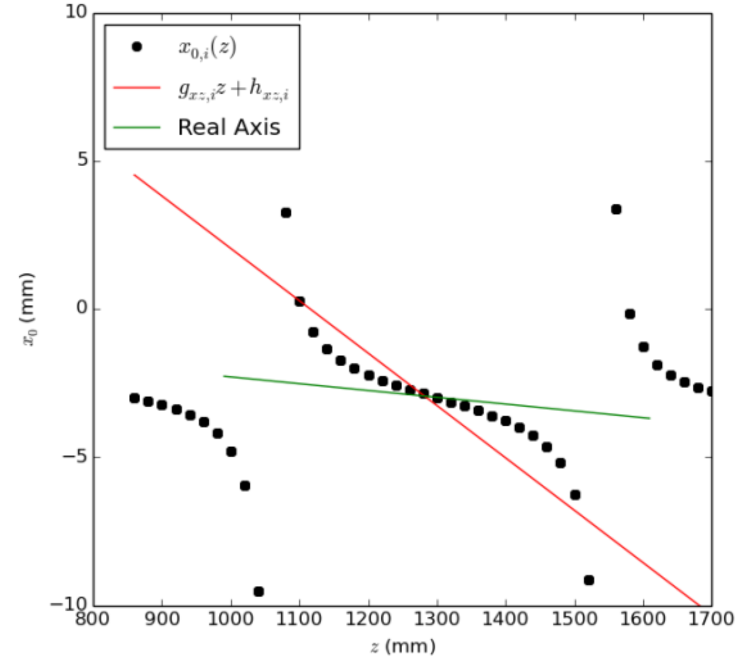
NB: This slide blatantly cheats at the fit to prove a point. We need to *find* θ_x and θ_x still!

Test Magnet: “FC-like”

- Using fitted values of $m_x, C, \theta_x, \theta_y$, estimate $\langle B_{x,m} \rangle$ (and similarly for y) and plot the residual
- Even if θ_x and θ_y are found perfectly, still limited by knowledge of $B_{z,c}$ at the level of 1G ($\sim$ error on Hall probe)



Test Magnet: “FC-like”



- Finding θ_x and θ_y:
  - x_0, y_0 calculated from $-\frac{C}{m_x}, -\frac{D}{m_y}$ (slide 13)
  - Excludes contributions from θ_x and θ_y
  - At the magnetic axis, we would measure,

$$B_{x,m}(x_o) = -\sin\theta_y \, B_{z,c}$$

$$B_{y,m}(y_o) = +\sin\theta_x \cos\theta_y \, B_{z,c}$$

  - Improve future iterations by calculating ϑ_x and ϑ_y using current ‘best fit’ line to x_0, y_0

$$\theta_x = \sum \vartheta_x \qquad \theta_y = \sum \vartheta_y$$

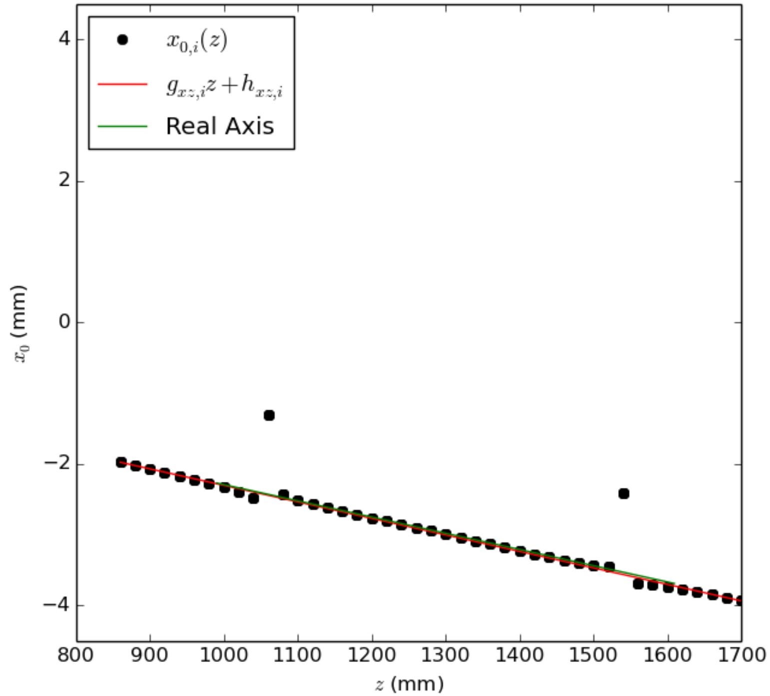
  - Then feed forward to next iteration (i.e. beginning at slide 14…)

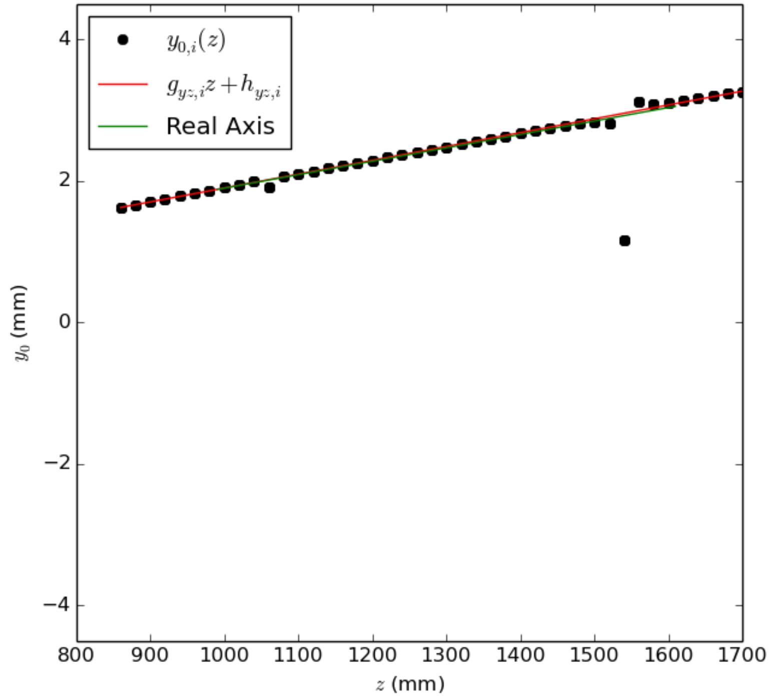
$$B_{x,m} = (m_x + C)\cos\sum\vartheta_y - B_{z,c}\sin\sum\vartheta_y$$

Test Magnet: “FC-like”

No cheating this time – attempt to retrieve θ_x and θ_y

$x_0(z) = -0.00233z - 2.972 \times 10^{-5}$	$\theta_x = 0.1106°$	$\theta_{x,true} = 0.1088°$
$y_0(z) = 0.00196z - 5.815 \times 10^{-5}$	$\theta_y = 0.1324°$	$\theta_{y,true} = 0.1316°$





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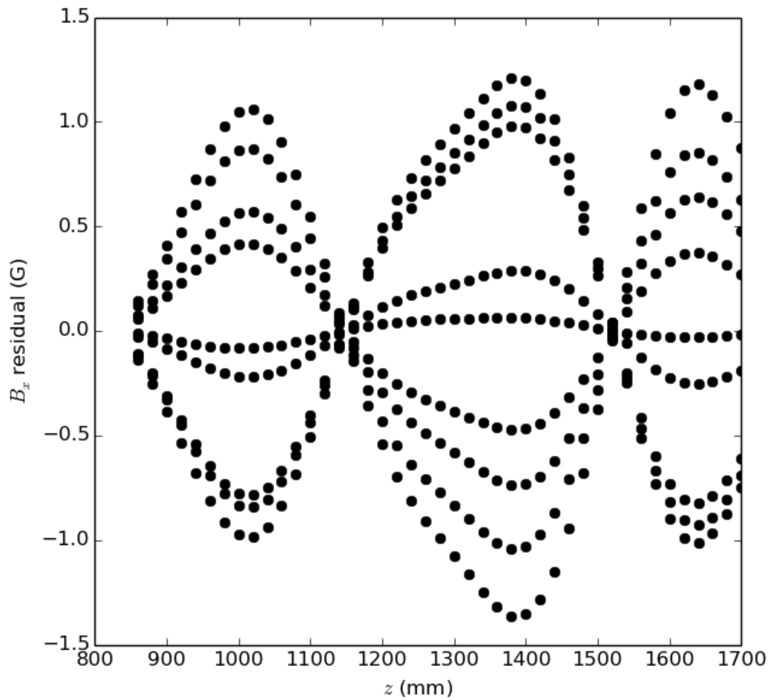
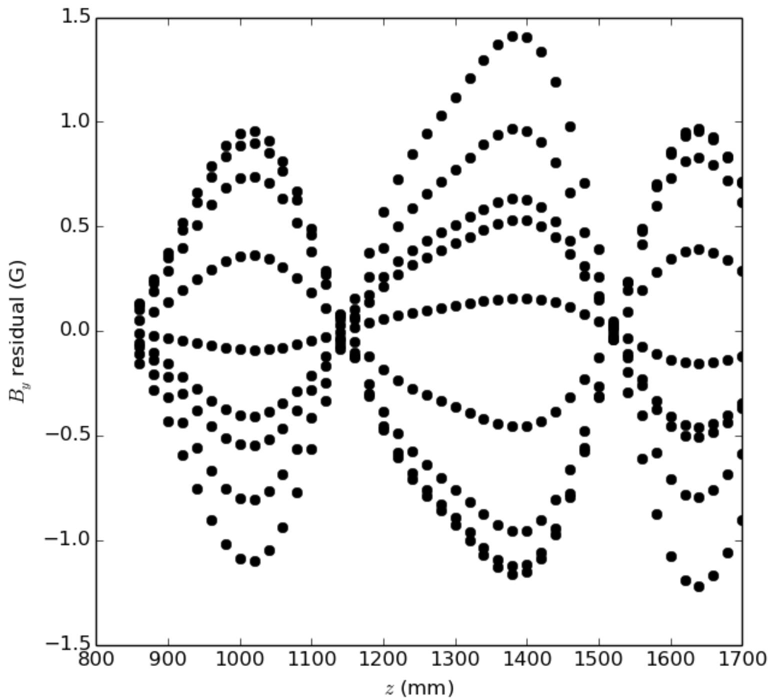




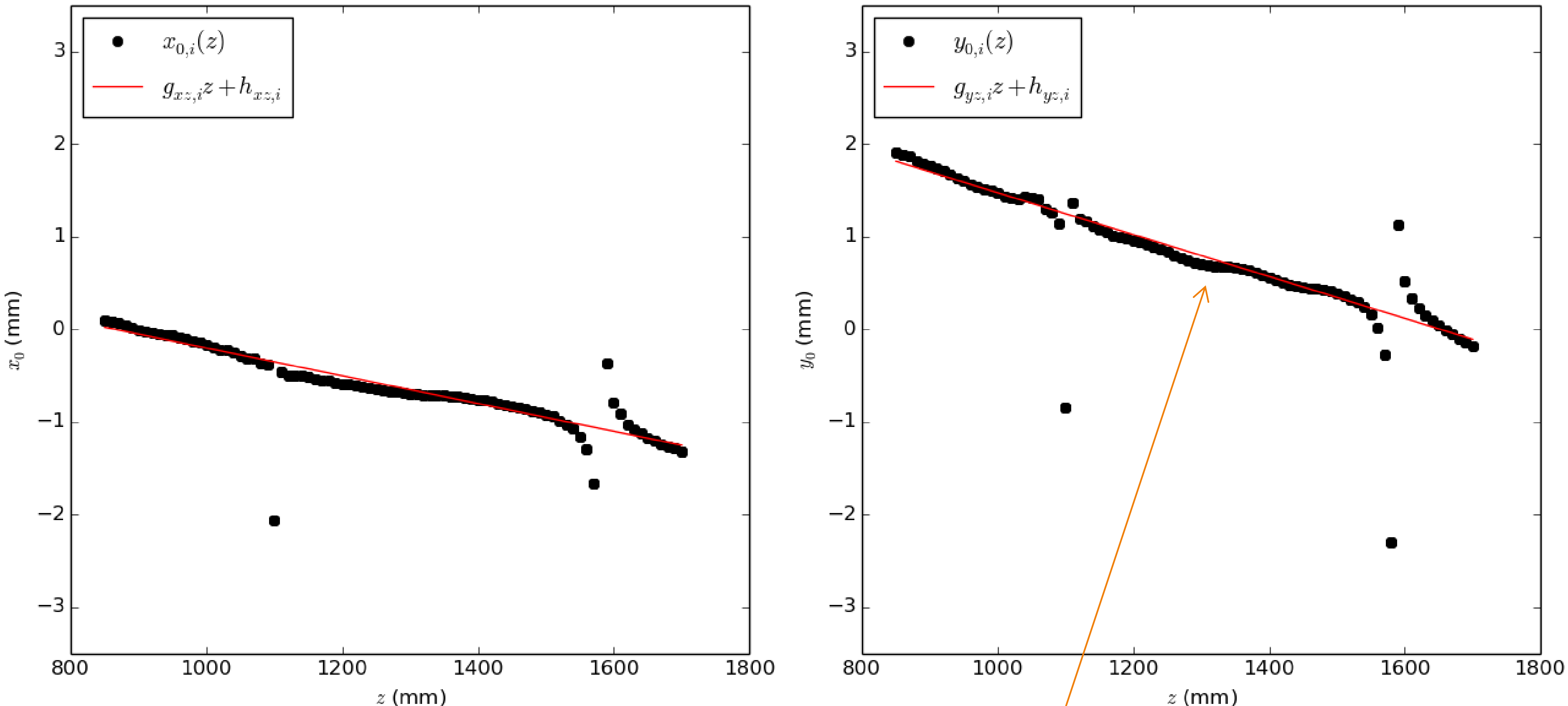
FC1

Finding the axis of FC1

- Run 3
- 100 A
- Flip mode

Try on FC1

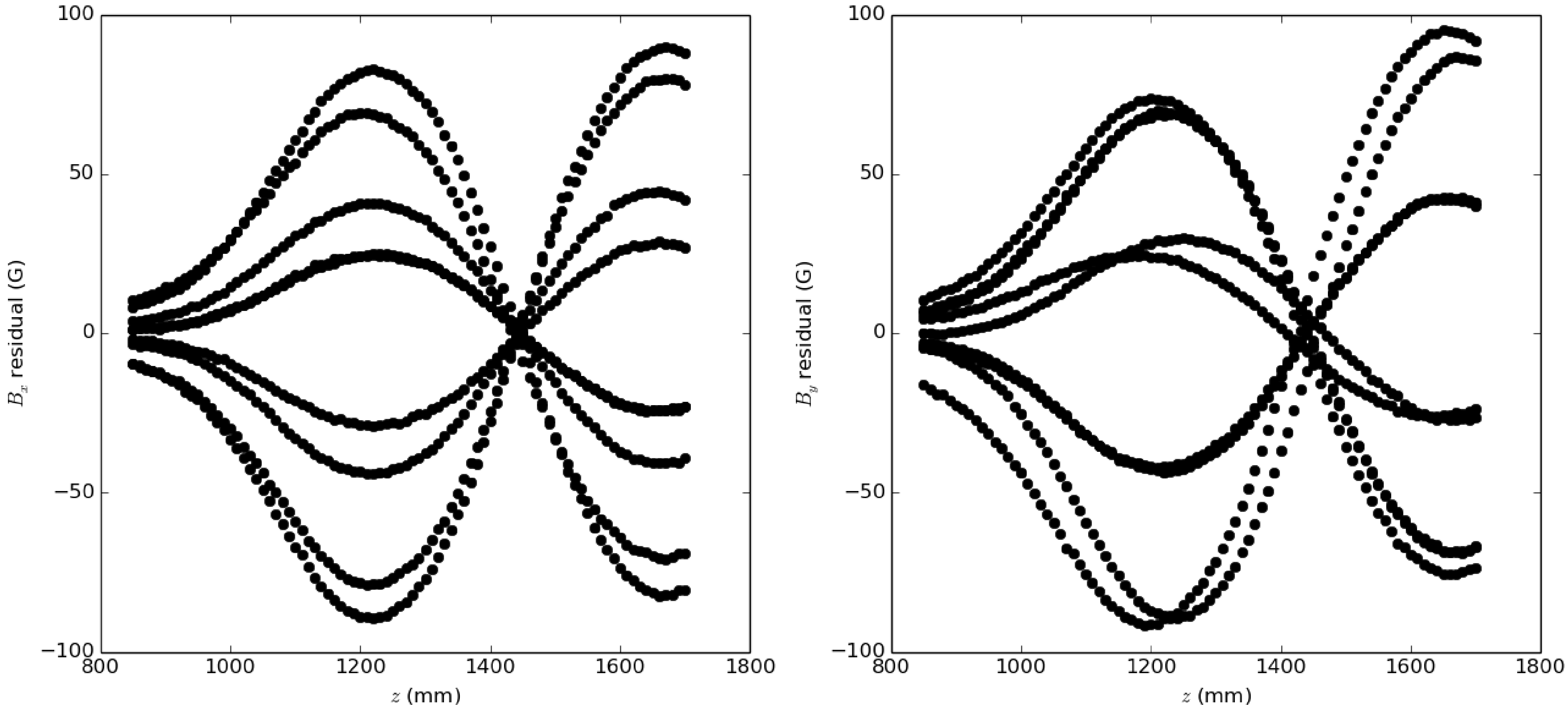
(Run 3, 100A, flip mode)



More 'wiggly' than model data

Try on FC1

(Run 3, 100A, flip mode)

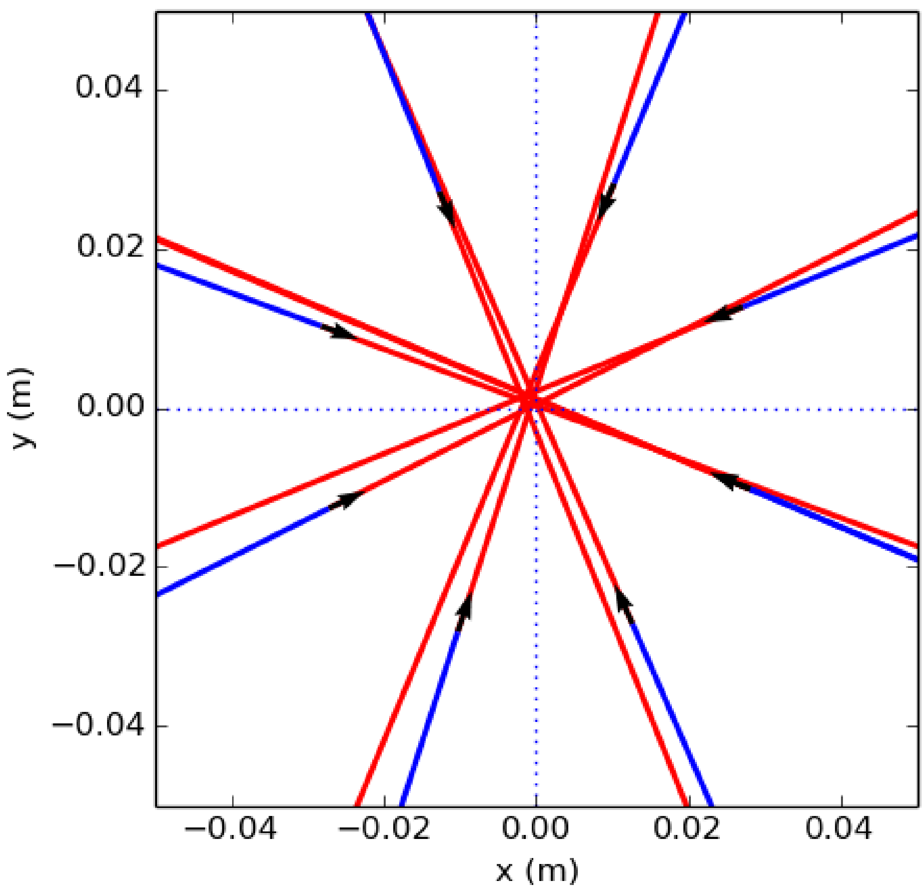


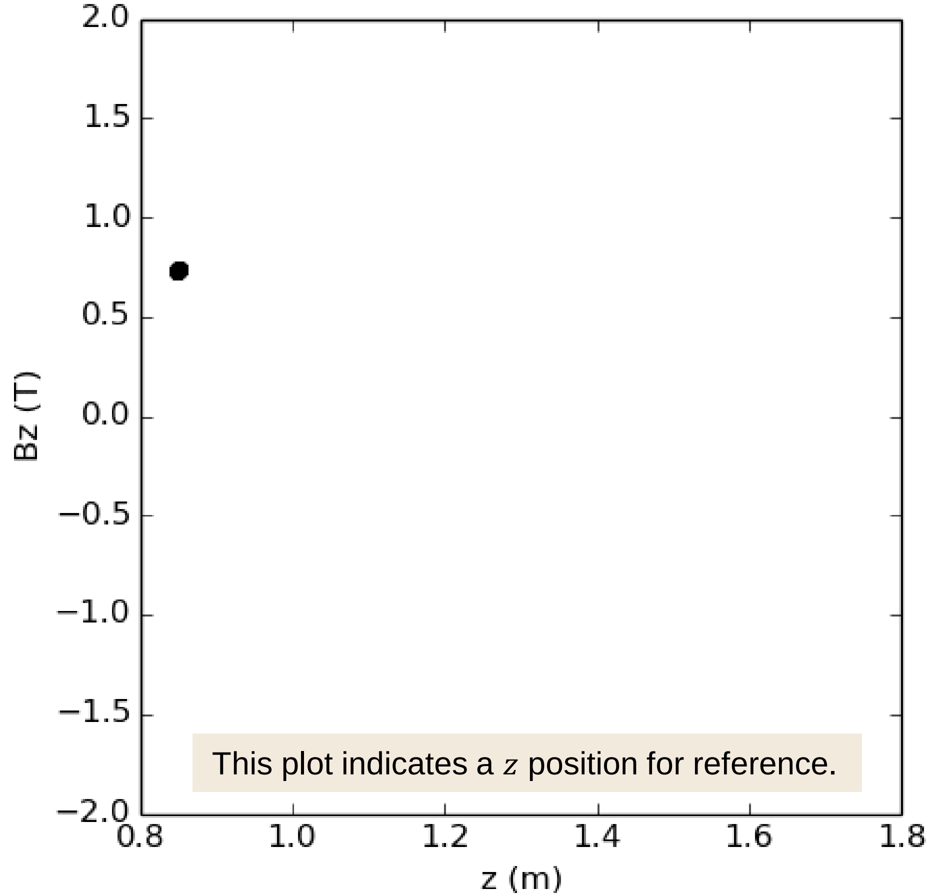
→ Residuals are <u>much</u> larger than expected – so what's going on…

Transverse vector field

- Field vector, $\overrightarrow{B_t} = (B_{x,m}, B_{y,m})$
- Points along vector (red)
- Points behind vector (blue)

A Maxwellian field's vectors should all point to the axis
→ some systematic effect (possibly additionally tilted probes)

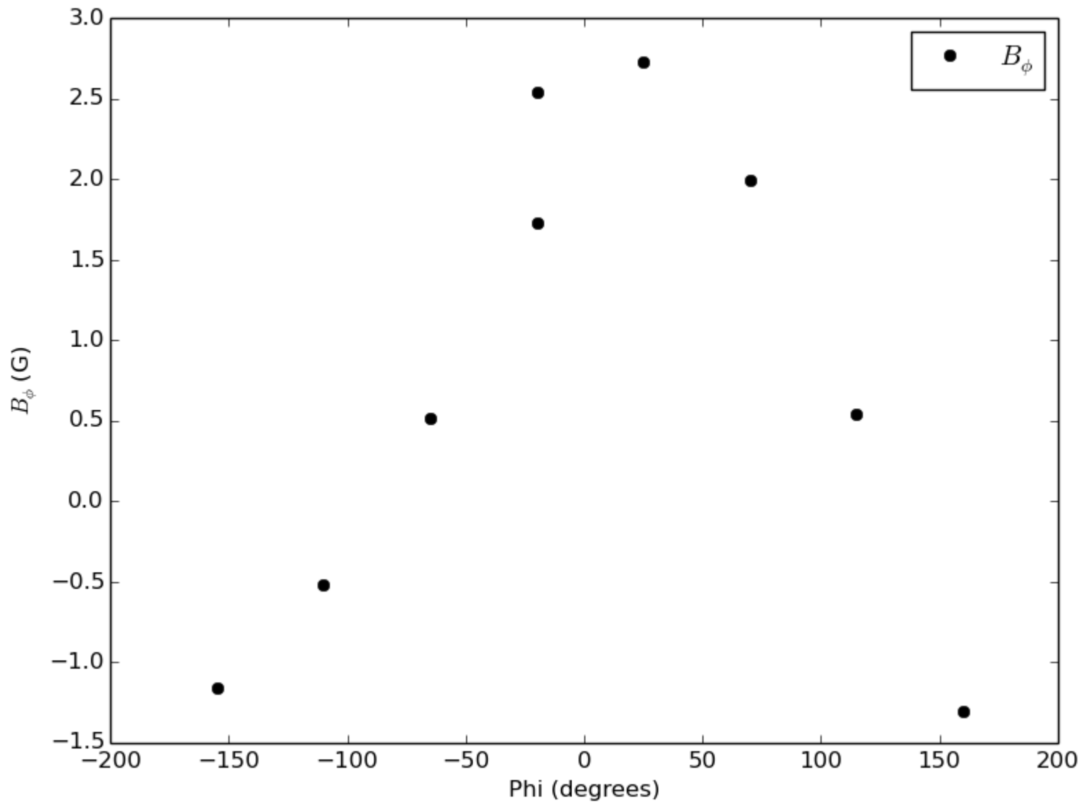




Correction?

At each z, look at $B_{\varphi,m}$. Should be 0 for all rotations of the mapper disc, but is not so.

Subtract the average $B_{\varphi,m}$ from each measurement…

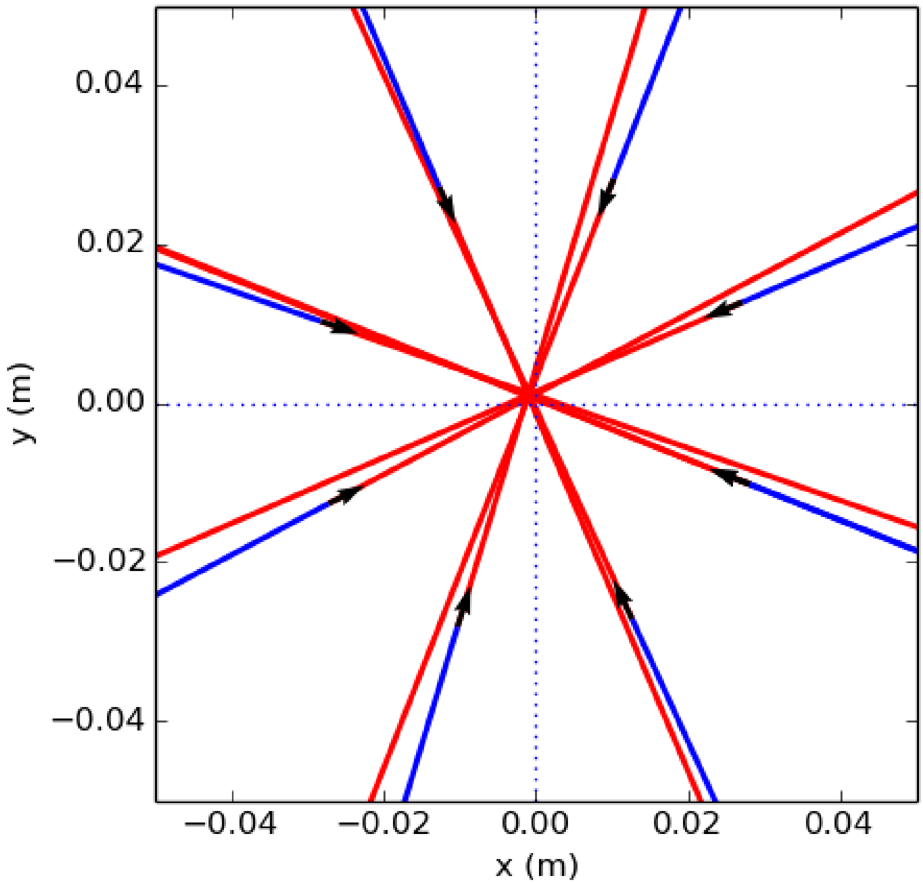


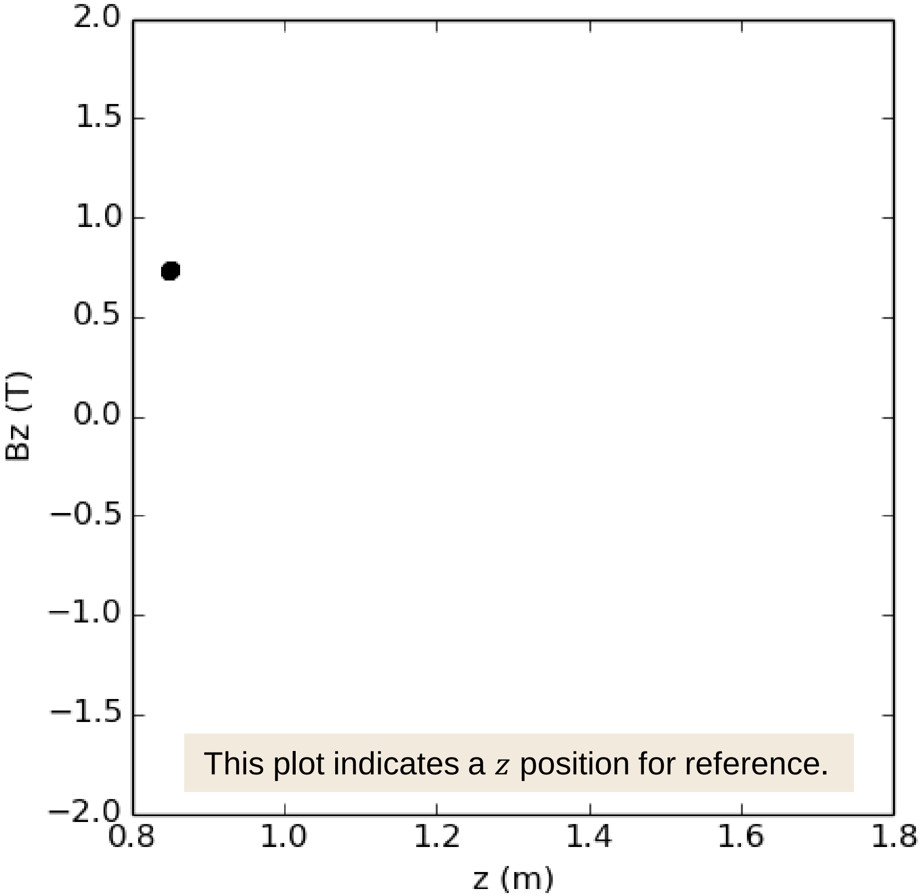
Transverse vector field

- Field vector, $\overrightarrow{B_t} = (B_{x,m}, B_{y,m})$
- Points along vector
- Points behind vector

Now vectors point towards "the axis".

But: Is a correction for $B_{r,m}$ needed?

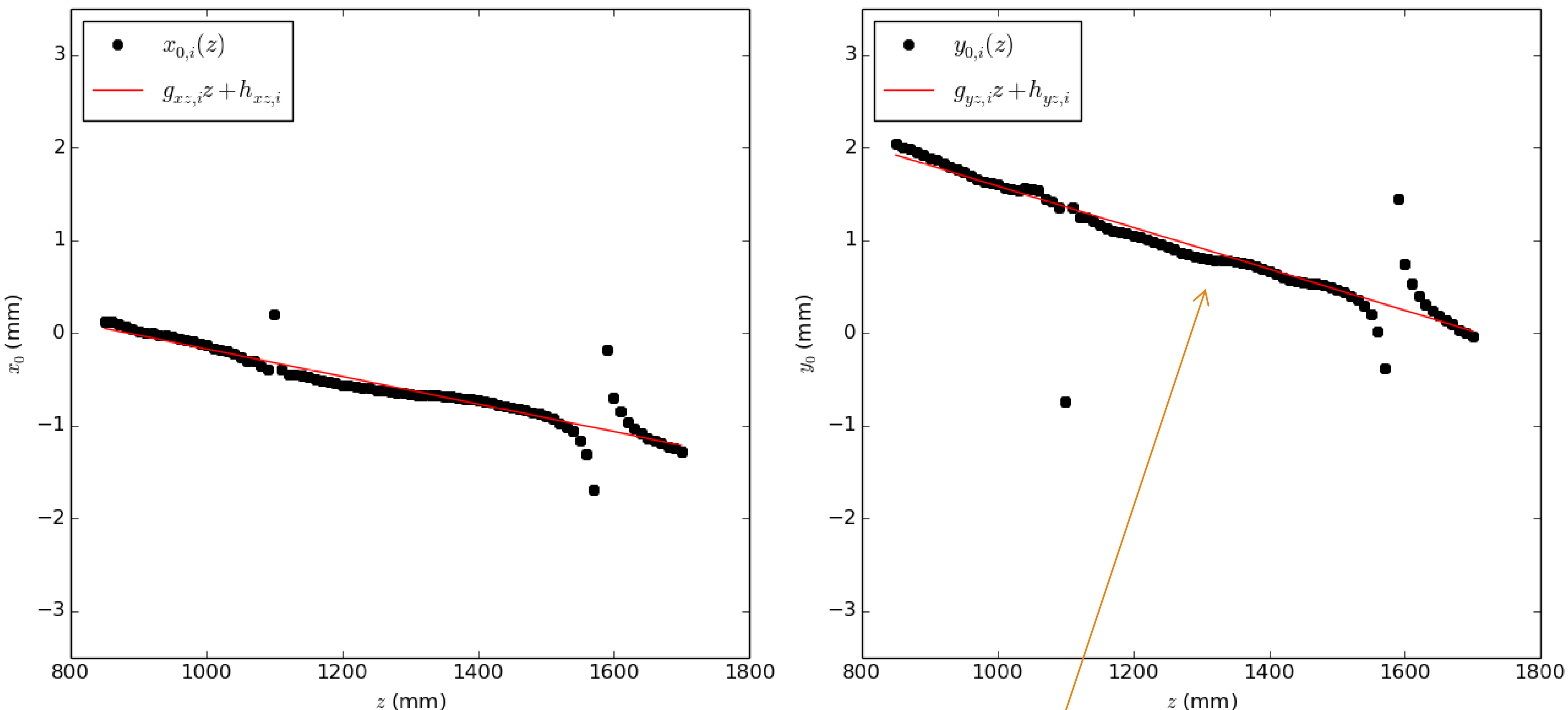




This plot indicates a z position for reference.

Try on FC1 (again)

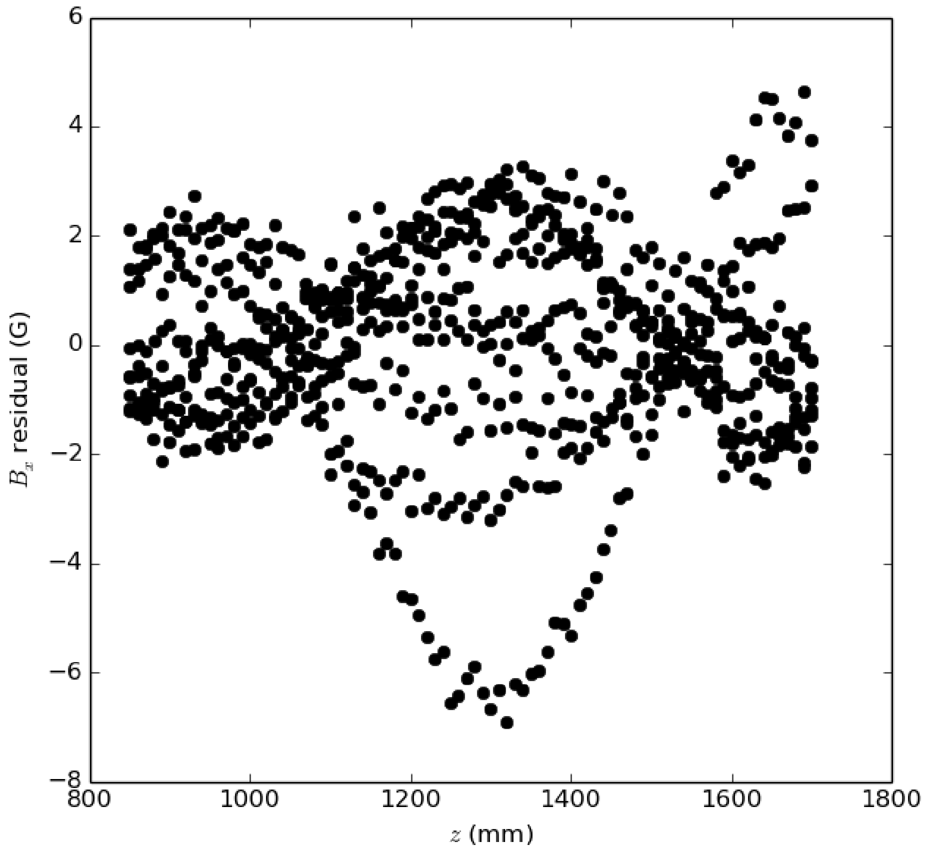
(Run 3, 100A, flip mode)

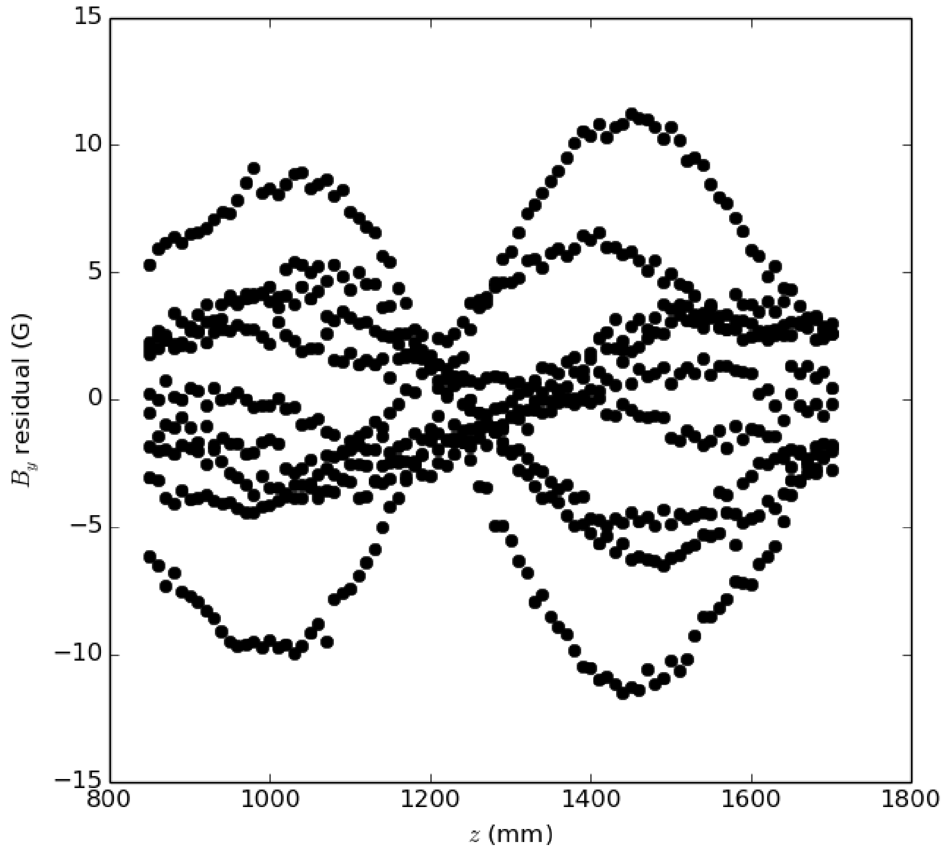


More ‘wiggly’ than model data

Try on FC1 (again)

(Run 3, 100A, flip mode)

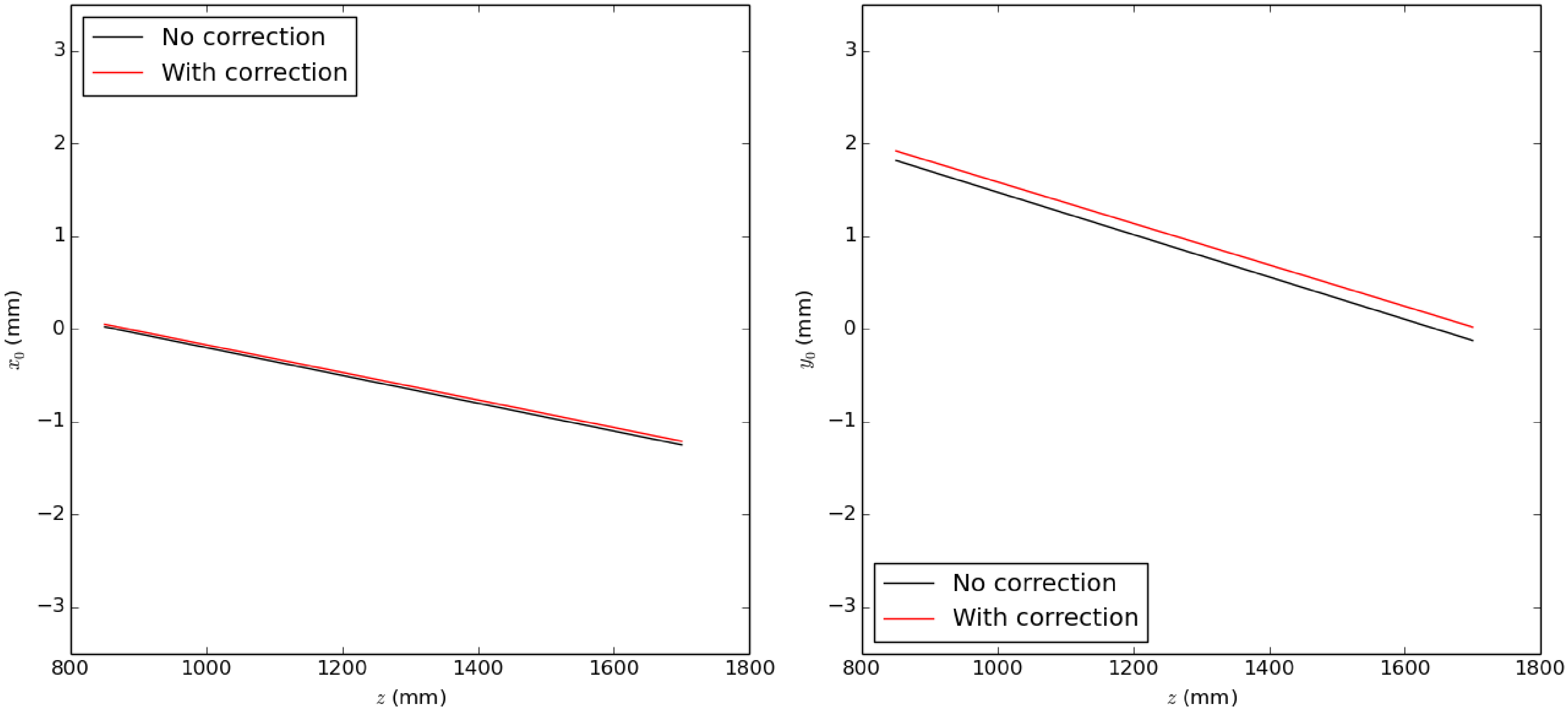




→ Better! Can compare axes with and without correction to get an idea of overall effect…

FC1

Correction had largest effect on y-axis result, but still small.



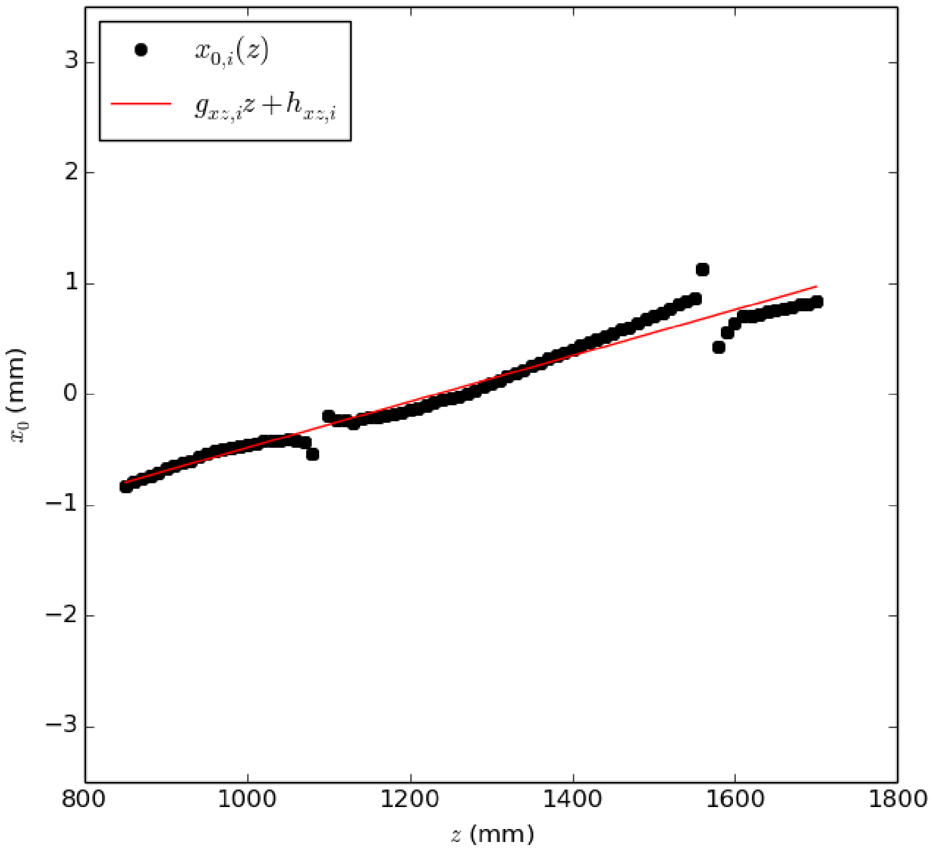
FC2

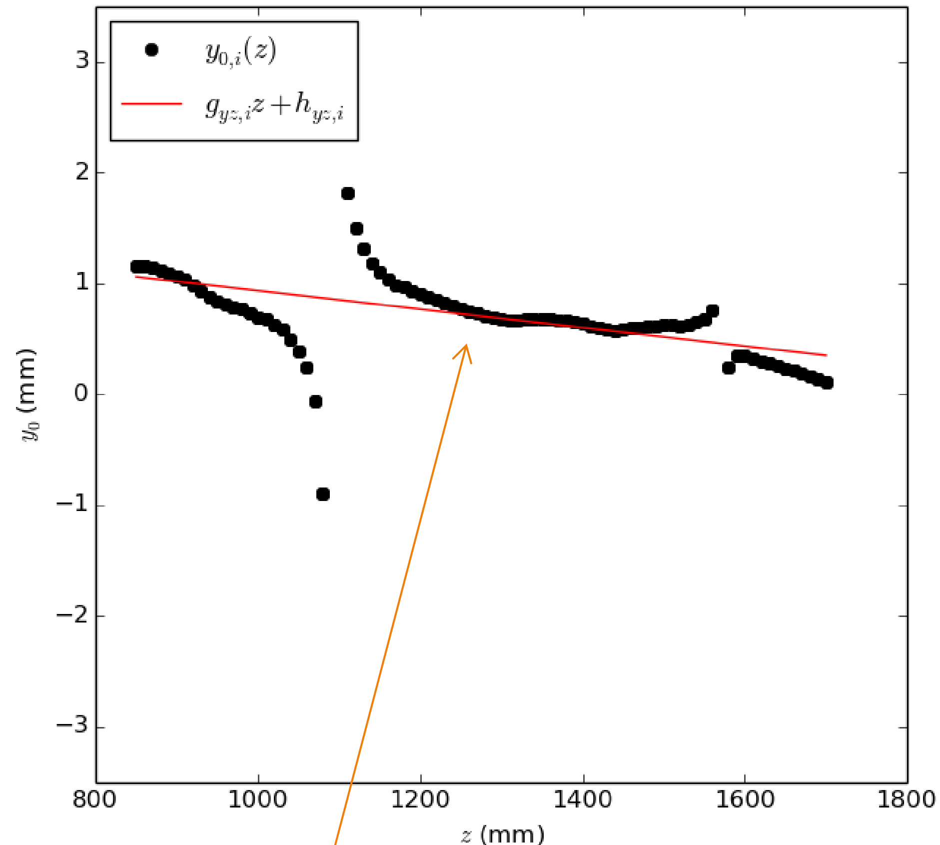
- “Run 3”
- 100 A
- Flip mode
- With $B_{\varphi,m}$ correction

Reminder: All lines are in the mapper co-ordinate system.

FC2

(Run 3, 100A, flip mode)

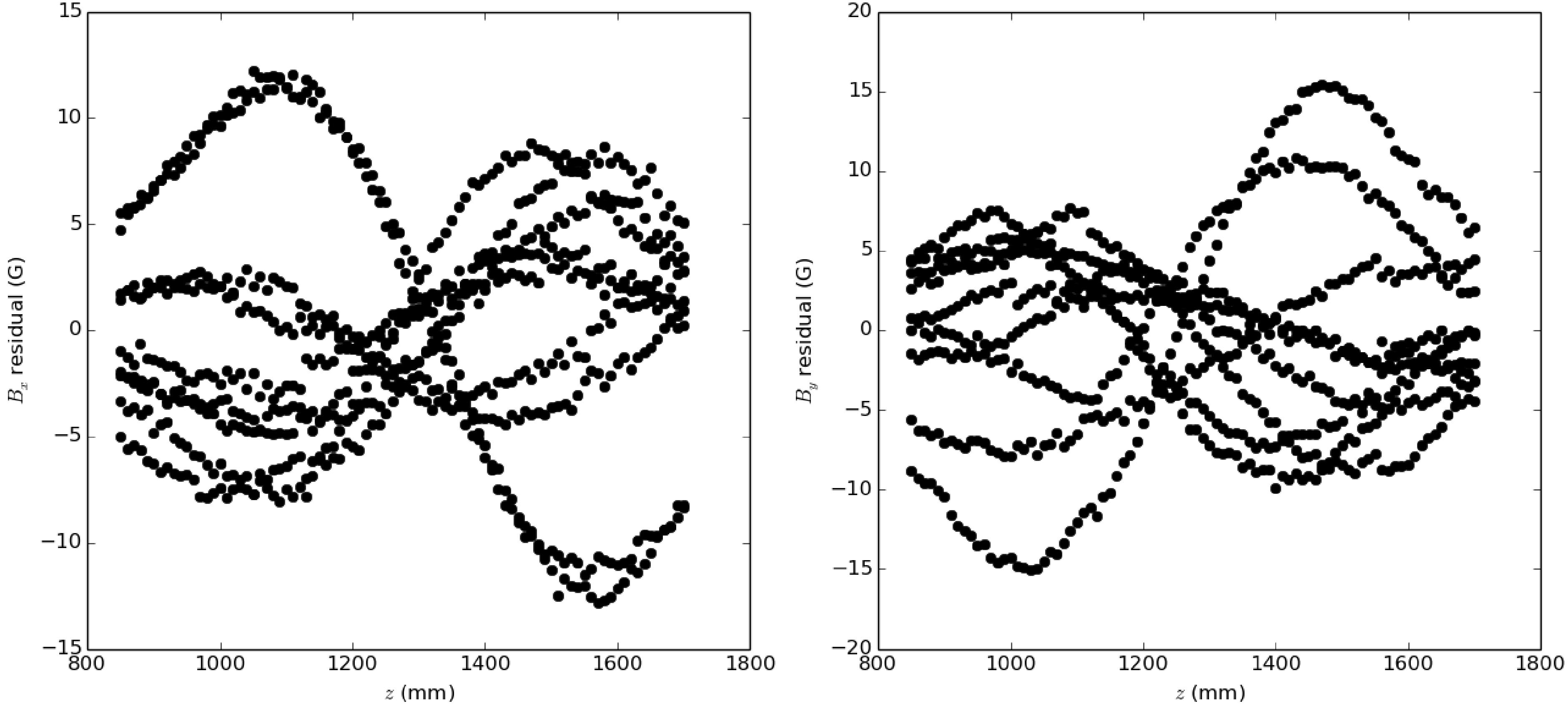




Has more 'character' than FC1

FC2

(Run 3, 100A, flip mode)



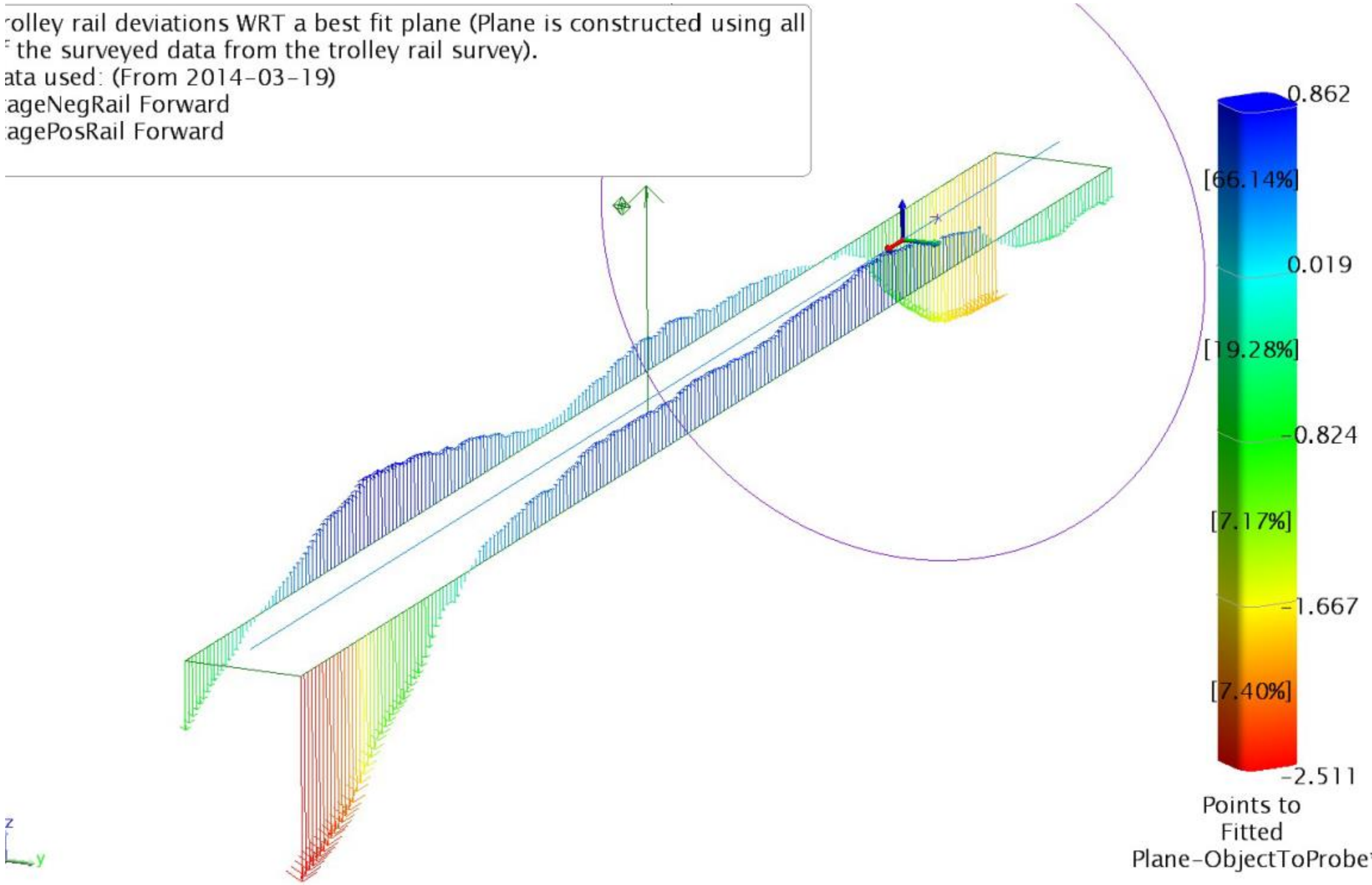
SPECTROMETER SOLENOIDS

Ode to awkward magnets

The ‘SS’ Saga

- Q1: In the 4T ‘flat field’ region...
  - Where is the axis of a uniform solenoid?
  - Will exclude this region from fits
- The mapper carriage is different for the SS mapping
  - Longer (~5m, rather than 3)
  - More flex and wobble
  - More difficult to align to the bore before measurements begin (?)
- Measurements taken slightly differently (a complete loop of the Hall probes is two “runs”
- Survey of the mapper movement during measurements for FC1 & FC2 show ~0.1mm movement.
- Much worse for SS’s… for example!

Beautiful survey plots from LBNL



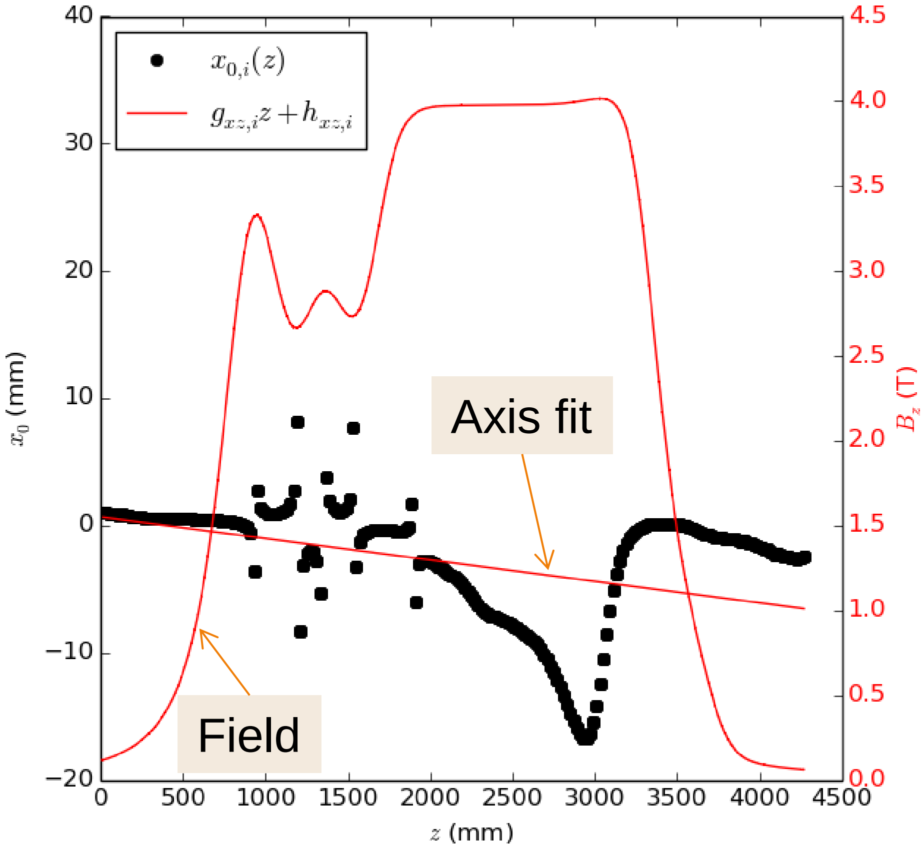
The mapper's movement is fairly complex – still digesting!

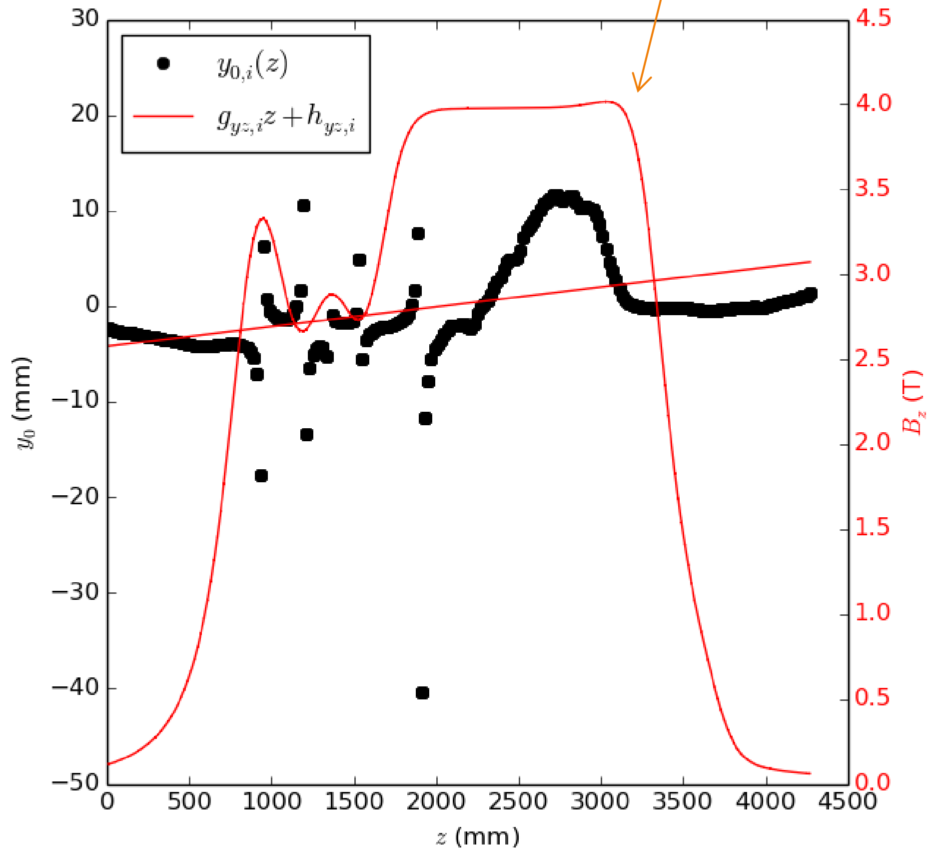
USS

- "Runs 21 & 22"
- "100% solenoid mode"
- Excluding $1.7 < z < 3.4$ m region
- With $B_{\varphi,m}$ correction
- (First magnet mapped)

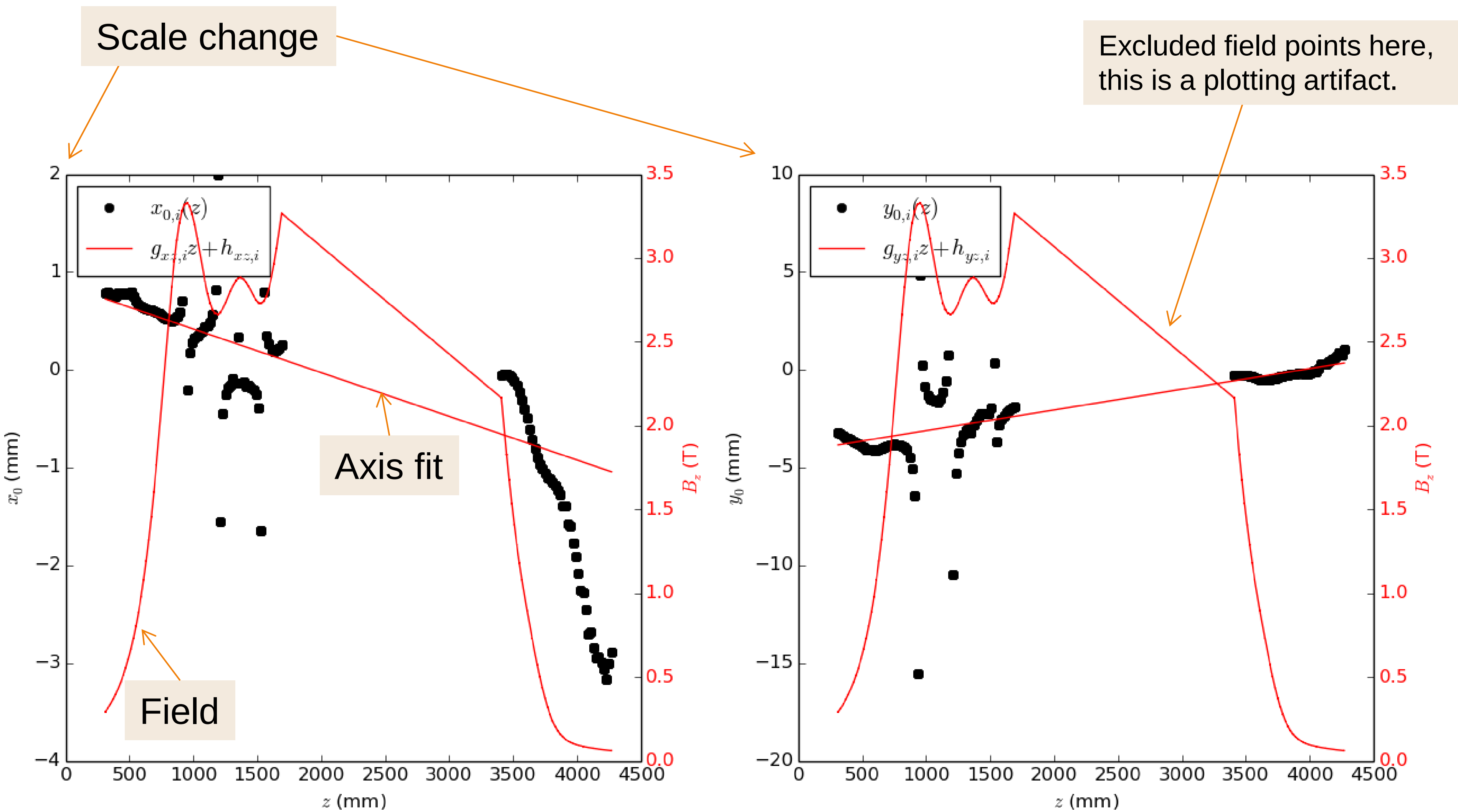
USS, fitting over full z-range

Non-uniform, E2 needs turning down (see DSS for 'tweaked' flat field) – Also see this in MAUS with 'default' currents.



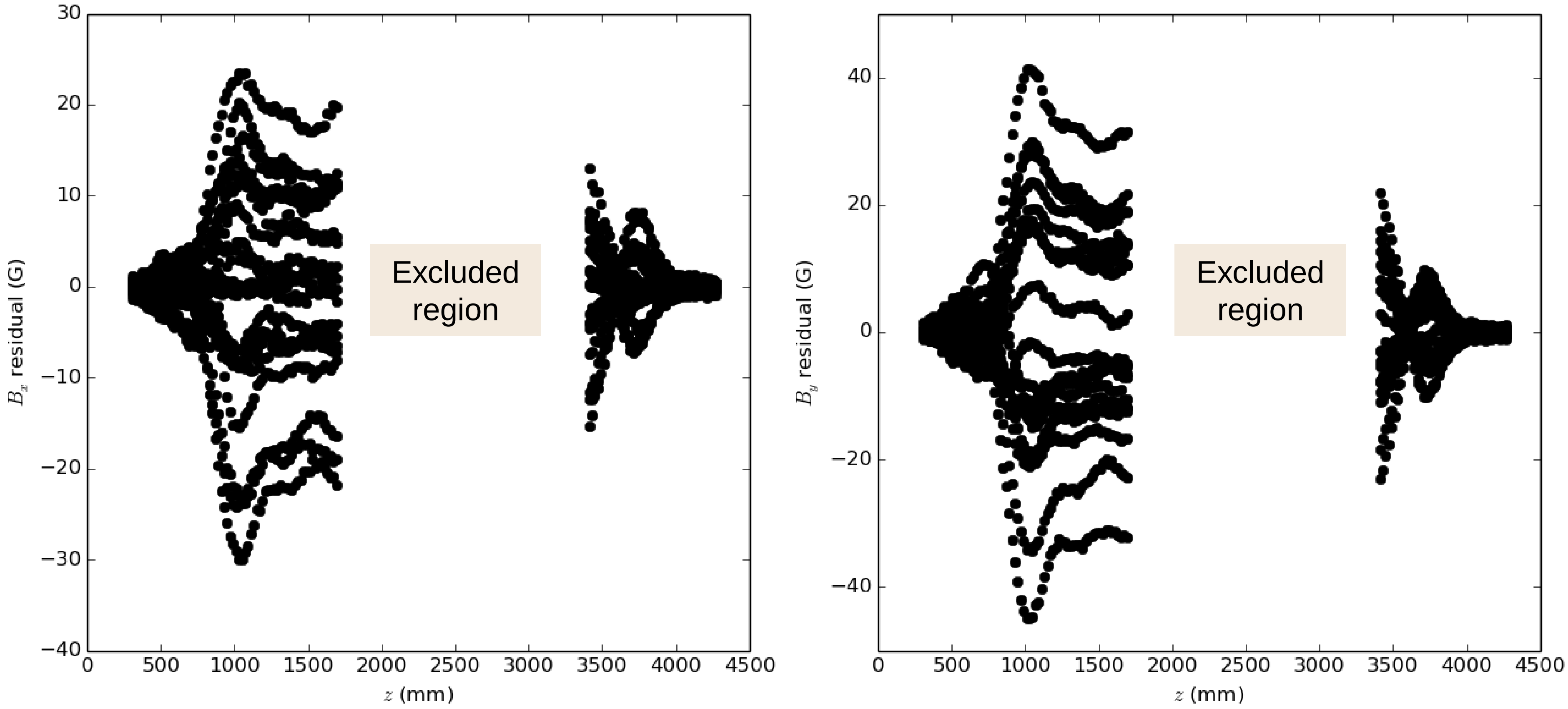


USS, excluding $1.7 < z < 3.4$ m region



USS, excluding $1.7 < z < 3.4$ m region

Larger residuals than for FC1 & FC2.
Still some oddities in transverse vector plots (see supporting material)

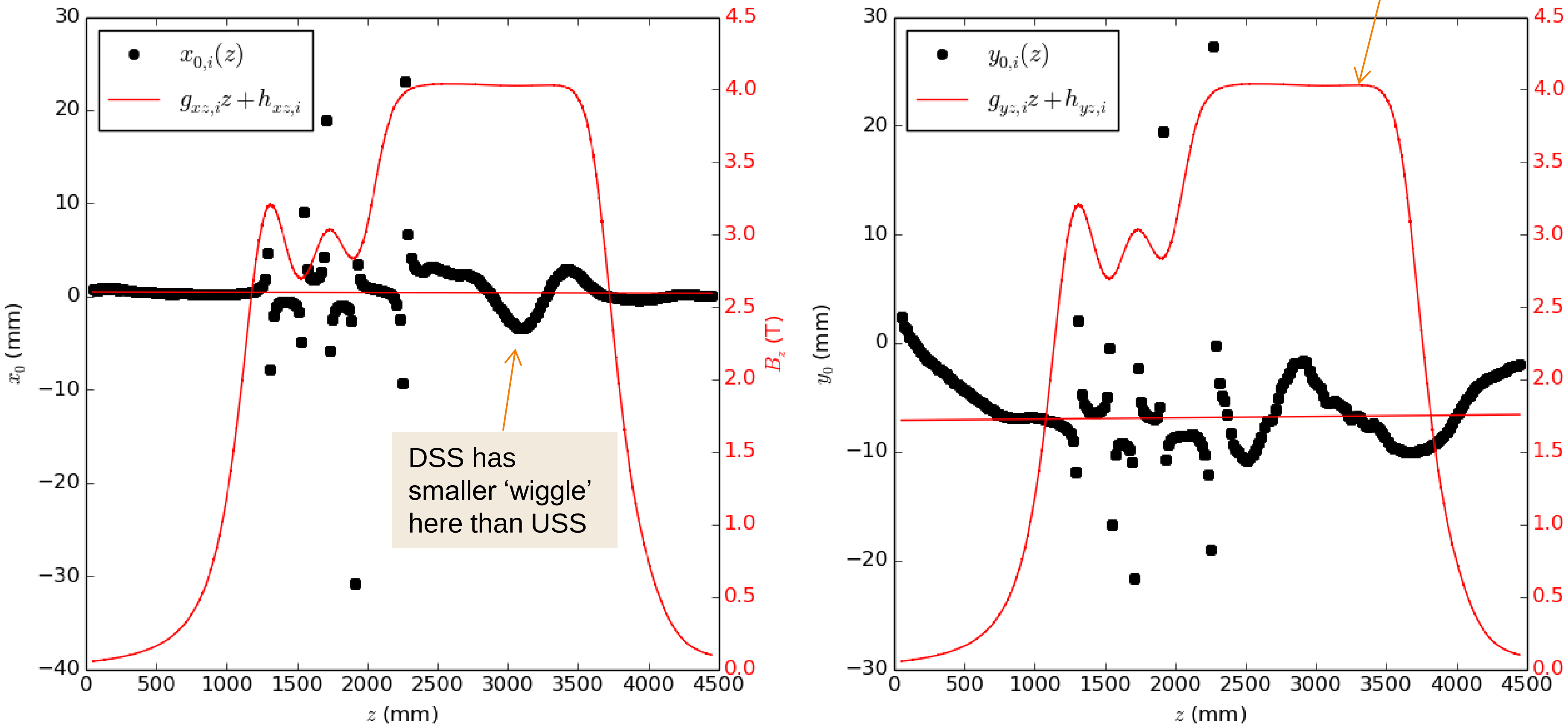


DSS

- "Runs 25+26"
- "100% flip mode"
- Excluding $2 < z < 3.8$ m region
- With $B_{\varphi,m}$ correction

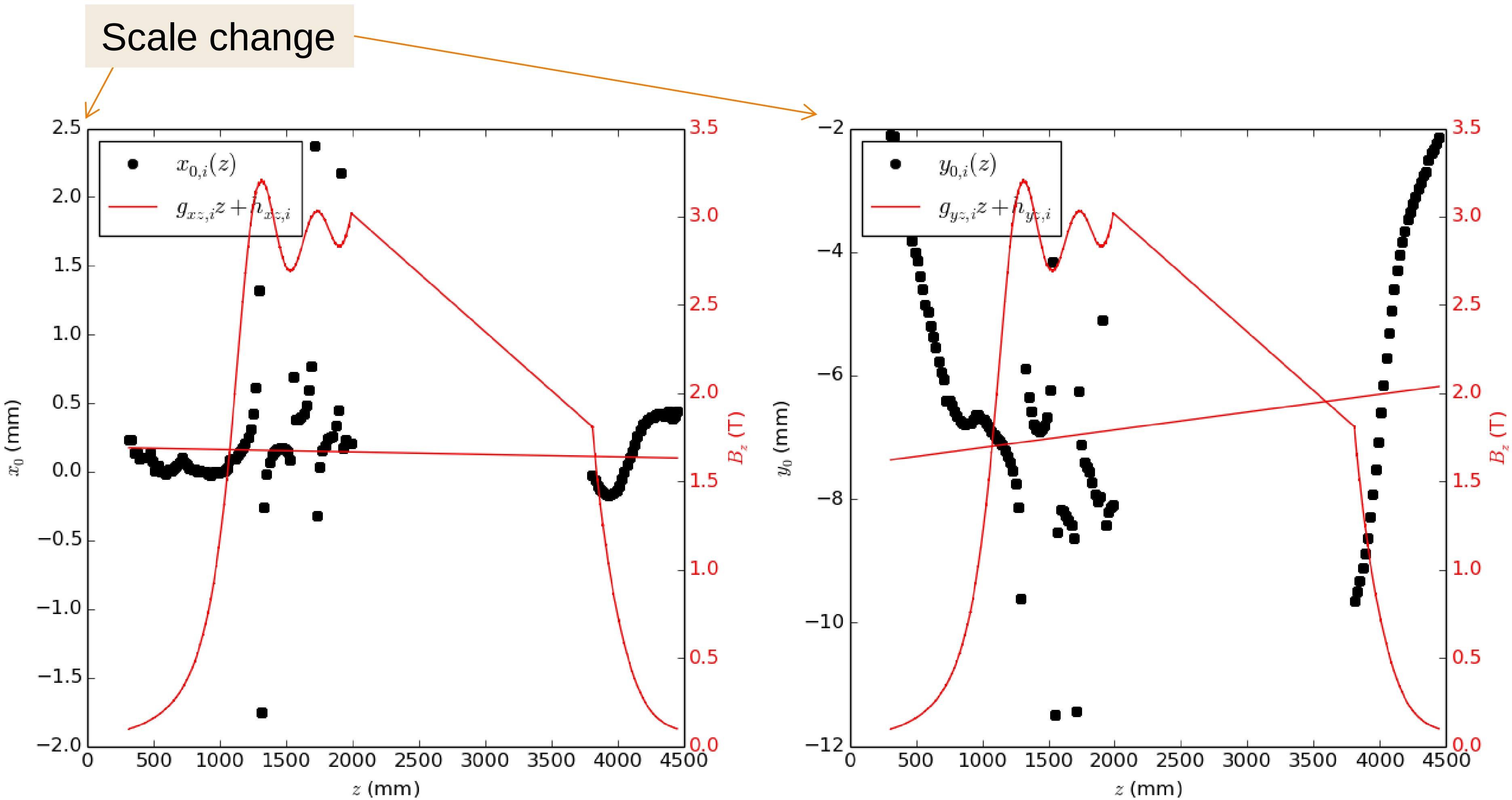
DSS, fitting over full z-range

Much flatter with tweaked currents.



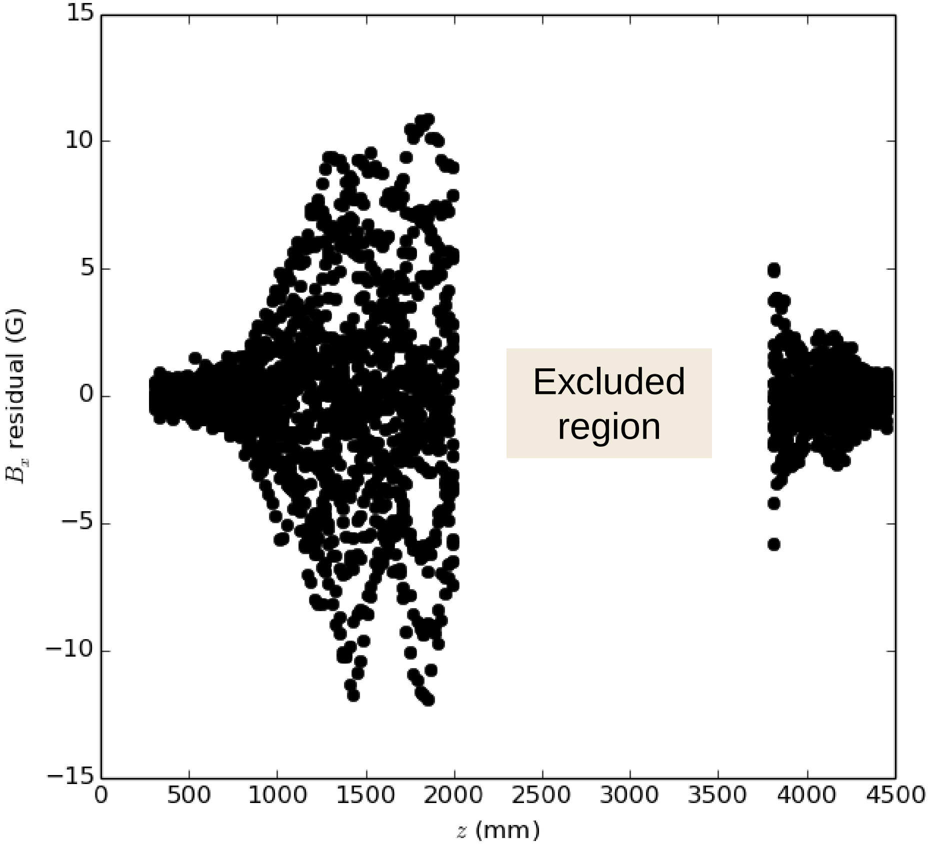
DSS has smaller ‘wiggle’ here than USS

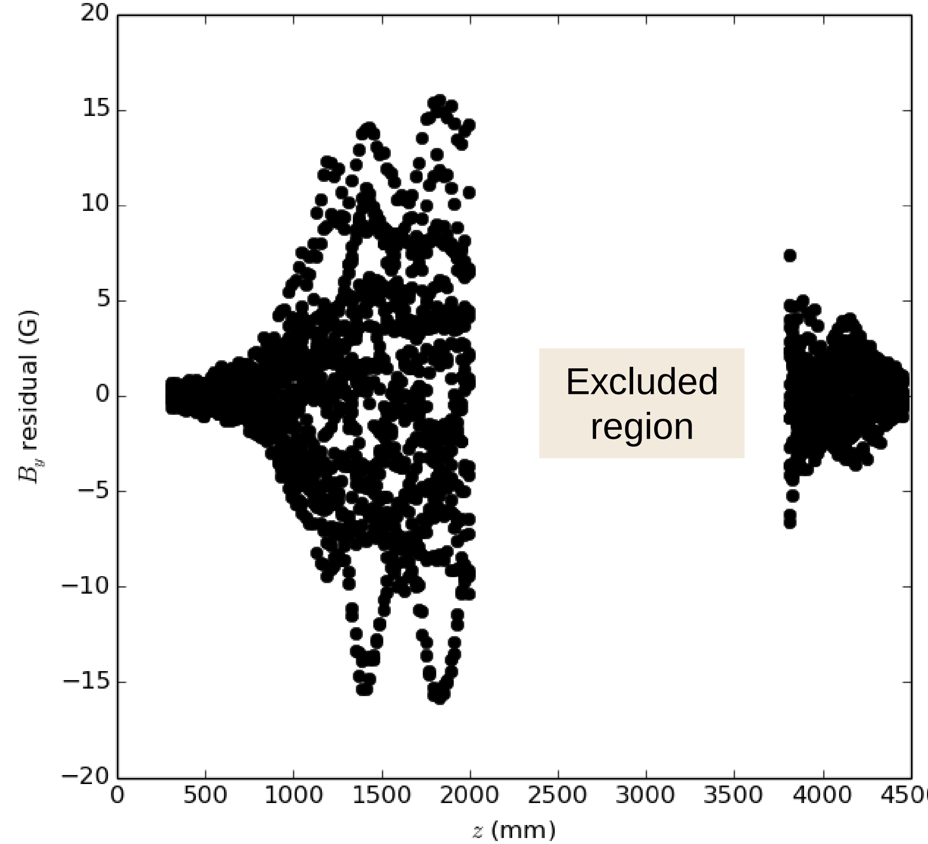
DSS, excluding $2 < z < 3.8$ m region



DSS, excluding $2 < z < 3.8$ m region

Residuals on par with FC2 (still worse than FC1)





Still more to learn (and still need error bars)

"Results"

Equations describing current (Feb 2015) best fit to magnetic axis in **mapper** co-ordinate system (units are m!)

FC1	
x	$-0.001485z + 0.001312$
y	$-0.002235z + 0.00383$
FC2	
x	$0.002076z - 0.002563$
y	$-0.000835z + 0.001769$
DSS (Excluding $2 < z < 3.8$ m region)	
x	$-1.7656 \times 10^{-5}z + 0.000179$
y	$0.000287z - 0.007454$
USS (Excluding $1.7 < z < 3.4$ m region)	
x	$-0.000446z + 0.000863$
y	$0.001057z - 0.004170$

To do:

- Investigate vector plots from SS's more thoroughly
- Correction to $B_{r,m}$ necessary?
  - One Hall probe cube 'contains' 3 independent Hall sensors
- Apply survey
  - 'Swingy' travel through SS's needs help!
- Think really, really hard about the errors
- … Then the remaining field map exercise!