MAGNET MAPPING

J. Cobb

V. Blackmore (not responsible for the content of this talk)

THE GOALS

- **Find the magnetic axes of the magnets**
  - ***Align magnetic axes of modules to beam axis***
    - ***Ideally to better than 0.5 mm***

- **Check fields agree with calculated fields**
  - **and / or**
- **Find effective conductor dimensions**

- **Almost finished finding axes**
  - **Final checks still to make**

- ***Have made first pass at as-is alignment in Hall***

THE SCOPE

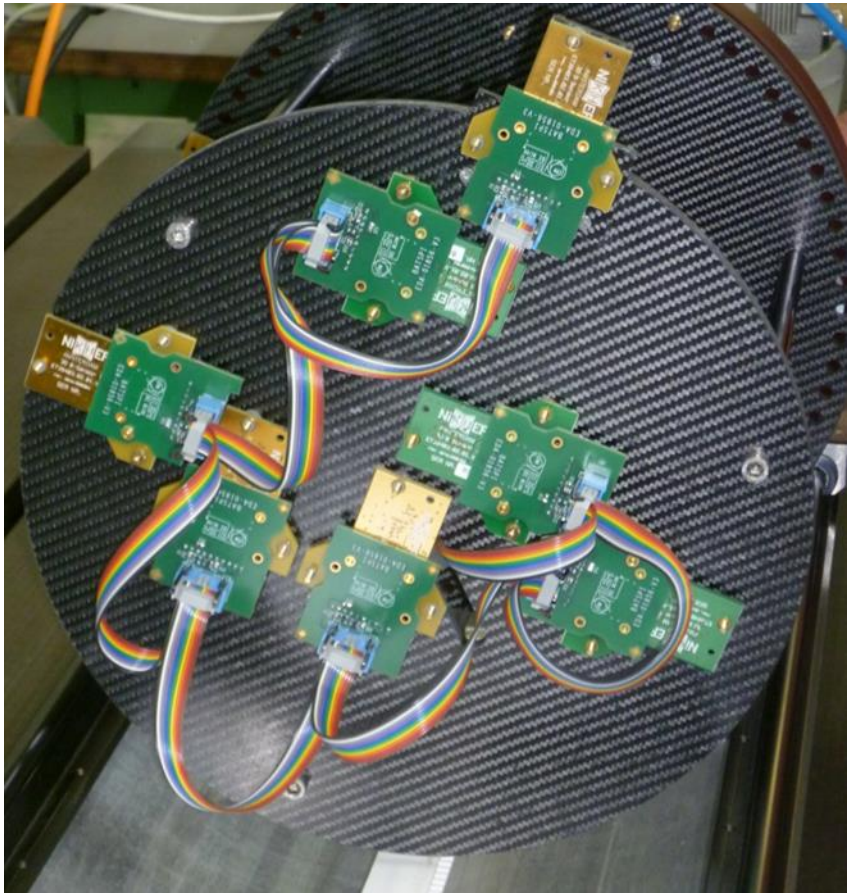
- Initially the two Focus Coils

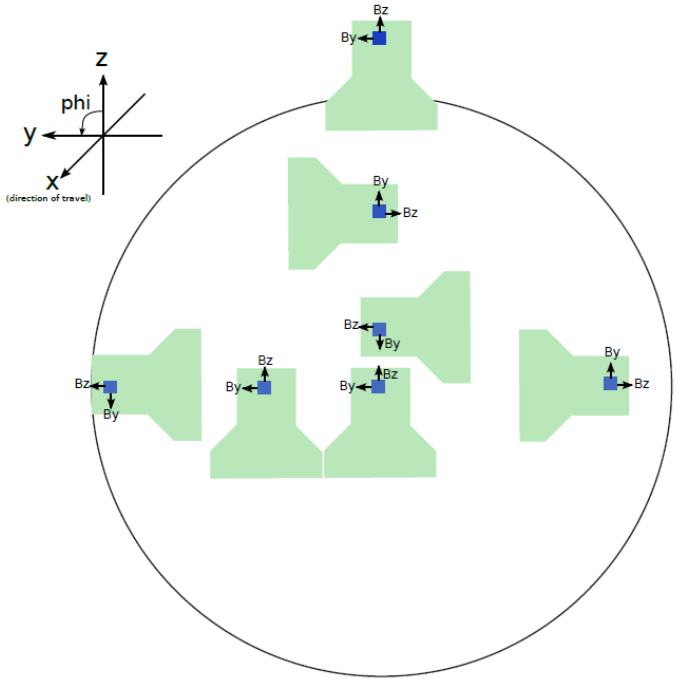
- Include the two Spectrometer Solenoids

- Four magnets
- Eight surveys (at least)
  - Including surveys in Hall
- All magnets & mappings subtly different
  - Not trivial – not impossible – to write general purpose code

- *Enough meat for at least two D. Phil. theses*

THE MAPPER





Seven 3-axis Hall probes at *r* = 0 … 180 mm

Disc rotates

Mainly use probe 1 at *r* = 30 mm

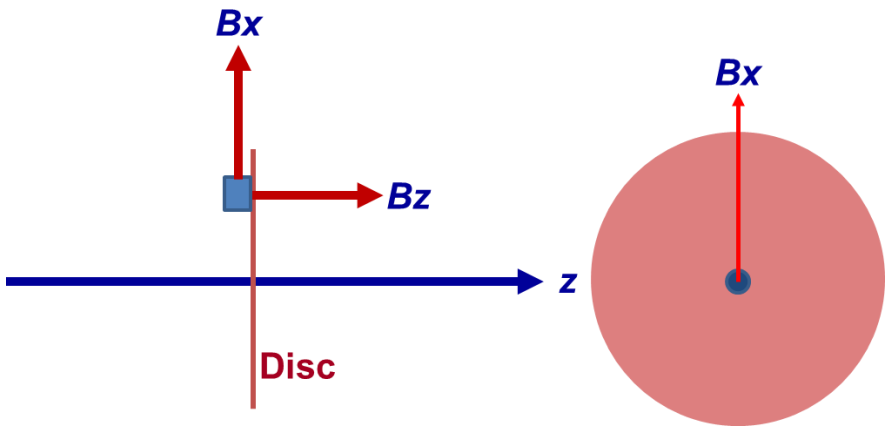
THE DATA

- All four modules mapped
  - FCs in R9
  - SSU & SSD at manufacturers

- Longitudinal (z) scan at fixed angle of disc (ϕ)
    - dz = 10, 20, 40 mm
  - Change ϕ and repeat
  - ϕ increments from 5, 20, 45 degrees

- A number of different currents
  - With/without VP for the SSs
- Huge amount of data
  - Much not looked at

THE ASSUMPTIONS

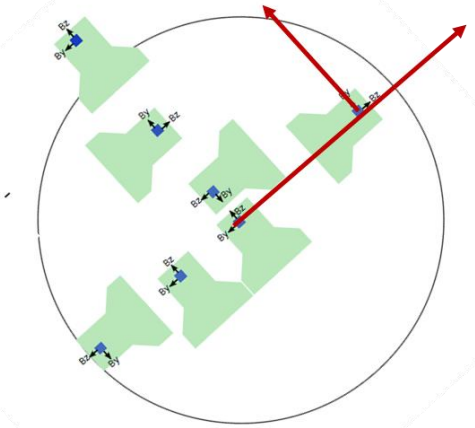


- Mapper mechanics are perfect:
  - Mapper disc:
    - Perpendicular to longitudinal axis of movement (*z*)
    - Rotates around longitudinal axis
  - Hall probes
    - *z* axes parallel to mapper *z* axis
    - *x* (or *y*) axes radial from mapper *z* axis

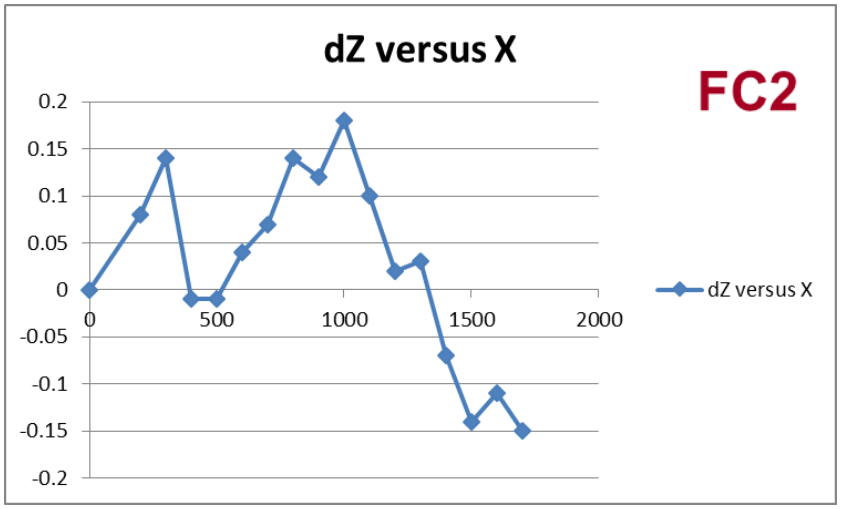
- Mapper position stable (i.e. not kicked!)

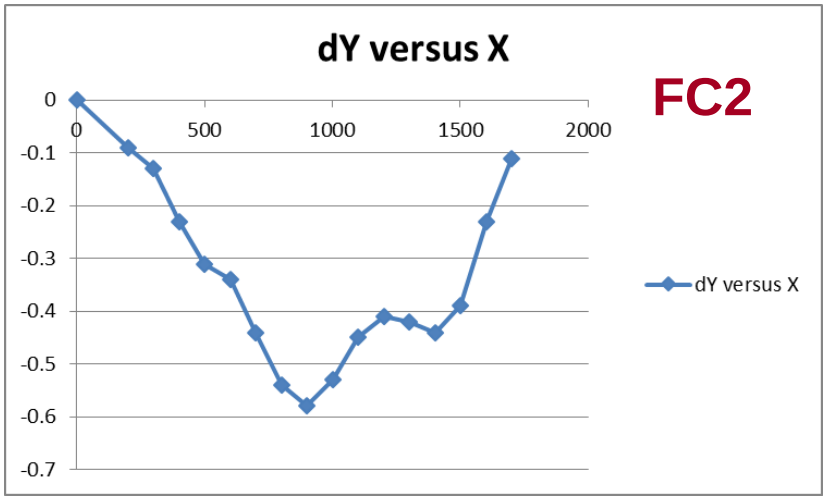
THE TRANSFORMATIONS

- **Mapper measures**
  - ***Br* and *Bϕ* at (*r*,*ϕ*) in disc system**
- **Rotate coordinates & field components to get:**
  - **(*x*,*y*) and *Bx*, *By* in mapper system**
- ***Br* and *Bϕ* aren't true radial & azimuthal field components because mapper axis is not magnetic axis – can be confusing**
- **Apply survey corrections to *x* and *y***



THE SURVEY CORRECTIONS





- **Mapper disc doesn't move in straight line**
  - **Transverse movement surveyed for each module**
    - **< 0.6 mm for FCs**
    - **~ 2 – 3 mm for SSU & SSD**
  - **Survey corrections applied to *x* and *y* coordinates**
    - ***Not applied to field components* (yet)**
    - ***Should we?***
      - ***Imply pitch & yaw of mapper disc?***

AXIS FINDING

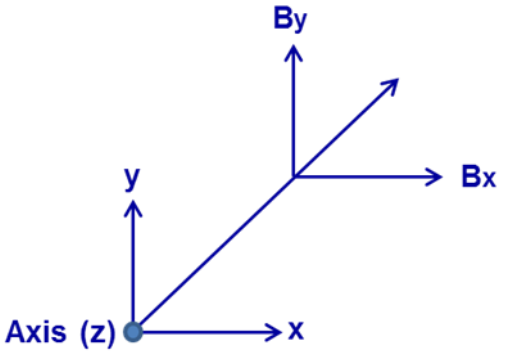
- Considered, briefly, global fit to measured fields:
  - Models of conductors
  - Rotations
  - Global $\chi 2$

  - But too awful to contemplate for very long
  - Too many parameters
  - Too slow to calculate fields &c.

- Use model-independent method to find axis
  - No field calculations required

AXIS FINDING 1

- **Magnetic axis ➔ Bperp = 0**
- **Cylindrical symmetry assumed**
- **Maxwell-Gauss:**



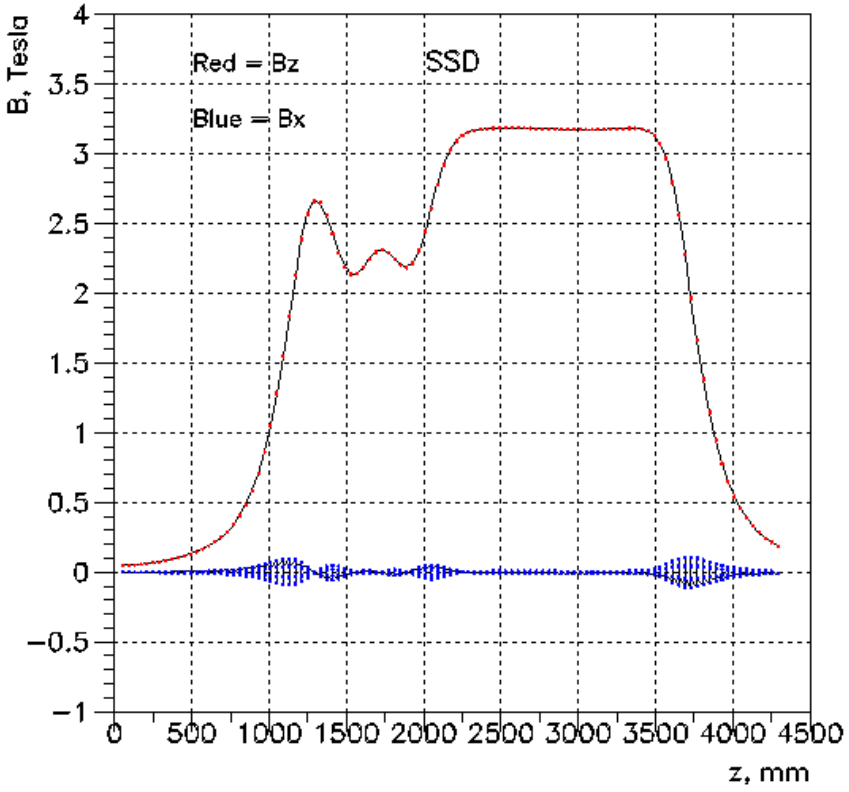
$$\nabla \cdot \mathbf{B} = 0$$

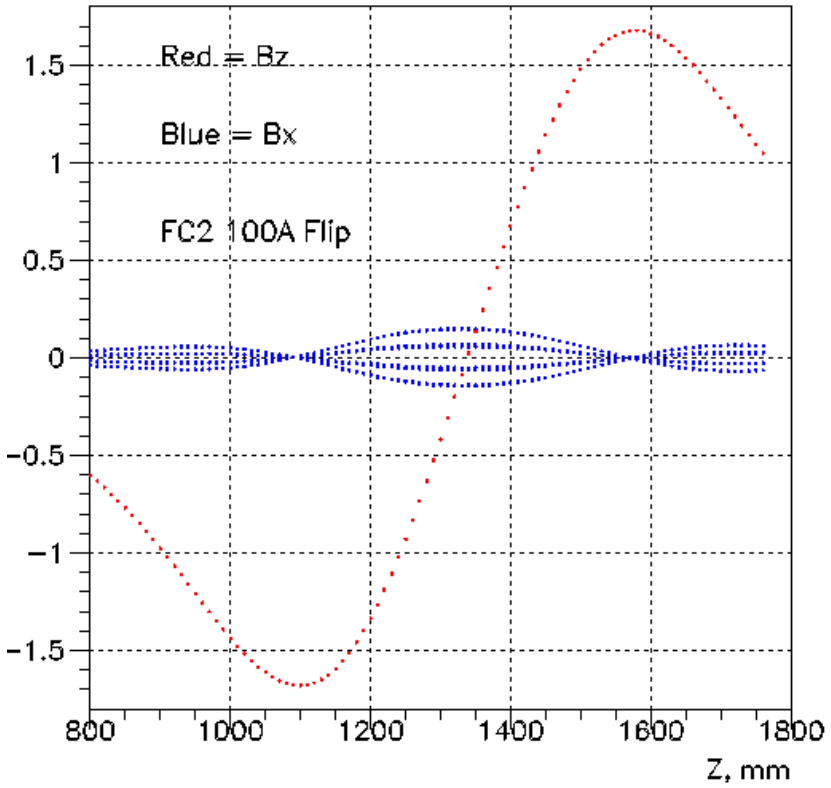
so

$$\frac{\partial B_x}{\partial x} = \frac{\partial B_y}{\partial y} = -\frac{1}{2}\frac{\partial B_z}{\partial z}$$

- **Expect *Bx* and *By* to be linear in *x* or *y* and zero on axis**

SOME FIELDS





- **Same scale for *Bx* and *Bz***
  - **8 (*x*,*y*) points at each *z***
- **Information about axis mainly from where *Bz* changing fast**

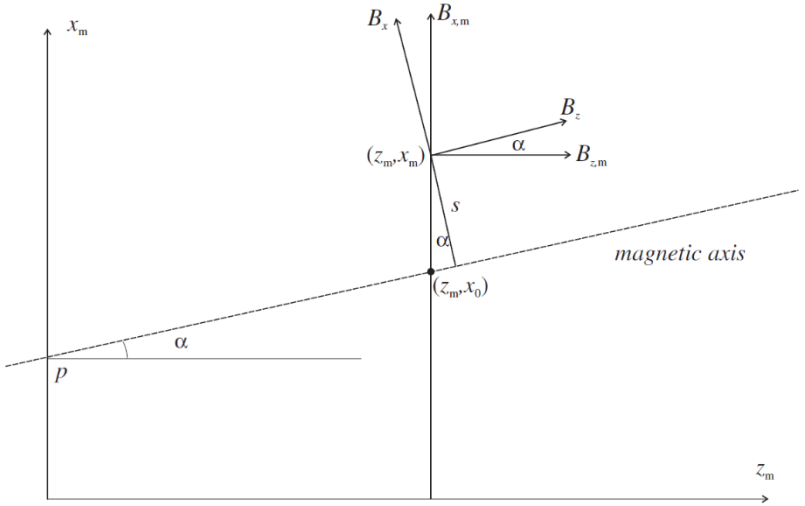
AXIS FINDING 2

- Expect *Bx* and *By* to be linear in *x* or *y* close to axis
  - zero on axis
  - Sounds simple enough

- But
  - *Bx* and *By* are small (< 1500 gauss) close to axis
  - *Bz* can be large (2kG – 40kG)

- Allow for components of *Bz* in (mapper) *Bx, By* due to inclination – up to a few mr – of axis in mapper system

AXIS FINDING 3



To first order, measured *Bx* at fixed *z* is

$$B_{x,m}(z_m, x_m) \quad = \quad k(x_m - p - \alpha z_m) + \alpha B_z$$

α = angle of magnetic axis in *x* – *z* plane, *p* is intercept

Angles are small and can work in projections

AXIS FINDING 4

Equation of x-axis in Mapper System:

$$x_0(z) = p + \alpha z$$

From previous slide $B_x(z, x) = k(z)x + B_0(z)$

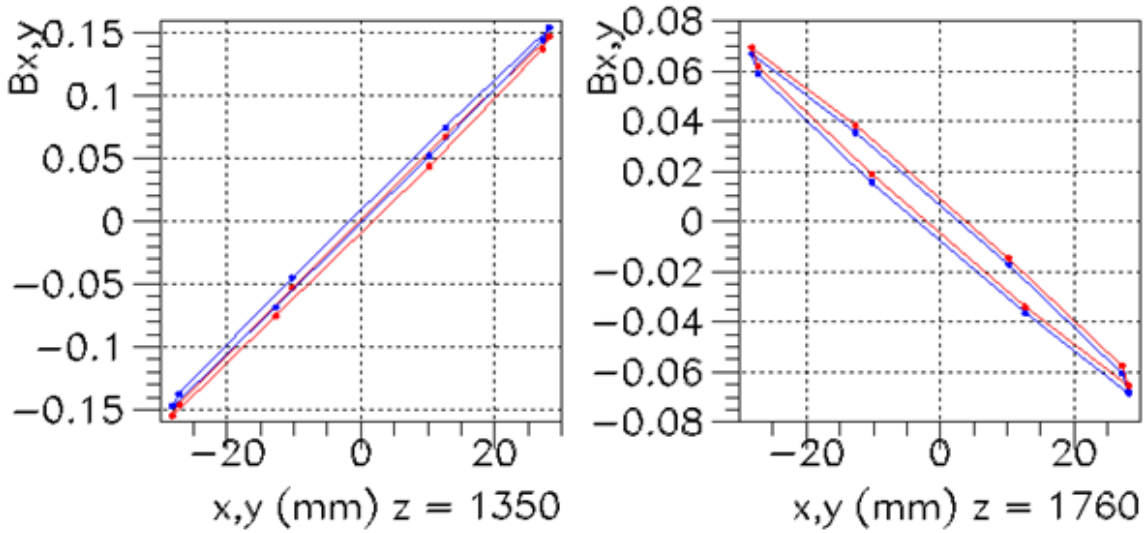
where

$$B_0(z) = -k(z)p - \alpha(k(z)z - B_z)$$

Fit proceeds in two steps:

- Fit B_x versus x at each z to obtain $k(z)$ and $B_0(z)$
- Use fitted values in a fit for $B_0(z)$ to obtain p and α.

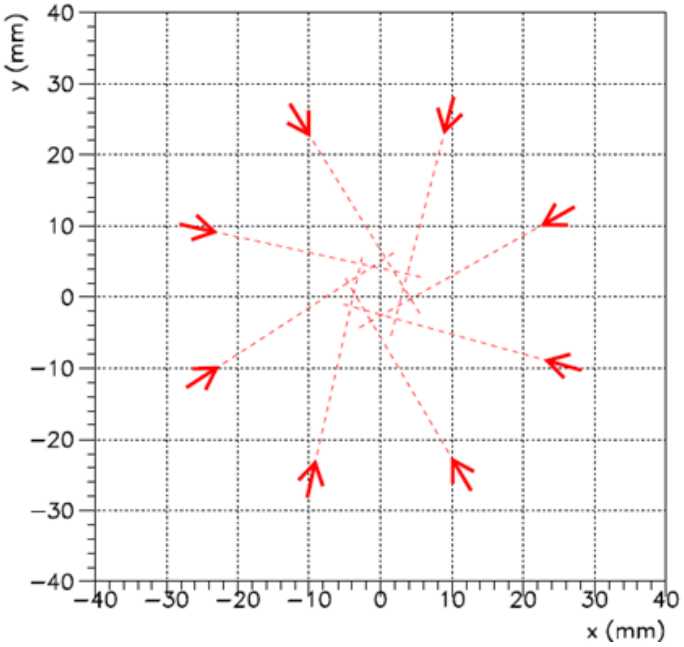
UNEXPECTED BEHAVIOUR



- ***Bx*** **(*By*) versus *x* (*y*) for full rotation of probe 1 at two *z*s in FC1**
  - **8 (*x*,*y*) from phi = 0, 45, 90 … degrees**

- **Why loops?**
  - **Look at transverse field vectors, (*Bx*,*By*)**

FIELD HAS A CURL ?



- **Transverse field vectors**
  - **Should converge to a point: the axis**

- **Measured field seems to have non-zero curl**
  - ***Ad hoc* correction…**

CURL CORRECTION 1

Ampères law states

$$\oint \mathbf{B} \cdot d\mathbf{l} = 0$$

If no current enclosed

Equivalently

$$\sum B_\phi = 0$$

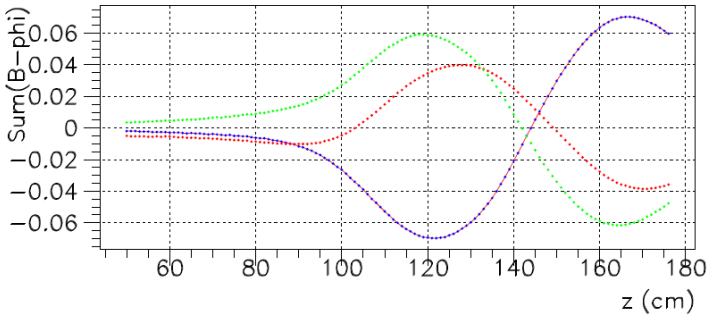
Correction is

$$B_\phi \rightarrow B_\phi - \frac{1}{N} \sum B_\phi$$

Measured fields of each probe corrected by mean $B\phi$ at each z

CURL CORRECTION 2

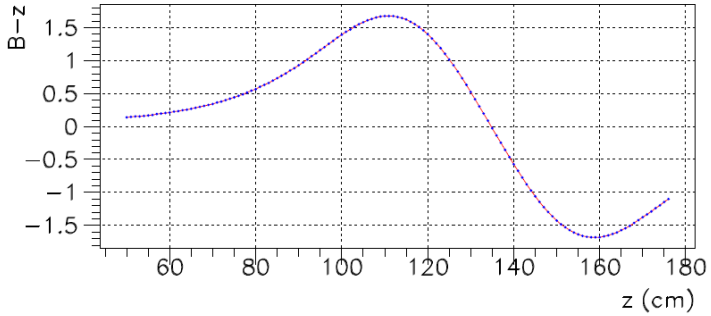
$\sum B_\phi$



Probes 1,2 & 3

Sum over 8 phi (0 – 315 degrees)

Bz

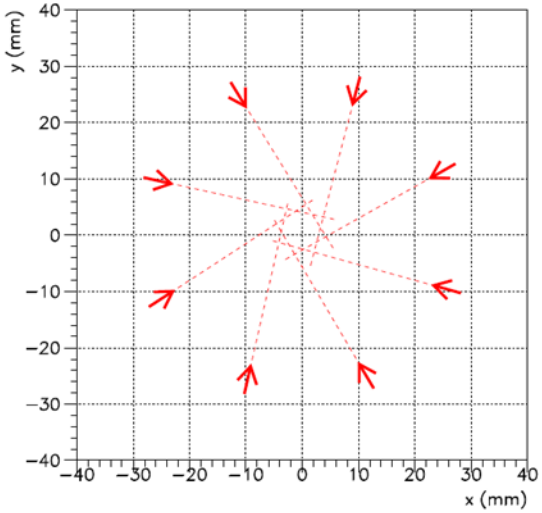


Each probe has different correction

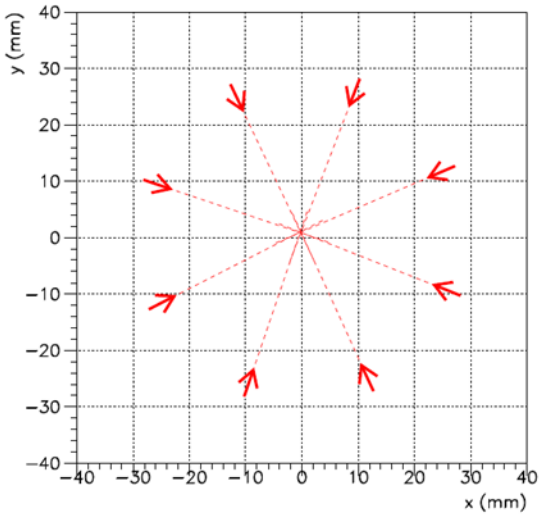
Can amount to 70 – 80 gauss

Attributable to one axis of probe not truly radial (by ~ 1 degree)

CURL CORRECTION 3



Before



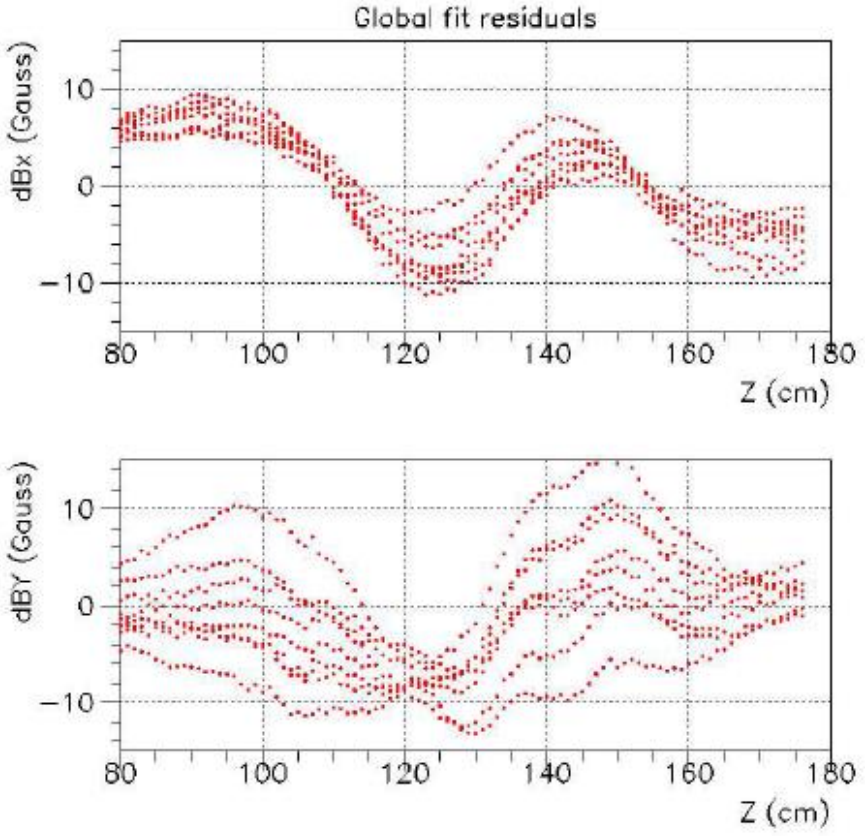
After

- Seems to work
  - but needs revisiting

THE FITS AND AFTER

- Most of the fits done by VB
  - Similar to above outline
    - Different in detail
    - Include
      - Mapper surveys
      - Curl corrections
  - Have my own simple ‘Poor Man’s Fit’
    - Works for FCs only
      - Useful reality check
  - Residuals suggest that errors dominated by systematics
- Parallel working / checking has been very useful
  - Find mistakes (mainly mine)
  - *Still work in progress*
- Decide ~ Easter to make first pass to see where we are globally

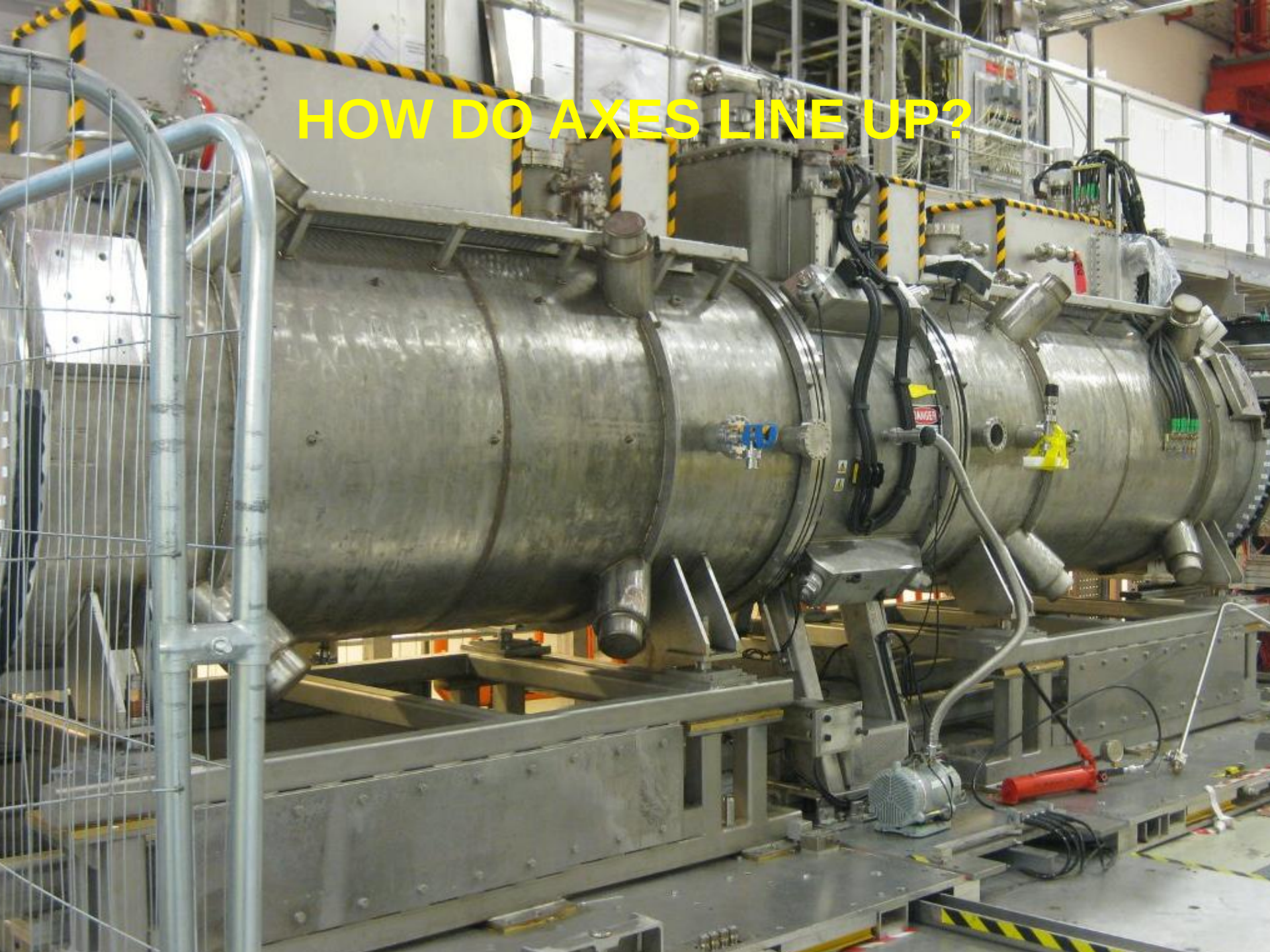
SOME AXIS FIT RESIDUALS



Horizontal

Vertical

FC1 Flip Mode


HOW DO AXES LINE UP?

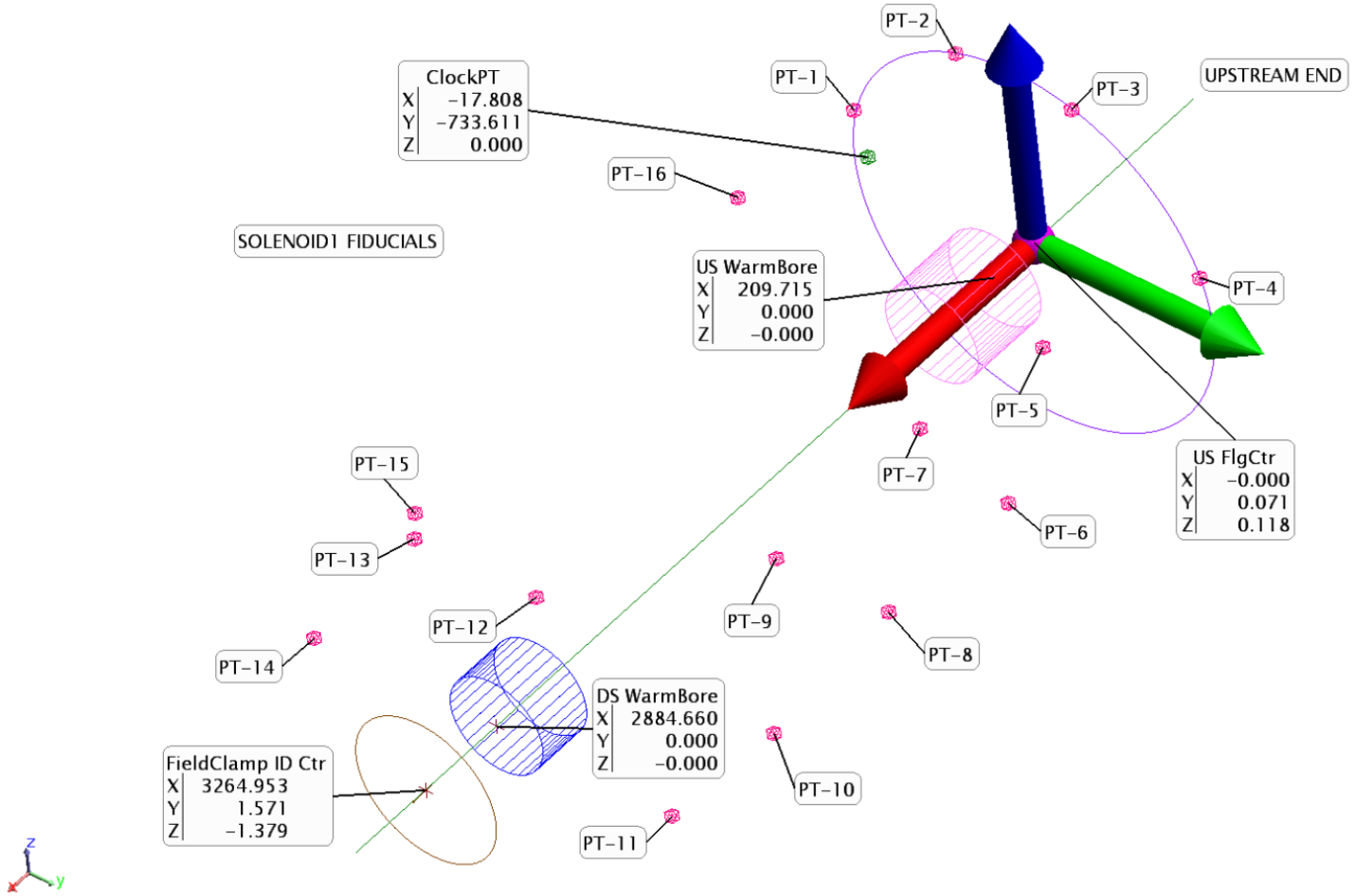
THE GLOBAL PICTURE

- Looked – *first pass* – to see how magnetic axes would line up
  - i.e. how magnetic axes relate to flanges on modules
    - In all cases mapper axis was aligned to bore tube
      - Doesn't immediately relate to flanges &c.

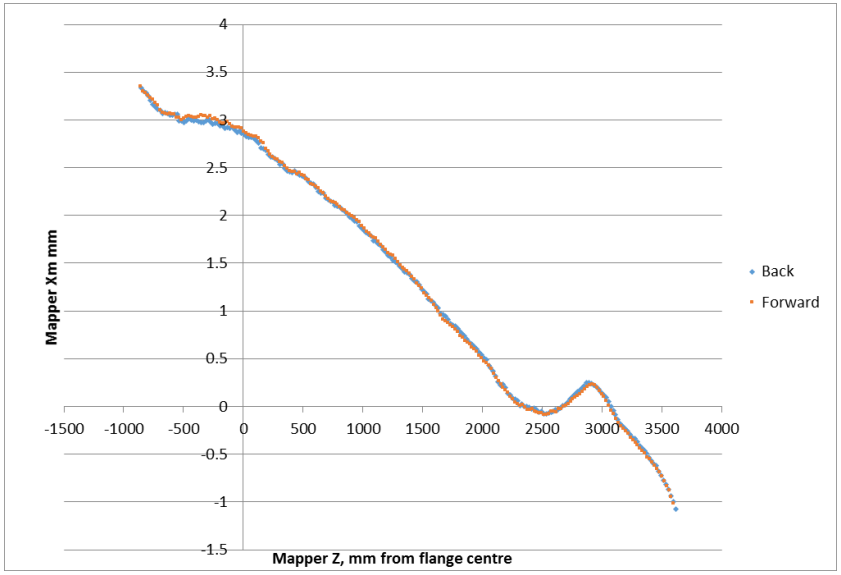
- Had to understand external surveys
  - Given in weird R9 coordinates for FC1 and FC2
    - FC2 re-surveyed
  - Simpler for SSD and SSU

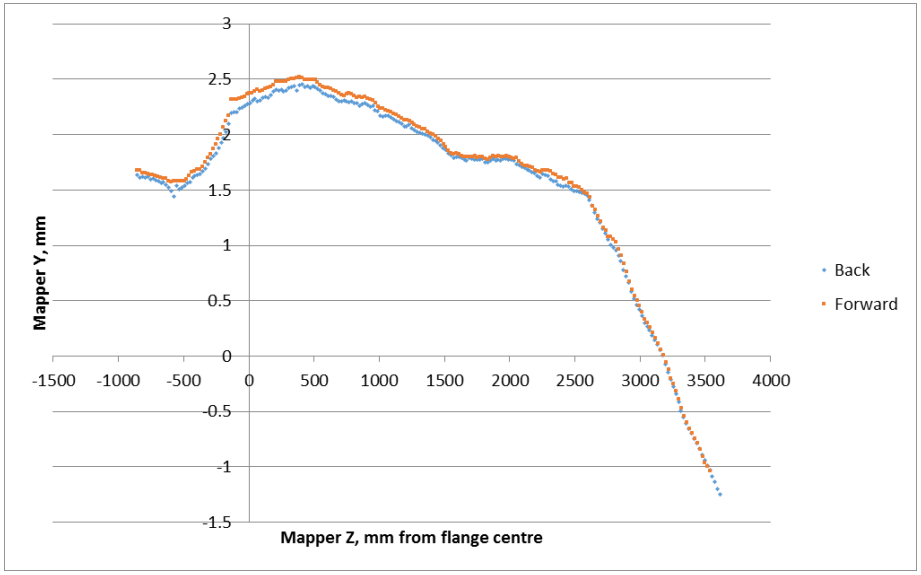
- Axes of SSU and FC2 seemed to be within ~ 0.5 – 1mm of centres of flanges
- SSD axis ~ 4 mm off at upstream end; ~ 10 mm off at DS end
  - Is this right?

SSD SURVEY


PT-2
PT-1
PT-3
UPSTREAM END
ClockPT
X -17.808
Y -733.611
Z 0.000
PT-16
SOLENOID1 FIDUCIALS
US WarmBore
X 209.715
Y 0.000
Z -0.000
PT-4
PT-5
PT-7
US FlgCtr
X -0.000
Y 0.071
Z 0.118
PT-6
PT-15
PT-13
PT-12
PT-9
PT-8
PT-14
DS WarmBore
X 2884.660
Y 0.000
Z -0.000
FieldClamp ID Ctr
X 3264.953
Y 1.571
Z -1.379
PT-10
PT-11
Z
y

SSD MAPPER SURVEY





x – z

+ 3mm upstream end

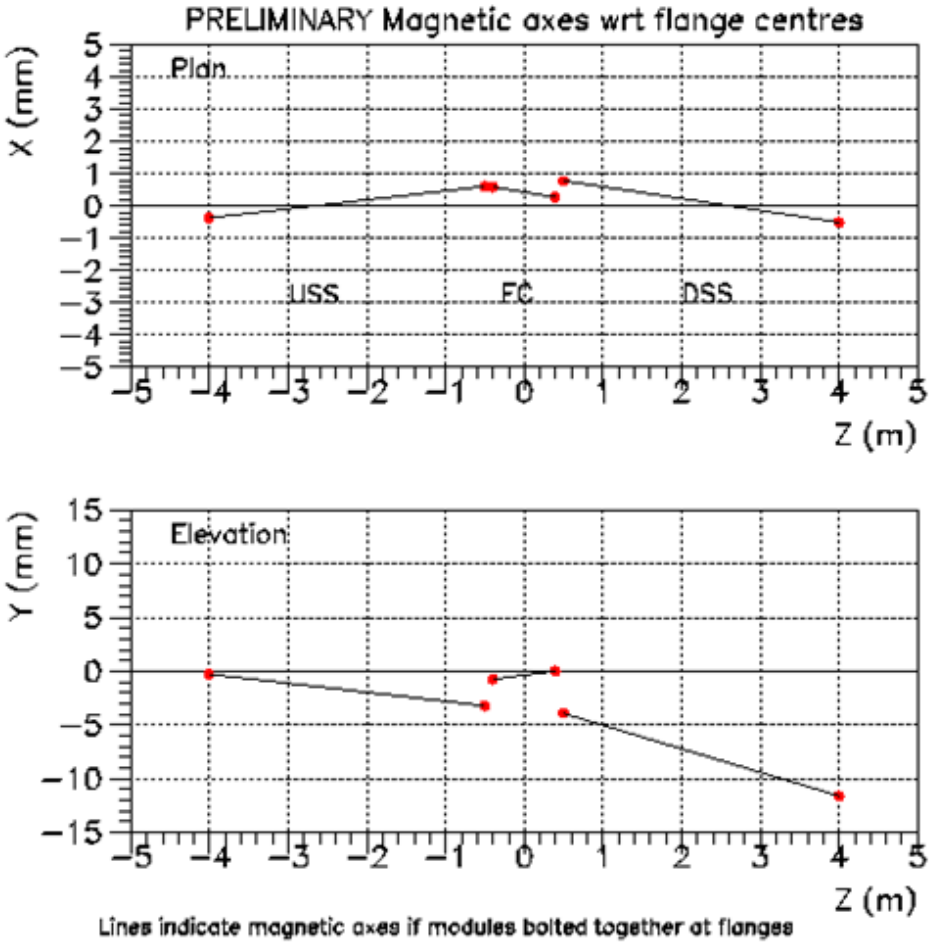
to -1 mm downstream

y – z

+2.5 upstream end

to -1 mm downstream

FIRST PASS AXES in HALL (as of 27/III/15)



Plan

Elevation

- **Assumes modules bolted *exactly* flange-centre to flange centre**
- **Assumes SS bore tubes perpendicular to flanges**

HOW CAN WE CHECK SSD AXIS?

- Check what we did (obviously)

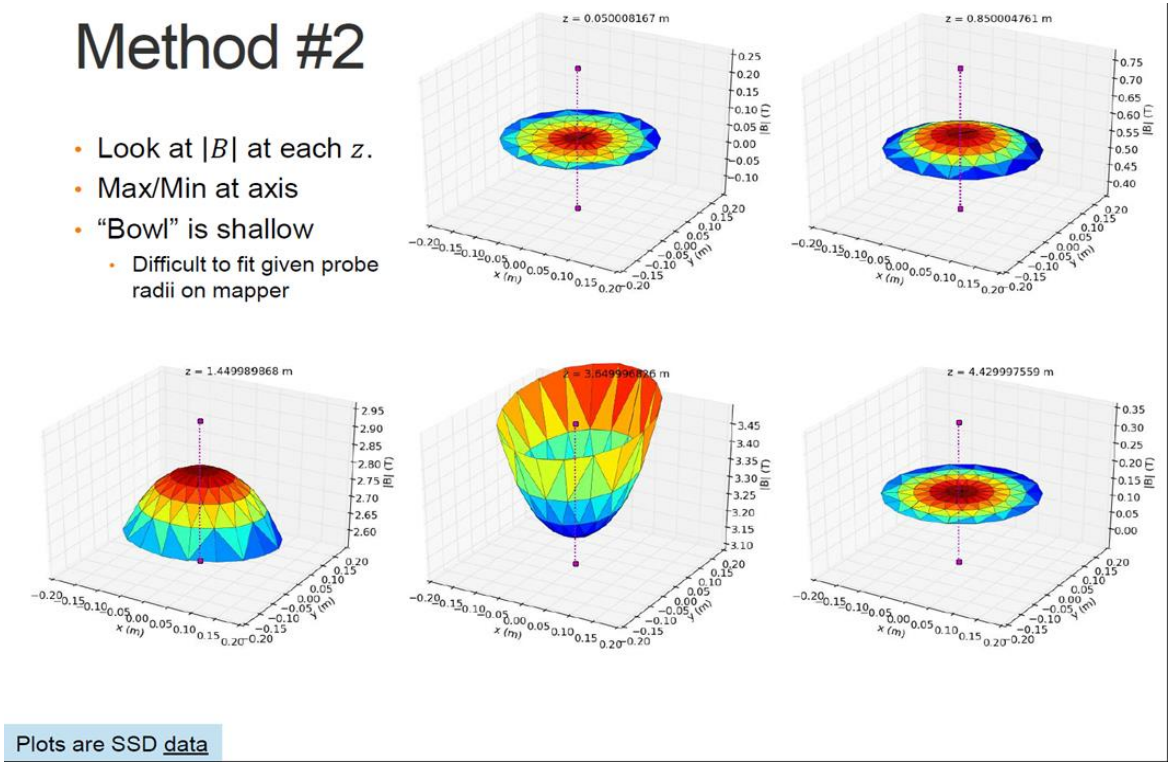
- FC bobbin axes aligned to < 100 microns to flange centres
  - Our only ‘calibration’
    - Fits should be good to roughly that level
  - But some ambiguities with FC2 mapper survey
  - *Work in progress*
    - *Shall say no more about FC2*
    - FC1 looked OK – but must revisit

- Invent different methods to find axis:
  - Peak finding (VB)
  - Field vectors (JC)

PEAK FINDING

Method #2

- Look at $|B|$ at each z.
- Max/Min at axis
- "Bowl" is shallow
  - Difficult to fit given probe radii on mapper

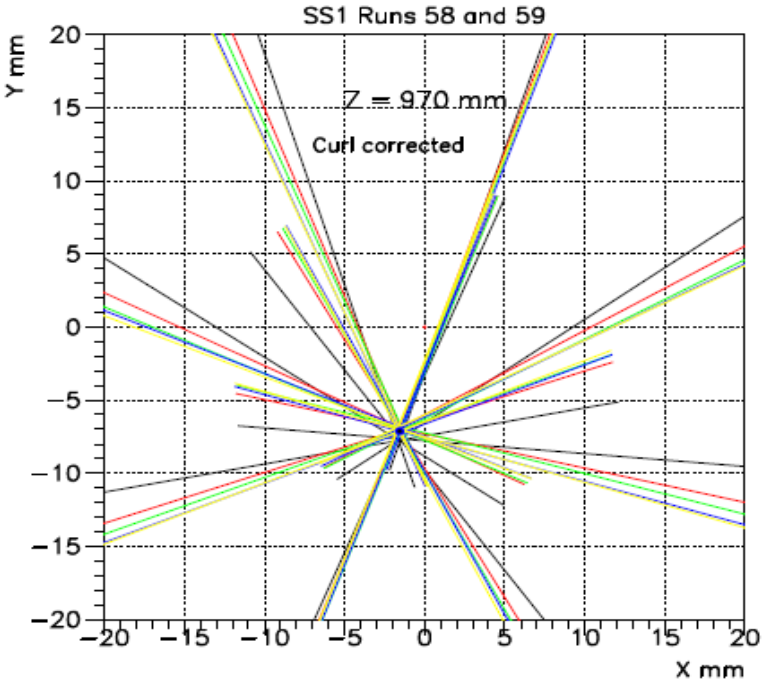


Plots are SSD data

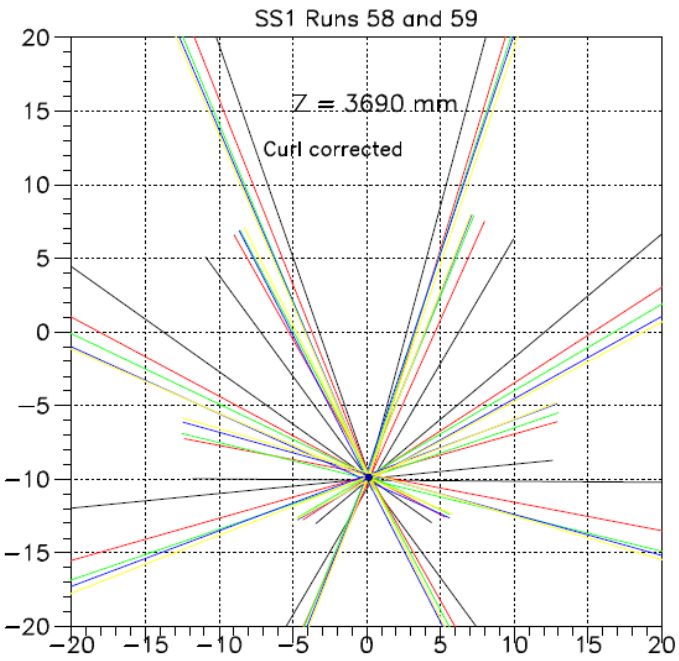
- **Btotal must be maximum or minimum on the axis**
  - **Needs fitting 2D function B(*x*,*y*) at fixed *z* & good relative calibration of probes**
  - **Not so useful**

VECTOR PLOTS

Upstream



Downstream



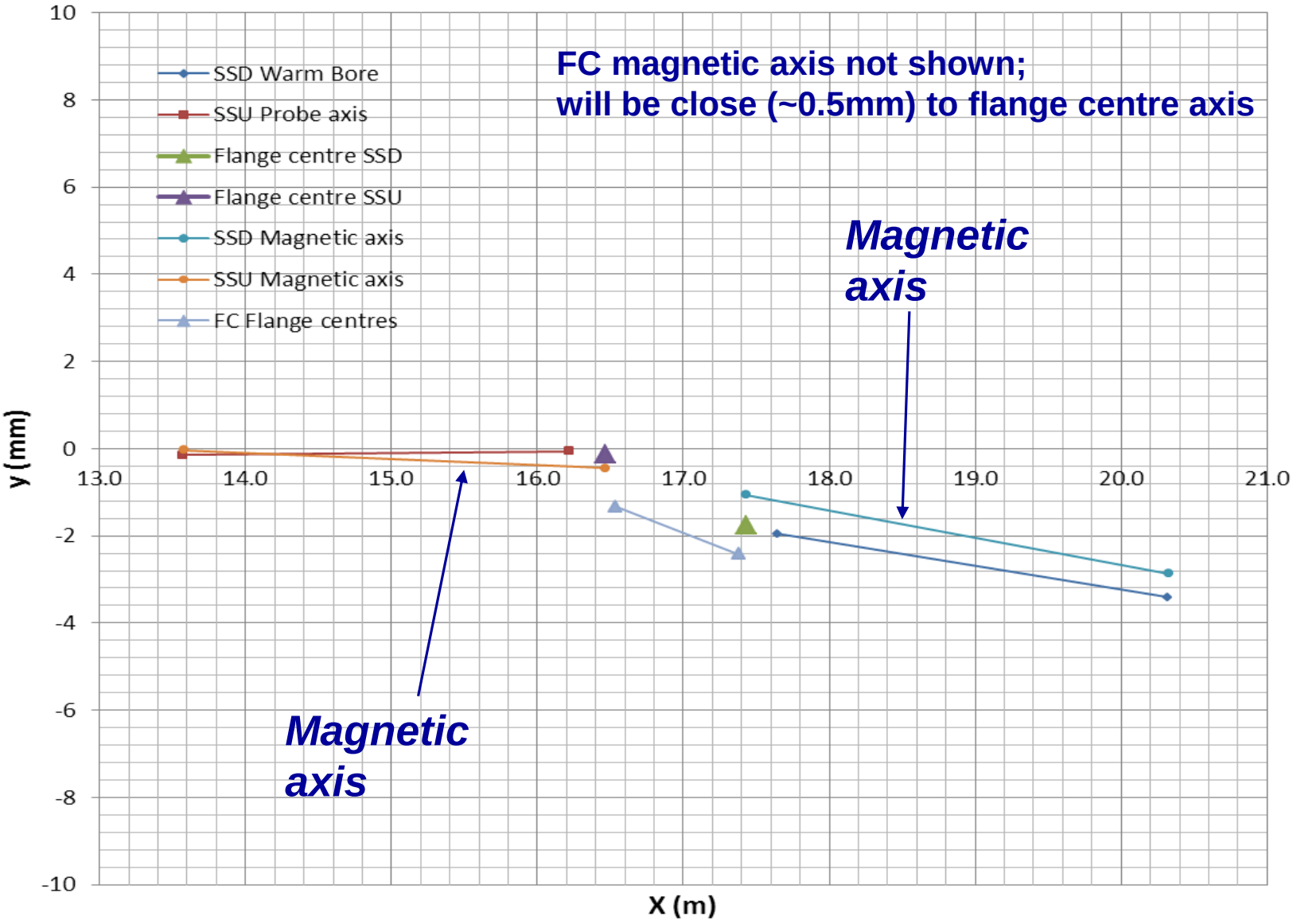
- **Draw transverse field vectors from probe positions**
  - **Uses all the probes independently**
  - **Vectors should intersect at the magnetic axis**
  - **Survey corrections (2 – 3 mm upstream end) can be applied afterwards**
- ***Result seems unambiguous & confirms fits***

IN THE HALL

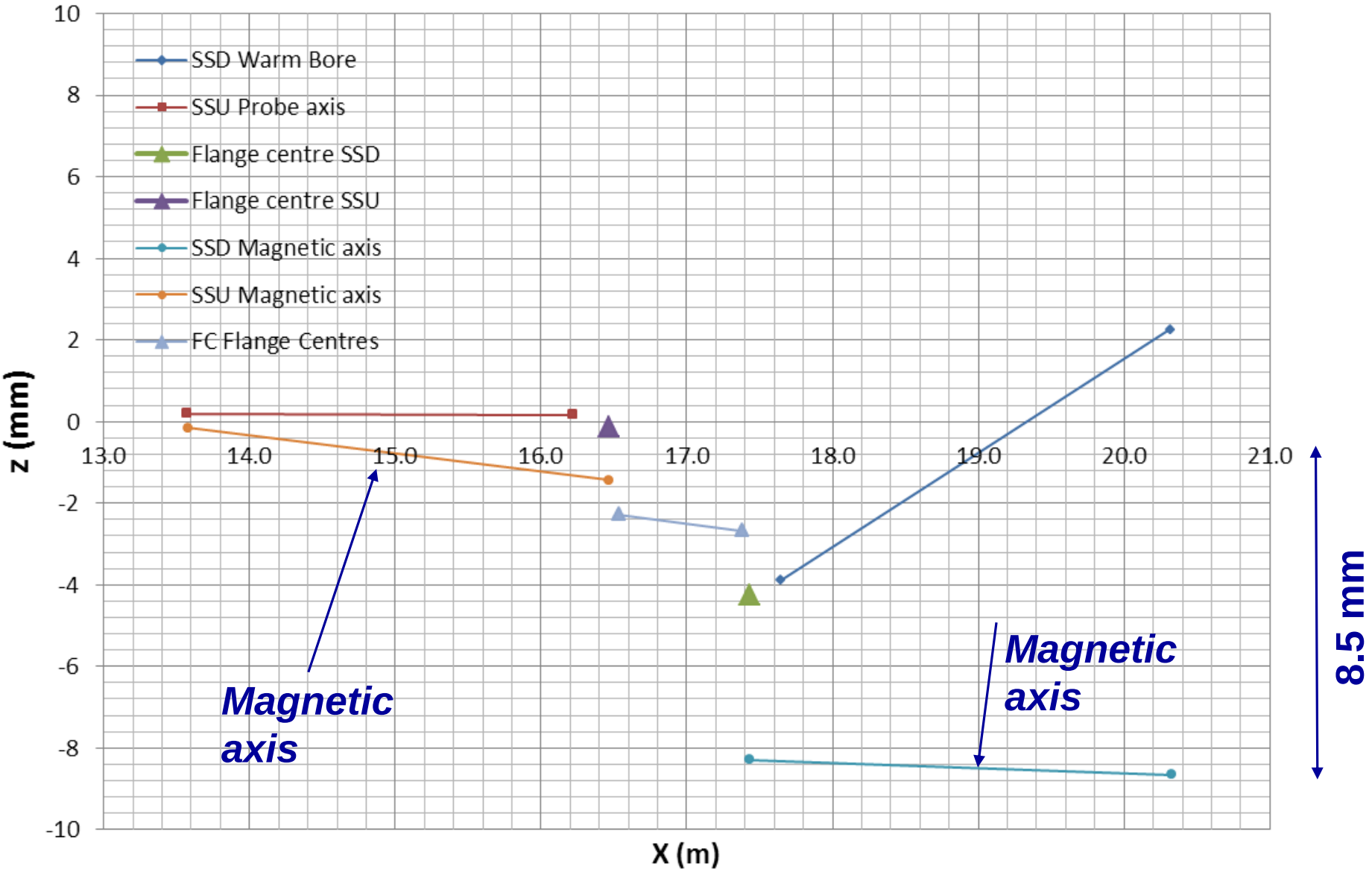
- **Assume:**
  - **We trust the results of the mapping**
    - ***Some details still to be understood***
  - **We understand the surveys**
    - ***Ditto***
  - **We trust the surveyors**

- **Add the real Hall survey of modules**
  - **How do the axes align in real life?**
    - **Ambiguous as to whether FC2 survey was before or after bolting modules together**

PLAN (HALL COORDINATES)



ELEVATION (HALL COORDINATES)



SUMMARY

- Simultaneous mapping of four modules is bit of a nightmare
  - All dead-reckoning / no real calibration
- Learnt ~ as much about the mapper as the modules
- As far as we can tell
  - Axis of SSD is out of spec.
- As far as I can tell
  - Modules not well-aligned in the Hall
- Haven't yet had opportunity to look at fields
  - Comparison with nominal dimensions
    - (know there's a ~1.5% discrepancy for FCs)
- TBC