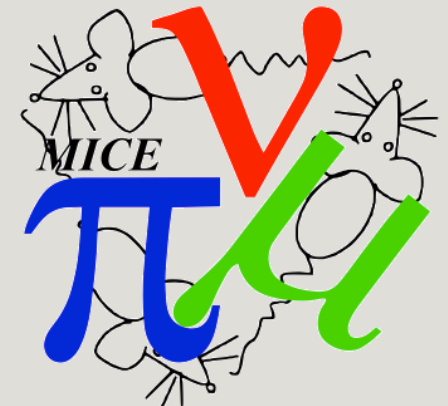


FIELD MAPPING

V. Blackmore

CM38

23rd February 2014



There is a lot of information in these slides, and not enough time to say it all. A lot of this will be revisited in future analysis meetings.

I have added notes to most slides (if you download the .ppt version), so they should be understandable “offline.”

As for now, we'll see just how far we get...

Contents

Survey plots presented at CM37.

Today:

- 4** Coordinate systems
- 17** Effect of the shielding plate
- 24** Linearity of field with current
- 29** Residual magnetic field
- 41** Probe Jitter
- 48** Hysteresis
- 50** Magnetic axis fits

Mapped Currents

Mode	% of I_{\max}	I_{M1} (A)	I_{M2} (A)	I_{E1} (A)	I_C (A)	I_{E2} (A)
Sol (Solenoid)	100	281	256	234	274	253
	95	266.95	243.20	222.30	260.30	240.35
	80	224.80	204.80	187.20	219.20	202.40
	50	140.50	128.00	117.00	137.00	126.50

Flip	100	265	280	234	278	249
	95	251.75	266.00	222.30	264.10	236.55
	80	212.00	224.00	287.20	222.40	199.20
	50	132.50	140.00	117.00	139.00	124.50

Runs cover the above currents, plus:

- 0A measurements (residual field)
- 30A individual coil measurements (superposition)
- With and without Virostek plate

A lot of data

COORDINATE SYSTEMS

Until the end of this talk...

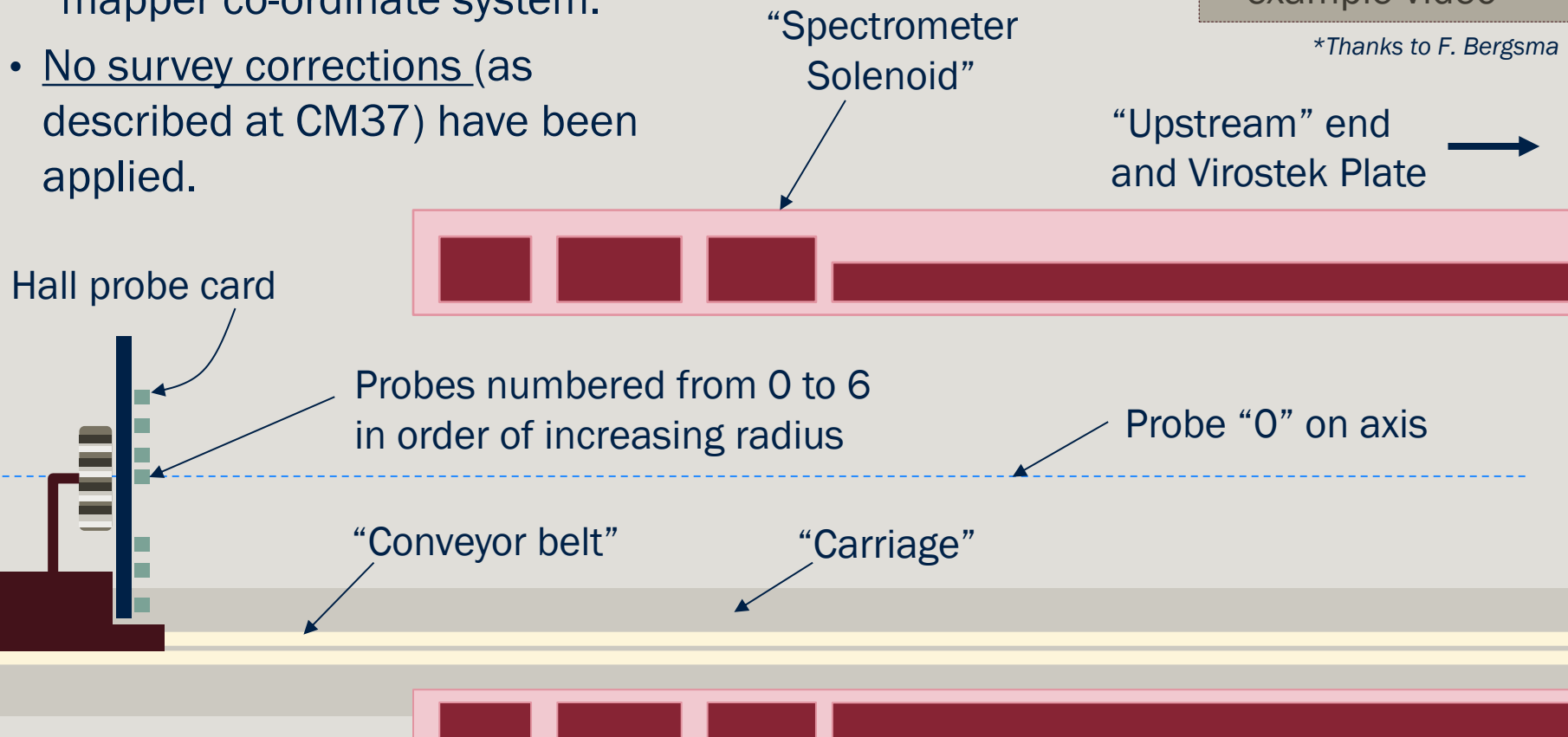
The “Mapper” Co-ordinate System

- *To avoid changing too many variables at once, all of the data (until it says otherwise) is in the “mapper co-ordinate system.”*
- No survey corrections (as described at CM37) have been applied.

Mapper: Movement
example video*

Mapper: Rotation
example video *

**Thanks to F. Bergsma*

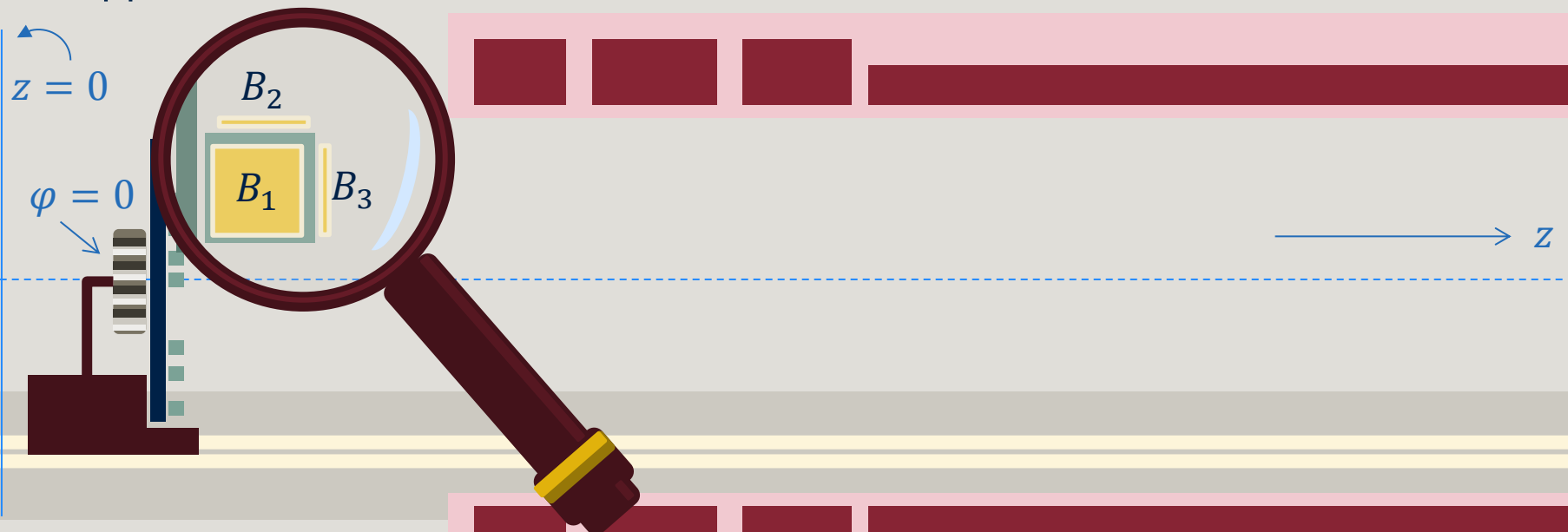


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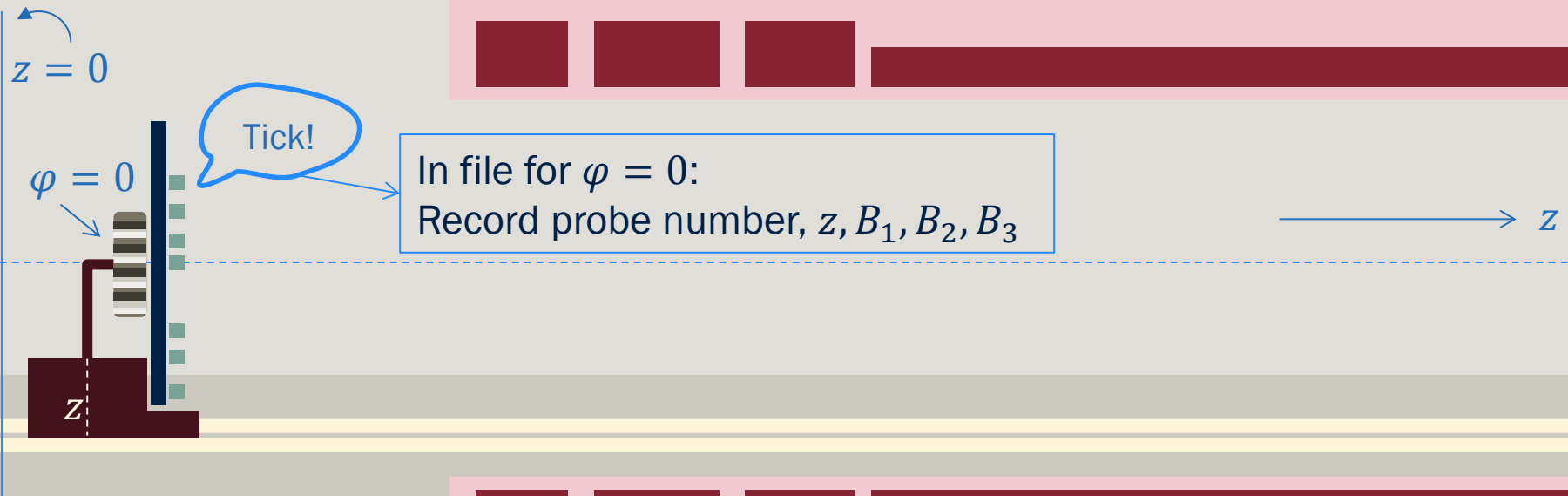


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example video

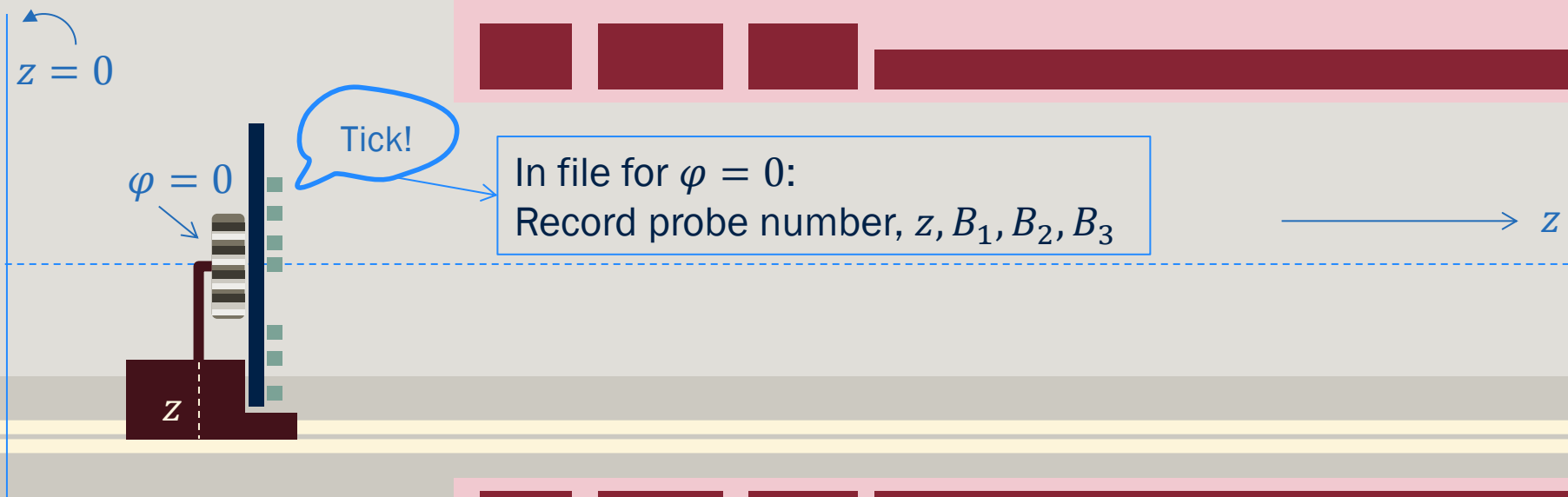


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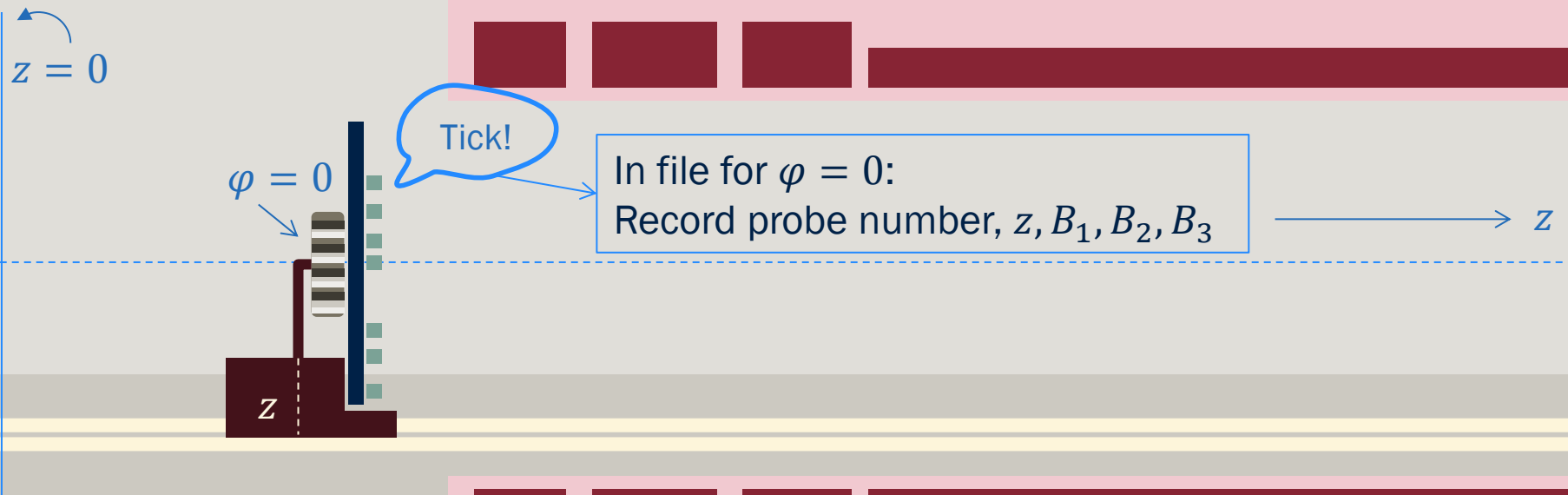


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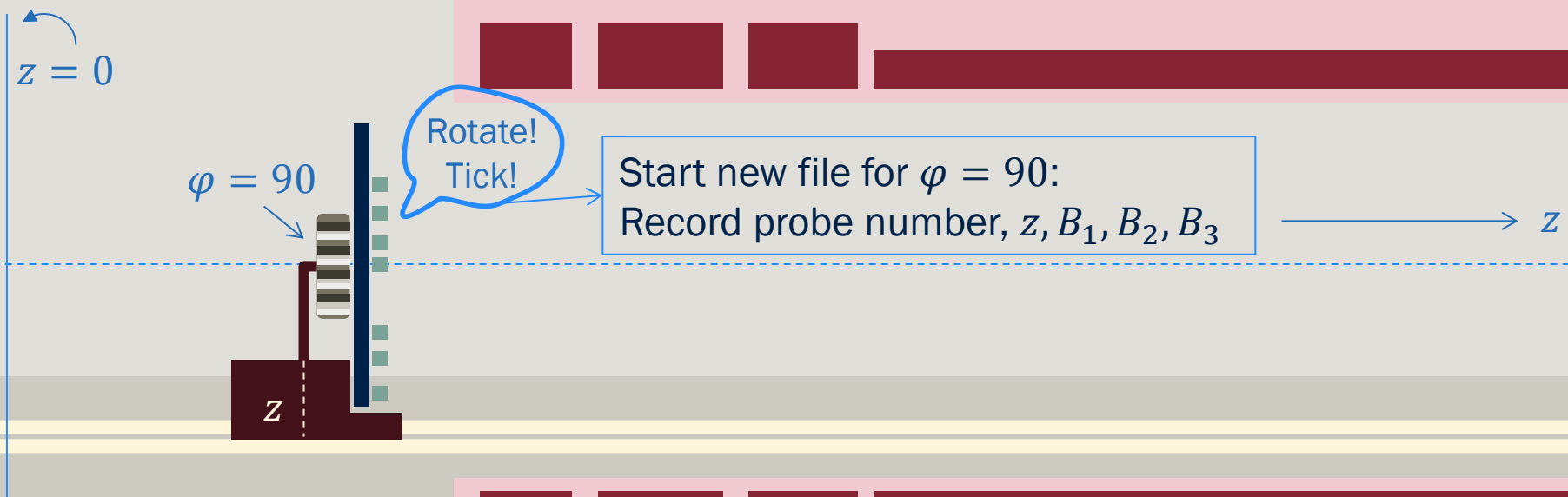


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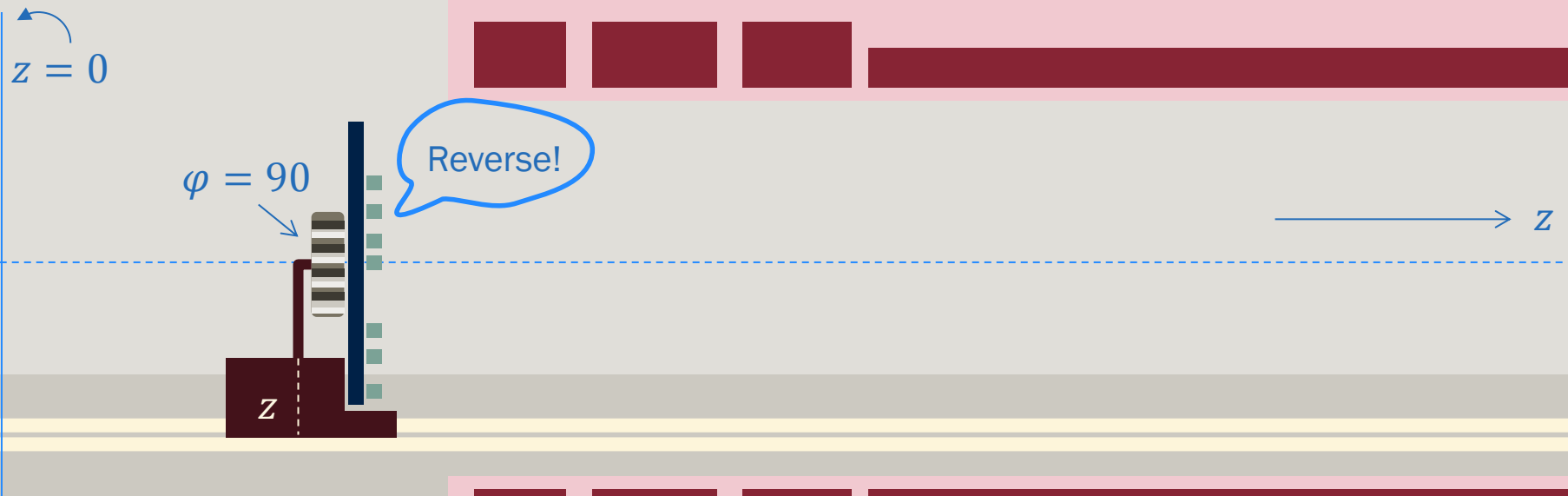


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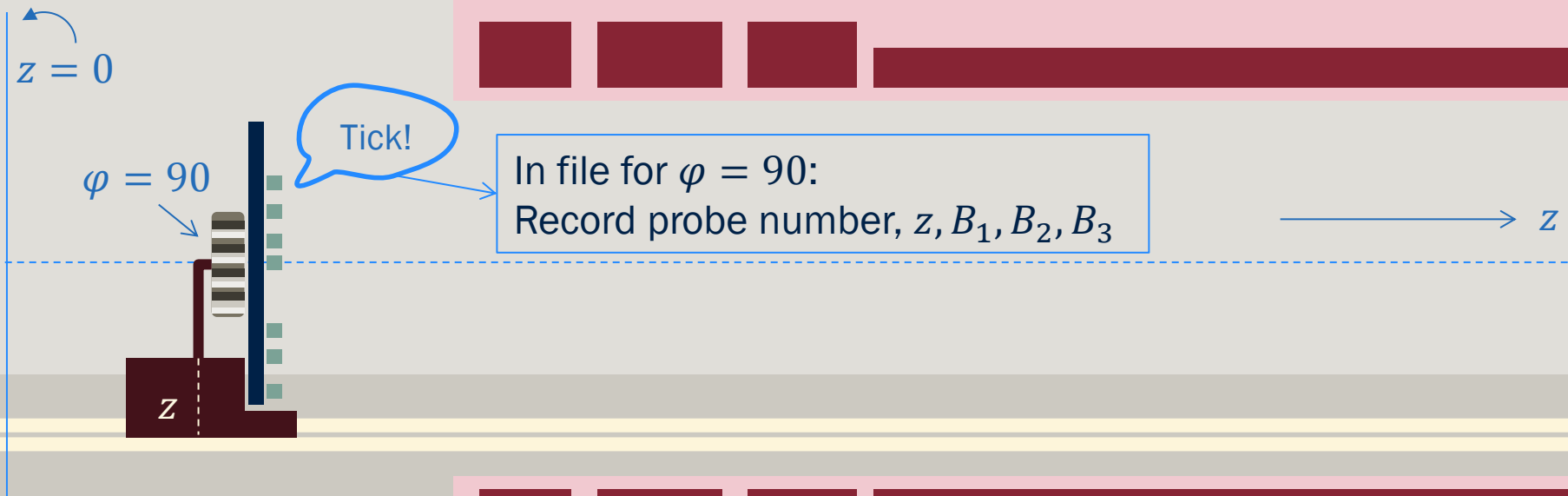


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example video

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example video

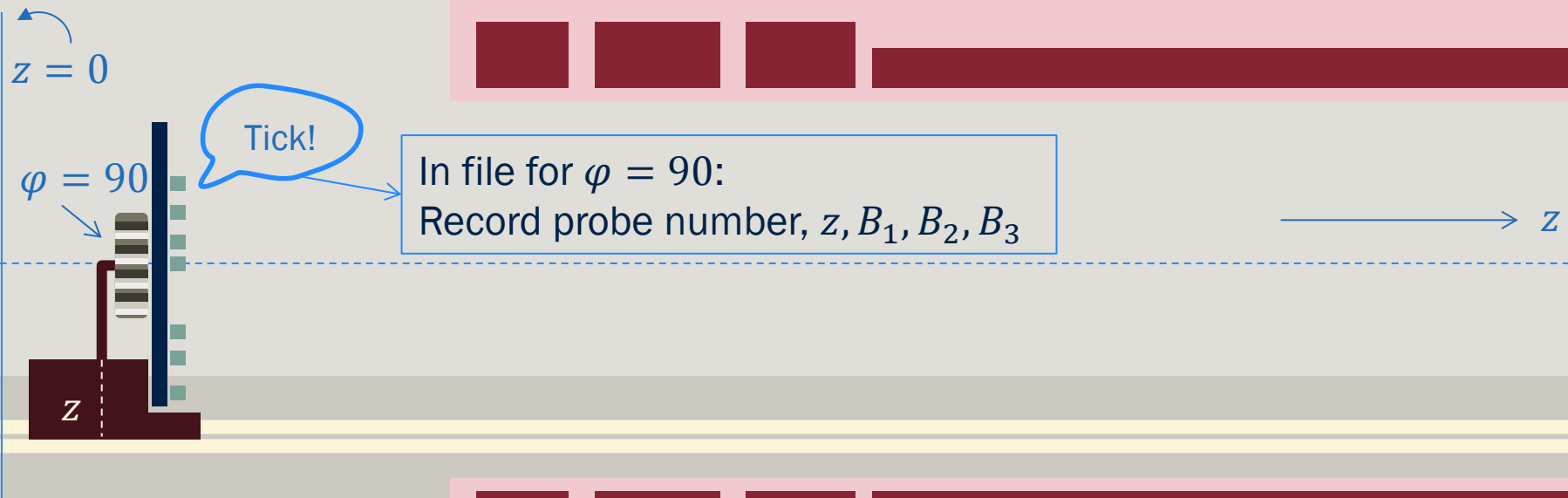


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example video

Mapper: Rotation
example video

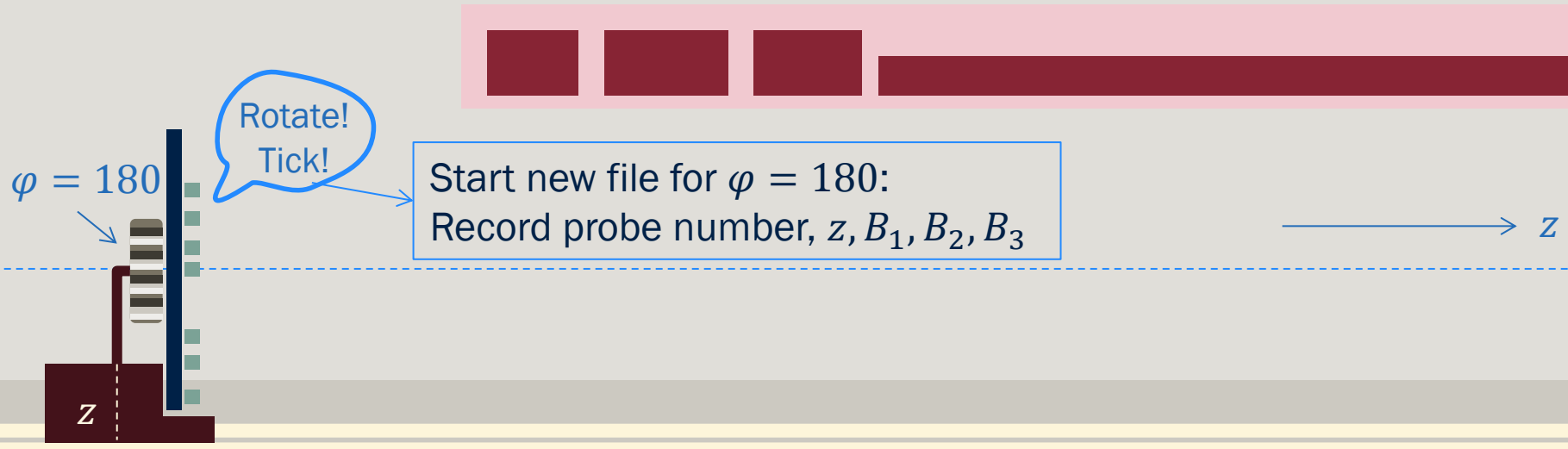


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Mapper: Movement
example video

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example video

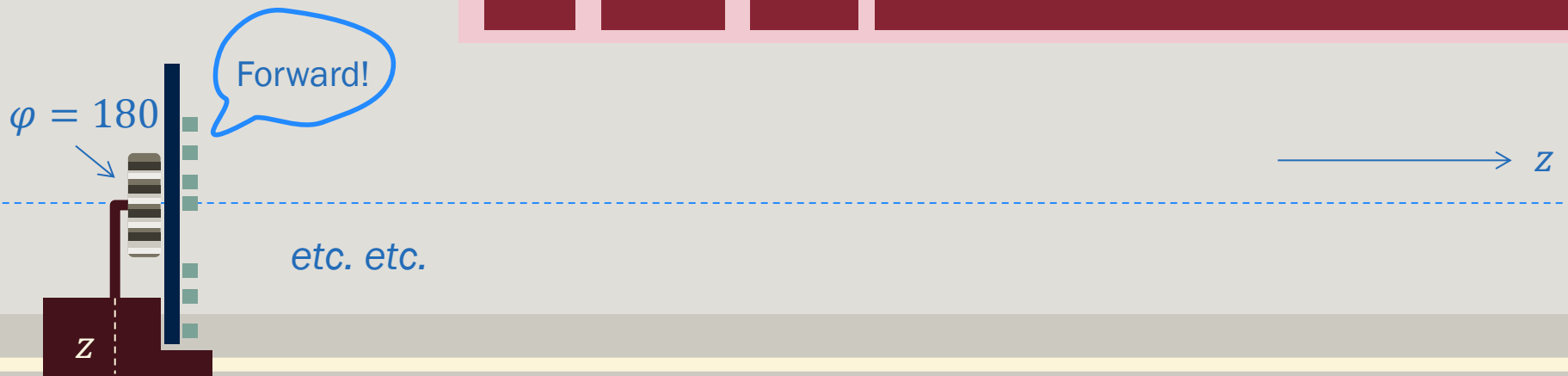


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example video

Mapper: Rotation
example video



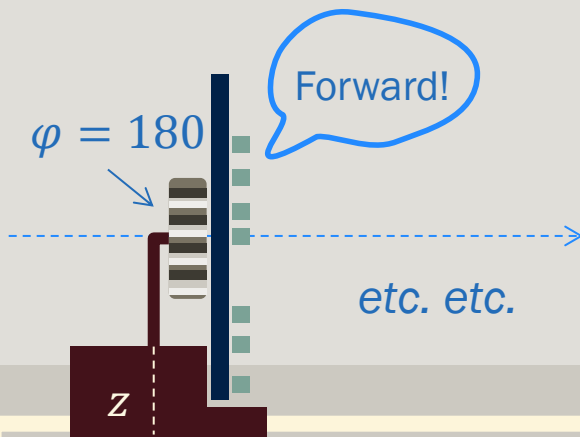
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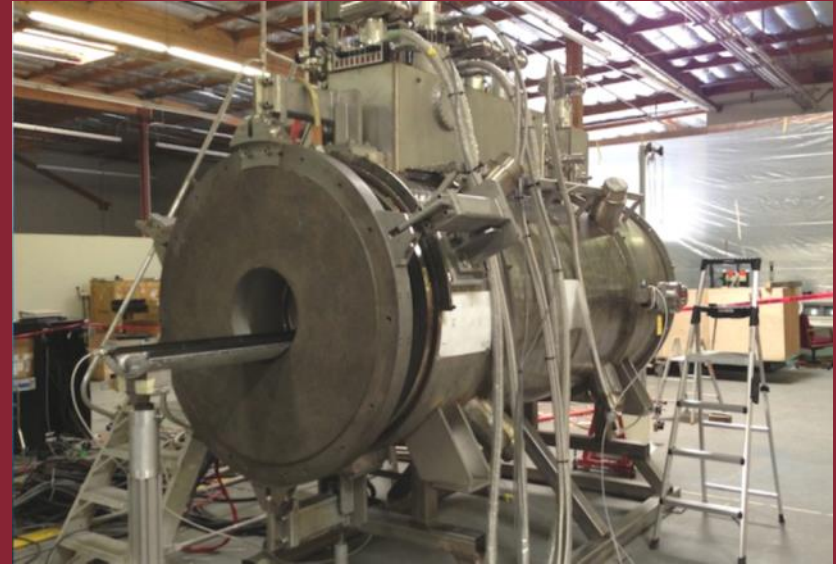
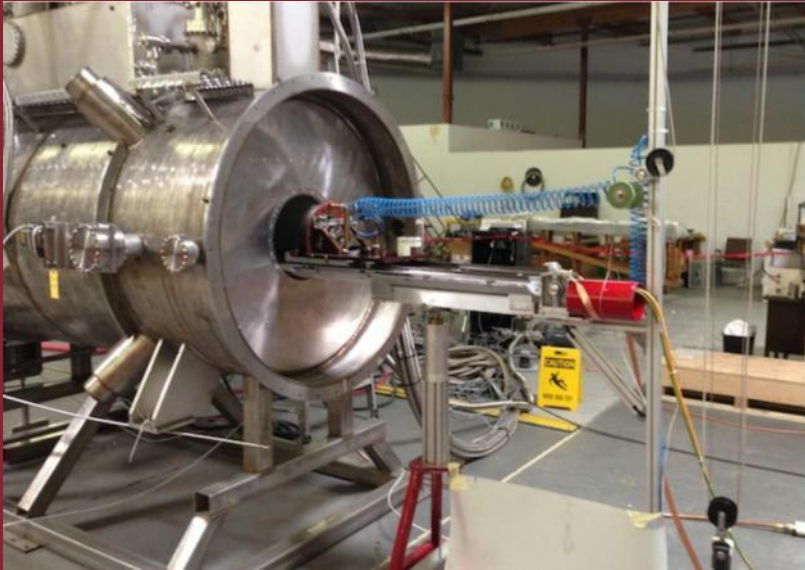
Mapper: Movement
example video

Mapper: Rotation
example video

- Each data “set” is taken over the same range of z in the same number of steps, and similarly for φ
- Each φ is recorded in a separate data file
- I do combine these files
- I do rotate $B_1, B_2 \rightarrow B_x, B_y$, and keep $B_3 \equiv B_z$ (see “backup slides”)
- z is what the mapper reports



Mapper $z = 0$ at this side



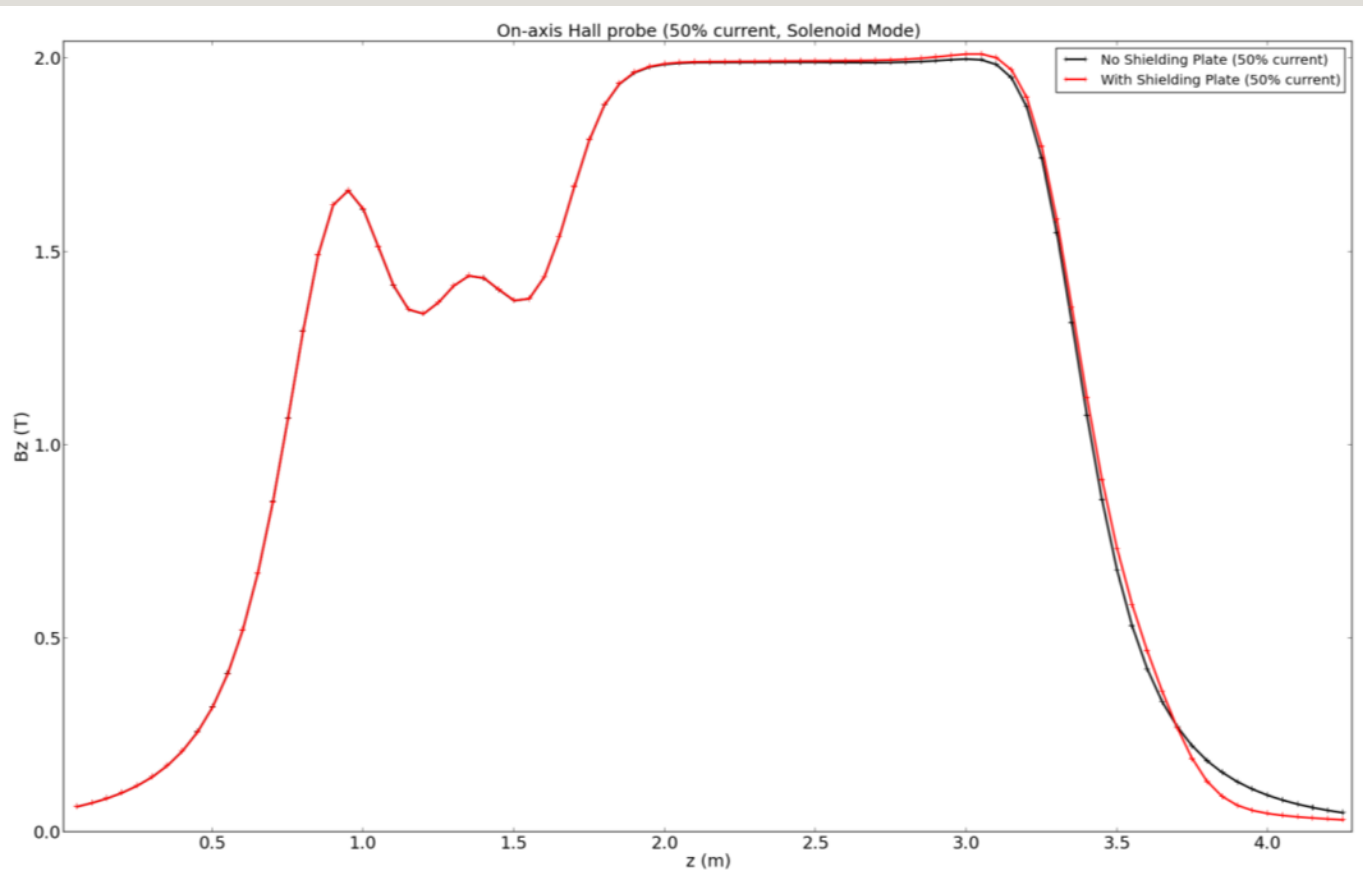
*
Mapper $z \sim 4\text{m}$

THE SHIELDING PLATE

Compare identical measurements with and without the shielding (“Virostek”) plate

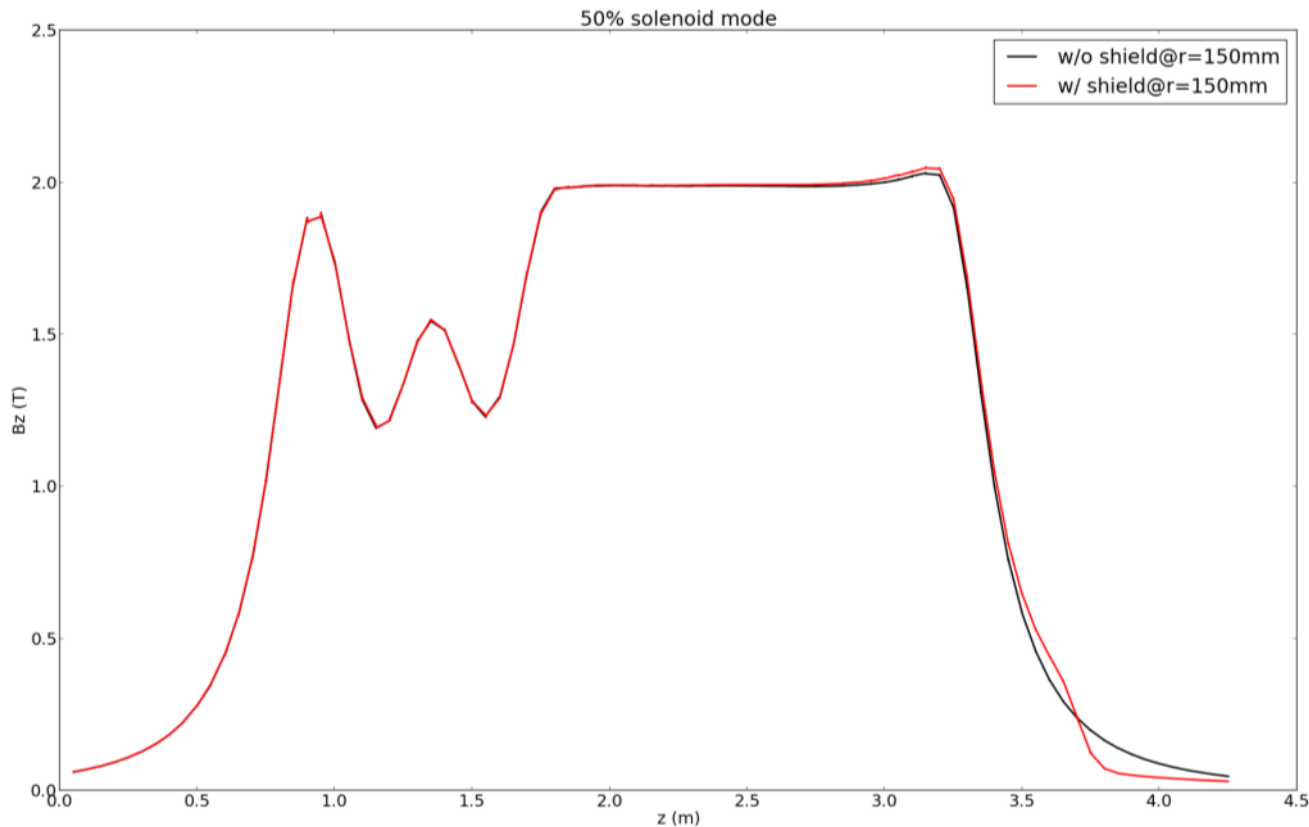
“Identical”: Same currents

Let's play Spot the Shielding Plate



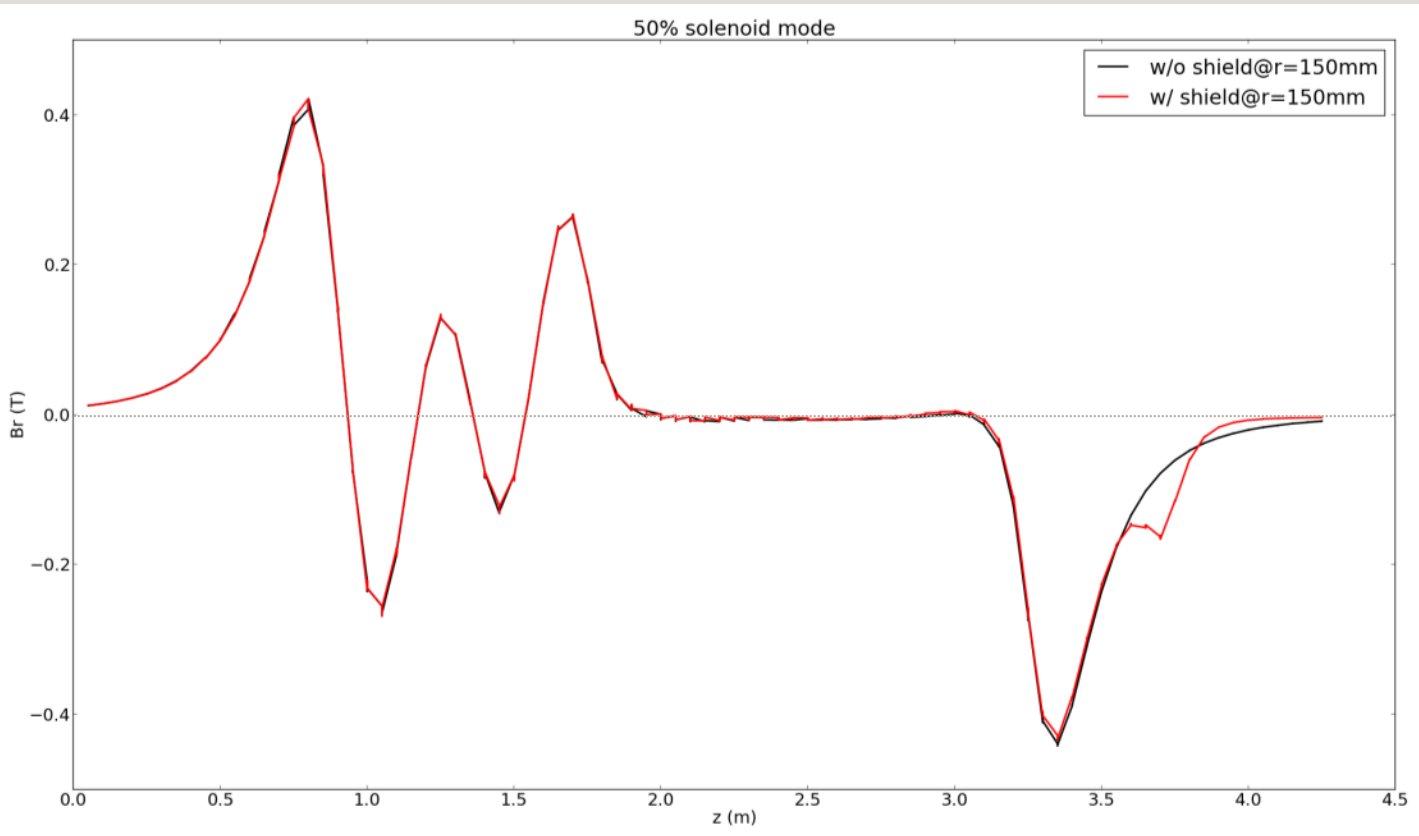
- “On-axis” probe, plotting B_z (i.e. B_3) w.r.t. mappers recorded z position at 4 angles of φ
- Measurements at 50% current, Solenoid Mode (will come back to linearity)

Let's play Spot the Shielding Plate



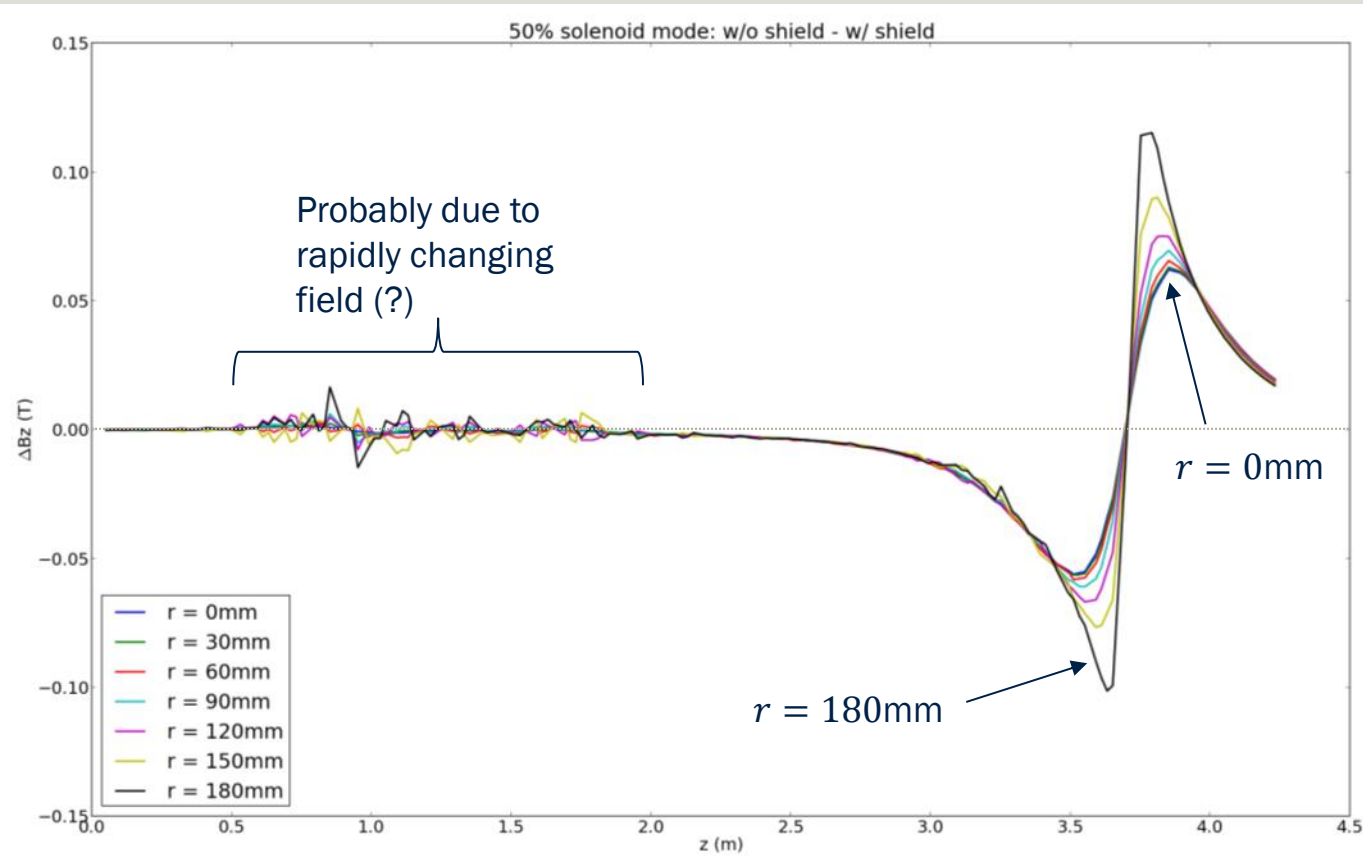
- 150mm probe, plotting B_z (i.e. B_3) w.r.t. mappers recorded z position at 4 angles of φ
- Measurements at 50% current, Solenoid Mode (will come back to linearity)

Let's play Spot the Shielding Plate



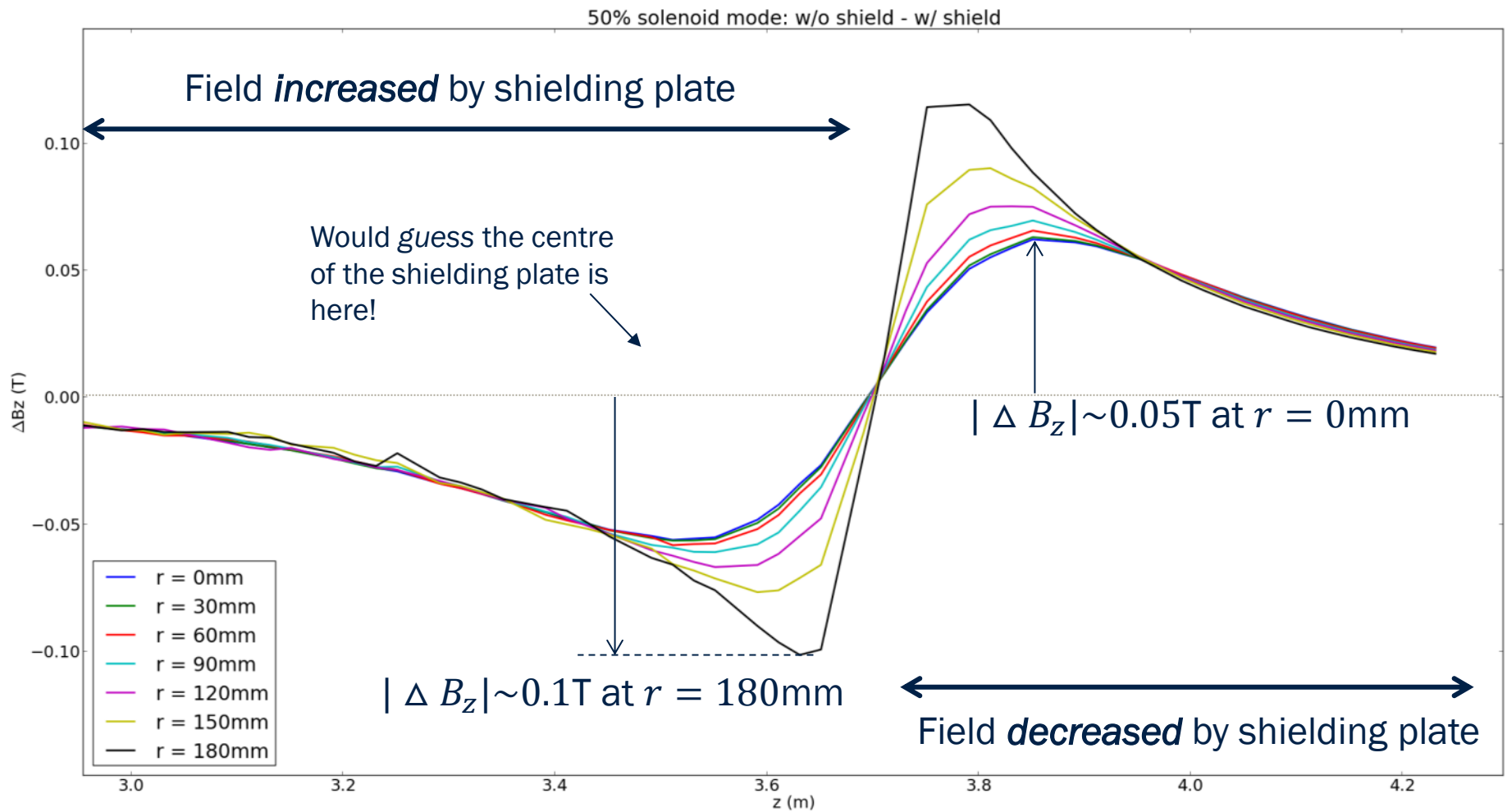
- **150mm** probe, plotting B_r w.r.t. mappers recorded z position at 4 angles of φ
- Measurements at 50% current, Solenoid Mode (will come back to linearity)

Let's play Spot the Difference: B_z

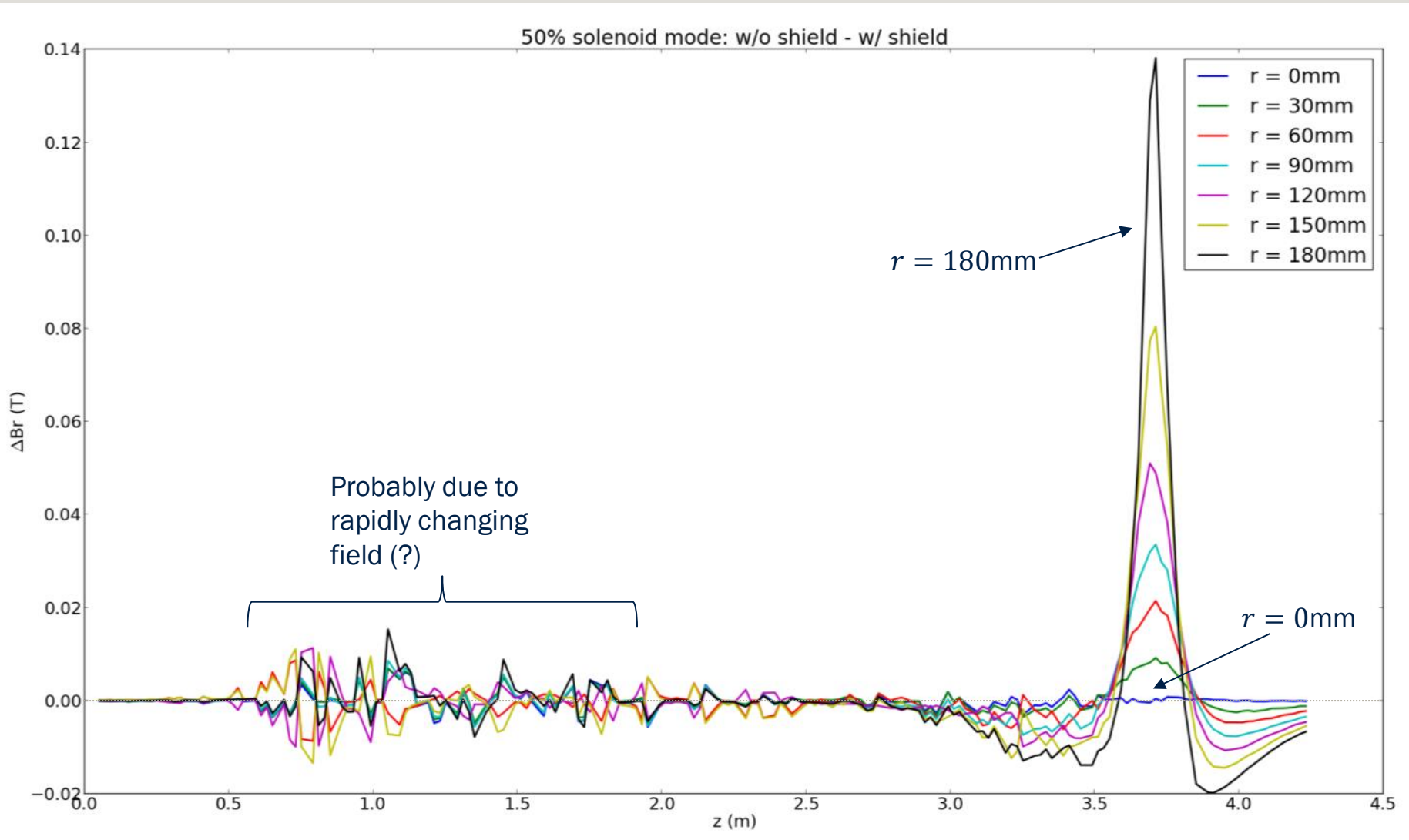


- B_z is interpolated along the z -axis
- Compare B_z at fixed z -points
- From $0.5 \leq z \leq 2.0$ the field changes quickly
- “Noise” in this region *probably* due to rapidly changing field

Let's play Spot the Difference (Again)



Let's play Spot the Difference: B_r

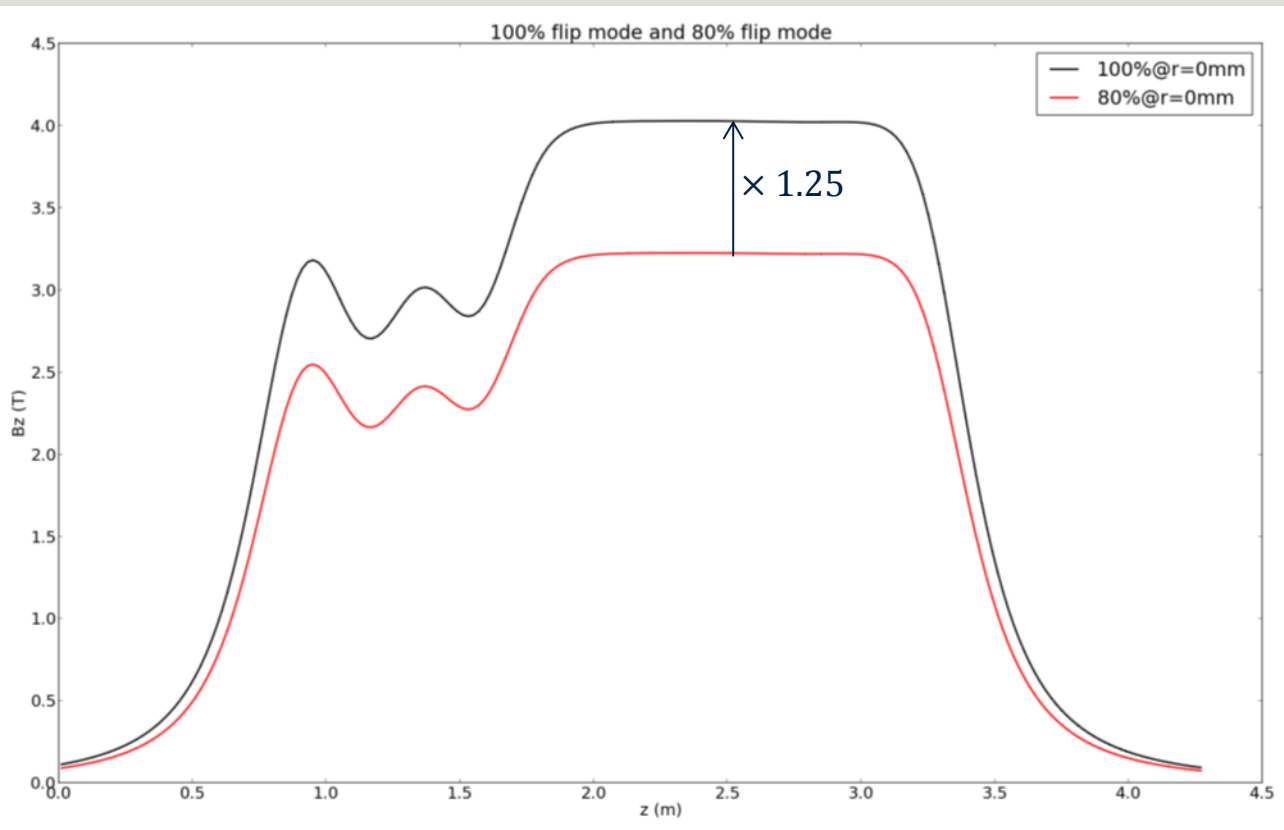


FIELD LINEARITY

With no shielding plate, field should be linear with current.

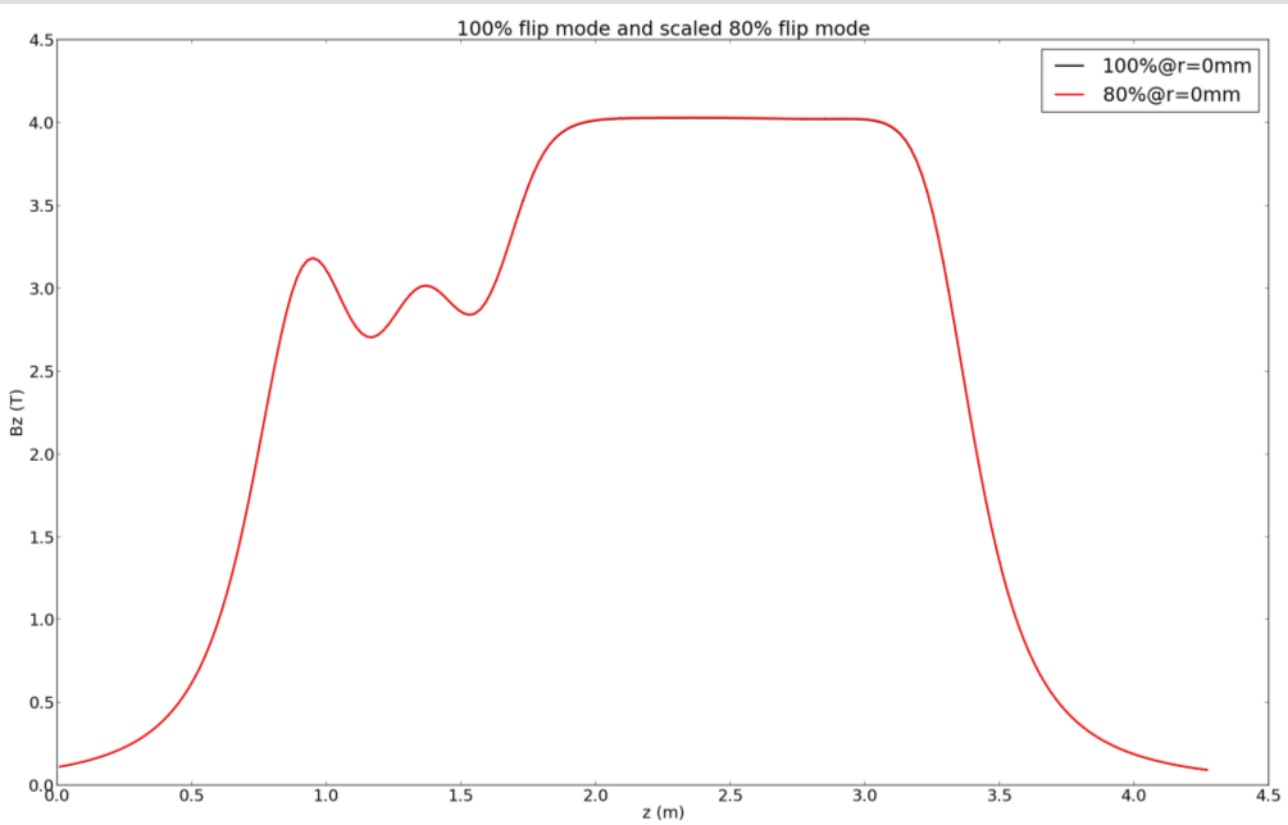
With shielding plate, field may be non-linear with current

Without the shielding plate...



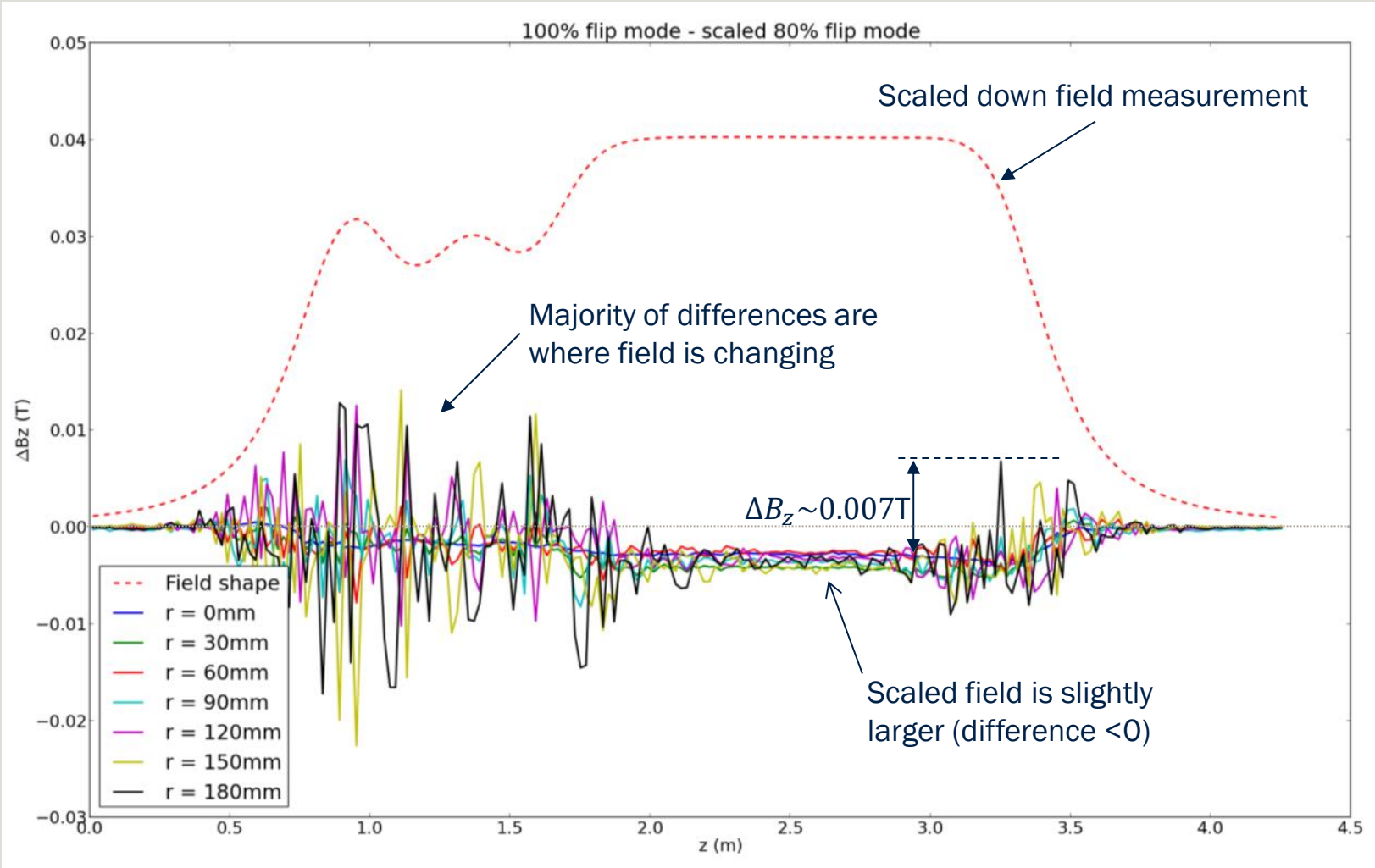
- (Black) 100% current in Flip Mode
- (Red) 80% current in Flip Mode
- Scale up 80% measurements and compare...

Without the shielding plate...

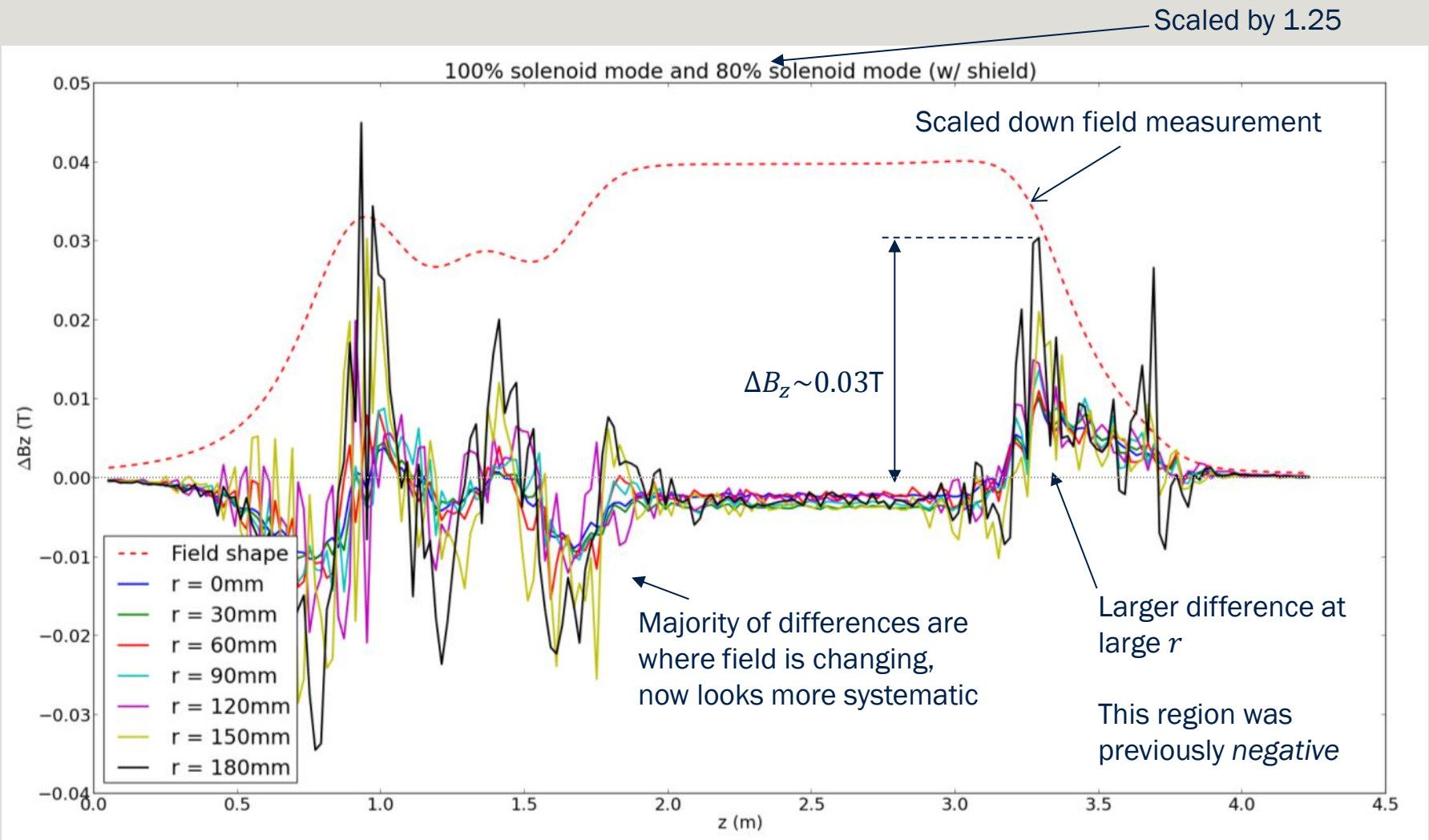


- (Black) 100% current in Flip Mode
- (Red) 80% current in Flip Mode
- Scale up 80% measurements and compare...
- First impression is good.

Without the shielding plate...



With the shielding plate...



RESIDUAL FIELD

We do have data sets that allow us to naively look at the residual field

Q: Does the residual field change depending on the previous operating current?

Residual Field Measurements

- Every day of measurements began/ended (or both) with a field map at “OA”
- Can compare measurements at 80/100% field and OA.
- Still using “mapper co-ordinates”
- Order of measurements does matter

Date (June)	% Current
7th	80% SM
10th	0%
10th	3.6% SM
11th	0%
11th	100% SM
13th	0%
19th	80% SM
19th	0%

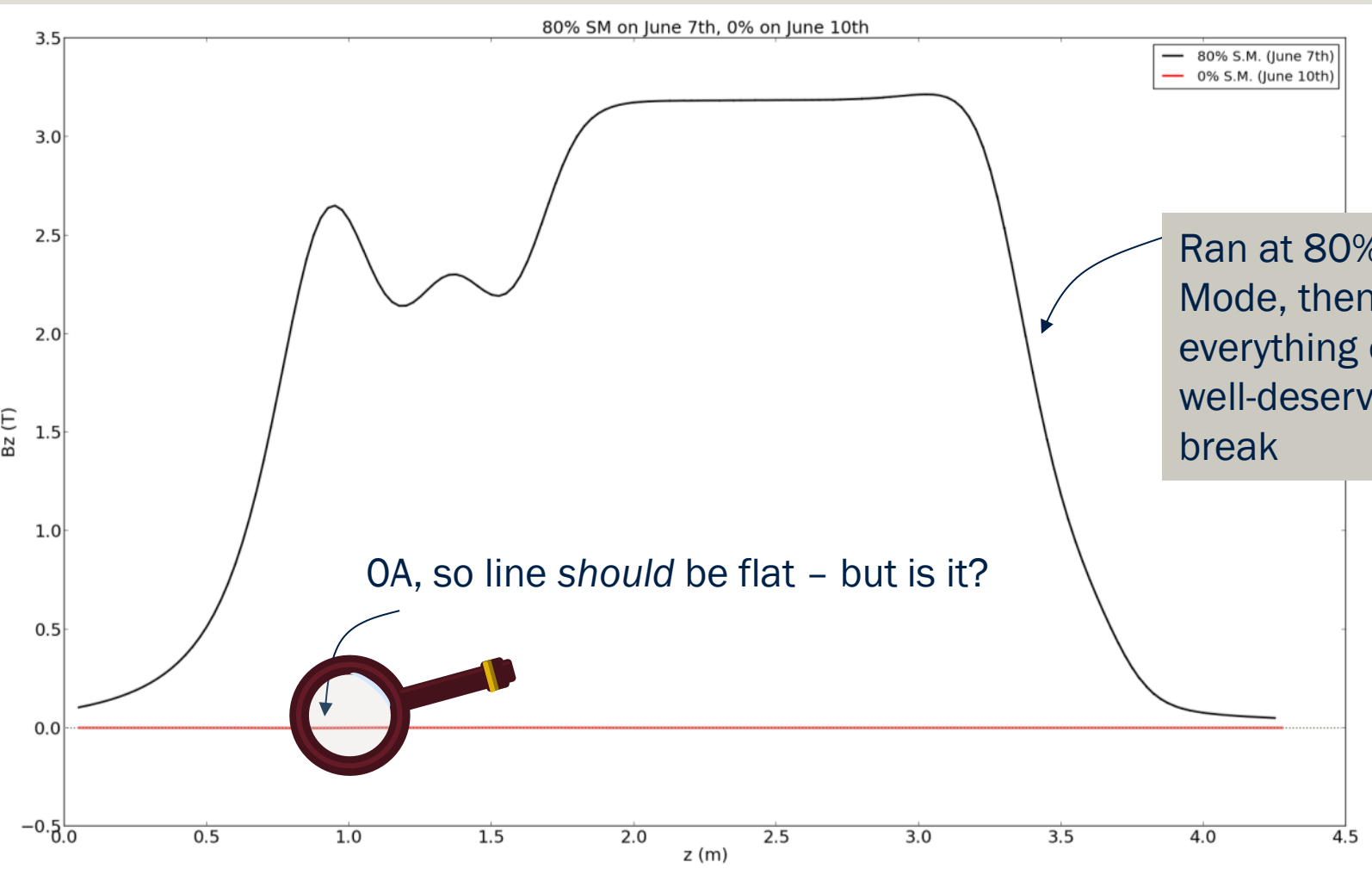
No intermediate measurements carried out between these pairs of data

Intermediate Flip Mode runs (not interspersed with OA data). Shielding plate removed 15th–16th June.

Colour-coded dots are meant to help those viewing later

On-axis probe only

7th—10th June: Previously at 80% Sol. Mode

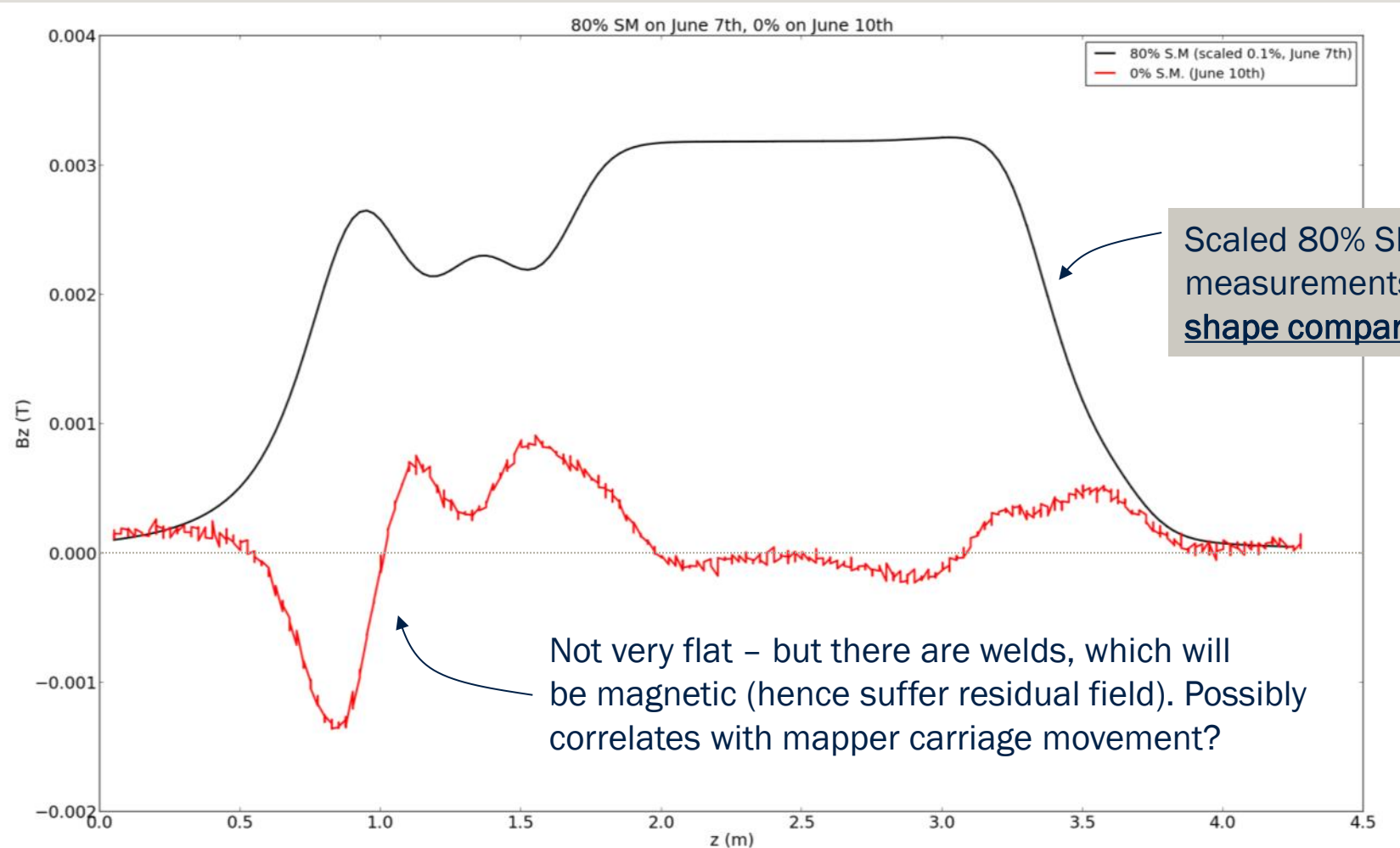


Ran at 80% Solenoid Mode, then turned everything off and took a well-deserved weekend break

7th—10th June:

Previously at 80% Sol. Mode

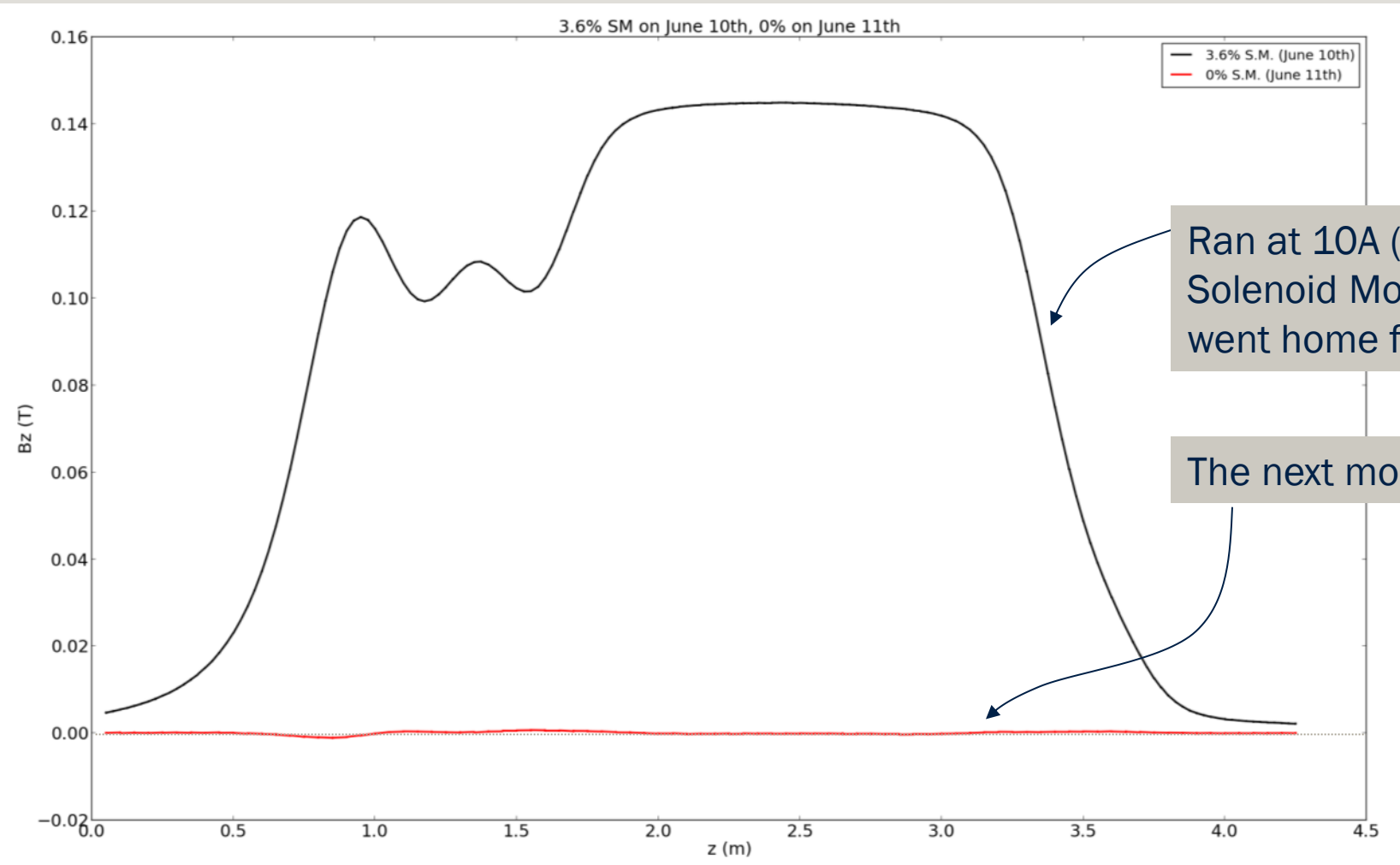
On-axis probe only



10th—11th June:

Previously at 3.6% Sol. Mode

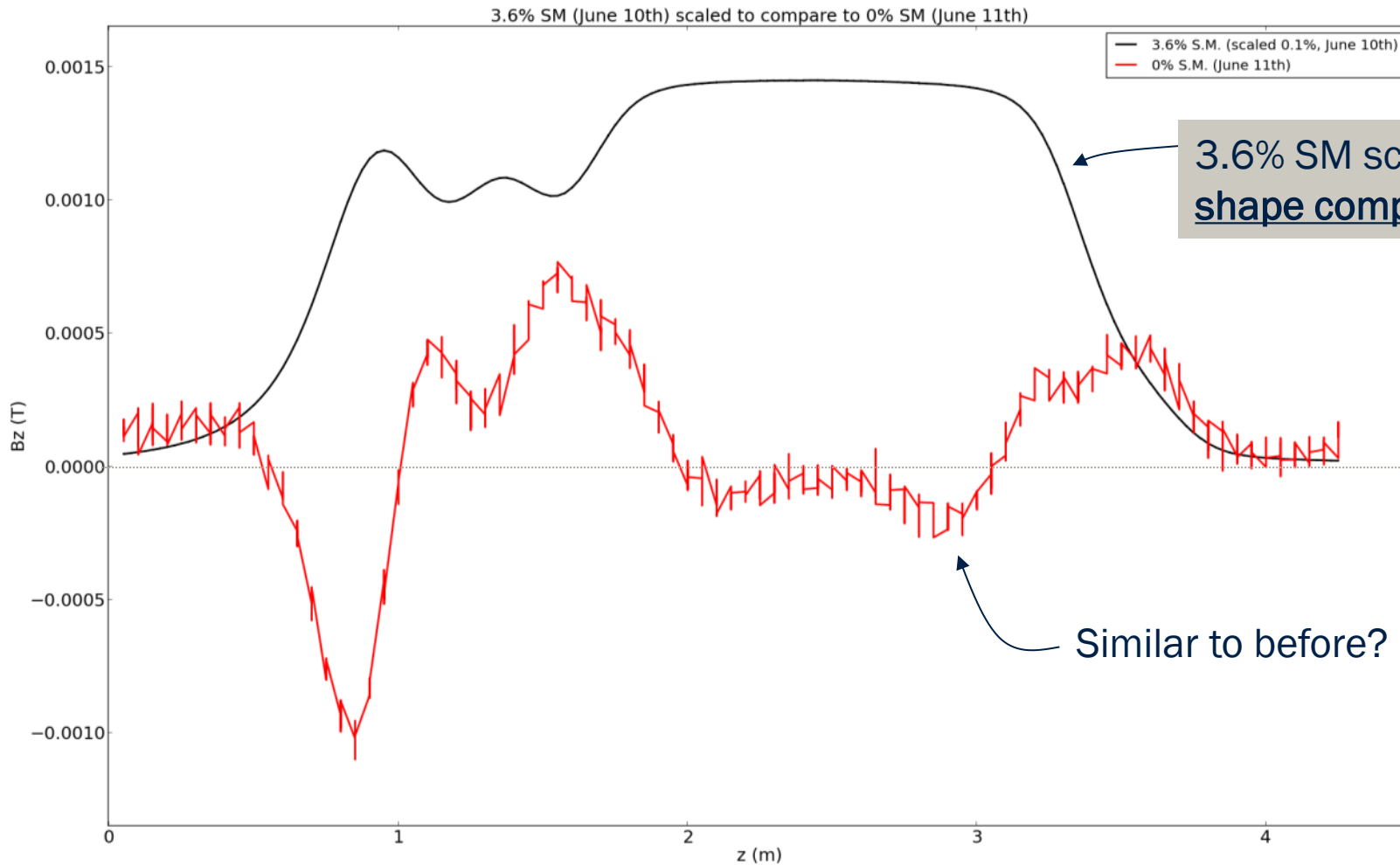
On-axis probe only



10th—11th June:

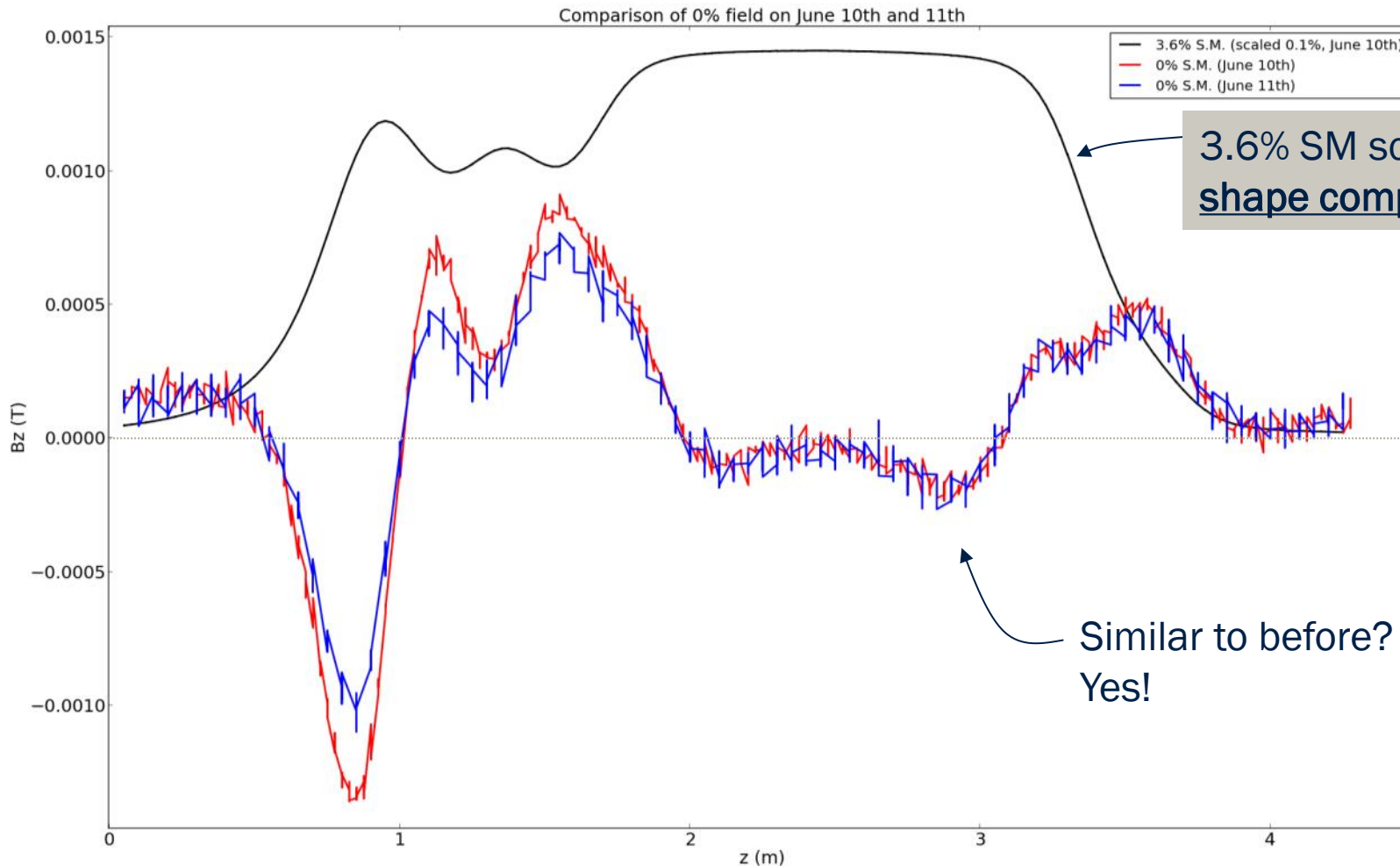
Previously at 3.6% Sol. Mode

On-axis probe only



10th—11th June:

Previously at 3.6% Sol. Mode

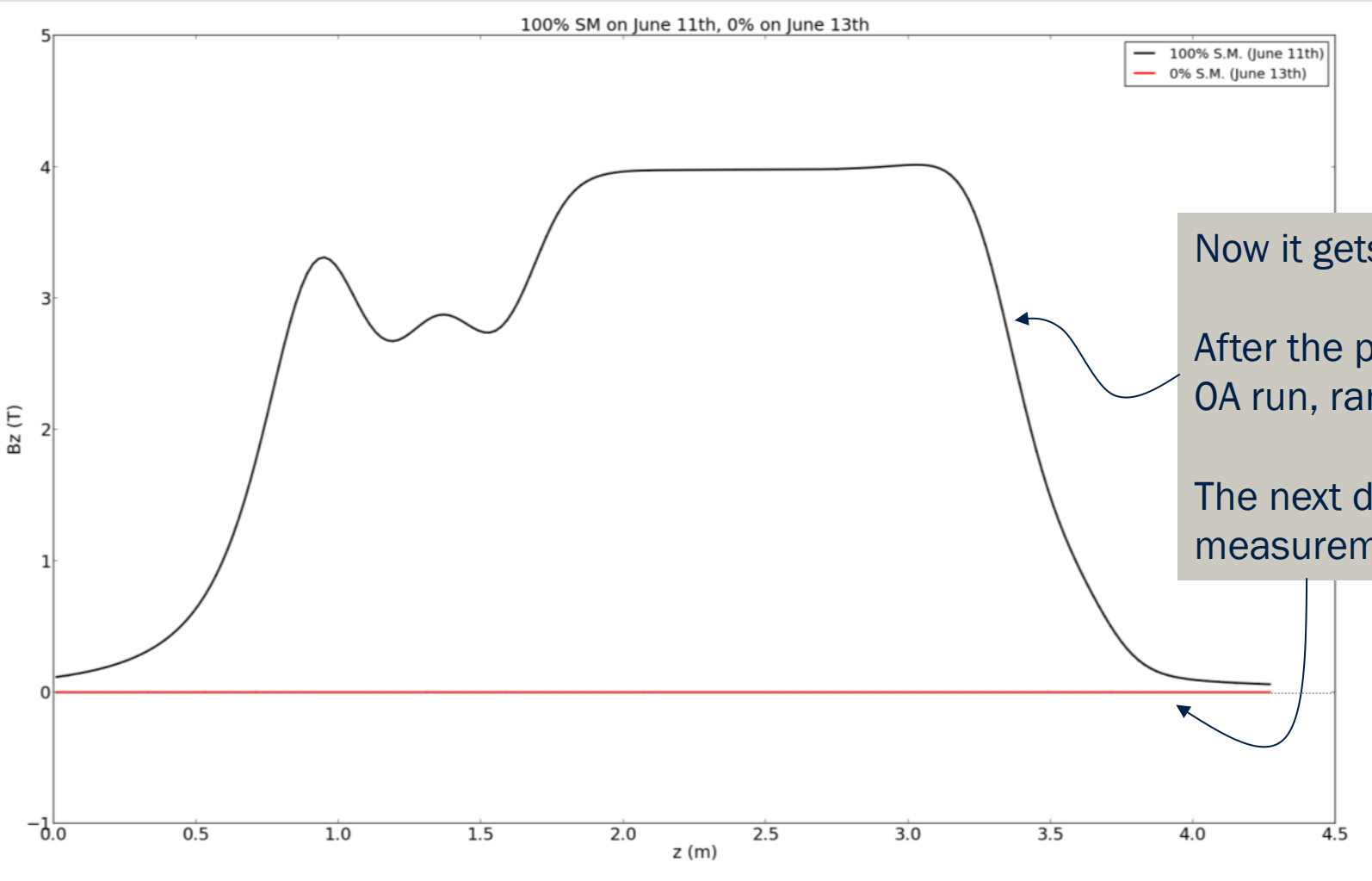


3.6% SM scaled for
shape comparison only

Similar to before?
Yes!

On-axis probe only

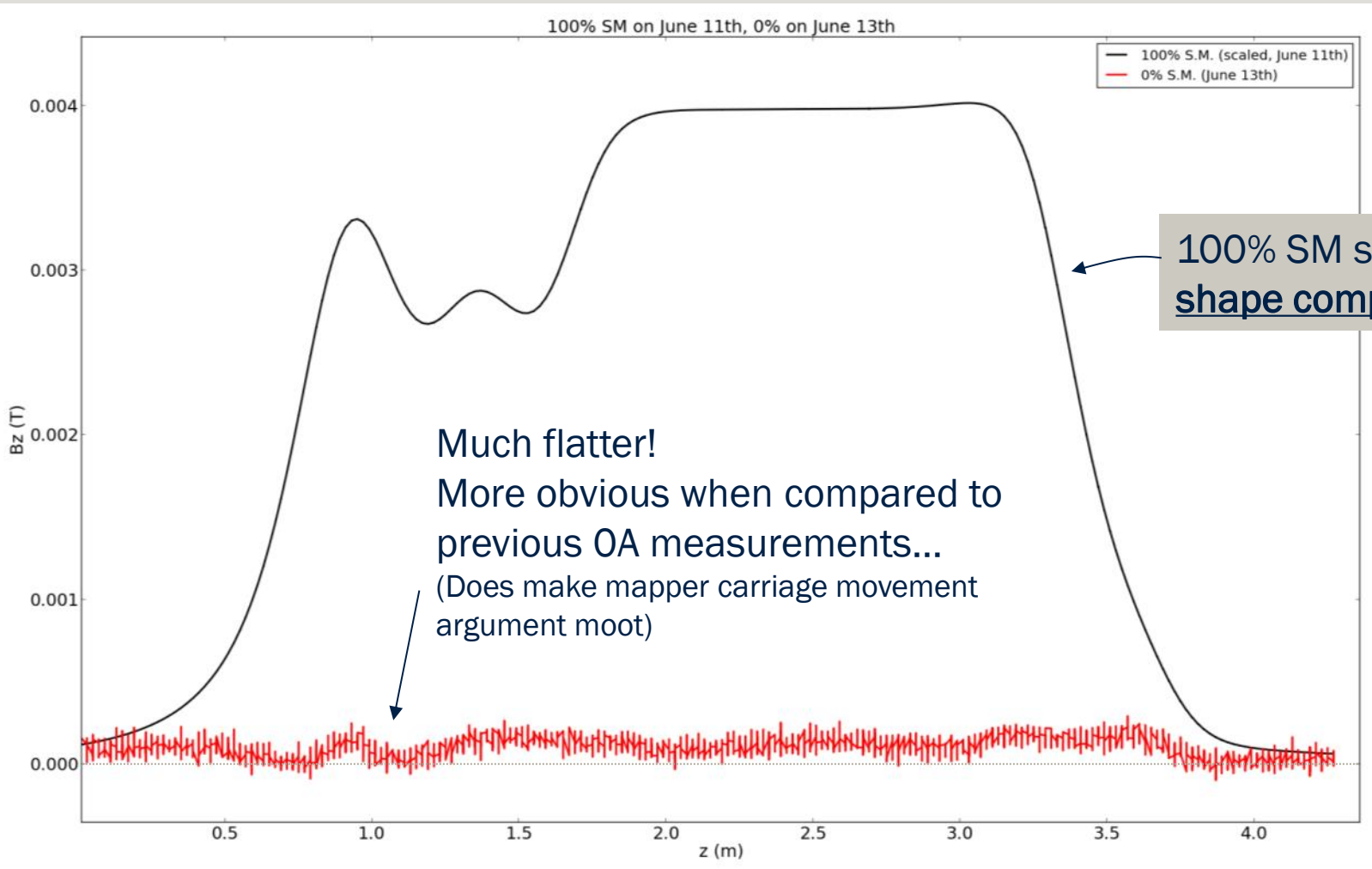
11th—13th June: Previously at 100% Sol. Mode



Now it gets interesting:
After the previous slide's OA run, ran at 100% SM.
The next day took a OA measurement...

11th—13th June:

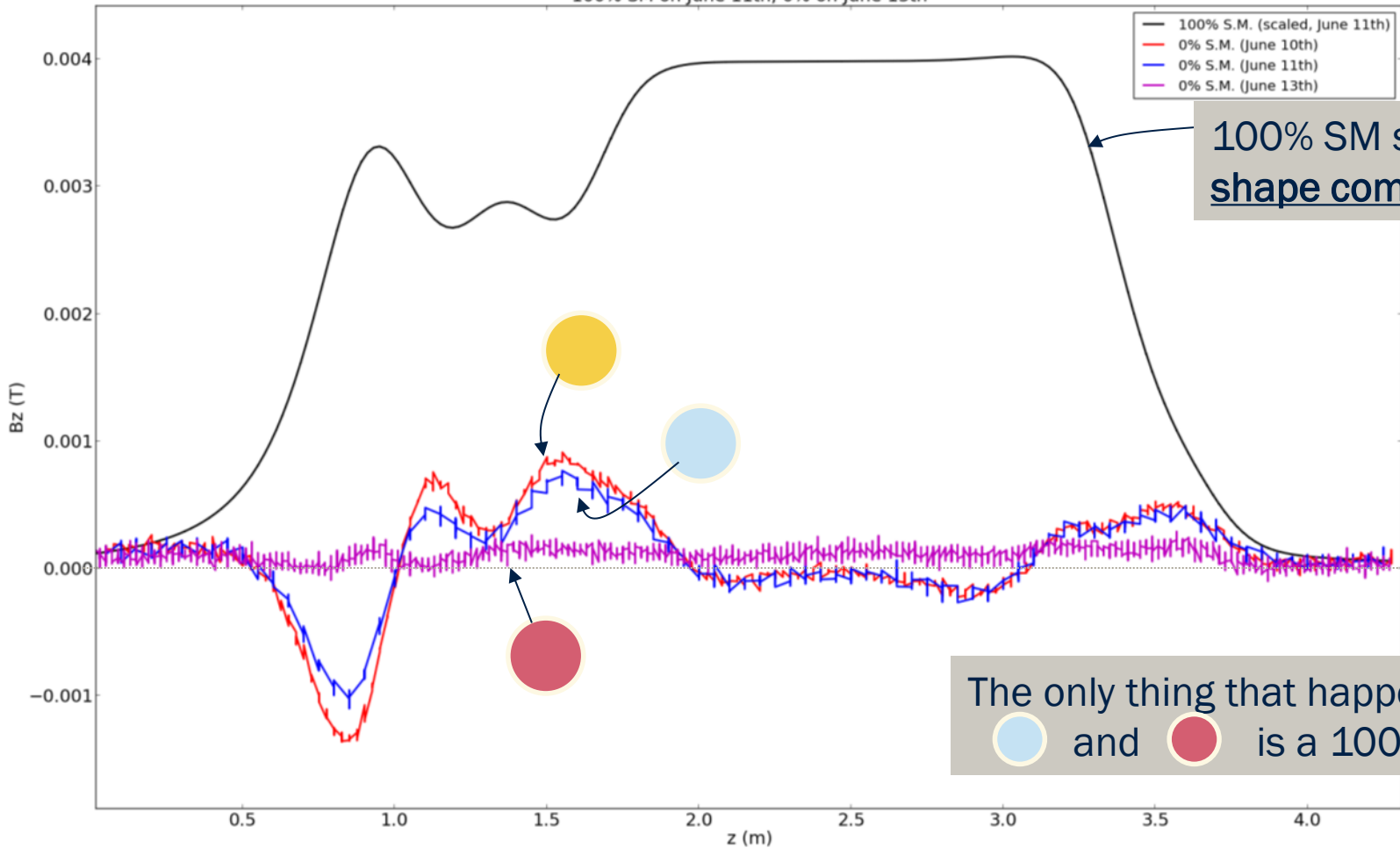
Previously at 100% Sol. Mode





On-axis probe only

11th—13th June: Previously at 100% Sol. Mode

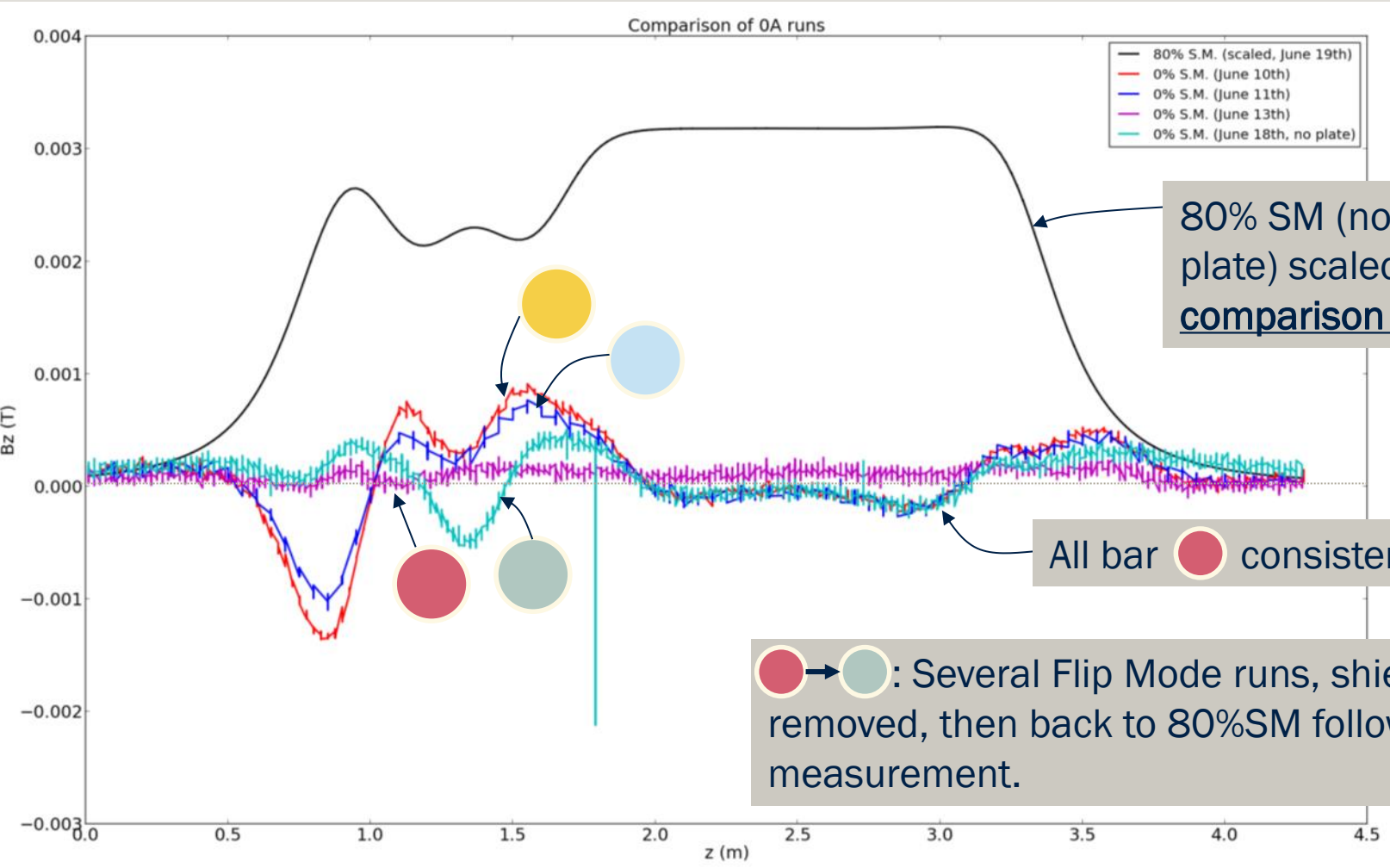
100% SM on June 11th, 0% on June 13th



100% SM scaled for shape comparison only



The only thing that happened between  and  is a 100% field run.

19th—19th June: Previously at 100% Sol. Mode

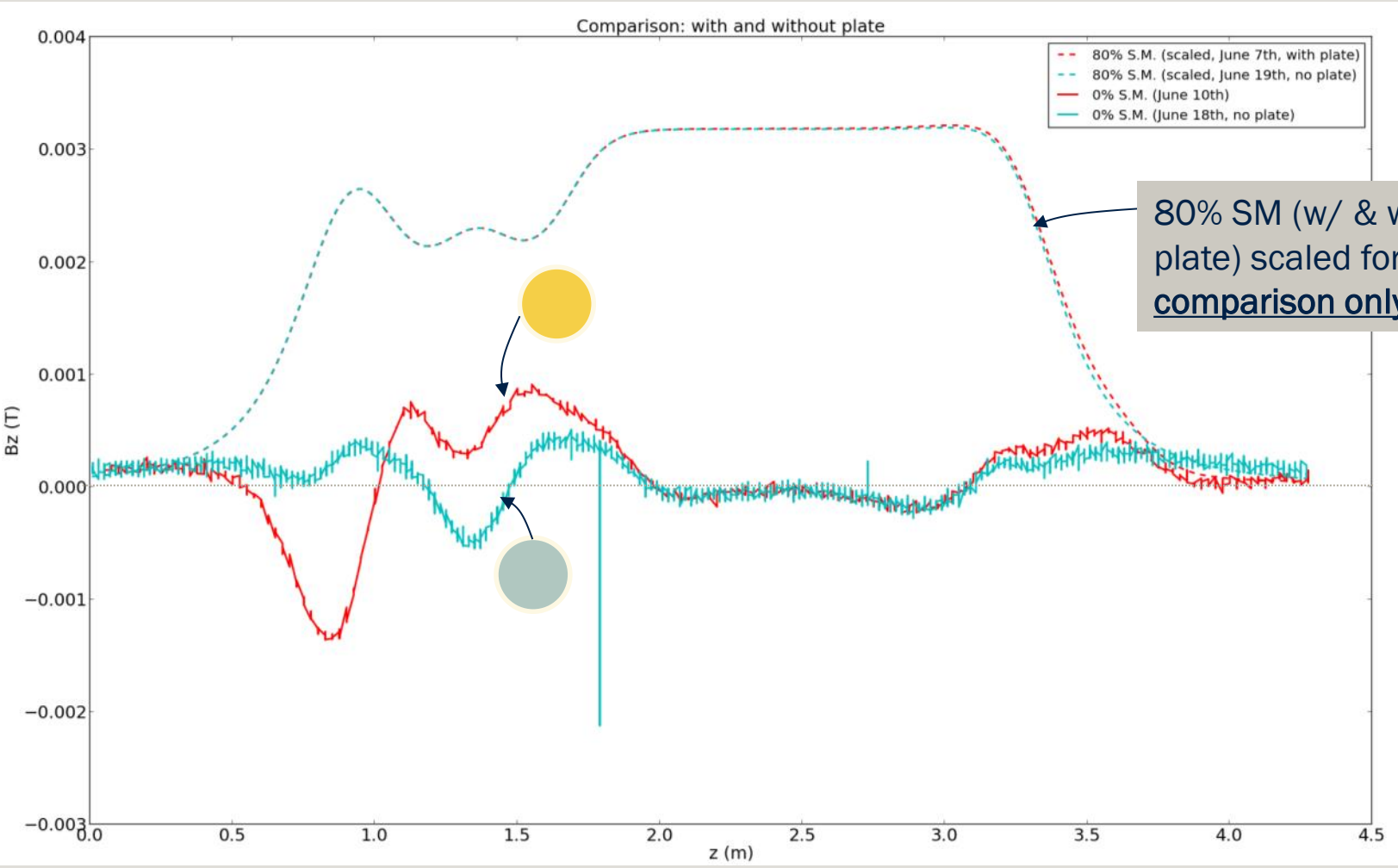


80% SM (no shielding plate) scaled for shape comparison only

All bar  consistent here

 → : Several Flip Mode runs, shielding plate removed, then back to 80%SM followed by OA measurement.

7th—19th June: Shielding plate differences



PROBE JITTER

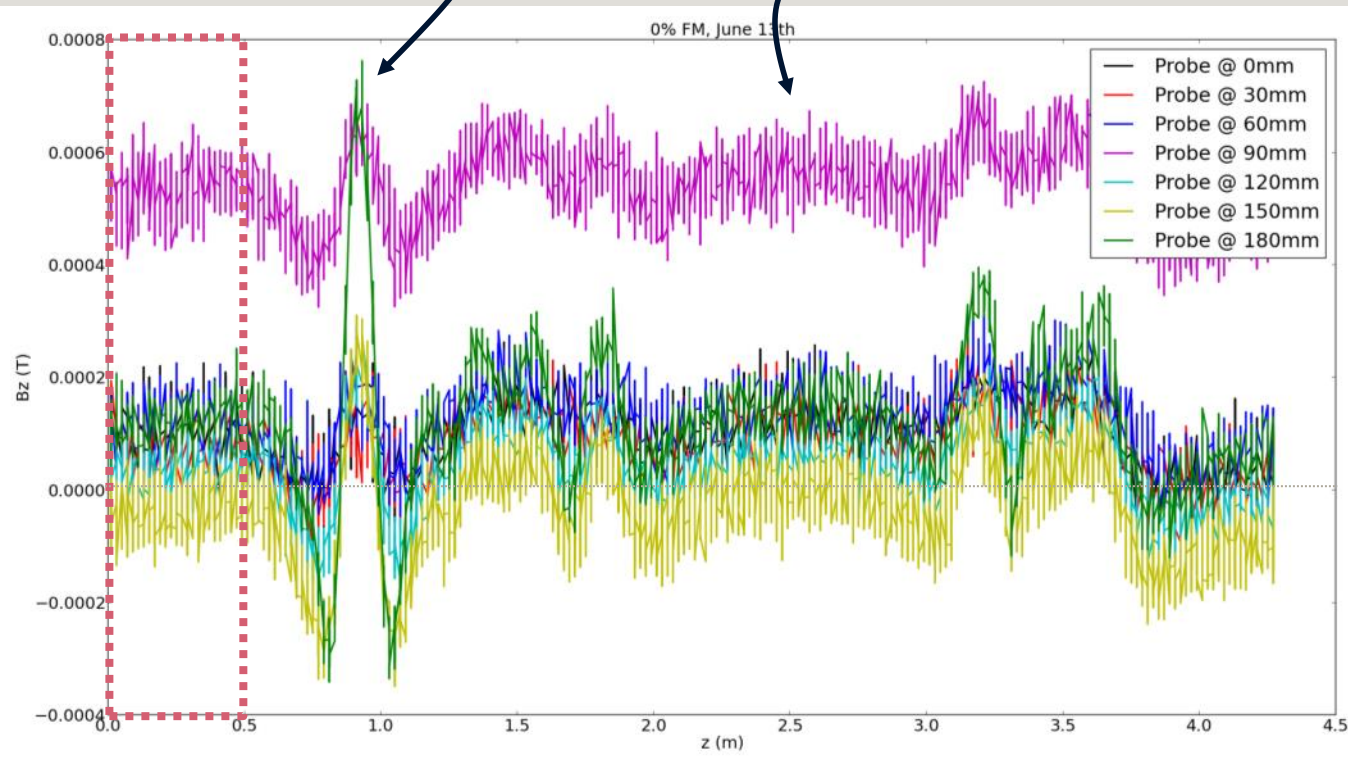
What kind of error bars should we be imagining on the previous plots?


Look at the “flat” regions of the OA measurements and see what variation there is in probe readout.

Region of Interest: $z \leq 0.5\text{m}$

180mm probe has a large spike here

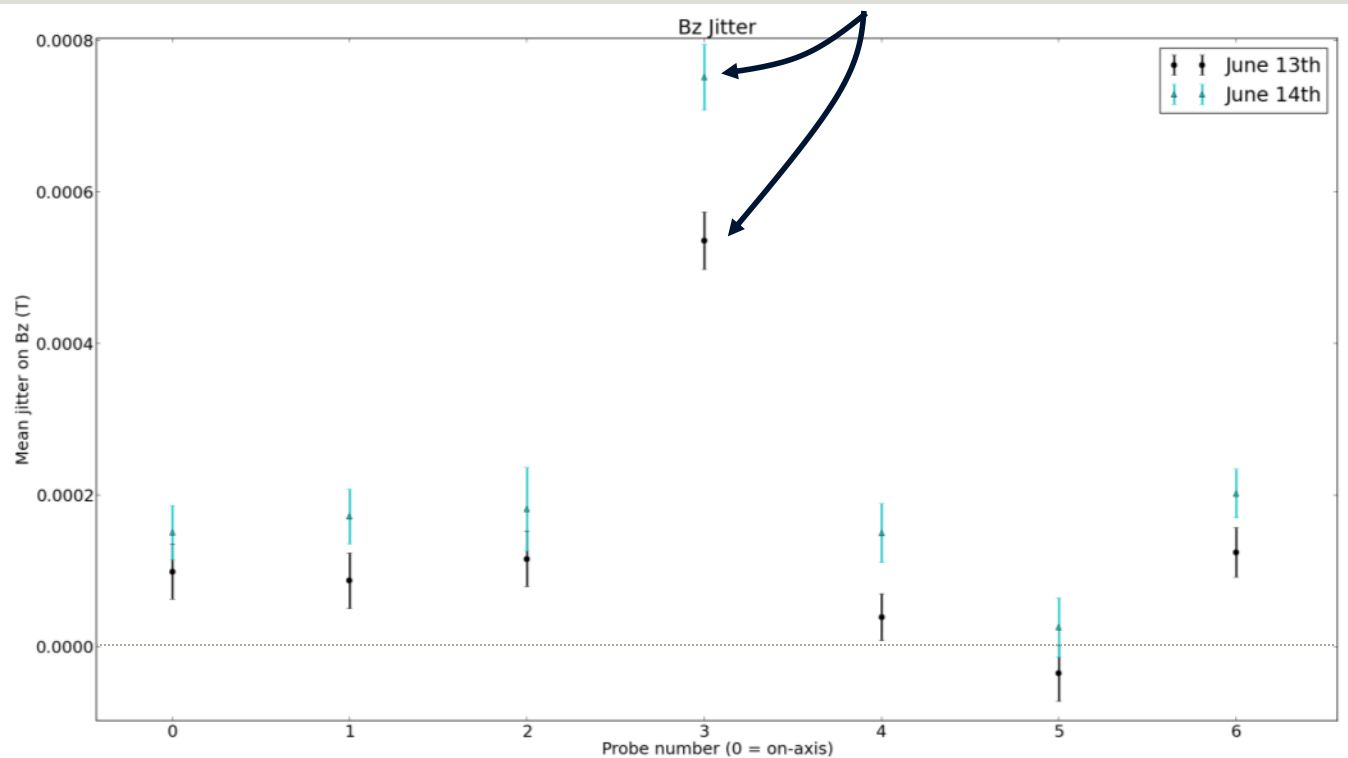
Probe at 90mm sees more residual field that the others



- Consider dotted region
- Is approx flat in all OA measurements
- Should have a negligible residual field
- Use , June 13th OA measurement, as it is “flattest”
- Compare with measurement from June 14th (not previously shown)
- Calculate mean and standard deviation in this ROI

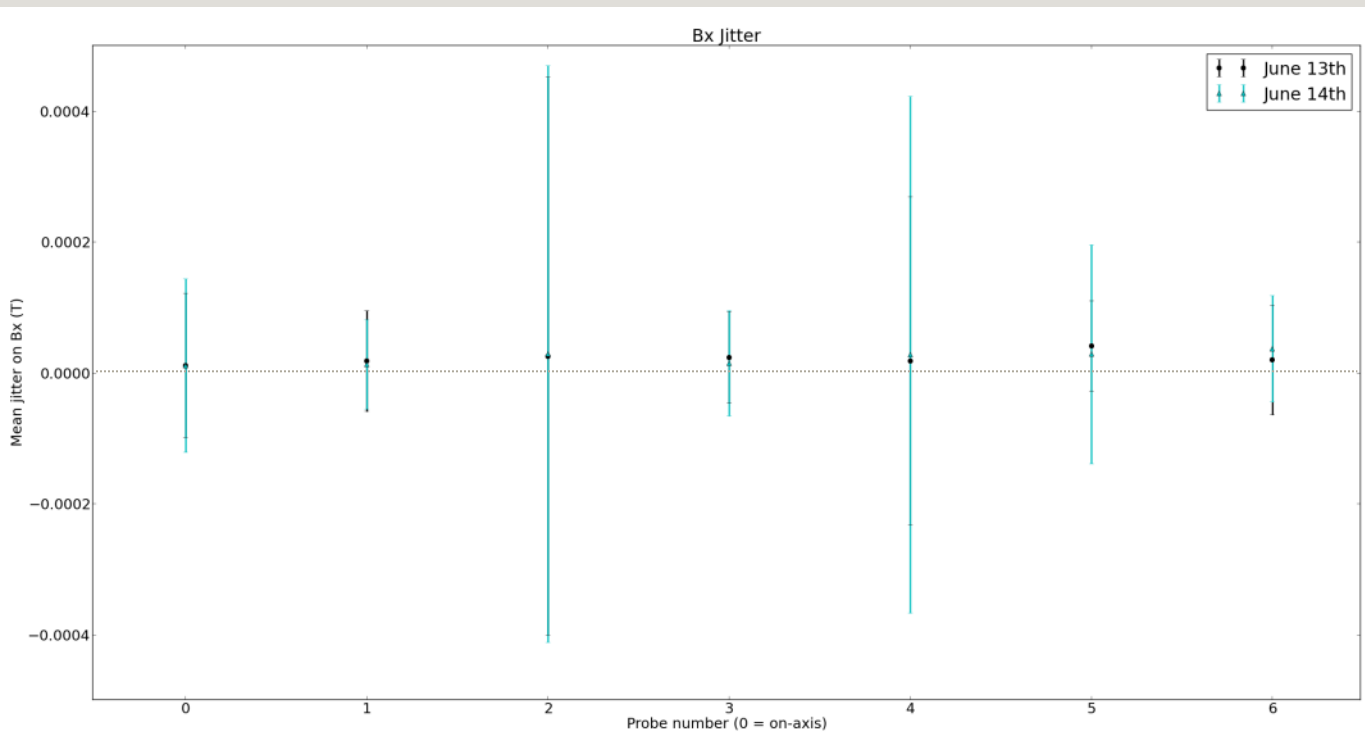
Mean Residual B_z

Probe at 90mm sees more residual field that the others



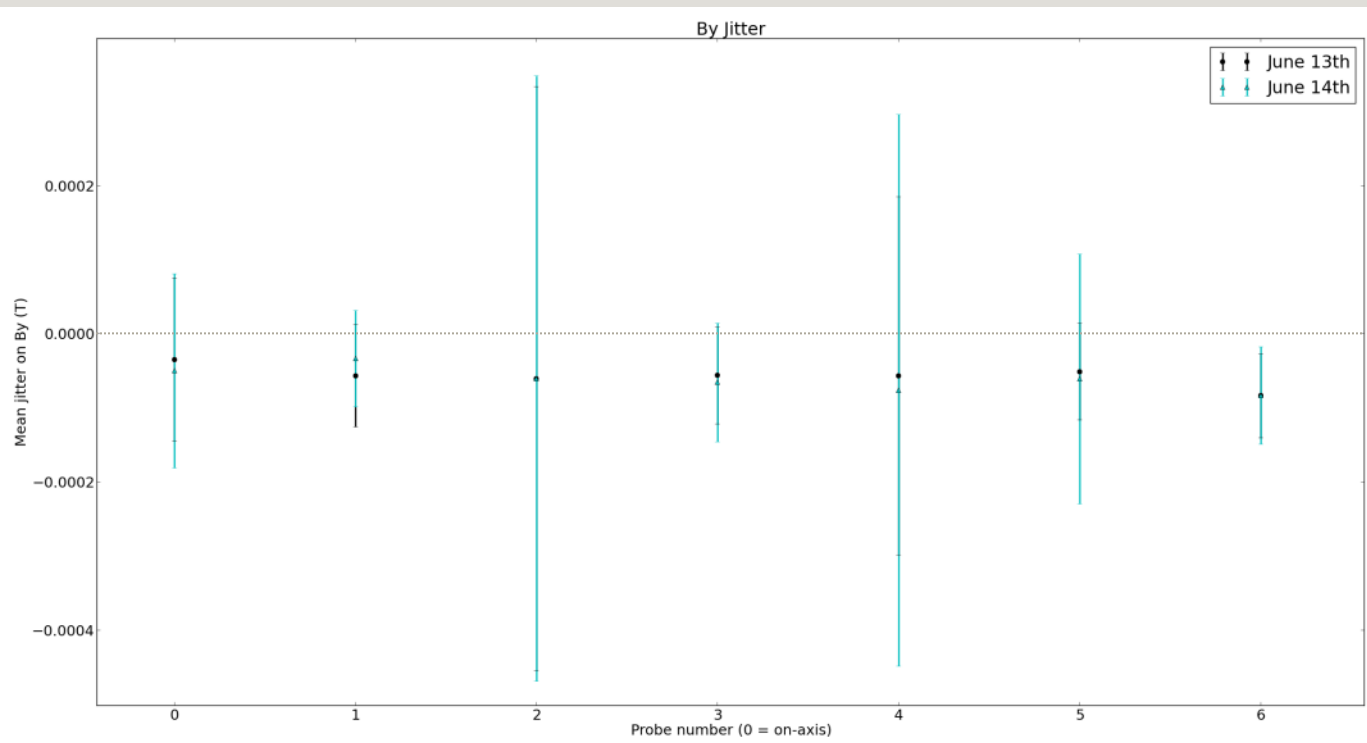
- Mean residual B_z is different after powering magnet
- Only probe 5 ($r = 120\text{mm}$) is consistent with zero
- Probe 3 sees consistently higher fields, but it should be *consistent* with other probes

Mean Residual B_x



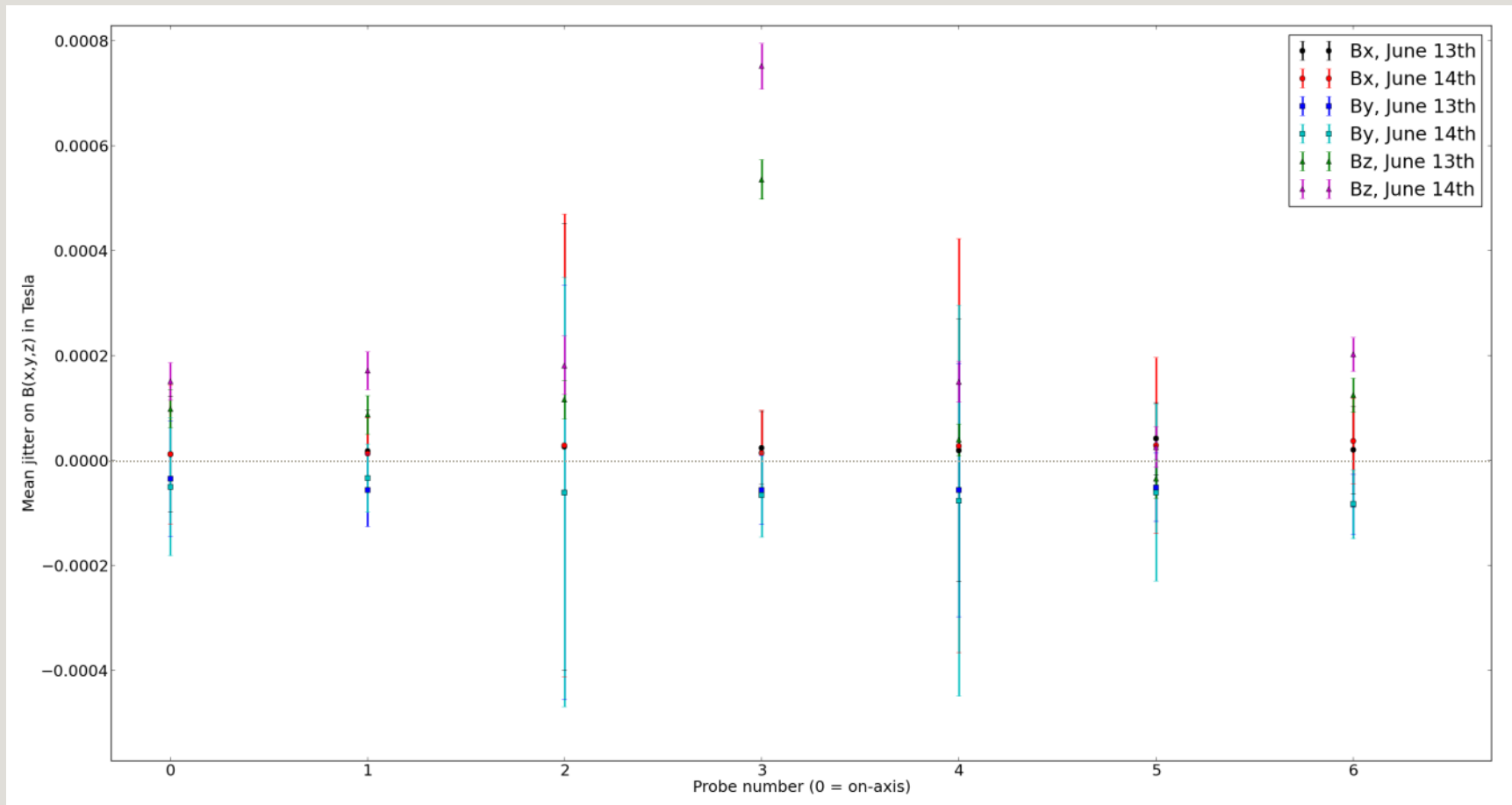
- Mean residual B_x are all consistent with 0 (including probe 3)
- Noisiest x -axis probes are 2 and 4
- Mean residual B_y are all consistent with 0
- Noisiest y -axis probes are also 2 and 4

Mean Residual B_y

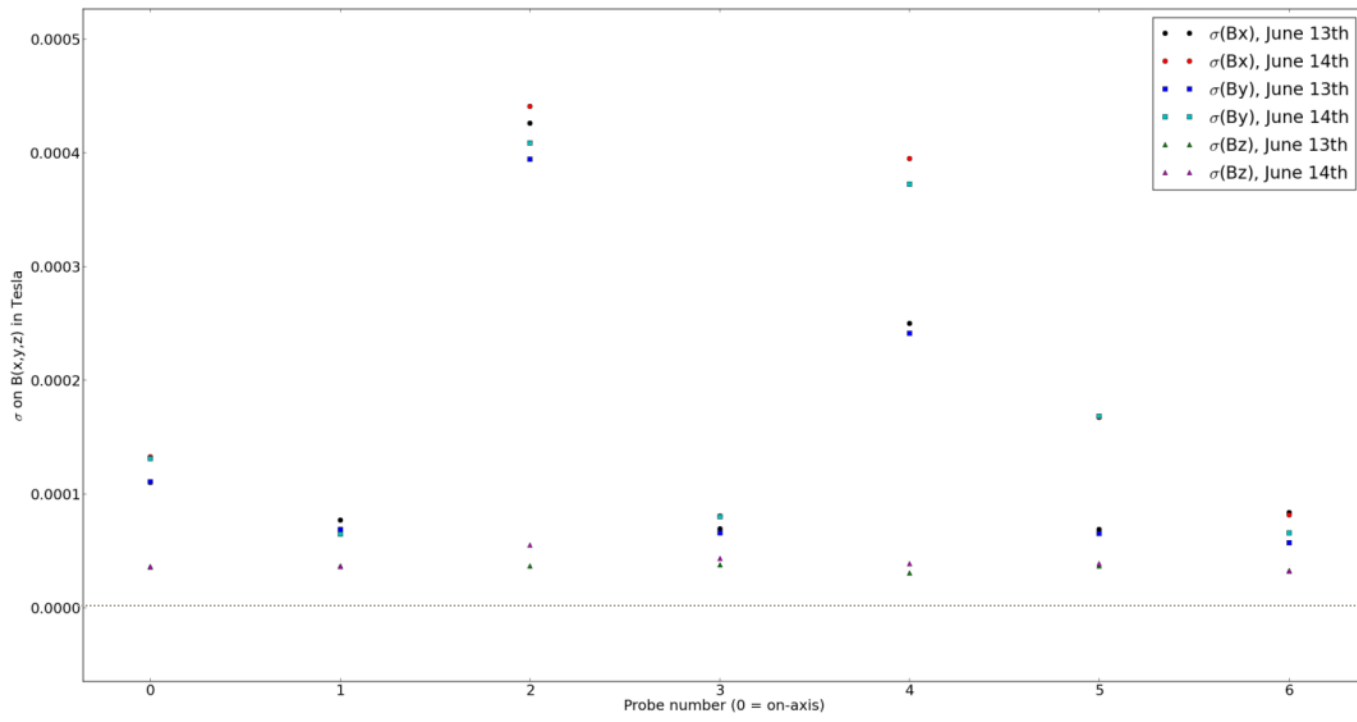


- Mean residual B_x are all consistent with 0 (including probe 3)
- Noisiest x -axis probes are 2 and 4
- Mean residual B_y are all consistent with 0
- Noisiest y -axis probes are also 2 and 4

Probe Jitter Comparison



Probe Jitter Comparison



- $\sigma \leq 15\text{G}$
- Exceptions are probes 2 and 4 in x and y
- No measurements without SS present, so residual field effects are difficult to quantify
- There are other 'uncertainties' to consider, but this is a start!

HYSTERESIS

Q: Do we achieve the same field when we approach it from below the operating current and above the operating current?

Hysteresis

- Ideally, requires consecutive four measurements with the shielding plate
 - 0% solenoid/flip
 - 80% solenoid/flip mode
 - 100% solenoid/flip mode
 - 80% solenoid/flip mode
- We have 0%→80%, and 0%→100%, but do not have 100%→80%
 - Mapping takes a long time
 - Time taken by shielding plate installation and removal
- Judging by changes in residual field, likely there will be a (very) small hysteresis effect
 - Should make this measurement when mapping final SS

FINDING THE MAGNETIC AXIS (FIRST PASS)

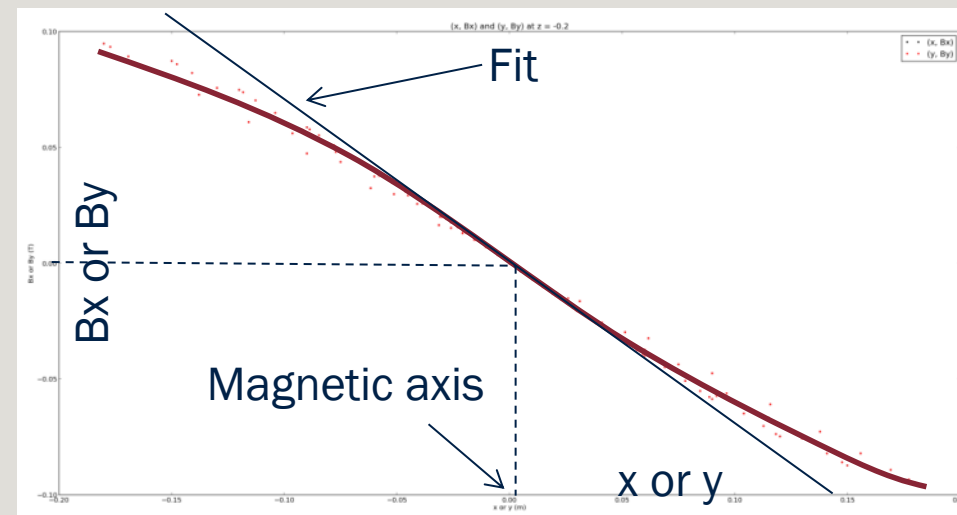
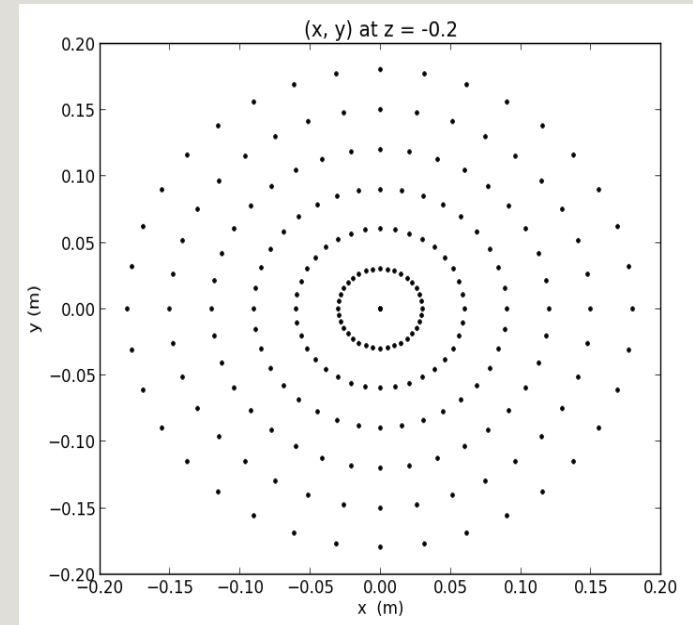
The mapper moves about by $\sim 1\text{mm}$ in (x,y) as it travels through the magnet

To first approximation, ignore this movement and use mapper coordinates to get an estimate of the magnetic axis

Finding the Magnetic Axis

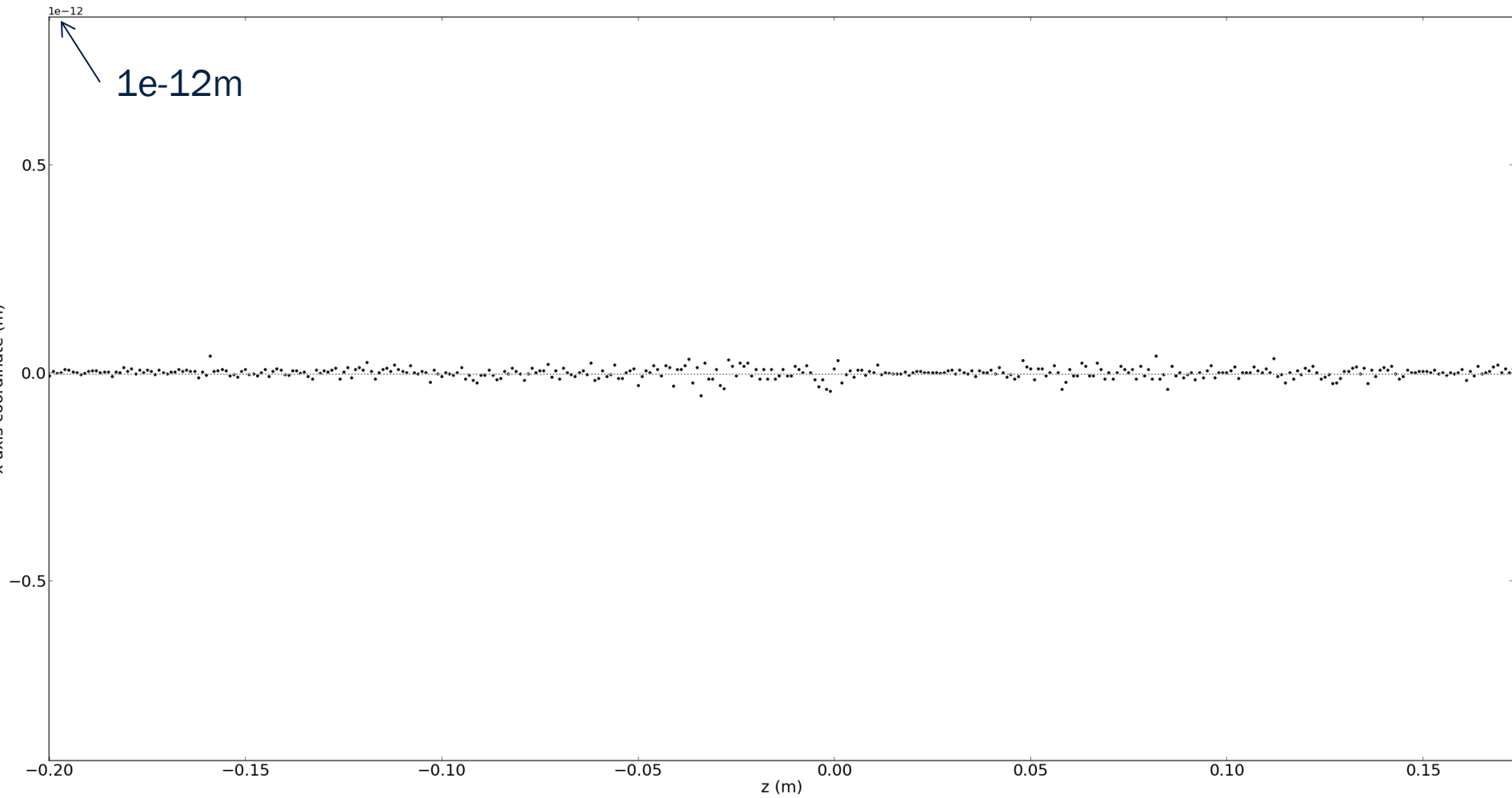
Simulation, 1 coil

- At each measured point along z , get all measurements of (x, B_x) and (y, B_y)
- In regions of $B_r \neq 0$, these should form lines passing through the magnetic axis
- Fit a line to (x, B_x) and find where it crosses the x -axis
- Fit a line to (y, B_y) and find where it crosses the y -axis
- Plot these points as a function of z
- Test on a 1-coil 'magnet'
- Use $\sigma = 20\text{G}$ (from probe jitter) in the fits



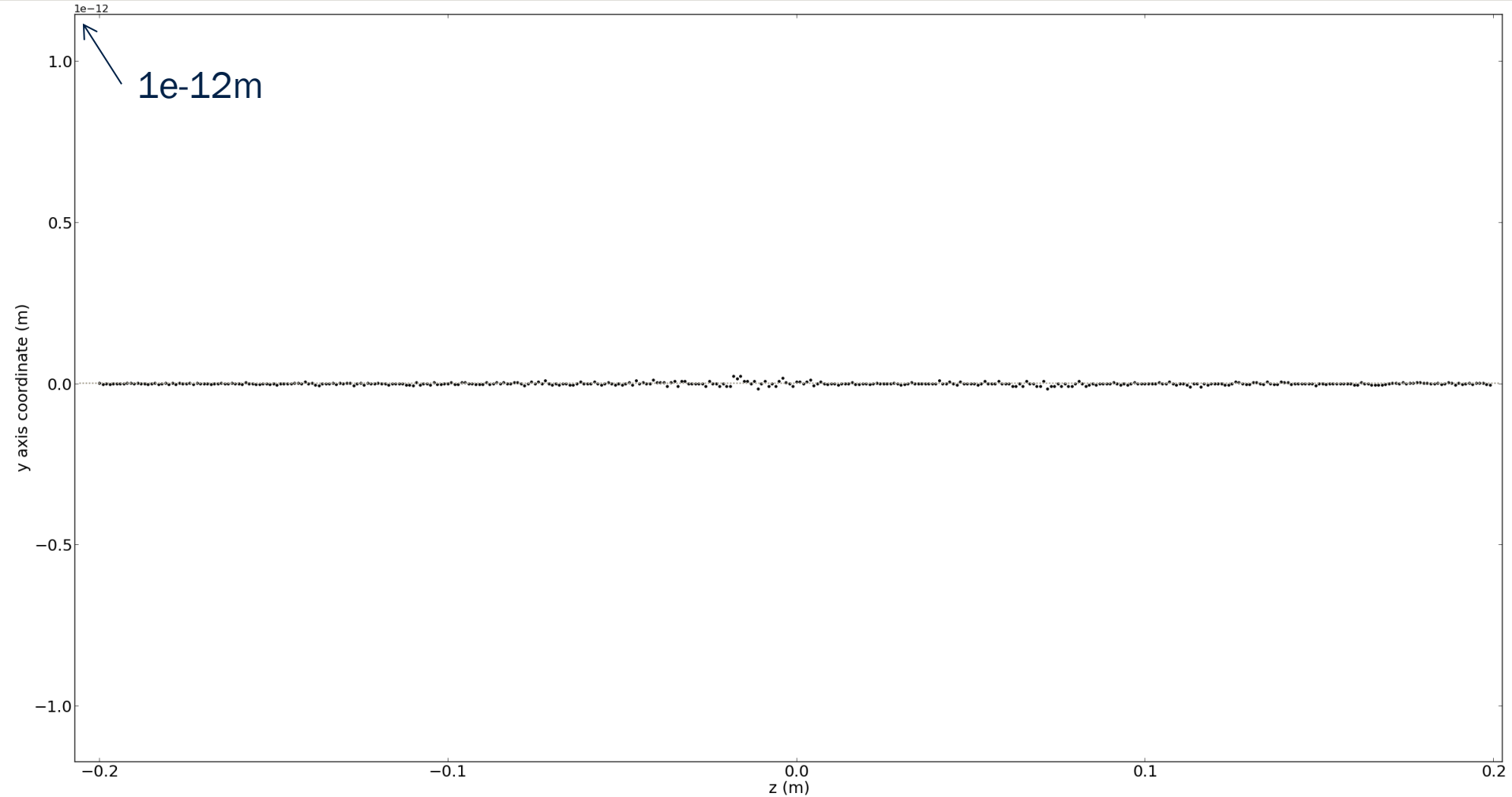
Finding the Magnetic Axis: x

Simulation, 1 coil

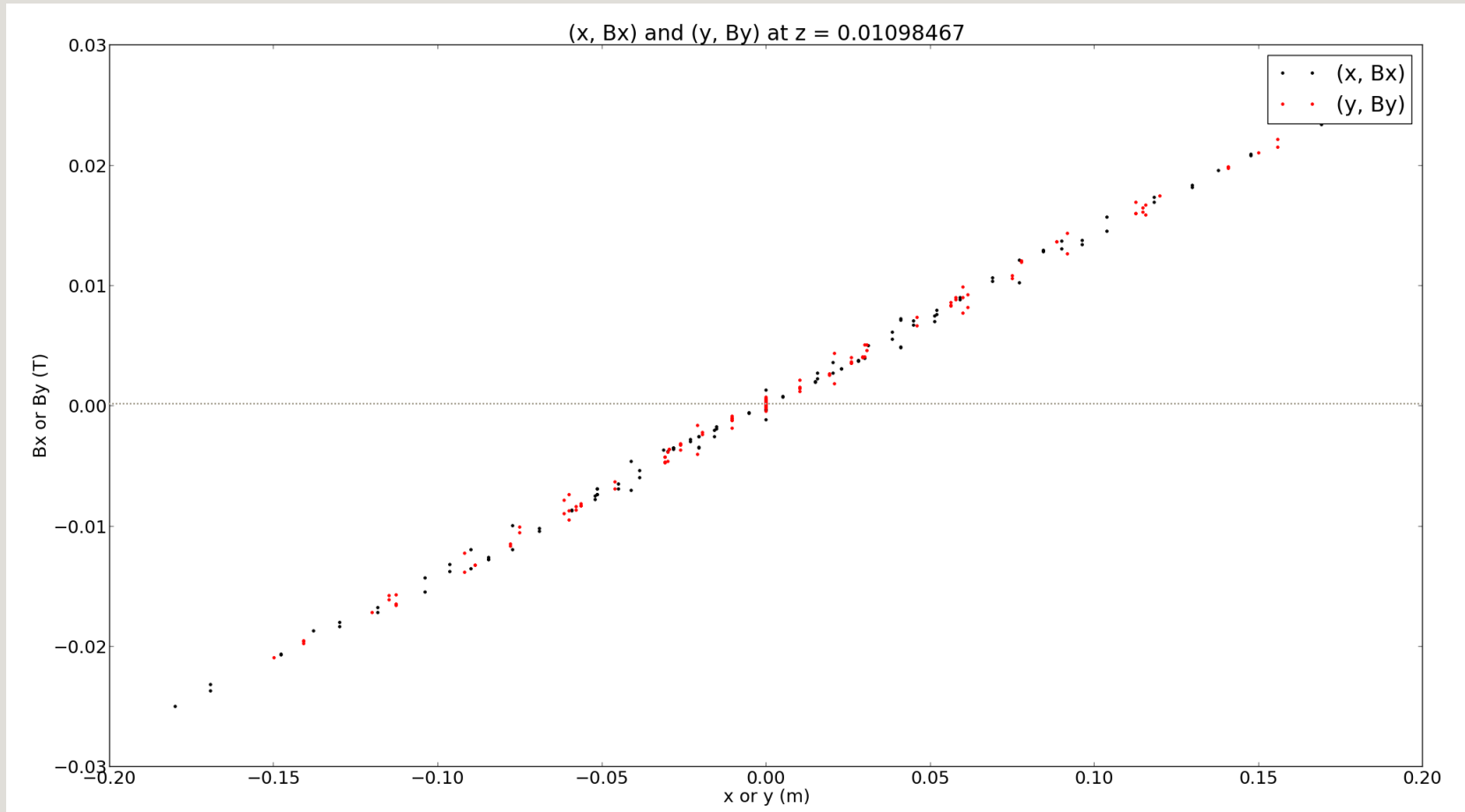


Finding the Magnetic Axis: y

Simulation, 1 coil

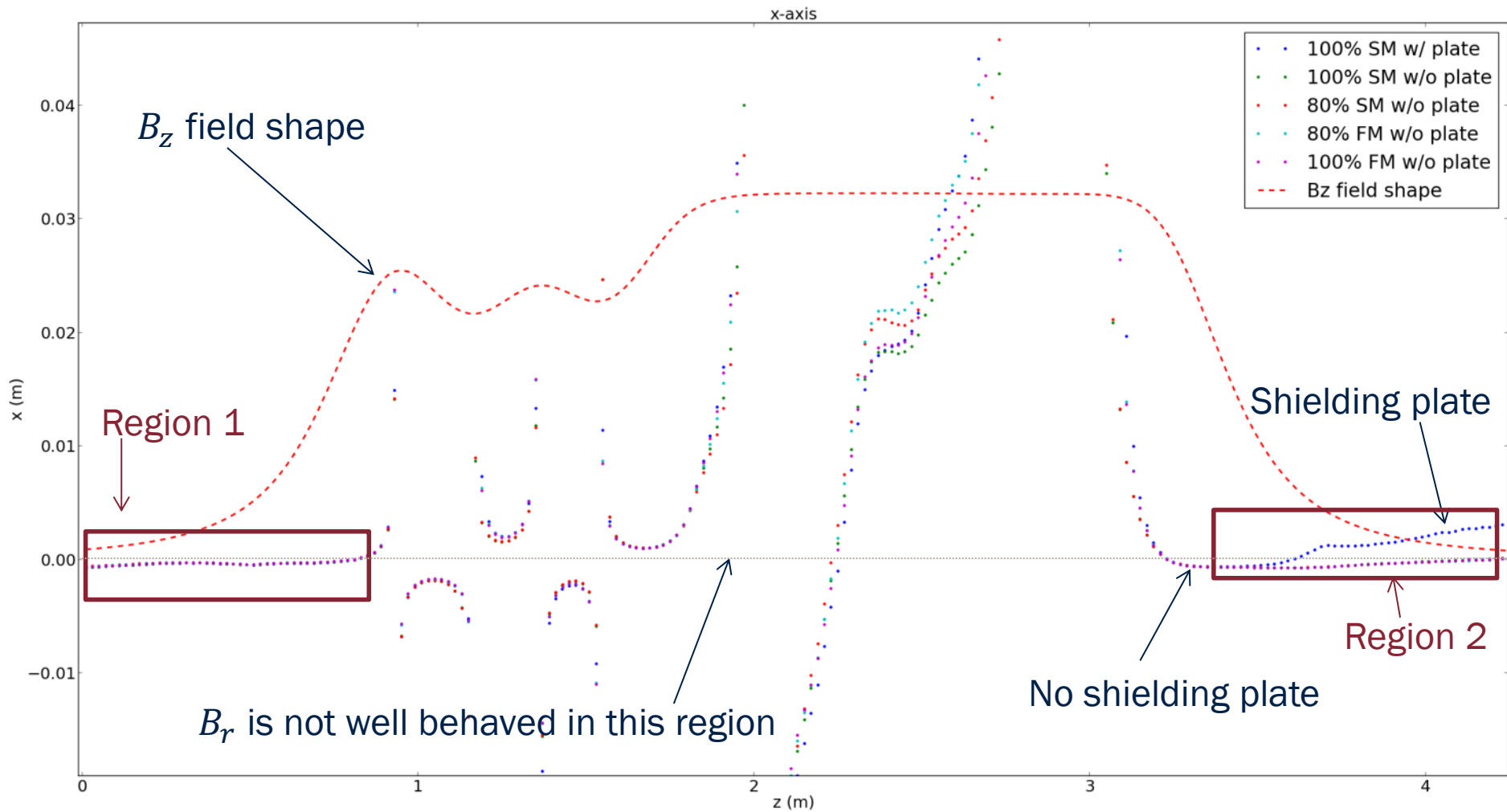


Real magnets

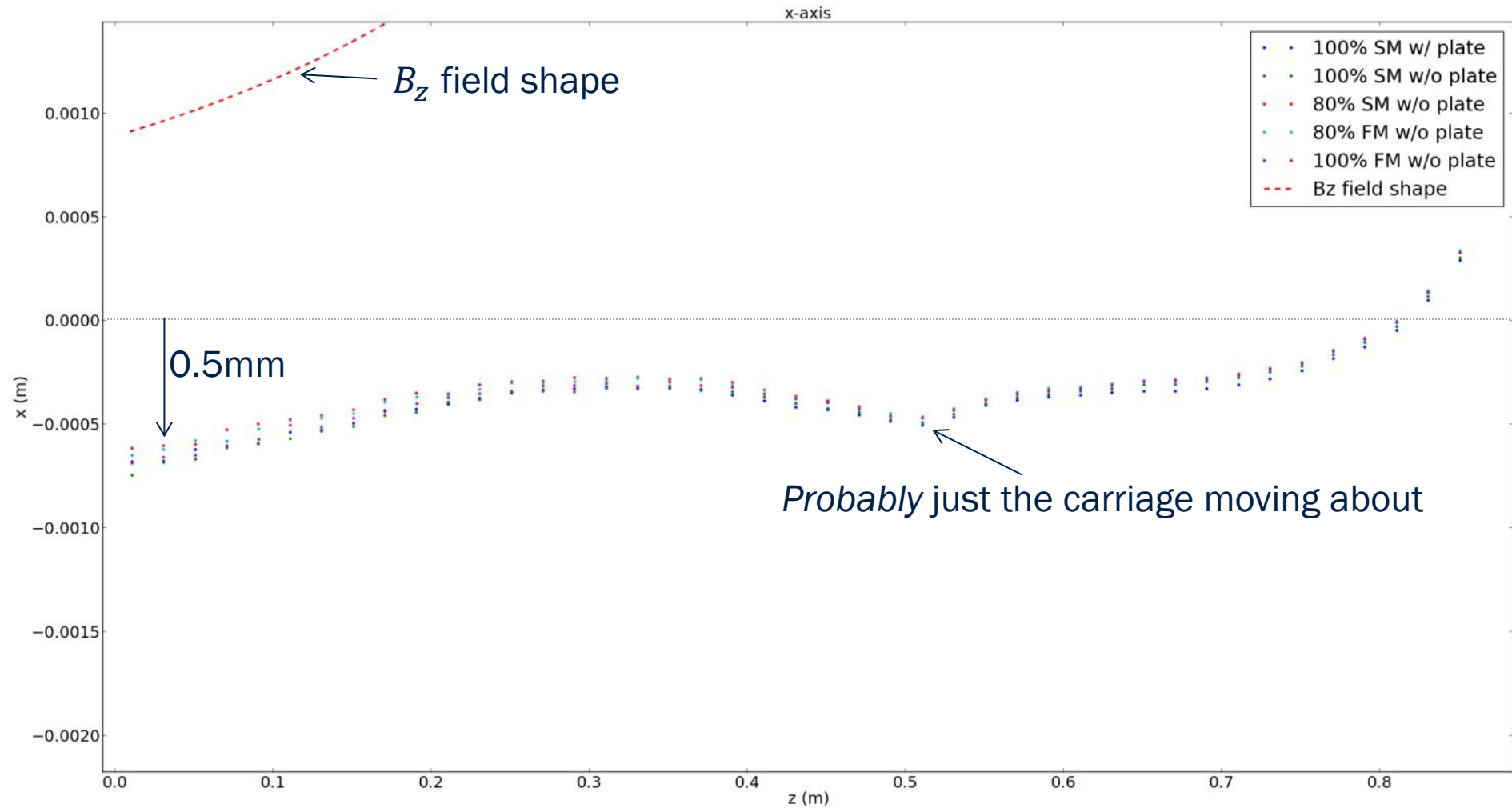


Note: No survey information has been applied to the data before the fits, and the mapper does wiggle around!

Real Magnets: x -Axis

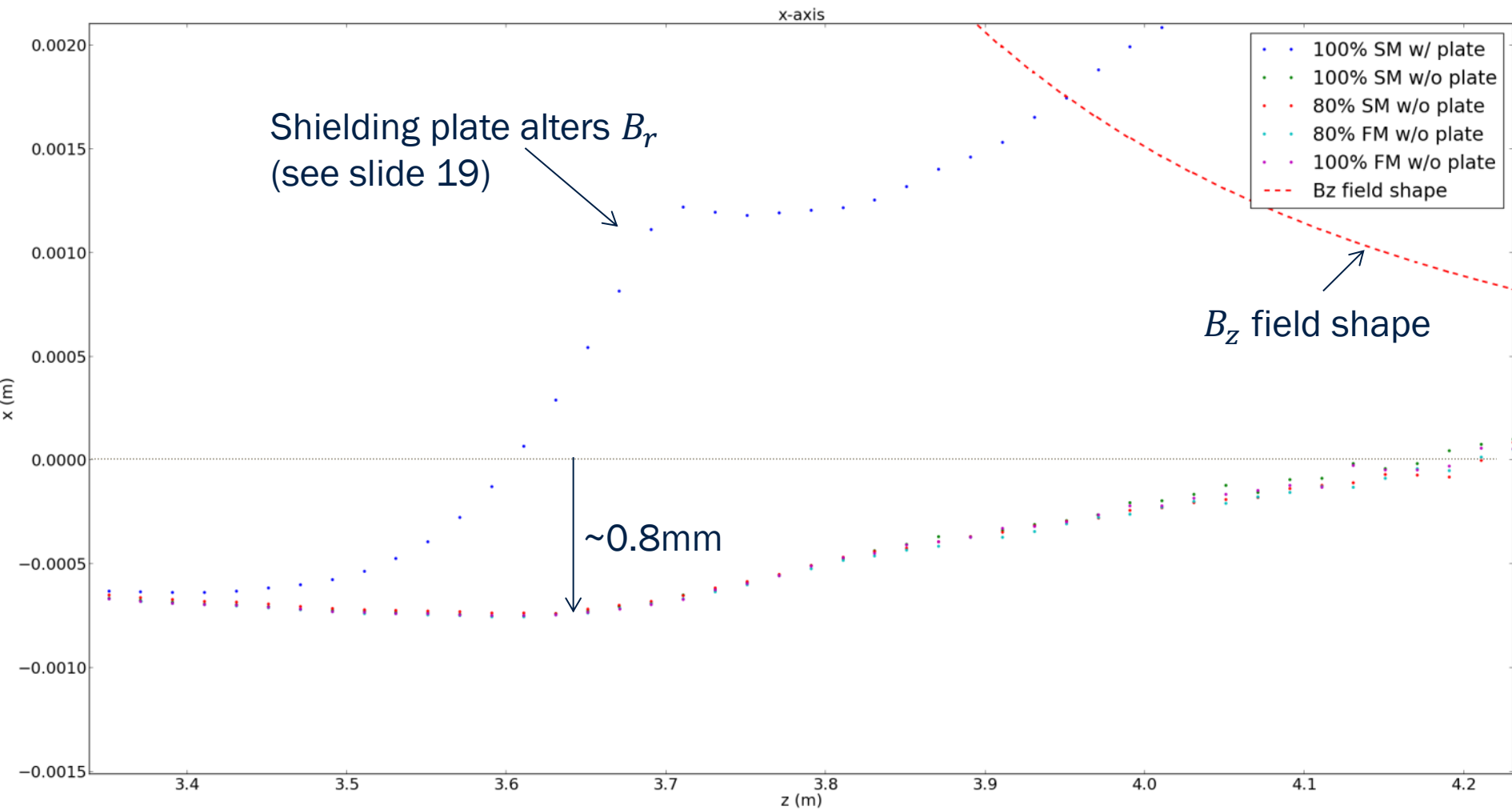


Real Magnets: x -Axis (Region 1)



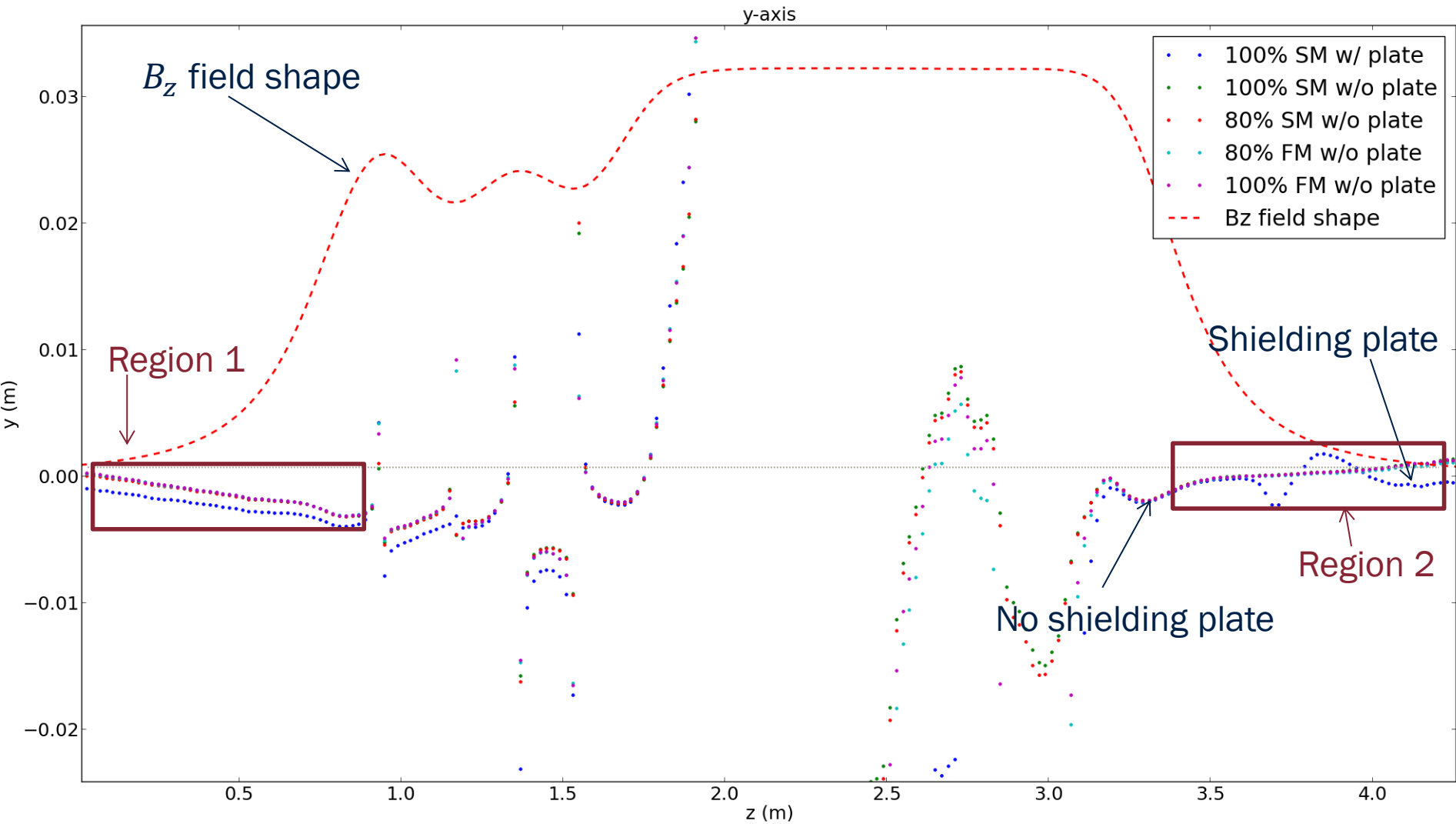
Mapper carriage moves around by ~ 1 mm, so axis is consistent with zero

Real Magnets: x -Axis (Region 2)

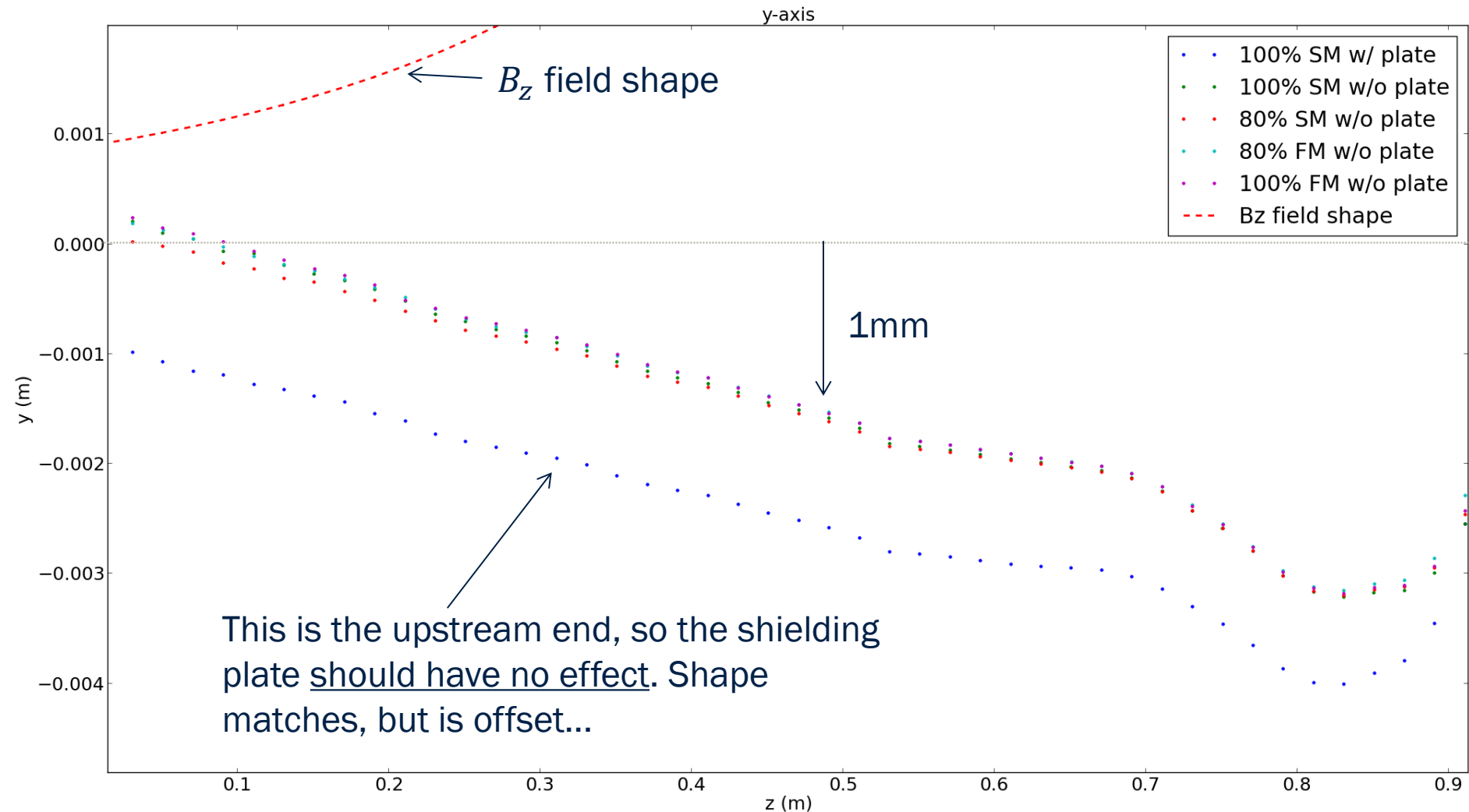


Mapper carriage moves around by ~ 1 mm, so axis is consistent with zero

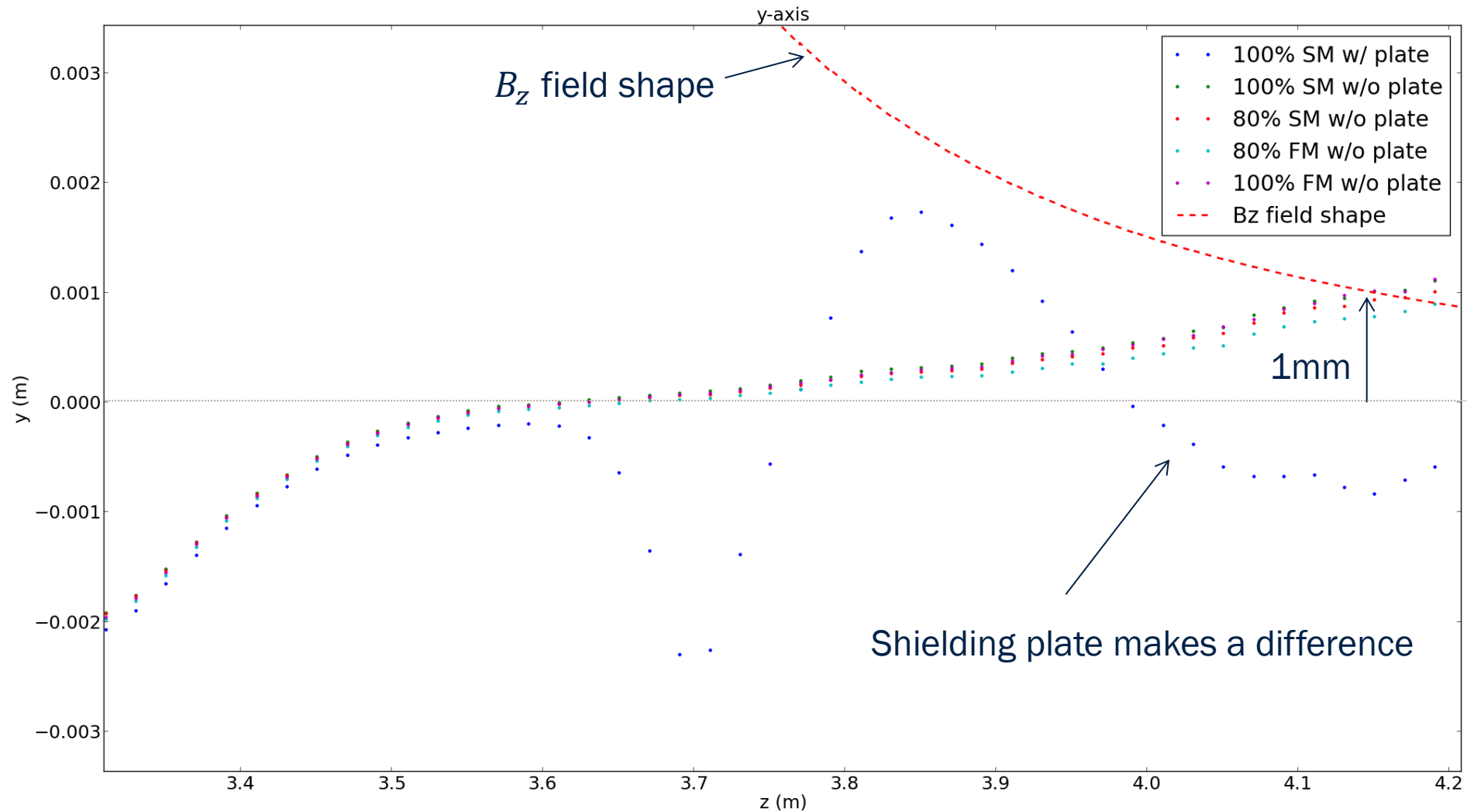
Real Magnets: y -Axis



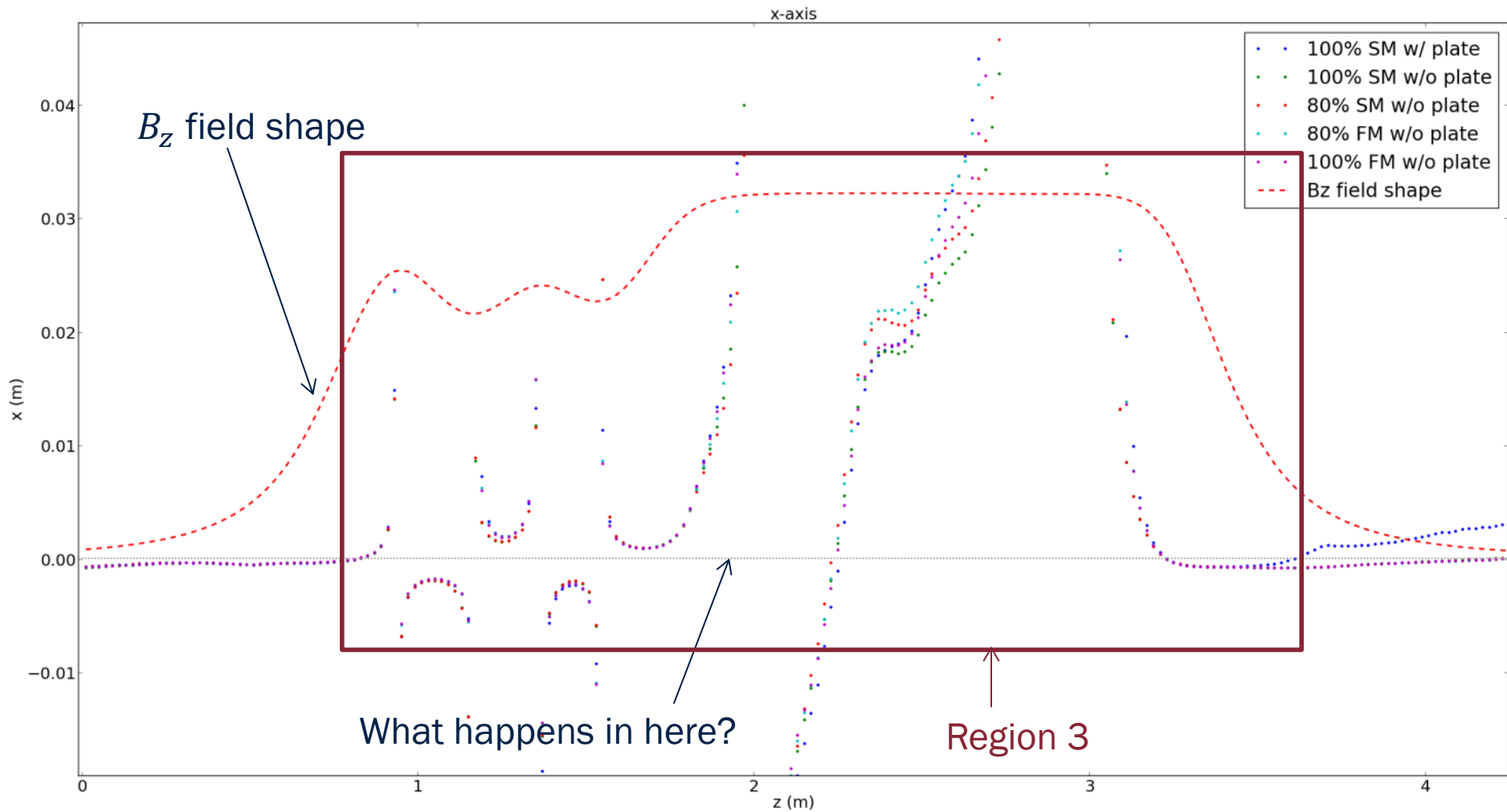
Real Magnets: y -Axis (Region 1)



Real Magnets: y -Axis (Region 2)

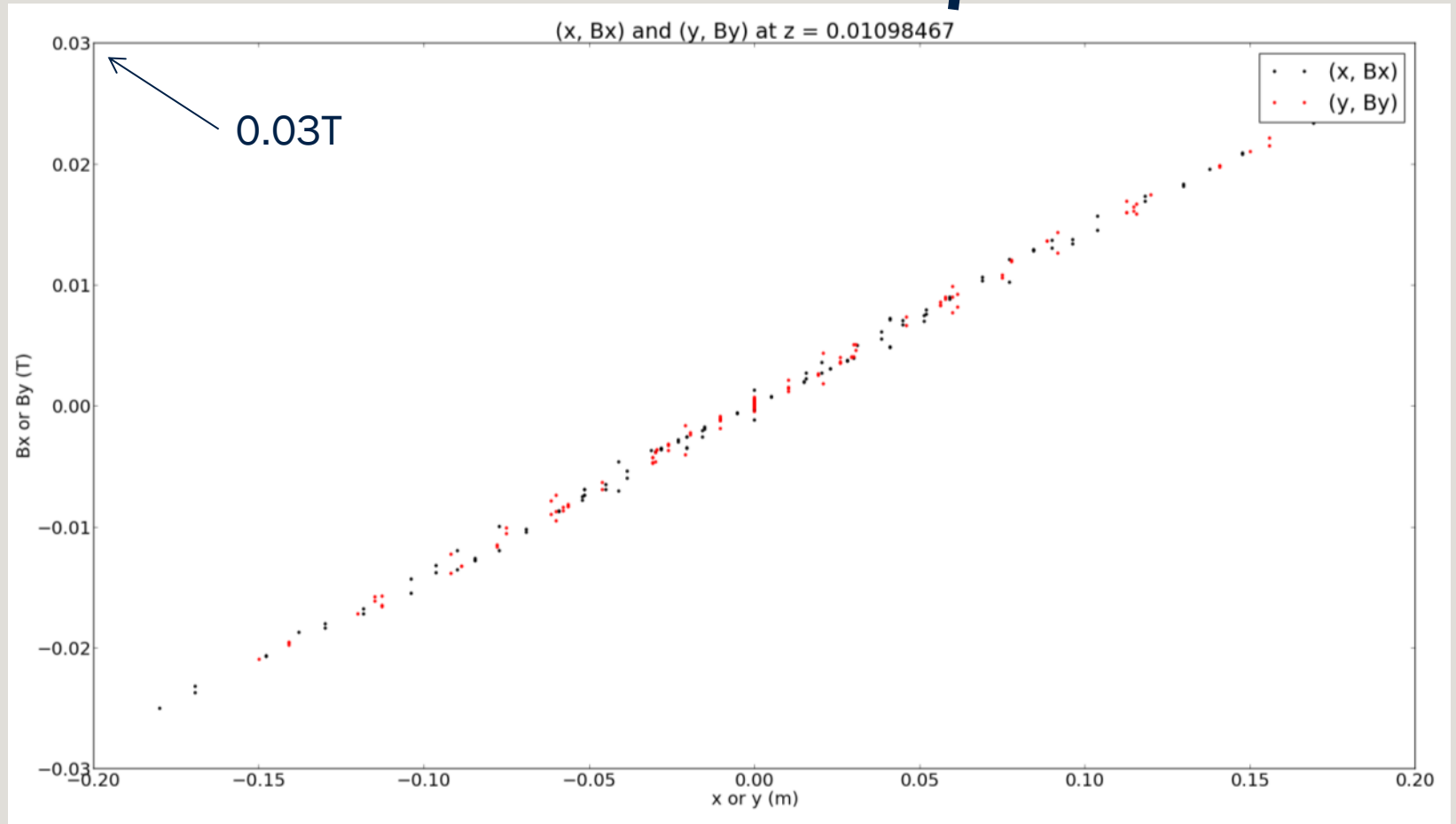
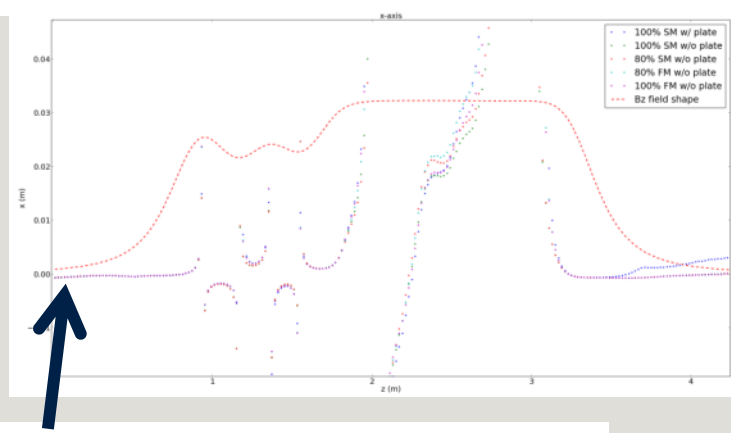


Real Magnets: x -Axis (again)



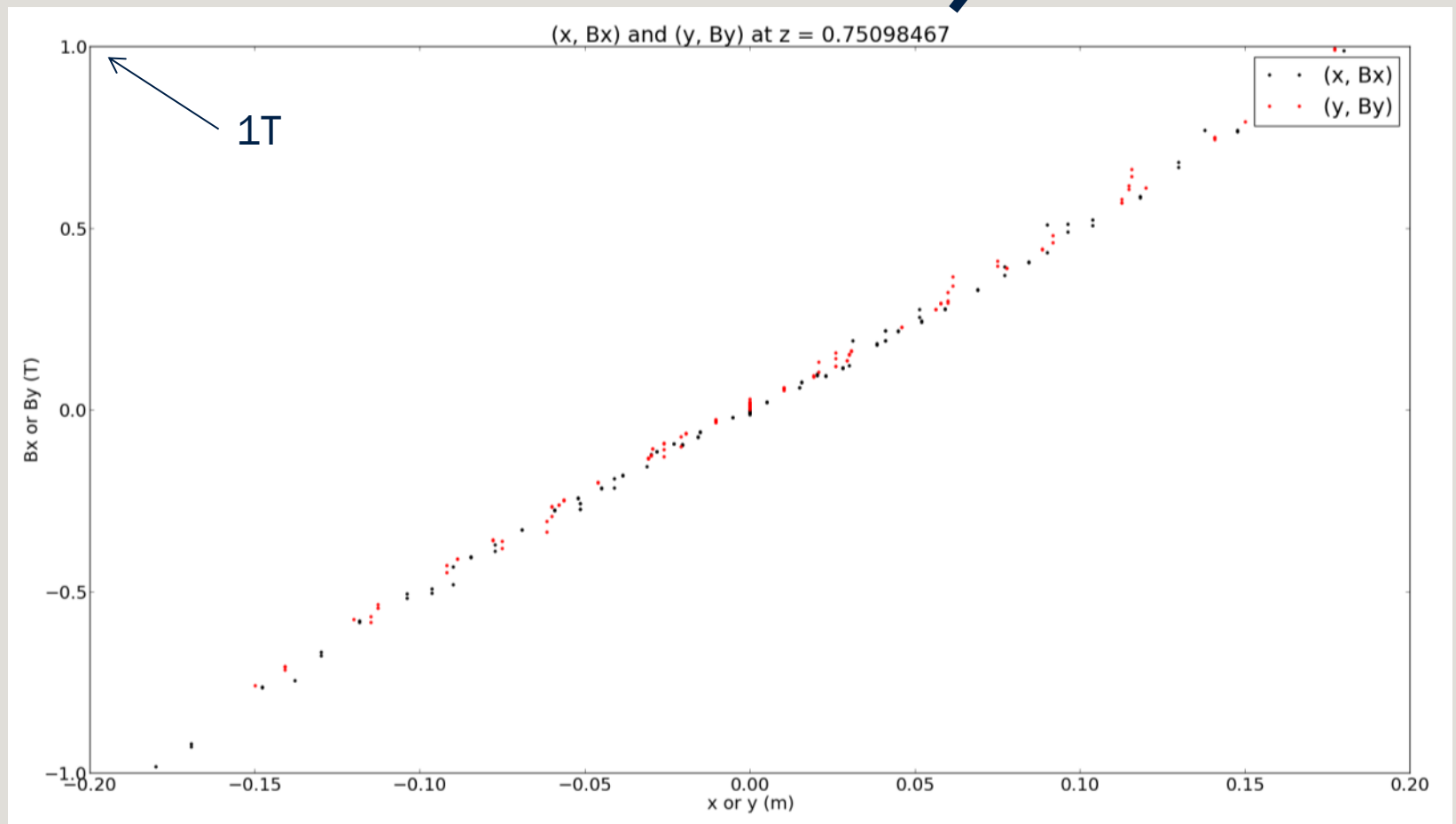
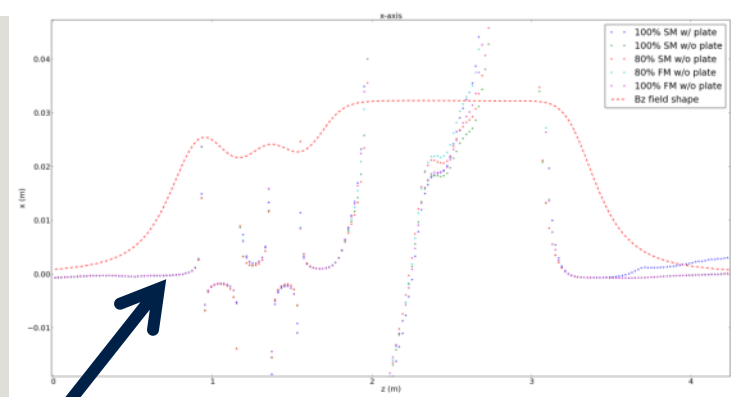
Region 3

100% Solenoid Mode, w/ Shielding Plate



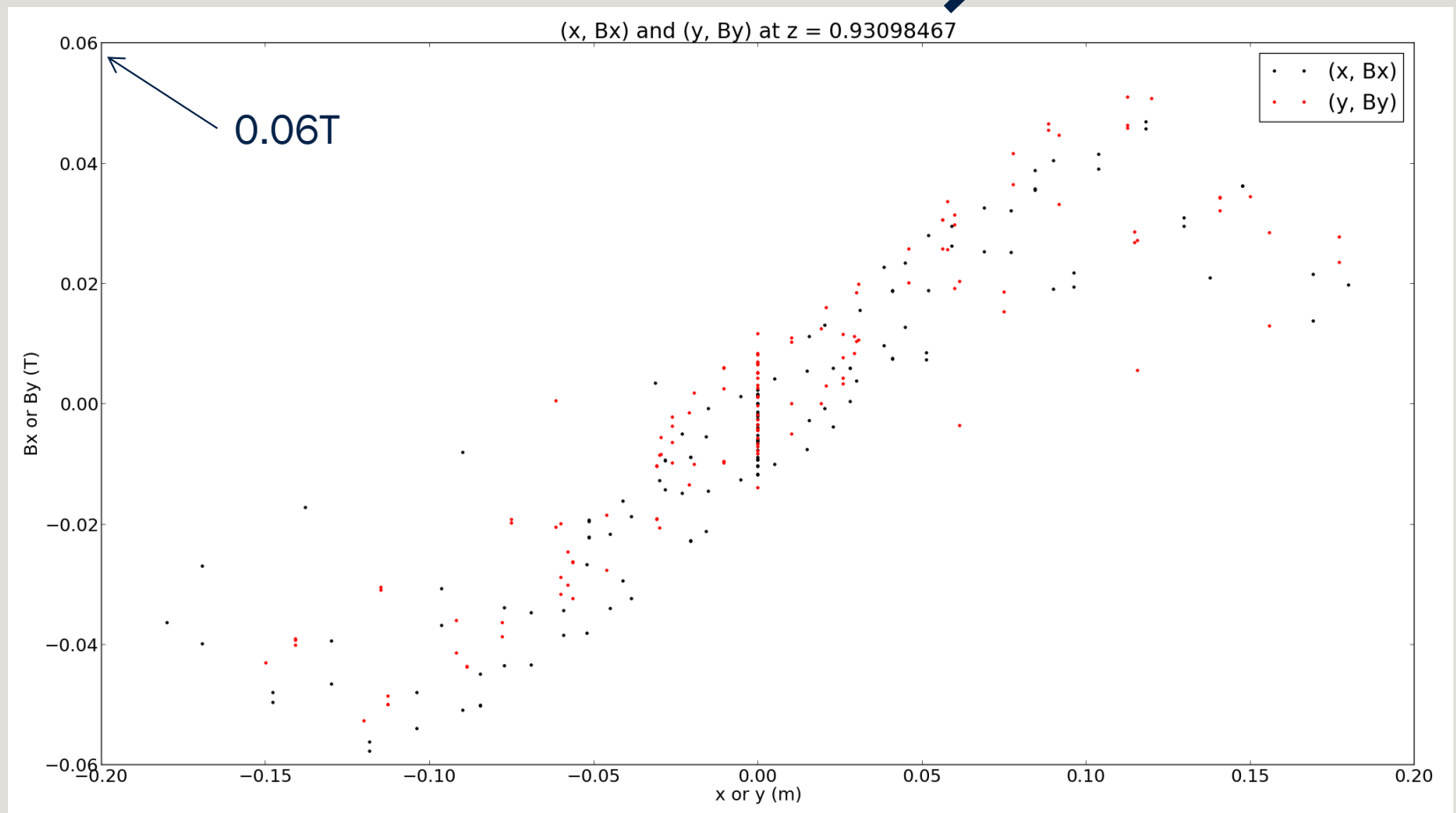
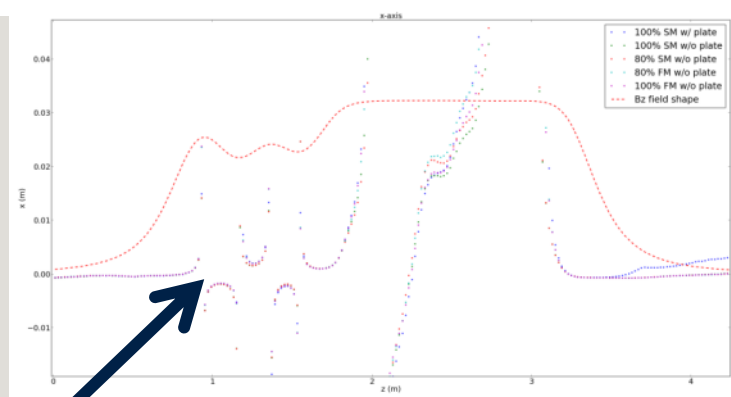
Region 3

100% Solenoid Mode, w/ Shielding Plate



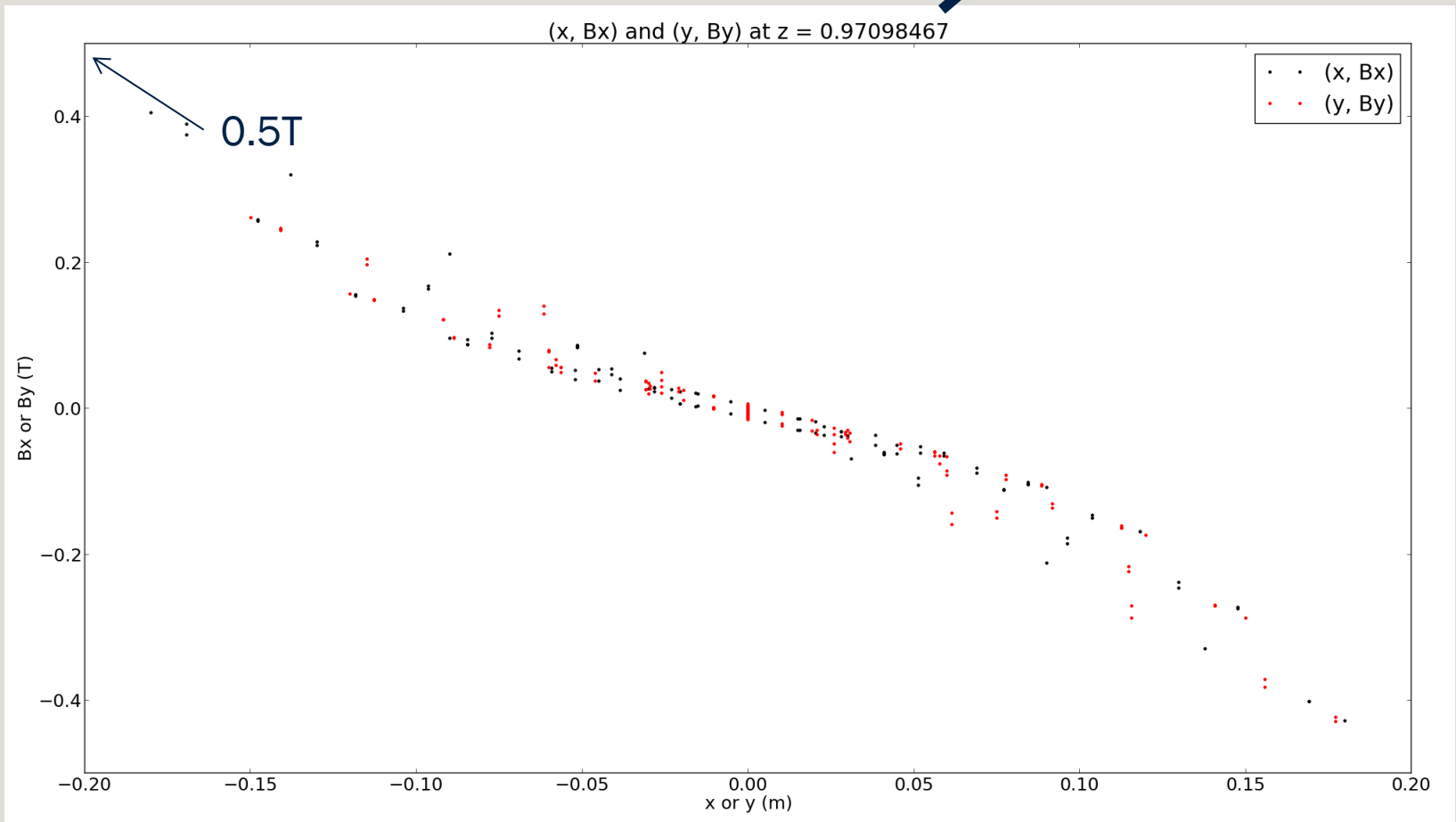
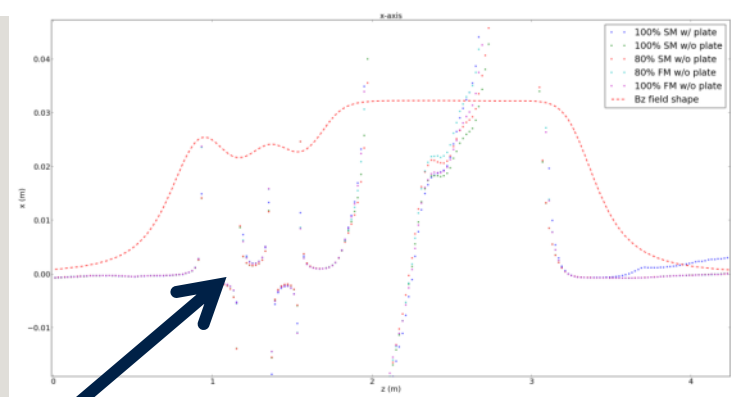
Region 3

100% Solenoid Mode, w/ Shielding Plate



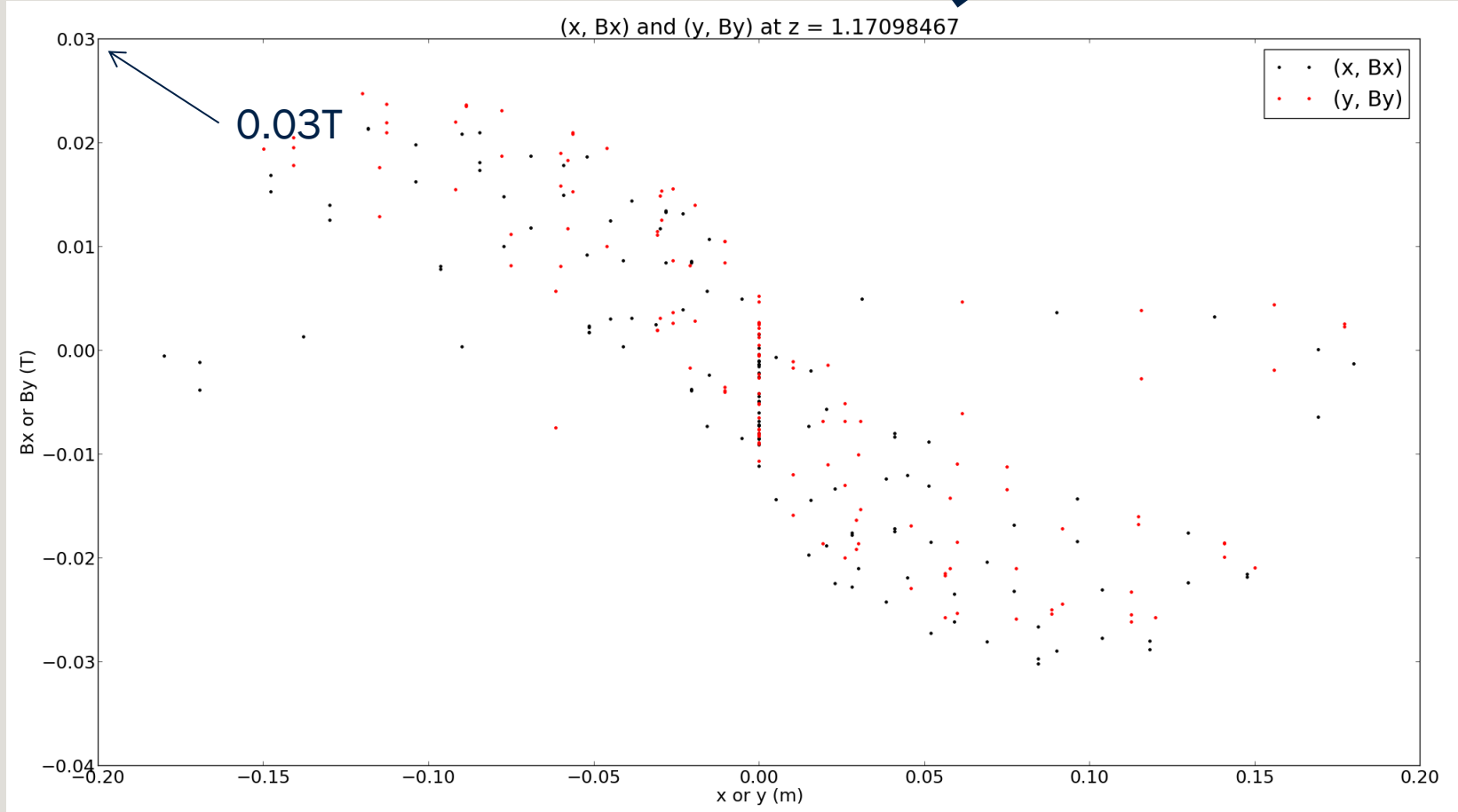
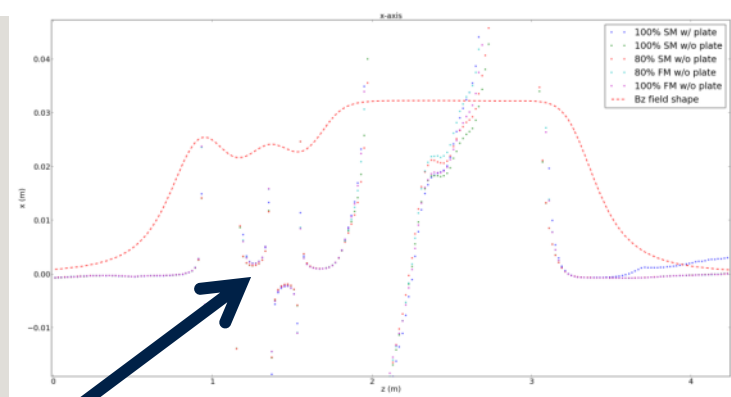
Region 3

100% Solenoid Mode, w/ Shielding Plate



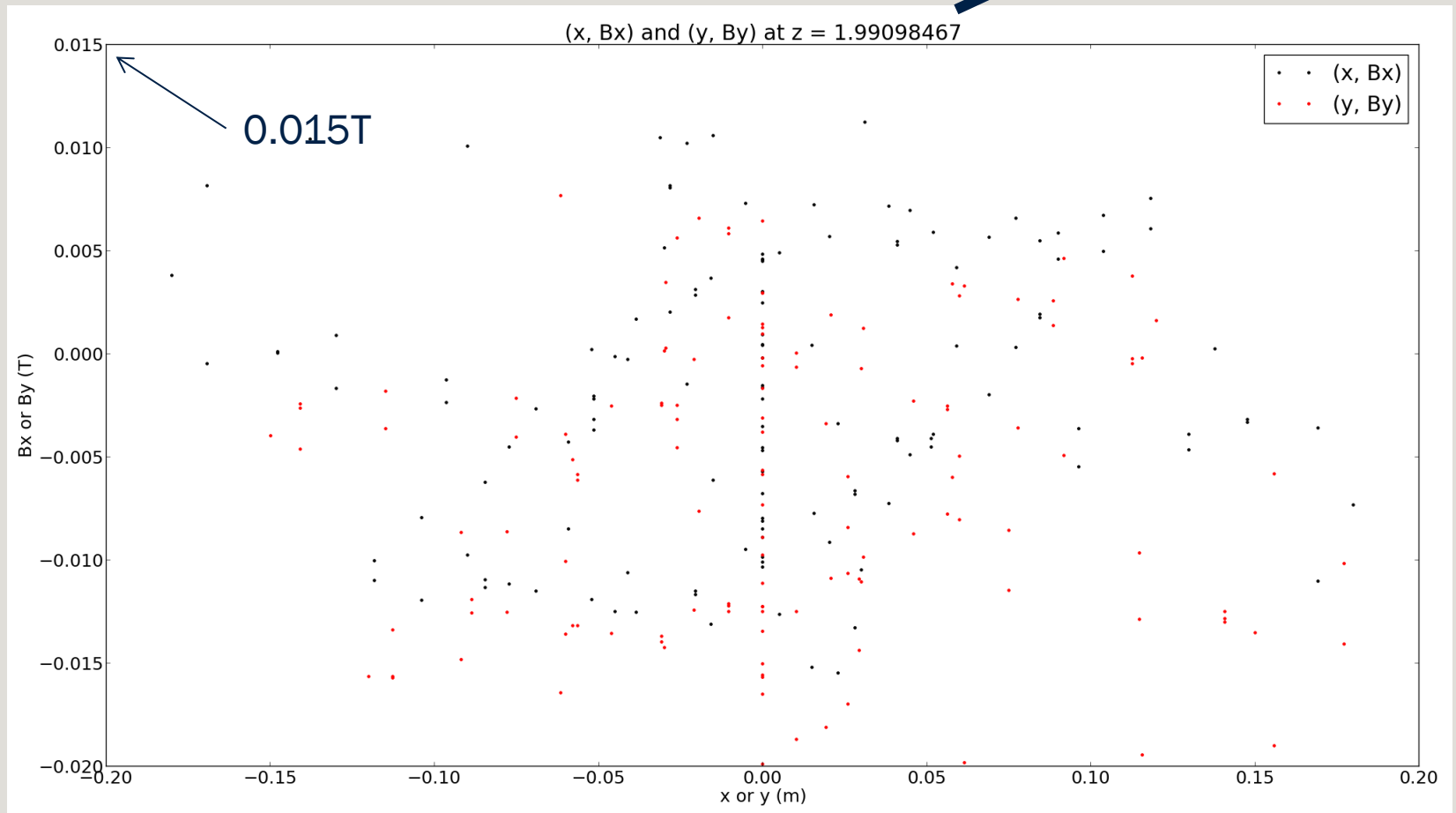
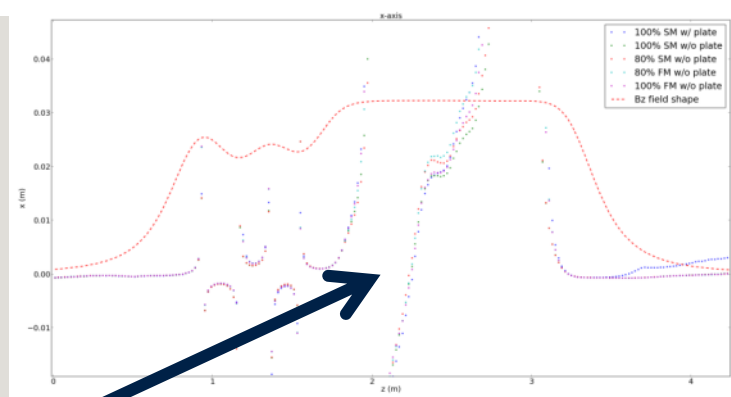
Region 3

100% Solenoid Mode, w/ Shielding Plate



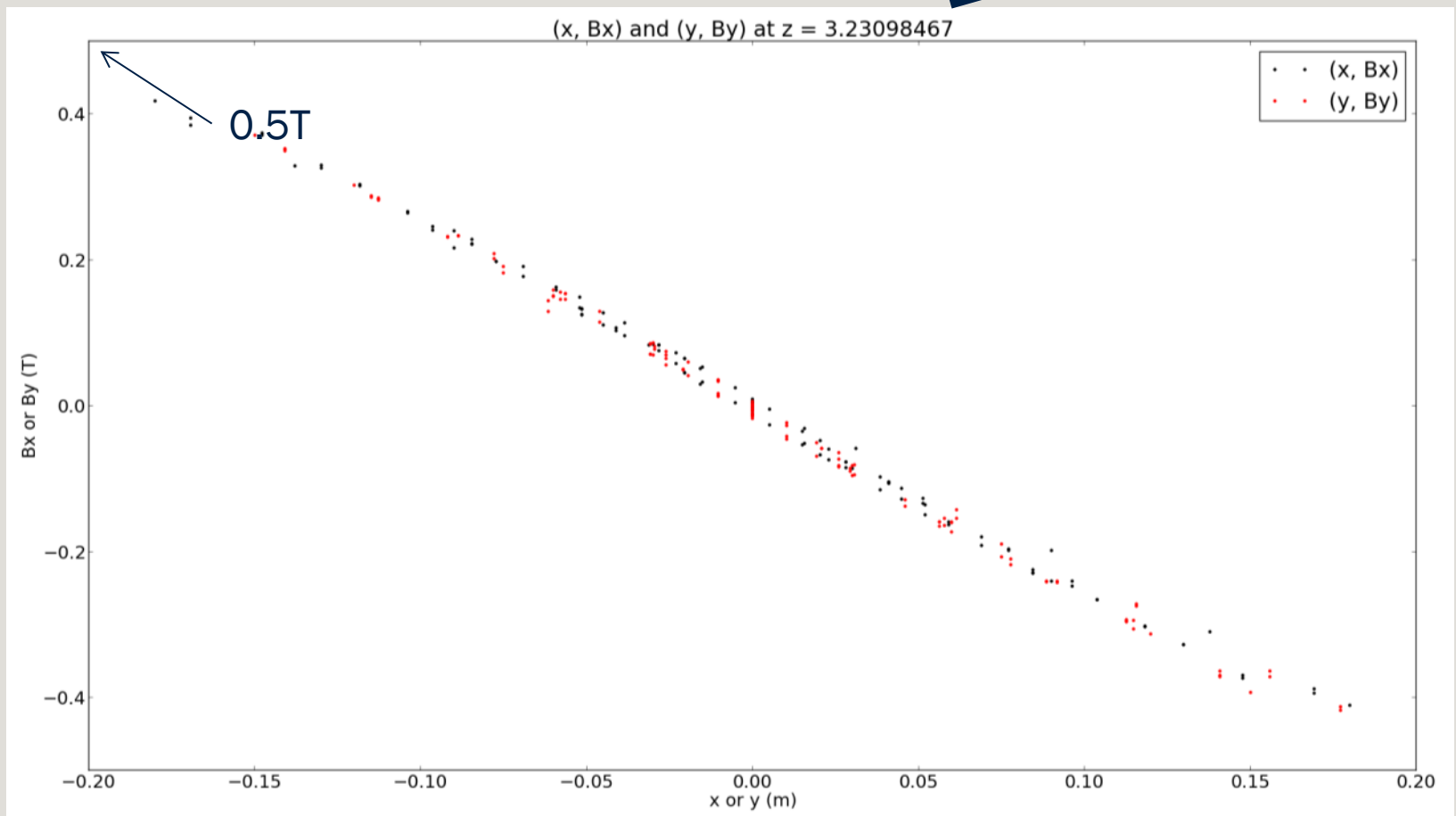
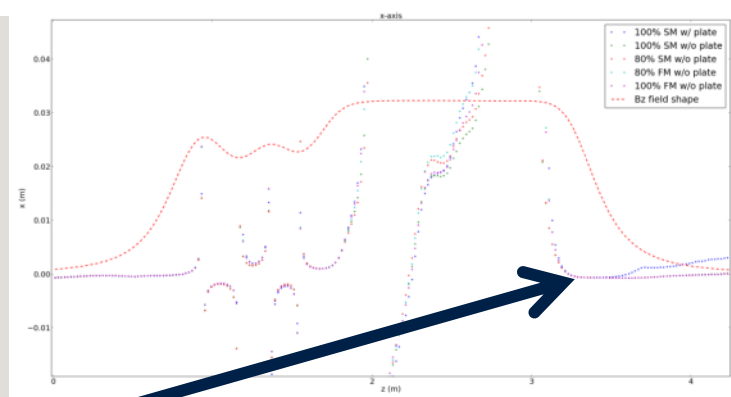
Region 3

100% Solenoid Mode, w/ Shielding Plate



Region 3

100% Solenoid Mode, w/ Shielding Plate



CONCLUSIONS

Conclusions & Next Steps

- We looked at the survey info at CM37, and have now looked at the raw data.
- The shielding plate does its job.
- Fields are *probably* linear, though the residual field needs understanding
- Residual field changes ‘oddly’ depending on its previously powered state.
- Hall probe measurement noise is difficult to quantify given the residual field, but estimate $\sigma = 15 - 20\text{G}$.
- More data is needed to look at hysteresis effects seriously
- The magnetic axis is approximately centred on zero, but this requires a significant uncertainty analysis and combination with the survey info to confirm.
- Next steps:
 - Evaluation of uncertainties
 - Cross-calibration of Hall probes
 - Refinement of magnetic axis fits
 - Field fits using 2-model scaling technique
 - Evaluation of difference between fitted and measured fields (Fourier-Bessel fits)
 - “Real magnet” model → MAUS
- More to come at analysis meetings!

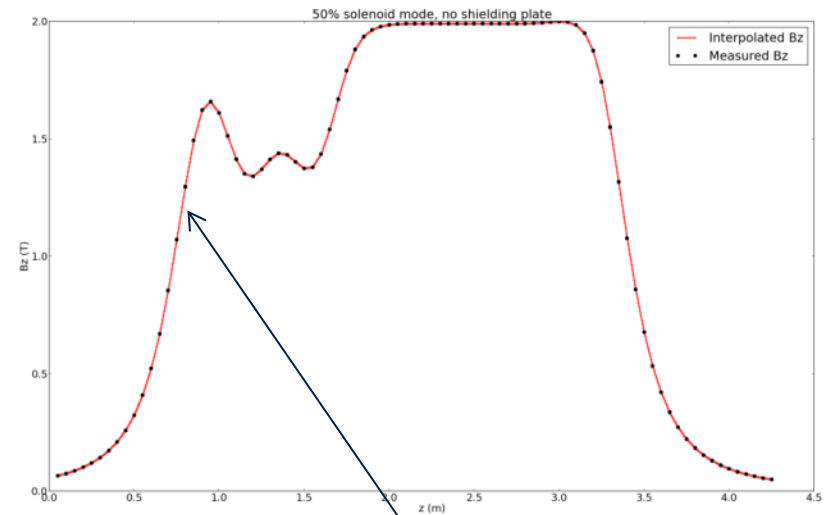
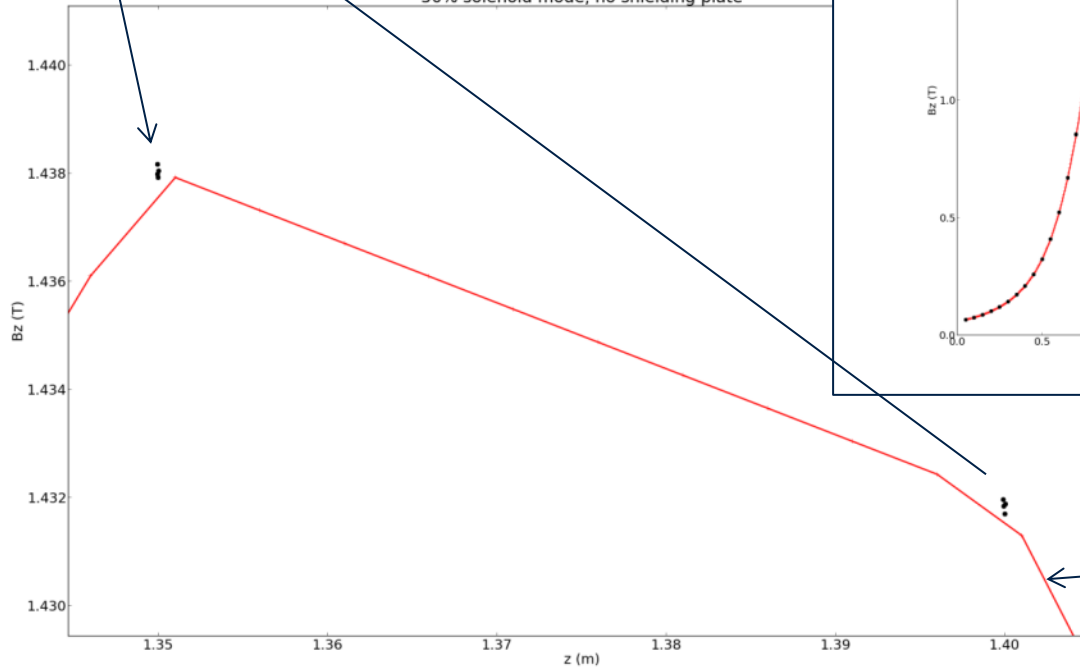
BACK-UP SLIDES

- A. Interpolation reliability
- B. Mapper co-ordinate transforms

Interpolation reliability

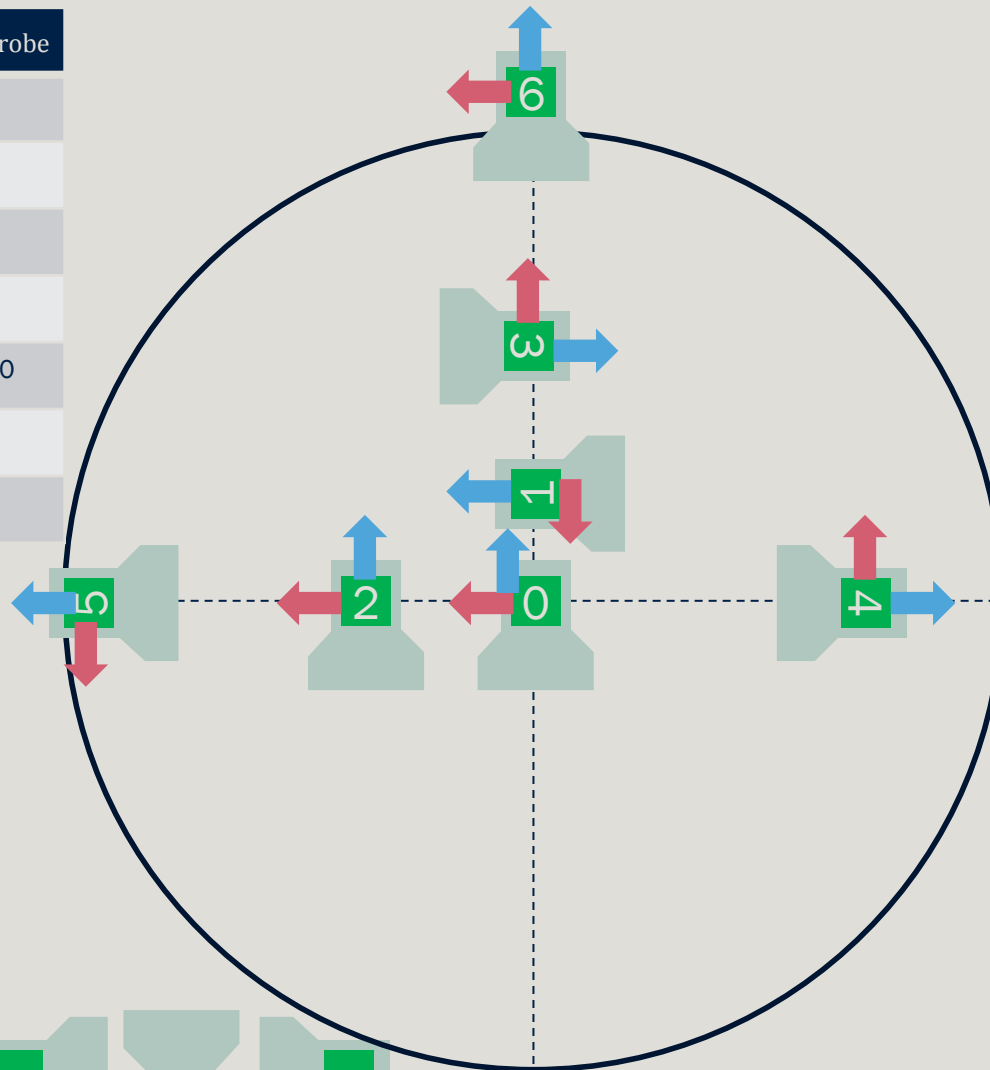
4 measurements with different rotations of the mapper disc


50% solenoid mode, no shielding plate

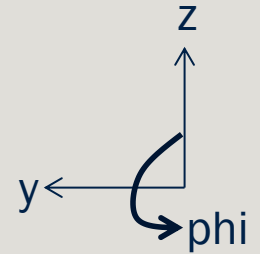


Mapper coordinate transformations

#	y	z	φ_{probe}	θ_{probe}
0	0	0	0	0
1	0	30	90	0
2	60	0	0	90
3	0	90	270	0
4	-120	0	270	270
5	150	0	90	90
6	0	180	0	0



 B_z
 B_y



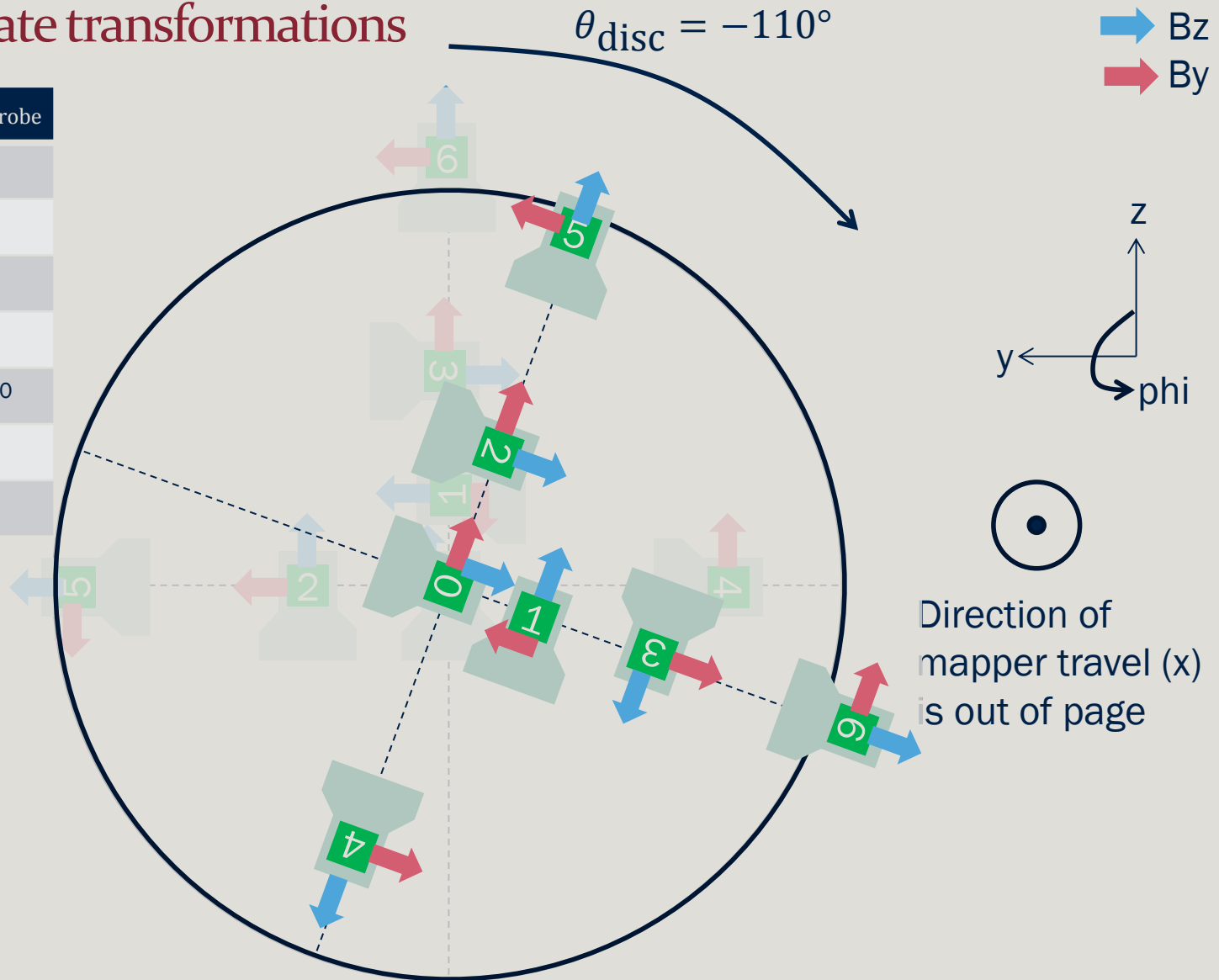
Direction of
mapper travel (x)
is out of page



$\varphi_{\text{probe}} = 0^\circ \quad 90^\circ \quad 180^\circ \quad 270^\circ$

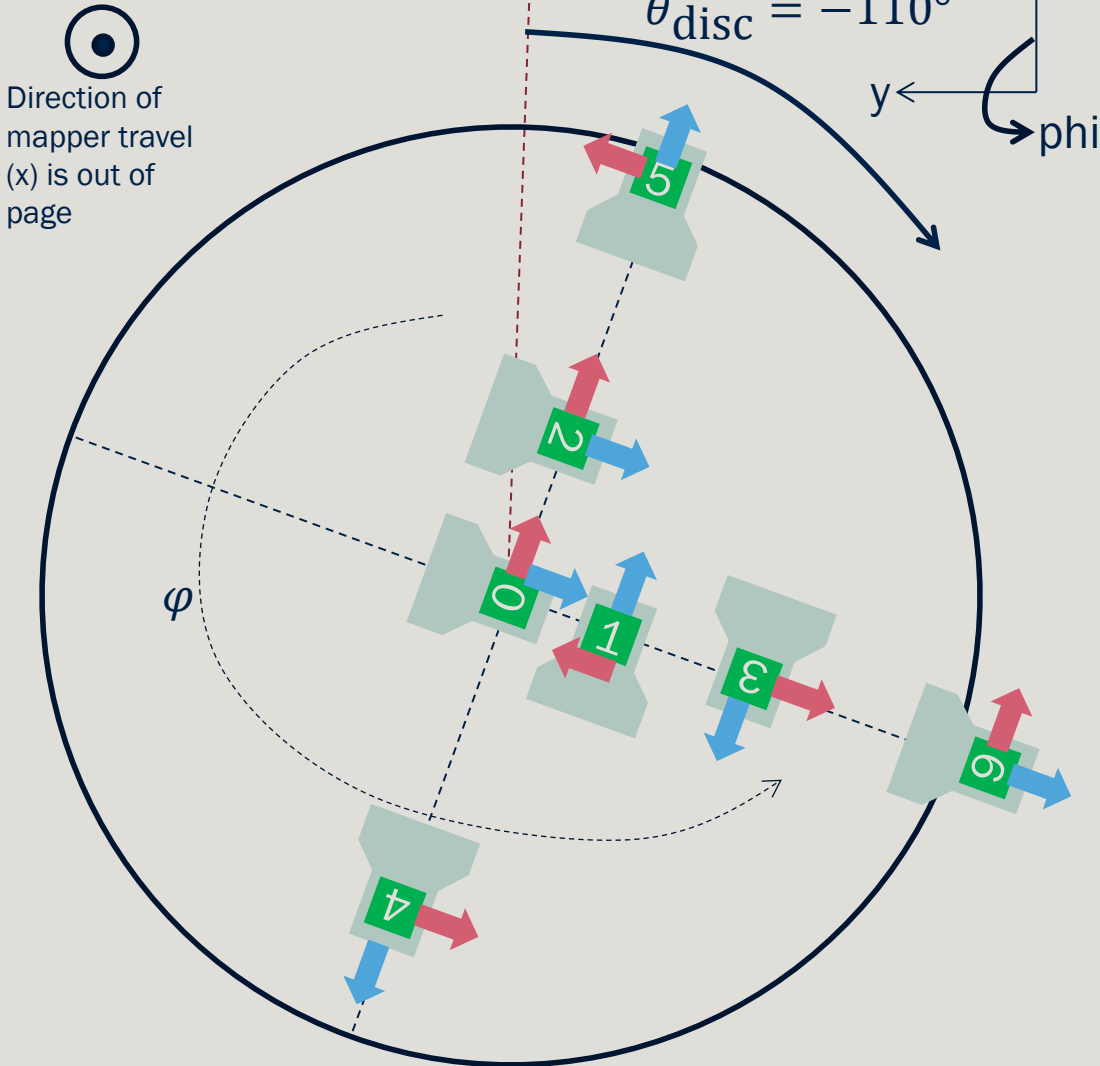
Mapper coordinate transformations

#	y	z	φ_{probe}	θ_{probe}
0	0	0	0	0
1	0	30	90	0
2	60	0	0	90
3	0	90	270	0
4	-120	0	270	270
5	150	0	90	90
6	0	180	0	0



Start by working in POLAR co-ordinates (B_r , B_{phi} , B_z)

Mapper coordinate transformations



$$B_{r1} = -B_y; B_{\phi1} = B_z$$

$$B_{r2} = B_y; B_{\phi2} = -B_z$$

$$B_{r3} = B_y; B_{\phi3} = -B_z$$

$$B_{r4} = B_z; B_{\phi4} = B_y$$

$$B_{r5} = B_z; B_{\phi5} = B_y$$

$$B_{r6} = B_z; B_{\phi6} = B_y$$

$$r = \sqrt{y^2 + z^2}$$

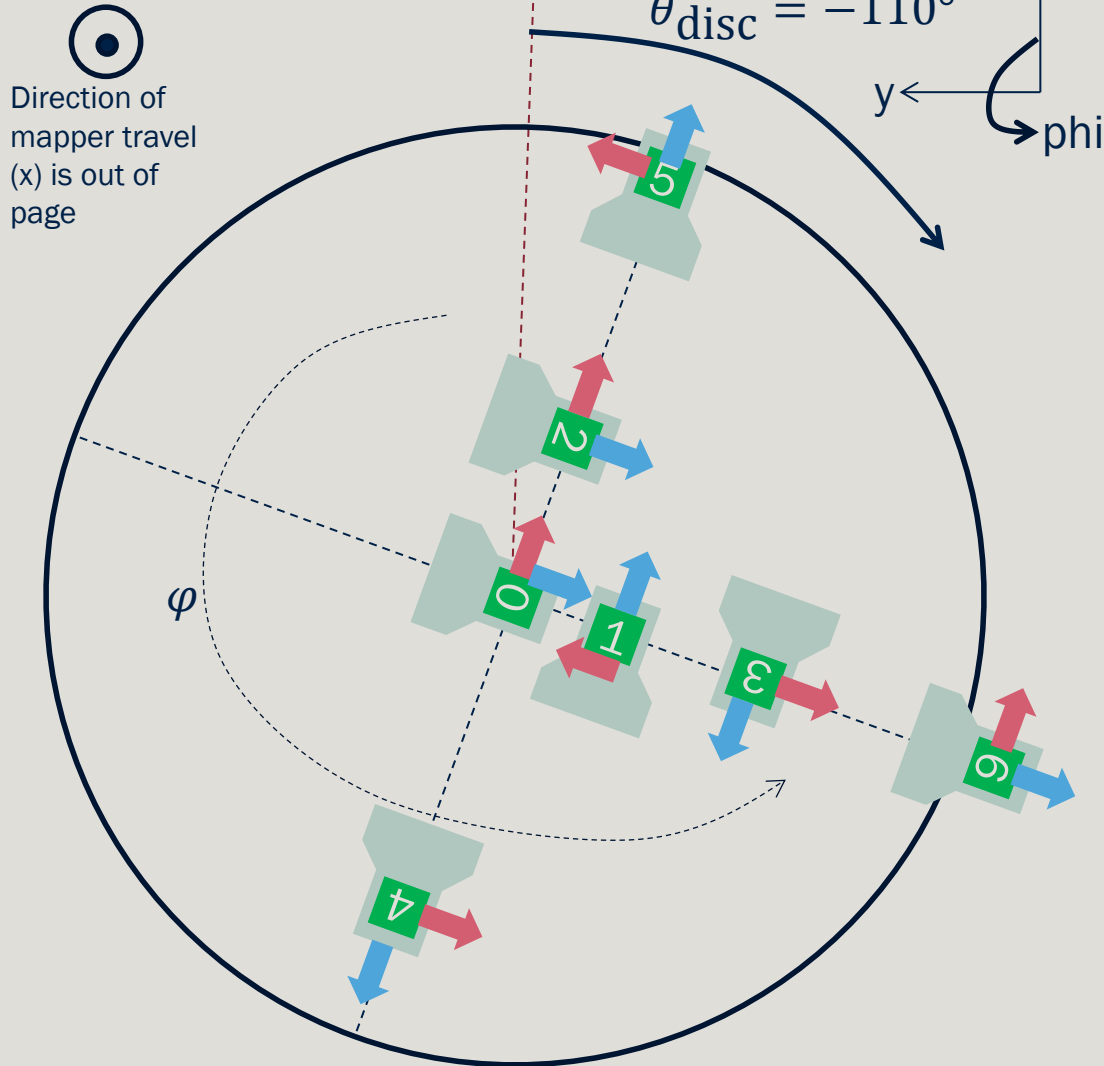
$$\phi = \theta_{\text{disc}} + \theta_{\text{probe}}$$

This will be true regardless of how we rotate the disc

Start by working in POLAR co-ordinates (B_r , B_ϕ , B_z)



Mapper coordinate transformations



From polar co-ordinates, get to Cartesian components for probe n by:

$$\varphi = \theta_{\text{disc}} + \theta_{\text{probe}}$$

$$\begin{pmatrix} B_{yn} \\ B_{zn} \end{pmatrix} = \begin{pmatrix} \sin\varphi & \cos\varphi \\ \cos\varphi & -\sin\varphi \end{pmatrix} \begin{pmatrix} B_{rn} \\ B_{\varphi n} \end{pmatrix}$$

$$y_n = r_n \sin\varphi$$

$$z_n = r_n \cos\varphi$$

For “MICE” co-ordinates:

$$B_{yn} \rightarrow B_{xn}$$

$$B_{zn} \rightarrow B_{yn}$$

$$B_{xn} \rightarrow B_{zn}$$