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Progress update on the prototype ZEPTO dipole magnet for CLIC

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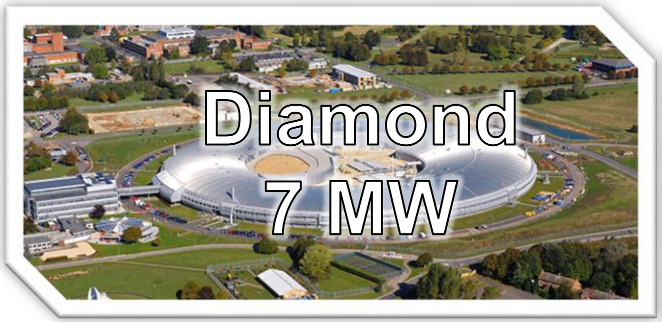
ZEPTO – An Introduction

ZEPTO (Zero Power Tuneable Optics) project is a collaboration between CERN and STFC Daresbury Laboratory to save power and costs by switching from resistive electromagnets to permanent magnets.



(Total facility consumption)

CERN
200 MW

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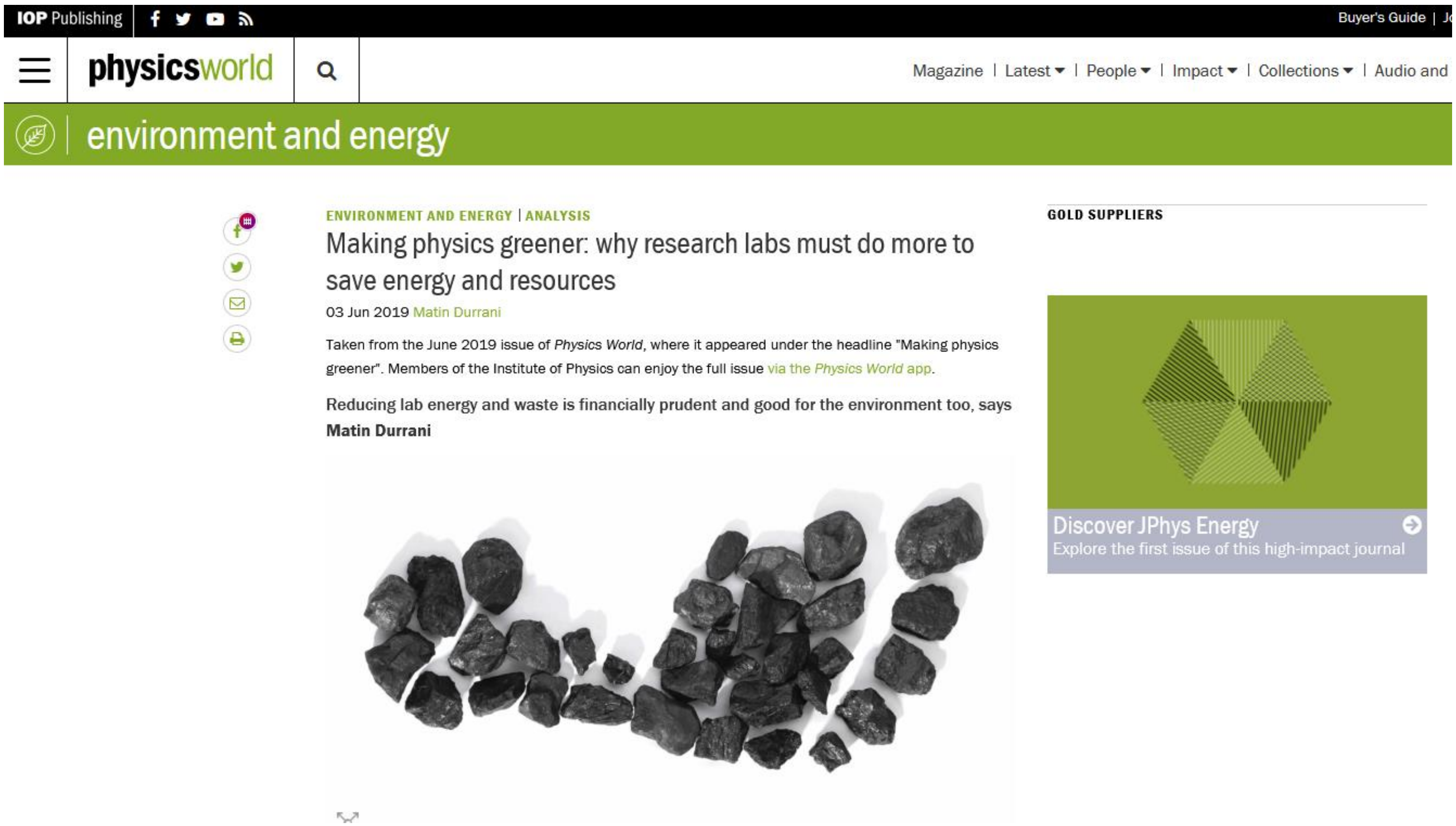
A hot topic!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ENVIRONMENT AND ENERGY | ANALYSIS

Making physics greener: why research labs must do more to save energy and resources

03 Jun 2019 Matin Durrani

Taken from the June 2019 issue of *Physics World*, where it appeared under the headline "Making physics greener". Members of the Institute of Physics can enjoy the full issue via the *Physics World* app.

Reducing lab energy and waste is financially prudent and good for the environment too, says **Matin Durrani**

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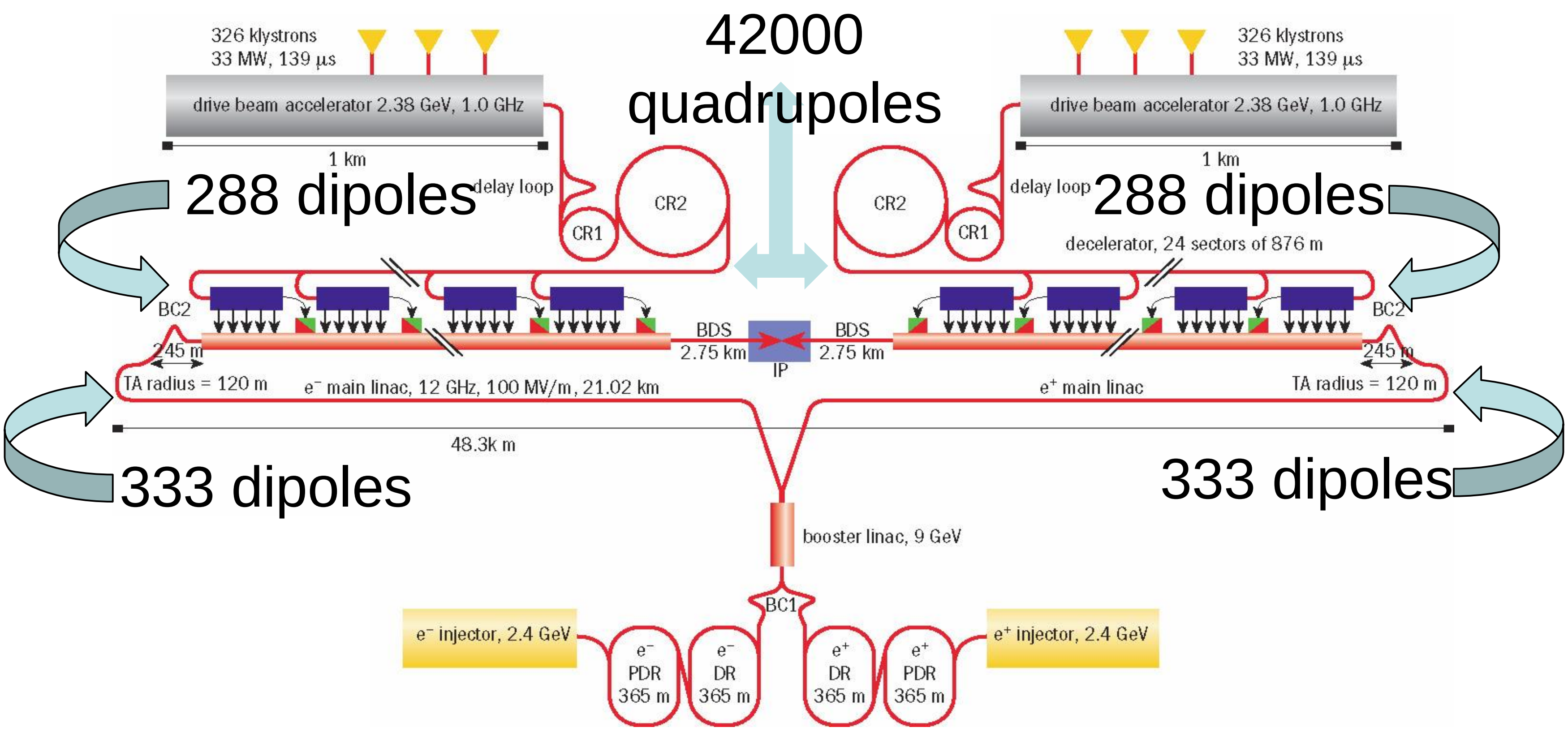
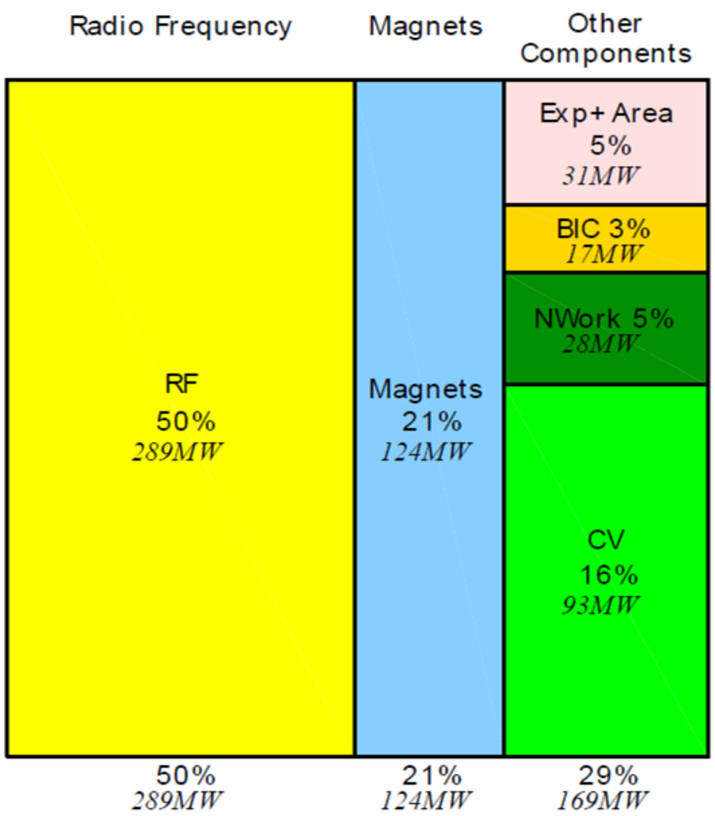
Physics World (magazine & online) June 2019 edition

Motivation - CLIC



Motivation - CLIC

The plan to use normal conducting systems on CLIC will result in high electrical power consumption and running costs.



The Challenge

Magnet Type	Number	Length	Strength	Range	0.1% good field	Power/total
Drive Beam Quads	41400	0.2 m	63 T/m	100-10%	26x26 mm	20 MW
Drive Beam Dipoles	576	1.5 m	1.6 T	100-50%	40x40 mm	12.4 MW
Linac Quads	1061	0.5 m	14 T/m	100-10%	80x80 mm	6.3 MW
Linac Quads	1638	0.25 m	17 T/m	100-10%	87x87 mm	10.3 MW
Main Beam Dipoles	666	1.5 m	0.5 T	100%	30x30 mm	2.5 MW
Damping Ring Quads	408	0.4 m	30 T/m	100-20%	80x80 mm	4.7 MW
Damping Ring Quads	408	0.2 m	30 T/m	100-20%	80x80 mm	3.3 MW
Chicane Dipole	184	1.5 m	1.6 T	100-10%	80x80 mm	7.7 MW
Chicane Dipole	236	1 m	0.26 T	100-10%	80x80 mm	1.1 MW

Previous work

Previously developed high and low strength variants of a tuneable permanent magnet quadrupole

More info @:

B. J. A. Shepherd et al., “Tunable High-Gradient Permanent Magnet Quadrupoles”, Journal of Instrumentation, Vol 9, T11006, 2014.

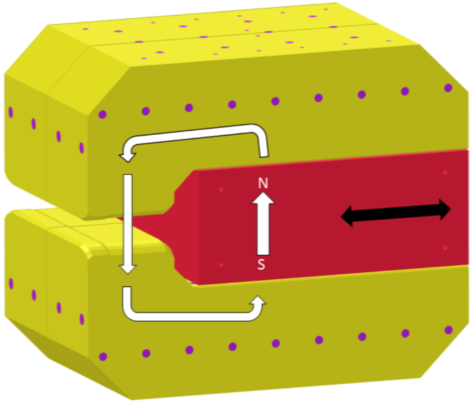
And

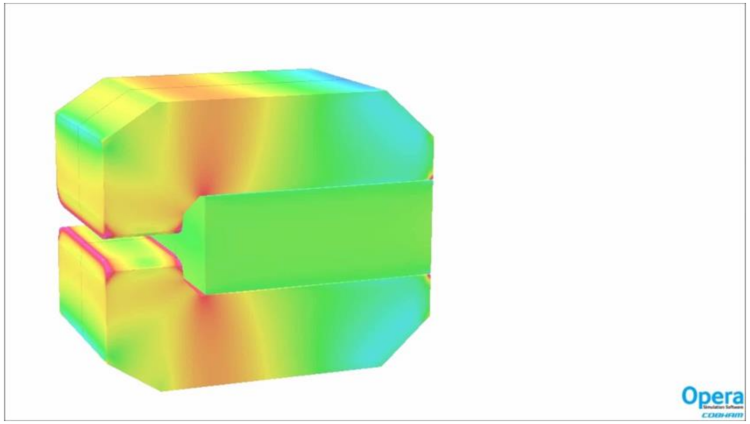
B. J. A. Shepherd et al., “Design And Measurement Of A Low-Energy Tunable Permanent Magnet Quadrupole Prototype”,Proc. 5th Int. Particle Accelerator Conf. (IPAC’14), Dresden, Germany, June 2014, paper TUPRO113, pp. 1316-1318.

Patent *WO-2012046036-A1*

Dipole Prototype

- Focus on the most challenging case (576 dipoles for drive beam turn-around loop).
  - Length 1.5 m, strength 1.6 T, tuning range 50-100%
- Settled on C-design that uses a single sliding PM block to adjust field





- Advantages:
  - Tunes without changing gap!
  - PM moves perpendicular to largest forces
  - Curved poles possible

Dipole Prototype

- Original plan was to build a 0.5m version of full size DB TAL magnet
  - Not possible within available budget (£100,000)
- So, instead we have constructed a scaled version
  - Cost was dominated by one off PM block costs (>50%)
  - Still demonstrates the tuneable PM dipole principle.

Type	Length (m)	Max Field Strength (T)	Pole Gap (mm)	0.1% good field (integrated)(mm)	Range (%)
DB TAL	**1.5**	**1.6**	**53**	**40 x 40**	**50–100**
Original Prototype	0.5	1.6	53	40 x 40	50–100
Scaled Prototype	0.4	**1.1**	**40**	**30 x 30**	**50–100**

Actually built as 44

Magnet Block

- Magnet block dimensions are **500x400x200 mm**, with 4 holes on 400mm axis for mounting rods.
  - Constructed from 80 individual blocks (each 100x50x100mm) in resin

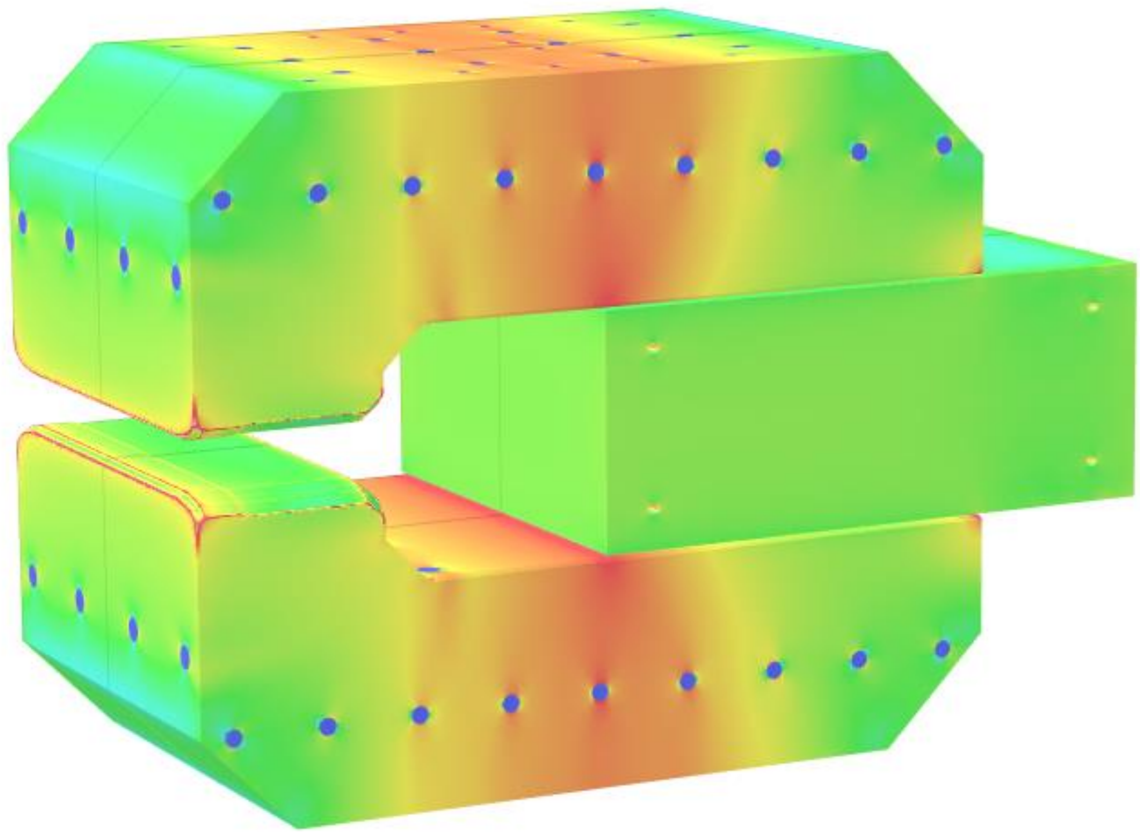
- Manufactured, measured & delivered by Vacuumschmelze
- Magnet material **NdFeB, Vacodym 745TP**
- **Br 1.38T min, 1.41T typical**

Modelling

Magnet simulations performed in OPERA 3D

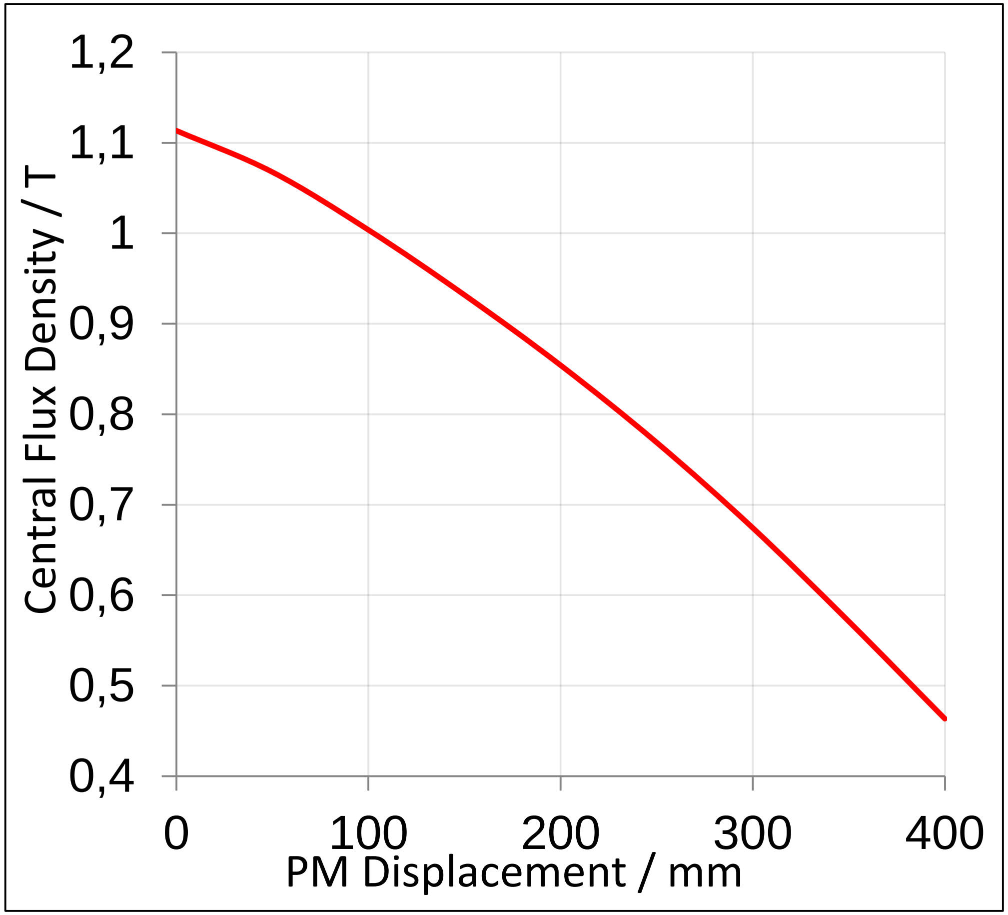
Mesh deals with small gaps and non-magnetic fasteners

Not component deflection



MODEL DATA
Position 150.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
4202266 elements
2036289 nodes
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in ZX plane (Z+X fields=0)

Predicted Flux Density

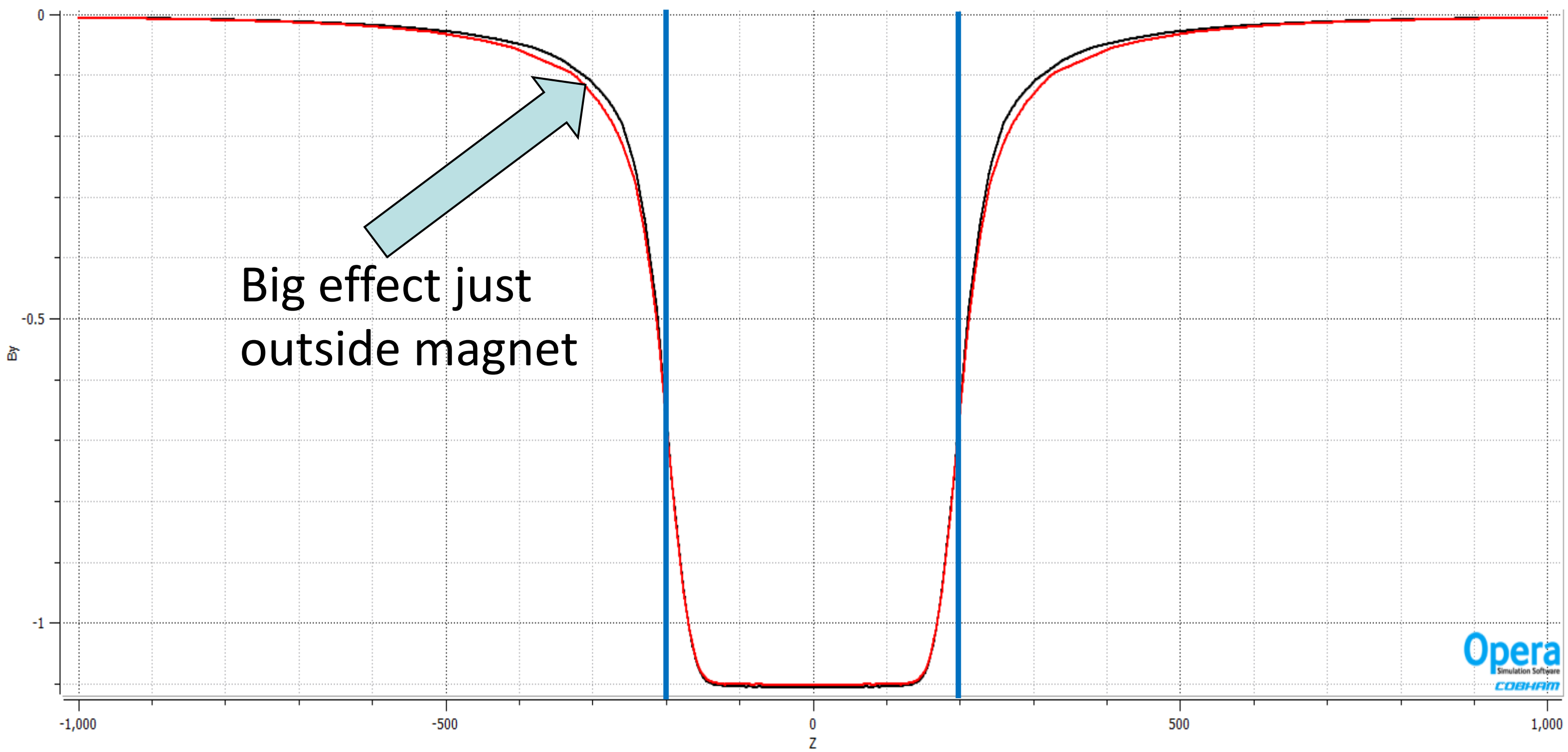


Predicted magnetic flux density at the geometric center of the magnet as a function of block displacement.

OPERA's 2 calculation methods agree to within the width of the fitting line.

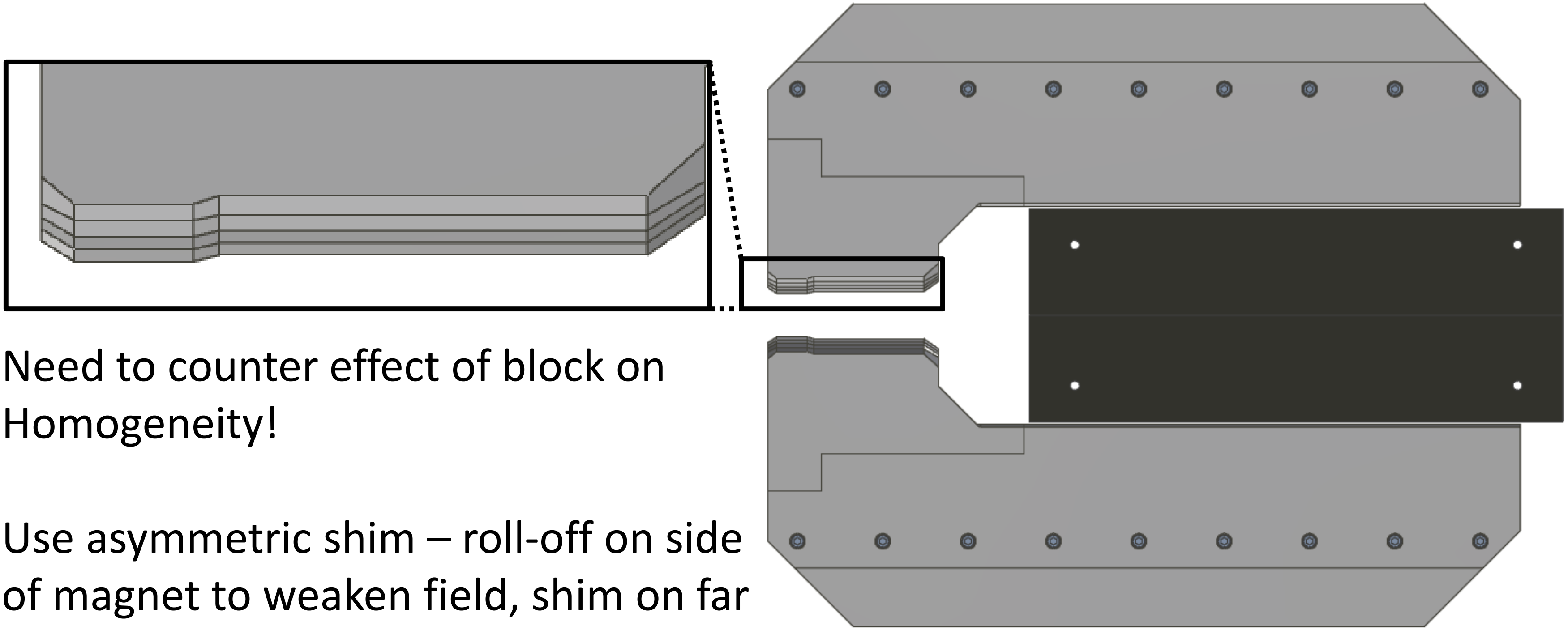
50 % tuning mark reached at 355 mm displacement.

Longitudinal Profile



Block affects longitudinal field profile differently at different positions in beam pipe.

Shim Structure



Need to counter effect of block on Homogeneity!

Use asymmetric shim – roll-off on side of magnet to weaken field, shim on far side to strengthen.

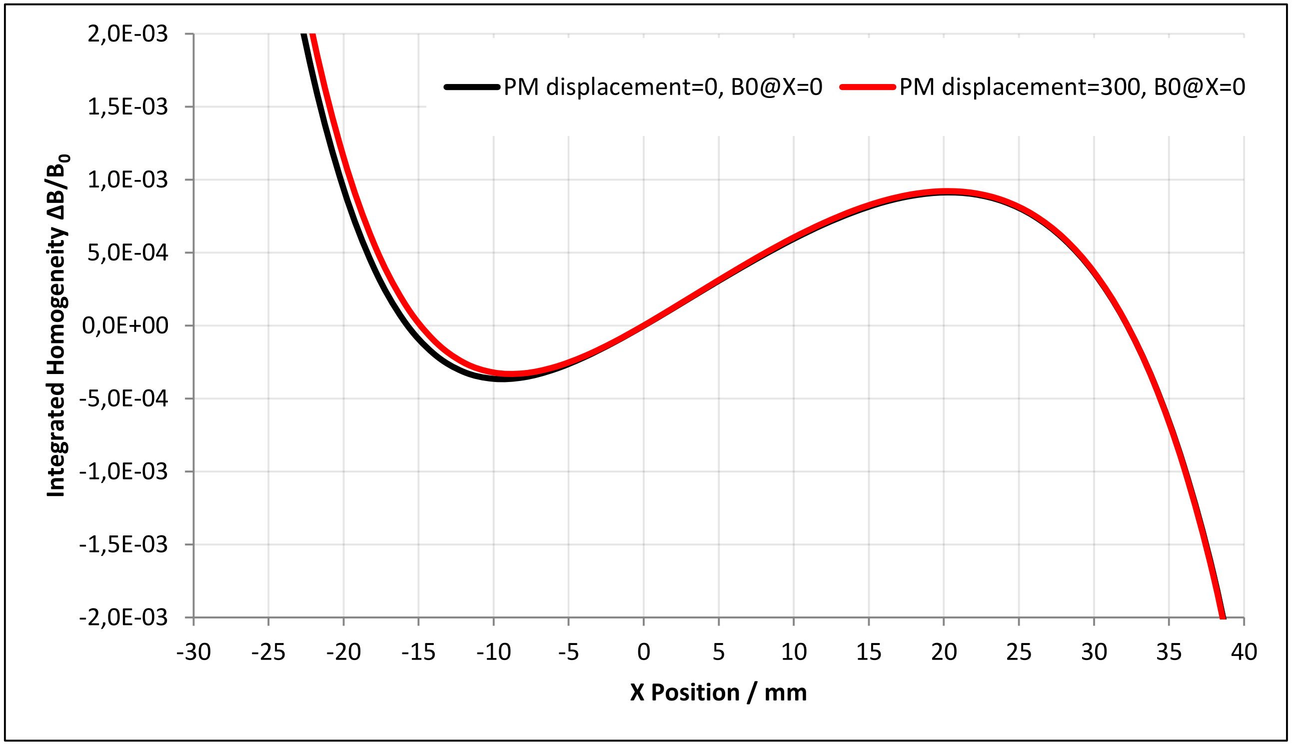
Big question – would this actually work in the real world???

Integrated Homogeneity

The optimised pole design meets the target to 20mm each side of the beam axis.

Balancing pole shape with saturation makes homogeneity relatively independent of PM block position.

IN SIMULATIONS!



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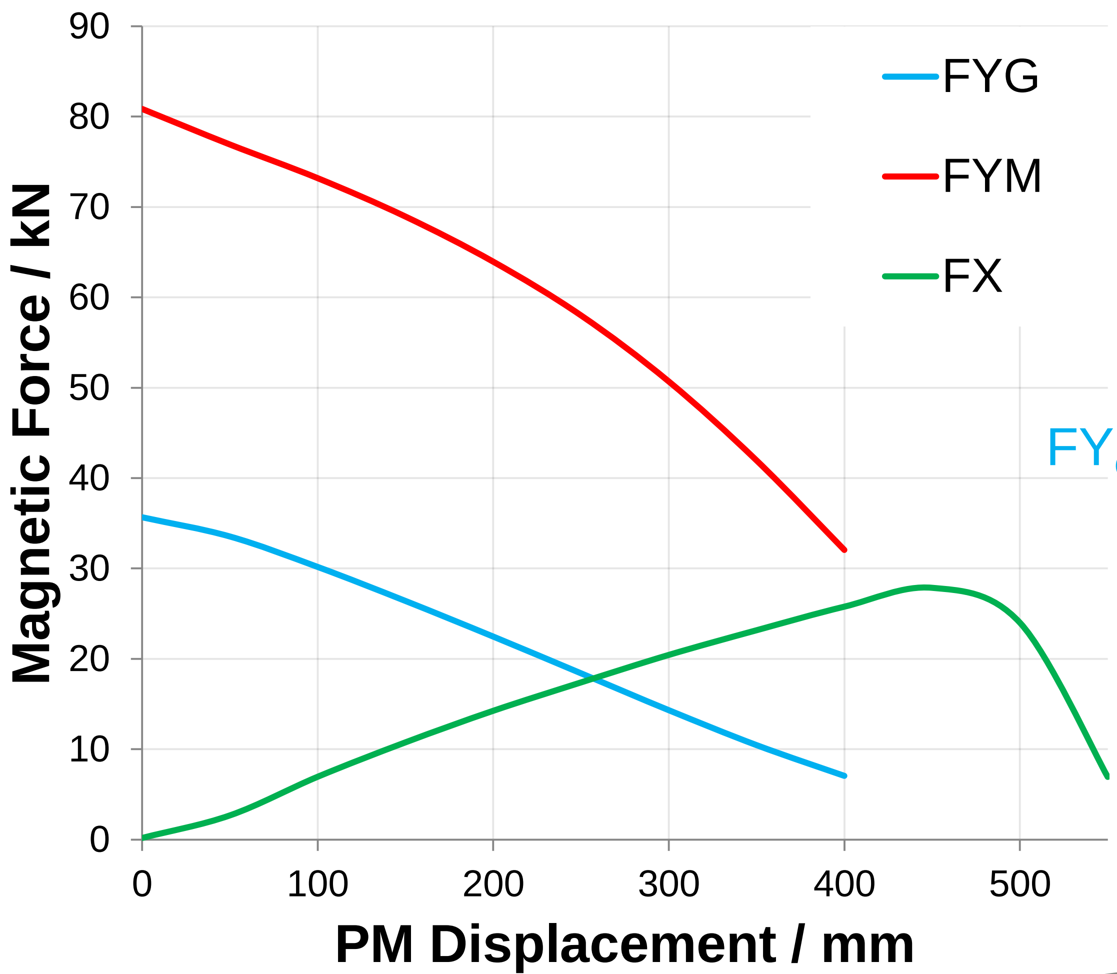
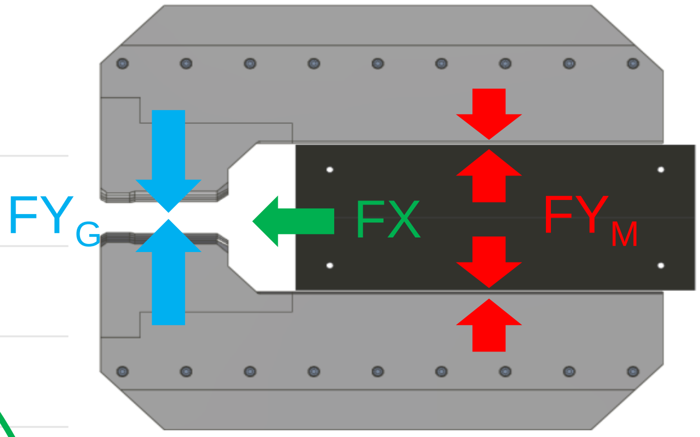
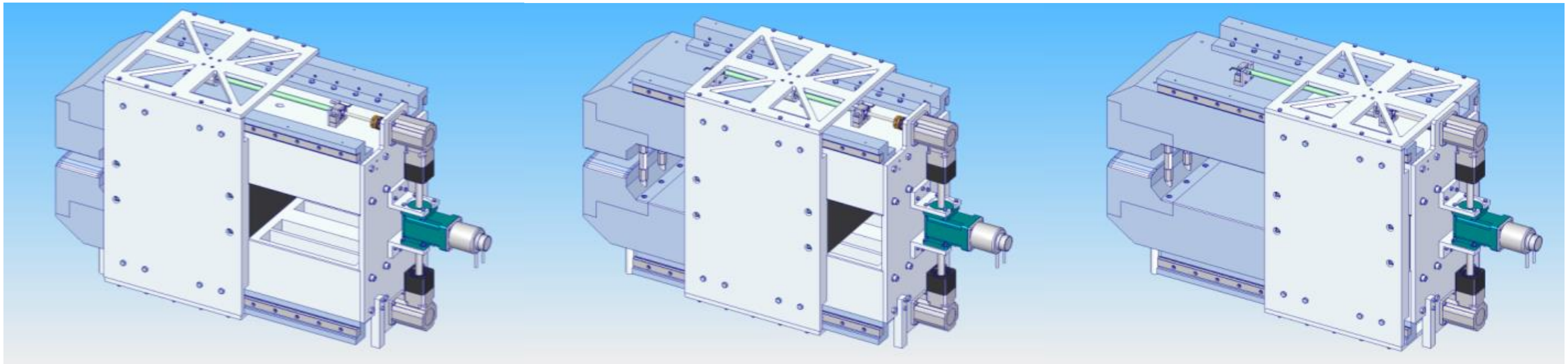
Magnetic Forces

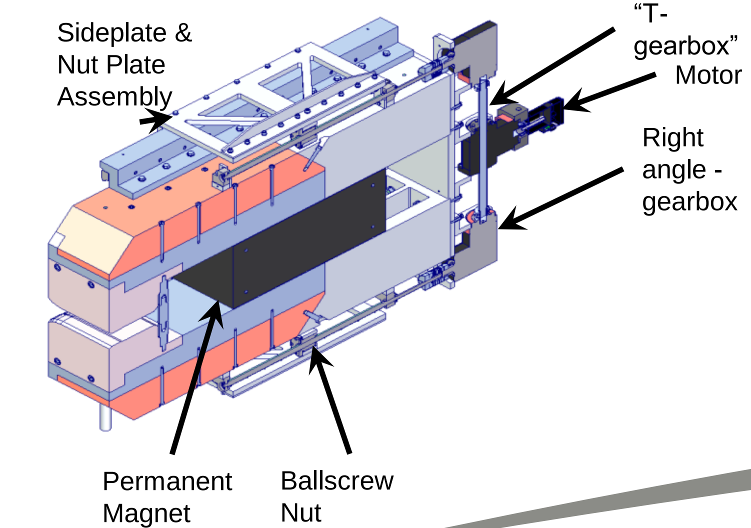




Engineering

- Sliding assembly using rails, stepper motor and gearbox.





3 support rods hold jaws of magnet fixed
Can be independently adjusted

Poles held 2 mm from surface of block

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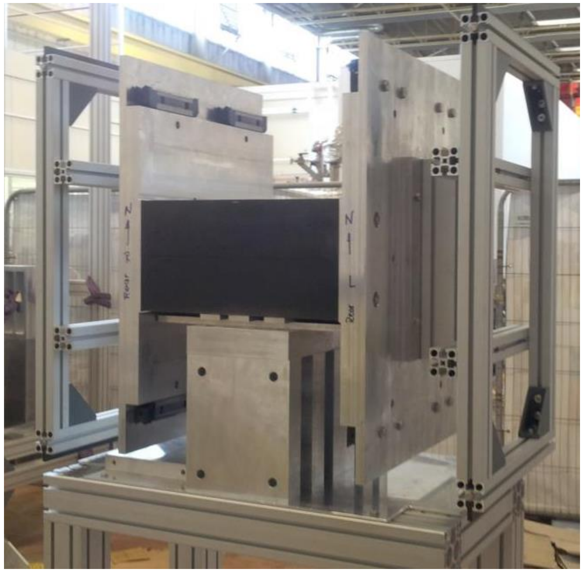
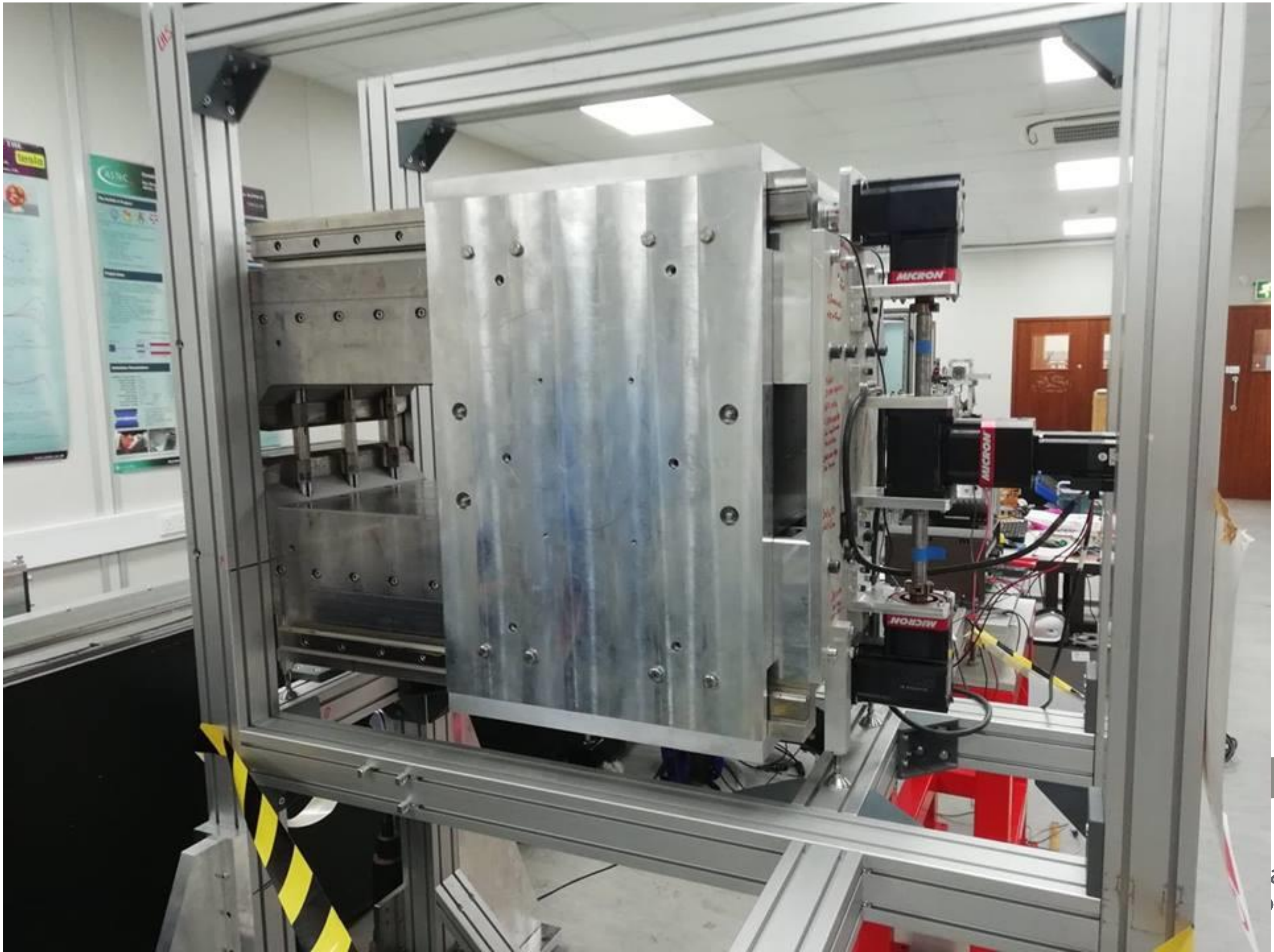
Assembly



The final assembly



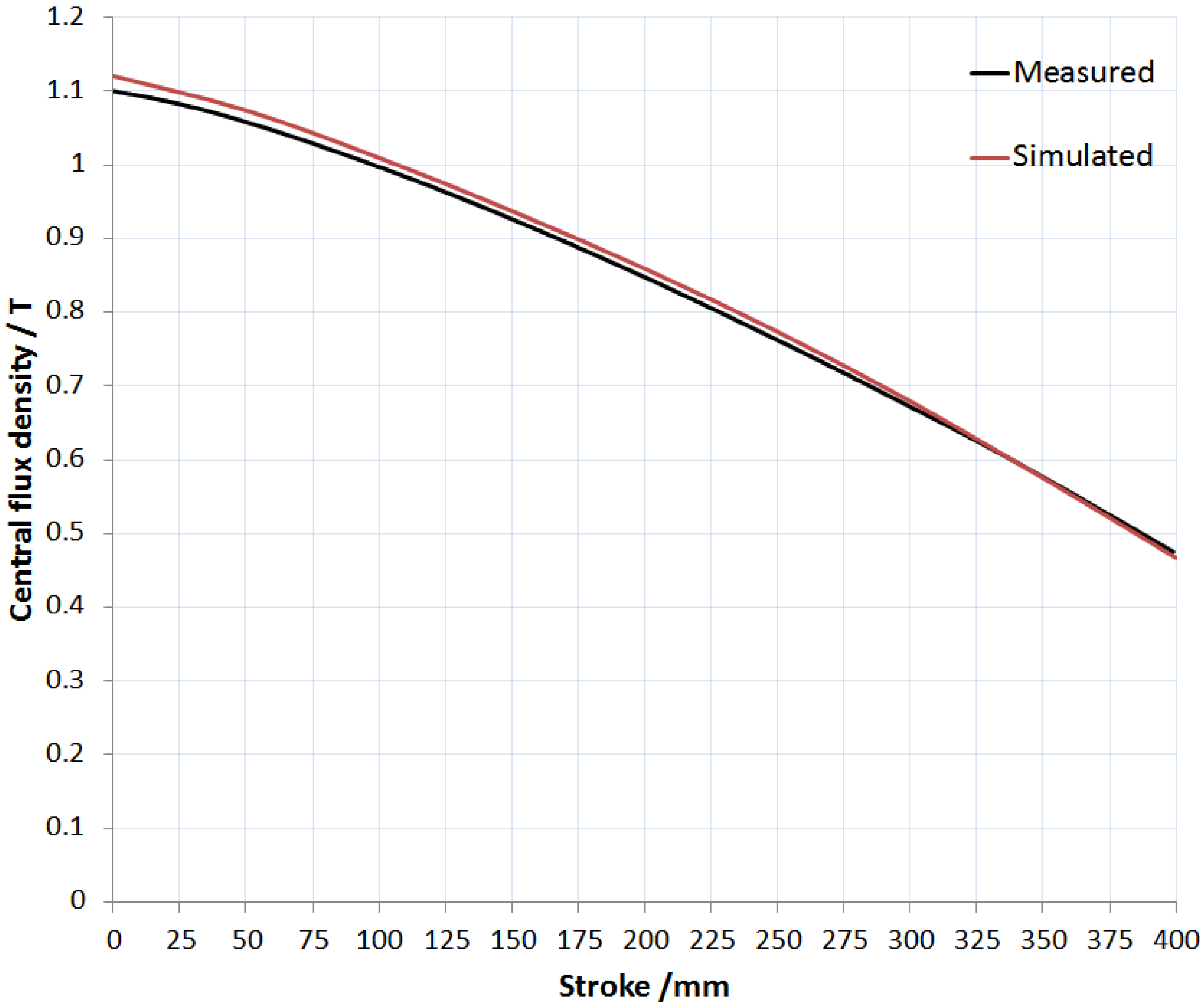
Methodology

Hall probe measurements were conducted at the magnet test facility at Daresbury (stretched wire also planned but not yet completed)

Laboratory features a granite measurement bench with 3-axis motion stages with 1 micron precision in X and Y and 5 micron on-the-fly in Z.

Equipped with a 3-axis Hall probe (MetroLab THM1176-HF), each measurement point is mean of 100 or 1000 rapid readings to reduce noise.

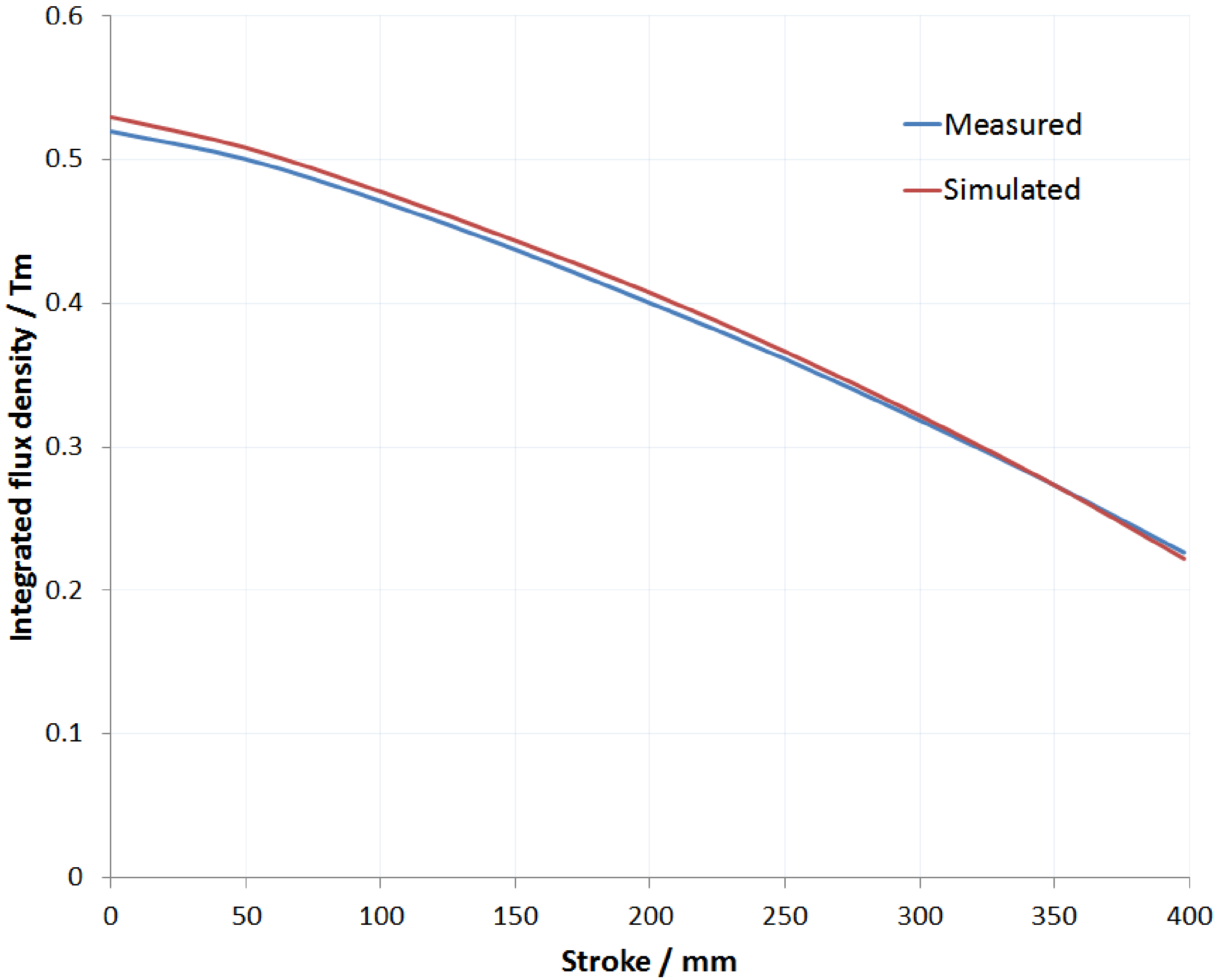
Flux density behaviour



We achieve the 50% tuning goal by displacing the block 363 mm

Well within magnet specification and very close to the simulation!

Flux density behaviour



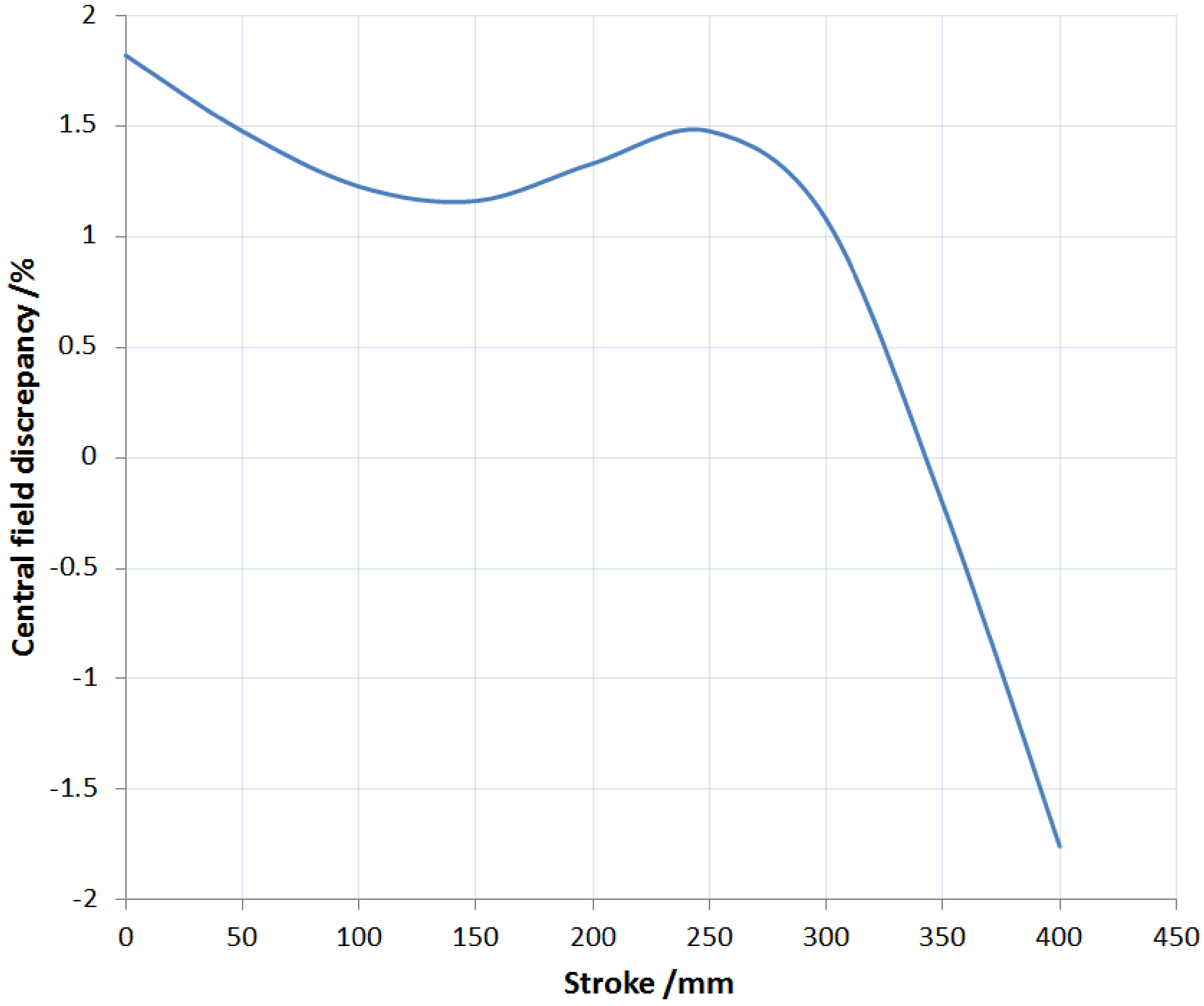
We achieve the 50% tuning goal by displacing the block 363 mm

Well within magnet specification and very close to the simulation!

Flux density behaviour

Simulated and measured flux density within 2% across entire range.

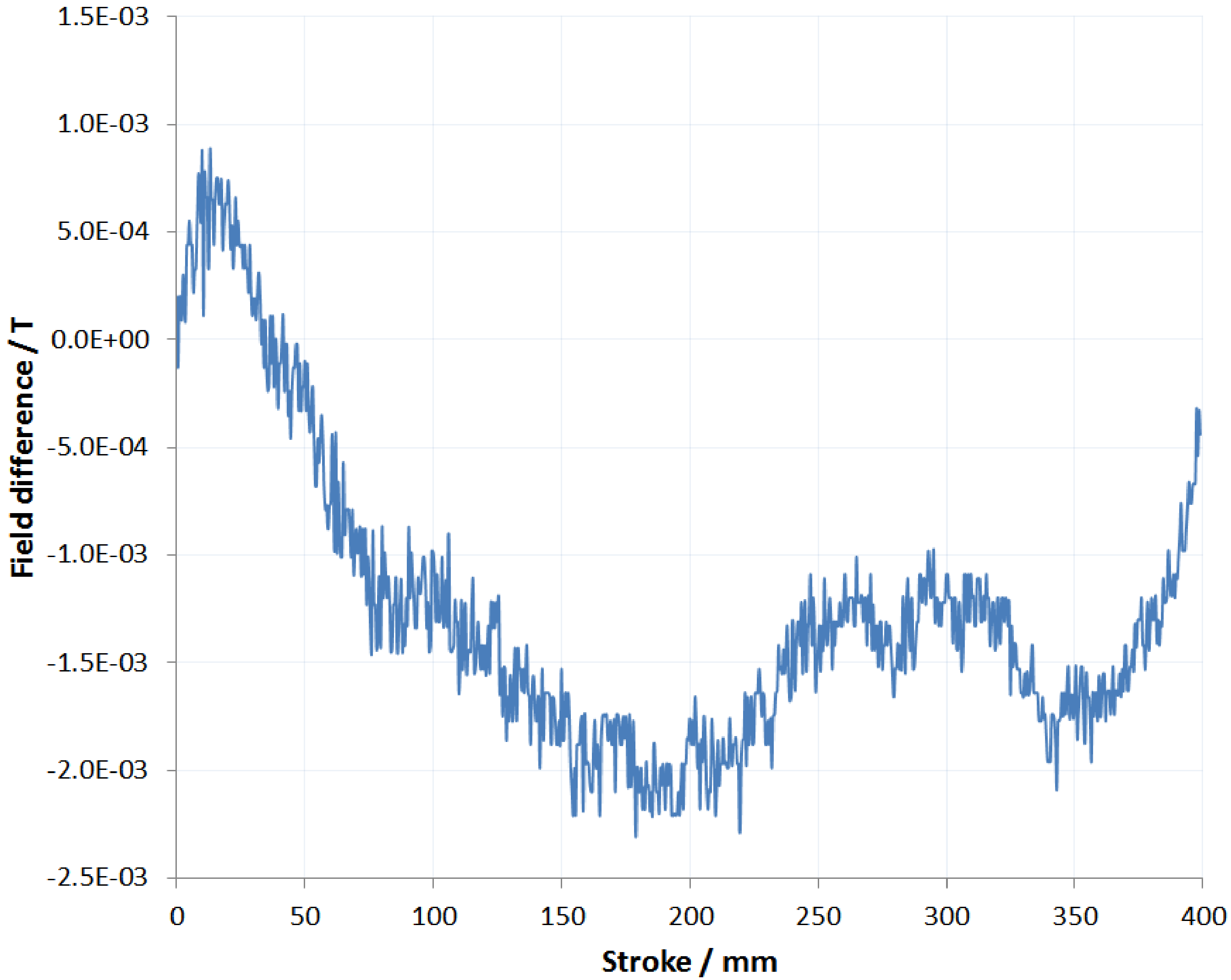
Very good result – discrepancy may arise from combination of PM material Hc/Br, steel BH curve, build tolerances and movement of components



Stroke hysteresis / backlash

Very low levels of hysteresis – much better than expected!

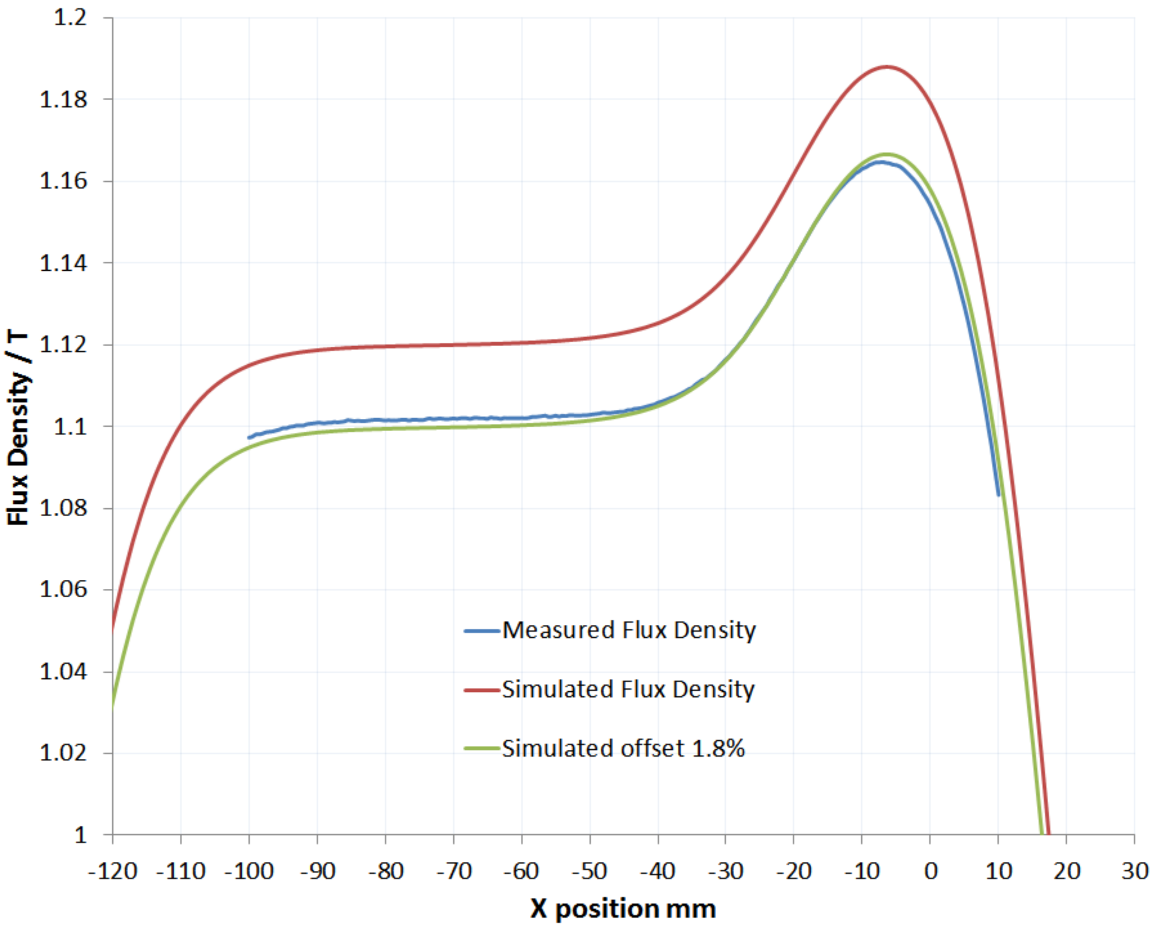
Will this remain true over several iterations of motion?



Transverse profile

Transverse profile matches simulations well, especially when adjusted to account for slight strength discrepancy.

This is the field at the dipole centreline, not integrated, hence unusual profile.



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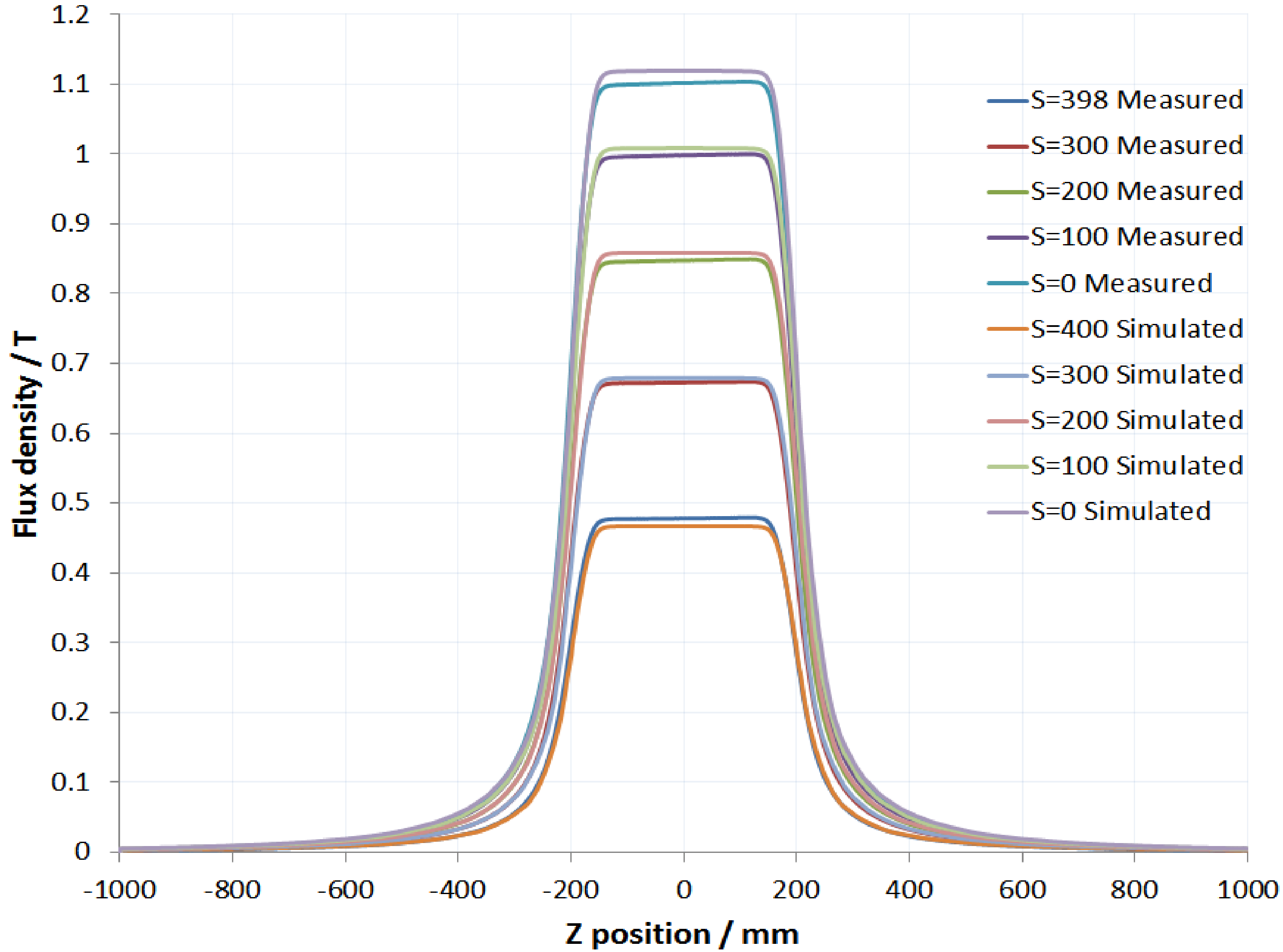
Longitudinal profile



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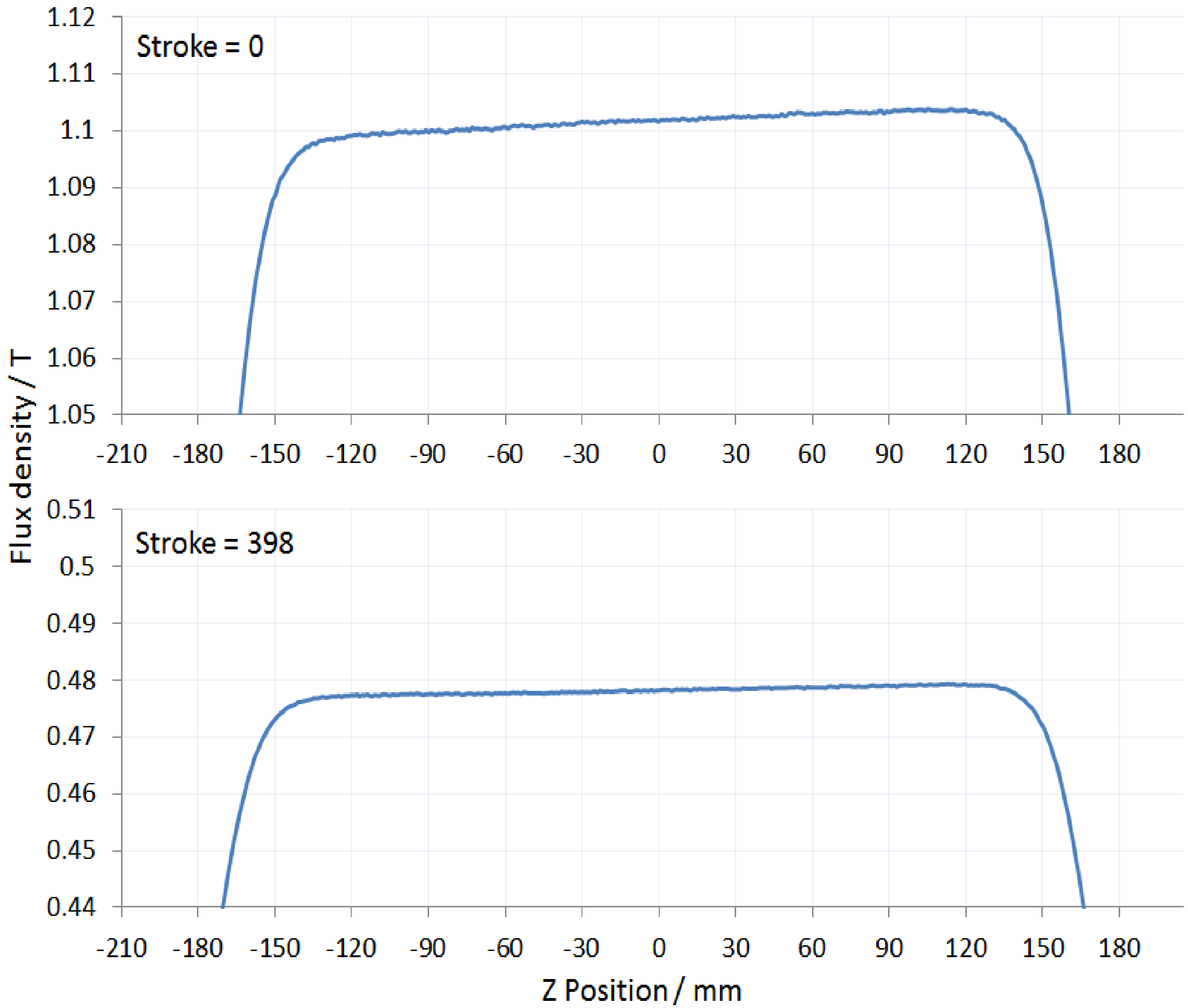
Slight problem!

Slip gauge measurements explain this – gap is almost 0.25mm wider at the –Z end!!!

Serious error in construction – important to measure carefully as separate components lead to increased likelihood of construction errors!



But fortunately fixable

Ceramic slip gauges used to examine the magnet gap –
movement during transport between assembly site and lab suspected. Also movement related to PM block position.

End	Block Pos	Slip gauge
Z-	398	44.3
Z+	398	44.07
Z-	0	44.18
Z+	0	43.91

(Nominal gap 44mm)

Gap changes by 0.23 mm along length at weakest position and 0.27 mm along length at strongest position.

Gap at –Z end changes by 0.12 mm during PM movement.

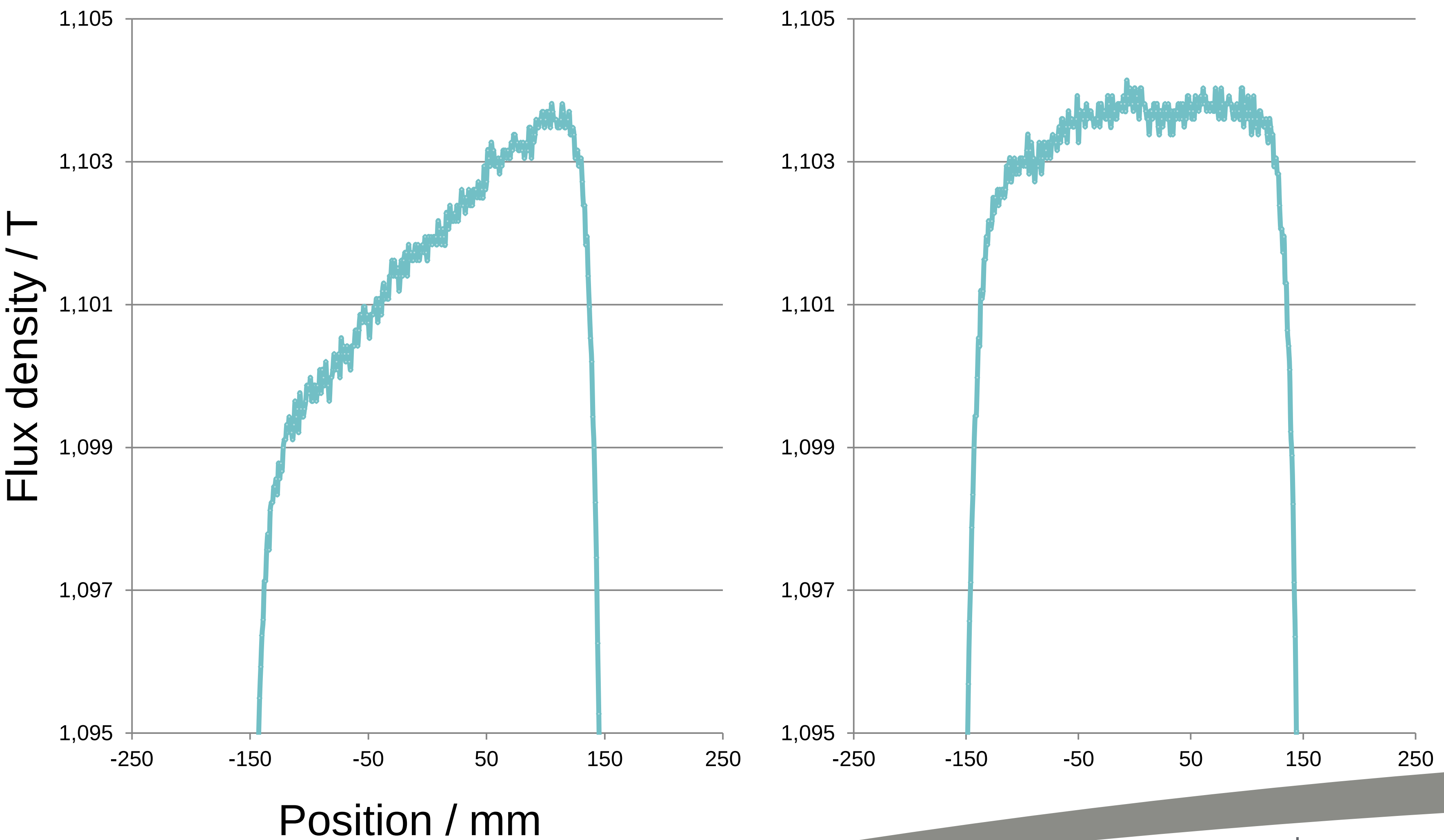
Gap at +Z end changes by 0.16 mm during PM movement.

But fortunately fixable

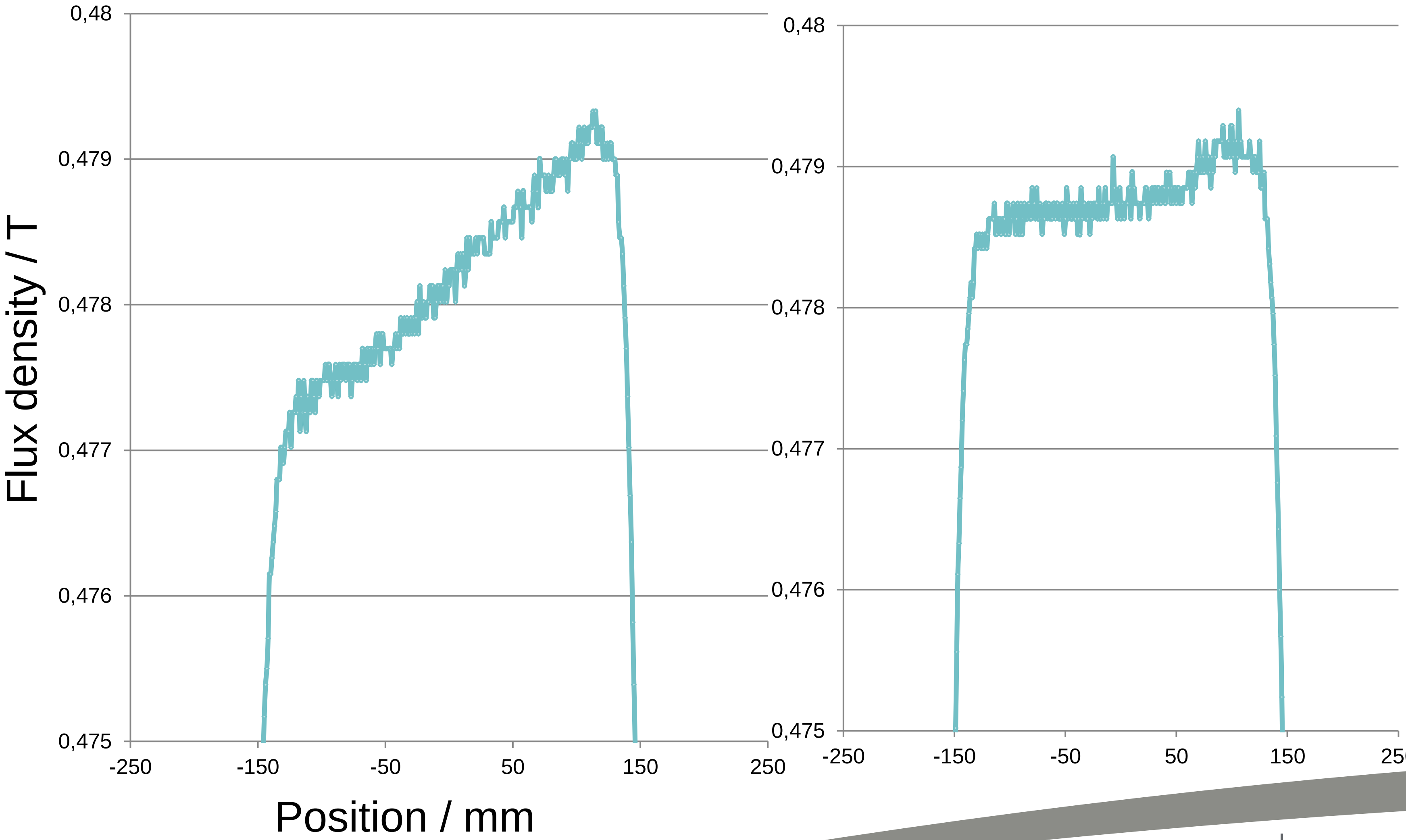
Cannot do any machining to pole faces once magnet is assembled.

However 3 support pillars have screw threads allowing independent adjustment with a very big (and non-magnetic!) spanner.

Before and after



Before and after



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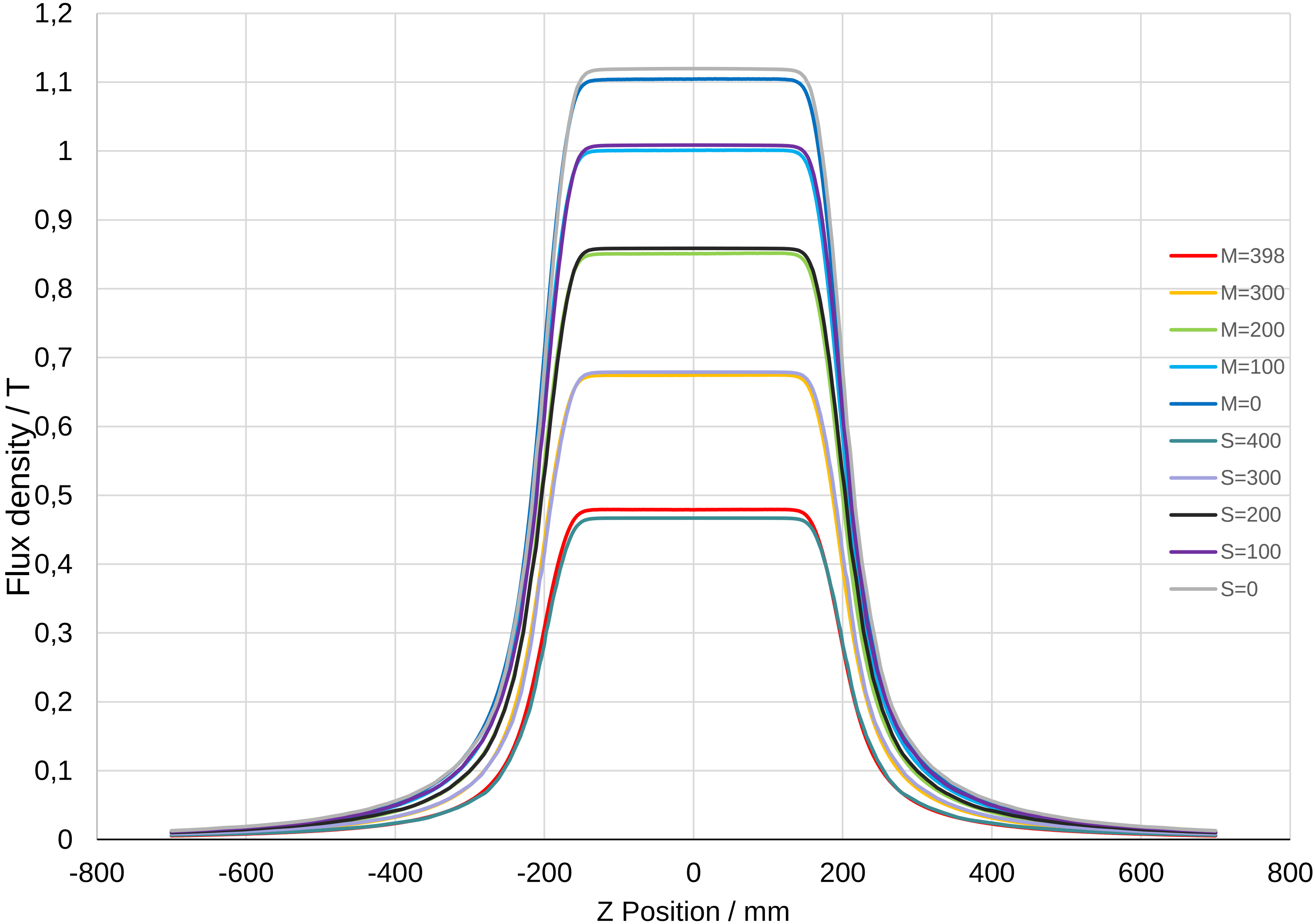
Longitudinal profile



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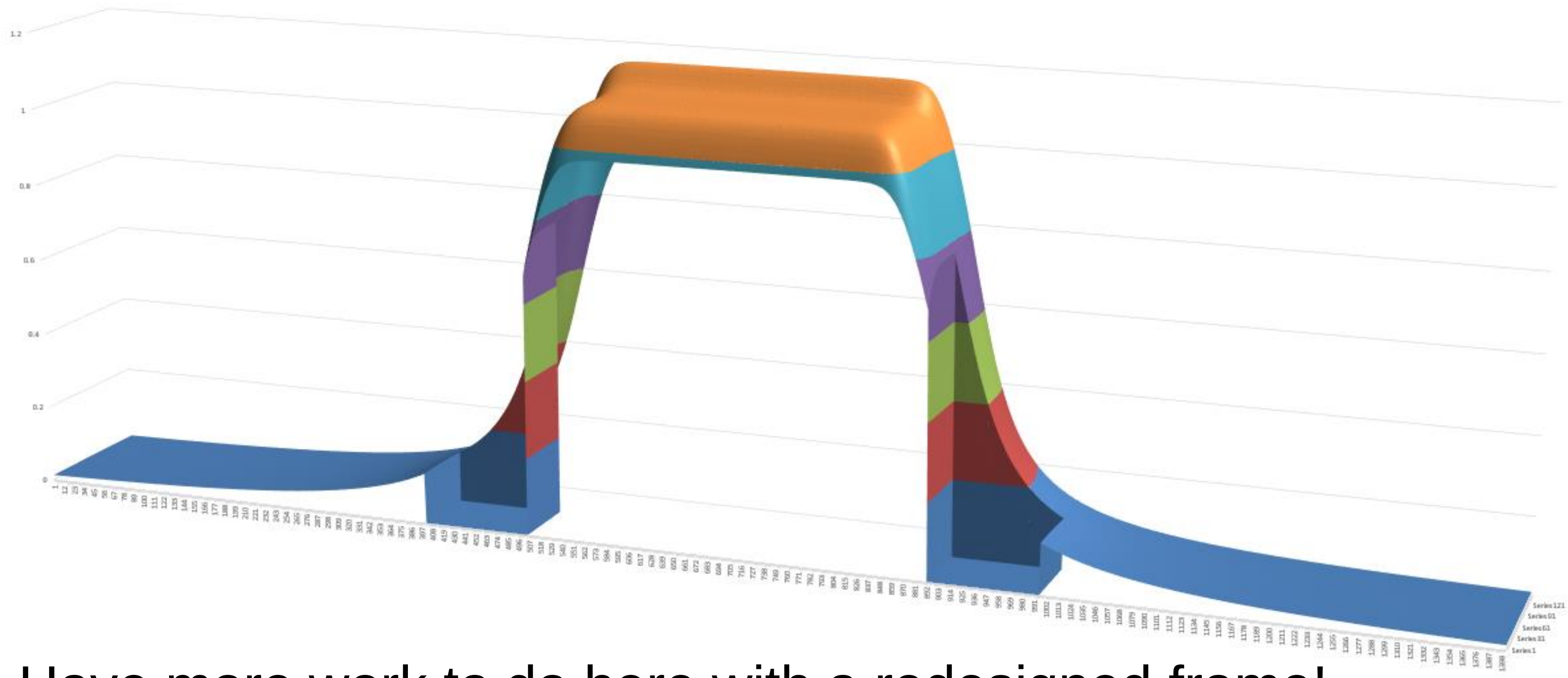
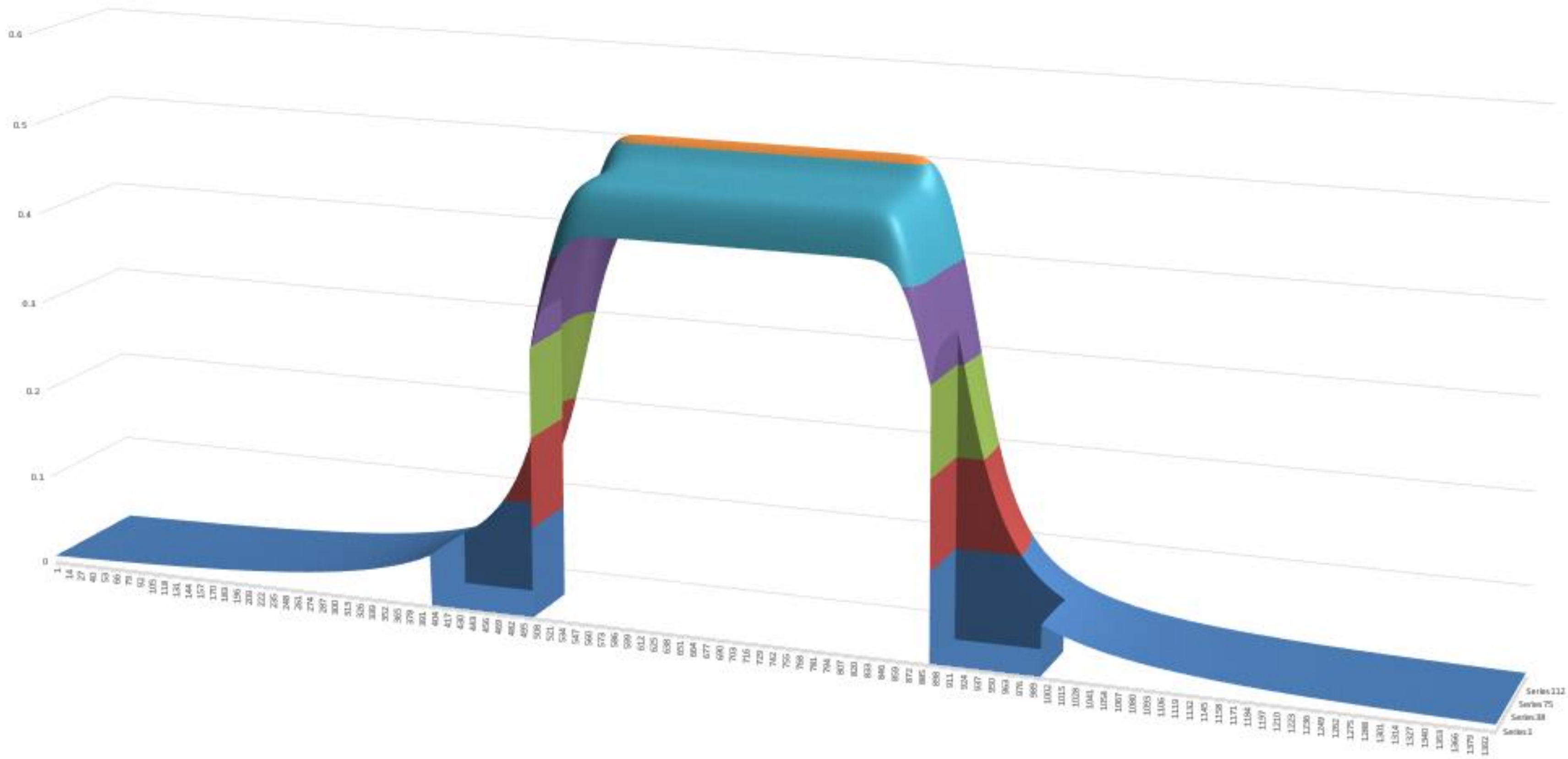
Plane mapping



Have more work to do here with a redesigned frame!

Plane mapping



Have more work to do here with a redesigned frame!

The next steps

1) Find a way of removing the pillars? Allows for completing plane maps and also proper stretched wire measurements.

2) Use new measurements to make a final assessment of the integrated field quality – did the asymmetric shim technique actually work as intended?

3) If time/money available, look at expanding on the design e.g. addition of secondary circuit, field clamping plates e.t.c.

Conclusions

- Tuneable permanent magnets have until recently been limited to fixed field or low tuneability applications – but large tuning ranges are now possible with purely permanent magnet systems.

- The dipole prototype design, despite representing a significant engineering challenge, is a viable system (albeit with room for significant development further). Simulations and measurements are reasonably well aligned.

- One needs to consider more than just the magnetic field when characterising such a magnet – mechanical considerations are serious and even with the most precise engineering small movements will occur and may have big effects!

- And finally something to bear in mind – these kind of magnets may or may not be right for you! Although they have significant savings in power and infrastructure over conventional electromagnetic dipoles, the larger they are they harder it gets!

Acknowledgements

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