# Construction and Measurement of a Tuneable Permanent Magnet Quadrupole for Diamond Light Source

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# Agenda

## 1 Introduction to ZEPTO

Development and motivation of ZEPTO tuneable permanent magnet technology.

## 2 Magnet assembly

Challenges of assembling a tuneable permanent magnet with strong forces present.

## 3 Measurements to date

Gradients and compensation magnetic centre movements.

## 4 Conclusions

Current and planned developments.

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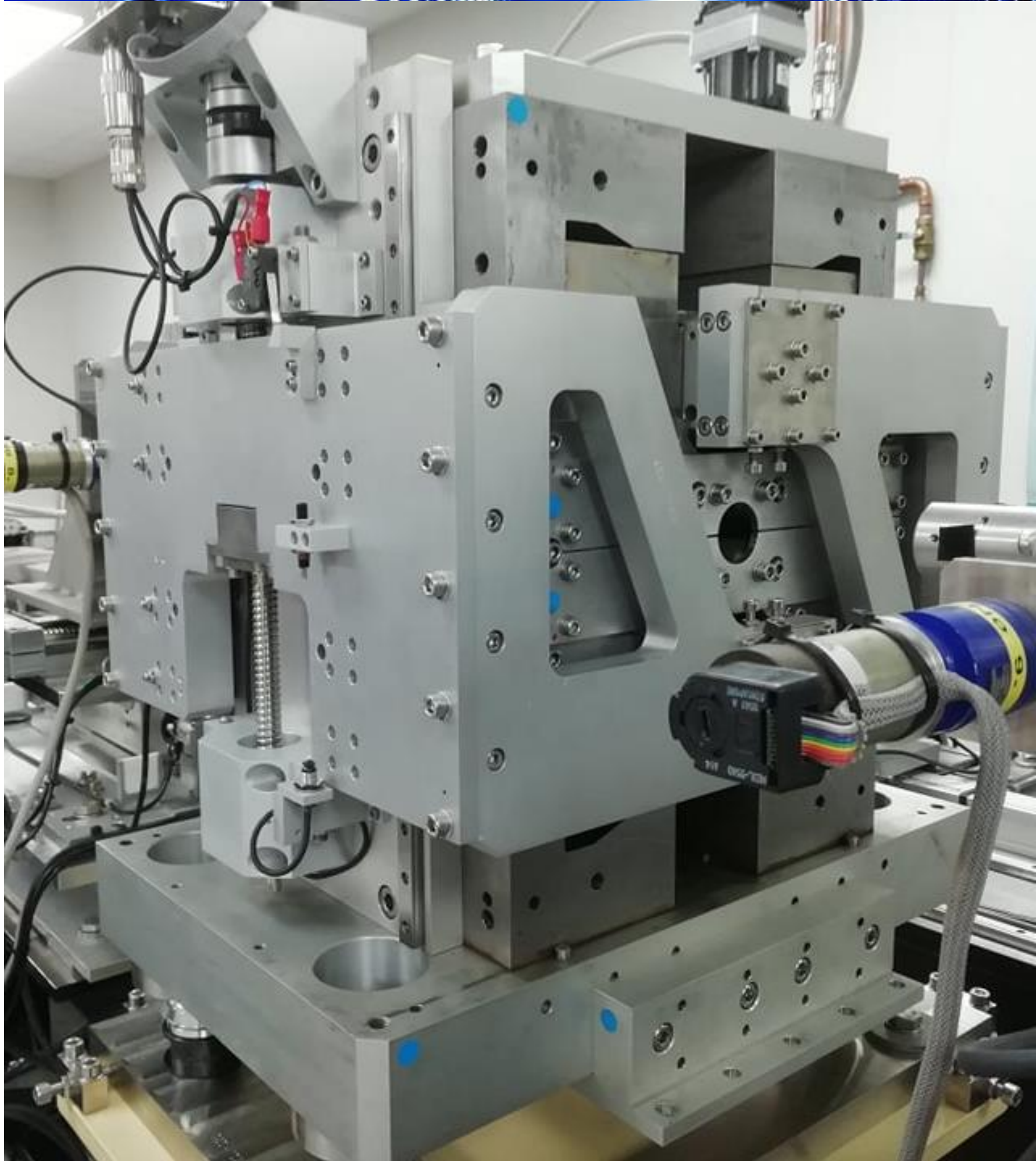

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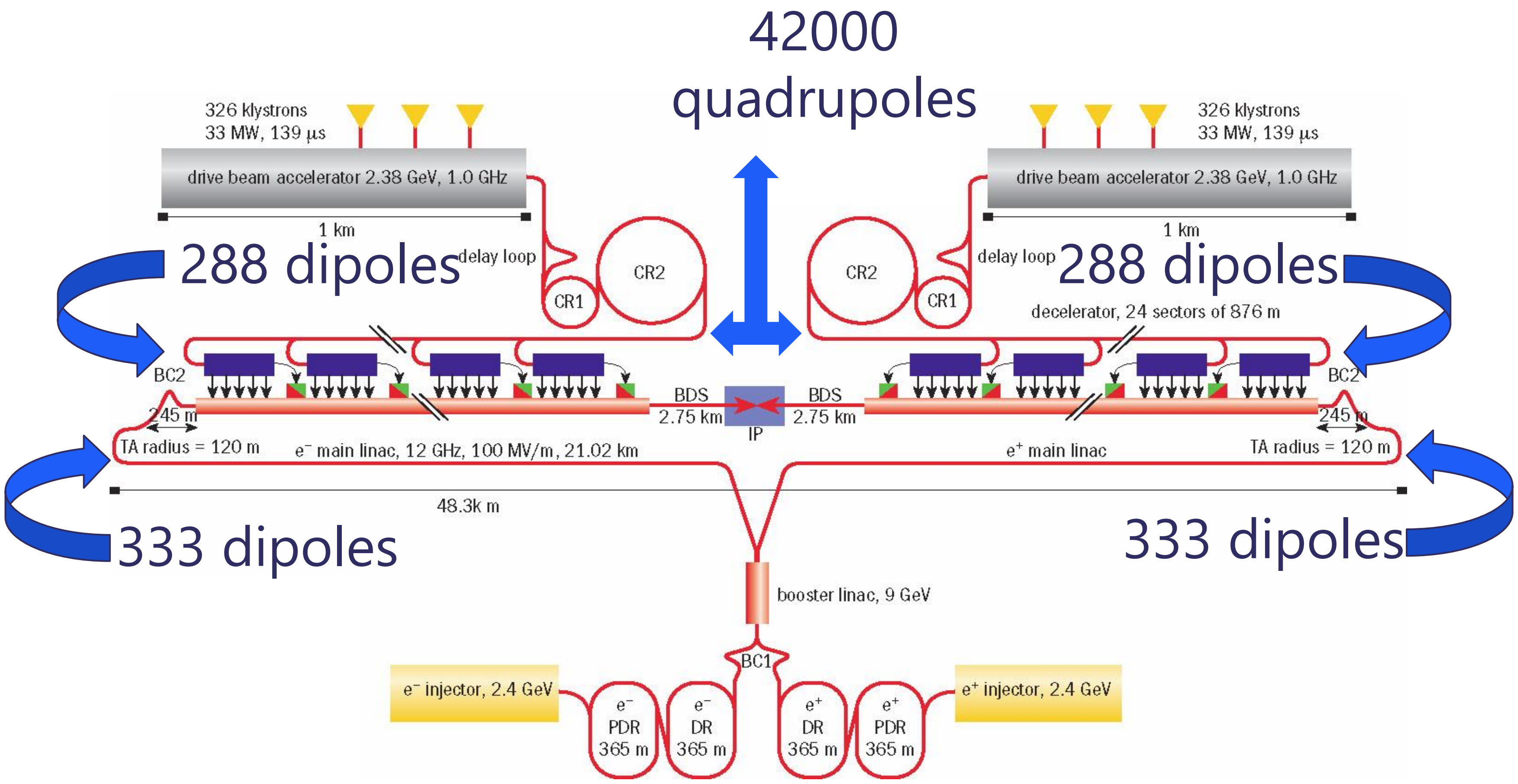
# Introduction to ZEPTO

Development and motivation of ZEPTO tuneable permanent magnet technology.

# Original project - CLIC




ZEPTO (Zero Power Tuneable Optics) project started as a collaboration between CLIC (Compact Linear Collider) and STFC Daresbury Laboratory.

Aim is to save **power and costs** (both financial and environmental) by switching from resistive electromagnets to **permanent magnets**.

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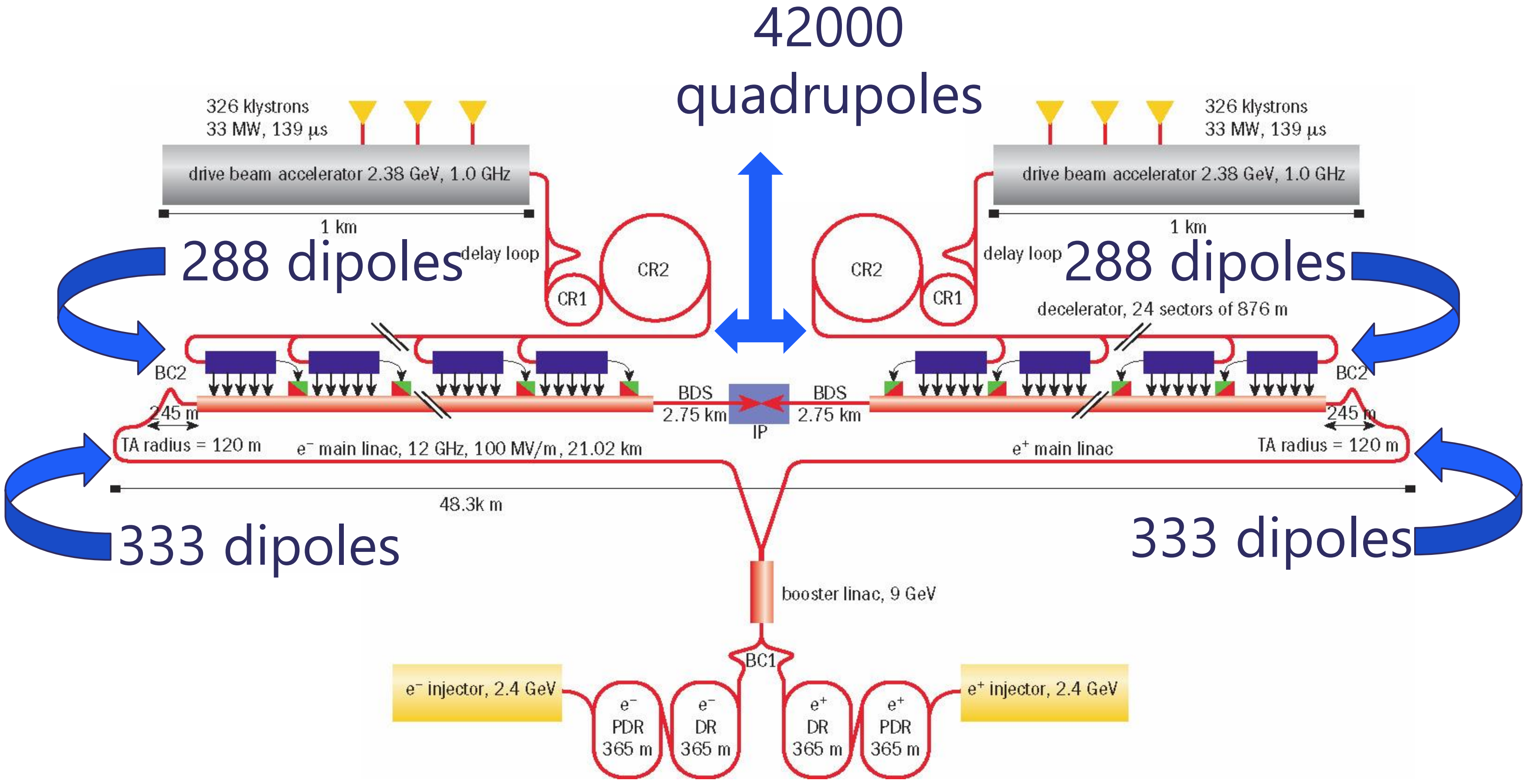
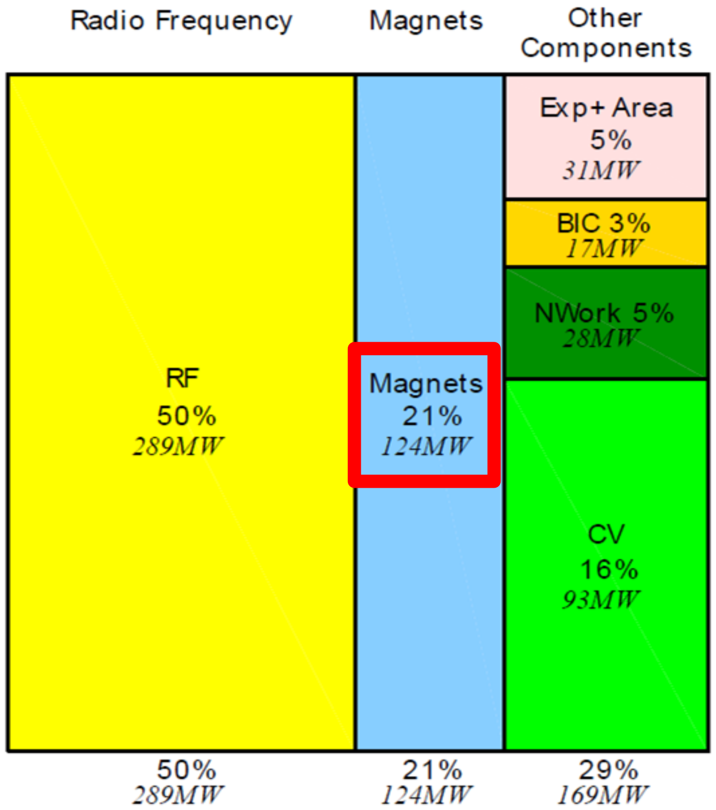
# Original project - CLIC

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# Zero Power Tuneable Optics (ZEPTO)

The ZEPTO project created 3 prototypes for CLIC.

All were designed, constructed and measured at STFC Daresbury Laboratory.

All use NdFeB magnet blocks attached to a motion system, **with fixed steel poles** defining the field shape.

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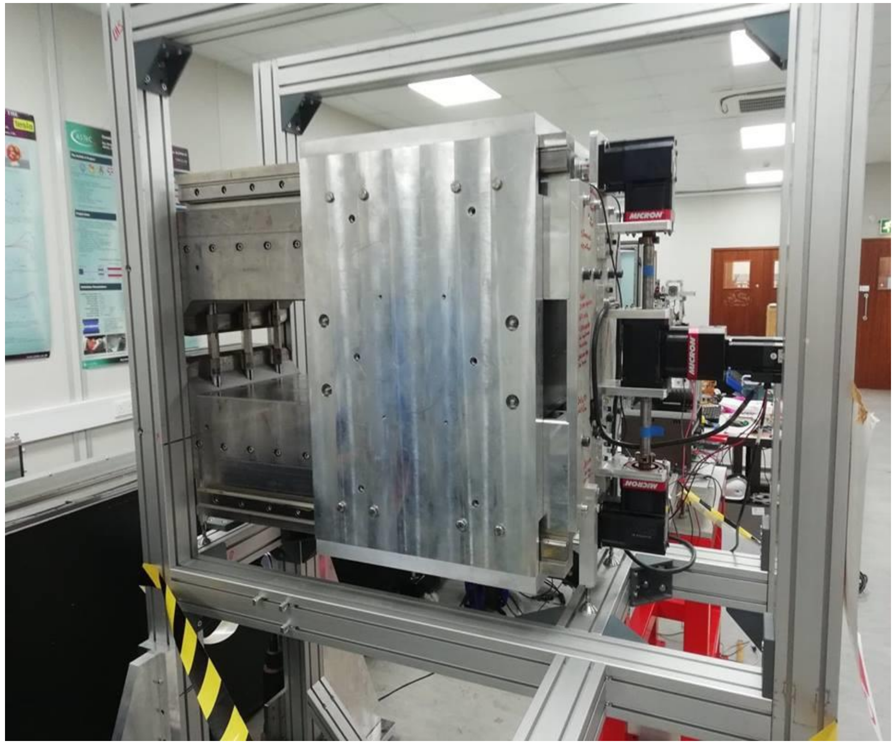
Project 1: High strength quad
B gradient from 60 – 15 T/m
*Shepherd et al, Journal of Instrumentation, Vol 9, T11006, 2014*

Project 2: Low strength quad
B gradient from 43 – 3.5 T/m
*Shepherd et al,* IPAC'14, Dresden, Germany, paper TUPRO113.

2012 - 2014

Project 3: Wide range dipole
B adjustable from 1.1 T to 0.45 T
Bainbridge et al., IPAC'17, Copenhagen, Denmark,, paper THPIK105.

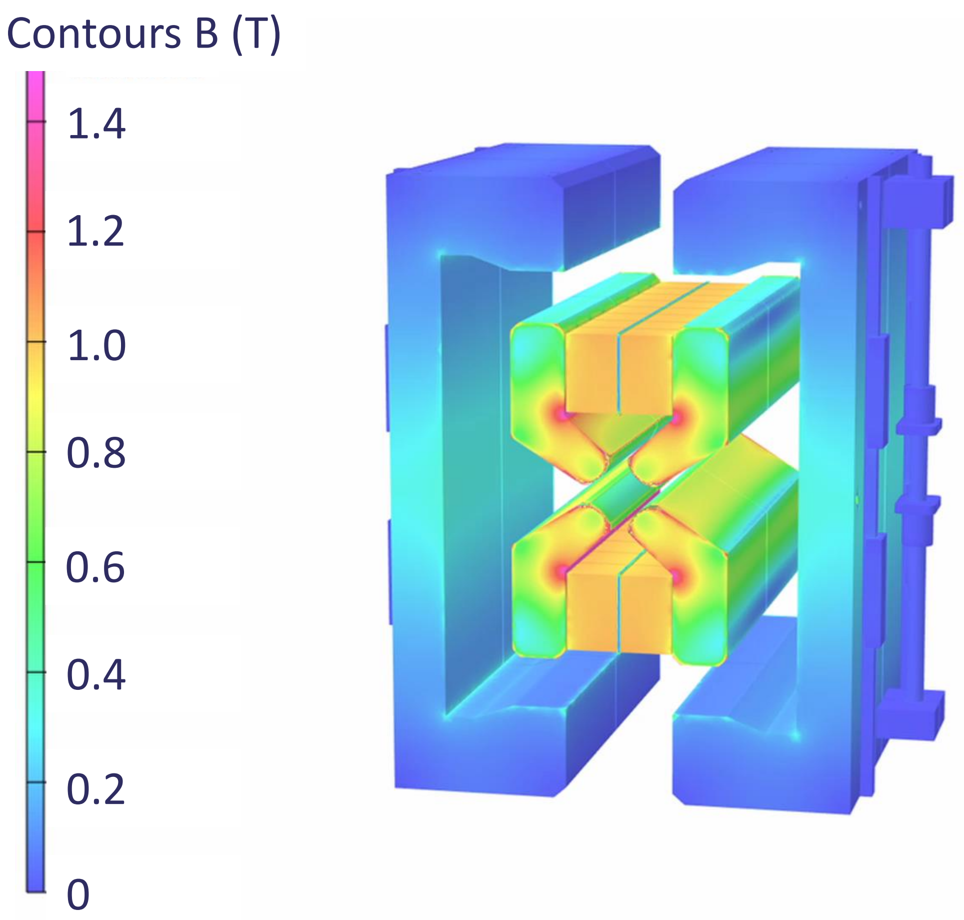


2017-2019

# New technology demonstrator

We want to show that the benefits of ZEPTO technology are not limited to CLIC, and can be used as an **energy saving** `drop-in' replacement for electromagnets on accelerators such as existing light sources.

We have developed a new ZEPTO quadrupole for the booster-to-storage ring section of Diamond Light Source.

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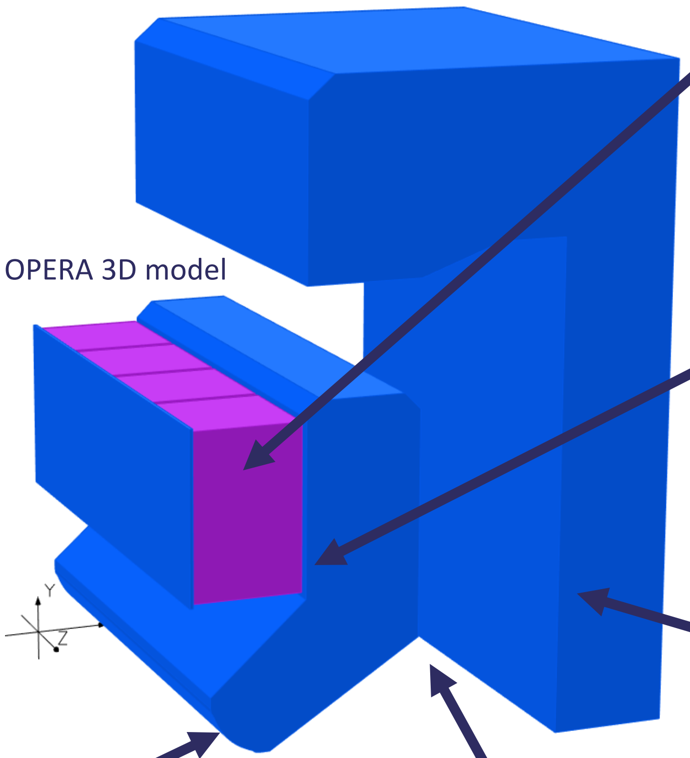
# New technology demonstrator

OPERA 3D model



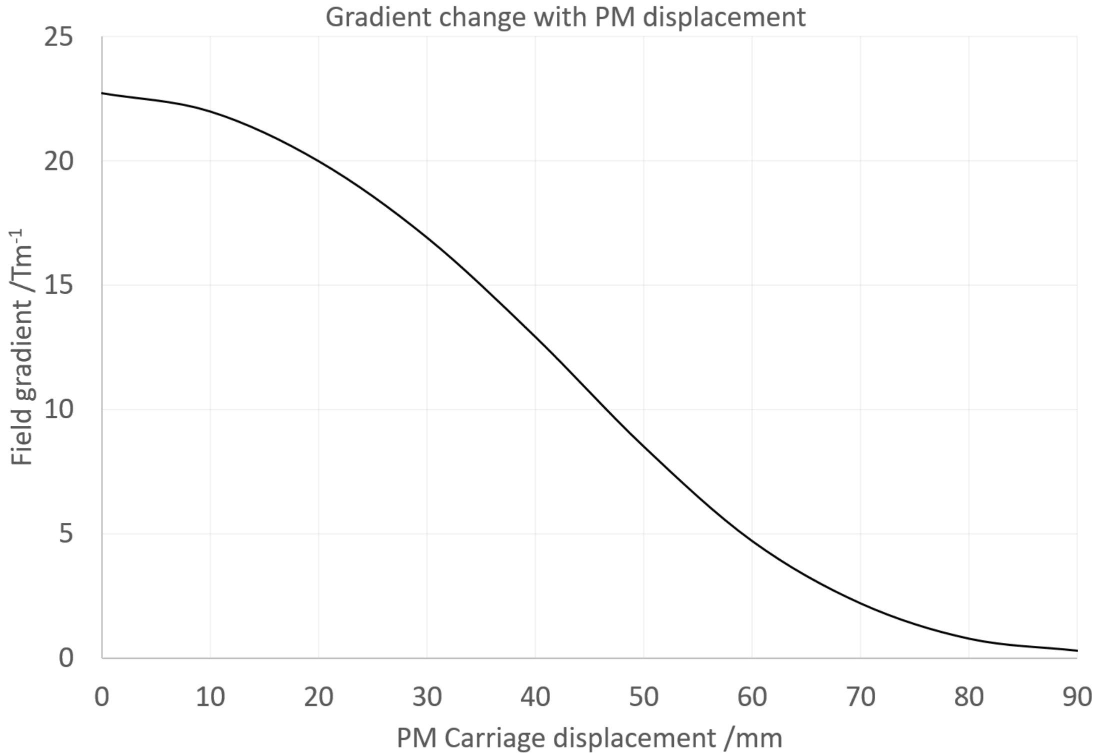
SmCo blocks attached to vertical motion system with 90mm movement range and 1 μm precision

Fixed “inner yoke” defines the quadrupole field

Fixed “outer yoke” can steer flux **away from the beam**, allowing the gradient to be adjusted

32 mm aperture

No magnetic contact between yokes, the gap between is filled with aluminium for rigidity




Simulations predicted a gradient tuning range from 23 T/m down to 0.35 T/m

The outer yoke acts as a short circuit for the flux, **allowing the magnet to be ‘turned off’.**

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# Magnet Assembly

Challenges of assembling a tuneable permanent magnet with strong forces present.

# Permanent magnets

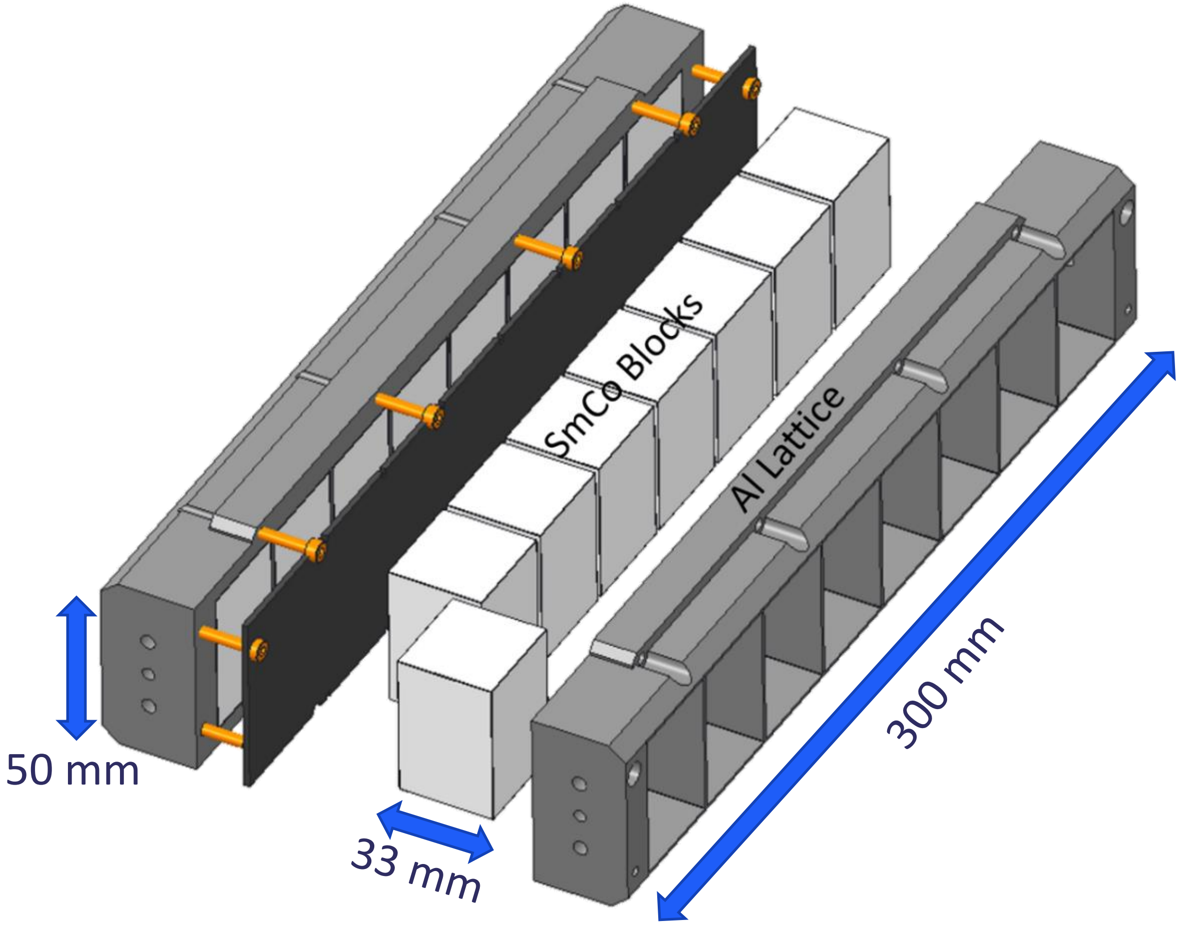
Previous ZEPTO magnets used large NdFeB blocks to produce the magnetic flux, which are difficult to manufacture and handle.

New magnet uses a “carriage” with a number of **smaller blocks** set into an aluminium latticework.

Advantages over larger single blocks which include:

- Blocks are easier and cheaper to manufacture.
- Damaged single blocks may be replaced instead of the entire carriage.
- Variation in block BH curves may be compensated.
- Modular magnet "families" may be created by strategic removal of blocks.

The gaps between blocks **do not affect field quality** as the flux must pass through a steel pole before reaching the beam.




We use SmCo instead of NdFeB for improved radiation hardness and temperature stability.

No thermal shunts are needed

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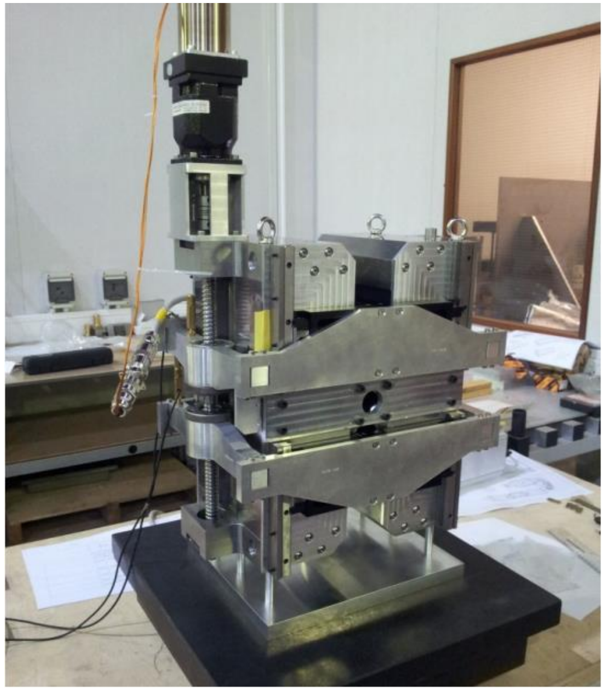
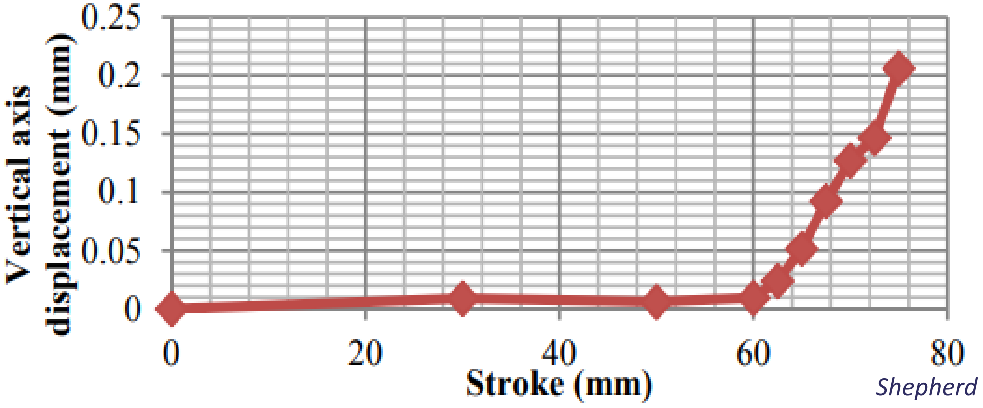
# Dual motor system

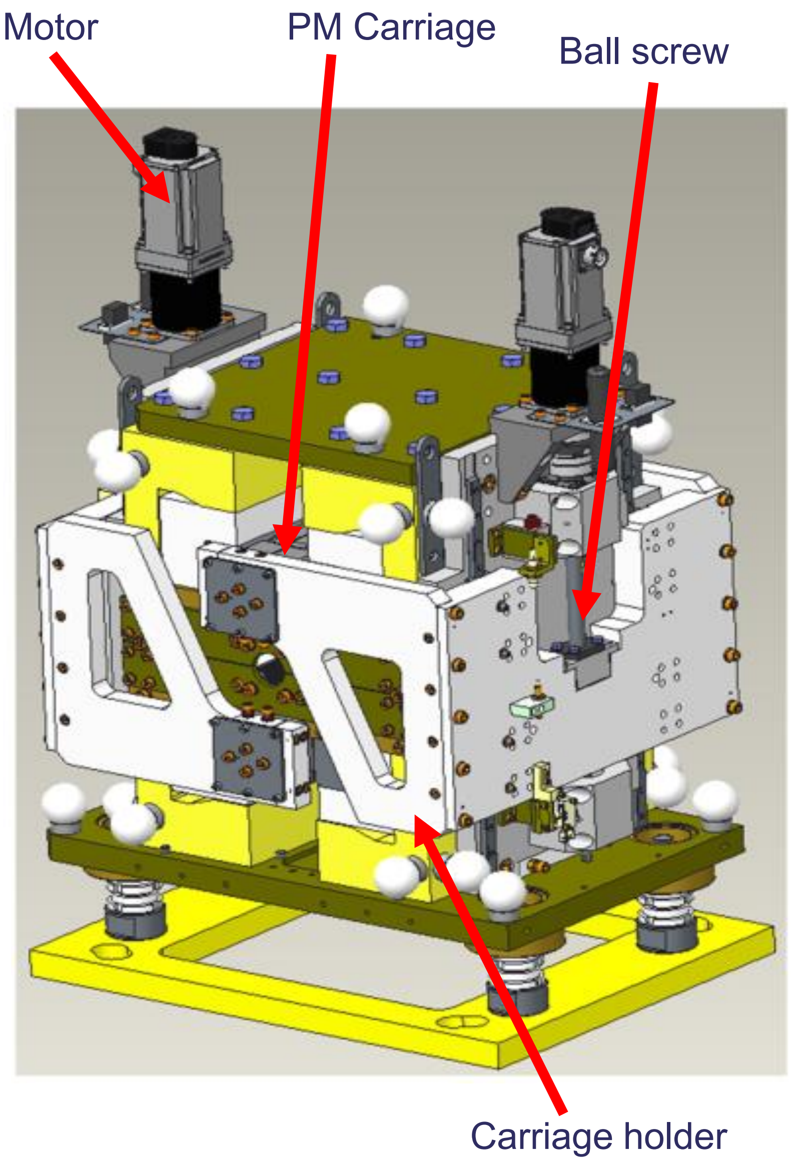
In previous ZEPTO quadrupoles field measurements revealed the magnetic centre **moving as function of magnet block position**, mostly vertically, due to unexpectedly magnetic components.

Expecting this, each magnet carriage now has a **dedicated motor** and associated driving ball screw to help compensate.

Look-up table can be applied to either carriage position to compensate and **restore the magnetic centre** to the geometric centre.






*Shepherd et al,* IPAC'14, Dresden, Germany, paper TUPRO113.

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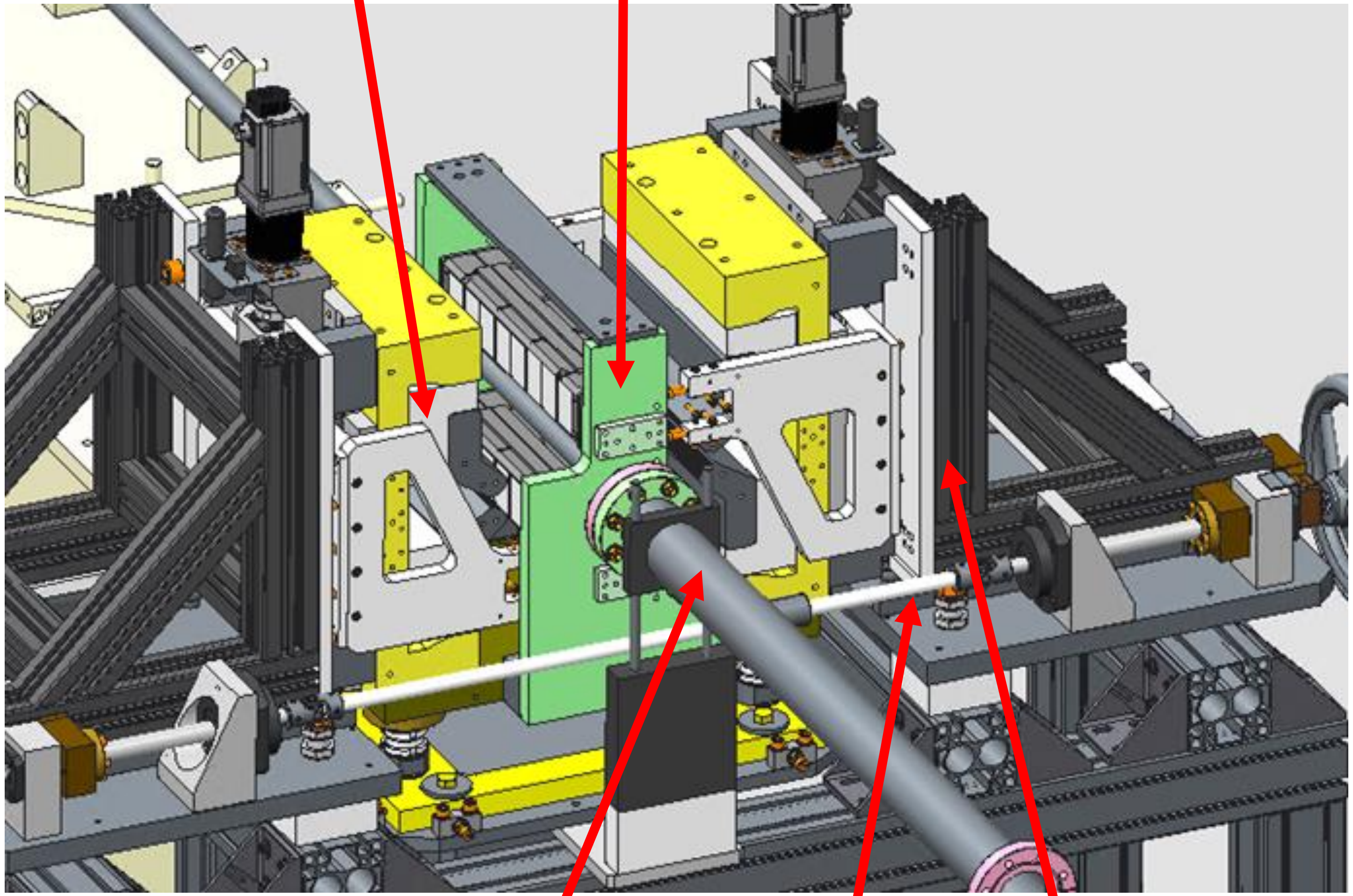
# Split design

Electromagnetic quadrupoles can typically be split for installation around an **existing vacuum vessel** – previous ZEPTO quadrupoles could not.

The new version may be **split about the vertical axis** and reassembled around an existing vacuum system using a dedicated assembly frame.

This allows replacements or repair to be conducted **without needing to keep the accelerator offline** for the additional time needed to restore the quality of the vacuum.

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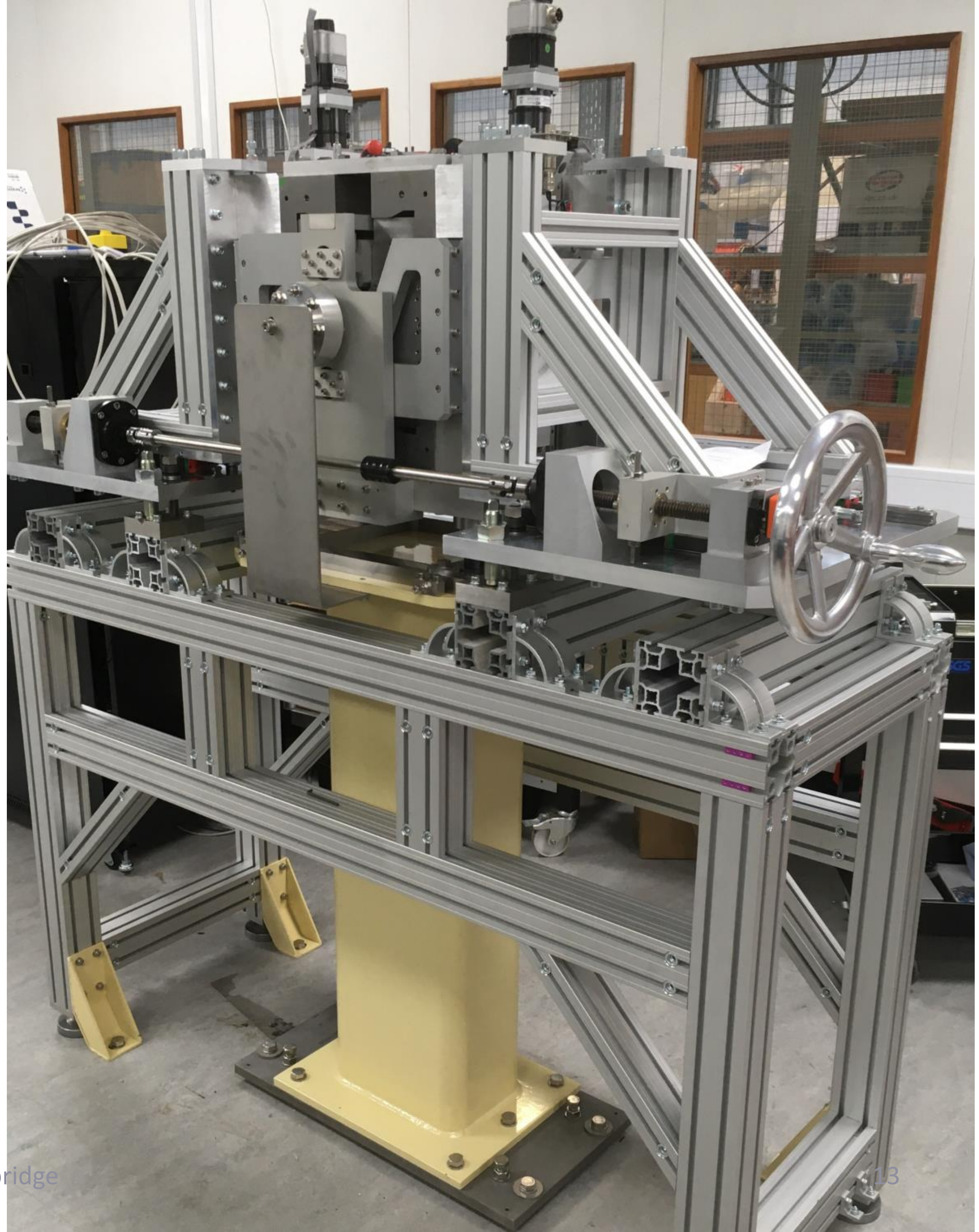

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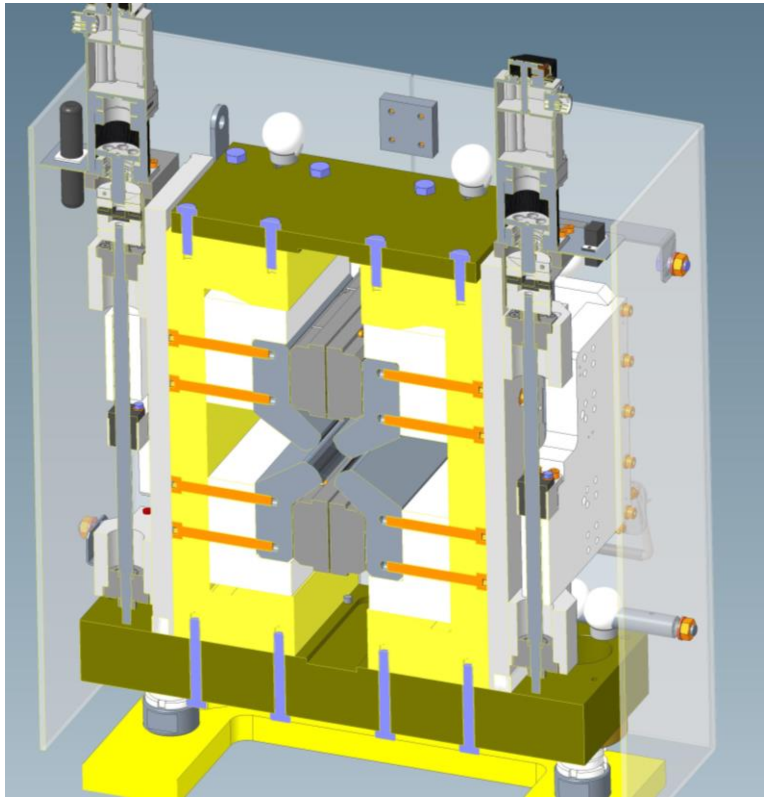
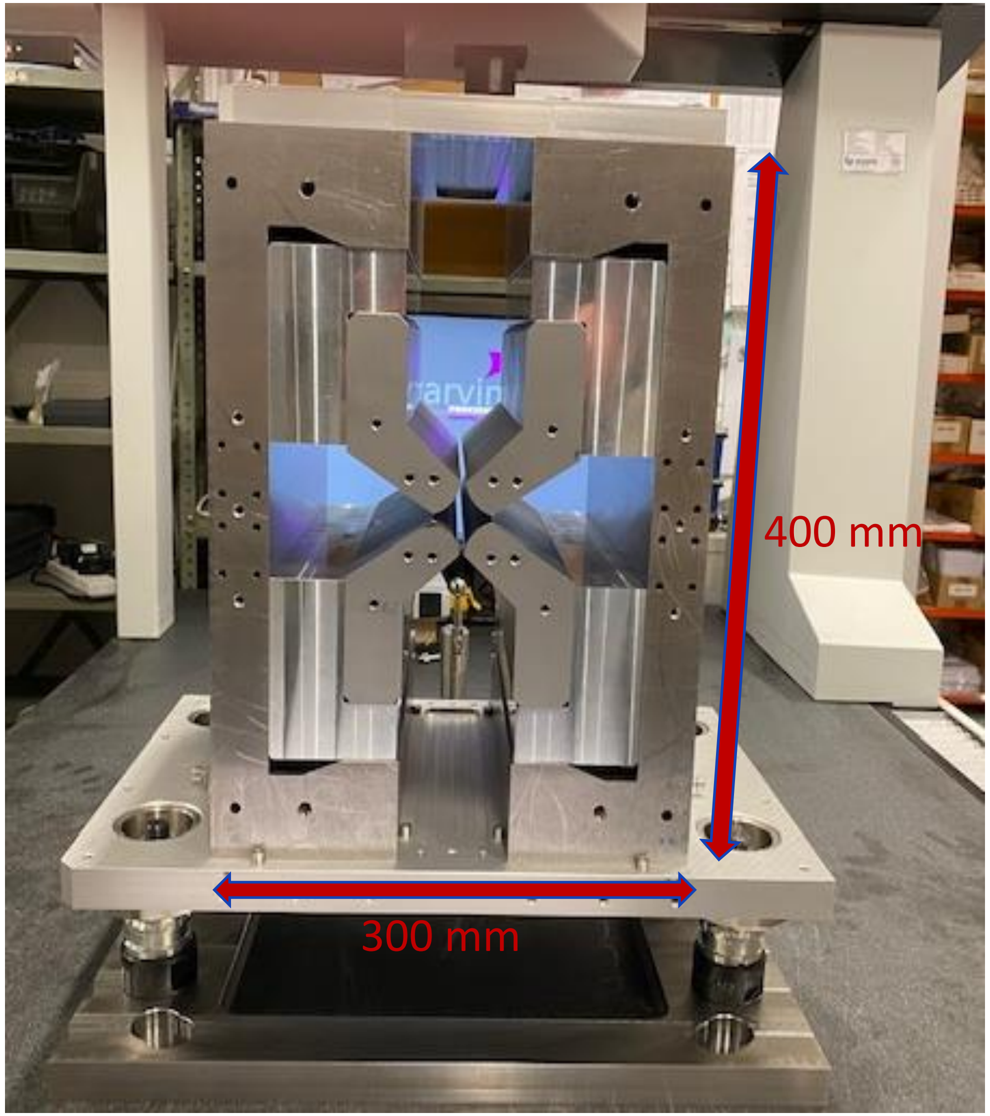
# Construction

To ensure that the inner yoke structure is properly positioned, both yokes were pre-assembled with Aluminium spacers before final machining.

Wire erosion used to achieve <30 µm precision on pole tips, regardless of tolerances of initial manufacture.

Dowel system should ensure repeatability of assembly



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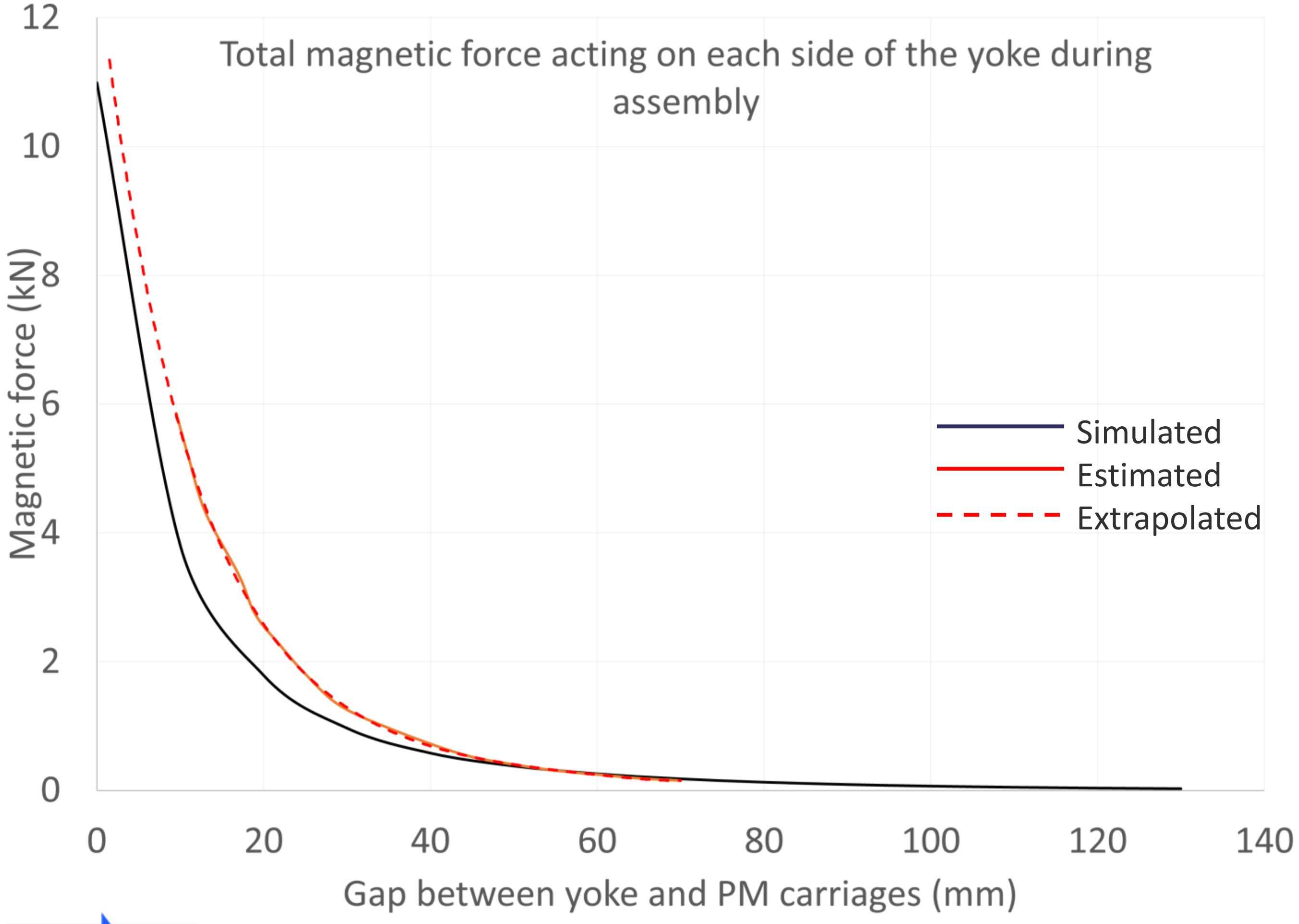
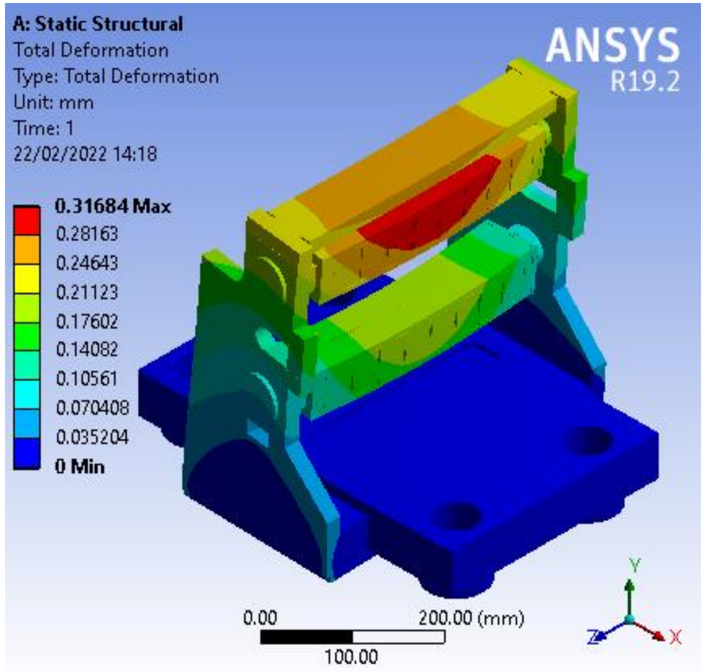
# Assembly forces




Forces between the PM blocks and steel yokes must be calculated in advance and managed during assembly!

A Hall probe was used to measure the flux density entering the steel yoke for as much of the approach as possible, and from this an estimate of the actual force was derived

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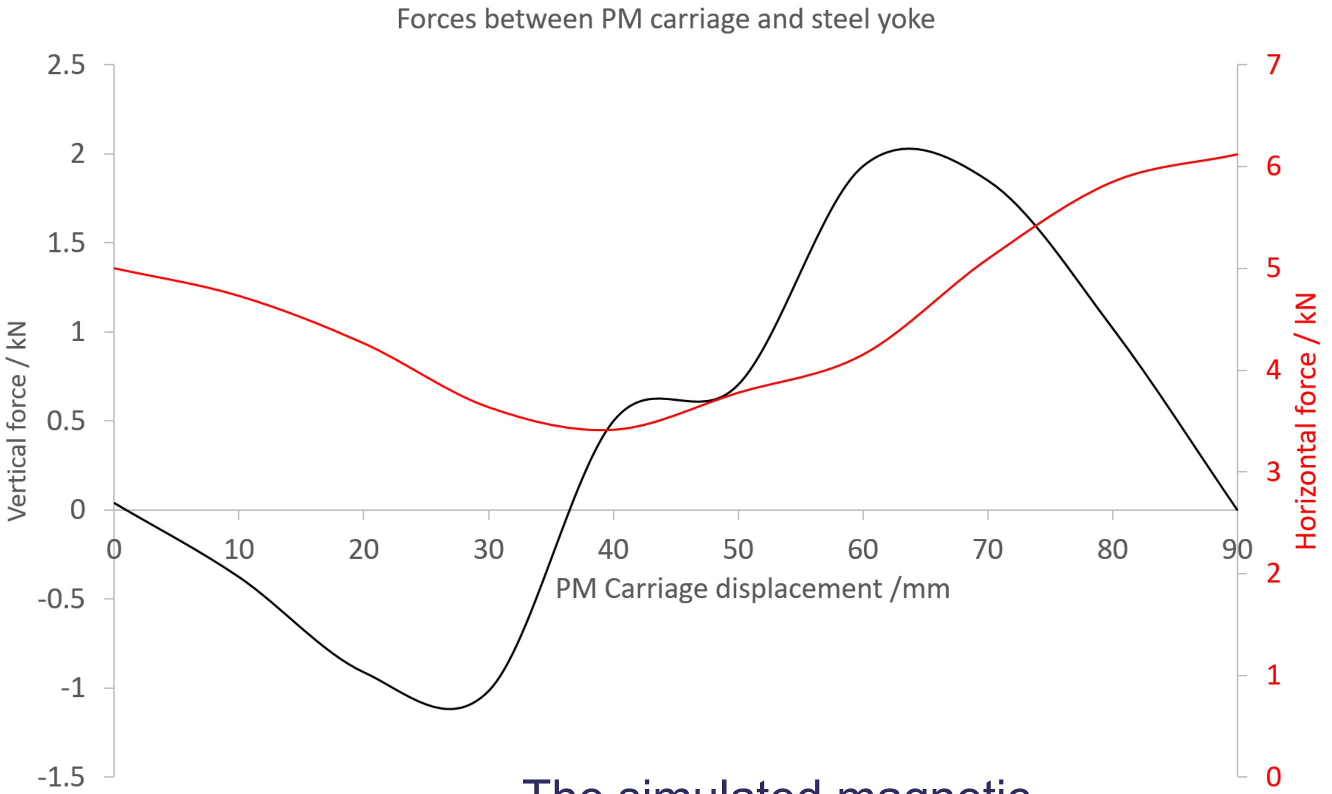
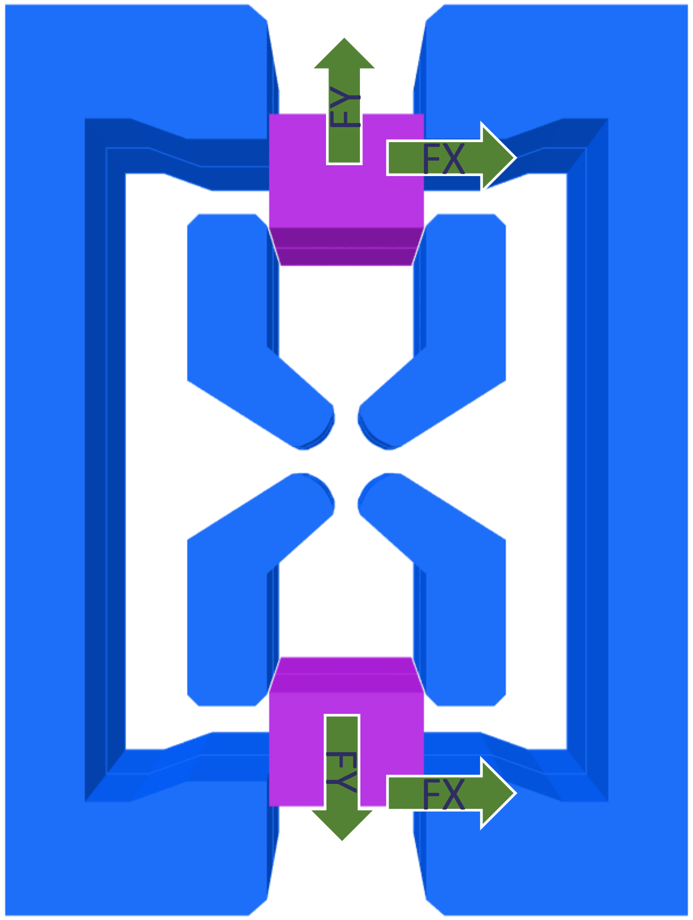
# Operational forces




Horizontal forces are balanced on each side of carriages but act on the steel yoke, causing a **movement risk** to components.




The simulated magnetic forces are a function of PM block position and are highly complex

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# Measurements to date

Gradients and compensation of magnetic centre movements.

# Gradient vs gap

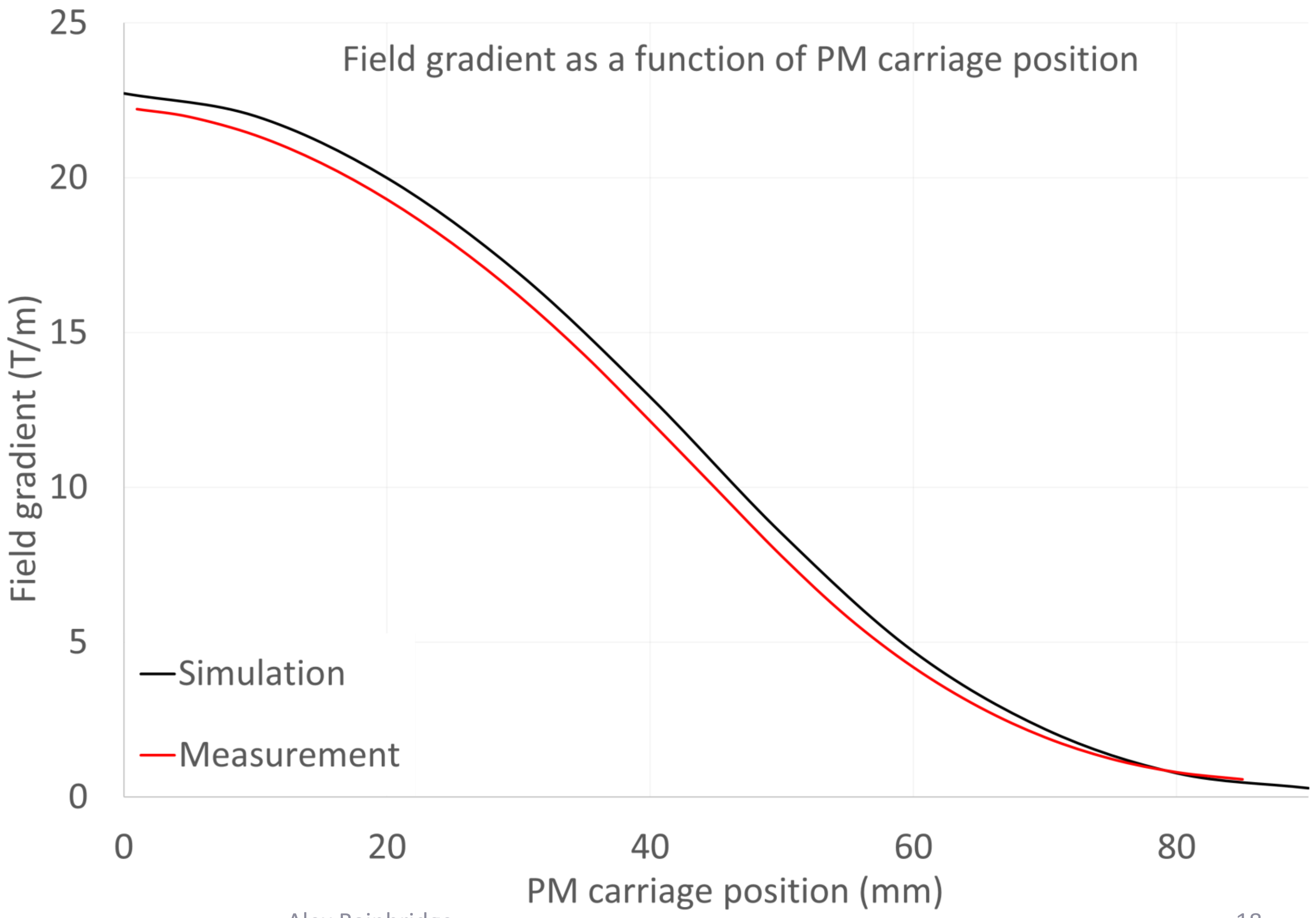
Some variation between simulated and measured gradients observed.

Gradient lower than predicted but still within requirements (19 to 0.5 T/m normal operation)

Actual range of sweep is 1-85 mm (instead of 0-90 mm) due to limit switch positions.

Tuneability **22.37 to 0.47 T/m**

Predicted range was 22.72 T/m to 0.3 T/m

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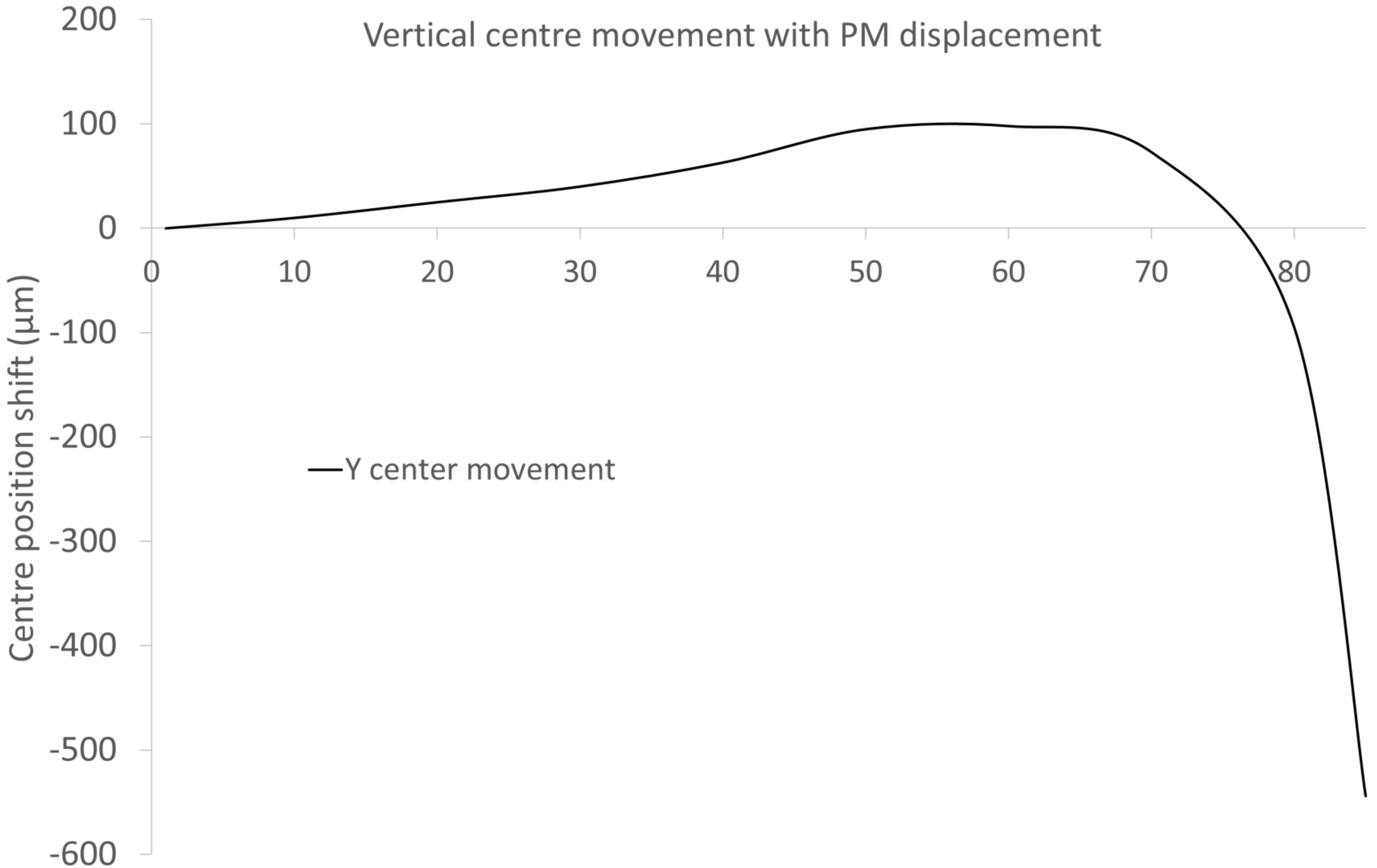
# Vertical centre position

Movements in Y centre observed as a function of carriage position.

Y centre slowly rises as gap enlarges and then suddenly starts to drop.

Cause of movement and direction reversal unknown – magnetic materials in pedestal? Uneven motion?

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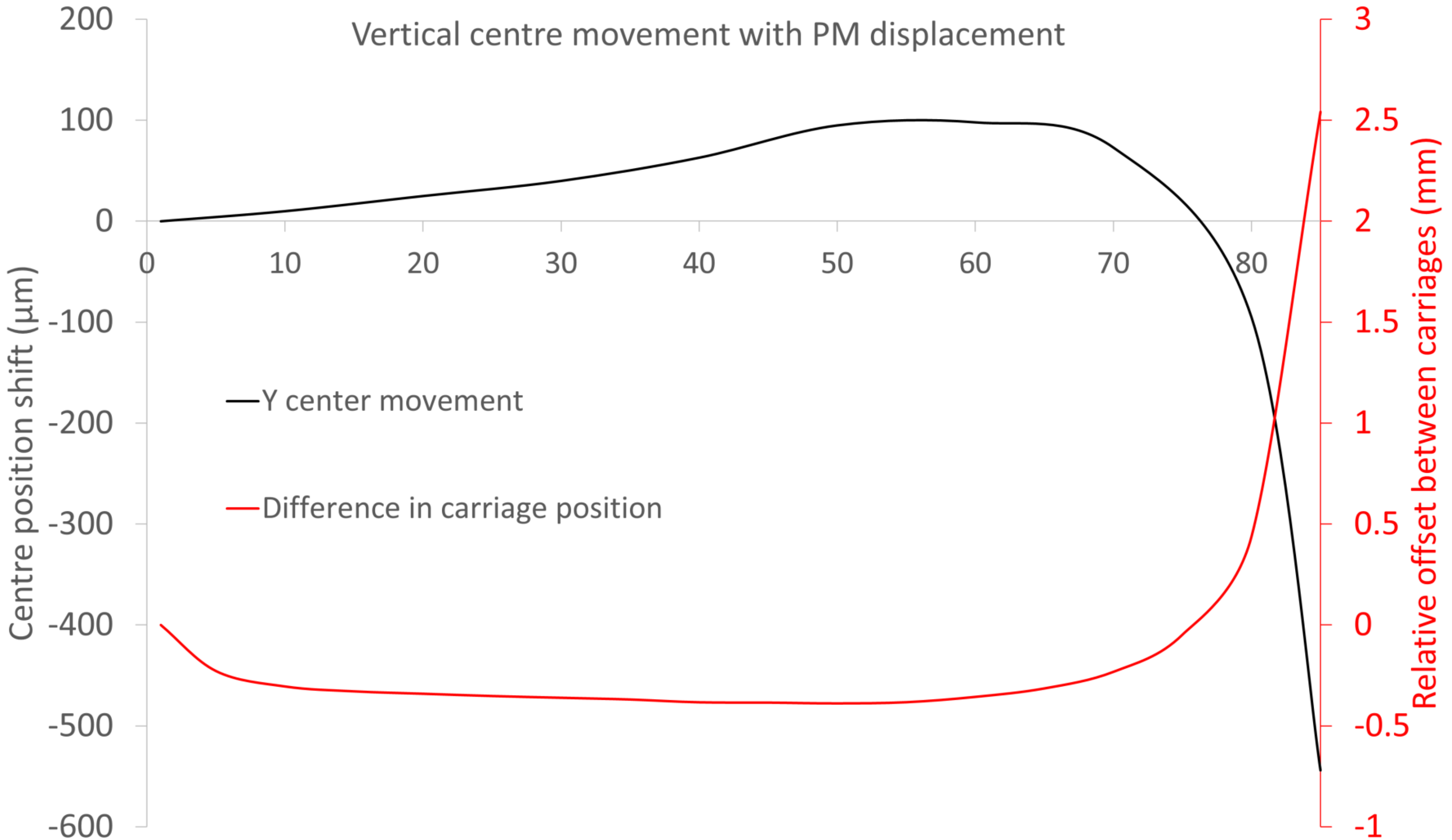
# Vertical centre position

By offsetting the bottom carriage position from the top carriage position we have found **this is correctable!**

Works with either carriage, but resulting look-up table is slightly different.

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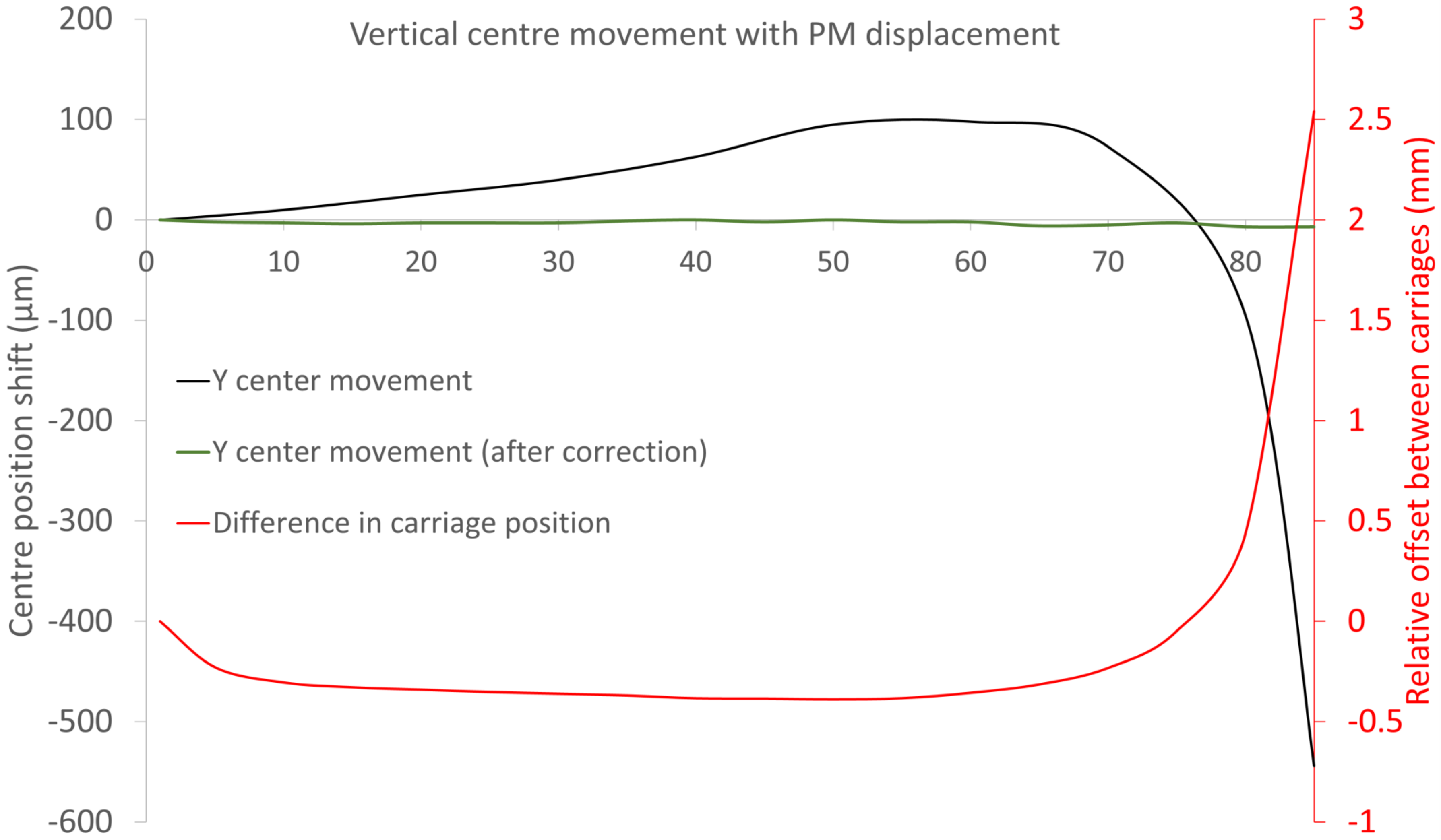
# Vertical centre position

By applying the look-up table we can effectively counter all **vertical movement** of the magnetic centre!

Dataset shown has 7 μm drop in centre position, with 5 μm drop expected from temperature variation alone (contraction of magnet pedestal).

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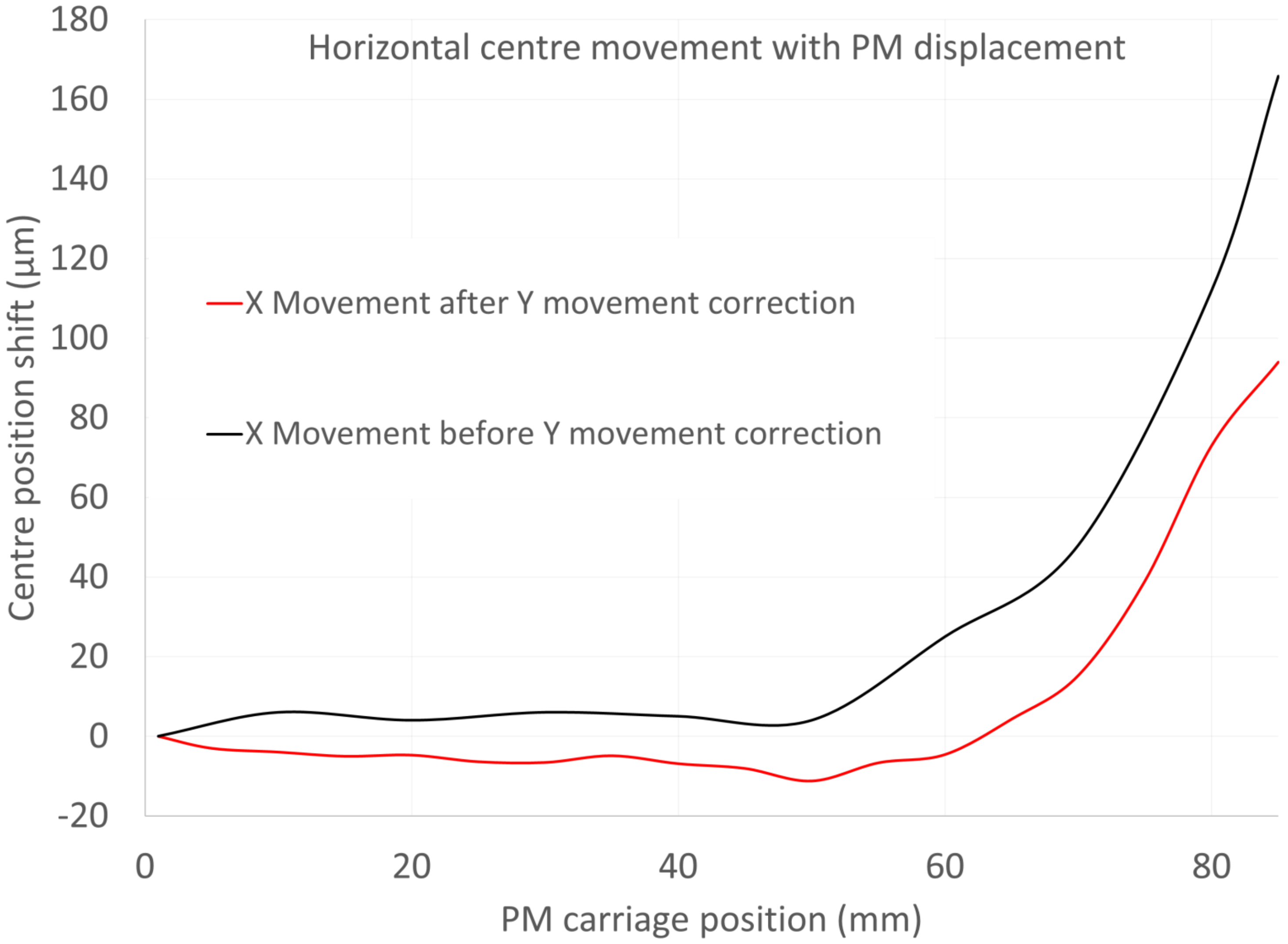
# Horizontal centre position

Movements in X centre also observed as a function of carriage position.

This is more of a problem – **cannot be countered** by offsetting magnet carriages!

Further concerns about the repeatability of the position – are parts sticking/slipping with changes to magnetic forces?

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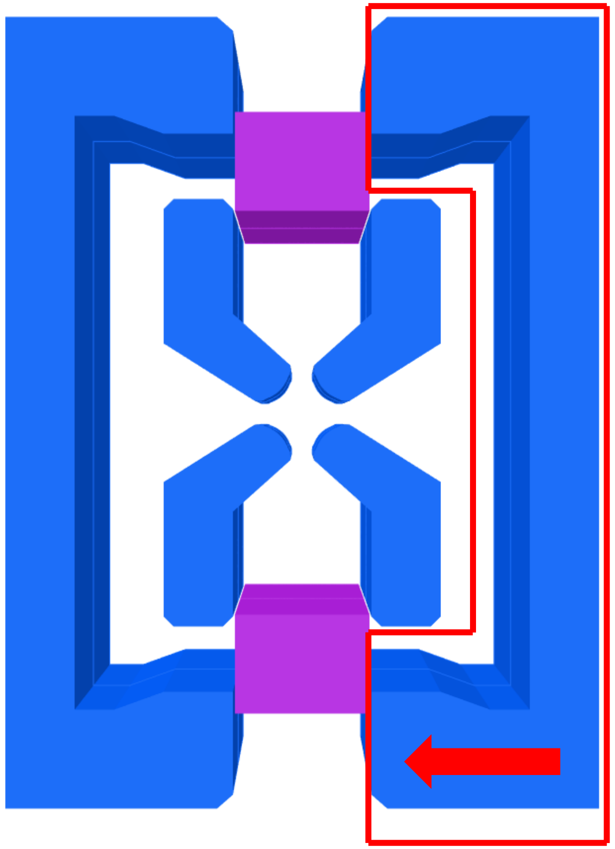
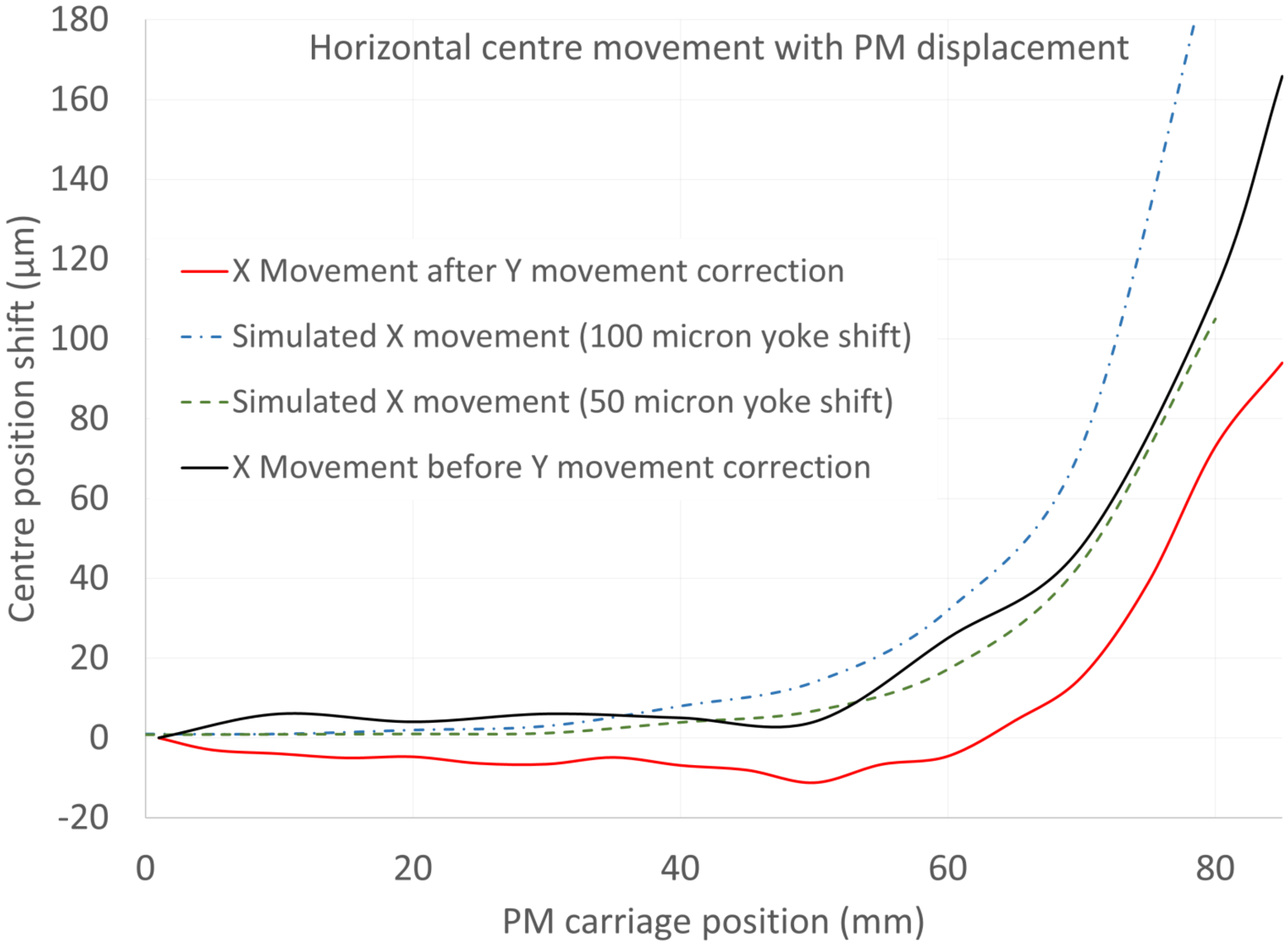
# Horizontal centre position – one explanation

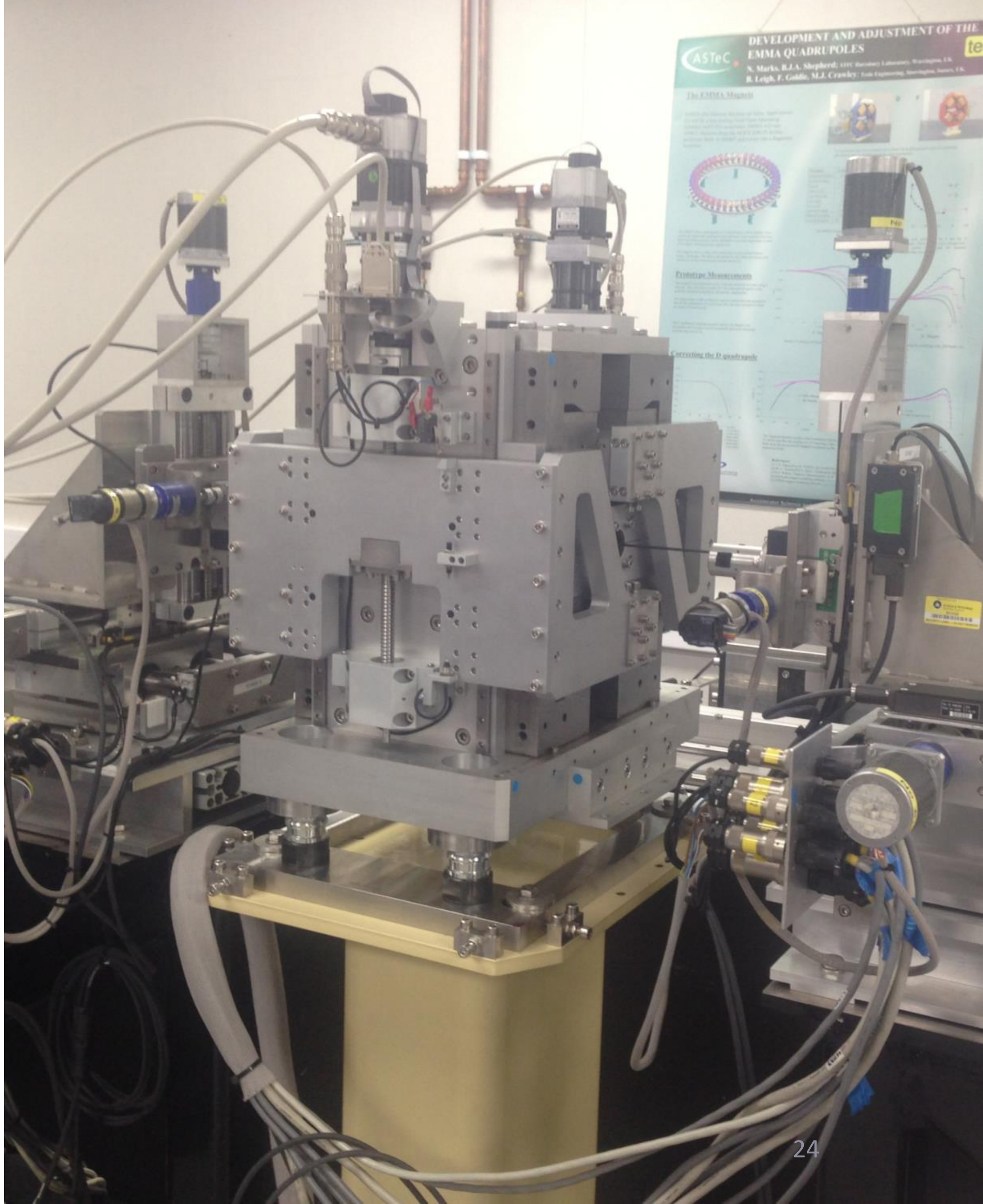
Can replicate trend by offsetting one half of outer yoke – Assembly issue?





# Planned project steps

- Perform additional measurements with a stretched wire system to confirm Hall probe data and **investigate integrated homogeneity**.
- Confirm that the **magnetic centre is stable** as the magnet runs through multiple gradient cycles and thermal cycles.
- Demonstrate that the assembly process is **repeatable**.
- Install the magnet on Diamond Light Source (planned for August 22) and examine the **long term performance**.
- Prove that ZEPTO is viable as a long term replacement for an existing electromagnetic quadrupole!

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# Conclusions

Current and planned developments.

# Conclusions

- We have built a new ZEPTO quadrupole prototype with **several evolutions** over the original prototypes.
- We have successfully demonstrated that it is possible to build a ZEPTO magnet that can be **split and installed around an existing beam pipe**.
- We have shown that it is possible to keep the vertical **magnetic centre position stable** by individually moving the magnet blocks according to a look-up table.
- More work is still needed to **understand and prevent** horizontal centre movement.
- The tolerances on the outer short-circuit yoke are just as important as on the pole tips!

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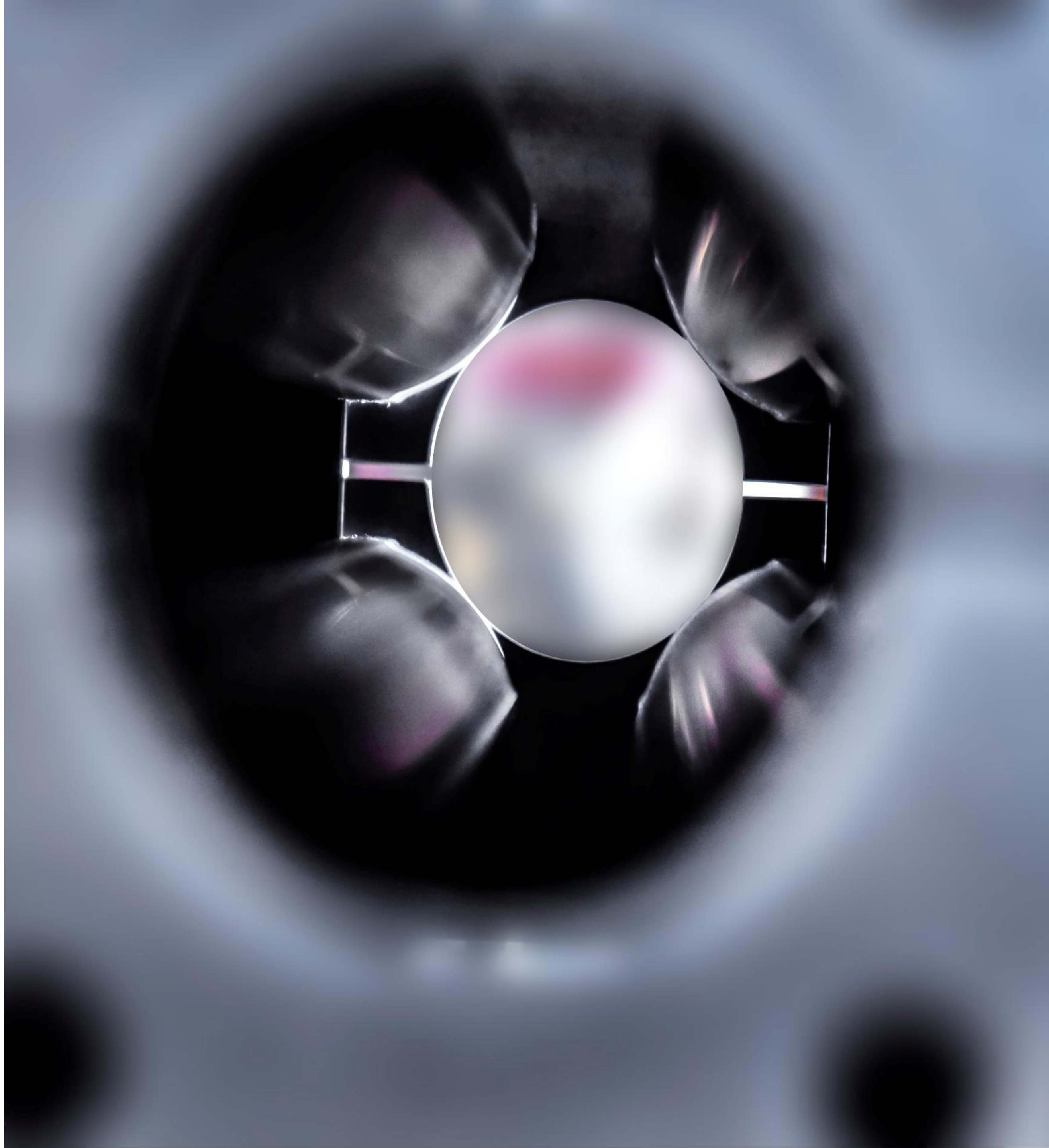


# Acknowledgements


## The team behind ZEPTO DLS prototype:

Ben Shepherd

Group Leader & ZEPTO co-inventor

Alex Bainbridge

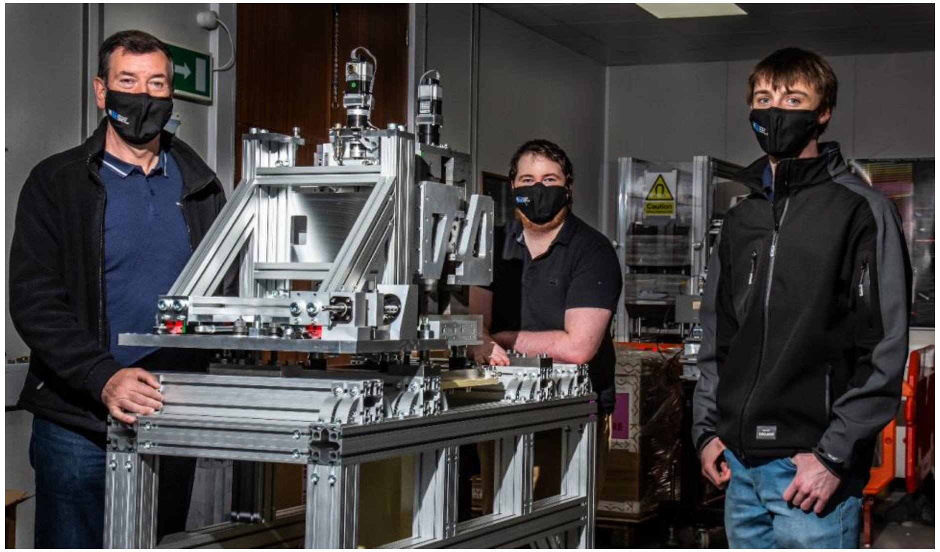
Design & Modelling

Nick Krumpa

Mechanical engineering

Alex Hinton

Measurements



+ Thanks to Walter Tizzano & Ian Martin from Diamond Light Source

+ Thanks to Alex Headspith, Callum Otter, Ryan Cash, Mike Liptrot, Paul Hindley and Mike Lowe

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This work was funded by the STFC Proof of Concept Fund

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# Thank You

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# Frequently Asked Questions

## 1 How much did this prototype cost?

The budget was approximately £100,000 as this was a one-off. Large production runs would be significantly cheaper.

## 2 How does the cost of a ZEPTO magnet compare to an electromagnetic quadrupole?

The up-front cost of the magnet is higher due to the cost of materials and the labour-intensive assembly process; but money is saved on power supplies, infrastructure, cooling systems and long-term energy bills.

## 3 Are permanent magnets really a green alternative?

Its complicated. Mining rare earth materials is environmentally damaging and the carbon release from manufacturing a ZEPTO magnet is likely higher than for an electromagnetic alternative. However, the reduced power use can offset this within 1 year depending on the power grid of the country where they are used, and permanent magnet materials are now recyclable.

## 4 What about higher harmonics?

This design does break symmetry about the 45 degree lines, and so a small octupole harmonic is present.

## 5 Is ZEPTO technology patented?

Yes, patent numbers WO-2012046036-A1 and PCT/GB2020/050714

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