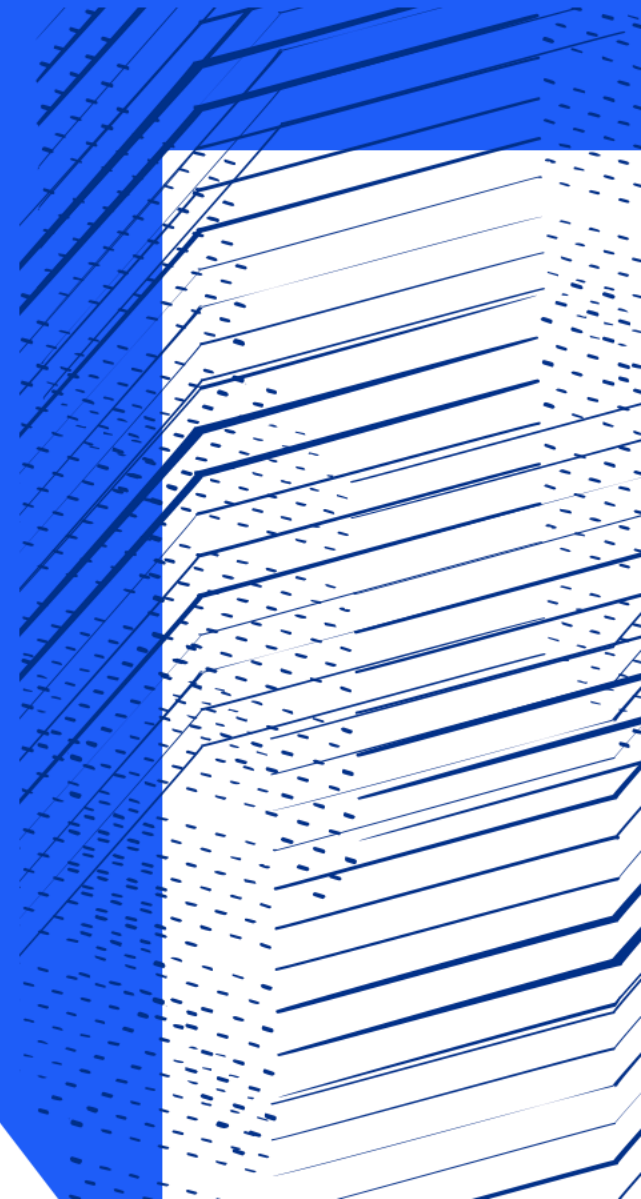




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# Construction and Measurement of a Tuneable Permanent Magnet Quadrupole for Diamond Light Source

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ASTeC, UKRI-STFC Daresbury Laboratory  
22<sup>nd</sup> International magnet measurement workshop  
26-30 September 2022  
Sao Paulo, Brazil (Virtual)



# Agenda

## 1 Introduction to ZEPTO

Development and motivation of ZEPTO tuneable permanent magnet technology.

## 2 Magnet assembly

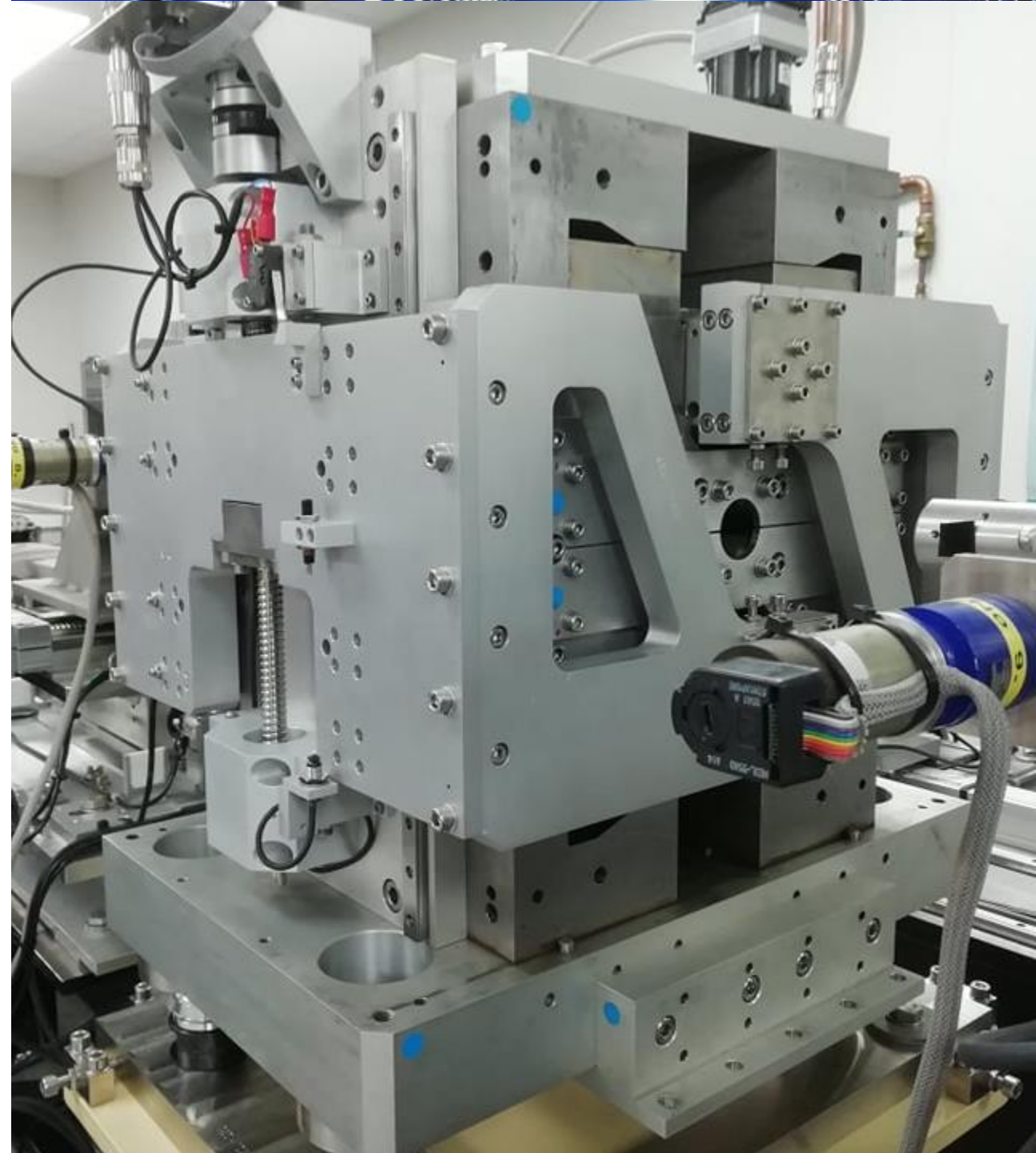
Challenges of assembling a tuneable permanent magnet with strong forces present.

## 3 Measurements to date

Gradients and compensation magnetic centre movements.

## 4 Conclusions

Current and planned developments.



# Motivation

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

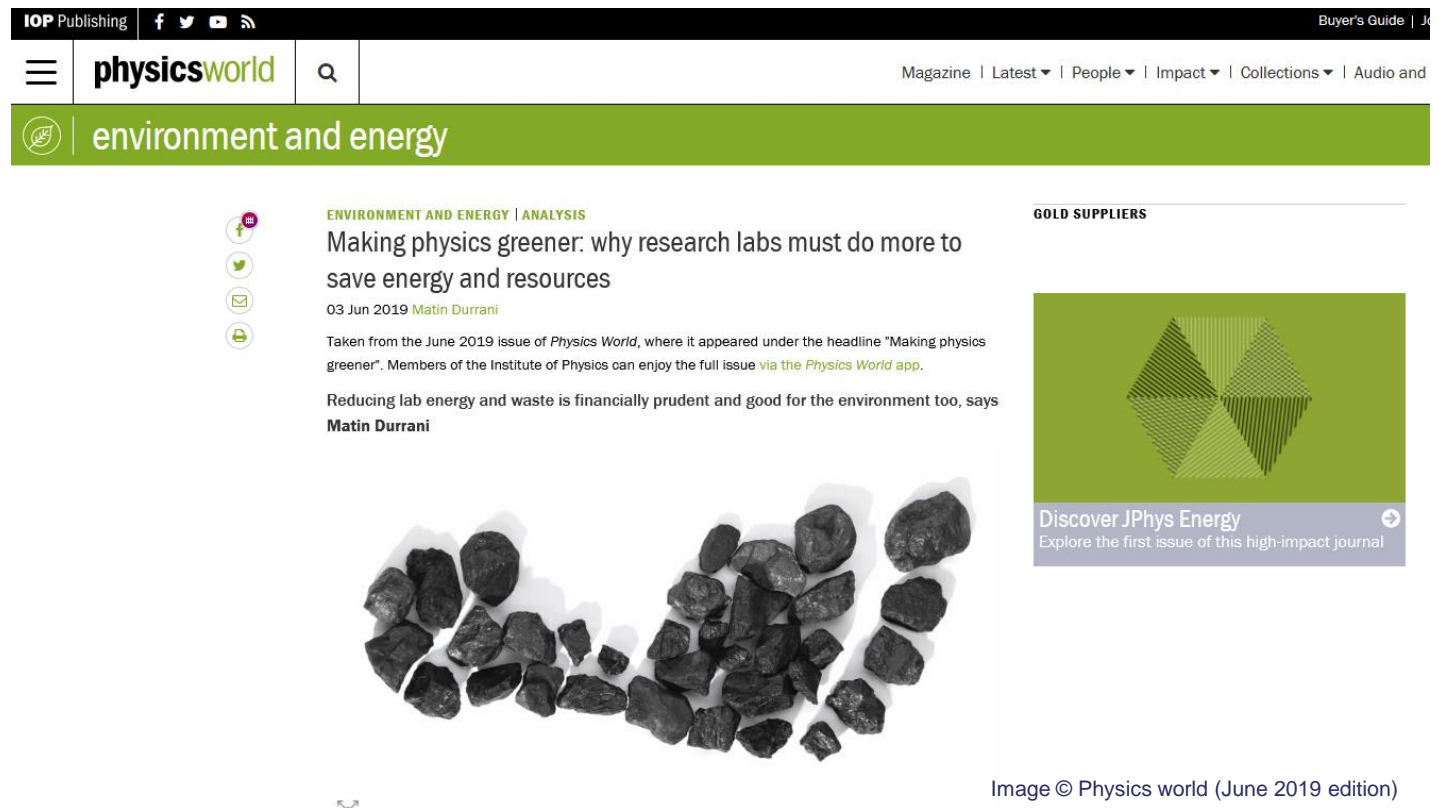
Aim is to save power and costs (both financial and environmental) by switching from resistive electromagnets to permanent magnets.



**Diamond 7 MW**



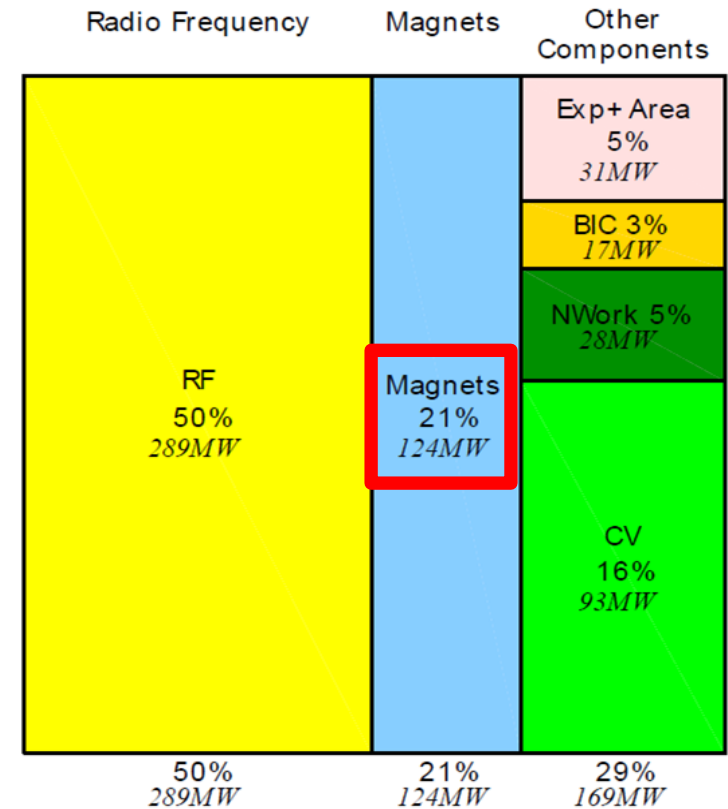
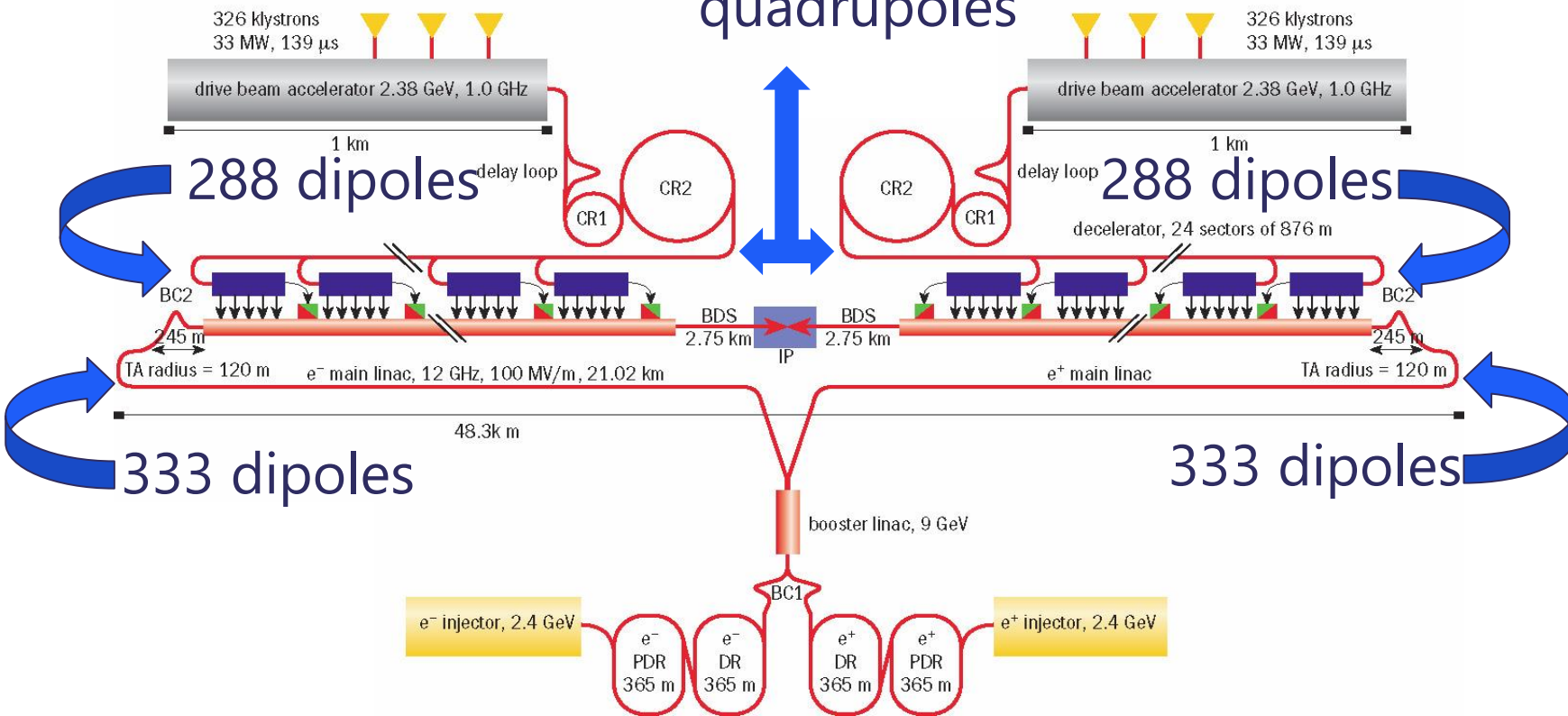
**LHC 90 MW**



The screenshot shows a webpage from IOP Publishing, physicsworld, with a search bar and navigation links. The main content area features an article titled "ENVIRONMENT AND ENERGY | ANALYSIS Making physics greener: why research labs must do more to save energy and resources" by Matin Durrani, dated 03 Jun 2019. The article text states: "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". Below the text is a photograph of several pieces of dark, irregularly shaped permanent magnets. To the right of the article is a "GOLD SUPPLIERS" section with a green graphic and a button that says "Discover JPhys Energy Explore the first issue of this high-impact journal".

# Original project - CLIC

42000  
quadrupoles



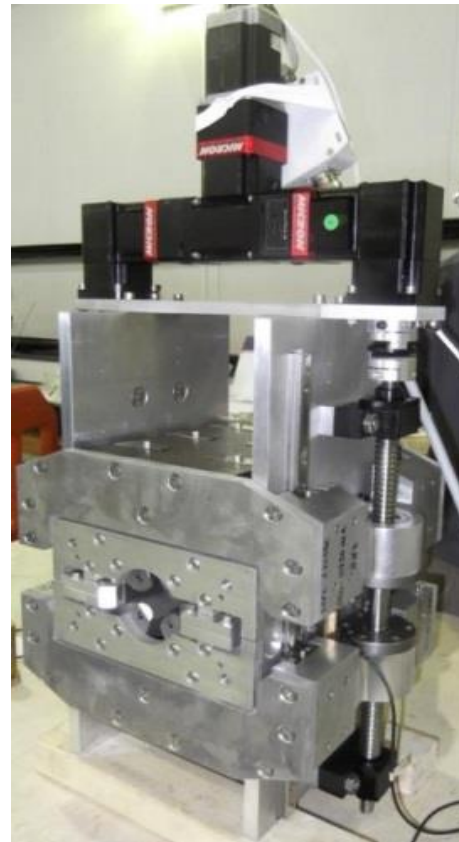
# Zero Power Tuneable Optics (ZEPTO)

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.

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



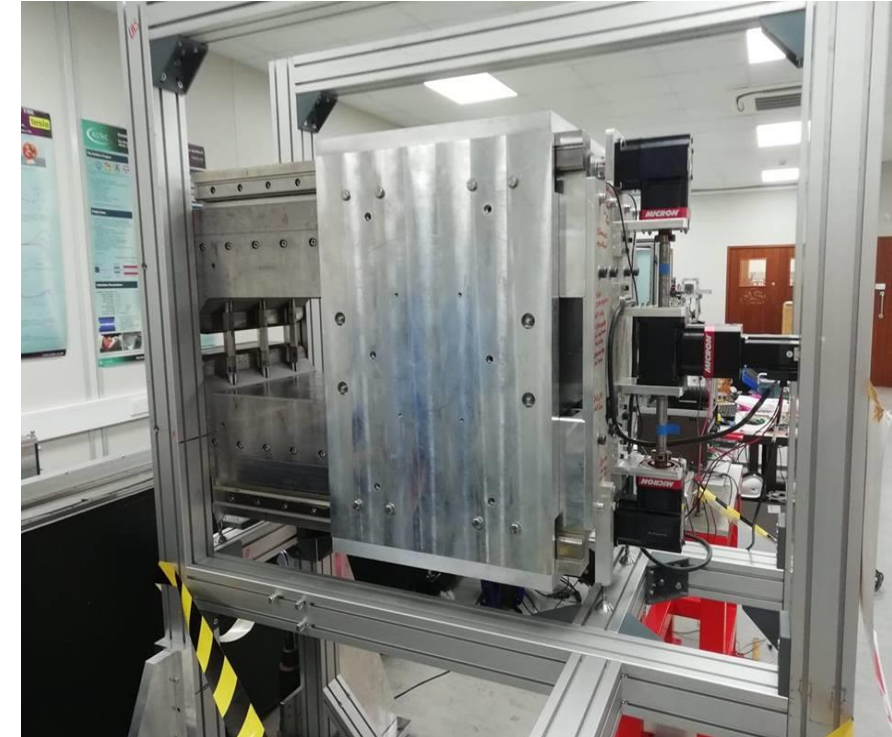
2012 - 2014

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



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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

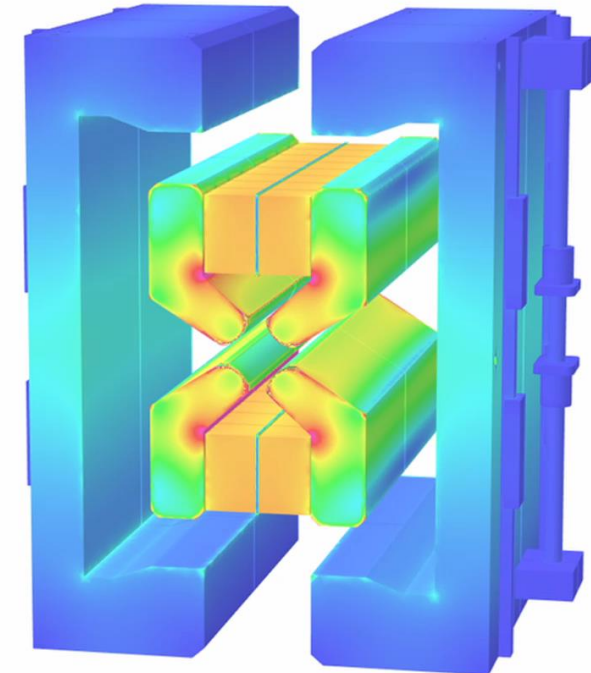
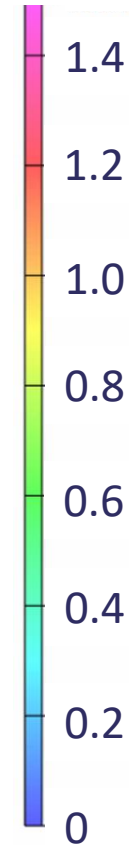
# New technology demonstrator

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.

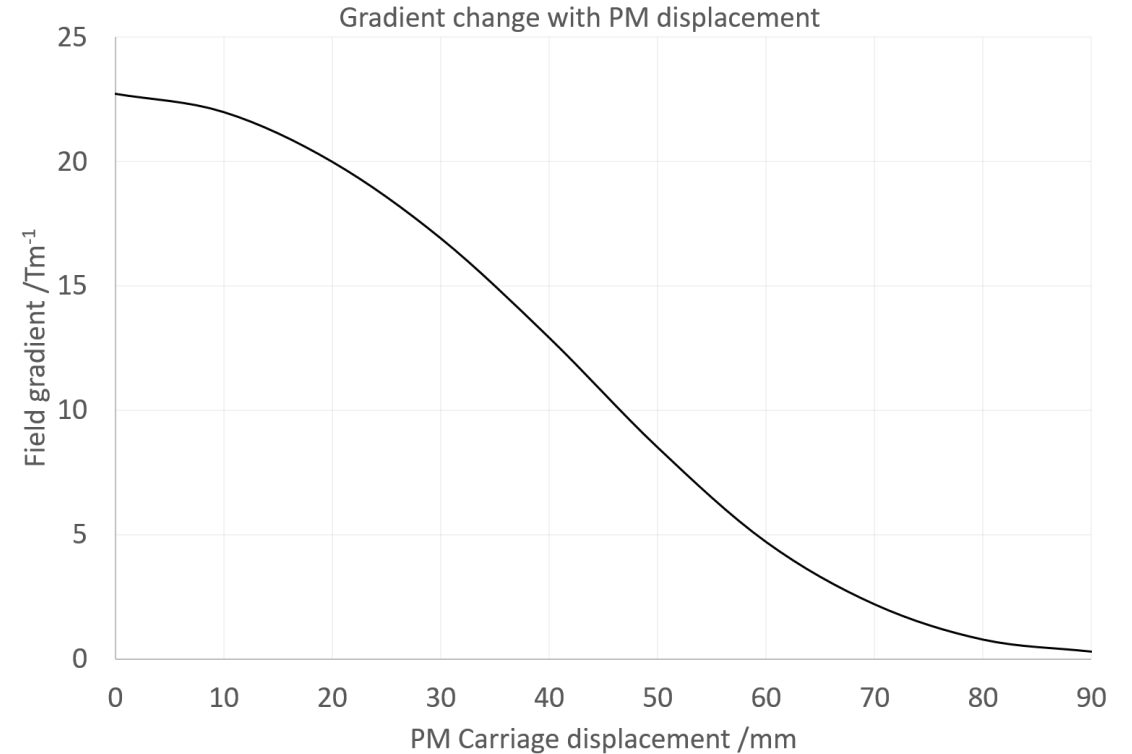
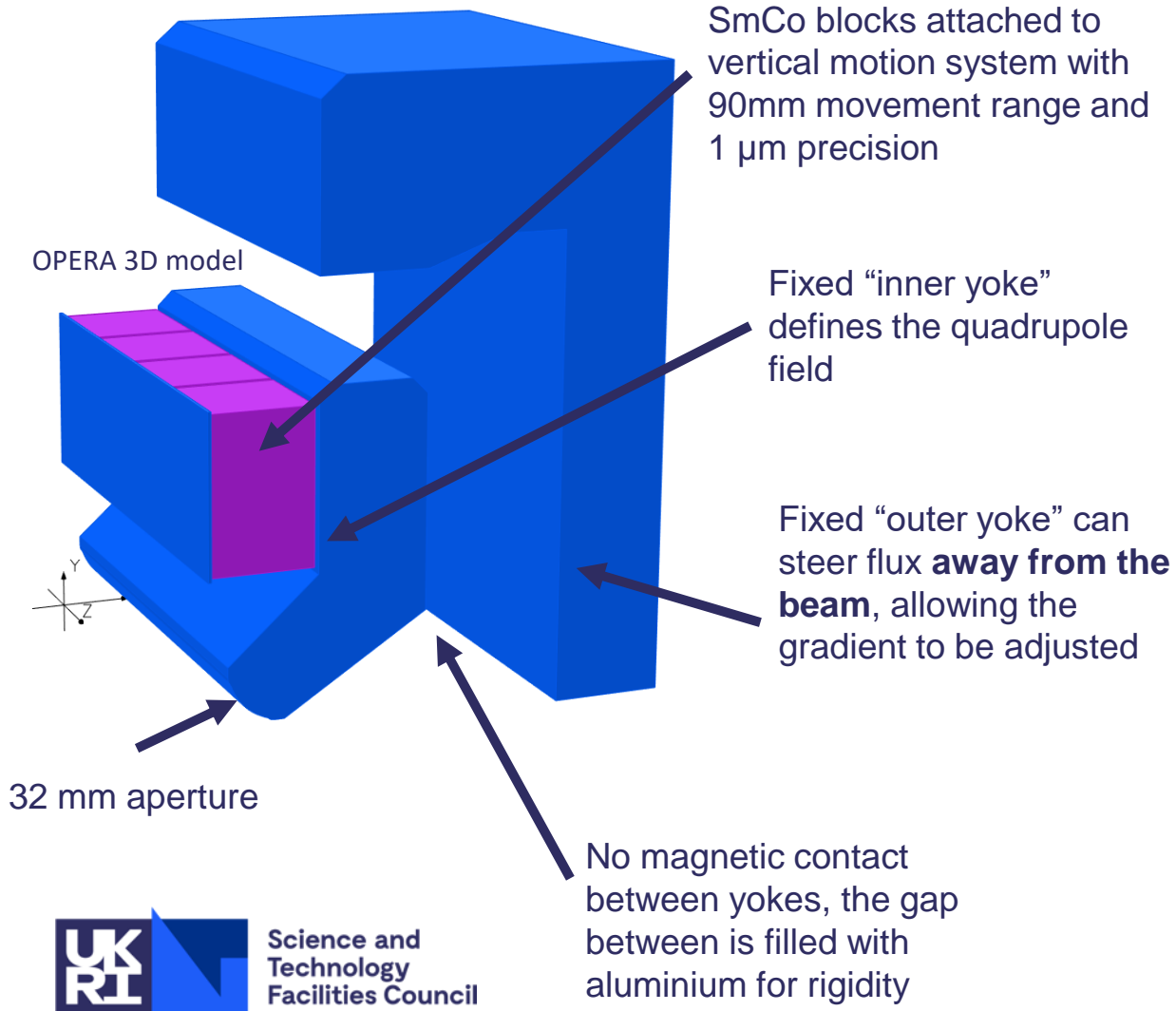
We have developed a new ZEPTO quadrupole for the booster-to-storage ring section of Diamond Light Source.



Contours B (T)



# New technology demonstrator



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'**.

# Permanent magnets

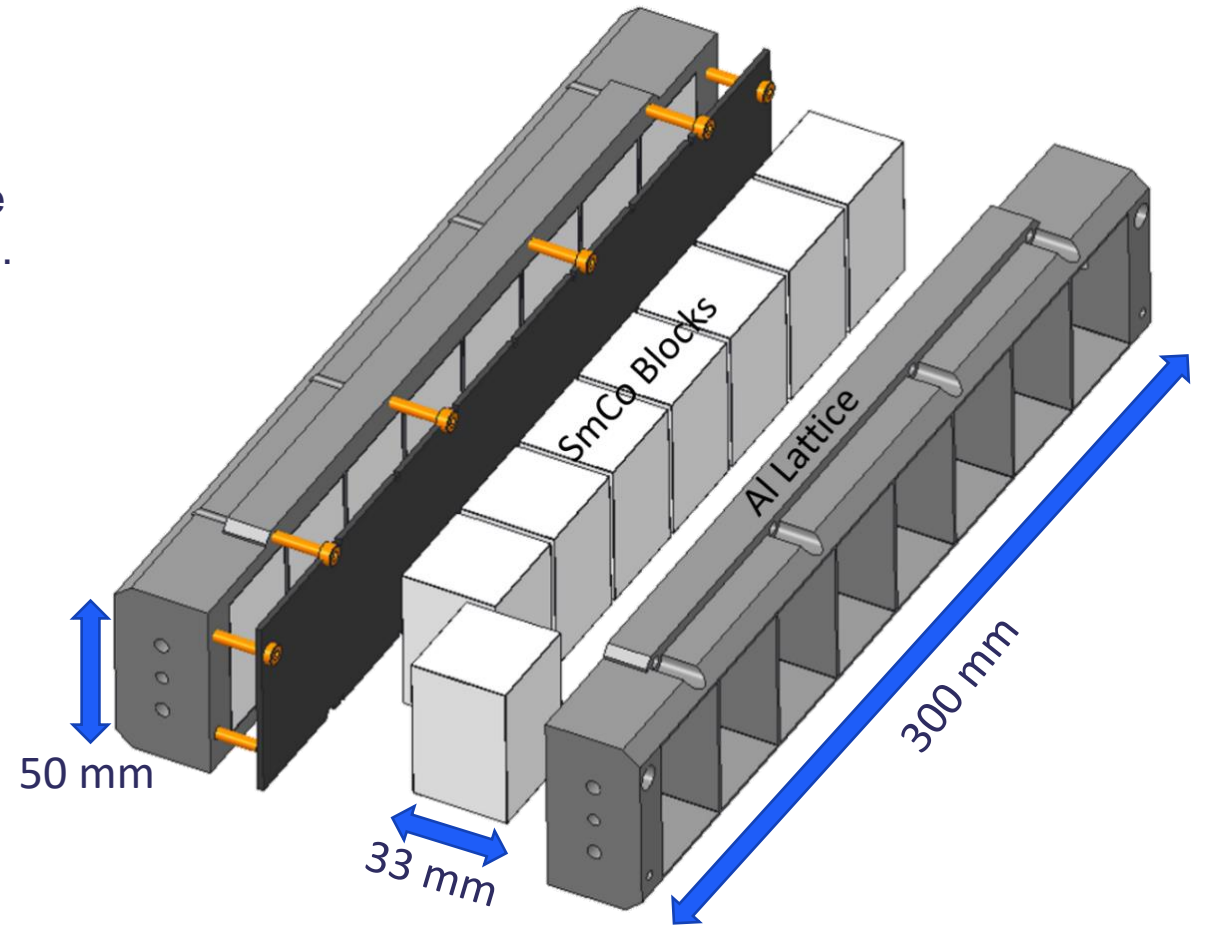
Previous ZEPTO magnets used large NdFeB blocks to produce the magnetic flux, which are difficult to manufacture and handle.

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.

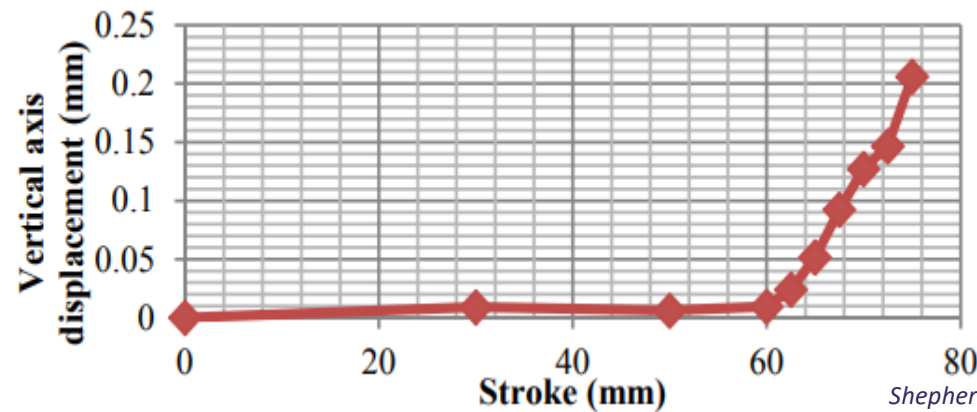
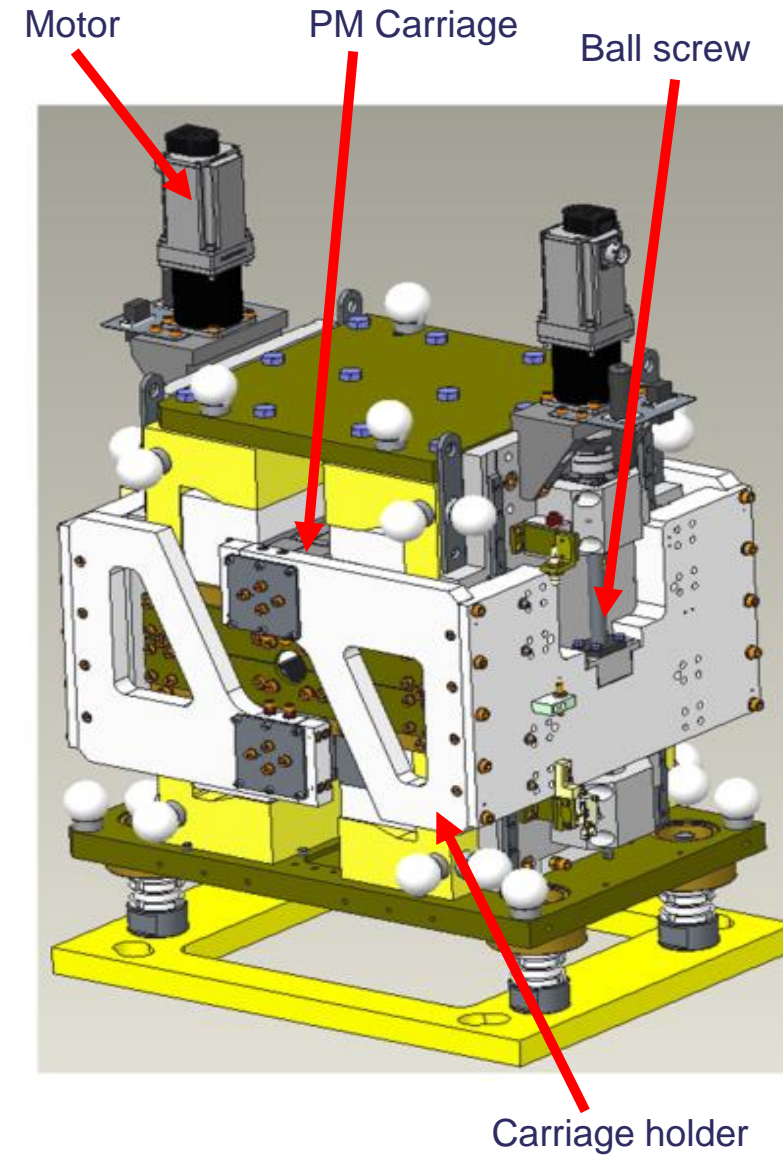
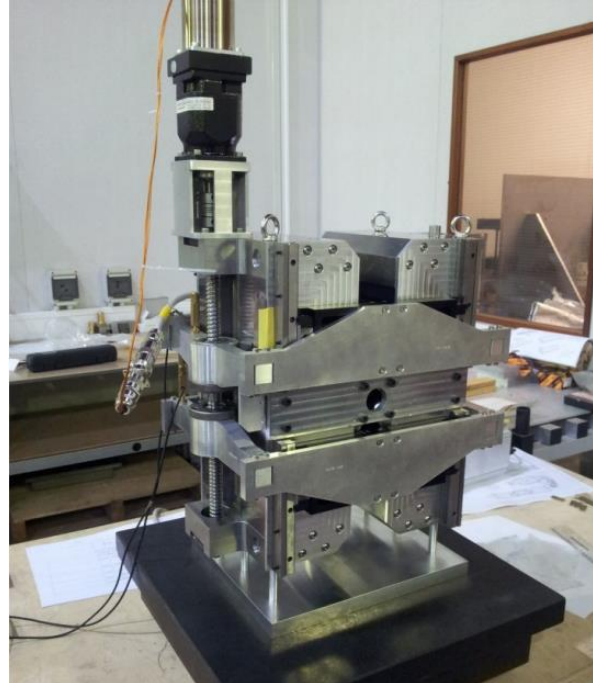
No thermal shunts are needed

# 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.



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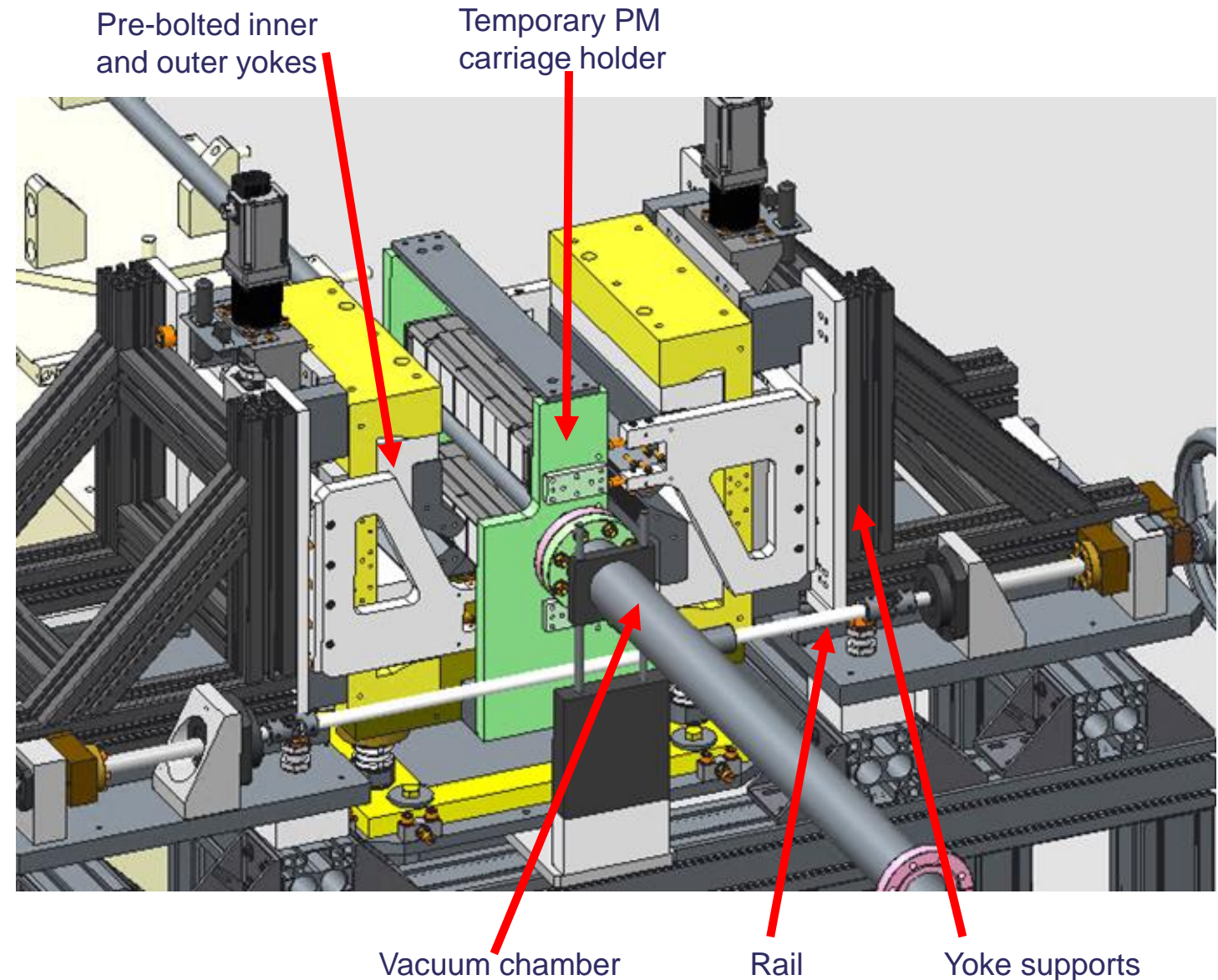
Shepherd et al, IPAC'14, Dresden, Germany, paper TUPRO113.

# 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.

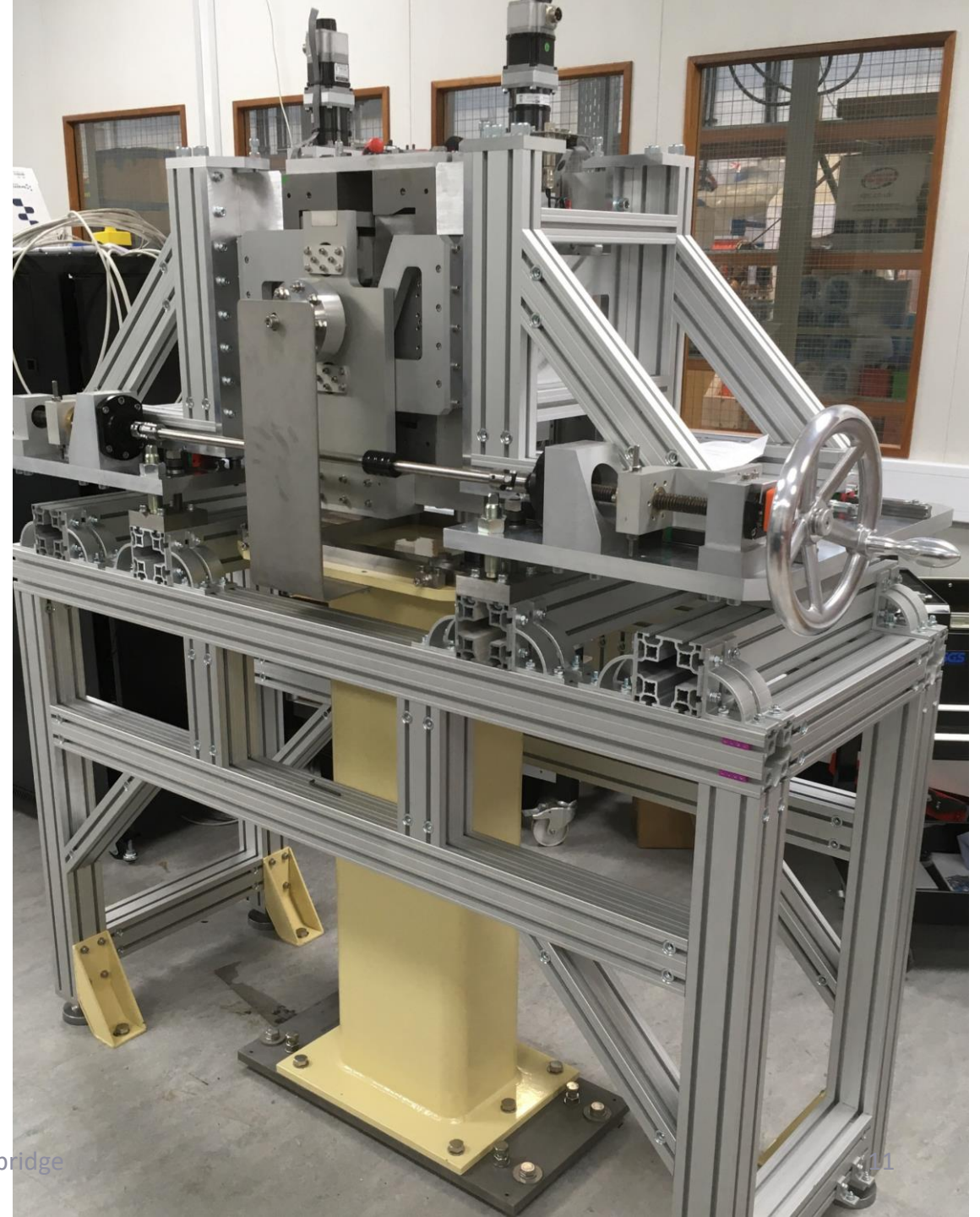


# Split design

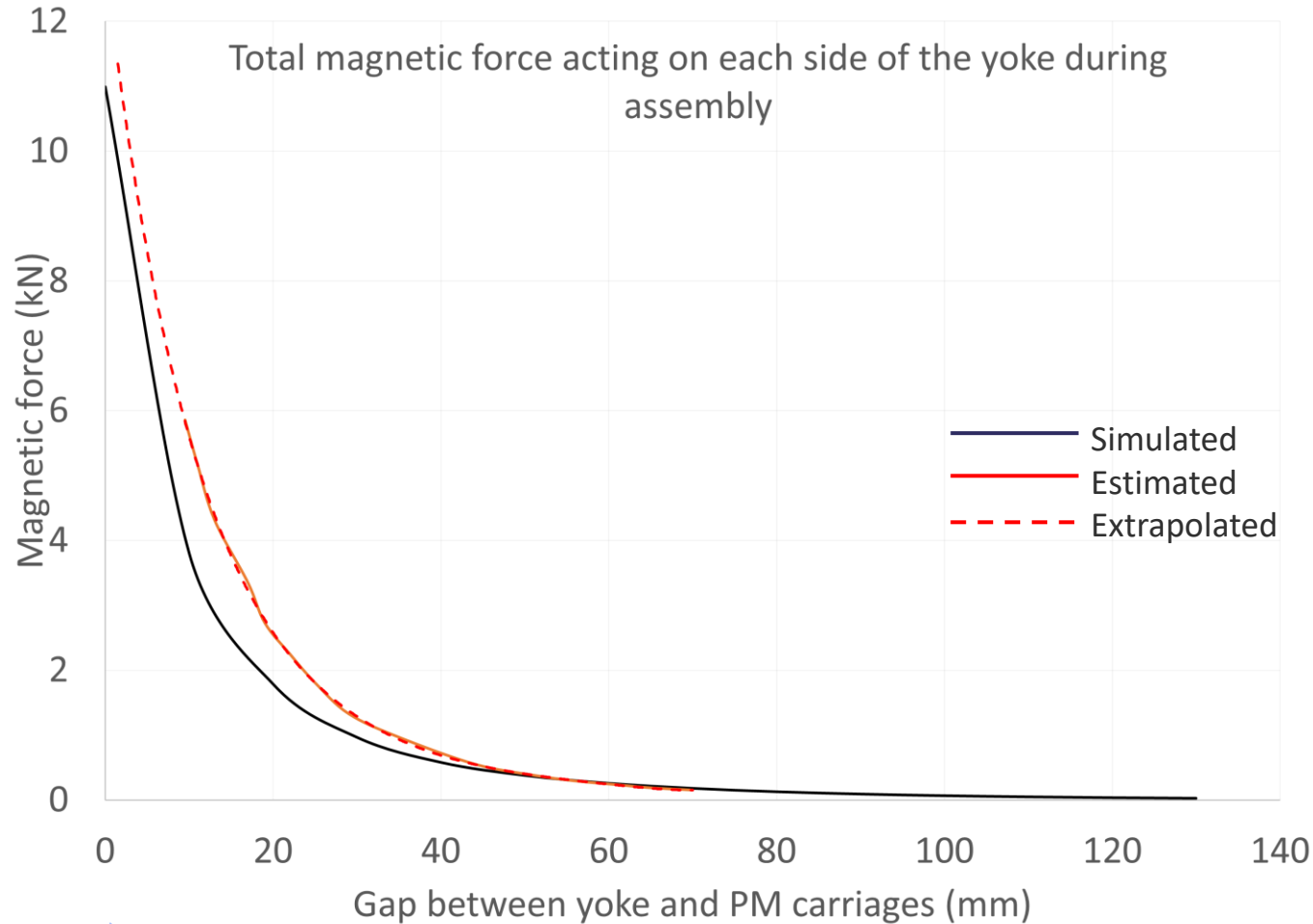
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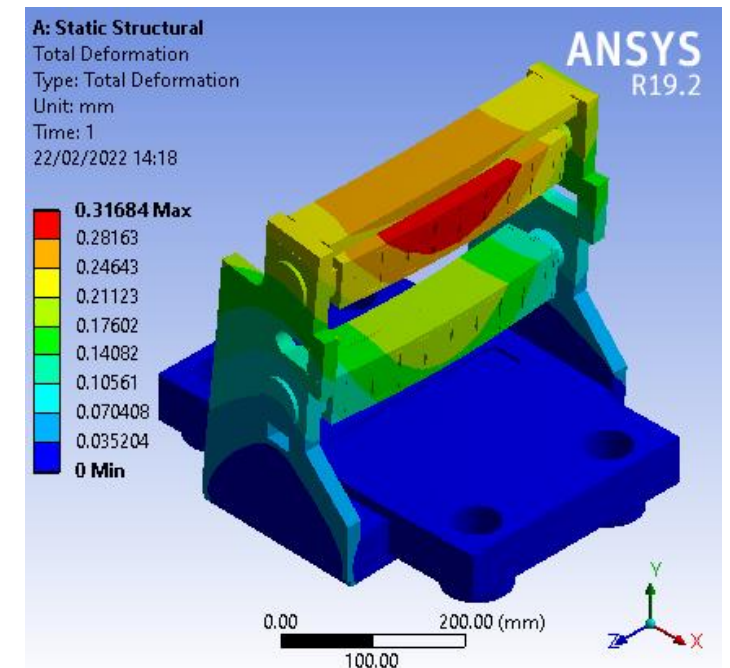


# Assembly forces



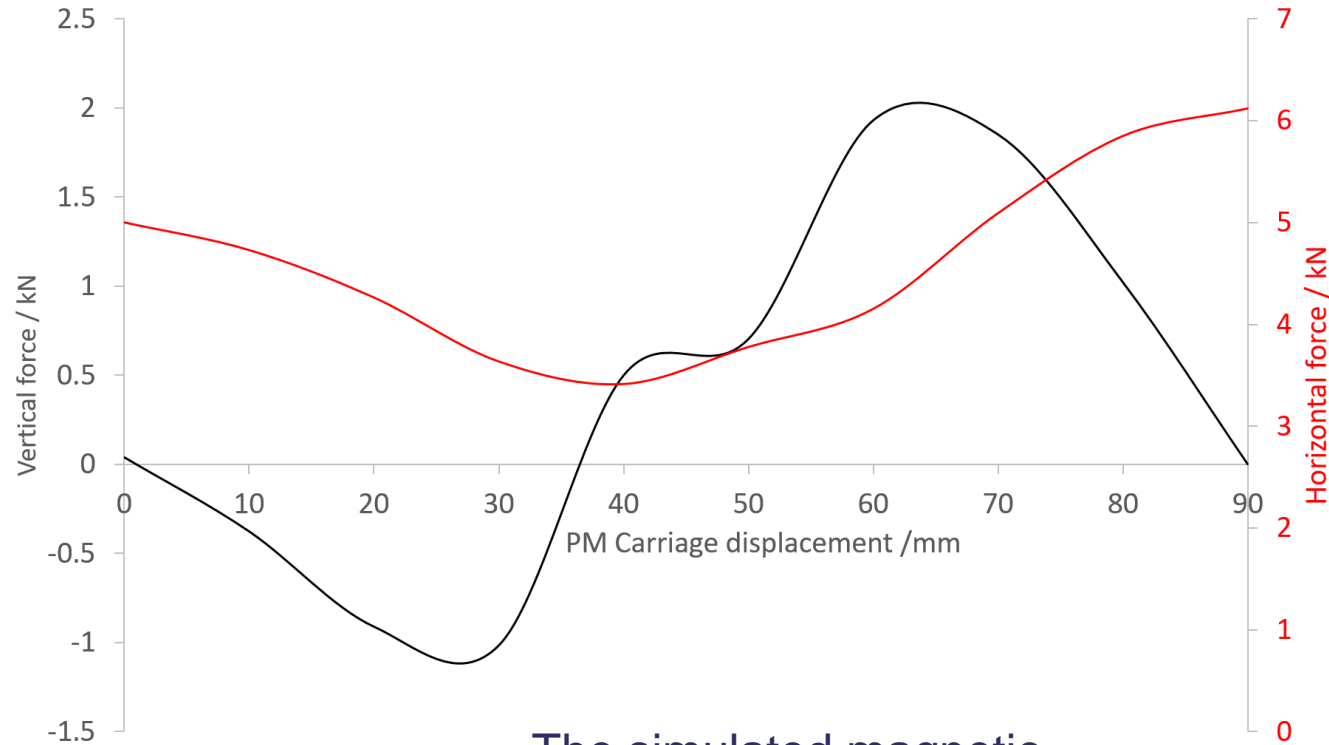
Forces between the PM blocks and steel yokes must be calculated in advance and managed during assembly!

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



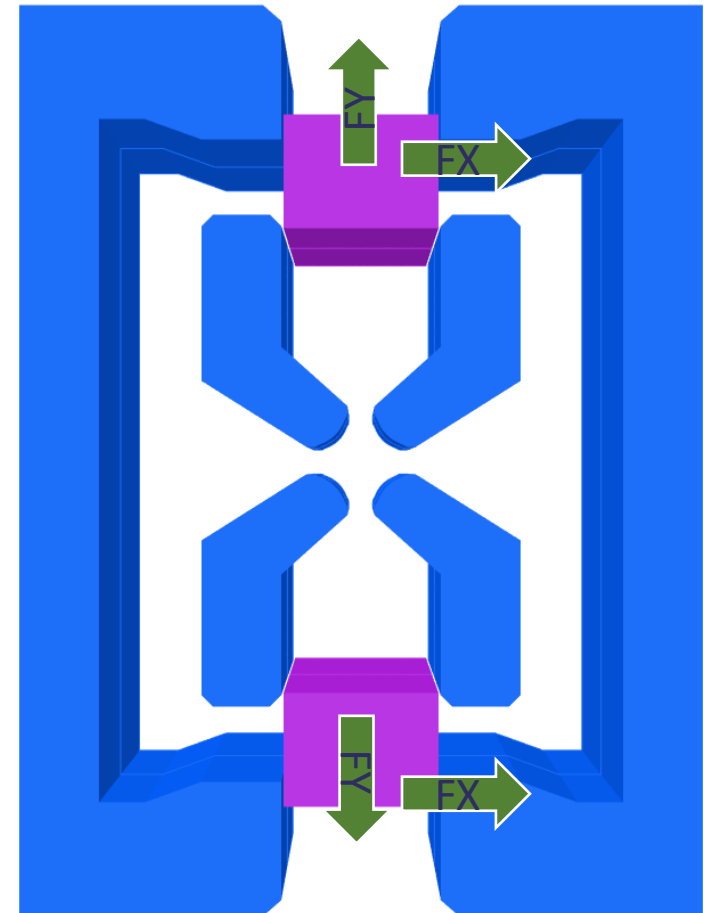
# Operational forces

Forces between PM carriage and steel yoke



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

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



# Gradient vs gap

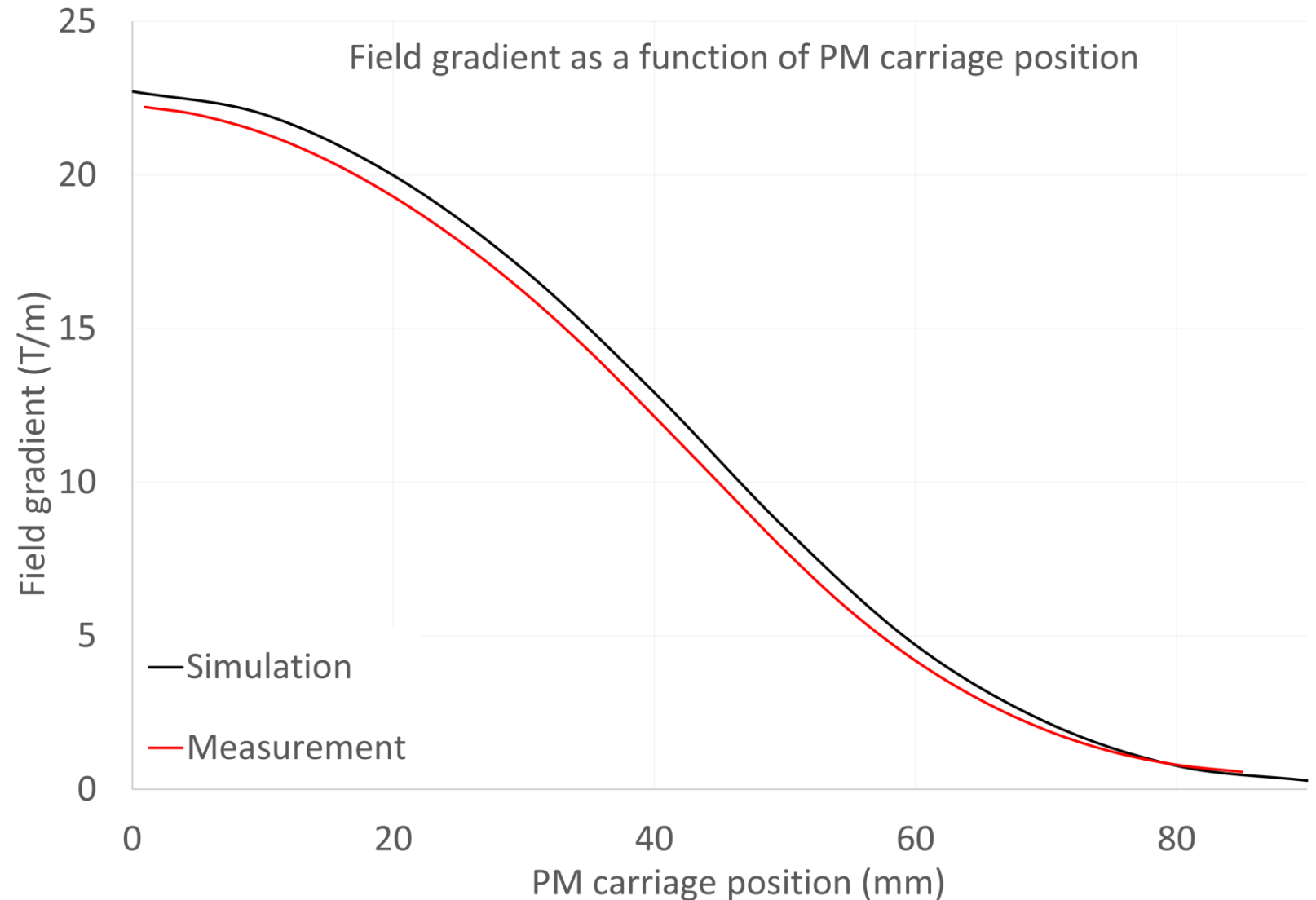
Some variation between simulated and measured gradients observed.

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

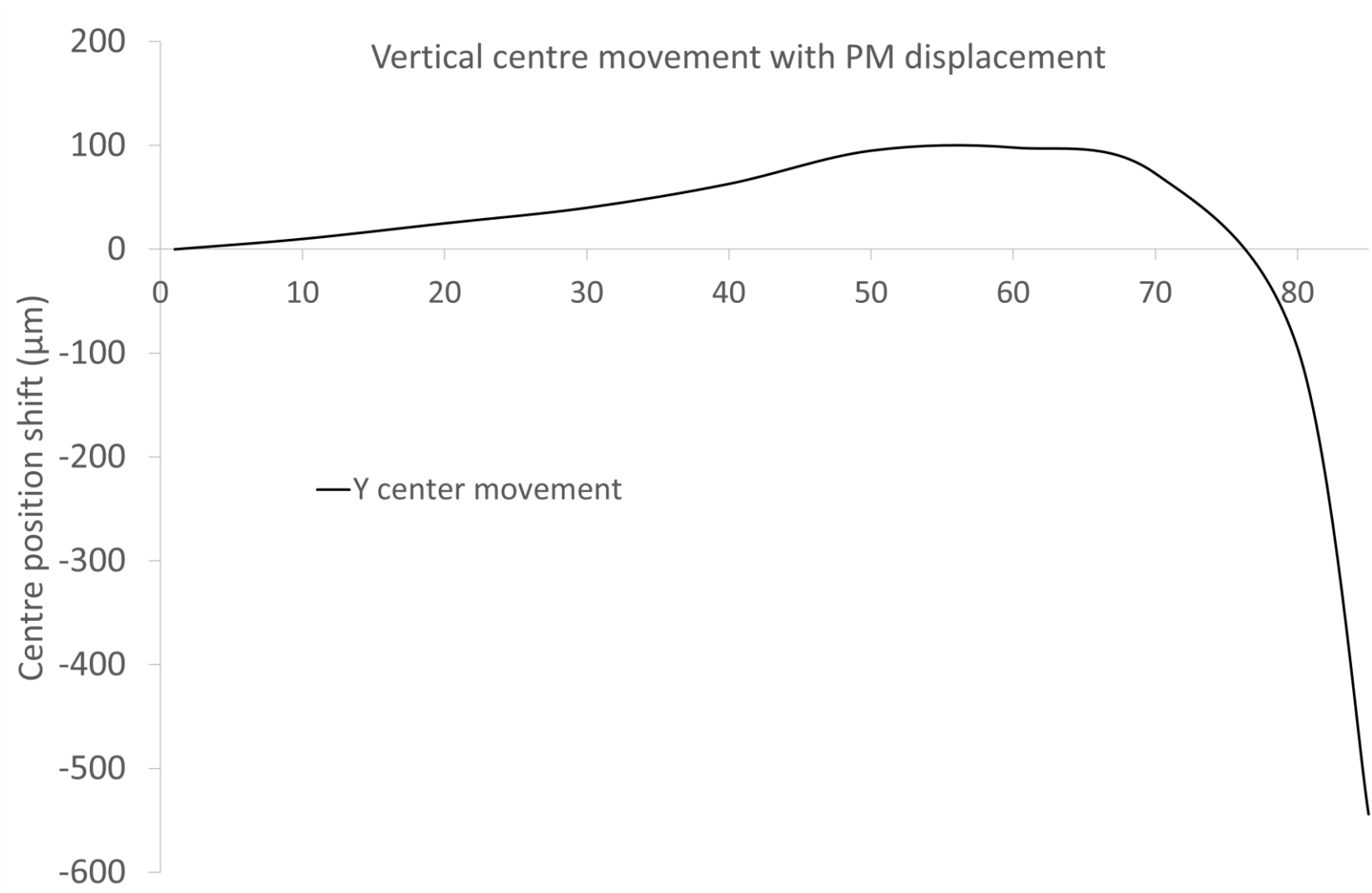


# Vertical centre position

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

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

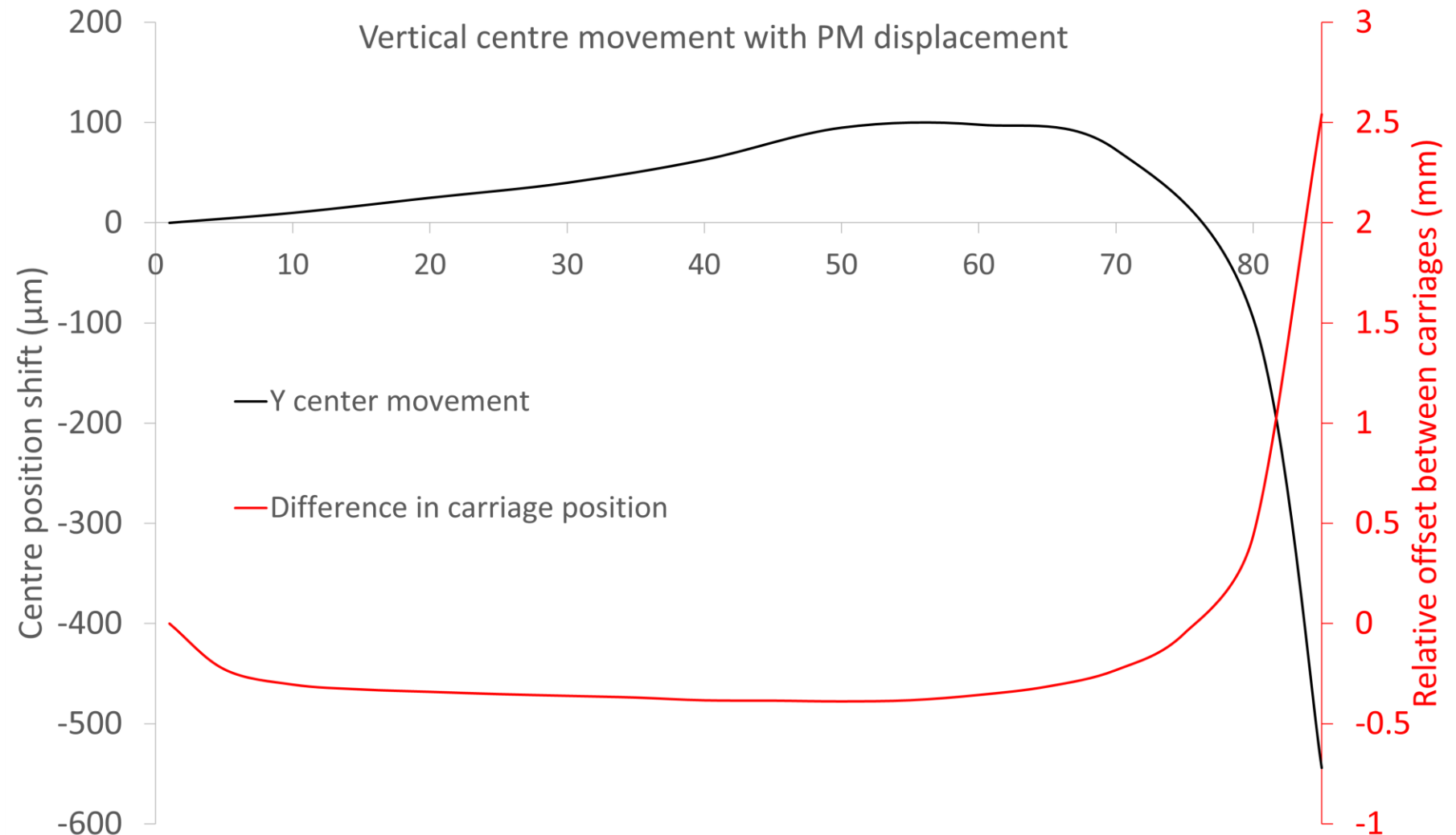
Cause of movement and direction reversal unknown – magnetic materials in pedestal?  
Uneven motion?



# Vertical centre position

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

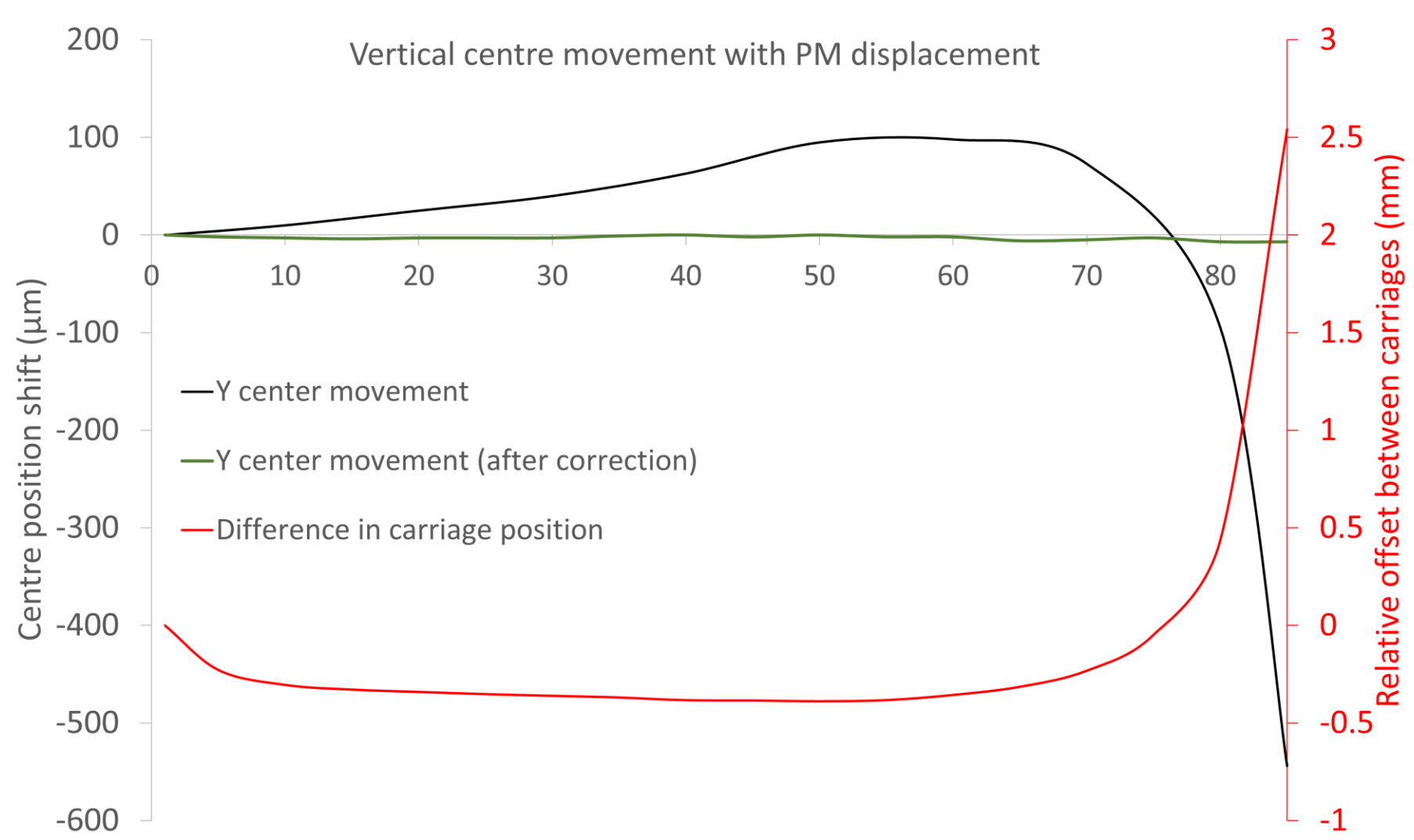
Works with either carriage, but resulting look-up table is slightly different.



# Vertical centre position

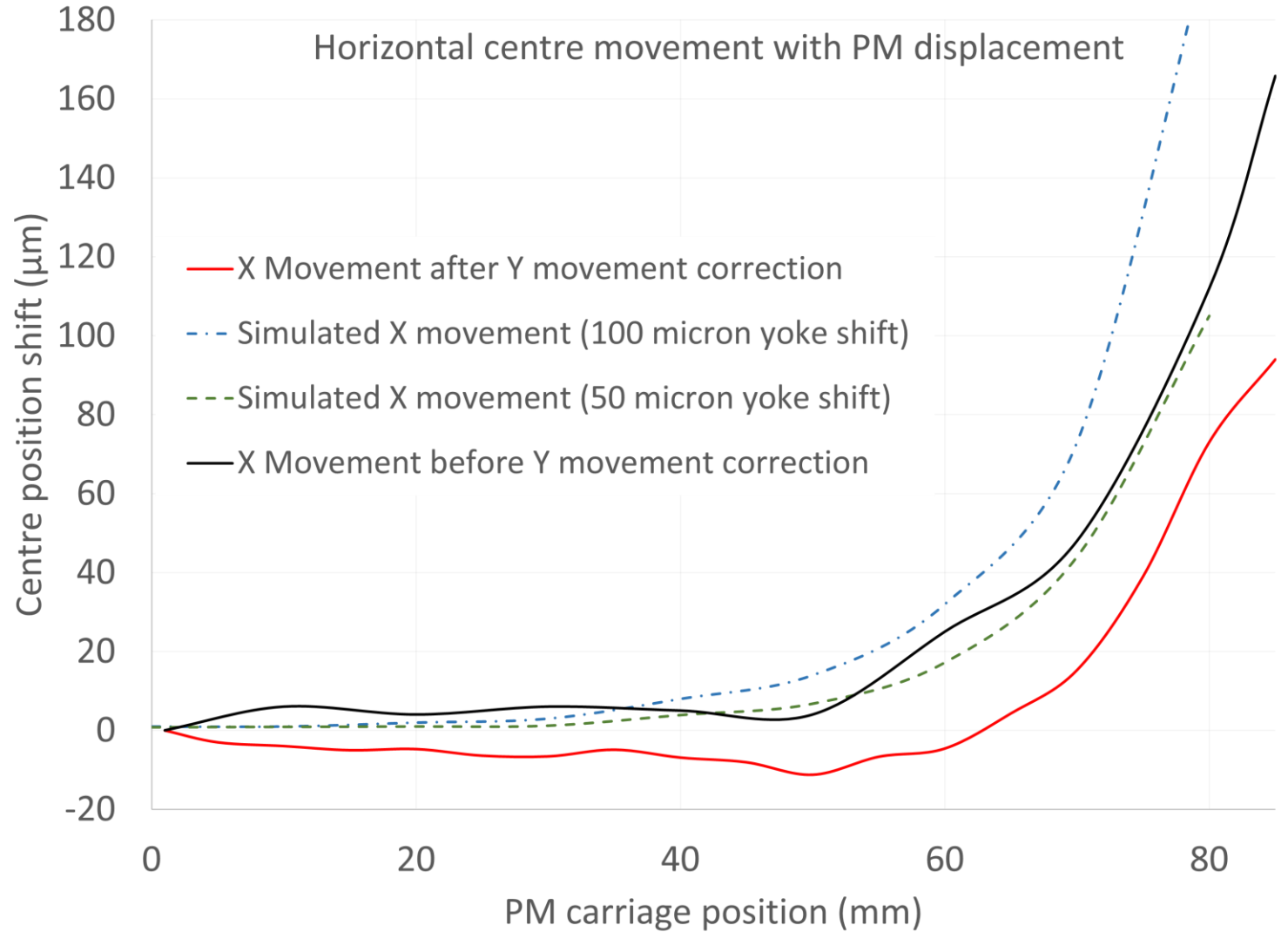
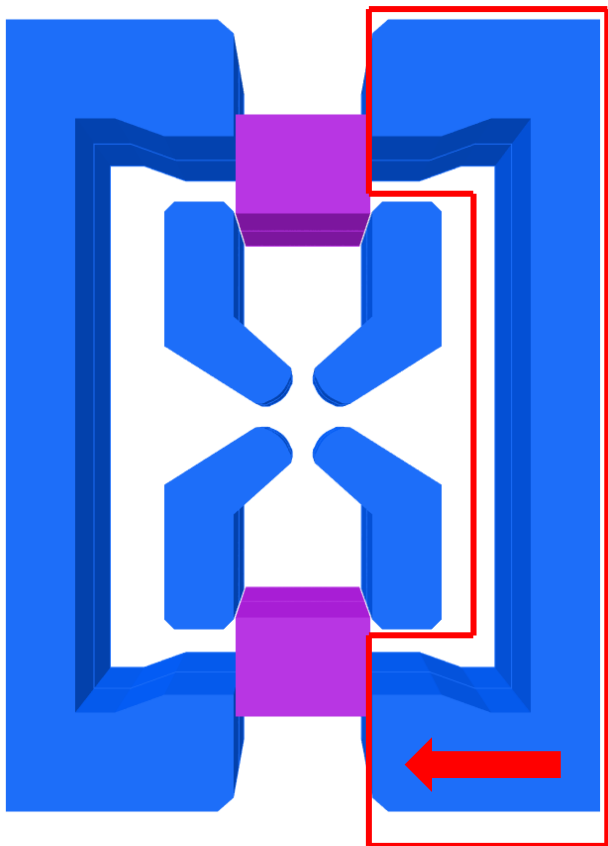
By applying the look-up table we can effectively counter all **vertical movement** of the magnetic centre!

Dataset shown has 7  $\mu\text{m}$  drop in centre position, with 5  $\mu\text{m}$  drop expected from temperature variation alone (contraction of magnet pedestal).



# Horizontal centre position

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



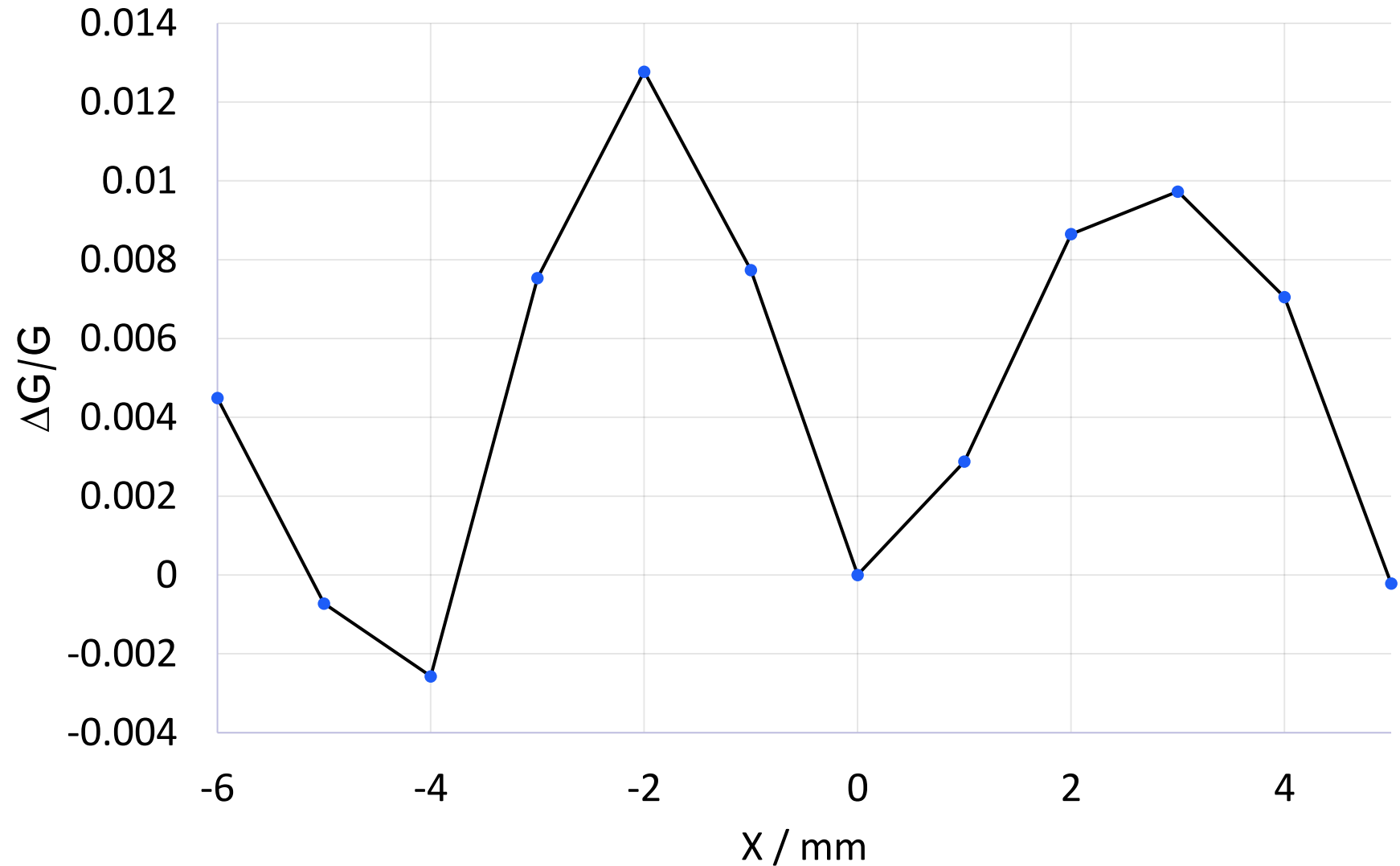
# Homogeneity – integrated

Integrated gradient homogeneity as function of X at max strength, from ZX map.

Follows similar pattern to sweep across x centre.

Integrated homogeneity is at worst 1.3%

Results almost identical at 40mm carriage position!

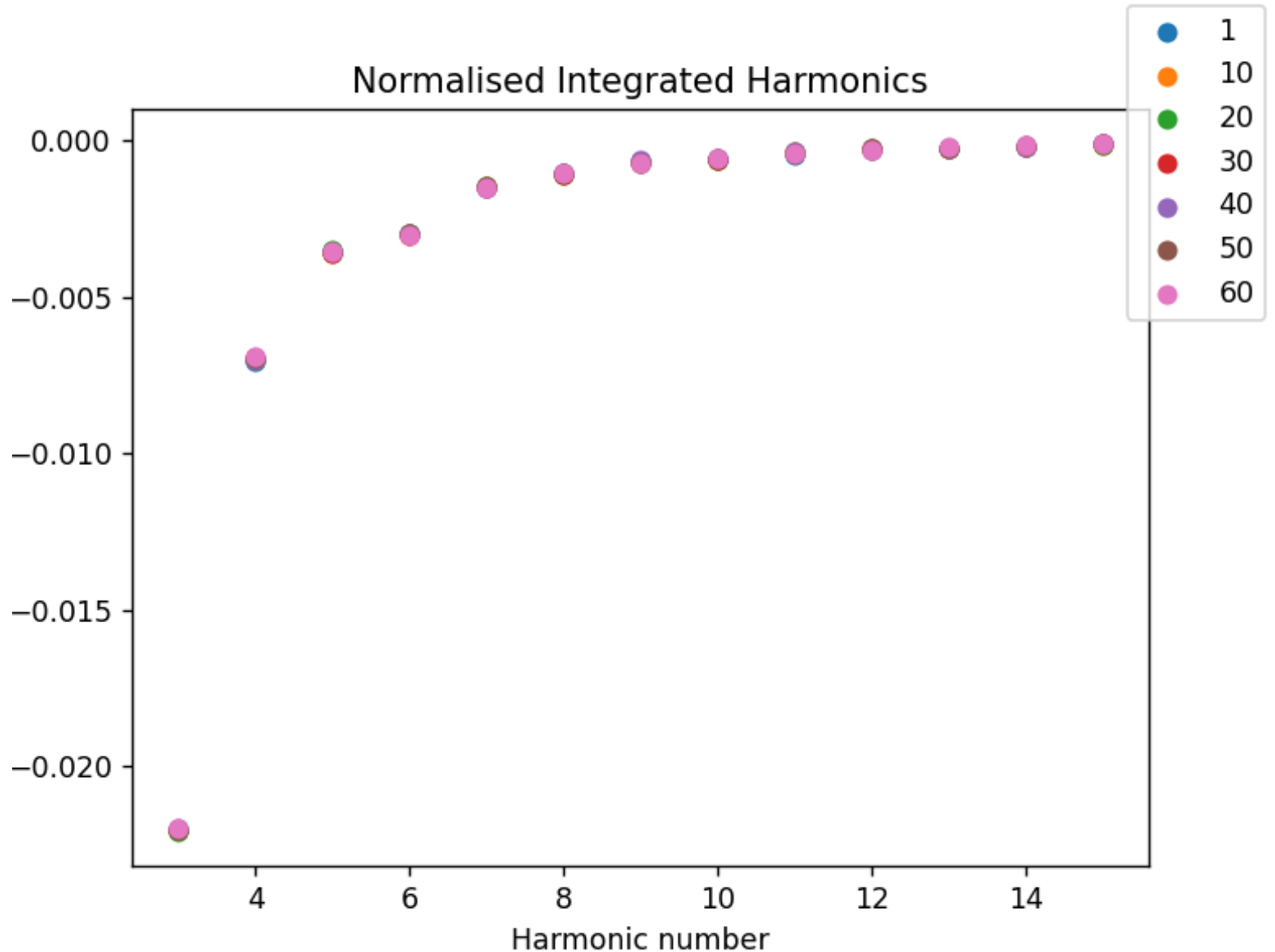


# Harmonics

Normalized integrated harmonics measured moving hall probe in a circle of radius 3mm at 5mm intervals in Z along ~43% magnet length.

Harmonics remain proportionally consistent as carriages move.

But design makes usually forbidden octupole harmonic allowed, and a sextupole harmonic suggests imperfect assembly.



# Installation on Diamond

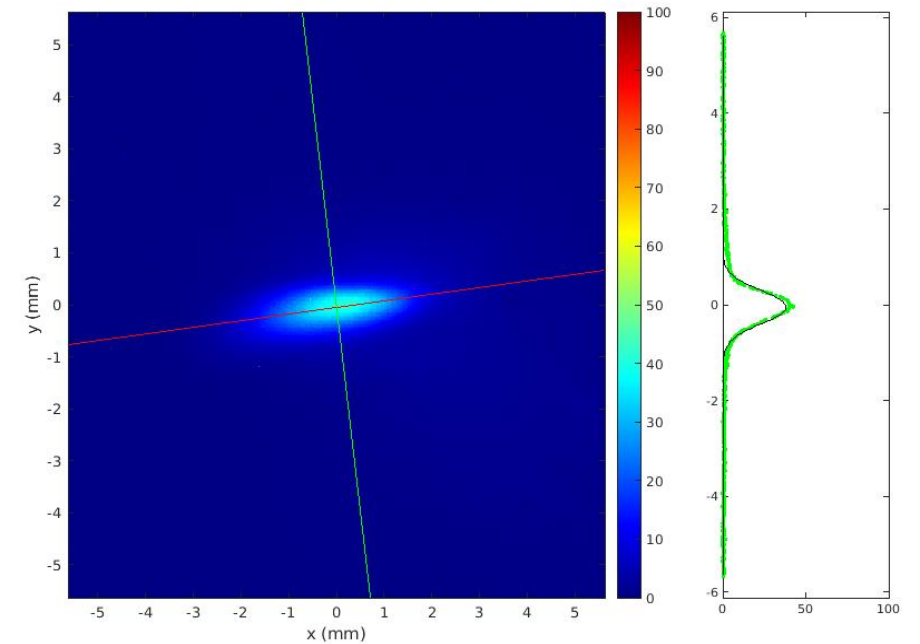
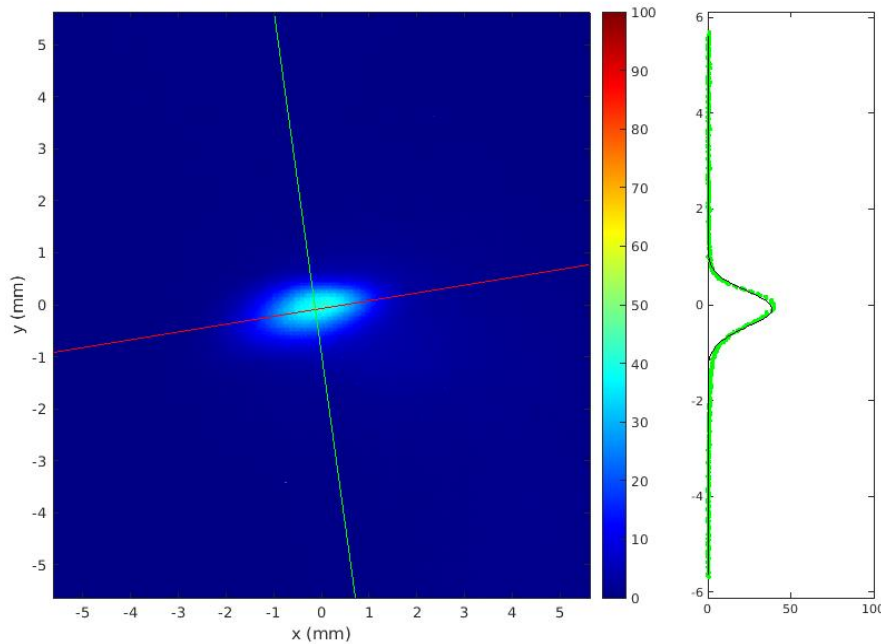
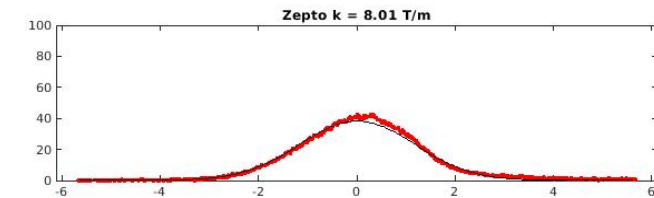
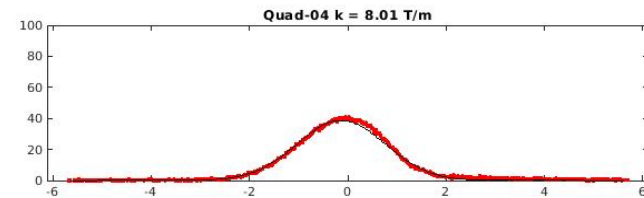
The magnet has now been successfully installed on the booster to storage ring transfer line at Diamond alongside the electromagnet it is “replacing”.

This represents the first use of the ZEPTO technology on a real accelerator, and we hope long term testing will show the viability of the technology for widespread commercial use.



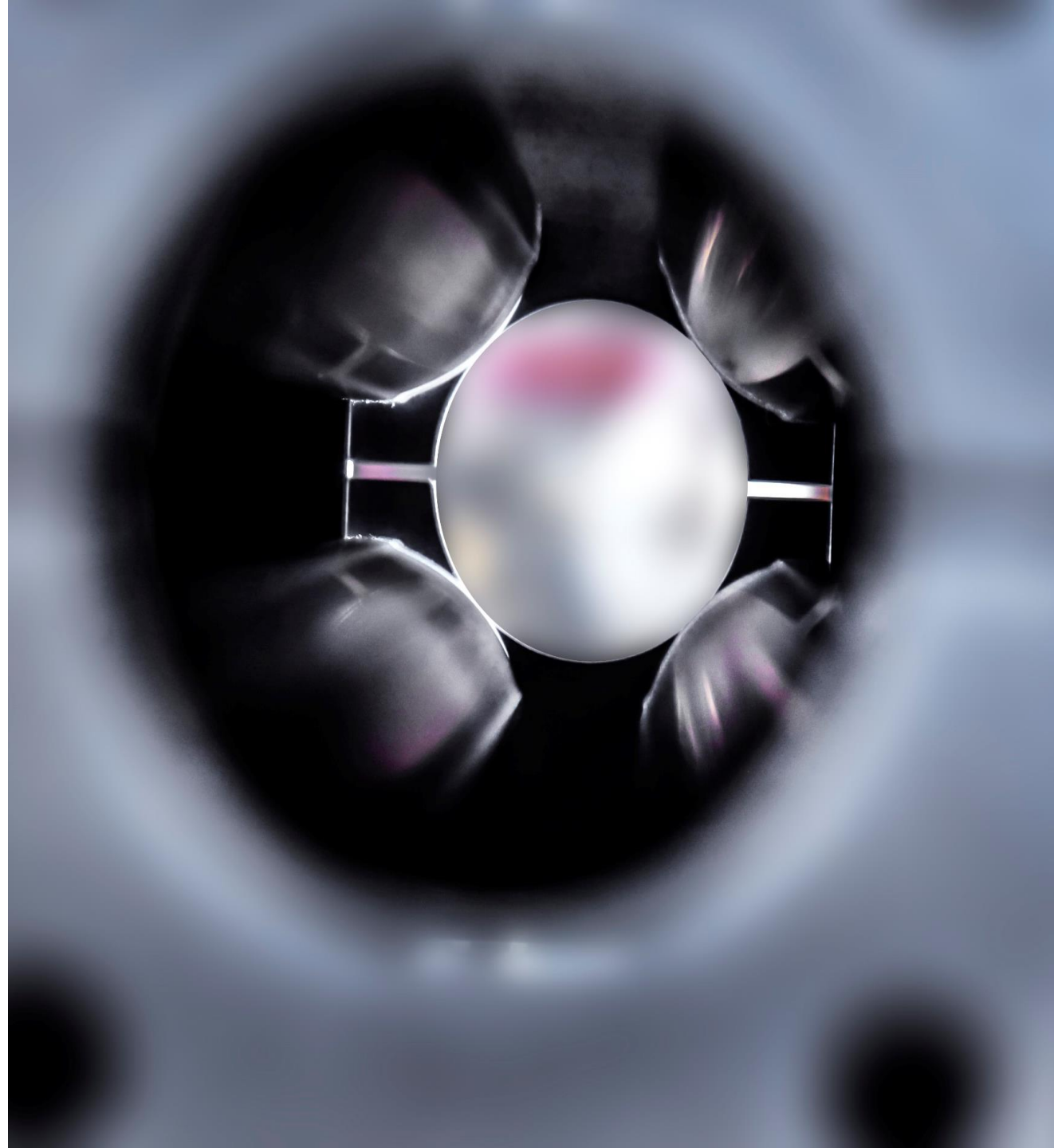
# First testing on Diamond

Diamond Light Source have confirmed that they are able to inject through the ZEPTO quad into the storage ring and maintain the same injection efficiency that the electromagnet provided, and that they are able to effectively switch the magnet



# 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!
- The magnet is now installed and working on Diamond!



# Acknowledgements

The team behind ZEPTO DLS prototype:

Ben Shepherd



Group Leader &  
ZEPTO co-inventor

Alex Bainbridge



Design &  
Modelling

Nick Krumpa

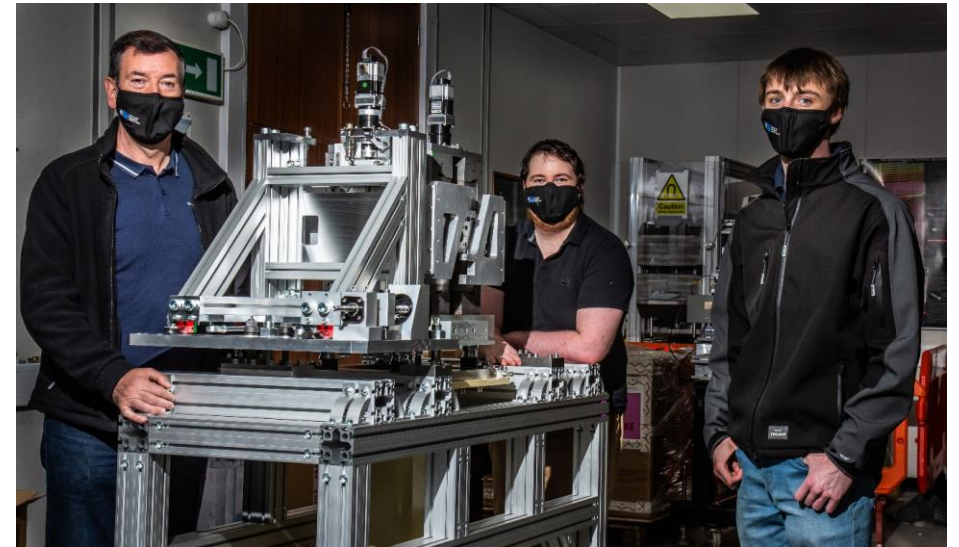


Mechanical  
engineering

Alex Hinton



Measurements



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

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



This work was funded by the STFC Proof of Concept Fund



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# Thank You



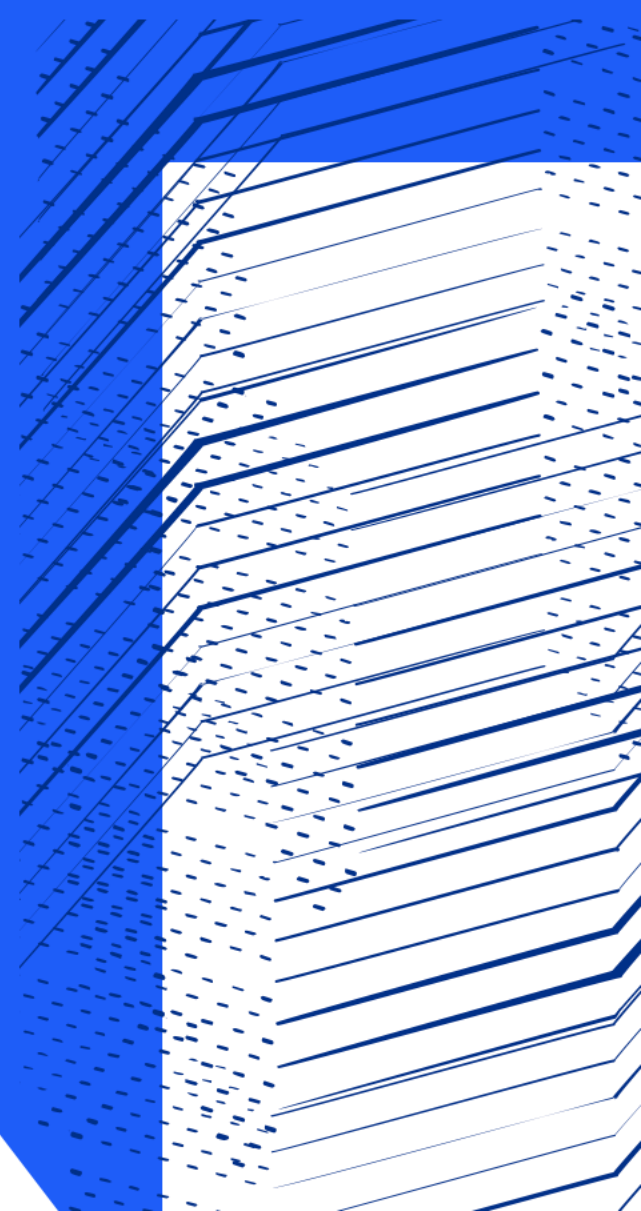
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@STFC\_matters



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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 will always be present. In addition, a sextupole harmonic has been measured suggesting the horizontal and vertical gaps between pole tips may not be equal.

## 5 Is ZEPTO technology patented?

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