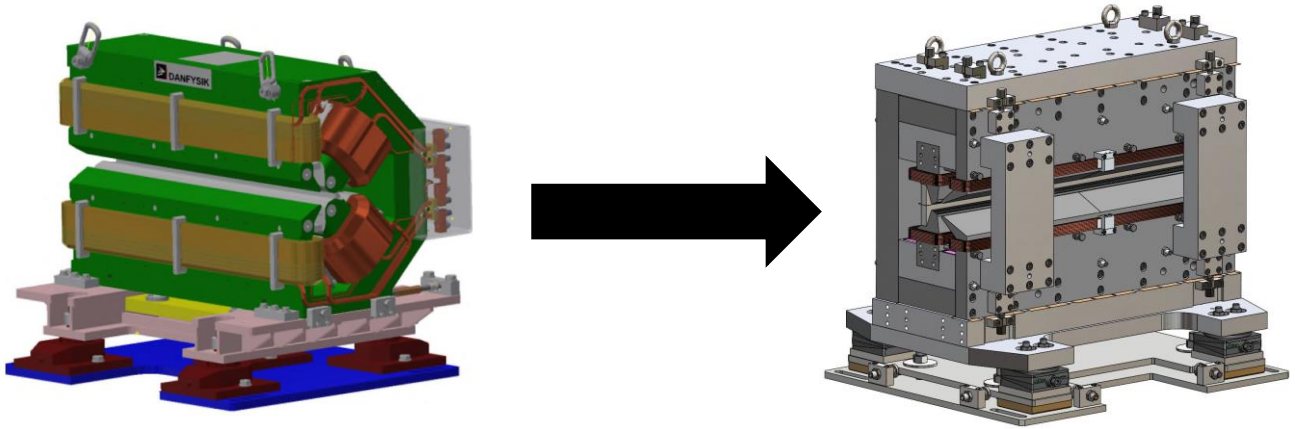
# I.FAST Final Meeting, CERN, 22 October 2025

**Ben Shepherd** and Alex Hinton

I.FAST WP11.3, STFC Daresbury Laboratory

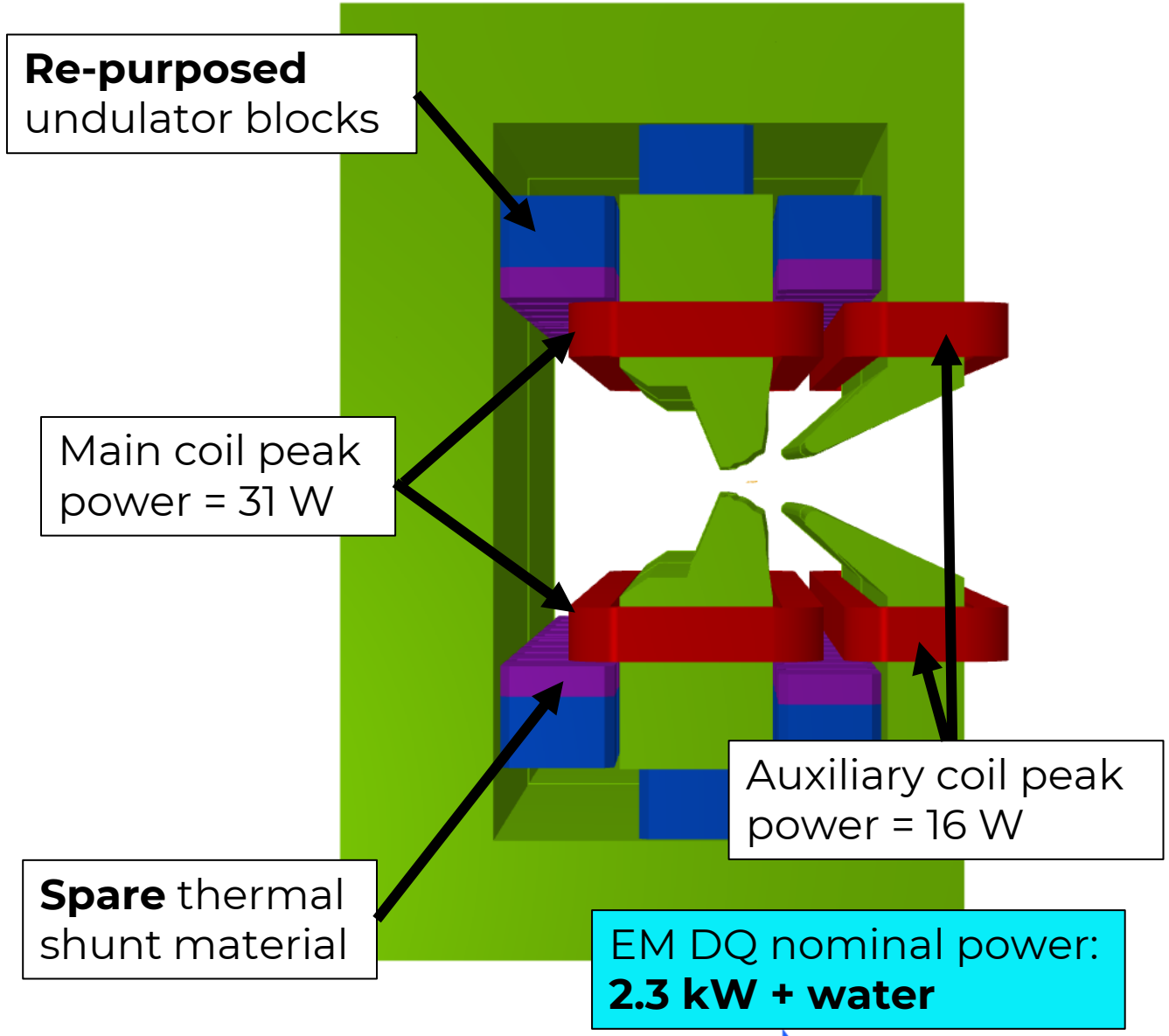
# Introduction

- I.FAST WP11.3: Permanent Magnet (PM) Combined Function Magnets for Ultra Low-Emittance Rings
- Development of prototype dipole-quadrupole (DQ) with equivalent parameters as existing electromagnet designed for Diamond-II lattice upgrade to save operating power



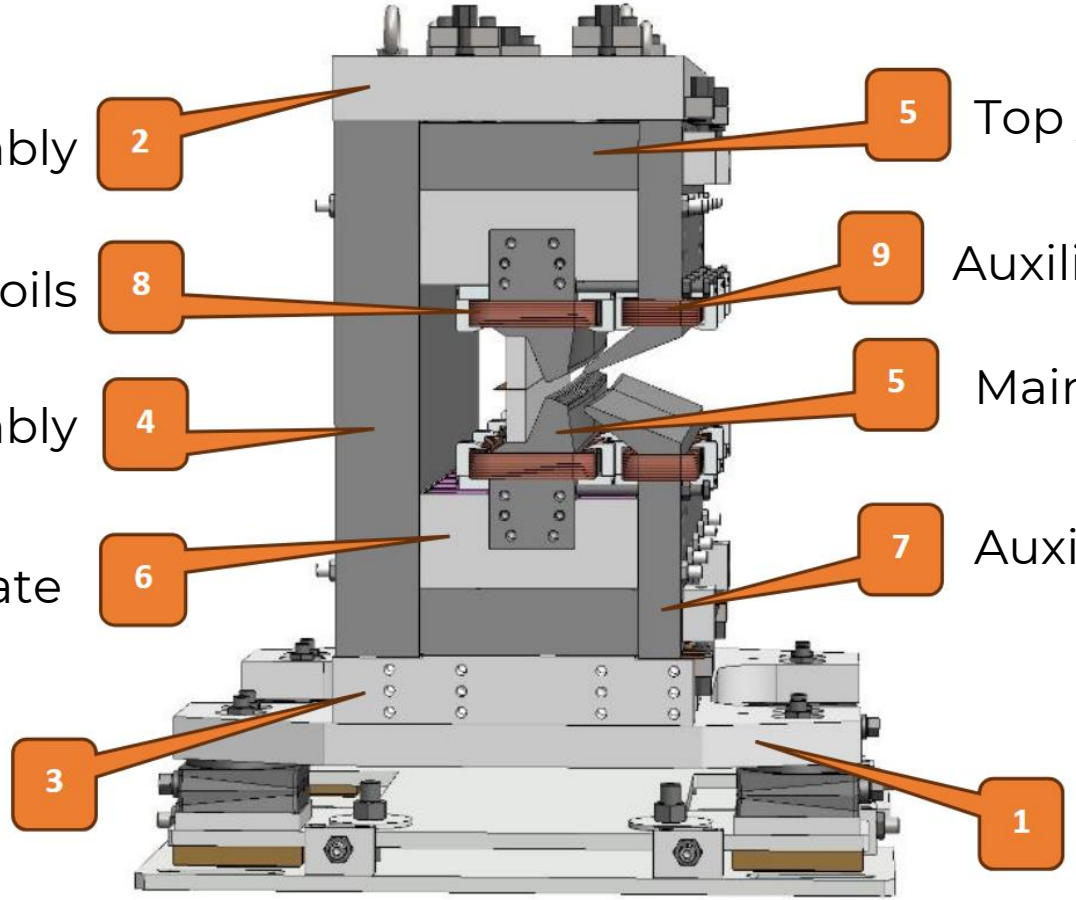
# Magnet Design

- Hybrid Electromagnet-Permanent Magnet Tuneable Optics (**HEPTO**)
- Dipole = **0.7 T**, Gradient = **33 T/m**
- Effective length = **0.870 m**
- Main source of field = **NdFeB** permanent magnet blocks
- Dipole and gradient fields require independent tuning of **±2.5%** for commissioning purposes
- Field tuning achieved by **air-cooled** trim coils
- Yoke and poles made from **low-carbon steel**



# Mechanical Design

**Pole and yoke:** ARMCO Pure Iron
**PM blocks:** NdFeB grade 45M6, 1.3T
**Support structure:** aluminium 5083
**Alignment system:** steel plates, $\mu_r$ = 1.0045




Top adjustment assembly

Top yoke plate

Main trim coils

Auxiliary trim coils

Yoke back plate assembly

Main poles

Interface tray plate

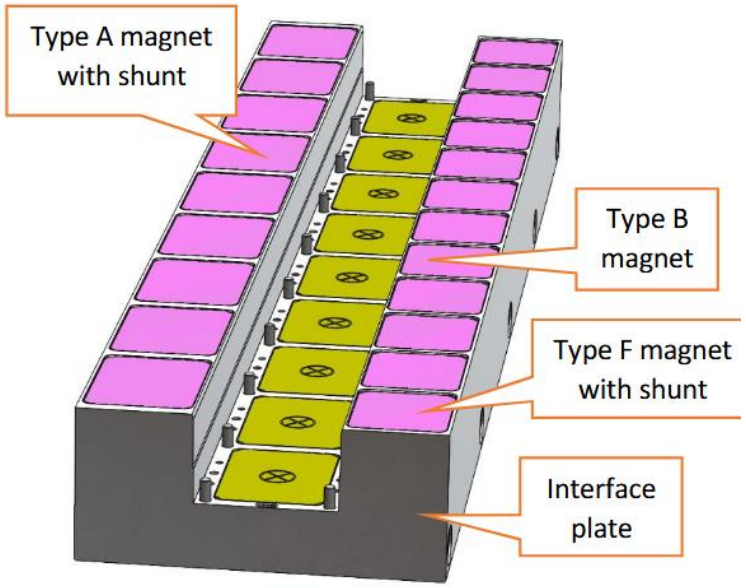
Auxiliary pole assemblies

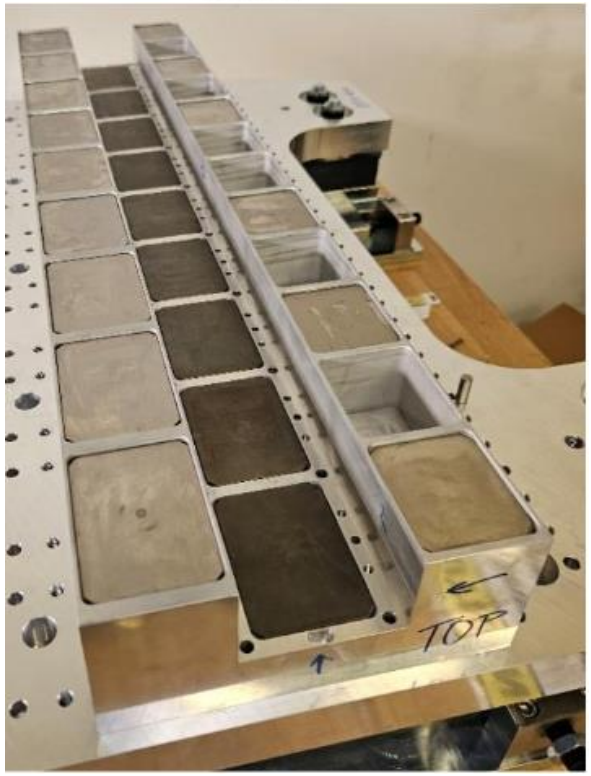
Bottom adjustment assembly

Feet assembly:
horizontal + vertical alignment

# Interface tray plate

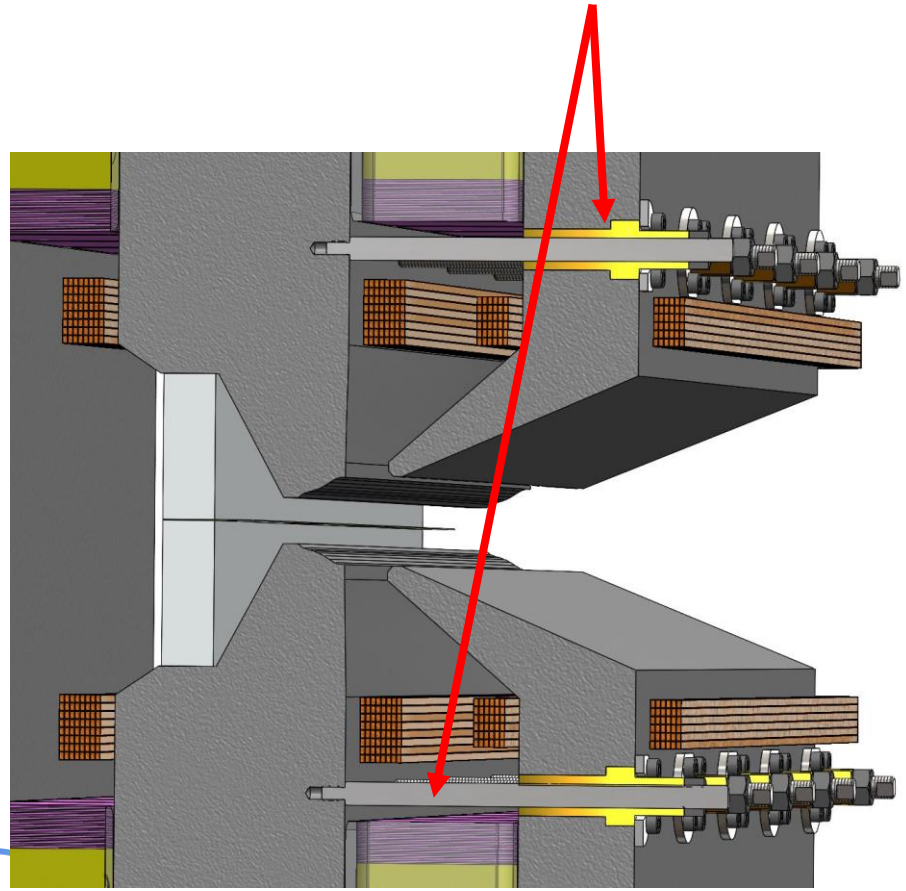
- **Ice cube tray** concept: many small blocks in non-magnetic holder
- Blocks permanently affixed using epoxy (no room for clamping screws)
- Specifically designed for “second-hand” blocks procured for this project
- Provides a stable position for main poles
- Slightly oversized: no pressure on blocks



# Mechanical Shimming

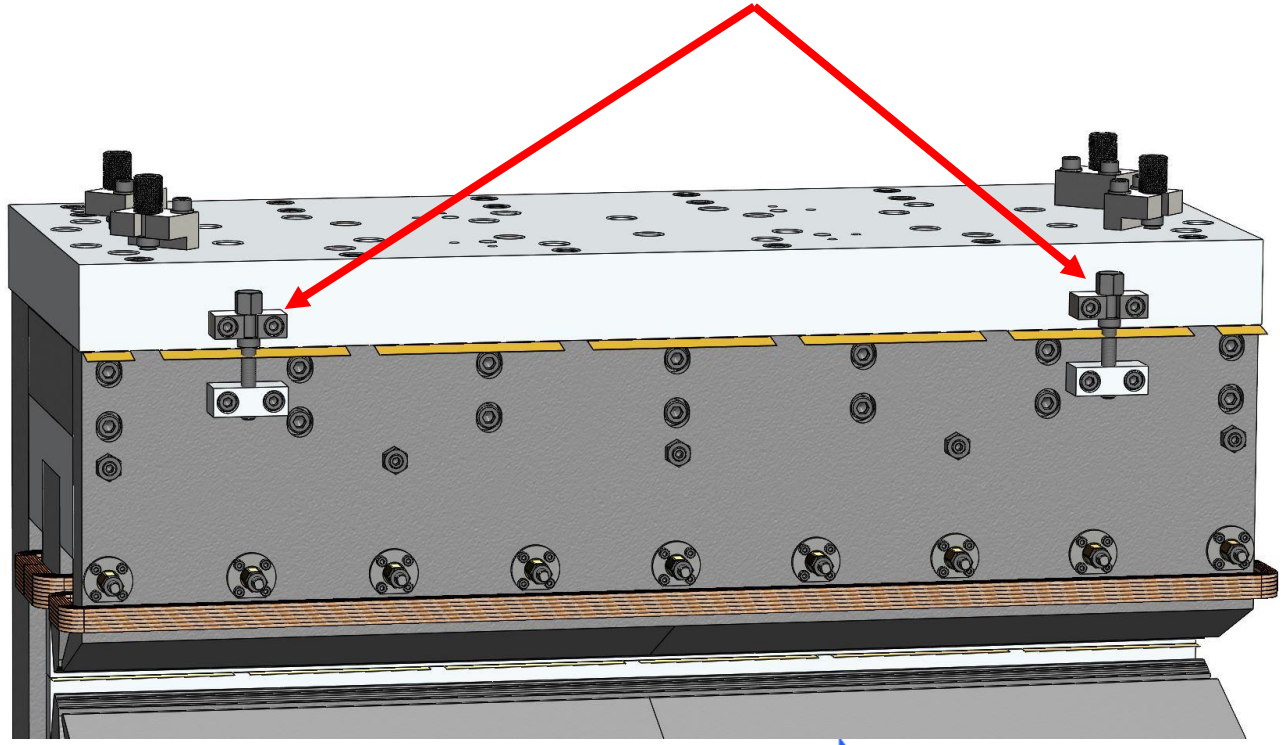
1. Threaded rods used to deform **auxiliary poles** for **horizontal** adjustment of auxiliary pole tips.



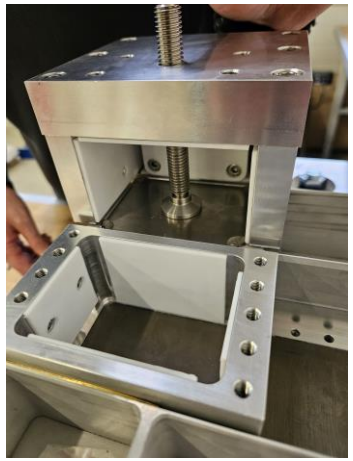
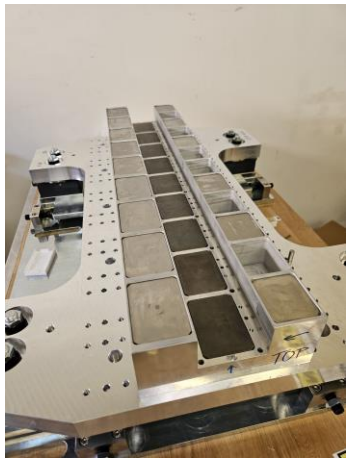
2. Two screws for opening gap between auxiliary pole and aluminium plate. Brass shims can be added/removed to adjust **vertical position of auxiliary pole.**

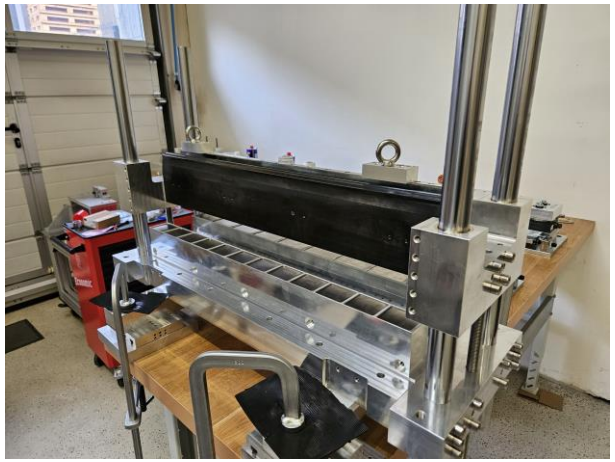
Gap is **pre-shimmed** with 300 μm thickness.

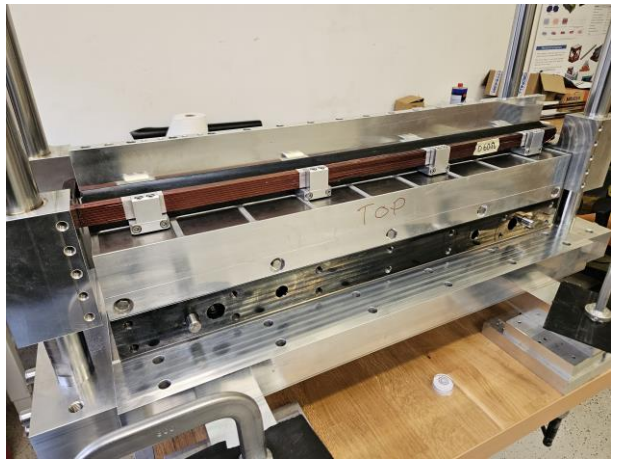
Shim thicknesses in range 10-300 μm.



# Mechanical Assembly @ Kyma





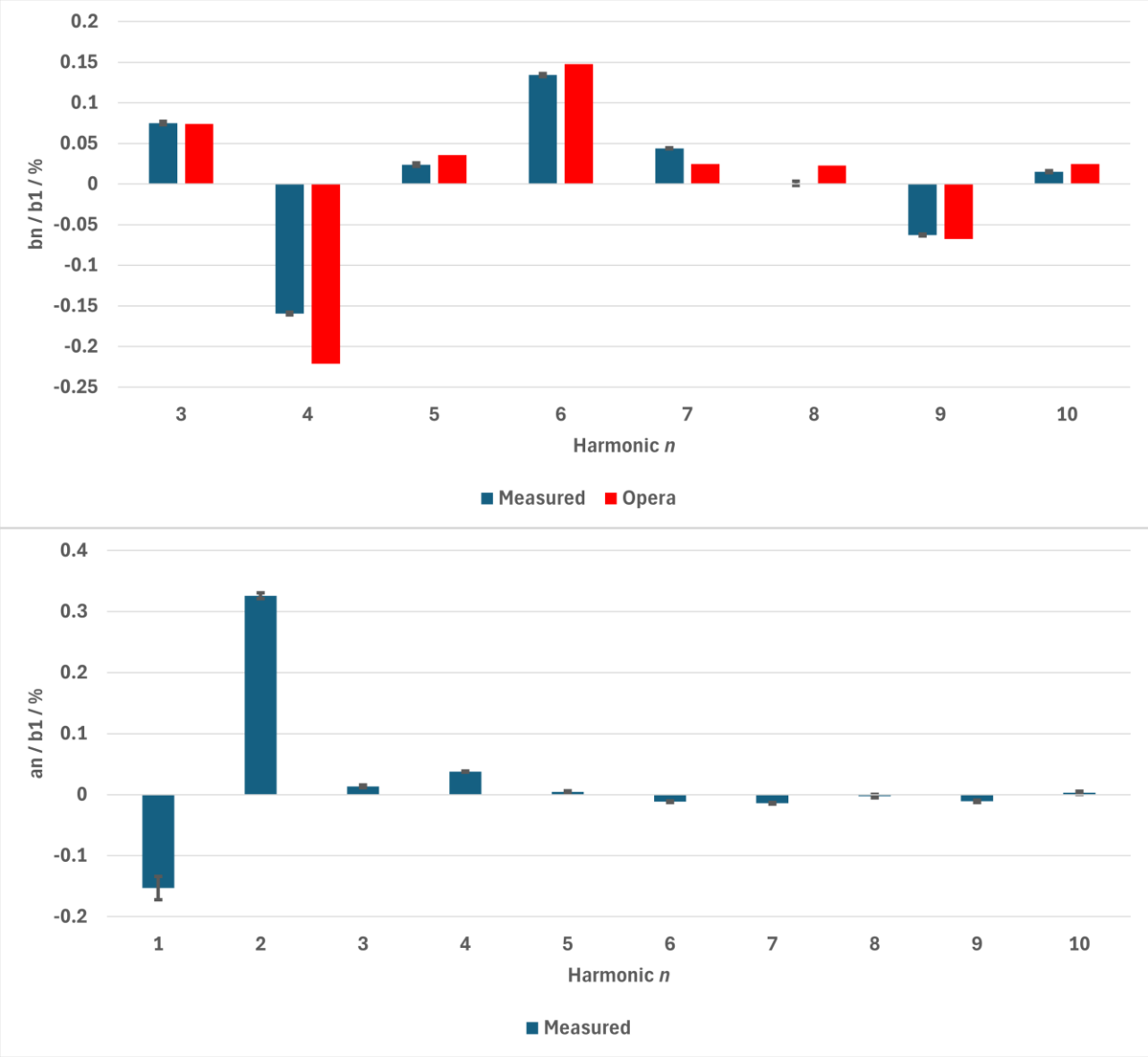
# Magnetic Measurements @ UKRI

SENIS Type H Hall probe

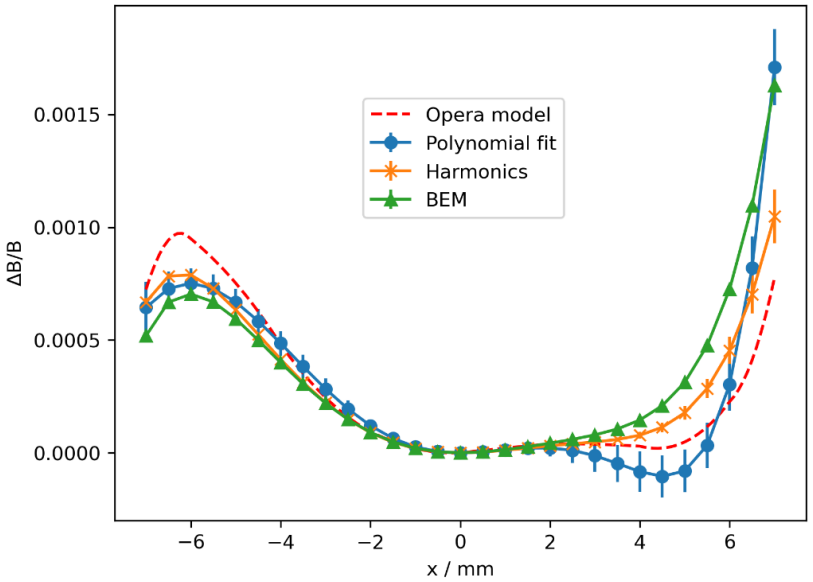
Dedicated magnet lab
at STFC Daresbury Laboratory

iFAST

# 2D Fields

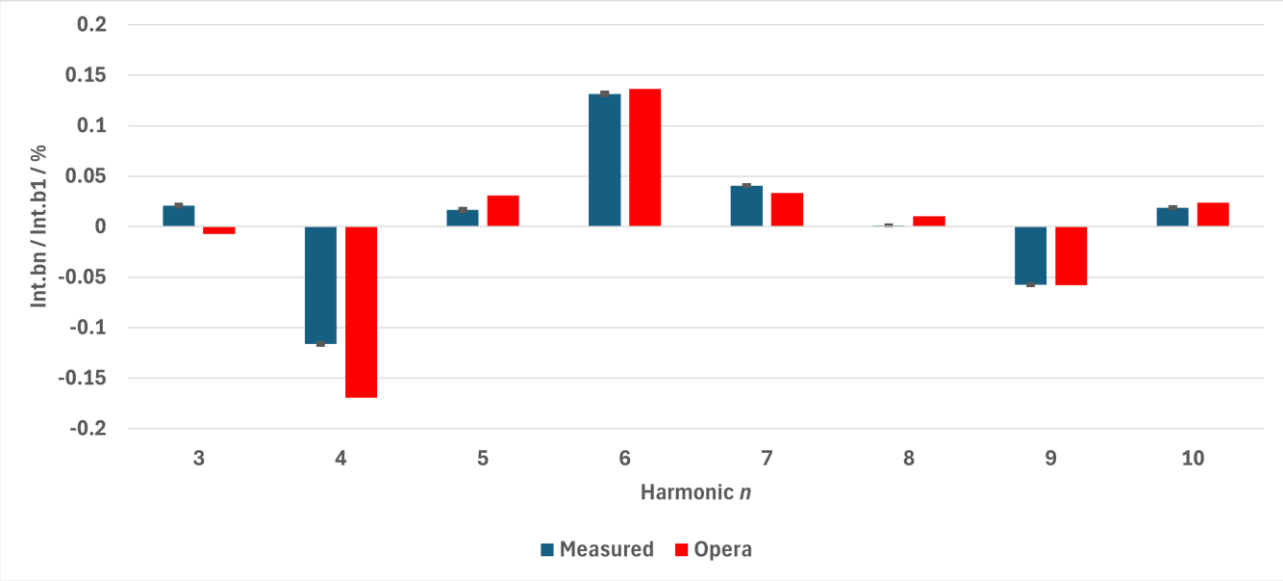


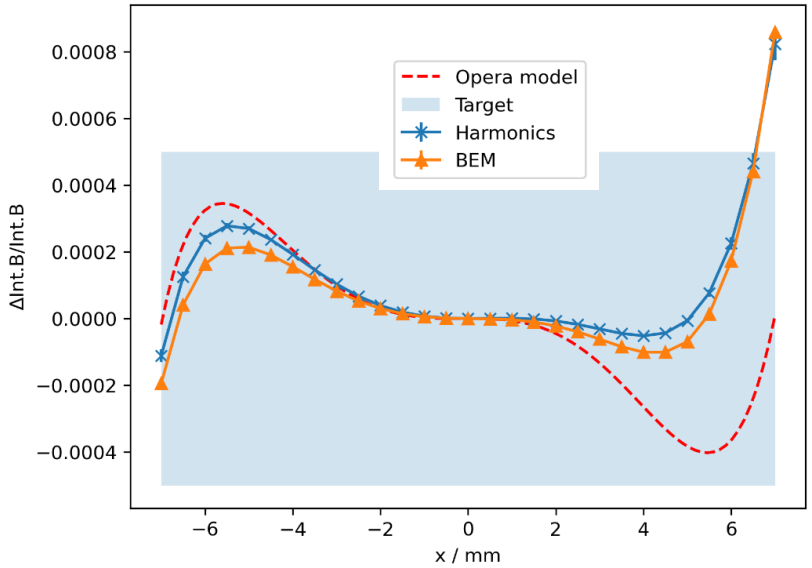

| Analysis | Gradient [T/m] | Maximum ΔB/B [$10^{-3}$] |
|---|---|---|
| Opera model | 33.1791 | 1 |
| Polynomial fit | 32.972 ± 0.004 | 1.7 ± 0.2 |
| Harmonic analysis | 32.901 ± 0.005 | 1.0 ± 0.1 |
| Boundary element method | 32.985 ± 0.002 | 1.60 ± 0.02 |

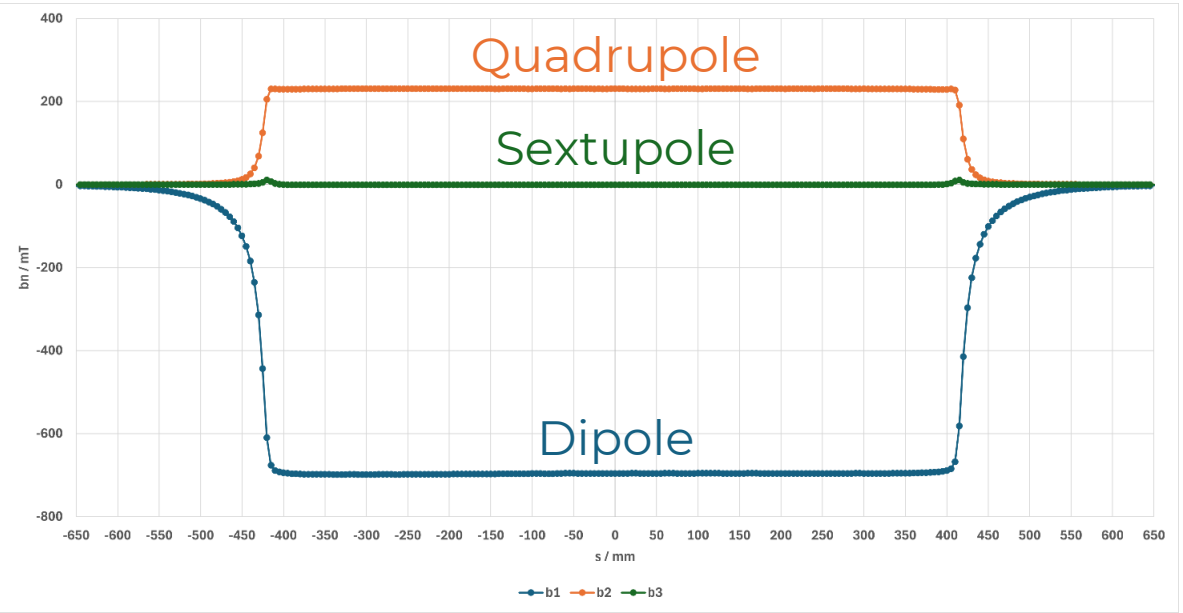



Facilities Council

# Integrated Fields



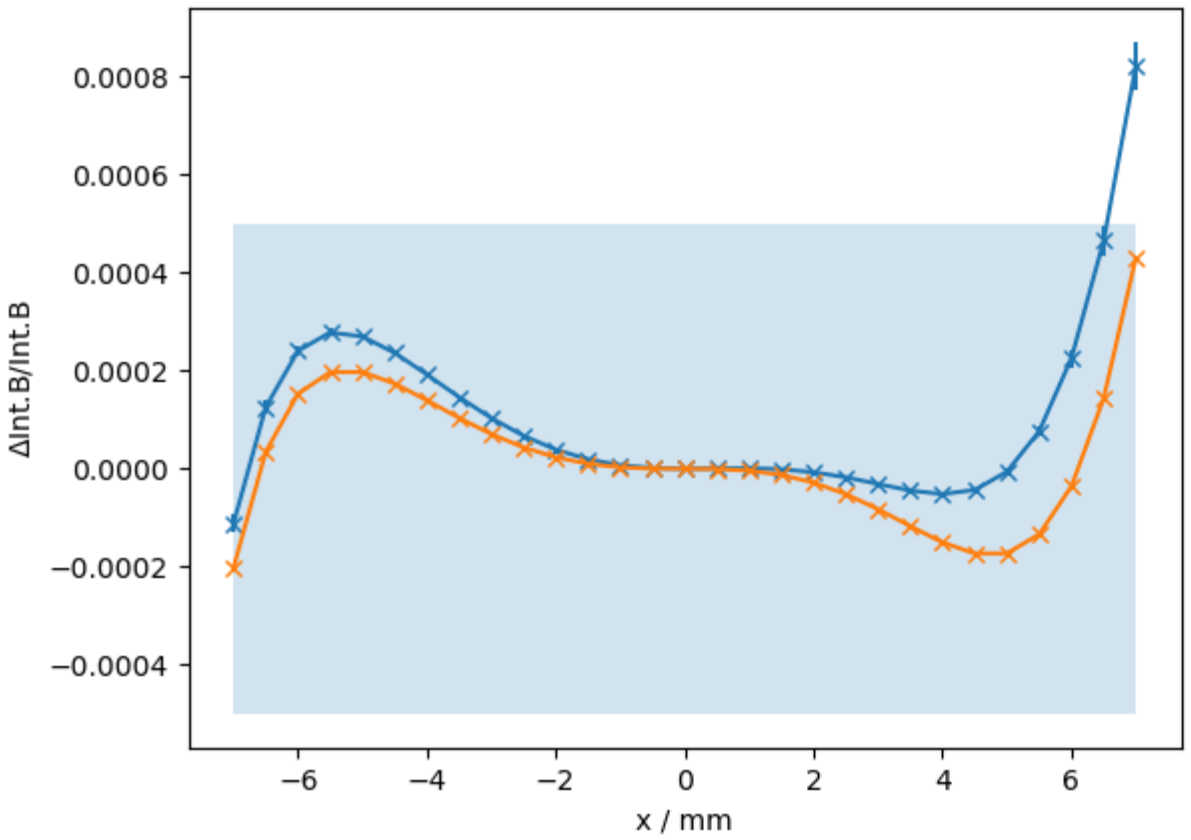



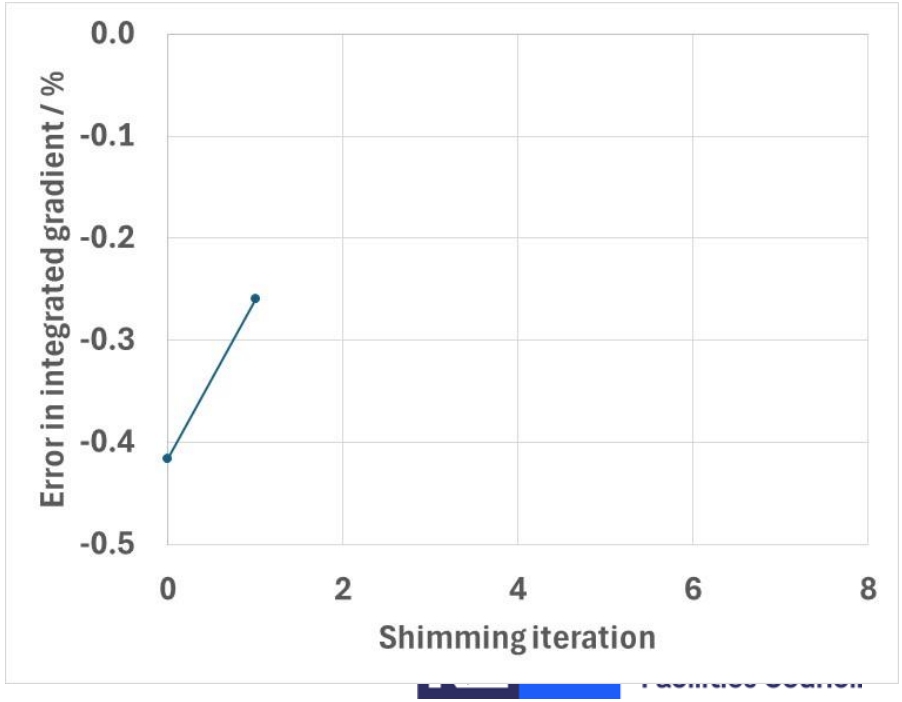

| | Integrated gradient [T] | Dipole magnetic length [m] | Quadrupole magnetic length [m] | Integrated ΔB/B [$10^{-4}$] |
|---|---|---|---|---|
| Opera model | 28.1857 | 0.870 | 0.850 | 5 |
| Harmonic analysis | 28.070 ± 0.002 | 0.8726 ± 0.0001 | 0.8524 ± 0.0001 | 8.2 ± 0.5 |
| Boundary element method | 28.096 | 0.8726 | 0.8515 | 8.6 |

Technology Facilities Council

# Shimming 1

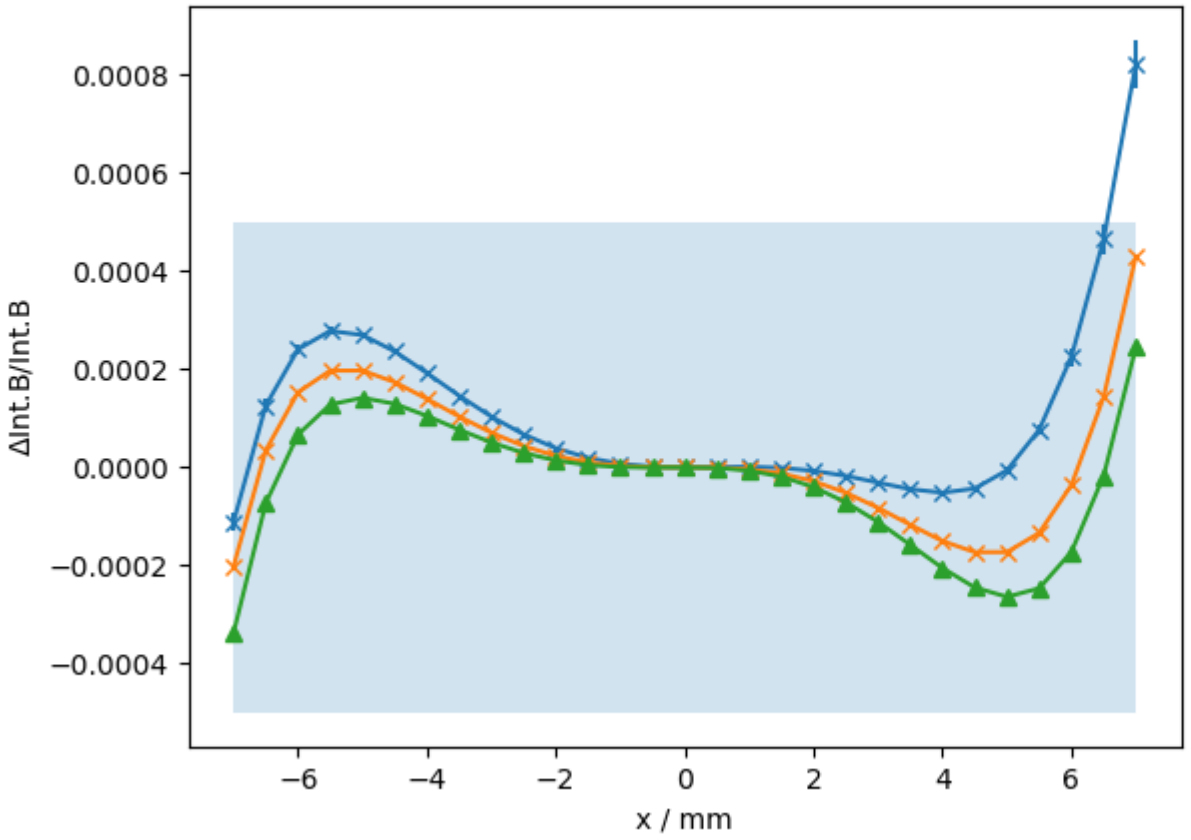
Auxiliary top pole height reduced
(increase shim thickness)

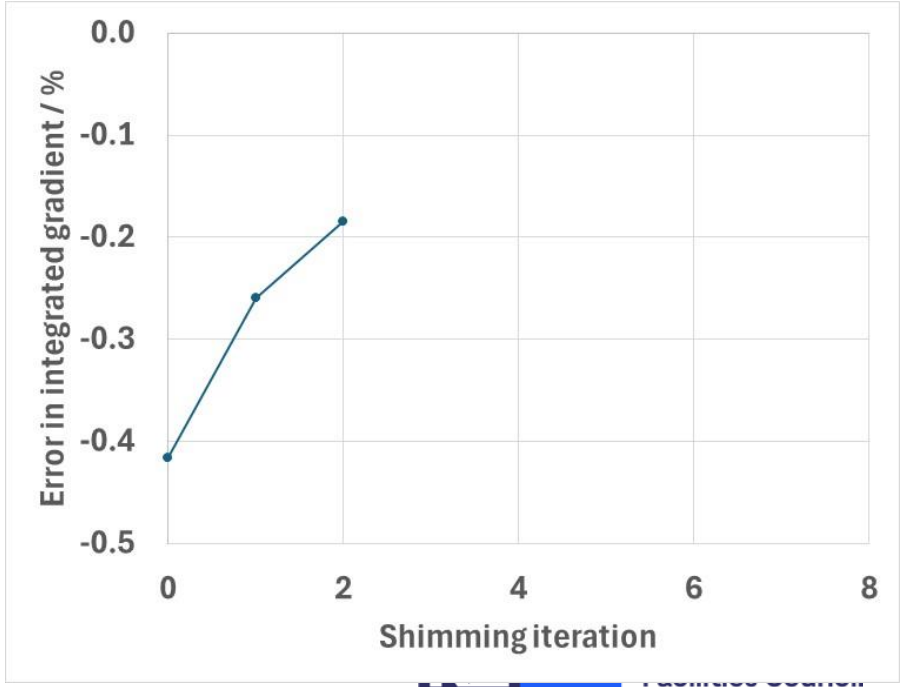


# Shimming 2

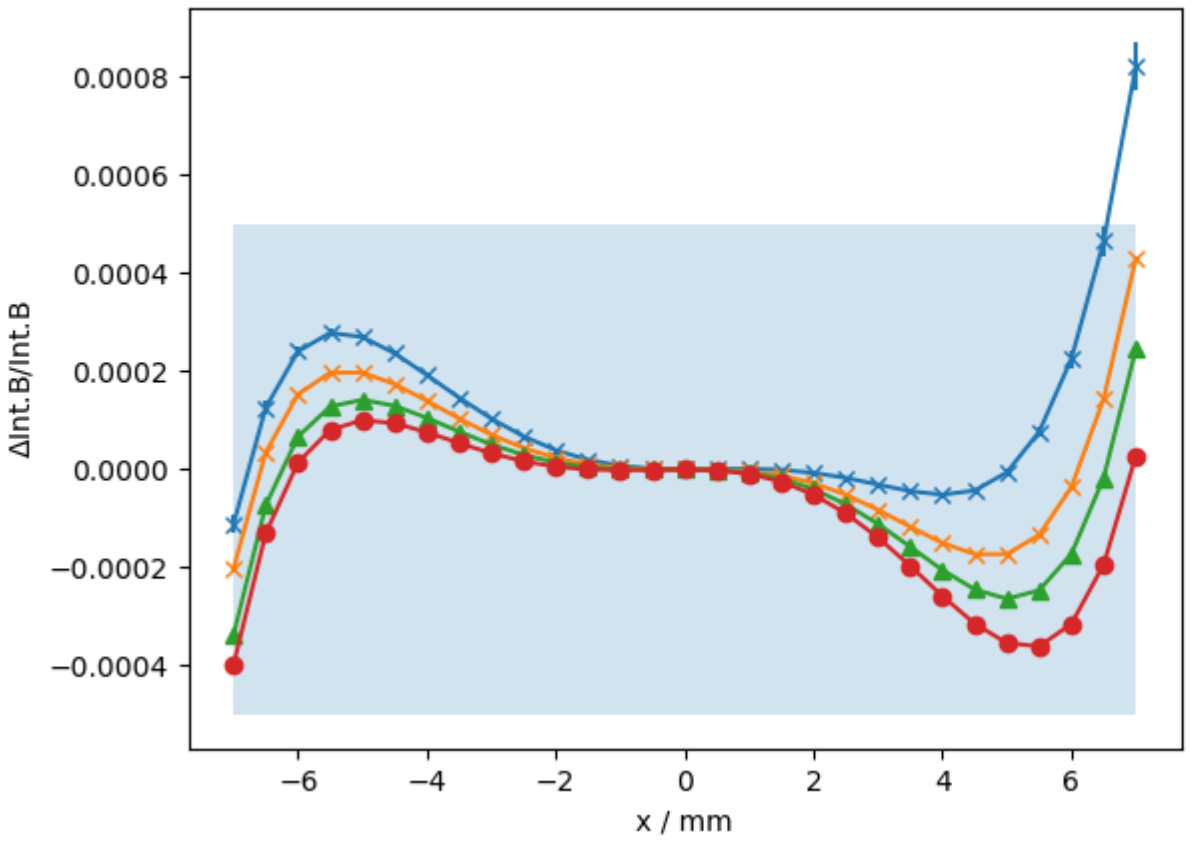
Auxiliary top pole height reduced
(increase shim thickness)

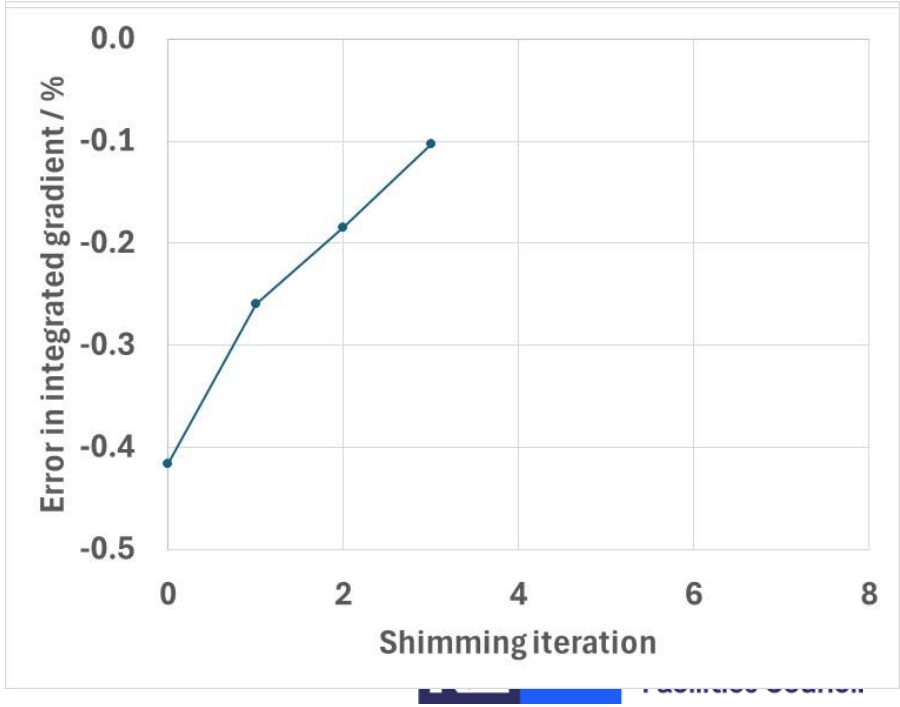


# Shimming 3

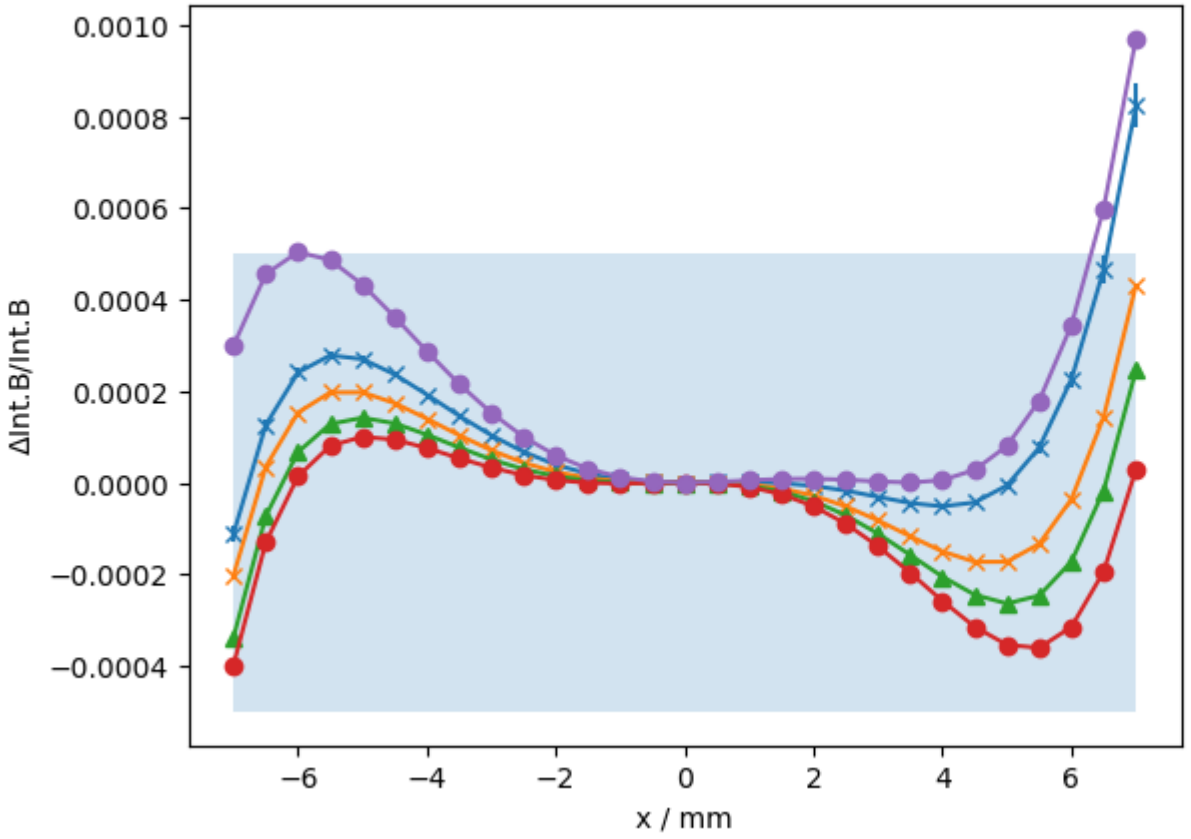
Auxiliary top pole height reduced
(increase shim thickness)

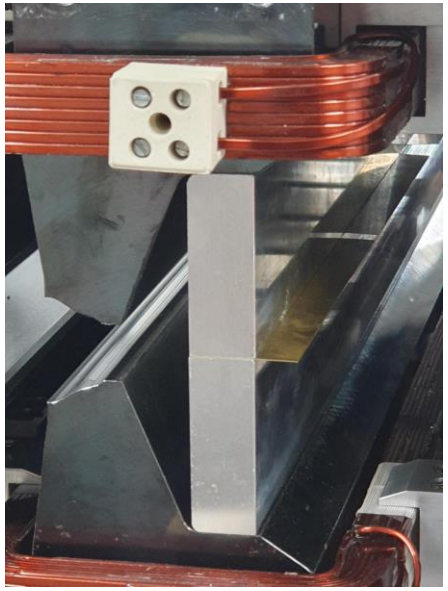


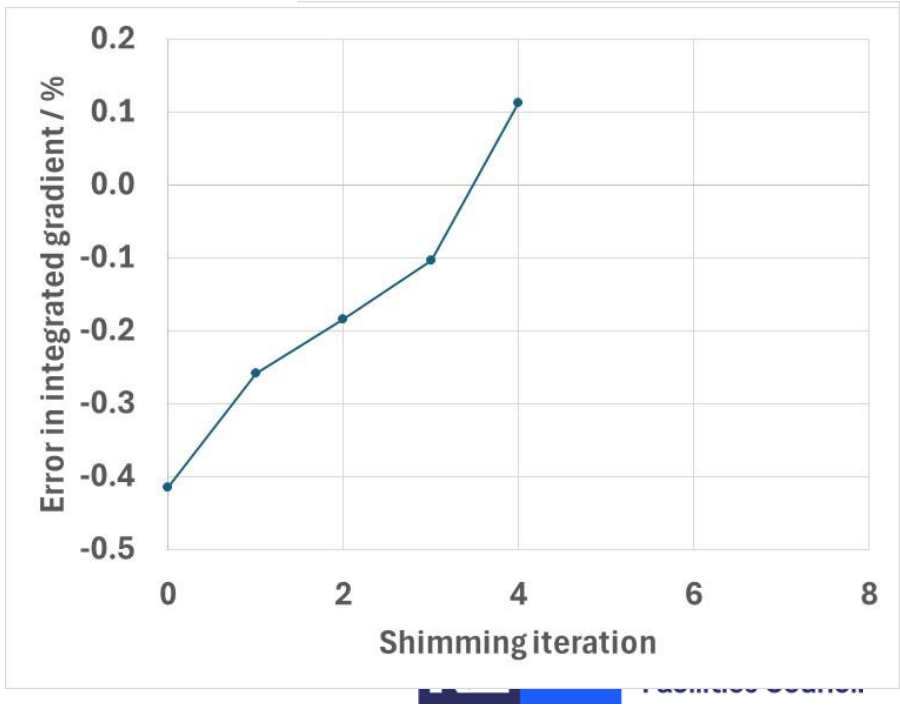



# Shimming 4

Reduce main pole shim:
increase gradient and ΔB/B

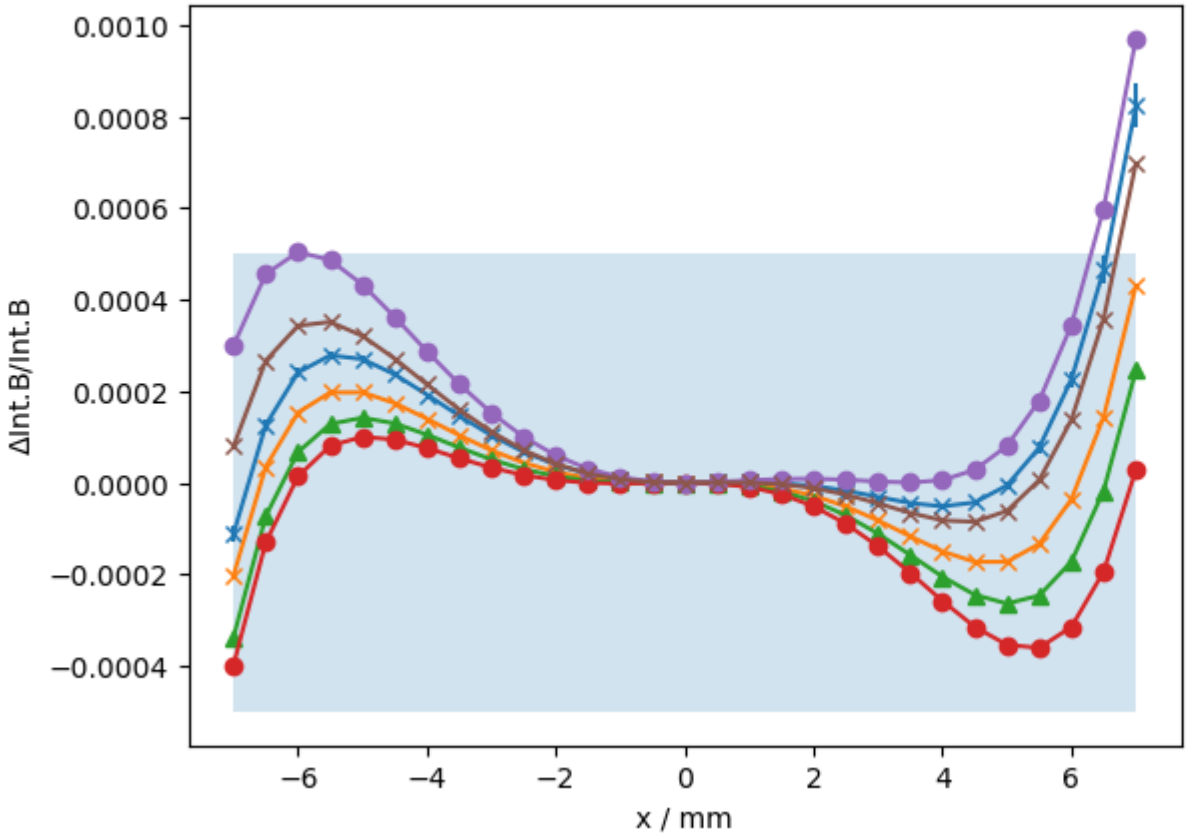


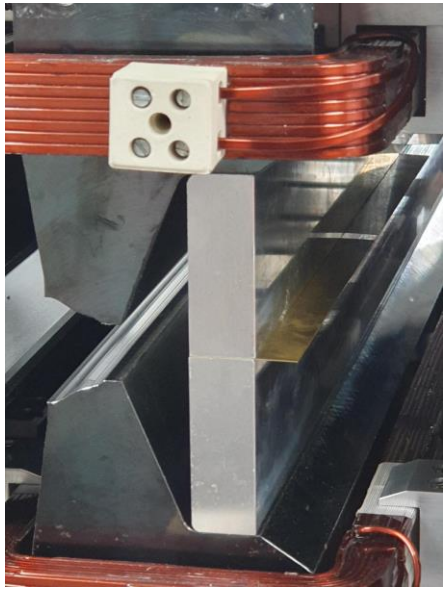


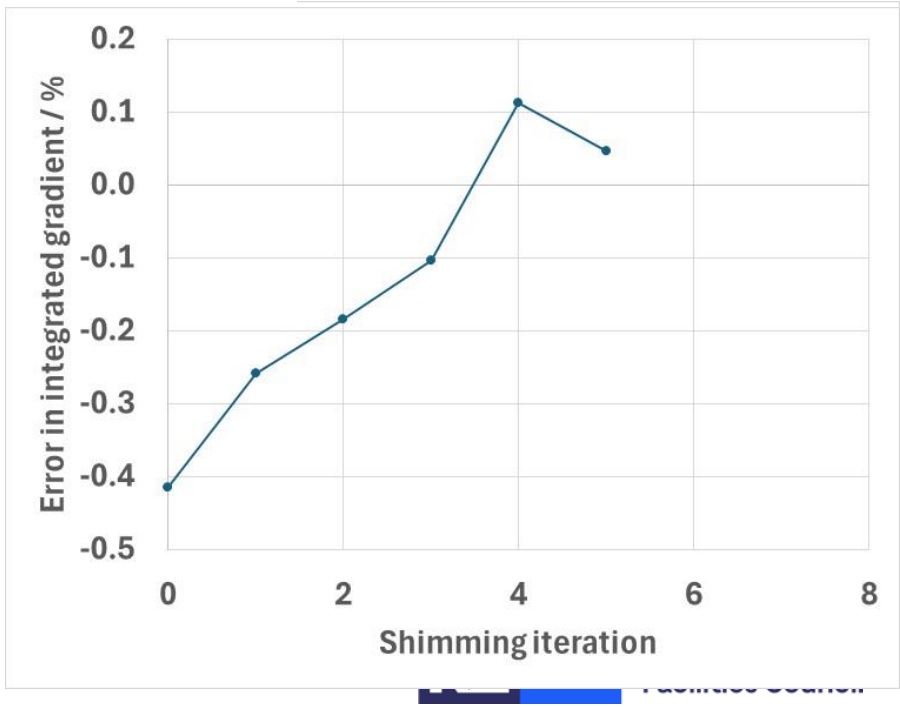


# Shimming 5

Increase main pole shim:
reduce gradient and ΔB/B

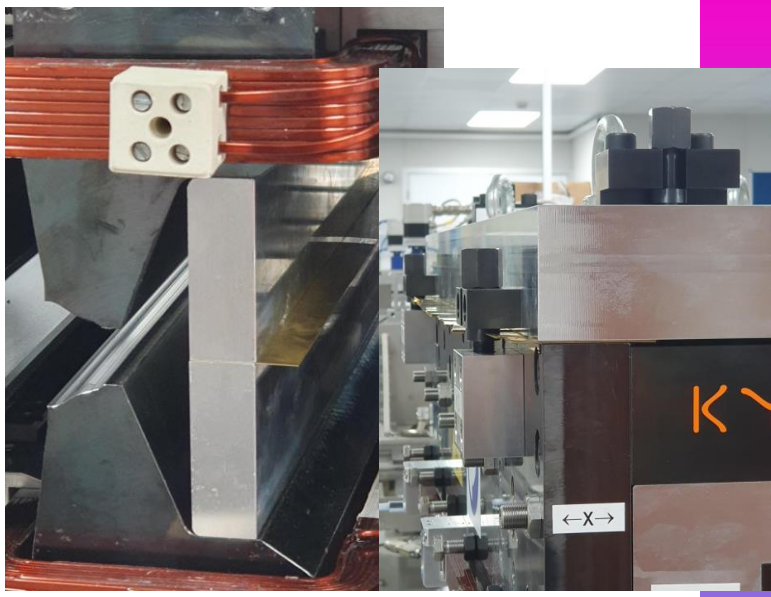


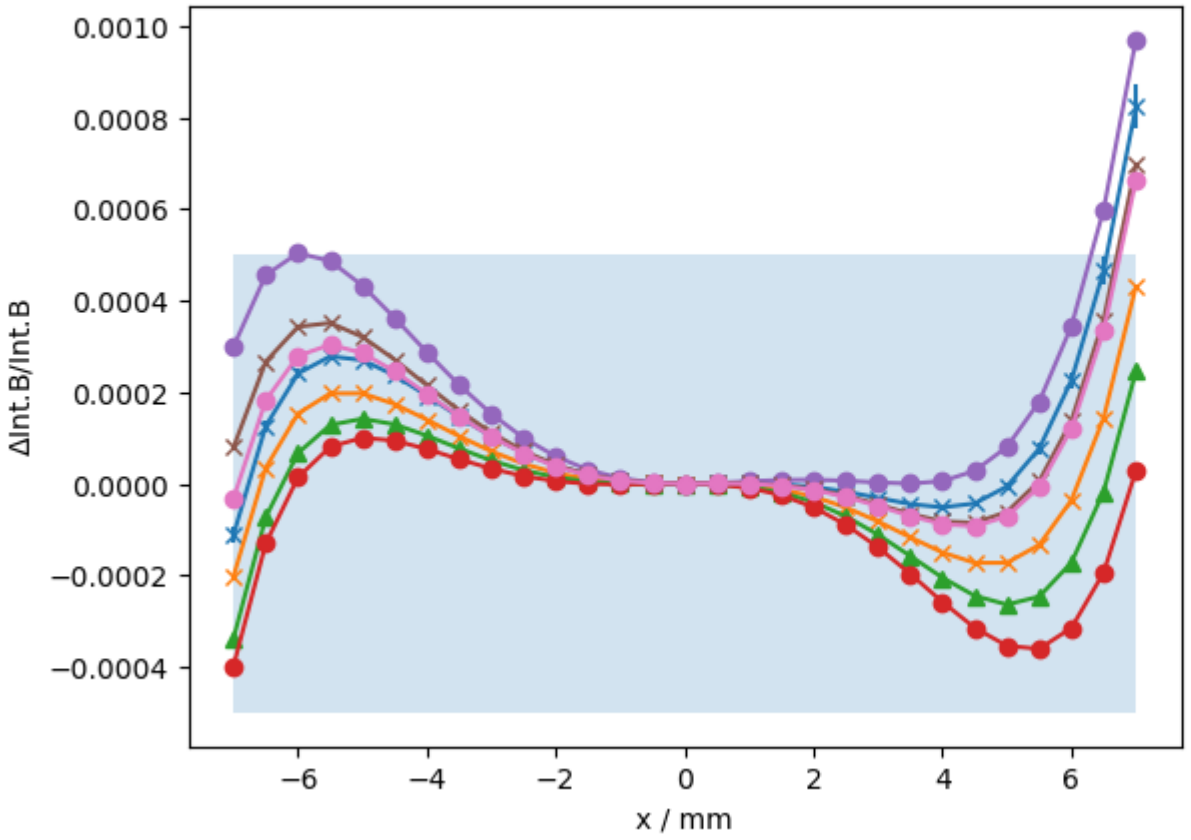


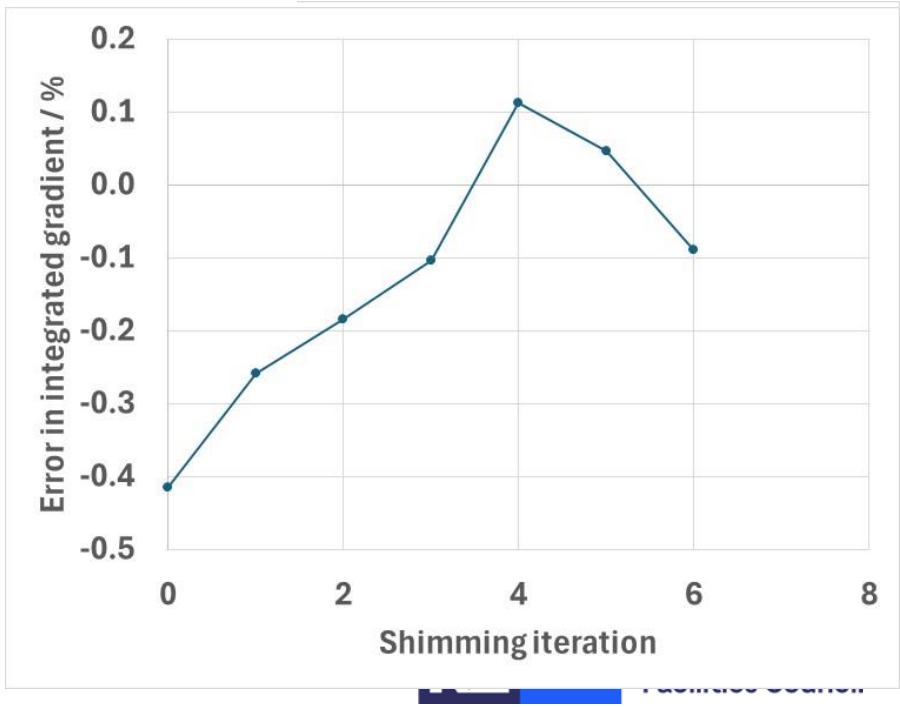


# Shimming 6

Increase main pole shim
and auxiliary top pole shim

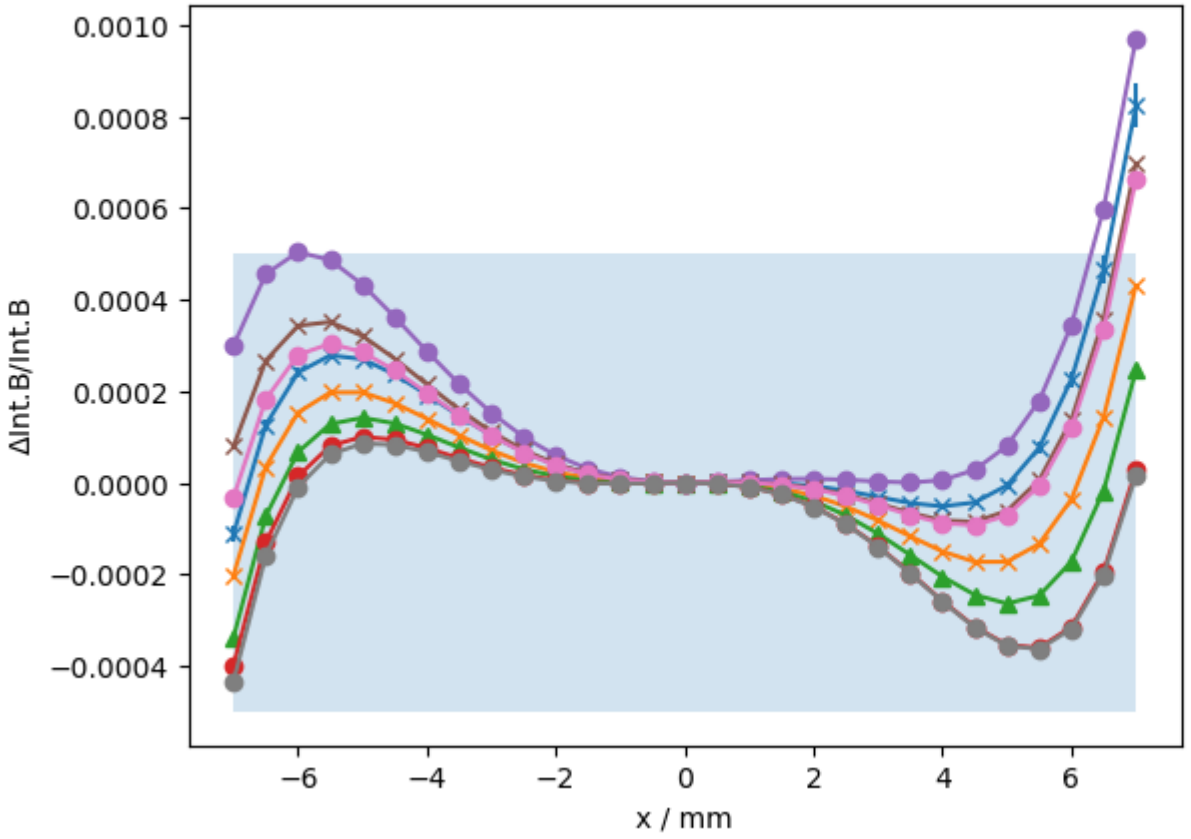


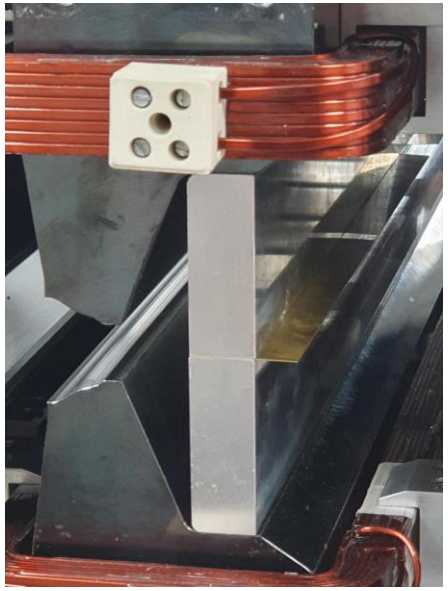


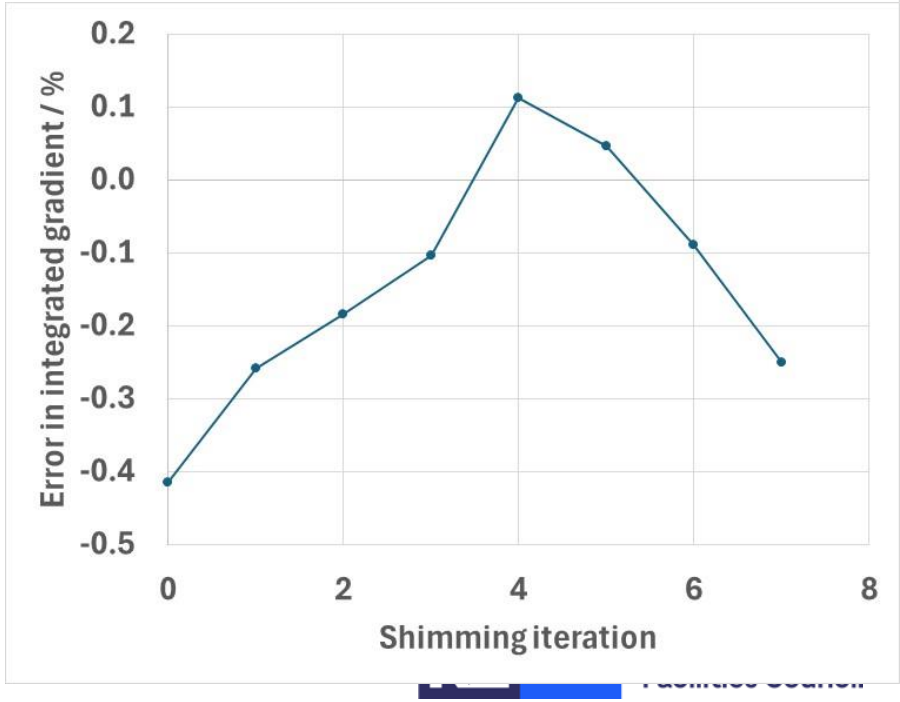



Increase main pole shim

# Shimming 7

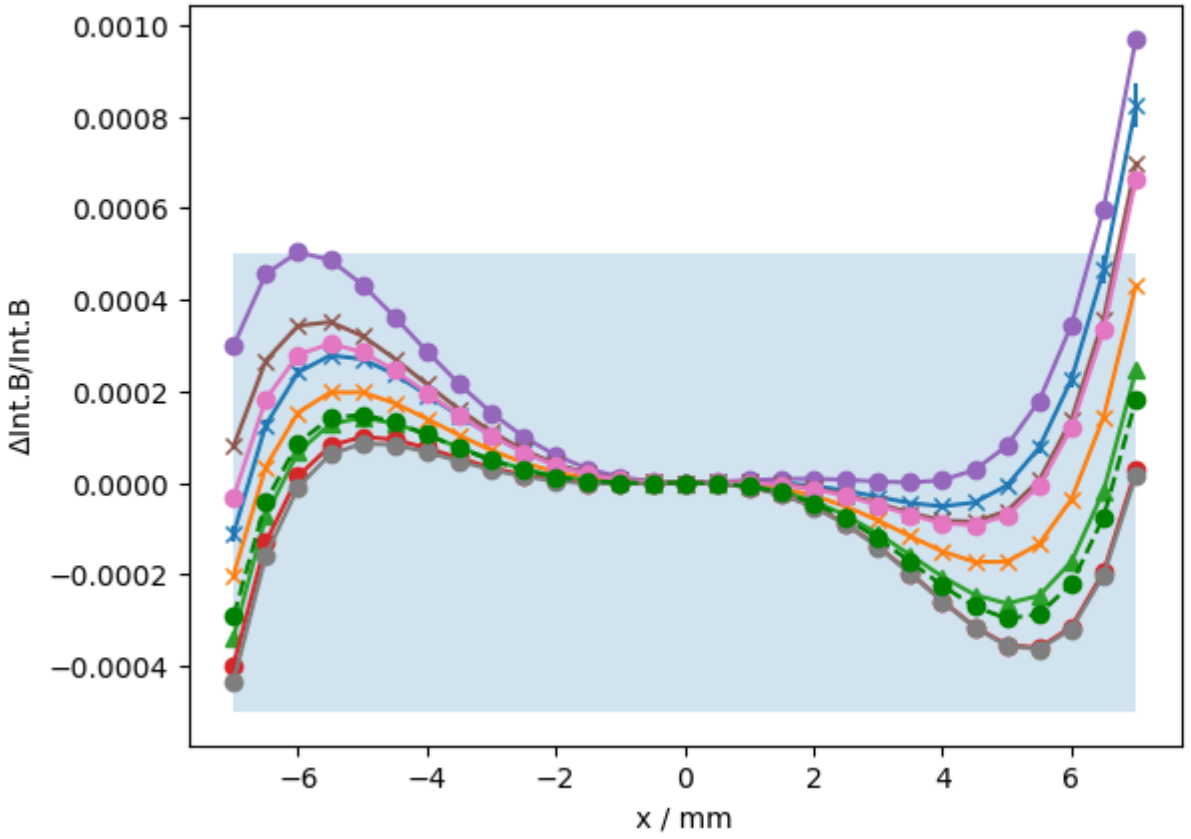


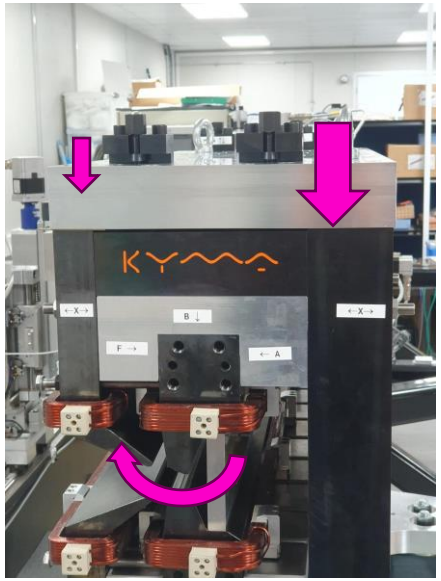


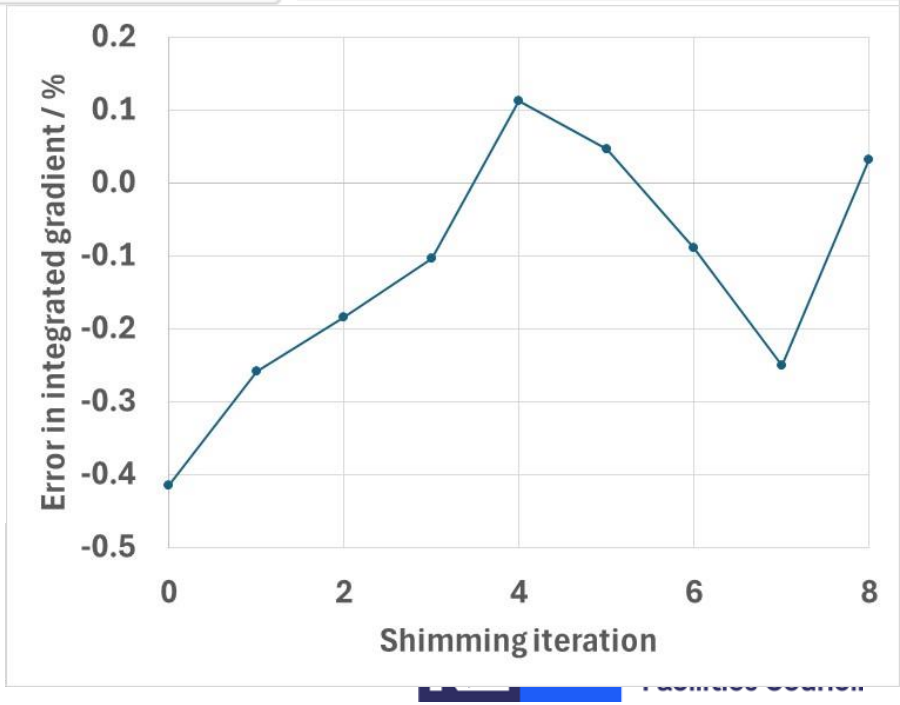


# Shimming 8

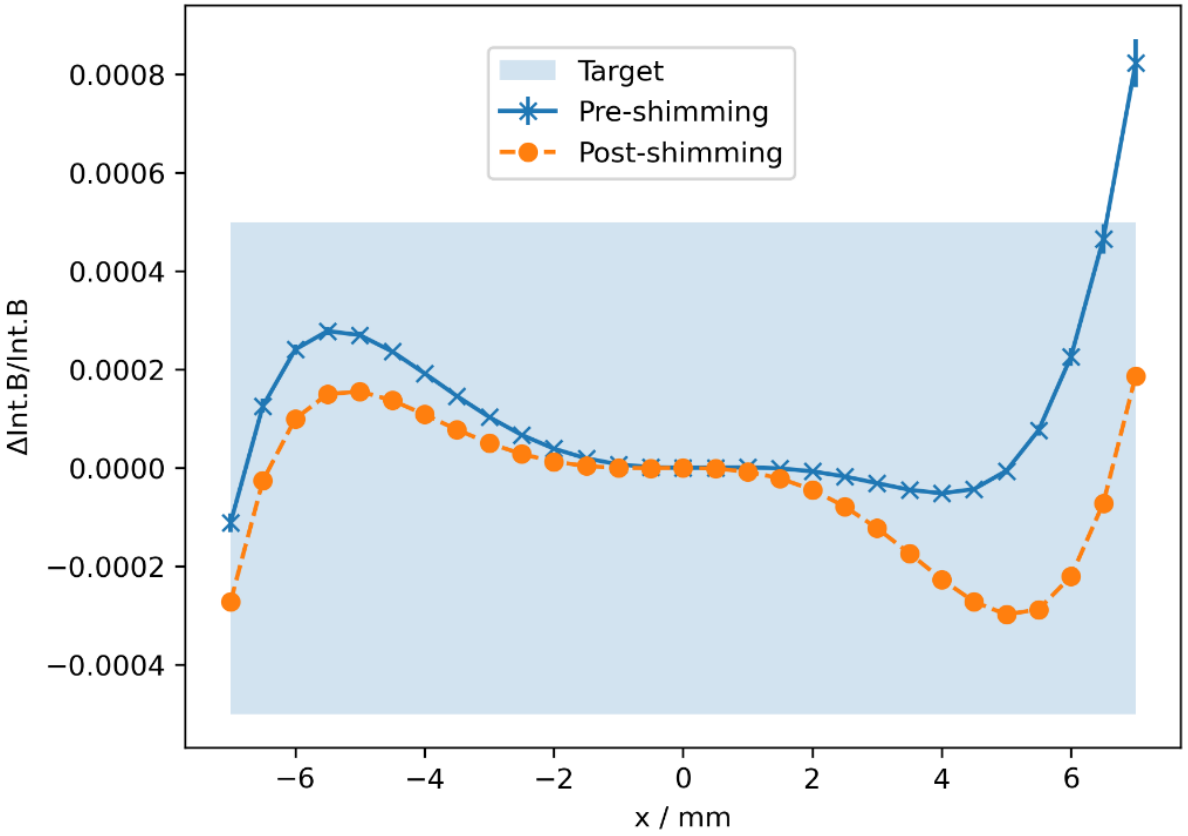
Reduce main pole shim
and rotate main pole

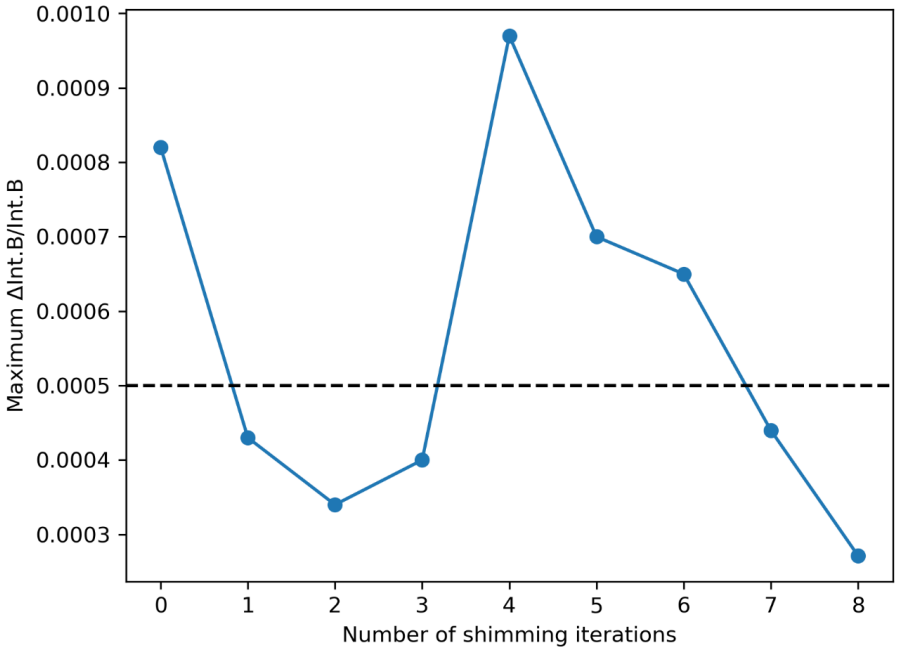


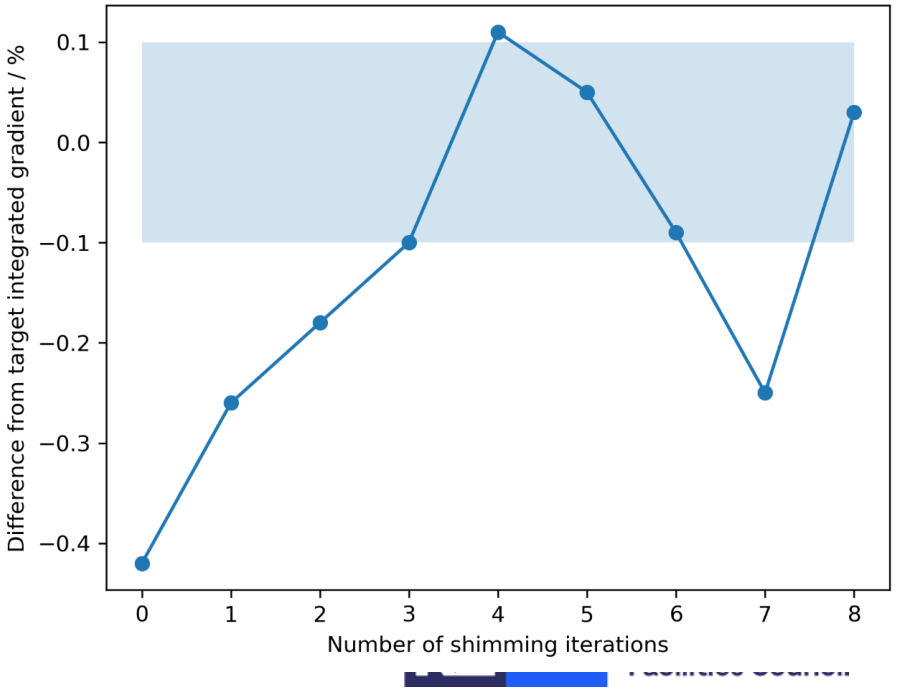




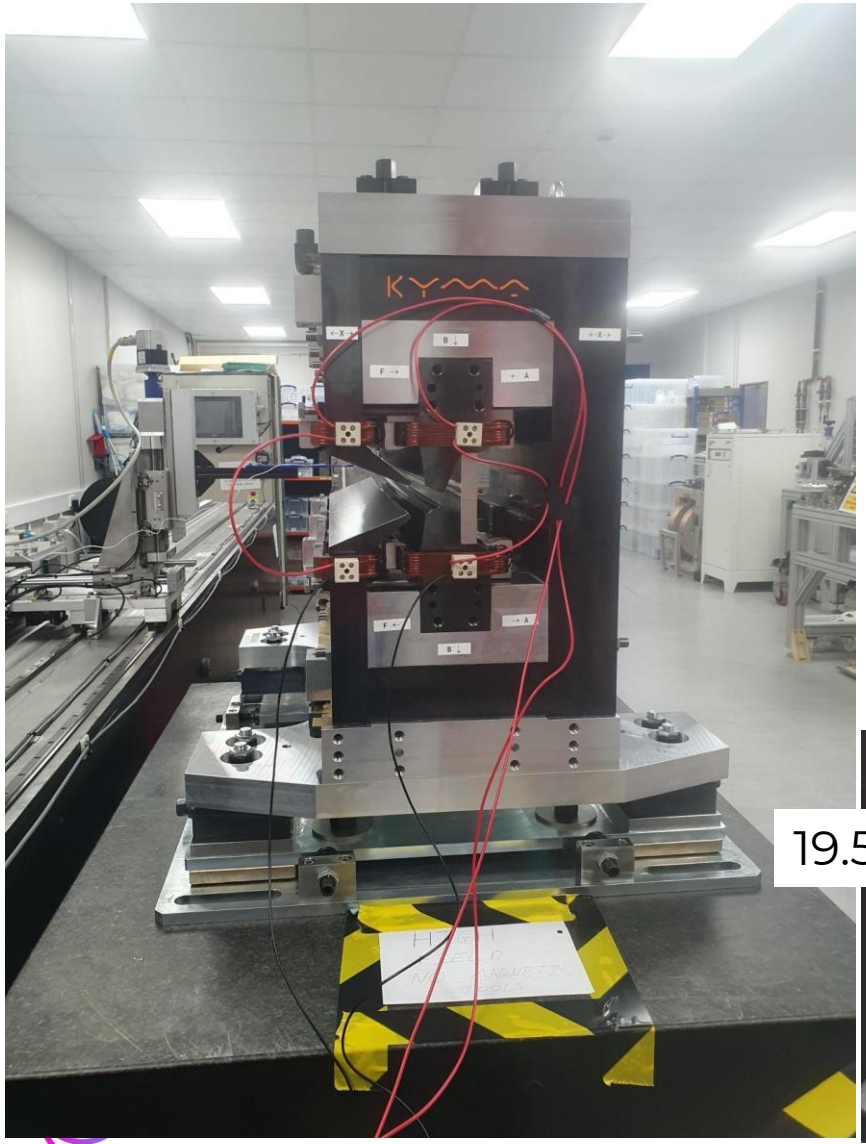
# Shimming: final results



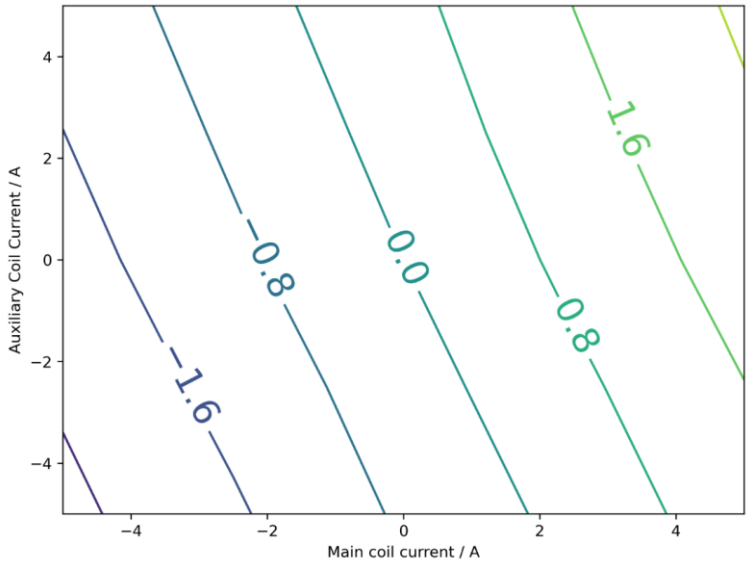



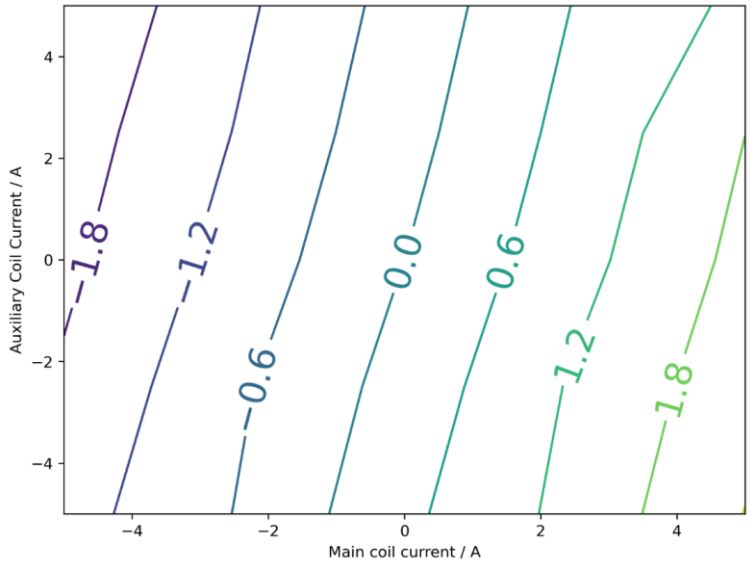
# Trim coils



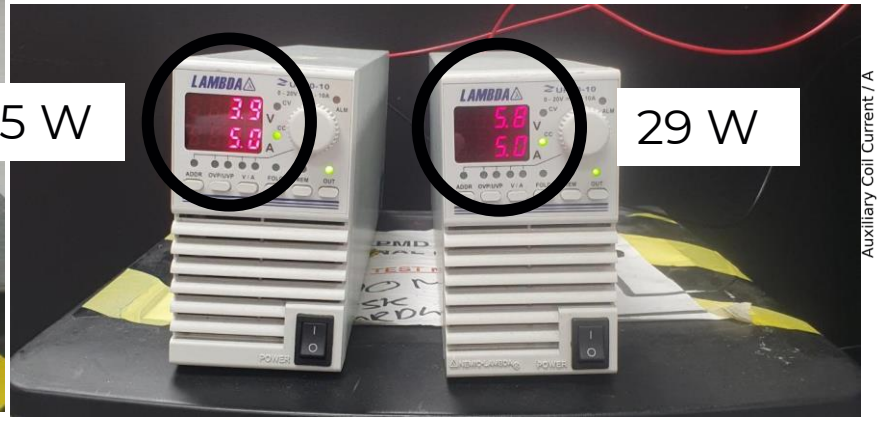
Change in dipole [%]



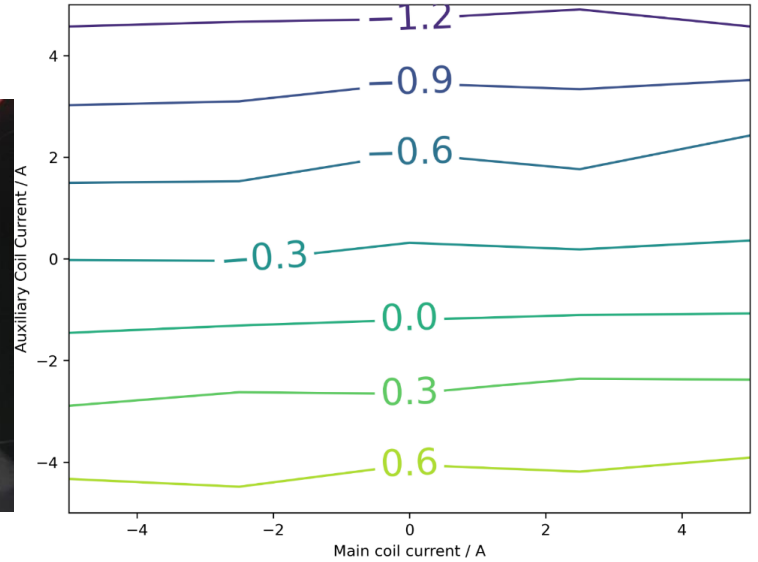

Change in quadrupole [%]




Target = independent tuning of dipole and quadrupole by **±2.5 %**

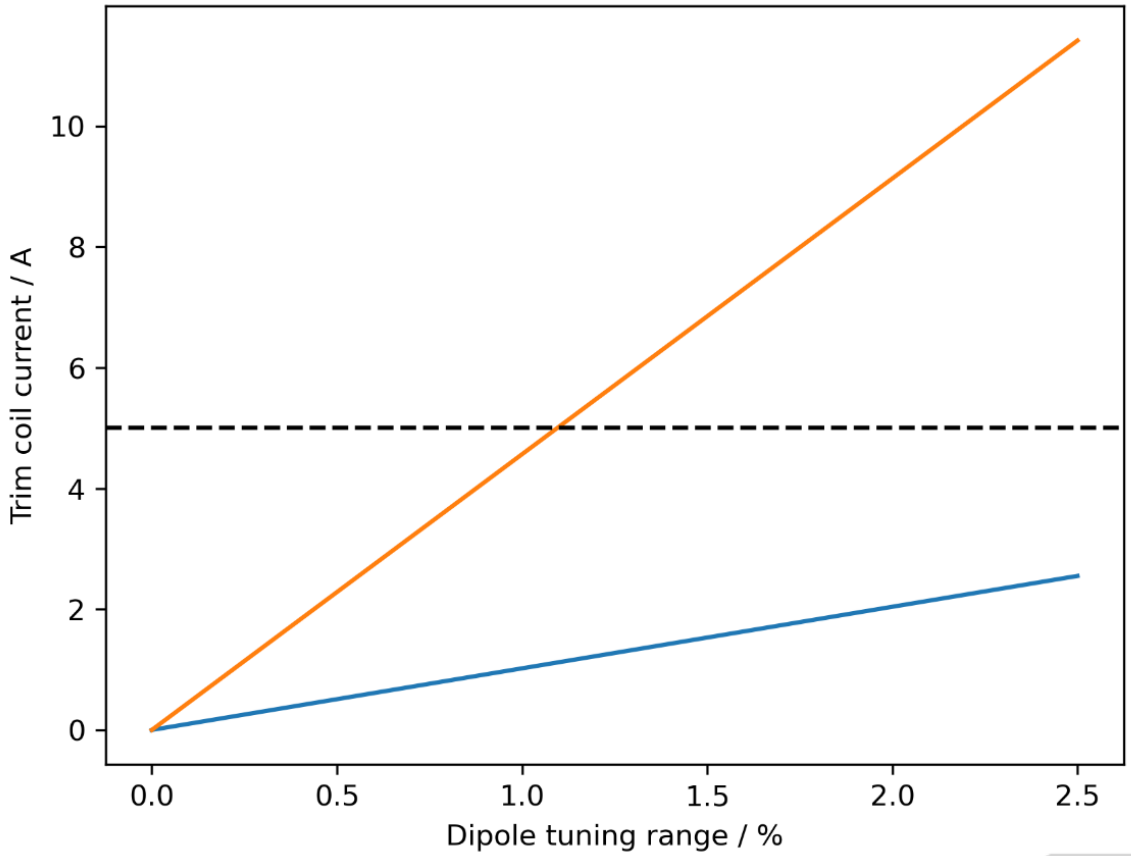


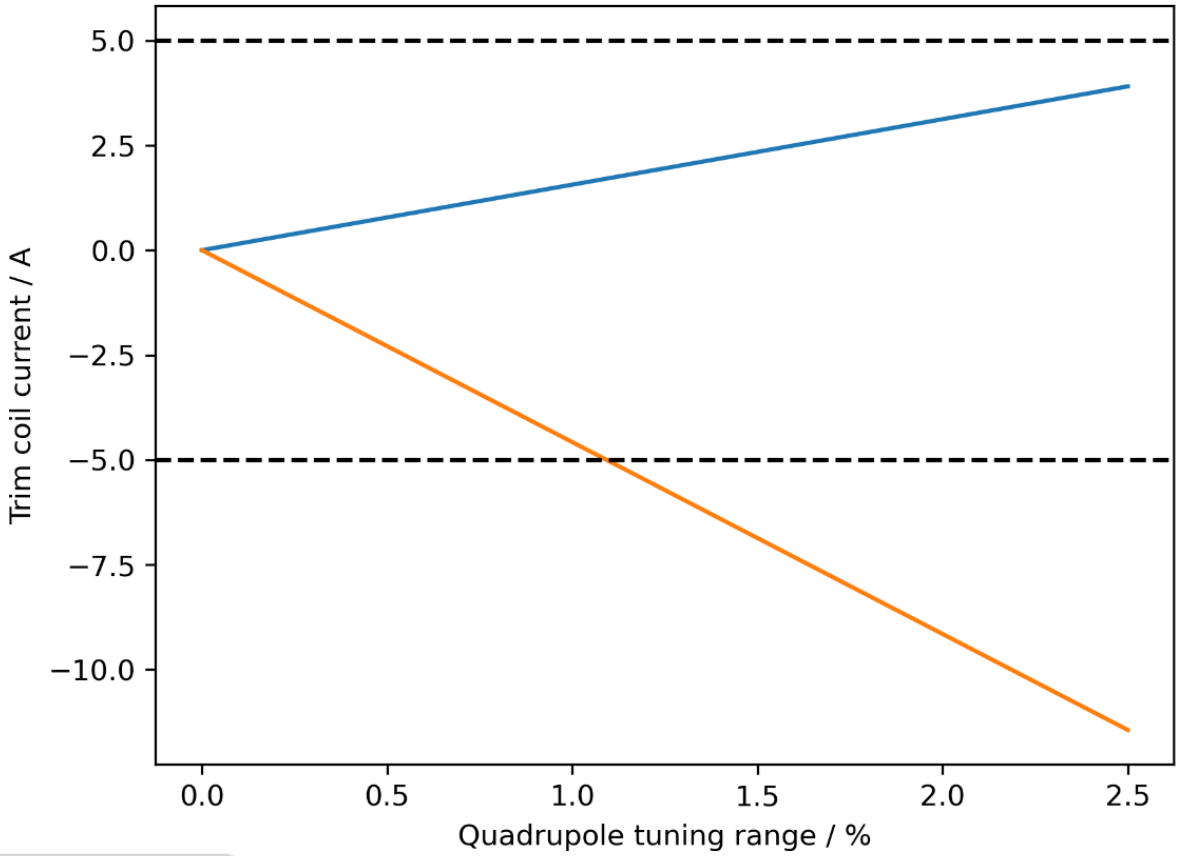

Change in sextupole coefficient [mT]

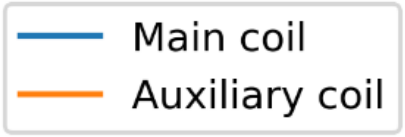


# Tuning Range

Independent tuning of up to **1.1%**
in dipole and quadrupole fields
using up to **5 A** peak current in coils



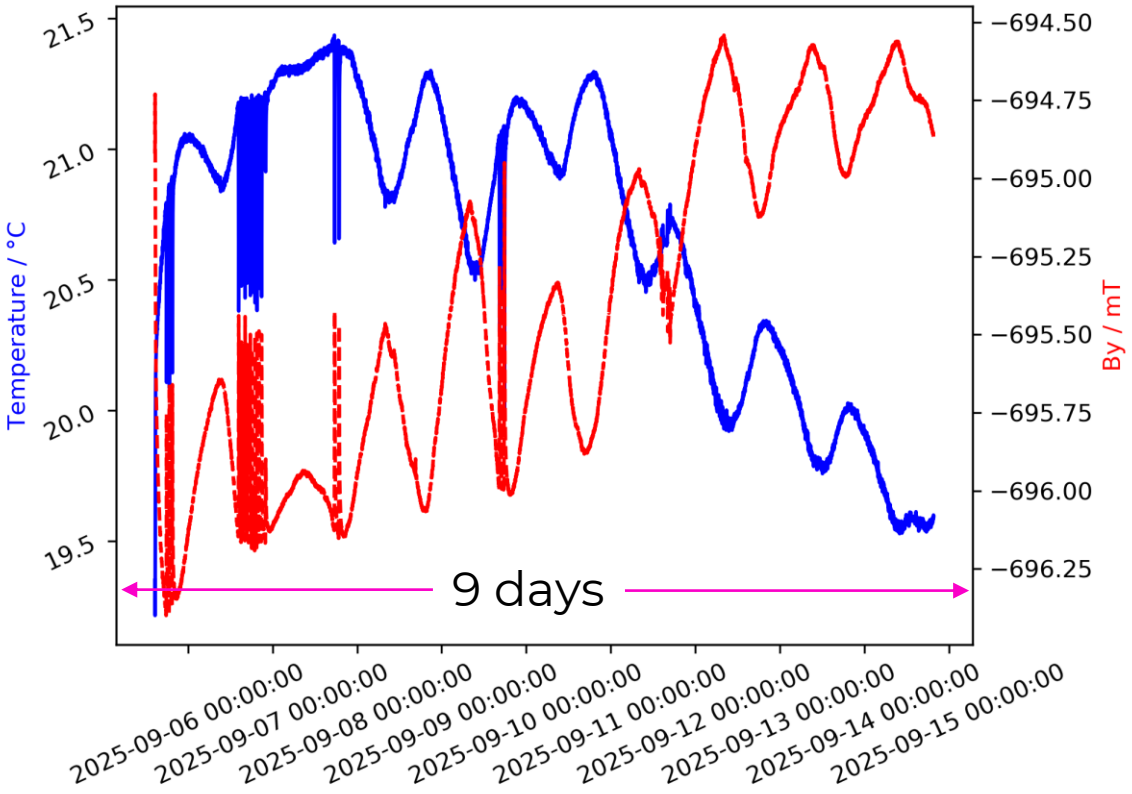



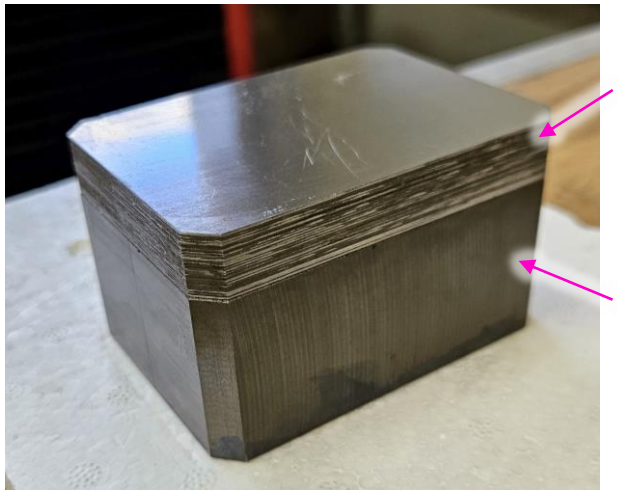

iFAST

UKRI Science and Technology Facilities Council

# Thermal Stability



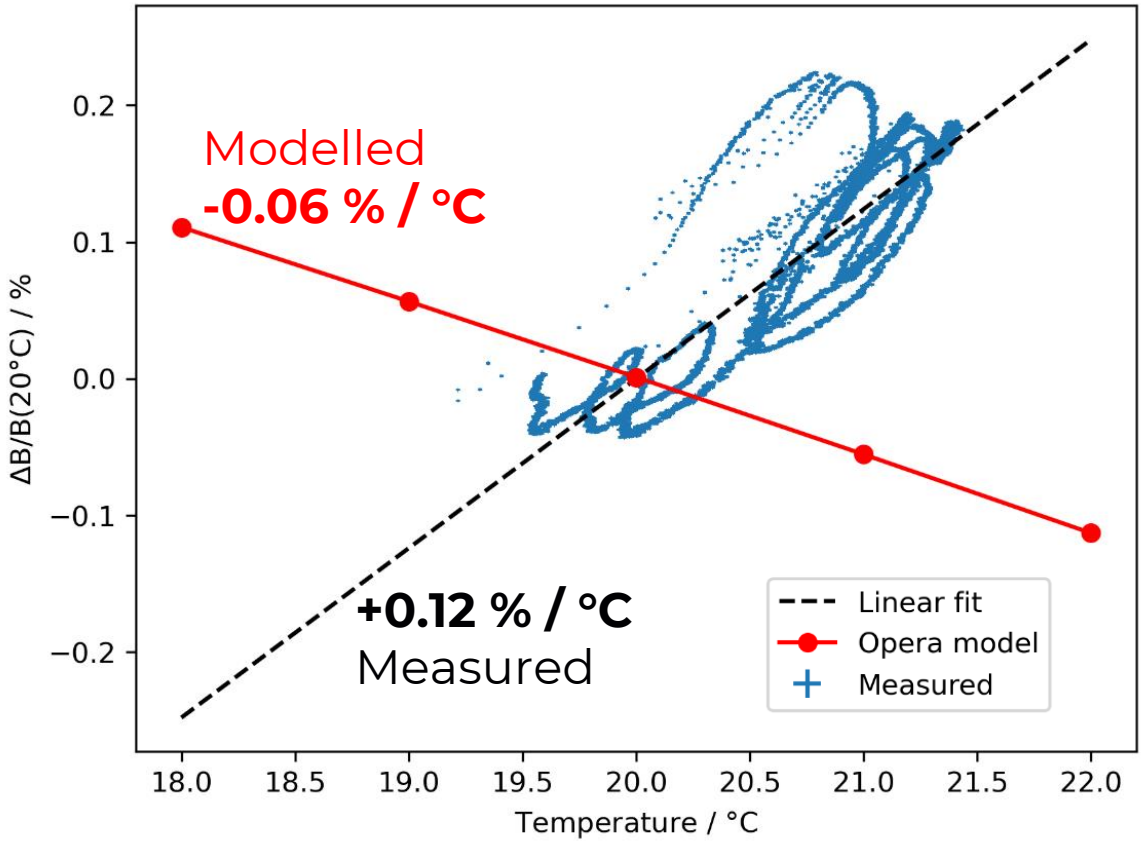

Hall probe kept in centre of magnet
Measure vertical field and temperature



Thermal shunts

PM block

Without shunts, expect **-0.21%/°C**



# Summary of results

| Parameter | Specified | Measured | Unit | Achieved? | Comments |
|---|---|---|---|---|---|
| Central dipole field | -0.6951 | -0.6951 | T | ✓ | |
| Central gradient | 33.179 | 33.083 | T/m | ✓ | |
| Effective dipole magnetic length | 870 | 873 | mm | ✓ | |
| Effective gradient magnetic length | 850 | 852 | mm | ✓ | |
| Integrated dipole field | -0.6047 | -0.6066 | T.m | ✓ | |
| Integrated gradient | 28.1857 | 28.196 | T | ✓ | |
| Bending radius | 16.795 | | m | | |
| Good field region (GFR) radius | 7 | | mm | | |
| Integrated field quality ΔB/B within GFR | $5 \times 10^{-4}$ | $2.7 \times 10^{-4}$ | | ✓ | |
| Integrated multipoles | $< 10^{-3}$ | $1.8 \times 10^{-4}$ | | ✓ | |
| Dipole tuning range | ± 2.5 | ± 1.1 | % | ✗ | Probable modelling error; possible to fit extra coils |
| Gradient tuning range | ± 2.5 | ± 1.1 | % | ✗ | |
| Temperature stability (3°C range) | 0.01 | 0.173 | % | ✗ | Discrepancy in thermal shunt B-H curve? |

# WP11.3: results

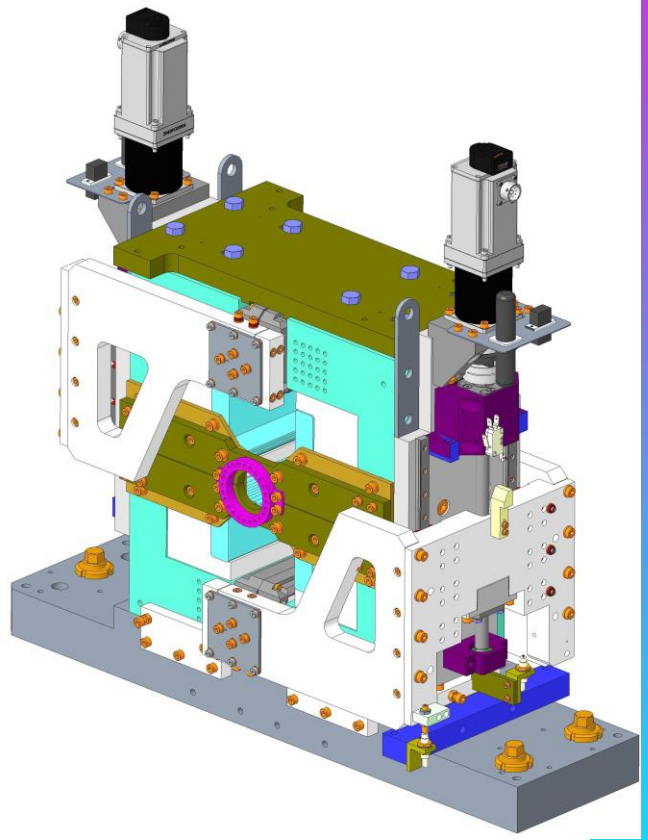
- We have produced a **light-source ready** DQ prototype design
- Our design fulfils the specifications, with almost zero power usage compared to the standard EM version
- Minor issues: **temperature compensation** and **tuning coils** (easily addressed through modelling / testing)
- TRL at start of project: **2 – Technology concept formulated**
- TRL at end of project: **4 – Technology validated in lab**

# WP11.3: lessons learned

- Issues with costs of materials (PMs and thermal shunts)
  - Particularly relevant for prototypes with small order quantities
  - Need to be careful and plan budgets more carefully
  - Resolved through donation of spare PMs, and networking with other groups at European RIs to obtain shunt material
  - We were lucky!
- Issues with lack of dedicated resources with our industrial partner
  - Probably unavoidable since they are subject to commercial pressures
  - Resulted in long delays for the project
- Best practice: realistic costing for staff and materials

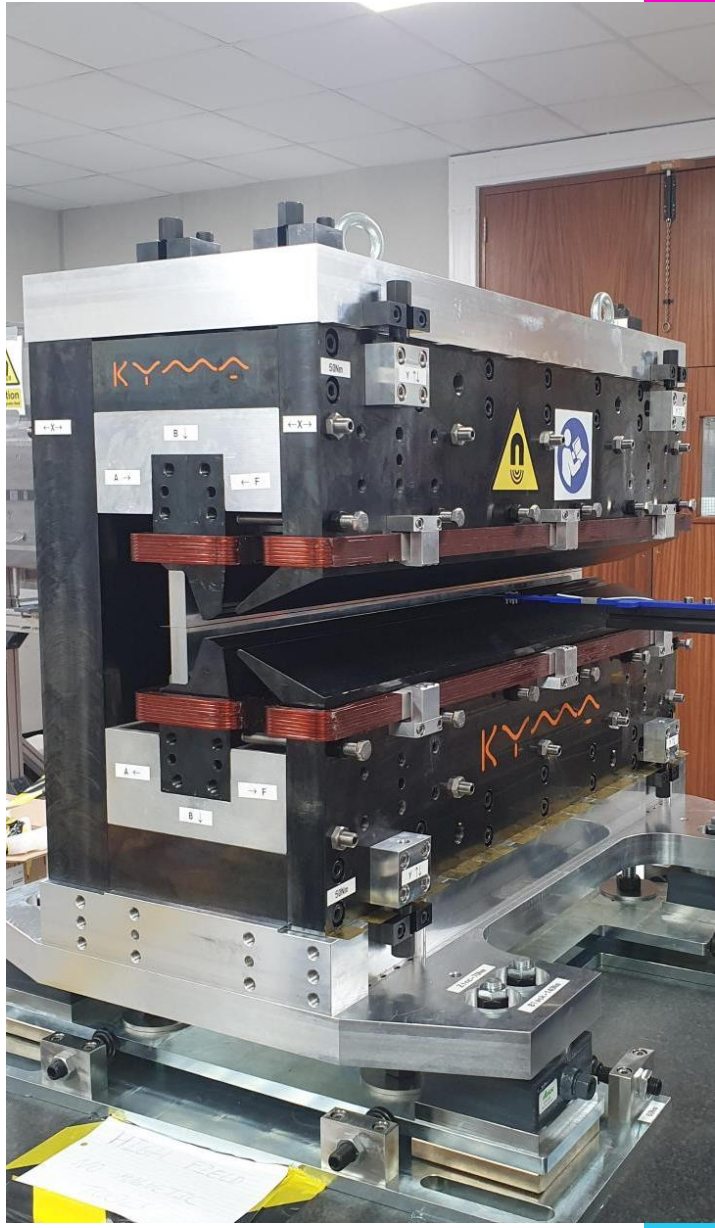
# Next steps

- We now have a working DQ prototype – available for accelerator-based testing
- ASTeC's PM programme continues
  - We are building a ZEPTO device for our CLARA facility: to be completed and installed early 2026
- As part of the EPITA bid: two tasks, aiming to take ZEPTO technology from **TRL 6 → 7**
  1. ZEPTO Performance Review & Accelerator Quadrupole Specification
     - Review progress; analyse costs; two workshops focused on magnet design and feasibility of EM replacement
  2. Modular ZEPTO Product Line Engineering
     - Production of a standardised modular ZEPTO design applicable across a range of accelerator applications



# Conclusions

- I.FAST WP11.3: successful collaboration between **UKRI**, **Diamond**, and **Kyma**
- Built and tested **HEPTO**, PM-based DQ combined-function magnet
- **Near-term outcomes**: continuation of UKRI-Kyma collaboration in EPITA programme
- **Longer-term impacts**: greater understanding and uptake of PM-based technology in accelerators




iFAST

KYMA

diamond

UKRI Science and Technology Facilities Council

iFAST

# Thank you

Acknowledgements:

- Alex Hinton (STFC)
- Dušan Topalović, Jure Počkar, Tadej Milharcic and Mirko Kokole (Kyma)
- Alfie Shahveh (Diamond Light Source)

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.