Results from the HEPTO Combined Function Permanent Magnet

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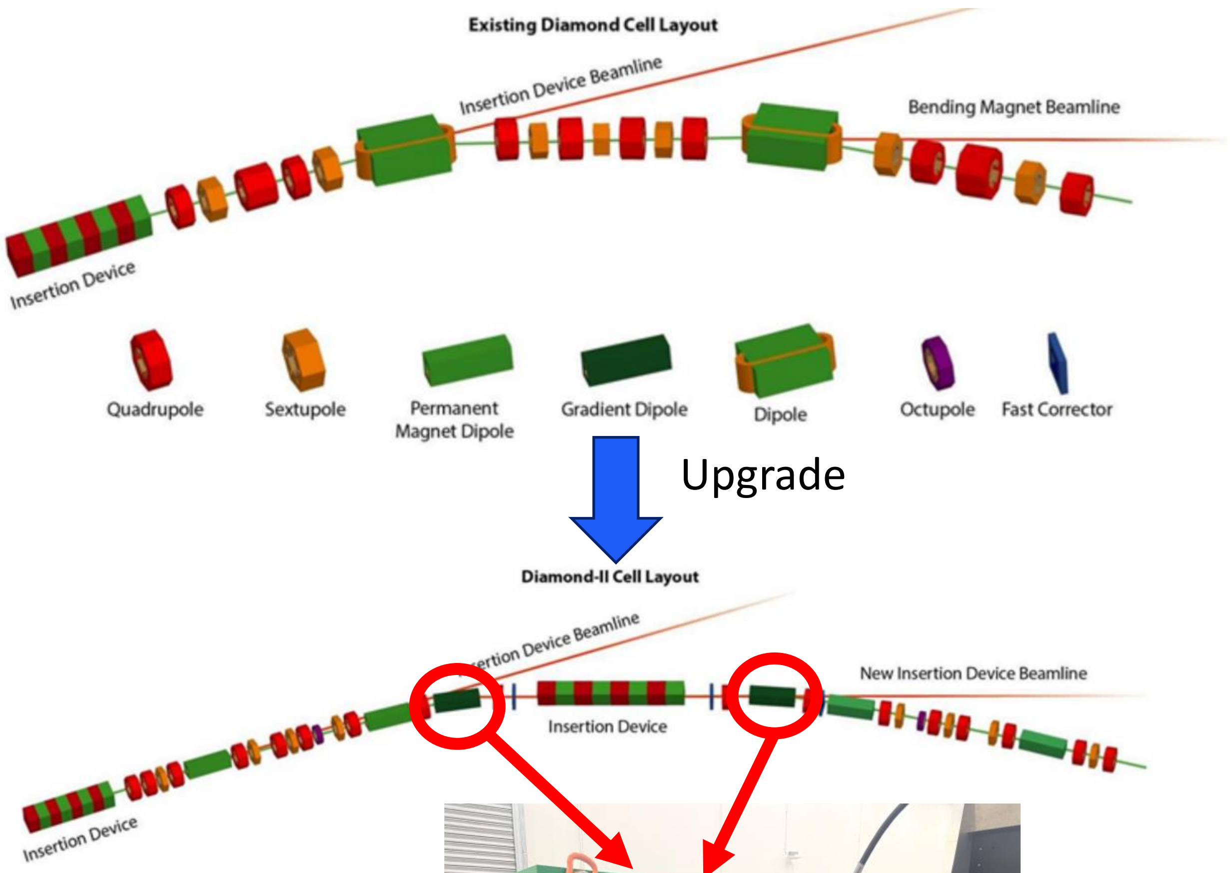
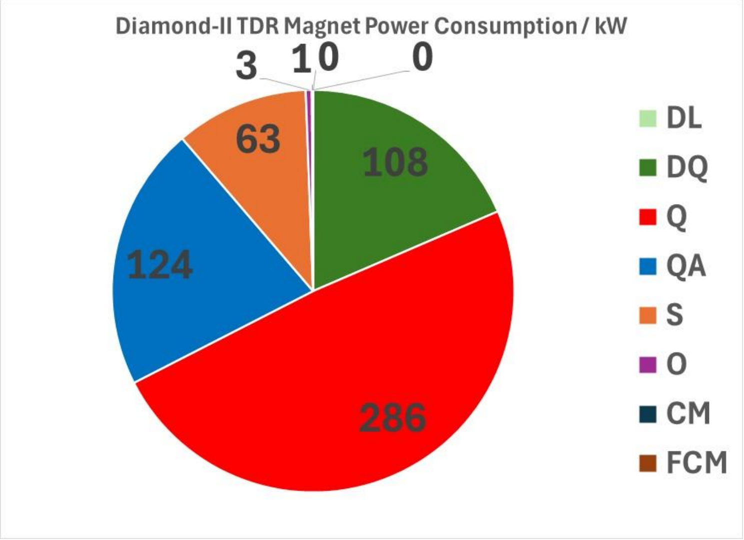
Introduction

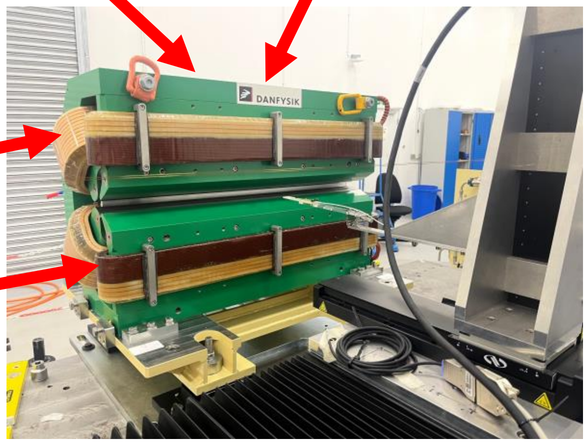
- I.FAST: EU funded project to develop new **sustainable accelerator technologies** and favour **partnerships with industry**.
- **Fourth generation synchrotron light sources** make use of **multi-bend achromat** lattices to reduce beam emittance and increase radiation brightness.
- Diamond-II: upgrade from double bend to 6-bend achromat.
- Lattice includes **48 transverse gradient (DQ) magnets: ~108 kW.**
- Task 11.3 – **Manufacture and test prototype permanent magnet** (PM) based DQ magnet as energy saving alternative to Diamond-II design.





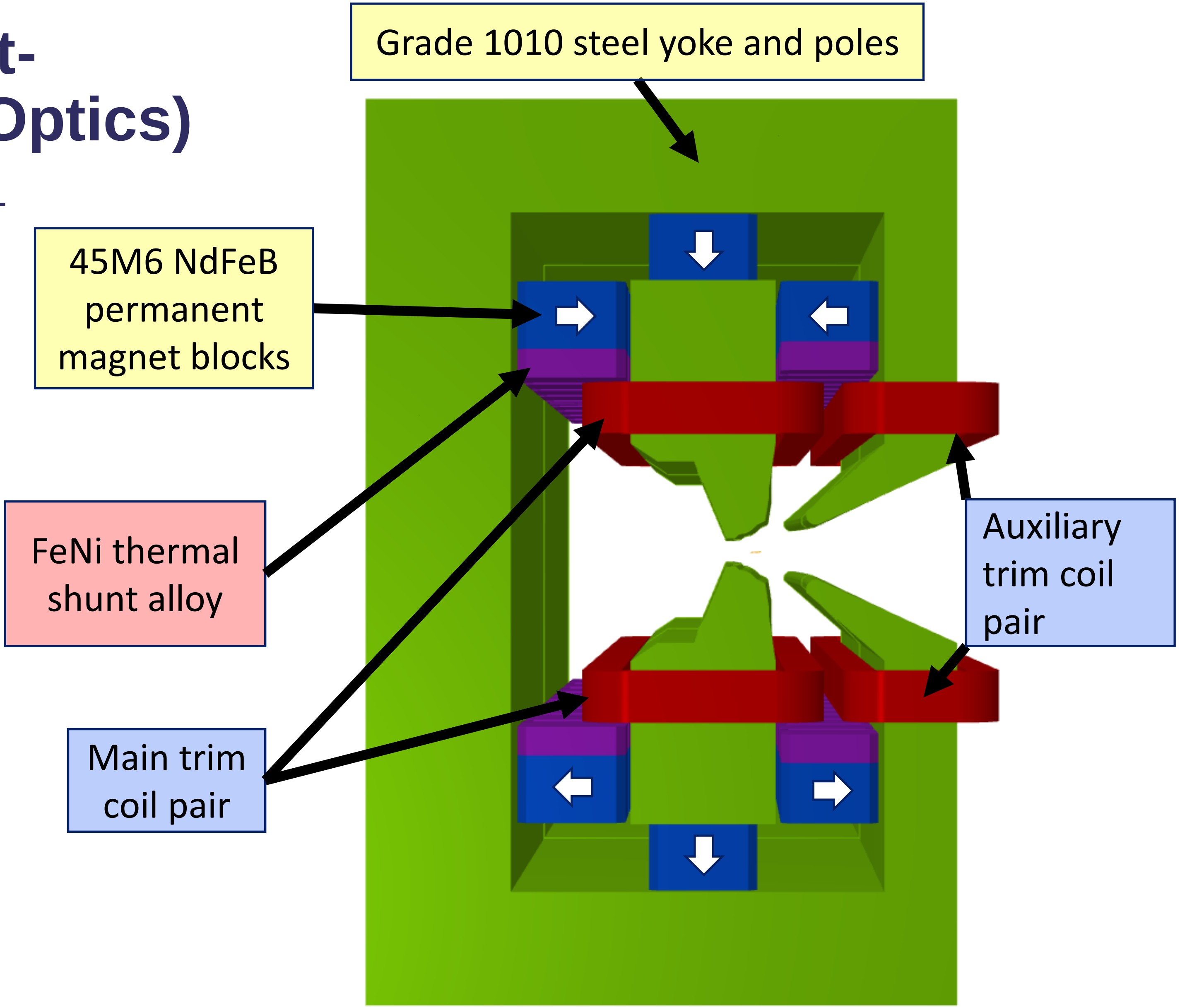
2.3 kW main coils
+ water cooling

80 W trim coils



HEPTO (Hybrid Electromagnet-Permanent Magnet Tuneable Optics)

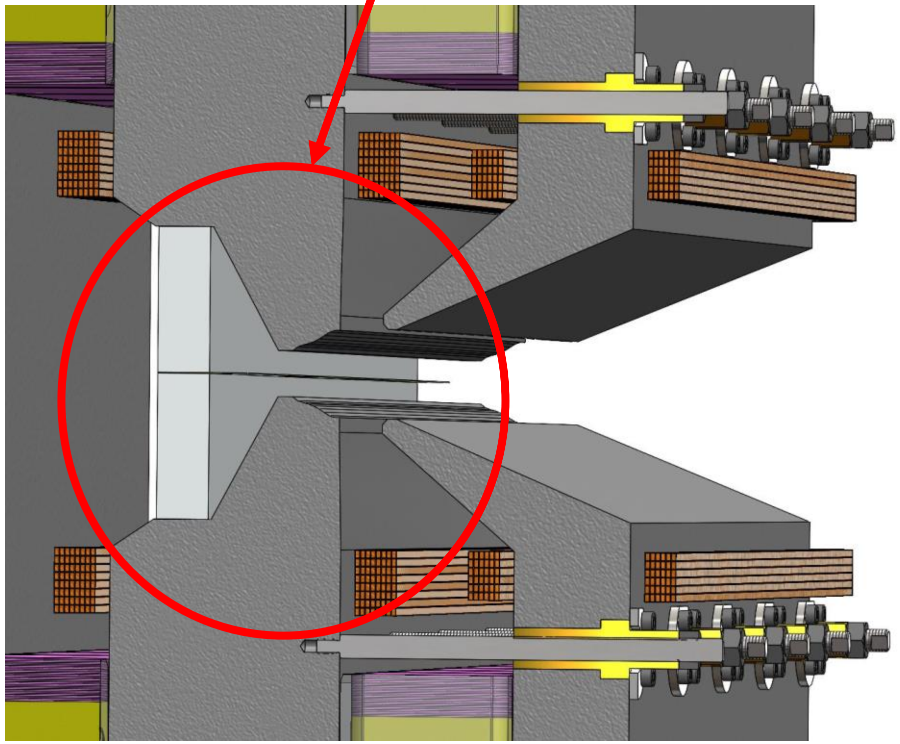
Parameter	Value	Units
Central dipole field	-0.6951	T
Central gradient	33.179	T/m
Effective dipole magnetic length	870	mm
Effective gradient magnetic length	850	mm
Integrated dipole field	-0.6047	T.m
Integrated gradient	28.1857	T
Bending radius	16.795	m
Good field radius (GFR)	7	mm
Integrated field quality (ΔB/B) in GFR	0.05	%
Gradient tuning range	±2.5	%
Temperature stability (3°C range)	±0.01	%



Mechanical Design Completed by Kyma

In-built **mechanical shimming** methods allow adjustment of field strength and homogeneity.

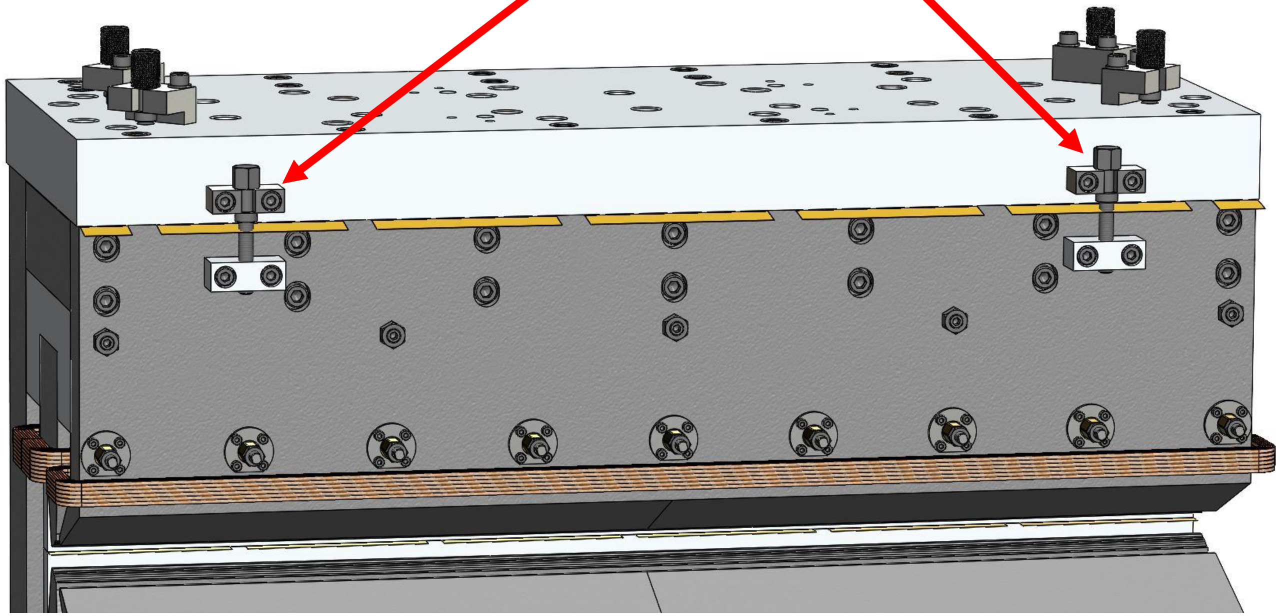
1. Vertical gap between main poles defined by pre-shimmed spacer.



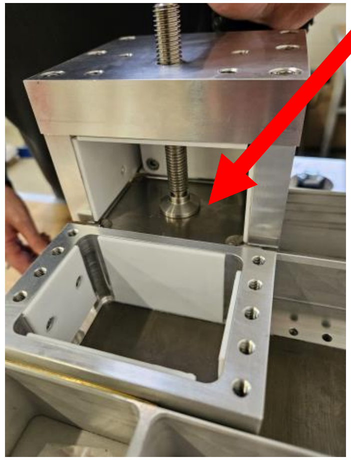
2. Two screws for opening gap between auxiliary pole and aluminium plate. Brass shims can be added/removed to adjust **vertical position of auxiliary pole.**

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

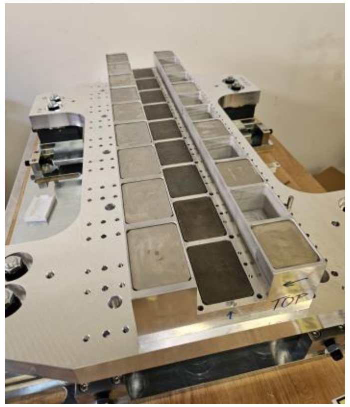
Shim thicknesses in range 10-200 µm.

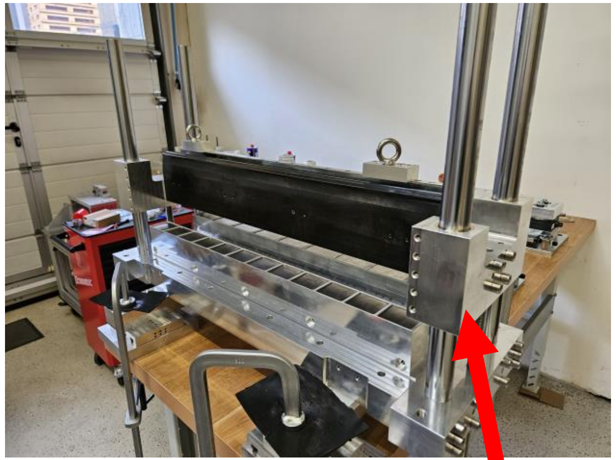


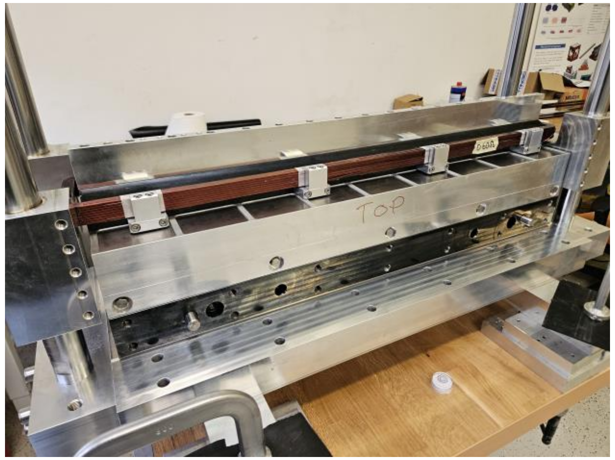
Magnet Assembly



60 kg peak force







2000 kg peak force

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Magnetic Measurements

Field measurements performed in dedicated magnet measurement laboratory at Daresbury.

Senis Type-H Hall probe

3-axis motion stage

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Field Multipoles

- Magnetic fields described in terms of "multipoles".

Complex multipole coefficients

n	Name	Function
1	Dipole	Bending
2	Quadrupole	Focussing
3	Sextupole	Chromatic aberrations
≥4	Higher order	Field errors

$$B(z) = B_y + iB_x = \sum_{n=1}^{\infty} \boxed{C_n} \left(\frac{z}{R_0}\right)^{n-1}$$

Complex representation of magnetic field

Complex representation of point in magnet aperture

Reference radius

- HEPTO pole tips curved – dipole constant along trajectory.
- Multipoles evaluated by measuring points around circular good field region and integrating over curved nominal electron beam trajectory.

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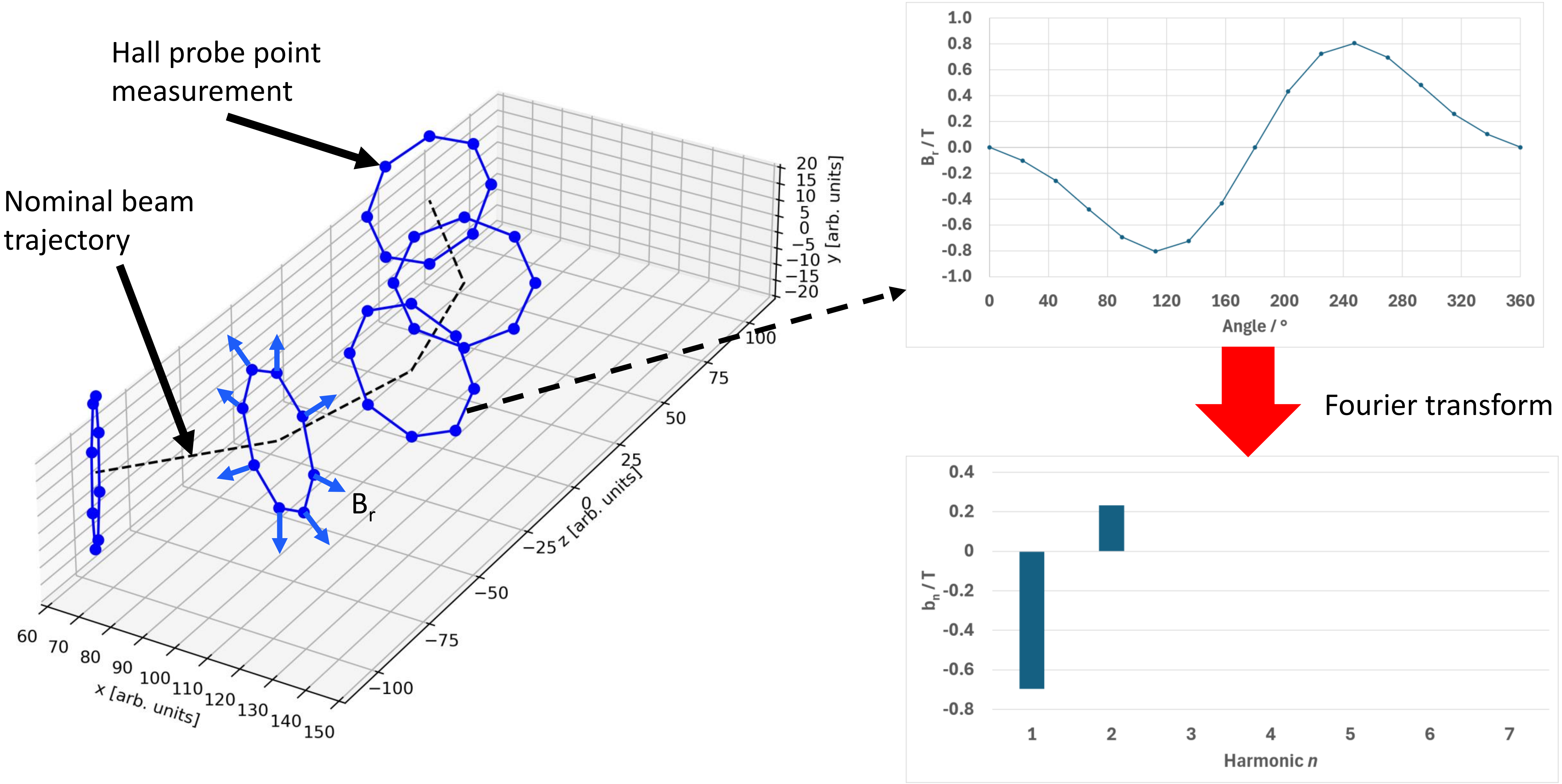
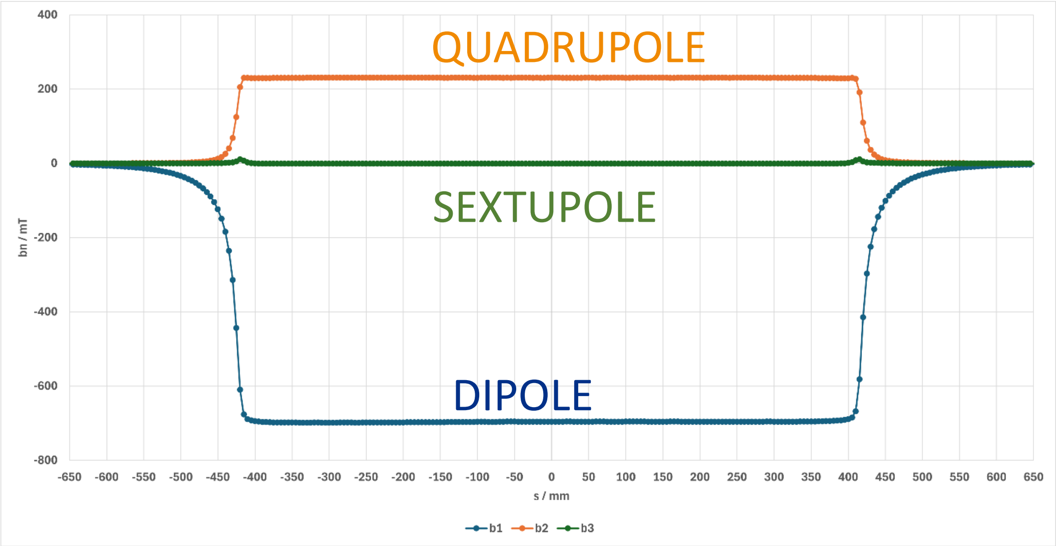
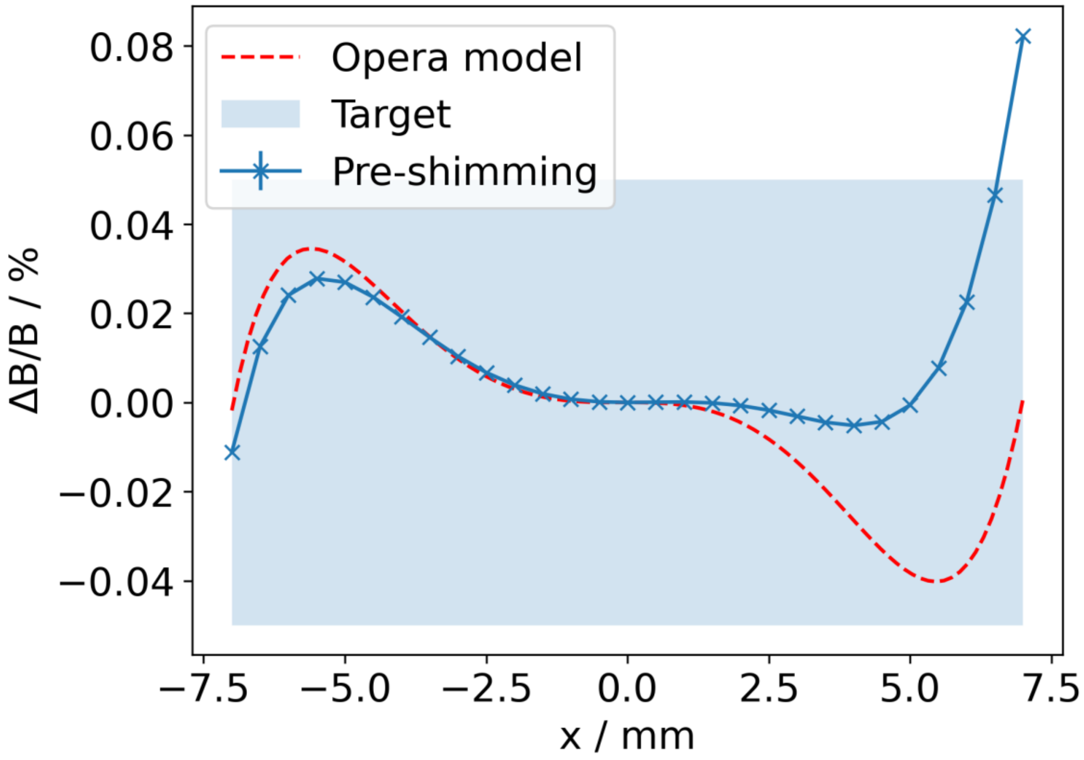
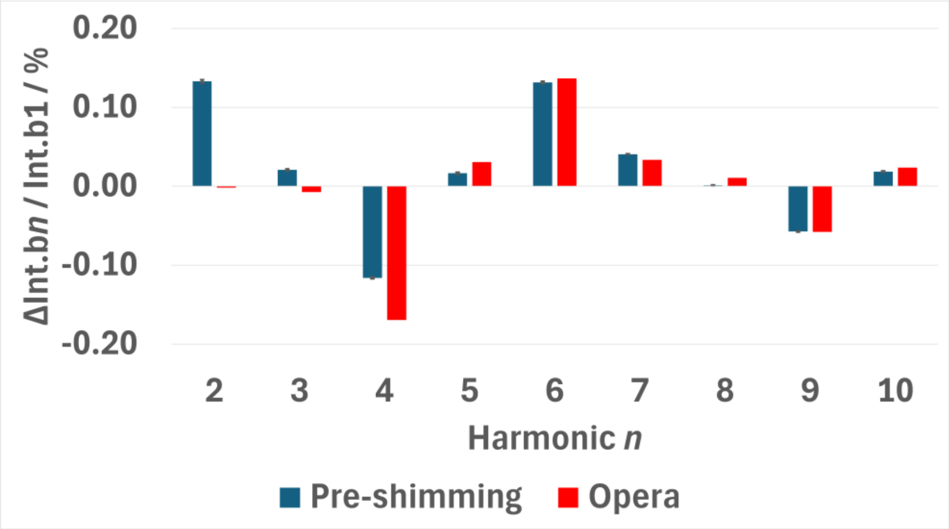

Hall probe point measurement
Nominal beam trajectory
B_r
x [arb. units]
y [arb. units]
z [arb. units]
60 70 80 90 100 110 120 130 140 150
20 15 10 5 0 −5 −10 −15 −20
−100 −75 −50 −25 0 25 50 75 100
B_r / T
1.0 0.8 0.6 0.4 0.2 0.0 -0.2 -0.4 -0.6 -0.8 -1.0
0 40 80 120 160 200 240 280 320 360
Angle / °
Fourier transform
b_n / T
0.4 0.2 0 -0.2 -0.4 -0.6 -0.8
1 2 3 4 5 6 7
Harmonic n

Initial Measurements



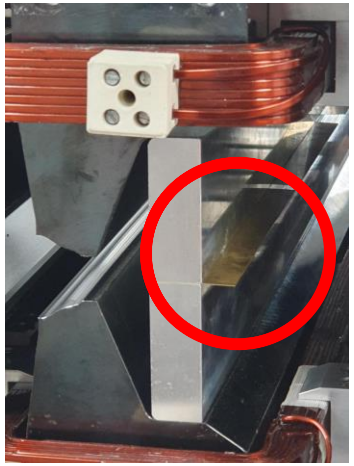


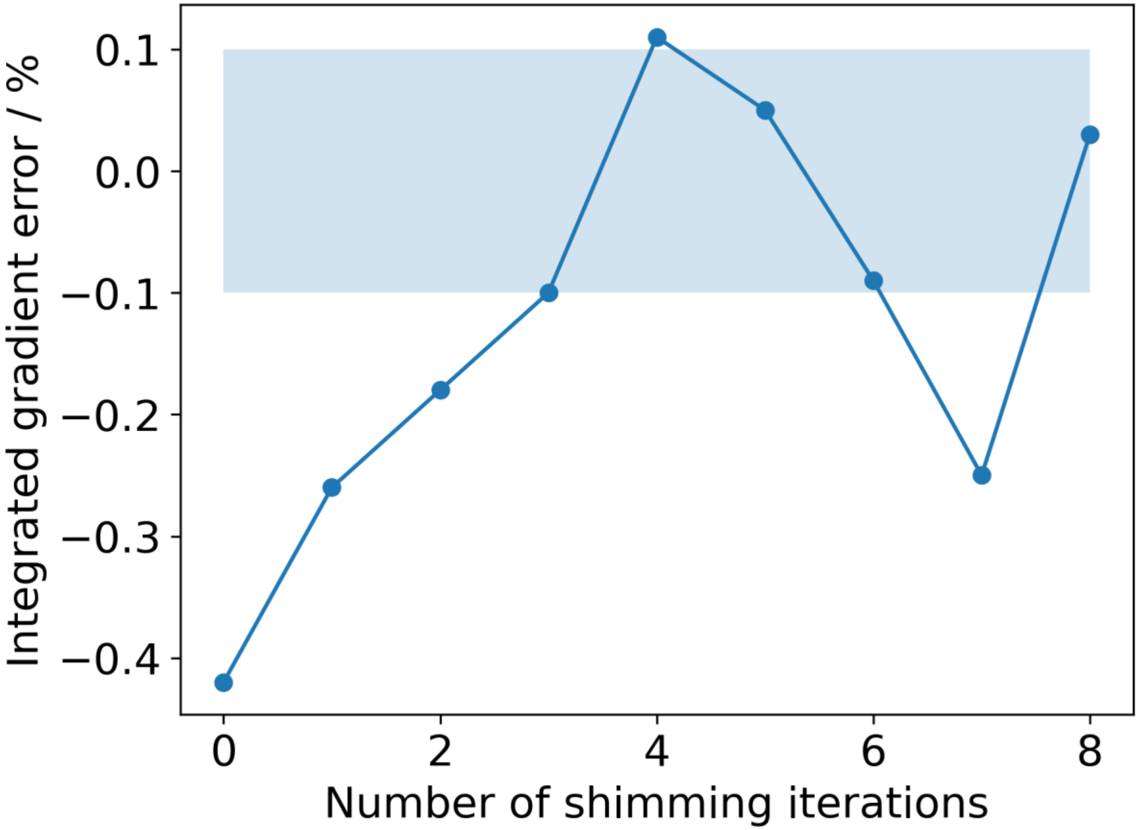


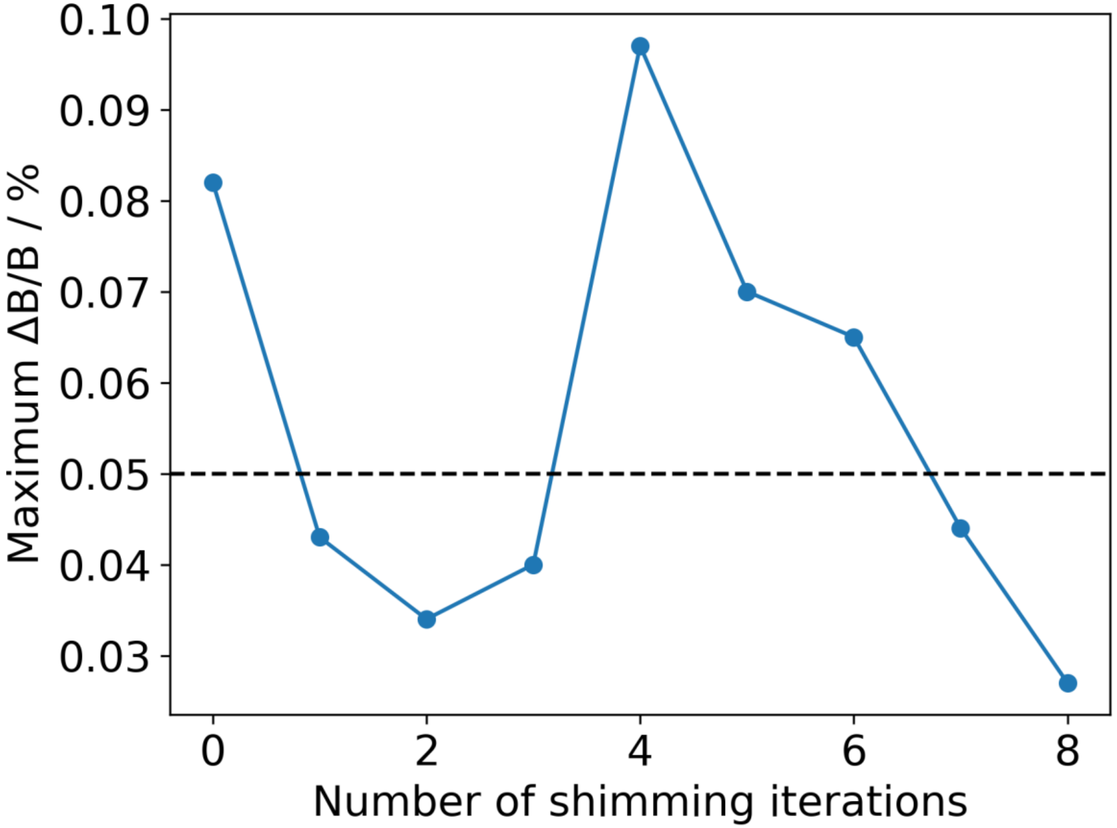
	Integrated Gradient / T	Integrated gradient error / %	Integrated Homogeneity ΔB/B / %
Requirement	28.1857		0.05
Measured	28.070 ± 0.002	-0.41	0.082±0.005

Shimming

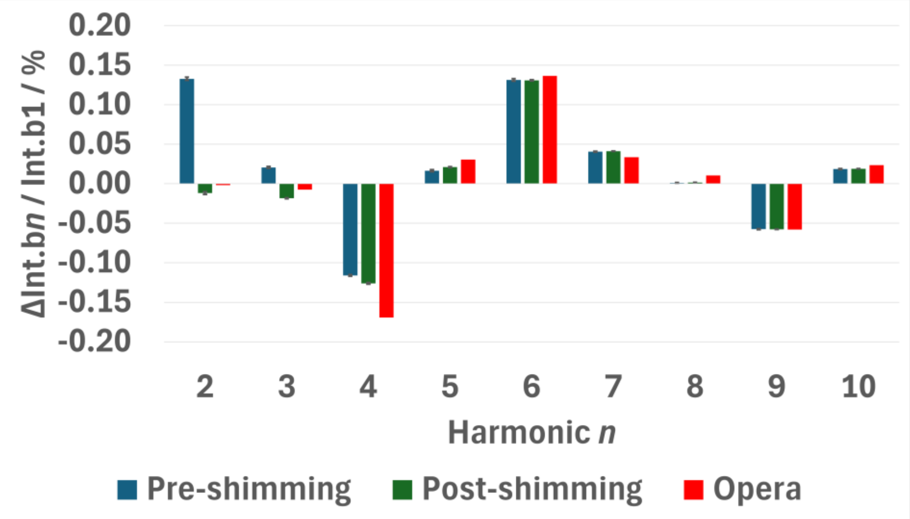
Vertical gaps between main and auxiliary poles adjusted via addition / removal of brass shims.

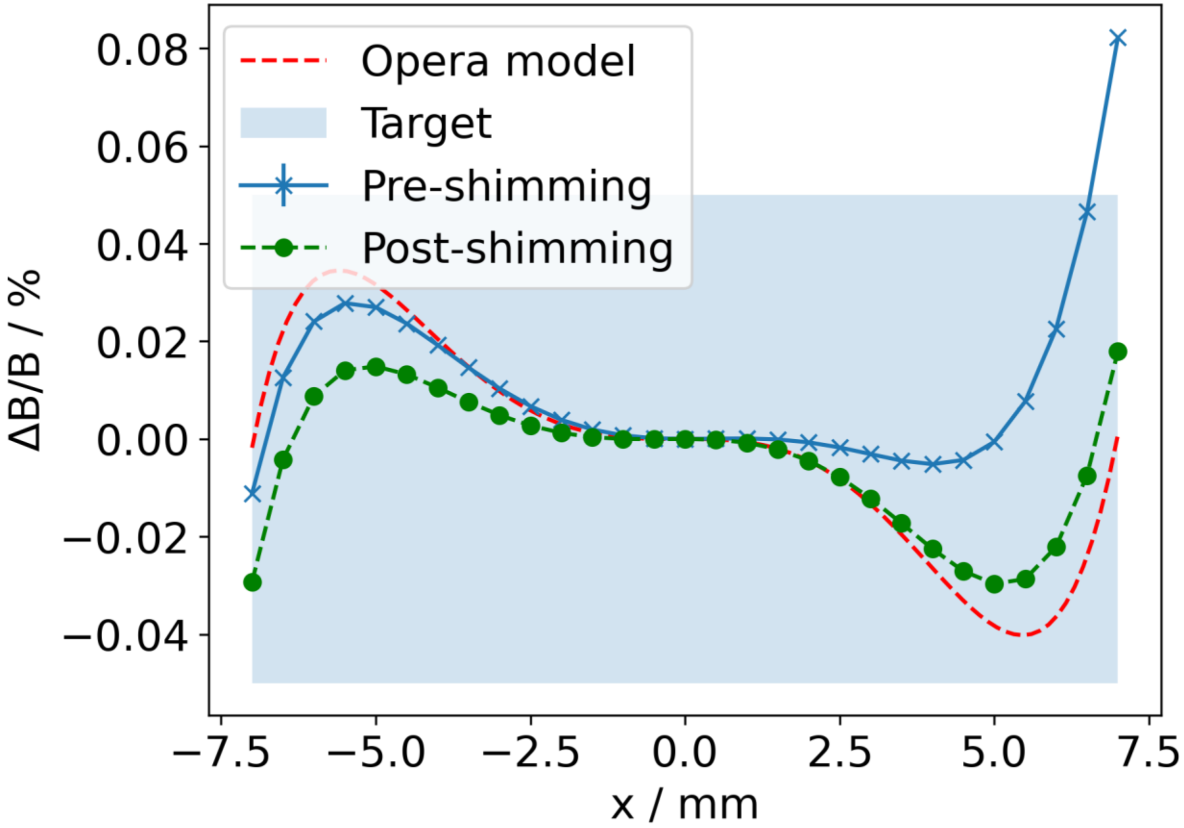






Post-shimming





	Integrated Gradient / T	Integrated gradient error / %	Integrated Homogeneity ΔB/B / %
Requirement	28.1857		0.05
Pre-shimming	28.070 ± 0.002	-0.41	0.082±0.005
Post-shimming	28.196 ± 0.001	+0.04	0.029±0.001

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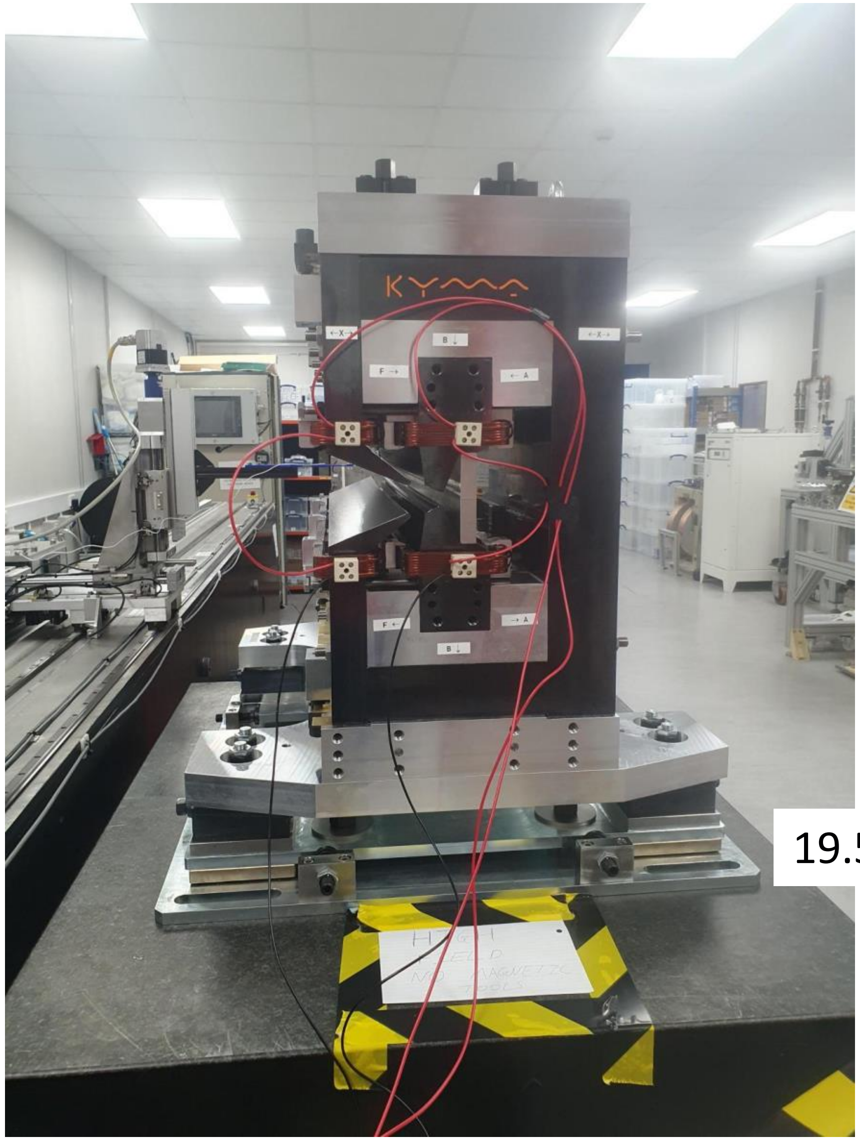
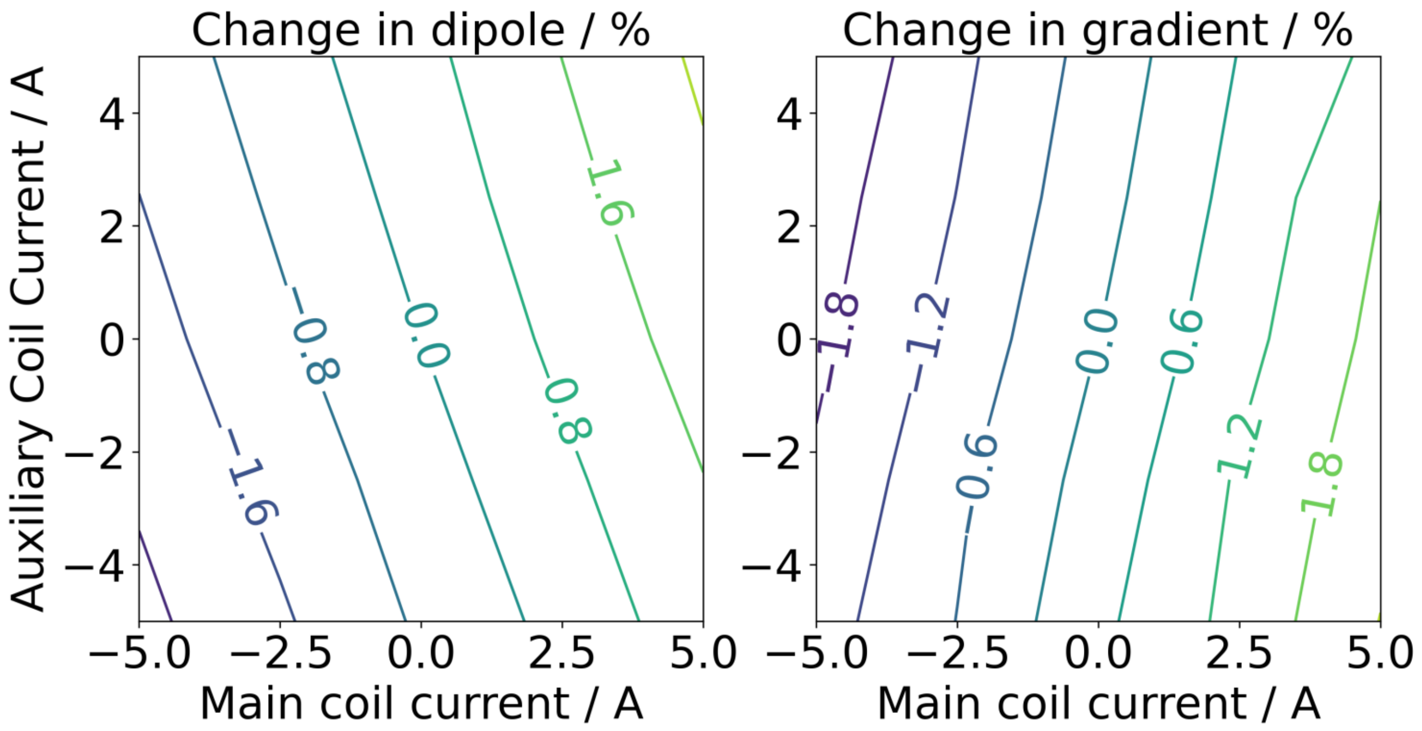
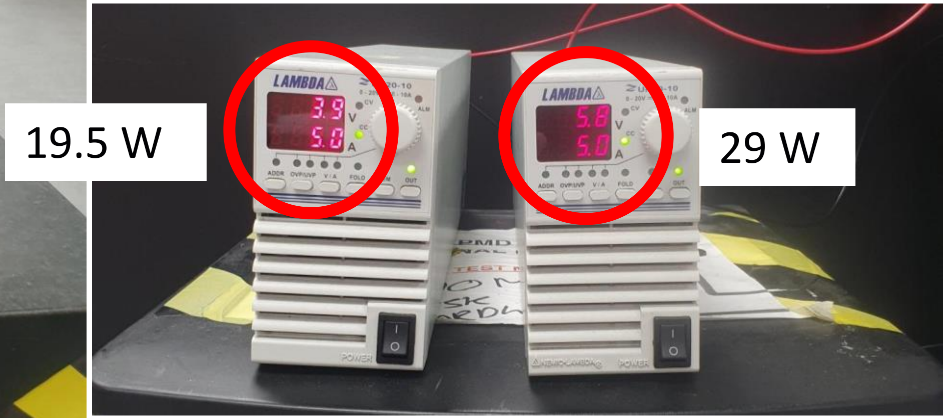
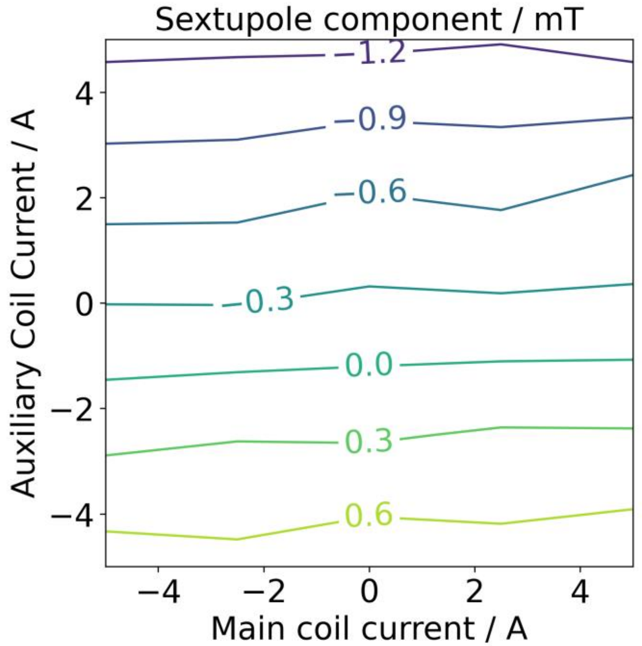
Trim coils





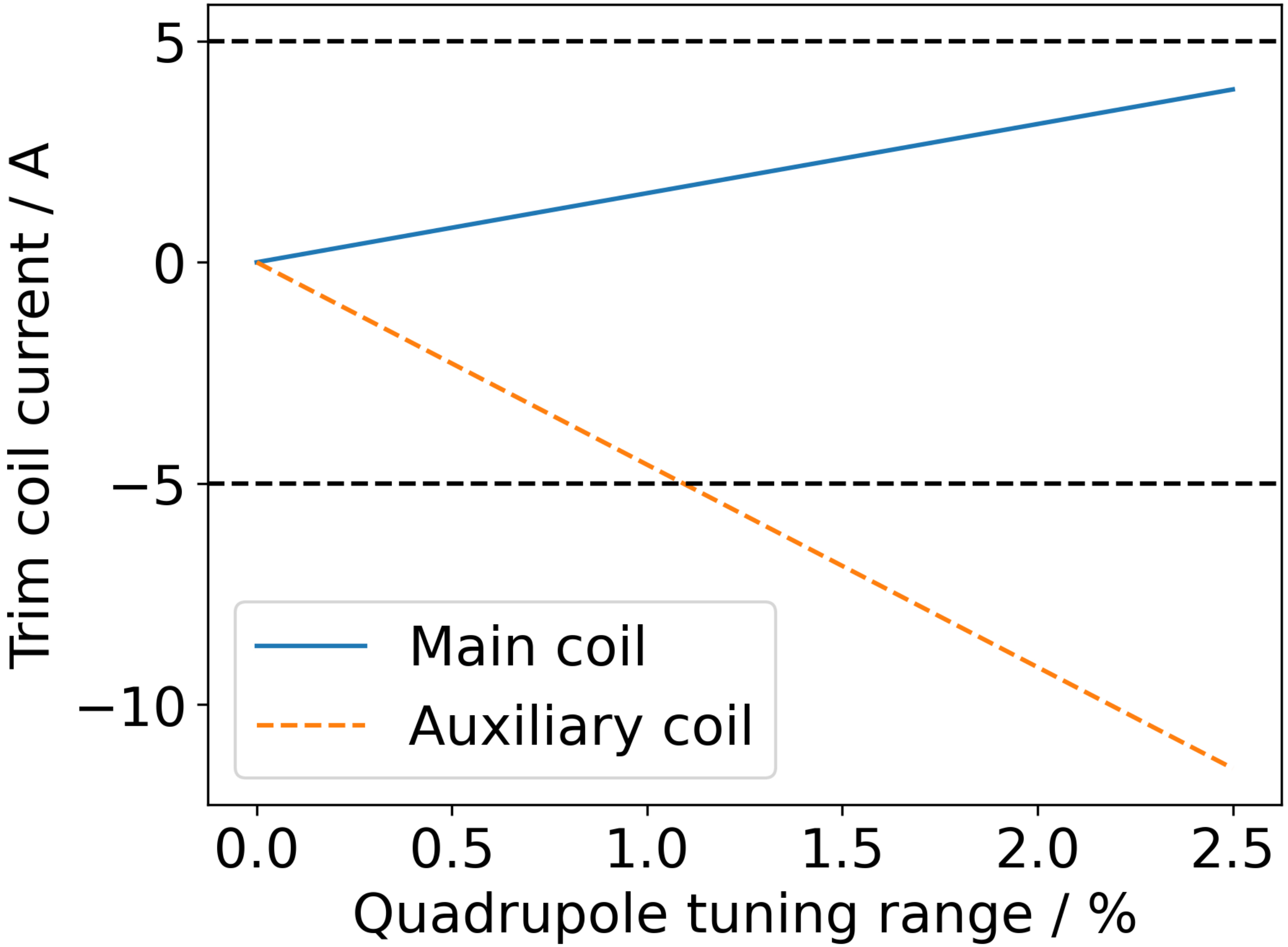
Target = independent tuning of dipole and quadrupole by ±2.5 %





Tuning Range

- Trim coil currents limited to ±5 A.
- Quadrupole tuned whilst keeping dipole field constant – emittance measurements.
- **Maximum achievable tuning range is ±1.1 %.**
- Less than target range of ±2.5 %.
- **Electromagnet tuning is inefficient** due to low magnetic permeability of permanent magnets in the magnetic circuit.



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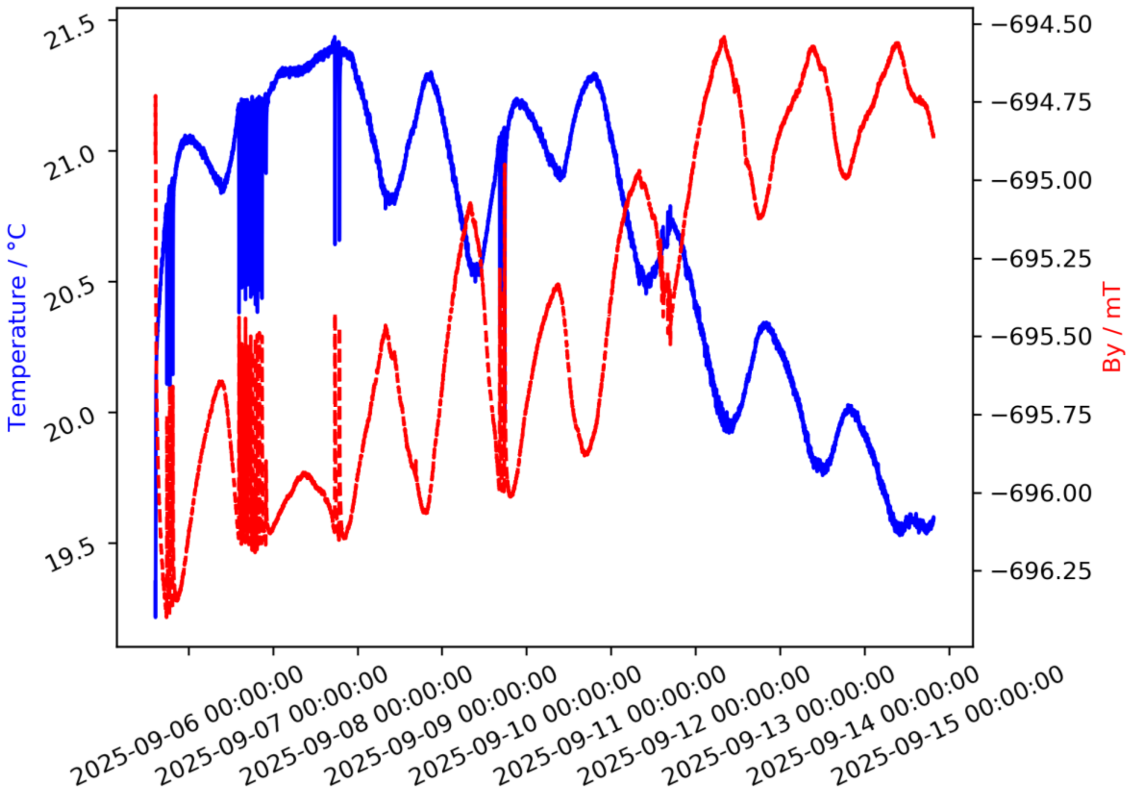
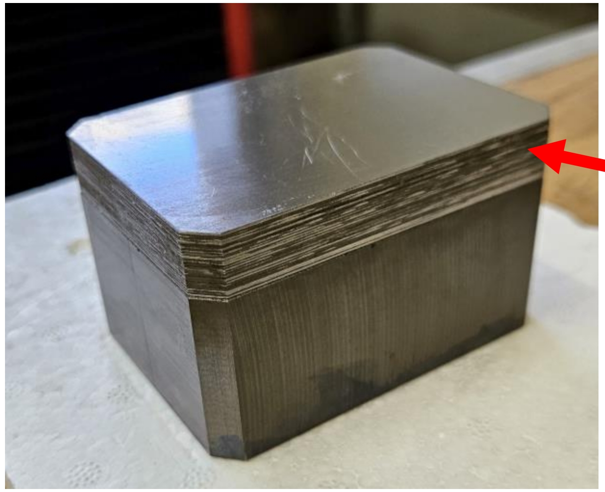
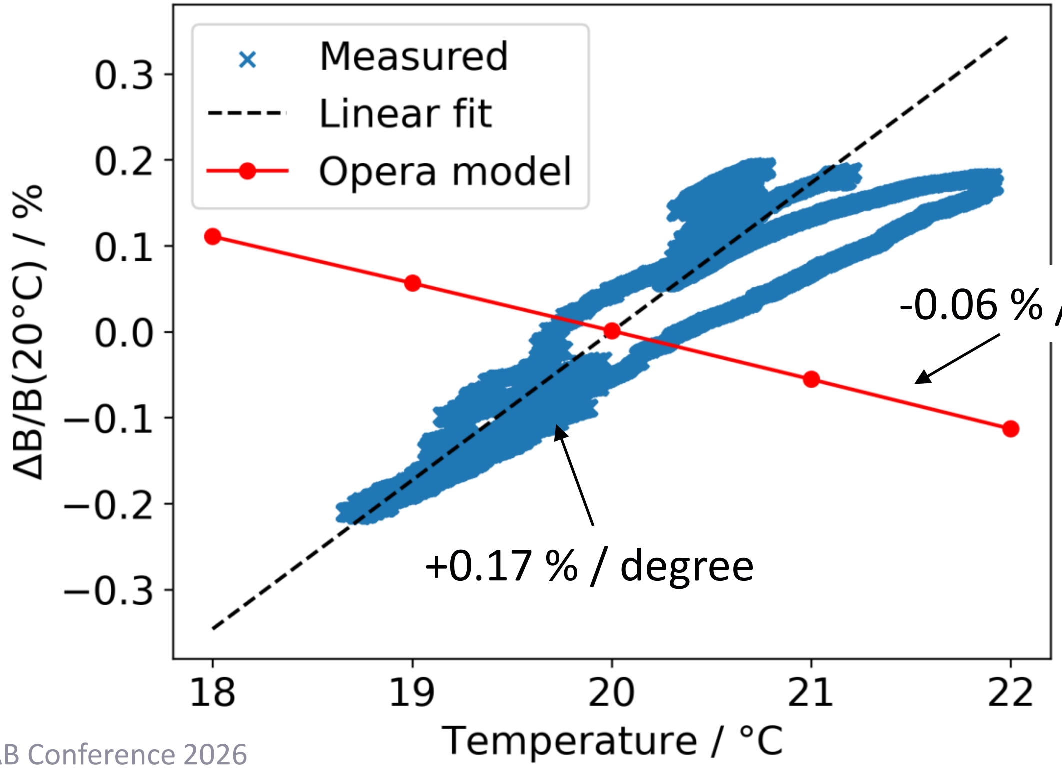
Thermal Stability





FeNi thermal shunt alloy glued to PM blocks



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Conclusion

- **HEPTO** magnet built and measured as part of **I.FAST** WP11.3.
- Demonstrator of **sustainable alternative** to electromagnets.

Parameter	Target	Achieved	Units
Integrated gradient	28.1857	**28.196 ± 0.001**	T
Integrated field quality (ΔB/B) in GFR	5E-4	**(2.9±0.1)E-4**	
Gradient tuning range	±2.5	**±1.1**	%
Trim coil power	<2.3	**0.05**	kW
Temperature stability (3°C range)	±0.01	**+0.51**	%

- Next steps: further collaboration between STFC and Kyma through **EPITA**.
- Development of scalable ZEPTO **tuneable permanent magnet** technology.

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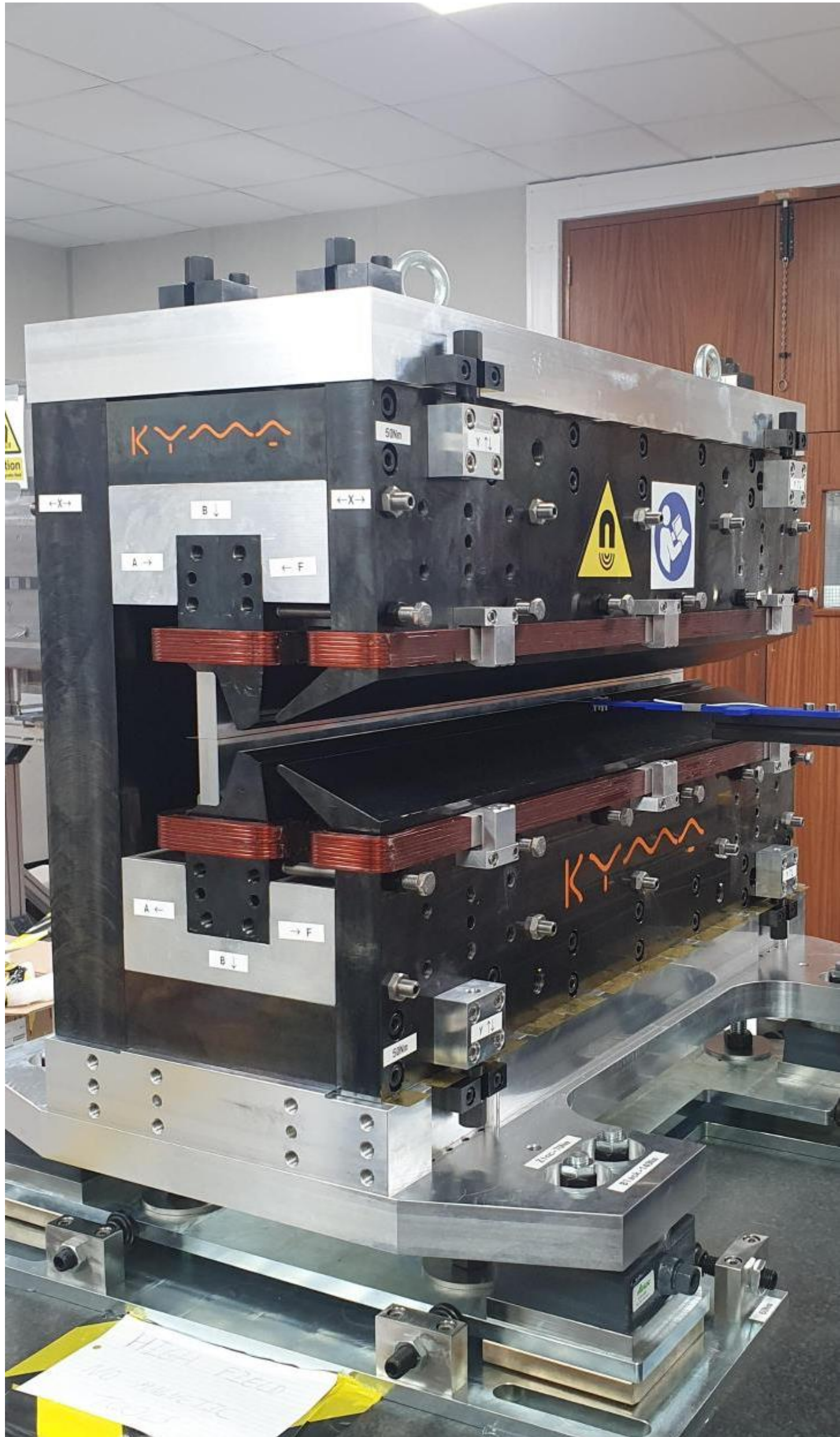
EPITA



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Questions?

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Thank you

Acknowledgements:

- Ben Shepherd (STFC)
- Alfie Shahveh (Diamond Light Source)
- Dušan Topalović, Tadej Milharcic, Mirko Kokole, Jure Počkar (Kyma S.p.A.)