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I.FAST 3rd Annual Meeting– Task 11.3 HEPTO Magnet Update

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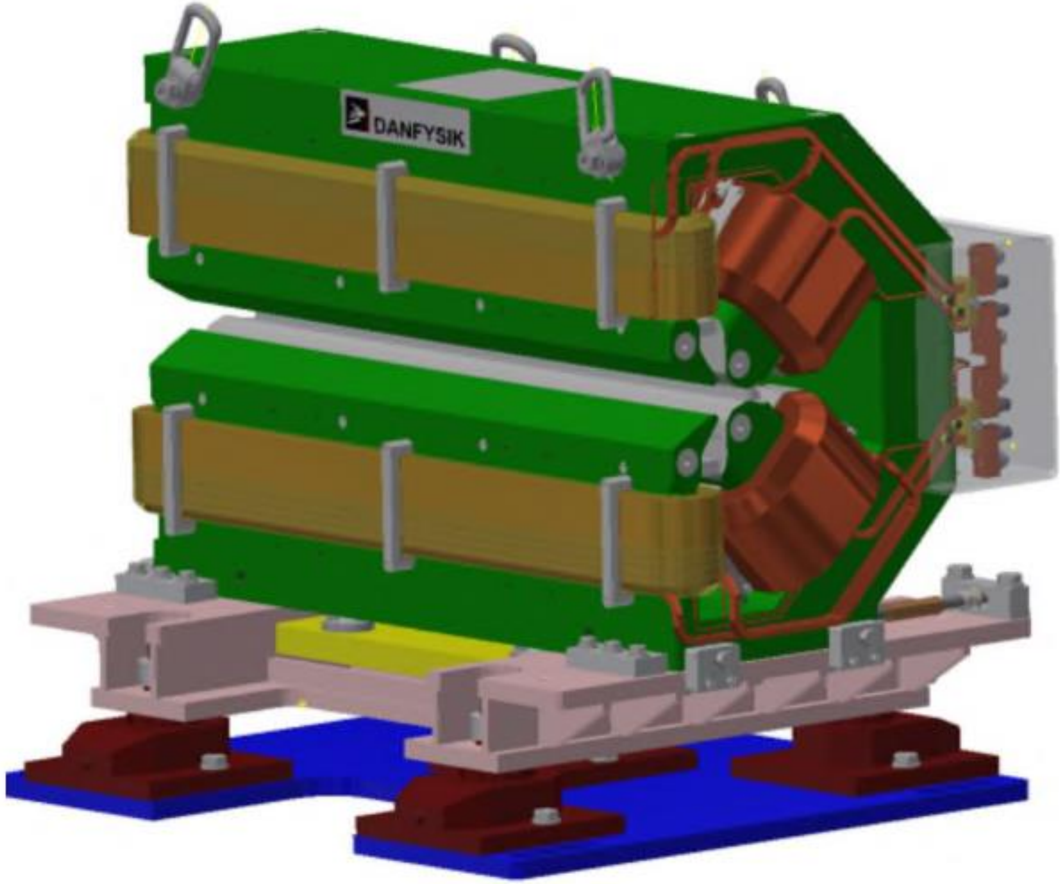
Introduction

- Fourth generation synchrotron light sources make use of multi-bend achromat lattices to reduce beam emittance and increase radiation brightness.
- Lattices require combined function dipole-quadrupole (DQ) magnets.
- Diamond-II upgrade will require 48 DQ magnets drawing 2.3 kW each.
- Can permanent magnets achieve the same purpose with negligible power?



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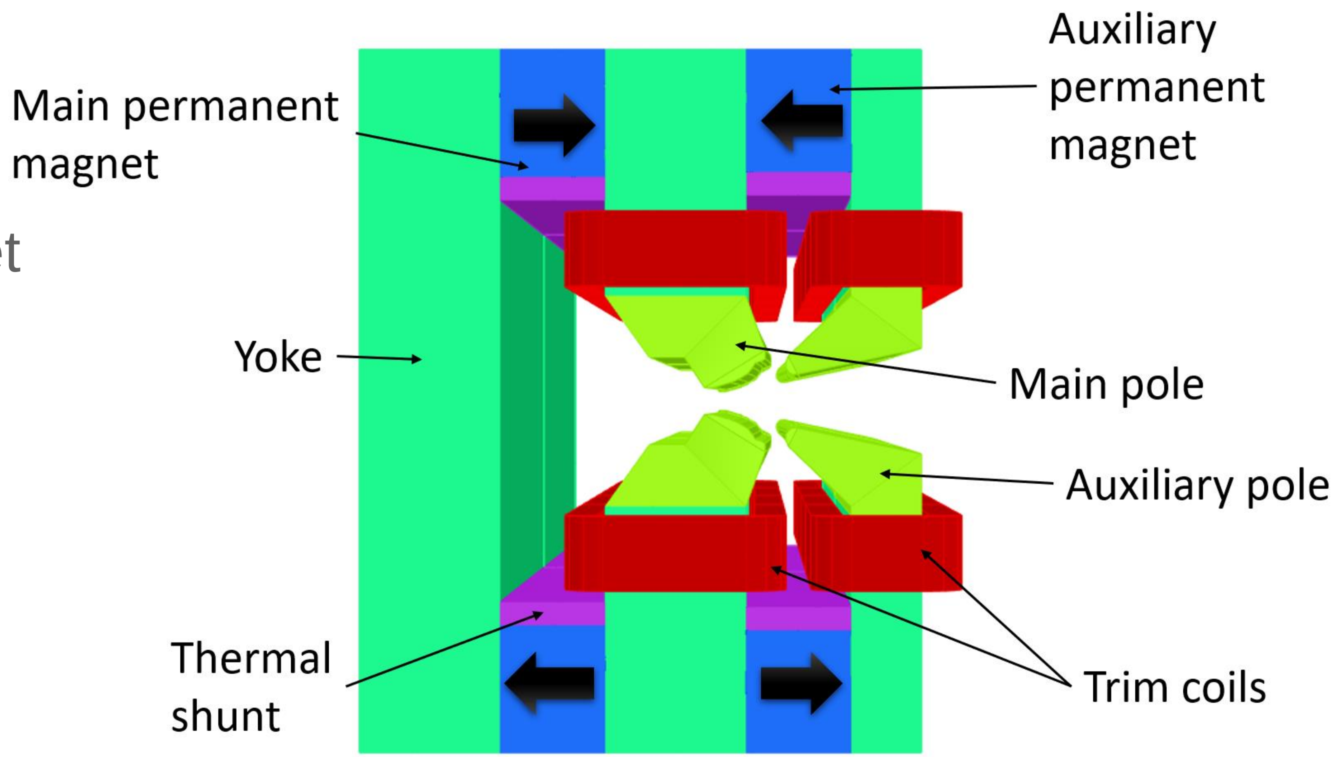
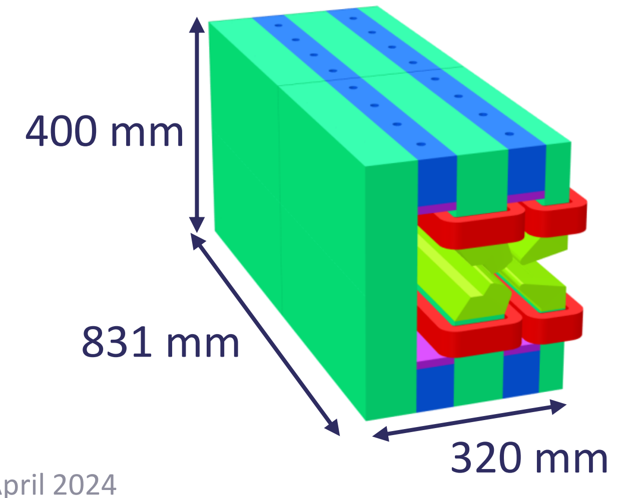
Initial Design

- 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 XC06 low-carbon steel.





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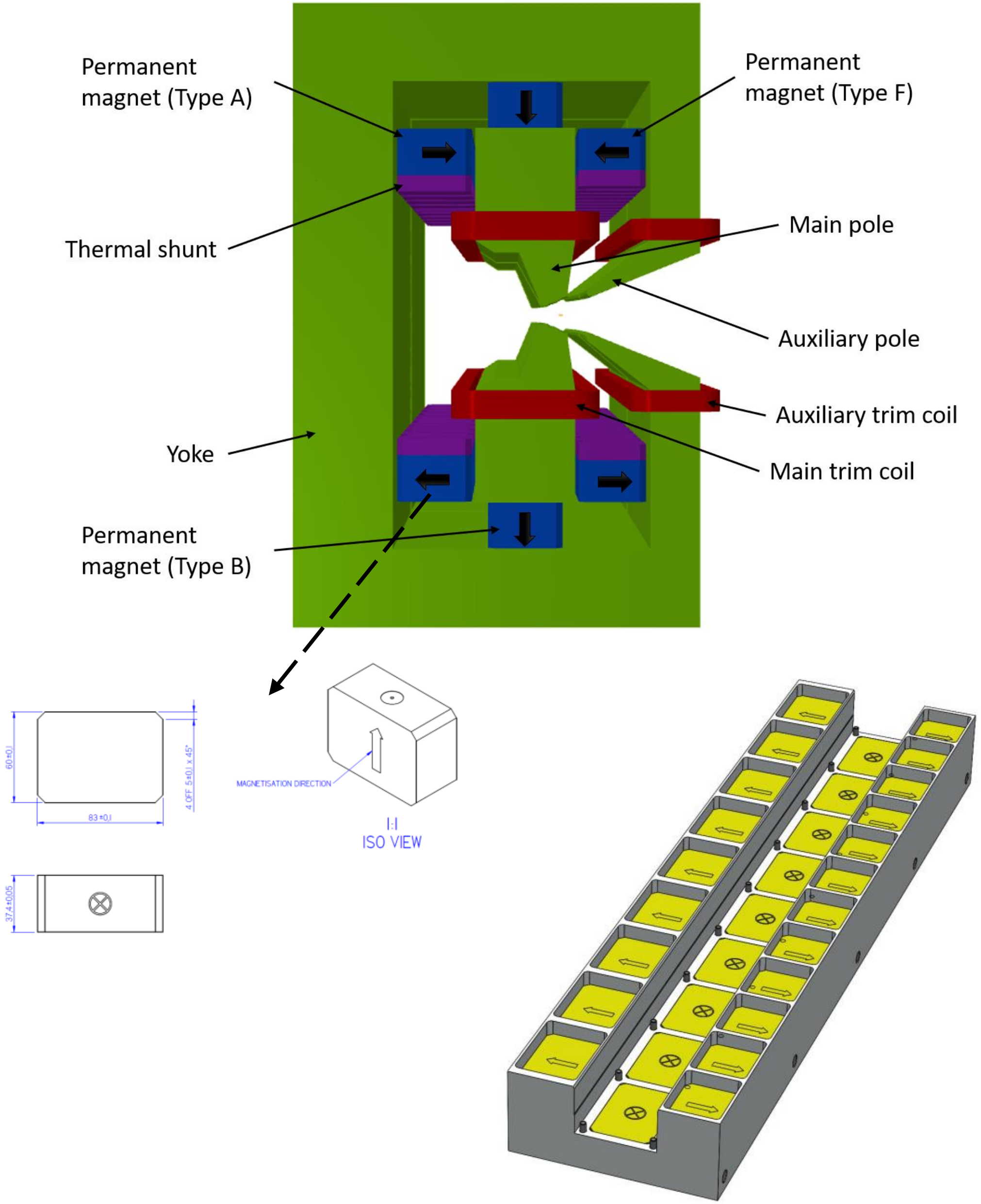
Updated Design

- Large costs and long lead times associated with purchasing large NdFeB magnets blocks.
- Design adjusted to use spare undulator permanent magnet blocks as main source of field.
- NdFeB blocks; Br = 1.3 T ± 1%.
- Same basic design concept.
- Magnets held in ice-cube tray structure.
- Additional arrays of permanent magnets (type B) required above/below main pole arms to achieve desired field strength.



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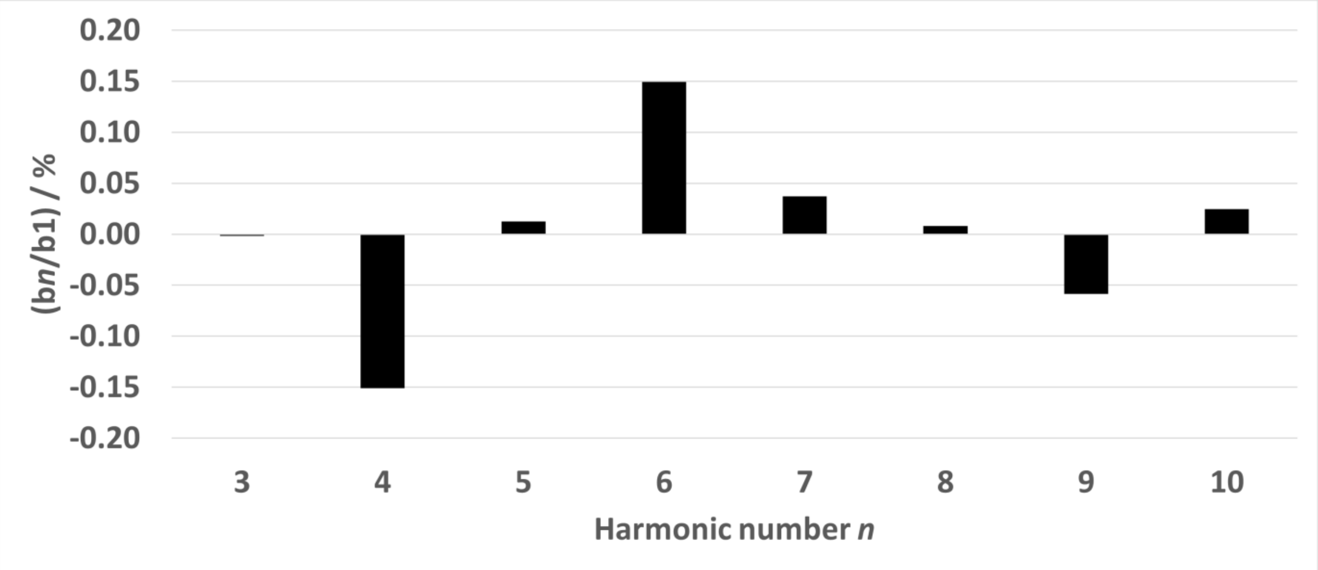
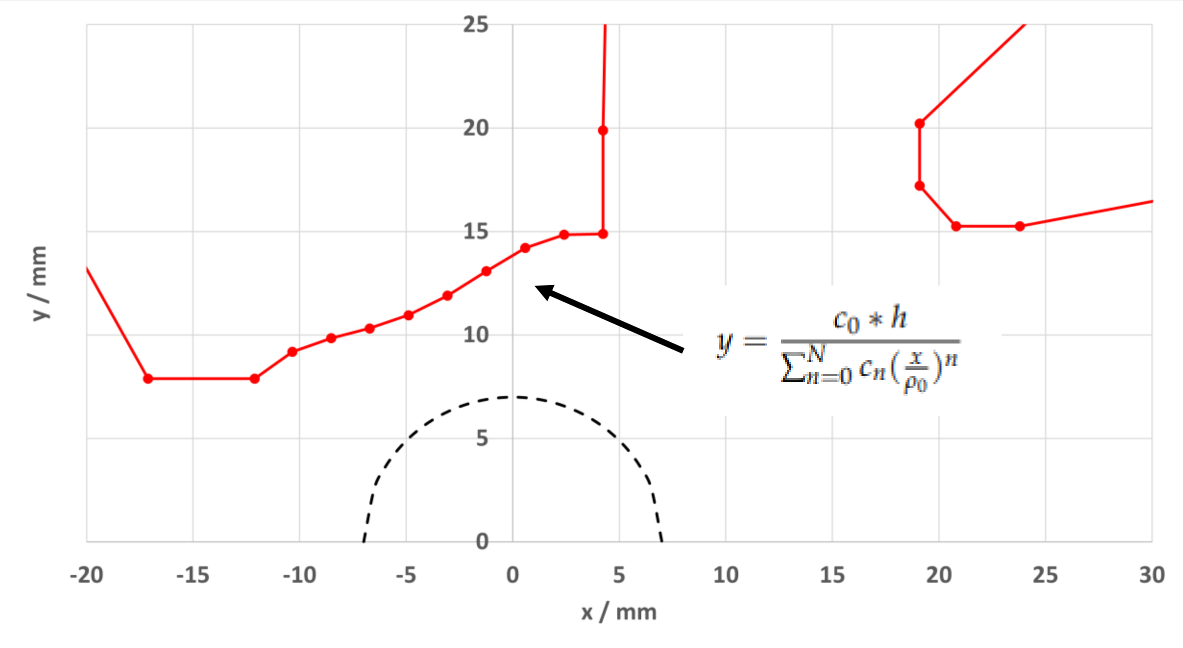
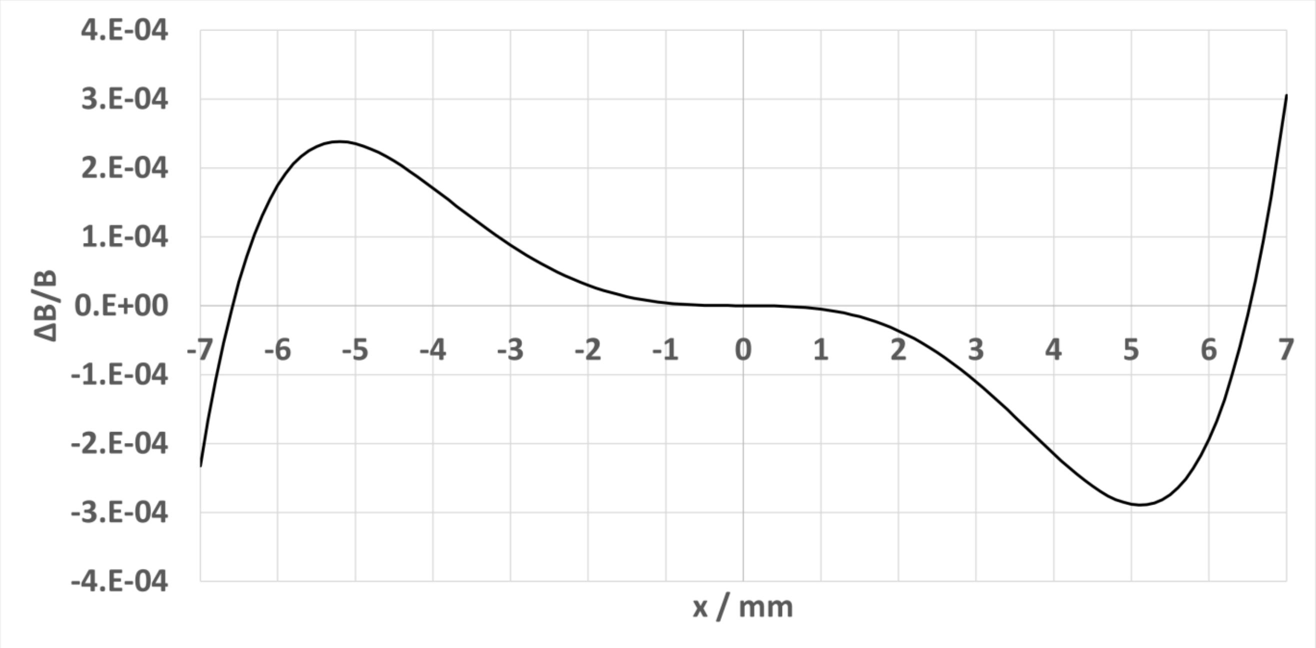
Pole Tip Re-Design

- Pole profile reoptimized to give nominal field strength and field quality.
- Fixed PM dimensions – no tuning of field strength independent from higher order multipoles.

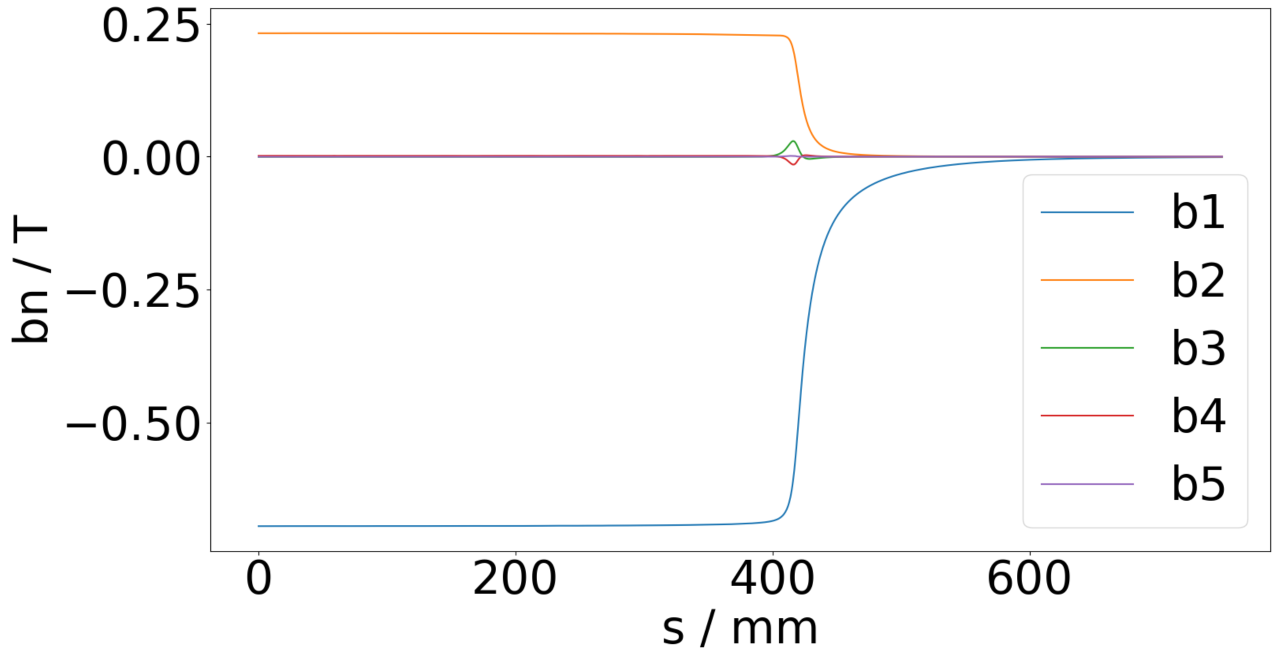


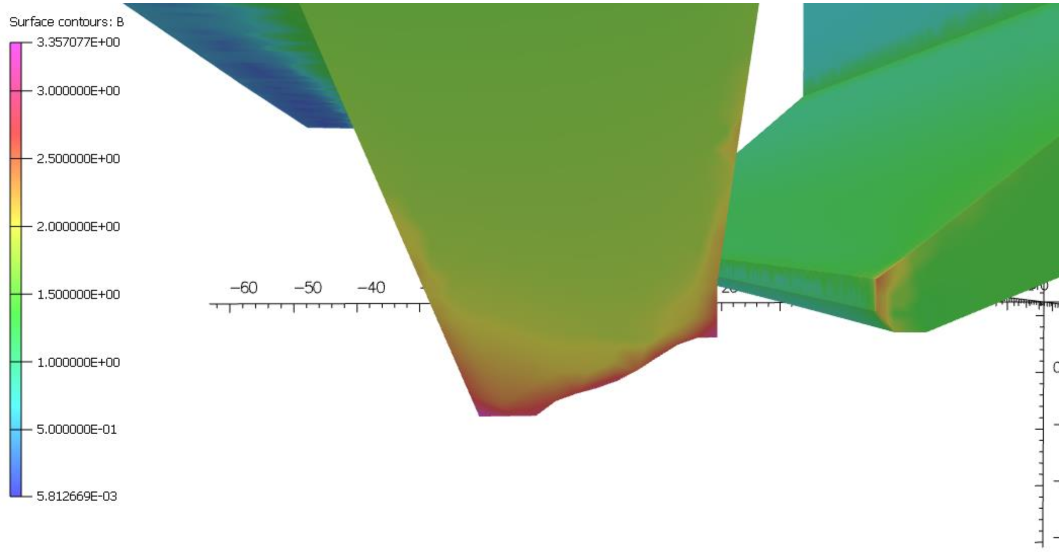


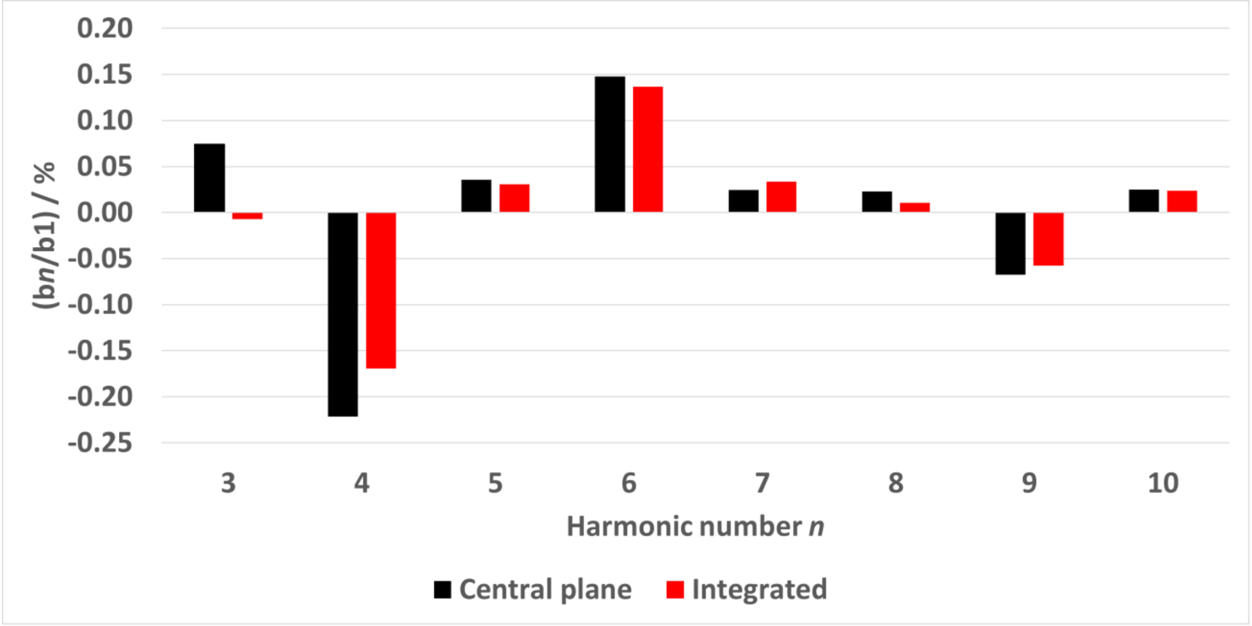


Integrated Fields

- Pole tips not chamfered – simplify machining.
- Non-zero sextupole field at ends of magnet.
- 3D design optimised to minimise integrated sextupole component.

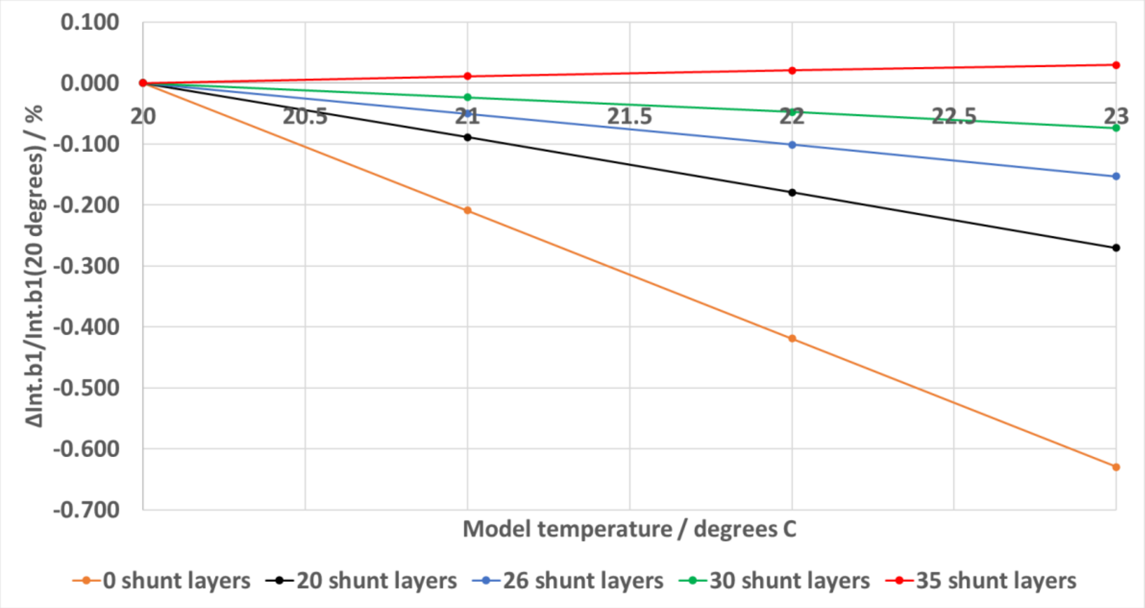


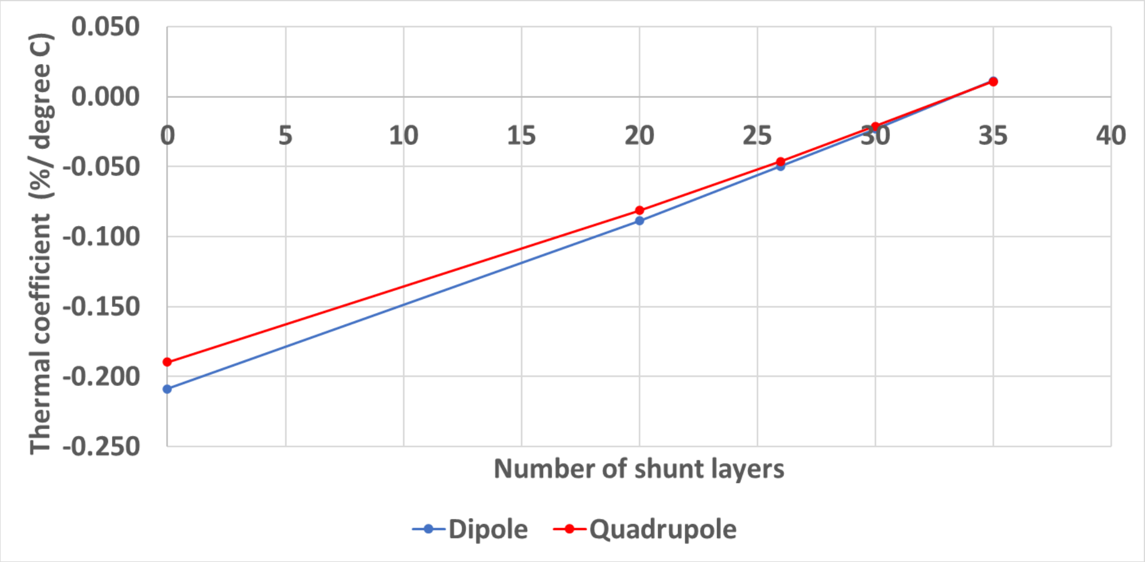


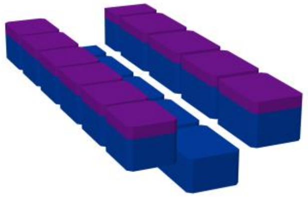


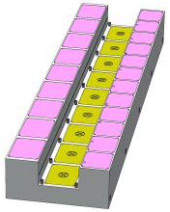
Thermal Shunts

- Thermal shunt material can only be purchased from suppliers in large batches.
- Spare FeNi thermal shunt material purchased from Soleil (42 sheets for €1600).
- Material cut and glued to type A and F magnet blocks.
- Enough material to produce 26 layers of 0.5 mm thick sheets.
- Predicted thermal stability -0.050 % / degree Celsius. 0.01% variation typical due to power supply fluctuation in electromagnets.



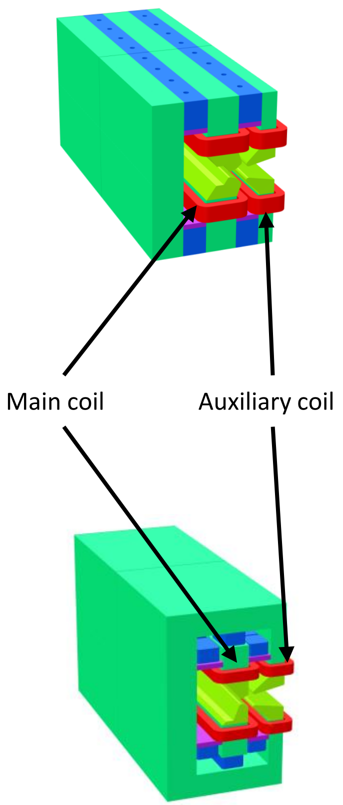




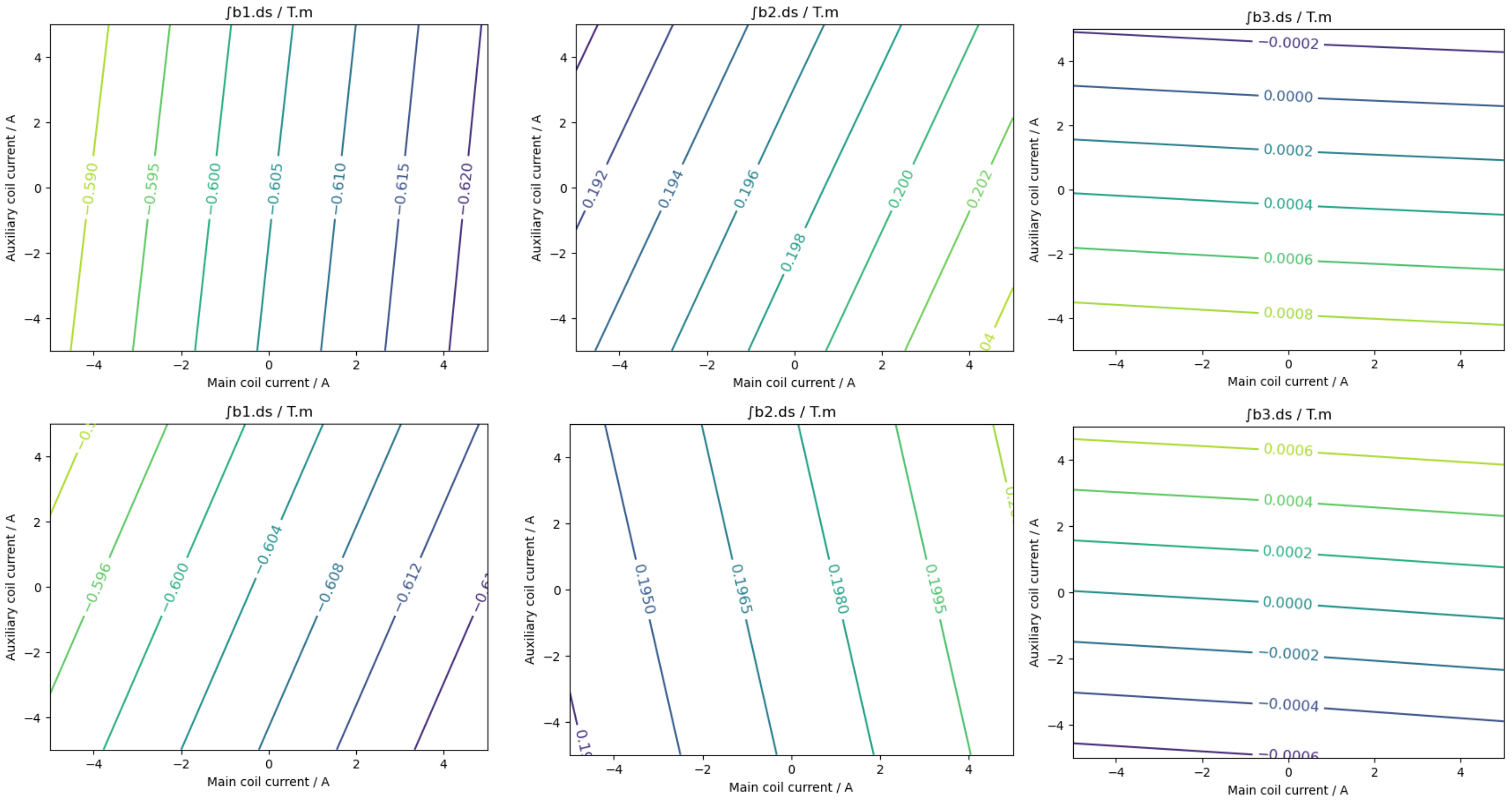


Field Tuning

Version 1



Version 2



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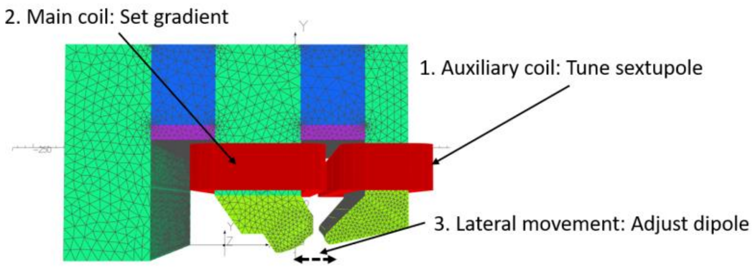
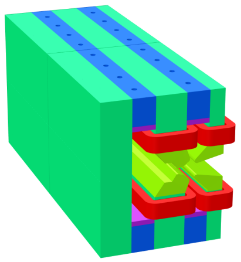
Coil Comparison

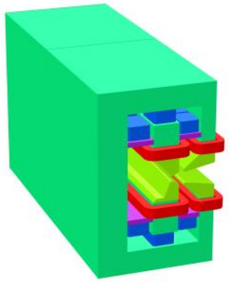
Physical movement of magnet needed to achieve tuning range in v1 design.





Version 1

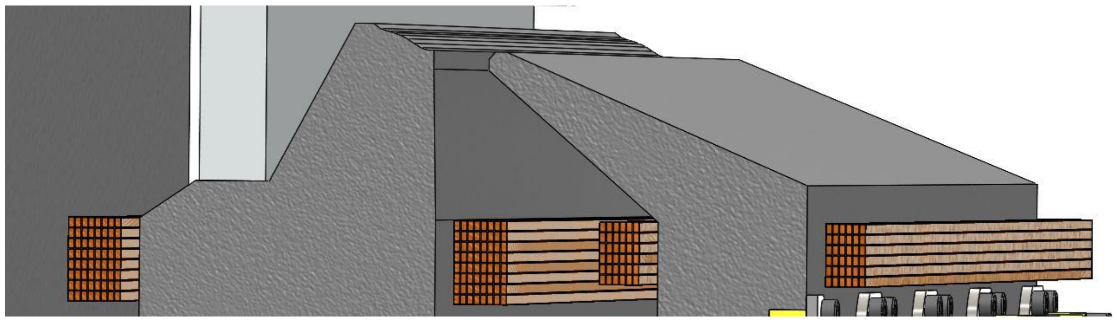
Change in $\int b_1$ .ds / %	Change in $\int b_2$.ds / %	Main coil current / A	Auxiliary coil current / A
0	0	-0.02	0.051
-2.5	0	5.72	16.60
+2.5	0	-5.76	-16.49
0	-2.5	-1.47	16.74
0	+2.5	1.42	16.84



Version 2

Change in $\int b_1$ .ds / %	Change in $\int b_2$.ds / %	Main coil current / A	Auxiliary coil current / A
0	0	-0.05	-0.01
-2.5	0	-4.93	-1.32
+2.5	0	4.82	1.32
0	-2.5	-1.65	-0.42
0	+2.5	1.54	-0.42

	v1	v2
Main coil turns	180	64
Main coil pair maximum power / W	78.5	30.6
Auxiliary coil turns	180	36
Auxiliary coil pair maximum power / W	75.3	16.4
Electromagnet DQ power dissipation / W	2300	



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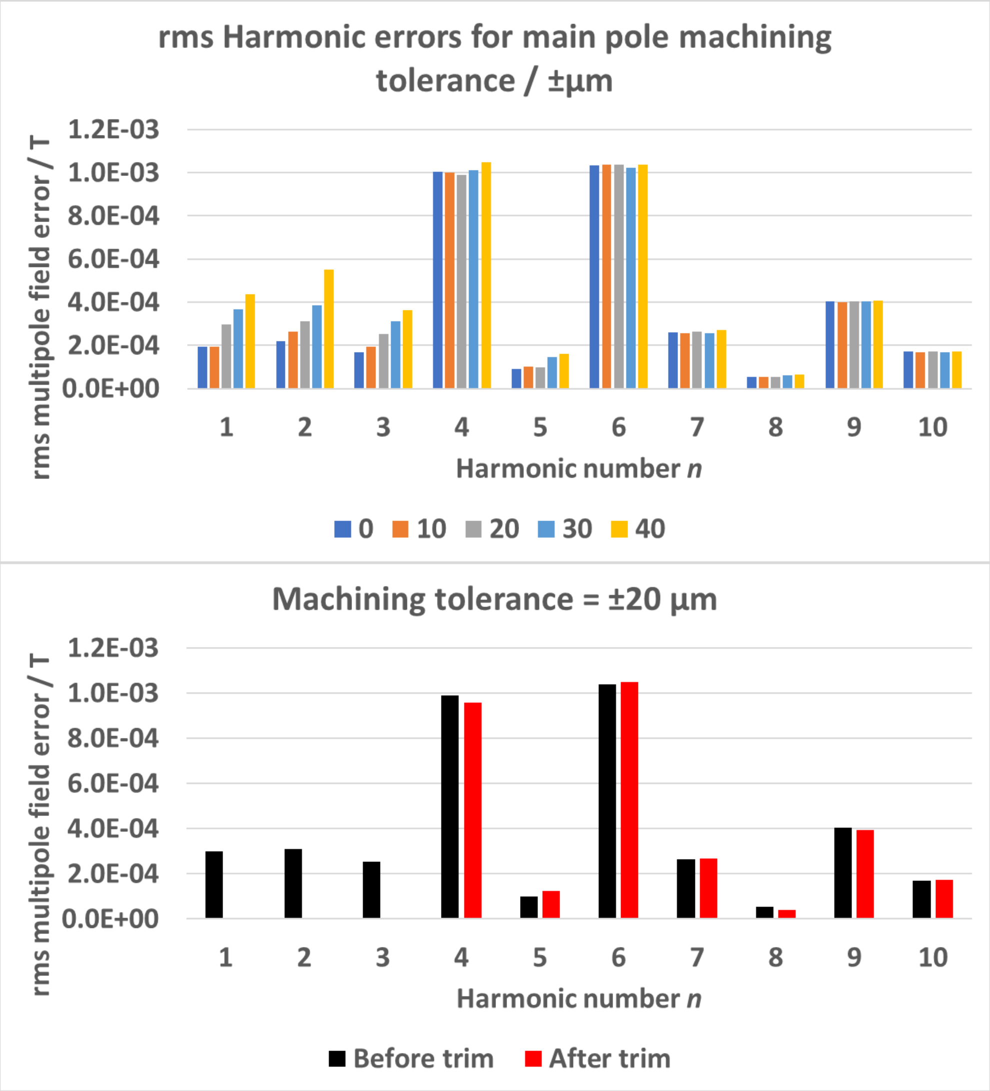
Tolerances and Trimming

- Machining tolerances modelled on profiles of main and auxiliary pole tips.
- Multipole errors for $n \geq 4$ reasonably independent of machining tolerance.
- Three-stage trimming process:
  1. Aux coil set to minimise sextupole.
  2. Main coil set to achieve gradient.
  3. Re-fiducialisation to set magnet centre/dipole.
- Trimming has little impact on higher order multipole errors.



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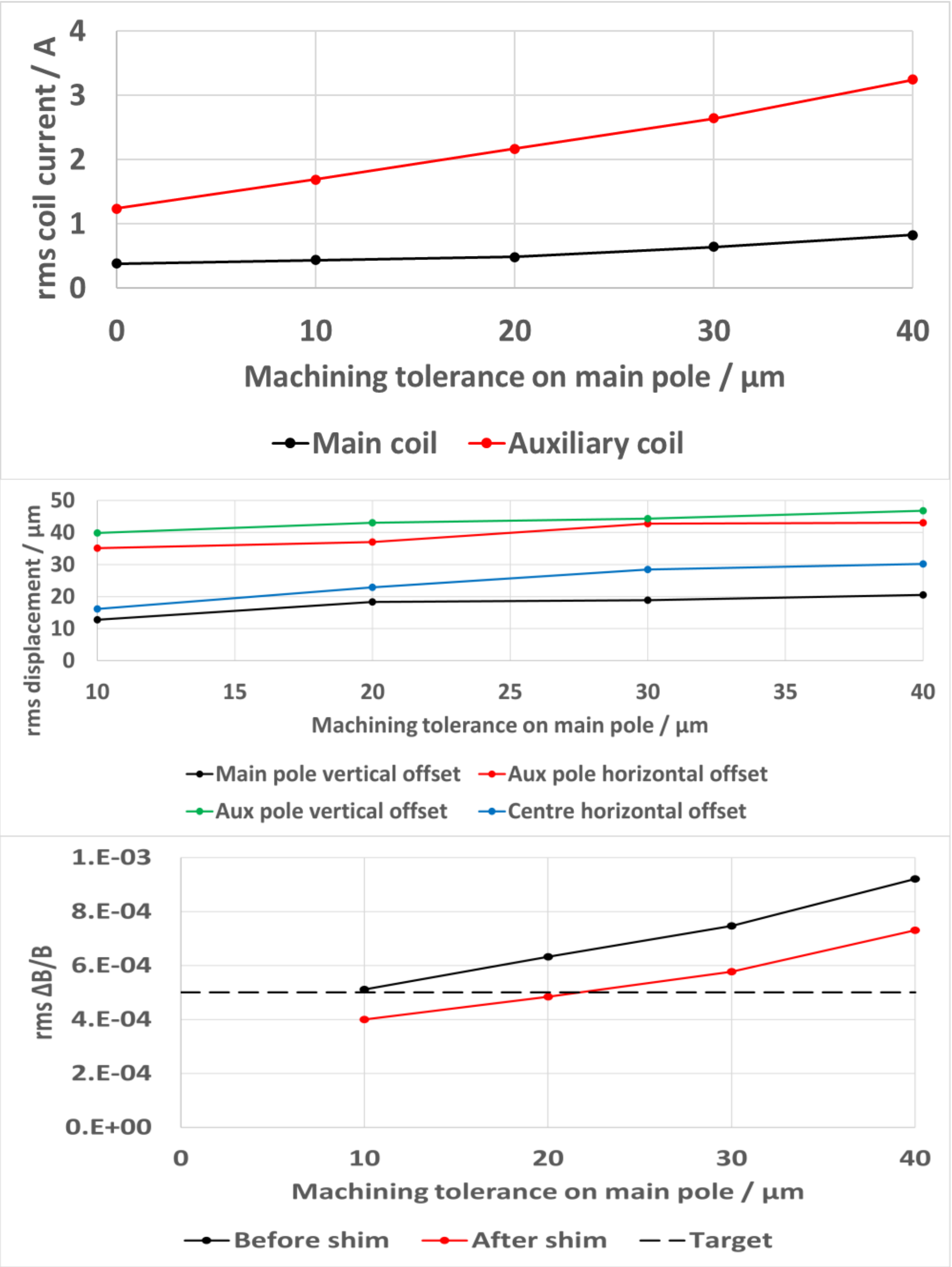
Mechanical Shimming

- Larger machining tolerances will require larger currents for trimming.
  - Higher nominal power.
  - Heat load on magnets during normal operation.
  - Reduced available tuning range.
- Can mechanically shim to nominal field values.
- Mechanical design will allow relative adjustment of horizontal and vertical pole offsets in range ±50 µm.
- Machining tolerances on main pole must be within ±20 µm to achieve target $\Delta B/B < 5 \times 10^{-4}$.



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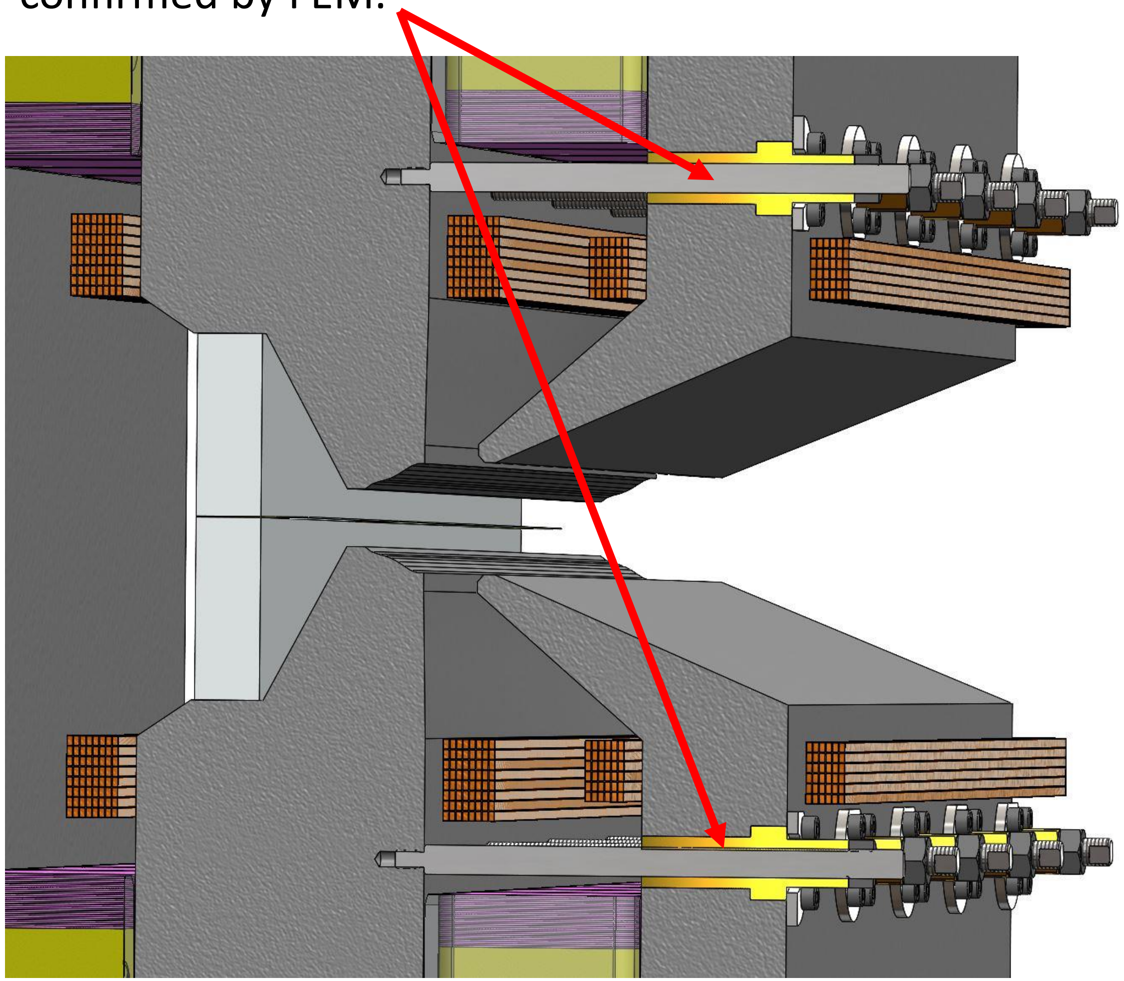
Mechanical Shimming

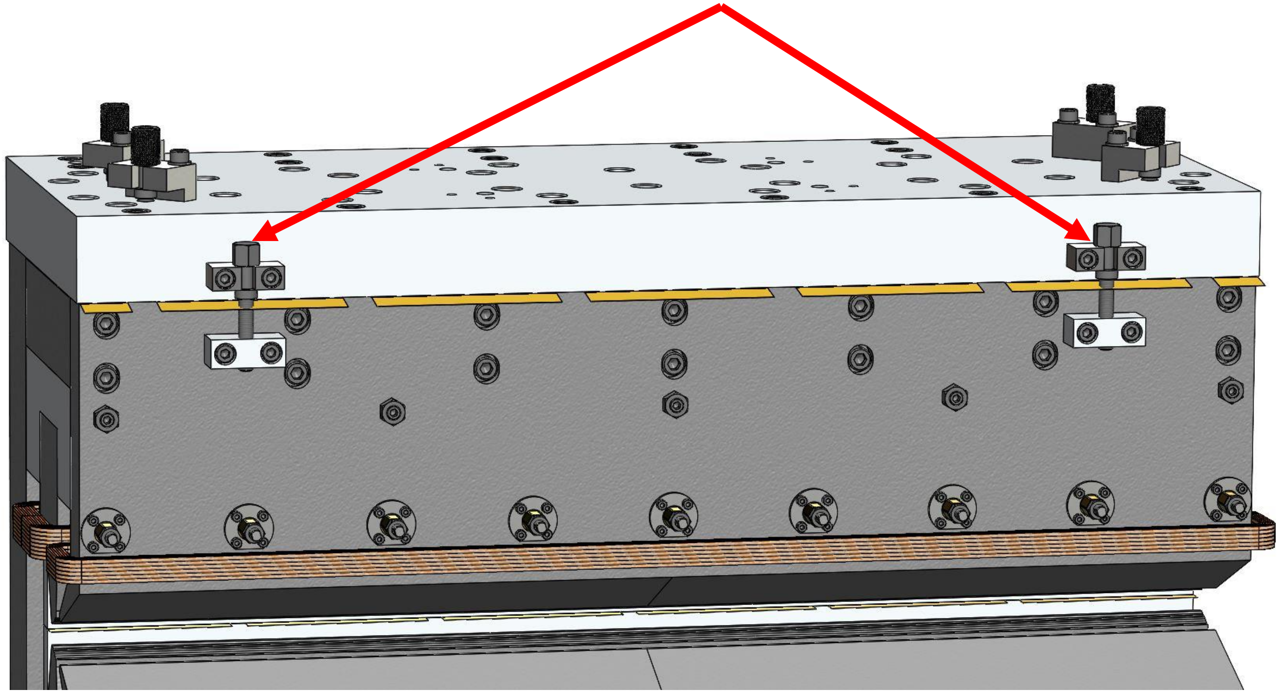
1. Threaded rods used to deform auxiliary poles for horizontal adjustment of auxiliary pole tips. Range of adjustment will be confirmed by FEM.



Note: vertical adjustment for main and auxiliary poles are pre-shimmed (300 µm thickness) to allow gaps to be increased or decreased.

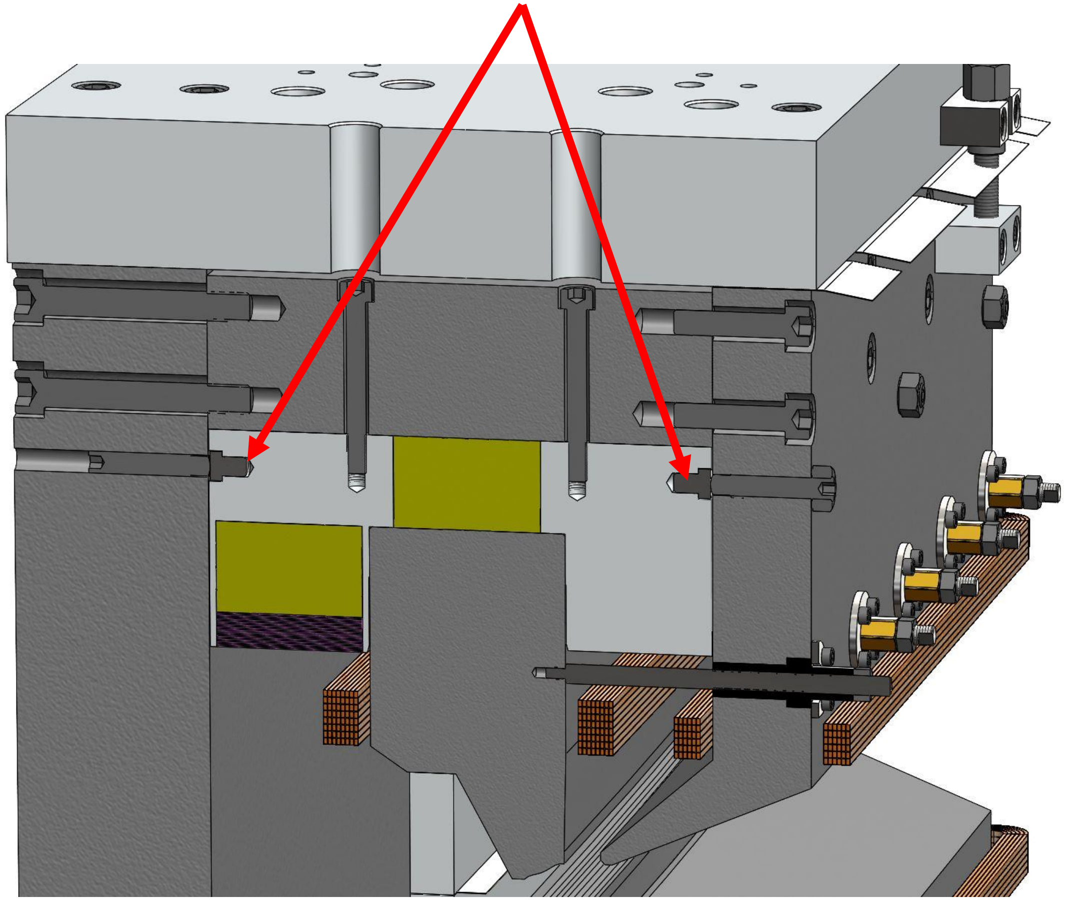
Shim thicknesses in range 10-50 µm.

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.

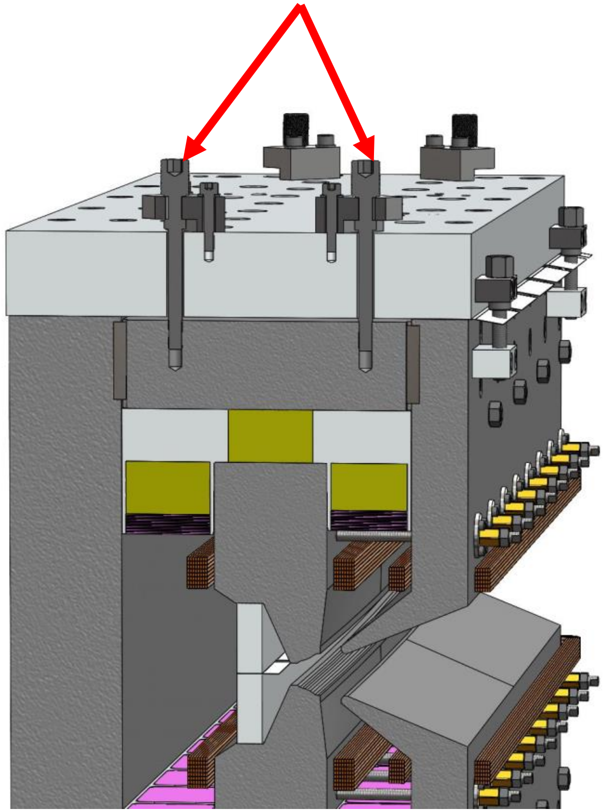


Mechanical Shimming

3. Two set screws used to move aluminium plate which holds the magnets and the top main pole horizontally. Bottom main pole will serve as a reference so will have no adjustment.

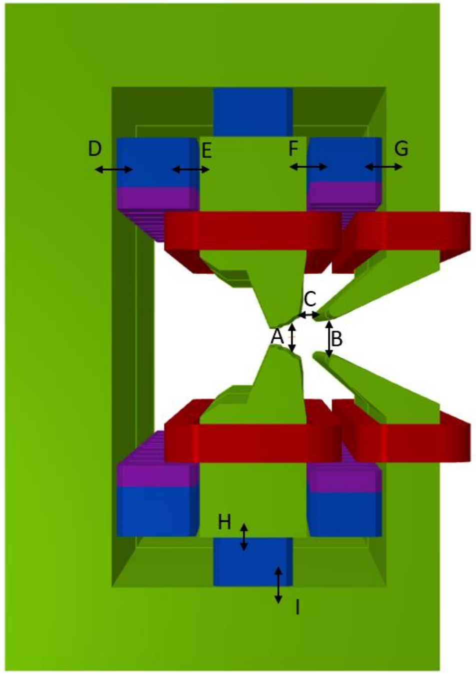


4. Screws for vertical adjustment of top main pole by moving top yoke arm vertically between the yoke backleg and the top auxiliary pole. These screws are used to open up the gap between main pole spacers to add/remove brass shims for vertical adjustment.

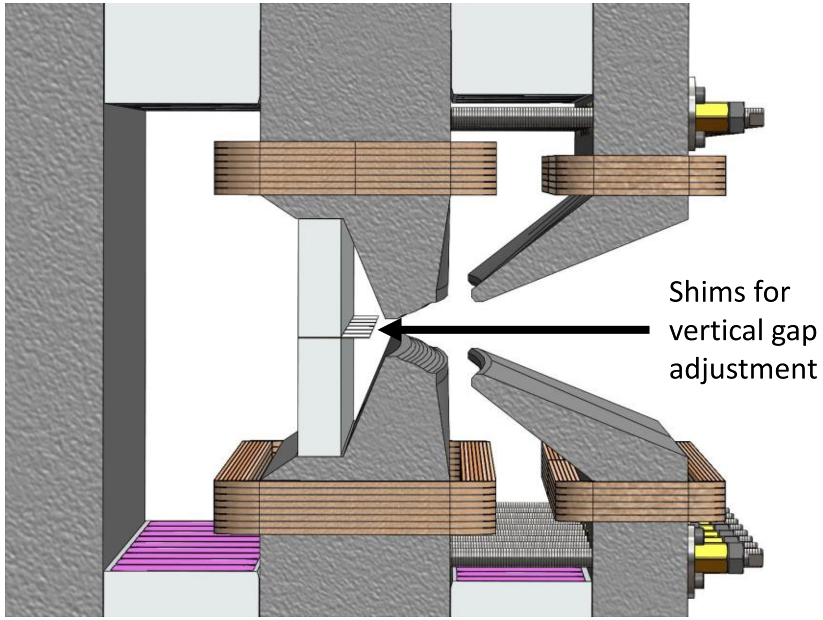


Magnetic Forces

- Large attractive forces between poles.
- Mechanical design must minimise deformations.
- Horizontal yoke arms in v2 design provide additional mechanical support.
- Gaps spacers can be used to fix vertical gap between main pole arms.



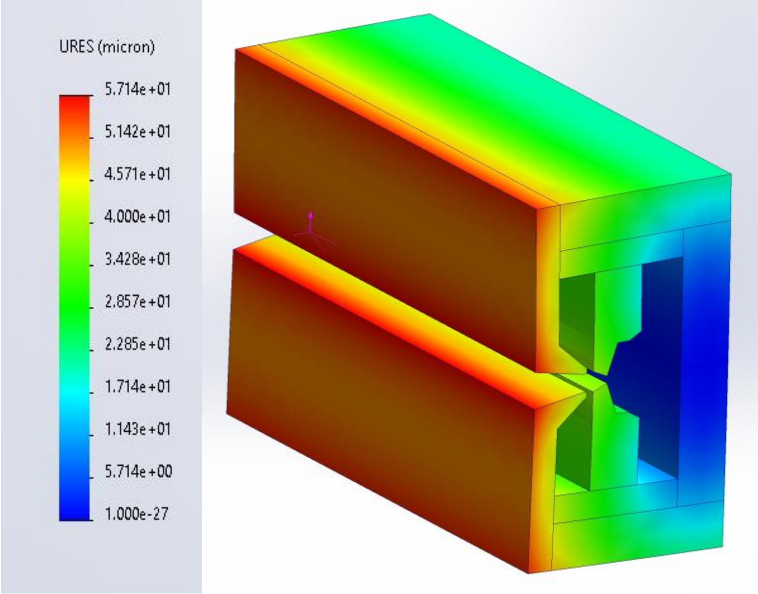
Label	Description	Force Magnitude / kN
A	Vertical force between main poles	9.8
B	Vertical force between auxiliary poles	<0.1
C	Horizontal force between main and auxiliary pole	1.7
D	Horizontal force between type A array and backleg	9.0
E	Horizontal force between type A array and main arm	6.5
F	Horizontal force between Type F array and main arm	5.7
G	Horizontal force between type F array and auxiliary arm	7.6
H	Vertical force between type B array and main arm	20.0
I	Vertical force between type B array and yoke	20.0



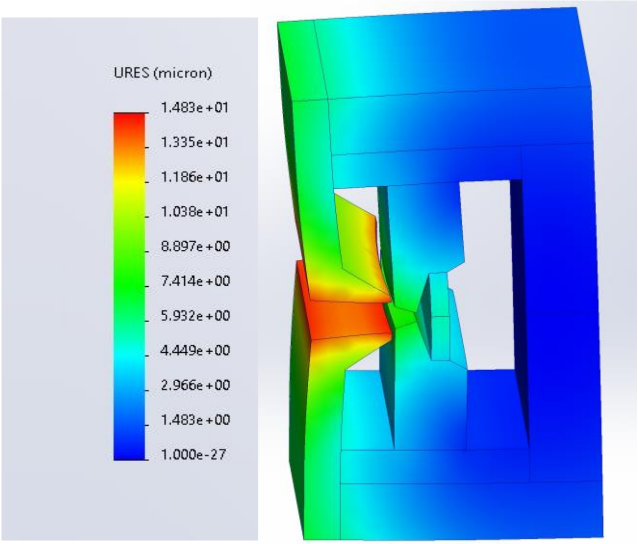
Calculated Displacements

- Model parameters (earlier design):
  - Vertical force between main poles: 30 kN
  - Horizontal force between main and auxiliary poles: 5 kN.
- Largest displacements on auxiliary poles (~57 μm).
- Adding spacers between main poles reduces displacements by ~4x.
- Spacers can also be used for shimming.
- Need to reperform analysis with latest model (smaller forces, smaller displacements predicted).

Without spacers



With spacers



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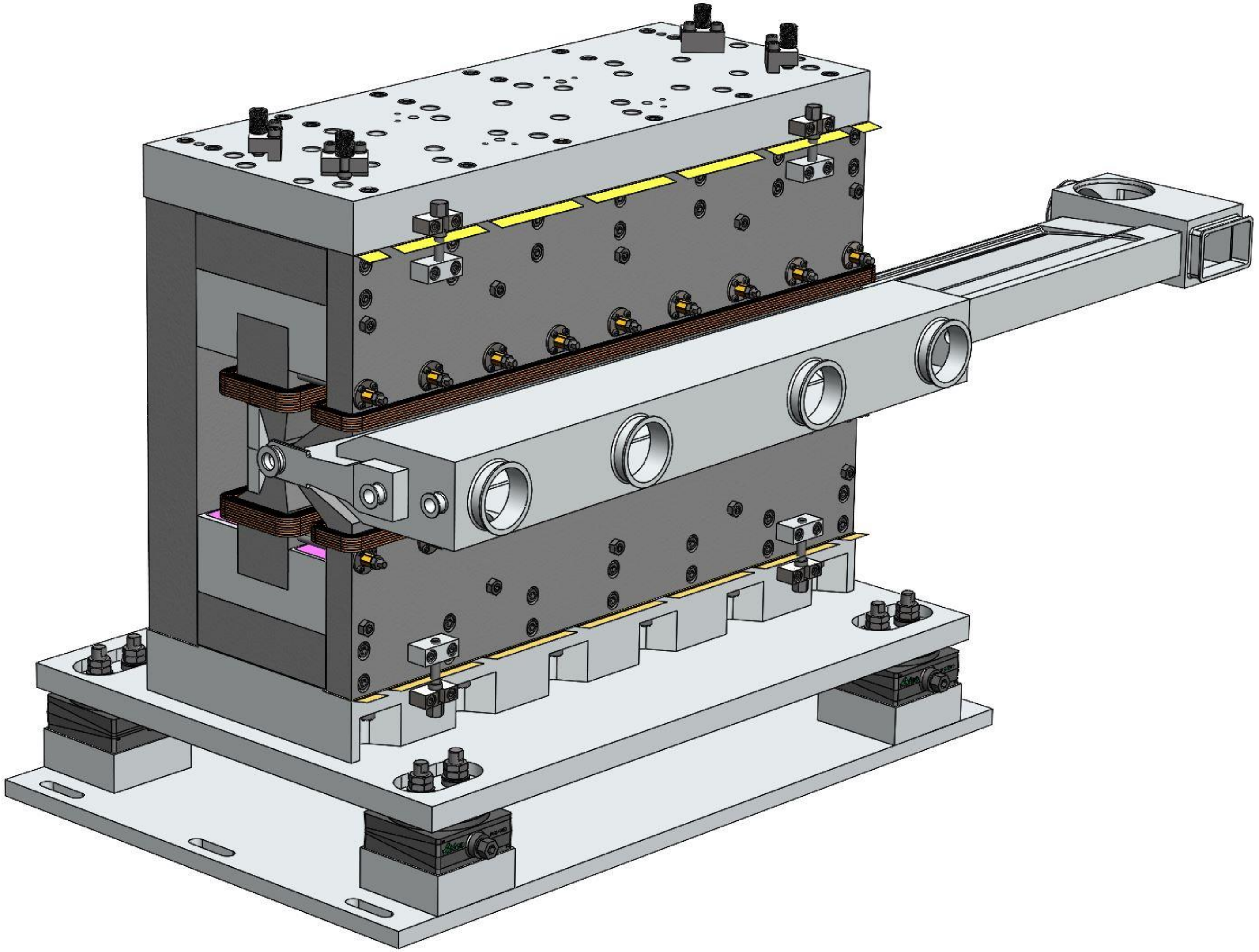
Full Mechanical Design

- Mechanical design of full assembly near completion.
- Need to finalise details of base plate for integration with Diamond girder.
- Need to finalise mechanical shimming design.
- Aim to complete mechanical design by 30/04/2024.



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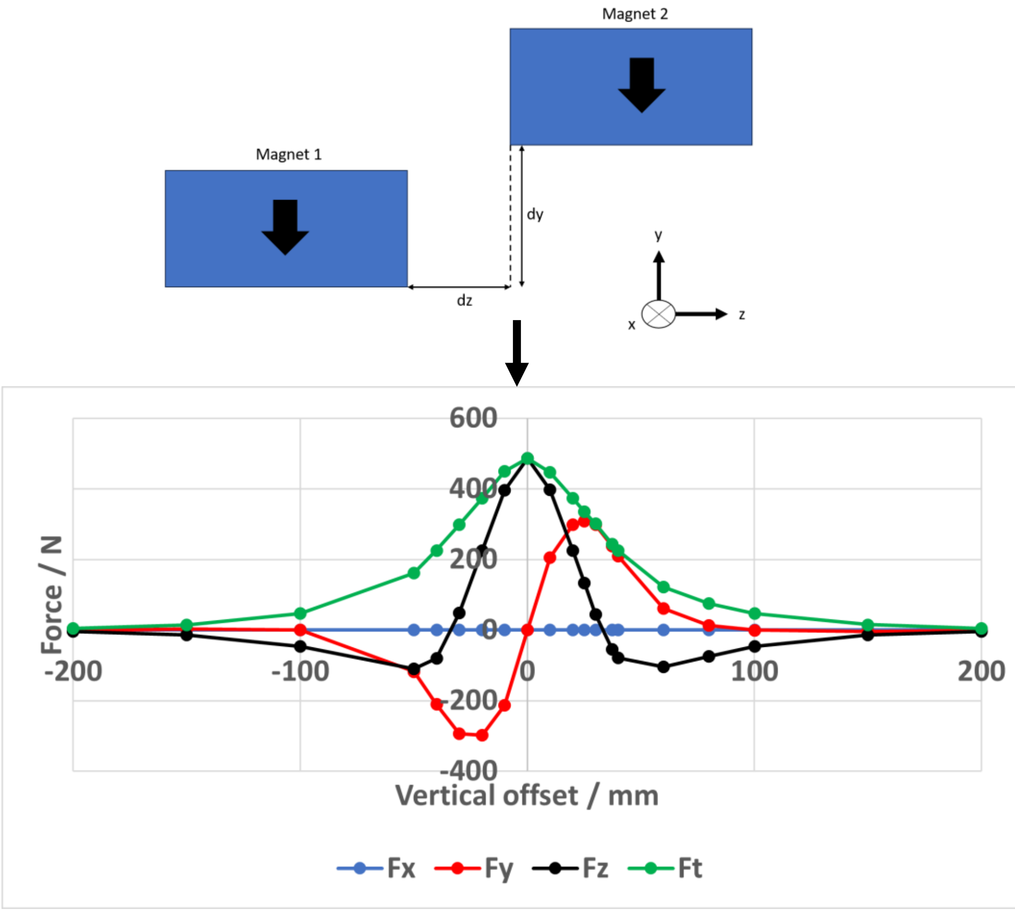
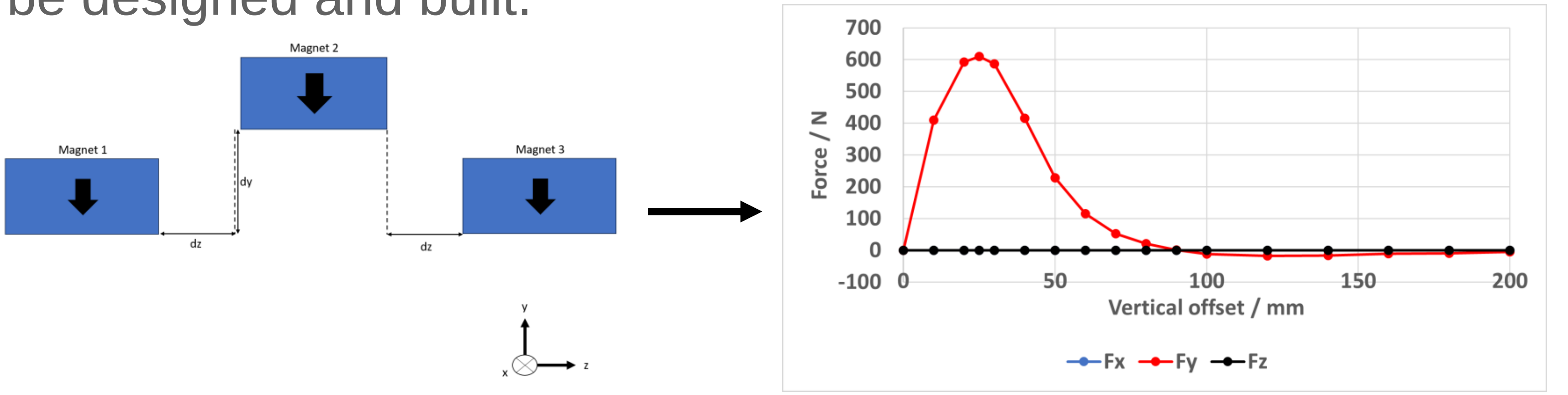
Assembly Forces

- Forces acting between magnet blocks during assembly.
- Mechanical design of assembly tooling must be able to handle these forces.
- Repulsive forces acting during assembly of type B magnet blocks.
- Negligible magnetic force at distances > 200 mm from fixed array.
- Assembly tooling needs to be designed and built.





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Conclusions and Future Planning

- Magnetic design of HEPTO v2 using spare undulator magnet blocks is complete.
- Mechanical design being finalised – plan to finish by end of April.
- Maximum power requirement per magnet (5 A per coil) = 50 W.
- Equivalent electromagnet requires 2.3 kW + water cooling.
- Next steps: procurement of materials for building prototype magnet.
- Plan is to construct prototype at Kyma by end of September 2024.
- Afterwards, magnetic measurements will be used to verify the performance of the prototype with respect to magnetic modelling at Daresbury.

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Thank you

Acknowledgements:

- Ben Shepherd (STFC)
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- Alfie Shahveh (Diamond Light Source)

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