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I.FAST 2nd Annual Meeting– Task 11.3 Permanent Magnet Quadrupoles & Combined Function Magnets for Ultra Low-Emittance Rings

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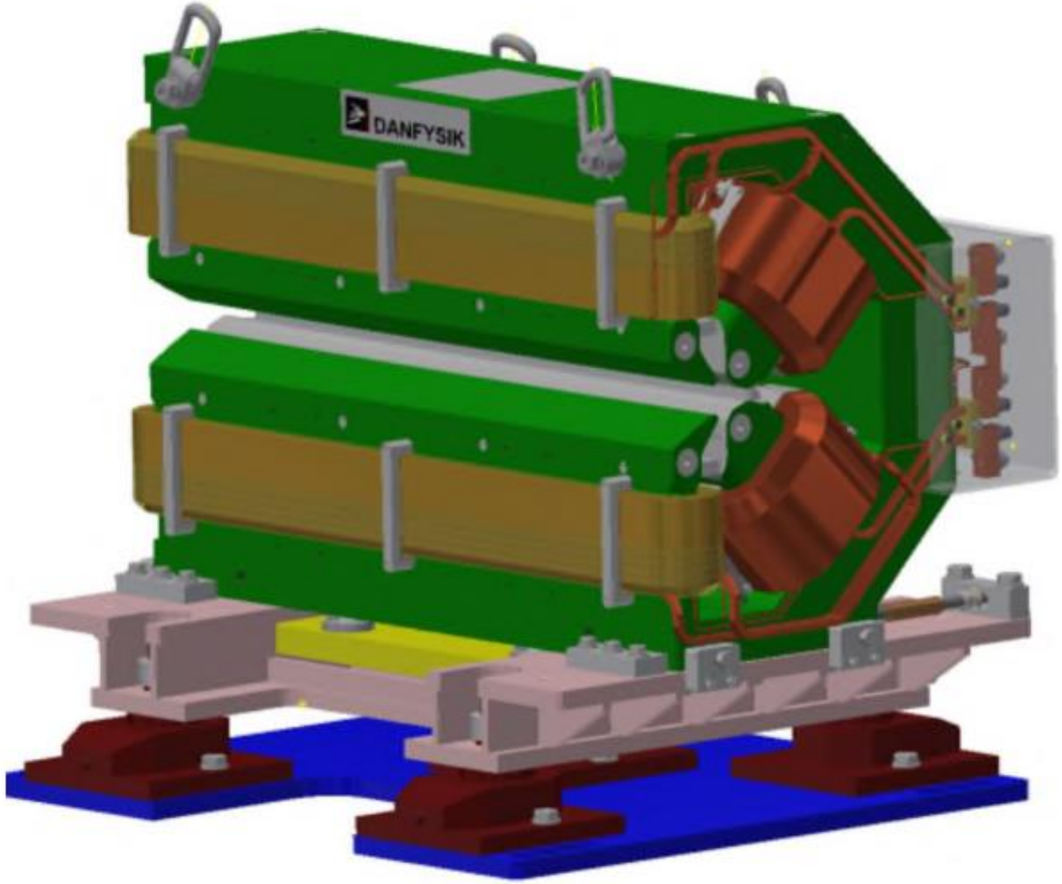
Introduction

- 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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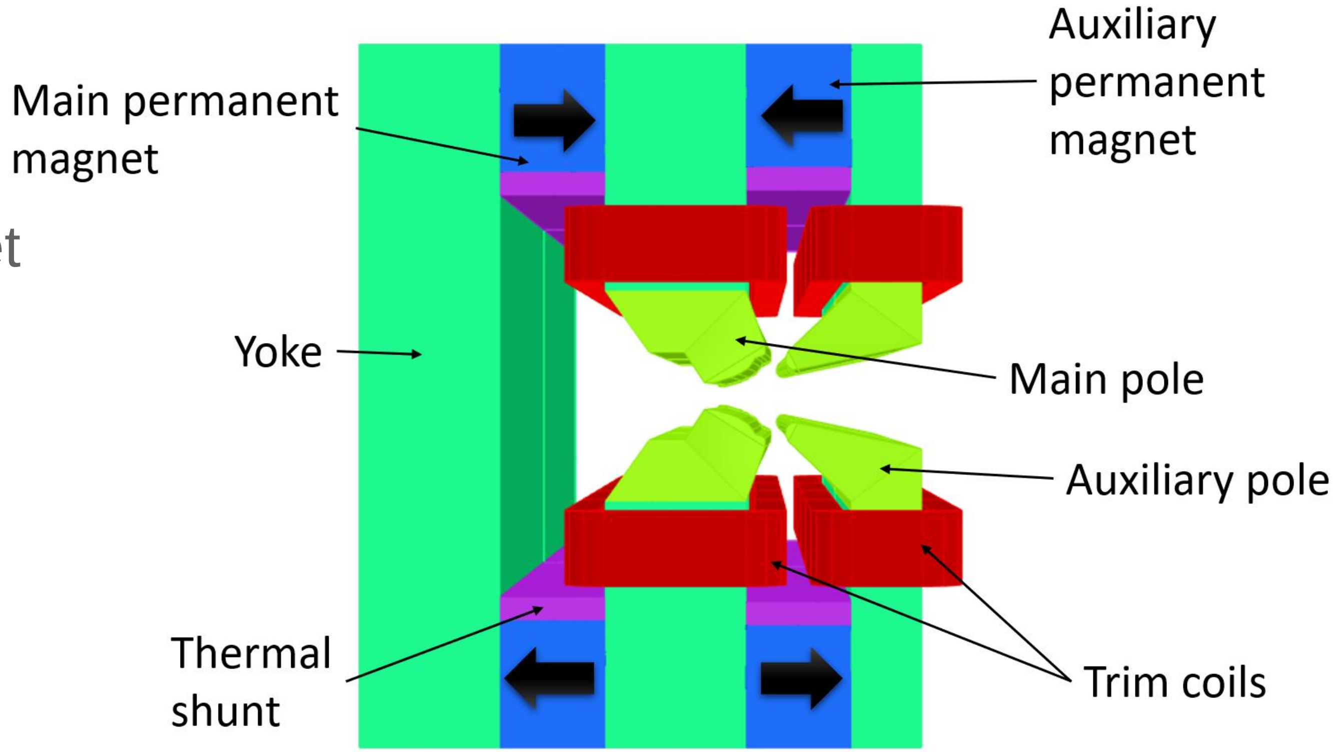
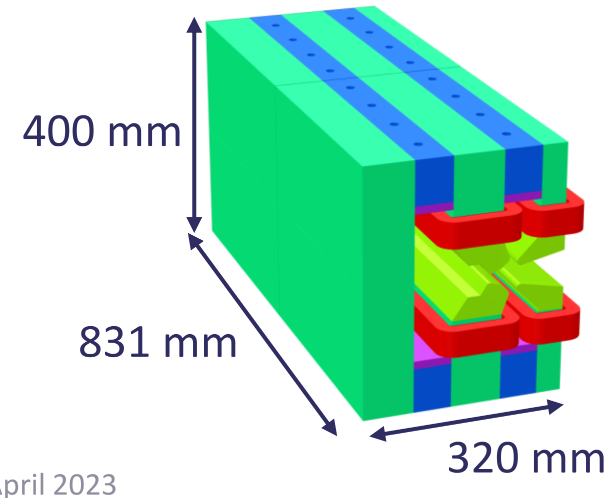
Design Overview

- 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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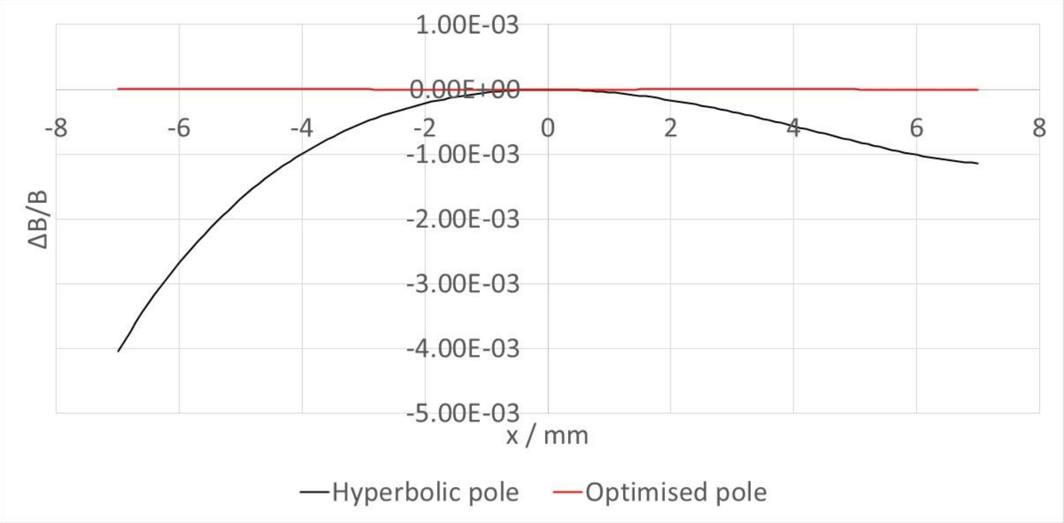
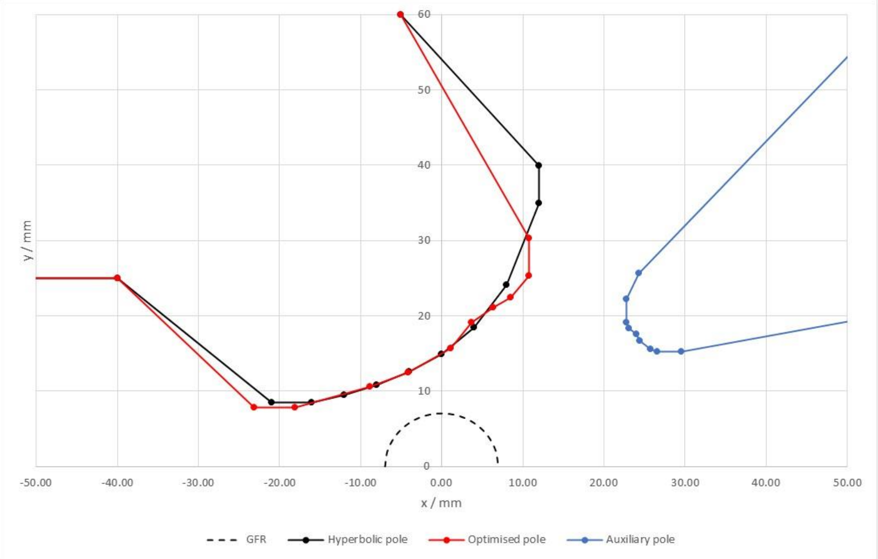
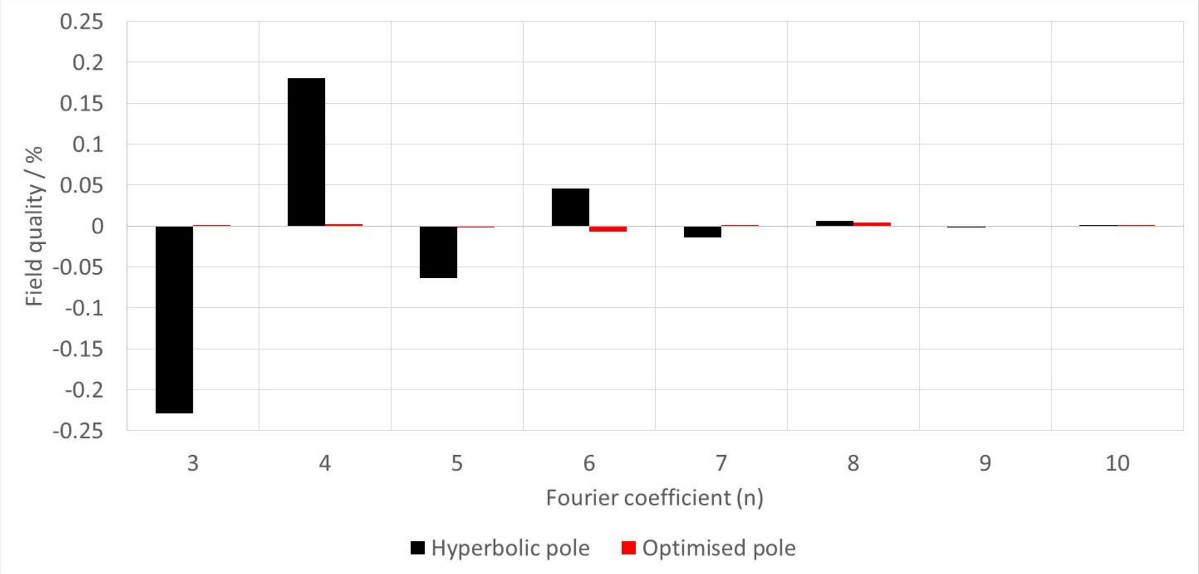
Pole Shape Optimisation

- Pole tip design optimised in Opera 2D.
- Pole shaping algorithm used to minimise multipole errors [1].
- Required field quality $\Delta B/B < 5 \times 10^{-4}$.







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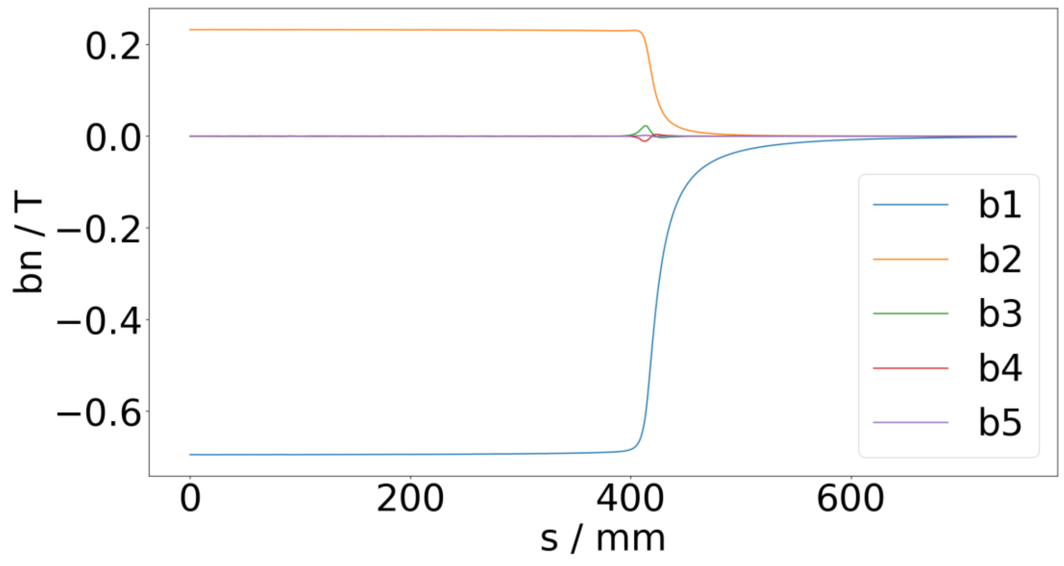
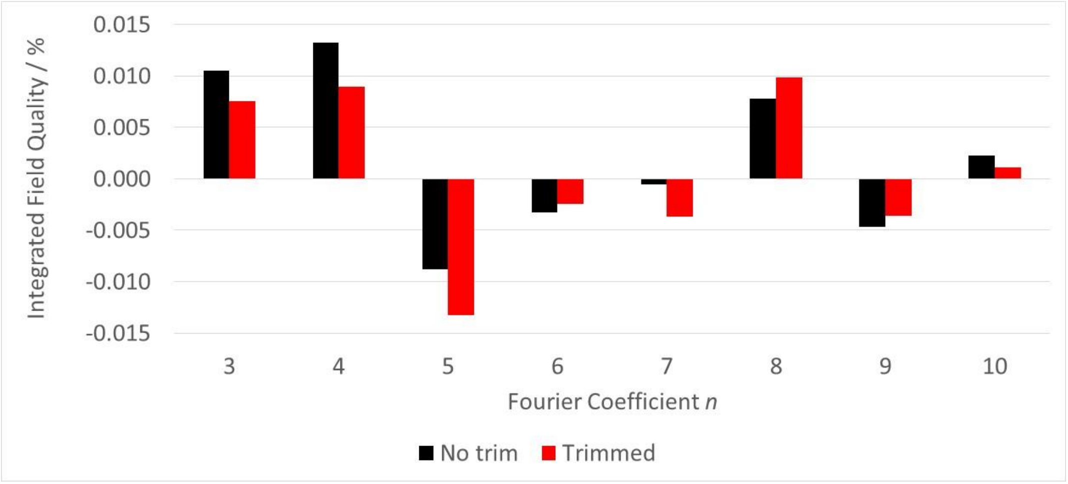
[1] G. Le Be, J. Chavanne and P. N'gotta, "Shape optimization for the ESRF II magnets," in *IPAC 2014: Proceedings of the 5th International Particle Accelerator Conference*, 2014.

3D Field Quality

- Integrated field quality assessed in Opera 3D.
- Pole tips curved to follow beam trajectory and give constant dipole field.
- Effective length of quadrupole shorter than dipole.
- Central gradient increased and pole profile adjusted slightly to give target field integrals.
- Trim coils reduce integrated sextupole, octupole terms.





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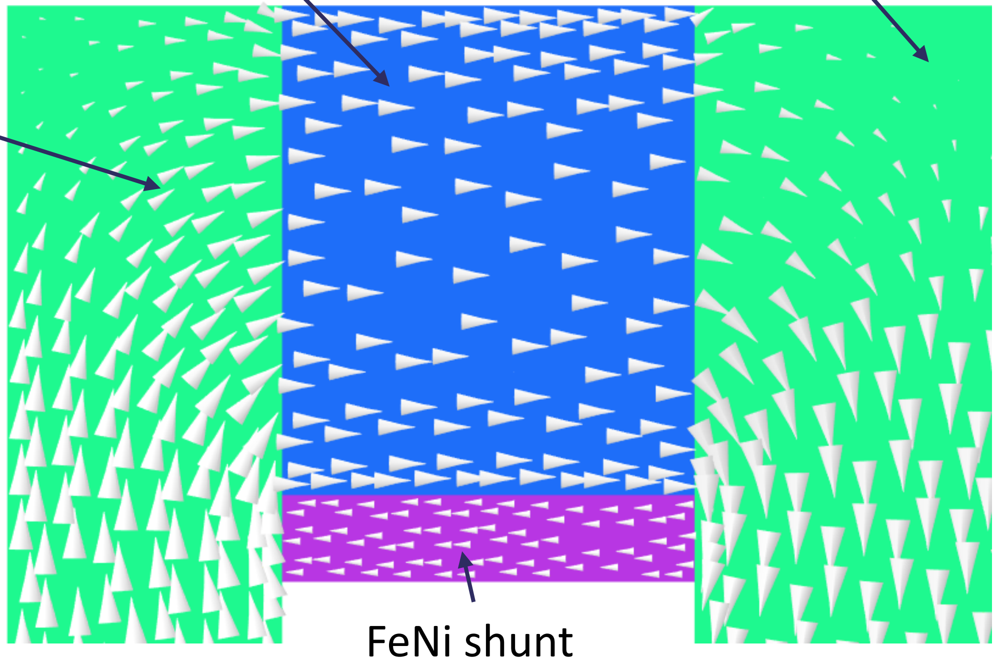
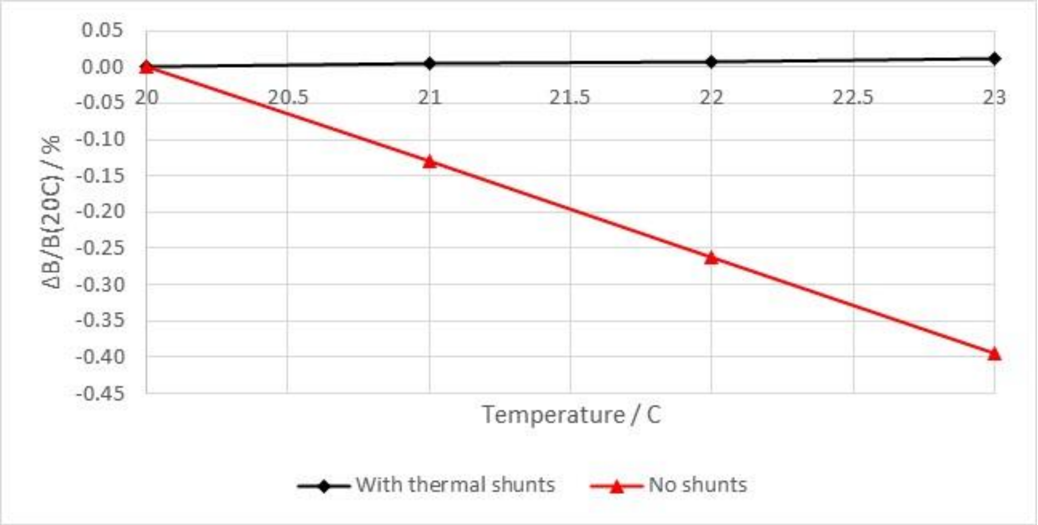
Thermal stability

- Permanent magnet strength decreases with increased temperature.
- FeNi shunts used to provide improved thermal stability.
- Shunt has negative temperature coefficient; as temperature increases, saturation polarisation decreases.
- Dipole thermal stability from -0.131% / degree without shunt to +0.004% / degree with shunt
- 0.01% variation typical due to power supply fluctuation in electromagnets.





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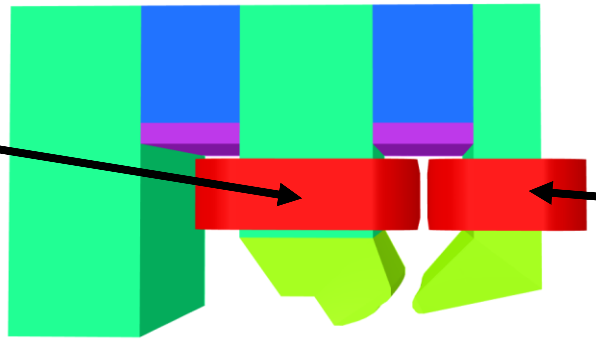
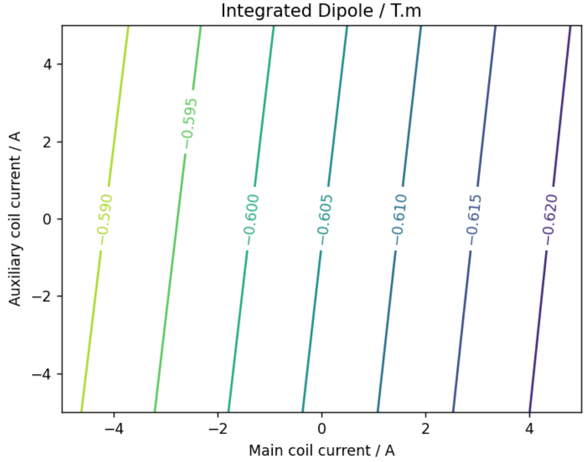
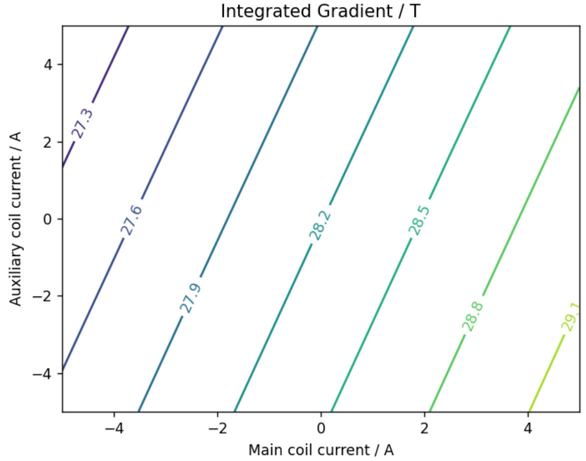
Tuning Range

- Air cooled coils used to independently trim dipole and quadrupole fields by ±2.5%.
- Currents limited to 5 A to allow air cooling.
- Tuning is inefficient due to permanent magnets in magnetic circuit.
- Required tuning range cannot be achieved with air-cooled coils.







Change in integrated dipole field from nominal / %	Change in integrated gradient field from nominal / %	Required main coil current / A	Required auxiliary coil current / A
0	0	-0.020	0.051
-2.5	0	5.718	16.597
+2.5	0	-5.759	-16.494
0	-2.5	-1.465	-16.741
0	2.5	1.424	16.843

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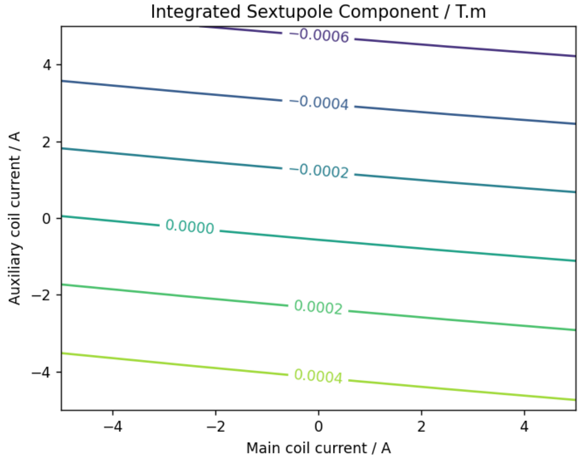
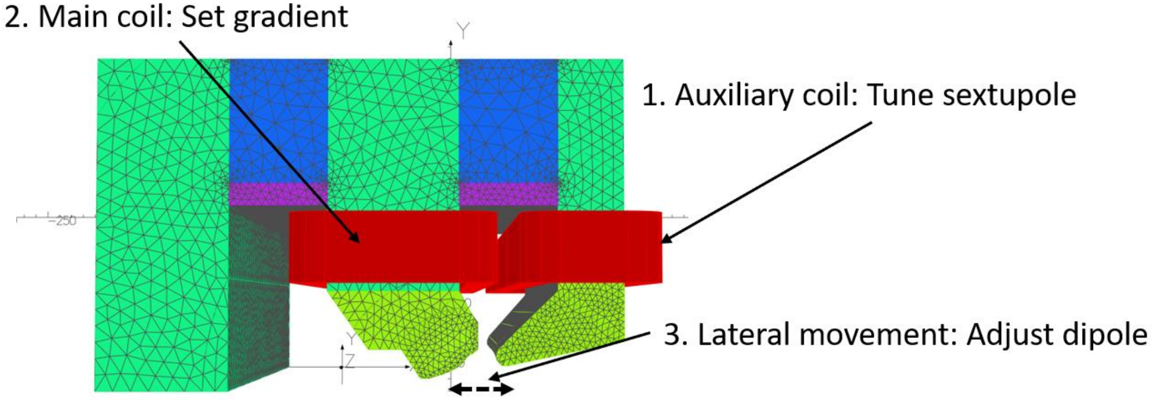
Mechanical Tuning

- Main and auxiliary coils cannot achieve independent field tuning in isolation.
- Lateral movement of magnet can tune on-axis dipole independent of gradient without coil currents.
- Auxiliary coil used to tune sextupole field component.
- Main coil used to tune gradient.
- With ±1mm lateral movement of magnet in-situ, required tuning can be achieved with air-cooled coils.





Change in integrated dipole field from nominal / %	Change in integrated gradient field from nominal / %	Estimated required main coil current / A	Estimated required auxiliary coil current / A	Required lateral offset / mm
0	0	-0.225	-0.539	0.02
-2.5	0	-0.225	-0.539	0.56
+2.5	0	-0.225	-0.539	-0.52
0	-2.5	3.985	-1.026	-0.50
0	2.5	-4.435	-0.051	0.56

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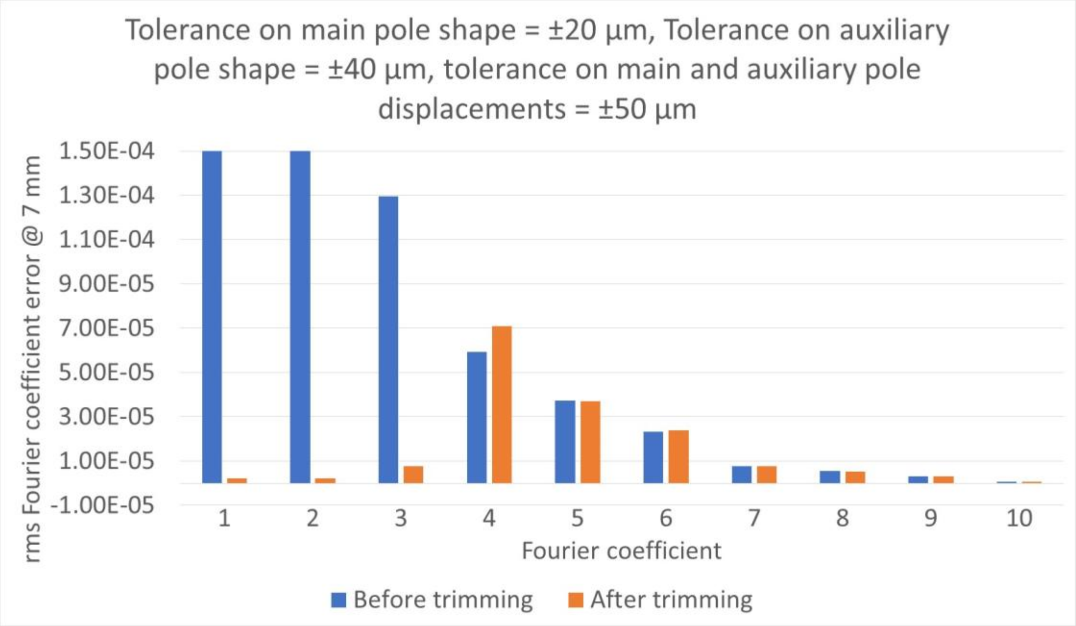
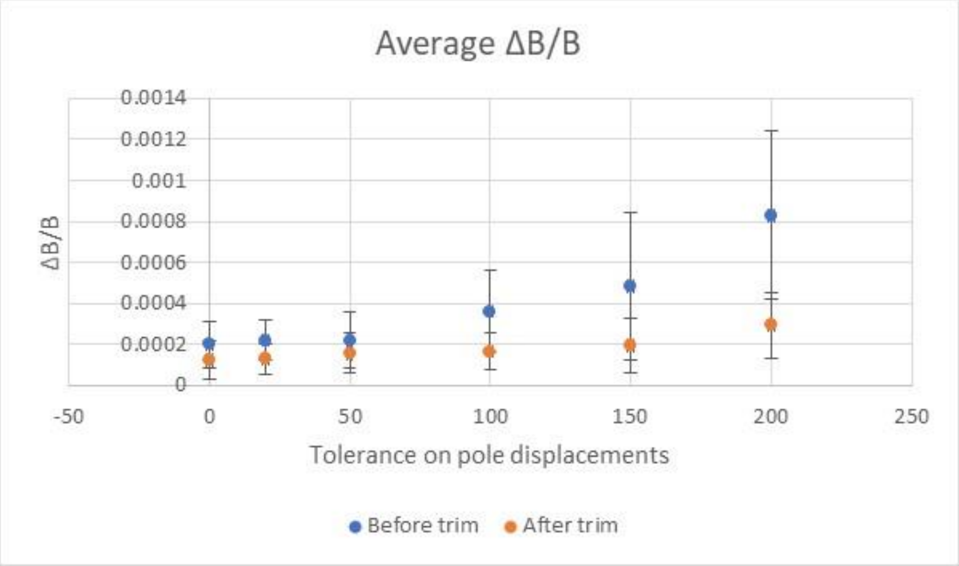
Tolerance Studies

- Required field quality ΔB/B < 5×10^{-4}.
- Sextupole component < 10^{-3}.
- Machining and assembly tolerances will negatively impact field quality compared to nominal magnetic design.
- Auxiliary coil can trim undesired sextupole component introduced by tolerances.
- Modelling shows required machining tolerances of ±20 μm on main pole, ±40 μm on auxiliary pole.
- Displacement tolerances < 200 μm.





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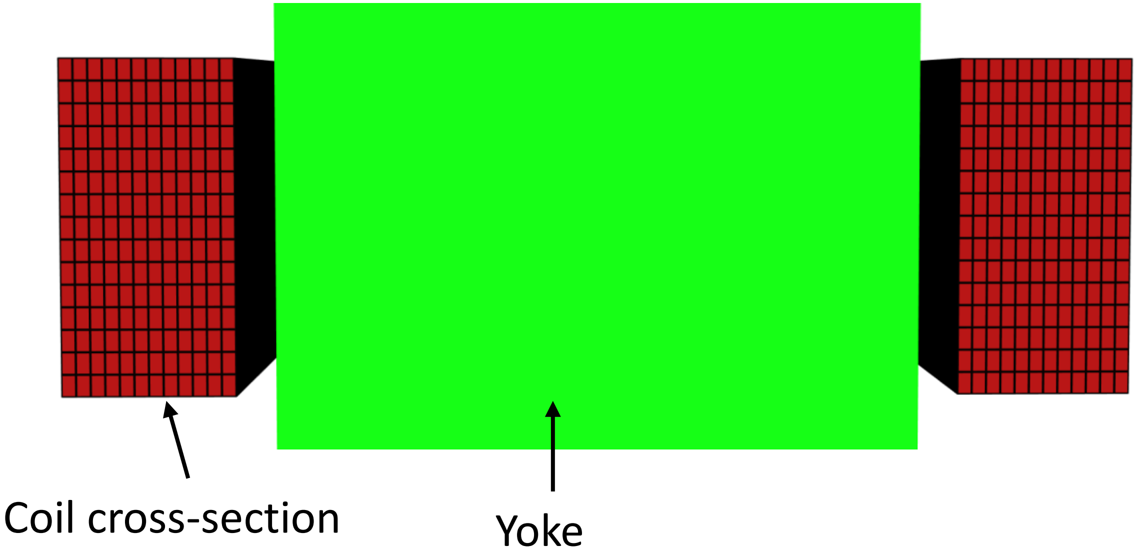
Final Coil Design

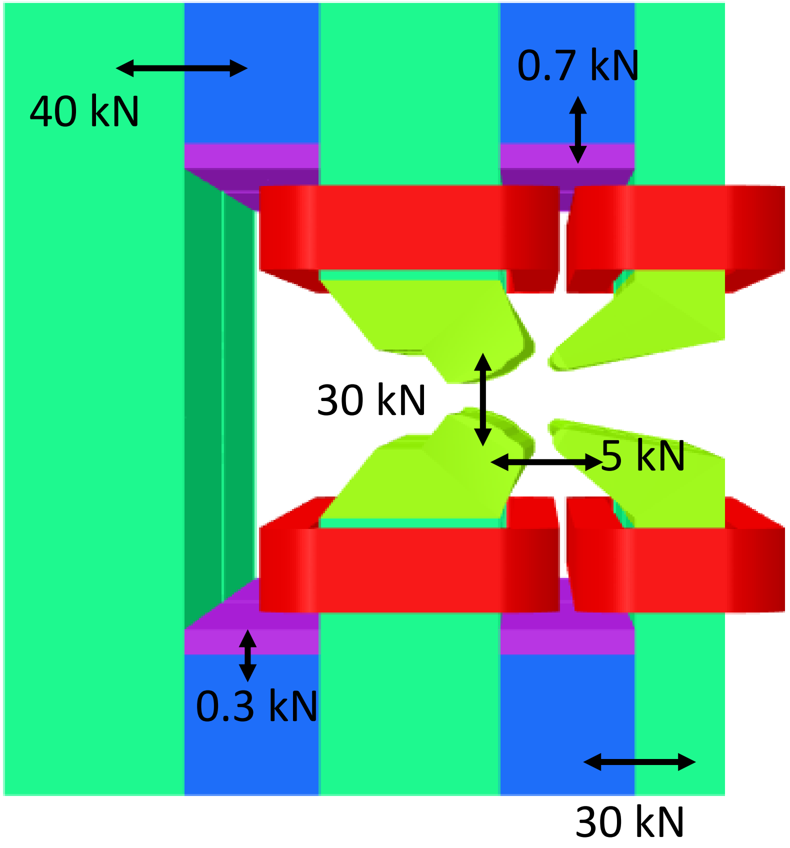
- Coils wound from solid insulated copper wire.
- Air cooled coils – no need for water cooling infrastructure.
- Some current expected at nominal operation to trim fields (account for magnetisation and machining tolerances
- Nominal power dissipation of equivalent electromagnet = 2.3 kW.
- Bipolar power supply required for field tuning.

	Main coil	Auxiliary Coil
Coil resistivity / Ω.mm	1.86E-5	
Maximum current / A	5	
Wire width bare (insulated) / mm	2.6 (2.8)	
Wire height bare (insulated) / mm	1.6 (1.8)	
Number of turns	180	180
Coil height / mm	42	42
Coil width / mm	21.6	21.6
Average turn length / mm	1951	1851
Coil resistance / Ω	3.14	3.01
Maximum voltage / V	15.7	15.1
Maximum power dissipation / W	78.5	75.3
Nominal current / A	-0.225	-0.539
Nominal power dissipation / W	0.16	0.88



Assembly and Forces

- Large attractive magnetic forces between permanent magnet blocks and steel yoke.
- Forces need to be considered during assembly of magnet to prevent injury or damage to the magnet.
- Forces between poles in assembled magnet could cause deformation and hence reduced field quality.
- Movement of components must be prohibited.



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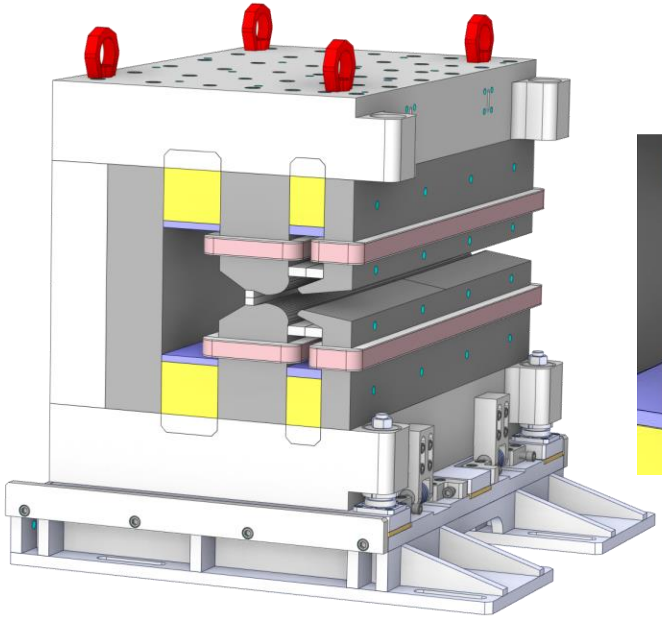
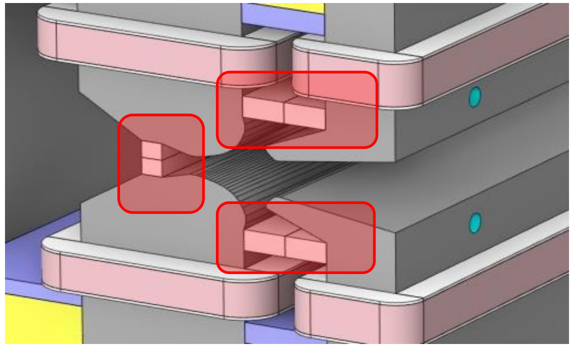
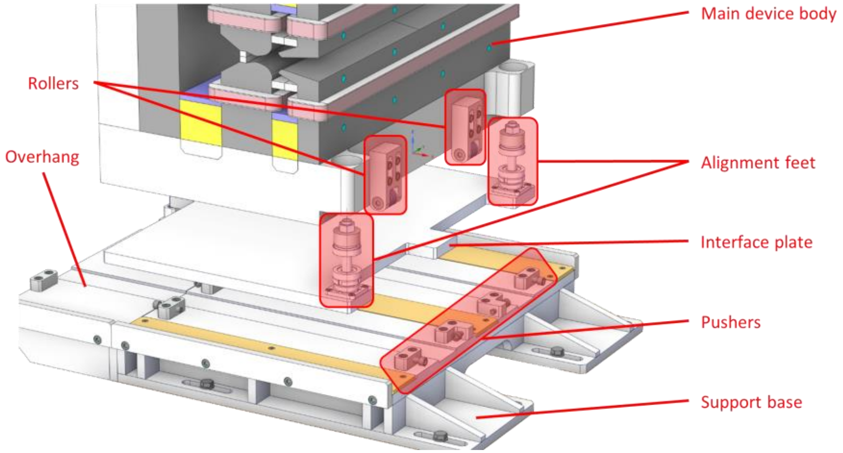
Mechanical Design Overview

- Conceptual mechanical design for assembling and mounting magnet produced by Kyma.
- Aluminium C-shape support frame.
- Device can be inserted around vacuum chamber.
- Gap spacers control separation of poles subject to attractive forces.
- Support base allows adjustment of displacement and angular alignment.
- Can in-situ lateral adjustment be achieved?







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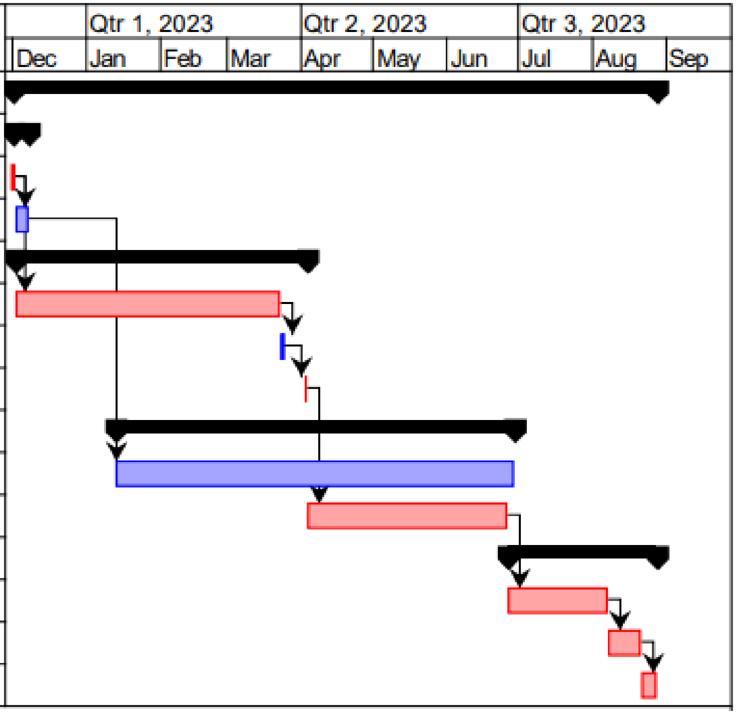
Future Planning

- Time plan correct as of 12/01/2023.
- Delays in procurement of permanent magnet and thermal shunt materials due to high prices.

		Name	Duration	Start	Finish	Predecessors
1		**HEPTO project**	**193 days**	**01/12/22 08:00**	**28/08/23 17:00**	
2		**Magnetic Design HEPTO**	**6 days**	**01/12/22 08:00**	**08/12/22 17:00**	
3		Final Magnetic Design Review	1 day	01/12/22 08:00	01/12/22 17:00	
4		Magnet and Pole Specifications	5 days	02/12/22 08:00	08/12/22 17:00	3
5		**Final Mechanical Design**	**87 days**	**02/12/22 08:00**	**03/04/23 17:00**	
6		Final mechanical design & assembly tools design	80 days	02/12/22 08:00	23/03/23 17:00	3
7		Final design review meeting	1 day	24/03/23 08:00	24/03/23 17:00	6
8		Mechanical design approval	1 day	01/04/23 08:00	03/04/23 17:00	7FS+5 days
9		**Production**	**120 days**	**13/01/23 08:00**	**29/06/23 17:00**	
10		Magnetic material production	120 days	13/01/23 08:00	29/06/23 17:00	4FS+25 days
11		Mechanical parts production	60 days	04/04/23 08:00	26/06/23 17:00	8
12		**Assembly and Measurements**	**45 days**	**27/06/23 08:00**	**28/08/23 17:00**	
13		Mehcanical & Magnetic Assembly	30 days	27/06/23 08:00	07/08/23 17:00	11
14		Magnetic Measurements	10 days	08/08/23 08:00	21/08/23 17:00	13
15		Final Reports	5 days	22/08/23 08:00	28/08/23 17:00	14



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Conclusions and Future Planning

- Magnetic design is complete.
- Mechanical design being finalised.
- Nominal power requirement per magnet (for field trimming) < 2 W.
- Maximum power requirement per magnet (5 A per coil) = 150 W.
- Equivalent electromagnet requires 2.3 kW + water cooling.
- Next steps: procurement of materials for building prototype magnet.
- Some delays due to prices and availability of permanent magnet and thermal shunt material.
- Plan is to construct and test prototype by end of August 2023.

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Thank you

Acknowledgements:

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