Vacuum chamber and Magnet design : Magnet tolerances & Magnet prototype

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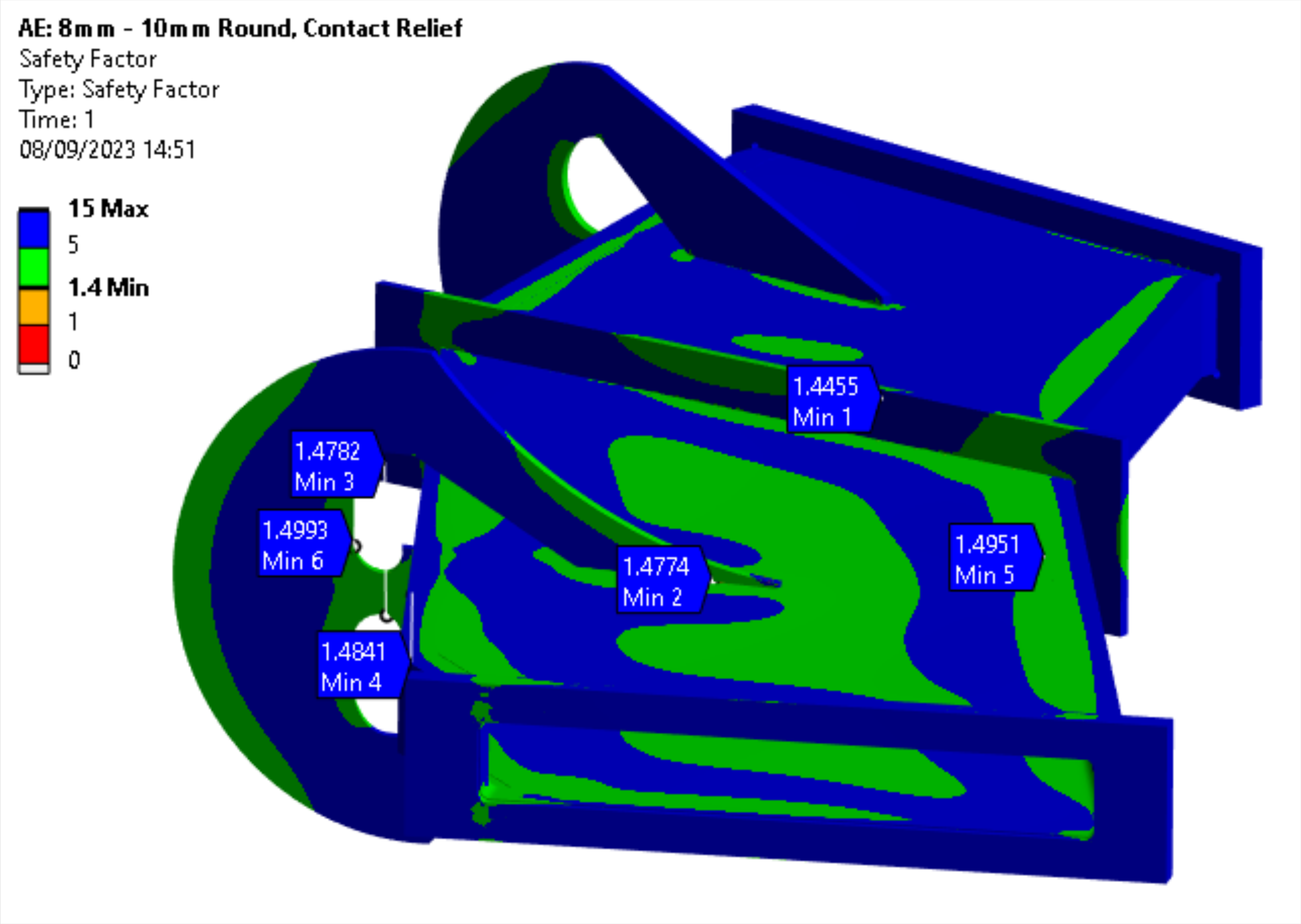
CSNS collaboration meeting

Vacuum chamber

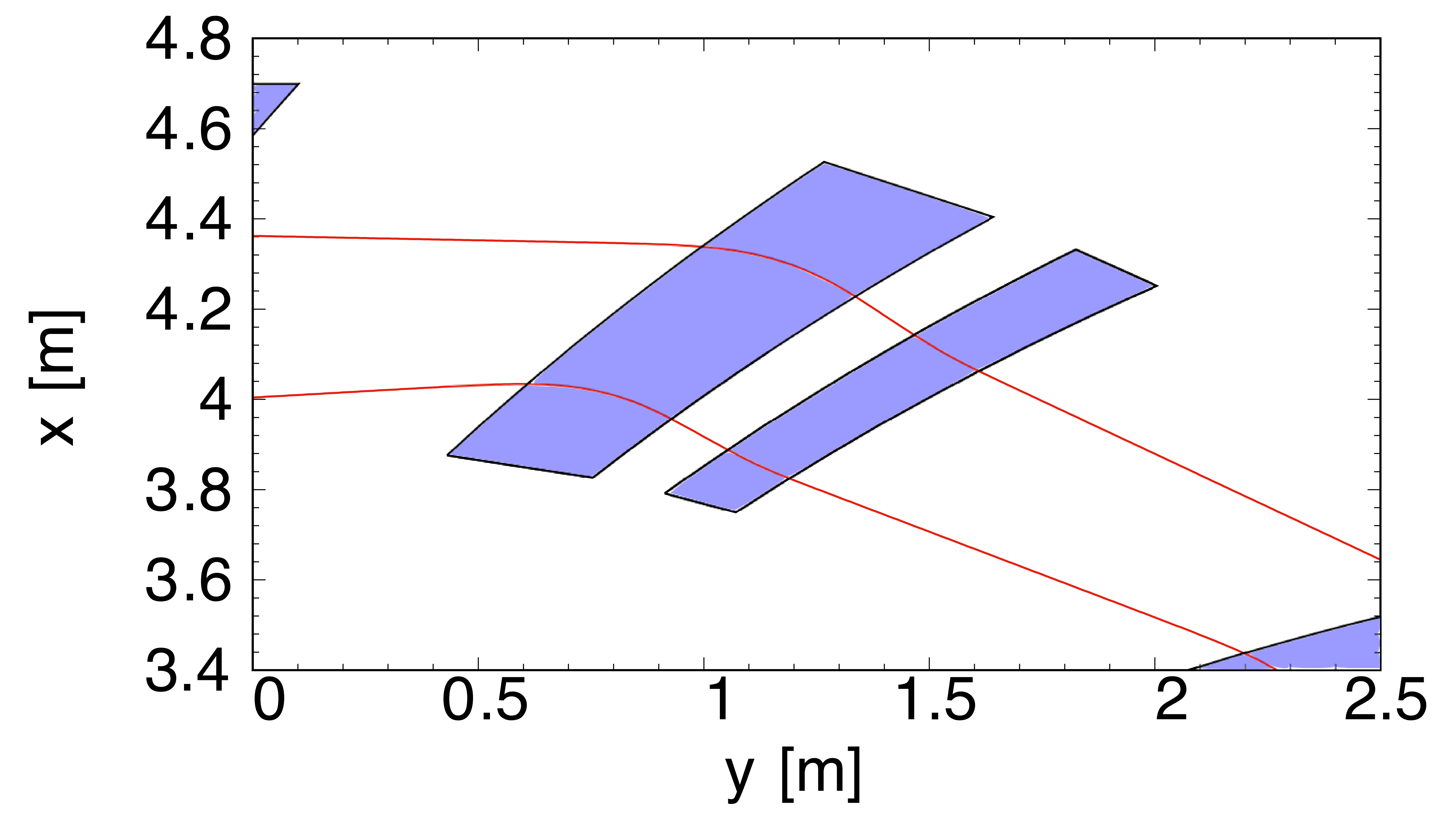
- Mechanical design (Ansis) to study the necessary thickness of the vacuum chamber
- Ansis study with maximum deflection of 2 mm
- Titanium (Ti-6Al-4V), Aluminium (6063 T6) and Stainless steel (316LN) were considered.
- Stainless steel with 8 mm thickness suitable with round internal corners and external optimised rib.



(Mitchell Kane)

Spiral FFA

- Fixed Field alternating gradient Accelerator option for ISIS-II
- DC magnets
- High longitudinal dynamics flexibility (repetition rate, several target stations)
- FETS-FFA ring: proof of principle for high power pulsed operation



Scaling FFA field law:

$$B = B_0 \left(\frac{r}{r_0}\right)^k \mathcal{F}\left(\theta - \tan\xi \ln\left(\frac{r}{r_0}\right)\right)$$

with B_0=$B(r_0)$, k: geom. field index, ξ: spiral angle

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- Magnet tolerances study
  - Dynamic aperture and COD
  - Tune precision and excursion
  - Correction scheme
- Prototype
  - Scale-down parameters
  - Magnet design
  - Power supplies and field measurement system
  - Manufacturer
  - Experiment plan

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Magnet specifications

- Magnet tolerances come from machine specifications:
  - Tune excursion and tune precision 10 times smaller compare to space charge tune shift (~0.1).
  - Dynamic aperture retained to avoid uncontrolled losses (less than 10% dynamic aperture degradation).

Estimation of error tolerances

Tune change ΔQ as a function of quadrupole gradient error Δk_q : $\Delta Q = \frac{1}{4\pi}\int \Delta k_q \beta ds$

Quadrupole gradient k_q as a function of k-value: $k_q = \frac{1}{B\rho}\frac{kB_0}{r_0}$

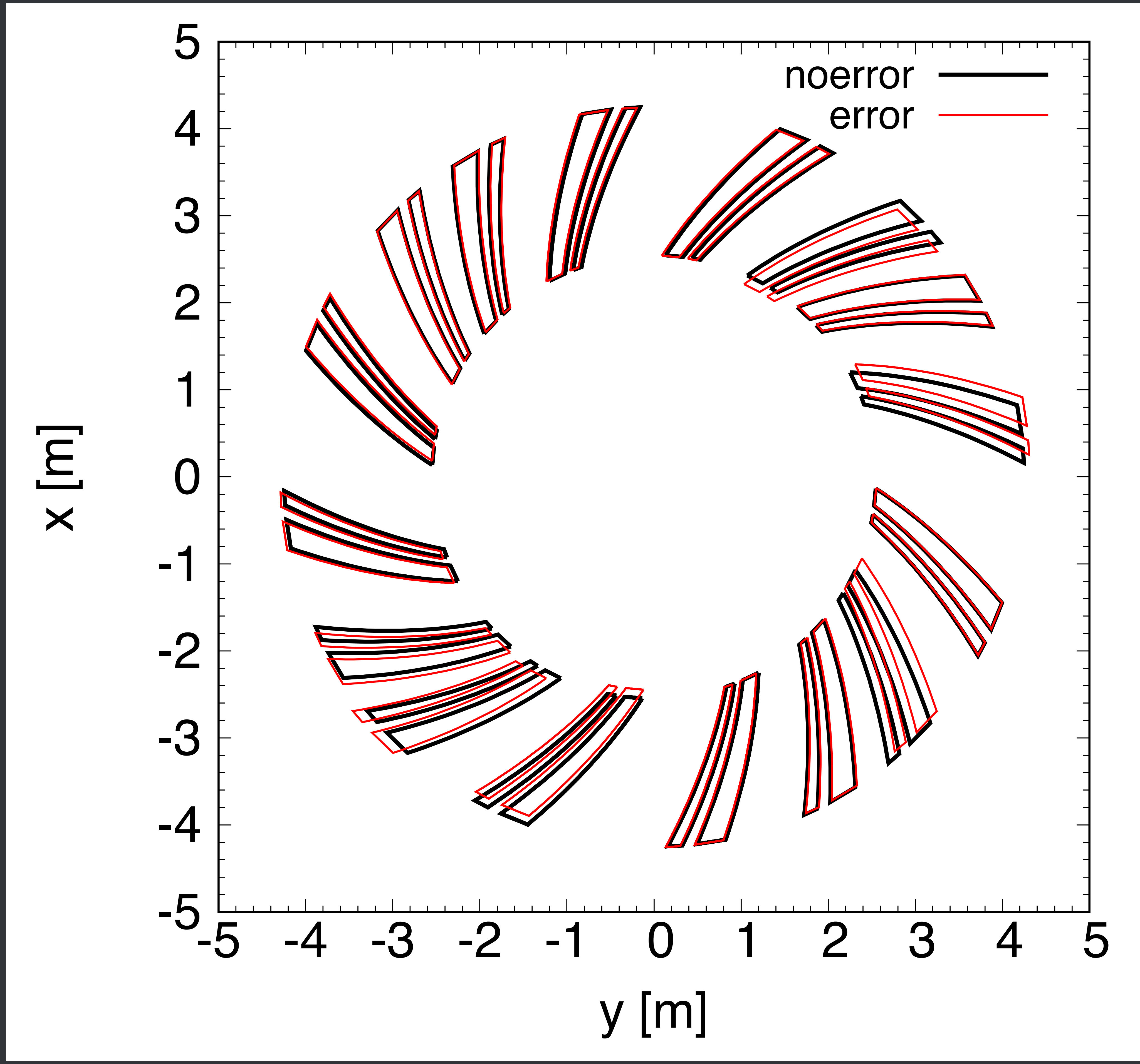
Numerical application in our case:
$\Delta k = 0.1 \rightarrow \Delta Q_h = 0.017$, $\Delta Q_v = -0.010$

Alignment study

- Translation error: direction of the displacement randomly and uniformly chosen 3D, gaussian amplitude truncated 5 sigmas

- Rotation error: gaussian rotational error centred around a uniformly randomly directed vector passing by centre of the doublet. Rotation rms value corresponding to the translation displacement of the corners of the doublet.

- For each rms error value, 1000 lattices were generated.



Science and Technology Facilities Council

Magnetic field error study

- Randomly change the k-value and spiral angle changes for each magnet following a gaussian distribution with null mean truncated to 5 sigmas.
- The change in k-value creates a field error $\Delta B \sim B_0 \Delta k - B_0 \Delta k \frac{r_{\text{clo}}}{r_0}$, which triggers a COD that affects the dynamic aperture.
- For each rms error value, 1000 lattices were generated.

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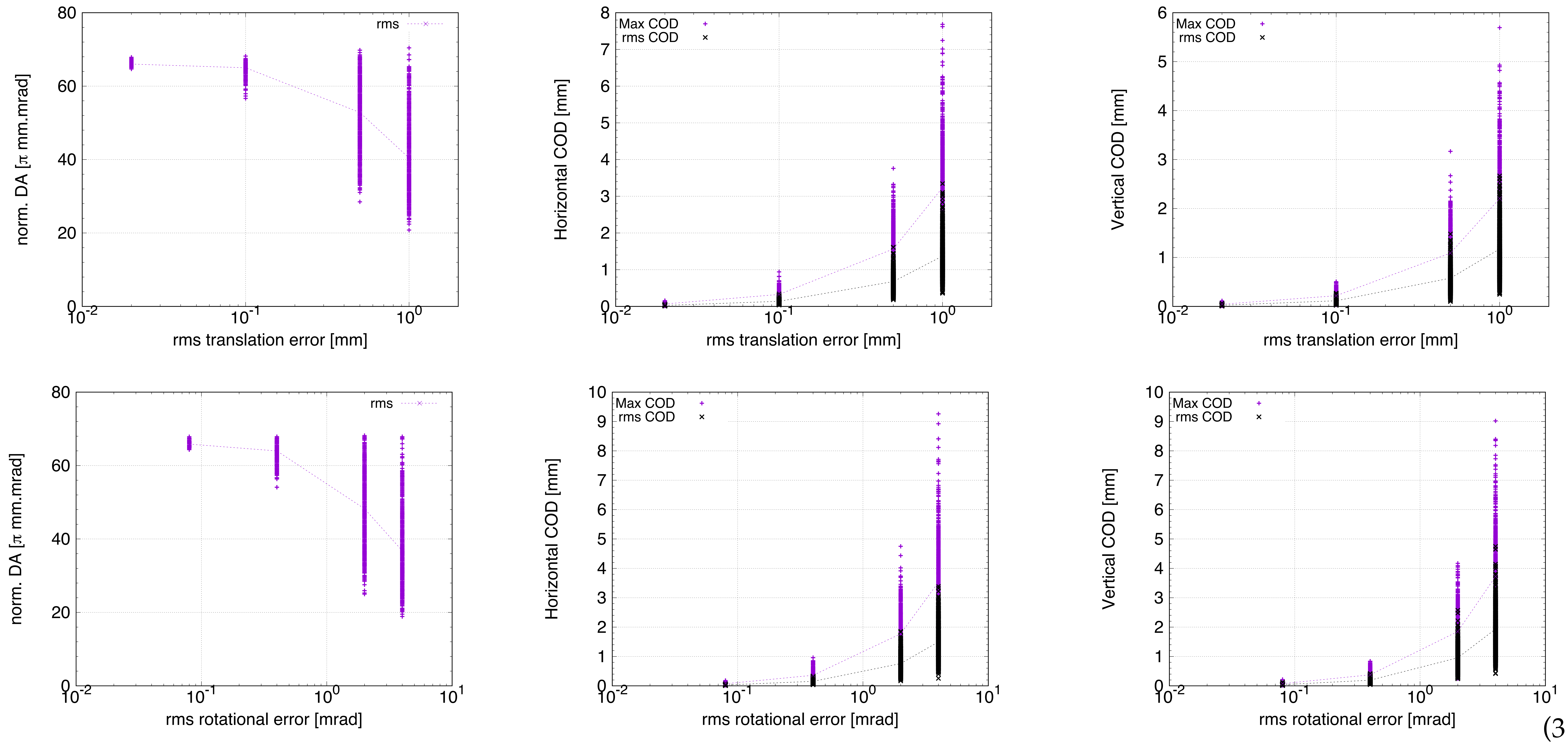
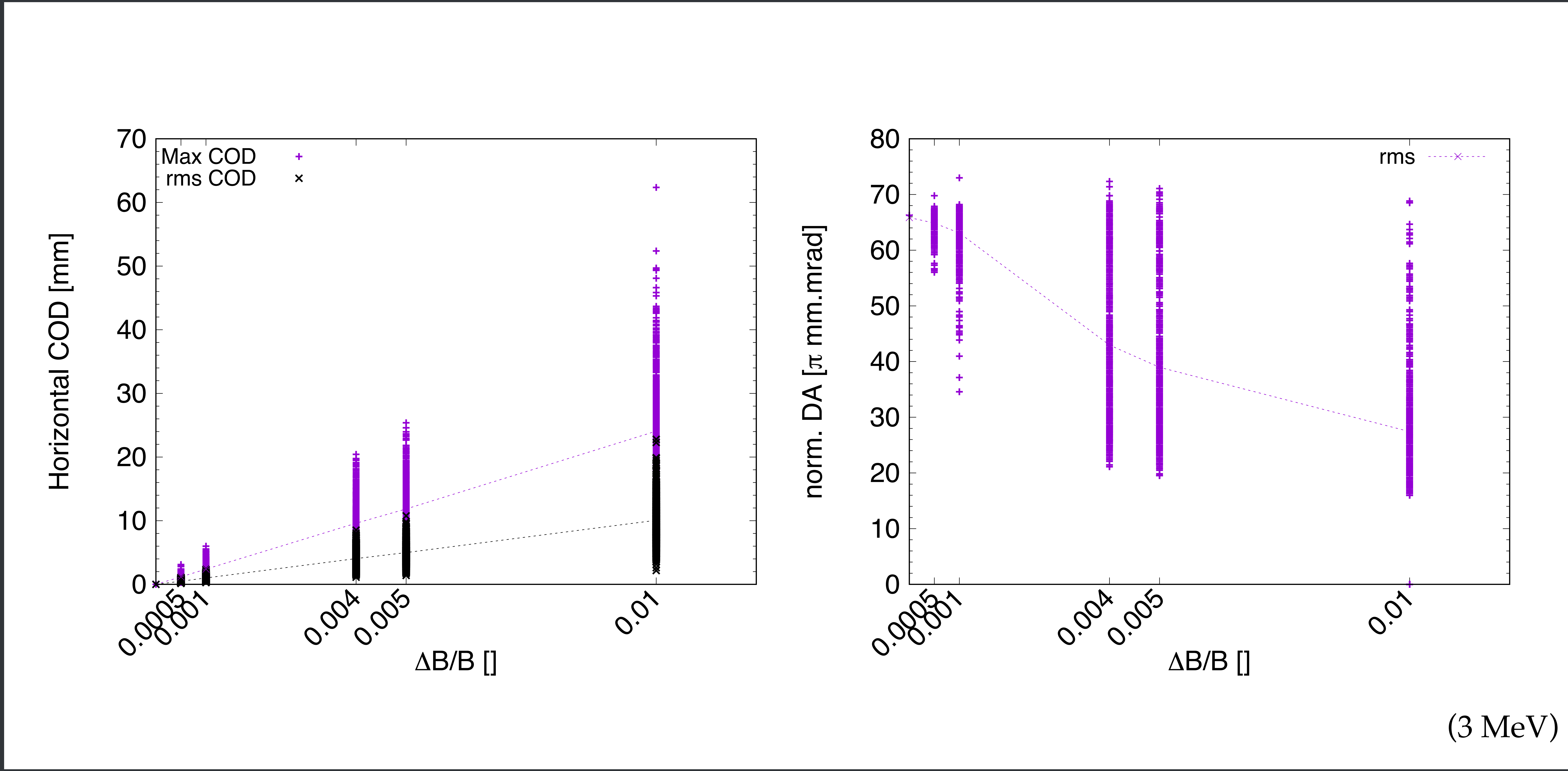
DA & COD (Alignment study)



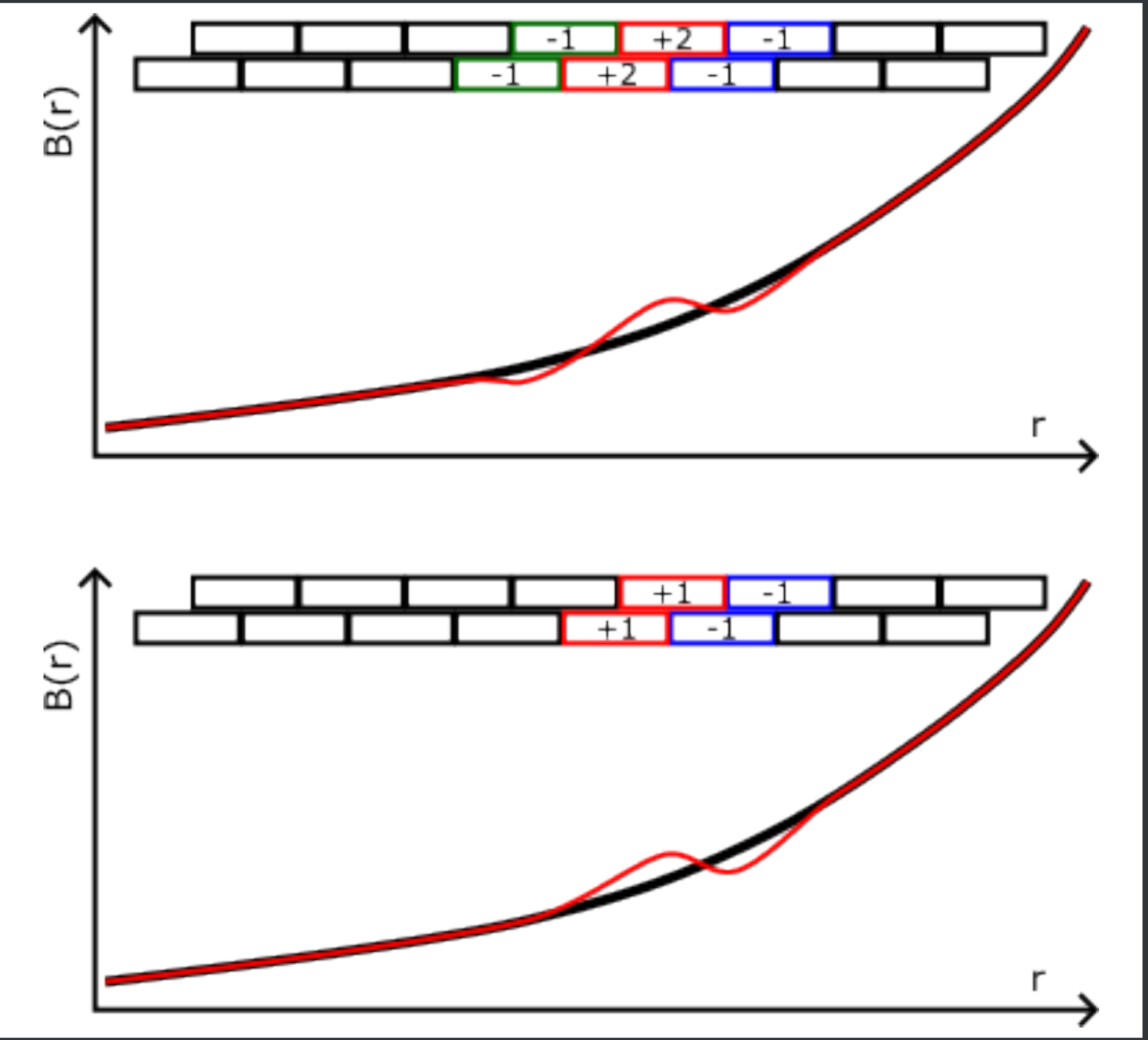
(3 MeV)

COD & DA (field error study)

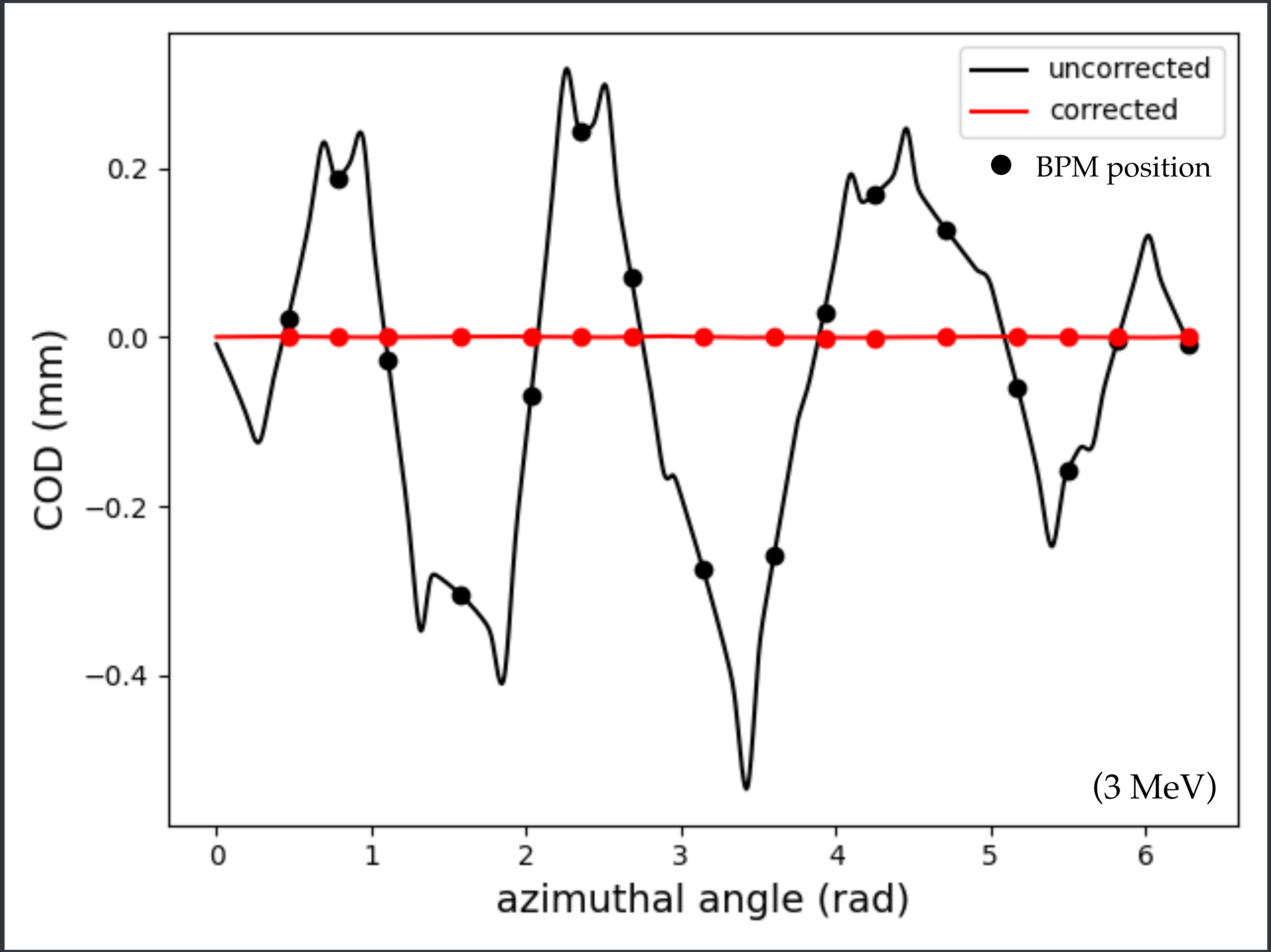


Correction scheme

- Trim coils in the main magnets can be used to correct local horizontal COD and local *k*-values if magnets are separately powered.
- Difficult to correct vertical COD with uniform horizontal field. The plan will rely on alignment requirements and field error requirements to limit vertical COD.



Example of idealised corrected COD



Correction applied based on BPM position (preliminary)

Magnet tolerances

- Tolerances for ring COD of less than 1 mm:
  - $\Delta B < 0.1\%$
  - Magnet alignement < 0.5 mm
- Tolerances for ring tune variation of 0.01 from lattice design:
  - $\Delta k < 0.04$
  - $\Delta \xi < 0.2$ deg

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Magnet prototype

Full scale prototype not feasible in the timeframe available due to project constraints. Scaled down single radial sector magnet designed for manufacture, in line with Recommendation 1 of Review report 2024

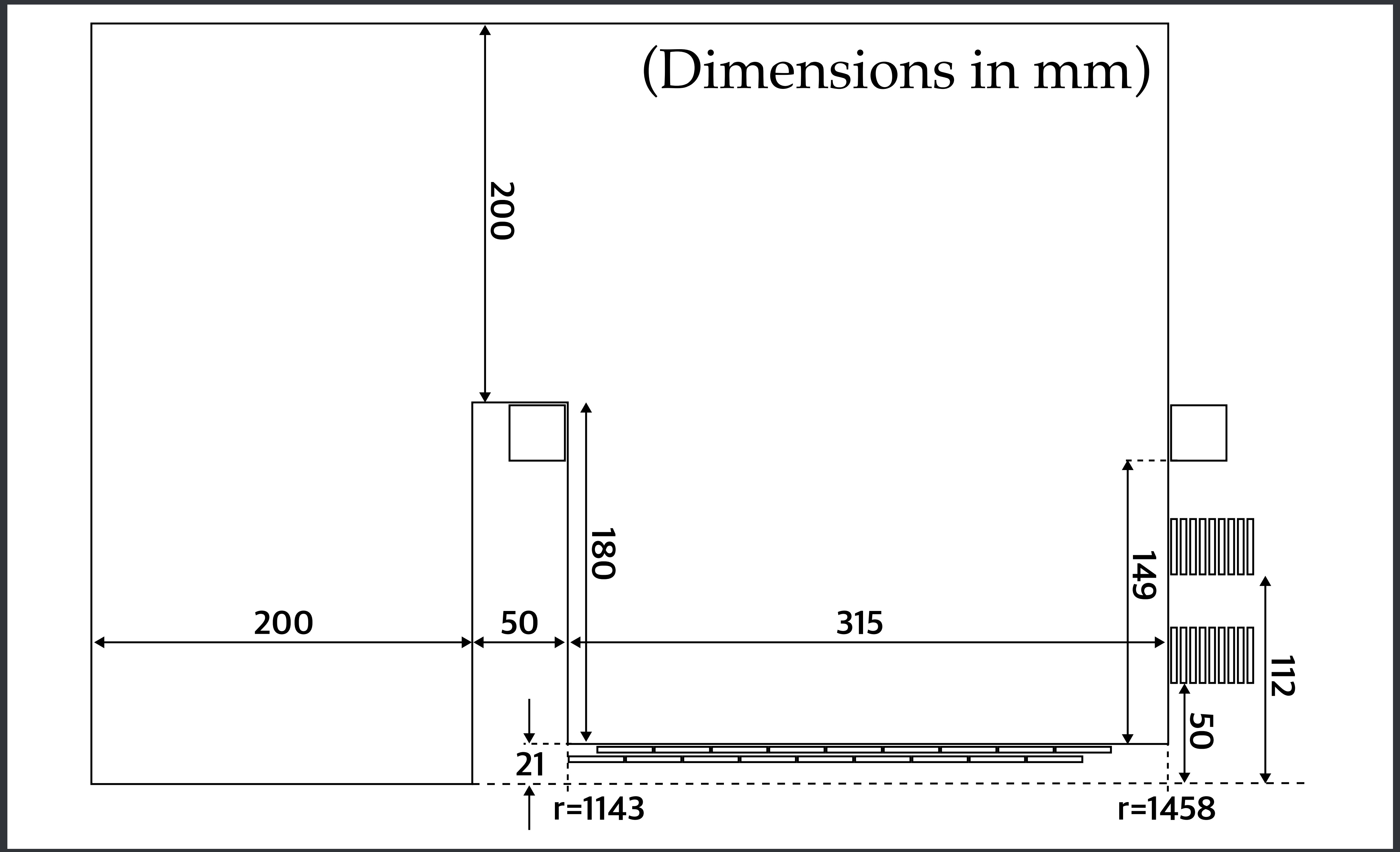
Magnet prototype scope

- Develop skills internally to design and build FFA magnet.
- Establish a method to control the magnet.
- Benchmark measurements with FEM model.
- Investigate correction scheme.
- Limitations:
  - Spiral effects of the magnet (manufacturing process of spiral nested coils, edge correction) → Manufacturing a set of spiral nested coils as a separate project.
  - Saturation effects not visible in normal operation mode → Short test on the prototype with high currents to benchmark simulations.

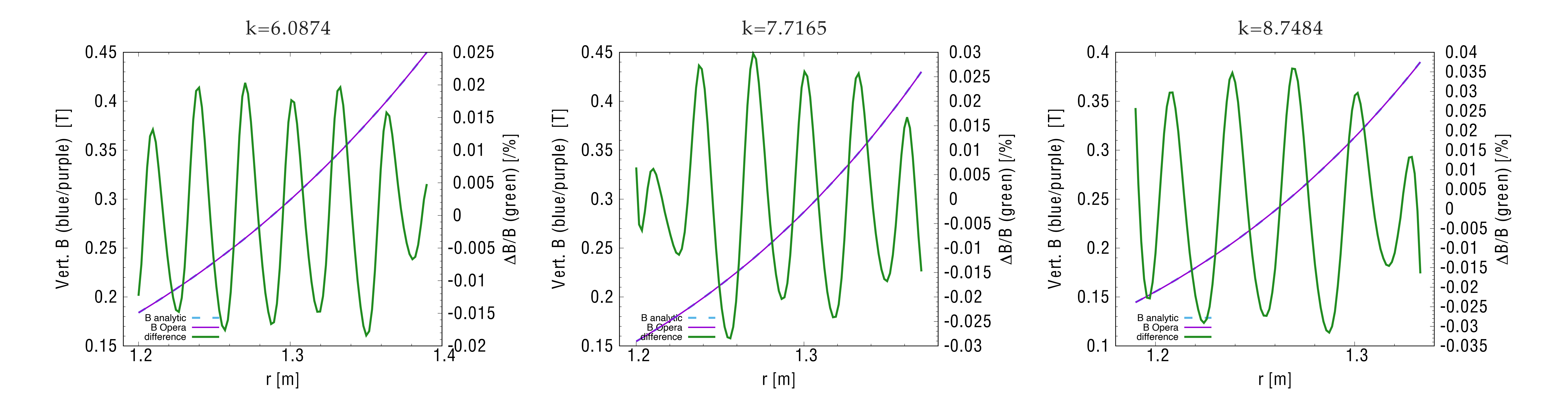
Scale down prototype

	FETS-FFA	Scale down
Magnet type	Doublet	Single
Shape	Sector spiral C-shape (30°)	Sector radial C-shape
GFR	4.26 m to 3.54 m (720 mm)	1.189 m to 1.411 m (222 mm)
Momentum excursion	x2	x2
Full Iron gap	112 mm	42 mm
Length/gap	1.4 (D), 2.7 (F)	5
Field strength	~1.2 T	1/3 scale
Iron weight	15 tonnes	0.6 tonne
Field gradient	Flat pole with overlapped trims	Flat pole with overlapped trims
Number of trim coils	80 (doublet)	36
k-value	6 — 9	6 — 9

2D model

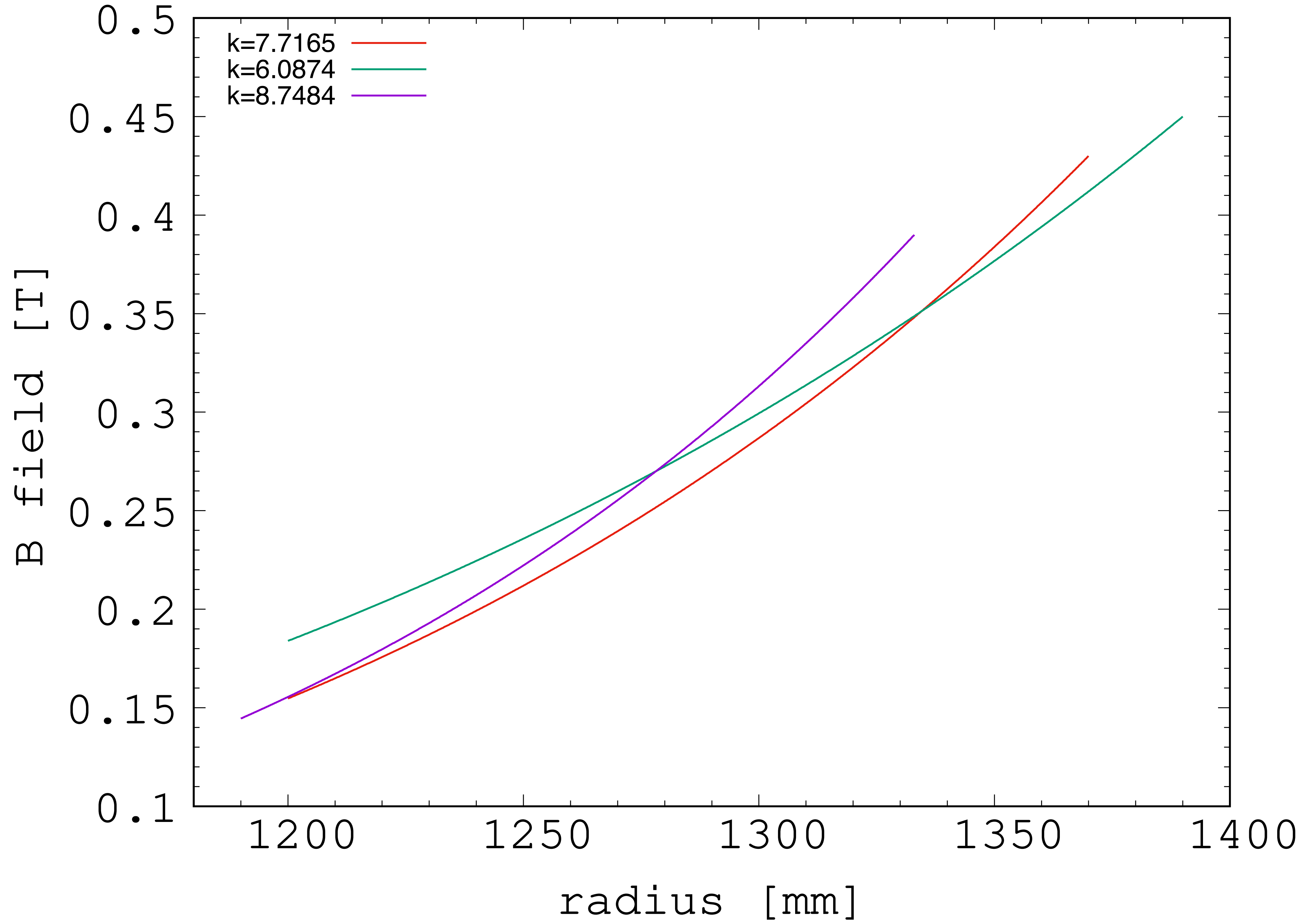


(Dimensions in mm)
200
200
50
315
180
149
112
50
21
r=1143
r=1458



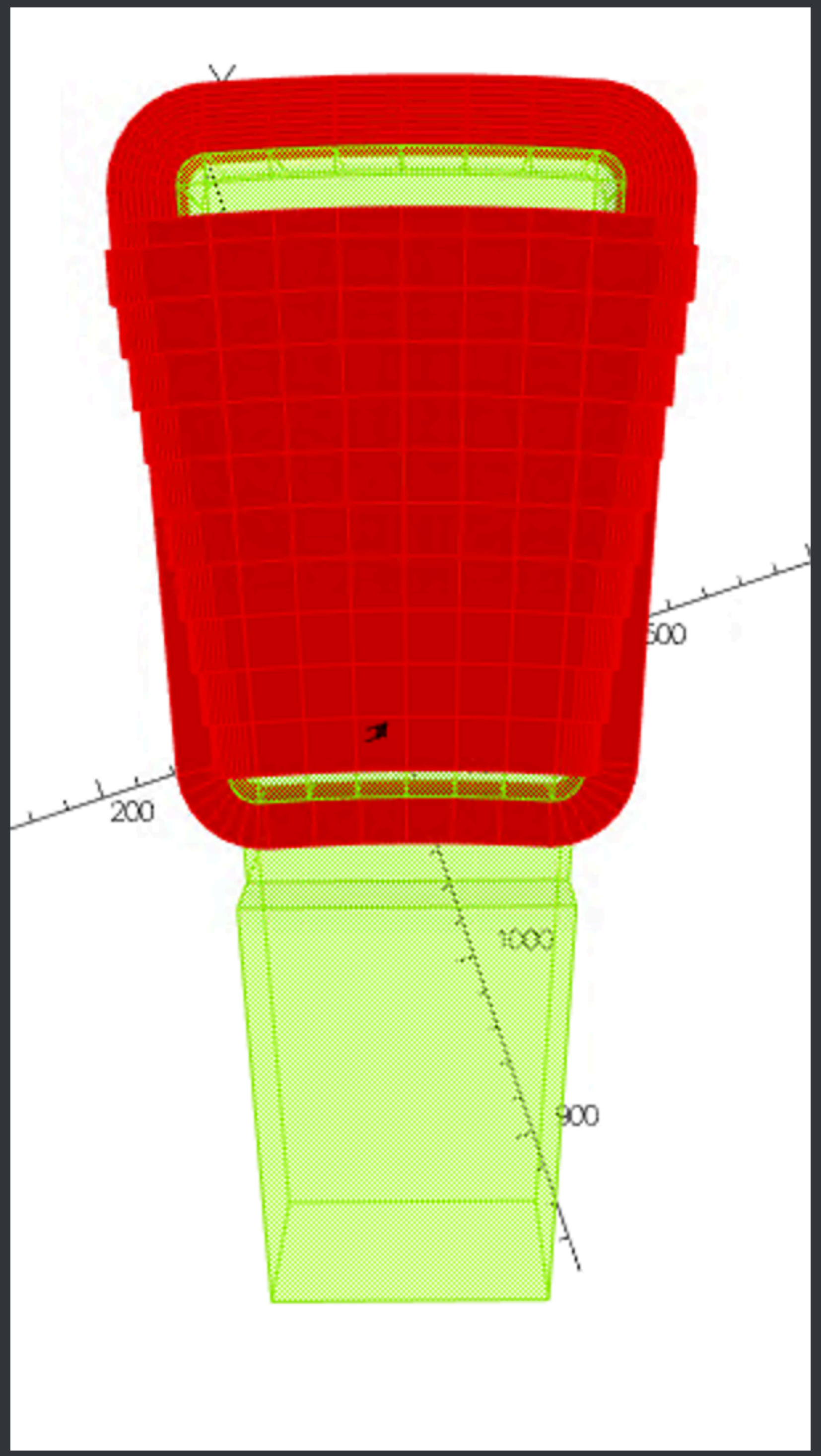
k=6.0874
k=7.7165
k=8.7484
Vert. B (blue/purple) [T]
ΔB/B (green) [%]
r [m]
B analytic
B Opera
difference

Max field for different cases

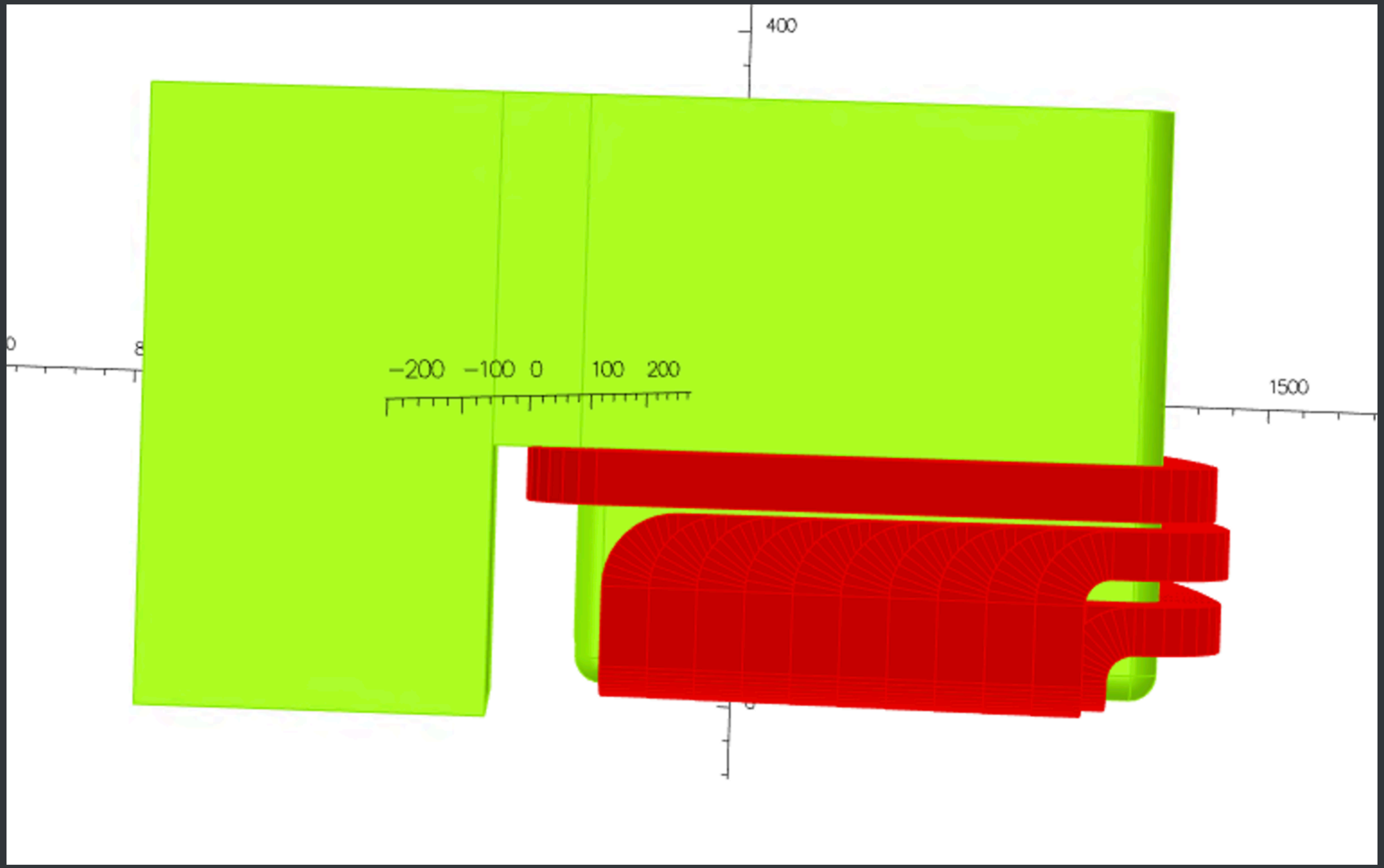


Currents	k=6.0874	k=7.7165	k=8.7484
main [A-turns]	2263.99	1398.81	1728.04
trim 9 [A-turns]	570.30	0.00	0.00
trim 8 [A-turns]	493.28	677.34	0.00
trim 7 [A-turns]	441.68	569.17	763.68
trim 6 [A-turns]	391.77	487.52	610.19
trim 5 [A-turns]	347.48	415.82	509.83
trim 4 [A-turns]	306.68	352.19	421.50
trim 3 [A-turns]	270.67	300.08	347.68
trim 2 [A-turns]	234.10	239.20	283.39
trim 1 [A-turns]	259.58	446.03	257.02

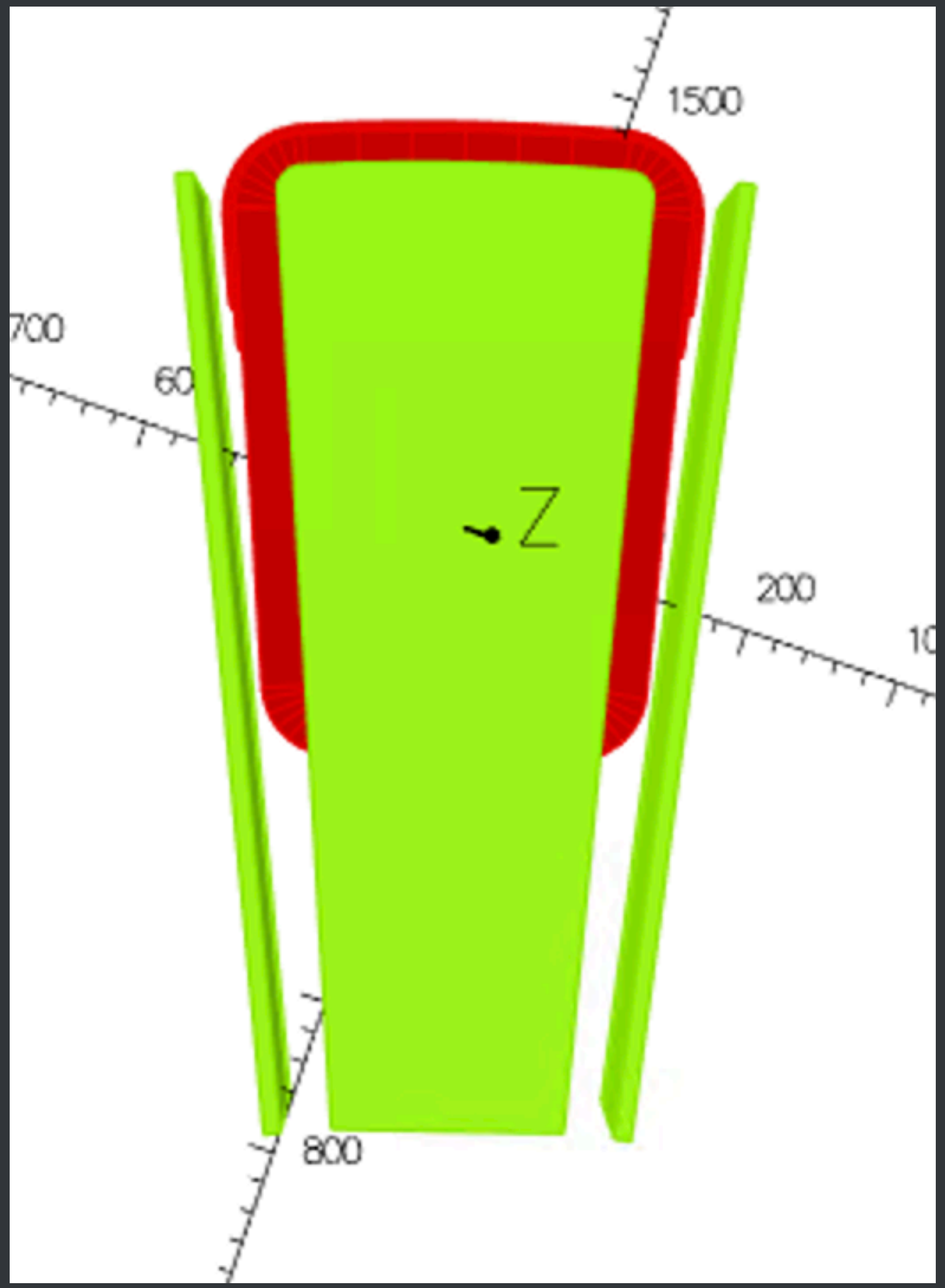
Opera model



Bottom view

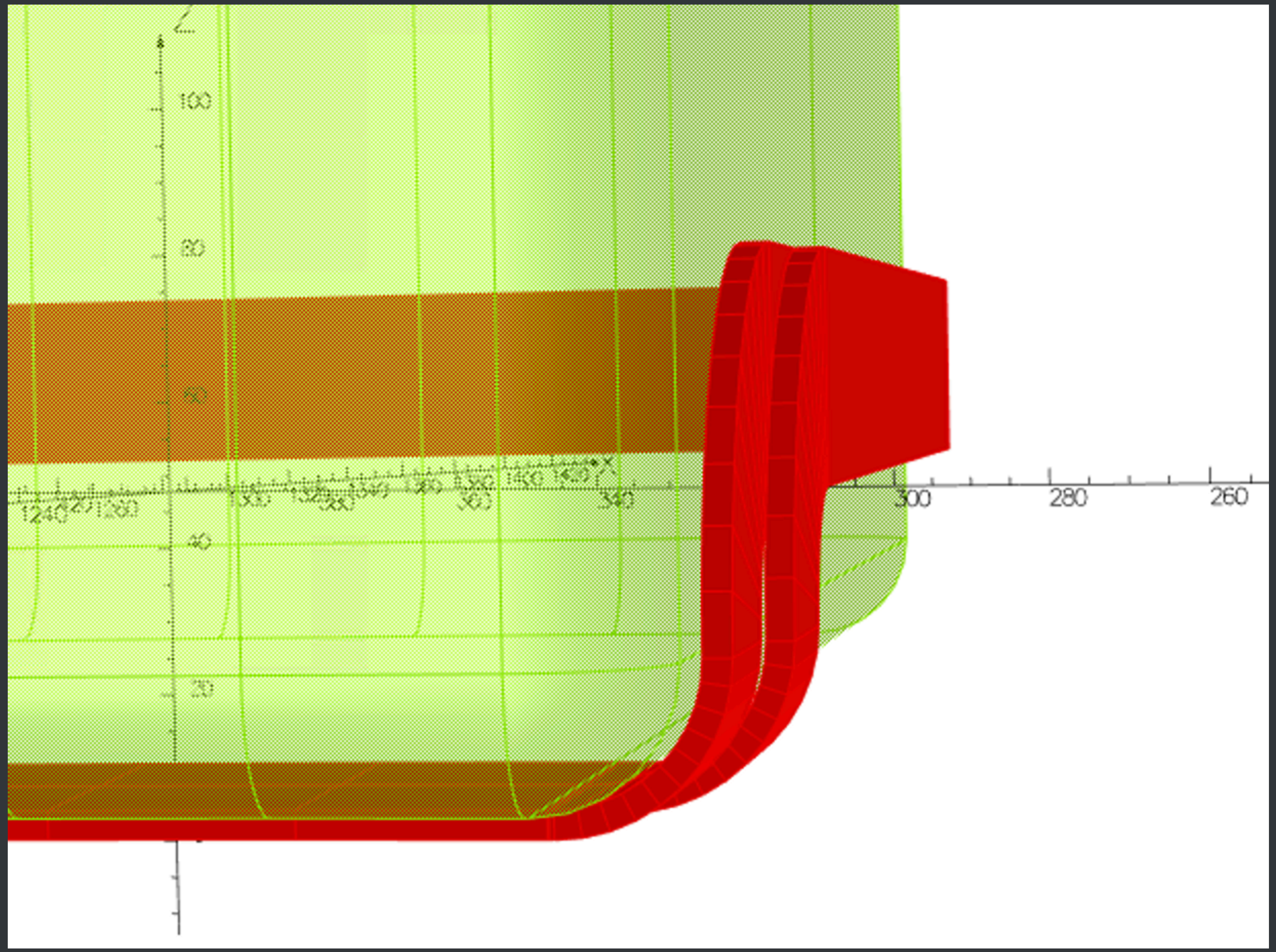


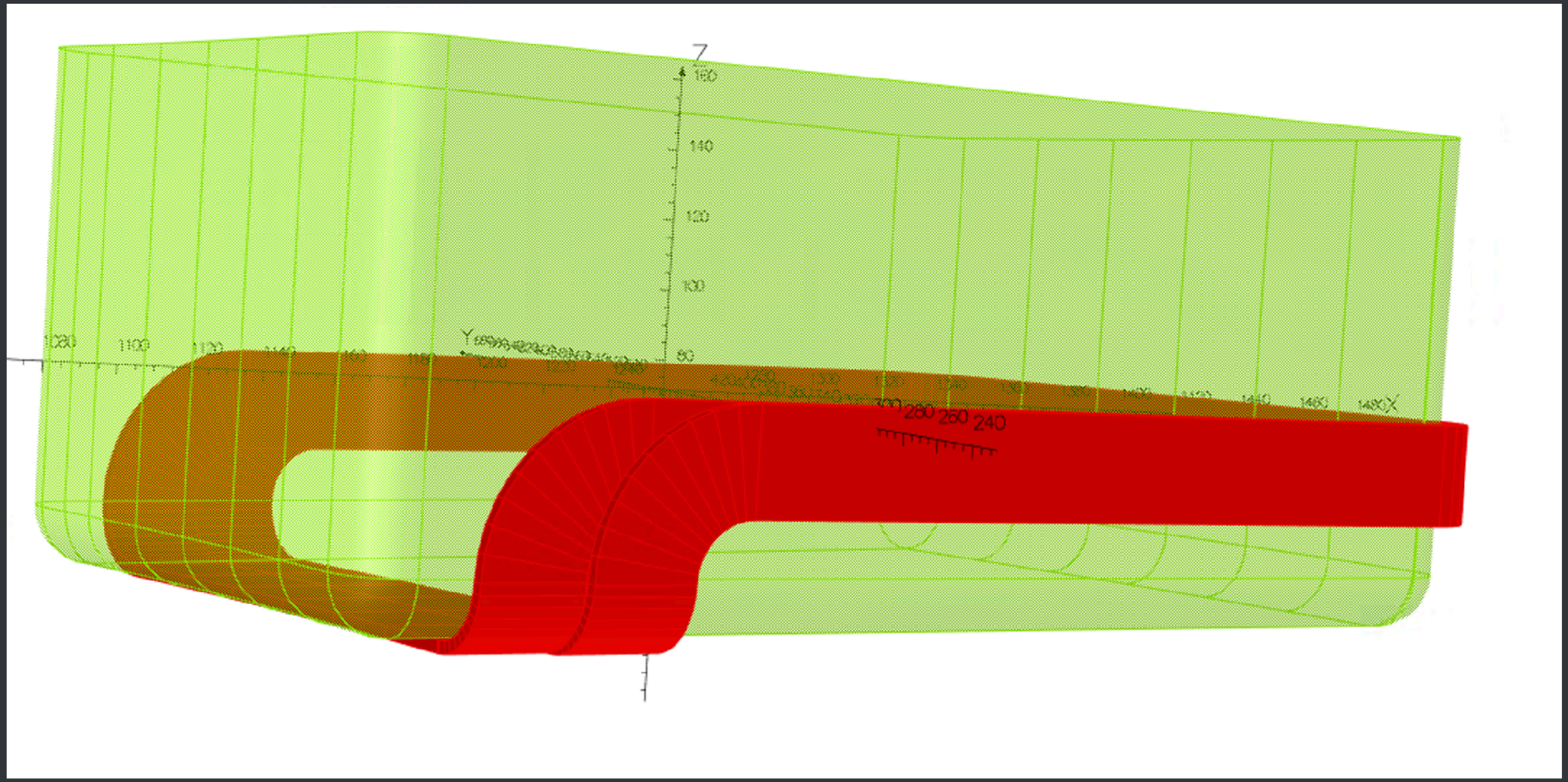
Side view



Top view
with clamps

Trim coils details





Mechanical model

- Main coil: 6x4 windings of hollow-conductor (7x7 mm, 3 mm ⌀)
- Trim coil: 6x1 windings of hollow-conductor (5x4 mm, 2 mm ⌀)

Power supplies & Magnetic measurement system

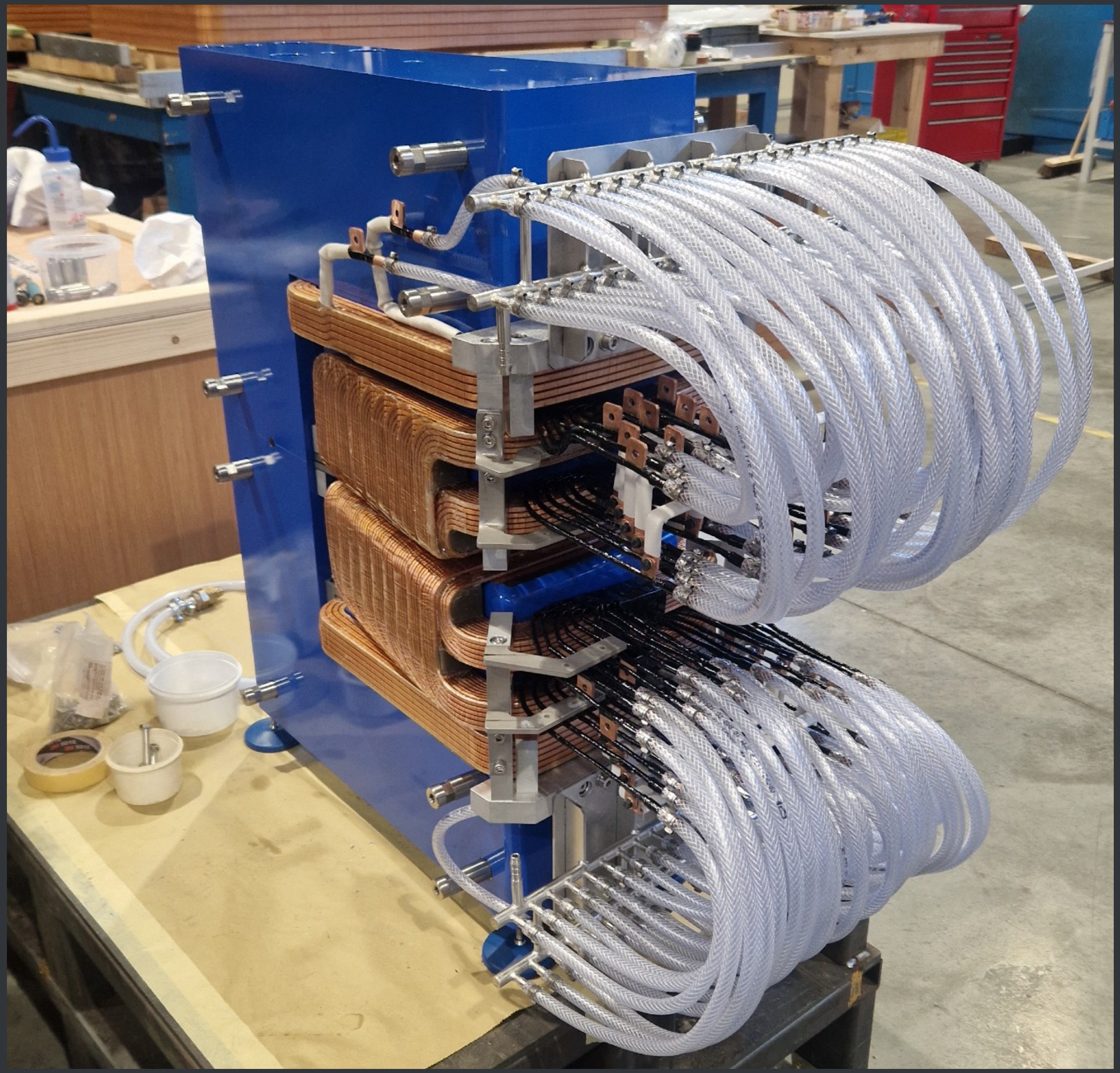
- 10 spare Danfysik PS given by ISIS PS group (free)
- Water-cooled PS, specific racks needed for these PS to be purchased
- Diamond purchased magnetic measurement system with 2 benches (3m and 6m long), installed in R79 with available water cooling in the building (to be tested).

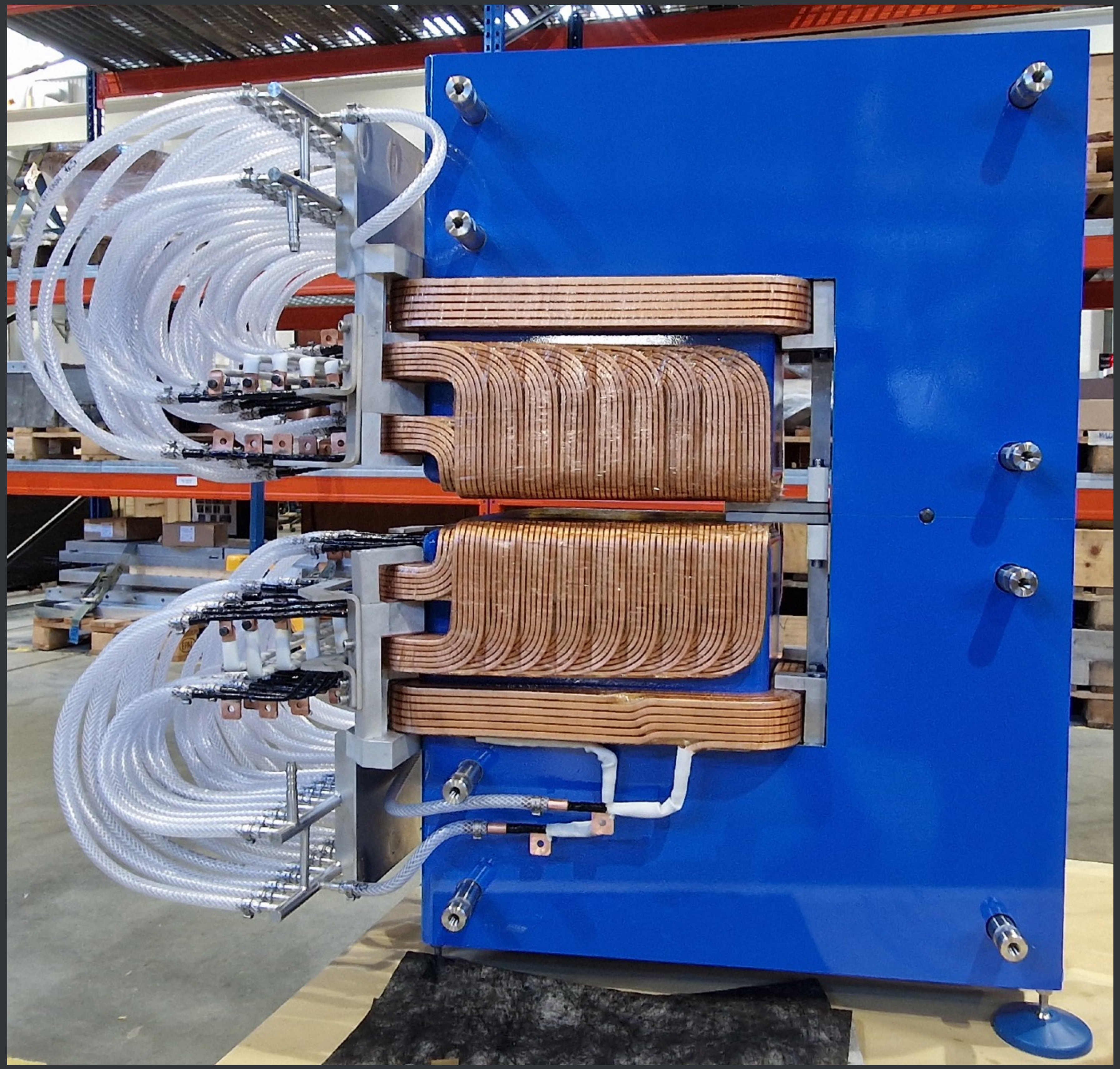
Manufacturing process

- Several manufacturers contacted, Tesla Eng. chosen, contract signed in July 2024.
- CAD model done by Tesla.
- Trim coils wound by hand (too small hollow conductor), and main coils wound by machine in Jan 2025.
- Pole and yoke cut and assembled in March 2025.

Prototype delivery in April 2025

Successful manufacturing of a prototype within the available time frame





Experiment plan

- Establish a control system to power the magnet (contact with ISIS Controls group)
- Measure magnet with nominal settings for each configuration (field strength, k-values)
- Benchmark these measurements with OPERA model.
- Create Jacobian matrix of change in fields for each power supply.
- Perform tracking in the created field maps
- Investigate local correction scheme efficiency (COD and k-value)

Thank you for your attention