

# FFA MAGNET FOR PULSED HIGH POWER PROTON DRIVER

J.-B. Lagrange\*, C. Jolly, D. Kelliher, A. Letchford, S. Machida, I. Rodriguez, C. Rogers, J. Speed, STFC/RAL, UK  
 T.-J. Kuo, Imperial College, UK  
 S. Brooks, BNL, US

## Abstract

Fixed Field Alternating gradient (FFA) accelerator is considered as a proton driver for the next generation spallation neutron source (ISIS-II). To demonstrate its suitability for high intensity operation, an FFA proton prototype ring is planned at RAL, called FETS-FFA. The main magnets are a critical part of the machine, and several characteristics of these magnets require attention, such as doublet spiral structure, essential operational flexibility in terms of machine optics and control of the fringe field extent from the nonlinear optics point of view. This paper will discuss the design of the prototype magnet for FETS-FFA ring.

## Introduction

ISIS-II is a major upgrade of the ISIS facility [1], and is under study with an established roadmap [2]. One of the considered options for the proton accelerator is the use of FFA. This arrangement has several advantages. First, it brings longitudinal flexibility and so allows beam stacking [3]. It is also more reliable, and more sustainable from an energy consumption point of view, as a whole accelerator system since the main magnets are operated in DC mode. Third, as long as acceleration voltage is sufficient, high repetition rate (more than 100 Hz) can be achieved. However, no high intensity pulsed FFA has been built so far. An FFA test ring called FETS-FFA is proposed [4] to confirm these features experimentally and to build engineering experience, using the 3 MeV beam from RAL's R&D injector, FETS [5]. As a critical part of the hardware a magnet prototype is being designed. Essential features for this magnet are zero-chromaticity during acceleration, dynamical aperture larger than physical aperture to avoid uncontrolled losses, flexibility in terms of tune point to allow different operation as a function of intensity. The scaling law keeps zero-chromaticity during acceleration and is used in our case. Other solutions can be used to retain the zero-chromaticity of the lattice [6]. A reverse bend magnet (D-magnet) is included to allow a change in vertical tune, while the  $k$ -value must be able to vary to change the horizontal tune. It leads to large change of beam excursion, that needs to be taken into account in the magnet design.

## MAGNET SPECIFICATIONS

- The magnet specifications are presented in Table 1. They are based on the 4-fold symmetry lattice design of the prototype ring [4].
- Vertical magnet gap of  $\pm 50$  mm (normalised  $40\pi$  mm.mrad emittance, 8 mm closed orbit distortion allowance and 10 mm vacuum chamber thickness).
- Horizontal magnet excursion of 738 mm (orbit excursion between 3 and 12 MeV for different tune scenarios as presented in Fig. 1, 40 mm beam size, and 8 mm closed orbit distortion allowance).

- 4th doublet (lowest in Fig. 1) chosen as prototype.
- The maximum outer radius of the machine must be below 4.7 m to fit the ring in the planned building at RAL, leaving not enough space for a return yoke on the outside of the ring. A **C-type magnet** is thus chosen to overcome this issue.

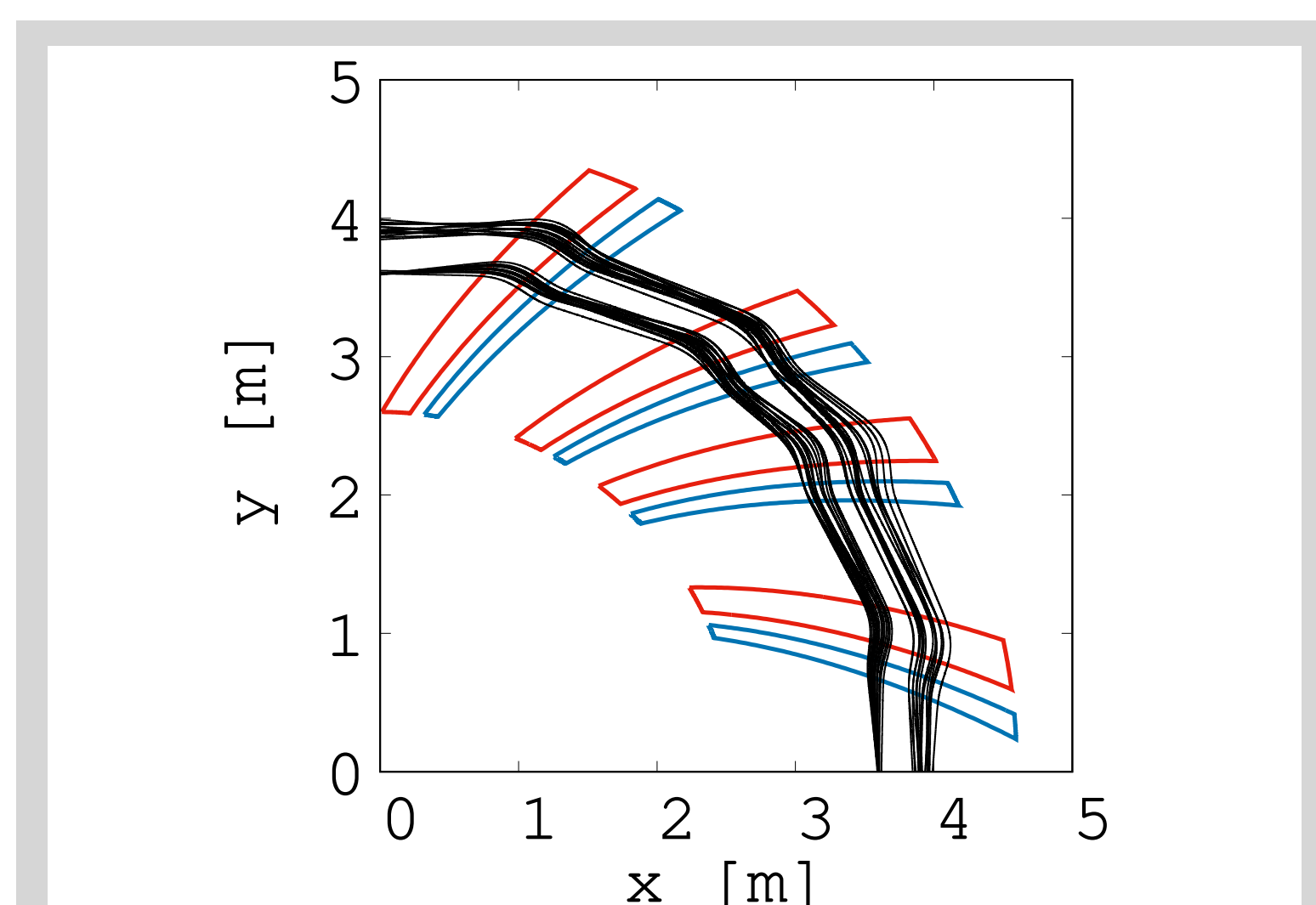


Fig. 1: Closed orbits (3 MeV and 12 MeV) in a superperiod of the lattice for different tune points.

Cell type	FD spiral
Spiral angle	30.0 deg.
$k$ -value range (central scenario)	6 - 9 (7.5)
Injection, Extraction proton energy	3, 12 MeV
F Magnet opening angle	4.50 deg.
D Magnet opening angle	2.25 deg.
Short drift opening angle	2.25 deg.
Full gap size	100 mm
Good field region excursion	738 mm
Maximum vertical field in GFR	1.5 T
Fixed injection radius	3.6 m

Table 1: Magnet Specifications from lattice design.

## MAGNET MANUFACTURING OPTIONS

Manufacturing options of the magnet studied in 2D using COMSOL [7] and OPERA [8]:

- Pole shaping.
- Flat pole covered with trim coils powered with different currents (necessary in any case due to flexible  $k$ -value)
- Anisotropic interpole [9]. Advantageous regarding fringe field extents compare to pole shape magnets, and low-pass filter in the case of discrete trim coils. However, limited maximum field due to saturated interpole.
- Total power consumption of the F magnet is comparable or lower for a flat-pole with trim coil than for a pole-shaped magnet.

- 10 trim coils chosen as a good balance between the number of coils and the field error.
- Overlapped trim coils as presented in Fig. 2 dampen the field errors.
- A **flat pole with overlapped trim coils** is chosen (satisfactory field quality, anisotropic interpole not required).
- 20 mm thick trim coils, leading to a full iron pole gap of 140 mm.
- A 3D model made in Comsol of a single magnet is presented in Fig. 3. However, the numerous and complex coils makes the use of COMSOL for the doublet case a difficult task, with a necessary RAM of more than 128 GB. The software OPERA can overcome this issue since the conductors are computed in a reduced potential area with the Biot-Savart law, while the rest of the model is computed with finite element methods. The doublet magnet model was then imported in OPERA, while adjusting the magnet parameters to fit the update of the lattice design from previous 16-fold symmetry lattice [10] to the present 4-fold symmetry lattice [4], and is presented in Fig. 5.

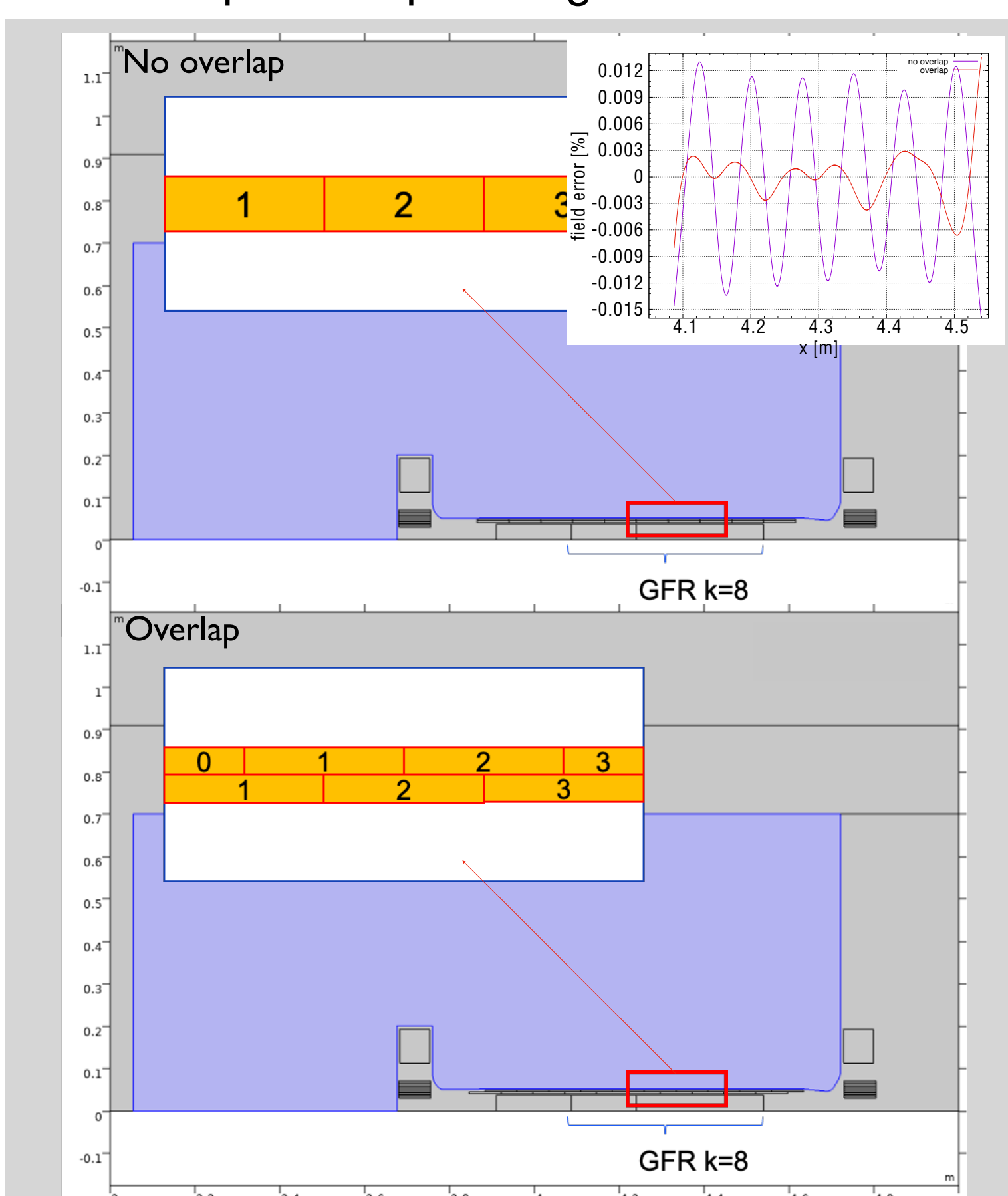


Fig. 2: 2D model of no overlapped (top) and overlapped (bottom) trim coils and field error along the radius line (top right) in the 2D model after current optimisation.

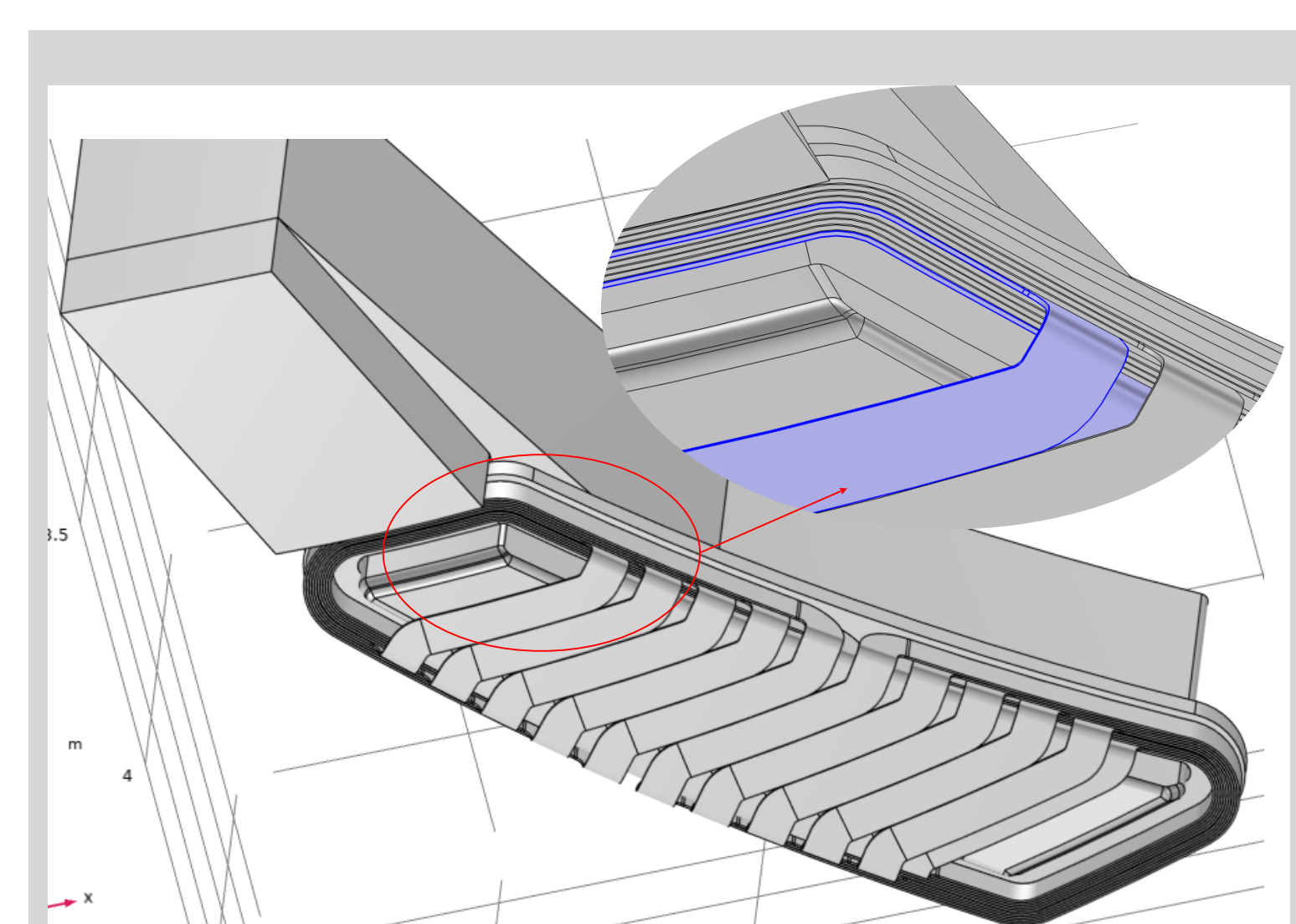


Fig. 3: 3D model of overlapped trim coils for a single magnet in COMSOL.

## 3D PRELIMINARY DESIGN

- The trim coils were designed with 8-node-brick conductors to adjust the shape of the coils, and one of the coils is presented in Fig. 4.
- The first lesson from the preliminary 3D design of the doublet was that the opening angle between the F and D magnets was too small to fit the return of the trim coils. The original 2.25 degrees becomes now 4.03 degrees.
- Another lesson was that considering the coils have a minimum bending radius of 15 mm, the trim coils would use some space to bend in 3D to snugly fit around the pole. If we consider that the trim coil has to follow the correct constant radius path for at least half of the pole length, then the minimum opening angle of the magnet would be 2.5 degrees in our case.
- It leads to an increase of the total size of the doublet, partially compensated by reducing the F magnet opening angle to 3.47 degrees.
- An iteration with the lattice design with this feedback is thus necessary to update the lattice parameters that would fit the targeted tune points.

- Field clamps have also been implemented to contain the field and have straight sections outside the doublet with a minimum field. Longitudinal clamps with 50 mm thickness are installed on the outside of the doublet.
- A transverse clamp is also added to prevent field leakage on the outer radius for safety and field reliability. A picture of the model in OPERA is presented in Fig. 6.

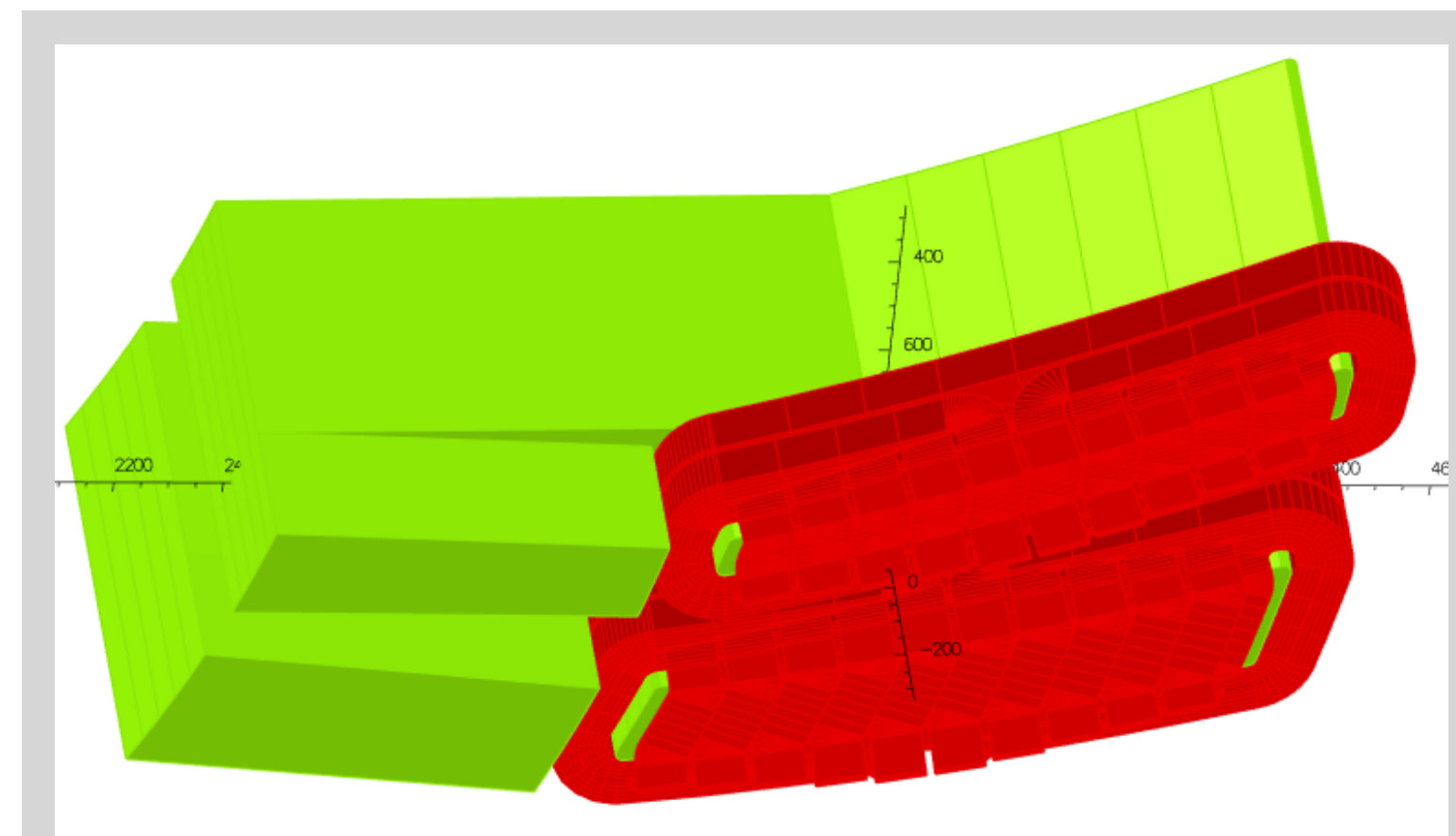


Fig. 5: 3D model of the doublet in OPERA software.

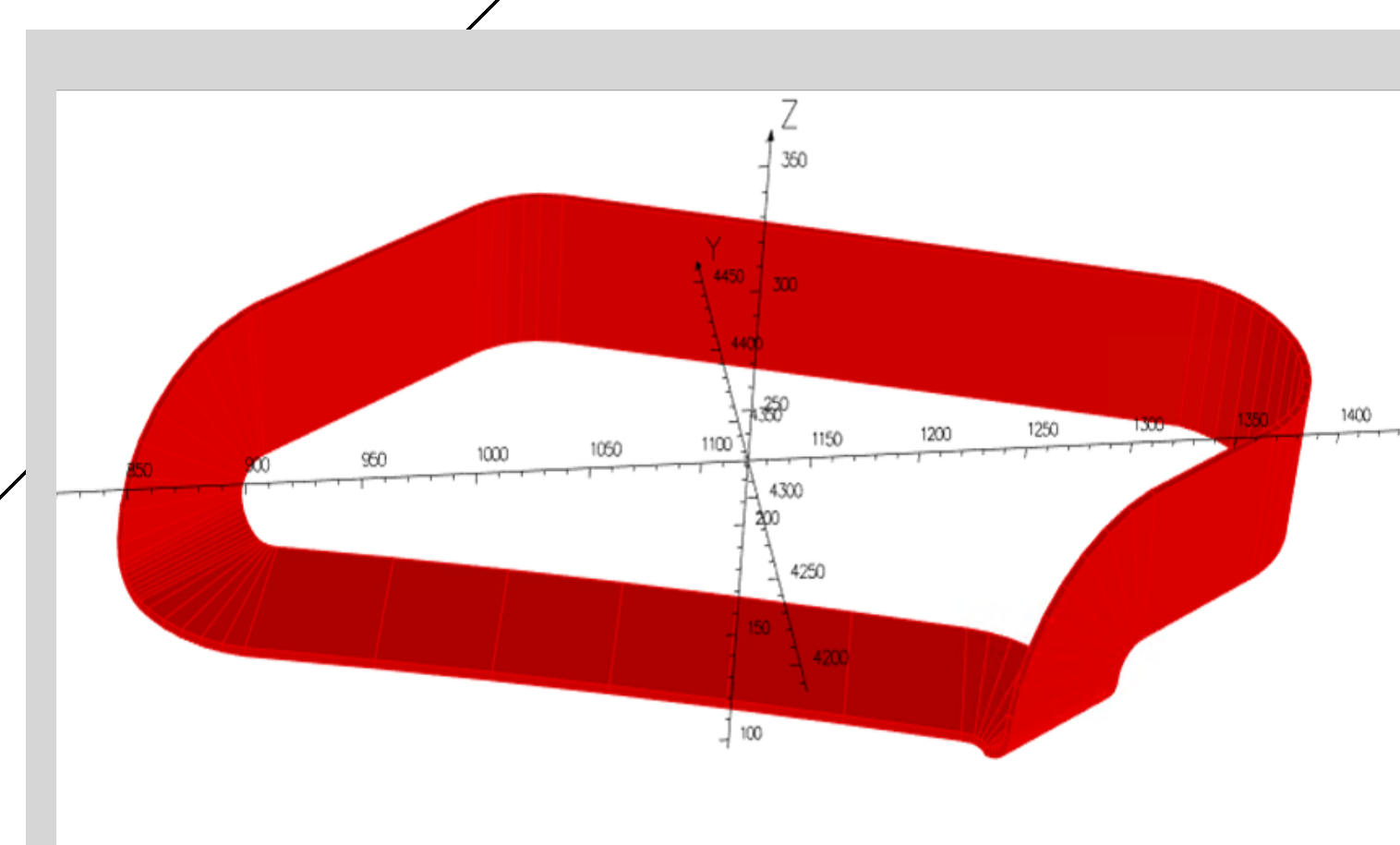


Fig. 4: 3D model of one trim coil in OPERA software.

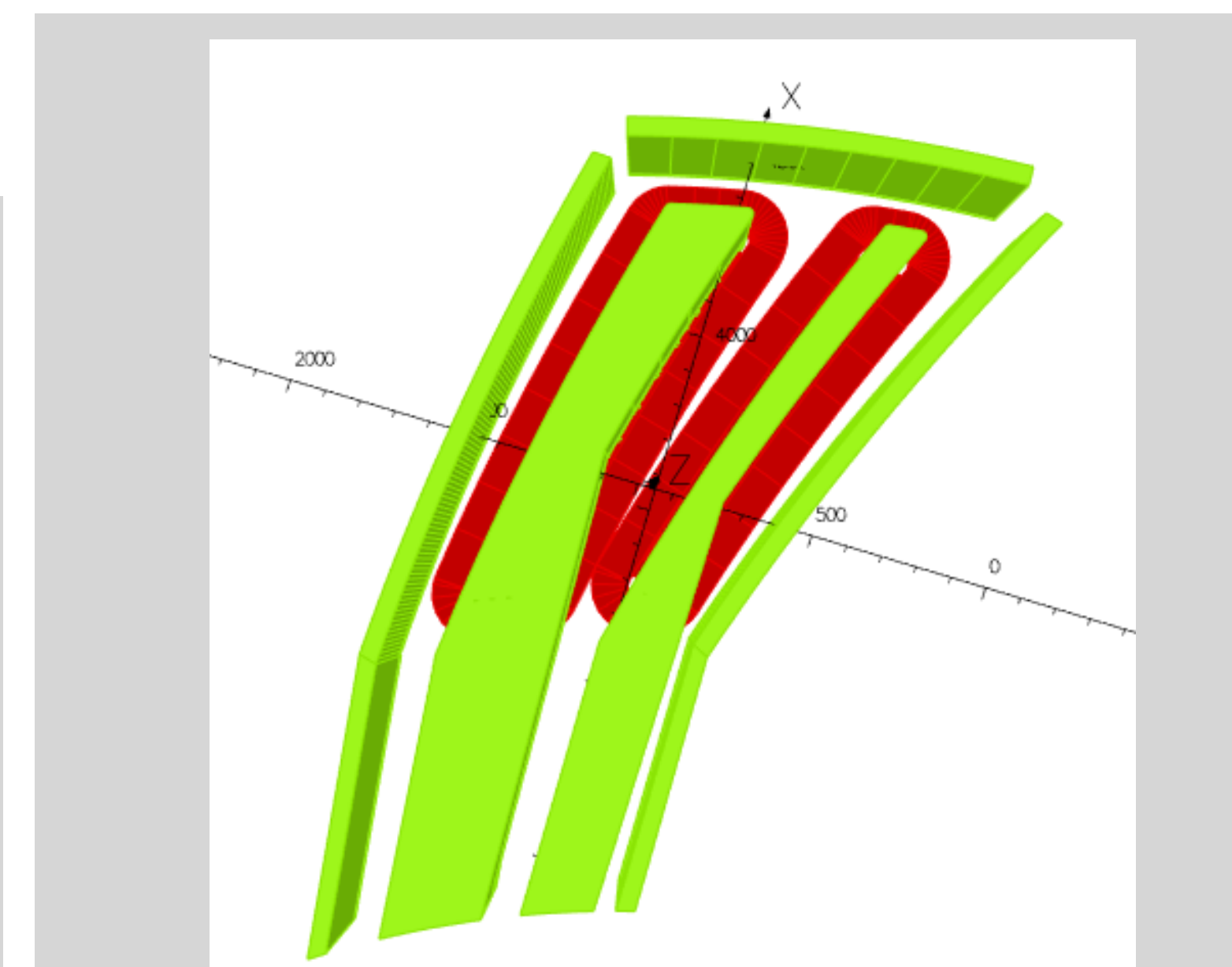


Fig. 6: 3D model of the doublet in OPERA software with field clamps.

## Conclusion

A roadmap for research, design and construction of a next generation, short pulse neutron source, ISIS-II, has been established. To demonstrate the feasibility of FFA as a high power pulsed proton driver, a prototype ring is planned at RAL. As part of this project, a magnet prototype is designed to meet the requirements of the ring. Several manufacturing options were investigated, and a flat pole with 10 overlapped trim coils was chosen. This choice was made to satisfy the required field quality while keeping the tight schedule of the project. Moreover, the total power consumption is comparable to a pole shape magnet for our application.

A preliminary 3D model was successfully implemented in OPERA, leading to an update of the magnet parameters for practical consideration. A fit of the magnetic field from the OPERA model is under way to update the fringe field parameters in the lattice design code. A mechanical design is planned and the manufacturing of the prototype is intended by the end of 2024. A more detailed publication on this work is planned in the near future.

## References

- [1] J. Thomason, Nucl. Instrum. Meth. A 917 (2019), 61-67.
- [2] J. Thomason, [www.isis.stfc.ac.uk/Pages/ISIS-II %20Roadmap.pdf](http://www.isis.stfc.ac.uk/Pages/ISIS-II%20Roadmap.pdf)
- [3] D. Kelliher et al., in Proc. of IPAC21, May 2021, TUPAB186.
- [4] S. Machida et al., in Proc. of IPAC23, May 2023, TUPA044.
- [5] A. Letchford, in Proc. of IPAC15, May 2015, THPF105.
- [6] S. Brooks, in Proc. of IPAC23, May 2023, TUPM031.
- [7] COMSOL AB, "COMSOL Multiphysics software", <https://www.comsol.com>
- [8] Dassault Systèmes, "OPERA FEA Software", <http://operafea.com>
- [9] Y. Iwashita et al., IEEE transactions on applied superconductivity, 16 (2), pp.1286-1289 (2006).
- [10] S. Machida, in Proc. of CYC2022, Nov. 2022, FRAI1, to be published.