68th Adv. Beam Dyn. Workshop High-Intensity High-Brightness Hadron Beams HB2023, Geneva, Switzerland JACoW Publishing
ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP02

FFA MAGNET FOR PULSED HIGH POWER PROTON DRIVER

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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 (Fixed Field alternating gradient Accelerator). 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,
- dynamic 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 by following the equation

$$B_z = B_0 \left(\frac{r}{r_0}\right)^k \mathcal{F}\left(\theta - \tan\xi \ln\left(\frac{r}{r_0}\right)\right), \qquad (1)$$

with B_0 the field at the reference radius r_0, ξ the logarithmic spiral angle, k the constant geometrical field index and $\mathcal{F}$ the arbitrary longitudinal function. 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 as seen in Fig. 1, that needs to be taken into account in the magnet design.

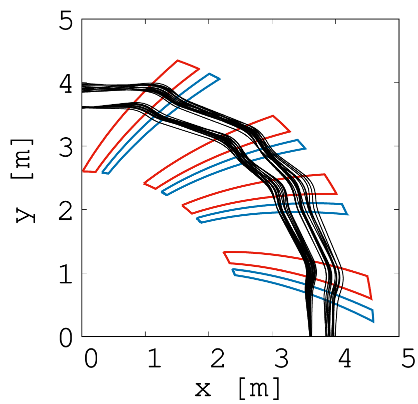

Figure 1: Closed orbits (3 MeV and 12 MeV) in black in one superperiod of the lattice for different tune points.

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]. The fourth doublet (lowest in Fig. 1) has been chosen as a prototype magnet.

Table 1: Magnet Specifications from Lattice Design

Parameter	**Value**
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

The lattice design computes a physical acceptance of ±32 mm, corresponding to a normalised 40 π mm mrad emittance. A closed orbit distorsion of 8 mm is added to this,

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ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP02

which leads to a ±40 mm beam stay clear region. Considering a 10 mm thick vacuum chamber, it leads to a vertical gap of ±50 mm. The horizontal magnet excursion is computed from orbit excursion between 3 and 12 MeV for different tune scenarios, as presented in Fig. 1 and a horizontal physical beam acceptance of 40 mm is added on the inner side and outer side of the beam excursion. A closed orbit distorsion allowance of 8 mm is also added, leading to a good field region excursion of 738 mm.

Since the maximum outer radius of the machine must be below 4.7 m to fit the ring in the planned building at RAL, it does not leave enough space for a return yoke on the outside of the ring. A C-type magnet is thus chosen to overcome this issue.

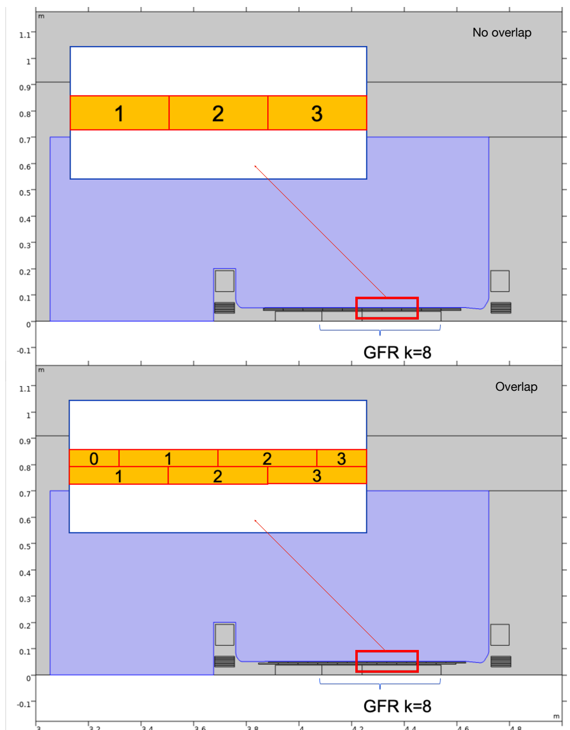

Figure 2: 2D model in COMSOL of no overlapped (top) and overlapped (bottom) trim coils.

MAGNET MANUFACTURING OPTIONS

Several options were considered for the manufacturing of the magnet, and 2D study was done to investigate them using the COMSOL [7] and OPERA [8] software. The conventional way to create the gradient of the combined function magnet is by shaping the pole. Another solution is by having a flat pole covered with trim coils powered with different currents. Due to the fact that the k-value has to be flexible, the use of trim coils is necessary in any case in this project, even if the required power of these trim coils would be smaller if a pole shape was used. In addition to that, it was found that the total power consumption of the F magnet is comparable or lower for a flat-pole with trim coil than for a pole-shaped magnet for gradient values considered in our

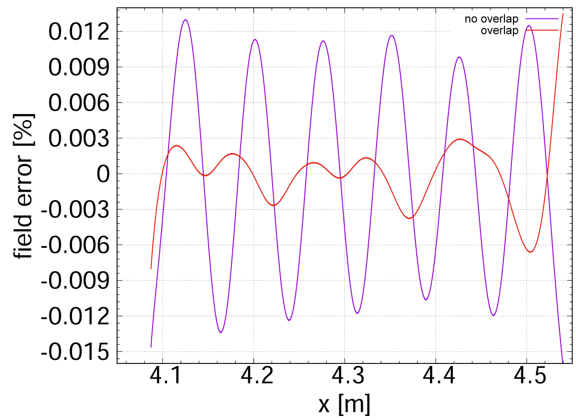

Figure 3: Field error along the radius line in the 2D model after current optimisation for no overlapped (purple) and overlapped trim coils (red).

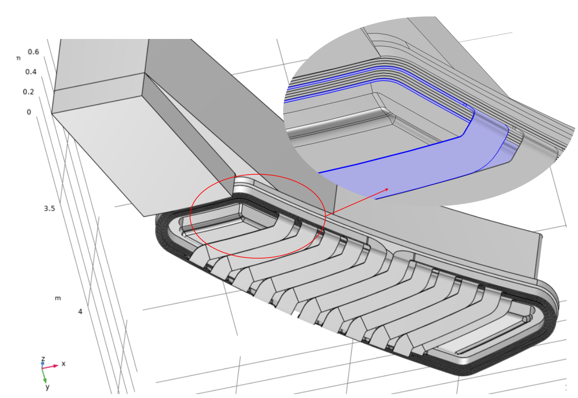

Figure 4: 3D model of overlapped trim coils for a single magnet in COMSOL software.

case ($k \approx 8$). This is due to the higher averaged gap that the main coil sees in the pole shape option, increasing the power consumption compared to an equivalent main coil in the flat pole option. The number of trim coils was chosen to be 10 since it was a good balance between the number of coils and the achievable field error.

A third solution was considered, using an anisotropic inter-pole [9]. This solution presents an advantage regarding fringe field extents compared to pole shape magnets, and plays the role of a low-pass filter in the case of discrete trim coils. However, the maximum field is limited since the interpole will saturate easily. It was found that overlapped trim coils as presented in Fig. 2 could also dampen the high orders oscillations due to the finite number of trim coils, like the anisotropic interpole solution. Indeed, the field error shown in Fig. 3 for equivalent cases is reduced by a factor 5 with overlapped trim coils compared to without overlapped coils (with an iron shape not optimised at larger radii).

We decided to choose a flat pole with overlapped trim coils since the field quality shown was satisfactory, it eases the future optimisation of the fringe field extents, and it speeds up the project by removing the design of a pole shape magnet. The field quality of the solution with overlapping trim

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coils made the anisotropic inter-pole not required. The trim coils have been chosen to be 20 mm thick, leading to a full iron pole gap of 140 mm. A 3D model made in COMSOL of a single magnet with these specifications was successfully computed [10] and is presented in Fig. 4. However, meshing of 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 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 [11] to the present 4-fold symmetry lattice [4], and is presented in Fig. 5. The trim coils were designed with 8-node-brick conductors to adjust the shape of the coils, as it is presented in Fig. 6.

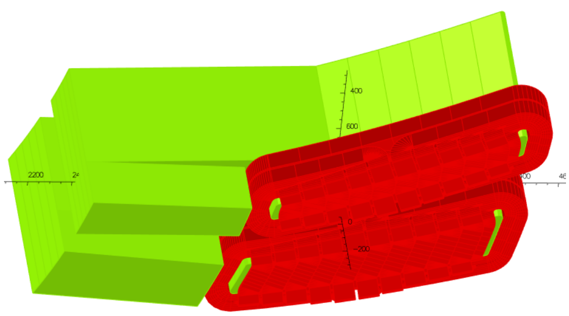

Figure 5: 3D model of the doublet in OPERA software.

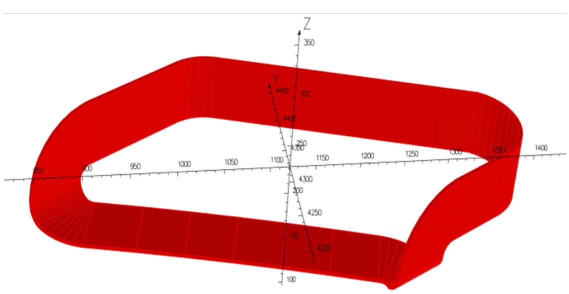

Figure 6: 3D model of one trim coil in OPERA software.

3D PRELIMINARY DESIGN

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 due to the internal cooling channel, 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. 7.

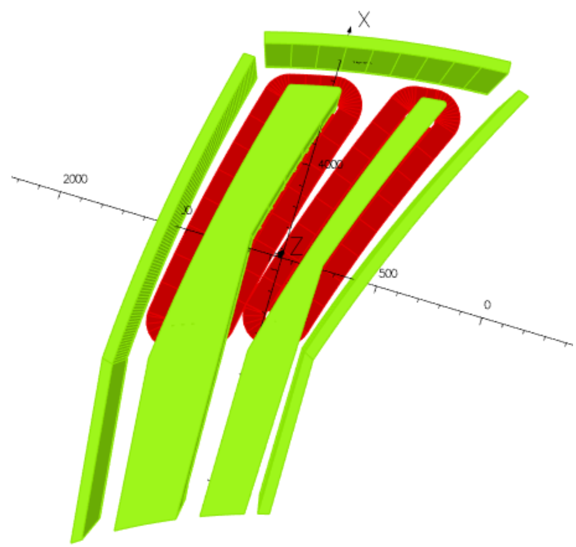

Figure 7: 3D model of the doublet in OPERA software with field clamps.

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.

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REFERENCES

[1] J. W. G. Thomason, "The ISIS spallation neutron and muon source – The first thirty-three years", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 917, pp. 61–67, 2019. doi:10.1016/j.nima.2018.11.129

[2] J. Thomason, "ISIS-II Roadmap". www.isis.stfc.ac.uk/Pages/ISIS-IIRoadmap.pdf

[3] D. J. Kelliher *et al.*, "Longitudinal dynamics in the prototype vFFA ring for ISIS2", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 1834–1837. doi:10.18429/JACoW-IPAC2021-TUPAB186

[4] S. Machida *et al.*, "FFA design study for a high intensity proton driver", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 1437–1439. doi:10.18429/JACoW-IPAC2023-TUPA044

[5] A. P. Letchford *et al.*, "Status of the RAL front end test stand", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 3959–3961. doi:10.18429/JACoW-IPAC2015-THPF105

[6] S. Brooks, "Non-scaling fixed-field proton accelerator with constant tunes", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 2257–2260. doi:10.18429/JACoW-IPAC2023-TUPM031

[7] COMSOL AB, "COMSOL Multiphysics software". https://www.comsol.com

[8] Dassault Systemes, "OPERA FEA Software". http://operafea.com

[9] Y. Iwashita, Y. Arimoto, and A. Sato, "Magnetic field distribution Control with anisotropic inter-pole magnetic field", *IEEE Trans. Appl. Supercond.*, vol. 16, pp. 1286–1289, 2006. doi:10.1109/TASC.2005.864300

[10] I. Rodriguez *et al.*, "FFA magnet prototype for high intensity pulsed proton driver", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 2261–2264. doi:10.18429/JACoW-IPAC2023-TUPM032

[11] S. Machida, "Developments and prospects of FFAs at RAL", in *Proc. Cyclotrons'22*, Beijing, China, Dec. 2022, paper FRAI01, to appear.