ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM032

FFA MAGNET PROTOTYPE FOR HIGH INTENSITY PULSED PROTON DRIVER

J.-B. Lagrange*, G. Aymar, J. Boehm, K. Geiger, 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 an option as a proton driver for the next generation spallation neutron source (ISIS-II). To demonstrate FFA suitability for high intensity operation, a 3 to 12 MeV 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 development. First the doublet spiral structure has never been designed before, and the essential feature of operational flexibility in terms of machine optics requires a wide range of changes for the field gradient. Finally, control of the fringe field is a challenge both mechanically and from the nonlinear optics point of view. This paper will discuss the design of the prototype magnet for FETS-FFA ring.

INTRODUCTION

A major upgrade of the ISIS facility [1], called "ISIS-II", is under study and a roadmap has been established [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,
- 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 by following the equation

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

* jean-baptiste.lagrange@stfc.ac.uk

with B_0 the field at the reference radius r_0, ξ the logarithmic spiral angle, k the constant geometrical field index and $\mathscr{F}$ 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. Two solutions are under study, with a fixed injection radius and a fixed extraction radius. So far, the magnet prototype study only investigated the fixed extraction option.

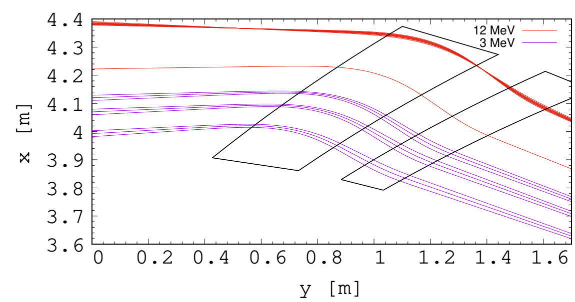

Figure 1: Closed orbits (3 MeV in purple, 12 MeV in red) in the lattice for different tune points. The average extraction closed orbit is fixed at 4.42 m.

MAGNET SPECIFICATIONS

The magnet specifications are presented in Table 1. They are based on the 16-fold symmetry lattice design of the prototype ring [7].

The lattice design computes a maximum vertical beta-function at injection of 1.85 m, corresponding to a vertical beam size of 34.1 mm for a normalised 50 π mm.mrad emittance. Considering a 5 mm thick vacuum chamber, it leads to a vertical gap of $\pm$40 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 maximum horizontal beta-function of 2.6 m and 2.9 m at injection and extraction, respectively.

While the average extraction design radius is fixed at 4.42 m, the maximum outer radius of the machine would be around 4.7 m to fit the ring in the planned building at RAL, which 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.

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM032

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

Table 1: Magnet Specifications

Cell type	FD spiral
Number of cells in the ring	16
Cell opening angle	22.50 deg.
Spiral angle	45.0 deg.
k-value range (central scenario)	6 – 11 (8)
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	80 mm
Good field region excursion	580 mm
Maximum vertical field in GFR	1 T
Fixed average extraction radius	4.42 m

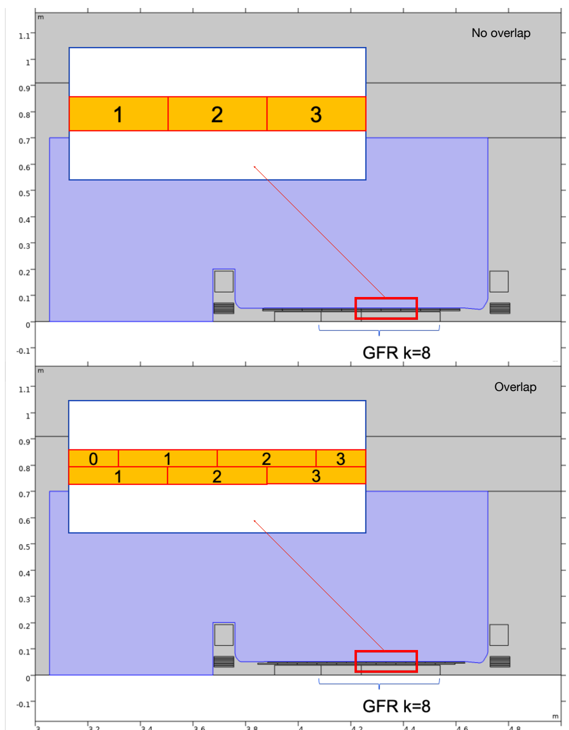

Figure 2: 2D model of no overlapped (top) and overlapped (bottom) trim coils.

MAGNET MANUFACTURING OPTIONS

Several options were considered for the manufacturing of the magnet, and 2D study was done to investigate them using the COMSOL [8] and OPERA [9] 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 will be smaller if a pole shape is 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

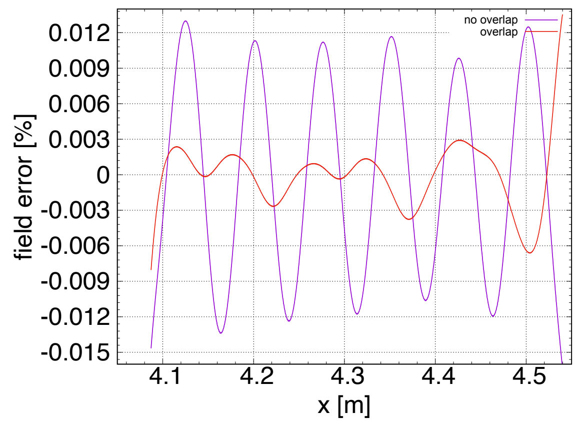

Figure 3: Field error along the radius line in the 2D model after current optimisation for no overlapped (purple) and overlapped trim coils (red).

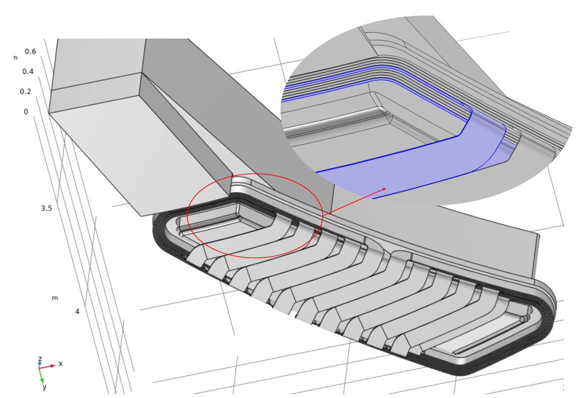

Figure 4: 3D model of overlapped trim coils for a single magnet.

a pole-shaped magnet for small gradient ($k \approx 8$). 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 anisotropic inter-pole [10]. 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 inter-pole will saturate easily. It was found that overlapped trim coils as presented in Fig. 2 could dampen the high orders oscillations due to the finite number of trim coils. 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 optimization of the fringe field extents, and it speeds up the project by removing the design of a pole shape

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM032

magnet. The field quality of the solution with overlapping trim coils made the anisotropic inter-pole not required. A 3D model made in COMSOL of a single magnet with these specifications was successfully computed and is presented in Fig. 4.

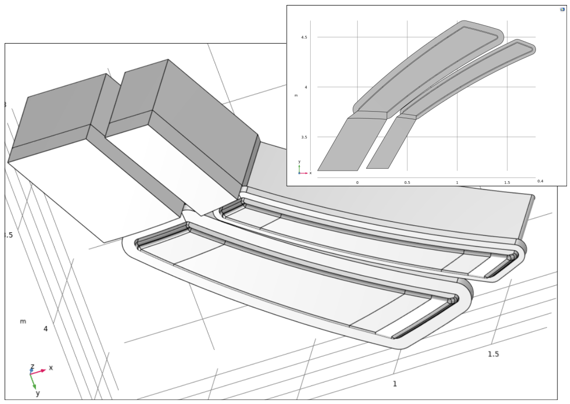

Figure 5: Preliminary 3D model doublet in COMSOL to study fringe fields A top view of the model is shown in the top right corner.

3D PRELIMINARY DESIGN

Dynamic aperture is mainly limited by the octopolar component of the field in the fringe field [11], so careful study is needed to check that the proper parameters of the lattice are chosen for our purpose. The first design was done with Enge fringe field model [12] with linear polynomial (equivalent to tanh), with constants taken from the Raccam project [13].

The trim coils have been chosen to be 20 mm thick, leading to a full iron pole gap of 120 mm. This gap is a major parameter for the fringe field extent of the magnet, and 3D preliminary magnetic model of the doublet was built to study the fringe field model. In this model with no trim coil and built in COMSOL (see Fig. 5), field profiles along constant radii have been calculated. These field profiles show that the linear Enge model used in the original lattice design was a poor fit compared to an Enge model up to the third order, especially for the F magnet. An example of these fits is presented in Fig. 6. The lattice design was thus shifted to a third order Enge model to match a more realistic fringe field behaviour.

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.

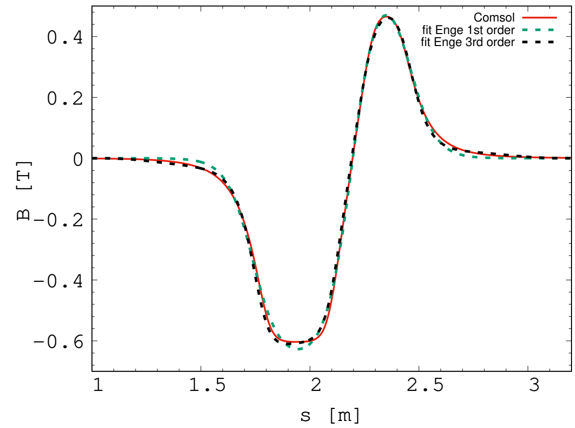

Figure 6: Fits of the vertical field profile along the cell in the preliminary field model at a constant radius of 4.087 m with linear Enge model (dotted green) and with Enge model up to the third order (black).

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 next step is thus to implement the doublet magnet in OPERA 3D with the trim coils to investigate the addition of field clamps on the outside of the doublet. 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. W. G. Thomason, "The ISIS Spallation Neutron and Muon Source—The first thirty-three years," Nucl. Instrum. Meth. A **917** (2019), 61-67 doi:10.1016/j.nima.2018.11.129

[2] J. Thomason, `www.isis.stfc.ac.uk/Pages/ISIS-II\%20Roadmap.pdf`

[3] D. J. Kelliher *et al.*, "Longitudinal Dynamics in the Prototype vFFA Ring for ISIS2", in *Proc. IPAC'21*, Campinas, 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", presented at the IPAC'23, Venice, Italy, May 2023, paper TUPA044, this conference.

[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", presented at the IPAC'23, Venice, Italy, May 2023, paper TUPM031, this conference.

[7] S. Machida, presented at CYC2022, 2022, paper FRAI1, to be published.

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

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

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM032

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

[10] Y. Iwashita *et al.*, "Magnetic field distribution control with anisotropic inter-pole magnetic field", IEEE Trans. Appl. Supercon., vol. 16, no. 2, pp. 1286-1289, 2006. doi:10.1109.TASC.2005.864300

[11] M. Aiba *et al.*, "Study of Acceptance of FFAG Accelerator", in *Proc. EPAC'02*, Paris, France, Jun. 2002, paper WEPLE063, pp. 1226–8.

[12] H.A. Enge, Deflecting magnets, Focusing of Charger Particles, academic press, Vol. 2, A. Septier, chapter 4.2, pp. 203–264 (1967).

[13] T. Planche, "Study of zero-chromatic FFAG synchrotron for muon acceleration", PhD thesis, Kyoto University, 2010.