FFA MAGNET PROTOTYPE FOR HIGH POWER PULSED PROTON DRIVER

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Abstract

The Fixed Field Alternating Gradient (FFA) accelerator is a natural candidate for a high-power pulsed proton driver, although no high-power FFA has yet been constructed. As a critical component of the accelerator, the main magnets have been the subject of particular study. Operational flexibility, in terms of machine optics, over a large range is an essential feature of such a machine. In order to explore this in more detail a dedicated FFA prototype magnet has been designed and manufactured. This magnet was manufactured and delivered to the Rutherford Appleton Laboratory (RAL) in the UK in 2025, and field measurements are subsequently planned to establish its characteristics. This paper will discuss the design, manufacture, and measurement plans of the prototype magnet.

INTRODUCTION

The Fixed Field Alternating Gradient Accelerator (FFA) is a compelling option for the next-generation high-power proton accelerator, such as the proposed ISIS-II facility at the Rutherford Appleton Laboratory (RAL). Unlike conventional synchrotrons, FFAs use DC magnets to enable high repetition rates and flexible longitudinal dynamics, making them ideal for high power pulsed applications like neutron and muon spallation sources. The FETS-FFA project [1] aims to design and build a 12 MeV proton FFA prototype ring as a proof-of-principle to validate the feasibility of high-intensity beam acceleration in an FFA, addressing key challenges such as beam loss control, machine tuneability and power efficiency. As a critical part of the hardware the main magnets have been designed [1]. Essential features for these magnets include zero-chromaticity during acceleration, dynamic aperture larger than the physical aperture to avoid uncontrolled losses, and flexibility in terms of tune point to allow different operation as a function of beam intensity. Zero-chromaticity is achieved when the magnet follows the scaling field law [2–4] defined by:

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

where B_0 is the reference field at radius r_0, k the geometrical field index, ξ the spiral angle and $\mathscr{F}$ the arbitrary fringe field function. For the FETS-FFA ring, the field index k ranges from 6 to 9, and the spiral angle is 30 deg. A reverse bend magnet (D-magnet) is included to allow a change in vertical tune by changing the field strength ratio between the F and D magnets, while the k-value must be able to vary to change the horizontal tune.

To balance practical constraints and feasibility, a scaled-down single radial sector magnet was designed instead of a full-scale doublet. The goal for this prototype is to investigate the manufacturing process of such a magnet, to benchmark measurements with the OPERA [5] model, to establish a method to control the magnet, and finally to elaborate and verify correction schemes to locally correct closed orbit distortions (COD) and higher-order errors. The spiral effects of the magnet cannot be investigated with this prototype (i.e. manufacturing process of spiral nested coils, edge correction), and the effects of saturation will be difficult to study under normal current operation. The cross-talk of neighbouring magnets will also not be observed. The manufacturing process of winding spiral coils could be tested by producing a set of nested coils as a separate project, and benchmarking OPERA simulations could provide an insight on the behaviour of the full-scale doublet.

MAGNET PROTOTYPE DESIGN AND MANUFACTURING

Design Specifications

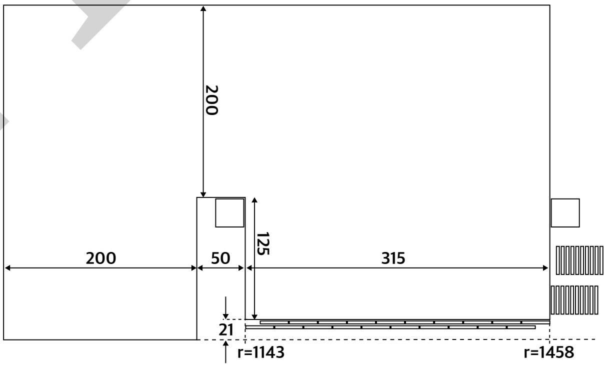

Figure 1: Transverse dimensions in mm of the prototype.

A flat gap with distributed coils was chosen to generate the field gradient, as in the FETS-FFA magnet [1]. Key parameters are summarised in Table 1. The transverse parameters are shown in Fig. 1, and the field errors after optimising the coil currents for the different k-value cases using OPERA 2D are presented in Fig. 2. The main coils are in a pancake shape, while the trim coils are saddled and nested, wound over 2 overlapping layers, and returning over 2 vertical layers.

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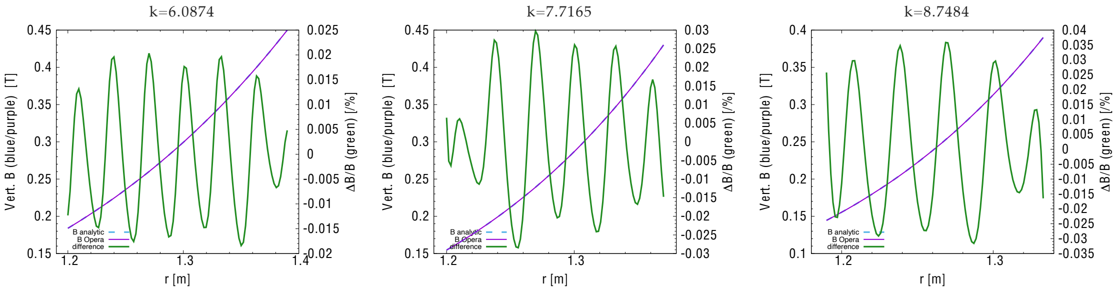

Figure 2: Magnetic field error of the prototype magnet for different k-values after coil current optimisation in OPERA 2D.

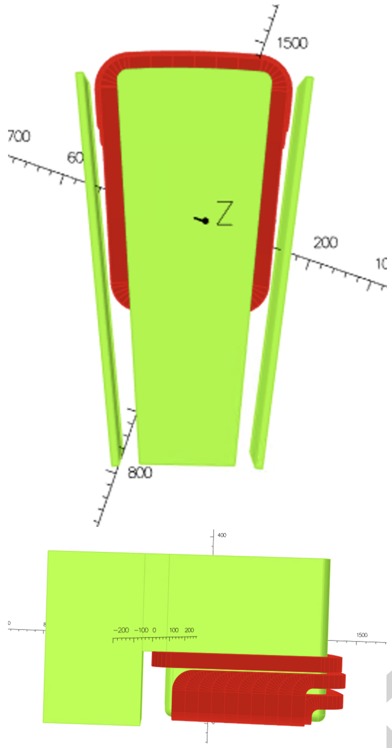

Figure 3: Top view(top) with field clamps and side view without clamps (bottom) of the OPERA 3D model of the prototype magnet, with the coils in red and iron in green. The main coil is shown above the trim coils, and trim coils are saddled around the pole, returning over 2 vertical layers.

The magnet was then modelled in OPERA 3D, with illustrative pictures presented in Fig. 3. Details of the windings of the trim coils can also be seen in Fig. 4. To control the fringe fields, clamps have been added on both sides. Starting from the optimised currents computed in 2D, an iterative optimisation process was conducted with OPERA 3D, and the final result is written in Table 2, with the corresponding magnetic field in the centre of the magnet for different configurations shown in Fig. 5.

The water calculations showed a temperature increase of less than 10 degrees Celsius with a uniform water pressure of 3.55 bar for all coils, achieving a Reynolds number of more than 4000 to ensure turbulent flow.

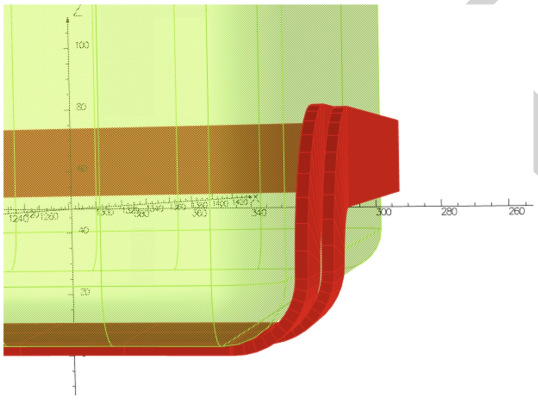

Figure 4: Trim coils details in the 3D OPERA model of the prototype.

Table 1: Magnet Specifications

Magnet shape	**C-shape**
Magnet type	Radial sector
Magnet opening angle	9.25 deg.
Pole shape	Flat
Pole width	315 mm
Full iron gap size	42 mm
Full physical aperture	21 mm
Good field region radii	1.189 m to 1.411 m
Transverse excursion	222 mm
Main coil shape	pancake
Main coil cross-section	7x7 mm, 3 mm diameter
Number of main windings	24
Number of main PSUs	1
Field gradient source	overlapped trim coils
Trim coil shape	saddled, overlapped
Number of trim coils	36
Trim coil dimensions	5x4 mm, 2 mm diameter
Number of trim windings	6
Number of trim PSUs	9

Manufacturing Process

The prototype was manufactured by Tesla Engineering Ltd [6], who also handled the mechanical design. The manufacturing process prioritised the precision in coil placement and fringe field control, with the clamps separate from the pole at the moment but with the possibility of easy modifi-

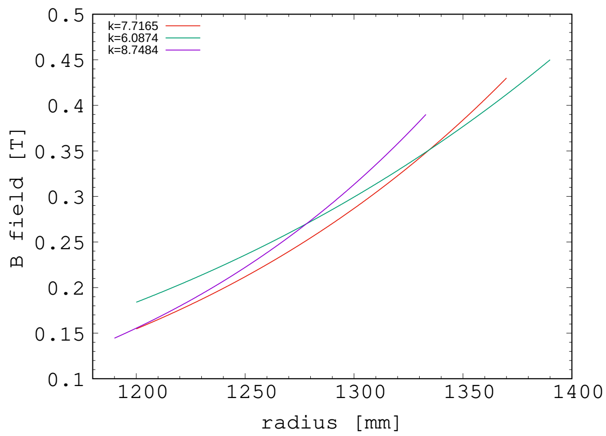

Figure 5: Magnetic field in the middle of the prototype magnet for different *k*-values from OPERA 3D.

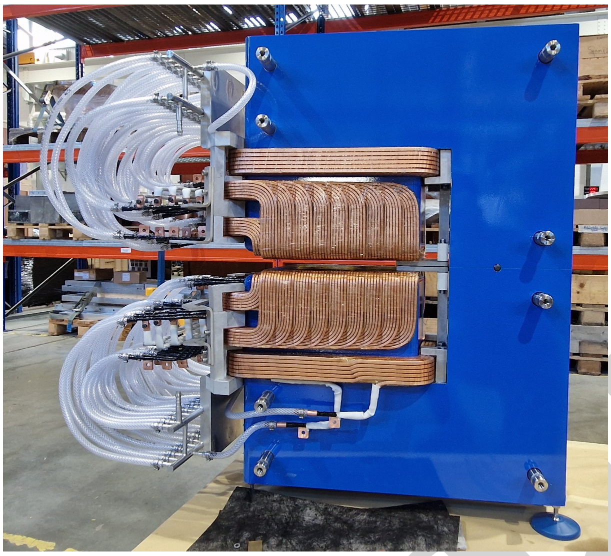

Figure 6: Picture of the magnet prototype without the field clamps, showing the return of the coils.

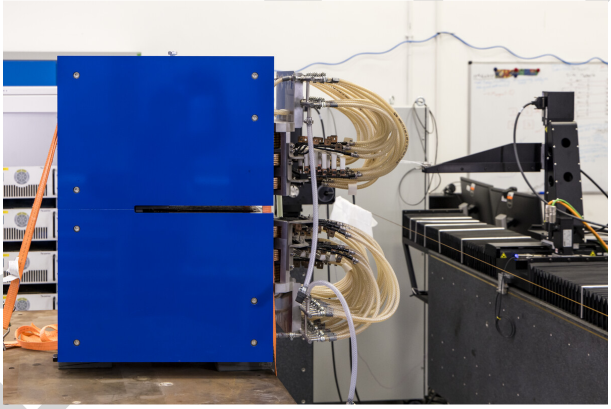

Figure 7: Picture of the magnet prototype with the magnet field mapping rig on the right.

Table 2: Optimised currents in Ampere-Turns of the prototype magnet in the coils for different *k*-values from OPERA 3D.

Currents	***k*=6.0874**	***k*=7.7165**	***k*=8.7484**
main [A-turns]	2347.2	2270.8	2314.4
trim 9 [A-turns]	533.5	0.00	0.00
trim 8 [A-turns]	468.7	580.0	0.00
trim 7 [A-turns]	419.5	624.8	688.7
trim 6 [A-turns]	373.9	538.3	579.5
trim 5 [A-turns]	332.8	462.4	483.9
trim 4 [A-turns]	294.6	396.2	403.5
trim 3 [A-turns]	261.6	286.9	333.5
trim 2 [A-turns]	223.4	247.4	282.3
trim 1 [A-turns]	295.0	70.0	39.8

cation for better fringe field shaping in future studies. While the main coils were wound using a standard machine, the trim coil cross-section was too small for the same method, so they were wound by hand using 3D printed moulds. The magnet was delivered in 2025 and a picture without clamps to show the coils is presented in Fig. 6.

MEASUREMENT SETUP

The validation of the prototype relies on a high-precision magnetic measurement system provided by Diamond Light Source. The mapping rig next to the magnet is presented in Fig. 7. The software Igor-Pro [7] will be used to operate the testing rig. A total of 10 Danfysik System 9700 Magnet Power Supply Units (PSUs) [8] have been recommissioned from ISIS operations for this project.

The experiment plan includes:

1. Powering the magnet with nominal settings for each *k*-value configuration.
2. Benchmarking measurements against the Opera model.
3. Creating a Jacobian matrix to quantify field changes per PSU adjustment, so that field correction can be predicted.
4. Investigating local correction schemes for COD and *k*-value tuning.

SUMMARY

The FFA magnet prototype represents a critical step to validate the FFA concept for high-intensity proton acceleration, offering a sustainable and high-performance alternative to conventional accelerator designs. The scaled-down design successfully balances project constraints with the need to test key parameters such as field accuracy, *k*-value control, and fringe field behaviour. Manufacturer Tesla Engineering delivered a functional prototype to RAL, where a high-precision magnetic measurement system provided by Diamond Light Source has been prepared for validation. Current plans will focus on benchmarking field measurements against OPERA simulations and testing correction schemes for COD and tune precision.

REFERENCES

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[8] Danfysik System 9700 Magnet Power Supply, `https://danfysik.com/en/products/power-supplies/system-9700/`.