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HIGH GRADIENT HYBRID HALBACH QUADRUPOLES WITH A NOVEL 3-BIT GRADIENT TUNING SYSTEM

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Abstract

This paper presents the magnetic design, mechanical design and assembly tooling design for four 500 T/m Hybrid Halbach Quadrupoles with an aperture radius of 4 mm. The quadrupoles will be used for capture of a 1-5 GeV electron beam produced in a plasma acceleration stage at the Extreme Photonics Applications Centre which is currently under construction at Rutherford Appleton Laboratory in the United Kingdom. In order to meet the stringent requirement dictated by beam dynamics studies, that the peak gradient of the four quadrupoles should vary by less than 1 % in the presence of economically achievable engineering tolerances and magnetic field uniformity of the permanent magnet blocks, the design features a novel '3-bit tuning system' in which three steel rods can be inserted in 8 different combinations into each steel magnet pole to tune the gradient in evenly spaced steps of 0.8 % over a full range of 6 %. This 3-bit tuning system can be used to ensure the specification on uniformity over the four quads is achieved.

BACKGROUND

EPAC is the Extreme Photonics Applications Centre, currently under construction at STFC Rutherford Appleton Laboratory in the UK. The Accelerator Science and Technology Centre (ASTeC) at STFC Daresbury Laboratory is responsible for designing an electron beamline to capture, transport and focus electron bunches accelerated in a plasma. To accommodate a variety of user applications the beamline must be flexible enough to capture high divergence bunches with energies from 100 MeV to several GeV and focus them at different interaction regions up to approximately 10 m downstream from the plasma. The full beamline [1] comprises 10 high strength fixed gradient small aperture quadrupoles, a number of electromagnetic quadrupoles of lower gradient and a two-dipole system for energy selection and spectrometry [2]. For the initial commissioning phase 4 small aperture high gradient quadrupoles are required, which will be installed inside a large vacuum chamber. The magnetic and engineering design of these quadrupoles is presented in this paper.

SPECIFICATION AND DESIGN ITERATION

The required specification of the quadrupoles is given in Table 1. Initial magnet modelling in Opera-2D indicated that a Halbach design could provide the required gradient and good gradient region with a 4 mm inscribed radius. However for ease of alignment during construction it was decided to increase the magnetic radius to 4.5 mm and use an internal stainless pipe of internal radius 4.0 mm. This small increase in magnetic radius meant that the external radius of the magnet blocks needed to be doubled to maintain the same gradient. In addition, first tolerance studies of the Halbach design using typical manufacturing errors in block dimensions of ±50 µm, remanent field errors of ±2 %, and magnetisation angle errors of ±2° indicated that the gradient variation over all the quadrupoles would exceed the specification of ±1 %.

Table 1: Quadrupole Specification.

Peak gradient	≈500 T/m
Maximum length	50 mm
Integrated gradient	>25 T
Internal radius	4 mm
1 % good gradient radius	≈2 mm
0.1 % good gradient radius	≈1 mm
Peak gradient variation	1 % full range

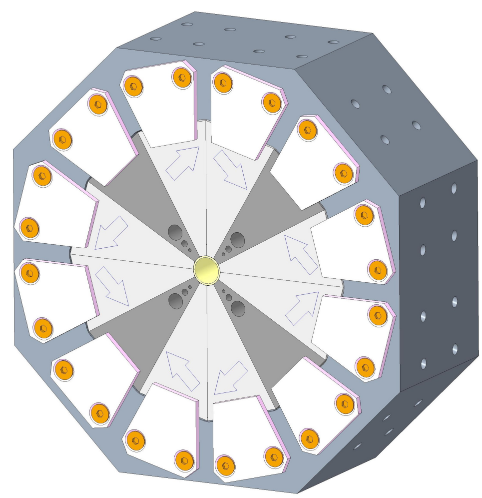

Figure 1: Hybrid Halbach Quadrupole. The arrows on the eight light-coloured permanent magnet blocks indicate the magnetisation directions. The darker coloured blocks are the steel poles.

FINAL DESIGN

For the final design a hybrid solution was adopted and is shown in Fig. 1. The blocks in which the magnetic field was orientated radially, referred to here as the 'poles', were replaced with 1006 magnetic steel, allowing the required gradient to be achieved with an acceptable outer magnetic radius of 46 mm. The fact that the poles were made of steel offered the opportunity to trim the field post-construction.

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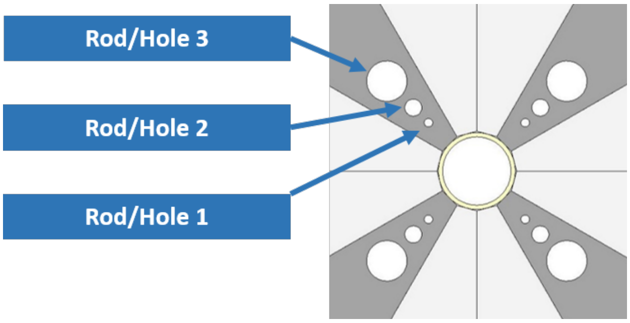

Figure 2: Tuning System

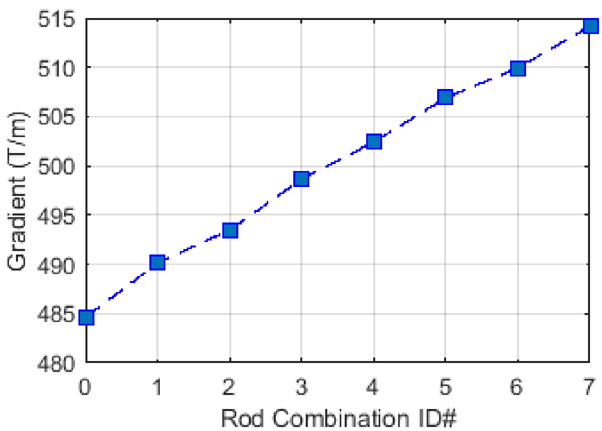

Figure 3: Gradient vs Rod combination ID#

To achieve this each pole has three holes into which 1006 magnetic steel rods can be inserted to adjust the gradient. Fig. 2 shows the arrangement of holes—Holes 1, 2 and 3 have diameters 1 mm, 2 mm and 4.75 mm respectively and each rod has diameter 0.1 mm smaller than its respective hole. Inserting Rod 1 increases the gradient by ≈4 T/m, inserting Rod 2 increases the gradient by ≈8 T/m, and inserting Rod 3 increases the gradient by ≈16 T/m—thus by the use of 3 rods the gradient can be adjusted to 8 different levels equally spaced by 4 T/m—hence the system is called **3-Bit Tuning**. Given that the peak gradient is 500 T/m, steps of 4 T/m are a relative variation of 0.8 % which is smaller than the required maximum variation of 1 % over all the quadrupoles hence the 8-bit tuning can be used to ensure that the gradient variation is within specification. Table 2 and Fig. 3 show the Opera 2D simulation results of inserting the rods in the 8 different combinations (ID#s) and confirm that the gradient can be tuned over a full range of 6 % in steps of 0.8 %.

TOLERANCE ANALYSIS

A tolerance analysis was done of the final design. Following feedback from suppliers on the standard errors that would be expected for an economical cost, errors were set to ±50 µm in block dimensions, ±3 % on dipole moment and ±3° on magnetisation angle. One hundred randomised models were created and solved. Fig. 4 shows that the mean

Table 2: Tuning

ID#	Rod-3	Rod-2	Rod-1	Gradient (T/m)
0	OUT	OUT	OUT	484.6
1	OUT	OUT	IN	490.1
2	OUT	IN	OUT	493.5
3	OUT	IN	IN	498.8
4	IN	OUT	OUT	502.4
5	IN	OUT	IN	506.9
6	IN	IN	OUT	509.9
7	IN	IN	IN	514.1

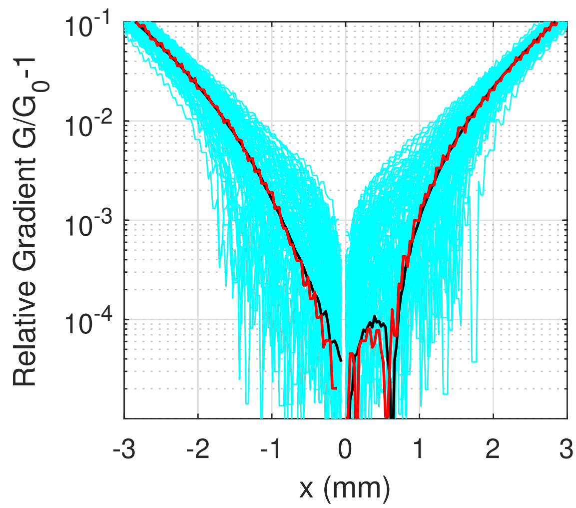

Figure 4: Tolerance analysis of good gradient extent for 100 randomised models.

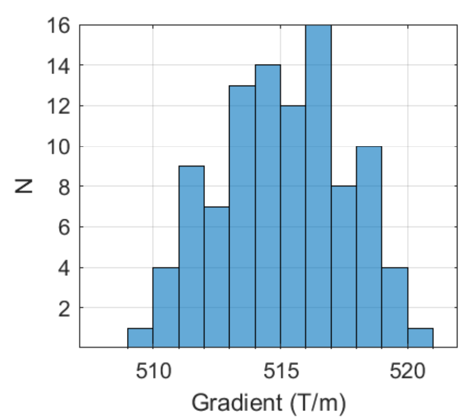

Figure 5: Tolerance analysis of gradient variation over 100 randomised models.

1 % good gradient radius was 1.67 mm and the mean 0.1 % good gradient radius was 0.93 mm—both these values are close to the approximate specification and confirmed acceptable based on beam dynamics analysis. Fig. 5 shows the full variation in gradient was 2.3 %, more than double the specification of 1 %, confirming that gradient tuning will likely be necessary.

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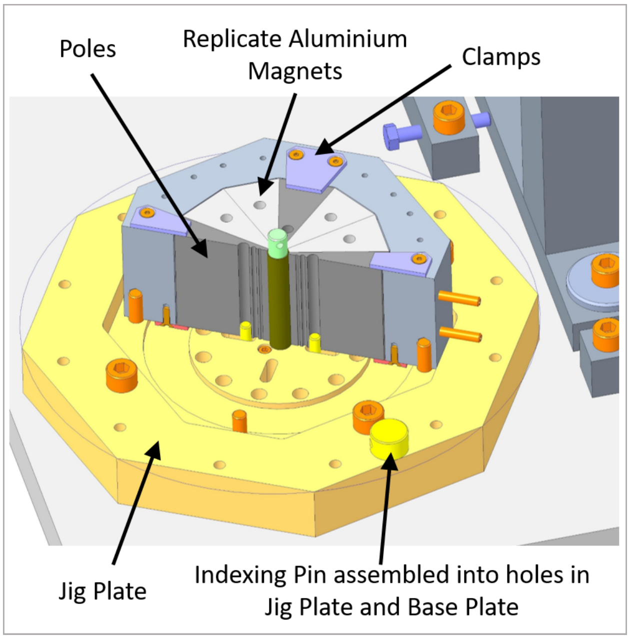

Figure 6: Pole assembly

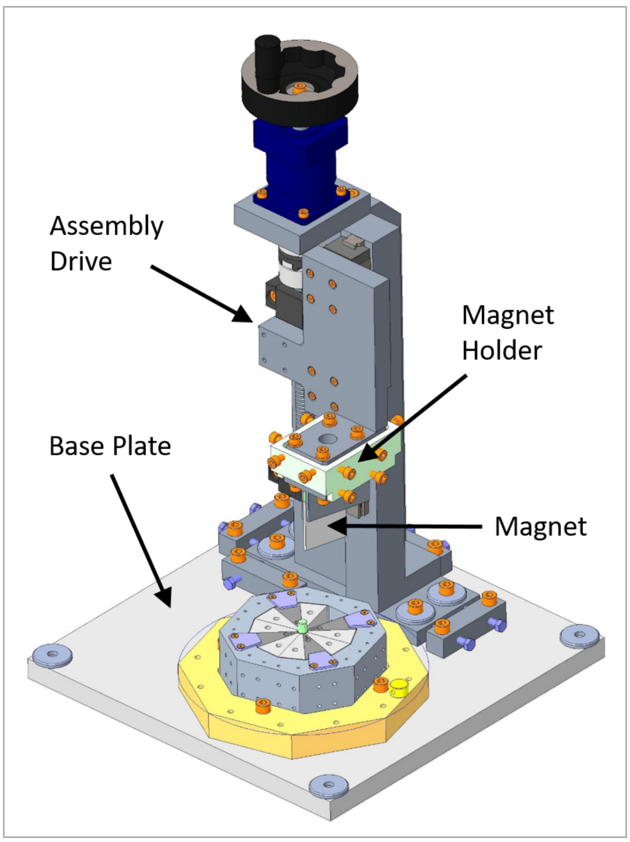

Figure 7: Assembly tooling

MECHANICAL DESIGN

The mechanical design of the magnet and its assembly tooling was carried out by the Technology Department at Daresbury Laboratory. The magnets and poles are clamped into an aluminium octagonal shaped holder which includes features for alignment and final mounting. The magnet aperture is defined with a stainless steel tube with outer radius of 4.5 mm and internal radius of 4.0 mm. The assembly will be achieved using bespoke assembly tooling to manage the forces between the poles and magnets. The magnet will be assembled onto a jig plate with features to aid assembly. The octagonal magnet holder will be clamped onto the jig plate and the centre steel tube assembled over a dowel screwed into the jig plate. The wedge shaped steel (AISI 1006) poles will be assembled with the end faces in contact with the centre tube as illustrated in Fig. 6. The position and orientation of the poles is set by inserting a temporary dowel into the 4.75 mm hole in the pole and corresponding aligning feature in the jig plate, and also by the use of aluminium replicate magnet wedges which will provide reference abutment surfaces. To secure the magnet centre tube, adhesive will be applied on the contact surfaces between the tube and poles. For the assembly of the magnet wedges the magnet assembly orientation will be achieved by rotating the magnet jig plate about a pin screwed into the baseplate on the magnet centre axis. The position will be set by inserting an indexing pin into corresponding holes of the jig plate and baseplate as illustrated in Fig. 7. The magnet wedge to be assembled will be clamped into a holder attached to the drive system. The corresponding replicate aluminium wedge will be removed from the magnet assembly and the magnet wedge translated into position from above using a linear guide and leadscrew and by the application of a handwheel driven through a gearbox. When in position the magnet wedge will be initially held with a temporary clamp to enable the assembly tooling to be removed and a permanent clamp to be assembled. The magnet wedge assembly process is repeated for all eight magnets.

SUMMARY AND OUTLOOK

A 500 T/m hybrid Halbach quadrupole has been designed to meet the beam dynamics requirements of the electron capture and transport line of the EPAC facility. A novel 3-bit tuning system will be employed to tune the gradients of the assembled magnets so that the variation is within the 1 % specification. All components for the magnets and tooling are currently being procured. Assembly will begin in September 2023, followed by magnetic measurement and gradient tuning.

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