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DESIGN OF A PERMANENT MAGNET BASED DIPOLE QUADRUPOLE MAGNET*

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Abstract

Permanent magnet technology can facilitate the design of accelerator magnets with much lower power consumption than traditional resistive electromagnets. By reducing the power requirements of magnets, more sustainable accelerators can be designed and built. At STFC, as part of the I.FAST collaboration, we are working to develop sustainable technologies for future accelerators. As part of this work, we have designed a permanent magnet based dipole-quadrupole magnet with parameters suited to meet the requirements of the proposed Diamond-II upgrade. We present here the magnetic design, which is based on a single sided dipole-quadrupole. The design includes the shaping of the pole tips to reduce multipole errors as well as methods of providing thermal stabilisation and field tuning. The mechanical design of the magnet is being undertaken by colleagues at Kyma and a prototype of the magnet will soon be built and tested.

INTRODUCTION

The I.FAST collaboration [1] aims to boost innovation in the particle accelerator community. A core theme of the collaboration is the development of more sustainable concepts and technologies. Magnets provide one of the largest sources of power consumption in modern accelerators. For instance, the dipoles and quadrupoles for the proposed Compact Linear Collider (CLIC) would dissipate an estimated 29.4 MW due to electrical resistance alone [2]. Therefore, if traditional electromagnets can be replaced by permanent magnets, future accelerators may be made to require less power and be more sustainable.

Table 1: Summary of Magnetic Design Requirements

Parameter	Value	Units
Central Dipole	-0.6951033	T
Central Gradient	32.3974035	T m^{-1}
Good Field Radius	7	mm
Field Quality ΔB/B	5×10^{-4}	
Gradient Quality ΔG/G	1×10^{-3}	
Integrated Dipole	0.6047	T.m
Integrated Gradient	28.1857	T
Integrated Multipoles	$<10^{-3}$	

The proposed Diamond-II upgrade will utilise multibend-achromat technology and an increase in electron beam energy to achieve gains in the brightness and coherence of the synchrotron radiation produced by the facility [3]. The lattice design relies upon the use of combined function dipole-quadrupole (DQ) magnets with high gradients to simultaneously bend and focus the beam. An electromagnetic DQ has been previously designed to meet the Diamond-II requirements. However, an alternative design, using permanent magnets as the main source of magnetic field (PMDQ) has been designed to demonstrate how the same magnetic field requirements can be met at reduced power consumption. The main magnetic requirements are summarised in Table 1.

DESIGN OVERVIEW

The design of the PMDQ is based on a single-sided electromagnetic combined function magnet [4]. This single sided design has been shown to produce larger gradients than traditional gradient dipole designs and is more efficient than an offset quadrupole [4]. Given the high field gradient that is required, a gradient dipole design would not have been suitable. A labelled image of the magnetic model of the PMDQ, generated using Opera 3D simulation software [5], is shown in Fig. 1. The different colours represent different materials and parts of the design. The thick black arrows indicate the direction of magnetisation of the permanent magnets.

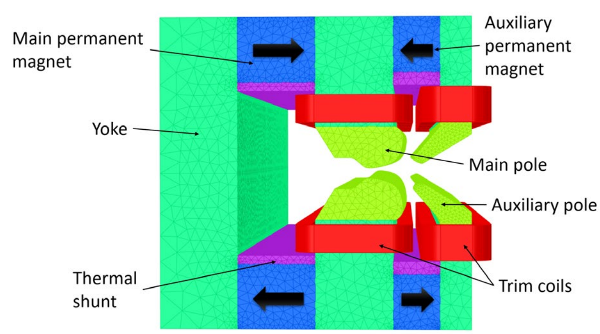

Figure 1: Labelled image of Opera 3D PMDQ model.

The primary source of the fields are permanent magnets, rather than current carrying coils. Therefore, the power and cooling requirements of the magnet can be greatly reduced.

The large magnet blocks shown in Fig. 1 will be split into carriages containing arrays of smaller magnets in order to ease the handling of the permanent magnet material. The blocks will be arranged with the magnetisation axes aligned horizontally in order to generate the desired combined function field in the bore.

The material and grade of magnet used in the design was Neodymium Iron Boron (NdFeB) grade 40EH from ZHmag [6]. The magnet grade was chosen to have a high

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remanent field (1.32 T at 20 degrees C) whilst maintaining a reasonably large coercive field (2388 kA m^{-1}). The choice of NdFeB over samarium cobalt (SmCo) was made because the permanent magnets are not located close to the beam. Therefore, there is limited risk of demagnetisation due to radiation damage. NdFeB has a higher remanent field despite having lower coercivity than SmCo. Therefore, less magnet material could be used to achieve the desired field strength.

The yoke and poles (dark and light green respectively in Fig. 1) will be made from XC06 low carbon steel so that the flux from the permanent magnets will flow through the yoke. A backleg has been included to provide a return path for the flux generated by the main permanent magnet blocks.

POLE OPTIMISATION

The main and auxiliary poles have been designed using an Opera 2D model. The pole shapes were first modelled as hyperbolae and the dimensions of the permanent magnets were adjusted to get close to the desired dipole and gradient fields, independent of the field quality. Then a pole shaping algorithm, based on the work presented in [7] was applied to the pole tips to minimise the multipole field errors. The resulting pole tip coordinates are shown in Fig. 2, with the good field region indicated by the dashed line.

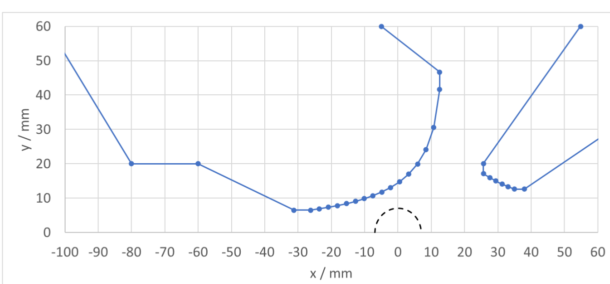

Figure 2: Plot of optimised pole tip coordinates.

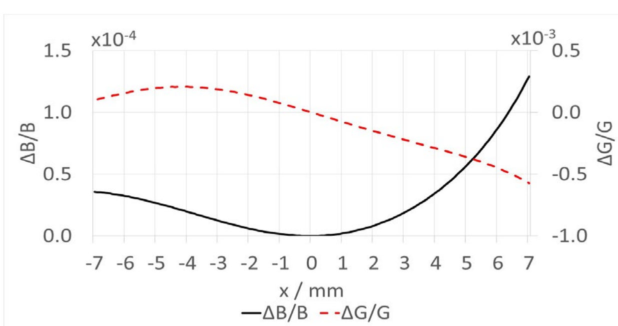

Figure 3: Field and gradient quality in centre plane of 3D model.

The pole tip profile was applied to the 3D Opera model, which was used to calculate the nominal magnet dimensions required to meet the field requirements listed in Table 1. The tips of the poles were curved to follow the reference electron beam trajectory. Therefore, the on-axis dipole field was kept constant through the magnet. The rest of the yoke and the permanent magnet material were kept straight to simplify the manufacture.

The field quality (ΔB/B) and gradient quality (ΔG/G) plotted in the centre plane of the 3D model with the nominal magnet dimensions are shown in Fig. 3. As can be seen from the figure, within the good field radius the field and gradient quality are within the defined limits of 5×10^{-4} and 10^{-3} respectively. Initial tolerance modelling indicates that a tolerance on the pole point coordinates of ±20 μm will be required to maintain the field quality within the limit of 5×10^{-4}. Future work will involve more detailed modelling of the tolerances on the pole shapes and alignment.

The physical length of the magnet model was set to achieve the nominal integrated dipole field of 0.6047 T.m. At this length, the integrated gradient is only 27.5350 T, which is shorter than the nominal value of 28.1857 T. The multipole fields in the 3D model plotted along the reference electron trajectory at the good field radius are shown in Fig. 4. The figure shows that the quadrupole field drops off more rapidly than the dipole, resulting in a shorter magnetic length. This effect has been seen in other combined function magnets [4]. Future work will investigate shimming techniques to reduce the difference between the dipole and quadrupole magnetic lengths. Higher order integrated multipoles are all below the target value of 10^{-3}.

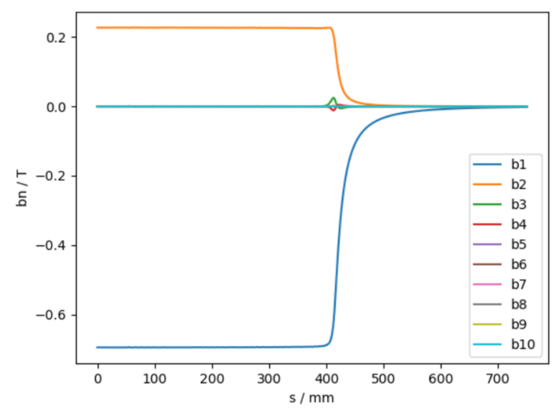

Figure 4: Integrated multipoles through 3D model.

THERMAL STABILITY

Fluctuations in temperature will affect the remanent field of the NdFeB magnets blocks and hence the field produced in the bore of the PMDQ. Thermal shunts (purple in Fig. 1) have been included in the design to improve the temperature stability of the magnet. These shunts are made from an iron-nickel alloy (Fe-Ni) with a negative temperature coefficient [8]. At a given temperature, a fraction of the flux at the surface of the permanent magnets its diverted through the shunt, rather than through the magnetic yoke and across the magnet bore. The total fraction of the flux that is shunted depends on the thickness and saturation polarisation of the shunt material. As the temperature increases, the remanent field of the permanent magnet decreases, but the saturation polarisation of the shunt also decreases. Therefore, at higher temperatures,

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less flux is shunted by the Fe-Ni alloy. If the thickness of the shunts is chosen correctly, the flux density at the pole tips can be kept stable with changes in temperature.

The thickness of the shunt material can be optimised to minimise the effect on the field in the bore with changes in temperature. Figure 5 shows the change in the dipole field with temperature relative to a model set at 20 degrees Celsius for models with and without the use of optimised thermal shunts. As can be seen from the figure, the dipole field decreases linearly by 0.13%/degree for the uncompensated model. However, with the presence of the thermal shunts, the linear dependence of the field with temperature can be removed and the dipole field is stable to within 0.01% over the 3-degree temperature range shown. This is comparable to the stability that can be achieved within power supply fluctuations of typical electromagnets [9].

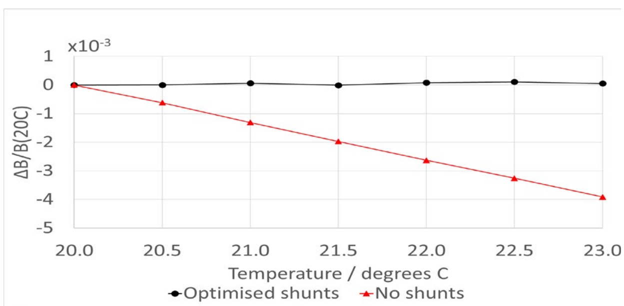

Figure 5: Relative change in dipole field as a function of temperature for models with and without thermal shunts.

FIELD TUNING

Trim coils (shown in red in Fig. 1) have been included in the design so that the field under normal operation can be fine-tuned. There will be two pairs of coils (located on the main and auxiliary pole arms respectively) which can be powered independently. This will allow the dipole and quadrupole fields to be trimmed independently.

Use of these coils will allow the nominal fields to be reached from permanent magnet blocks of finite size and account for magnetisation and machining tolerances. Assuming that the dimensions of the NdFeB blocks are limited to a precision of 0.1 mm, a nominal power requirement of 5.8 mW per magnet will be required to trim the field during normal operation. The power requirements for the equivalent electromagnetic design are 2.56 kW per magnet [3]. The conceptual design of the Diamond-II lattice contains 48 DQ magnets [3]. Replacing all of these electromagnets with PMDQs would result in a power saving of approximately 120 kW from electrical resistance alone. This is a significant reduction in power requirements that could lead to a reduction in facility operating costs and carbon footprint.

Assuming a coil packing fraction of 0.5, the coil current densities under nominal operation will be of the order 10 mA mm^{-2}. This is a sufficiently low current density to allow the trim coils to be air cooled under normal operation. Negating the need for water cooling of the coils under normal operation will further reduce the operating costs and power requirements of the magnet.

The coils must also be capable of being used to sweep the dipole and quadrupole fields independently over a range ±2.5% of the nominal values for use during commissioning. Figure 6 shows how the central dipole and quadrupole can be trimmed independently by adjusting the current densities in the main and auxiliary coil pairs. Where the gradient is tuned to ±2.5 %, the power requirements are of the order 10 W per magnet. This is significantly higher than the nominal operating power of the PMDQ, but still 2 orders of magnitude less than for the nominal electromagnet design. The coils must have the option of water cooling to allow operation at current densities up to 10 A mm^{-2} during the field sweeping.

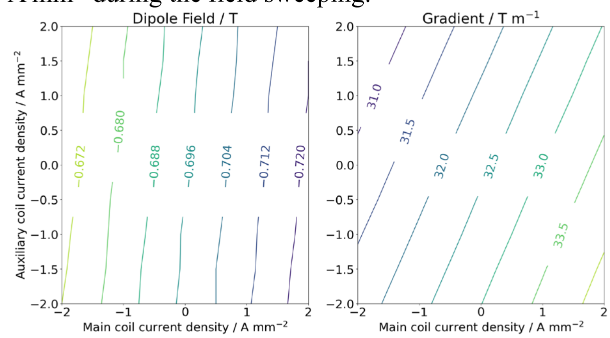

Figure 6: Central dipole and quadrupole trimming with coils.

MECHANICAL DESIGN

The mechanical design for the PMDQ is being developed by colleagues at Kyma [10]. Concepts for manufacturing, assembling, tuning and installing the magnet have been generated. The design accounts for the large magnetic forces between the yoke and magnet materials during assembly and makes use of non-magnetic gap spacers to maintain the separation between pole pieces despite the attractive forces between them. Future work will involve the construction and magnetic measurement of a prototype magnet to demonstrate the feasibility of this technology for future facilities.

CONCLUSION

A permanent magnet based dipole-quadrupole magnet has been designed to meet the same field requirements as an equivalent electromagnetic design aimed at the Diamond-II upgrade project. By replacing water cooled resistive coils with NdFeB permanent magnets as the primary source of the magnetic field, the total power requirements of the magnet can be reduced by 2 orders of magnitude with the nominal operating power reduced by 6 orders of magnitude. This can facilitate the design of a more sustainable accelerator facility.

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