

RESULTS FROM THE HEPTO COMBINED FUNCTION PERMANENT MAGNET*

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Abstract

The Hybrid Electromagnet-Permanent Magnet Tuneable Optics (HEPTO) magnet has been designed and built as part of the I.FAST collaboration as an energy saving alternative to traditional resistive electromagnets. The prototype magnet has been designed to meet the magnetic field requirements of the combined function dipole-quadrupole (DQ) magnets required for the Diamond-II upgrade. The prototype contains several design features for maintaining and tuning the field strength and quality, including a novel mechanical shimming method, trim coils and passive temperature compensation. We present here the results of the magnetic measurements of the built prototype magnet and demonstrate the ability to tune the field using the design features. We demonstrate that the nominal integrated field strength and homogeneity can be achieved with the permanent magnet solution, representing a 2.3 kW reduction in nominal power consumption compared to the equivalent electromagnet.

INTRODUCTION

Fourth generation synchrotron light sources make use of multi-bend achromat (MBA) lattices to enable a reduction in beam emittance and hence order of magnitude increase in brightness relative to third generation sources [1]. These MBA lattices contain large numbers of magnets, and complex magnet designs, including combined function magnets [2]. The increase in number of lattice magnets results in an increase in the electrical power requirements and corresponding carbon footprint of the facilities.

Permanent magnets provide an attractive alternative to traditional resistive electromagnets to reduce both the operating costs and environmental impact of accelerator facilities [2].

As part of the I.FAST collaboration [3], the Hybrid Electromagnet-Permanent magnet Tuneable Optics (HEPTO) prototype has been built as a technology demonstrator of a permanent magnet based combined function dipole-quadrupole magnet with application for fourth generation light sources.

MAGNET DESIGN

The HEPTO magnet (Fig. 1) has been designed to meet the same integrated field strength and homogeneity requirements as the dipole-quadrupole (DQ) electromagnets de-

signed for the Diamond-II storage ring upgrade [4]. The nominal integrated dipole and gradient of the HEPTO magnet are $-0.6047 \text{ T.m} \pm 0.1 \%$ and $28.1857 \text{ T} \pm 0.1 \%$ respectively. The specified field homogeneity $\Delta B/B$ in the 7 mm radius good field region was $5E-4$. These values are the same as those defined for the equivalent electromagnet in order to give the same performance. [5].



Figure 1: Photograph of the HEPTO prototype magnet.

The HEPTO design is based on a single-sided quadrupole [6]. The main source of the field is provided by grade 45M6 NdFeB permanent magnet blocks with a remanent field of $1.3 \text{ T} \pm 1 \%$. Nickel-iron thermal shunts [7] located parallel to the permanent magnet blocks to the sides of the main poles provide passive temperature compensation. Small air cooled coils provide the ability to scan the quadrupole field independent of the dipole field for emittance measurements.

Material, machining and assembly tolerances all contribute to errors being introduced in the field profile produced by the built magnet. In traditional electromagnets, the current can be varied to achieve the target integrated field strength. Permanent magnets are fixed field devices, making adjustment of the field strength more challenging. With this in mind, the HEPTO magnet has been designed with a comprehensive mechanical shimming method to allow for adjustment of the field strength and homogeneity of the built magnet. This shimming method primarily relies on the use of brass shims placed between spacers to finely adjust the mechanical separation between the main and auxiliary poles.

* Work supported by funding from the I.FAST collaboration

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MECHANICAL SHIMMING

The impact of the magnet on the electron beam can be described in terms of the integrated field harmonics [8]. The pole tips of the HEPTO magnet are curved in order to keep the dipole field along the curved electron beam trajectory constant. Therefore, it was not possible to measure the integrated field components along the magnetic axis using a stretched wire [9] or rotating coil [10]. Instead, the integrated multipole components were measured using a Hall probe. A precision 3-axis motion system was used to trace circular arcs along the nominal curved trajectory. The multipole fields were evaluated along each arc and integrated along the nominal trajectory. The probe used was a Senis type H 3-axis Hall sensor connected to a 3MH3 Teslometer [11].

Initial measurements indicated that the integrated gradient ($n=2$) of the built HEPTO magnet was 28.070 ± 0.002 T. This value was 0.41 % less than the specification and not within the allowable 0.1 % of the specified gradient. The measured integrated higher order harmonics ($n \geq 3$) were in good agreement with those predicted by the Opera [12] magnetic model, as shown in Fig. 2. The largest discrepancies in the higher order harmonics between the models and the measurements are in the sextupole ($n=3$) and octupole ($n=4$). These differences from the design harmonics result in the field homogeneity $\Delta B/B$ along the horizontal axis exceeding the target value of $5E-4$ at the low field end of the magnet. The low field end corresponds to positive x coordinates in Fig. 3. The maximum absolute value of $\Delta B/B$ was measured as $(8.2 \pm 0.5)E-4$. This was primarily attributed to the assembly tolerances on the auxiliary poles and slight deformation due to attractive magnetic forces between the main and auxiliary poles.

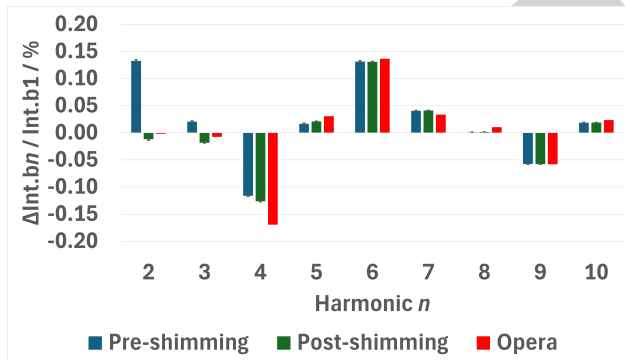


Figure 2: Plot of the integrated multipole errors normalised to the integrated dipole for the HEPTO magnet as first built, after mechanical shimming, and as predicted by the Opera magnetic model.

The mechanical shimming mechanism was used to correct the errors in the integrated gradient strength and field homogeneity. By sequential addition and removal of brass shims, the relative vertical gaps between the main and auxiliary poles were adjusted and the integrated multipoles remeasured. After shimming, the integrated gradient was increased to 28.196 ± 0.001 T, which is within the target of 0.1 % of the specified field. The main impact of the shimming was on the

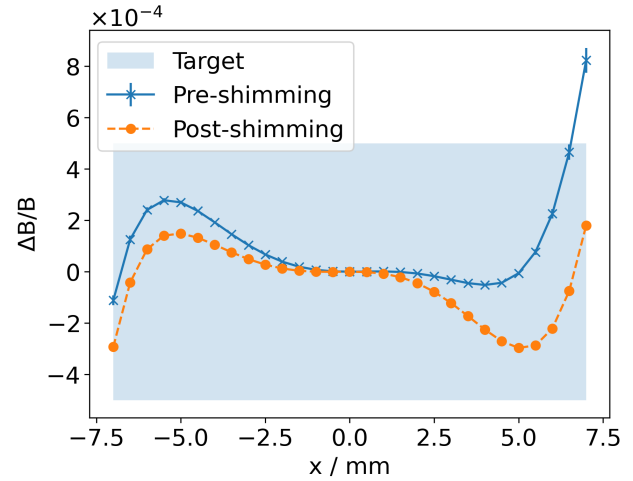


Figure 3: Plot of the integrated field homogeneity $\Delta B/B$ along the horizontal axis for the HEPTO magnet as first built and after mechanical shimming.

quadrupole and sextupole harmonic fields, as shown in Fig. 2. The shimming changed the sextupole from (0.021 ± 0.001) % to (-0.018 ± 0.001) % of the dipole, which is in better agreement with the Opera model (-0.007) %. The harmonics at higher order than sextupole were largely independent of the mechanical shimming. The maximum absolute field error along the horizontal axis was $(2.9 \pm 0.1)E-4$, which was within the specification of $5E-4$, as shown in Fig. 3. This demonstrates that the mechanical shimming method was very effective for correcting the field strength and quality of the as-built magnet. This is an important feature as otherwise the performance of the magnet would be inherently limited by manufacturing tolerances.

COIL TUNING

The magnet has also been designed with small air cooled electromagnet coils. These coils serve two purposes: in-situ trimming of the integrated dipole and quadrupole fields for correction of the fields and independent tuning of the quadrupole field for beam emittance measurements. The mechanical shimming mechanism has been used as the primary method of correcting the fields. This is intended to minimise the nominal trim coil currents required. This both reduces the operational power requirements of the magnet, and improves the effective tuning range of the coils.

In order to determine the practical tuning range of the dipole and quadrupole fields, the multipoles in the central plane of the HEPTO magnet were measured for different combinations of current in the main and auxiliary trim coils. The relative changes in the dipole and quadrupole fields with trim coil current are shown in Fig 4.

The two pairs of trim coils can be used in conjunction to tune the quadrupole field independently of the dipole. Figure 5 shows a plot of the coil currents required in both trim coils to achieve a given change in the gradient. The current in the coils is limited to 5 A by the conductor used. Therefore, the maximum achievable independent tuning range of the

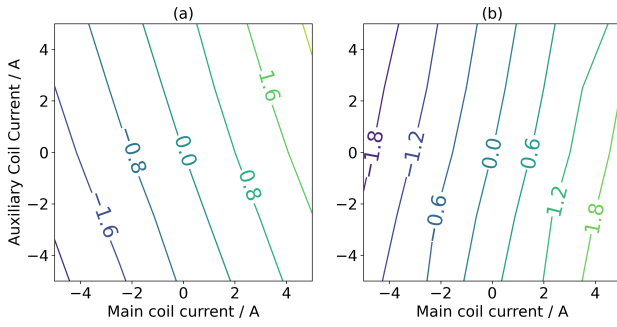


Figure 4: Contour plots showing percentage changes in (a) dipole and (b) quadrupole fields with trim coil currents.

quadrupole field is $\pm 1.1\%$. This is less than the tuning range of $\pm 3\%$ for the equivalent electromagnet [5]. The tuning range is reduced due to the smaller allowable currents, and the less efficient magnetic circuit caused by the permanent magnet blocks. The tuning range could be increased by adding more turns to the auxiliary coil whilst maintaining the same maximum current. However, this would increase the risk of large temperature rises inside the coil, which could impact the performance of the permanent magnets. The achievable tuning range on the order of a few percent is comparable to other permanent magnet designs employing small trim coils [13].

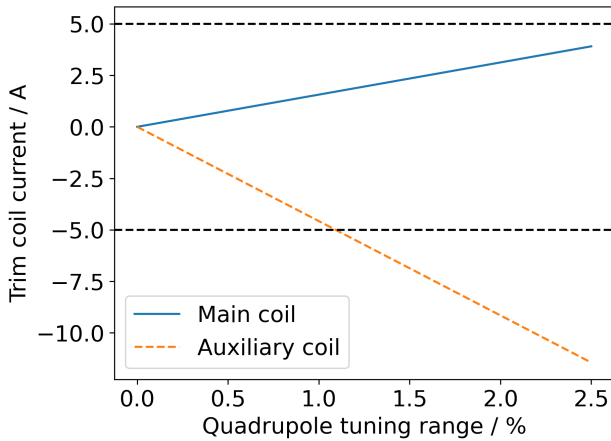


Figure 5: Required trim coil currents as a function of quadrupole tuning range for fixed dipole field.

The maximum power consumption of the HEPTO magnet with both coil pairs at 5 A is 25 W. This is a significant saving compared to the nominal operating power of 2.3 kW of the electromagnet [5]. The Diamond-II lattice is designed with 48 DQ magnets. Replacing all of the electromagnets with HEPTO magnets would therefore provide a total power saving of 109.2 kW.

THERMAL STABILITY

Iron nickel thermal shunts were included in the design to help reduce changes in the field strength in the bore of the magnet with changes in the ambient temperature of the accelerator hall. The temperature stability of the magnet was measured by mounting a Senis type C Hall probe connected to a

3MH6 teslameter [14] in the magnetic centre of the HEPTO magnet. The point dipole field and probe temperature were recorded whilst the laboratory climate control system was used to vary the ambient temperature between 19 °C and 20 °C. The relative change in field strength compared to the average field at 20 °C is shown in Fig. 6. A linear fit of the data gives a temperature coefficient of $(0.173 \pm 0.001)\%/\text{°C}$. This is much larger than the coefficient predicted from the Opera model of $-0.056\%/\text{°C}$. However, the coefficient is still lower in magnitude than the $-0.209\%/\text{°C}$ that was predicted for a design with no thermal shunt material. Therefore, the shunt material does provide an increase in the stability of the field with respect to external temperature.

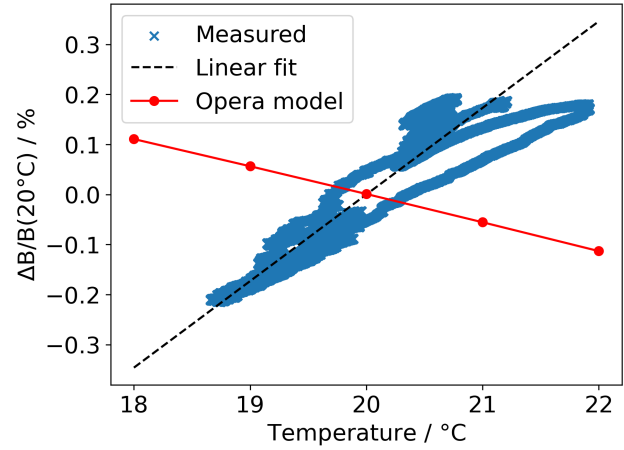


Figure 6: Measured relative change in dipole field with ambient room temperature relative to the field measured at 20 °C.

The positive sign of the measured temperature coefficient indicates that too large a volume of thermal shunt material has been used. The discrepancy between the modelled and measured temperature coefficients is most likely due to variations in the thermal shunt material properties. Many factors could have impacted the shunt material properties, including the thermal annealing and cutting processes. This highlights the need for careful measurements of the shunt material properties before construction of permanent magnets. Alternatively, a design allowing for addition and removal of shunts could improve the thermal performance. However, this was not practical here due to the nature of the assembly of the HEPTO magnet.

CONCLUSION

The measurements of the HEPTO magnet demonstrate that the same field strength and quality can be achieved, whilst realising a 2.3 kW power saving, compared to the equivalent resistive electromagnet. This positions permanent magnets as a suitable technology solution for future, more sustainable accelerators. The mechanical shimming method has shown an effective method of improving both the field strength and homogeneity of an otherwise fixed field magnet. Electromagnet coils provide a $\pm 1.1\%$ tuning range required for in-situ field tuning or emittance measurements.

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