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CONSTRUCTION AND MEASUREMENT OF A TUNEABLE PERMANENT MAGNET QUADRUPOLE FOR DIAMOND LIGHT SOURCE

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Abstract

Particle accelerator facilities around the world are becoming increasingly interested in permanent magnet (PM) technology as a replacement for traditional resistive electromagnets. This change is driven by the desire to save energy for both financial and environmental reasons. For fixed field systems the use of PMs is now established as a viable alternative to electromagnets however difficulties in using PMs remain where tuneability of field strength is a required feature. The ZEPTO project, a collaboration between CLIC and STFC, sought to address this by developing a system where PM blocks were moved inside fixed steel structures to allow field strength to be changed without sacrificing homogeneity. We discuss here the construction and measurement results to date of a magnet which will test this principle in reality by running on Diamond Light Source.

INTRODUCTION

The ZEPTO (ZEro Power Tuneable Optics) project is a long term magnet development activity conducted by the Accelerator Science & Technology Centre (ASTeC) based at STFC Daresbury Laboratory, UK, and was originally funded by the CLIC (Compact Linear Collider) collaboration at CERN [1]. The original purpose of the project was to reduce the power consumption of CLIC by replacing the electromagnets in the CLIC drive beam with permanent magnet (PM) alternatives which draw no power during normal operation.

Previous works have discussed the prior outputs of the ZEPTO project; two permanent magnet quadrupole designs (high strength [2] and low strength [3]), as well as an experimental dipole [4]. Whilst all these magnets were developed for CLIC, we aim to demonstrate that ZEPTO is a versatile technology concept that can be used as an energy saving replacement for electromagnets on accelerators ranging from existing light sources to new facilities such as XFELs. To this end we have developed a new ZEPTO quadrupole based on the design detailed in [3], but with a number of engineering and usability improvements over previous designs. This magnet is specifically designed to replace an existing electromagnetic quadrupole located on the booster-to-storage ring transfer line of Diamond Light Source (DLS), and is intended to demonstrate the principle of ZEPTO on a real accelerator for the first time, and provide us with valuable data on the long term reliability, field repeatability, and any issues with usability or assembly/installation procedures that may be useful in improving further iterations of the design. The replaced magnet typically operates at 14 T/m over 400 mm length, and the technology demonstrator is capable of operating at 22 T/m over 300 mm length.

In [5] we presented the design details of this technology demonstrator and described magnetic measurements as ongoing. Those measurements revealed a serious error in the construction of the magnet necessitating major modifications to the assembly frame. These modifications have now been made, the magnet has been reassembled and new measurements have been conducted. These measurements, combined with testing on DLS, will allow the ZEPTO concept to be refined in a real-world setting and create learning opportunities to help refine the engineering. Some important features requiring design changes for future iterations have already been revealed by the measurement of the prototype, particularly with regard to movement of the magnetic centre.

ASSEMBLY PROCESS

This magnet has advanced over previous iterations of ZEPTO quadrupoles by being symmetrically splittable such that it can be installed around an existing beam pipe without breaking vacuum conditions. To achieve this a dedicated assembly frame is required which was described in [5] and is shown in Figure 1. The steel yoke is split into two preassembled halves which attach to vertical brackets which are then slid along the frame symmetrically towards the carriages, driven by a ball screw turned manually by a handle. Once in the final position the top and bottom plates are bolted to lock components into position, and the frame detached and removed.

The magnetic forces acting on each half of the yoke as they approach the PM carriages are complex and non-linear. Numerous assembly trials were conducted, with the forces proving a challenge to manage. The forces were observed to cause slippage of components and twisting of load bearing brackets during assembly. The original frame used a single ball screw with manual handle to bring the magnet together. This has been adapted with a second linked ball screw on the opposite side, as well as a gearbox on the handle. Gas springs are employed to help manage the non-linear nature of the magnetic forces. It has also proven important to properly brace the assembly frame to the magnet pedestal to prevent minor movements that can cause the magnet halves to come together asymmetrically.

Figure 2 shows the simulated forces during assembly as the steel yokes are moved towards the magnet carriages. During the assembly a Hall probe was used to measure the flux

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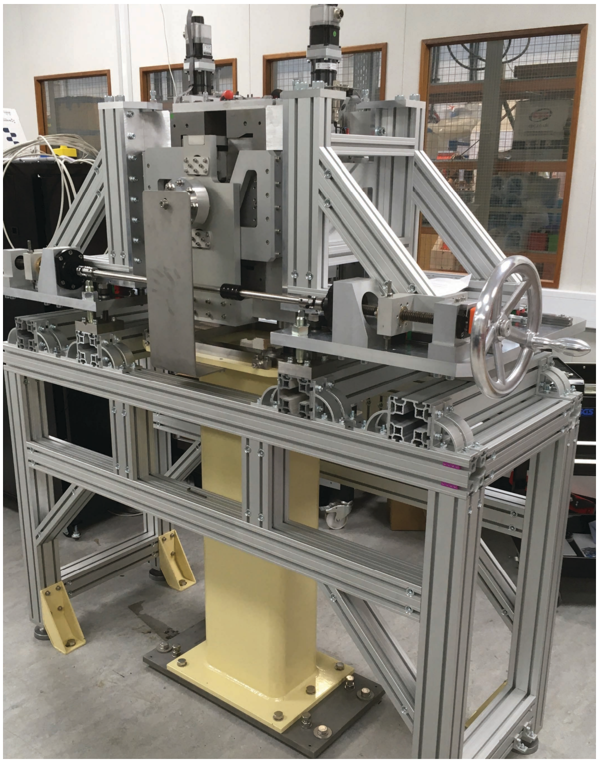

Figure 1: Photograph of the technology demonstrator and assembly frame showing the successful installation around a dummy beam pipe.

density entering the steel yoke for as much of the approach as possible, and from this an estimate of the actual force was derived assuming that the flux density acted over 0.02 m^2. This estimation predicts slightly higher forces than simulated, however due to the complex shape of the field the action area (and thus the force) is likely overestimated.

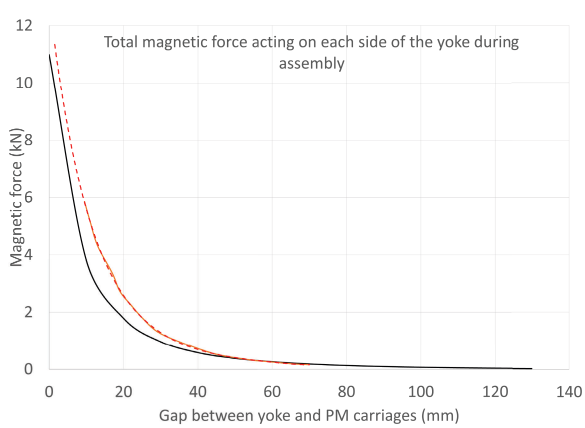

Figure 2: Simulated magnetic forces (black) during assembly, compared to an estimate of the force from field measurements (red) and extrapolation of the estimate (dashed) where measurements were not possible. The estimate assumes the force is acting on an area of 0.02 m^2 and is likely a slight overestimate.

GRADIENT MEASUREMENTS

The flux in this magnet is provided by blocks of SmCo. This material was chosen over the more common alternative of NdFeB due to being less susceptible to radiation damage [6] and to changes in remanent field resulting from ambient temperature drift [7]. Finite element simulations conducted in OPERA 3D predicted that the field gradient would be tuneable between 22.7 T/m at maximum strength to 0.3 T/m at minimum, allowing the magnet to be effectively "turned off" for all but the lowest energy beams. The gradient homogeneity was predicted to be $< 2 \times 10^{-3}$ in a 10 mm radius which should, external effects aside, remain consistent as the gradient is adjusted due to the fixed steel poles acting to define the field shape. Measurements of the gradient were conducted using a SENIS 3MH6 Gaussmeter with a type C Hall probe. The result of these measurements are plotted against the predictions in Figure 3.

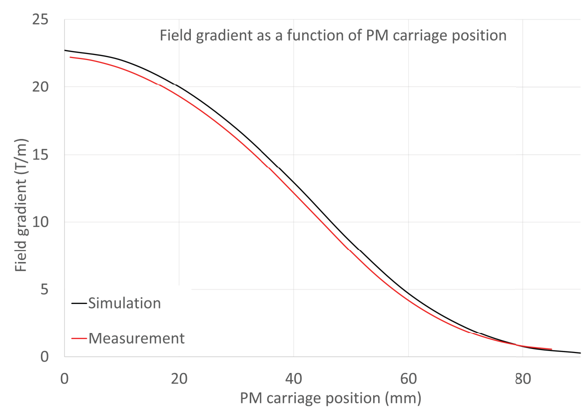

Figure 3: Plot of simulated and measured field gradient as a function of magnet carriage displacement from the "fully inserted" position.

The PM carriages cannot be swept over the full 0-90 mm movement range due to limit switch positioning, so a range of 1-85 mm is used. The gradient is tuneable from 22.2 to 0.57 T/m over this range. This is below predictions by up to 0.5 T/m at 20°C. The most likely explanation is a discrepancy between the simulated and real BH curves of the SmCo and steel.

MAGNETIC CENTRE STABILITY

Vertical Movement

Previous ZEPTO quadrupoles suffered from an issue causing the magnetic centre to move as a function of magnet block position, which persisted despite best efforts to ensure symmetry in the design which should in theory prevent this from occurring. The movement was particularly noticeable in the vertical direction, matching the axis of movement of the PM material. Measurements and simulations found this was only partially explainable by the presence of unexpectedly magnetic components.

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In anticipation of the same movement occurring again for this magnet, the technology demonstrator presents a potential solution by separating the movement mechanisms of the top and bottom PM blocks instead of linking them via the same ball screw as in [3]. Each magnet carriage has a dedicated motor and associated driving ball screw, allowing them to be driven independently. This allows a look-up table to be applied in software to the relative carriage positions. In theory this allows any measured movement in the magnetic centre when changing the gradient setting to be corrected by making small alterations to the position of one carriage until the magnetic centre is restored to the location of the centre at the original gradient setting.

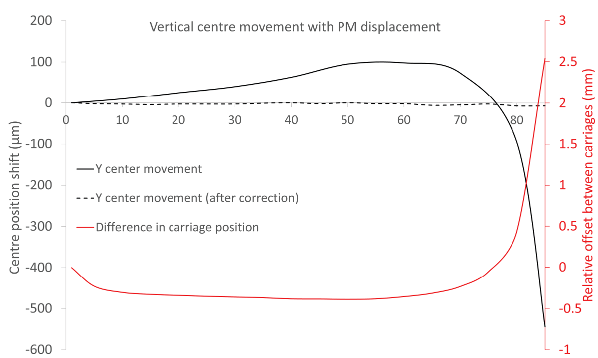

Figure 4: Observed movement in the vertical centre before (black) and after (black dashed), the application of a relative offset to the carriage positions (red, secondary axis) is applied, demonstrating that vertical movement of the magnetic centre can be limited by independent carriage movement.

The measurements shown in Figure 4 demonstrate that this principle works with great success. Due to an as yet unidentified combination of causes, the magnetic centre moves significantly in the vertical direction, first up then down. However, by moving either PM carriage (in Figure 4 the bottom carriage is displaced) from the nominal setting the magnetic centre can be forced back to the original position. This allows the vertical movement of the magnetic centre to be limited to just 7 µm, which should not have an adverse effect on machine performance.

Horizontal Movement

The ability to offset the relative positions of the carriages does not provide a solution to movement of the magnetic centre in the horizontal direction as a function of carriage position. Measurements shown in Figure 5 reveal that horizontal movement of the magnetic centre does occur, although the position is relatively stable until the carriages are displaced by 55 mm, above which the centre moves noticeably by up to 160 µm at the 85 mm carriage position. The movement is observed to have different values but a similar trend when the carriage look-up table for the vertical movement is applied.

The sudden jump coincides with the point at which the carriages begin to overlap with the outer shell of the magnet,

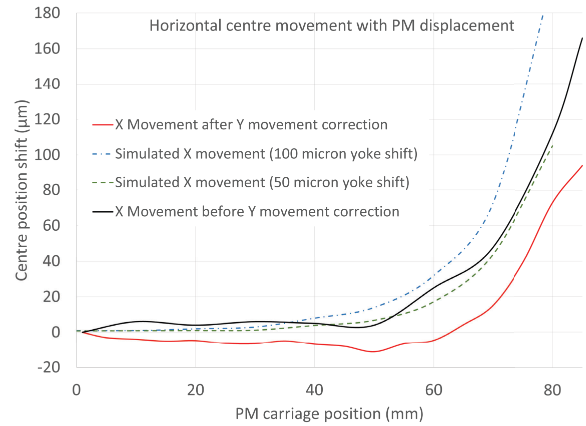

Figure 5: Observed and simulated horizontal movements in the magnetic centre as a function of PM carriage position.

providing a potential explanation for their origin. Simulations were performed examining the movement of the magnetic centre if one half of the outer yoke were offset inwards from the vertical centreline. Figure 5 includes results from a 100 µm and 50 µm offset for comparison. There is strong correlation between the 50 µm simulated results and the observed movement, indicating that the movement arises from a component positioning or machining error. The scale highlights the need for the outer yoke to be subject to the same high precision machining and assembly as the inner poles.

ONGOING WORK AND CONCLUSIONS

Hall probe measurements as presented here are complete on the reassembled magnet. Stretched wire measurements are currently being performed to verify magnetic centre data and to determine whether the integrated gradient homogeneity matches the model, as the Hall probe motion system used is unable to traverse the entire aperture due to physical constraints. The magnet is now due to be installed on Diamond Light Source, pending approval, in August 2022 where it will be used as a focussing quadrupole on the booster-to-storage ring transfer line.

The magnet's effect on the beam for a variety of gradients will be monitored to determine the long-term reliability of the technology in a real high radiation environment with temperature stability of $\pm 0.1\,^{\circ}$C. The validity of the look-up table will be investigated, and refined using beam based alignment if necessary. If a significant drift in performance or a lack of repeatability with regards to field gradients and magnetic centre positions are detected the magnet may be set to the "off" position and neighbouring electromagnets will be used to compensate.

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