DEMONSTRATION OF 'ZEPTO' PERMANENT MAGNET TECHNOLOGY ON DIAMOND LIGHT SOURCE

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Abstract

The use of permanent magnet (PMs) in place of traditional electromagnets is becoming more common in accelerator systems around the world. This change is being driven by the desire to reduce both the energy costs and carbon footprint of accelerators. The problem remains that it is difficult to adjust the field strength of PM systems. STFC and CERN have a longstanding collaboration in the Zero-Power Tuneable Optics (ZEPTO) project which aims to develop PM systems that are tuneable via moving the PM blocks within a static pole structure. This collaboration has previously produced 3 prototype magnets (2 quadrupoles and 1 dipole) for the proposed CLIC accelerator, and aims to expand the suitability of PMs to a variety of accelerators. We are now demonstrating this technology on a real machine by installing a ZEPTO magnet on the Diamond Light Source (DLS). We outline the design and construction of this technology demonstrator, highlighting the innovations over previous generations of ZEPTO technology that account for previously observed drawbacks.

INTRODUCTION

The ZEPTO project collaboration between STFC and CERN is part of the development process for the proposed Compact Linear Collider (CLIC), a 3 TeV linear electron-positron collider [1]. The proposed design of CLIC features a two-beam acceleration scheme where a high current drive beam is accelerated in normal conducting RF cavities before entering a decelerating structure which harvests the drive beam energy to accelerate the lower current main colliding beams to energies up to 3 TeV. This design necessitates a large number of magnets in the drive beam accelerator lattice, including 42,000 quadrupoles.

The CLIC project faces a number of hurdles before becoming reality, particularly the issue of power consumption associated with normal-conducting accelerators. The electrical consumption of CLIC is predicted to exceed 500 MW, with 124 MW allocated for resistive electromagnets. The ZEPTO project aims to solve this by replacing normal-conducting electromagnets with permanent magnet (PM) systems that draw no power during normal operations and require no cooling except for atmospheric temperature stabilisation. An advantage of electromagnets over PM systems is the ability to change their field strength by adjusting the current. The difficulty of dynamically adjusting PM systems has limited their use to date, although there are increasingly used where only static fields or small field adjustments are required. With the ZEPTO project we aim to bring this tuning capability to permanent magnets by moving magnetic material in a fixed steel structure to redirect flux towards or away from the beam without adversely affecting field homogeneity.

The ZEPTO project has previously produced two permanent magnet quadrupoles designs (high strength [2] and low strength [3]), as well as an experimental dipole [4]. We now aim to demonstrate that the benefits of ZEPTO technology are not limited to CLIC, and can be used as an energy saving 'drop-in' replacement for electromagnets on accelerators such as existing light sources. We have developed a new ZEPTO quadrupole with a number of critical innovations over previous designs, with field parameters which match an existing electromagnetic quadrupole located on the booster-to storage ring transfer line on Diamond Light Source (DLS). The intent is for this magnet to act as a technology demonstrator, allowing us to measure for the first time the long term reliability and capability of ZEPTO technology in a real accelerator environment.

MAGNET PARAMETERS

The design of the technology demonstrator closely resembles the design of the original 'low strength' ZEPTO quadrupole [3] with a number of alterations and innovations described below. A pair of moving carriages containing rare-earth PM material are situated directly above and below the beam pipe, and are moved vertically between an inner and outer steel structure. The inner structure directs and shapes the flux through the beam pipe, the outer structure provides a short circuit which directs the field away from the beam pipe. By moving the position of the PM carriages relative to these structures the proportion of flux passing through each structure is adjusted, resulting in an increase or decrease of the field gradient around the beam, as illustrated in Fig. 1.

Whereas previous ZEPTO prototypes used NdFeB to provide the flux, this technology demonstrator uses SmCo. This material is sufficient to provide the flux required by DLS, whilst having the benefit of being less susceptible to radiation damage [5] and to changes in remnant field resulting from ambient temperature drift [6]. The central field gradient may be tuned between 22.7 T/m and 0.3 T/m, allowing the magnet to be effectively turned off. The magnetic length is 300 mm. The gradient homogeneity is $< 2\text{x}10^{-3}$ in a 10 mm radius; this remains consistent as the gradient is adjusted due to the fixed steel poles defining the field shape.

The magnetic forces are a key concern in the mechanical design of ZEPTO style magnets and are carefully simulated

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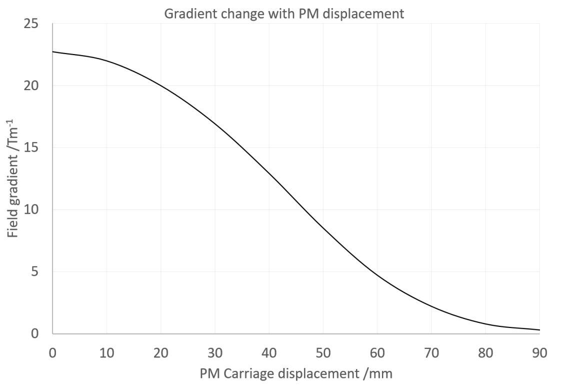

Figure 1: Simulated field gradient as a function of magnet carriage displacement from the highest gradient position.

during the design process. Only static magnetic forces require consideration as the slow motion system makes Lorentz forces negligible. The simulated forces between each magnet carriage and the surrounding steel are shown in Fig. 2. The horizontal forces are balanced on each side of carriages but pose a movement risk to steel components. This force is strongest when the blocks overlap with the outer shell and weakest at the halfway point between the inner and outer steel structures. The vertical force acts to pull the carriages towards the inner structure until a crossover point where field behaviour becomes complex as flux is split between inner and outer steel structures.

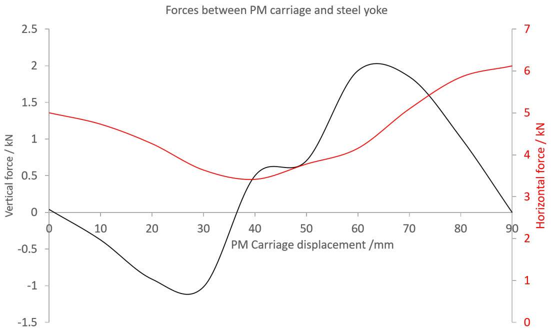

Figure 2: Simulated vertical (black) and horizontal (red) magnetic forces between each magnet carriage and the steel structure as a function of displacement from the highest gradient position. A negative vertical force acts towards the center, positive toward the outer shell.

DESIGN IMPROVEMENTS

Permanent Magnet Arrangement

Previous iterations of the ZEPTO project used relative large NdFeB blocks to produce the magnetic flux. The technology demonstrator replaces these blocks with a ‘carriage’ which consists of a number of smaller PM blocks set into an aluminium latticework, as shown in Fig. 3. This has a number of advantages over larger single blocks which include:

- PM blocks become easier and cheaper to manufacture.
- In the event of damage single blocks may be replaced instead of the entire carriage.
- Variation in block BH curves may be compensated by sorting positions within the lattice.
- Modular magnet “families” may be created by strategic removal of blocks.

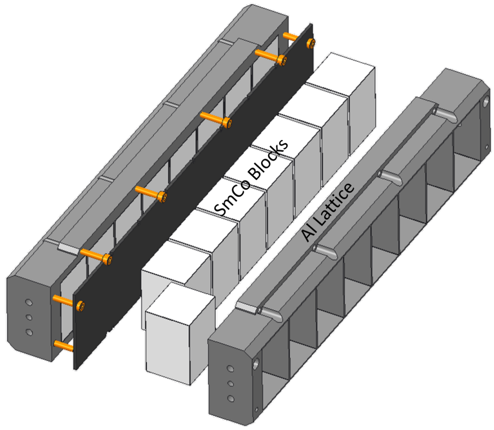

Figure 3: CAD model showing the structure of the PM carriage. SmCo Blocks are inserted into an aluminium lattice either side of a central spine made of high permeability steel. Individual blocks may be replaced in case of damage, and over/under strength blocks may be paired together around the central spine.

Dual Motor Design

A significant fault in both previous ZEPTO quadrupoles was revealed in field measurements; the magnetic centre may move as function of magnet block position despite best efforts to ensure symmetry in the design which should in theory prevent this from occurring. The movement was particularly pronounced in the vertical direction, and was only partially explainable by erroneously placed ferromagnetic components. Movement of the quadrupole centre is a significant concern that is not tolerable, even on µm scales in most machines.

The technology demonstrator resolves this issue by separating the movement mechanisms of the top and bottom PM blocks which are no longer intrinsically linked. Each magnet carriage has a dedicated motor and associated driving ball screw, visible in Fig. 4. The relation between these motors may be established at the software level. If magnetic measurements reveal movement in the magnetic centres a look-up table can be applied to either carriage to be moved to compensate and restore the magnetic centre to the geometric centre.

Assembly Improvements

A traditional advantage of room temperature electromagnet systems is that they are typically designed and manufactured so that it is possible to physically split them in such a way that they can be installed around an existing beam pipe without breaking vacuum conditions. This is an extremely

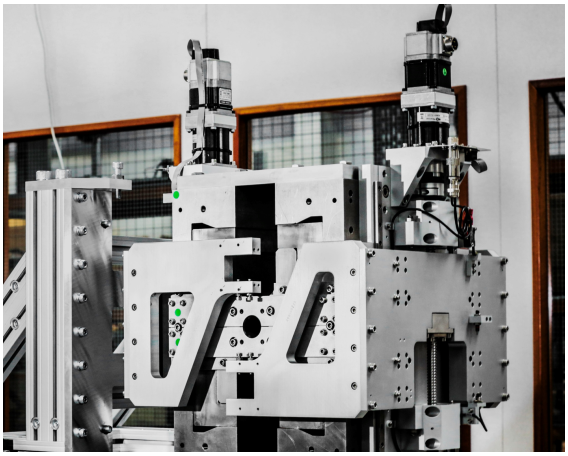

Figure 4: Photograph of the partially assembled magnet (without PM material), showing the dual motor arrangement, the carriage holders, and the ball screw mechanism by which the carriages may be moved.

useful feature which allows for replacements or repair to be conducted without needing to keep the accelerator offline for the additional time needed to restore the quality of the vacuum, which may involve extensive cleaning, long pumping periods, and bake-out time. Furthermore when reassembling an electromagnet the only forces of concern which pose a risk to personnel or components are the masses of the magnet parts. This is not so with permanent magnet systems where magnetic forces, which are a non-linear function of distance, may routinely peak at >10 kN and require active management during assembly.

It was not possible to split previous versions of ZEPTO quadrupoles about an axis of symmetry, which necessitated the magnet being installed without an existing chamber under vacuum being present. This has now been resolved with the current technology demonstrator prototype, which with a dedicated assembly frame may be symmetrically split about the central vertical axis and reassembled around an existing vacuum system, as shown in Fig. 5. The system consists of a holder which slots over vacuum chamber and locks the PM carriages in place above and below the beam pipe. The two halves of the steel yoke structure are then bolted to vertical brackets keeping them 10 cm away from the PM carriages. These brackets 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 during the approach are highly non-linear as shown in Fig. 6. This force is primarily handled by the ball screw but for safety it is also partially compensated by gas springs pushing against the yokes.

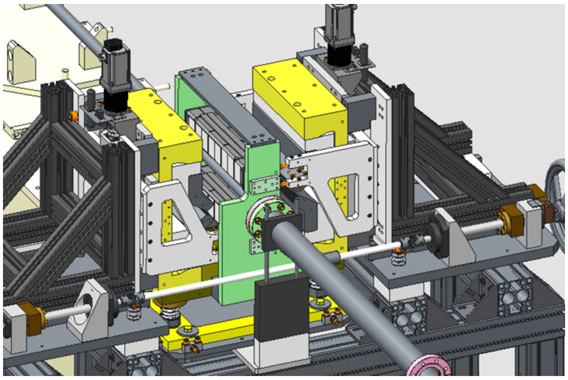

Figure 5: Illustration of the mechanism by which the ZEPTO prototype may be split and reassembled with a dedicated frame.

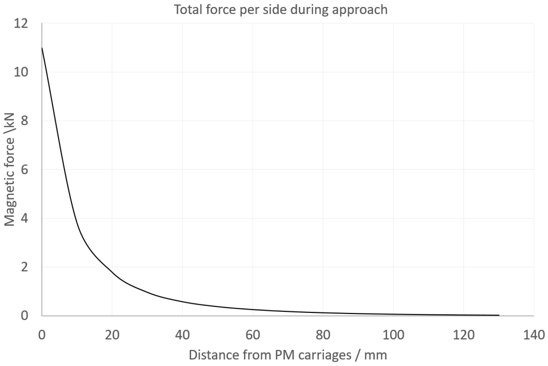

Figure 6: Magnetic forces as a function of separation distance between yoke and carriages during assembly.

CURRENT WORK AND CONCLUSIONS

Magnetic measurements of this prototype magnet are ongoing as of the submission of this paper. We intend to maintain the use of this magnet as a focussing quadrupole on Diamond Light Source transfer line for a period of approximately one year. Over the course of the year the magnet gradient will be swept to perform emittance measurements as a functional test, and its effect on the beam as a function of PM position will be monitored to determine the long-term longevity of the PM's in a real use, high radiation environment. This will allow assessment of the effectiveness of ZEPTO technology as a "drop-in" alternative to traditional resistive electromagnets. In the event that a significant drift in performance is detected over this time the magnet carriages will be moved to the "off" position and neighbouring electromagnet will be reinstated in its place. Should the magnet maintain its performance throughout the year, we believe this demonstrates the viability of ZEPTO technology in the real world and the magnet will remain operational at the discretion of the Diamond Light Source.

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