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TESTING OF A ZEPTO TUNEABLE PERMANENT MAGNET QUADRUPOLE AT DIAMOND LIGHT SOURCE

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Abstract

Electromagnets have traditionally been used in accelerators due to their wide range and ease of tuneability, but are a major factor in power consumption due to resistive losses in the coils and inefficiencies in power and cooling systems. Use of permanent magnets can greatly reduce power consumption, but it has proved difficult to produce the same range of tuning with comparable field accuracy and stability. A tuneable permanent magnet quadrupole has been developed at STFC Daresbury Laboratory that moves permanent magnet blocks relative to fixed steel structures that define the field, allowing strength to be changed without significantly affecting the field homogeneity or harmonics.

This prototype magnet has been installed in the Diamond Light Source booster-to-storage ring transfer line, aiming to demonstrate the operation of ZEPTO (Zero-Power Tuneable Optics) technology on a real accelerator. We present results of beam-based measurements of gradients and magnetic centre with comparison to an existing electromagnet in the same transfer line. We show that it is capable of maintaining the same injection efficiency as a traditional resistive electromagnetic quadrupole during normal operation.

INTRODUCTION

The development of ZEPTO magnet technology [1, 2] is motivated by the desire to save large amounts of energy compared to equivalent resistive electromagnets by replacing coils with Permanent Magnet (PM) blocks. Reduced energy consumption translates directly to lower operating costs from both a financial and environmental perspective, as well as simplified facility infrastructure by removing high-current cabling and water-cooling systems.

The potential of PM technology is attracting attention in accelerators around the world, but until recently PMs have rarely been used except in undulators. Electromagnets are tuneable via changing the current, a necessity in many accelerator magnets, though recently PM technology has found increasing use in magnets operating at a fixed field, such as in storage rings [3–5]. The ZEPTO project aims to replicate the variability of resistive magnets by moving PM blocks relative to fixed steel pole pieces, which are the primary determinant of the magnet homogeneity. The ZEPTO technique offers a competing solution to other recently developed techniques for constructing tuneable PM quadrupoles [6–8].

Whilst the technology was originally developed for CLIC, the development of a prototype for Diamond Light Source aims to demonstrate that the technology is versatile and that PMs are a viable and reliable replacement for electromagnets even in areas where quadrupole gradients may be regularly changed, under the operating conditions of a real machine.

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THE ZEPTO PROTOTYPE

The ZEPTO magnet prototype built for Diamond has a design gradient of 22 T/m tuneable to 0.5 T/m, and a pole length of 300 mm. It replaces an electromagnet of length 400 mm and a maximum gradient of 14 T/m. The magnet aperture is 32 mm in diameter. This quadrupole differs from the previous iteration described in [2] in a number of ways. It is designed to be split to allow installation around an existing beam pipe, the magnet blocks are split into carriages containing a lattice of smaller blocks that are easier to manufacture, and each magnet carriage can be moved independently allowing correction of vertical drift of the magnetic axis. This prototype also uses SmCo instead of NdFeB material to provide the magnetic flux due to its reduced temperature sensitivity and increased radiation resistance. The details of the design, modelling and measurement of this prototype magnet are discussed in more detail in [9, 10].

Before installation, field measurements were performed [10] which showed that the gradient strength and tuning range were within acceptable parameters, and that vertical magnetic axis movement could effectively be countered by independent control of the PM ca, oxforshirerriage positions. Movement in the horizontal axis position could not be corrected but can be explained by matching modelling against machining tolerances and can be corrected for future iterations.

Between the measurements presented in [10] and installation on Diamond, further measurements were performed on the magnet harmonics. The strongest ”forbidden” harmonic detected was, as expected given the asymmetric construction of the quadrupole, the $n = 4$ octupole component. Additional harmonics at $n = 5$ and $n = 6$ were also detected and are shown in Fig. 1 for a variety of magnet set-points.

INSTALLATION IN ACCELERATOR

The ZEPTO magnet was installed in the Diamond booster-to-storage-ring (BTS) transfer line in August 2022, 1.155 m downstream of quadrupole-04. Pictures of the ZEPTO as installed can be seen in Fig. 2, with the layout of the surrounding BTS components shown in Fig. 3.

Diamond uses the EPICS control system with a machine model built in Matlab middlelayer (MML) [11]. All existing

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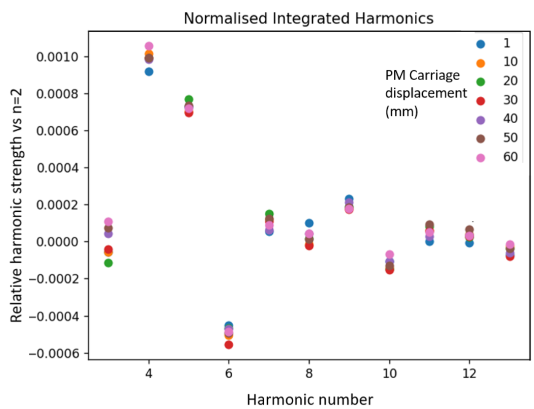

Figure 1: Measured integrated harmonics of ZEPTO at 3 mm radius, normalised to the $n = 2$ fundamental. For PM displacements greater than 60 mm the field weakness prevented accurate measurements.

quadrupoles are resistive electromagnets, so some modifications were required to the MML interface to enable control of a motorised system in a way that is transparent to the user.

Since ZEPTO is longitudinally displaced from the magnet it replaces, some disruption to the BTS optics is unavoidable. In addition, whilst the ZEPTO gradient can be reduced to below 0.5 T/m, it cannot quite be reduced to a true zero field, so while it is installed the BTS optics cannot be quite identical to their nominal settings. For both cases, ZEPTO at minimum gradient and ZEPTO at nominal operating gradient, new quadrupole settings were calculated to minimise the differences. As shown in Fig. 4, the beta functions are well corrected, with only some minor differences in the region of the ZEPTO magnet.

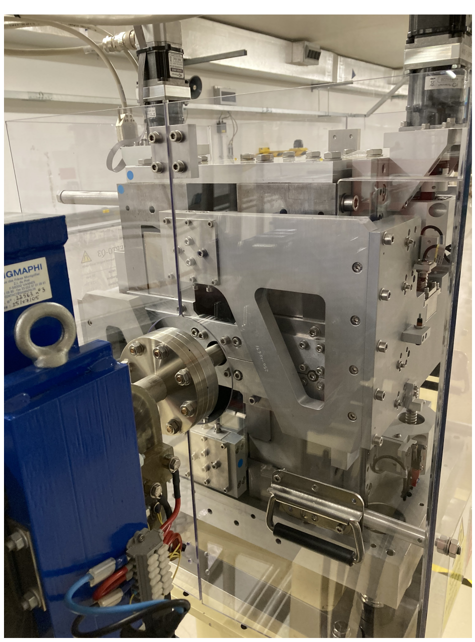

Figure 2: Photograph of ZEPTO installed in Diamond BTS with perspex surround for safety.

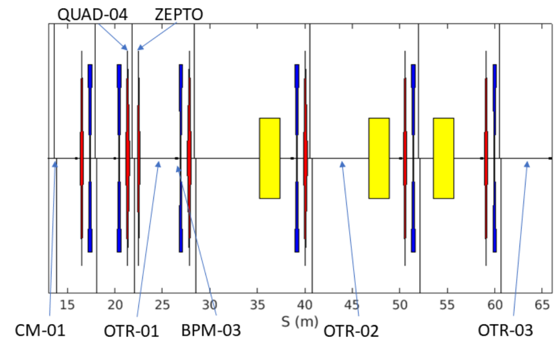

Figure 3: Annotated BTS lattice. QUAD-04 is switched off when ZEPTO is operating.

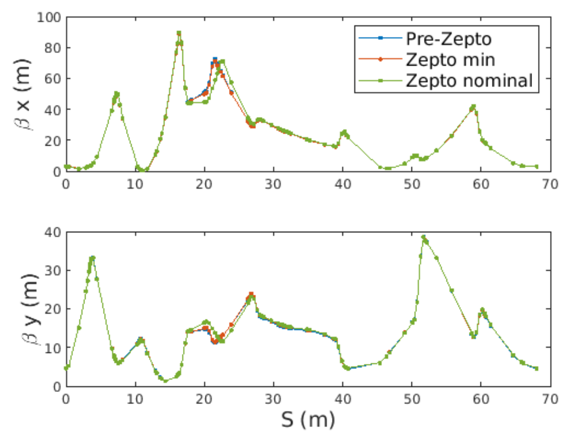

Figure 4: Modelled BTS beta functions comparing before ZEPTO installation, with ZEPTO installed at minimum field and other quadrupoles adjusted to compensate, and with Quad-04 off and ZEPTO at nominal field.

Machine Operation

Initial operation after installation kept ZEPTO at minimum gradient with quadrupoles adjusted to compensate as described above. Some minor adjustments to the beam steering were required to recover injection efficiency to the storage ring to normal levels. The machine drifts by small amounts normally due to environmental changes so it is not clear if these adjustments were required due to the ZEPTO itself, the changes to other quadrupoles, or just normal drift.

Following this, the ZEPTO was set to a nominal operating gradient of 6.36 T/m, with the other quadrupoles set to their associated set-points. This resulted in a more significant change to the trajectory through the BTS, since the trajectory is known to pass off-centre through the quadrupoles. Empirical corrections were carried out, and injection efficiency to the storage ring was recovered to be equivalent to before the ZEPTO installation.

MEASUREMENTS

The gradient of the ZEPTO was measured using a beam-based method, with independent measurements in the horizontal and vertical planes. The beam was initially centred

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in the magnet, then the strength of an upstream corrector was scanned to produce different offsets through the magnet. Passing off-centre through a quadrupole produces a dipole kick, which can be calculated by observing the downstream trajectory, allowing the gradient to be calculated.

The gradient measurement was carried out for a range of hardware set-points over the full range of motion, and compared with the values from lab-based measurements taken before installation. The results in the horizontal plane, seen in Fig. 5, show good agreement, although with the beam-based measurement consistently reading higher by about 0.6 T/m. The results in the vertical plane do not agree well, especially at higher gradients, and show high variability when different corrector strengths are used in the measurement. The same measurement was carried out for Quad-04, with the results shown in Fig. 6. The results are similar to ZEPTO, with a similar offset at low gradients but better agreement at high gradients. The same issue with the measurement in the vertical plane is present, although it was possible to find one set of parameters that allow good results. This suggests that the difficulty measuring in the vertical plane is due to sensitivity of the BTS to vertical changes in the trajectory rather than a problem with ZEPTO.

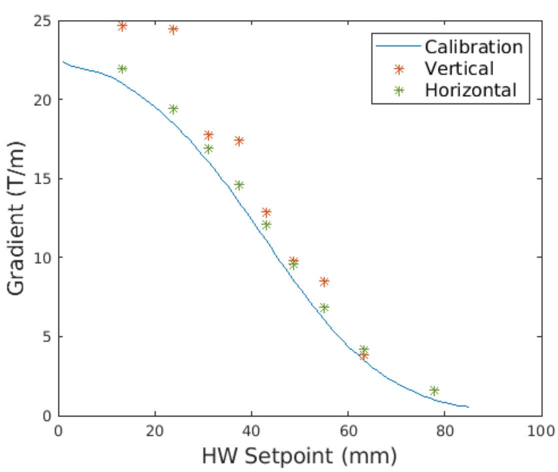

Figure 5: Beam-based measurement vs lab calibration of ZEPTO gradient.

Beam-based measurements of the magnetic axis position of ZEPTO were also performed to assess axis movement against gradient, shown in Fig. 7. These show that any changes in axis position as the gradient is adjusted are small and unlikely to cause adverse effects.

RADIATION MONITORING

A thermoluminescent dosimeter (TLD) was installed on the upstream end of the ZEPTO magnet next to the beam pipe for one week in November 2020. This included six days of routine operation and one day of machine development, resulting in a total measured dose of 524 mSv. Six more TLDs were installed at various positions around ZEPTO in January 2023, to better establish the location of received

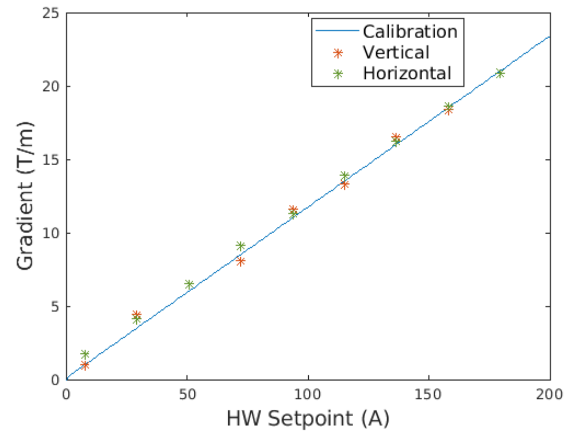

Figure 6: Beam-based measurement vs calibration of Quad-04 gradient.

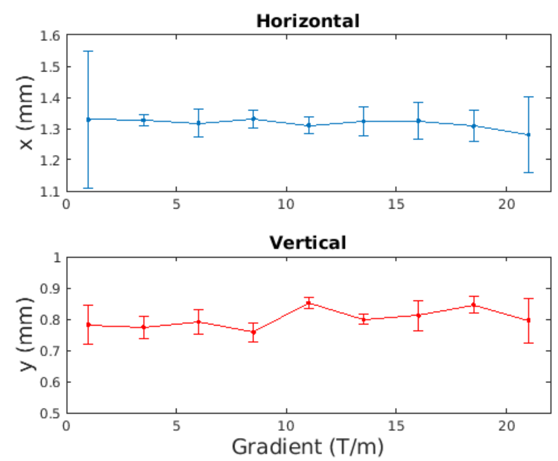

Figure 7: Measured centre of ZEPTO magnet vs gradient, mean and standard deviation of five measurement sets.

radiation. These remain in place so accumulated doses are not yet available. At the time of writing no degradation in performance due to radiation exposure has been observed.

CONCLUSIONS AND OUTLOOK

We have successfully demonstrated that ZEPTO permanent magnet technology can replace an existing electromagnet on a working accelerator without loss of performance to the beam. With the ZEPTO magnet incorporated into the BTS lattice the beam injection efficiency remains nominal. The beam-based measurements of the magnet are consistent with the magnetic field mapping. The magnet is now being monitored during operation to assess long-term reliability and resilience to radiation damage.

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