# ADVANCES IN MAGNETIC FIELD QUALITY FOR ZEPTO TUNABLE PERMANENT MAGNET QUADRUPOLE

A. R. Bainbridge*, C. Hill, A. G. Hinton, P. O'Donnell, B. J. A. Shepherd.
ASTeC, STFC Daresbury Laboratory, Warrington, UK
and The Cockcroft Institute, Sci-Tech Daresbury, Warrington, UK

## *Abstract*

The Zero Power Tunable Optics (ZEPTO) project has developed tunable permanent magnets for accelerators as an alternative to resistive electromagnets, with a focus on quadrupoles. The project has previously produced three quadrupole prototypes, with the 3rd spending two years installed on Diamond Light Source. A 4th prototype has been designed and is under construction for installation on the CLARA electron accelerator at Daresbury Laboratory. This prototype features two novel improvements over previous iterations to offset the risk of the complex manufacturing and assembly procedures resulting in poor field homogeneity and magnetic axis displacement as a function of strength. We discuss the design of this prototype and show how these new features can correct the unique challenges in designing and building a permanent magnet with very high tuning range.

## INTRODUCTION

The Zero Power Tunable Optics (ZEPTO) project at STFC Daresbury Laboratory has developed several prototype Permanent Magnet (PM) quadrupoles with tunable magnetic field gradient [1–5]. This area has attracted much attention globally, with several institutes working on tunable PM systems of varying designs and tuning ranges [6–12]. However, the ZEPTO design retains the largest tuning range so far demonstrated for PM quadrupoles. While other designs tend to focus on rotating magnetic rods [9–12] or Halbach rings [7, 8], ZEPTO magnets move PM blocks relative to fixed steel structures that define the flux path, allowing gradient to be adjusted while homogeneity remains defined by the steel shape. This arrangement is mechanically complex, however, maintaining stable field homogeneity and magnetic axis position during adjustment remains a challenge that requires extremely high precision during manufacture and assembly to achieve.

Based on learnings from the 3rd ZEPTO prototype [3–5], which operated for 2 years installed on Diamond Light Source, we have designed a 4th prototype which is currently under construction. This will be installed on CLARA [13], the 250 MeV electron linear accelerator at Daresbury Laboratory, replacing an equivalent electromagnetic quadrupole. This new prototype improves over predecessors to overcome the difficulties in manufacturing and assembly precision. If measurements reveal poor field harmonics, or magnetic axis shift as a function of gradient adjustment, the new prototype can correct these errors without re-assembling the magnet or re-machining components. We show here an overview of this magnet and that by adding magnetic steel shims in defined patterns we can correct excessive higher order field components, and that by removing rods of material from the yoke in predefined patterns we can tune the level of field saturation in one half of the magnet to correct horizontal magnetic axis movement as a function of strength. We propose that, once demonstrated by measurement, these will be key steps to bringing the ZEPTO tunable PM concept into direct competition with resistive electromagnets in terms of quality, convenience and reliability.

## MAGNET OVERVIEW

The general concept of ZEPTO tuning has previously been explained in multiple publications [1–5], we refer the reader to these rather than explaining the principle in detail here. This 4th prototype has a specified strength range of $\geq 3$ T integrated gradient at maximum and $\leq 0.18$ T integrated gradient at minimum. The aperture diameter is 42 mm and magnetic length is 178 mm. The target for integrated field homogeneity is $\leq 1 \times 10^{-3}$ to a radius of 17 mm.

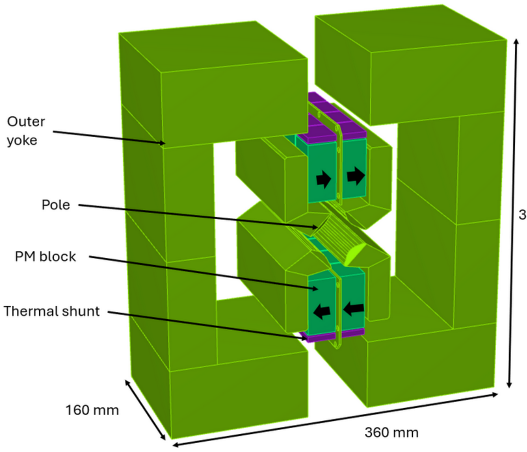

Figure 1: Simplified OPERA model of the new ZEPTO prototype, without the button shims and tuning rods described below.

A simplified 3D FEA model, produced in OPERA [14], is shown in Fig. 1. There are 16 PM blocks of grade N52 NdFeB, each measuring $30 \times 60 \times 36\,\mathrm{mm}^3$. The yokes are AISI grade 1010 low carbon steel. The magnet carriages each move by up to 70 mm. The simulated integrated gradient as a function of magnet carriage position is shown in Fig. 2. Unlike previous iterations of ZEPTO there are passive thermal shunts in a 6 mm layer on each magnet carriage which, in simulation, provide temperature stability in the

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[*] alex.bainbridge@stfc.ac.uk

integrated gradient of better than 0.1 %/°C while operating at integrated gradients above 2 T.

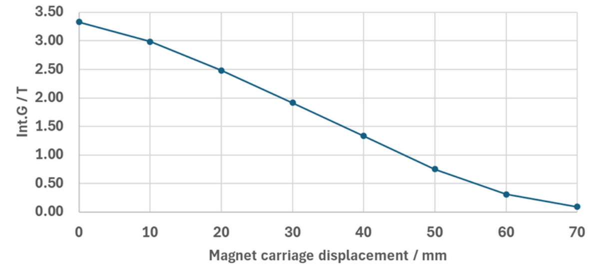

Figure 2: Simulated integrated gradient as a function of magnet carriage position, with 0 being fully inserted into the inner circuit.

## CORRECTION OF HOMOGENEITY AND MULTIPOLE COMPONENTS

CLARA requires a specification for the integrated gradient homogeneity of $\Delta G/G_0 \leq \pm 0.1\%$ within a 34 mm diameter. While homogeneity may be defined as the ratio $\Delta G/G_0$ along a line, normally on the horizontal axis, in cases where strong asymmetries may be present it may also be more comprehensively defined in terms of a summation of the higher order multipole components within a circle [15] according to:

$$\frac{\Delta G}{G_0} = \frac{1}{C_2} \sum_{n<2}^{\infty} (n-1) C_n \left(\frac{Z}{R_0}\right)^{n-1} \tag{1}$$

Where $R_0$ is the reference radius and $Z$ is any complex coordinate $Z = X + iY$ within that radius. Here we use $n = 18$ as a suitable approximation for $\infty$, as the accuracy of the FEA calculation of the multipole values is poor at higher orders. Ordinarily, the "allowed" higher harmonics for a quadrupole are $n = 2, 6, 10, 14$ etc.; however for ZEPTO the 45° symmetry line only holds to a low level approximation and so $n = 4, 8, 12$ etc. may also be treated as allowed harmonics. The complex construction of ZEPTO means that machining tolerances of all components, even non-magnetic or peripheral ones, risk creating additional asymmetries in the pole tips and hence forbidden harmonics or excessive allowed harmonics in the magnetic field.

To compensate for this, numerous techniques were examined for post-measurement adjustment of harmonics including removable machinable shim plates [15] and adding permeable rods in a ring in the aperture [16]. These techniques are powerful and versatile, however machining the shim plates or predicting correct rod lengths are expensive in terms of time and effort. With inspiration from these methods a "button shim" idea was conceived; using two aluminium rings, one with 20 cylindrical slots at one end of the magnet and another with 24 slots at the other end. These slots can then be filled with discs of similar steel to the yoke. Using discs of differing thickness alters the pattern of the harmonics in the fringe fields. To shim an n-pole multipole field in a quadrupole field, the shim must have a $(2+n)$-fold rotational symmetry. For instance, to trim a sextupole field, the shimming must be 5-fold rotationally symmetric about the magnetic axis.

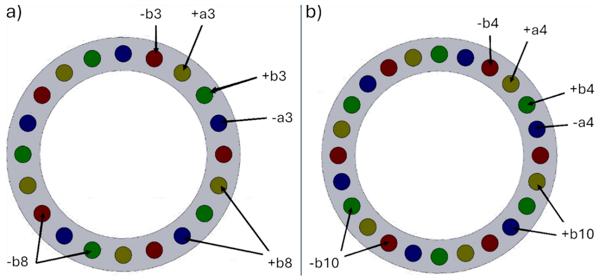

Figure 3: a) The 20-slot ring which acts primarily as a sextupole corrector. b) The 24-slot ring which acts primarily as an octupole corrector. The labels represent the skew (a) and real (b) Fourier coefficients of the cylindrical harmonics, such that "b3" is the real positive sextupole field and "-a4" is the negative skew octupole field.

The layout of these rings is shown in Fig. 3. The first corrector ring (20 slots) acts primarily as a sextupole corrector. The colours of the slots indicate the different 5-fold symmetric options. By filling different coloured slots, the integrated real and skew sextupole and real $n = 8$ (16-pole) multipole can be either increased or decreased in magnitude, independent of the other error multipoles. The corrections can be superimposed. Similarly, the second corrector ring (24 slots) allows independent shimming of the real and skew octupole and real 20-pole multipoles, independent of the other error multipoles. A comparison between the simulated integrated higher-order components of the magnetic field with and without the usage of the button shimming technique is shown in Fig. 4.

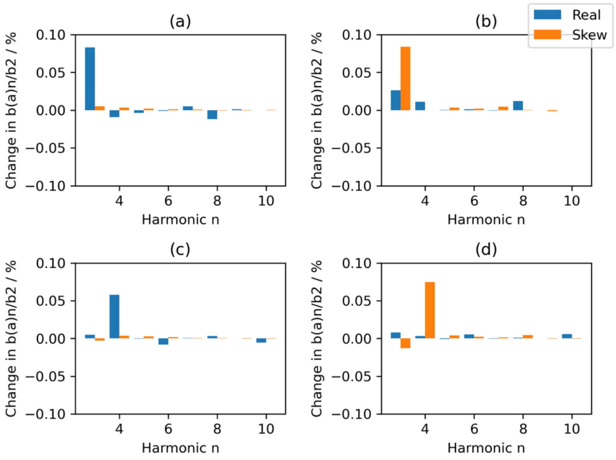

Figure 4: Relative change in integrated harmonics by application of a 1 mm button shim to correct harmonics (a) real sextupole, (b) skew sextupole, (c) real octupole and (d) skew octupole.

## CORRECTION OF AXIS DRIFT

All ZEPTO magnets to date have shown some vertical movement of the magnetic axis when the PMs are moved to the low strength positions. Prototype 3 solved this with independent carriage motion via dual motors, allowing a motion lookup table to be built, where adding slight asymmetry to carriage positions drags the magnetic axis back to the desired point. However, other features of the 3rd prototype to allow more versatile construction made the magnet more susceptible to this effect than the 1st and 2nd prototypes, and it could not be compensated for. In particular, machining errors that result in one half of the outer yoke being offset from the centreline can cause onset of horizontal axis drift at the low strength positions where the magnet carriages start to physically overlap with the outer yoke.

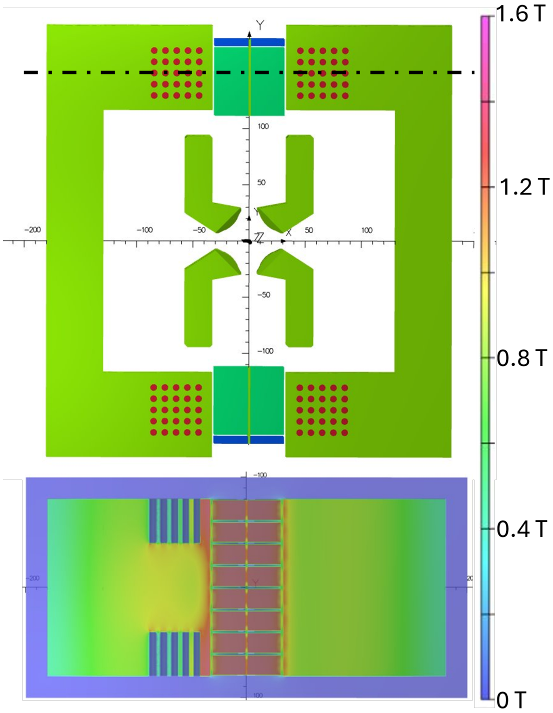

Figure 5: Top: OPERA model showing the tuning hole positions (red dots). Bottom: Cut view along the plane of the dashed line showing imbalanced saturation. Colour scale for bottom only.

This 4th prototype includes a new way of correcting both horizontal and vertical drift of the magnetic axis. The dual motor design of the 3rd prototype is retained as the primary method for correcting vertical drift, however horizontal and vertical drift can now also be corrected by introduction of tunable controlled saturation into eight dedicated sections of the outer yoke.

These sections, shown in Fig. 5, each consist of 25 threaded M6 holes in a grid pattern, with 50 mm depth. These are then filled in with screw-threaded rods of magnetic steel with similar properties to the yoke steel. The removal of a rod then creates a hole in the yoke, reducing the available material volume, and inducing a small amount of magnetic saturation in the surrounding steel of the yoke. This saturation slightly increases the path length for the flux through that half of the yoke. Crucially, this saturation only has effect when the magnet carriages are overlapping the outer yoke. Simulations show that if the holes were drilled all the way through the yoke, magnetic axis offsets of up to 6 mm could be corrected by this technique, however the tuning is highly non-linear and in this case it is also mechanically difficult. By limiting the depth of the holes to 50 mm the tuning resolution can be improved at the cost of reducing the maximum correctable offset. The tuning can be made finer-grained again by using five 10 mm grub screws in each hole instead of a single 50 mm rod.

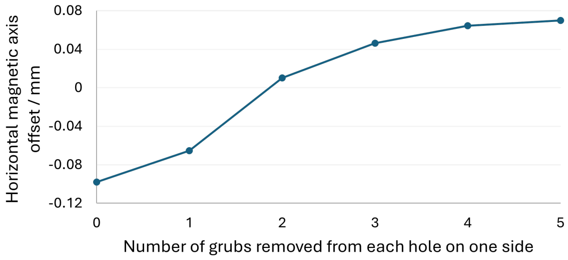

Figure 6: Simulation of correction of magnetic axis position arising from a 50 µm offset of one half of the outer yoke.

There are many degrees of freedom in this technique. An example is shown in Fig. 6 where a horizontal displacement of 50 µm was applied to one half of the outer magnet yoke with the magnet carriage in the lowest strength position, resulting in the magnetic axis being displaced by approx. 100 µm from the nominal position. In this case removing two grubs from each tuning hole brings the magnetic axis back to within 10 µm of nominal. More precision can be obtained by removing grubs selectively.

## CONCLUSION AND OUTLOOK

We have further developed the concept of ZEPTO tunable permanent magnet technology to demonstrate that it can replace electromagnets without loss of performance on the beam. We have developed ways to fine-tune and control the field quality. Harmonics resulting from the inherent asymmetry and assembly precision of ZEPTO can now be corrected, as can both horizontal and vertical drift of the magnetic centre position as a function of strength setting. The new prototype is under construction which, after laboratory testing, will replace an electromagnet on CLARA to compare performance under real operational conditions.

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