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DESIGN AND MEASUREMENT OF A LOW-ENERGY TUNABLE PERMANENT MAGNET QUADRUPOLE PROTOTYPE

B.J.A. Shepherd#, J.A. Clarke, P. Wadhwa, N.A. Collomb, STFC Daresbury Laboratory, UK
A. Bartalesi, M. Modena, M. Struik, CERN, Geneva

Abstract

The 42 km long CLIC Drive Beam Decelerator (DBD) will decelerate beams of electrons from 2.4 GeV to 240 MeV. ASTeC in collaboration with CERN has developed a novel type of tunable permanent magnet quadrupole for the DBD. Two versions of the design were produced, for the high energy and low energy ends of DBD respectively. This paper outlines the design of low energy version which has a tuning range of 3.5-43 T/m. A prototype was built at Daresbury Laboratory in 2013, and extensive measurements were carried out at Daresbury Laboratory.

INTRODUCTION

The Drive Beam Decelerator (DBD) section of the proposed Compact Linear Collider (CLIC) decelerates the drive beam from 2.4 GeV to 240 MeV, transferring its energy to the main beam [1]. To keep the drive beam focused, a total of 41,848 quadrupoles are required, spaced 1m apart.

The two beamlines are placed in a 4.5 m diameter tunnel where the maximum heat load has been set at 150 W/m. This is very challenging from the point of view of the magnets (not to mention many other heat-generating components), as the high currents used in typical electromagnets generate large amounts of heat and usually require active water cooling. To get around this, CERN and STFC are collaborating to design quadrupoles based on permanent magnets (PMs).

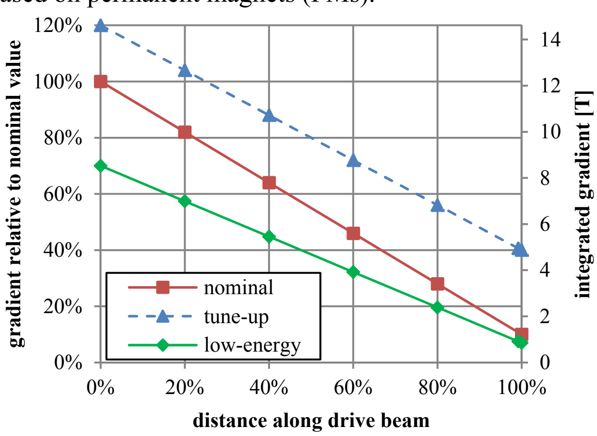

Figure 1: Tuning range required for DBD quadrupoles.

For CLIC's nominal operating regime, the drive beam energy will change linearly along its length from 2.4 GeV to 240 MeV. The quadrupole strengths would be fixed in this scenario. But alternative operating regimes will require the quadrupole strengths to be set differently, and so all the quadrupoles must be adjustable within a certain range. Figure 1 shows the tuning range needed along the length of the DBD. The percentage value on the left-hand axis is relative to the 'nominal' integrated quadrupole strength of 12.2 T. Assuming a magnetic length of 180 mm, this translates to a gradient of 68 T/m.

The ZEPTO (Zero-Power Tunable Optics) project aims to develop PM-based, highly adjustable magnets. To date, two versions of the permanent magnet quadrupole (PMQ) have been designed using Opera-3D [2]. The first 'high-strength' version can be varied between 3.5T and 14.6 T, and covers the first 60% of the DBD. The second 'low-strength' version covers the final 40% with a range of 0.7-8.9 T. Both are based around the same concept, which uses movable PMs to adjust the gradient. The two designs are quite distinct however, mainly because the range of adjustment (in terms of the ratio between high and low gradient) is much higher for the second design.

A prototype of the high-strength version (ZEPTO-Q1) was built in 2012 at Daresbury Laboratory; the design and measurements of this magnet were the subject of an earlier paper [3].

The low-strength magnet (ZEPTO-Q2) was prototyped in 2013 at Daresbury. The remainder of this paper describes the design and measurements of this magnet.

MAGNET DESIGN

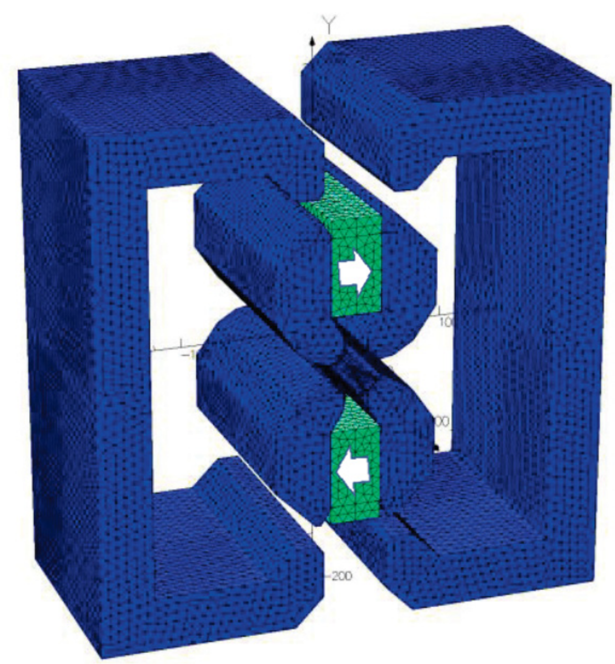

Figure 2: A 3D representation (using Opera) of the design of the low-strength quadrupole. Magnetic steel is shown in blue and the PMs in green.

#ben.shepherd@stfc.ac.uk

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The low-strength magnet design is shown in Fig. 2. The magnet consists of two NdFeB permanent magnet blocks which are placed above and below the beam axis. These blocks are the only movable ferromagnetic parts in the magnet and they translate along the vertical direction to change the field gradient within the aperture.

A ferromagnetic shell is placed around the outside of the magnet which provides an alternate flux path as the PMs are retracted and helps to further reduce the minimum gradient.

As the PMs are moved perpendicular to their magnetisation direction, the vertical force required to translate them is only 0.7 kN per side. They are controlled simultaneously using a single motor placed at one side of the magnet driving a left-hand/right-hand ballscrew. A rigid aluminium frame contains the PMs and is linked to an unthreaded shaft at the opposite side to keep the PMs on the vertical axis. Figure 3 represents the CAD model of the complete low-strength permanent magnet quadrupole.

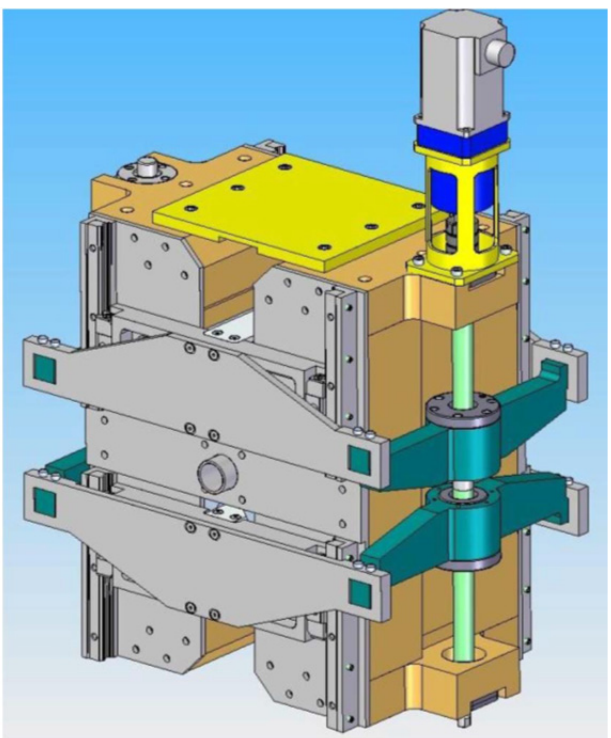

Figure 3: A 3D representation of the complete magnet. The motor is shown in grey and blue at the top right; the ballscrew is shown in light green; the PM blocks are contained within aluminium frames and are hidden from view.

Table 1 summarises the design parameters of the low-strength quadrupole, together with the values from the CLIC specification where applicable.

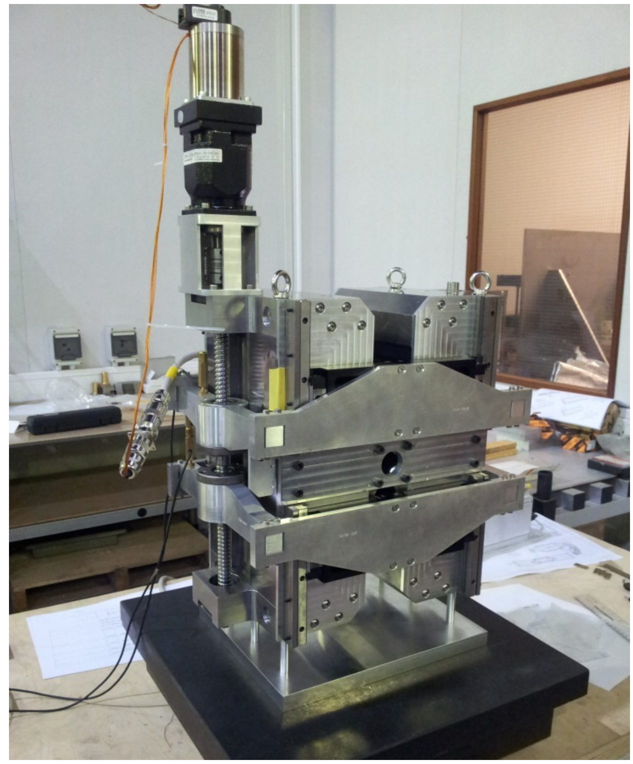

Figure 4: The low strength quadrupole prototype magnet assembled at Daresbury Laboratory.

Table 1: Quadrupole Design Parameters

Parameter	Specified	Model	Units
Gradient	N/A	2.9-43.8	T/m
Integrated gradient	1.22-4.9	0.6-8.5	T
Outer dimensions (excluding motor)	W 390 max H 390 max L 270 max	W 390 H 388 L 264	mm
Inscribed radius	13.6	13.6	mm
Integrated gradient quality	±0.1%	±0.1%	
Good gradient region	±11.5	±11.5	mm

MAGNET MEASUREMENTS

The low strength permanent magnet prototype was built at Daresbury Laboratory in 2013 (Fig. 4), and measurements were made in STFC's magnet test laboratory. The measurements were made on the entire magnet using the Hall probe technique. The probe used was a single-axis Arepoc Hall probe [4]. Figures 5-8 show the main results, and Table 2 shows a summary.

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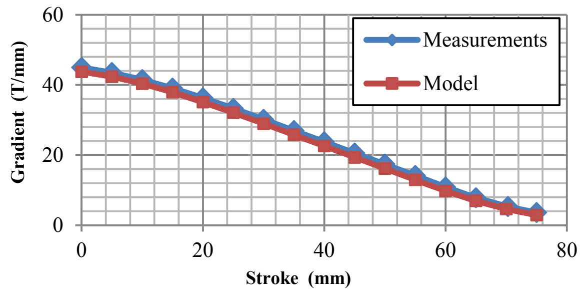

Figure 5: Comparison of gradient values for all strokes.

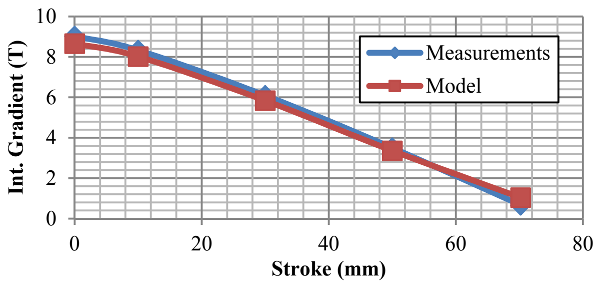

Figure 6: Variation of integrated field with stroke.

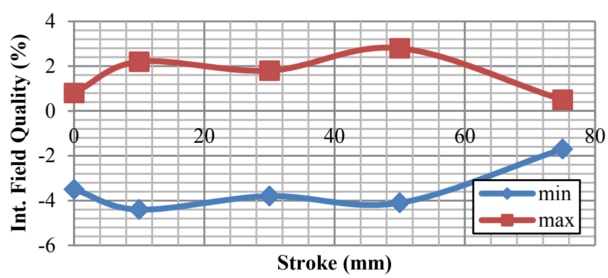

Figure 7: Variation of integrated field quality with stroke.

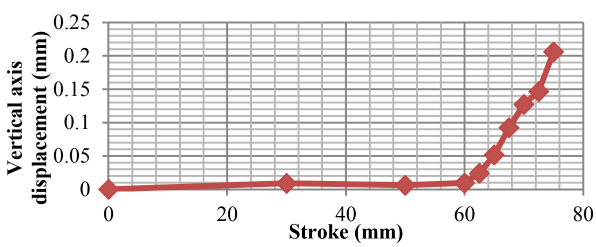

Figure 8: Variation of vertical axis displacement with stroke.

The variation of the central gradient agreed reasonably well with the model; the actual value was typically around 1.2 T/mm more than that predicted by the model.

Due to limitations of the magnet measurement bench, the complete length of the magnet could not be measured using the Hall probe. The integrated gradient and field quality measurements were extrapolated from data over about 70% of the length of the magnet. Integral measurements are planned to be repeated later in 2014 using stretched-wire and rotating coil techniques.

The integrated gradient agreed well with the model as well as can be seen in Table 2. The variation of the integrated gradient with stroke can be seen in Fig. 6 where the measurements made using the Hall probe are compared with the model. However, the integrated gradient field quality was found to be much more than the specification of ±0.1% in the central aperture of 23 mm. Table 2 also shows the variation of field quality with stroke. The reduction in field quality is likely to be due to poor positioning of the poles; future improvements in manufacture techniques are envisaged to mitigate this.

The measurements were also carried out for displacement in the vertical axis. The vertical axis variation with the stroke was found to be stable up to 50 mm with a larger variation at 75 mm as can be seen in Table 2. The integrated field quality for vertical axis was found to be similar to the horizontal axis. For minimum stroke the field quality was -3.3% to 0.5% whereas the field quality was -0.9% to 2.3% for maximum stroke.

CONCLUSION

A novel type of highly adjustable permanent magnet quadrupole has been designed, built and tested by the STFC-CERN collaboration. The magnet's performance has been accurately measured in the lab using a Hall probe. The gradient agrees well with the model; there is some room for improvement in the field quality.

REFERENCES

[1] M. Aicheler *et al*, "A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report", CERN, 2012.
[2] Opera magnetic modelling software, from Cobham (Vector Fields): http://www.cobham.com/
[3] B.J.A. Shepherd *et al*, "Prototype Adjustable Permanent Magnet Quadrupoles For CLIC", IPAC'13, Shanghai (2013).
[4] Arepoc Hall probes, http://www.arepoc.sk/

Table 2: Results of Hall Probe Measurements on the Low-Strength Quadrupole Prototype

Stroke (mm)	Corrected Integrated Gradient over whole magnet (T)	Model Integrated Gradient (T)	Central Gradient (T/m)	Integrated Field Quality	Vertical Axis Displacement (mm)
0	9.03	8.66	45.0	-3.5% to 0.8%	0
10	8.33	8.02	41.5	-4.4% to 2.2%	-0.01
30	6.09	5.84	30.2	-3.8% to 1.8%	-0.02
50	3.50	3.36	17.4	-4.1% to 2.8%	-0.01
75	0.67	0.71	3.6	-1.7% to 0.5%	-0.21