PROTOTYPE ADJUSTABLE PERMANENT MAGNET QUADRUPOLES FOR CLIC

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Abstract

The 42 km long Drive Beam Decelerator for the Compact Linear Collider (CLIC) requires over 41,000 quadrupole magnets. ASTeC and CERN are investigating the possibility of permanent magnet quadrupoles (PMQs) to reduce running costs and heat load inside the CLIC tunnel. A prototype of a high-strength adjustable PMQ has been built, based on a simple concept using two moving sections each containing a pair of large permanent magnets. The gradient can be adjusted within a range of 15-60 T/m (3-15 T integrated gradient). The prototype has undergone extensive magnetic testing at Daresbury Laboratory and CERN, and performs well in line with expectations. A prototype of the low-strength version (0.9-9T) is currently under construction.

INTRODUCTION

The Drive Beam Decelerator (DBD) section of the proposed Compact Linear Collider (CLIC) decelerates the drive beam from 2.37 GeV to 237 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).

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.

Two versions of the permanent magnet quadrupole (PMQ) have been designed using Opera-3D [2]. The first 'high-strength' version can be varied between 4T 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 magnet was built in 2012 at Daresbury Laboratory. The remainder of this paper describes the measurements of this magnet.

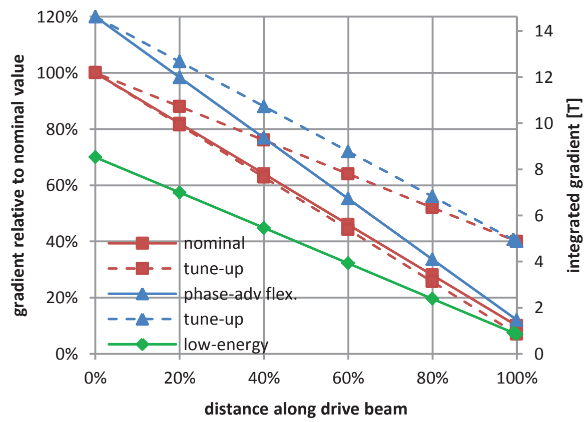

Figure 1: Tuning range required for DBD quadrupoles.

MAGNET DESIGN

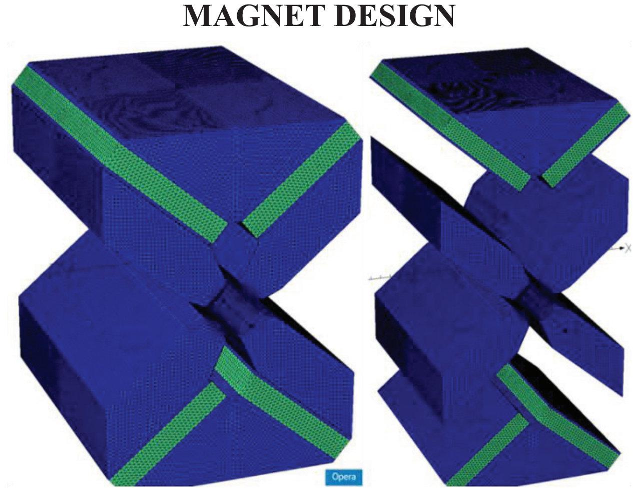

Figure 2: A 3D representation (using Opera) of the design of the high-strength quadrupole.

The high-strength magnet design is shown in Fig. 2. Two pairs of PMs are placed above and below the poles, in a movable carriage that also contains a 'bridge' of magnetic steel across the top to complete the magnetic circuit. The PMs move up and down, which has the effect of changing the flux path and thus the strength of the quadrupole field. The poles stay fixed, ensuring that the field quality is constant regardless of the amount of movement (referred to as the 'stroke').

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Both moving sections are controlled using a single motor, which is mounted above the magnet and connects, via a 'T' gearbox and two right-angle gearboxes, to two ballscrews. The gearing arrangement gives a movement resolution of 4000 steps/mm. The position is read back using a pair of encoders mounted either side of the magnet, with a resolution of 1 µm. Figure 3 shows a 3D representation of the whole magnet, including the motion system. The design is documented fully elsewhere [3].

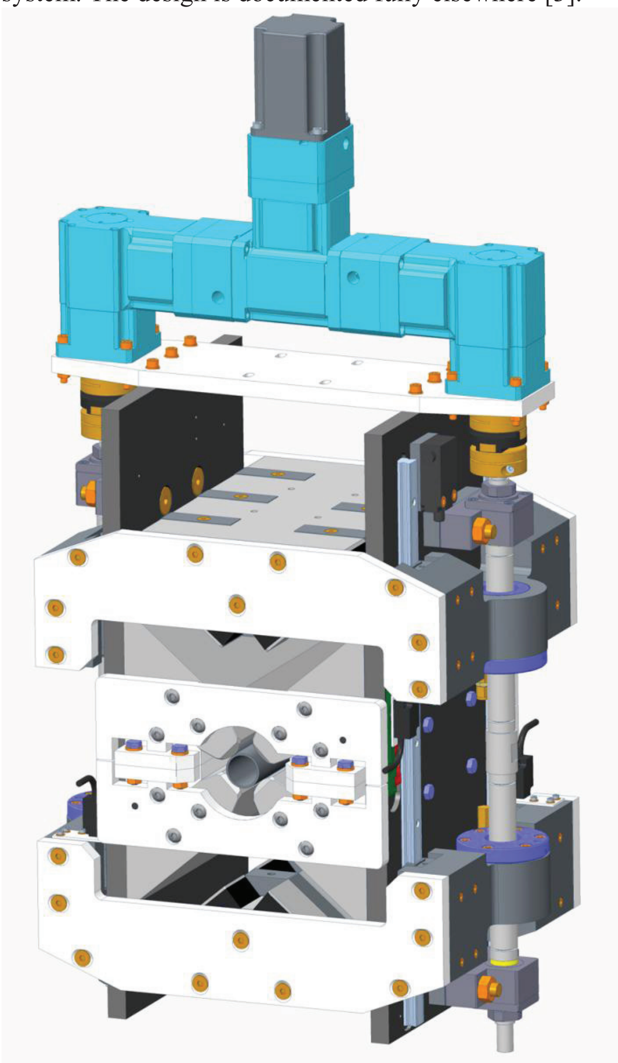

Figure 3: A 3D representation of the complete magnet.

MAGNET MEASUREMENTS

The magnet was built in summer 2012 at Daresbury Laboratory, and measurements were made in the magnet laboratory there. The first phase of measurements took place before the motion system was completed, to remove the effect of any magnetic steel components (rails, ballscrews etc.) on the results. These results could then be compared with the second phase of measurements, which took place after the magnet had been completely assembled. Several parts of the motion system, including the ballscrew and the rails, are made from steel, and the Opera-3D model suggested that these would have a small detrimental effect on the magnet strength.

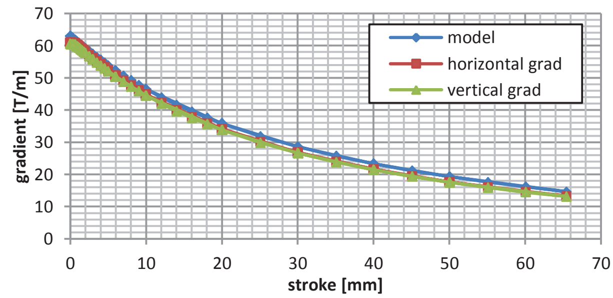

Figure 4: Gradients measured in the first phase.

The variation of the gradient agreed reasonably well with the model; the actual value was typically around 1.2-1.4 T/m lower than that predicted by the model. However, the field quality was much worse than expected; the gradient varied by up to 2% in the central 23 mm aperture, while the specification calls for ±0.1%. This was thought to be due to incorrect positioning of the poles. The magnet was subsequently completely rebuilt, paying close attention to the precise horizontal and vertical gaps between the poles. This made a big difference, bringing the field quality almost within specification for most of the gradient range. This demonstrates that the field quality is controlled by the position of the poles, and that variation in the magnetisation strength or direction of the PM blocks has far less of an effect.

Integral measurements were performed at CERN, using a stretched-wire bench and a rotating coil bench. The stretched-wire measurements showed that the measured gradients were slightly closer to the modelled values than previously thought, but also that there is some movement of the magnetic centre when the gradient is adjusted. In fact, the magnetic centre moves vertically by about 100µm between the high and low gradient setting. This result was later confirmed using the rotating coil bench.

Further modelling using Opera-3D demonstrated that this movement was partly due to the fact that the rails are slightly offset – they extend about 50mm further above the magnet than below it – and partly due to the influence of the motor and gearboxes, the central shafts of which are made from steel. This influence means that the magnetic centre (the point at which $B_x = 0$) is shifted slightly upwards. A sample of the rail material was analysed by the UK's National Physical Laboratory, to ensure an accurate B-H curve was used in the modelling.

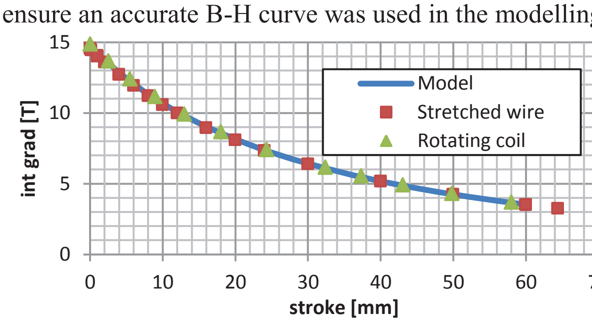

Figure 5: Integrated gradients measured at CERN, compared with the 3D model.

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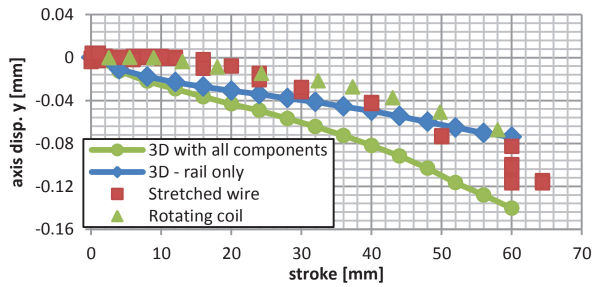

Figure 6: Measured axis displacements, showing comparisons with modelled values.

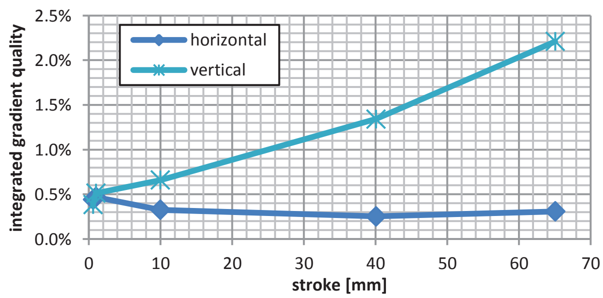

Figure 7: Measured values of integrated gradient quality over the 23mm aperture.

The results from the integral measurements taken at CERN are shown in Figs. 5-7, and a summary of all the measurements is made in Table 1.

The measured values of gradient and integrated gradient compare favourably to the model. In this respect, the magnet has performed very well. The main problems are the field quality and axis displacement, as discussed above. Some suggestions to mitigate these issues have been made. The pole faces for the low-strength prototype will have 2 mm flats added to the corners, to make it much easier to get the pole gaps correct during construction. The rails have a vertical offset which can be removed to improved the magnet's symmetry. Additionally, a 'counterweight' could be added to the underside of the magnet, consisting of a small block of magnetic steel to counter the effect of the motor and gearbox above the magnet. Since the composition of these components is only approximated in the Opera model, some experiments will be carried out on the high-strength prototype to determine the best configuration for this counterweight. Any proposed solution involving extra pieces of material outside the envelope of the existing design will of course have to be carefully integrated with the existing girder design.

LOW-STRENGTH PROTOTYPE

A prototype of the low-strength version of this magnet is under contruction at Daresbury Laboratory and will be tested in the summer of 2013. This magnet operates on the same principle of moving permanent magnets, but uses horizontally-magnetised PMs which greatly reduces the vertical forces involved. The design also incorporates an outer 'shell' which acts as a secondary flux circuit and increases the tunability of the magnet. The integrated gradient range of the low-strength magnet will be 0.7-8.9 T; all other parameters remain the same.

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 several different techniques, and has been found to be very good. Some issues have come to light in the measurement process which have since been reproduced in the model, notably the sensitivity of field quality to the positions of the poles and the variation of the magnetic centre as the gradient is adjusted. The gradients and integrated gradients meet the demanding specification.

[1] H. Braun *et al*, "CLIC 2008 Parameters," CLIC Note 764.

[2] Opera magnetic modelling software, from Cobham (Vector Fields): http://www.cobham.com/.

[3] B.J.A. Shepherd *et al*, "Permanent magnet quadrupoles for the CLIC Drive Beam decelerator", CLIC Note 940.

Table 1: Modelled and measured parameters. In each case, "min" and "max" refer to values at minimum and maximum strength respectively. Greyed-out boxes either were not specified, or could not be measured using that technique.

Parameter		**Specification**	**Model value**	**Measured values**			**Units**
				Hall probe	Stretched wire	Rotating coil	
Gradient	**min**		14.4	14.6			T/m
	max		60.7	61.0			
Integrated gradient	**min**	4.0	3.52	3.50	3.51	3.53	T
	max	14.6	14.67	14.57	14.54	14.88	
Gradient quality (23mm aperture)	**min**	0.2%	0.1%	2.6%			%
	max		0.1%	0.2%			
Maximum axis displacement	**horiz**		0	24	22	21	µm
	vert		74	82	104	72	