CONSTRUCTION AND MEASUREMENT OF NOVEL ADJUSTABLE PERMANENT MAGNET QUADRUPOLES FOR CLIC

B.J.A. Shepherd[#], J.A. Clarke, N.A. Collomb, Science and Technology Facilities Council, Daresbury Laboratory, Warrington WA4 4AD, UK

Abstract

The CLIC Drive Beam Decelerator (DBD) requires 41,848 quadrupoles to keep the beam focused along its length. Due to the stringent heat load requirements of the CLIC tunnel, a permanent magnet (PM) design is under investigation in a collaboration between CERN and STFC Daresbury Laboratory. The design incorporates a novel method of adjustment based on moving PMs. To cover the full length of the decelerator, two families of quadrupoles have been designed. This paper outlines the challenges of building an adjustable PM quadrupole, and explains the features of the two designs and how they will meet the demanding specifications of the CLIC DBD.

INTRODUCTION

The Compact LInear Collider (CLIC) is an international project to build a 3 TeV electron-positron collider, based on the concept of two-beam acceleration. A high-current, low-energy drive beam transfers its energy via RF power transfer structures to the low-current, high-energy main beam [1].

The Drive Beam Decelerator (DBD) transports the electron drive beam from 2.4 GeV to 240 MeV, transferring its energy to the main beam in the process. Twenty-four sectors of 876m each contain a quadrupole every 1m, arranged in a FODO lattice to focus the beam along the length of the DBD. A total of 41,848 quadrupoles are required.

The tunnel containing the drive beam and main beam has a diameter of 4.5 m. A challenging heat budget of 150 W/m has been set across all components. For this reason, a quadrupole design based on permanent magnet (PM) technology is being investigated by STFC in collaboration with CERN.

For nominal operation of CLIC, the energy decreases in a linear fashion from 2.4 to 0.24 GeV along the length of the decelerator. In this mode, the quadrupole strengths would be fixed. However, various different commissioning and operating scenarios are envisaged, where different quadrupole strengths would be required at each drive beam energy. Thus, all of the quadrupoles must be adjustable by a certain amount depending on their position in the decelerator line. This requirements are illustrated in Figure 1.

DESIGN CONCEPT

The selected design concepts employs PMs to drive the flux circuits which create the gradient at the magnet centre. To adjust the strength, the PMs are moved vertically away from the centre, creating an air gap and reducing the gradient seen by the beam. Adjustable PM quadrupoles have been built before [2-4] but we believe our designs have several advantages:

- The motion system is very simple – only two moving parts, with motion in opposite directions on a single axis and so driven by a single motor.
- The steel poles define the quality of the field, so errors arising from PM magnetisation direction errors of the blocks are small.
- Since the movement creates an air gap, the adjustment range can be very large. The minimum gradient is only set by the height restriction of the magnet.

Two quadrupole families are envisaged, one for the high-energy end of the decelerator and one for the low-energy end. The designs have been patented [5].
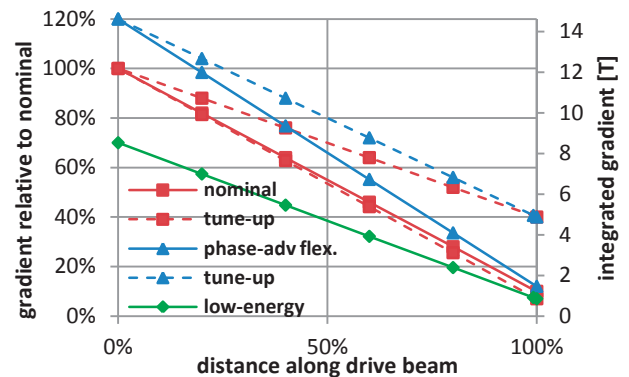

Figure 1: Required values of quadrupole strength as a function of distance along the drive beam decelerator line, for different operating scenarios. The percentage values on the left-hand axis are relative to the nominal strength of 12.2T for a 2.4 GeV beam.

HIGH-STRENGTH VERSION

In the design for this quadrupole, the flux is driven through the magnetic circuit by four permanent magnets at an angle of 40° to the horizontal. Each pair of PMs is attached by a wedge-shaped 'bridge' of ferromagnetic material. The bridge and PMs are moved together, vertically away from the magnet centre to create an air gap and reduce the magnet strength (Figure 2). The size of the air gap is referred to as the 'stroke'.

Due to vertical space constraints imposed by the CLIC module layout, the maximum stroke is 63mm. The integrated magnetic gradient can be varied between 120% and 30% of the nominal strength of the DBD quadrupoles. making. this magnet suitable for 67% of the length of the decelerator without any modifications.

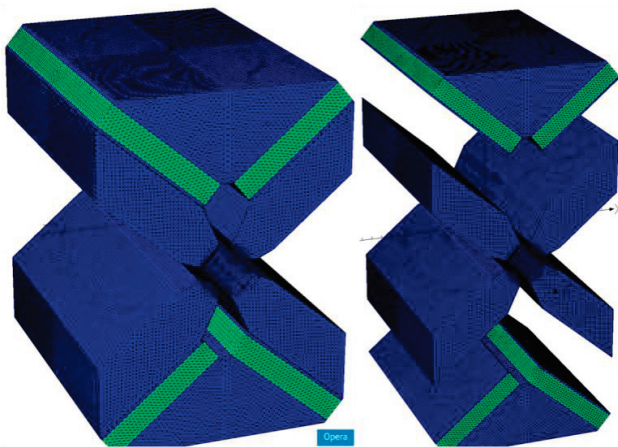07 Accelerator Technology and Main Systems

T09 Room-Temperature Magnets

Figure 2: A 3D representation of the high-strength quadrupole, modelled in Opera-3D [6]. The magnet is closed (left) and open (right) for maximum and minimum gradient respectively. The green blocks represent the PMs, which are magnetised parallel to their shortest dimension.

Due to the large size of the PMs, the forces involved are very strong – a maximum of about 16.4 kN in the vertical direction. This large force is the single biggest disadvantage of this design, and places tight constraints on the engineering of the motion system. The gap between the PMs and the poles must be precisely controlled along the length of the quadrupole in order to maintain the field quality.
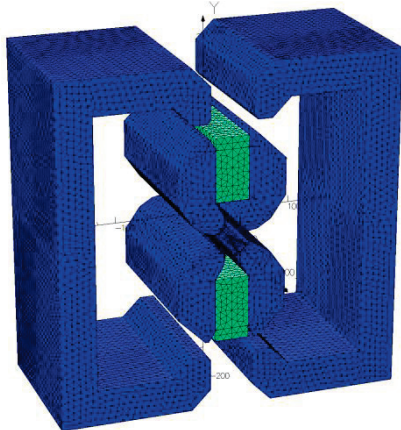
LOW-STRENGTH VERSION

Figure 3: A 3D representation of the low-strength quadrupole, modelled in Opera-3D. The PMs, which are magnetised parallel to the shortest dimension, are shown in their lowest position to generate the highest gradient.

This quadrupole uses an alternative design concept. Two horizontally-magnetised PM blocks provide the flux that produces the gradient at the magnet centre (Figure 3). These blocks are the only moving parts, and are moved up and down as in the previous design. However, as they are moved perpendicular to their magnetisation direction, the vertical forces are considerably reduced.

A ferromagnetic 'shell' is placed around the outside of the magnet, with a substantial gap between it and the rest of the quadrupole. This provides an alternative flux path when the PM is retracted, and helps to further reduce the minimum gradient, increasing the adjustment range of this design. The corners of the shell and of the upper part of the pole have been 'rounded off' so there will be no regions of high flux density as the magnet is adjusted.

Table 1 summarises the design parameters for the two versions of these quadrupoles, along with the specified values for comparison.

CURRENT STATUS

A prototype of the high-strength design has been assembled, and magnetic measurements have begun. Using STFC's magnetic measurement lab, the gradient and field quality can be assessed as a function of stroke, and compared with the model. Initially, the magnet is set up on the bench without the motion system, and the stroke will be changed by inserting shims. The second stage of measurements will be on the fully assembled magnet; this allows us to check the effect of the slightly magnetic rails and ballscrews on the field strength and quality.

The fully engineered design is shown in Figure 4. Both of the moving sections (top and bottom) are controlled by a single motor and gearbox, reducing the cost and complexity of the design. The precision of the motion system will be 10 μm, ensuring that the magnet strength can be precisely and reproducibly set. A photograph of one of the PM-wedge assemblies is shown in Figure 5.
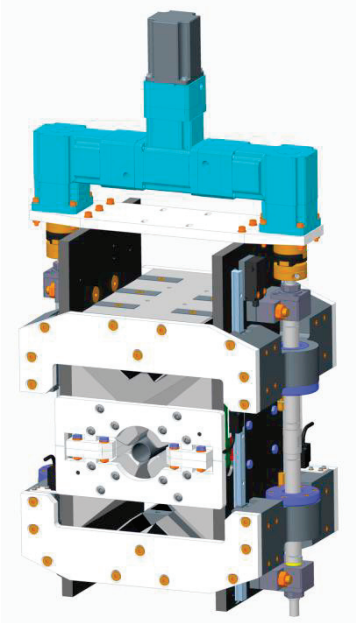

Figure 4: A CAD model of the high strength quadrupole.

Table 1: Quadrupole Parameters

Parameter	Specification		High-strength version		Low-strength version	
Inscribed radius	$\geq$ 13 mm		13.6 mm		13.6 mm	
PM size			18 x 100 x 230 mm		37.2 x 70 x 180 mm	
PM angle			40°		90°	
Magnet pole length	$\leq$ 230 mm		230 mm		180 mm	
Maximum stroke			64 mm		75 mm	
Gradient			60.4 T/m	15.0 T/m	43.8 T/m	2.9 T/m
Magnetic length			241 mm		194 mm	
Integrated gradient	14.6 T	0.9 T	14.6 T	4.4 T	8.5 T	0.6 T
Relative to nominal	120%	7%	120%	30%	70%	5%
Good gradient region (0.1%)	$\pm$11.5 mm		$\pm$12.0 mm		$\pm$12.0 mm	
Movement precision			10 μm		10 μm	
Relative strength precision	$\leq 5 \times 10^{-4}$		3.2×10^{-4}	1.7×10^{-4}	6.5×10^{-5}	7.6×10^{-4}
Force on moving section			16.4 kN	1.0 kN	0.7 kN	0 kN

Figure 5: One of the two assemblies of PMs and steel wedge, prior to assembly into the quadrupole.

CONCLUSION

Two new types of PM quadrupole with wide adjustment range and excellent field quality have been designed for the CLIC Drive Beam Decelerator. Two different designs have been produced for the CLIC study; a prototype of the high-strength version has been built and measurements have commenced, a low strength prototype will be assembled and measured later this year.

The adjustable PM-based designs presented here could easily be adapted for other multipole magnets and could also be a useful technology for other accelerators in the future, especially those where the power consumption should be minimized for either reasons of operating cost or heat load.

REFERENCES

[1] D. Schulte, "CLIC Conceptual Design and CTF3 Results," p961, Proc. IPAC 2011, San Sebastian, Spain.

[2] K. Halbach, "Permanent Multipole Magnets with Adjustable Strength," IEEE Trans. Nucl. Sci. 30(4), (1983) 3323, doi:10.1109/TNS.1983.4336645.

[3] S. C. Gottschalk, K. Kangas, T. E. DeHart, J. T. Volk, C. M. Spencer, "Performance of an Adjustable Strength Permanent Magnet Quadrupole," Proc. 2005 Part. Accel. Conf., Knoxville, 2005, p. 2071.

[4] J. T. Volk et al, "Adjustable Permanent Quadrupoles for the Next Linear Collider," Proc. 2001 Part. Accel. Conf., Chicago, 2001, p. 217.

[5] B. J. A. Shepherd, J.A. Clarke, and N. Marks, "Improved Multipole Magnet," UK Patent Application No. 1101859.5.

[6] Vector Fields Opera software package, from Cobham Technical Services: http://www.vectorfields.com