Tunable high-gradient permanent magnet quadrupoles

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TECHNICAL REPORT

Tunable high-gradient permanent magnet quadrupoles

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ABSTRACT: A novel type of highly tunable permanent magnet (PM) based quadrupole has been designed by the ZEPTO collaboration. A prototype of the design (ZEPTO-Q1), intended to match the specification for the CLIC Drive Beam Decelerator, was built and magnetically measured at Daresbury Laboratory and CERN. The prototype utilises two pairs of PMs which move in opposite directions along a single vertical axis to produce a quadrupole gradient variable between 15 and 60 T/m. The prototype meets CLIC's challenging specification in terms of the strength and tunability of the magnet.

KEYWORDS: Accelerator Subsystems and Technologies; Acceleration cavities and magnets superconducting (high-temperature superconductor; radiation hardened magnets; normal-conducting; permanent magnet devices; wigglers and undulators)

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1 Introduction

The Compact Linear Collider (CLIC) is an ambitious design study for a 46 km long electron-positron collider using the principle of two-beam acceleration [1]. In this scheme, a high-current, low-energy drive beam transfers its energy via Power Extraction Transfer Structures (PETS) to a low-current, high-energy main beam. At the interaction point, the main beams each have an energy of 1.5 TeV. The drive beam starts with an energy of 2.38 GeV and is decelerated along the Drive Beam Decelerator (DBD) to a final energy of 240 MeV. The two DBD lines each have 24 sectors of 876 m each, and have a combined total length of 42 km. Quadrupoles are placed at approximately one-metre intervals to keep the beam focused in a FODO lattice configuration. In total, 41,848 quadrupoles are required.

The electrical power requirements for conventional electromagnetic quadrupoles (EMQs) have been estimated at around 34 MW. Combined with the cost of running the water cooling plant, this is a major operational cost. A proposal that attempts to reduce the environmental impact of the collider project has obvious benefits. The maximum allowable heat dissipation into the tunnel, over all components of the drive and main beams, has been set at a challenging level of 150 W/m. For these reasons, ASTeC and CERN have formed the Zero-Power Tunable Optics (ZEPTO) collaboration. This project aims to investigate the possibility of producing tunable quadrupoles based on permanent magnet (PM) technology, with no coils.

PMs have several other advantages over electromagnets for accelerator applications.

- They are potentially more compact (although the magnet discussed here is similar in size to the EMQ version);

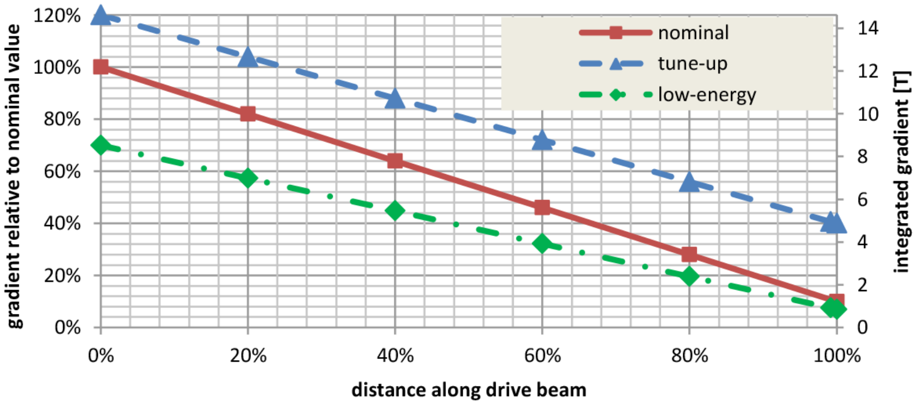

Figure 1. Variation of quadrupole strength along the DBD for different operating scenarios.

- the need for power supplies and long cables is eliminated;
- there is no need for water cooling, eliminating a large element of infrastructure, vibrations within the magnet, and one of the most common failure modes for electromagnets [2];
- there are no risks related to the high current and voltage employed for electromagnets;
- magnetic field continues to be generated when the adjustment mechanisms are switched off, leading to enhanced stability;
- the infrastructure and running costs are significantly reduced.

Tunable quadrupoles using PMs have been built by others, and have taken many different forms. Several are based on a 'tuning rod' concept, using rotating PM rods or small movable shunts [3, 4]; others use printed circuit boards wrapped around the inside of Halbach-type PM quadrupoles [5]. The degree of tunability of either of these designs seems to be limited to around 20%. For the CLIC DBD, at the low-energy end the magnets must be tunable by at least a factor of 5, as is obvious from figure 1. Other types of PMQs achieve a variable gradient by adjusting the drift lengths within a triplet [6] and using counter-rotating Halbach rings [7, 8]. These were also found to not be suitable, the former due to lack of space and the latter due to the difficulty of achieving the required high gradient and field quality at the same time. The classical Halbach design uses PMs as the poles, which leads to an increased reliance on the uniformity of the PMs' magnetisation strength and direction.

Gottschalk et al. [9] demonstrated the feasibility of a design using four large retractable PMs embedded in the outer part of a quadrupole. The design described in this paper uses a similar concept, but uses only two moving PM assemblies, which move in opposite directions along the same axis, and can therefore be attached to a single motor drive. The angle of the PM has been adjusted to optimise the PM working point and maximise the gradient.

Advances in PM and motion control technology have made this magnet possible. Magnetic materials are now available with energy densities in the region of 400 kJ/m^3 [10], whilst reliable motion control systems are available with positioning accuracies at the $10\,\mu$m level (without the use of encoders, which is problematic in a radiation environment).

Table 1. Outline of specified parameters for drive beam decelerator quadrupoles.

Parameter	**Value**	**Units**
Maximum integrated gradient	14.6	T
Minimum integrated gradient	0.85	T
Field quality	±0.1%	
over aperture	23	mm
Maximum dimensions: width	391	mm
height	391	mm
length	270	mm
Gradient setting accuracy	5×10^{-4}	

The PMQ feasibility study is taking place at the same time as a study involving conventional EMQs. The PMQ proposal is therefore in direct competition with the EMQ one, and must conform to the same rigorous standards. The specifications are outlined in table 1.

At the start of the DBD, the beam has an energy of 2.38 GeV, and the nominal integrated gradient required is 12.2 T. At the end, the beam's energy is 240 MeV, and the nominal integrated gradient is 1.2 T. So in normal operation, the gradient required at each quadrupole is fixed. However, a number of different operating scenarios are envisaged which would require each quadrupole to have a certain range of operating gradients. These scenarios, and the expected range, are shown in figure 1. Fixed-gradient PMQs are therefore ruled out, and each quadrupole must be adjustable within a certain range.

The large number of magnets required for this project means that the final design must be simple and straightforward to build. During the build phase, around fifty quadrupoles per day must be manufactured, so automation of the process will be very important. A major part of the collaboration between ASTeC and CERN is the development of automated assembly processes for mass production.

2 Design process

Several different design concepts were initially tried (figure 2). The first design was for a quadrupole with PMs embedded in the return yoke, with coils to provide some adjustment of the field. This was rejected on the grounds that the reluctance of the PMs in this magnetic circuit is very high, and therefore the current density in the coils for any reasonable amount of adjustment would also have to be very high — in fact, nearly as high as the current density for the standard EMQ.

A Halbach array of PMs was considered. This has the advantage that the gradient can be very high. However, the adjustment (using a rotating mechanism) was thought to be too complex, and a high gradient could only be achieved at the expense of field quality. There is also the problem that errors in the magnetisation strength or direction of the PMs give rise to a reduction in the field quality.

A third design concept uses fixed poles, with the magnetic flux driven by PMs that can be moved up and down to control the gradient. The field quality is determined by the shape of the poles and is independent of the motion of the PMs. Similar designs have been employed by Gottschalk et al. [9]; the concept we settled upon simplifies this by using two moving parts instead of four.

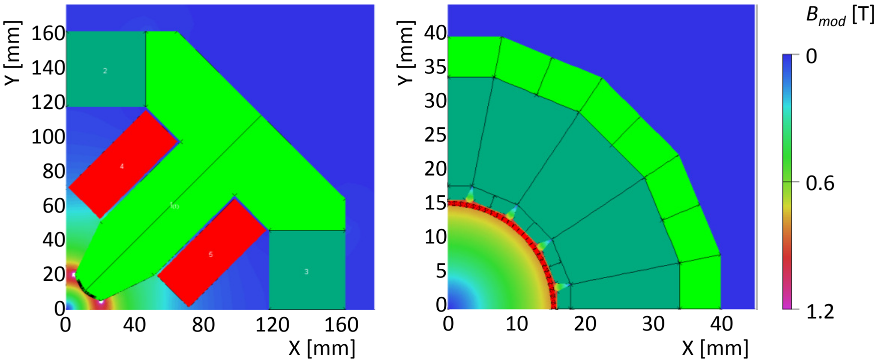

Figure 2. Initial designs for a variable quadrupole. The left-hand figure shows an EMQ with permanent magnets as part of the backleg (labelled regions 2 and 3), and the right-hand figure shows a Halbach-type quadrupole with wedge-shaped PMs, and small adjustment coils inside the gap.

The two moving sections (each comprising two PMs and a bridging steel piece) move in opposite directions along the same (vertical) axis, and can be controlled by a single motor drive.

The magnet must fit into the physical space available for it on the CLIC module. The maximum integrated gradient of 14.6 T (when considered against the minimum inscribed radius of 13 mm) is particularly challenging (for the electromagnetic version as well), so the magnet must form an efficient magnetic circuit. Adjustment of the angle of the PMs to the horizontal allowed us to fulfil both of these criteria: efficient use of space and optimisation of the PM working point to maximise the quadrupole gradient. Additionally, we tried to keep the flux density in the steel down to a maximum of around 1.6 T, in order to ensure the magnet stayed in a linear regime. This should ensure that the field quality is constant as the gradient is adjusted, and that hysteresis is not a big effect.

During the design process, it became clear that the complete tuning range (0.7–14.6 T) could not be covered using a single magnet design, within the constraints outlined in table 1. Instead, two magnet designs are proposed, using slightly different geometries. This paper concentrates on the design of the high-energy quadrupole (ZEPTO-Q1), which covers the first 60% of the DBD, and requires a tuning range of about a factor of 4. The remaining 40% of the beamline operates at a lower energy, but the ratio of maximum to minimum gradient is much higher — about 12. It would not be sufficient, therefore, to simply reduce the length of the high-strength magnet while keeping the same geometry. A different design is needed, which is outlined briefly elsewhere [11].

2.1 Final design

The quadrupole magnet was modelled in Opera [12], initially in 2D and finally in 3D to improve the integrated field quality. The poles are made from 40 mm thick 1006 low-carbon steel plate, tapering down to 22 mm at the tip. The profile of the pole is hyperbolic out to a width of 14 mm, with a tangent extending from there to the edge of the pole. This ensures the integrated field quality falls within the limits of the specification. Additionally, the ends of the poles have a 3 mm chamfer to reduce the high field which arises at the corners. The flux density in the steel remains in the linear region of the B-H curve, reaching a maximum of 1.67 T. Figure 3 shows a 3D layout of the magnet. Further details of the magnetic design can be found in a CLIC Note [13]. An international patent application has been submitted and is awaiting approval, covering the design of this magnet and of the low-strength version [14].

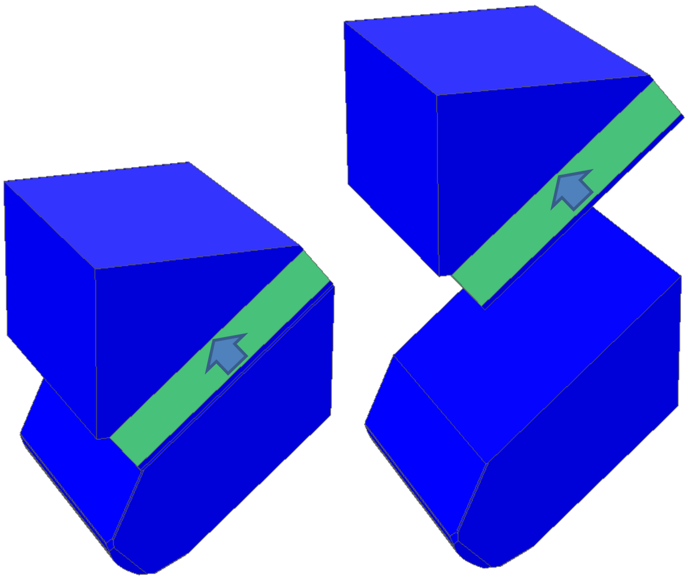

Figure 3. Opera-3D models of the quadrupole, in the fully closed (left) and fully open (right) positions. Only one quadrant is shown.

The PMs are made from NdFeB, grade VACODYM 764 TP [10], with a quoted energy density of 360 kJ/m^3 and remanence of 1.37 T. The overall size of each PM is 18 × 100 × 230 mm, and they are fixed together in pairs with a wedge-shaped 'bridge' piece (constructed from magnetic steel) connecting the two PMs in each pair. The bridge is bonded to the PMs, and a thin steel plate is also bonded to the base of each PM to prevent damage as the PMs are brought into contact with the poles. Additionally, three tensioned steel straps hold the PM-bridge assembly together, to reduce the risk of the PM breaking under the large vertical forces (16.4 kN maximum). When the gap is fully closed, the maximum integrated gradient is 14.6 T. As the gap is opened, the gradient reduces to a minimum of 3.6 T with a gap of 64 mm. This range of adjustment (a factor of about 4) means this type of magnet could be used for approximately 67% of the DBD line. The lower limit of the range is set by the vertical space constraint; clearly if this constraint was removed, the range could be much greater.

The mechanical design was realised as follows. The moving sections are operated by a Mclennan 23HSX-306B stepper motor positioned above the magnet. A Renishaw magnetic rotary encoder is used to provide closed-loop control of the motor's position. The motor is attached to two THK ball screws on each side of the magnet via a high-accuracy 'T' gearbox and two high-accuracy right-angle gearboxes. The ball screws have two threaded sections with threads running in opposite directions, so the two moving sections (top and bottom) are moved in opposite directions by the same amount. In this way, the adjustment of the gradient can be controlled using a single motor. 4000 steps of the motor corresponds to 1 mm of movement, so the movement has a resolution of 0.25 μm. The moving sections are guided along four THK rails, made from stainless steel. Omron limit switches are attached to the magnet at the far extents of motion, to stop the PMs from going too far. A CAD representation of the mechanical design, showing these components, is shown in figure 4.

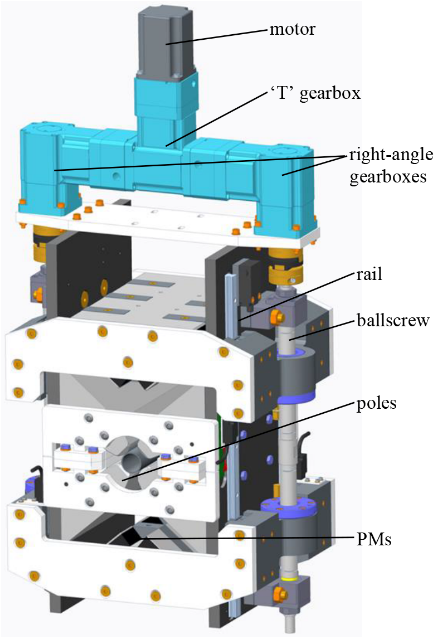

Figure 4. A CAD representation of the magnet.

The prototype magnet was equipped with a Heidenhain LIP481 linear encoder (±0.5 μm accuracy) on each side of the magnet to check the repeatability of the stepper motor. If the repeatability can be shown to be good enough, the encoders can be left out of the final design.

A summary of the final design parameters can be found in table 2.

2.2 PM pre-assembly measurements

Prior to integrating the PMs in the PM-bridge assembly, the magnetisation of PMs was measured using a Helmholtz coil. Table 3 shows the results. The range of variation is very small. It was decided to use blocks 1 and 4 for the upper assembly, and blocks 2 and 3 for the lower one. We tried to pair blocks of similar strength, so that any differences would manifest as a vertical offset rather than a field distortion. The field quality is set by the pole shape in any case, so the order of blocks should not make a big difference, especially when the variation is so small.

2.3 Prototype assembly

A prototype of the high-strength quadrupole was built at Daresbury Laboratory in 2012. The build took place in two phases. In the first phase, the magnet was held in an aluminium frame, and the moving sections were operated by hand (figure 5). This arose from concerns about some of the components used in the mechanical design, notably the rails (which restrict the carriage's transverse movement) and the ballscrews. Both are made from low-permeability steel (induction surface hardened ANSI 440C). These parts, when placed into the Opera-3D model of the magnet, had a noticeable but small effect on the overall field gradient — the maximum was reduced by approximately 1%. The magnet was initially assembled without these components in order to assess their real effect on the field. Following these tests, the magnet was assembled again with the complete motion system, and retested.

Table 2. Final design parameters for the high-strength quadrupole. The left-hand column shows the parameters at maximum strength (stroke 0), and the right-hand column shows the parameters at minimum strength (stroke 60 mm).

Parameter		**Max strength**	**Min strength**	**Units**
Stroke		0	60	mm
Integrated gradient		14.6	3.6	T
Relative to DBD nominal		120%	30%	
Central gradient		60.4	15.0	T/m
Vertical force on each moving section		16.4	1.6	kN
PM working point	B	1.004	0.548	T
	H	289	660	kA/m
	BH	290	362	kJ/m^3
Integrated gradient quality		±0.1%		
Good gradient region		±12.0		mm
Maximum flux density in pole		1.67	0.61	T

Table 3. Magnetisation measurements of the PMs.

PM label	**Alpha angle [°]**	**Beta angle [°]**	**Magnetic moment [arb. units]**
1	-0.08	-0.14	561.7
2	-0.03	-0.16	560.3
3	0.23	-0.23	560.5
4	0.14	-0.17	561.0
Range	*0.31*	*0.09*	*0.2%*

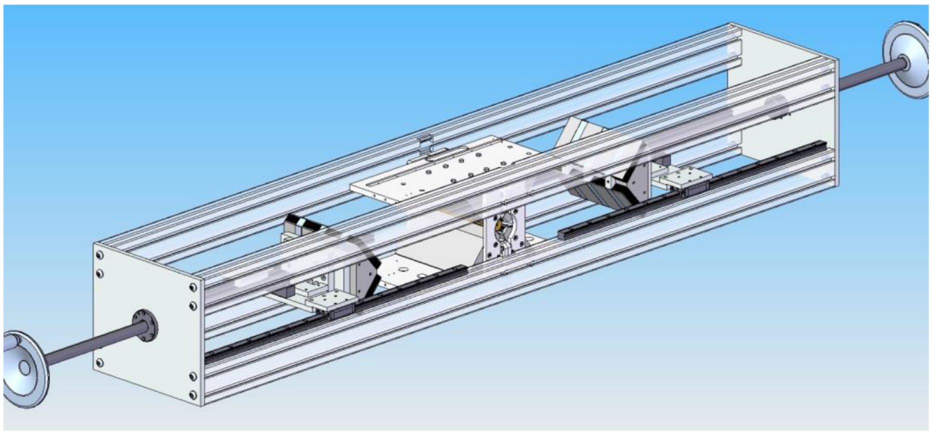

Figure 5. Non-magnetic jig to hold the quadrupole magnet in place, with handwheels to adjust the PM positions. Plastic shims were inserted between the PM section and the poles to ensure the position was set accurately.

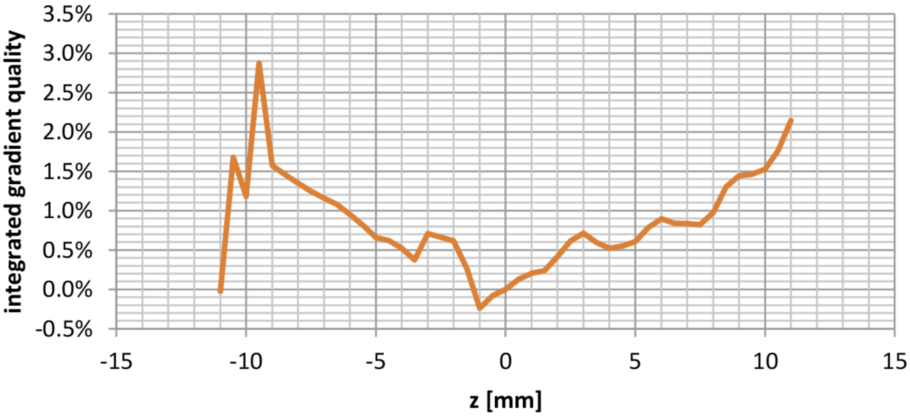

Figure 6. Plot of the gradient quality of the quadrupole, integrated over half the magnet length.

3 Magnetic measurements

At Daresbury, point-by-point measurements were carried out using the Hall probe bench. The bench uses a remotely-controlled movable Hall probe with a position resolution of 1 μm in three dimensions. The probe was able to reach about halfway along the length of the magnet due to the length of the Hall probe holder. The probe used was a customised Arepoc AXIS-3 probe, with three orthogonal Hall plates measuring three components of the magnetic field at each point.

Integral measurements were carried out at CERN. Tests were done on the stretched-wire bench and on the rotating coil bench to measure its integrated gradient, field quality, and magnetic centre stability.

3.1 Initial measurements

The first phase of measurements took place at Daresbury, in a non-magnetic support as discussed above. These tests showed that the gradient variation followed the model reasonably well, with the measured values typically being about 1.2–1.6 T/m less than the modelled values. The field quality was rather worse than expected (figure 6); the gradient varied by up to 2% within the central 23 mm. The specification called for 0.1%, so clearly this was a problem that needed to be rectified.

In this first phase, the moving sections of the magnet were operated using handwheels. This allowed us to attach a torque wrench and make an almost direct measurement of the force required to move the PMs. The force can be estimated using:

$$F = \frac{2\pi\nu T}{l}$$

where T is the measured torque, ν is the drive efficiency between the handwheel and the moving section, and l is the ball screw lead (5 mm). Assuming a 90% efficiency between the torque applied to the handwheel and the lateral force on the PMs, we measured the force required to move each side of the moving section at 13.6 kN. Considering the simple nature of this test (an expected accuracy of around 2.5%), this is a good agreement with the 16.4 kN predicted from the model. The discrepancy could be attributed to the fact that the moving section is not held as rigidly (during movement) in this non-magnetic support, and it is possible to pull one side away before the other, requiring slightly less initial force.

3.2 Rebuild and second phase of measurements

The quadrupole was rebuilt, including the motor, gearboxes and the other components. Unfortunately the field quality was not improved from the results obtained in the initial testing phase, and some further investigations were carried out to find the cause.

The field quality is effectively set by the poles; if the poles are incorrectly placed, the field quality will be much worse. This is true for all accelerator magnets, including a standard EMQ. Some physical measurements were carried out using slip gauges to check the gaps between the poles, and these showed that the poles had indeed not been set in the right place. The gap between the upper and lower poles was approximately 0.1 mm larger than the model value. When these differences were put into an Opera-2D model of the magnet, the field quality in the model matched up reasonably well with the measurements, indicating that this hypothesis was correct.

The quadrupole was rebuilt again, this time paying more careful attention to the precise positioning of the poles before building the rest of the magnet including the motion system.

Hall probe measurements were carried out again to verify the improvement in field quality. It was measured at 0.4% — a vast improvement, although still not quite up to the 0.2% demanded by the specification. The minimum and maximum gradients were measured as 13.3 T/m and 61.0 T/m respectively; this agrees very well with the model values.

3.3 Third phase of measurements

At CERN, the magnet was measured using a rotating coil bench to more accurately determine the harmonic content of the magnet. This gives a more detailed picture of the reasons behind the observed field quality, but has the limitation of measuring only inside the radius of the coil, which was 7.5 mm. Measurements are summarised in figure 7. The sextupole terms (B_3, A_3) are clearly dominant, showing that the field errors arise from errors in the alignment of the poles. The field quality measured on this radius varies from 0.3% at zero stroke to 0.09% at maximum stroke. Figure 8 shows a comparison with modelled field harmonics. In the 2D model, the harmonics are insignificant. The 3D model shows B_4 and B_6 terms (8-pole and 12-pole respectively) which are somewhat larger than those measured. These terms presumably arise from the fact that the magnet does not have full quadrupole symmetry. They are not so obvious (but still present) in the measured data; they are perhaps ‘masked’ by the much larger sextupole term.

Stretched-wire bench measurements at CERN [15] demonstrated that the integrated gradient was closer to the modelled values than previously thought (figure 9). However, they also brought to light a problem that had been previously overlooked — as the PMs were moved outwards to adjust the magnet’s strength, the magnetic centre shifted significantly, especially in the vertical direction. The axis displacement was about 20 μm horizontally and 90 μm vertically over the full range of adjustment. Measurements using the rotating coil bench confirmed this result, and upon further investigation it was also evident in the data from the Hall probe measurements. Figure 10 shows the effect.

This effect was unexpected, and had not been considered in the magnetic modelling before the quadrupole was built. A large vertical shift in the magnetic centre could have two possible causes:

- mechanical deformations of the moving parts, or
- a difference in the magnetic flux path between the top and bottom halves.

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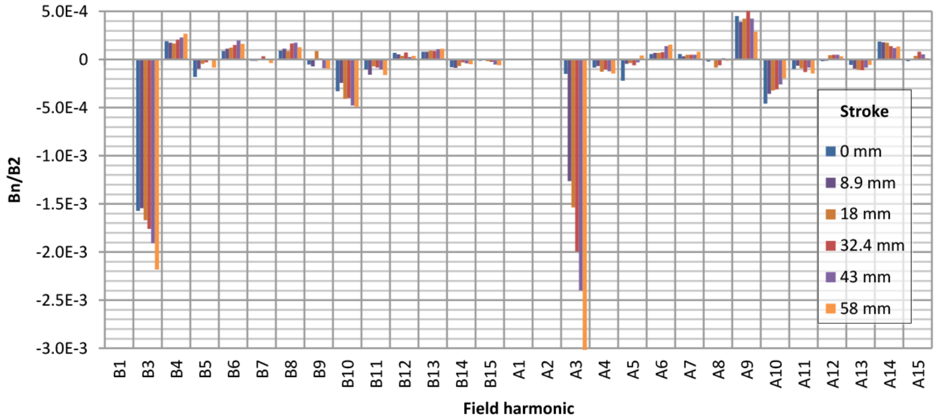

Figure 7. Measured field harmonics, relative to the main quadrupole harmonic B_2, using a rotating coil bench.

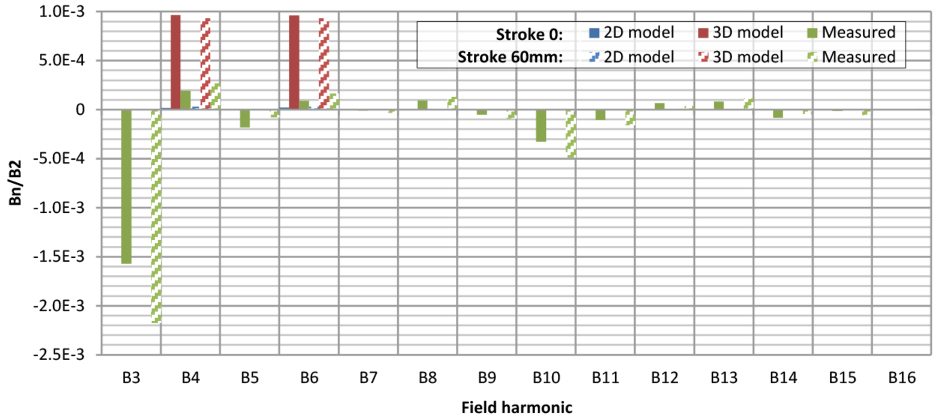

Figure 8. Comparison of modelled and measured harmonics.

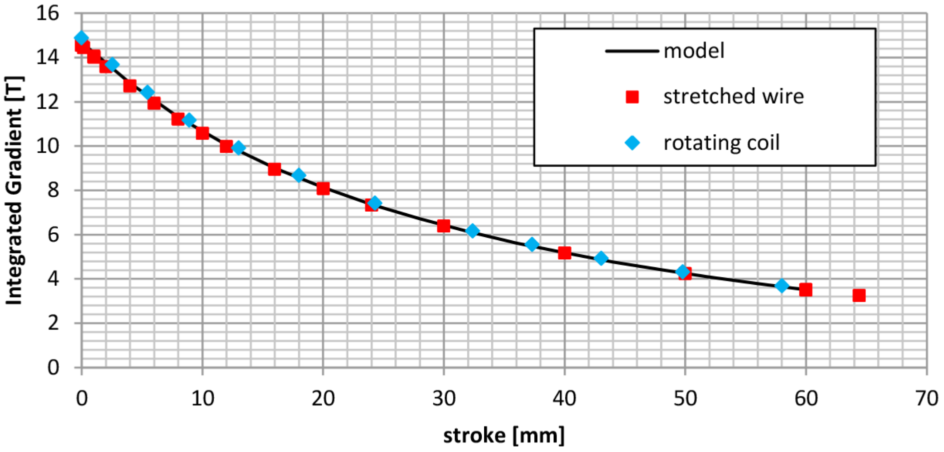

Figure 9. Integrated gradient versus stroke, measured on the stretched-wire and rotating coil benches, and compared with a model of the magnet.

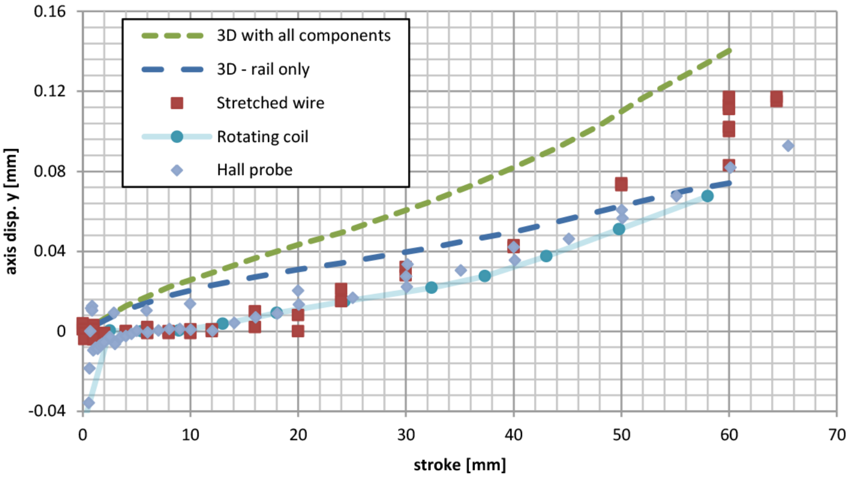

Figure 10. Displacement of the magnetic axis versus stroke, measured using all three techniques, and compared with two different magnet models.

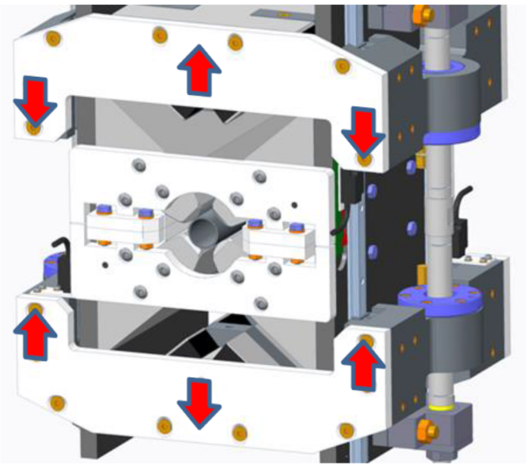

Figure 11. Flex observed using a CMM at the CERN metrology lab. The arrows indicate the direction of movement as the PMs are moved *away* from the centre (i.e. the gradient is decreased).

Exhaustive tests were carried out using a coordinate measuring machine (CMM) at the metrology lab at CERN [15] to try to determine whether mechanical deformations were significant. A measurable amount of *flex* in the moving section was observed — see figure 11. The amount of movement observed was shown to be on the order of tens of microns. However, this movement is symmetric about the magnet's vertical centre, and so cannot explain the observed axis shift.

The CMM was also used to measure the positions of several points along the edges of the poles. A hyperbola was fitted to these coordinates, allowing us to calculate the geometric centre of the poles. Figure 12 shows the results obtained. The vertical centre shift is around 15 μm at maximum stroke — significant but not enough to explain the large axis shifts seen in the magnetic measurements.

Mechanical effects, therefore, can not completely explain the axis shift, and there must be a magnetic effect as well — in other words, some asymmetry in the ferromagnetic parts that make up

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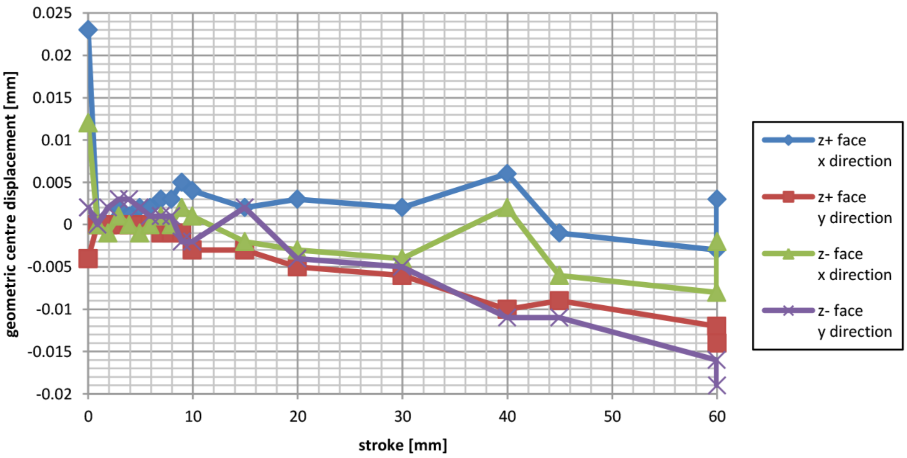

Figure 12. Measured change in geometric centre of the poles.

the magnet. Since the poles and PMs are vertically symmetric, other parts should be considered. The motor and gearboxes are obvious candidates, since they are only present at the top of the magnet, and not underneath it. The drive shafts inside these components are made from steel, but the exact grade used is unknown.

A further measurement was made using the stretched-wire bench with the magnet at its maximum stroke (64 mm) and the motor and gearboxes removed. The axis shift was reduced by about a third (from 90 μm to 60 μm), indicating that some (but not all) of the effect was due to the presence of the motor and gearboxes.

The only other component with a vertical asymmetry is the guide rails for the moving sections. These were built from 'off-the-shelf' components which had a fixed length, and so had to be positioned with a slight vertical asymmetry to avoid fouling the girder underneath the magnet. They are made from a slightly magnetic grade of steel. Since the effect on the magnet is quite important, and the rails are positioned relatively close to the magnet, a sample of the material used to make the rails was sent to the U.K.'s National Physical Laboratory to determine its DC B-H curve. The measured curve is shown in figure 13. The maximum relative permeability is about 150, so there is a good argument for including the rails in a model.

Two further Opera models were produced, both with the vertical symmetry broken. One included the rails and ballscrew, and the second also added an approximation of the motor and gearbox. The outer dimensions of the latter two are known, but the proportion and grade of steel that makes them up is not. It was assumed that they were made up of 50% steel by volume, of the same grade as that used for the rails. The effect of PMs and coils in the stepper motor was not included to reduce complexity in the model — this is also the component that is furthest from the centre of the magnet. All the extra components were modelled using the measured B-H curve for the rail. The results are shown in figure 10; it can be seen that most of the axis offset is due to the asymmetry in the rails. Adding the motor and gearboxes results in overestimating the axis offset, so the permeability of these components is perhaps smaller than that of the rails.

A summary of all the measurements can be found in table 4.

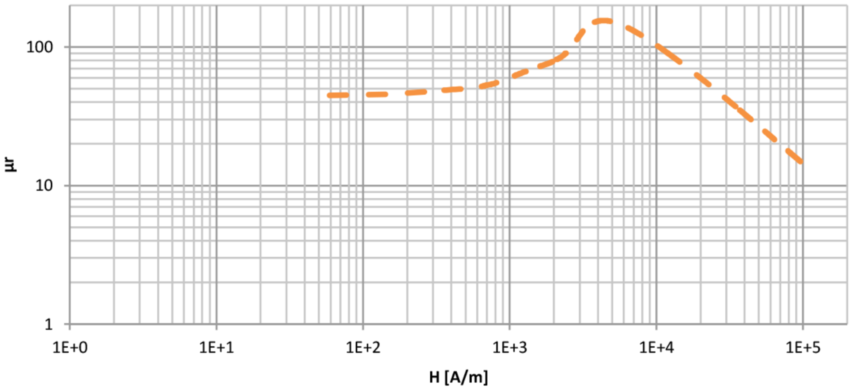

Figure 13. Measured B-H curve of the steel grade used for the guide rails. The calculated relative permeability is also shown.

Table 4. Summary of magnet measurements, compared with specified and modelled values. The measured gradient quality values using the rotating coil are measured at a reference radius of 7.5 mm, and therefore give a better value than that measured at the specified good field radius of 11.5 mm.

Parameter		**Specification**	**Model value**	**Measured values**			**Units**
				Hall probe	Stretched wire	Rotating coil	
Gradient	min		14.4	13.3			T/m
	max		60.7	61.0			
Integrated gradient	min	< 8.5	3.52	3.50	3.51	3.53	T
	max	14.6	14.67	14.57	14.54	14.88	
Gradient quality (23 mm aperture)	min	0.2%	0.1%	2.6%		0.3%	%
	max		0.1%	0.2%		0.1%	
Axis displacement	horiz	20	0	24	22	21	μm
	vert	20	74	82	104	72	

4 Discussion

The magnetic measurements are in excellent agreement with the model; the integrated gradient values match to within 1%. This is a very good result and shows that the magnet is performing well in terms of the gradient it produces and the tuning range.

It has been clearly demonstrated that the problems experienced with the field quality were due to the alignment of the poles (and not due to variations in magnetisation of the PMs, for instance). When the magnet was assembled for the third time, paying closer attention to the gaps between the poles, the field quality was markedly improved. It is highly likely that the poor vertical field quality at large strokes is related to the magnetic axis displacement.

The axis displacement was an unexpected issue that only became apparent when integral measurements were made. Further detailed 3D modelling, including medium-permeability stainless steel components related to the motion system, showed that these components were a strong candidate for the cause of the problem.

These issues will be considered in the design of the next prototype; for instance, horizontal and vertical flats will be added to the edges of the poles so it is easier to set them in the correct position during manufacture. Another issue of ongoing concern is that of mass production. The magnet needs to be straightforward to build and quick to assemble, using ‘off-the-shelf’ and easily available components where possible. The quality of this small batch of PMs was very high, with almost no variation between them. For a larger batch, it may be necessary to ‘sort’ PM blocks and pair up blocks with similar strengths.

Other issues that have not been fully explored yet are those of temperature variation and radiation damage. The two issues are not unrelated; magnets that exhibit a large degree of temperature variation also tend to be susceptible to radiation damage. The CLIC tunnel will have good temperature stabilisation — of course, using PM-based magnets makes this easier — but the amount of radiation produced by the beam is likely to be quite high. Radiation-resistant motors are available, and samarium-cobalt (SmCo) PMs have lower radiation degradation thresholds than the NdFeB used for this prototype. Using SmCo may reduce the maximum achievable gradient, however — so it may not be possible to use it for the very highest-gradient quadrupoles.

5 Conclusion

We have designed a novel type of adjustable permanent magnet based quadrupole. A prototype has been designed and built at Daresbury Laboratory. Extensive magnetic measurements have demonstrated that it meets the values for gradient and tunability specified by the CLIC drive beam decelerator. Further tests will explore a number of outstanding issues, including the stability of the magnetic axis, temperature dependence and radiation resistance.

A prototype of the low-strength version will be built and tested at Daresbury in 2014.

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