DEVELOPMENT AND ADJUSTMENT OF THE EMMA QUADRUPOLES

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Abstract

The non-scaling FFAG EMMA, now under construction at STFC's Daresbury Laboratory, requires 84 quadrupoles. Because of their unusual nature [1], prototypes for the F and the D type quadrupoles were required. These magnets were ordered, constructed and measured by Tesla Engineering. Subsequently, design changes were made and modifications to the prototypes carried out. This paper gives details of the protoryppe measurement results obtained using a rotating coil magnetometer and subsequent adjustments to pole profiles needed to obtain optimum three dimensional gradient quality. The construction of the 84 magnets for the complete ring is now underway.

INTRODUCTION

The Electron Machine for Many Applications (EMMA) [2] will be a non-scaling Fixed Field Alternating Gradient (nsFFAG) accelerator. Such machines could be used to accelerate ions for cancer therapy, as well as for particle physics. EMMA is part of the CONFORM project [3] and is a proof-of-principle machine. It will take 10MeV electrons from the ALICE (ERLP) facility [4], accelerate them to 20MeV and extract into a diagnostic beamline.

The EMMA lattice quadrupoles (42 F and D types) will be radially offset to provide dipole and quadrupole field and hence have combined function; their horizontal positions will be adjustable to provide independent control of the dipole and quadrupole components.

The magnets are very thin, with clamp plates at one end and present unique challenges. The field is dominated by end effects and design was carried out in three dimensions from the outset [1]. Two prototypes have been constructed to check the modelling and to carry out necessary adjustments prior to manufacturing the main quadrupoles.

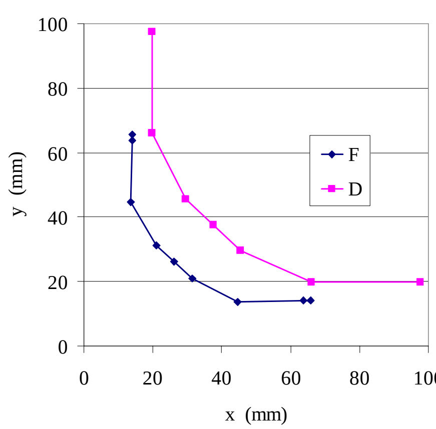

Figure 1: Pole profile for F and D magnets.

MAGNET PARAMETERS

Table 1 shows a list of magnet parameters, whilst Figure 1 shows the pole profile for the F and the D magnets. These magnets use a 'straight-line' pole profile rather than the standard hyperbolic curve.

Table 1: List of current magnet parameters for EMMA.

Parameter	F magnet	D magnet	Units
Integrated gradient	-0.387	0.347	T
Inscribed radius	37	53	mm
Current	350	350	A
Turns in coil	10	15	
Yoke thickness	55	65	mm
Pole width	73	110	mm
Horizontal movement range	-2.711 +2.604	-5.280 +14.535	mm
Offset from centre	7.507	34.025	mm
Good field region	-32…+16	-56…-10	mm

MAGNET PROTOTYPES

A prototype of each type of magnet (F and D) was built by Tesla Engineering. Figure 2 shows photographs of the prototype magnets.

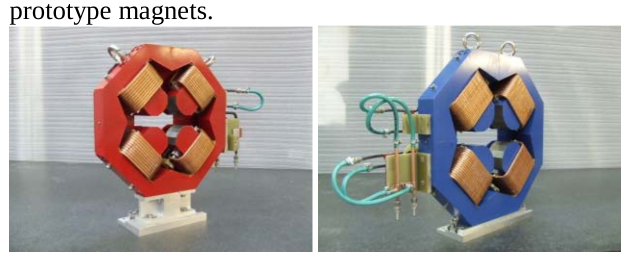

Figure 2: The prototype magnets (F left, D right).

The magnets were measured by Tesla using a rotating, four coil magnetometer [5]. A long 4-coil array of 35mm radius was rotated within the quadrupoles' apertures and the magnetometer produced data on the strength and harmonic contents of each magnet. The field components of the prototypes were measured in the following configurations:

1. with the magnet powered at 50%, 80% and 100% of nominal excitation;
2. with the clamp plate removed;
3. with the clamp plate moved longitudinally by up to 1mm in either direction;
4. with 5mm diameter, 1mm thick steel 'buttons' attached to the pole ends, in various positions.

The clamp plates on the production magnets will be built and adjusted so that all the quadrupoles of a given type have the same strength to within the limits of measurement. Test 3 aims to establish that the range of movement is enough to provide sufficient adjustment.

The purpose of Test 4 is to show that the field quality of the magnets can be adjusted by adding small pieces of steel to the ends of the poles. Figure 3 shows where the steel buttons were added.

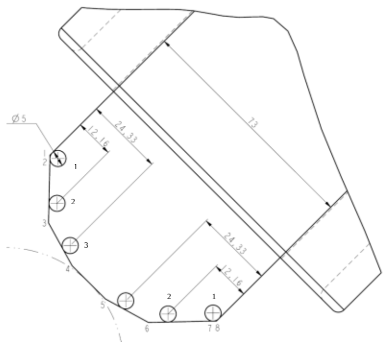

Figure 3. Pole profile showing labels for placement of buttons. Positions 4, 5, and 6 are the same as 1, 2, and 3 respectively but at the other end of the magnet.

MEASUREMENT RESULTS

A full set of measurements for each magnet were carried out, and the field gradients calculated from the multipole components. Figure 4 shows the normalised integrated gradient (G/G_0, where G_0 is the integrated gradient at the magnetic centre) for each magnet. The nominal (100% current, no modifications) measurement is shown with a solid black line.

The model predictions using the 3D code e.m.studio [6] are also shown in Figure 4. In both cases, the measured gradient drops off quicker than the model predicted. For the F magnet, this is actually an improvement – the gradient variation is +0.4% / -2% within the specified aperture of 32mm. The magnet was judged to be acceptable with this profile.

For the D magnet improvement was necessary. At the outer radius of the coil (35mm), the gradient is reduced by 1% of its central value. Extrapolation beyond this radius is not strictly valid, but the model predicted a much greater reduction in gradient at the edge of the required aperture (56mm).

Clearly the differences between the model and the measurements need to be resolved. Models of the magnets were built using OPERA-3D [7]. They proved to be much more accurate in predicting the multipole components found using the rotating coil measurements.

Clamp Plate Tests

Test 2 involved removing the clamp plate entirely; the magnet strength was increased by doing this, as expected. However, when the clamp plate was reattached and its longitudinal position was varied, some of the results were different to those expected.

For the F magnet, the magnet strength increased as the clamp plate was moved away from the magnet yoke, as expected. The difference in strength is about 0.25% per mm of movement, indicating that the magnets can be adjusted using this method to meet the specification of less than 0.1% difference between all the production magnets.

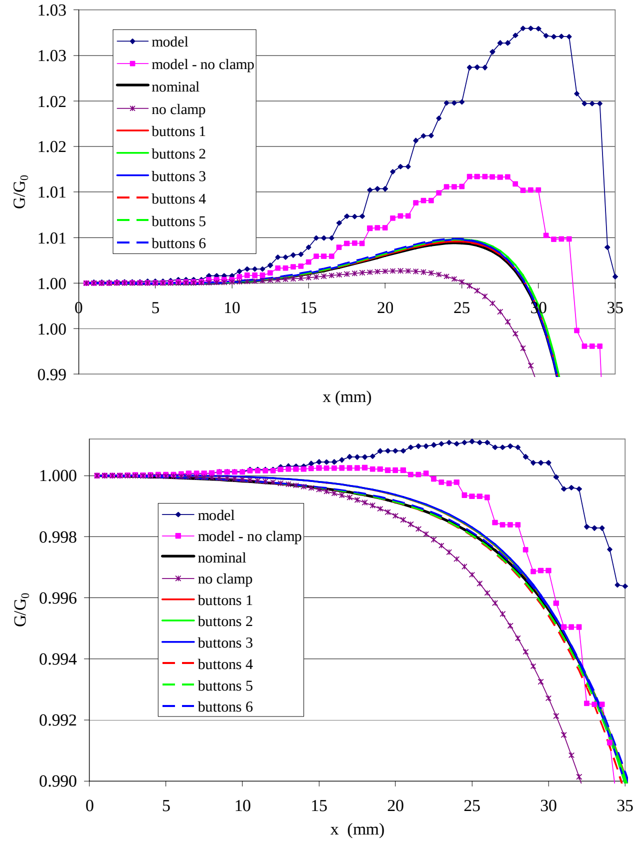

Figure 4: Normalised integrated gradient vs transverse (x) position (from coil rotational centre) for the F (top) and D (bottom) magnets. The model predictions are shown with blue and purple lines in each figure.

However, for the D magnet, the strength actually appeared to **decrease** very slightly as the clamp plate was moved away. This was confirmed in the OPERA model, and was shown to be caused by saturation in the clamp plate. Unless the clamp plate was moved a much greater distance away from the magnet, the saturation remained, and the magnet strength did not change much. The clamp plate thickness was therefore increased from 5mm to 8mm to reduce the flux density in the steel.

With the thicker clamp plate, the clamp plate is not saturated, and magnet strength has the expected variation, increasing as the clamp plate is moved away by about 0.8% per mm. This will provide the required adjustment.

Buttons

Test 4 involved adding small (5mm diameter) steel buttons to the ends of the magnet poles to investigate the effect on the field quality. The field harmonics were measured using the rotating coil, and the transverse gradient profile was calculated from these. There was a measurable difference but not of sufficient magnitude to correct the D magnet's gradient. The concept of adding buttons to adjust the gradient distribution was abandoned.

Combined Tests

In order to assess how the field of each magnet is clamped by the other magnet in very close proximity, further tests were performed. Both magnets were mounted on the bench, with longitudinal and horizontal spacing of 117.25mm and 22.61mm respectively between magnet centres. The magnets were powered first individually, and then simultaneously.

Figure 5 shows the results for the F magnet. The presence of the D magnet with an offset clearly adds an asymmetry to the F quadrupole field. However, the gradient quality is still within the required ±1%.

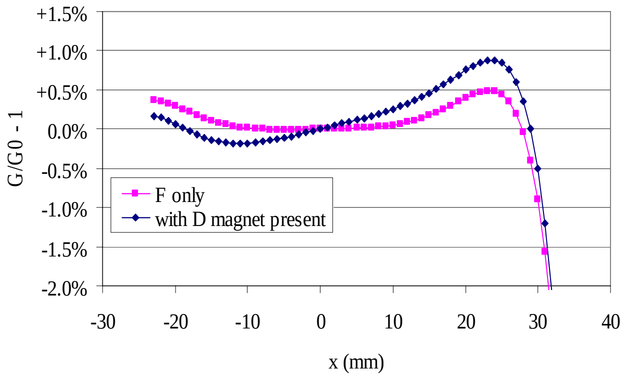

Figure 5: Comparison of F integrated gradient quality with and without the un-powered D magnet present.

D QUADRUPOLE SHIMMING

The field quality in the 'D' quadrupole was much worse than expected – the value of the gradient dropped off immediately away from the magnetic centre. To counteract this, 2mm thick shims were added to the outermost facets of each pole; modelling was carried out in OPERA to determine their optimum width. The best results came from adding 27mm wide shims to the poles – nearly the entire width of the outermost facet. The effect of varying the shim width is shown in Figure 6.

The D magnet, with 25mm shims (which were easier to align to the edge of the poles) was measured on the rotating coil bench with the un-powered F magnet in position. The results in Figure 7 indicate that the gradient quality with the shimmed pole is much improved.

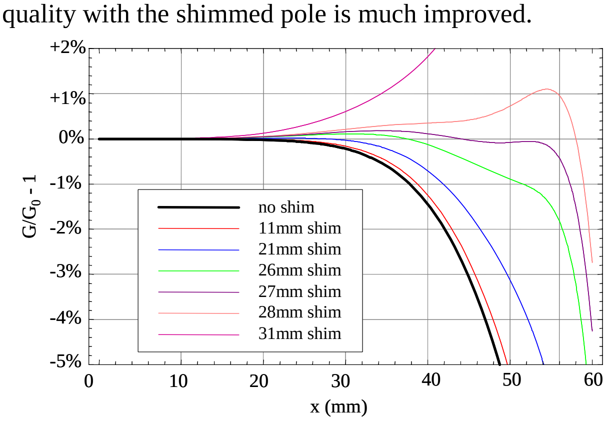

Figure 6: Modelled effect of adding shims.

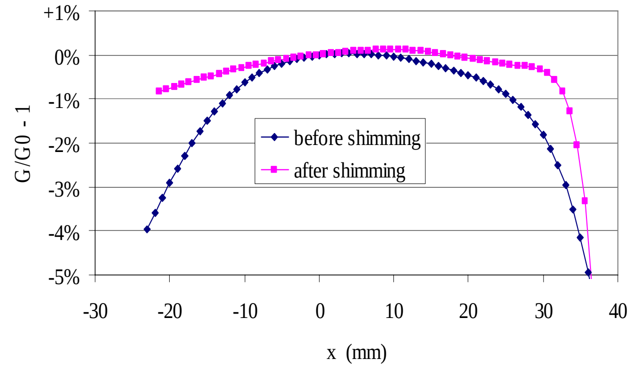

Figure 7: Relative integrated gradient quality of the D magnet before and after shimming; the D's magnetic centre is at -22.6 mm; the F magnet is un-powered.

The pole was adjusted in OPERA to incorporate these shims, using shallow angles instead of 90° corners; the production magnets will be built accordingly.

FURTHER WORK

The pole profiles are now fixed and the production magnets will be built to this geometry. The prototype magnets will be mounted on motorised slides to assess the performance of the slides and to ensure the mechanical forces between the magnets are not too great. Hall probe tests will also be carried out on the complete cell.

CONCLUSIONS

The prototype ring magnets for EMMA have been built and measured. The gradient quality of the D magnet needed improvement; this was achieved by adding shims to the side of each pole. The pole profile of the production magnets have been adjusted to match the changes. The production magnets are now being manufactured and will be completed in September 2008.

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