SUPERSTRONG ADJUSTABLE PERMANENT MAGNET FOR A LINEAR COLLIDER FINAL FOCUS

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Abstract

A superstrong permanent magnet quadrupole (PMQ) is one of the candidates for the final focus lens for the linear collider because of its compactness and low power consumption. The first fabricated prototype of our PMQ achieved a 300T/m superstrong field gradient with ϕ100mm overall magnet radius and ϕ7mm bore radius, but a drawback is its fixed strength. Therefore, a second prototype of PMQ, whose strength is adjustable, was fabricated. Its strength adjustability is based on the "double ring structure", rotating subdivided magnet slices separately.

This second prototype is being tested. Some of the early results are presented.

INTRODUCTION

A 4.45T high magnetic field has been demonstrated with just permanent magnets. It is based on the modified Halbach's configuration, which introduces some saturated iron to enhance the field strength [1,2]. This technique has been applied to a quadrupole to generate a high gradient (see Fig. 1). The first prototype was fabricated and tested [3]. This PMQ, which is compact and strong, is good to use as the final focus lens in a linear collider because the outgoing beam from the interaction point passes very close to the final focus lens (separated by only 7cm).

The remanent field strength of a permanent magnet changes with temperature. NdFeB, which is used for the PMQ has a relatively large temperature coefficient. A special temperature compensation alloy, MS-1, was added to the core to cure this problem. Then the temperature coefficient decreased from -7×10^{-4} to -3×10^{-5} [4,5].

DOUBLE RING STRUCTURE

The final focus lens for the linear collider needs a strength-adjustable quadrupole with 1% adjustment steps. A method for varying the strength is to divide the magnet into sections along the beam axis and rotate the sections separately [3, 4, 5]. Any section is rotated only by 90° so as not to introduce any skew multipoles.

Because mechanical errors in rotation may introduce unwanted skew components and a shift in the magnetic field axis (i.e. the magnetic center where the field is zero), we extended this technique into a "double ring structure" (Fig. 2). The inner region of a PMQ has a larger influence on its field quality in the bore than its outer region. If we split a PMQ into two nested concentric rings and rotate only the outer ring or parts of it, to change the total strength, while the inner ring is fixed, then, we supposed, the skew component would be reduced, and also any shift of the quad's magnetic axis. We confirmed this by calculations and computer modeling [4].

We fabricated a second prototype of a PMQ with a double ring structure. This prototype also has the temperature compensation material. We will make long term measurements to confirm these features.

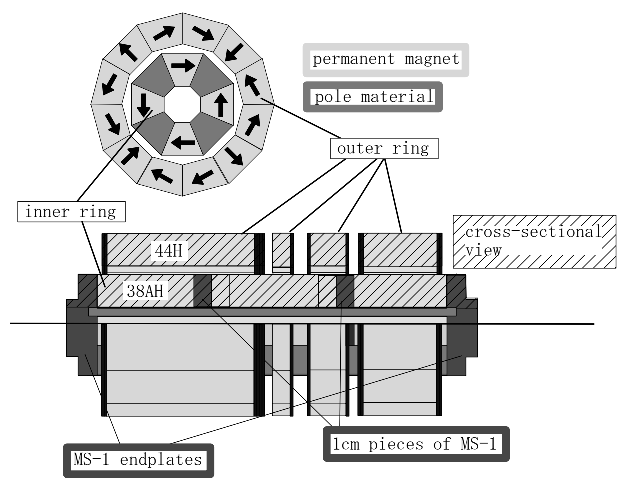

Figure 2: The double ring structure.

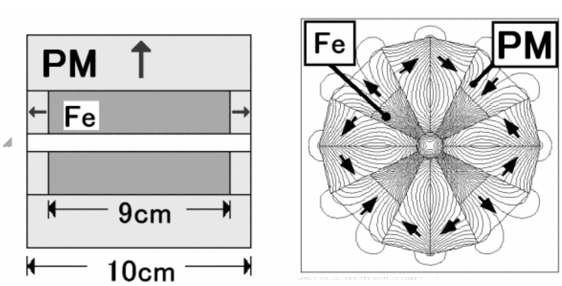

Figure 1: The first prototype of the PMQ.

SECOND PROTOTYPE OF THE PMQ

Figure 3 shows the second prototype of a PMQ, with the "double ring structure" and hence adjustable. The outer rings are rotated by worm gears powered by DC motors [6]. The design parameters are shown in Table 1. The pole material is Permendur. Four poles are welded onto two endplates made of MS-1, which compensates for the NEOMAX strength variation with temperature [4]. Considering that the maximum length of a permanent magnet piece that can be fabricated is about 5cm, three

5cm permanent magnets are installed in each quadrant (see Fig.2). Two 2cm spaces between the 5cm permanent magnets are available for either permanent magnet or MS-1 material. We filled each space with 1cm magnet and 1cm MS-1 material as the initial configuration. Although this configuration has a smaller maximum integrated strength (25.2T) than that filled by all magnets (28T), it can reduce the risk of demagnetization. It also enables us to investigate the overcompensated case.

The second prototype of our PMQ has four outer rings that can be separately rotated from their strong position ("on") to weak position ("off"). Therefore it can generate 16 levels of integrated gradients (see Table 2). It takes less than 1 minute to rotate an outer ring from "on" to "off" and vice versa and these rotations are controlled remotely.

MEASUREMENT

The measurement of the field strength of the adjustable PMQ has been performed with a rotating coil system at SLAC. The measurement set up is shown in Figure 4. The room temperature was kept to 21.7±0.2°C.
We measured its integrated strength at different ring positions.

Integrated Gradient

The adjustable PMQ can generate 16 levels of integrated gradients. When all of the outer rings are switched "on" ("off") the integrated gradient has its maximum (minimum) value. The integrated strength will be measured at 16 combinations of positions (see Table 2) Combination No.1 corresponds to the strongest case and No.16 corresponds to the weakest case. The integrated gradient is designed to change by 1.4T with each step from No.1 to No.16. In a preliminary measurement these 6 positions were measured in the following sequence: 16,1,8,12,14 and 15.

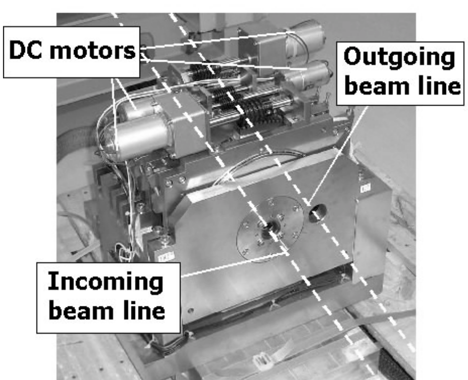

Figure 3: Fabricated 2nd prototype PMQ.

Table 1: Design Parameters

Bore radius	1cm
Inner ring radii	In 1cm out 3cm
Outer ring radii	In 3.3cm out 5cm
Outer ring section length	1cm, 2cm, 4cm, 8cm
Physical length	23cm
Pole material	Permendur
Magnet material(inner ring)	NEOMAX38AH
Magnet material(inner ring)	NEOMAX44H
Integrated gradient(strongest)	25.2T
Integrated gradient(weakest)	4.8T
Int. gradient step size	1.4T

Table 2: 16 cases of positions of the outer rings

No.	8cm	4cm	2cm	1cm	No.	8cm	4cm	2cm	1cm
1	on	on	on	on	9	off	on	on	on
2	on	on	on	off	10	off	on	on	off
3	on	on	off	on	11	off	on	off	on
4	on	on	off	off	12	off	on	off	off
5	on	off	on	on	13	off	off	on	on
6	on	off	on	off	14	off	off	on	off
7	on	off	off	on	15	off	off	off	on
8	on	off	off	off	16	off	off	off	off

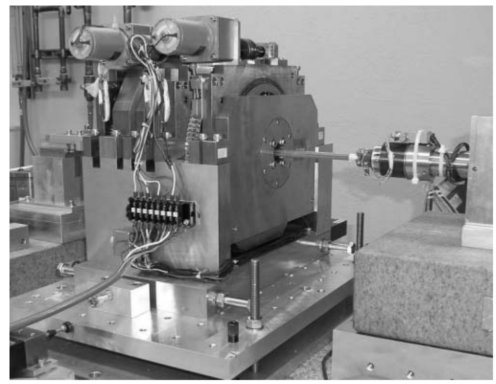

Figure 4: The measurement of PMQ.

PRELIMINARY RESULTS

Some preliminary data is available. Figures 5 and 6 show repeated measurements of integrated strength over several hours in the strongest case and weakest case respectively. Each strength measurement takes about 3 minutes. The strongest and weakest integrated strengths are 24.2T and 3.48T, respectively. The discrepancy between the design value and the measured value is about 5% in the strongest case. The discrepancy of the weakest case is also about 5 % of the strength in the strongest case. We consider that they are not far from the design values.

Figures 5 and 6 also show that the integrated strength of the PMQ changes very slightly with time. These variations are well correlated with the temperature of the magnet. The strength of the strongest case changes by about 10^{-4} T in four hours. That of the weakest case fluctuates about 10^{-3} T over 80 hours of repeated measurements. The effective temperature coefficients of the strongest and weakest case are -4×10^{-4}/°C and 2×10^{-3}/°C. The designed values of the temperature coefficient in the strongest and weakest cases are -1×10^{-4}/°C and 2×10^{-3}/°C, respectively. The effect of the temperature compensation is a little less than the design value. This difference can be explained as following.

The Curie Temperature of MS-1 fluctuates from batch to batch by as much as 20% variation in its saturated magnetic flux density. Whereas the design calculation was performed with the catalogue values of MS-1 parameters.

The "switched-on" length is defined as the summation of the lengths of the outer rings in the strong position. Figure 7 shows the measured strength of six cases at various "switched-on" lengths. The strength is proportional to the cumulative "switched-on" length as expected.

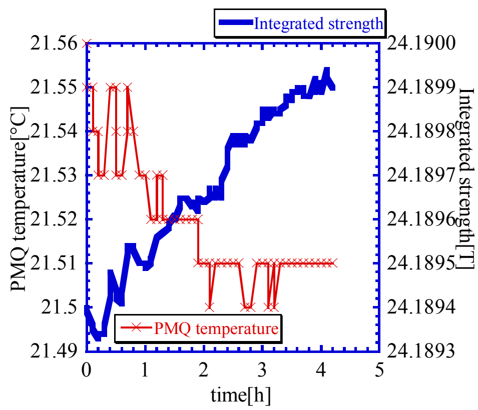

Figure 5: The strongest integrated strength vs time.

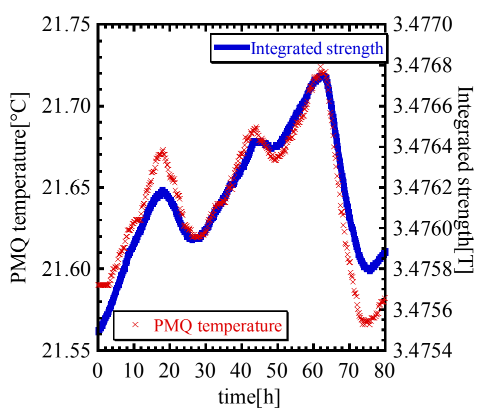

Figure 6: The weakest integrated strength vs time.

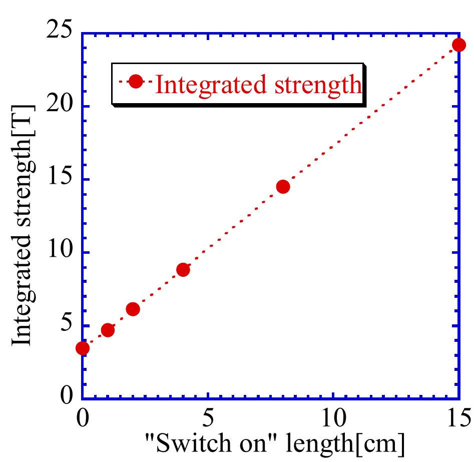

Figure 7: The variation of integrated strength.

CONCLUSIONS

The Integrated Strength

The integrated strength of the strongest case and weakest case of PMQ were 24.2T and 3.48T, respectively. They agree with the calculated values within 5%.

The integrated strength will be increased to its final value by replacing the inner ring with one that is filled with permanent magnet pieces.

Temperature Coefficient

The effective temperature coefficients of strongest and weakest cases were -4×10^{-4}/°C and 2×10^{-3}/°C, respectively. The difference of the temperature coefficient between the strongest case and weakest case comes from the overcompensation of the inner ring.

Strength Adjustability

Figure 7 shows that the integrated strength can be varied in proportion to the "switched on" length. The step size is 1.4T/cm. It agrees with the calculated value well. We will have more measurements to confirm that the PMQ can generate 16 levels of the integrated strength with a 1.4T step between them.

Possible Improvement

The strength of the PMQ can be made further stronger by replacing inner and/or outer ring permanent magnet pieces with stronger ones. The strength can be 5% more when the inner magnet (NEOMAX 38AH) and the outer magnet material (NEOMAX 44H) are replaced by NEOMAX44AH and NEOMAX50BH, respectively.

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