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A Super Strong Permanent Magnet Quadrupole for the Final Focus in a Linear Collider*

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Abstract

A super strong permanent magnet quadrupole (PMQ) was fabricated and tested. It has an integrated strength of 28.5T with overall length of 10 cm and a 7mm bore radius. Two drawbacks should be considered to this NdFeB based PMQ: the negative temperature coefficient of its field strength and its fixed strength. A thermal compensation material was added and tested to cure the first problem. The correct amount was determined to compensate the PMQ's temperature coefficient. The required field variability can be obtained by slicing magnet into pieces along the beamline direction and rotating these slices. But this technique may lead to movement of the magnetic center and introduction of a skew quadrupole component when the strength is varied.

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A SUPER STRONG PERMANENT MAGNET FOR THE FINAL FOCUS QUADRUPOLE IN A LINEAR COLLIDER *

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Abstract

A super strong permanent magnet quadrupole (PMQ) was fabricated and tested. It has an integrated strength of 28.5T with overall length of 10 cm and a 7mm bore radius. Two drawbacks should be considered to this NdFeB based PMQ: the negative temperature coefficient of its field strength and its fixed strength. A thermal compensation material was added and tested to cure the first problem. The correct amount was determined to compensate the PMQ's temperature coefficient. The required field variability can be obtained by slicing the magnet into pieces along the beamline direction and rotating these slices. But this technique may lead to movement of the magnetic center and introduction of a skew quadrupole component when the strength is varied.

1 INTRODUCTION

A dipole magnetic field as high as 4.45T has been demonstrated without superconducting technology [1]. It is based on the modified Halbach configuration [2], which introduces a saturated iron pole to the original configuration to enhance the magnetic strength. This technique was applied to a quadrupole magnet. Fig 1. shows the permanent magnet quadrupole with a modified Halbach configuration. This super strong permanent magnet quadrupole was fabricated and tested. It has an integrated strength of 28.5T with overall length of 10cm and a 7mm bore radius. It agrees with calculated value of 29.7T.

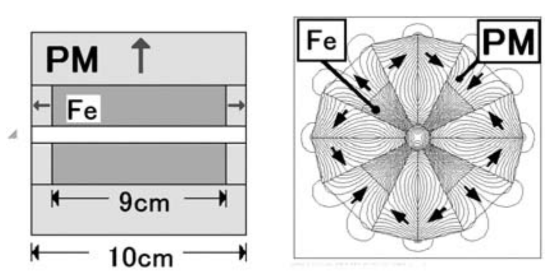

Fig. 1

Two weak points of this design are discussed. One is that the remanent field strength of permanent magnet materials decreases with their temperature rise while that of an electro magnet is fairly stable. Add-on parts using a special thermal compensation alloy were tested on the prototype PMQ.

The Final Focus system of a linear collider needs several quadrupoles with variable focal strength. If the PMQ is sliced along the beam axis, rotation of the slices can change the focal strength.

2 TEMPERATURE COMPENSATION

Materials with large temperature coefficients are widely used to compensate magnetic circuits in watt-hour meters, for instance magnetic flux is shunted by a compensation strip (high coefficient material) in parallel with the pole piece, such as shown in Fig 2. At low temperature, flux density between the pole pieces is reduced because of the shunt with high permeability. When the temperature rises, the field strength of the permanent magnet reduces, while

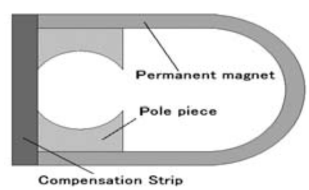

Fig. 2 An example of temperature compensation with compensation material. Compensation strip shunts the flux.

the shunt flux is also reduced. As a result, the flux density between the pole pieces is kept constant.

2.1 Application for the prototype PMQ

This technique can also be applied to the PMQ. MS-1, an alloy of Ni and Fe (made by Sumitomo Special Metal Co., Ltd.), was chosen as the compensation material.

Fig. 3 shows the modified prototype PMQ with temperature compensation parts, designed by calculation with TOSCA. This, however, makes the mechanical length of the PMQ longer and thus the strength per unit length is reduced.

The thickness of MS-1 shown in the left figure of Fig. 3

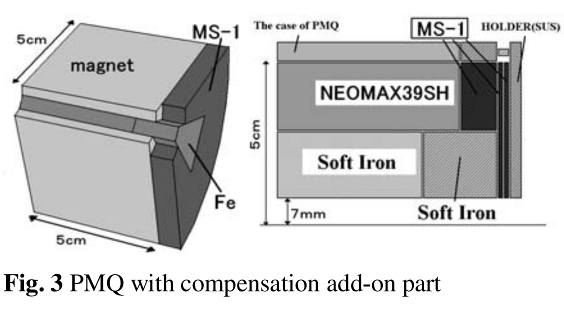

Fig. 3 PMQ with compensation add-on part

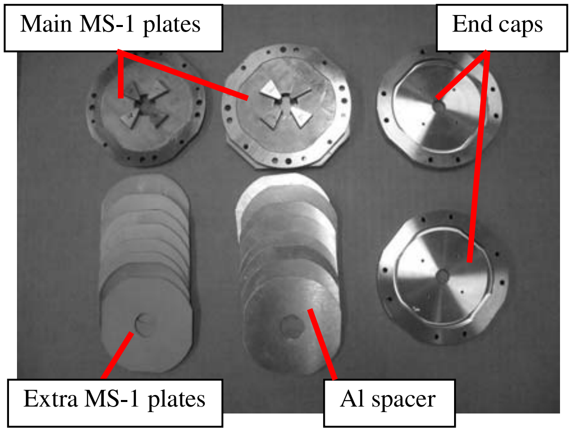

Fig. 4 Temperature compensation parts

is 10mm. The calculation was performed with the nominal B-H curve of MS-1, while the quality of MS-1 actually fluctuates in every lot (up to 20% variation). Thus the main part of MS-1 is designed to be smaller than the optimal size, so that additional plates of MS-1 can be added for adjustment. Fig. 4 shows the fabricated compensation parts. The main plate contains 5 pieces of 1.6mm thick MS-1 plates. Four more 1.6mm thick MS-1 plates can be inserted between the endcap and main plate. If an extra plate isn't needed, Al plates can be added as a non magnetic spacer.

2.2 Measurement results on compensated PMQ

Temperature compensation parts were shipped to SLAC where the PMQ was being measured with a rotating coil system[3]. The PMQ was placed on Al V-blocks. A sheet heater was wound around the body of PMQ, thermocouples were placed near the heater and. on the endcaps. All were wrapped with thermal insulation tape and covered with foam sheet to keep the magnet temperature, once it had been changed, constant and uniform. The temperature of the PMQ was controlled by a sensitive automated temperature controller.

For a typical measurement, the PMQ was heated about 3° C above room temperature and kept there with its strength being measured every 5 minutes for tens of hours.

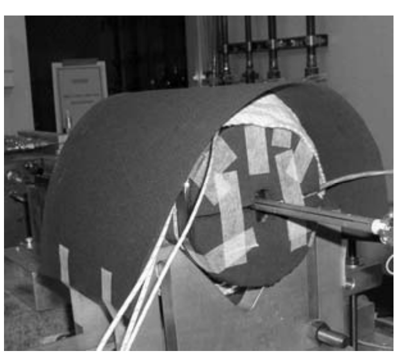

Fig. 5 PMQ, covered with foam sheet, measured with rotating coil[3].

Fig. 6 shows the measured strengths for nearly 120 hours after heating up. Even though the PMQ is covered with thermal insulators, the heater temperature and endcap temperature were still different by about 0.5 degree C after ten hours and we did not have a thermocouple inside the PMQ where the pm pieces are. So we took a simple average of heater temperature and endcap temperature as the temperature of the PMQ to estimate the measured temperature coefficient. Fig. 6 shows it takes more than 60 hours for the integrated strength to settle, which does not agrees with the thermal time constant of the PMQ roughly estimated as 20 minutes. Although the temperature coefficient should be evaluated with the value taken from a stable point, we used strength data at about half day after heat up to prepare figure 7.

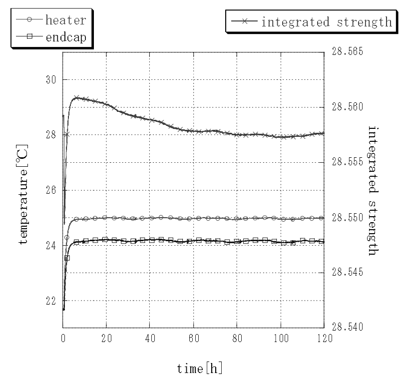

Fig. 6 Measurement of the PMQ with 4 extra MS-1 plates

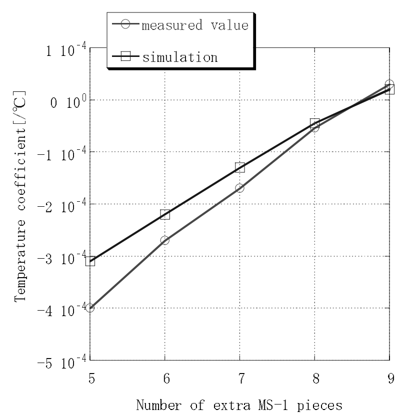

Fig. 7 Measured and calculated values of temperature coefficient with various numbers of MS-1 plates

3 ADJUSTABILITY

The final focus quadrupole of a linear collider needs a variable focal strength with 1% steps. A method for varying the strength is to divide the magnet into sections along the beam axis and rotate the sections contrary to each other [4], [5], which usually introduces unwanted skew components. On the other hand, if the sections rotate only in multiples of 90° around the beam axis then the quad only switches its polarity without any skew component being introduced. If one flips a section that is 0.5% of the full length of PMQ, 1% of the total strength is changed, so that 1% resolution is accomplished.

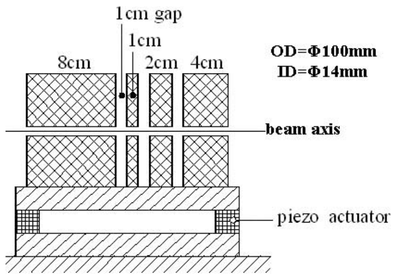

Fig. 8 Strength Adjustable PMQ.

3.1 Double ring structure

The final focus lens of a linear collider is required to have its skew component suppressed. The structure shown in Fig. 8 would directly convert any mechanical errors in rotation to the skew component and a shift of the magnetic axis. In order to reduce these effects, a "double ring structure" is proposed. The inner region of a PMQ has a larger effect on its field quality in the bore than the outer region. If we split a PMQ into two nested rings and rotate only the outer ring or parts of it, to change the total strength, while the inner ring is fixed, then, we suppose the skew component will be reduced, and also any shift of the magnetic axis of quadrupole (see Fig. 9). The resolution becomes high with this structure. This adjustable PMQ needs large torques in rotation because the magnets of the inner ring and outer ring affect each other. The torque was estimated with TOSCA and PANDIRA [5]. Estimated torque values are being accounted for while designing the second, adjustable strength, prototype.

3.2 Skew Component and Shift of Axis

We made some calculations to confirm the above scheme. With the simple structure shown in Fig. 8, an error of 1 degree in the rotation angle results in 1° of skew. With the double ring structure in Fig. 9, 1° of rotational error in the outer ring corresponds to about 0.015° of skew on quadrupole component. In addition, a 1 mm shift of the pm material perpendicular to the beam axis causes 1mm of shift of magnetic center in the simple structure. With the double ring structure, a 1mm of shift of an outer ring corresponds to about 0.1mm of axis shift. Both effects are greatly reduced. This property of a double ring structure eases the mechanical fabrication limitations.

3.3 Adjustable Range

When the step size resolution of the variation is less than 1 %, the collider luminosity can be kept up by adjusting electromagnets located upstream in the beam line. Another requirement is that a beam energy calibration

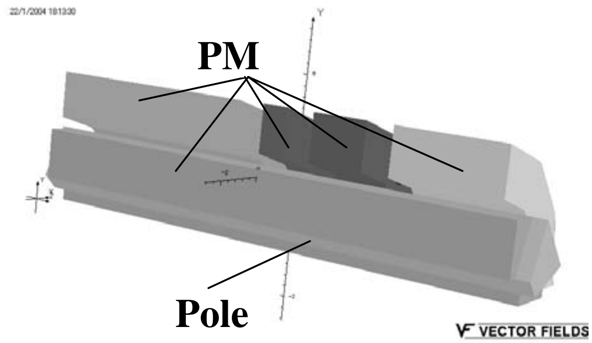

Fig. 9 Double ring structure

process requires the strength to go down to 20 % of its maximum. Finer resolution can be accomplished by reducing the volumes of the outer rings. [4]

4 SUMMARY

The measured ∫Gdl value 28.5T of the prototype PMQ was very high considering its small overall size. It agrees with the calculated value 29.7T with less than 5 % difference.

The first prototype PMQ has had thermal compensation material added and the optimal amount found. The uncompensated temperature coefficient (0.075%/deg C) was reduced to about 1/25th (0.003%/deg C) (see Fig. 7).

A second prototype PMQ with a double ring structure is being fabricated. A double ring structure is good for reducing the effect of errors in mechanical rotation.

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