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Super Strong Permanent Magnet Quadrupole for a Linear Collider[*]

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Abstract

The field strength generated by permanent magnets has been further extended by the introduction of saturated iron. A permanent magnet quadrupole (PMQ) lens with such saturated iron is one of the candidates for the final focus lens for an e^+e^- Linear Collider accelerator, because of its compactness and low power consumption. The first prototype of the PMQ has been fabricated and demonstrated to have an integrated strength of 28.5T with an overall length of 10 cm and a 7mm bore radius. Two drawbacks should be considered: its negative temperature coefficient of field strength and its fixed strength. A thermal compensation material is being tested to cure the first problem. The other problem may be solved by rotating sectioned magnet bricks, but that may lead to movement of the magnetic center and introduction of multipoles beyond some strict requirements.

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Super Strong Permanent Magnet Quadrupole for a Linear Collider

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Abstract—The field strength generated by permanent magnets has been further extended by introduction of saturated iron. A permanent magnet quadrupole (PMQ) lens with such saturated iron is one of the candidates for the final focus lens for an e^+e^- Linear Collider accelerator, because of its compactness and low power consumption. The first prototype of the PMQ has been fabricated and demonstrated to have an integrated strength of 28.5T with an overall length of 10 cm and a 7mm bore radius.

Two drawbacks should be considered: its negative temperature coefficient of field strength and its fixed strength. A thermal compensation material is being tested to cure the first problem. The other problem may be solved by rotating sectioned magnet bricks, but that may lead to movement of the magnetic center and introduction of multipoles beyond some strict requirements.

I. INTRODUCTION

A magnetic field as high as 4.45T has been demonstrated with a permanent magnet dipole. It is based on the modified Halbach's magnet configuration [1]. This makes use of saturated iron to enhance the magnetic field strength.

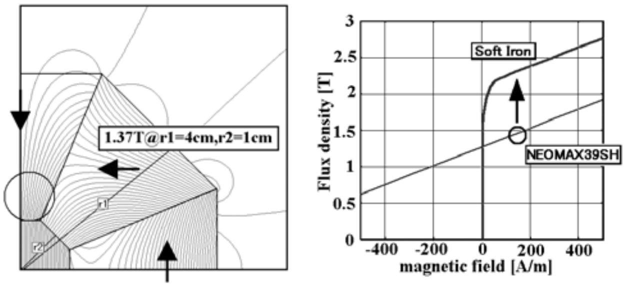
The same technique can be used in a permanent magnet quadrupole (PMQ) to further increase the field gradient over that achievable by a room temperature electromagnet. This feature may have an advantage in an e^+e^- linear collider application where an overall small magnet but a rather strong magnetic field gradient is needed. A prototype of the PMQ with such saturated iron has been designed, fabricated and measured. It produces a measured $\int$Gdl value of 28.5T with an overall length of 10cm and bore radius of 7 mm.

Two weak points are discussed. One is that the remanent field strength of permanent magnet materials decreases with temperature rise while that of electromagnets is fairly stable. Add-on parts using a thermal compensation alloy for the prototype PMQ are designed and planned to be tested at SLAC.

The Final Focus System of a linear collider needs a quadrupole with variable focal strength. Rotation of PMQ sections divided along the beam axis can change the focal strength, but maybe at the expense of field quality.

II. MODIFIED HALBACH CONFIGURATION FOR PMQ

With strong permanent magnet material NEOMAX made from NdFeB (by Sumitomo Special Metal Co, Ltd), a super strong permanent dipole magnet was fabricated with a modified Halbach configuration [2]. It makes good use of saturated iron. Fig. 1(b) shows the comparison of the B-H curve of soft iron and permanent magnet material. The circled region signifies the operating point of the permanent magnet. The flux density of simple iron is stronger than a permanent magnet at this working point. Fig. 2 shows the modified Halbach dipole magnet, in which the appropriate part of the permanent magnet is replaced by soft iron; the soft iron increases the flux density and hence the field in the gap.



(a) (b)

Fig. 1 (a): Halbach's dipole magnet generates 1.37T in the bore. (b): B-H curves of iron and permanent magnet. Marked region in the right figure is the operating point at the circled region in **Fig. 1**(a). At the operating point, soft iron is stronger than permanent magnet.

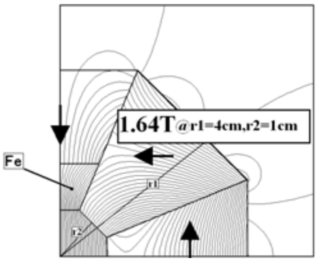


Fig. 2 Dipole with soft iron

This technique is applicable to a PMQ. Fig. 3 shows the

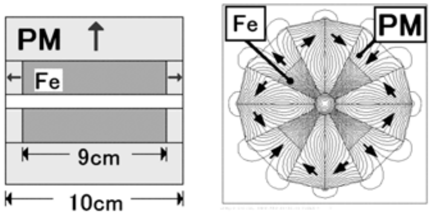


Fig. 3 Outline of the designed PMQ

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outline of the PMQ designed with modified Halbach configuration whose bore radius is about 7 mm. The left figure shows the cross section parallel to the beam axis. The right figure shows the cross sectional view perpendicular to the beam axis together with the flux plot. Both ends of the iron poles are capped by permanent magnet pieces, which push the flux in and reduce the fringing field.

III. PERFORMANCE OF THE PROTOTYPE

Fig. 4 shows a photo of the prototype PMQ. The performance of this prototype was tested at SLAC with rotating measuring coils [3]. Its integrated field gradient was 28.5T. Field harmonics of the integrated flux as a percentage of the quad component at 4 mm radius are shown in Fig. 5. Although the prototype has four fold symmetry, components except n=2, 6, 10…, are larger than expected. Because such higher order harmonics are sensitive to asymmetries in the wedges' magnetizing directions the differences seem to come from manufacturing problems.

IV. THERMAL COMPENSATION

The field strength of the PMQ decreases with temperature rise; because NEOMAX has a relatively large temperature coefficient (about $-1.1\text{x}10^{-3}$ K^{-1} at room temperature) because of its relatively low Curie temperature. On the other hand, the strength of an electromagnet quadrupole is stable with temperature, which is mostly dependent on current except for the expansion rate of iron which is less than 10^{-5} K^{-1}. Thermal compensation is needed for any permanent magnet in a linear collider.

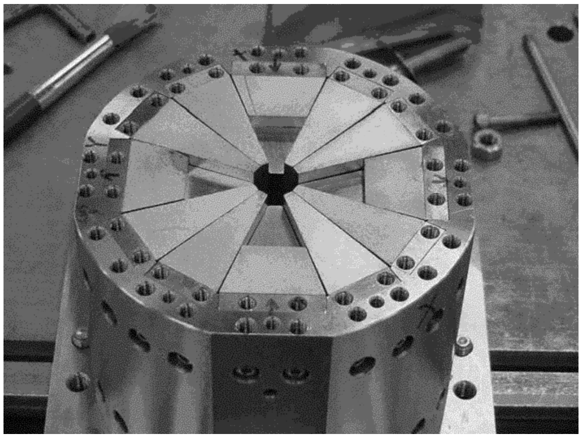


Fig. 4 The prototype of PMQ

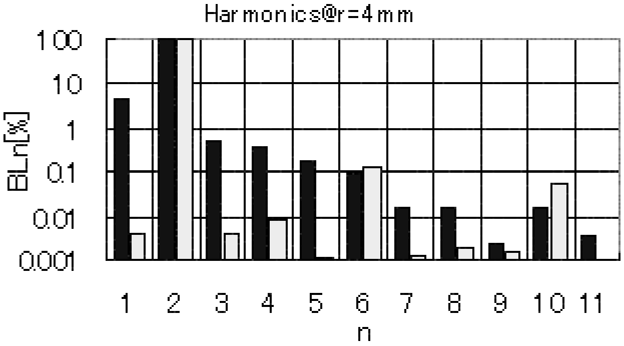


Fig. 5 Field harmonics of prototype. Left, darker, bars: measured value. Right bars: calculated value.

A. The principle of thermal compensation

Materials with large temperature coefficients are widely used to compensate magnetic circuits in watt-hour meters, for instanceFig. 6 shows an example of temperature compensation with compensation material. Magnetic flux is shunted by a compensation strip (high coefficient material) in parallel with the pole piece. 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 the shunt flux is also reduced. As a result, the flux density between the pole pieces is kept constant.

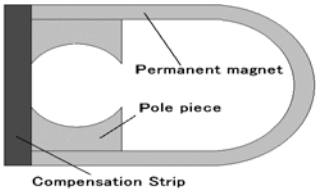


Fig. 6 An example of temperature compensation with compensation material. Compensation strip shunts the flux.

B. Application for the prototype of 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. The variation of the saturated flux density of MS-1 is linear around the room temperature (-0.6mT/℃ (see Fig. 7)) .The variation of the remanent flux density of NEOMAX is about -0.13mT/° C.The needed volume of MS-1 is about 20% of that of the permanent magnet in PMQ.

Because of MS-1's large temperature coefficient compared to the NEOMAX, the temperature coefficient of the prototype PMQ can effectively be compensated with a slight reduction of field gradient (about -5%). Fig. 8 shows the modified prototype PMQ with temperature compensation parts, designed by calculation with TOSCA. This, however, makes the mechanical

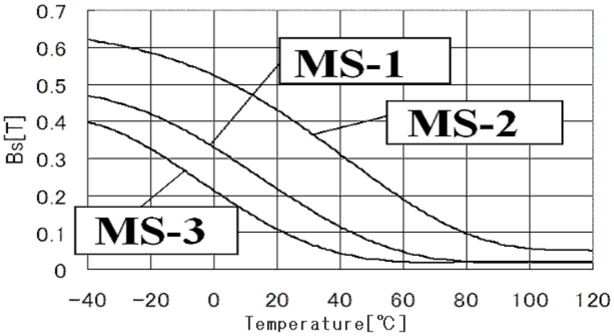


Fig. 7 Thermal performance of various MS alloys

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. 8 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.

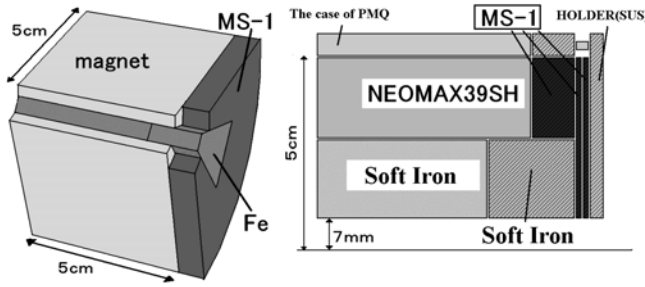


Fig. 8 PMQ with compensation part

V. ADJUSTABILITY OF TOTAL STRENGTH

The final focus quadrupole of a linear collider needs 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], 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. 9 shows a unit where a 20cm PMQ is divided into 4 sections of shorter PMQ's. A 2m length final focus quadrupole will have ten of these units.

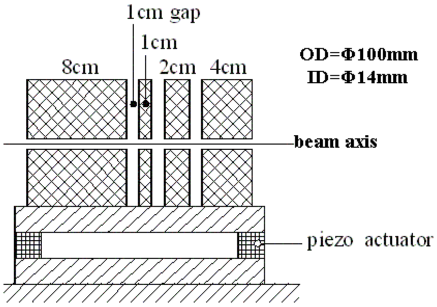


Fig. 9 Binary switching structure. Each PMQ can be rotated 90deg around beam axis.

VI. DOUBLE RING STRUCTURE

The final focus lens of a linear collider is required to have its skew component suppressed. The structure shown in Fig. 9 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 the any shift of the magnetic axis of quadrupole (see Fig. 10). The resolution becomes high with this structure.

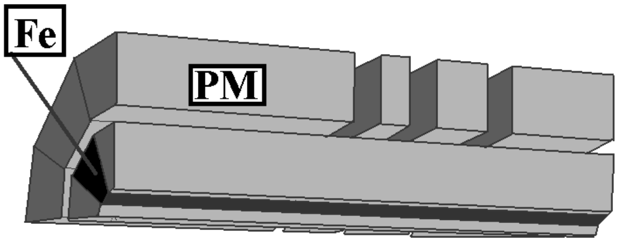


Fig. 10 Double ring structure with 8cm,1cm,2cm,4cm long pieces of outer ring of PMQ with 1cm gaps between. The length of the inner ring is 20cm. The outer radius of the outer ring is 5cm. the inner radius of the outer ring is 2.8cm. Outer radius of inner ring is 2.5cm. Bore radius is 7mm.

A. *Skew Component and Shift of Axis*

We made some calculations to confirm the above scheme. With the simple structure shown in Fig. 9, an error of 1 degree in the rotation angle results in 1° of skew. With the double ring structure in Fig. 10, 1° of rotational error in the outer ring corresponds to about 0.03° 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 0.03mm of axis shift. Both effects are reduced to about 1/30th.This property of a double ring structure eases the mechanical limitations.

B. *Adjustable Range*

When the step size resolution of the variation is less than 1 %, the luminosity can be kept up by adjusting electromagnets located upstream in the beam line. Another requirement is that a beam energy calibration process requires the strength can go down to 20 % of its maximum. Finer resolution can be accomplished by reducing the volumes of the outer rings. Table I shows variation range for different outer rings. In Table I, sizes written like 3.5-3.8, stand for 3.8cm of inner corner radius of outer ring and 3.5cm of outer corner radius of inner ring. The gap between inner ring and outer ring is kept constant. The thickness of the outer ring does not affect the maximum strength much, while a thinner outer ring has smaller variation range.

Size [cm]	Maximum field strength (T/mm)	Minimum field strength (% of maximum)	Torque [Nm/cm]
3.5-3.8	0.292	44.1	7.45
3-3.3	0.289	30.1	7.33
2.5-2.8	0.290	8.8	6.30

Table I Torque and range of variable strength.

C. *Torque estimation*

Rotating slices of the outer ring against the fixed inner ring requires a large torque. Table I also shows torques for different outer rings, they are in the values per 1cm of length, obtained from the difference of stored energy between 45° and 46°.

because maximum torque occurs around 45° of rotation (See Fig. 11). The thickness of the outer ring slices does not affect the torque much.

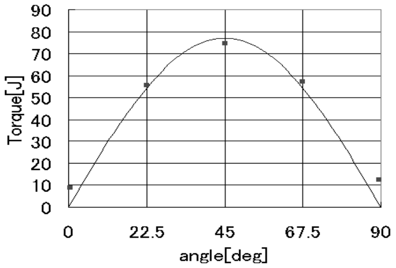


Fig. 11 Torque as a function of the rotation angle.

D. Strength Variation

Fig. 12 shows the ∫Gdl values versus the length switched on the double ring structure (Fig. 10) calculated by TOSCA. ∫Gdl value is proportional to the flipped length.

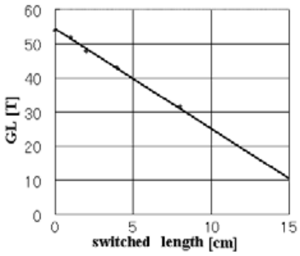


Fig. 12 GL integral value as a function of length flipped

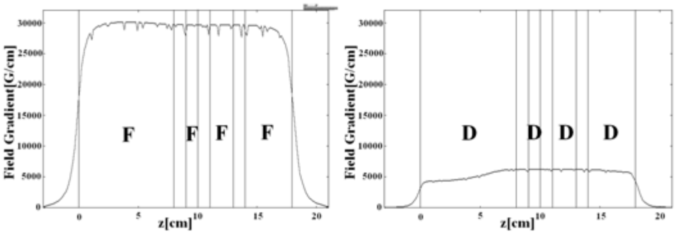
VII. CONCLUSIONS

The measured ∫Gdl value of the prototype PMQ was very high. Even using thermal compensation material and dividing up the PMQ , which reduces its focal strength, nevertheless a very strong PMQ can be achieved.

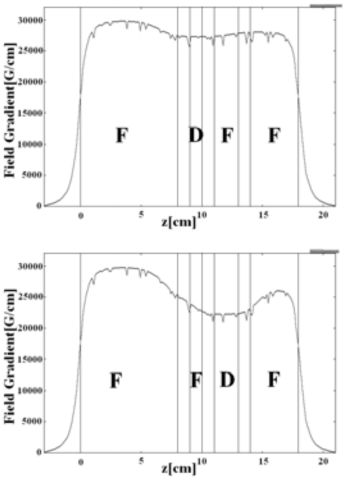
MS-1 is selected because its coefficient is linear over a wide range at room temperature. But the ambient temperature of the final focus lens may fluctuate as little as 2 ℃. So a more effective material may be available.

Thermal compensation has been worked out for the first prototype PMQ. A double ring structure would need another set of compensation pieces, because its structure changes its situation by rotation. Both outer ring and inner ring will need to be compensated independently. This is now under investigation. Torques of rotation were calculated with 2D simulation by PANDIRA, a 3D simulation can check the more complicated situation. It is under investigation.

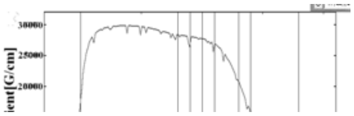
Fig. 13 shows the field gradients as functions of the axial coordinate for various configurations in the double ring structure. The ∫Gdl value is proportional to the switched length (Fig. 12) The mean position of the lens moves along the axis when the slices are switched. Such an effect has to be considered when we adjust the strength of each unit from the point of view of beam optics.



a) 0 cm switched **b)** 15cm switched



c) 1 cm switched **d)** 2cm switched



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