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A Superstrong Adjustable 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.

The final focus quadrupole of a linear collider needs a variable focal length. This 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. A "double ring structure" can ease these effects.

A second prototype PMQ, containing thermal compensation materials and with a double ring structure, has been fabricated. Worm gear is selected as the mechanical rotating scheme because the double ring structure needs a large torque to rotate magnets. The structure of the second prototype PMQ is shown.

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

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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. Fabricated super strong permanent magnet quadrupole was 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.

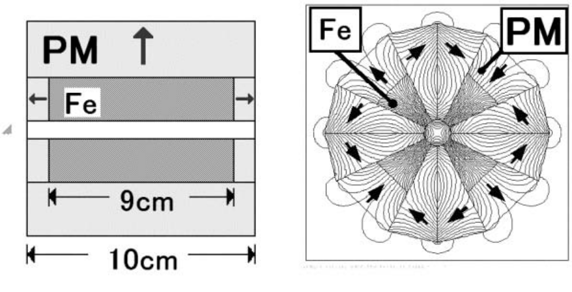

Fig. 1 Modified Halbach Quadrupole

the remanent field strength of permanent magnet materials decreases with their temperature rise while that of an electromagnet is fairly stable. Add-on parts using a special thermal compensation alloy were already tested on our first prototype PMQ [5], this technique has also been applied to our second prototype.

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 separately [3,4], which usually introduces unwanted skew components. On the other hand, if the sections rotate only in 90° around the beam axis, only the polarity of the sections are switched without any skew component. 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.

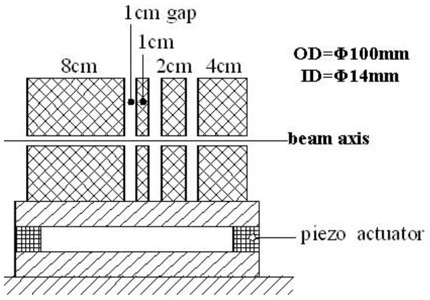

Fig. 2 Strength Adjustable PMQ.

Double ring structure

The final focus lens of a linear collider is required to have its skew component suppressed. The structure shown in Fig.2 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 influence 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 supposed, the skew component would be reduced, and also any shift of the quad’s magnetic axis (See figure 3). We confirmed this by calculations and computer modeling [5].

The resolution becomes high with this structure. This adjustable PMQ needs large rotational torques to move the rings because the permanent magnets of the inner ring and outer ring affect each other. The torques were estimated with TOSCA and PANDIRA. Estimated torque values were accounted for designing the mechanics of our second, adjustable strength, prototype.

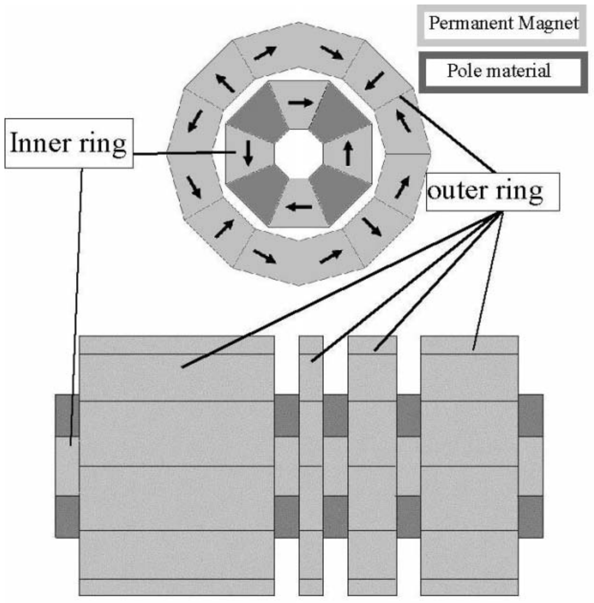

Fig. 3 The double ring structure

FABRICATION OF 2ND PROTOTYPE

A second prototype PMQ has been fabricated to test the double ring structure. Table I shows the design parameters of this prototype determined by calculation.

On this structure, the largest torque is about 100N-m for the rotation of the 8cm parts of the outer ring. That means the rotation scheme must be able to deal with large torques. A worm gear was selected as the rotation scheme. This is because worm gears don’t need a large space in spite of producing a large torque.

Fig.4 is a photo of the fabricated adjustable prototype PMQ. There is an another hole at the side of the incoming beam hole. This is the outgoing beam hole of the linear collider. Crossing angle at the interaction point (IP) is 20mrad on NLC. The distance between the edge of final focus quadrupole and IP is about 3.5m. Therefore there must be a beam hole at 7cm side of the incoming beam hole.

Table I Design Parameters

Bore radius	1.0cm
Inner ring radii	In 1.0cm out 3.0cm
Outer ring radii	In 3.3cm out 5.0cm
Outer ring section lengths	1.0,2.0,4.0,8.0cm
Overall effective length	20.0cm
Pole material	Permendur
Magnet material(inner ring)	NEOMAX38AH
Magnet material(outer ring)	NEOMAX44H
Integrated gradient(max)	33.4T
Integrated gradient(min)	9.8 T
Int. gradient step size	1.6 T

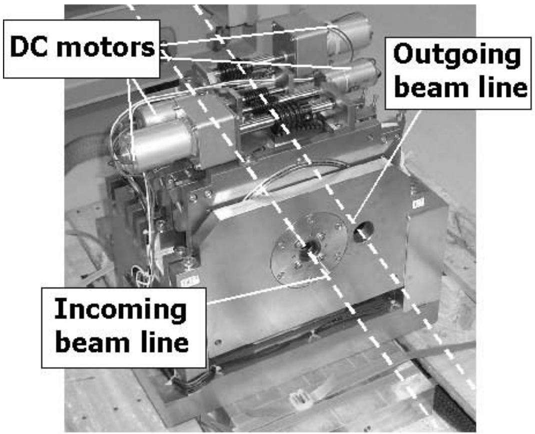

Fig. 4 Fabricated 2nd prototype PMQ

Inner ring structure

Fig.5 shows the inner ring structure. The structure is supported by Vanadium Permendur poles and MS-1, a thermal compensation material. Magnet pieces are attached on the Permendur with glue. NEOMAX38AH was selected for the inner ring magnets because it has very high intrinsic coercive force (iH_c, about 25kOe). The reverse magnetic field is higher than 20kOe at the severe region of inner ring in TOSCA and PANDIRA simulation. Therefore inner ring must have enough high iH_c magnets to avoid being demagnetized.

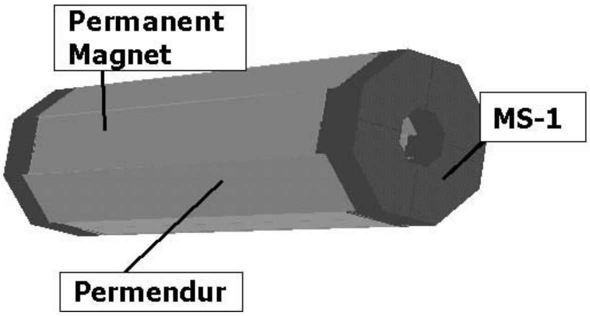

Fig. 5 Inner ring structure:4 pieces of permendur and 2 pieces of MS-1 support this structure.

Outer ring structure

The outer ring of magnets is attached to the inside of a cylindrical SUS cover (see Fig 6). The SUS cover is inserted in a SUS case, supported by the bearing to be rotated. The mechanical accuracy of the SUS plate to be attached on the base plate guarantees the axes of the 4 outer rings will be coincident within required tolerances.

NEOMAX44H was selected as the outer ring magnet material because it has high remanent flux density. The outer ring material does not have to have high iH_C because the reverse magnetic field isn’t high in outer rings in the TOSCA and PANDIRA simulation.

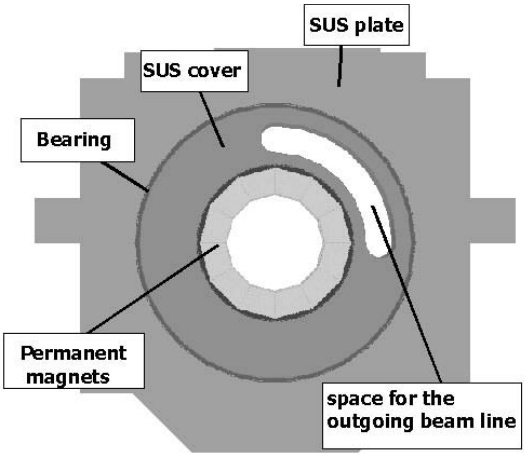

Fig. 6 Cross section showing outer ring and cover

Construction of the whole PMQ

The inner ring is fixed on the SUS base plate. Each of outer rings is inserted in the SUS case which is fixed on the base plate. Base plate was made carefully to accurately keep the outer ring and inner ring in their right places when the inner ring and SUS covers are fixed in their correct positions on the base plate. The four pieces of outer rings are positioned on the same axis accurately. Plastic retainers with small ceramic balls are put between the outer rings to keep their magnetic axes parallel to that of the inner ring. All of the ceramic balls are accurately the same size. They keep the outer rings parallel to each other, then the axes of these rings are bound to be parallel.

All of the effort is to accomplish the accuracy of the position of axis better than 20 μm and the angle of the axis better than 100μrad. The result is being measured.

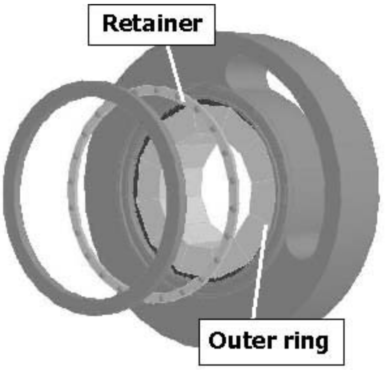

Fig. 7 Retainer with ceramic balls .
Left: Plastic retainer with ceramic balls.
Right: Retainer is put between two outer rings.
Worm gear material

Worm gear scheme

Outer rings are rotated by worm gears. Each spur gear is fixed on each SUS case of the outer rings. Worm gears are attached to motors fixed on the base plate. Three points are considered in deciding the materials of the gears. The first is that gears must be made of strong material to rotate against the large torque. The second is that the spur gears must be made of a non-magnetic material because they cover the region near the bore. The last is that materials for spur-worm pair must be chosen to have enough abrasion resistance. Large torques may cause the wearing away of gear materials where they touch each other. Aluminium bronze was selected for the spur gears according to these three points. Then the worm gear material was chosen to be steel.

Stopping angle

Each of worm gears are rotated by a DC motor. A mechanical stopper is attached on the SUS plate of an outer ring to stop the rotation when an outer ring has rotated 90° . Then a motor control system detects the overload of the motor and shut the current. Each stopper is finely adjusted so as to make a deliberate 90° rotation.

DISCUSSION

The material of the worm gears could not be a magnetic material. TOSCA and PANDIRA calculations tell us that if the spur gear is made of steel, the shift of the magnetic axis is a few μm.

The properties of the permanent magnet materials change with time. The magnet can be stabilized by heating it to a temperature well above its operating temperature for a few hours. This process speeds up the initial aging and slows down the rate of change thereafter [6,7]. The outer ring is heated to 40°C and Inner ring is heated to 60°C. Their field gradients were measured before and after the heating process. The measurement is performed with the accuracy of 1%. Their properties changed less than the accuracy of the measurement.

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