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

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Abstract

A permanent magnet quadrupole (PMQ) with variable strength was fabricated for a feasibility study for its use as the final focus lens in a linear collider. An over 120T/m field gradient over a bore diameter of 20mm was achieved by the introduction of saturated iron and a "double ring structure". The integrated gradient was 24T with 20cm length and the outer magnet diameter was ø100 mm. A recent change is to raise the absolute field gradient further by reducing the bore diameter down to ø15mm. This paper describes the modification and the variable PMQ from the viewpoint of linear collider final focus application.

INTRODUCTION

A permanent magnet quadrupole (PMQ) is one of the candidates for the final focus lens in a linear collider. Halbach configurations [1] are known to generate strong magnetic fields. The strength was found to be increased further by the introduction of saturated iron (so called extended Halbach configuration) and a 4.45T dipole magnet was demonstrated without superconducting technology [2]. A PMQ with this technique was fabricated and demonstrated an integrated field gradient of 28.5 T, where the length, bore and outer diameters are 10cm, ø14mm and ø13cm, respectively [3]. After the demonstration of a fixed strength PMQ, a variable PMQ was designed and fabricated.

VARIABLE PMQ PROTOTYPE

The variable PMQ uses the "double ring structure"; the PMQ is split into two nested rings; the outer ring is sliced along the beam line into four parts and is rotated to change the strength (see Figure 1)[4,5,6,7,8]. It produced over a 120T/m field strength and achieved 24T integrated gradient with ø20 mm bore diameter, 100 mm outer magnet diameter and 20cm pole length. The integrated strength of the PMQ was adjustable in 1.4T steps. Because the inner ring is fixed and only the outer ring is switched between zero and 90-degree rotation angles, the magnetic center movement is less sensitive to the mechanical error. The skew components are suppressed because of the binary rotation angles (there is no source of skew components for a perfectly symmetric case). The large temperature coefficient (~ -10^{-3}/°C) in remanent magnetic field (B_r) of magnet material NdBFe is compensated by putting MS alloy materials [5,6]. The structure of inner ring is shown in Figure 2. The four Vanadium Permendur poles are welded to MS-1 (a thermal compensation material) endplates. The prototype has two beam holes: one with the quadrupole field for incoming beam and the other with a low stray field for outgoing beam (see Figure 3). The assumed crossing

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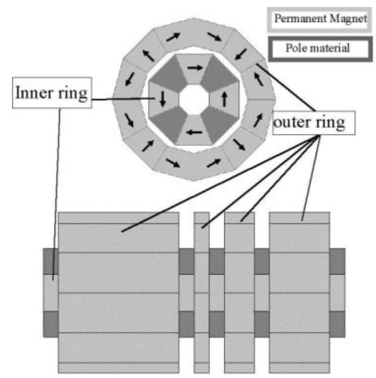

Figure 1: The double ring structure

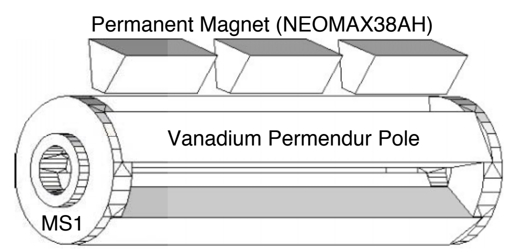

Figure 2: Inner ring structure:4 pieces of Permendur pole pieces are supported by two MS-1 endplates. Three 50 mm long bricks are inserted in a quadrant between the pole pieces. Two 20 mm long MS1 blocks fill the space between the bricks. These are glued to the poles.

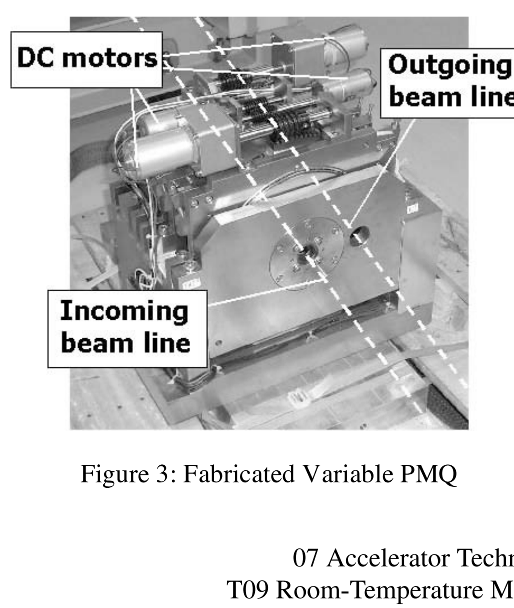

Figure 3: Fabricated Variable PMQ

angle at the IP was 20 mrad and the distance between the two holes is 70mm. The distance between the edge of final focus quadrupole and IP (L*) is 3.5m. Although the net diameter of the outer magnet is only ø10cm, this extra hole and the rotation mechanism make the external form three times large (see Figure 4). A second prototype model, to be designed after the decision of the crossing angle and L* will have a smaller profile. Table I summarizes the fabricated PMQ data and actual magnetic center behavior.

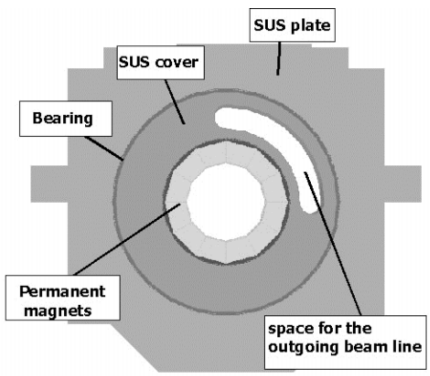

Figure 4: Cross section showing outer ring and cover

Table 1: Variable PMQ summary

Bore Diameter		ø20mm
Inner Ring Diameters		ø 20 – ø 60 mm
Outer Ring Diameters		ø 66 – ø100 mm
Outer ring lengths		10, 20, 40, 80 mm
Pole Material		Permendur
Pole Length		200 mm
Physical Length		230 mm
Magnet Material (inner)		NEOMAX38AH
Magnet Material (outer)		NEOMAX44H
Integrated Gradient (max)		24.2 T
Integrated Gradient (min)		3.47 T
Integ. Grad. Step Size		1.4 T
Number of Steps		16
Magnetic Center Reproducibility	Weak side	< 3 μm
	Strong side	< 0.1 μm
Mag. Cent. Shift (shim effect)	Before	< 30 μm
	After	< 10 μm

CONSIDERATIONS FOR FINAL FOCUS

Some issues concerning using a PMQ for a final focus lens are discussed in this section.

Crossing Angle

The choice of the ILC crossing angle is being discussed extensively. The probable crossing angles are 0, 2 and 20 mrad for the time being. The PMQ can be adapted to almost any crossing angle by modifying the configuration of the inner magnet. Figure 5 shows schematic views for various crossing angles and Table II shows corresponding magnet parameters. The bore diameters are assumed to be ø20mm. This value may be revised according to optics requirements such as background radiation from the IP.

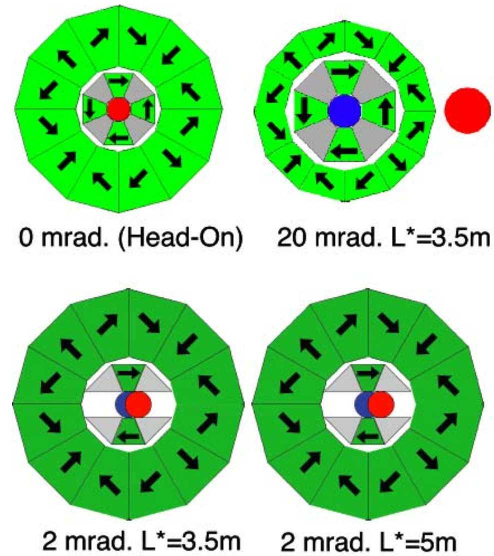

Figure 5: Inner magnet configurations for crossing angles. Blue and red dots denote the location of the incoming and outgoing beam, respectively.

Table 2: PMQ parameters for various crossing angles.

Crossing angle [mrad]	0	2	20
Outer Diam. [mm]	180	180	100
Max. Gradient [T/m]	18 0	130	120
Min. Gradient [T/m]	-20	-60	8

Solenoid Field Effect

The effect of the external axial magnetic field that is generated by superconducting solenoid coils of a detector is estimated (see Figure 6). Although the magnet poles are supposed to be highly saturated, the axial field has big influence on the integrated strength. This is because the axial field is perpendicular to the quadrupole field (rotation of magnetization) and the pole pieces are long in axial direction (form factor). This effect may be reduced by introduction of anisotropy in the pole piece material. An anti-solenoid coil, however, would be needed together with a magnetic field shield even if such anisotropic material is available, because the magnetic saturation

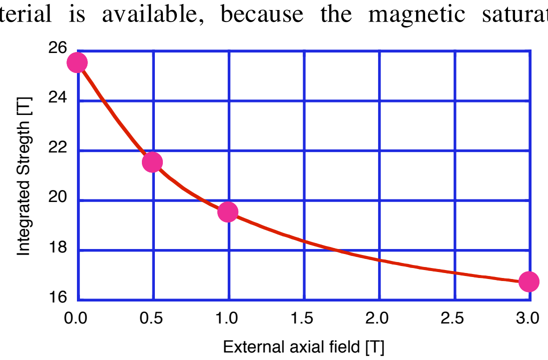

Figure 6: Effect of external axial magnetic field on the PMQ.

level changes with the adjusted field value of the PMQ. This axial magnetic field canceller also should ease the design of the optics of the final focus to the IP.

Radiation Damage

Some information on radiation damage is available [9,10]. According to the references, PM materials with higher iH_c seem resistant to the demagnetization effect. Since information on radiation doses at the final focus system is very limited, it is not straightforward to estimate the damage. If we assume neutron flux rate of 10^5 n.cm^2/s [11], one month continuous operation may cause 0.01 % decrease in field strength. Since this change is very slow, a feedback system could compensate for it.

RECENT WORK

We are working to demonstrate a higher field gradient by reducing the bore size from ø20mm down to ø15mm. We have changed the magnet material from NEOMAX38AH to NEOMAX32AH because the inner ring must have enough high iH_c magnets to not be demagnetized. In PANDIRA and TOSCA simulations the reverse magnetic field at the inner magnet surface of the first prototype was higher than 20kOe at the severe region of inner ring. Therefore NEOMAX38AH was selected for the inner ring bricks of the first prototype because it has high intrinsic coercive force (iH_c, about 25kOe). When we reduce the bore size, the reverse magnetic field increases and the magnet material has to be changed to have even higher iH_c. NEOMAX32AH, which has iH_c of 33kOe, was selected. The amount of MS-1 material was adjusted by measuring temperature coefficient of the inner ring itself before its installation into the outer ring. 2.6mm MS-1 sheets in total are inserted into each of the 20mm spaces between the bricks. Figure 7 is a photo taken during the adjustment. The measurement of the assembled system with a new rotating coil system is under preparation.

DISCUSSIONS

Permanent magnet systems can have fairly strong field gradients with less power consumption for the ring

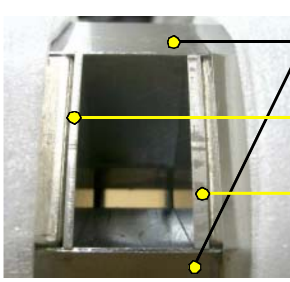

Figure 7: 1 mm (left) and 1.6 mm (right) MS-1 trapezoidal plates are seen in a 2cm space between magnets (during the adjustment). Permendur pole pieces run horizontally. Plastic foam sheets are wound around the magnet sections (left and right most edges of the picture).

rotation (temperature control systems such as air conditioning may be required, which would be needed in any case). This feature becomes evident when the number of poles increases. For example, a permanent magnet octupole can have higher field gradient than in a conventional style: the magnetic field at the bore radius can be 2T; such a magnet may be used for manipulating beam halo. This option is under discussion.

In addition to the optics for the incoming beam, the outgoing beam optics are also important. PMQs may be also applicable to the extraction system.

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