Permanent Magnet Final Quad

Y. Iwashita[1], T. Okugi[2], T. Tauchi[2], T. Omori[2], K. Kuroda[2], H. Yamamoto[3], M. Kumada[4]

1 – Kyoto University – Institute for Chemical Research, Gokanosho, Uji, Kyoto 611-0011 – Japan
2 – KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801 – Japan
3 – Tohoku University – Graduate School of Science Research Center for Neutrino Science, 6-3 Aoba, Aramaki, Aoba-ku, Sendai-shi 980-8578 – Japan
4 – National Institution of Radiological Sciences, 4-9-1, Anagawa, Inage-ku, Chiba, 263-8555 – Japan

A quadrupole magnet for a final focus doublet of a linear collider made of permanent magnets has been investigated. The advantages of a permanent magnet quadrupole as a final focus quadrupole magnet would be its vibration free property together with its compactness. In order to make full use of these properties in a beamline strength adjustability has to be added. Current activities and future plans for R&D are described after a short history is presented.

1 Short History of the R&D

The series of R&D tasks were started from JFY (Japanese Fiscal Year) 2002 fllowing approval of the program. A "Super Strong Permanent Magnet" scheme was utilized in the fabrication of magnets during this program. This is a so called extended Halbach configuration that enhances the field strength generated by use of soft magnetic materials such as permedur at the pole regions. A fixed strength Permanent Magnet Quadrupole (PMQ) was fabricated in the first FY, which achieved an integrated strength of 28.5T in 14mm bore diameter, where the outer diameter and the length were 130mm and 100mm, respectively (see Figure 1). The peak field gradient corresponds to 290T/m [**2**].

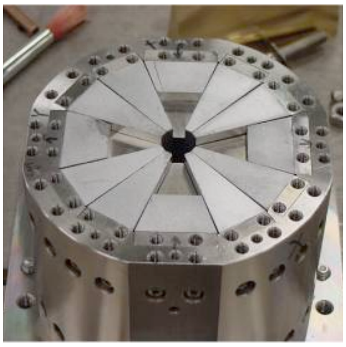

Figure 1 First prototype

A variable type PMQ was fabricated in FY2003, which uses the double ring structure (see Figure 2). The PMQ was divided into two nested rings with a rotatable outer ring while the inner ring is fixed. The rotation angle was restricted to only 0° and 90° to eliminate the skew component, which must be highly inhibited in Final Focus system in ILC. The outer part is further split lengthwise into four rings in a binary manner. It was measured in the next year at SLAC and found that it achieved integrated strength of from 3.47T to 24.4T with 1.4T steps at 20mm bore diameter (see Figure 3) [3,4]. FY2005

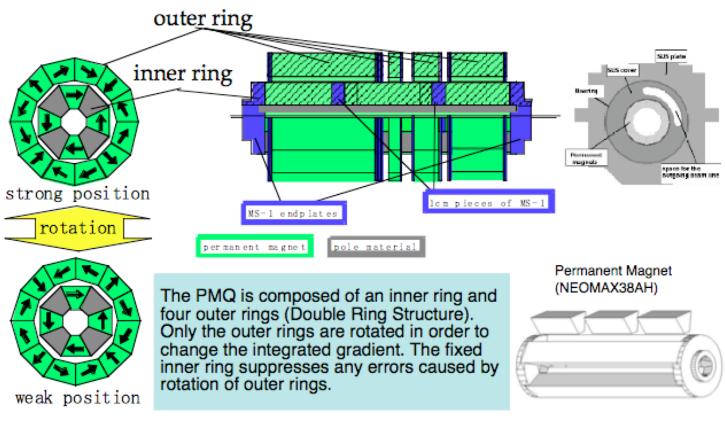

Figure 2 The double ring structure

was the last year of the first program and a minor modification was made to the second model to demonstrate a higher gradient by reducing the bore radius.

From FY2006 a subsequent program was approved (18204023(2006)), which includes a Permanent Magnet Sextupole (PMSx) for focusing of cold neutron beams. From this year a study of higher multipole field generation by permanent magnets is started, such as sextupoles and octupoles. Compact strong octupoles may be useful for beam tail folding. A PMSx that can modulate its strength at 25Hz was fabricated in the first FY (see Figure 4). The frequency corresponds to that of the shortly coming pulsed cold neutron source at JPARC. The final system will have to be scaled twice to a 30mm bore diameter and about one meter length. Its gradient and capability of modulation was confirmed through experiments where the outer ring was driven by a 1.5kW motor. In order to overcome the large torque needed to rotate the outer ring, a flywheel helps to keep the rotation of the outer ring.

A second variable PMQ will be fabricated in FY2007 for 14mr crossing angle interaction point.

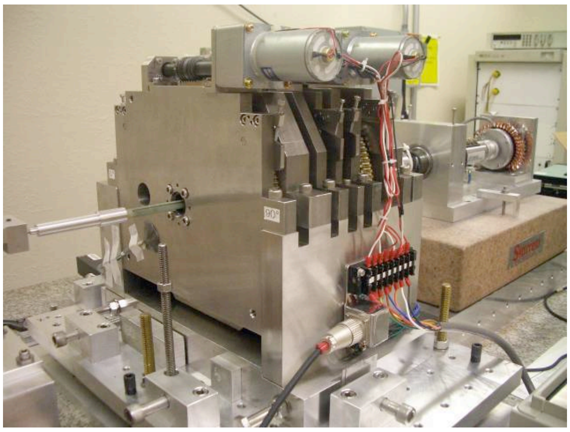

Figure 3 The 20mr Variable FFQ Magnet

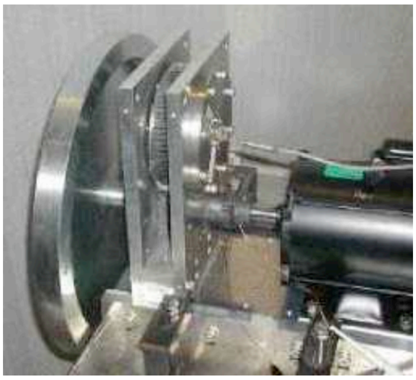

Figure 4 A half scale model of a rapid cycling PMSx

2 PMQ for 14mr

The reduced crossing angle of 14mr made the double ring structure not applicable at least the closest part to the IP. Because of the narrow space available between the incoming beamline and outgoing beamline (4m x 14mr – 10mm x2), just a single ring structure has to be used, where both of the beamlines are assumed to require 10mm radius at the 4m location. In 1983, R.L.Gluckstern suggested a five-ring singlet [5]. Figure 5 shows the configuration of such a set of five rings whose lengths are the ratios as shown in the figure. The rotation angles, ø of the PMQ rings at even positions are opposite in sign against those at odd positions. The transfer matrix for such a system should be expressed by 4x4 matrix M, while those for each PMQ are written as:

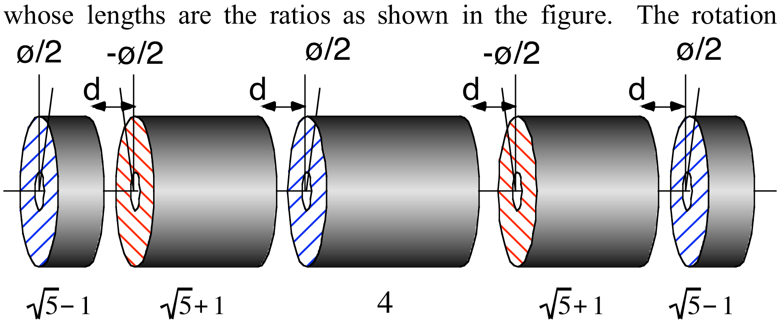

Figure 5 Five ring singlet. The numbers under the rings are the length ratios for the skew less condition when d=0.

$$\mathbf{M}0 = \begin{pmatrix} \mathbf{M}0_{xx} & \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \mathbf{M}0_{yy} \end{pmatrix}, \mathbf{M}1 = \begin{pmatrix} \mathbf{M}1_{xx} & \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \mathbf{M}1_{yy} \end{pmatrix}, \mathbf{M}2 = \begin{pmatrix} \mathbf{M}2_{xx} & \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \mathbf{M}2_{yy} \end{pmatrix}.$$

Then the total transfer matrix **M** is calculated as:

$$\mathbf{M} = \mathbf{R} \cdot \mathbf{M}2 \cdot \mathbf{R}^{-2} \cdot \mathbf{M}1 \cdot \mathbf{R}^{2} \cdot \mathbf{M}0 \cdot \mathbf{R}^{-2} \cdot \mathbf{M}1 \cdot \mathbf{R}^{2} \cdot \mathbf{M}2 \cdot \mathbf{R}^{-1} .$$

By rewriting with sub matrices, **M** can be written as

$$\mathbf{M} = \begin{pmatrix} \mathbf{M}xx & \mathbf{M}xy \\ \mathbf{M}yx & \mathbf{M}yy \end{pmatrix},$$

and the off-diagonal sub matrices become negligible when the lengths of the rings satisfy the relations stated before. It should be noted that the distances between rings are zero (d=0) in above case. A similar problem was solved for a case with d=1cm case where summed PMQ length L0+2L1+2L2 is 20cm (total length is 24cm including four gaps), keeping L0+2L2-2L1=0. The rotation matrix **R** should be substituted by $\mathbf{R} \cdot \mathbf{D}$, where matrix **D** denotes a 1cm drift space. The off diagonal sub matrices are expanded in series up to 5th order for a solution. The ratios are solved as L2:L1:L0=1.81046: 5: 6.37909.

3 Preliminary Simulation Results

Assuming a field gradient of 140T/m and using 12 units of the five-ring-singlets, the total length becomes about 3m. Using this singlet train as a QD0, a preliminary fine tuning was carried out with matching requirement for Twiss parameters: $\alpha_x=\alpha_y=0$, $\beta_x=0.021$m, $\beta_y=400\mu$m, $\eta_x=0$ at IP, starting with the ILC deck “ilc2006b.ilcbds1” (14mrad version). The final ø of PMQ is 6.58 degree. Then off momentum matching was performed by re-optimizing K2 of sextupoles looking at the beam size at IP. The coupling between x and y was well suppressed and the final beam sizes at IP are σ_x/σ_y = 656/5.44nm for γ_{ex}/γ_{ey}=9.2e-6/3.4e-8m and σδ=6e-4 (636 / 5.25nm for original design). Although the optimization was

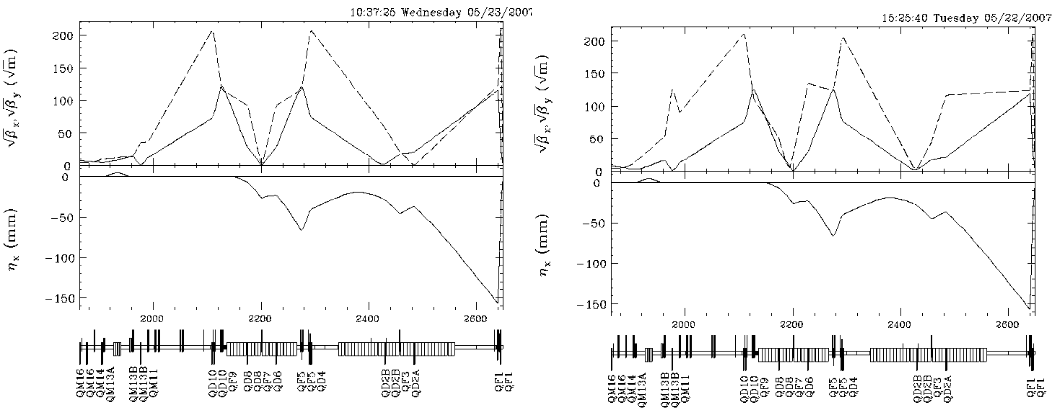

Figure 6 Optics with PMQ. top: original, bottom: using PMQ with partial optimization.

not fully performed such that octupoles were fixed, the result seems promising (see Figure 6). Further optimization will improve the results.

4 External Field of PMQ

The external field of the Halbach configuration is much smaller than that of coreless superconducting magnets, because the main part of the flux returns in the magnets (see Figure 7 and Figure 8). The leakage can be reduced if an iron case is used instead of nonmagnetic material such as stainless steel. Although it reduces the external field, solenoid field in the detector will magnetize the material. The magnitude depends on the number of segmentations of the ring; the more segmentations, the smaller leakage out side. Therefore such magnetic case for the external field shield may not be needed if the segmentation is fine enough. More than 20 segmentations may be enough to suppress the external field at a location of 46mm from the incoming beamline less than 30 gauss.

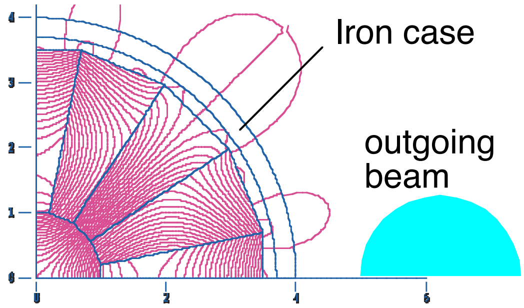

Figure 7 PMQ and out going beam.

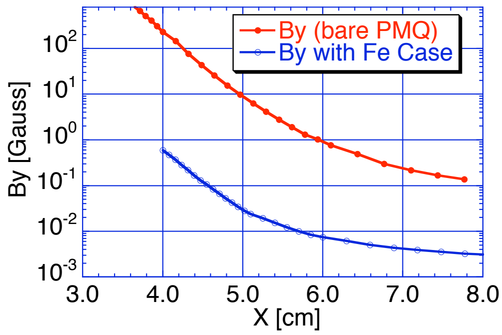

Figure 8 External stray field of PMQ.

5 Acknowledgements

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6 References

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