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# UPDATE OF ADJUSTABLE PMQ LENS

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*Abstract*

Gluckstern's adjustable permanent magnet quadrupole (PMQ) lens based on five rings is revisited to achieve a compact focusing system for laser-accelerated beams. The first prototype was fabricated for bore diameter of 50 mm. The integrated gradient was up to 6.8 T. A new PMQ with a bore diameter of 25 mm is under fabrication based on the same geometry. While the first prototype unit was developed for the final focus magnet of the ILC, the second unit is the first doublet element for laser-accelerated electron beam focusing to be combined with this first unit. The current status of the development is reported.

## INTRODUCTION

Adjustable Permanent Magnet Quadrupole lens based on Gluckstern's five-ring configuration has been studied [1]. While changing the intensity of the PMQs is not easy, Gluckstern proposed a method to adjust the strength without skew rotating the five PMQs alternately in opposite directions around the beam axis. The rotation angle φ at even positions of the PMQ ring is opposite in sign to the rotation angle φ at odd positions (see Fig.1).

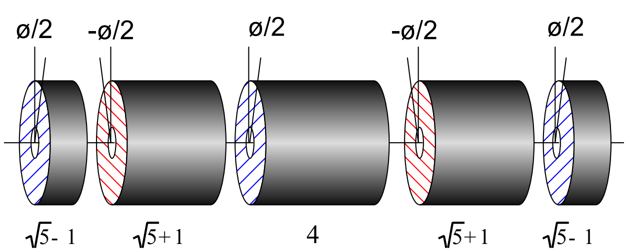


Figure 1: Gluckstern's five ring singlet.

The transfer matrix of such a system is represented by a 4 x 4 matrix *Mn* to account for the x-y coupling and the matrix of n-th PMQ is written as:

$$Mn = \begin{pmatrix} Mn_{xx} & \mathbf{0} \\ \mathbf{0} & Mn_{yy} \end{pmatrix}, \text{( n=1,2,3,4,5).} \quad (1)$$

Since $M5 = M1$ and $M4 = M2$, the total transfer matrix $M$ is calculated as:

$$M = R \cdot M1 \cdot R^{-1} \cdot M2 \cdot R \cdot M3 \cdot R^{-1} \cdot M2 \cdot R \cdot M1, \quad (2)$$

where $R$ represents the rotation of a magnet. By rewriting with 2 x 2 sub matrices, equ. (2) 4 x 4 matrix $M$ can be written as

$$M = \begin{pmatrix} M_{xx} & M_{xy} \\ M_{yx} & M_{yy} \end{pmatrix}. \quad (3)$$

The off-diagonal sub matrices $M_{xy}$ and $M_{yx}$, can be negligible when the lengths of the rings satisfy a relation. It should be noted that the distances $d$ 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 $2L1+2L2+L3+4d$ is 26cm, keeping $2L1-2L2+L3=0$. The rotation matrix $R$ should be substituted by $R\&D$, where the transfer 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 $L1:L2:L3$ = 1.81046:5:6.37909. Actual lengths are rounded to 20 mm, 55 mm, and 70 mm, respectively. The first prototype developed for the ILC was built with a 50mm bore diameter to get practical experience at ATF2 [2-7]. External dimensions are designed to fit into the beam tube of the detector at the interaction point (see Fig. 2). The exit hole is located 56 mm from the incoming axis to allow the outgoing beam to escape at a crossing angle of 14 milli-radians at 4 m from the interaction point.

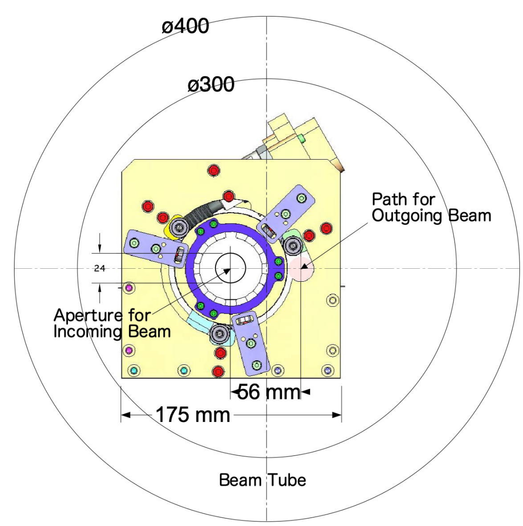


Figure 2: Adjustable PMQ in a beam tube.

## REVIEW OF THE FIRST UNIT

Figure 3 shows the fabricated magnet. The five rings are rotated around an axis with three rollers holding the circumference of each ring, assuming that the circumference of each ring is a regular circle. The positions of the three rollers must be adjusted so that the axis of each ring is aligned. Therefore, care must be taken to ensure roundness. The odd-numbered rings were connected by a bridge and rotated by a single motor, while the even-numbered rings were rotated by individual motors. Thus, three motors were used in all. Because the rings strongly repel and attract each other, a large force is required to rotate them against each other, and a worm gear is used to rotate the

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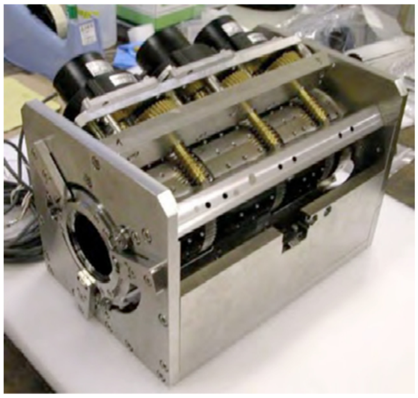

Figure 3: Fabricated magnet.

gear fitted to the outer circumference of the rings. Because the first unit was designed to be used in a strong magnetic field, all motors were supersonic motors and required a rotary encoder to control the angles of rotations. The origin of each angle is set by a limit switch using a photo interrupter.

The assembly process was from each magnet. Each ring was assembled with rough shape adjustment, then rotated with the outer frame of the magnet and the magnetic field center was calculated with a fixed radial coil inserted in the bore (see Fig. 4). One path of the radial coil passes through the center of rotation and the other path is 10 mm away from the center. This coil had four turns. A 16-turn half-size coil was also installed to allow output correction that cancels the quadrupole component and emphasizes the smaller dipole component. The coil voltage is measured with a 24-bit ADC board attached to a PC while rotating the magnet at 1 RPS. Since four revolutions of data were analyzed, only a quarter of the results are valid values, the rest can be considered noise, and the noise level can be estimated (see Fig. 5). In this case, the signal-to-noise ratio seems to be more than 5 orders of magnitude. The dipole component corresponds the magnetic center displacement. While the magnets are fixed by pushing screws from outside, the fine tuning of the magnetic centers were performed by adjusting the screws.

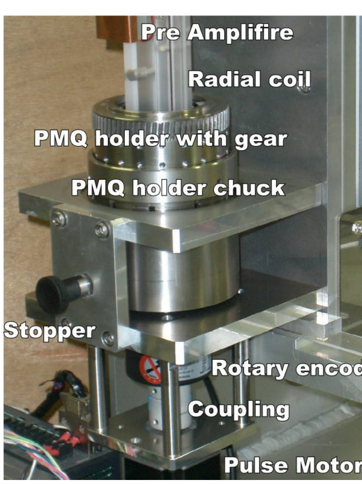


Figure 4: Magnetic center measurement against the holder.

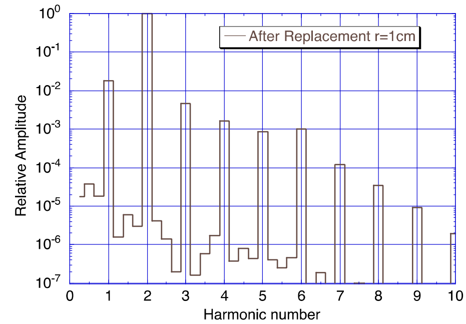


Figure 5: Typical measured data. Non-periodic spurious components appear between integer points, which are considered noise.

The assembled unit was measured by a rotating coil system at KEK. Figure 6 shows a typical data of the measured integrated field gradient as a function of the rotation angle, together with the tilt of quadrupole plane. The maximum strength was 6.8 T and the strength went down to almost zero as expected. Since the repulsive force is maximum at the position of maximum strength, the sign of the rotational force changes, resulting in poor stability of the tilt angle. Since the intensity variation in this region is small, it can be suppressed to less than 1 mrad by limiting the range of rotation angles used and keeping the intensity variation to about 90~20% of the total.

Figure 7 shows typical measured magnetic center excursions as functions of rotation angle. There are three sets of measurement data, all of which showed a good reproducibility except for the first run. The magnetic center displacement is evaluated from the ratio of dipole and quadrupole components, and the quadrupole component is smaller on the weak side, resulting in a relatively large free-running rate on the weak side.

The excursions were attributed to the magnetic center offset of the five rings, which was planned to be adjusted. Unfortunately, this was not completed within the budget period. Even with these excursions, a mover can compensate for the excursion if the excursions are known as functions of the rotation angle.

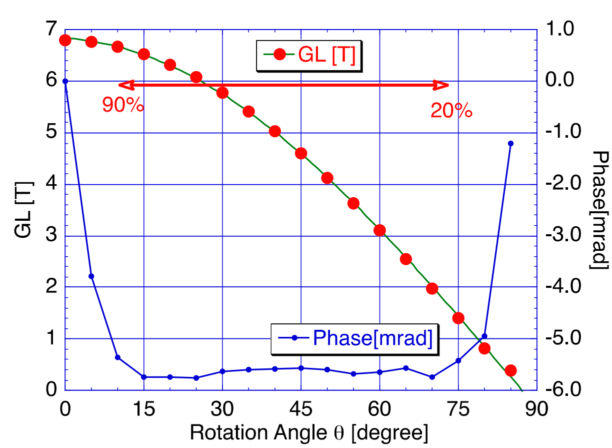


Figure 6: Integrated field gradient as a function of the rotation angle. The quadrupole plane tilt is also plotted.

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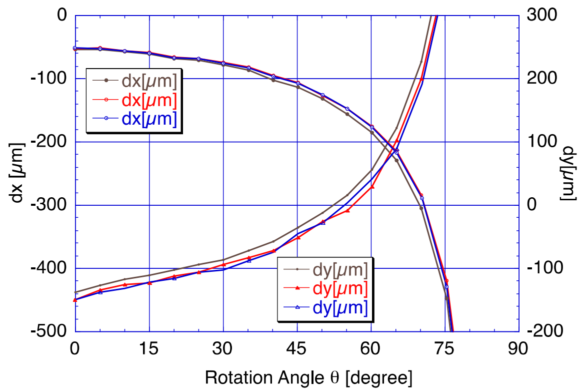


Figure 7: Magnetic center excursion as functions of the rotation angle. Three lines correspond to three runs of measurements.

## THE SECOND UNIT

The second unit is requested as the first element of the initial doublet for laser-accelerated electron beam focusing and will be combined with the first prototype. A new PMQ based on the same configuration with a bore diameter of 25 mm is under fabrication which is close to the original ILC specification.

The ultrasonic motors in the first unit are replaced by stepping motors for ease of operation. In addition, the number of motors is reduced by connecting an even number of rings. (see Fig. 8). Since the lens is not in a strong magnetic field environment, the outer shell of the magnet ring is made of magnetic stainless steel (SUS430) to reduce the stray magnetic field around the lens unit.

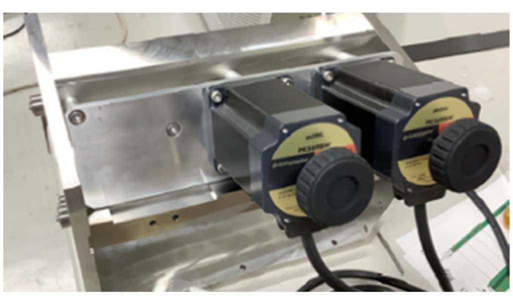

Figure 8: Electromagnetic stepping motors are used.

The ten-year-old magnetic field measurement systems are refurbished. A smaller coil was prepared for the smaller diameter of the magnets in the rotating magnet system. Since the coil voltage does not change much, the same amplifiers are used replacing the failed IC.

Since the PC was outdated, a digital oscilloscope with 11-bit ADC resolution was used for the ADC. As a result, the signal-to-noise ratio was reduced but still at a usable level (see Fig. 9). 2 rotations were made, so noise was generated at each rotation, which was larger than the previous measurement.

To date, rough adjustments have been completed on all five magnet rings (see Fig. 10). The assembly and fine-tuning is planned to be performed within the next few weeks.

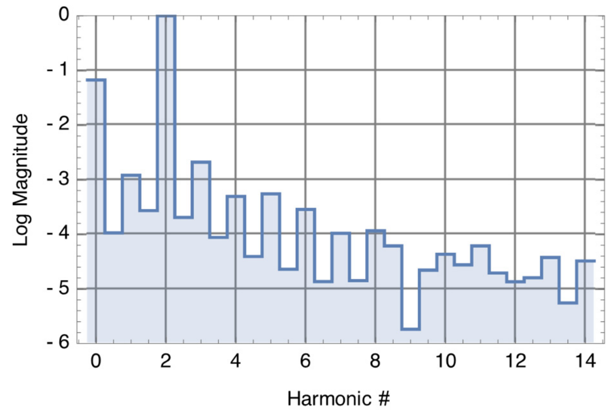


Figure 9: Typical measured harmonic components.

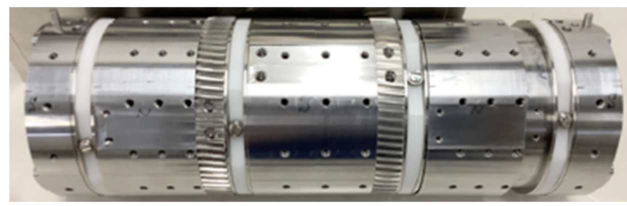

Figure 10: The five rings. They attract each other facing in the direction of a 90-degree turn from their strongest state.

## ACKNOWLEDGEMENT

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