DEVELOPMENT OF THE CONTINUOUSLY ADJUSTABLE PERMANENT MAGNET QUADRUPOLE FOR ATF2

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Abstract

A quadrupole magnet for the final focus system of the International Linear Collider (ILC) is required specific properties, that is comparatively 'compact' (because the crossing angle of the Interaction Point (IP) of ILC is planned to be very small (~14mrad) and so out-going beam-line is installed passing close by the Final Focus Quadrupole (FFQ)), 'solid and stable' (so that beams with the very small beam-size at IP (~several nm in y-plane) needed can be realized and be handled stably) and so on. A super-conducting magnet scheduled now is not always suitable for that, for instance because of a huge cryostat needed outside of it (since it may have the mechanical vibrations due to liquid helium flow and also the magnet. This may prove not to be good). Since the continuously field-strength adjustable Permanent Magnet Quadrupole (PMQ) designed by Gluckstern [1][2] satisfies these properties, we are developing FFQ of this type for ILC, and for ATF2 (the Acceleration Test Facility 2) firstly.

However the magnet of this type has a risk of x-y coupling more greatly influenced than magnets of other types. For it is five discs singlet, which comprises five PMQ discs with appropriate skew each other. A nominal beam for ILC has different scales in x-plane and y-plane, so we need to avoid x-y coupling sufficiently.

We estimated the effect of field-error brought by skew of each PMQ disc. Then we used the way of calculation of transfer matrices neglecting fringe field and multipoles except for Q. In addition we produced this type of the magnet experimentally and measured field-strength and harmonics in the magnet. Then we fabricated an instrument measuring harmonics of fields in the magnets. The harmonic analysis is discussed compared with the estimation above.

We explain these schemes and show the conclusion. At the same time we are adjusting and aligning the magnets for reducing errors. We fabricated a jig then, so we explain it too.

INTRODUCTION

Since recent development for a PMQ enables high degree of field strength, a PMQ can be used as a focus magnet for a high-energy beam. However a focus magnet requires the tuning of field strength for the sake of practical beam energy and focal length. A five-discs-singlet configuration proposed by Gluckstern works as a PMQ, whose strength is continuously adjustable. Each disc of a Gluckstern's PMQ comprises a PMQ, and the field strength in it is altered by rotating the discs with respect to each other (Fig. 1). Though x-y coupling effect caused by a skew of each disc can be theoretically cancelled in this design, fabrication errors and rotation errors alter the situation. The effect of x-y coupling may prove fatal to a beam whose size in x-plane and y-plane are considerably different as in a case at IP of ILC.

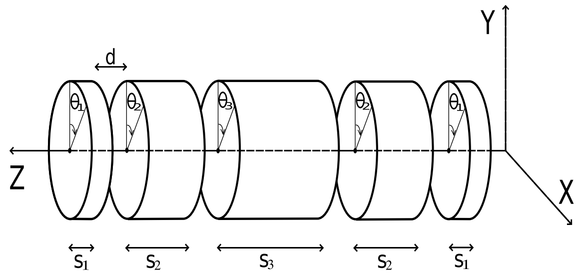

Figure 1: A Gluckstern's PMQ.

Though six parameters exist in the five-discs-singlet, five conditions constrain these parameters. So only one parameter is free. Using this parameter total field strength is continuously adjustable. The five constraint conditions are as follows.

- The absolute values of three rotation angles of five discs are the same. It should be noted that this statement represents two constraint conditions. The statement is namely
$$\theta \equiv \theta_1 = -\theta_2 = \theta_3 . \qquad (1)$$
- The minimum of the total focusing force is decided. Here we chose the minimum zero, and strength of focusing is approximated in proportion to length of the magnetic filed. Then this constraint condition is
$$2s_1 - 2s_2 + s_3 \equiv S_0 . \qquad (2)$$
We decided S_0 to be zero here.
- The maximum of the total focussing force is decided. We chose the maximum the value needed by ATF2. The total focussing force is represented as the total length when field gradients of discs are the same and decided. By the way, with the aim at ILC we are planning to choose the same total length and smaller bore of discs.
$$2s_1 + 2s_2 + s_3 \equiv S_t . \qquad (3)$$
Here S_t is 220mm.
- In order to cancel the effect of x-y coupling at all angles of discs, the proportion of the lengths of discs should be optimized. In this optimization we used the proportion of the length of first and fifth discs to the total length.
$$\lambda \equiv s_1 / S_t . \qquad (4)$$
Here λ is 0.07877.

ESTIMATION OF ERRORS

We estimated an x-y coupling effect caused by three types of errors associated with each disc, namely a rotation error, a length error and a shift. This estimation includes the calculation of transfer matrices neglecting fringing field and multipole components [3].

The effect of an x-y coupling can be calculated with nominal parameters at IP in ILC. When nominal beam size and divergence at IP is represented as $\boldsymbol{X}$, practical beam size and divergence at IP can be represented as $\boldsymbol{X}^*$, nominal transfer matrix of FFQ is $\boldsymbol{M_Q}$ and the practical transfer matrix of a Gluckstern's PMQ as FFQ is $\boldsymbol{M_Q}^*$, and so on. Namely $\boldsymbol{X}$ and $\boldsymbol{X}^*$ are defined as follows,

$$\begin{aligned} X &= M_{DS} M_Q X_0 \\ X^* &= M_{DS} M_Q^{\ *} X_0 . \end{aligned} \qquad (5)$$

The effect of an x-y coupling at IP, $\boldsymbol{\Delta X}$ is

$$\Delta X = X - X^* = M_{DS}\left(E - M_Q^{\ *} M_Q^{\ -1}\right) M_{DS}^{\ -1} X . \qquad (6)$$

A Rotation Error

We calculated with ILC parameters $\boldsymbol{\Delta X}$ when a rotation error $\delta\theta$ exists on each disc of a Gluckstern's PMQ with ILC parameters. Then we fixed length of a Gluckstern's PMQ to 220 mm, and used the optimum length as a length of each disc. For $\boldsymbol{\Delta X}$ is to be less than 10 percent of $\boldsymbol{X}$, $\delta\theta$ on each disc has to be less than the value shown in Table 1. We can say that the x-y coupling effect is about in proportion to the length of each disc.

Table 1: Nominal $\delta\theta$ on each disc

Disc	**Optimum length [mm]**	**Nominal $\delta\theta$ [rad]**
First	17.33	$< 2.2 * 10^{-4}$
Second	55.00	$< 7.0 * 10^{-5}$
Third	75.34	$< 5.3 * 10^{-5}$
Forth	55.00	$< 7.6 * 10^{-5}$
Fifth	17.33	$< 2.5 * 10^{-4}$

A Length Error

It was found that a length error of each disc has to be less than 100 μm for $\boldsymbol{\Delta X}$ be within less than 10 percents of $\boldsymbol{X}$. Since a fabrication error can be controlled within 100 μm, the x-y coupling caused by a length error isn't as bad as a rotation error. When fringing field in edges of each disc exists, since effective length of the field is changed a little, it is also shown the cause of the x-y coupling at IP never affected a change of the field length derived from fringing field.

A Shift

A shift of a disc does hardly affect x-y coupling at IP in ILC, but shifts the position of interaction of beams instead. If the shift at IP less than 1 nm is wanted, a shift of each disc must be less than 1 μm. It is understood that a shift of each disc less than 1μm is difficult to realize but not impossible. As a first step, we measured the shift of a disc experimentally. It was found that the shift was in an order of 10 μm. This value is rather large and is attributable to fabrication errors. It can be improved so the shift less than 1 μm is not impossible.

MEASUREMENT

We fabricated only two discs (disc-3 whose length is 70mm and disc-4 whose length is 55mm). Though we fabricated more two discs precisely, for adjustment we disassembled or took to pieces those discs. Here we mentioned about only two discs assembled now.

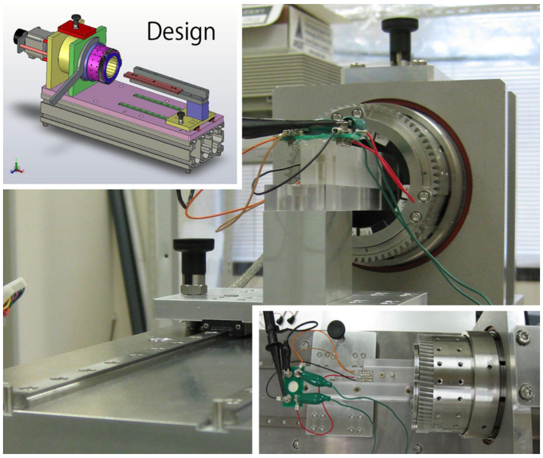

Figure 2: The Rotation Magnet Instrument

We fabricated an instrument for measuring harmonics of fields (Fig. 2). The instrument can measure voltage of two induction coils inserted in a disc as rotating the disc. One coil has the area twice as larger as the other's and its rolled number is a quarter of the other's (Fig. 3). Since the difference of induced voltages of two coils does not include the quadrupole component theoretically, other components still more little than the quadrupole component can be measured more accurately. A blue line in the upper picture of Figure 3 shows the position of the axis of symmetry of a disc when the coils are inserted in the disc.

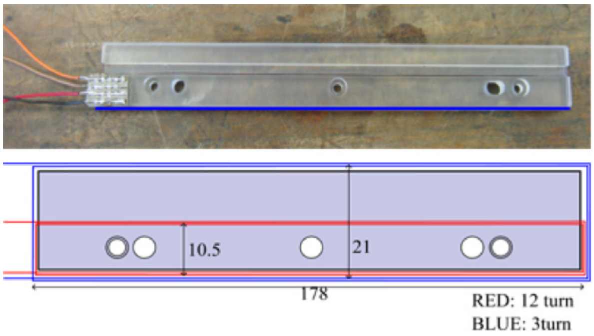

Figure 3: the Coils of the Rotation Magnet Instrument

In practice filed strength as complex expression in perpendicular plane to the axis of symmetry of a disc $B(r,\theta)$ is written as follows,

$$B = B_r + iB_\theta = \sum_n \frac{B_n r^{n-1}}{(n-1)!} \exp[in\theta], \qquad (7)$$

where B_n is a complex coefficient of 2n-pole component. Therefore induced voltage V is

$$
\begin{aligned}
V &= -\oint_C E dl = \int_S \frac{d}{dt} B_\theta d\sigma \\
&= N\omega L_{eff} \int_0^R \mathrm{Re}\left[\sum_n \frac{nB_n r^{n-1}}{(n-1)!} \exp[in\theta]\right] dr \\
&= N\omega L_{eff} \,\mathrm{Re}\left[\sum_n \frac{B_n R^n}{(n-1)!} \exp[in\theta]\right],
\end{aligned}
\tag{8}
$$

where N is a turn number of a coil, ω is a angular frequency of a disc, L_{eff} is an effective length of magnetic field along the axis of symmetry of the disc and R is defined that RL_{eff} is the effective field area of the coil.

We analyzed harmonics with the FFT (Fast Fourier Transfer) after smoothing of the plane data measured. The smoothing is the filter that equates the duration of 0.01 seconds around each point and that means the low pass filter of 100 Hertz. With this filter we removed a noise caused by the pulse motor in the plane data at first.

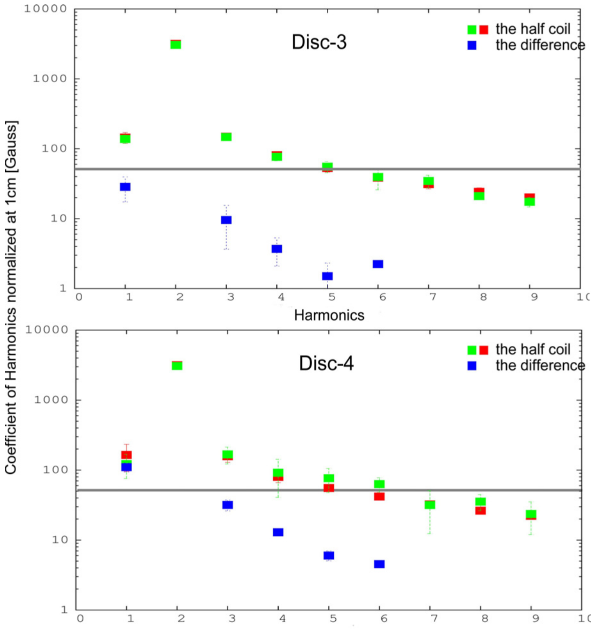

Figure 4: The analysis of harmonics.

We measured induced voltage three times with oscilloscope. Each measurement includes the data of 16 periods. Induced voltage of the half coil (red one in Fig. 3) was measured twice, and the difference of induced voltages of the full coil (blue one) and the half was measured once (see Fig. 4). The oscilloscope we used has only the accuracy of few percent, so when the data includes quadrupole component other components, which are more little influenced than one percent of quadrupole component, cannot be measured precisely. The gray lines in Fig. 4 show this mechanical accuracy limit. By the way of measuring the difference, since quadrupole component is not included theoretically, with the accuracy of few percent of dipole component, which is the secondary component of the field, other components can be measured precisely. Values in Tab. 2 show multipole components obtained the third measurement but normalized where the distance from the centre of the discs is one centimeter. Quadrupole component in Tab. 2 is however the mean of previous two measurements.

Table 2: Harmonics and Shift Measured

Disc	Dipole (Err) [G]	Quadrupole (Err) [G/cm]	Shift (Err) [μm]
Third	29 (11)	3120 (10)	91.5 (36.3)
Fourth	110 (16)	3120 (10)	353 (52)

ADJUSTMENT

We fabricated a jig adjusting and aligning pieces of magnets (see Fig. 5). We think an error of alignment of each piece of magnet of a disc is dominant to the shift error (or dipole component) of the disc. Though magnetic pieces were fixed by the force of outside screws, this time we developed a jig which can make force from the inside the pieces to the outside of them. The outside diameter of the jig is changed by the taper of the jig (the red part in Fig. 5) going up and down.

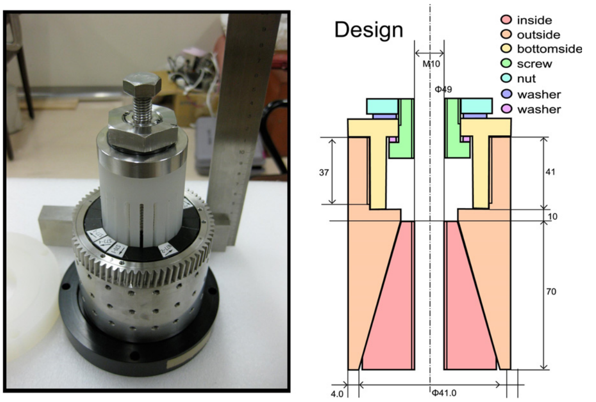

Figure 5: The jig adjusting magnetic pieces.

CONCLUSIONS

We fabricated an instrument measuring harmonics and estimated shift errors of discs (the third disc and the fourth disc). It was found that when we measured induced voltage including quadrupole component other components could not be estimated precisely.

We fabricated a jig adjusting and aligning magnetic pieces. We think using the jig we can force magnetic pieces into appropriate places, as the result we can reduce other components including dipole.

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