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Small Gap Magnet Prototype Measurements for eRHIC*

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Abstract

In this paper we present the design and prototype measurement of small gap (5mm to 10 mm aperture) dipole and quadrupole for the future high energy ERL (Energy Recovery Linac). The small gap magnets have the potential of largely reducing the cost of the future electron-ion collider project, eRHIC, which requires a 10GeV to 30 GeV ERL with up to 6 energy recovery passes (3.8 km each pass). We also studied the sensitivity of the energy recovery pass and the alignment error in this small magnets structure and countermeasure methods.

1 INTRODUCTION

The proposed Electron Ion Collider (EIC) in BNL, named eRHIC, exploit multi-pass Energy Recovery Linac (ERL) to accelerate the electron beam up to 3-30 GeV, taking advantage of the its flexibility. This ERL based scheme opens a way to deliver luminosity higher than 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, an order of magnitude higher than an electron ring scheme.

In multi-pass ERL, multiple energy recovery passes are demanded. Particularly in eRHIC, the energy recovery passes will be built in the existing RHIC tunnel with circumference 3833m. Therefore the total path length for a 6-pass ERL is over 20 kilometers. To reduce the cost significantly, we proposed the small gap magnets (dipoles and quadrupoles) with the gap of 5mm to 10mm and a common vacuum chamber. In [1], we presented the engineering designs of the magnets and the vacuum chamber, alone with the 2-D magnetic field simulation. In this paper, we present the measurement results of the prototypes and the analysis of the errors.

2 THE MAGNET PROTOTYPE

Both dipole and quadrupole (Figure 1) prototypes are built in BNL onsite workshop. The 1006 extra-low carbon steel is used as high μ material and copper blocks as the wire to conduct the current for reducing the current density. Since the magnet gaps are small, the parallelism and flatness of both surfaces are essential to reduce the unwanted high order component of the magnetic field.

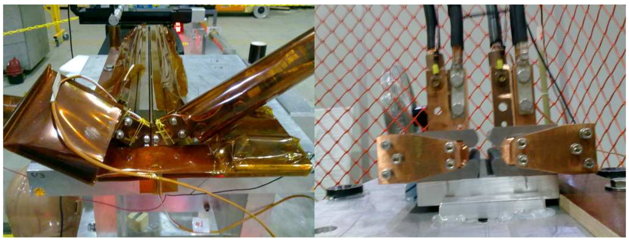

Figure 1: The dipole (left) and quadrupole (right) prototypes at measurement platform. The gap for the dipole is 5mm and 10mm for quadrupole.

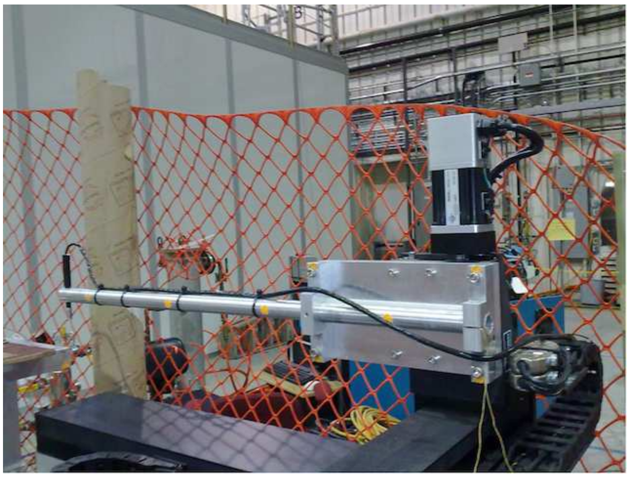

Figure 2: The Hall probe on a 3-axis translation stage

3 MEASUREMENT PLATFORM

We use Group 3 Hall probe mounted on a 3-axis translation stage (Figure 2) to map the field. The probe and its holder as the thickness of 3mm which will fit even the 5 mm gap. This measurement system has the ability to do both longitudinal (z direction) and vertical (y direction) scans. However, due to the limitation of the small gap, the ability of horizontal (x direction) scan is very limited, even for 10 mm gap quadrupole. The movement acuracy of the translation stage can be as low as 1 micron. In real measurement, the minimum movement step is 25 microns. The relative coordinate of the magnets with respect to the probe home position is measured through the geometric survey

Through the measurement, the probe measures the average normal field of its active area and sends the signal to the teslameter. We can obtain the the field at varying positions to calculate the higher order harmonics other than the

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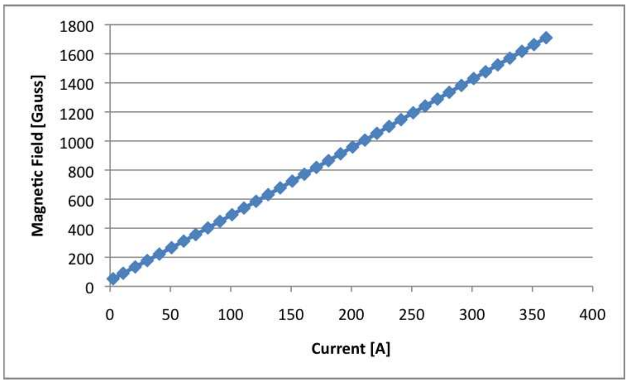

Figure 3: The center field as function as current.

linear terms.

4 RESULTS OF THE DIPOLE MEASUREMENT

We measured the dipole at 245 Amperes per pole, the resulting field is about 1170 Gauss. We did not test the full design current 700A because of the limitation of the power supply. We first put the probe at the center of the magnet, determined by survey, and measure the field as function of the current after 3 hysterisis cycles from 0 to 380A. Figure 3 shows a perfect linear function as we expected.

Then, while keeping the survey center in horizontal direction, we scan the field along longitudinal positions with different vertical positions to examine field flatness. The design 'good field' region is ±2mm and we scan ±4mm in y direction to gather full knowledge of the field.

In the first measurement as shown in the Figure 4 (top), the discrepancy of the field between different vertical coordinates is small, which shows the quadrupole and higher components are not significant (not visible in this scale). However, the variation along the longitudinal is huge, and becomes main imperfection of this prototype. In the flat field region, the full width of the field variation is about 2.7% of the average field. This variation can be caused by surface flatness (e.g. the stress relief is not properly accomplished) or the permeability of the material is not uniform. To examine the source of this imperfection, we perform the mechanical measurement of the flatness of the gap between 2 poles, and get the maximum fluctuation is about 3% and the variation shape meet the variation of the field.

Therefore we grind the pole to make the surface flat and fluctuation decreases to about 0.7%. The corresponding field is shown in Figure (bottom). The field discrepancy drops to 0.8%. This implies the imperfection of field is mainly caused by the defection of the pole surface. For a 5mm gap, the surface accuracy should be around 5 microns if the desired field variation is 0.1%.

At the center of the longitudinal dimension, we take the field as function of vertical positions with small step size to study the high harmonic components of the transverse field.

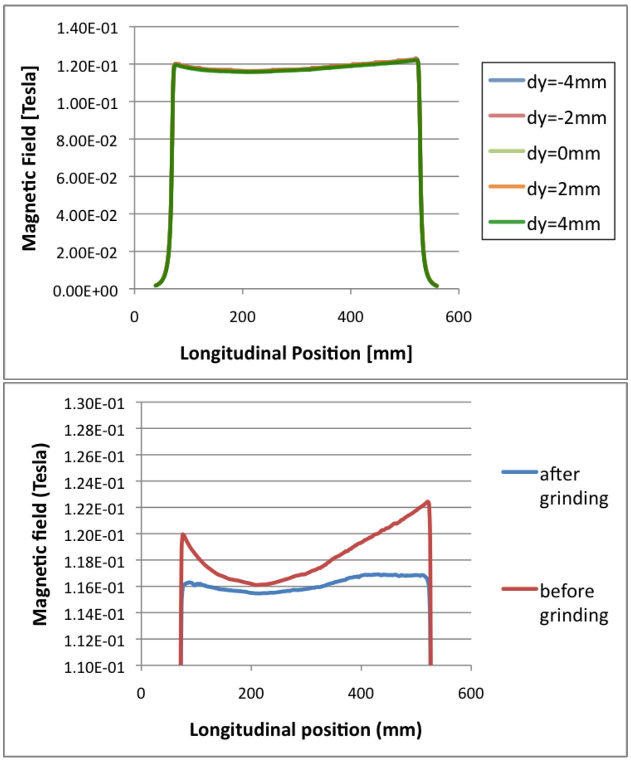

Figure 4: The longitudinal field map at different vertical position (top), the comparison of the field at $y = 0$ before and after the magnet pole surface is grinded (bottom).

Table 1: The high harmonic component of the field at 2mm and 4mm off center. They are measured by units, 0.01% of the average dipole field.

Harmonic number	At 2 mm	At 4 mm
1 (Quadrupole)	-17	-34
2 (Sextupole)	7	26
3 (Octopole)	3	25
4	-3	-50
5	-0.7	-22
6	0.3	17

The survey center of the vertical center is 33.749 mm. In the polynomial fitting, we set the center at this value and measure the harmonics at 2mm and 4mm off center.

From table 1 and figure 5, we learn that only quadrupole component is significant within ±2mm region. This quadrupole component can be reduced to 2 units, if two poles are perfectly parallel with each other. However, the field degrades at around ± 4 mm off center. Currently, a new prototype of dipole is being manufactured with the goal of decreasing the mechanical error. With the new dipole, a better uniqueness along the longitudinal axis and smaller transverse harmonic component are expected.

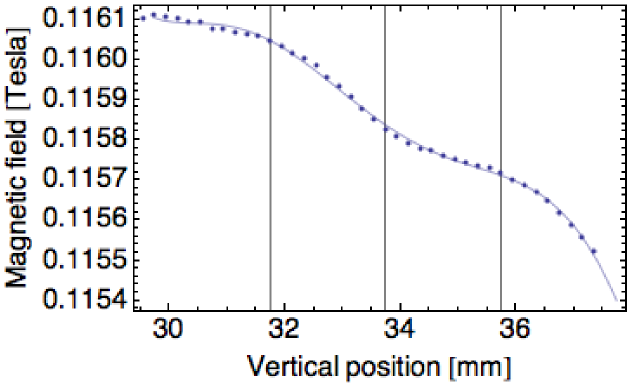

Figure 5: The magnetic field near vertical center and its polynomial fit. The fit function reads as $B = 0.1158 - 9.859\times10^{-5}\,(y-y_c) + 1.887\times10^{-5}\,(y-y_c)^2 + 4.658\times10^{-6}\,(y-y_c)^3 - 2.278\times10^{-6}\,(y-y_c)^4 - 2.499\times10^{-7}\,(y-y_c)^5 + 4.781\times10^{-8}\,(y-y_c)^6$ Tesla, where $y_c = 33.749$ mm. The grid lines corresponds to 33.749 mm and ±2 mm.

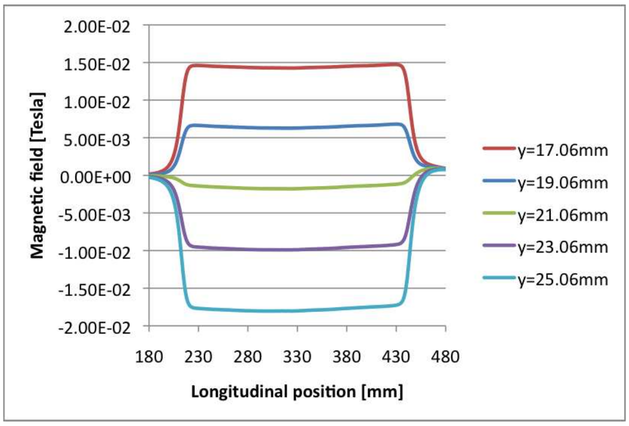

Figure 6: The field map of the quadrupole prototype.

5 RESULTS OF THE QUADRUPOLE MEASUREMENT

The quadrupole prototype is measured at exact same platform as the dipole. Figure 6 shows the field map of it. We applied 150A to each pole of the magnet. From this figure, the field center is slightly smaller than the survey center (21.06 mm). According to the linear fitting of the integral field $\int Bdl$, it locates at $y = 20.69$ mm with field gradient 0.397 KG/cm.

Again, the quality of this prototype is degraded by the surface uniqueness of the pole surface. It can be observed in figure 6. Instead of fitting the integral field, we can fit the field gradient and center at each longitudinal position, and find the fluctuation of gradient and field as 0.87% and 0.72% respectively.

Followed by same procedure, the transverse higher order harmonics are found in Table 2.

Table 2: The high harmonic component of the field at 2mm and 4mm off center. They are measured by units, 0.01% of the quadropole component at same location.

Harmonic number	At 2 mm	At 4 mm
2 (Sextupole)	43	88
3 (Octopole)	7.2	19
4	-4.2	-34
5	-2.8	-44
6	0.3	8.2

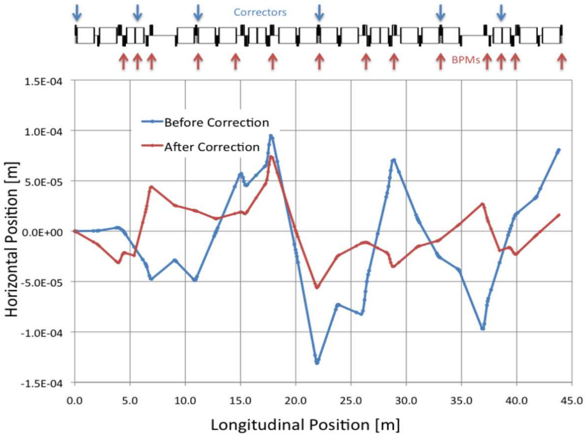

Figure 7: The beam trajectory at presences of offset error of quadrupoles.

Two new quadrupole prototypes will be built for further study. The first will have same dimension as the present one with higher manufacture precision. The other one will have 5mm gap as the dipole, which is feasible for higher field gradient.

6 BEAM PASS CORRECTION USING SVD

The linear errors of the small magnets can be corrected using SVD, as it was implemented in storage rings[2]. Figure 7 shows the application of SVD in an example arc. Each quadrupole is given a random offset with rms value 100 microns. We insert 14 BPMs and 7 correctors to illustrate the effect. Each BPM is set to have random offset error with rms size 50 microns. It shows clearly that the trajectory can be corrected as expected.

The study of nonlinear errors and its effect to the beam is undergoing.

7 REFERENCES

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[2] A.W. Chao, M. Tigner, “Handbook of Accelerator Physics and Engineer”, World Scientific, 1999