

## MAGNETIC FIELD MEASUREMENTS FOR THE IAC-RadiaBeam THz PROJECT

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### Abstract

At the Idaho Accelerator Center (IAC) of Idaho State University, recently, a new chicane with four dipoles and quadrupole triplet magnets were installed in a 44 MeV linac to perform the IAC-RadiaBeam Terahertz (THz) project. To generate high power THz radiation, a THz radiator with numerous periodic gratings was also installed downstream of the quadrupole triplet. However, the electron beam shape at the radiator has to be horizontally focused strip-like one due to a tiny radiator gap with a width of 1.2 mm, and electron bunch length should be about a few picosecond (ps) to generate high power THz radiation in the radiator. By using the quadrupole triplet and chicane dipoles, we can control the transverse beam profile and bunch length freely. In this paper, we report the measured field maps of the dipole and quadrupole magnets, their effective lengths, and field strength or gradient as a function of the magnet power supply current.

### INTRODUCTION

Recently, many laboratories around world have been working for various technologies to generate high power THz radiation with accelerators. Most of them would like to use Free Electron Lasers (FELs) [1]. However, generation of the high power THz radiation with low energy accelerators may be much more attractive. Since the IAC has been operating nine low energy accelerators [2], the IAC and RadiaBeam Technologies collaborated to demonstrate a radiator based compact high power THz light source. The high power THz radiation will be generated by sending ps-long electron beams with an energy between 4 MeV and 8 MeV into the THz radiator [3]. In addition, to generate THz radiation with the radiator properly, we have to send the horizontally focused strip-like short electron bunch to the radiator due to its tiny gap. Therefore, we installed a chicane and triplet quadrupole magnets upstream of the radiator to control the shape and bunch length of the electron beam at the radiator freely. The field of those magnets have to be extensively mapped to calculate their effective lengths and to correctly predict the transverse shape and bunch length of the beam. In this paper, we describe our recent magnet field measurement results with the chicane dipoles and quadrupole triplet. The mapped fields were then used to calculate the effective lengths and to predict the required currents of magnet power supplies for proper control of the transverse beam shape and bunch length.

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Figure 1: The Hall probe on a 2D translation stage.

### EXPERIMENTAL SETUP

The field mapping has been performed using a Hall probe mapping system. This system has been built with a Hall probe mounted on a 2D translation stage as shown in Fig. 1. The Hall probe was mounted in such a way to measure the vertical component of the magnetic field, and the Hall probe was connected to a digital gauss meter. The probe tip has an active area of 5 mm × 5 mm. The probe arm could also rotate 360° around its axis. The Hall probe was set to zero by using a zero-gauss chamber. The magnets were placed on an adjustable table and then leveled to the Hall probe. The vertical magnetic field profile was measured as a function of the longitudinal directions while current of a magnet power supply is supplied to the magnet. Due to our operation at a low energy, the maximum applied current of the magnet is only 20 A. To obtain reproducibility of the hysteresis, the magnets were cycled three times by ramping to 20 A and down to 0 A. The data were taken by using an automated program. The magnet properties, such as the effective length and the correlation of magnetic field and excited current, were calculated by using MATLAB.

### MAGNETIC FIELD MEASUREMENTS

The vertical magnetic field profiles along the longitudinal position of the dipole and quadrupole magnets have been measured from 0 A to 20 A. The measured magnetic fields can be obtained as a function of the excited current by using the 3rd order polynomial fitting [4, 5].

#### *Dipole Magnet*

Figure 2 is a photo showing the dipole magnets with a bending angle of 7 degree. These dipole magnets can produce the maximum magnetic field of 0.35 T at the maximum current of 138 A. As the field of the dipole was expected to have only a vertical component, the Hall probe must be arranged in the midplane of dipole magnets, and



Figure 2: The photo of dipole magnets.

the vertical direction of a Hall probe is parallel to the magnetic field of dipole. To align the Hall probe, the arm of the probe has been rotated to obtain the maximum vertical field. The vertical field profile along the longitudinal direction is shown in Fig. 3. Where the magnetic field strength under the iron core is flat, and the strength is the same as that of the vertical magnetic field in the center of dipole,  $B_0$ . Thus this magnetic field profile is called the rectangular field profile [4, 6–8]. Figure 4 shows the measured vertical magnetic field at the center of a dipole for a hysteresis loop when the excitation current was cycled between 0 A and 20 A. A blue line is a measured vertical magnetic field when current is increased, and a red line is a measured vertical magnetic field when current is decreased. As shown in Fig. 4, it is certain that there is a hysteresis of the vertical magnetic field though the field difference between two curves is small. By using the polynomial fitting, for all dipoles in the chicane, the mean value of the vertical magnetic field can be given by

$$\begin{aligned}
 B[\text{gauss}] = & 12.375 + 27.076 \cdot I \\
 & + 4.074 \times 10^{-2} \cdot I^2 \\
 & - 4.858 \times 10^{-3} \cdot I^3, \quad (1)
 \end{aligned}$$

where  $B$  is the vertical magnetic field, and  $I[\text{A}]$  is the current of the magnet power supply. To compress the beam by using these dipoles, the current has to be estimated de-

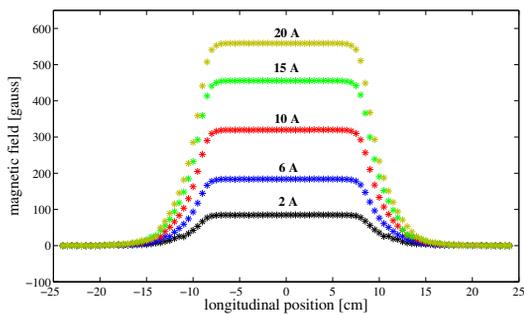


Figure 3: The vertical magnetic field profile of a dipole magnet.

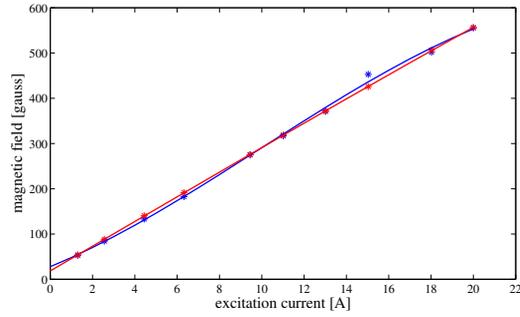


Figure 4: The magnetic field vs. the excited current for a hysteresis loop of a dipole.

pending on the total energy  $E$  of an electron beam traveling along the longitudinal direction with a bending angle  $\alpha$  [4, 6]. The correlation between the total energy of the electron beam and the excited current can be found by using Eqs. (1) and (2). As shown in Eq. (3), the effective length of the dipole,  $l_{\text{eff}}$ , can be calculated by an integral along the longitudinal direction and then a normalization with the vertical field at the center of the dipole,  $B_0$  [4–8]. The average effective length over all dipoles in the chicane is about 20.84 cm.

$$E = \sqrt{c^2 e^2 \cdot \frac{B^2 l_{\text{eff}}^2}{\sin^2 \alpha} + m^2 c^4} \quad (2)$$

$$l_{\text{eff}} = \frac{1}{B_0} \int_{-\infty}^{\infty} B(z) \cdot dz \quad (3)$$

### Quadrupole Magnet

The quadrupole magnet, as shown in Fig. 5, is made by the company TESLA. At a limited operating current of 102 A, the maximum magnetic field gradient is about 19 T/m. We set the center of the quadrupole magnet by using steel yoke to find a reference. Although the steel yoke of the quadrupole magnet is leveled with the measurement instrument, there may be an error causing the field to be rotated through some angle and the center of the field to be

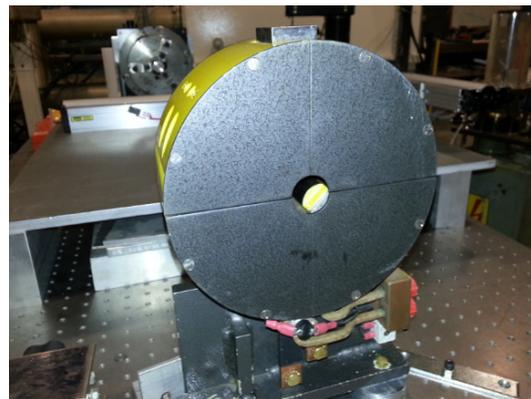


Figure 5: The photo of a quadrupole magnet.

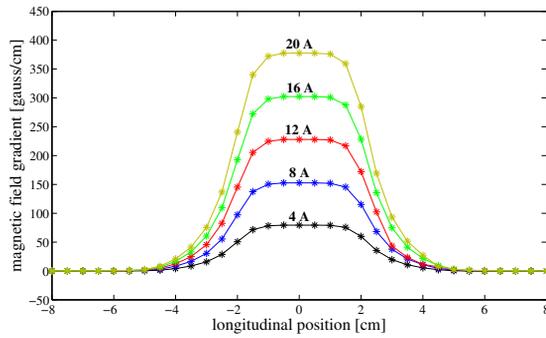


Figure 6: The magnetic field gradient profile of a quadrupole magnet.

shifted [5, 9]. The vertical magnetic field component of a quadrupole with the rotational angle  $\phi$  and the offset of the field center  $(x_0, y_0)$  is given by [9]

$$B(x, y) = g(y - y_0) \sin \phi + g(x - x_0) \cos \phi, \quad (4)$$

where  $g$  is the magnetic field gradient of a quadrupole. To find the rotation angle and the field gradient  $g$ , we measured the magnetic field  $B$  at four different  $x$  and  $y$  coordinates  $\{(d, 0), (-d, 0), (0, d), (0, -d)\}$  along the longitudinal coordinates. After that, we subtracted the measured magnetic field by using three Eqs. (5), (6), and (7) to get the rotated angle of the field,  $\phi$ . By inserting the rotated angle in Eq. (5) or (6), one can calculate the magnetic field gradient,  $g$  as shown in Fig. 6. The magnetic field gradient inside the quadrupole is also flat with the maximum magnetic field gradient,  $g_{\max}$ .

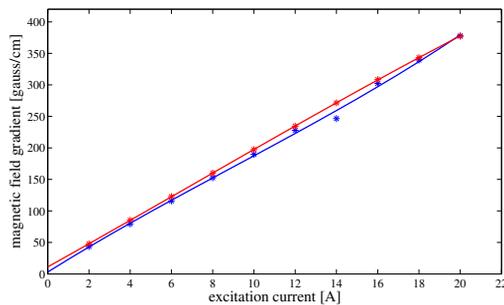


Figure 7: The magnetic field gradient vs. the excited current of a quadrupole.

$$B(d, 0) - B(-d, 0) = 2gd \cos \phi \quad (5)$$

$$B(0, d) - B(0, -d) = 2gd \sin \phi \quad (6)$$

$$\tan \phi = \frac{B(0, d) - B(0, -d)}{B(d, 0) - B(-d, 0)} \quad (7)$$

Figure 7 shows a hysteresis loop of a quadrupole when the excitation current is changed between 0 A and 20 A. Here, the blue curve was obtained when the current was increased, and the red curve was obtained when the current

was decreased. As shown in Eq. (8), using the 3rd order polynomial fitting, the gradient can be described as a function of the excitation current  $I$ .

$$g[\text{gauss/cm}] = 11.727 + 19.116 \cdot I + 8.402 \times 10^{-2} \cdot I^2 - 3.891 \times 10^{-3} \cdot I^3 \quad (8)$$

To calculate the effective length of the quadrupole, an integral was performed along the longitudinal direction and then normalized using the maximum gradient value [5, 9]. From Eq. (9), we found that the effective length of a quadrupole is about 4.96 cm.

$$l_{\text{eff}} = \frac{1}{g_{\max}} \int_{-\infty}^{\infty} g(z) \cdot dz \quad (9)$$

## CONCLUSIONS

The field maps of dipole and quadrupole magnets have been measured. The magnetic field of dipole as a function of an excited current has been approximated with the 3rd order polynomial fitting. This approximated field was used to determine the value of magnetic current for each beam energy and each bending angle. As was mentioned earlier, the magnetic field of this dipole is rectangular field profile which has the effective length of about 20.84 cm. For the quadrupole magnet, one is more interested in the field gradient than the magnetic field strength. By using the measurement of the  $B$  field at 4 points, the field gradient can be expressed in term of the excitation current. The estimated effective length of a quadrupole is about 4.96 cm.

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