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A New Method of Field Measurement for Solenoid Magnet

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A three-dimensional Hall probe mapping system for measuring the solenoid magnet of the Pohang Light Source (PLS) photo-cathode RF e-gun has been developed. It can map the solenoid field either in Cartesian or in cylindrical coordinates system with a measurement reproducibility better than 0.5 G. The system has three axis motors: one for the azimuthal direction and the other two for the x and the z direction. This architecture makes the measuring system simple to fabricate. The magnetic center was calculated using the measured axial component of the magnetic field, B_z, in a Cartesian coordinate system because the accuracy of the magnetic axis measurement could be improved significantly by using B_z instead of the radial component of magnetic field B_r. This paper describes the measurement system and summarizes the measurement results for the solenoid magnet of the PLS photo-cathode RF e-gun.

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I. INTRODUCTION

The Pohang Accelerator Laboratory plans to install a FIR (femto-second IR) and self-amplified spontaneous emission (SASE) X-ray free electron laser (XFEL). A photo-cathode RF e-gun is being developed for the injector of the PLS to accommodate the FIR and SASE XFEL. The gun should have a small emittance and a high operating charge. A small emittance is very crucial to have a reasonable saturation length for the SASE XFEL. A solenoid is widely being used to obtain a precise focusing after extraction of the electron beam [1]. The solenoid should have minimal aberration and negligible field strength at the cathode region. The magnetic axis of the solenoid has to be aligned precisely to the electron beam axis of the cathode.

Various methods for measuring the magnetic axis of the solenoid have been reported [2, 3]. Almost all the methods reported to present measure the radial component B_r of the magnetic field [4, 5]. However, the B_r in a solenoid is much lower than the axial component B_z, except at the ends of the solenoid, and it is difficult to improve the accuracy for the magnetic axis measurement.

We built a solenoid measurement system that can measure the magnetic field either in Cartesian or cylindrical coordinates system. The axial magnetic B_z of the solenoid was measured while stepping the Hall probe in the Cartesian coordinate system. The B_r component was measured at a radius of 5 mm and at a step of 10 mm along the z-axis. The magnetic axis was calculated using the measured data. The system and the measured results for the solenoid of PLS RF e-gun are presented in this paper. Also, a method for determining the magnetic axis of the solenoid from the measured field profile is described.

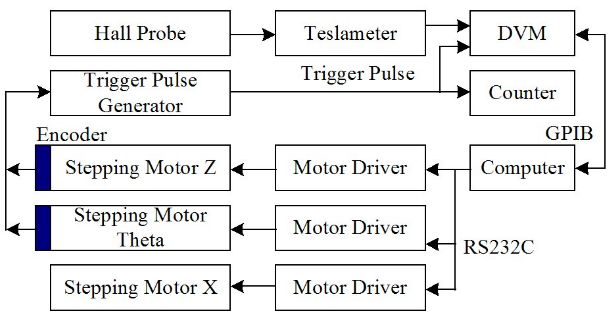

Fig. 1. A block diagram of the solenoid magnetic-field measurement system.

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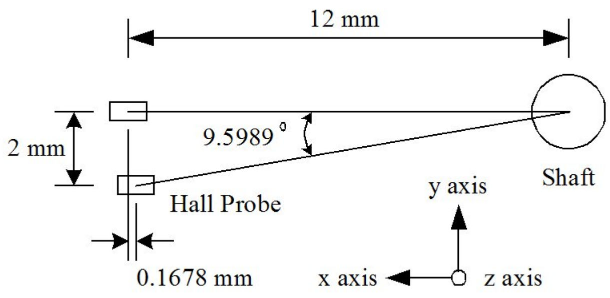

Fig. 2. A y-axis movement using Theta and x-axis stepping motors.

Table 1. Differences between the outputs of the PT2025 NMR Teslameter and the DTM-141 Teslameter A and B at $0 \sim 1.2$ T.

Items	NMR	TM A	TM B	Diff.
Field [T]	0.72734	0.72738	0.72732	4.0e-5

II. MEASUREMENT SYSTEM

As Figure 1 shown, the field measurement system consisted of a computer, a Hall probe and Teslameter, a digital volt meter (DVM), a mechanical assembly, and three stepping motors and drivers. The magnetic field was measured using the DTM-151 Teslameter and MPT-141 Hall probe from Group 3 Technology Ltd. The output voltage of the Teslameter was digitized in a HP3458A DVM from Agilent Technologies whenever the DVM received a trigger pulse from the trigger pulse generator. The trigger pulse generator counted the stepping motor encoder pulses and outputted one trigger pulse in steps of 1 mm for measuring B_z and in steps of 0.72° for measuring B_r. The control program was written in Labview, and the data were post-processed by using Matlab.

We used the method shown in Figure 2 for a three-dimensional mapping of B_z because the system had no stepping motor for the y direction. The probe was rotated in the θ direction first to achieve a y movement and then moved in the x direction to compensate for the offset. Because the encoder of the stepping motor had an angular resolution of 0.0144°, the positioning error in the y direction was less than 1.8 μm.

III. MAGNETIC FIELD MEASUREMENT

We used the 'flying' mode measurement method for the solenoid measurement system because the Teslameter DTM-151 could not sample data during a field measurement using an external trigger pulse [6]. The trigger pulses for the positions where the data should be sampled were generated using the stepping encoder signals. Because the magnetic field could not be measured using the

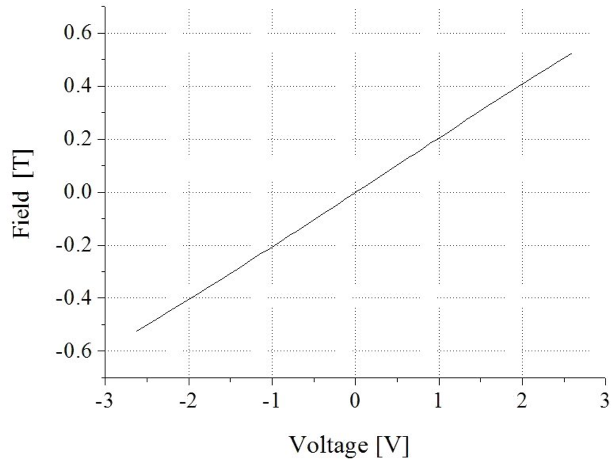

Fig. 3. An external calibration table for the Teslameter.

internal calibration table of the Teslameter, an external calibration table was built using the following procedure: a given condition, the magnetic field was measured with the Hall probes and NMR Teslameter PT2025 from Matrolab. Two Hall probes that read a magnetic field close to the NMR Teslameter output were selected. Magnetic fields in the range of $0 - 1.2$ T measured by using the two selected Teslameters differed by $\sim$0.4 G from the field measured by using the NMR Teslameter, as shown in Table 1. After selecting the Hall probes, they were put into a calibration magnet and the analogue voltages of the Teslameter were sampled and stored in a computer by using the DVM 3458A while increasing the excitation current of the reference magnet in steps. An external calibration table shown in Figure 3, which converted the measured voltages to the magnetic field, was constructed for the range of $0 \sim 0.6$ T. It was used for the 'flying' mode measurement.

The measurement coordinate system was the same as the other measurement systems: x-, y-, and z-axes in the horizontal, vertical, and beam directions, respectively. The ranges of the measurement for B_z were $-5 \leq x \leq 5$ mm, $-5 \leq y \leq 5$ mm, and $0 \leq z \leq 500$ mm. The geometrical center of the solenoid was located at (0, 0, 250 mm). The diameter and the length of the solenoid were 80 and 227 mm, and a scan length of 500 mm was sufficient for the measurement.

To check the measurement reproducibility of the system, we mapped the axial components of the magnetic field B_z over the full measurement range twice, and the measured B_z versus x at $y = 5$ and $z = 150$ mm are shown in Figure 4. The difference in the measured values was less than 0.5 G. A two-dimensional profile of the measured B_z at $z = 250$ mm is shown in Figure 5. This profile confirms that the error of the measurement system was less than 0.5 G.

The profiles of B_z along the z-axis at different excitation currents in the range of $160 - 210$ A were measured, and the results are shown in Figure 6. The B_z at 200

Table 2. Table comparing the magnetic field center to the mechanical center.

No.	z	Magnetic Center			Mechanical Center (0,0)	Difference [T]	Min. or Max.
	[mm]	x [mm]	y [mm]	Field [T]	Field[T]	(Magnetic - Mechanical)	
1	50	0.99	0.57	1.9589×10^{-3}	1.95769×10^{-3}	1.21×10^{-6}	max
2	100	0.14	0.09	0.0114076	0.01114056	2.0×10^{-7}	max
3	150	0.05	0.55	0.13415	0.13414	1.0×10^{-5}	max
4	200	−0.03	−0.02	0.28472	0.28472	0	min
5	250	3.01	−1.39	0.29856	0.29858	2.0×10^{-5}	min
6	300	−0.07	−0.04	0.28464	0.28464	0	min
7	350	0.38	−0.48	0.13398	0.13397	1.0×10^{-5}	max
8	400	−0.03	−0.16	0.111029	0.111028	1.0×10^{-7}	max
9	450	0.33	0.08	1.92877×10^{-3}	1.92872×10^{-3}	5.0×10^{-8}	max

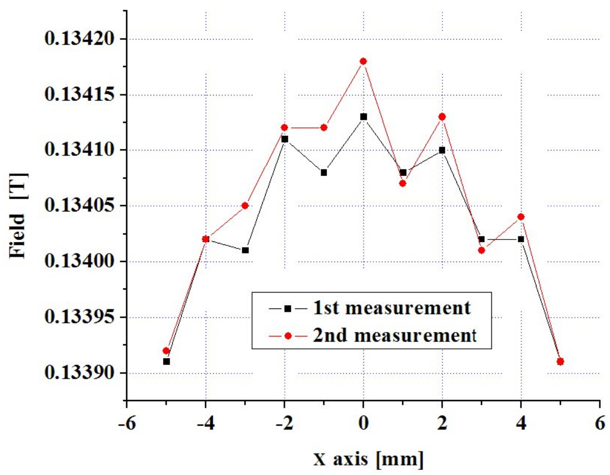

Fig. 4. The measured B_z versus x at $y = 5$ and $z = 150$ mm.

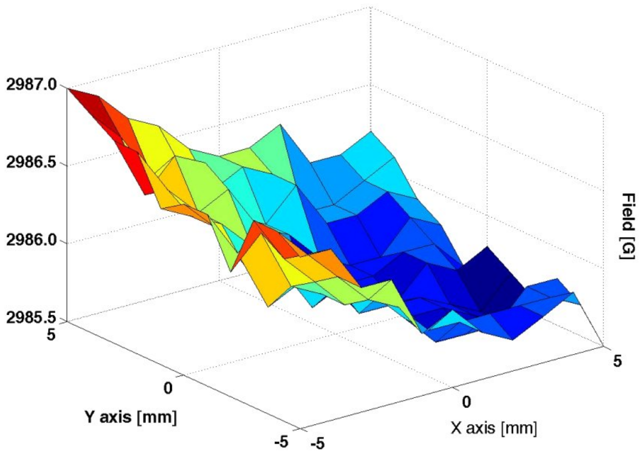

Fig. 5. A two-dimensional profile of the measured B_z at $z = 250$ mm.

A was ~3000 G, and it increased by 149 G for a 10 A increase in the excitation current.

To measure the radial component of the magnetic field,

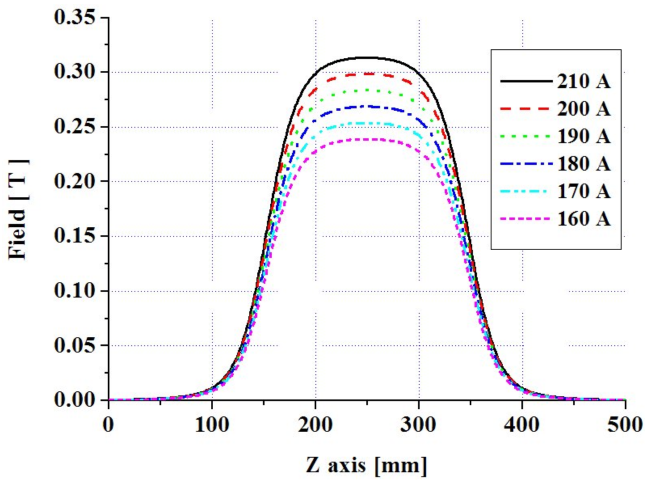

Fig. 6. Field profiles of B_z along the z-axis at different excitation currents.

B_r, we mounted the Hall probe on a holder located at a radius of 5 mm, and we aligned its normal direction to the radial direction. The probe was rotated in the θ direction and scanned in the z direction in steps of 10 mm. The measured B_r was 16.131 G at $z = 250$ mm, which was the geometrical center of solenoid where B_r should be close to 0 G according to the first order equation

$$B_r \cong \frac{-(r/2)dB(z)}{dr} \tag{1}$$

The measured B_r of 16.131 G would be observed if $B_z = 3000$ G, and the Hall probe were tilted by $\Delta\phi \equiv 0.296°$ to the z-direction. When we corrected the measured B_r by an amount $B_z \sin\Delta\phi$, the corrected B_r agreed well with the theory, as shown in Figure 7. This result indicates that the accuracy of magnetic axis measurement would be improved significantly by using B_z instead of B_r.

Measured two-dimensional field profiles of B_z at $z = 250$ mm and 200 mm for $-5 \leq x \leq 5$ mm and $-5 \leq y \leq 5$ mm are shown in Figure 8. Because there was some measurement error due to noise and probe positioning error,

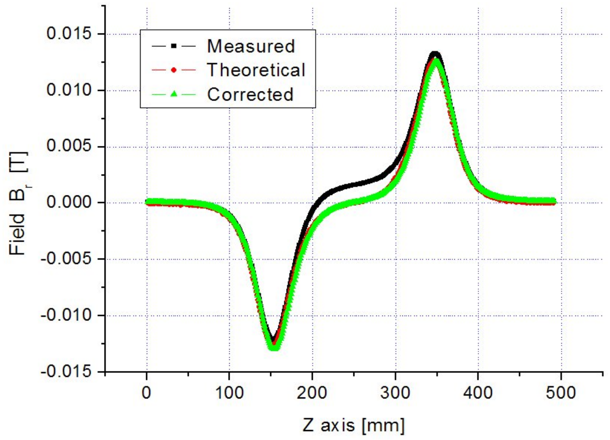

Fig. 7. Measured, corrected, and theoretical B_r along the z-axis.

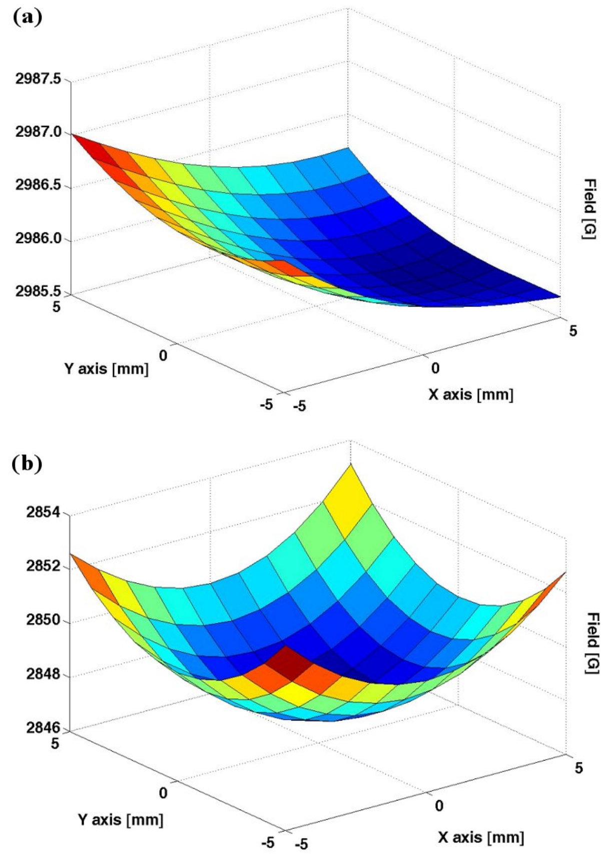

Fig. 8. Measured two dimensional field profiles of B_z at z = (a) 250 mm and (b) 200 mm, for an excitation current of 200 A.

as observed in Figure 5, the raw data were smoothened before plotting the field profiles shown in Figure 8. At $z = 250$ mm, the deviation of B_z for $-5 \leq x \leq 5$ mm and $-5 \leq y \leq 5$ mm from the one at the center was less than 1.5 G, which is acceptable for a maximum field intensity of 2986 G. For the PLS RF e-gun, the area of interest is 1×1 mm^2, so the deviation of B_z can be ignored at the solenoid center.

To obtain the magnetic center, we processed the measured two-dimensional field profiles at different positions along the z-axis in steps of 50 mm. Because the magnetic field was mapped in the x-y plane in steps of 1 mm, the measured data were interpolated. Then, the magnetic axis along the z-axis was calculated with a resolution of 0.01 mm by using the conditions $\partial B_z/\partial x = \partial B_z/\partial y = 0$. After calculation of the magnetic center, the B_z at the magnetic and mechanical centers were obtained from the measured field data, and the results were shown in Table 2. The magnetic center at $z = 250$ mm was located at $x = 3.01$ and $y = -1.39$ mm. As Table 2 shown, the difference between the B_z at the magnetic and mechanical centers was 0.2 G, and was the largest for $0 \leq z \leq 500$ mm, indicating that the mechanical axis of the solenoid could be used for the magnetic axis.

IV. CONCLUSION

A three-dimensional Hall probe mapping system for measuring the solenoid magnet of the PLS photo-cathode RF e-gun solenoid was developed. This system can map the field either in a cylindrical or in a Cartesian coordinate system with a measurement reproducibility better than 0.5 G. The shape of the measured B_r in the cylindrical coordinate system was similar to the one calculated using the measured B_z. However, it had an offset field of 16.1 G at the geometrical center of solenoid. This offset magnetic field originated from the 0.296° tilt of the Hall probe to the z direction. The offset magnetic field gives an error in measuring the magnetic center. The magnetic center was calculated using the B_z measured in the Cartesian coordinate system because the accuracy of the magnetic axis measurement could be improved significantly by using B_z instead of B_r. The difference between values of B_z at the magnetic and the mechanical centers was less than 0.2 G for $0 \leq z \leq 500$ mm, so the mechanical axis of the solenoid could be used for the magnetic axis.

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