ELECTROMAGNET MEASUREMENT TECHNIQUES FOR PARTICLE ACCELERAOTOR*

J. Yoon†
Department of Physics, POSTECH, Pohang, South Korea

Abstract

Precise control of magnetic fields is essential for the stable operation of particle accelerators, where electromagnets deflect and focus high-energy beams. However, accurately evaluating the magnetic characteristics of these magnets and producing ideal field configurations remain technical challenges. In this study, we investigated a series of experimental devices used for magnet design and testing, including a Hall sensor, a reference dipole electromagnet, and a 5-axis coil winding robot. We calibrated the Hall sensor using a dipole electromagnet that generates a stable $1T$ field, ensuring accurate field measurements in real applications. This allowed us to quantitatively evaluate magnetic fields in accelerator components with high reliability. Additionally, we explored the use of robotic winding technology to manufacture saddle-shaped coils that enable precise multipole field generation. These experiments reflect the importance of both accurate field measurements and precision coil winding in accelerator magnet design.

INTRODUCTION

An electromagnet is vitally employed in the particle accelerator to accurately transport particles such as heavy ions or electrons to the target trajectory with desired energy [1]. The particle can be controlled according to the number and arrangement of magnets. The dipole magnet bends the particle beam to the desired path, and the quadrupole magnet controls whether the beam is focused or not. In addition, the sextupole and corrector magnets contribute to improving the stability and quality of the beam. These electromagnets enable accurate beam delivery and high-energy acceleration, and directly affect the performance of the accelerator and the precision of the experiment. Therefore, the arrangement, strength control, cooling, and power supply systems of the electromagnets are very important factors in the design and operation of the accelerator.

We visited the electromagnet test facility and learned how to measure electromagnetic fields by operating the apparatus. There are three kinds of equipment: Hall sensor to measure the intensity of the magnetic field, standard dipole electromagnet to calibrate the magnetic sensor by setting standard magnetic field, and 5-axis robot arm which can conduct the coil winding. All of these tools are related to designing the magnets in the accelerator. Before installing the electromagnets, it is important to examine and optimize their condition and discuss how and where the magnets will be placed. Therefore, we studied a series of equipment mentioned above and explored the process of testing the performance of magnets in the field.

By testing these experimental equipment, we could deepen our understanding of the principle of how they work and think about how to use these in real-field experiments. We expect that this will help us with conducting the future research during the graduate course by utilizing a variety of apparatus we need. An accelerator has numerous parts in addition to electromagnets, and appropriate measuring equipment must be selected or designed, depending on the purpose of each part. Taken together, this research shows such equipment, particularly focusing on the electromagnet.

ELECTROMAGNETIC THEORY

The force that a particle receives in an accelerator determines its speed that is almost close to the speed of light or particle bunch's position so that it remains in a normal orbit. It is necessary, first of all, to fix the particle trajectory, in general an arbitrary curve in the circular accelerator like storage ring, and then to repeatedly steer the diverging particles back onto the intended trajectory. This is made by means of electromagnetic fields and corresponding Lorentz force [2]. The Lorentz force is the force exerted on a charged particle as it moves in a magnetic field. It is written as the following equation:

$$\boldsymbol{F} = e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) = \dot{\boldsymbol{p}} \tag{1}$$

where e is the charge of an electron particle and E and B mean electric field and magnetic field, respectively. Here, a magnetic field can be produced by an electric current, and an electromagnet can use this to generate a magnetic field of a desired value. This phenomenon can be summarized as the Biot-Savart law. This is the fundamental law for calculating the strength and direction of the magnetic field formed around a current-carrying wire. According to this law, the infinitesimal current $\mathrm{d}\vec{l}$ generates $\mathrm{d}\vec{B}$ and these are related by the following equation depending on the magnitude and direction of the current and the distance from the measurement point.

$$\mathrm{d}\vec{B} = \frac{\mu_0}{4\pi} \cdot \frac{I\ \mathrm{d}\vec{l} \times \hat{r}}{r^2} \tag{2}$$

where μ_0 is the permeability of the free space and r is the distance between the current and the observation point. It is widely used when interpreting the magnetic field distribution of an electromagnet or theoretically analyzing the magnetic field characteristics of a coil structure. In this

* Work supported by Pohang Accelerator Laboratory (PAL)
† yoonics@postech.ac.kr

experiment, this law can be used as a theoretical basis for understanding and predicting the magnetic field formed around an electromagnet.

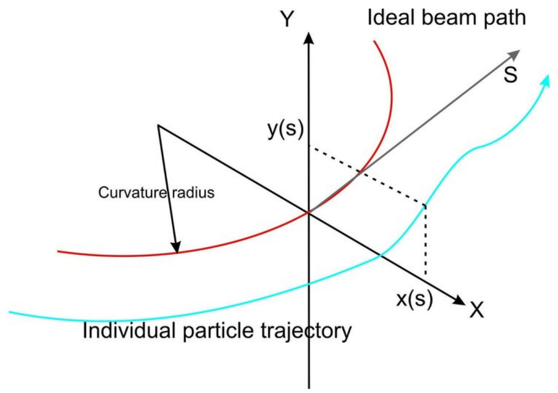

Figure 1: A trajectory of particle in the accelerator. [3]

Ultimately, the purpose of the magnet is to change the direction of the particle beam and form a conservative field to prevent the beam from deviation. In an accelerator with a cyclic beam orbit, it is important to create a closed trajectory so that the beam forms an equilibrium orbit. In addition, a conservative force must be created at the center of the orbit to prevent it from getting out too far.

LIST OF EXPERIMENTAL EQUIPMENT

We studied three types of machines associated with the electromagnet. By operating these under supervision, we acquired the method for measuring the magnetic field intensity and interpreting the data. We participated in the demonstration of the Hall sensor and dipole magnet, and then was explained prototype of coil winding robot arm.

Hall sensor

Figure 2: An overview of the Hall sensor and electromagnet. The tip of the sensor measures the magnetic field by scanning between two magnets.

A Hall sensor is a sensor that detects the strength of a magnetic field by measuring the Hall voltage that occurs when an external magnetic field acts perpendicularly on a conductor or semiconductor through which current flows. This phenomenon is based on the Hall effect, and the stronger the external magnetic field, the more the electron trajectories bend, generating a voltage difference. Since the Hall sensor has the advantage of being able to measure precisely in real time, it is widely used to measure the magnetic field of an electromagnet in a non-contact manner. By applying current to the electromagnet and placing the sensor in various locations, the spatial magnetic field distribution can be identified, and the uniformity or strength of the central magnetic field can be quantitatively evaluated. This makes the Hall sensor an essential tool in experiments requiring accurate characterization and calibration of magnetic fields, such as those conducted in particle accelerator facilities. The calibration of the Hall sensor is conducted by the following apparatus.

Dipole electromagnet

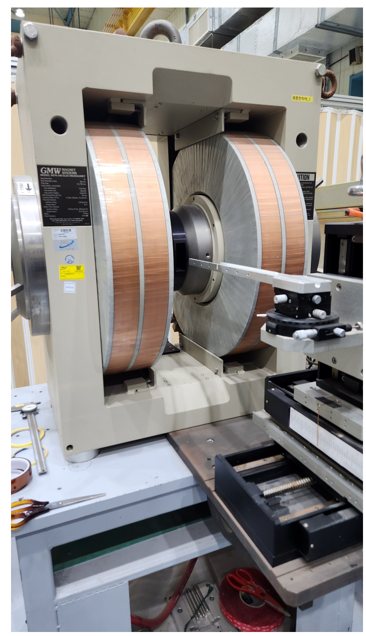

Figure 3: A dipole electromagnet model 3474-140 manufactured by GMW Association.

Before running the Hall sensor in a real experiment, it is of importance in calibrating its reliability by establishing the reference value. We could adjust the Hall sensor by inserting it between the dipole electromagnet generating a continuous and constant $1T$ magnetic field, which guarantees the reliability of the sensor. If the sensor does not read $1T$, this means that there is an error in the sensor or the initial settings are incorrect, so it must be corrected before using the sensor for other magnetic field measurements. In this context, this dipole electromagnet can be regarded as a reference one, and it actually gives an exact $1T$ field with high uniformity. This calibration process allows for the correction of systematic errors and ensures consistency across repeated measurements. Once the sensor has been accurately calibrated using the reference magnet, it can be confidently deployed in other experimental settings to measure unknown magnetic fields. This step is essential to maintain precision in magnet characterization tasks, particularly in accelerator applications where magnetic field accuracy directly affects beam quality and system performance.

5-axis coil winding machine

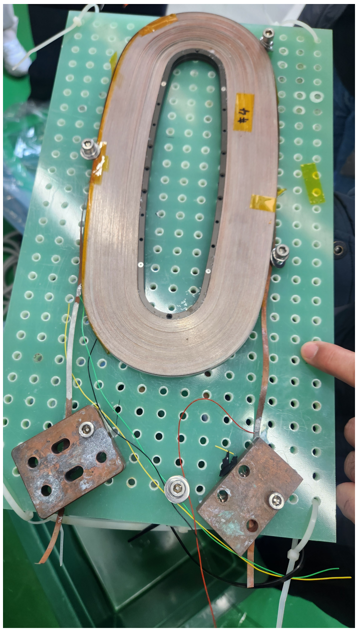

Figure 4: A bundle of coil wound by the robot arm.

Saddle-shaped coils are advantageous for generating ideal multipole magnetic fields in the magnet with a cylindrical bobbin [4]. However, it is challenging to wind a coil along the shape of the saddle. By means of 5-axis robot arm, we can precisely wind the coil, not breaking the coil's intrinsic characteristics. As we can see in Figure 4, the coil is well wound and is arranged in a flat plane. This can withstand high-current and thermal load, keeping the ideal multipole field that is useful in the accelerator. The robot arm draws the trajectory of the coil to wind the coil in a seamless shape or without the bending part. The operation of these robots could be used to generate strong magnetic fields by manufacturing uniform coil bundles. As a result, the use of a 5-axis robotic arm not only enhances manufacturing efficiency but also ensures that the electromagnetic characteristics of the coil match the intended design with minimal deviation. In the context of accelerator magnet production, this method offers a promising approach for building advanced magnets that demand both high mechanical stability and magnetic precision.

CONCLUSION

In this experiment, we explored three core apparatus of accelerator magnet technology: Hall sensor, Dipole electromagnet, and Coil winding robot arm. We demonstrated how a Hall sensor can be precisely calibrated using a high-uniformity dipole electromagnet, establishing it as a reliable tool for field measurements. This calibration enabled us to assess the magnetic properties of other magnets with improved accuracy. Furthermore, we examined a 5-axis robot arm to wind the coil that is capable of producing saddle-shaped coils for generating ideal multipole fields. These coils maintain their electromagnetic characteristics under high current and thermal stress, contributing to the quality of the accelerator beamline. Through hands-on experiment with these devices, we have deepened our understanding of how precision and reproducibility are achieved in magnet design. In the future, we can diversify the purpose of the Hall sensor, find out new method for calibrating the sensor, and improve the movement of the 5-axis robot. These advances will be essential for the development of next-generation accelerator facilities that require higher precision and efficiency.

REFERENCES

[1] C. M. Spencer and S. J. Rhee, "Comparison study of electromagnet and permanent magnet systems for an accelerator using cost-based failure modes and effects analysis," *IEEE transactions on applied superconductivity*, vol. 14, no. 2, pp. 413–416, 2004.

[2] K. Wille, *The physics of particle accelerators: an introduction*. Clarendon Press, 2000.

[3] B. Cheymol, *Development of beam transverse profile and emittance monitors for the CERN LINAC4*. PhD thesis, Université Blaise Pascal-Clermont-Ferrand II, 2011.

[4] S. Yang, W. Song, J. Park, G. Kim, J. Y. Huang, S. Hahn, S. Choi, H. Kang, and G. Hahn, "Development of a 5-axis winding method for saddle-shaped coils using coated rebco high temperature superconductors," *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1–4, 2024.