PHYS719P REPORT NO.1: BEAM PHYSICS FOR ELECTROMAGNETS AND PRACTICAL APPLICATIONS

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Abstract

Electromagnets serve as one of the key components of the accelerator. The electromagnets are capable of generating stronger fields compared to permanent magnets and allow fine adjustment of particle trajectories. This report summarizes the basic principles of electromagnets and practical applications to the synchrotron located in POSTECH: Pohang Light Source-II (PLS-II). Furthermore, application of superconducting magnets to generate higher magnetic fields in advanced accelerators is discussed.

I. INTRODUCTION

Electromagnets play several key roles in modern accelerators, especially in the manipulation and guidance of charged particle beams. There are various types of electromagnets utilized in particle accelerators. Dipole magnets are used in synchrotrons and storage rings such as the Large Hadron Collider (LHC) and Pohang Light Source-II (PLS-II) to generate a uniform magnetic field which guides charged particles to orbit a desired trajectory. Quadrupole magnets which are used in linacs and synchrotrons focus the beam in a particular direction while defocusing in its perpendicular direction. Sextupole magnets are used for controlling beam quality by correcting chromatic aberrations.

When designing a magnet for accelerators, the principle of beam optics is utilized to ensure that the particles stay on a well-defined path and maintain a desired profile. The behavior of beams as they travel through an accelerator consisting of magnets is very similar to traditional optics dealing with the focusing and guiding of electromagnetic waves.

In order to ensure that the particles reach the target efficiently while maintaining a desired beam profile, not only is the proper design of magnets based on the principle of beam optics important, but also the in-situ evaluation of fabricated magnets is crucial to improve experimental precision.

In this report, the dynamics of beams under dipole, quadrupole, sextupole magnets will be briefly explained in section II. Following in section III, practical methods to validate the magnet performance through simulations and laboratory tests will be introduced. In section IV, facilities to develop superconducting magnets for applications to next-generation accelerators will be introduced. Finally, section V gives a summary of this report.

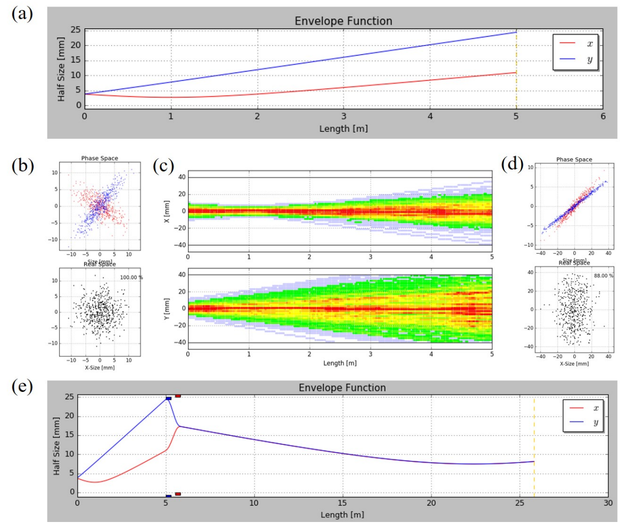

Figure 1: (Adopted from ref. [1]) Characteristics of a drifting beam and that corrected by a quadrupole magnet. Subplot (a) shows the size of the beam which varies according to position. (b) shows the initial beam distribution in the phase-space (top) and the real-space (bottom). (c) shows the traverse beam profile, and (d) shows the beam distribution in the final state. Subplot (e) show the size of beam which is passed through an quadrupole magnet.

II. BRIEF INTRODUCTION ON BASIC BEAM PHYSICS FOR DESIGNING MAGNETS

Phase space provides a comprehensive picture of a particle's transverse (i.e. perpendicular to the particle trajectory) position and momentum. Since the initial conditions of accelerating particles are nonuniform, it is necessary to express particle motion in a statistical manner. The beam *emittance* is a critical parameter that quantifies beam quality, determined by the spatial and momentum distribution of particles.

As charged particles travel through a dipole magnet, they undergo a deflection due to the Lorentz force. This bending effect introduces a natural drift in the beam, resulting in the variation of particle position and momentum (i.e.beam dispersion). Since the dipole magnets serve as an essential component in an accelerator to steer particle beams along a predefined path, the beam dispersion should be corrected to secure beam coherence and luminosity.

To mitigate the effects of drift and to enhance beam focusing, quadrupole magnets can be employed. Figure 1 shows the characteristics of a beam having drift in the y direction

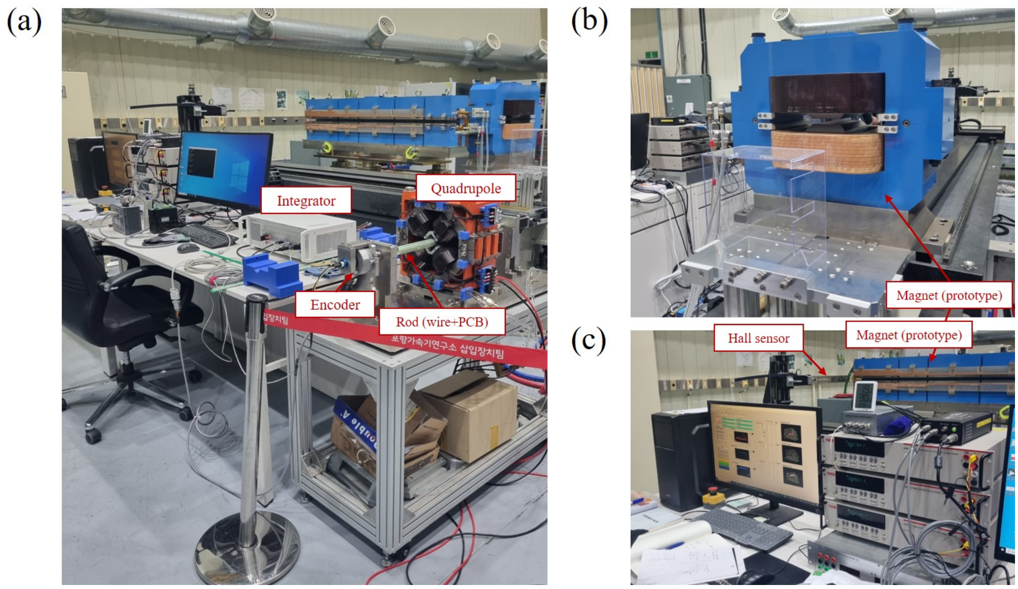

Figure 2: Prototype of measurement system in PLS-II: (a) Setup of rotating coil method, (b) Prototype of magnet to calibrate the Hall sensor, and (c) Setup of hall sensor method. In the rotating coil method, the encoder averages $\sim 10^4$ data points and sends to the integrater, where temporally resolved data is acquired. Hall sensor is mounted on linear guides to scan the magnetic field. Note that the system is placed on the granite stage, to minimize expansion due to thermal expansion and minimize error due to mechanical vibrations. On the right of the monitor is placed the trigger distributor, which ensures the simultaneous measurement of magnetic field components in 3 directions.

(subfigures a-d) and that corrected with a quadrupole magnet (subfigure e). Unlike dipole magnets, which generate a uniform magnetic field, quadrupoles produce a field gradient that exerts a focusing force in one transverse plane while simultaneously defocusing the beam in the orthogonal plane. Generally, the magnetic field by quadrupoles can be expressed as follows [1]:

$$\begin{aligned} B_x &= 2\left(J_2 x + K_2 y\right), \\ B_y &= 2\left(K_2 x - J_2 y\right). \end{aligned} \tag{1}$$

Despite the advantages of quadrupoles, chromatic aberrations can arise due to the variation of particle energy in a beam. This is because the focal length of a quadrupole magnet is inversely proportional to a particle's momentum - higher energy particles experience weaker focusing. To mitigate these aberrations, sextupole magnets are introduced. Sextupoles generate a nonlinear magnetic field, which exerts a corrective force proportional to the particle's energy deviation. The magnetic field by sextupoles can be expressed as follows [1]:

$$\begin{aligned} B_x &= 3\left[J_3\left(x^2 - y^2\right) + 2K_3 xy\right], \\ B_y &= 3\left[K_3\left(x^2 - y^2\right) - 2J_3 xy\right]. \end{aligned} \tag{2}$$

Sextupole magnets are important for ensuring high-performance operation, restoring beam coherence which may be affected by quadrupoles and minimizing beam divergence.

III. IN-SITU EVALUATION OF FABRICATED MAGNETS

Characterization of accelerator magnets is important to ensure that their performance matches the design specifications. Following measurement techniques can be employed to evaluate the magnetic field produced by fabricated magnets in practice: rotating coil method, Hall sensor method, stretched wire method, and pulsed wire method.

Rotating coil method

In this method, a coil mounted on a cylindrical support is rotated inside the magnet's aperture, measuring the induced voltage generated according to Faraday's law. The Fourier components of induced voltage provide information on the field strength and uniformity. This technique is highly effective for measuring multipole magnet components and widely used for assuring the quality of the magnet during fabrication and installation. A setup of rotating coil method is shown on figure 2(a).

Hall sensor method

A Hall sensor measures the local magnetic field at specific points by measuring the voltage due to charge separation of a current-carrying conductor under an external magnetic field. By scanning the sensor across the magnet, a spatially-resolved field map can be constructed. Provided that the calibration is well performed, the Hall sensor method can provide a precise and high-resolution distribution of mag-

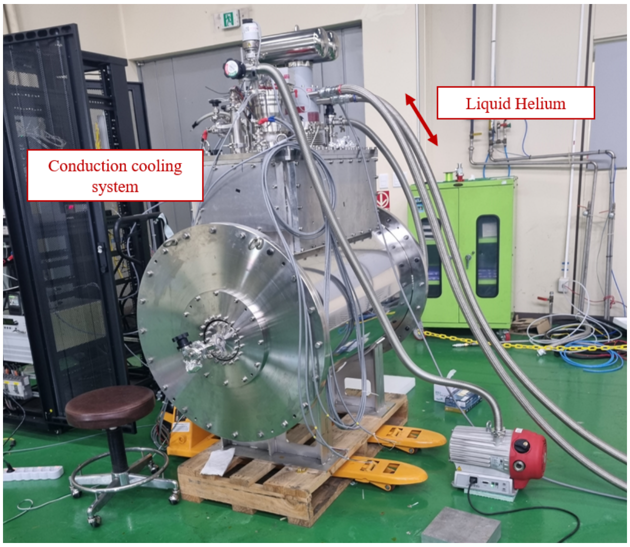

Figure 3: A cryostat equipped with conduction cooling system to test superconducting magnets.

netic field but is limited to static field measurement. A setup of Hall sensor method is shown on figure 2(c).

Stretched wire method

In this method, a thin wire is placed along the magnet axis. When a current is applied on the wire, the force exerted on the wire due to the external magnetic field causes a displacement. Then the integral magnetic field is measured, as a displacement of the wire induces a voltage. This method is used as an alternative technique for magnetic alignments.

Pulsed wire method

The pulsed wire method provides rapid characterization, feasible of measuring dynamic fields. Similar to the stretched wire method the wire is along the magnetic axis, but this method involves sending a short pulse onto the wire. A transient Lorentz force by the electric pulse causes the wire to oscillate, and the resulting displacement is recorded using electrical sensors. This method is particularly useful for time-varying magnetic field but may be difficult for spatially long magnets.

IV. DEVELOPMENT OF NEXT-GENERATION SUPERCONDUCTING MAGNETS

High-temperature superconductors (HTS) are expected to serve as a key component for next-generation accelerators, by allowing stronger magnetic fields ($\sim$ 30 T) and higher current tolerance ($\sim \times 10^3$ that of copper). As shown in figure 3, conduction cooling systems are employed to test superconducting materials, since they enable a more efficient cooling compared to the traditional liquid helium bath cooling. The low temperature is maintained through thermal contact with cryocoolers by copper rods.

V. SUMMARY

The role of electromagnets in particle accelerators are discussed, such as dipole, quadrupole, and sextupole magnets. Beam physics concepts such as phase space, emittance and how different magnets influence beam dynamics are introduced. Understanding the principles of magnets dealt in this report is essential for optimizing beam dynamics, minimizing emittance growth, and achieving the high luminosities.

Furthermore, practical methods for evaluating fabricated magnets are explained with pictures on in-situ measurements. These measurement methods play a crucial role in ensuring the precise calibration and performance of accelerator magnets, ultimately contributing to the overall stability and efficiency of accelerators. Advancements in high-temperature superconductors for the next generation accelerators are discussed as well.

ACKNOWLEDGEMENTS

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REFERENCES

[1] G. Hahn, *Lecture note on beam physics for magnets and their designs*, Division of Advanced Nuclear Engineering (DANE), POSTECH, Pohang, Korea, Mar. 2025