Hands-on Accelerator Experiments I, accelerator electromagnet

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I. THEORY

I.1. Introduction to Magnetic Elements in Accelerators

In particle accelerators, magnetic elements are essential components used to control the trajectory, focus, and stability of charged particle beams. These elements, such as dipole, quadrupole, and sextupole magnets, work in conjunction to bend, focus, and correct the beam's path, ensuring its accurate and efficient movement through the accelerator.

Magnetic fields in accelerators are designed to manipulate the beam's momentum and position with extreme precision. The role of each type of magnetic element varies depending on the desired beam dynamics and the specific functions of the accelerator. Dipoles are used for bending, quadrupoles for focusing, and sextupoles for correcting higher-order effects like chromaticity.

I.2. Lorentz Force and Beam Dynamics

Charged particles in a magnetic field experience the Lorentz force, which influences their motion. The Lorentz force equation is given by:

$$= q(E + v \times B), \tag{1}$$

where E is the electric field, B is the magnetic field, q is the particle's charge, and v is the velocity of the particle. In accelerators, the magnetic field is primarily used to bend the beam, while electric fields accelerate the particles along their path.

The interaction between the charged particle and the magnetic field causes the particle to move along a curved trajectory. The magnitude of the force depends on the velocity of the particle and the strength of the magnetic field. This is fundamental in controlling the particle's trajectory and ensuring that it follows a specific path within the accelerator.

I.3. Magnetic Field Design in Accelerators

Magnetic fields in accelerators are generated by various types of magnets, each serving a specific purpose. The design of these magnetic fields is crucial for controlling the beam's path and achieving the desired beam dynamics. The three main types of magnets used in accelerators are:

- Dipole Magnets: Used for bending the beam, dipole magnets create a uniform magnetic field that causes particles to move in a circular or helical path.
- Quadrupole Magnets: These magnets focus the beam in one direction while defocusing in the perpendicular direction. They are essential for maintaining beam size and preventing divergence.
- Sextupole Magnets: Used for higher-order corrections such as chromaticity, sextupole magnets help correct for energy-dependent beam displacement.

The magnetic field within an accelerator is usually carefully mapped to ensure uniformity and accuracy. Imperfect field designs can lead to beam instability, energy losses, or misalignment, making precise magnetic field control critical for successful particle acceleration.

I.3.1. Field Mapping and Quality

Magnetic field mapping is essential in accelerator design to ensure that the magnetic fields are as uniform as possible, with minimal distortions. By mapping the field in two or three dimensions, engineers can verify that the magnetic elements are performing as expected and make adjustments if necessary.

Field quality can be described using multipole expansions, which allow for a more detailed understanding of the field components:

$$B^*(z) = i\frac{dF}{dz} = i\sum_{n=1}^{\infty} nC_n z^{n-1}, \tag{2}$$

where C_n are the coefficients of the magnetic field's multipole components. This series expansion helps identify higher-order magnetic components that might affect beam stability and dynamics.

I.4. Beam Stability and Focusing Mechanisms

Beam stability is a key aspect of accelerator design, as particles need to remain focused and aligned to follow the desired path. Magnetic fields are used to stabilize the beam and prevent it from diverging. The primary mechanisms for maintaining beam stability are:

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- Cyclic orbits in accelerators: In cyclic accelerators, such as synchrotrons, the beam must follow a closed orbit. This is achieved using dipole magnets, which bend the beam back onto its original trajectory.

- Focusing with quadrupoles: Quadrupole magnets are used to focus the beam in one direction while defocusing it in the perpendicular direction. The proper alignment and strength of these magnets are crucial for maintaining beam stability and preventing the beam from spreading out.

I.4.1. Phase Space and Emittance

The concept of phase space is important in accelerator physics. Phase space refers to the space of possible states of the beam, defined by both its position and momentum. The area of phase space occupied by the beam, known as the beam's emittance, is a measure of its quality and stability. A smaller emittance corresponds to a more focused and stable beam.

The dynamics of the beam in phase space are governed by the laws of motion, with the beam's trajectory influenced by the electromagnetic fields in the accelerator. The emittance is conserved in ideal conditions, but it can increase due to various factors such as magnetic imperfections or beam losses.

I.5. Chromaticity and Higher-Order Effects

Chromaticity refers to the energy dependence of the beam's position. A beam with varying energy will experience different forces from the magnetic field, causing it to deviate from its expected path. Sextupole magnets are used to correct for chromaticity by introducing higher-order magnetic fields that compensate for the energy-dependent deviations.

I.5.1. Sextupoles and Chromaticity Correction

Sextupole magnets are designed to correct chromaticity by introducing a magnetic field that varies quadratically with position. The field generated by a sextupole magnet is given by:

$$B_y = K_3(x^2 - y^2), \quad B_x = 2K_3xy. \tag{3}$$

These magnets are used in conjunction with quadrupoles to ensure that the beam remains stable despite variations in energy. Proper chromaticity correction is essential for maintaining beam quality and ensuring that the beam follows the correct trajectory.

I.6. Measurement Techniques and Field Quality Control

Accurate measurement of the magnetic field is essential for ensuring the proper functioning of an accelerator. Tools such as rotating coil magnetometers are commonly used to measure the magnetic field inside the accelerator magnets. These measurements provide critical feedback for optimizing the field design.

I.6.1. Rotating Coil Magnetometers

A rotating coil magnetometer works by rotating a coil of wire within the magnetic field. As the coil rotates, it measures the magnetic flux, allowing for the determination of the field strength at various points. This technique is commonly used for mapping the field inside dipole and quadrupole magnets, providing valuable data on field quality.

Through advanced techniques such as multipole field expansions and the use of precision measurement tools like rotating coil magnetometers, accelerators can achieve high-performance levels. The precise control of magnetic fields is essential for producing high-quality beams necessary for experiments in particle physics and other applications.

II. EXPERIMENT

It was a time to briefly find out what is in general and what principles it has. I will list the photos taken in the training class first and then provide additional explanations.

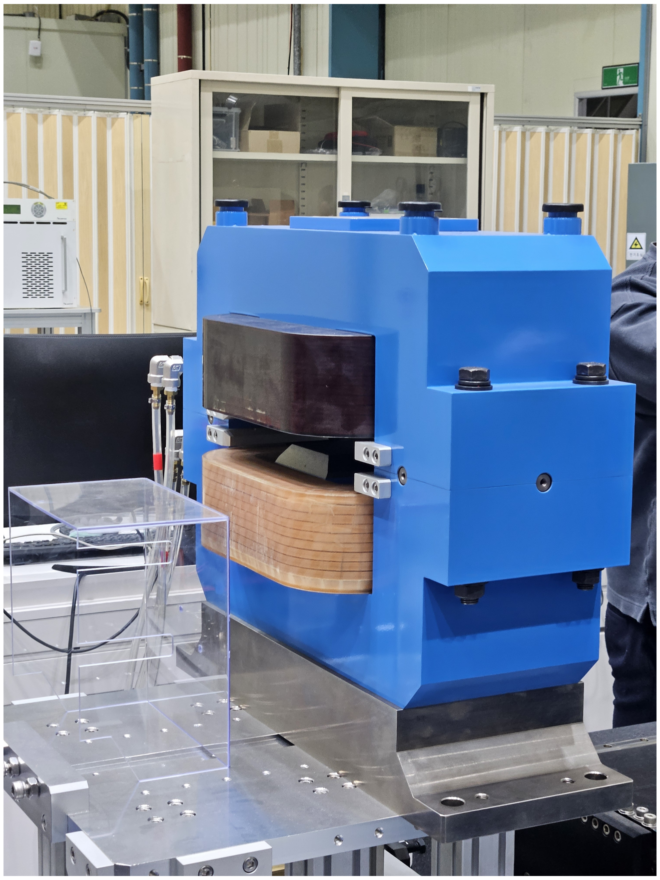

FIG. 1.

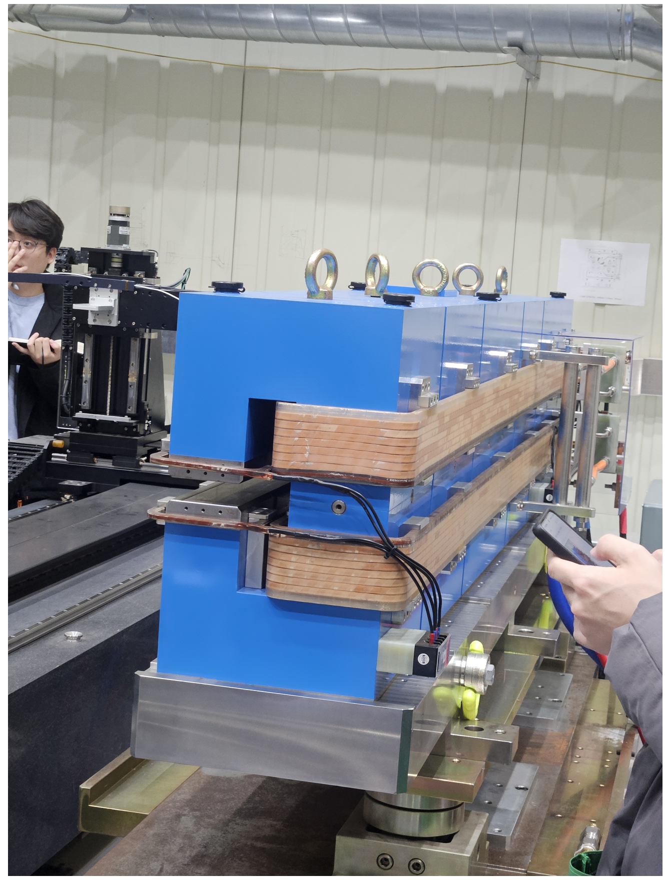

FIG. 2.

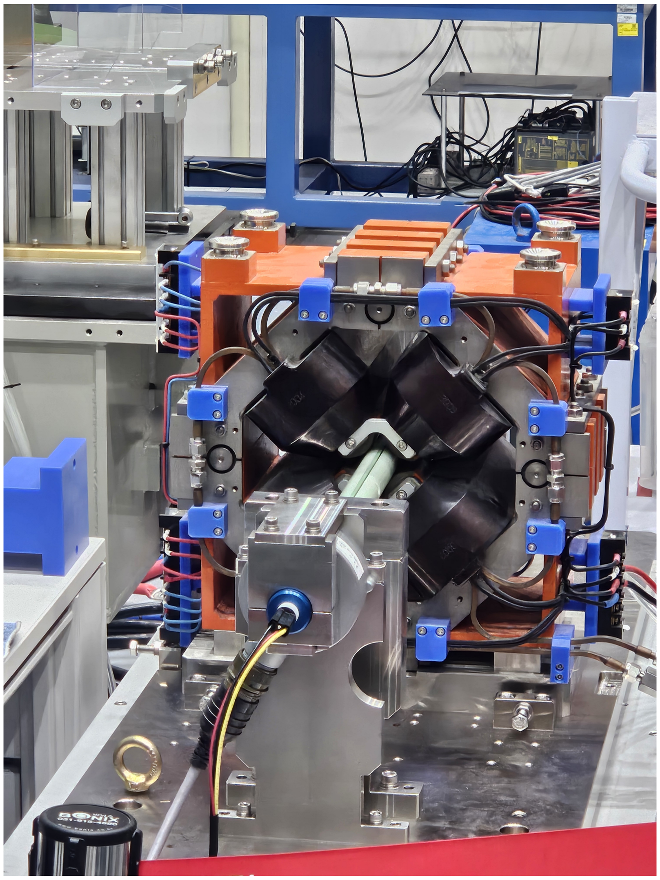

FIG. 3.


Stop
Variables
Button
Set Current
Read Current
GO Zero Gauss
All Stop
GO Start POS
De Mag
GO Magent Center
START
EXIT
Bx DVM Graph
By DVM Graph
Bz DVM Graph
Bx DVM Data
By DVM Data
Bz DVM Data
X axis
Z axis
LG

FIG. 4.

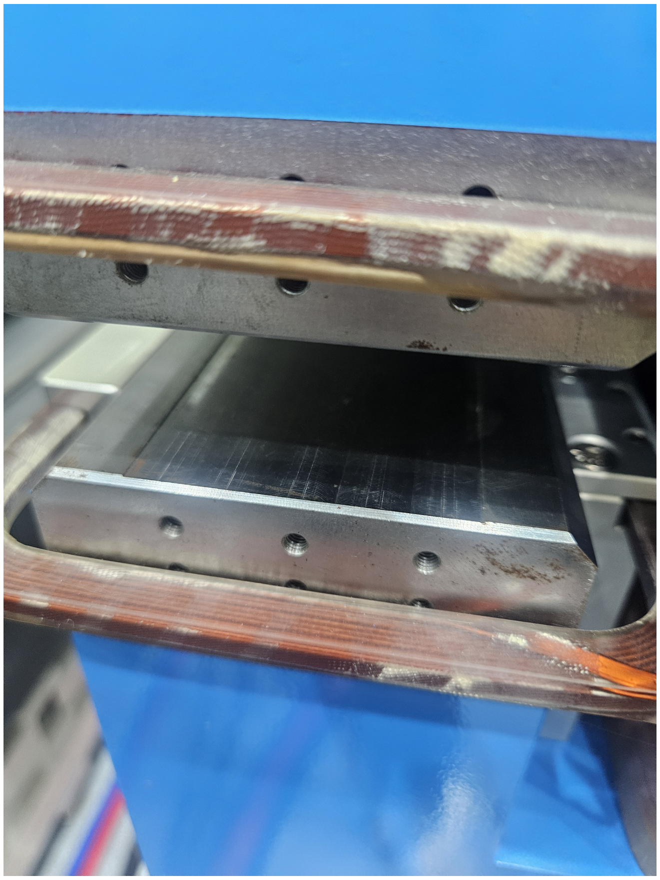

FIG. 5.

FIG. 6.

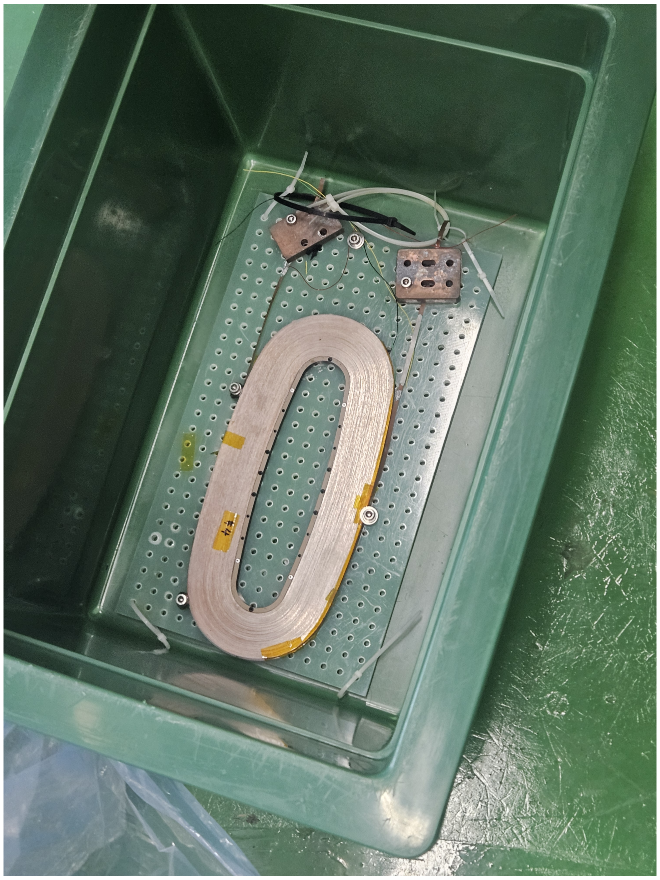

FIG. 7.

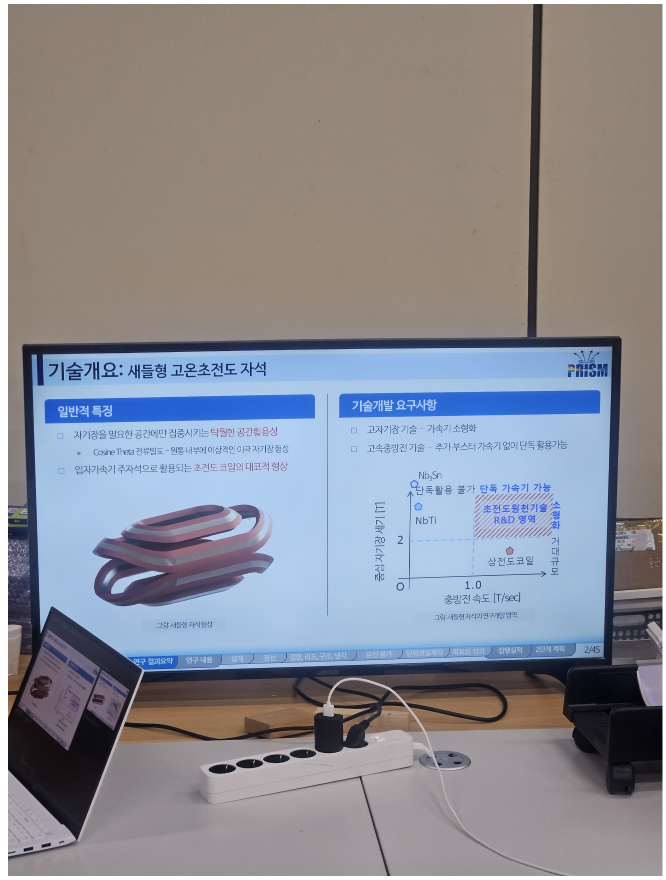

FIG. 8.

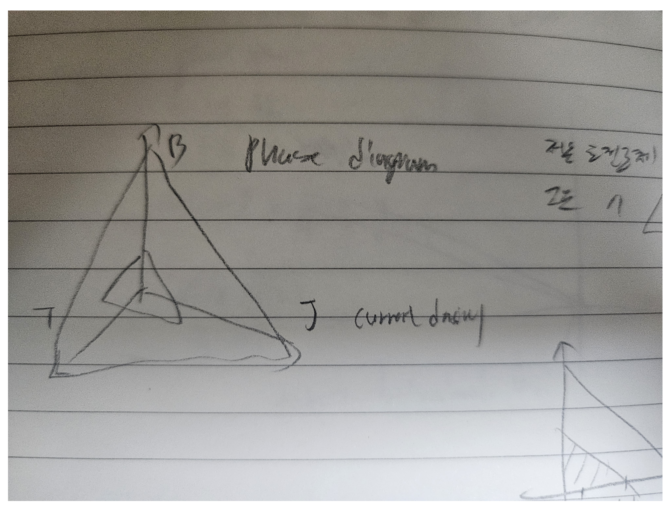

FIG. 9.

FIG. 1. is a dipole magnet.
FIG. 2. is the part of the scene where the magnetic field is measured with a Hall sensor. FIG. 4 shows the physical quantities measured by an elongated sensor over that long path.
Granite is often used at this time, and the reason is that it is often used because there is no change in variables

such as temperature. It was a long piece of equipment, but it doesn't seem to have been taken.
FIG. 3. is a quadrupole magnet.
FIG. 5. is an enlarged edge of FIG. 2. with boundaries in the corners (which seem to be a smooth side to the eye but actually feel very fine when touched by hand). But I can't remember why it was designed like that.
FIG. 6. is a photograph measured when the location was moved, and in memory, it was experimental equipment related to cooling.
FIG. 7. is a copper wire.
FIG. 8. was a recent project by a doctor that I worked on with a company, and I finished by listening briefly to the explanation of this.
FIG. 9. was written down while listening to the explanation of the (high temperature?) superconductor, and it was said that the three beats of magnetic field, current density, and temperature should be right.

In addition, I heard a number of things about high-temperature superconductors, and ReBCO (which may not be accurate) has superconductivity, but I don't know why, and he also said that if you find an equation related to it, you will get a Nobel Prize.

III. REFERENCE

[1] Garam HAHN, "accelerator electromagnet - part 1", *POSTECH*, 2025, pp. 1-38.

[2] Garam HAHN, "accelerator electromagnet - part 2", *POSTECH*, 2025, pp. 1-26.