# Magnet Design in Collider Physics

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In collider physics, the design of magnets is paramount to the control and manipulation of high-energy particle beams. This review explores the critical roles of dipole, quadrupole, and higher-order multipole magnets in steering, focusing, and stabilizing particle beams within colliders. Furthermore, the review discusses the importance of superconducting magnets and delves into the problem of cooling superconducting materials. Additionally, the paper discusses recent advancements made by CERN in the development of superconducting magnets, particularly focusing on the use of niobium-titanium. Innovations in superconducting technology, including the potential application of high-temperature superconductors and materials such as niobium-tin (Nb3Sn), are examined for their implications on future magnet performance and collider efficiency. Through improved magnetic field strength, stability, and energy efficiency, these advancements promise to significantly enhance collider performance, paving the way for new discoveries in collider physics.

## I. INTRODUCTION

In the field of particle physics, collider experiments are instrumental in exploring the fundamental components of matter. These experiments rely heavily on sophisticated magnet designs to manipulate and control particle beams at high energies. The magnets used in colliders like the Large Hadron Collider (LHC) at CERN are critical for steering, focusing, and maintaining the stability of particle beams as they travel at near-light speeds. This review discusses the various types of magnets used in collider physics, focusing on dipole, quadrupole, and other multipole magnets. We discuss the role of magnets in these particle colliders as well as innovations in technology that aid the development of stronger and more efficient magnets for the future. Additionally, we specifically highlight CERN's recent advancements in superconducting magnet technology, particularly using niobium-titanium, and explore future advances in superconductivity that could enhance magnet performance in particle colliders.

## II. ROLE OF MAGNETS IN COLLIDERS

### A. The Lorentz Force

The Lorentz force is fundamental to the operation of particle accelerators and colliders, serving as the primary mechanism for steering charged particles. Describing the interaction between charged particles and electromagnetic fields, the Lorentz force is given by the equation:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

where $\vec{F}$ is the Lorentz force, $q$ is the charge of the particle, $\vec{E}$ is the electric field, $\vec{v}$ is the velocity of the particle, and $\vec{B}$ is the magnetic field. In the context of particle accelerators, where magnetic fields play a more critical role in steering, dipole magnets are utilized to exert the Lorentz force on moving charged particles, thereby steering them along the desired circular or curved paths. The force is always perpendicular to both the velocity of the particles and the magnetic field, causing the particles to follow a curved trajectory. The relevant form of the Lorentz force simplifies to the following where since we have perpendicular magnetic field, we can derive the radius of curvature as well [1]:

$$\vec{F} = q(\vec{v} \times \vec{B}) \Rightarrow R = \frac{mv}{qB}$$

This relationship underscores the necessity of precise control over the magnetic field strength in steering particles effectively in colliders. Higher magnetic fields can achieve tighter curvatures, allowing for more compact accelerator designs.

Beyond mere redirection, the control of beam dynamics using the Lorentz force involves maintaining beam stability and minimizing dispersion. This necessitates a delicate balance between magnetic field strength, particle velocity, and beam density, factors that are also influenced by multipole magnets [1].

## III. MAGNET TYPES AND FUNCTIONS

The primary types of magnets used in colliders are dipole and quadrupole magnets, although more complex multipole magnets are also employed for specific purposes [2].

Dipole magnets, by generating a uniform magnetic field perpendicular to the particle's motion, are the primary tools for implementing control over the direction/trajectory of particles. They generate a uniform magnetic field with two poles (north and south), creating the Lorentz force required to bend the paths of charged particles. As particles traverse through these magnetic fields, they are continuously redirected, maintaining their path within the collider following through with the accelerator's vacuum tube due to the strategic placement of the magnets.

Quadrupole magnets, on the other hand, are used for beam focusing. Their four-poled magnetic field setup creates gradient fields that can focus or defocus particle beams, countering the natural tendency of the charged particles to repel each other and spread out. This is essential for maintaining a tight beam cross-section and combating the natural tendency of the beam to spread out due to mutual repulsion among particles.

Sextupoles, octupoles, and others are used to correct for more complex beam dynamics issues, such as chromaticity and beam instabilities. These magnets provide additional levels of control over the beam shape and trajectory, which are crucial for achieving high collision rates and effective data collection [1, 2].

## IV. SUPERCONDUCTING MAGNETS

Superconducting materials, such as niobium-titanium (Nb-Ti) and niobium-tin (Nb3Sn), transition to a superconducting state below specific critical temperatures and magnetic field strengths. Maintaining temperatures well below these critical points is essential to prevent the superconductor from transitioning back to a resistive state, which would result in energy losses and potential system failures. Thus, these superconducting materials allow us to use strong field electromagnets which are necessary for directing particles as discussed in the previous section. For many superconducting materials used in magnets, these temperatures are often below 10 Kelvin, meaning that we need to engineer cooling technologies and methods to allow the material to be superconducting.

### A. Cooling Technologies

Liquid helium is the most commonly used coolant in superconducting magnet systems due to its extremely low boiling point of 4.2 Kelvin at atmospheric pressure. By circulating liquid helium around the coils of a superconducting magnet, the system can be kept at a temperature conducive to superconductivity.

Liquid nitrogen is also used as it has relatively low boiling point (77.15 Kelvin) and is also much cheaper than liquid helium.

To cool the electromagnets, they are encased in a cryostat, an insulated vessel designed to maintain cryogenic temperatures. Helium is circulated through channels surrounding the magnet coils, absorbing heat and keeping the magnet superconducting. Furthermore, outside this chamber, we can have different cooling methods constrained by the nature of the particular collider experiment.

Cooling superconducting magnets is not without its challenges. The primary issues include cost and scarcity. The operation and maintenance of cryogenic systems, particularly those relying on liquid helium, are costly due to the high price of helium and the energy required for

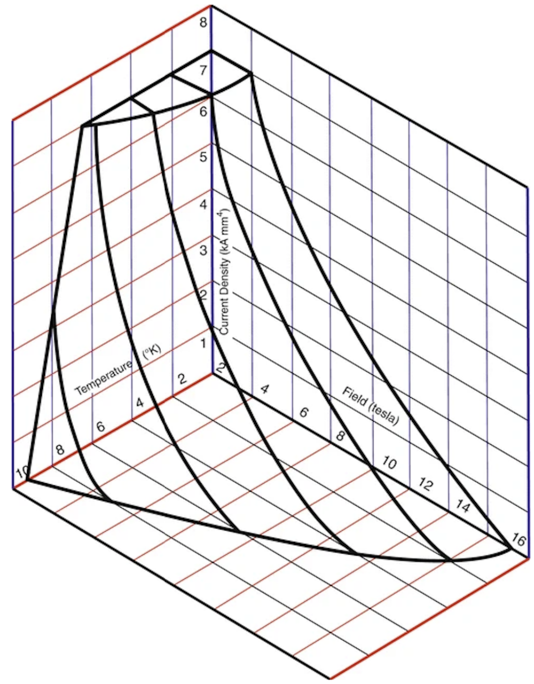


FIG. 1. Diagram showing the critical surface of the niobium-titanium superconducting material [3].

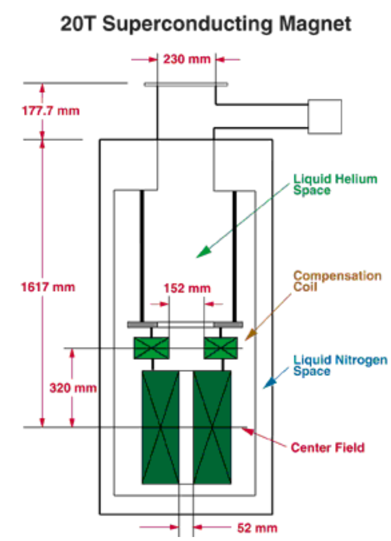


FIG. 2. Cooling technology for a 20 Tesla superconducting magnet used in the Los Alamos National Laboratory [4].

refrigeration. Furthermore, Helium is a non-renewable resource with fluctuating availability and price, prompting the need for helium recovery and recycling systems.

## V. INNOVATIONS IN TECHNOLOGY

Looking forward, innovations in superconductivity hold the key to next-generation collider magnets. Research into high-temperature superconductors (HTS) could potentially allow for superconducting magnets that operate at higher temperatures than traditional electromagnets. This would reduce the reliance on expensive liquid helium cooling systems and lower the overall energy consumption of collider operations [1, 5].

CERN has been at the forefront of developing superconducting magnets for collider applications. These magnets are crucial for achieving the high magnetic fields required while maintaining manageable operational costs. CERN's use of niobium-titanium as a superconducting material has been pivotal and more recently, the research into niobium-tin as a more efficient superconducting material is quite promising[5]. These alloy becomes superconducting at cryogenic temperatures, allowing it to carry large electric currents without resistance, thus creating intense magnetic fields necessary for high-energy particle acceleration.

Recent innovations at CERN include enhancing the performance of these superconducting magnets through improved design and material engineering. The development of more robust superconductors, capable of operating at higher magnetic fields and temperatures, promises to significantly enhance collider performance. For instance, techniques to enhance the flux pinning properties of niobium-titanium and niobium-tin have led to magnets that are more efficient and capable of generating stronger and more stable magnetic fields [5].

Advancements in material science that allow for higher critical current densities and improved thermal properties could help with the coiling of wire in electromagnets to increase efficiency. Most notably, CERN has investigated the use of the MgB2 cable which has shown significant promise in improving magnetic field strength [5].

## VI. CONCLUSION

In conclusion, the development and refinement of magnet technologies are central to the success of collider physics. Dipole and quadrupole magnets, along with more complex multipole arrangements, play critical roles in steering and focusing particle beams, enabling high-precision experiments. CERN's ongoing work in improving superconducting magnets, particularly through the use of niobium-titanium and the exploration of new superconducting materials, is set to significantly enhance the capabilities of future colliders. However, cooling technologies must develop hand-in-hand with these superconducting materials and constrict collider experiments by cost and scarcity of materials. As superconductivity technology evolves, the next generation of collider magnets will undoubtedly bring us closer to unlocking more secrets of the universe.

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