

Demonstration of Different Magnet Technology in Colliders

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Abstract. The large hadron collider in high-energy physics is a very frontier and the state-of-art facilities in high energy physics with high level technical content and requirement. It is mainly composed of a particle accelerator that accelerate the particles, the detector which observe the reaction and the product of collision and the application of the high temperature and low temperature superconductor. However, due to the operation cost is pretty expensive, it requires high technical support. In this paper, we looking at the integration of data analysis that was established online as the study of the accelerator, detector and the superconductors, The operating principles , conditions required and the academic content of these three parts are analyzed, and then corresponding suggestions are given, such as reducing the low temperature environmental cost required by superconductors, improving the accelerators and detectors, future prospects and the suggestions given for the future development of superconductor materials. These results shed light on guiding further exploration of magnetic designs for colliders.

Keywords: Magnets; colliders; superconductor; accelerator; detector.

1. Introduction

Magnetic technology has been playing a crucial role in important particle colliders today, including FCC, CLIC, and ILC. To improve the performance of this colliders in future high energy physics experiments, magnetic components with strict limitations on technical specifications to meet need of different colliders become necessary. On this basis, physics communities around the globe have been working actively to propose novel designs of magnet system to meet these new requirements [1]. However, many of proposals of new magnet system are published as a part of the entire collider component design, with few publications collectively introducing and comparing different designs of magnet systems, especially elaborating their different designed purposes or how they each function properly in different colliders. This paper, therefore, aims to summarize several important proposals of new magnetic system in current and future colliders. To make a better comparison of different designs, these magnet systems are first classified into three major fields: superconductors, accelerators, and detectors. Within each field, the desired specifications of magnet of the specific usages are explained, and several noticeable designs are introduced and compared.

The first topic discussed in this essay is the application of superconductor technology in collider magnet systems. Currently, the researches on superconductor technology are aiming to achieve two major goals: the first is to increase the temperature that the superconductive property may remain to eliminate the need for expensive cooling system, and the second is to increase the magnetic field strength that a superconductor may endure. As for superconductor technologies utilized in colliders, two different kinds of materials are introduce: Bi2212 which is a material that can be more easily made into Rutherford cables, and REBCO which is suitable as a coating material. In past researches finished by the high energy physics community, the novel designs proposed have significantly increases the carrying current and critical field of superconductors, but some colliders may require higher, while there are still some issues present. These issues will be discussed in detail in this study.

Accelerator is the essential part of all types of colliders. The particle beam is led by the magnetic field in pipes. To guide a high speed particle beam, strong magnetic fields are necessary. Generating

these fields requires plenty of power, which promotes the development and application of superconducting materials. For example, The Large Hadron Collider is a 26.7 km ring whose proton beam energy is designed to be 7 TeV [2]. The superconductor not only create requisite magnetic field but also save energy. The chief design of accelerator components is multipole structure. The dipole, quadrupole and sextupole are widely used.

As for detector magnets, this essay discusses designs including IDEA, ILD, and CLD. To improve the preciseness of detector, the magnet system need to be able to both respond sensitively to the events caused by the phenomena of interest happening during the colliding process, and avoid unwanted mutual disturbance with accelerator component. To meet this requirement, IDEA use a double magnet system, including a very light major solenoid for detecting which is designed to be both sensitive and cost-effective, and a large solenoid wrapping around the entire detector to attenuate the magnetic disturbance [3]. In order to meet different requirements of experiments with the same collider and therefore reduce building cost, some magnet systems also have specially designed features. Examples of such designs discussed in later chapters are that functioning magnetic field strength of ILD can be adjusted from default 3.5 T to up to 4T [4], and the way to design of CLD resizes the magnet system from original CLIC design to accommodate the low field strength in FCC collider [5].

2. Super Conductor

Applications in high energy physics are particularly relevant to the special characteristics of high temperature superconductors. When there are considerable heat loads on the magnet cold mass, operating at higher temperatures may provide advantages like enhanced overall efficiency. The additional characteristic of HTS materials is an unusually high upper critical field B_{c2} , which is possibly most significant for collider applications. With B_{c2} values of 100 T for both Bi2212 and REBCO, the path may be open for extraordinarily high field magnets. In order to control the enormous forces, it is necessary to learn how to achieve these high magnetic fields. Overcoming these obstacles is the main objective of the US MDP. High-temperature superconductors (HTS) are needed to create dipole fields at and beyond 20 T, despite ongoing material research increasing Nb₃Sn conductors' capacity to do so at 4.2 K [6]. The two primary HTS options are round wires made of Bi-2212 and conductors covered with REBCO [7]. A multi-filament composite wire may be produced when producing the superconductor Bi2212 using the powder-in-tube method, a well-known superconductor design. This has a lot of benefits.

Since the conductor is multifilamentary and isotropic, which reduces magnetization losses. The magnet inductance is a crucial part of magnet protection because it is necessary to efficiently recover the magnetic energy that has been stored in the event of a quench. The industry now possesses equipment and processes that are easily adaptable to the development of Bi2212 wire, so the production capacity may be significantly increased. Additionally, it employs well-established wire drawing fabrication methods. For accelerator magnets above 16 T, Bi2212 is now a highly sought-after opponent since it is competitive with Nb₃Sn over 14 T. Additionally, the wire's transport current has increased significantly during the last 10 years. Despite these benefits, only HEP and the high field NMR community are currently working on the conductor. The difficulty of employing Bi2212 in magnets, which requires a heat treatment at a high temperature (about 890 °C in an oxygen environment with one bar), is largely to blame for this. To get the best results, 50 bar of "overpressure" must be applied during the heat treatment. Last but not least, since the superconductor is brittle and strain-sensitive like other modern superconductors, handling must be kept to a minimum. For this reason, the "wind-and-react" method is often used in magnet research [8]. For effective accelerator use, it is essential to assess the strain sensitivity and degradation thresholds of the transport current, especially under transverse pressure.

The problems listed above taken together impose limitations on the tooling material and design. With constant advancement, the technical problems associated with the reaction process are being solved. The first use of Bi2212 in a hybrid HTS/LTS magnet, where the reaction temperature will be

higher than in a standard HTS/LTS magnet, is currently being worked on. A supplemental whitepaper provides an overview of the Bi2212 accelerator magnet research and discusses how the material may become crucial for HEP in the next decades. In terms of HTS materials for accelerator magnets, Bi2212 is a top choice since it makes advantage of many of the conductivity characteristics that HEP has long used to great effect. Bi2212 is a top HTS candidate material for HEP applications because to a number of significant characteristics. It is now challenging to transfer the significant advances in transport current made possible. Coated conductors are both uncommon and are only available in tape form and have an aspect ratio of at least 10.

Out of the two, the HTS candidate conductor REBCO deviates from LTS conductors the greatest. The conductor that the supplier supplies to the manufacturers of magnets already has the sensitive REBCO coating. Care must be taken while handling the tape in order to maintain a tensile strain of no more than 0.6% for the production and usage of magnets. For a number of reasons, we put a lot of effort into learning how to utilize this stuff. Although raw materials are cheap, there won't be much potential expenditure. the capacity to produce strong magnetic fields across a wide temperature range (1.9–40 K). These two aspects may have a considerable influence on future efforts to construct high-field magnet colliders. They have a good reason to concentrate on REBCO, according to the most current European Accelerator R&D Roadmap. We will go further into these issues and provide other viewpoints in a follow-up white paper that was submitted to the Snowmass Community Study. The potential of REBCO has long been acknowledged by the US MDP. The demonstration and measurement of a dipole field of at least 5 T is one of the main objectives of MDP. The hybrid LTS/HTS dipole magnet has been emphasized in the most recent version of the MDP roadmap as a tool to investigate, develop, and use the potential of HTS insert magnet technology. We want to develop REBCO magnet technology along the lines of the following approach in order to achieve these aims. Concurrently develop REBCO magnet and conductor technology. Utilize the magnet discoveries to provide the conductor vendor important input that will enhance the magnet's performance. For high-field dipole magnets, the optimal conductor design must be found. Currently, we concentrate on the round-wire cable topologies that American technology companies are pursuing, but we also keep an eye on the different conductor designs that our European 22 counterparts are pursuing. The round wire design can be scaled up more easily and used to innovative magnet topologies since it is virtually isotropic in terms of mechanics and magnetics. Magnet technology is improving, hopefully fast. Focus on larger dipole fields while keeping in mind the "minimum feasible magnet" notion.

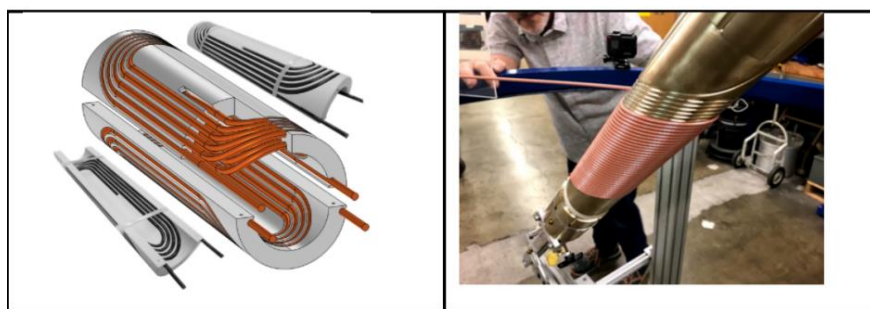


Fig. 1 A sketch of the designs for magnets of 14T.

Preventing hasty optimization of crucial aspects like field quality and quench prevention by understanding the implications by introducing and analyzing a small number of new characteristics in the following magnets, drawing on the knowledge gathered and the lessons discovered from the previous stages. Utilize the DOE SBIR, MDP/CPRD, and synergetic fusion activities to move prospective suppliers' goods closer to becoming magnet conductors and to create pertinent and essential magnet technologies that might aid MDP in achieving its goals. Building a multi-tape conductor out of a highly valued tape is a particularly difficult task for REBCO technology. Multi-tape REBCO cables come in a variety of unique varieties that may be utilized with high-field dipole magnets. Due in part to the limited magnet findings, a thorough assessment of the benefits and

drawbacks of each theory is not yet accessible, and a down-selection is not yet practical. The REBCO community has been researching various CORC wire-based dipole magnet designs for a number of years in an attempt to create a high-field dipole magnet technology. Common Coil on Barrels (CCT) at BNL, Conductor on Molded Barrels (COMB) at FNAL, and CCT at LBNL are the three magnet configurations. To create the different dipole magnet combinations, MDP is now working with Advanced Conductor Technologies, LLC, a company based in Colorado that sells CORCwires.

The STAR conductor from the Texas-based AMPeers LLC is another option that MDP is considering for its REBCO tape round-wire design (seen in Fig. 1). The single most significant objective for the REBCO teams over the next years will continue to be increasing the dipole field that a REBCO magnet can produce for two reasons. As it approaches a dipole field of 20 T, a higher dipole field is required to maintain the strategic hybrid LTS/HTS dipole magnet arrangement. According to the continuing design studies of the 20 T hybrid dipole magnet, the insert must produce at least a 10 T dipole field when tested alone in order to produce a 5 T dipole field in a background field of 15 T [9]. Only 5 T may be created at this time, which is a significant number. Second, for standalone applications, a REBCO magnet with larger dipole fields can prove to be a great choice. As already established, REBCO magnets are capable of producing powerful fields (more than 10 T) at high temperatures. There are two outcomes from this. It first makes it possible to run without liquid helium. superior heat extraction as compared to operating at 1.9 or 4.2 K/s. For applications that need a lot of heat, like the next-generation pp machine and muon colliders, this would be quite tempting. A previously unheard-of degree of public and private investment has been sparked by a number of fusion technology firms' development of small high-field fusion magnets. In the center of these magnets is REBCO. It is not surprising that HEP and Fusion magnets are compatible. If the fusion application is successful, a sustained market for REBCO conductors may emerge, which would help down the presently high conductor cost. In order to achieve the technical requirements for high-field REBCO magnets, the MDP is aware of the significant synergy and aims to work in partnership. For HTS insert and fusion cable testing, the facility's magnet will offer a 15 T dipole background field. A path to extremely high field accelerator magnets is provided by the concept of "stress management," or "intercepting magnetic forces before they build up to dangerous levels and harm structural components." Bi2212 is a prime candidate for accelerator magnets in the HTS and benefits from a number of conductor properties that HEP has successfully used for many years. There will need to be a continuous and expanded strategic investment in the development of REBCO conductor and magnet technologies in order to establish American leadership in this recently developed.

3. Accelerator

The magnets in accelerator are designed to guide and focus the particle beams. They are essential to all types of accelerators. This section will discuss the principle of accelerating magnets and mention several typical conceptional design magnets colliders.

3.1. Basic Technology

Normally, the magnets of accelerator are long (up to a few m), and their transverse apertures are small (few cm). For a 2-dimensional case, it can be described as

$$B_y + iB_x = \sum_{n=1}^{\infty} (B_n + iA_n)(x + iy)^{n-1} \quad (1)$$

B_n and A_n represent the normal and skew multipole components of the field, and $2n$ means the amount of poles. For n equals to 1 it represents dipole [10].

3.2. FCC-ee magnets

The FCC is probably constructed in the Lake Geneva basin [11]. Its mission is to offer four energy channel for collision with luminosity about $2 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1}$ [12]. Its magnets can be considered as a combination of 3 types of multipoles. The arcs of FCC-ee main magnet requirements include plenty

of long, weak-field bending magnets [5]. Fig. 2 illustrates the conceptual design of chief multipoles magnets [13].

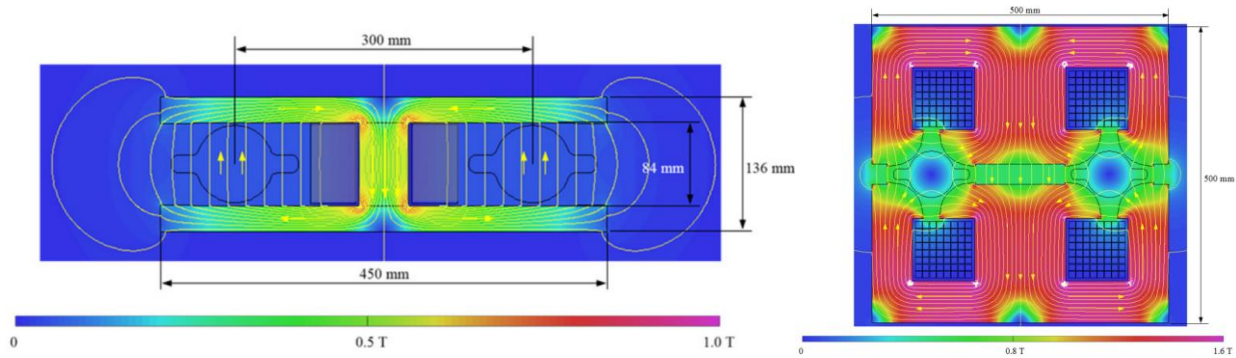


Fig. 2 FCC-ee main dipole (top), quadrupole (bottom) magnets.

3.3. SCCP Magnets

SPPC is considered as an very powerful machine with center-of-mass energy can reach 75 TeV. To reach such high energy (75TeV) and make a modest magnetic field of 12T, the iron-based High Temperature Superconductor (HTS) magnet technology is applied to SCCP. Because iron-based HTS probably will be cheaper and generate a field higher than 20T within 15 years. To make the high energy proton beams bend and concentrate, SPPC requires more than a thousand high-field multipoles installed around a tunnel of 100 km in one circle. The nominal aperture of these magnets is 50 mm. The main dipoles field strength is 12 T [14].

3.4. CEPC Magnets

The CEPC has a linear accelerator (Linac). The elements distribution of every ring are complex. 8 quadrupoles and 16 sextupoles are made from superconductor and the rest magnets are conventional types. Such large amount of magnets brings problems to expenditure of both materials and power. Therefore, most of dipoles and over a half of quadrupoles are dual aperture magnets when they are generated. As a result, they can provide magnetic field in two sides so that much cost of magnets and energy can be saved [15]. The cross section is exhibited in Fig. 3.

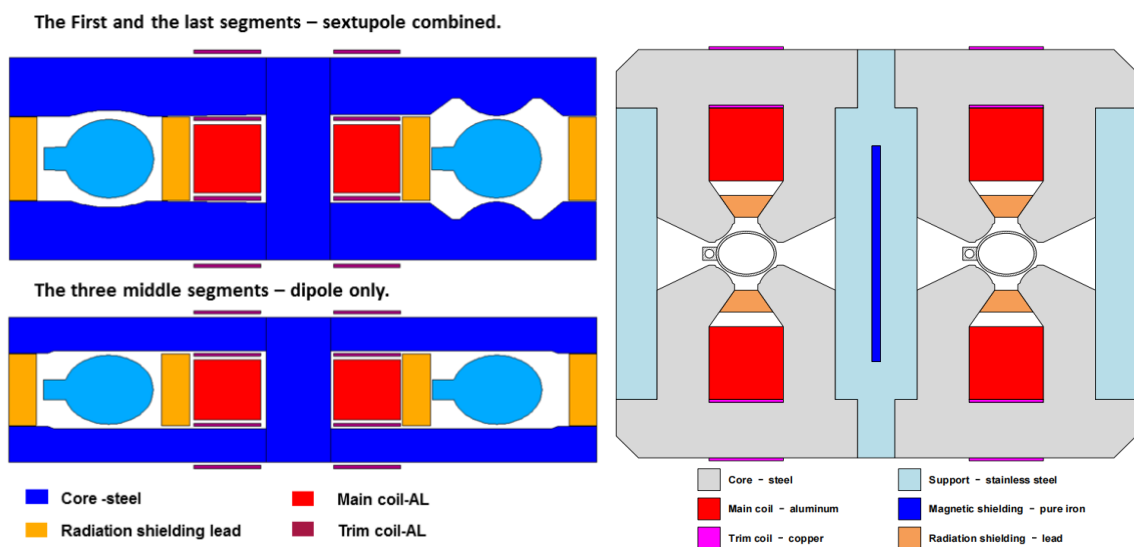


Fig. 3 Cross section of the dual aperture dipole.

4. Detectors

Another key component of a collider that depends on magnetic technology is the detector. Detectors are devices appended to collider to measure several physical parameters of particles generated in experiments, and superconductive coils are widely used for this purpose [1]. Although the magnetic technology has dramatically improved in recent years, there are still many considerations for designs of detector magnets. Currently, there are multiple proposed future collider projects, including FCC, CLIC, and ILC, etc., and each of the project has their distinct design and operational purpose for collider. While it's important to design detector respectively, considering the different conditions and needs, the function of magnetic system in different colliders is similar: a critical component of a fast and accurate detector system, and a neutralizer of unwanted field. Many innovative designs has been proposed to ensure proper functioning of the detector achieving the aforementioned double goals, facing the different constraints of different collider designs.

For instance, IDEA is a detector system designed for FCC-ee [3]. The nature of circular collider requires is detector to be fast and accurate with a wide range, and to function property under a comparatively lower magnetic field. Facing these constraints, IDEA implements a double solenoid system. The major solenoid belongs to the detective part, and is extremely low in thickness and weight. Such a light structure is beneficial for reducing the building cost, by reducing both the materials needed, and the difficulty of packaging. According to the proposer of the design, the low field strength of the solenoid can limit the influence of the detector on the collider beam, and through placing the solenoid inside the main chamber, the stored energy is also reduced, leading to a significantly less cost. The other solenoid is a part of the packaging, wrapping around the whole detector structure to neutralize the magnetic flux, preventing such emission to impact the function of collider. This design is a good example of using multiple solenoids to achieve two critical roles of magnets in detectors, both as a sensor and a protective component.

When considering the specific environment of a certain collider design, some special designs become necessary. For example, as for ILD [4], the detector system designed for International Linear Collider, is set to function at 3.5 T strength by default. This field is beneficial for the more precise measurement of particle momentum, and helps to neutralize the background. But as a large collider project, to increase the efficiency of construction cost, it's critical to have ability to accommodate the need for different types of experiments. Therefore, the solenoidal field strength can also be adjusted up to 4 T, and many extra components, including a device correcting the direction of particle beam and a dipole system, can be combined with the main magnet system to allow multifunction. Another example is CLD [5], a detector system designed for FCC, but resembles CLICdet, the detector system designed for CLIC collider. To resolve the impact of low magnetic field strength limitation in FCC collider, CLD has to significantly increases the radius of the detecting system. Owing to the essential difference between continuously operating circular FCC collider and linear CLIC collider, the entire supporting system has to be redesigned, implicating some newly proposed structure, which results in an increase in material used surrounding the detector. These two examples display that careful design is critical for magnetic system of collider detectors in order to accommodate the needs.

5. Conclusion

In conclusion, colliders are main research tools in High Energy Physics and magnets technology is key to the development of colliders. The research and development of superconductor may help to produce a higher magnetic fields in the future. According to the temperature, the superconductor can be sorted into HTS and low temperature superconductor LTS. The latest HTS are Bi2212 and REBCO which are applied to accelerators. The common accelerators are circular and linear type. Many accelerator components are in multipoles structure. Detectors allow researchers to measure and analyze particle physical parameters. The normal magnets in detectors are IDEA, CLD and ILD. The Superconductor developing program will benefit the colliders design and it should be attached. The limitation of this article is that we only do the online research. There is no chance to visit any collider

for example the LHC and communicate with the local researchers. The magnet technology especially the superconductor area keeps making progress and we believe it will provide a better circumstance for the particle colliding experiment. Besides, it may bring innovative design for accelerators and detectors in the future. This article gives introduction to the superconductors and its application in colliders. We hope it will raise more motivation in magnet technology research and development. Overall, these results offer a guideline for further designs of magnets for collider.

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