

# Snowmass'21 Accelerator Frontier – Magnets

## Working group report

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## Executive summary

The performance of high energy colliders is strongly dependent on their magnet system: arc dipoles for energy reach, and interaction region quadrupoles for luminosity. As the HEP community explores its best options to enable future discoveries, magnet technology considerations are essential for informed decisions on the feasibility and cost of achieving the physics goals.

Hadron colliders at the energy frontier are optimized based on circumference and the available dipole field. The cost scales linearly with circumference, while the dipole field limit and cost are strongly dependent on superconductor properties. Three technologies can be considered: Nb-Ti up to 8 T, Nb<sub>3</sub>Sn up to 16 T, and High Temperature Superconductors (HTS) beyond 16 T. These materials can be also combined in hybrid designs to optimize magnet cost and performance. Hadron colliders presently under consideration include: the very large circumference “Collider-in-Sea” based on cost-efficient 4 T Nb-Ti magnets; the 100 km ring FCC-hh, based on 16 T Nb<sub>3</sub>Sn dipoles, the practical limit for this material; the 50-100 km ring SPPC based on 12 T or 20+ T hybrid LTS/HTS dipoles; and two smaller circumference machines, HE-LHC and CHC, where existing site/infrastructure considerations limit the ring size, requiring dipole fields within the range of 16-26 T to achieve sufficient beam energy.

Muon colliders require very strong solenoids for efficient muon production and cooling. Additional challenges to the magnet system are posed by the radiation load at the muon production target. The short muon lifetime motivates novel magnet and optics schemes to enable very rapid acceleration from production target to the storage ring where collisions occur. Examples include very-fast ramping magnets in a synchronous multi-pass configuration, e.g., using high-temperature superconductors in novel configurations, and/or large momentum acceptance magnet optics, such as fixed-field alternating gradient (FFAG) designs that enable the beam acceleration via multiple passes with fixed magnetic field. Finally, since even at relativistic velocities the lifetime of the muon is limited, luminosity considerations motivate the most compact storage ring possible, requiring the highest field dipoles possible to minimize the ring circumference, while coping with severe radiation load from muon decay.

IR magnets are also of critical importance for the Collider physics reach. In addition to hadron and muon colliders, this includes electron-positron colliders, both linear and circular. As already demonstrated by past projects from LEP to HL-LHC, special magnet technology can be deployed in the IR, different from the rest of the machine. The relatively small scale of these systems makes it possible to adopt solutions that push the state of the art, and with potentially higher unit cost, in order to achieve the highest possible luminosity.

Superconducting detector magnets are a key component of particle physics experiments. Over the past four decades, the design and fabrication of detector magnets have made significant progress thanks to the introduction and demonstration of specific technologies such as: high current, high strength, Al-stabilized superconducting cables; coil winding technique and coil support structures; improved transparency using indirect magnet cooling; etc. Detector magnets for future colliders will be based on these technologies but further improvements will be required to cope with larger size, radiation loads and physics performance requirements. A sustained R&D effort is needed to preserve and further develop the technologies for application in future detector magnets. A collaborative framework between institutes and industries is critical.

The development of accelerator and detector magnet technologies has benefitted from a strong network of worldwide programs and collaborations. Activities include fundamental R&D on conductors, magnet design and fabrication technologies; directed R&D aimed at demonstrating prototypes for specific applications; and series production for individual accelerator projects. Following the 2013 Snowmass and P5, the US HEP General R&D (GARD) magnet programs were integrated in the US Magnet Development Program (MDP). MDP explores a broad range of concepts and designs based on both low-temperature and high-temperature superconductors, as well as advanced modelling tools, instrumentation and diagnostics techniques. MDP is closely collaborating with advanced magnet programs worldwide and has developed growing synergies with the NSF-funded NHMFL; with other DOE

offices, in particular DOE-OFES; and with industry, both for conductor development and through the SBIR program.

In the EU, the Particle Physics Strategy update process resulted in several recommendations for investments in critical technologies for future colliders. The European Laboratory Directors Group (LDG) initiated the development of roadmaps for each area, including magnet technology - the European High Field Magnet program (HFM). That process is now completed, and a report has been issued teams from multiple European laboratories and Universities are currently organizing to deliver on the European magnet roadmap.

In Japan, superconducting accelerator magnet programs have been conducted at KEK for more than 40 years. Following the successful development and operation of the LHC insertion quadrupole MQXA, KEK is now developing the large-aperture beam separation dipole D1 for HL-LHC. Magnet development for Japan-based experiments includes the superconducting beam line for the T2K neutrino experiment facility and solenoid magnets for detector and muon experiment program such as COMET and  $g-2/EDM$  at J-PARC. Due to the requirements of these experiments, the KEK program has a strong focus on developing materials and technologies for high radiation environments.

The magnet technology program in China is designed to support the CEPC and SPPC projects. A double aperture “common coil” design is being used as a reference for the SPPC magnet development, aiming at up to 24 T using a combination of LTS and HTS materials, with a particular interest in iron-based conductors.

The LHC Accelerator Research Program (LARP) started in 2004 as a directed R&D effort to develop Nb<sub>3</sub>Sn IR Quadrupoles for the High Luminosity LHC. By 2013, it had achieved its main goals leading to the US LHC Accelerator Upgrade Project. This was made possible by the successful combination of fundamental R&D by GARD and directed R&D by LARP. Following this success, the new Leading-Edge technology And Feasibility-directed (LEAF) Program aims at achieving readiness for a future collider decision in the next decade. LEAF is foreseen to start in ~2024-2025 with a 10-year timescale of ~2025-2035, at the funding level of ~25-30 M\$/year across the spectrum of participants (US National Laboratories & Universities). The main focus is on large-scale prototypes, with close attention paid to the requirements of a successful industrialization process. A specific program component is tasked with achieving cost savings and improving process uniformity. This requires revisiting all aspects of the design and fabrication, based on the experience from the LHC AUP production.

The development of novel SC magnet technology at the high-field frontier requires specialized fabrication and test infrastructure, often of large size. In the U.S. the magnet R&D infrastructure exists at the three National Laboratories (BNL, FNAL, LBNL) as well as at NHMFL and TAMU. It includes R&D magnet development and test capabilities. This infrastructure can be and is also used for production of small quantities of full-scale accelerator magnets, e.g., for the LHC HL upgrade. Conductor R&D facilities at ASC-FSU and OSU... The necessary investment is considerable, so the effort should extend across national and international labs.

FNAL in collaboration with LBNL is building a new high-field cable-testing facility with capabilities similar to the European facilities EDIPO and FRESKA2. This facility will serve two US national programs within the DOE Office of Science, the Magnet Development Program and the US Fusion Energy Science Program for testing HTS samples in a 15 T field. This facility will allow testing HTS-LTS hybrid magnets which are an important step toward providing 20+ T operation fields in future high-energy colliders. This new test facility is planned to be available at FNAL within the next 3-5 years.

## **1 Introduction**

The Snowmass community exercise started in April 2020 to help define the US HEP priorities in the coming decades. The AF7-Magnets working group was charged to a) address the potential contributions of magnet technology to future HEP facilities, b) evaluate the R&D required to enable these opportunities, c) estimate the time and cost scales of these efforts, and d) assess the needs for associated fabrication infrastructure and test facilities.

Following a series of meetings to introduce the program goals and process, the Letters of Interest (LoI) from the community were solicited. By October 2020, the AF7-Magnets topical group had received a total of 50 LoI which were subdivided in 6 groups: Regional Plans (8 LoI), Conductor (16 LoI), High Field Magnet Development (9 LoI), Magnet Technologies (8 LoI), Detector Magnets (4 LoI) and Special Magnets (5 LoI). Because of the coronavirus pandemic, a pause was decided in January 2021. The process resumed in fall 2021 with a call for White Papers describing technical progress and opportunities in specific areas, as well as recommended plans and priorities for the next decade. In March 2022, the Magnet topical group received 22 White Papers (WPs) [1]-[22] which were used as a basis for this summary report.

This report addresses the working group charge, summarizes the status of accelerator and detector magnet technologies, and discuss ideas and plans to push this key area of the US and international HEP to new horizons.

## 2 Overview of the HEP accelerator magnet programs

The magnet system is a critical component and major cost driver for future HEP colliders. Magnet R&D programs are underway to take advantage of new developments in superconducting materials, achieve higher efficiency and simplify fabrication while preserving accelerator-class field quality. This section provides a summary of the major ongoing and planned activities worldwide.

### 2.1 United States

#### 2.1.1 HL-LHC Accelerator Upgrade Project

The US government is making an investment of more than 750 M\$ in the upgrade of the LHC to achieve the High Luminosities necessary to fully exploit the HEP frontier at the LHC energies. These investments will support the construction of upgraded CMS and ATLAS detectors, and the new Interaction Regions (IRs) that will enable a 10-fold increase of the luminosity delivered to the detectors. The upgraded machine, called HL-LHC, is presently in its construction phase. The US is contributing to the accelerator part of HL-LHC through the DOE Accelerator Upgrade Project (AUP) [2.1.1], executed by a collaboration of National Labs (FNAL, BNL, LBNL) and to be deployed at CERN for installation and commissioning of HL-LHC in the 2026-2029 period.

#### 2.1.2 US Magnet Development Program

Following the 2013-2014 Snowmass and P5 process, DOE-OHEP initiated the US Magnet Development Program (MDP), a general R&D program that integrates DOE magnet laboratories and University programs under a common collaboration [MWP1]. The program has oversight through a longstanding Technical Advisory Committee, composed of internationally recognized - and international - membership, as well as a Steering Council composed of laboratory leadership from the MDP collaborating institutions.

MDP advances fundamental aspects of magnet technology with potential benefits to a broad range of collider applications, including hadron colliders and muon colliders. Over the years, the MDP collaboration has expanded through synergies with the NSF-funded NHMFL; with other DOE offices, in particular DOE-OFES; and with industry, for example through the SBIR program. Furthermore, international collaborations exist on a range of technical topics. The program goals are articulated in four main elements:

- Explore the performance limits of Nb<sub>3</sub>Sn accelerator magnets, with a focus on minimizing the required operating margin and reducing training
- Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater, compatible with operation in a hybrid HTS/LTS magnet for fields beyond 16 T
- Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction
- Pursue Nb<sub>3</sub>Sn and HTS conductor R&D with clear targets to increase performance, understand present performance limits, and reduce the cost of accelerator magnets

In the magnet design and fabrication area, a major theme is the development of methods to control the conductor strain, in particular through the use of “stress-managed” coil layouts and support structures. Two main

approaches are being explored, the “Canted Cosine Theta” [2.1.2] and the Stress-Management Cosine-Theta [2.1.3]. While initially developed on Nb<sub>3</sub>Sn, these principles are being applied to other stress/strain sensitive superconductors, such as High Temperature Superconductors (HTS).

The development of advanced superconductors specifically optimized for accelerator magnet applications is at the base of the MDP effort. Over the years the US has built a strong technical and industrial leadership in this area, with significant contributions from projects like the Tevatron and SSC, as well as the HEP-funded Conductor Development Program. MDP is now coordinating these efforts, working closely with the new Accelerator R&D and Production Office (ARDAP) to develop a strategic plan that can strengthen US industry in this arena and support HEP's long term needs for conductor performance and cost-effective conductor production.

In the area of high field solenoids for muon production and for muon beam cooling MDP has strong synergies with ongoing R&D at the National High Magnetic Field Laboratory (NHMFL), as well as advances in REBCO magnet technology by DOE and by private industry toward compact, very high field magnets for fusion reactors.

Supporting technologies critical to design optimization and performance assessment are also of major interest. These include advanced modelling capabilities, novel diagnostics, and new concepts that can impact the rate at which accelerator magnets “train” up to full field [MWP15]-[MWP18]. Advances in these areas provide lasting benefit for HEP, and are highly valued by the broader superconducting magnet community, both within the DOE Office of Science, and also in industry.

A long-range magnet R&D program, designed to advance magnet technology while fully leveraging the broader community's strengths, is vital to HEP and the future of particle physics. The MDP experience indicates that the scale of investment needed to pursue fundamental magnet R&D to provide a foundation for a directed program aimed at project-specific design demonstration and production readiness is 15M\$ per year, with an additional 20% (i.e. 3M\$) in conductor procurement from industry to support the magnet development needs.

### 2.1.3 Directed R&D

The development and demonstration of maturity of advanced magnet technology for application in the present upgrades to the LHC (called the High Luminosity LHC Upgrade, HLLHC) was made possible by a ~15 years-long US national program of directed R&D (called LHC Accelerator Research Program, LARP) working in combination with generic and complementary R&D efforts (Conductor Development Program, General Accelerator R&D GARD, university programs, etc.).

A similar Leading-Edge technology And Feasibility-directed (LEAF) Program is proposed [MWP2] to achieve readiness for a future collider decision on the timescale of the next decade. As for its predecessor, the LEAF Program would rely on, and be synergetic with, generic R&D efforts presently covered in the US by the Magnet Development Program (MDP), the Conductor Procurement and R&D (CPRD) Program and other activities in the Office of HEP supported by Early Career Awards (ECA) or Lab Directed R&D (LDRD) funds. Where possible, ties to synergetic efforts in other Offices of DOE or NSF are highlighted and suggested as wider Collaborative efforts on the National scale. International efforts are also mentioned as potential partners in the LEAF Program.

The LEAF Program will concentrate on demonstrating the feasibility of magnets for muon colliders as well as next generation high-energy hadron colliders, pursuing, where necessary and warranted by the nature of the application, the transition from R&D models to long models/prototypes. The LEAF Program will naturally drive accelerator-quality and experiment interface design considerations. LEAF will also concentrate, where necessary, on cost reduction and/or industrialization steps.

The LEAF Program is foreseen to be a decade-long effort starting around 2024-2025 to be concluded on the timescale of 2034-2035. Based on the experience of the proponents, the appropriate funding level for the LEAF Program should be 25-30M\$/year across the spectrum of participants (US National Laboratories & Universities).

## 2.2 Europe

Over the past several decades, a strong magnet R&D effort was pursued in Europe through programs such as EU FP6 Coordinated Accelerator Research in Europe (CARE), EU FP7 European Coordination for Accelerator Research & Development (EuCARD), EU FP7 Enhanced European Coordination for Accelerator Research & Development (EuCARD2), EU FP7 Accelerator Research and Innovation for European Science and Society (ARIES), and current work such as HL-LHC, EU H2020 Innovation Fostering in Accelerator Science and Technology (I-FAST), and CERN-HFM.

Looking at the future, in 2021 the European Laboratory Directors Group (LDG) was mandated by CERN Council to oversee the development of an Accelerator R&D High Energy Physics Accelerator Roadmap. High Field Magnets (HFM) is one of this R&D axes and are among the key technologies that will enable the search for new physics at the energy frontier.

The present state of the art in HFM is based on Nb<sub>3</sub>Sn, with magnets producing fields in the range of 11 T to ~15 T. Due to the challenges associated with the brittle nature of this material, more work is required including conductor manufacturing since it is not robust enough to be considered ready at an industrial scale. Great interest has been also stirred by the recent progress achieved on HTS, not only in the fabrication of demonstrators for particle physics, but also in the successful test of magnets in other fields such as fusion and power generation [*add refs*]. This shows that the performance of HTS magnets will exceed that of the Nb<sub>3</sub>Sn, and that the two technologies can be complementary to produce fields in the range of 20 T, and possibly higher.

The R&D program proposed in EU [*MWP4*] has two main objectives. The first is to demonstrate Nb<sub>3</sub>Sn magnet technology for large-scale deployment. This will involve pushing it to its practical limits in terms of ultimate performance (towards the 16 T target required by FCC-hh), and moving towards production scale through robust design, industrial manufacturing processes and cost reduction. The second objective is to demonstrate the suitability of HTS for accelerator magnet applications beyond the range of Nb<sub>3</sub>Sn, with a target of 20+ T. The determination of a cost-effective and practical operating field will be one of the main outcomes of the R&D work. Sub-scale and insert coils will be used as a vehicle to demonstrate performance and operation of HTS beyond the range of Nb<sub>3</sub>Sn. The development of both a hybrid LTS/HTS accelerator magnet demonstrator, and a full HTS accelerator magnet demonstrator, is proposed. Special attention will be devoted to the possibility of operating in an intermediate temperature range of 10 K to 20 K in particular to make progress on energy efficiency of future accelerator projects.

The expected duration of the R&D phase is 7 years. At least 5 more years will be required to develop HTS demonstrators with all the necessary accelerator features, surpassing Nb<sub>3</sub>Sn performance or working at temperatures above the liquid helium. Taking Nb<sub>3</sub>Sn as the natural reference for future accelerator magnets, HTS represents a real opportunity, provided the current trend of production and price reduction is sustainable.

The cross-cutting technology activities will be a key seed for innovation. The scope includes materials and composites development using advanced analytics and diagnostics, new engineering solutions for the thermal management of high-field magnets, and the development of modelling tools within a unified engineering design framework. Alternative methods of detection and protection against quench (especially important for HTS) including new measurement methods and diagnostics will be explored. Finally, dedicated manufacturing and test infrastructure required for the HFM R&D programme, including instrumentation upgrades, needs to be developed, built and operated through close coordination between the participating laboratories.

## 2.3 Japan

R&Ds on superconducting magnets for accelerator applications have been conducted at KEK for more than 40 years. Although these project-based magnets were developed with the Nb-Ti superconductor, R&Ds of magnet technologies with advanced superconductor such as A15 or HTS are being also conducted. The A15 Nb<sub>3</sub>Sn conductor development, aiming for the Future Circular Collider (FCC-hh), is now being conducted in collaboration with CERN, Tohoku Univ., Tokai Univ., NIMS, and two Japanese industrial partners. For HTS developments, US-

Japan collaboration is formed by KEK, Kyoto Univ., LBNL, and BNL for high field and high radiation environment applications. The quench protection as well as effects of shielding current in the HTS conductors are also studied.

The next mid-term goals for the superconducting magnet technologies at KEK are defined in three categories [MWP6]: 1) high-precision 3D magnet technology based on the g-2/EDM magnet developments, 2) rad-hard magnet technology based on the COMET magnet developments, and 3) high-field superconducting magnet technology for future colliders based on the LHC MQXA and HL-LHC D1 developments.

Radiation-hard magnet materials and technologies are needed for future projects such as a second target station at J-PARC Material and Life Science Facility (MLF), and IR magnets for FCC-hh. To develop radiation-hard HTS magnets, R&D is now on going within the US-Japan cooperation. The series of irradiation tests using various ReBCO conductor such as GdBCO, EuBCO, or YBCO will be compared, and most sustainable conductor will be selected. In parallel, A15 conductors are also being developed. The development of Nb<sub>3</sub>Sn conductor is now under way in collaboration with CERN, Tohoku Univ., Tokai Univ., NIMS, and two Japanese manufacturers. One of the R&D conductors has reached 1100 A/mm<sup>2</sup> at 16 T, and the test production of 5 km level conductors with the similar specification is now in progress.

## 2.4 China

In 2012, after the discovery of Higgs boson, Chinese scientists proposed a 240 GeV Circular Electron Positron Collider (CEPC) for Higgs studies [2.4] - [2.5]. The tunnel of CEPC will also provide space for a 75-150 TeV Super Proton Proton Collider (SPPC) [2.6], a candidate of next generation high-energy colliders after the operation of CEPC and LHC. To reach the 75-150 TeV center-of-mass energy, SPPC needs thousands of 12-24 T accelerator magnets to bend and focus the particle beams. SPPC demands advanced or new type of superconducting materials with low cost and capable of working at high fields. Since 2008, iron-based superconductors (IBS) have been discovered and attracted wide interest for both basic research and practical applications. IBS have high upper critical field beyond 100 T, strong current carrying capacity and lower anisotropy. The Institute of Electrical Engineering, Chinese Academy of Sciences (IEE-CAS) manufactured the world's 1st 100-m long 7-filamentary Sr122 IBS tape with critical current of  $1 \times 10^4$  A/cm<sup>2</sup> at 10 T successfully. This tape can now be used to fabricate IBS coils.

R&D of high-field accelerator magnets is ongoing at IHEP in collaboration with related institutes working on fundamental sciences of superconductivity and advanced HTS superconductors. The R&D will focus on the following key issues related to high-field superconducting magnet technology:

1) Exploring new methods and related mechanism for HTS materials with superior comprehensive performance for applications. Reveal key factors in current-carrying capacities through studying microstructures and vortex dynamics. Develop advanced technologies of HTS wires for high field applications with high critical current density and high mechanical strength.

2) Development of novel high-current-density HTS superconducting cables, and significant reduction of their costs. Exploration of novel structures and fabrication process of high field superconducting magnets, based on advanced superconducting materials and helium-free cooling method.

3) Search of novel stress management and quench protection methods for high-field superconducting magnets, especially for high-field insert coils with HTS conductors. Complete the prototype development with high field and 10<sup>-4</sup> field quality, lay the foundation for the applications of advanced HTS technology in high-energy particle accelerators. The R&D of the high-field magnet technology and related advanced superconducting materials is being funded by the Chinese Academy of Sciences (CAS) and the Ministry of Science and Technology (MOST). The total amount is about 60M\$ for 2018-2024.

### 3 HEP Accelerator Magnets Status and Future

This section describes conceptual designs and parameters of superconducting accelerator magnets being considered for the electron, proton and muon colliders under consideration. The discussion starts with magnets for electron and proton colliders planned for construction in Europe and China, and concludes with magnets for muon collider under consideration in the future.

#### 3.1 Electron Collider Magnets

##### 3.1.1 FCC-ee magnets

The FCC-ee main magnet requirements are quite similar to those of LEP: the arcs contain many long, low-field bending magnets interleaved with short straight sections, containing quadrupoles and auxiliary magnets [3.1.1]. The resistive magnet system resembles those used in LEP and in some other large lepton machines such as HERA electron ring and SLC. Many of its features can be retained, for example, modular cores with aluminium busbars. However, as a major innovation, for FCC-ee it is possible to exploit a dual-aperture approach. Coupling the two collider rings through twin-aperture arc magnets does not only halve the total number of main magnets, but it also saves of 50% in electric power consumption compared with two separate sets of magnets. For operation at high energy, especially at or above the  $t\bar{t}$  threshold, the SR energy sawtooth is important. To compensate for its effect, the arc dipole and quadrupole fields have to be tapered, i.e. adjusted for the local beam energy. This tapering could be achieved, for example, with individual-aperture trim coils added to the main magnets. Such trim coils for the main bending magnets could also serve as horizontal orbit correctors.

Figure 3.1 shows the conceptual design for the main dipole, quadrupole and sextupole magnets. For the dipoles, the design of the magnetic yoke is based on an I-type configuration, combining two back-to-back C-type layouts. In this way, the return conductor for one aperture provides the excitation current for the other. The quadrupoles cannot be considered to be low field magnets because although the beam, which is quite small with respect to the physical aperture, sees at most 100 mT (that is, 10 T/m at 10 mm), the pole tip field reaches 0.42 T. This has an impact on the Amp-turns and the power consumption. It will be even more critical for large aperture sextupoles, where the field grows quadratically from the centre. Therefore, a twin aperture layout providing significant power savings is also particularly interesting for the quadrupoles, even if they are relatively short compared to the dipoles

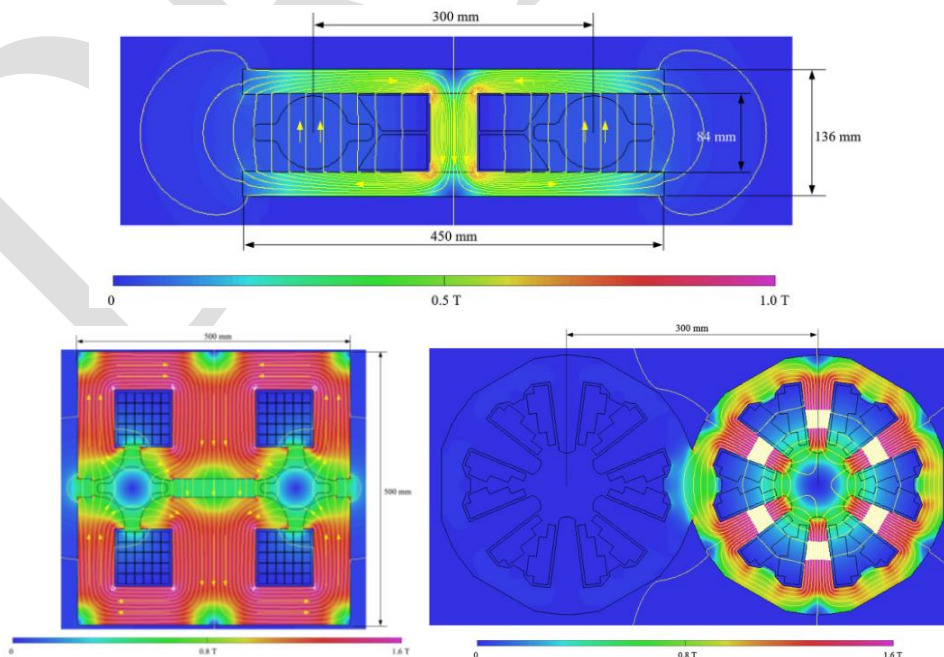


Figure 3.1. FCC-ee main dipole (top), quadrupole (bottom, left) and sextupole (bottom, right) magnets.



The Canted Cosine Theta (CCT) technology without an iron yoke has been chosen for the final focusing quadrupoles (Figure 3.2). This technology provides the required field quality and has many possibilities for customisation of the field which is necessary for cross talk compensation (the tips of the FF quadrupoles closest to the IP are only 66 mm from the beams).

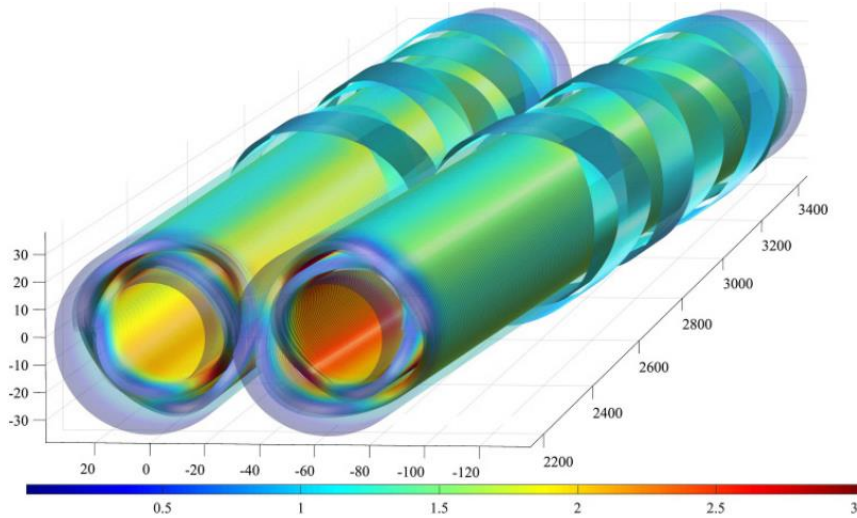


Figure 3.2. Focusing quadrupoles based on the CCT technology.

### 3.1.2 CEPC magnets

The dipole field for CEPC main bending dipoles is 0.07 T. Each magnet has four C-shaped steel-concrete cores of about 4.5 m length, installed end to end in groups. The cores are composed of stacks of low carbon steel laminations, 1.5 mm thick, spaced by 6 mm gaps filled with cement mortar. The filling factor of 0.2 gives a small drop of ampere turns at the maximum field. Because of large quantity of 1,984 magnets and their long length of 18 m, the scheme of steel-concrete core not only increases the working field in the yokes of the dipole magnets but also reduces their cost significantly. The design of the quadrupoles is similar to that of quadrupole magnets in LEP. Hollow aluminium conductor is used for the coils. The iron core is made of laminated low carbon silicon steel sheet with a thickness of 1.5 mm. The pole has parallel sides so that simple racetrack shaped coils can be used. The magnet will be assembled from four identical quadrants and can also be split into two halves for the installation of the vacuum chamber. There are two types of sextupole magnets in the Main Ring, with the same aperture and cross section but of different lengths. The cores of the sextupole magnets are made from 1.5 mm thick low carbon steel laminations. To reduce cost, the coils will be wound from hollow aluminium conductors. Figure 3.3 shows a cross section of the quadrupole magnet and the 3D view of the sextupole [3.1.2].

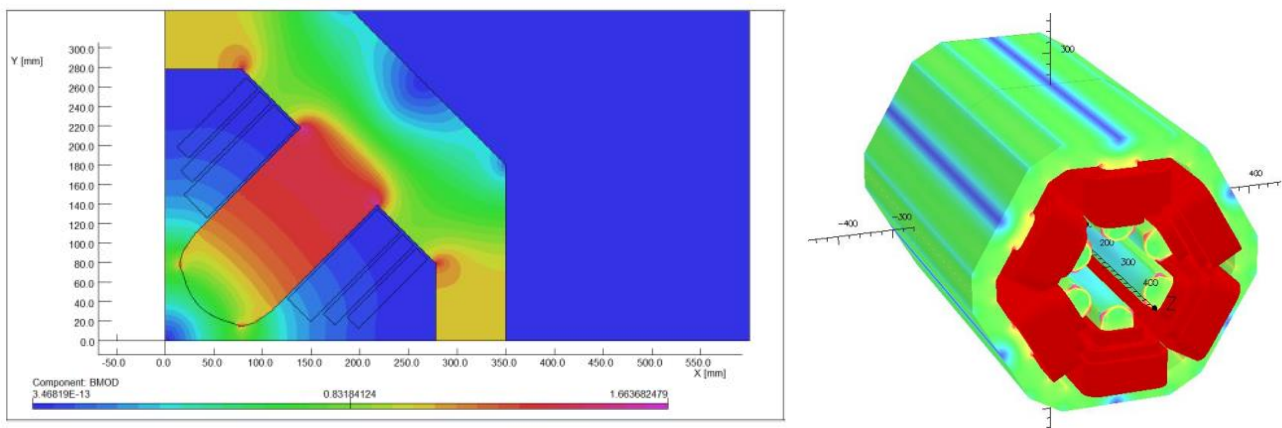


Figure 3.3. CEPC quadrupole (left) and sextupole (right) magnets.

### 3.2 High Field Proton Collider Magnets

High field magnets are critical to energy-frontier circular colliders. For the main ring dipole magnets of a hadron collider, the linear relationship between beam energy, ring radius, and magnetic field strength provide the basis for facility optimization for physics reach and for cost. A reasonable estimate for the beam energy is  $E = 0.3BR$ , with energy  $E$  in TeV, field  $B$  in T, and radius  $R$  in km. The maximum affordable dipole field, together with the dimension of the tunnel, set the maximum achievable energy, so the focus is set on the development of cost-effective high-field accelerator dipoles. In the insertion and straight section regions, where the experiments are housed, special magnets are needed for the strong focusing of the beam in the interaction point or for the crossing in the beam. Nb<sub>3</sub>Sn is today the natural reference for future collider magnets, but HTS provides the opportunity to operate at higher fields (20 T target) and/or intermediate temperature range of 10 to 20 K.

#### 3.2.1 FCC-hh magnets

A Future Circular Collider (FCC) [3.2.1] require bending magnets operating at up to 16 T [3.2.2]. This is about twice the magnetic field amplitude produced by the Nb-Ti LHC magnets, and about 5 T higher than the one produced by the Nb<sub>3</sub>Sn magnets being developed for the High Luminosity LHC (HL-LHC). To explore the design and manufacture of these magnets, several development programs have been initiated [3.2.3]. The design of the magnets was explored within the WP5 EuroCirCol Program. A specific feature of the program is that different design options are considered with the same specification, to provide a 16 T dipole field in a 50 mm aperture. The target critical current density is 1500 A/mm<sup>2</sup> at 4.2 K and 16 T, corresponding to 2300 A/mm<sup>2</sup> at 1.9 K and 16 T. The margin on the load line was at least 14% for all designs and the maximum allowable stress in the conductor was 150 MPa at room temperature and 200 MPa at 1.9 K. A considerable effort has indeed been devoted to finalize optimum common design parameters and assumptions, as well as setting up and validating the design and analysis tools, in particular the ones for quench protection. Since the beginning of the activity in July 2015, the program went through several major evolutions. In 2016 a redefinition of the conductor and load line margin parameters allowed the design of electromagnetically efficient coil cross sections, new features implemented in the common coil design [3.2.6] allowed to partially fill the gap of amount of conductor needed with respect to the cosine-theta [3.2.4] and the block-coil [3.2.5] configurations, and finally a new concept of canted-cos-theta using large cables was introduced [3.2.7]. The electromagnetic cross section of each of these options is shown in Figure 3.4. Their salient features, with respect to the baseline cosine-theta, are shown in Table 3.1.

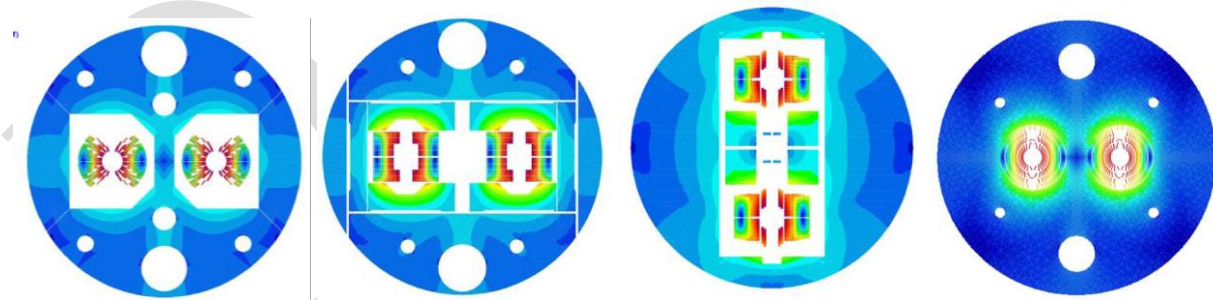


Figure 3.4. Cross section of the four main dipole design options explored within the EuroCirCol program. From left to right, cos-theta (INFN), block (CEA), common coil (CIEMAT), and CCT (PSI) designs.

Table 3.1. Salient features of design options for 16 T magnets.

Parameter	Cos-theta	Block-coil	CCT	Common-coil
Peak field on conductor (T)	16.40	16.73	16.35	16.57
Operating current (A)	11 441	10 176	18 135	15 880
Inductance @ 16 T (mH/m)	38	48	18	26
Outer yoke diameter (mm)	660	616	750	650
Mass of conductor (kg/m)	115	120	148	145

The FCC main quadrupoles (MQ) are twin-aperture magnets based on a cos-theta coil configuration assembled in a 20 mm thick helium II vessel [3.2.8]. Like the main dipole magnet, the inter-beam distance is 250 mm and the physical aperture is 50 mm in diameter. Each aperture is mechanically independent from the other due to the use of a collar-and-key mechanical assembly. Each double pancake is made of 18 turns of Nb<sub>3</sub>Sn Rutherford cable with a 0.4 degree keystone angle. The electromagnetic cross-section is shown in Figure 3.5.

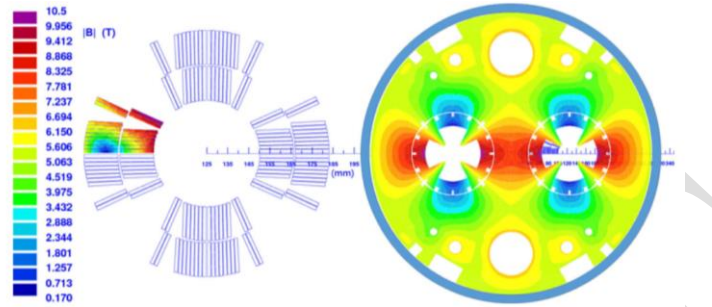


Figure 3.5. Left: coil cross-section with magnetic field map. Right: cold-mass cross-section.

For the FCC-hh, the FODO cell length in the arc is 213 m, roughly double the length of the LHC FODO cell. The FCC-hh has 8 long arcs, each with 36.5 FODO cells, and 4 short arcs, each with 15 FODO cells. Each FODO cell has 12 dipoles and 2 Short Straight Sections (SSS). As in the LHC, each SSS contains one quadrupole MQ, and sextupole (MS) and dipole corrector magnets (MC). Depending on the SSS location in the arc, there may be in addition octupole corrector magnets (MO), tuning quadrupoles (MQT) or skew quadrupoles (MQS). The magnet types and their main parameters are listed in Table 3.2. All these magnets, except the DIS quadrupole (MQDA), use Nb–Ti technology [3.2.9], whereas the MQDA relies on Nb<sub>3</sub>Sn.

Table 3.2. Other magnets in the arc

Magnet type	Technology	Number	Strength	Length
Lattice sextupoles (MS)	NbTi	696	7000 T/m <sup>2</sup>	1.2 m
Lattice octupoles (MO)	NbTi	480	200 000 T/m <sup>3</sup>	0.5 m
Dipole correctors (MCB)	NbTi	792	4 T	1.2 m
Trim quadrupoles (MQT)	NbTi	120	220 T/m	0.5 m
Skew quadrupoles (MQS)	NbTi	96	220 T/m	0.5 m
MCS	NbTi	2 × 4668	3000 T/m <sup>2</sup>	0.11 m
DIS quadrupole (MQDA)	Nb <sub>3</sub> Sn	48	360 T/m	9.7 m
DIS trim quadrupole (MQTL)	NbTi	48	220 T/m	2.0 m

The low-beta triplets are composed of quadrupole magnets and corrector magnets. There are two types of low-beta triplets for installation in the high- and low luminosity interaction regions, respectively. The magnet types and their main parameters are listed in Table 3.3. The magnets around the collision points will be exposed to high radiation levels which may adversely affect their performance. It is assumed that the conductor performance can be maintained until a displacement-per-atom (DPA) value of  $2 \times 10^{-3}$  and that the magnet insulation can withstand an accumulated radiation dose of 30 MGy. These values may be exceeded over the machine lifetime, going up to 40–50 MGy assuming the use of the baseline 35 mm thick tungsten shield.

Table 3.3. Low-beta triplets

Magnet type	Technology	Number/IP	Strength	Length	Aperture
Q1 high lumi	Nb <sub>3</sub> Sn	4	130 T/m	14.3 m	164 mm
Q2 high lumi	Nb <sub>3</sub> Sn	8	105 T/m	12.5 m	210 mm
Q3 high lumi	Nb <sub>3</sub> Sn	4	105 T/m	14.3 m	210 mm
Q1 low lumi	Nb–Ti	4	270 T/m	10.0 m	64 mm
Q2 low lumi	Nb–Ti	4	270 T/m	15.0 m	64 mm
Q3 low lumi	Nb–Ti	4	270 T/m	10.0 m	64 mm

### 3.2.2 SPPC magnets

The SPPC design study is considering accelerator dipole magnets with nominal magnetic fields in the range of 12-24 T, an aperture of 40-50 mm and the field uniformity on the level of  $10^{-4}$  in  $\sim 65\%$  of their aperture. The magnets have two apertures with opposite field direction inside the common iron yoke to minimize the magnet transverse size and reduce its cost. The aperture separation in the main dipoles is presently estimated on the level of 200-300 mm. This parameter in the final magnet design will be optimized to achieve the acceptable crosstalk between two apertures and minimize the overall magnet cross-section. The outer diameter of the arc dipole and quadrupole cold masses is limited by 900 mm to be installed inside vacuum vessels with an outer diameter of 1.5 m. The total magnetic length of the main dipoles is  $\sim 65.4$  km at the total collider ring circumference of 100 km. For the dipole length of about 15 m, approximately 4360 dipole magnets will be needed [3.2.10].

SPPC magnets with operation fields up to 15-16 T will need advanced  $\text{Nb}_3\text{Sn}$  superconductors. To increase the nominal operation fields up to 24 T, High Temperature Superconducting (HTS) materials with acceptable cost are needed. Special attention at the present time is being paid to Iron Based Superconductors (IBS) discovered in 2008. Conceptual design studies of twin-aperture 12 T dipole magnets for the SPPC based on the IBS technology are being performed. In addition to the significant increase of the current carrying capability, it is also anticipated that the IBS will have better mechanical properties than the present  $\text{Nb}_3\text{Sn}$ , REBCO or Bi2212, and substantially lower cost. Cross-sections of the two design options under consideration for the 12 T SPPC dipole based on the IBS conductor are shown in Figure 3.6. The coil aperture in both cases is 45 mm and the nominal field in the two magnet apertures is 12 T with the geometrical field quality on the level of  $10^{-4}$ . The coil layout uses the common-coil configuration due to its simple structure compatible with the tape-type conductor and simplicity for fabrication.

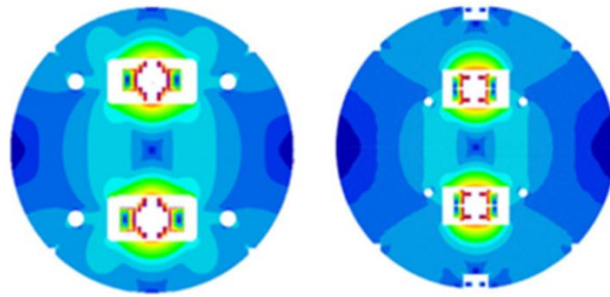


Figure 3.6. Cross-sections of the two design options for the 12 T SPPC dipole based on IBS.

## 3.3 Muon Collider Magnets

### 3.3.1 Muon collider magnet system

Muon Collider (MC) magnet needs and challenges are discussed in [MWP5]. The pictures of main MC magnets are shown in Figure 3.7. The US MC studies [3.3.1], [3.3.2] provide the most consistent baseline, including an overview of the magnet requirements for a Muon Collider. The MAP results provide a broad envelope of the required magnet performance. The WP gives a summary of the perceived challenges, authors view on technology options, and selected magnet engineering tasks.

### 3.3.2 Muon production

Muons are produced by the decay of pions generated by interaction of intense proton beams with a target placed inside a high-field production solenoid. This solenoid captures the pions and guide them into a decay channel to produce muons. The production solenoid produces a high magnetic field of 20 T in a 150 mm aperture. A present baseline option is based on the 12-15 T, 2.4 m bore superconducting (SC) outsert solenoid and the 5-10 T, 150 mm bore normal conducting (NC) insert. As an alternative, a large bore LTS and HTS hybrid solenoid is also considered, although high resistance to radiation and heat load of this design would need to be demonstrated. The key advantages of an HTS-based solution would be the reduction of the outer diameter, the large temperature margin of HTS, the possibility to operate at higher temperature than liquid helium, and the reduction of the

operation costs. The main challenges of the production solenoid include high operation field, strong electromagnetic forces, large stored energy, high-radiation environment. While an LSC+NC hybrid solenoid, originally planned in MAP, can be built based on the extrapolation of known technology, an HTS+NC or LTS+HTS hybrid versions would require a comprehensive R&D. The requirements and technological challenges of the production solenoid broadly overlap with those of magnets for high-magnetic field science, as well as solenoids for Tokamaks. The technology for a LTS+HTS option has overlap with that of ultra-high-field NMR magnets, and such development would profit from synergy with the development of HTS windings for High Energy Physics (e.g. HEP dipoles) and light sources (e.g. super bends).

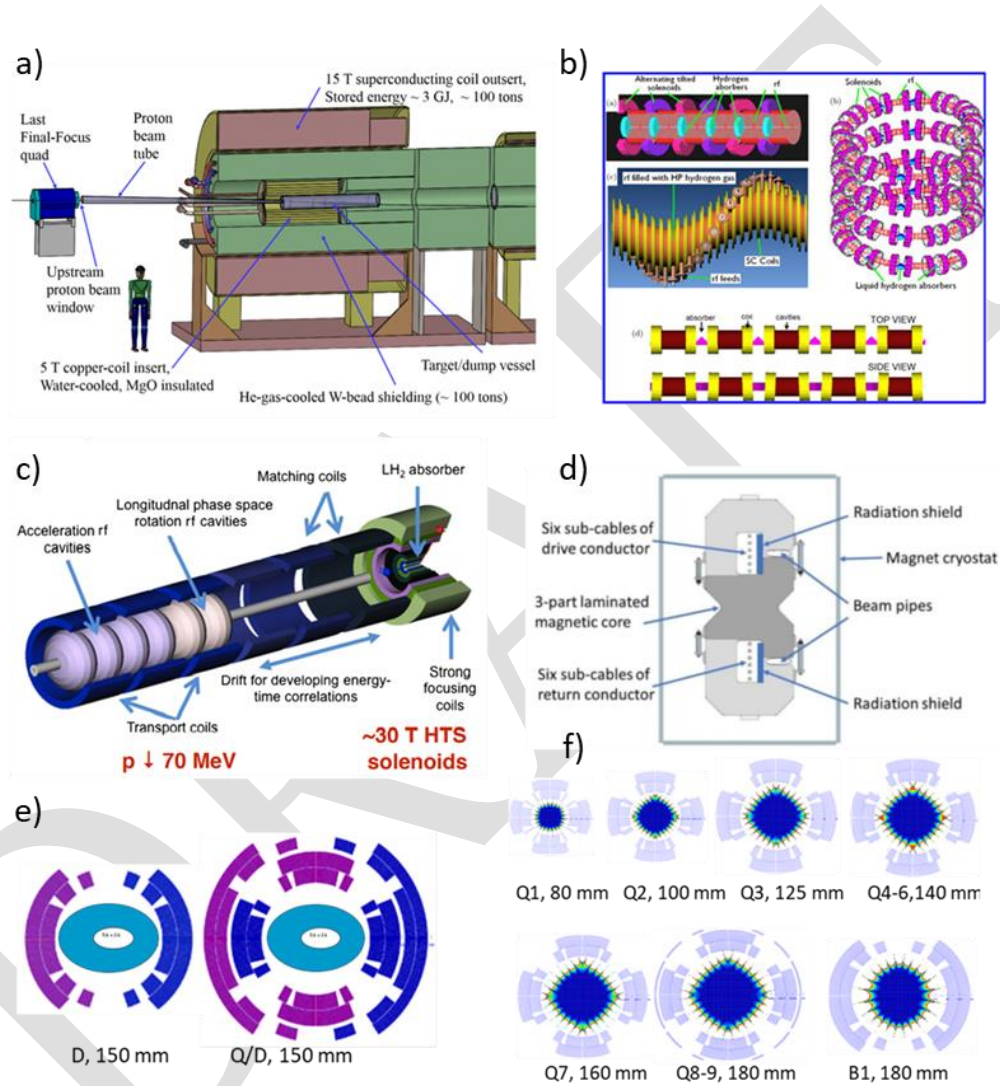


Figure 3.7. MC magnets: a) production solenoid; b) 6D muon cooling solenoids; c) final muon cooling system; d) fast-cycling muon acceleration magnet; e) collider ring magnets; f) IR magnets.

### 3.3.3 Muon cooling

The cooling of muon beams occurs in a channel formed by solenoids and RF cavities. Since the final emittance of the muon beam is inversely proportional to the magnetic field of the final cooling solenoids, the goal for the final cooling solenoid is to produce a magnetic field of 40-60 T in a 50 mm aperture. The preferred design approach in this case is an LTS+HTS hybrid magnet. The main challenges of this ultra-high field solenoid are the large electromagnetic forces and stresses, quench protection as well as the mechanical, thermal and powering integration of the LTS and HTS coils. These solenoids go beyond available technology and, thus, will require considerable R&D and demonstration. The challenges for the final cooling solenoids are similar to magnets for high-field magnet

user facilities based on all-superconducting solenoids, and ultra-high field NMR solenoids. The R&D on the final cooling solenoids is also synergetic with the HTS accelerator magnet R&D for High Energy Physics (HEP) and light sources.

### 3.3.4 Acceleration

After cooling, muon beams have to be rapidly accelerated to relativistic momentum to extend their laboratory lifetime. After an initial acceleration stage in a Linear Accelerator (LINAC) and Recirculating Linear Accelerators (RLA) a sequence of Fixed Field Alternating Gradients (FFAG) Rapid-Cycled Synchrotrons (RCS) and Hybrid Cycled Synchrotrons (HCS) is used. The preferred option at the present time is RCS and HCS based on either NC fast ramping magnets (RCS) or a combination of NC fast ramping and static SC magnets (HCS). Both synchrotrons require fast ramping magnets. In the front end HCS, the fast ramped magnets for the muon acceleration need a magnetic field sweep of  $\sim 4$  T ( $\pm 2$  T) within 0.4 ms, which corresponds to a field ramp rate of 10 kT/s, in a rectangular bore of 80 mm by 40 mm. A resistive approach looks preferred for these specifications. The far end HCS require 4 T change over  $\sim 10$  ms, or a field ramp rate of  $\sim 400$  T/s, which makes HTS promising. A larger swing of field would be beneficial, which may be also the key advantage of HTS. Besides the engineering challenges of such magnets, the stored energy of an accelerator ring of the appropriate size is large, of the order of several tens of MJ, and operation at high-pulse rate requires managing of peak power in the range of tens of GW. Energy storage based on capacitor banks seems to be the only viable solution, or alternatives such as SMES and flux-pumps with high Q-factor to improve the energy efficiency. The work required on magnets and powering for the accelerator stage has clear synergies with the design of RCS for nuclear physics machines, as well as accelerator driven transmutation and fission systems.

A practical opportunity to build fast-cycling dipole magnets using second generation (G2) HTS is discussed in [MWP20]. Besides being superconducting at relatively high temperatures, rare-earth HTS tapes have shown very small AC losses compared to low-temperature Nb-Ti cables. Recent tests of the 0.5 m long twin-aperture HTS-based dipole demonstrated record-high field ramp rate of  $\sim 300$  T/s at 10 Hz repetition rate and 0.5 T field amplitude. No temperature rise in 6 K cooling He was observed within the  $\sim 0.003$  K error which is setting the upper limit on the cryogenic power loss in the magnet conductor coil below 0.2 W/m. Based on this result a possible upgrade of this magnet design to 2 T in the 10 mm beam gap with the field ramp rate up to 1000 T/s is discussed.

### 3.3.5 Collision

The final stage of the muon collider complex is a storage ring (SR) and an interaction region (IR). The SR needs to have the smallest possible size to maximize the number of muon collisions within their limited lifetime. Radiation shielding, from the collisions, and neutrino flux mitigation, due to muon decay, need to be addressed. As a result, the SR and IR magnets have to produce high fields in large apertures for shielding and, in the case of the IR magnets, to achieve high luminosity. For a 10 to 14 TeV muon collider, SR dipole magnets are required to generate a steady-state magnetic field up to 16 T in a 150 mm aperture. To reduce straight sections, and mitigate radiation dose, the collider magnets are presently assumed to have combined functions (D+Q and D+S). SR magnets need to sustain a heat load of 500 W/m from muon decay and synchrotron radiation. In a 3 TeV c.o.m. MC, IR quadrupoles with steady-state gradient of 250 T/m in an 80 mm aperture and 125 T/m in 180 mm aperture (coil peak field up to 12 T), are foreseen for the final beam focus. With appropriate operation margins, these parameters seem to be marginally within reach of Nb<sub>3</sub>Sn. At higher energies the required dipole field and field gradient will need to be increased the level of 20 T which would require using HTS superconductors. The main challenges of SR and IR magnets are driven by the high field and large aperture required, as well as the radiation dose and heat load. These challenges are broadly shared with the development of high-field magnets for future collider, and in particular the need to manage stress in compact windings with high engineering current density.

The results of 3 TeV c.o.m. MC studies and a design concept of the 6 TeV c.o.m. MC optics, the SC magnets, and a preliminary analysis of the protection system to reduce radiation loads on the magnets and particle backgrounds in the MC detector are discussed in [MWP9]. The SC magnets and detector protection considerations

impose strict limitations on the design of the collider optics, magnets and Machine Detector Interface (MDI). SC magnets based on traditional cos-theta coil geometry and Nb<sub>3</sub>Sn superconductor were used to provide realistic field maps for the analysis and optimization of the arc lattice and IR design, as well as for studies of beam dynamics and magnet protection against radiation. An important issue to address is the stress management in the coil to avoid substantial degradation or even damage of the brittle SC coils. Stress management concepts for shell-type coils are being developed for high-field accelerator magnets based on LTS (Nb<sub>3</sub>Sn) and HTS (Bi2212 and REBCO) cables by the US MDP (see section 2.1.2).

A low-energy medium-luminosity MC as a possible Higgs Factory (HF) has been also studied and is discussed in [MWP10]. Electrons from muon decays will deposit more than 300 kW in the HF SR, which imposes significant challenges to SC magnets used in the HF SR and IR. The distribution of heat deposition in the HF SR lattice elements requires large-aperture magnets to accommodate thick high-Z absorbers to protect the SC coils. Magnet conceptual designs which provide the required high operating gradients and dipole fields in large apertures to accommodate the large size of muon beams, as well as a cooling system to intercept the large heat deposition from the showers induced by decay electrons, were developed. In the IR, the coil aperture of the IR magnets varies from 320 mm in Q1 and to 500 mm in Q2–Q4 and B1. Outside of the IR, the coil aperture varies between 270 mm and 160 mm. The maximum design field in coils in the HF SR and IR magnets is on the level 16-18 T to provide the necessary operation margin. High field level and large magnet apertures require using the Nb<sub>3</sub>Sn technology and stress management approach. A sophisticated radiation protection system was designed for the SR and IR to bring the peak power density in the SC coils below the quench limit and reduce the dynamic heat deposition in the cold mass by a factor of 100. The system consists of tight tungsten masks in the magnet interconnect regions and elliptical tungsten liners in the magnet aperture optimized individually for each magnet.

#### 4 Detector Magnets Progress and Future Requirements

Superconducting detector magnets are a key component to analyze the momentum and polarity of charged particles in particle physics experiments. A large warm bore is required.

Over the past four decades, the design and fabrication of detector magnets has made significant progress thanks to the introduction and demonstration of specific technologies such as: high current, high strength, aluminum-stabilized superconducting cables; coil winding performed directly in the outer support cylinder to support large hoop stress; improved transparency using indirect cooling to eliminate the liquid helium vessel and no mechanical structure in the winding; pure aluminum strips as temperature equalizer and fast quench propagation.

The detector solenoids design study is in progress for future big projects in Japan and Europe, that is, ILC, FCC and CLIC [MWP19]. The proposed design parameters for each solenoid are summarized in Table 4.1.

Table 4.1. The proposed design parameters for the detector solenoids for future projects

Project	Magnet	Bc (T)	Rinner (m)	Length (m)	E/M (kJ/kg)	Stored Energy (GJ)
FCC-ee	IDEA	2	2.24	5.8	14	0.17
	CLD	2	4.02	7.2	12	0.6
FCC-hh		4	5	20	11.9	13.8
CLIC		4	3.65	7.8	13	2.3
ILC	ILD	4	3.6	7.35	13	2.3
	SID	5	2.5	5	12	1.4

Detector magnets for future colliders will be based on these technologies but further improvements will be required to cope with larger size, radiation loads and physics performance requirements. At the same time there is a risk that expertise and industrial capabilities are gradually lost due to the long time between projects. The industrial technology of Al-stabilized superconductor production is of particular concern. In other cases, precise control of the magnetic field distribution required high precision simulation, and tight control of fabrication tolerances. If the calorimeter is placed outside the magnet, such as ATLAS, high transparency is also required for

charged particles passing through with a minimum energy. Otherwise, particle detectors need to be installed inside the magnet bore (except for muon detectors) resulting in larger bore, higher field and longer coil length.

#### 4.1 FCC-ee

Three detector designs have been proposed for FCC-ee [4.1.1], [4.1.2]: the Innovative Detector for Electron-positron Accelerators (IDEA, [4.1.3]), the CLIC-Like Detector (CLD, [4.1.4]) and a design comparable to the IDEA detector that remains to be named. Each of these three designs includes a 2 T superconducting solenoid. The CLD solenoid is positioned outside of the calorimeter while the two other solenoids are situated inside the calorimeter barrels. Since the IDEA solenoid is inside the calorimeter there are strict requirements on the particle transparency. The concept of the solenoid of the IDEA is similar to the ATLAS Central Solenoid (CS) [4.1.5] whereas the CLD solenoid is similar to the CMS solenoid [4.1.6]. However, the free-bore diameter of the IDEA solenoid is almost two times bigger than the free bore of the ATLAS CS. This also means that the IDEA magnet has around four times the stored magnetic energy of the ATLAS CS at 170 MJ. The free-bore diameter of CMS is 6 m with a stored energy of 2.6 GJ. The CLD design has a larger free bore of 7.2 m and its stored energy is 600 MJ. The design parameters for the IDEA and the CLD are summarized in [4.1.7].

The challenges of the IDEA and CLD designs are well illustrated by their energy density. The energy density in IDEA solenoid is 14 kJ/kg, which is twice as high in ATLAS, whereas the CLD magnet has an energy density of 12 kJ/kg which is close to 11 kJ/kg in CMS. The large free bores in combination with the high stored energies translate to strong requirements on quench protection design, mechanical support and strength of the materials used. Preliminary protection studies are using energy extraction in combination with quench heaters and aluminum strips for faster propagation. For both detectors a safe peak temperature of about 60 K can be maintained.

#### 4.2 FCC-hh

The FCC-hh [4.2.2] detector magnet (Fig. 4.1) features three 4 T superconducting solenoids. The central solenoid has free 10 m diameter aperture and a length of 20 m, whereas the forward solenoids have a cold mass length of 3.4 m and a free bore diameter of ~5 m. The basic detector layout is similar to CMS, featuring a tracker, electromagnetic calorimeter (E-CAL), and a hadron calorimeter (H-CAL) in the bore of the magnet, and muon chambers on the outside of the magnet. The muon chambers utilize the magnetic return flux of the main solenoid for the purpose of muon tagging. However, unlike CMS, the FCC-hh detector does not feature iron yokes.

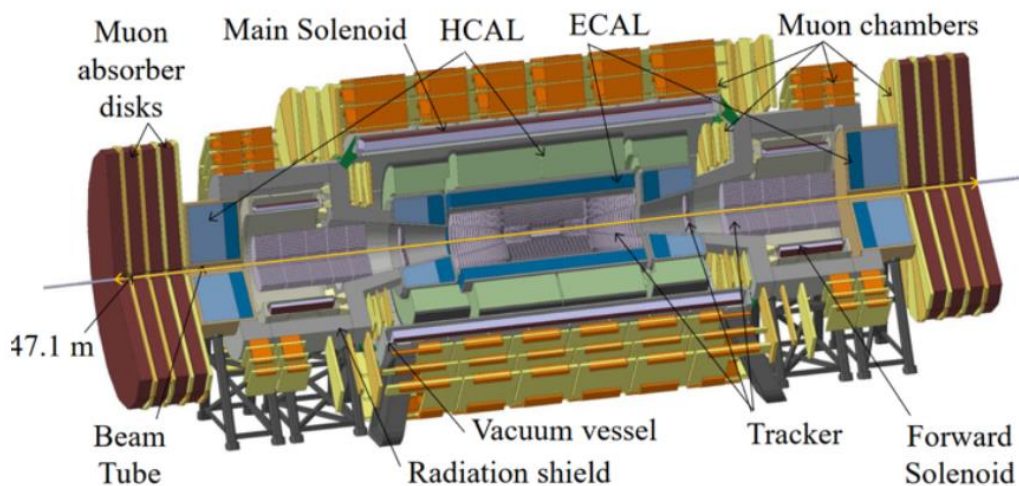


Figure 4.1. Proposed FCC-hh detector base-line layout

The bore field of 4 T and the energy density of 11.85 kJ/kg are a bit higher than CMS, while the total stored energy of 13.8 GJ is more than five times higher. The peak Von Mises stresses in the main and the forward solenoids are at 100 MPa under nominal conditions which shows that, similar to CMS and ATLAS Central Solenoid, a



reinforced conductor is needed to handle the Lorenz forces. The conductors include Nb-Ti/Cu Rutherford cables surrounded by nickel-doped aluminum stabilizer. The cables feature 40 strands with a diameter of 1.5 mm, a Cu/non-Cu ratio of 1:1, and a current sharing temperature of 6.5 K. The operating current is 30 kA

The solenoids are powered in series by a single power supply with slow dump circuit which is sufficient to charge and discharge the solenoids. In case of a quench, the different operating current densities in the main and forward solenoids necessitates a current decoupling of these two different magnet types, and therefore the two magnet types each feature their own fast discharge dump system comprising diodes and resistors. In parallel protection heaters are used to initiate quenches in different areas of the coils, thus avoiding strong temperature gradients even under fault conditions where the fast dump units fail to discharge the magnets. The calculated peak hot-spot temperature is well below 100 K under nominal conditions.

### 4.3 CLIC

The CLICdet design is based on a 4 T solenoid and is designed to operate at the three stages of the CLIC accelerator phases with c.o.m. energies of 380 GeV, 1.5 TeV, and 3 TeV. It takes advantage of the technical approaches developed for the CMS solenoid [4.3.1] and the Atlas Central Solenoid (CS) [4.3.2]. The conductor comprises a Rutherford cable composed of 32 Nb-Ti strands that is stabilized with an aluminum sheath. Both ATLAS CS and CMS approaches for a reinforced conductor are considered at this stage. The Rutherford cable will be co-extruded with the high Residual Resistivity Ratio (RRR) aluminum stabilizer. The end coils are used both to limit the magnetic field in the machine detector interface region, in particular on the QD0 final focusing quadrupoles located just in front of the end caps, and to limit the stray field outside the detector to 16 mT at a radial distance of 15 m in the service cavern. The use of these ring coils also contributes to limit the amount of iron in the yoke. It was proposed to build these end coils with normal conducting windings operated at room temperature and water cooled, but we see here a good application of more sustainable solutions in order to limit the heat losses due to the dissipated power by using high temperature superconductor coils, connected in series.

Several technology R&D and pre-industrialization programs will be needed before launching the manufacturing of such a magnet. Power leads and superconducting busbars are typical applications that can be developed using high temperature superconductors. Other developments can also be performed for powering DC converters and dumping circuit. Dedicated studies applied to the detector magnet applications will be needed.

### 4.4 ILC – ILD and ILC-SID

The design parameters of the magnet for the International Large Detector (ILD) feature a central field of up to 4 T, with useful diameter 6.88 m over a length of 7.35 m. Its conceptual design has been done by CEA, DESY and CERN. Many technical solutions successfully used for CMS are proposed for the ILD magnet. Similarly to CMS, a 4-layer coil is retained, with a nominal current of 20 kA, so the conductor for the ILD magnet has larger cross-section of  $74.3 \times 22.8 \text{ mm}^2$ . It consists of a superconducting Rutherford cable, clad in a stabilizer and mechanically reinforced. Two solutions are considered for the reinforcement. The first option is a micro-alloyed material such as the ATLAS central solenoid, which acts both as a stabilizer and a mechanical reinforcement. A R&D program on the Al-0.1wt%Ni stabilizer has been launched at CERN and is underway to demonstrate the feasibility of producing a large conductor cross section with this material. The second option is a CMS-type conductor with two aluminum alloy profiles welded by electron beam to the central conductor stabilized with high purity aluminum.

A conceptual design study for a 5 T superconducting solenoid for the ILC Silicon Detector (SiD) has been done by FNAL. The solenoid has a clear bore diameter of 5 m and a length of 5 m, where 5 T magnetic field is produced for inner detectors. The coil utilizes the CMS conductor as the starting point. Major R&D subject for SiD magnet is its conductor required to sustain large EMF in the coil. A more advanced and likely cheaper conductor was proposed based on high-purity aluminum Al-0.1%Ni alloys, which were used in the ATLAS central solenoid. Other conductor stabilizer possibilities are also under consideration and study. These include  $\text{TiB}_2$  grain refinement aluminum matrix composites, and cold working via the equal area angle extrusion process.

## 5 Magnet technology R&D for High Energy Physics

### 5.1 Superconducting composites

There is a large variety of technical superconductors with critical parameters, such as critical temperature  $T_c$ , upper critical field  $B_{c2}$  and critical current density  $J_c$ , sufficient for using in large magnet systems. Important features of practical materials for superconducting magnets include performance (appropriate combination of critical parameters) and its reproducibility in long lengths, commercial production and affordable cost. The superconducting materials described below belong to the class of practical superconductors being used in various accelerator and detector magnets. Table 5.1 summarizes the critical performance and production parameters of the superconductors available for procurement in industry in 1 km length that also meet needs for accelerator magnets. Cross-sections of the practical wires and tapes are shown in Figure 5.1. Magnet conductors are discussed in [MWP8].

Table 5.1. Critical performance parameters and production parameters of the conductors.

SC material	$T_c$ , K	$B_{c2}(4.2K)$ , T	Mechanical property	Billet or batch mass, kg	Annual production scale, tons	Relative cost	Final cost /material cost
Nb-Ti	9.2	11	ductile	200-400	>100	1	3
Nb <sub>3</sub> Sn	18	26	brittle	45	1-10/1*	5/8*	5-7
Nb <sub>3</sub> Al	18	26	brittle	45	1	8	?
MgB <sub>2</sub>	39	20	brittle	20	< 1	2	?
Bi-2212	85	100	brittle	20	< 1	20-50	~10
REBCO	92	>120	brittle	10	< 1 <sup>#</sup>	20-50	>>10

\* RRP/PIT

<sup>#</sup> few tons planned for fusion

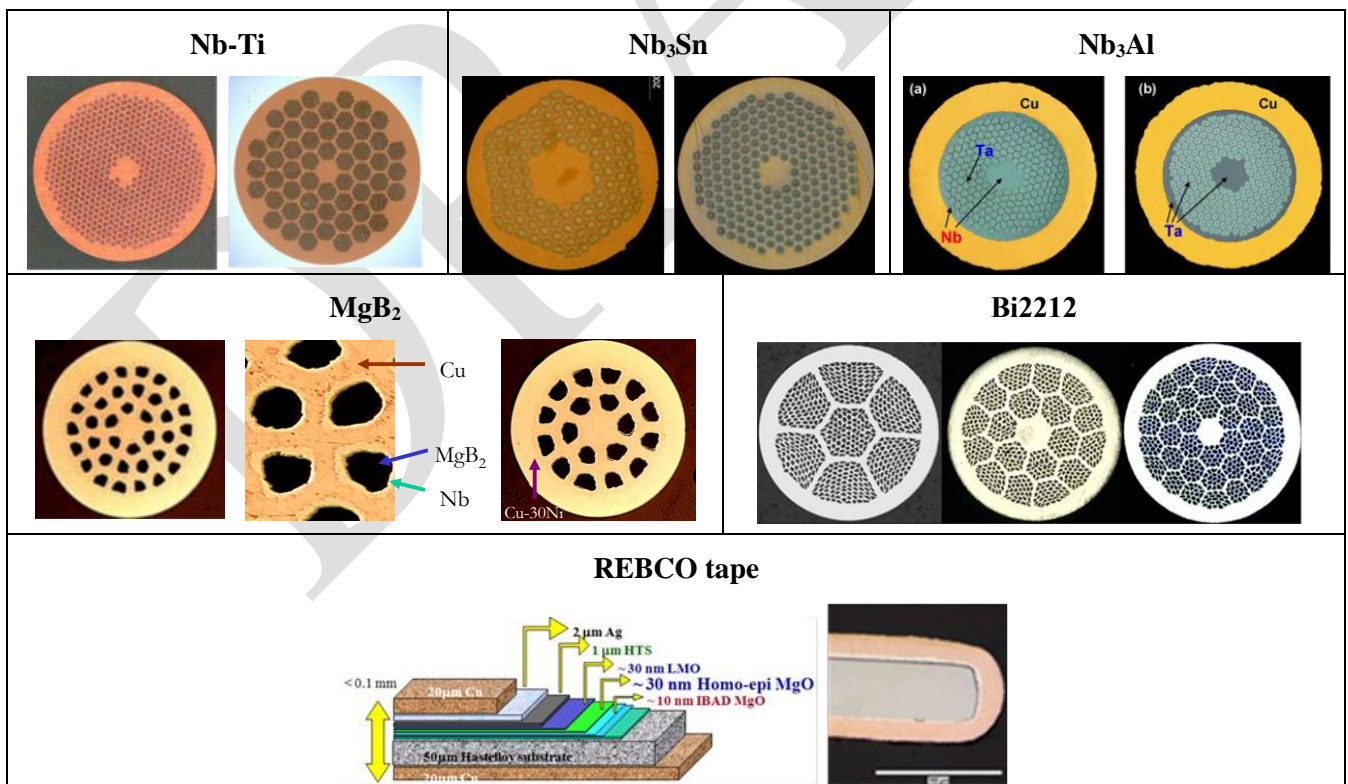


Figure 5.1. Composite SC wire and tapes.

### 5.1.1 LTS composite wires

*Nb-Ti composite wires.* Since its discovery in the 1960s, Nb-Ti is the most successful practical superconductor. A composite Nb-Ti wire is manufactured by a co-drawing process with intermediate heat treatments to achieve an optimal pinning structure. Diameters of practical wires are in the range of 0.1 to 3 mm and piece lengths are of a few km. The typical RRR value of the Cu matrix is in the range of 50–200. A thin Nb barrier separates the Nb-Ti alloy from the Cu to avoid the formation of brittle CuTi intermetallic composite during the high-temperature extrusion and the annealing heat treatments. The number of filaments in a wire may reach  $\sim 10^5$  and the filament diameter is 5–50  $\mu\text{m}$  (the practical low limit is  $\sim 1\text{--}2\ \mu\text{m}$ ). The number of filaments and, thus, the filament size are determined mainly by stability criteria and by hysteresis magnetization or AC loss values. Figure 5.1a shows typical cross-sections of Nb-Ti superconducting composite wires. The single stack design is limited to  $\sim 10^4$  filaments. Using the double stack design allows achieving larger-number and smaller-size filaments.

Artificial Pinning Centers (APC) based on thin normal metal rods incorporated in the Nb-Ti filaments were proposed in the 1970s to improve and control flux pinning. This method has resulted in enhanced performance at lower fields with respect to conventional Nb-Ti, as needed in some magnet applications. It was found also that ternary Nb-Ti-Ta alloys have the potential to provide a small gain in upper critical field (up to 1.25 T at 1.8 K) while preserving the traditional wire manufacturing process. Low-loss Nb-Ti composite wires with ultrafine filaments ( $\sim 0.1\ \mu\text{m}$ ) and extra resistive Cu-Ni matrix are also produced for AC applications.

*Nb<sub>3</sub>Sn composite wires.* Nb<sub>3</sub>Sn is an intermetallic composite, the second practical superconductor most widely used in superconducting magnets. Its superconducting properties were discovered in the 1960s. Nb<sub>3</sub>Sn composite wires are currently produced using three main methods: bronze, internal tin (IT), and powder-in-tube (PIT) methods. The last two are most interesting for accelerator magnets due to high  $J_c$ .

The Nb<sub>3</sub>Sn wires produced by IT Restacked-Rod-Process (RRP) use an architecture, wherein rods of Nb, Nb-Ta alloy, or Nb-Ti alloy are sheathed in Cu and extruded, drawn, stacked in an annulus around a central core, wrapped with a diffusion barrier, and extruded a second time. Part of the core is then replaced with Sn, and this assembly forms what is called a sub-element. After further drawing, the sub-elements are re-stacked and further drawn to the final size. A reaction sequence produces mixed Cu-Sn phases at low to moderate temperatures (below 600°C) before a final high-temperature segment facilitates a diffusion reaction between Cu-Sn and Nb (or Nb-alloy) to form Nb<sub>3</sub>Sn (or Nb<sub>3</sub>Sn alloyed with Ti, Ta, etc.). Conductor naming typically refers to the number of sub-elements that occupy a theoretical number of sub-element sites. RRP research strands explored configurations restacks from 61 up to 217 sub-elements, including Cu. Procurements in 2021-2022 focuses on 150/169 and 162/169 designs and 1.0 to 1.1 mm final diameter.

The tube-based Nb<sub>3</sub>Sn approaches, such as Powder-in-tube (PIT) and rod-in-tube (RIT), replace the annulus of stacked rods in RRP conductors with a solid tube of Nb or Nb-alloy. The Sn source, often combined with Cu, can be a powder or a rod inserted in the center of the tube, whereby a radial diffusion reaction following a similar path as for RRP conductors is used to form the Nb<sub>3</sub>Sn layer. The assembled tube and core material is restacked as described for RRP conductors, where design flexibility is provided by hexagonal or round tube shape, separation and composition of components in the tube core. Since the tube starts off with much less deformation strain than that used to create the RRP annulus, it is plausible that tube-type conductors can achieve larger re-stack counts and smaller diameters before reaching deformation limits. Reports investigated restacks with as many as 744 tube sub-elements ( $n=18$  with 169 sub-elements being Cu) at tube diameter approaching 15  $\mu\text{m}$  for 0.7 mm wire diameter.

There are two areas where tube-like Nb<sub>3</sub>Sn wires need R&D to improve properties comparable to RRP wires. First, transverse pressure studies of Rutherford cables show that PIT wire tolerate less transverse strain than RRP wires, with respective onset of degradation at 50–120 MPa vs 170–250 MPa. Second, studies of round and rolled wires noted the tendency for PIT reactions to retain a higher degree of radial symmetry than for RRP, which results in a lower conversion of the available Nb to Nb<sub>3</sub>Sn in distorted sub-elements. While high levels of deformation lead to RRR reduction for both designs, the associated loss of  $J_c$  for PIT wires presents challenges for magnets.

Further enhancement of tube-type Nb<sub>3</sub>Sn conductors could result also from improved manufacturing of tubes with reliable mechanical properties and fine powders of Nb-Sn and Cu-Sn intermetallic compounds.

The continued improvement of Nb<sub>3</sub>Sn wires is vital to future colliders. It includes using advanced Nb-alloys and incorporating high-C<sub>p</sub> materials into the wire architecture. Several the potential benefits of using internal oxidation to improve flux pinning and increase J<sub>c</sub> at high field providing retention or increase of B<sub>c2</sub> in Nb<sub>3</sub>Sn conductors is being explored. Development of both RRP and tube routes is presently underway using advanced alloys. These developments are presently bridging from nascent wires to industry R&D. Adequate conductor development resources could encourage development by industry practical wires over a 5-year timeframe. Development of Nb<sub>3</sub>Sn wires with high-C<sub>p</sub> additives is underway in parallel with investigation of advanced alloys. Challenges exist in identifying and optimizing powders for both properties and compatibility with manufacturing. Support from conductor development programs could extend promising wires to industry R&D within 5 years. In addition to these opportunities, improvement of RRP conductors also needs research attention given to a) reducing d<sub>eff</sub> without concomitant loss of performance, loss of yield, or increase of cost; b) scaling production to 100 kg billets or larger; and c) modifying the conductor architecture and heat treatment to optimize properties above 15 T.

Nb<sub>3</sub>Al composite wires. The NIMS group in Japan invented a rapid-heating quench treatment (RHQT) process that circumvented thermodynamic limitations of the Nb-Al system. They attained excellent properties of the Nb<sub>3</sub>Al phase in wires of kilometer length. However, the treatment temperature is above the melting point of Cu, which required manufacturing to develop special processes, such as ion plating, to add Cu stabilizer. Conductor development at Ohio State and some cabling and magnet studies at FNAL provide additional background.

MgB<sub>2</sub> composite wires. MgB<sub>2</sub>, a binary intermetallic superconductor, is a promising material for application in superconducting magnets. It is brittle, but relatively easy to fabricate in long lengths. The traditional PIT method and a variety of sheath materials with appropriate barriers or reinforcing components are used to fabricate MgB<sub>2</sub> composite wires. The MgB<sub>2</sub> superconducting phase is formed during a reaction heat treatment at 700°C for 20 minutes. Since both components Mg and B, and the sheath materials are inexpensive, the cost/performance ratio for MgB<sub>2</sub> is much lower than that for other superconductors. Thanks to the relatively high T<sub>c</sub>, MgB<sub>2</sub> is suitable for use in superconducting magnets cooled at 10–30 K. The density of MgB<sub>2</sub> is lower than the density of other superconductors making it attractive for specific applications in lightweight magnets or in supporting accelerator magnets as it has been done for the CERN Superconducting Link.

### 5.1.2 HTS conductors

Conductors made from high-temperature superconductor (HTS) also are capable of extremely high fields. The 1990s advanced three main HTS conductors in long length under the auspices of the DOE Office of Electricity: Bi2223 (Bi<sub>2</sub>Sr<sub>2</sub>Ca<sub>2</sub>Cu<sub>3</sub>O<sub>14</sub>) called also “1G-HTS”, representing a first generation; Bi2212 (Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>10</sub>) and REBCO (RE<sub>1</sub>Ba<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> where RE stands for Y or a rare earth element) often called “2G-HTS”, representing a second generation of electricity conductor. For high-field magnets, Bi2223 still offers some interest in its present form but its current density is comparatively low for most applications in the accelerator sector. Bi2212 attain stronger flux pinning by virtue of its lower anisotropy compared to Bi2223.

Bi2212 round wires. Since Oxygen is evolved during the phase transition, and other gases are present between the powder grains, an external pressure must be applied to prevent coalescence of gas bubbles and blockage of the filaments by gaps. This requires a wind-and-react magnet approach. Present reactions are carried out at 50 bar pressure in specially designed furnaces at Florida State University. A round HTS wire is important for the accelerator magnets in several ways. First, wire-drawing techniques presently applied to copper-clad superconductors can be applied to Bi2212. This could permit scale-up and quality control which has been essential to large-scale production of Nb-Ti and Nb<sub>3</sub>Sn conductors for accelerator magnets. Second, twisted conductors are needed to reduce magnetization and losses upon ramping of accelerator magnets. Third, cabling techniques are generally unchanged between Nb-based conductors and Bi2212. Fourth, existing insulation winding and braiding schemes can be adapted to accommodate the temperature and chemical interactions for Bi2212.

Many of the basic requirements for using Bi2212 in magnets were worked out by the Very High Field Superconducting Magnet Collaboration between 2009 and 2013, which combined investigators from the former DOE Office of Electricity program with HEP national laboratory teams and university groups. Further progress was achieved by advancing the production of Bi2212 powder between 2013 and 2018, where the present standard composition, the so-called “521” formulation, traces back to that effort. Multiple, but small-scale, manufacturers now produce uniform fine powders that facilitate conductor fabrication with low breakage. Continued support from both DOE-HEP and the National Science Foundation (NSF) via the National High Magnetic Field Laboratory (NHMFL) has led to demonstrations of good reproducibility for coil reactions based on conductor witness samples.

*REBCO tapes.* REBCO became a viable high-field magnet conductor when high-strength Hastelloy substrates entered development thanks to the many methods to incorporate pinning centers. Further advances to reduce the Hastelloy thickness to 30  $\mu\text{m}$  provide a significant enhancement of the winding current density, especially in the so-called “no insulation” condition. This enhancement led to achievement of winding current densities of over 1400  $\text{A}/\text{mm}^2$  and reaching beyond 45 T field. The importance of thin Hastelloy is the ability to make compact round “wires” from REBCO tapes. Conductor on round core (CORC<sup>®</sup>) and symmetric tape round (STAR) are two variants envisioned for accelerator magnets. Each consists of a REBCO tapes wound in a helical fashion around a conductive core. Thin substrates reduce the strain applied to the REBCO layer, or alternatively permit winding to smaller wire diameter and higher current density. Wires with typical diameter of  $\sim 3$  mm are facilitated by the 30  $\mu\text{m}$  Hastelloy product. Flexibility to bend either CORC<sup>®</sup> or STAR conductors is related to the tape width and winding pitch, where tapes that are narrower (now pushing below 2 mm width) and wound with a shorter helix pitch have the best flexibility. Unfortunately, these trends drive up cost by requiring more conductor per unit length of cored wire and increasing the losses due to damaged material at the slit edges. The vulnerability to stress is receiving new attention in accelerator magnets and in some fusion tests.

As conductor technology progressed, REBCO has become the basis for the 32 T user magnet at NHMFL, Bruker Biospin’s 28.2 T, 1.2 GHz NMR system, and numerous other magnets above 25 T. Several projects are underway aiming at 40 T magnets. Conductor being procured for privately funded fusion magnets is a significant production run that will provide large amount of data for the evaluation of manufacturing readiness. Smaller production runs associated with the fabrication of large magnets such as the 32 T user magnet at NHMFL have yielded insight about the readiness of this conductor for accelerator magnets.

### 5.1.3 Other high-field conductors

*Chevrel phase.* HEP resources were provided to develop materials with so-called Chevrel structure  $\text{PbMo}_6\text{S}_8$ , based on  $T_c$  of  $\sim 15$  K and  $B_{c2}$  of  $\sim 60$  T at low temperature. Powder-in-tube wire technologies could not emerge from R&D status due to lack of densification of the powder core and persistent contamination by oxygen. These challenges are similar to those discussed for iron-based superconductors below. Manufacturing with stainless steel sheaths, hot isostatic pressing, and hot-rolling or hot-drawing has been used to make laboratory scale wires with high density, but the process complexity is too high to compete with HTS conductors.

*Iron-based superconductors.* Iron-based superconductors (IBS) present the interesting opportunity of an extremely rapid increase of critical field with reduction in temperature. Nascent wires and tapes are emerging, more often following the path of REBCO coated conductors than that of multifilamentary round wires. Powder-in-tube wires are beginning to show promising  $J_c$ , but requisites for magnet technology still need to be demonstrated. Some processes are compatible with Cu based on temperature and chemical reactivity. However, densification is an underlying requisite for further development, where addition of substantial high-strength sheathes appear to be necessary to constrain powders and achieve high utilization of the powder core. The same underlying challenge has prevented multifilamentary wires and tapes made from Bi-2223,  $\text{PbMo}_6\text{S}_8$ , and  $\text{MgB}_2$  from realizing the full potential of properties shown on the small scale. While continued support of basic research to advance IBS wires is needed, it is unclear where the transition point lies for more focused development for accelerator magnets. High density powder cores must be achieved without requirements of excessive iron or steel sheaths. Coated conductors

need to demonstrate advantages over the much more mature REBCO, and cost obstacles connected with reel-to-reel manufacturing capital must be overcome.

A practical plan to make the IBS  $\text{AEFe}_2\text{As}_2$  (122) (AE = alkaline earth, here Ba or Sr) into a much cheaper, higher stability, round, twisted and effectively isotropic multifilament conductor suitable for 16-20 T magnets is discussed in [MWP7]. Compared to  $\text{Nb}_3\text{Sn}$ , 122 is still at the early stage of development. The progress acceleration could be achieved by providing a fundamental understanding of what controls the transport critical current density  $J_c$  of 122 polycrystals and then fabricating it into wire form. High grain-to-grain  $J_c$  is the one key property not yet fully demonstrated in this new superconductor and this is the key breakthrough that would make 122 a practical superconductor. Whereas the intragrain  $J_c$  is already high enough to compete with  $\text{Nb}_3\text{Sn}$ , the unpredictable superconducting connectivity at grain boundaries (GBs) is the critical problem that limits the long-range  $J_c$ .

In the next 10 years, the following key issues need to be addressed so that IBS potential can be fully evaluated and transformed into a practical conductor with  $J_c > 1500 \text{ A/mm}^2$  at 4.2 K and 16-20 T: a) define the most effective synthesis for high quality 122 powder to eliminate extrinsic current blockers at GBs; b) comprehensively evaluate the true nature of GB superconductivity; and c) define the most effective wire design and fabrication route to transfer the effective synthesis into long-length multi-filamentary wire form. These thrusts are inter-related and must be addressed in series with long term commitment. Evaluation of the true nature of GBs in the polycrystalline forms is critical before focusing on wire fabrication.

## 5.2 High-Current Cables

Large superconducting accelerator and detector magnets require high-current multistrand cables. To achieve in a cable the required current level, several strands are connected in parallel and twisted or transposed in the axial direction. Using multistrand cables allows limiting the piece length requirement for wire manufacturing, the number of turns in coil winding, the coil inductance, and also allows current redistribution between strands in the case of a localized defect or quench. Four main designs of superconducting cable are shown in Figure 5.2. They include the rope-type and Rutherford-type designs used with round strands, and the Roebel-type and Conductor-on-round core (CORC<sup>®</sup>) cable suitable for ribbon or tape conductors.



Figure 5.2. Rope-type (top left), Rutherford-type (top middle), Roebel-type (bottom left), and CORC<sup>®</sup> (right) multistrand superconducting cables.

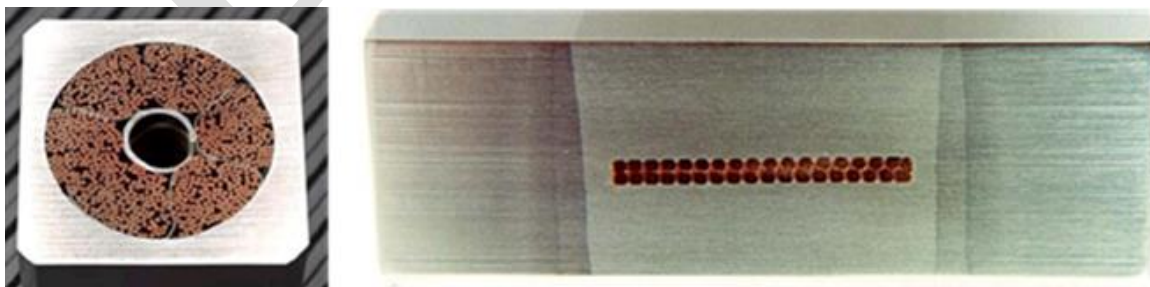


Figure 5.3. Heavily stabilized and mechanically reinforced large current cables: cable-in-conduit-conductor (left) and Al-clad Rutherford cable (right).

The maximum current  $I_c$  of a cable is the sum of strand currents or slightly less. It depends on strand degradation during cabling and current distribution in the cable cross-section. Due to strand coupling inside the cable, its

magnetization and AC losses have additional eddy current components controlled by the inter-strand resistance and strand twist pitch. To reduce coupling, strands can be coated with resistive metal, such as Sn-5%Ag, Cr, Ni, or a thin resistive core can be used in the cable.

In large solenoids used in detectors, additional amounts of a normal metal or stabilizer are used to provide cable mechanical reinforcement in the transverse and axial directions, and improve cable stability and quench protection. Depending on the cooling scheme, gaps or channels for coolant flow can be added. Two examples of such cables are shown in Figure 5.3. The Cable-In-Conduit-Conductor (CICC) is a version of rope-type cable with strong jacket (conduit) and free space between strands for liquid helium. This arrangement combines good support of the strands against Lorentz forces with a low shielding loss and high current. The copper or Al-clad cables are fabricated using soft-soldering, rolling or co-extrusion processes. High purity Al is used to reduce weight, provide high electric and thermal conductivity, and achieve small radiation length.

### 5.3 Magnet Development and Test Technologies

The field range up to 10 T has been scientifically explored and practically realized in all the present HEP colliders such as Tevatron, HERA, RHIC and LHC as well as some smaller machines using Nb-Ti magnet technology. Magnets with a higher field are the most efficient way to achieve higher collision energies in future colliders. To produce higher fields, new superconducting accelerator magnets and technologies based on advanced superconductors and structural materials are being studied.

#### 5.3.1 Approaches and Status of high-field Nb<sub>3</sub>Sn accelerator magnet R&D

The present “work horse” that is readily available on an industrial scale is Nb<sub>3</sub>Sn. Over the last three decades, several programs have probed a variety of accelerator magnet concepts, with record dipole fields in multiple configurations [5.3.1]. As examples:

- The Cosine-Theta approach, used in all high-energy collider magnets to-date. The D20 cosine-theta magnet was a flagship 4-layer magnet built in the late 1990’s that achieved a peak field of 13.5 T at 1.9 K. Most recently, the MDPCT1 magnet, built at FNAL within the MDP program, achieved the record field of 14.5 T at 1.9 K in a 50 mm bore, with excellent field quality [5.3.2].
- The Common Coil dipole configuration, wherein racetrack coils are energized in reverse polarity and create a magnetic field between the coils, yielding effectively twin apertures. Examples include the RD3c magnet built by LBNL, the HFDC01 magnet developed by FNAL, and the DCC017 magnet built and tested by BNL. The latter continues to be in use, serving as a magnet facility for a variety of high field (~10 T) tests for experiments for collaborators.
- The Block Dipole magnets, as the common-coil layout but energized in same polarity, resulting in a single, high-field bore. To maximize field while allowing access for the particle beam, the ends are flared. The concept was most thoroughly explored by LBNL in the mid 2000’s, culminating in the HD3 magnet that achieved 13.8 T at 4.2 K. The technology was ultimately utilized in the CERN FRESCA2 magnet, which achieved 14.6 T with a large, ~100 mm bore. The magnet was not designed as an accelerator magnet, but rather serves as a test facility for superconducting cables.
- The Canted Cosine-Theta (CCT) concept, wherein the cable is directly placed in individual grooves machined into a cylindrical support structure. The tilted winding results in a solenoidal field component, which is compensated by the next layer in the structure, and uniform transverse component. The cross-section shows the intrinsic cos-theta current distribution, resulting in excellent field quality.

#### 5.3.2 The 12-14 T operation field range for large scale deployment

Develop Nb<sub>3</sub>Sn magnet technology for collider-scale production, through robust design, industrial manufacturing processes and cost reduction. The present benchmark for Nb<sub>3</sub>Sn accelerator magnets is HL-LHC, with an ultimate nominal field of 12 T and a production of the order of a few tens of magnets. Nb<sub>3</sub>Sn magnets of this class should be made more robust, considering the full spectrum of electro-thermo-mechanical effects and the processes adapted to an industrial production on the scale of a thousand magnets. The success of this development

should be measured through the construction and performance of long demonstrator and prototype magnets, targeting the 12 T field. The Nb<sub>3</sub>Sn magnet development will improve areas of HL-LHC technology that have been found to be sub-optimal, notably the degradation associated with the fragile conductor, targeting the highest practical operating field that can be achieved. The plan is to work jointly with wire and cable development to mitigate degradation associated either with length or electro-thermo-mechanical effects. The R&D will explore design and technology variants to identify robust design options for the field level targeted. In Europe, the program includes the construction and test of short and long model magnets [MWP4].

[MWP3] discusses the development and demonstration of new technologies for next generation of Nb<sub>3</sub>Sn accelerator magnets with operation fields in the range of 12-14 T. The main goal is to reduce magnet cold-mass cost at least by a factor 2 with respect to the present Nb<sub>3</sub>Sn magnets produced in the US by AUP for the HL-LHC upgrade. To achieve the goal, significant reduction of labour and components costs with higher operating fields and improved performance reproducibility is expected. A key factor for the cost reduction is development of fabrication process based on the experience gained in US national laboratories through the production of the AUP magnets with early industry involvement. This partnership will lead to technologies that will be easily transferable to industry for mid- and large-scale production of Nb<sub>3</sub>Sn accelerator magnets in the 12-14 T field range. This step is critical to enable next generation colliders such as the FCC and Muon Collider. This “directed” R&D is driven by the field range and industry involvement for high-automation and industry-ready technology. The plan includes 3 phases with total 10 milestones, to be achieved in 6-8 years at the cost of 5-7 \$M/year. This program is proposed as self-standing program, or it may be part of the Leading-Edge technology And Feasibility-directed (LEAF) Program [MWP2] aimed at the demonstration of magnet technology readiness for Energy Frontier Circular Colliders (hadron, muon) by the next decade.

### 5.3.3 Accelerator magnets in the 14-16 T operation field range

The projected upper field limit for a Nb<sub>3</sub>Sn dipole is presently 16 T and relies upon mastery of the magnet mechanics. Finding the right balance between cost-efficiency, maximum field, and robustness is at the core of the R&D activity to provide satisfactory input to the High Energy Physics community. Nb<sub>3</sub>Sn is strain- and stress-sensitive and brittle. Besides the known reversible critical current dependency on applied strain, the main concern is that stress or strain exceeding allowable limits lead to a permanent reduction of critical current and eventual damage through fracture of the superconducting phase. Thus, it is paramount to minimise stress concentrations on the conductor. In the last years, and within the FCC-Conceptual Design Studies, the WP5 of EuroCirCol gathered CEA, CERN, CIEMAT, INFN, KEK, the University of Geneva, the University of Tampere and the University of Twente to explore different design options for 16 T dipole magnets to give a baseline for future development. The focus was on the design of electromagnetically efficient coil cross sections. In the US, the MDP program focused in the stress management approaches to reduce the stress in the strain-sensitive Nb<sub>3</sub>Sn conductor.

Advanced magnet technology is the driving technology for any energy-frontier circular collider envisioned by the community, fundamentally impacting both science reach and facility cost. There are many elements of technology development that lie at the heart of advanced magnet R&D. It includes new diagnostics and testing techniques, materials and composites development, new solutions for detection and protection and the development of modelling tools together with the required specialized testing infrastructure. Finally, dedicated manufacturing and test infrastructure required, including instrumentation upgrades, needs to be developed, built and operated through close coordination between the participating laboratories.

#### 5.3.3.1 Coil stress management

To reduce conductor stress, the US MDP program [MWP1] is focused on stress-management approaches introduce internal structures and additional interfaces when compared to more traditional magnet designs. The concept of stress-management, i.e. intercepting magnetic forces to structural members before they can accumulate to damaging levels, promises a path towards very high field accelerator magnets. Two stress management design approaches are shown in Figure 5.4.



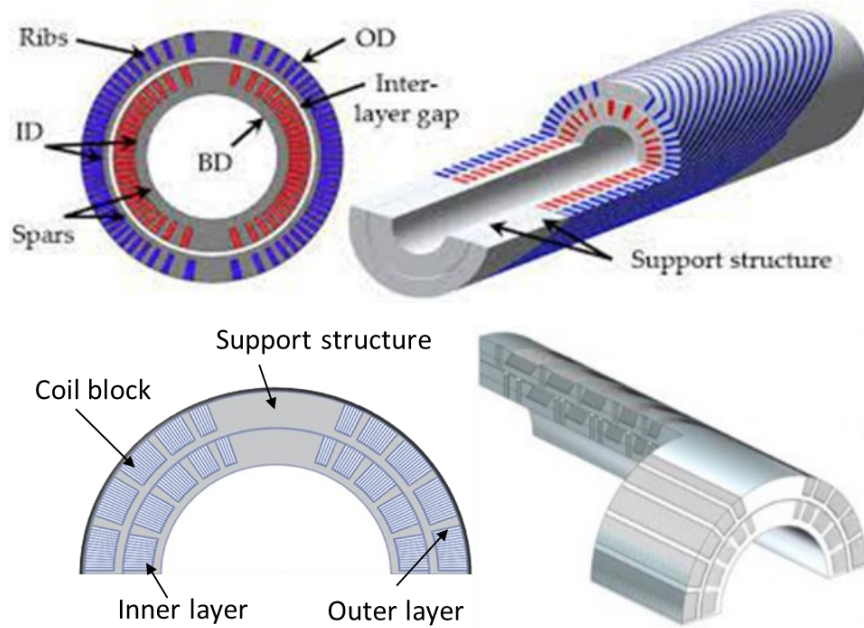


Figure 5.4. Top - the Canted Cosine Theta (CCT) concept, wherein the individual turns are placed and supported in support structure grooves. Bottom - the Stress Managed Cosine Theta (SMCT) concept, wherein turn groups are placed and supported in support structure grooves.

To take full advantage of these technologies, further understanding and development in several areas is necessary. Below are some key issues that are being investigated to develop these stress-management approaches:

- Development stress management coil structures and their fabrication methods including exploration of conventional machining methods as well as additive manufacturing approaches;
- Investigate and optimize external structures for use in stress-managed magnets with increases internal structure rigidity.
- Understand the influence of interfaces on stress-limits and training under different interface conditions;
- Explore the limits of stress-management approaches on high field / large bore demonstrators.
- Develop efficient and cost-effective fabrication methods using minimal tooling to reduce overall magnet fabrication cost and complexity;
- Investigate approaches for scale up to larger magnets;

#### 5.3.4 Considerations for accelerator magnets beyond 20 T

Bore fields at 15 to 16 T level are considered as the practical limit for  $\text{Nb}_3\text{Sn}$  superconductor [5.3.1]. To further push the magnetic field of dipole magnets, HTS need to be considered. Taking into account the higher HTS cost and the present level of HTS magnet technologies with respect to the  $\text{Nb}_3\text{Sn}$  conductors and magnets, hybrid approach to the magnet design looks the most practical.

Judicious magnet design, incorporating concepts such as stress management and optimized pre-stressing, indicates 20 T dipole fields may be achievable with existing superconducting materials in a variety of magnet configurations. Magnetic analysis of a 20 T hybrid magnet in a 50 mm aperture with at least 15% of load-line margin are on-going within MDP (see [MWP12] and [MWP21]), considering different layouts: traditional Cos-theta (CT), Stress Management Cos-theta (SMCT), Canted Cos-theta (CCT), Block (BL), and Common-Coil (CC) designs (see Figure 5.5). Two HTS conductors are considered at the present time: Bi2212, in the form of a Rutherford cable with  $J_e$  of  $740 \text{ A/mm}^2$  at 20 T, and REBCO tape in a CORC<sup>®</sup>/STAR<sup>®</sup> cable with  $J_e$  of  $590 \text{ A/mm}^2$  at 20 T.

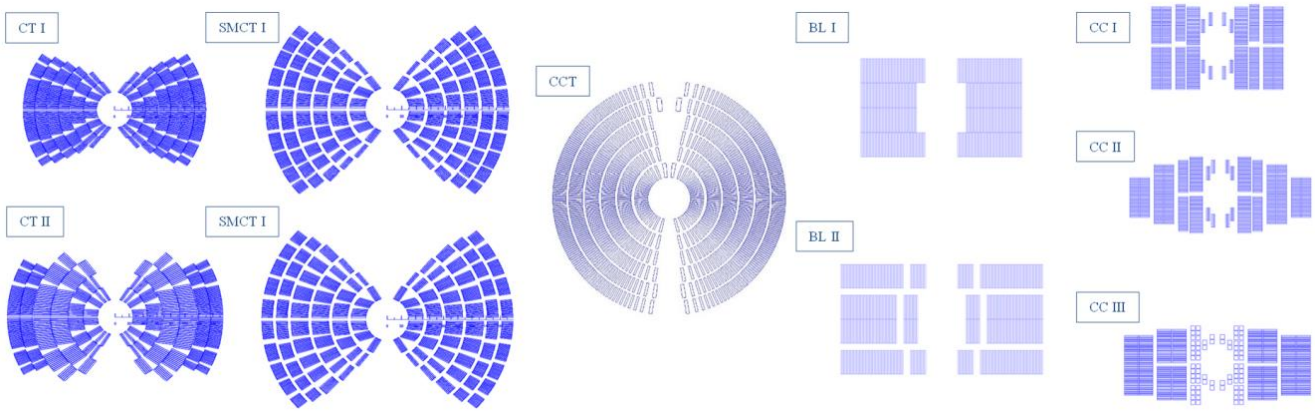


Figure 5.5. Preliminary cross-sections of 20 T hybrid dipole coils. From left to right: Cos-theta (CT) design, with 4 (top) and 2 (bottom) layer Bi2212 coils; Stress management Cos-theta (SMCT) design, with 4 (top) and 2 (bottom) layers Bi2212 coils; Canted Cos-theta (CCT) design, with 4-layer Bi2212 coil; Block (BL) design, with and without stress management; Common Coil (CC) design, with Bi2212 (top, with 3 external Nb<sub>3</sub>Sn layers, and center, with 5 external Nb<sub>3</sub>Sn layers) and REBCO CORC<sup>®</sup> coils (bottom, with 4 external Nb<sub>3</sub>Sn layers). For all the CC designs, only one aperture is shown.

A strategy by which a tape-stack REBCO cable may be configured in a conformal winding in such a way that the favourable  $\mathbf{B} \parallel$  orientation is sustained everywhere in the winding is presented and discussed in [MWP14]. A dipole geometry is presented in which such a conformal REBCO insert winding is configured within a cable-in-conduit Nb<sub>3</sub>Sn outsert winding so that the sub-windings can be separately fabricated, and then assembled in a common structure and preloaded for effective stress management. The total cost of superconductor in this dipole is a minimum among the design options for 18 T. Plans for development of the coil technologies and a model dipole are presented. Figure 5.6 shows an example field design for such a dipole. The insert winding consists of a tape-stack cable in which 25 REBCO tapes are stacked face-to-face, and each turn of the cable is oriented closely parallel to the field at that location.

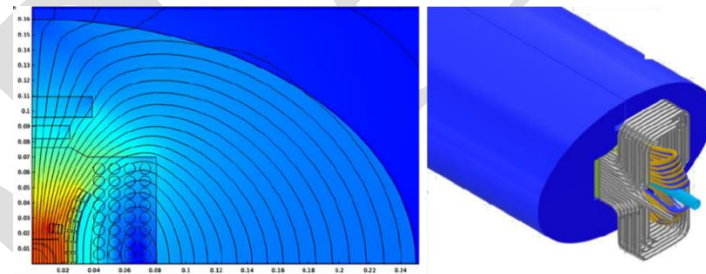


Figure 5.6. TAMU Hybrid dipole models.

#### 5.3.4.1 HTS insert technology R&D plan

The HTS inserts are the key most complicated part of the hybrid magnet design. The plans to develop HTS dipole inserts for high field hybrid magnets are discussed below based on submitted WPs. Technologies of Nb<sub>3</sub>Sn outserts will be produced as a part of Nb<sub>3</sub>Sn HFM R&D.

**Bi2212 inserts.** Bi2212 model magnet R&D program is discussed in [MWP13].: As the only high-temperature superconductor (HTS) available as an isotropic, twisted, multifilamentary round wire, Bi2212 is very promising for expanding the high-field superconducting accelerator magnet technologies beyond the round-wire, isotropic Nb-Ti and Nb<sub>3</sub>Sn conductors. The document describes the technology status and define appropriate steps to develop Bi2212 into a practical very high field (>15 T for accelerator magnets, and >25 T for solenoids) magnet technology, from superconductor development, to design and development leading to the construction of model coils and magnets fulfilling accelerator-quality needs for muon or hadron colliders. The first and most relevant target is to develop high-field accelerator dipole magnets capable of generating 16-20 T in a bore of 40-50 mm suitable for colliders. The second target is to develop large-bore, high-field >15 T quadrupole magnets for interaction regions. A third target is to develop 25 T or greater commercial solenoid magnets in collaboration with the US magnet

industry and to develop the essential elements of the technology needed to build >30 T solenoids for muon colliders. Given the potential helium shortage, a fourth relevant target is to develop Bi2212 magnets, both solenoids and accelerator magnets, for other special uses at higher work temperatures (10-25 K).

There are certain challenges to be studied and addressed for Bi2212 magnet technology.

Preliminary data show that Bi2212 Rutherford cables can show 5% critical current degradation under ~120 MPa transverse pressure. To increase the safety margin, two stress management accelerator magnet concepts have been proposed, the Canted Cosine-Theta (CCT) at LBNL and the Stress Management Cosine-Theta (SMCT) at FNAL.

Similar to Nb<sub>3</sub>Sn, Bi2212 magnets are fabricated using a wind and react process. A key advance for Bi2212 since the 2014 P5 is the introduction of the overpressure processing heat treatment, which uses a high-pressure mixed Argon and Oxygen (50 bar typically with 98% Ar and 2% O<sub>2</sub>) to densify the superconducting filaments and obtain a high wire J<sub>E</sub>. For single wires a TiO<sub>2</sub> coat on the wire and a braided mullite insulation works well but this is not yet working as well for Rutherford cables because an application of a robust TiO<sub>2</sub> has not yet been achieved. The result is some Bi2212 leakage through the encasing metal (Ag or Ag alloy) at high temperatures which can react with surrounding SiO<sub>2</sub>-containing insulation. Leakage degrades wire JE because it depletes a portion of filaments and interrupts current flow. Methods to evade these restrictions are under active development.

Nb-Ti and Nb<sub>3</sub>Sn magnets are prone to quench due to a low T<sub>c</sub> and enthalpy margin. However, it is much easier to spread out the stored energy for Nb-Ti and Nb<sub>3</sub>Sn magnets due to fast normal zone propagation velocity. Slow growth of normal zones in HTS magnets makes reliable quench detection critical to reliable quench protection.

To fabricate accelerator magnets of >15 T and solenoids of >25 T, HTS coils are combined with Nb-Ti and Nb<sub>3</sub>Sn to minimize overall costs. Typical designs use HTS inserts nested concentrically inside Nb-Ti and/or Nb<sub>3</sub>Sn outsert magnets, setting up issues of magnet assembly and integration for both accelerator and solenoid magnets given their very different stabilities and quench velocities. This magnet integration will require careful modeling, design, and experimental validation.

The main ring dipole magnets for circular colliders range from 5-15 m long. Scaling the magnet fabrication from ~1 m long demonstration magnets to 5-15 m presents another challenge. The coil reaction will require building heat treatment facilities adequate to handle such long magnets. The magnet stored energy goes up linearly with the magnet length and thus quench protection may become an issue.

Proposed paths to developing Bi2212 magnet technologies for accelerator applications include:

- All Bi2212 magnets depend on a stable supply of good conductors with reliable properties. As for Nb-Ti and Nb<sub>3</sub>Sn, an essential component of the background R&D is to understand the conductor, especially present limitations on properties so that ongoing collaborations in the university-industry-lab nexus can drive further improvements.
- Use CCT and SMCT Bi2212 designs as R&D vehicles to drive conductor development and accelerator magnet design, technology, and test towards maturity. The goal is to build multiple short (up to 1 m long) dipole model magnets with a bore of 40-50 mm in standalone configuration with incremental dipole field from 5 T to 10 T. Several critical technology elements are to be optimized and developed: a) Master technology knowhow of the reaction of ~1 m long coils and demonstrate reliability. b) Optimize Bi2212 Rutherford cable fabrication including its packing factor and insulation, especially to minimize the contribution of insulation materials to the thermodynamic ceramic leakage.
- In hybrid magnet configuration, fully explore the hybrid magnet technology and its reproducibility. Gain experience with magnet operation and quench protection for the new kind hybrid magnets.
- With technology maturing, build multiple, 1 m long >16 T, series-connected (one power circuit) Nb<sub>3</sub>Sn/Bi2212 hybrid accelerator dipole magnets with a projected bore diameter of 40-50 mm. Gain fabrication and operation experience.
- Perform a critical assessment in the feasibility of scaling up accelerator magnets (technologies and infrastructure, etc.) to 5-15 m long.
- For both accelerator and solenoid magnets, explore special uses at higher work temperatures (10-25 K).

- Engage the US superconductor and magnet industry to develop production capabilities for large scale raw materials, wire and cable fabrication, and to reduce cost and supply chain risk.

*REBCO inserts.* REBCO model magnet R&D plan is discussed in [MWP11]. The paper concerns two issues: the ultimate high field to meet the physics needs, and the ultimate low cost. REBCO material has a high irreversibility field with an upper limit of 110 T at 4.2 K and 100 T at 20 K. Such a high irreversibility can allow REBCO magnets to generate a dipole field of at least 20 T over a temperature range of 1.9-20 K. REBCO coated conductors have significant room for cost reduction due to the raw material cost. Operating at elevated temperatures without liquid Helium can be another opportunity that REBCO can offer to further reduce the magnet and collider operation cost.

Although REBCO shows great potential for addressing the high-field and low-cost needs, the challenges to realize the potential are significant for two reasons. First, REBCO magnets and conductors R&D is at the very yearly stage. Second, more conductors is needed to make magnets and to learn in a sufficiently fast pace. The following steps are recommended to improve the situation:

- Engage REBCO conductor vendors and couple the development of conductor and magnet technology. Use the magnet results as critical feedback to the conductor development that, in turn, can help improve the magnet performance.
- When sufficient funding is available, fast-track the development with the goal to quickly progress on the maximum dipole field a REBCO magnet can generate. Aim for 10 T dipole field within three years and 15 T within five years.
- Collaborate with the fusion magnet community and support the development of REBCO fusion magnet systems.

Two material properties of REBCO exacerbate the situation.

First, the ceramic REBCO material is brittle. The REBCO layer can crack, when subject to a tensile strain of around 0.6% and higher, and permanently degrade its current-carrying capability. Bending or twisting the tapes that are necessary to wind coils or making multi-tape cable must not exceed this strain limit. REBCO coated conductors are also weak to withstand a tensile force applied transverse to its broad surface; a stress of several MPa can delaminate the tape and degrade the REBCO layer. Epoxy impregnation can degrade REBCO conductor if the thermal contraction of the epoxy mismatches that of the conductor. Similar mechanical issues appear again during magnet operation when the Lorentz forces become excessive on the conductor. The maximum dipole field a REBCO magnet can generate will likely be determined by the mechanical limit of the conductor. One particular concern from the brittleness of REBCO is the potential performance degradation in conductor and magnet. Such a degradation has been observed in high-current REBCO fusion cable samples.

Second, REBCO coated conductors are only available as a tape with an aspect ratio of at least 10. The tape conductor can be bent, but only as a developable surface with limited exibility. This geometric constraint limits the potential magnet designs that one can work with REBCO conductors. One solution is a round-wire conductor form assembled from multiple tapes, such as CORC<sup>®</sup> and STAR<sup>®</sup> cables, both are actively pursued in the U.S. with a strong support from SBIR programs.

High-field dipole magnets require large-current conductors, operating at 10-20 kA, to reduce the magnet inductance and to accelerate current ramping. Various concepts exist for multi-tape REBCO cable for high-field magnets, such as twisted-tape stack and Roebel, CORC<sup>®</sup> and STAR<sup>®</sup> cables. CERN developed dipole magnets using a stack of tapes and Roebel cables. The U.S. MDP is developing dipole magnets using CORC<sup>®</sup> cables with different magnet concepts. The current maximum dipole field achieved by a REBCO magnet is 5.4 T at 4.2 K in a racetrack magnet from the European EuCARD program and 4.5 T at 4.2 K in a Roebel-cable based magnet from the European EuCARD2 program.

There is a significant technology gap between where we are today and a REBCO high-field dipole magnet. Here are some important questions that need to be addressed for REBCO dipole magnet and conductor technology:

- How to make high-field accelerator magnets using multi-tape REBCO conductor?

- What is the maximum field a REBCO dipole magnet can achieve? What factors limit the maximum dipole field a REBCO magnet and how can we address them? How to develop magnet structures to limit stress on conductors? What is the long-term performance of REBCO magnets under Lorentz loads? Will the performance under strong Lorentz forces degrade the conductor and magnet performance?
- How do REBCO magnets transition from superconducting to normal state and how can we detect the transition?
- What is the field quality of REBCO accelerator magnets?
- What is the required performance for REBCO conductors to achieve the desired magnet performance?
- How to determine the performance of a long multi-tape REBCO conductor for predictable magnet performance?

### 5.3.5 *Diagnostics and testing techniques, technology, advanced modeling.*

New diagnostics and testing techniques are providing important insight into magnet behaviour and provide critical feedback to conductor and magnet designers. The main diagnostics and testing technique development plans are discussed in, [MWP15]-[MWP18]. They include:

- Develop a next-generation acoustic emission diagnostic hardware capable of self-calibration to improve disturbance triangulation accuracy and “fingerprinting”;
- Establish fiber-optic based diagnostic capabilities through the use of Fiber Bragg Grating (FBG) and Rayleigh scattering-based sensors;
- Develop new methods for reliable and robust quench detection and localization for HTS magnets and hybrid LTS/HTS magnets using Rayleigh sensors;
- Develop flexible multi-element quench antennas, large-scale Hall sensor arrays and non-rotating field quality probes, aiming at understanding electromagnetic instabilities in LTS magnets and imaging current-sharing patterns in superconducting cables and HTS magnet coils;
- Develop new algorithms for current flow reconstruction and disturbance localizations;
- Apply machine learning and deep learning approaches to process diagnostic data and identify real-time predictors of magnet quenching;
- Develop non-invasive surface and insulation failure detection and localization using electrical reflectometry, to protect magnets due to unexpected defects on the surface or insulation;
- Develop cryogenic digital and analog electronics to facilitate, simplify and improve reliability of diagnostic instrumentation by enabling pre-processing of magnet diagnostic data in the cryogenic environment.

A number of potential techniques and technologies aiming to affect magnet parameters and performance need to be further investigated including a) the development of high-Cp conductor and insulation that can lead to conductors and coils with optimized characteristics enabling stable operation against perturbations; b) artificially increasing the coil current during a quench by discharging a large capacitor at quench detection; c) using diffuse field ultrasonic techniques to enable targeted delivery of vibrational excitation to the conductor, for a non-invasive structural local probing of SC coils; d) development of composite and structural magnet components, with a specific focus on the characterisation of insulation systems (polymers and reinforcement) for both Nb<sub>3</sub>Sn and HTS magnets; e) thermal management of high field magnets including internal heat transfer, heat transfer to coolant, and external heat transfer to cryo-plant.

Advances in modelling are providing more detailed insight into stress and strain states in magnets, including full 3D effects and complex nonlinear material and interface behaviour. An analysis of the data acquired by the diverse diagnostic tools and advance modelling is the key to guide the potential techniques to affect magnet performance. A diverse and challenging set of new modelling tools are required to continue this effort and ultimately improve design time, cost, and performance of future superconducting accelerator magnets. The new developments include simulation and advanced modelling of a) conductors and cables, b) interfaces and other potential sources of training in stress-managed designs, c) LTS/HTS hybrid magnets, and d) radiation-induced thermal effects on magnets in synergies with the broader accelerator modelling community [MWP22].

### 5.3.6 Magnet Fabrication and Test infrastructures

The development of novel SC magnet technology at the high-field frontier requires specialised fabrication and test infrastructure, often of large size. The necessary investment is considerable, so the effort should extend across national and international labs. In the U.S. the magnet R&D infrastructure exists at the three National Laboratories (BNL, FNAL, LBNL) as well as at NHMFL and TAMU. It includes R&D magnet development and test capabilities. This infrastructure can be and is also used for production of small quantities of full-scale accelerator magnets, e.g., for the LHC HL upgrade.

*Conductor R&D facilities at ASC-FSU and OSU...*

*Add comments on facilities in Europe, maybe Japan*

FNAL in collaboration with LBNL is building a new high-field cable-testing facility [5.3.3] with capabilities similar to the European facilities EDIPO and FRESCA2. This facility will serve two US national programs within the DOE Office of Science, the Magnet Development Program and the US Fusion Energy Science Program for testing HTS samples in a 15 T field. This facility will allow testing HTS-LTS hybrid magnets which are an important step toward providing 20+ T operation fields in future high-energy colliders. This new test facility will be available at FNAL within the next 3-5 years.

## 5.4 Technologies for Detector Magnets

The development of technologies for detector magnets is discussed in [MWP19].

The main development item for future detector solenoids is Al-stabilized superconducting cable with both higher strength and high RRR. The most likely solution is a combination of technologies used in ATLAS-CS (reinforcement of the aluminum stabilizer, with Ni doping and simultaneous cold-work hardening) and CMS (reinforcement by pure-aluminum stabilized conductor and high strength aluminum alloy, which are mechanically bonded by electron beam welding). By combining these approaches, a yield strength of more than 300 MPa is expected.

Future detector magnets will also take advantage of technologies such as coil winding inside the outer shell; indirect cooling to reduce materials used in magnet structure; pure aluminum strips as temperature equalizer in the steady operation and fast quench propagation; lightweight and high-transparency vacuum vessels. High temperature superconductors are of great interest to reduce cryogenics power consumption of detector magnets. While solenoids have been prevalent in past detectors, other types of magnets, such as split coil and saddle shape coil, could be candidates depending on the requirements from a physics viewpoint. Solenoids for mid-scale experiments often do not need the development of unique conductors, as much as precise control of magnetic field distribution with precision simulation and coil fabrication technology to meet tight tolerances.

## 6 Conclusions

Superconducting accelerator magnets are the key enabling technology for present and future particle accelerators in modern high energy physics. All the present accelerator magnets have used for decades the Nb-Ti superconductor. The practical performance limit of this technology in accelerator magnets is limited by 8-9 T. This field level was realized in various LHC magnets. The technology will continue to be developed and widely used in various accelerators, such as ILC, FCC-ee, EIC, SEPC, etc., to steer beams of low-energy or small-mass particle. This technology continues to be the baseline approach for large detector magnets.

The development of a new generation of accelerator magnets based on Nb<sub>3</sub>Sn superconductor with operation fields up to 15-16 T has shown in the last two decades a good progress in the USA, EU and Asia. On the short term, within the next five years, this technology will be implemented in HL-LHC by using large-aperture high-gradient final-focus quadrupoles in ATLAS and CMS experiments. On the longer term, dipole and quadrupole magnets with nominal operation fields up to 16 T are planned for FCC-hh and 3 TeV MC. Several key technological issues important for the performance of these magnets need to be resolved. They are in the focus of national magnet R&D

programs in USA and EU. Demonstrating performance retention throughout the whole magnet life, mastering electro- and thermo-mechanical loads, and achieving a considerable simplification of manufacturing will be necessary to exploit the Nb<sub>3</sub>Sn magnet technology on large scale.

More ambitious R&D work towards 20+ T magnets, considered for SPPC and high-energy MC and based on cost-effective HTS/LTS coils has also been started recently. HTS materials promise higher fields and improved energy efficiency through operation at higher cryogenic temperature, or helium free configurations. This technology is still at its early stage. Much work needs to be done on the way to realize the potential of HTS materials, starting from their basic conductor characteristics through cable and magnet design, technology and quench protection, including their mass production and cost optimization issues.

## 7 Acknowledgment

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## 8 References

- [1] [MWP1] S. Prestemon et al., “A Strategic Approach to Advance Magnet Technology for Next Generation Colliders”, [arXiv:2203.13985 \[physics.acc-ph\]](https://arxiv.org/abs/2203.13985) (pdf)
- [2] [MWP2] G. Ambrosio et al. ”Leading-Edge technology And Feasibility-directed (LEAF) Program aimed at readiness demonstration for Energy Frontier Circular Colliders by the next decade”, [arXiv:2203.07654 \[physics.acc-ph\]](https://arxiv.org/abs/2203.07654) (pdf).
- [3] [MWP3] G. Ambrosio et al., “Development and demonstration of next generation technology for Nb<sub>3</sub>Sn accelerator magnets with lower cost, improved performance uniformity, and higher operating point in the 12-14 T range”, [arXiv:2203.07352 \[physics.acc-ph\]](https://arxiv.org/abs/2203.07352) (pdf).
- [4] [MWP4] P. Védrine, et al., ”High Field Magnet Development for HEP in Europe : A Proposal from LDG HFM Expert Panel”, [arXiv:2203.08054 \[physics.acc-ph\]](https://arxiv.org/abs/2203.08054) (pdf).
- [5] [MWP5] L. Bottura et al., ”A Work Proposal for a Collaborative Study of Magnet Technology for a Future Muon Collider”, [arXiv:2203.13998 \[physics.acc-ph\]](https://arxiv.org/abs/2203.13998) (pdf).
- [6] [MWP6] T. Ogitsu et al., ”R&D works for Superconducting Magnet for Future Accelerator Applications in Japan”, [arXiv:2203.12118 \[physics.acc-ph\]](https://arxiv.org/abs/2203.12118) (pdf).
- [7] [MWP7] F. Kametani et al., ”Fe-based high field superconductors for cost-effective future accelerator magnets”, [arXiv:2203.07551 \[cond-mat.supr-con\]](https://arxiv.org/abs/2203.07551) (pdf).
- [8] [MWP8] Cooley, Superconductor white paper, TBD
- [9] [MWP9] Yu. I. Alexahin et al., ”Critical problems of energy frontier Muon Colliders: Optics, Magnets and Radiation”, [arXiv:2203.10431 \[physics.acc-ph\]](https://arxiv.org/abs/2203.10431) (pdf).
- [10] [MWP10] Yu. Alexahin et al., ”Solving Critical Problems of the Muon Collider Higgs Factory: Optics, Magnets and their Protection, Detector Backgrounds“, [arXiv:2203.09010 \[physics.acc-ph\]](https://arxiv.org/abs/2203.09010) (pdf).
- [11] [MWP11] X. Wang et al., ”REBCO – a silver bullet for our next high-field magnet and collider budget?”, [arXiv:2203.08736 \[physics.acc-ph\]](https://arxiv.org/abs/2203.08736) (pdf).
- [12] [MWP12] R. Gupta et al., ”Common Coil Dipole for High Field Magnet Design and R&D”, [arXiv:2203.08750 \[physics.acc-ph\]](https://arxiv.org/abs/2203.08750) (pdf).
- [13] [MWP13] T. Shen et al.. ”High Temperature Superconducting Bi-2212 Magnets for Energy Frontier Circular Colliders“, [arXiv:2203.10564 \[physics.acc-ph\]](https://arxiv.org/abs/2203.10564) (pdf).
- [14] [MWP14] P. McIntyre, “Hybrid conformal REBCO dipole for a next hadron collider,” <https://arxiv.org/ftp/arxiv/papers/2203/2203.08132.pdf>
- [15] [MWP15] M. Baldini et al.. ”Fiber-optic diagnostic system for future accelerator magnets”, [arXiv:2203.08309 \[physics.acc-ph\]](https://arxiv.org/abs/2203.08309) (pdf).
- [16] [MWP16] S. Stoynev. ”Test samples and infrastructure for accelerator magnet developments”, [arXiv:2203.07274 \[physics.acc-ph\]](https://arxiv.org/abs/2203.07274) (pdf).

- [17] [MWP17] M. Marchevsky et al. "Advancing Superconducting Magnet Diagnostics for Future Colliders", [arXiv:2203.08869](https://arxiv.org/abs/2203.08869) [[physics.acc-ph](#)] ([pdf](#)).
- [18] [MWP18] M. Marchevsky, "Understanding training in superconducting accelerator magnets using acoustic emission diagnostics", [arXiv:2203.08871](https://arxiv.org/abs/2203.08871) [[physics.acc-ph](#)] ([pdf](#)).
- [19] [MWP19] M. Mentink et al., "Superconducting detector magnets for high energy physics", [arXiv:2203.07799](https://arxiv.org/abs/2203.07799) [[physics.ins-det](#)] ([pdf](#)).
- [20] [MWP20] H. Piekarczyk et al., "Fast cycling HTS based superconducting accelerator magnets: Feasibility study and readiness demonstration program driven by neutrino physics and muon collider needs", [arXiv:2203.06253](https://arxiv.org/abs/2203.06253) [[physics.acc-ph](#)] ([pdf](#)).
- [21] [MWP21] G. Ambrosio et al. "A Strategic Approach to Advance Magnet Technology for Next Generation Colliders", [arXiv:2203.13985](https://arxiv.org/abs/2203.13985) [[physics.acc-ph](#)] ([pdf](#)).
- [22] [MWP22] S. Biedron et al., "Snowmass21 Accelerator Modeling Community White Paper by the Beam and Accelerator Modeling Interest Group (BAMIG)", [arXiv:2203.08335](https://arxiv.org/abs/2203.08335) [[physics.acc-ph](#)].
- [23] [2.1.1] G. Apollinari et al., "US contribution to the High Luminosity LHC Upgrade", J. Phys. Conf. Ser. 1350 (2019) 1, 012005
- [24] [2.1.2] S. Caspi et al. "A Concept for High Field Accelerator Magnets", IEEE TAS, 24.3 (2014). doi: 10.1109/tasc.2013.2284722.
- [25] [2.1.3] A.V. Zlobin et al, "Large aperture high field Nb<sub>3</sub>Sn dipole magnets", 9th International Particle Accelerator Conference. doi: 10.18429/jacow-ipac2018-wepml026.
- [26] [2.4] "The CEPC Conceptual Design Report," Vol I: Accelerator, [arXiv:1809.00285](https://arxiv.org/abs/1809.00285), 1112 [http://cepc.ihep.ac.cn/CDR\\_v6\\_201808.pdf](http://cepc.ihep.ac.cn/CDR_v6_201808.pdf), 2018. 1113
- [27] [2.5] "CEPC Accelerator," submitted to European Strategy in 2019: [ArXiv:1901.03169](https://arxiv.org/abs/1901.03169)
- [28] [2.6] J. Tang et al., "Concept for a Future Super Proton-Proton Collider," [arXiv:1507.03224v1](https://arxiv.org/abs/1507.03224) [[hep-ex](#)]
- [29] [3.1.1] Future Circular Collider Study. Volume 3: The Hadron Collider (FCC-hh) Conceptual Design Report, preprint edited by M. Benedikt et al. CERN accelerator reports, CERN-ACC-2018-0058, Geneva, December 2018. Published in Eur. Phys. J. ST.
- [30] [3.1.2] CEPC-SPPC Preliminary Conceptual Design Report. 2. Accelerator; IHEP-CEPC-DR-2015-01 <https://inspirehep.net/files/f7ee2a25def72c5431deb795ff049e8a>
- [31] [3.2.1] Future Circular Collider Study. Volume 4: The High Energy LHC (HE-LHC) Conceptual Design Report, preprint edited by F. Zimmermann et al. CERN accelerator reports, CERN-ACC-2018-0059, Geneva, December 2018. Published in Eur. Phys. J. ST.
- [32] [3.2.2] D. Tommasini et al., "Status of the 16 T Dipole Development Program for a Future Hadron Collider," IEEE TAS, vol. 28, no. 3, April 2018, Art no. 4001305, doi: 10.1109/TASC.2017.2780045.
- [33] [3.2.3] V. Marinuzzi et al., "Conceptual Design of a 16 T cos  $\theta$  Bending Dipole for the Future Circular Collider," IEEE TAS, vol. 28, no. 3, April 2018, 4004205, doi: 10.1109/TASC.2018.2795533.
- [34] [3.2.5] C. Pes et al., "Magnetic and Mechanical Design of the Block-coil Dipole Option for the Future Circular Collider," Presented at the ASC, Seattle, USA (2018) 167.
- [35] [3.2.6] F. Toral, "Magnetic and mechanical design of a 16 T common coil dipole for FCC," FCC Week (2018), [https://indico.cern.ch/event/656491/contributions/2920132/attachments/1629665/2597178/FCCweek2018\\_common\\_coil\\_ftoral.pdf](https://indico.cern.ch/event/656491/contributions/2920132/attachments/1629665/2597178/FCCweek2018_common_coil_ftoral.pdf) 168.
- [36] [3.2.7] B. Auchmann et al., "Electromechanical Design of a 16-T CCT Twin-Aperture Dipole for FCC," IEEE TAS, 28, 1, April 2018, doi: 10.1109/TASC.2017.2772898.
- [37] [3.2.8] C. Genot et al., "FCC-hh Conceptual Designs and Windability of the Main Quadrupoles," IEEE TAS, vol. 31, no. 2, March 2021, 4000107, doi: 10.1109/TASC.2020.3045876.
- [38] [3.2.9] A. Louzguiti et al., "Optimization of the Electromagnetic Design of the FCC Sextupoles and Octupoles," IEEE TAS, vol. 29, no. 5, Aug. 2019, 4000805, doi: 10.1109/TASC.2019.2892839.
- [39] [3.2.10] E.S. Kong et al., "Conceptual design study of iron-based superconducting dipole 1115 magnets for SPPC", International Journal of Modern Physics A, 34, 2019, p. 1940003.
- [40] [3.3.1] R.B. Palmer, "Muon Colliders", RAST, Vol. 7, p. 137 (2014).



- [41] [3.3.2] M.A. Palmer, “The US Muon Accelerator Program,” <https://arxiv.org/ftp/arxiv/papers/1502/1502.03454.pdf>
- [42] [4.1.1] M. Benedikt et al., “Future Circular Colliders,” *Ann. Rev. Nucl. Part. Sci.*, vol. 69, pp. 389–415, 2019.
- [43] [4.1.2] A. Abada et al., “FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2,” *Eur. Phys. J. ST*, vol. 228, no. 2, p. 261, 2019.
- [44] [4.1.3] M. Antonello, “IDEA: A detector concept for future leptonic colliders,” *Nuovo Cim. C*, vol. 43, no. 2-3, p. 27, 2020.
- [45] [4.1.4] N. Alipour Tehrani et al., “CLICdet: The post-CDR CLIC detector model,” CLICdp-Note- 2017-001. Revised 2019.
- [46] [4.1.5] A. Yamamoto et al., “The ATLAS central solenoid,” *Nucl. Instrum. Meth. A*, vol. 584, p. 53, 2008.
- [47] [4.1.6] A. Herve, “Construction a 4-Tesla large thin solenoid at the limit of what can be safely operated,” *Mod. Phys. Lett. A*, vol. 25, p. 1647, 2010.
- [48] [4.1.7] N. Deelen et al., “Design and Quench analysis of superconducting solenoids for the lepton Future Circular Collider,” *IEEE TAS*, vol. 32, no. 6, September 2022, 4100204, doi: 10.1109/TASC.2022.3149682.
- [49] [4.2.1] “FCC-hh: The Hadron Collider”, *EUR. Phys. J. Special Topics* 228, p. 755 (2019)
- [50] [4.2.2] M. Mentink et al., “Evolution of the Conceptual FCC-hh Baseline Detector Magnet Design”, *IEEE TAS*, 28, 4002710 (2018)
- [51] [4.3.1] CMS Collaboration. CMS, the magnet project: Technical design report. CERN-LHCC-97-10. May 1997.
- [52] [4.3.2] ATLAS Collaboration. ATLAS central solenoid: Technical Design Report. CERN-LHCC- 97-021; ATLAS-TDR-9. April 1997.
- [53] [5.2.1] A.V. Zlobin, “Superconducting Magnets - Principles, Operation, and Applications,” *Wiley Encyclopedia of Electrical and Electronics Engineering*, John Wiley & Sons, Inc., December 2014, doi: 10.1002/047134608X.W4520.pub2
- [54] [5.3.1] “Nb<sub>3</sub>Sn Accelerator Magnets – designs, technologies, and performance”, editors - D. Schoerling and A.V. Zlobin, ISBN 978-3-030-16117-0, Springer, 2019.
- [55] [5.3.2] A.V. Zlobin et al., “Reassembly and Test of High-Field Nb<sub>3</sub>Sn Dipole Demonstrator MDPCT1”, *IEEE TAS*, Vol. 31, Issue 5, February 2021, doi: 10.1109/TASC.2021.3057571
- [56] [5.3.3] G.V. Velez et al., “Design and Construction of a High Field Cable Test Facility at FNAL,” *IEEE TAS*, Vol. 31, Issue 5, February 2021, doi: 10.1109/TASC.2021.3068847