The Role of High Temperature Superconductors for a 10 TeV Muon Collider

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Abstract*—The international particle physics community, among various options for developing future high-energy particle colliders and exploring fundamental interactions, considers Muon Colliders (MC) as a significant opportunity to achieve high discovery potential and integrated luminosity compatible with a compact and cost-effective accelerator machine. An international muon collider collaboration (IMCC) has recently been established, following the recommendations of the European Strategy for Particle Physics (ESPP), to develop a conceptual design for a Muon Collider with a 10 TeV center-of-mass energy. From the analysis of the collider's various magnetic components, large stored energies for the capture and cooling solenoids, very high magnetic fields up to 40 T for the final cooling solenoids, and large bore (up to 140 mm) and high-field combined function magnets for the accelerator and collider rings are required. High-temperature superconductors (HTS) enable the technology to address these challenges and achieve the required collider performances. Given the peculiar accelerator stages of the muon collider, most superconducting magnets are required to operate in steady-state mode, with normal-conducting dipoles handling rapid acceleration and fast field variations, allowing the use of HTS-coated conductors to enhance magnet performance compared to low-temperature superconductors (LTS) technology. This aspect is also fundamental in advancing the energy efficiency and sustainability goals of next-generation accelerator facilities for high-energy physics. By enabling magnet operation at temperatures above liquid helium, HTS offer the potential to significantly reduce the energy consumption of entire accelerator complexes. This energy-saving capability must be increasingly prioritized in magnet design strategies with different impacts on the collider performance, cost, and feasibility. In this paper, we elaborate on the above aspects, discussing the technological challenges for the 10 TeV muon collider configuration and how HTS will make them viable and efficient to pave the way to new compact and high-performance particle collider machines capable of overcoming the current energy frontier.

***Index Terms*—Superconducting accelerator magnets, muon collider, high temperature superconductors.**

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I. Introduction

In RECENT years, the discovery potential arising from the construction of a muon collider complex has gained renewed interest [1] in the particle physics community, mainly driven by the need for next-generation facilities after the High Luminosity Large Hadron Collider (HL-LHC) project at CERN. A high-energy muon collider offers unique opportunities [2], combining the clean experimental environment typical of lepton colliders with the high center-of-mass energy reach usually associated with hadron colliders, allowing one to probe the Standard Model (SM) with high precision and, second, to search for Beyond Standard Model (BSM) phenomena at the multi-TeV energy scale.

However, several technological developments are required to demonstrate the feasible realization of a muon collider complex at the multi-TeV energy scale. The short lifetime of muons (2.2 μs in the rest frame) heavily affects the design of the accelerator complex, demanding extremely rapid production, capture, cooling, and acceleration schemes. Among these challenges, the design and implementation of high-field, high-efficiency superconducting magnets are critical to enable novel collider architectures that can deal with the unstable nature of muons.

High-Temperature Superconductors (HTS) have emerged as the key enabling technology in this context from the preliminary conceptual design studies within the recently established International Muon Collider Collaboration (IMCC) [3]. Due to their superior performance at higher operating temperatures and in high magnetic fields, HTS materials offer significant advantages over conventional superconductors such as Nb-Ti and Nb_3Sn. This paper explores the role of HTS in the development of a 10 TeV muon collider, highlighting key applications, current R&D efforts, and the broader implications for future high-energy physics infrastructures.

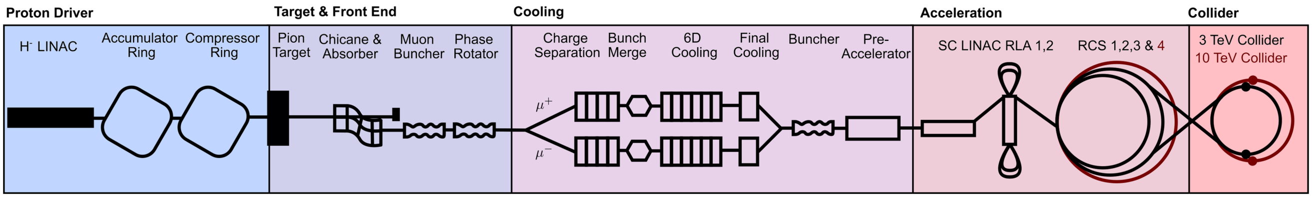

Fig. 1. Sketch of the accelerator scheme under study in the International Muon Collider Collaboration for the realization of a muon collider complex with two different staging phase: firstly 3 TeV proposal requiring 3 rapid cycled synchrotron (RCS) and a 5 km collider ring (*black lines*) and secondly a 10 TeV upgrade phase with the use of a fourth RCS and a 10 km collider ring (*red lines*).

II. Challenges for a Muon Collider

The design of a muon collider accelerator complex presents the solution to several limitations affecting both electron and proton colliders. Being leptons, the full energy in the center of mass reference frame can be exploited for the interactions and the production of particles for high-energy physics experiments. By using heavier particles compared to electrons (m_μ=105 MeV/c^2 compared to m_e=0.511 MeV/c^2), synchrotron radiation is no longer a limiting factor like hadron colliders, opening the possibility to explore the multi-TeV regime in high-energy experiments with compact circular accelerators at high integrated luminosities with higher energy efficiency [4] compared to linear or hadron colliders. Despite these advantages, the implementation of a muon collider architecture involves unique constraints [5] related to the short muon lifetime. Even if we consider relativistic energies, the available time for beam manipulation ($\tau_\mu = 21$ ms @ E = 10 TeV and $\gamma = 10^4$) imposes very fast particle acceleration from the production target up to their collision in the storage ring. Each different section of the collider complex (muon production, phase space cooling, acceleration, and collision, see Fig. 1), must be globally optimized to achieve the highest transport efficiency, with the final target of 10^{12} particles in each muon beam, and minimize the accelerator dimension. To account for the limited muon lifetime while maximizing discovery potential over 5–10 years of operation, the collider design targets a luminosity of $2 \cdot 10^{34}$ cm^{-2} s^{-1} at 3 TeV and $2.0 \cdot 10^{35}$ cm^{-2} s^{-1} at 10 TeV [6]. Given these constraints, the corresponding luminosity lifetimes are 1039 turns for a 4.5 km storage ring @ 3 TeV and 1158 turns in a 10 km storage ring @ 10 TeV, respectively [7]. All muon bunches are presently considered to be generated via high-intensity proton interactions on a fixed target (approximately $5 \cdot 10^{14}$ and 5 Hz repetition rate [6]), leading to the production of charged pions that subsequently decay into muons. The capture and transport of these secondary muons is mandatory to achieve high collection efficiencies, requiring high field solenoids with large bore apertures to account for shielding of the high radiation and thermal loads resulting from muon decay products. Moreover, ionization cooling of the muon beam is a critical step to minimize the final colliding beam energy spread and emittance, see [8], [9]. This process heavily depends on the integration of different technological innovations in the accelerator community, involving absorbers, radiofrequency (RF) cavities, and solenoids in the same compact design. Different accelerating stages, optimized to minimize particle losses, need to be precisely controlled and designed to reach the final injection energy in the final storage ring. Given the unstable nature of the particles and the number of revolutions in the collider ring lattice, the muon decay products, especially electrons, and the synchrotron radiation generate significant radiation load up to 500 MW/m [10]. This effect has a major impact on the design and optimization of the storage ring lattice. Minimized straight sections and interaction region lengths are mandatory to avoid collimated radiation, especially neutrinos, requiring different compensation methods that are not used for conventional lepton and hadron colliders. In this context, magnet technology is not only a key performance driver but a critical enabler for the entire collider concept. Magnet technology readiness level for large-scale production is a mandatory requirement for several sections of the accelerator complex, affecting both achievable target performances, like maximum collision energy in the storage ring, beam intensity, and integrated luminosity.

III. The Enabling Technology: ReBCO

All particle accelerator superconducting magnets used in large colliders up to now are based on low-temperature superconductor technology (LTS). To overcome the performance of NbTi technology, limited at 10 T, 1.9 K for particle accelerator superconducting dipoles, Nb_3Sn conductors are mandatory, opening the possibility to achieve magnetic fields of the order of 14–16 T @ 1.9 K. In contrast, High-Temperature Superconductors (HTS), particularly REBCO-based coated conductors, offer a unique combination of high field performances, mechanical robustness when used in combination with certain coil layout or load configurations, and high thermal stability, making them ideal candidates for next-generation accelerator magnets. A critical advantage of HTS conductors lies in their ability to operate at high current density ($J_c \approx$1000 A/mm^2 @ 16 T) at significantly higher temperatures, typically in the range of 15-20 K, compared to LTS conductors. This allows for a substantial increase in cryogenic efficiency, by nearly an order of magnitude, compared to LTS-based systems operating at 1.9 K. The corresponding reduction in helium inventory, refrigeration power, and operational cost (OPEX) needs to be deeply investigated, despite the higher capital cost (CAPEX) compared to LTS technology, in terms of sustainable and scalable collider infrastructure. From a performance perspective, HTS materials might enable reaching 20 T for particle collider

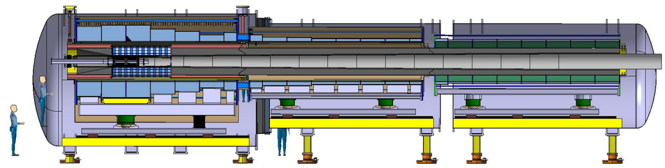

Fig. 2. Detailed cross-section view of the target and capture high-temperature superconducting solenoids within the assembly structure in the target area.

superconducting magnets or ultra-high-field compact solenoids, which can be used in the muon collider cooling section. Despite the reduced quench propagation velocity compared to LTS technology and the more difficult coil protection during a quench event, novel winding techniques, such as non-insulated (NI) and metal-insulated (MI), are now being explored to enhance stability and reliable performance. These techniques are particularly valuable in high stored energy coils, where complex quench detection and protection schemes are mandatory. Lastly, contrary to conventional ramped superconducting magnets for hadron colliders, all superconducting magnetic elements presently considered in muon collider acceleration schemes are operated in steady-state mode. This aspect offers unique possibilities to overcome several drawbacks afflicting REBCO-based HTS superconducting magnet design, such as large magnetization effects or higher hysteresis losses compared to LTS technology.

IV. HTS Applications in the Accelerator Complex

The present performances of HTS REBCO conductors, over a broad range of operating temperature enable the achievement of high-field operation across multiple areas of the muon collider complex. Since each subsystem is subject to specific constraints, different superconducting technologies must be employed, optimizing their features for several individual functions.

A. Target and Capture Solenoids

To maximize the number of muons in the circulating beam of the accelerator complex, a multi-MW pulsed 5–10 GeV proton beam is directed onto a fixed cylindrical target with an outer diameter in the range of 150–250 mm. Surrounding the target area and the following beamline, large bore solenoids, see Fig. 2 (up to 1.4 m in diameter), with the highest achievable field [11] (up to 20–21 T on the rotational axis) are used to efficiently capture the pions produced in the collision and the muons originating from their subsequent decay while operating in a harsh radiation environment. Considering the coil dimension and the high magnetic field value, high-temperature superconductor technology is the main solution presently considered [12] to achieve the required performances. The optimization of the HTS superconducting coil design aims to provide the required field profile [13], to maximize the collection efficiency, while minimizing the wall plug power consumption of the solenoid package by operating the superconductor material at cryogenic temperature above liquid helium (up to 20 K). A preliminary evaluation of the superconducting HTS coil design shows a significant reduction of the wall plug power consumption from a total of 21 MW for the hybrid coil design of the US-MAP study report [14], [15] down to 1 MW while storing only a third of the electromagnetic energy produced by the coil (1 GJ for the HTS coil design and 3 GJ for the hybrid design). A further advantage of this superconductor technology is the reduction in coil weight and supporting structure required to withstand mechanical stress during energization, estimated to be about half that of the hybrid coil design [16]. The design of the superconducting coil conductor [17] is based on a variant [18] of the VIPER-like cable [19] made of 4–6 stacked HTS tapes with a central cooling hole and a steel jacket to provide thermal stability and mechanical robustness, respectively. The large bore required for the superconducting coil is required to accommodate heavy shielding layers (neutron moderators and thermal absorbers) to minimize both heat load and radiation level on the superconducting material.

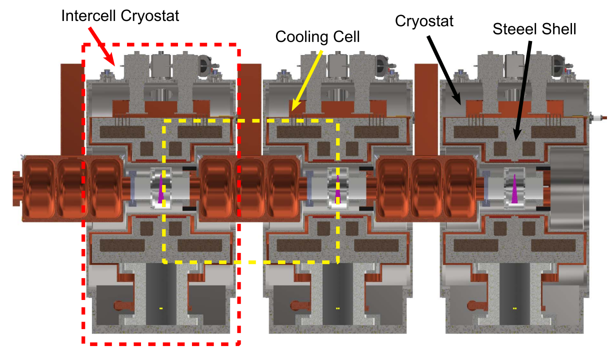

Fig. 3. Schematic view of a periodic cooling cell module cross-section. Each cryostat for the superconducting magnets contains a steel outer shell that connects mechanically half of the HTS solenoids of two consecutive cooling cells. The cooling cell structure, considering the superconducting solenoids, the RF cavity, and the absorber, is highlighted.

B. 6D Ionization Cooling: Compact, High-Field Solenoids

After collecting the particles inside the target and capture solenoid, a series of cooling cells is used to reduce the emittance of the muon beam and manipulate the bunch size to meet the requirements for the next acceleration and collision phases. To rapidly cool down the muon beam in the 6D phase space (space and momentum), each cooling cell is composed of a modular system of absorbers, RF cavities, and split coil solenoids to allocate the space for the mechanical structure between the magnetic system and the cavities, see Fig. 3.

Each separated beam of $\mu/\bar{\mu}$ is focused by roughly 3,000 compact HTS split coil solenoids distributed along a $\sim$1 km long line and divided into 14 different cooling cell types (cells A1 to A4 and cells B1 to B10). Each cooling cell magnet must provide an axial field ranging from 2 to 14 T with a precise field gradient along the cell to focus the particles before and after the interaction with the absorber placed between two different RF cavities. The main driver for the solenoid bore dimension, ranging from

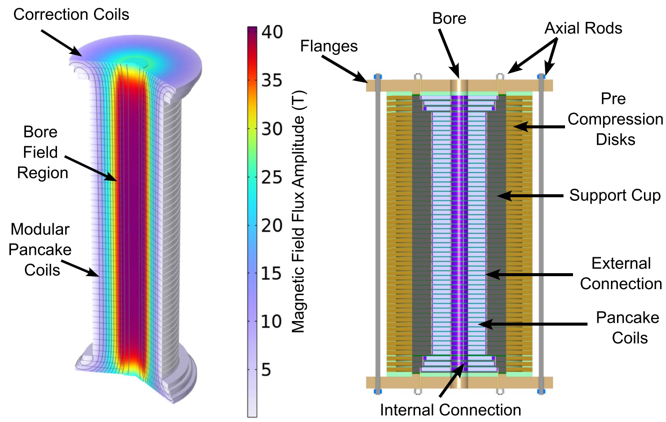

Fig. 4. Field map (*left*) [23] and mechanical design (*right*) [24] of the 40 T HTS solenoid for the final cooling of the muon collider. A modular pancake approach is considered with integrated correction coils to shape the field profile. Details about the axial rods, for longitudinal loading, and pre-compression disks to withstand Lorentz forces and align the coil are visible.

90 mm (at high field) to 1.5 m (with modest field), is the RF cavity frequency and the mechanical structure dimensioning to support the forces acting on the conductor during the energization. Being limited by the longitudinal distance between the different cells and the transversal dimension of the cooling channel, high current density windings are presently considered using dry metal-insulated high-temperature superconductor technology, as already used for high field dipole magnets [20]. Detailed analysis [21] of the mechanical performances of a prototype proposal for the B5 cooling cell split coil solenoids shows the possibility to limit the mechanical stress on the conductor below ReBCO material limits, both for the hoop stress (up to 300 MPa corresponding to 0.18% of hoop strain, 60 MPa for the axial stress, and 80 MPa in compression/10 MPa in tension for the radial stress). Extensive analysis of the electromagnetic and mechanical behavior of the split-coil solenoid is also being performed to properly account for the interaction between two consecutive cooling cells, where the fringe field and repulsive forces between same-polarity solenoids are not negligible. Considering the number of superconducting solenoids required for the cooling process, a mandatory cryogenic operating temperature above liquid helium (presently fixed at 20 K using conduction cooling solutions) is required for the thermal design to minimize the total cryogenic power consumption, reduce the liquid helium inventory and improve sustainability of the entire collider complex operation both in the 3 TeV and 10 TeV configuration scheme.

C. Final Cooling Solenoids: Ultra-High Field Performance

The final cooling stage aims to achieve ultra-low transverse emittance, requiring 500 mm long solenoids that generate magnetic fields exceeding 40 T [22] in very small apertures (~50 mm), see Fig. 4. To achieve the required magnetic field level while minimizing the outer solenoid radial dimension high-temperature superconductor technology performances are pushed at the limit by operating the solenoid at $T_{\mathrm{op}} = 4.2$ K, achieving engineering current densities on the conductor above 600 A/mm^2 [23]. To reliably achieve the target performances on all 18 ultra-high field solenoids, a modular pancake approach is used for the manufacturing of the not insulated (NI) high-temperature superconducting winding, considering both pre-soldered and hot-winded soldered HTS tapes with single or double tape cable configurations [23]. High mechanical forces, produced by the required high current densities and fields, are one of the main challenges for the design of the solenoid. Detailed mechanical simulations of the magnet cool down and energization have been performed [25], without considering the contribution of HTS persistent current magnetization, optimizing the pre-compression of the stainless steel disks around the HTS pancake at 200 MPa to limit the radial stress during energization below 290 MPa in compression and 10 MPa in tension [24]. Preliminary evaluations of the variation of the Lorentz forces due to the persistent current magnetization effect are currently being performed to mitigate the increment of the radial and hoop stress on different pancake windings by using striated tape configurations [26]. Multi-physics simulations are being developed to fully characterize the quench dynamics of the ReBCO solenoid and evaluate the effect of the induced currents, both from thermal and mechanical points of view. To safely discharge the large stored magnetic energy, the inter-turn electrical resistance has to be precisely measured and tuned, balancing the magnet stability with the maximum ramp rate achievable during magnet powering. Several protection schemes are currently being explored, considering different assumptions on the winding characteristic time and inter-turn resistance [27]. The aim is to trigger large current pulses in either the complete solenoid or in individual pancake coils, using radial turn-to-turn resistance to dissipate energy in the conductor and thereby raise its temperature beyond critical limits.

D. Superconducting dipoles for the HCS

A key technological development for the muon collider accelerator ring is the design of large-aperture high-field steady-state dipole magnets based entirely on HTS technology, as described in [28], using only resistive magnets for the fast acceleration of the particles. The superconducting dipoles are designed to provide a nominal central field of 10 T within a clear bore aperture of 30 x 100 mm^2 to accommodate particle trajectory variations during the fast acceleration. The proposed magnetic layout [29] employs a racetrack coil configuration using REBCO tapes wound into 3 metal-insulated (MI) single pancakes, see Fig. 5. By using an open mid-plane design as a baseline, HTS ReBCO coils can be used to simplify the winding procedure and accommodate a tungsten shield within the coil aperture to protect the conductor from the muon decay products and heat load during operation. The mechanical structure around the coil consists of stainless steel sectors surrounding each racetrack to prevent stress accumulation on the coil while simplifying the alignment and assembly procedure of the magnet. Finite

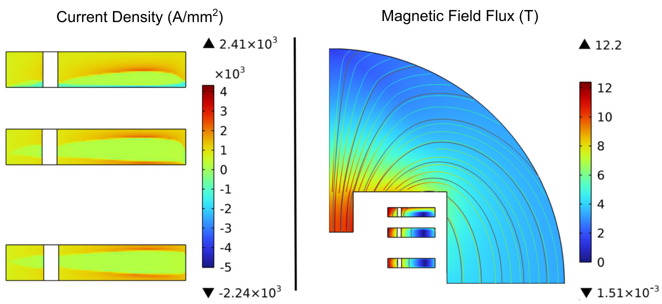

Fig. 5. Electromagnetic simulation of the HTS dipole magnet designed for the muon collider accelerator ring. Details about the conductor magnetization at nominal current are reported (*left*). The field map in the open mid-plane racetrack superconducting coils and in the iron yoke of the cross-section is highlighted (*right*).

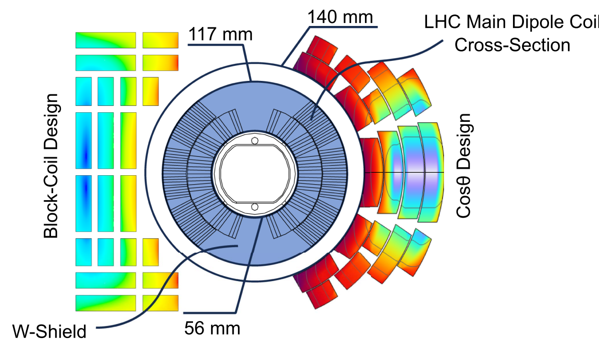

Fig. 6. Coil cross-section comparison between the two proposed designs under investigation for the high field HTS superconducting coil of the arc magnets. Block coil design (*left*) and Cosθ coil design (*right*) apertures are compared to the NbTi Large Hadron Collider (LHC) main dipole coil cross section.

element simulations have confirmed that the stress distribution remains within acceptable limits, including persistent current effects inside HTS conductors and ensuring mechanical robustness. Additional iterations on the design will focus on the field quality provided by the superconducting coil and iron magnetization inside the good field region (20×50 mm^2) for the different trajectories of the particles during the acceleration phase.

E. Collider Ring Magnets: High Fields with Large Apertures

The main challenge for the superconducting magnets of the collider ring is imposed by the effect of the muon decay products and the requirement to maximize the accelerator integrated luminosity (10 ab^{-1} target), considering the muon decay rate. High field dipoles (14–16 T) are mandatory to minimize the collider dimension, given a fixed collision energy, which translates to a maximum length travelled by the particles before their decay. Large bore apertures (up to 140 mm) must accommodate heavy tungsten shielding from muon decay products to reduce the maximum displacement per atom (DPA), integrated dose after 10 years of operation [30] and heat load, from 5 to 10 W/m, on the coil material, which can be evacuated in the cold mass. To evaluate the maximum performances of different superconductor technologies and provide feedback for the lattice design, analytical evaluations [31], [32] have been used, accounting for design constraints of the superconducting magnet (maximum mechanical stress on conductor, operating margin from superconductor critical surface, and quench protection stability). Assuming to optimize the coil geometry to withstand up to the REBCO tape maximum transversal stress (400 MPa), the main limitation for the superconducting magnet performances is the quench protection, followed by the margin on the loadline. Results from analytical evaluations have been validated with simplified FEM analysis showing high temperature superconductors as the enabling technology to reach both the required performances for the arc dipoles, at $T = 20$ K, and interaction regions (IR) quadrupole, at 4.5 K. Operating the arc magnets at 20 K not only reduces the overall cryogenic power consumption of the collider complex but also allows for reduced tungsten shielding thickness within the coil aperture, thereby improving magnet performance given the lattice design. Two different coil layouts for the arc dipole superconducting magnet, see Fig. 6, are being investigated using FEM simulations to account for persistent current magnetization in the HTS tape and evaluate mechanical performances and field quality in the bore aperture. Both block coil design [33] and cosθ magnet design [34] are being optimized to reach 16 T–140 mm bore aperture with a minimum 2.5 K of temperature margin using stacked-tapes cable configuration. To minimize the stress on the REBCO conductor during magnet energization and intercept the accumulation of Lorentz forces, vertical and horizontal ribs have been implemented in the block coil design cross-section [33] separating each coil block of the winding, as already considered for similar high field superconducting magnets for hadron colliders [35]. Different superconducting coil end designs are under evaluation to better cope with the stacked-tape conductor behaviour during winding and prevent hard way bending of the tape, like in conventional flared end coil designs. Persistent current magnetization effect is already being considered in the electromagnetic optimization of the cosθ coil design, showing the possibility to reach accelerator-grade field quality, profiting from the different sectors' fine-tuning and the small free bore aperture diameter equal to 23.5 mm compared to the 140 mm coil aperture.

A key challenge for the collider ring design is the extensive use of combined-function magnets to avoid short straight sections in the lattice where collimated neutrino radiation produced by muon decay products can build up, exceeding radiation limits for the environment. The analytical evaluations used to evaluate dipole and quadrupole maximum performances have been extended to account for nested combined function magnet configurations, considering both dipole-quadrupole and dipole-sextupole magnet configurations. A detailed finite element analysis (FEM) of the combined-function magnet configuration will be carried out to evaluate the expected magnetic performance and to investigate the engineering aspects of the two nested coil layouts.

V. HTS Development Efforts and Outlook

The successful implementation of HTS-based superconducting magnets in the muon collider complex relies not only on the material performance but also on significant advancements in the conductor behaviour modeling, mechanical integration analysis, and magnet engineering. Different research activities across multiple domains within the International Muon Collider Collaboration have already started, with direct support by the EU through the design study MuCol [36].

A. Material Science and Conductor Characterization

Recent research activity has focused its efforts on the understanding of the mechanical behavior of REBCO-coated conductors under operational stress conditions for the development of a technological demonstrator for the Muon Collider accelerator complex. Different micro-mechanical tests like nanoindentation measurements or micrometric pillars stress-strain analysis [37] aim to correlate key parameters such as fracture toughness, plasticity, and fatigue resistance with measured macroscopic behaviour and performances of HTS tape [38], which are essential for detailed mechanical analysis of coil structure and magnet behaviour.

B. Modeling and Simulation

Accurate multiphysics modeling is essential for assessing the performance of HTS magnets. Within the Muon Collider magnet working group, advanced coupled electromagnetic–thermal–mechanical simulations are being developed to predict field distribution, stress accumulation, and current redistribution in REBCO conductors during quench events, while accounting for magnetization hysteresis and non-uniform conductor performance. These tools are particularly critical in high-stored-energy systems, such as the final cooling solenoids, where turn-to-turn resistance has to be precisely controlled for the quench protection of the metal-insulated winding. Dedicated hybrid formulation approaches are being developed [39] to study current redistribution dynamics in non-insulated (NI) and metal-insulated (MI) winding schemes.

C. Prototype Development and magnet R&D

A critical step for the implementation of a staged muon collider accelerator complex is the R&D development required on superconducting magnet technology in the next decade [40]. Different magnet demonstrator configurations (including high field, high stored energy density solenoids, large bore split coil solenoids, and high field large aperture dipoles and quadrupoles) have been identified to focus research activity on the development of next-generation superconducting magnets, particularly using High-Temperature Superconductors (HTS). The proposed program [41] aims to close key technology gaps, reach high technological readiness levels (TRL 6), and deliver broad impacts beyond particle physics.

D. Synergies and Impact on large-scale applications

Synergies between different R&D programs in the particle physics community are vital for the technological advancement of high-energy particle colliders. As already started in the past years for Nb_3Sn technology, collaborative efforts towards the development of high-temperature superconductor technology can promise to reach significant improvement for high-field accelerator-grade superconducting dipoles and quadrupoles. The proposed R&D development for the muon collider magnets has common aspects with the HTS superconducting magnet development activity within the High Field Magnet program [42] for particle accelerator dipoles like CEA focusing on metal insulated windings [43] or PSI working on not insulated positron-capture solenoids [44] and HTS sub-scale racetracks for common coil magnet designs [45]. Understanding of conductor properties, winding techniques, mechanical integration, and quench protection strategies focused on ReBCO conductors can be leveraged from existing prototype developments within the particle accelerator community like INFN with a 10 T dipole magnet within the IRIS project [46], research programs like US-MDP [47], [48] and research institutes like IHEP-CAS both developing hybrid high field magnets for next generation particle colliders. Beyond the particle physics community, the technological advancements driven by HTS magnet development are expected to have a significant impact on several scientific and industrial sectors. High-field HTS magnets are already under investigation for applications in nuclear fusion (e.g., 20 T tokamaks like in the SPARC [49] and ARC project or 20+ T stellarator projects [50]), high-resolution NMR, and compact medical accelerators for heavy ion gantries [51].

VI. Conclusion

The development of multi-TeV muon colliders, in particular within the scope of the IMCC targeting a 10 TeV accelerator complex, presents an extraordinary challenge in terms of novel accelerator design schemes, beam dynamics optimization, and magnet technology development. The short muon lifetime, intense radiation environment, and need for compact, high-field accelerator sections place new interesting and highly demanding constraints for the design of superconducting magnets. High-Temperature Superconductors (HTS), and in particular REBCO-based coated conductors, have emerged as the key enabling technology to meet these requirements. Their ability to operate at higher temperatures and magnetic fields, combined with high mechanical robustness and thermal stability, makes them essential for several critical components of the collider complex, from target and cooling solenoids to final focus and ring magnets. In addition to the high performance, HTS technology could provide a shift toward more energy-efficient and sustainable accelerator infrastructures. The potential to significantly reduce cryogenic power consumption has a huge impact on the long-term operation target of high-energy particle accelerators. Extensive R&D activity is still mandatory to fully characterize HTS for collider-scale applications, including progress on conductor manufacturing, novel quench protection strategies, and magnet design. HTS-based magnet technology will not only enable the realization of a next-generation muon collider. Still, it will also drive innovation across multiple large-scale and societal applications, paving the way for compact, high-field, cost-effective, and energy-efficient systems.

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