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IPAC-2025: International Particle Accelerator Conference 2025 (Taipei, 1-6 June 2025)

Collider ring magnet design for a Muon Collider

Barbara Caiffi, Samuele Mariotto , Luca Alfonso, Andrea Bersani, Luca Bottura, Stefania Farinon, Francesco Mariani, Daniel Novelli, Alessandra Pampaloni

The Muon Collider represents a promising candidate for a post-LHC accelerator, offering a unique opportunity to probe the frontiers of high-energy physics in a more cost-effective and energy-efficient manner compared to traditional hadronic colliders. The International Muon Collider Collaboration (IMCC) is currently conducting an extensive feasibility study for a cutting-edge facility designed to achieve 10 TeV center-of-mass energy within a compact 10 km circumference ring. This ambitious project faces a variety of technical and scientific challenges, requiring breakthroughs in multiple areas of accelerator technology. A key focus of this endeavor is the development of advanced superconducting magnets for the collider ring, which are critical components due to their demanding specifications. These magnets must deliver very high magnetic fields, accommodate large bore sizes, and maintain low energy consumption. Also the magnets of the interaction region present a significant technological challenge due to the demanding high gradients required to achieve the necessary emittance and luminosity, as well as the extremely high levels of radiation expected. This contribution will discuss the challenges associated with such magnets, presenting the status of the preliminary conceptual designs under investigation and the required R&D necessary for such configurations.

Progress on the design of solenoids for the 6D cooling channel of a muon collider

Siara S. Fabbri, Luca Bottura, Marco Statera

In the current and most evolved design concept of a muon collider, there exists two long (~ 1 km) channels for cooling newly created muons and anti-muons, termed the `6D cooling channels'. There the beam is cooled in momentum and position space using a series of alternating polarity solenoids, which create an oscillating field in the beam direction, through absorbers and radio-frequency cavities. In total there are around 3000 solenoids per channel, contributing to a significant portion of the cost and engineering demands of the entire machine. The integration of the requirements of the field profile with feasible solenoid configurations is a difficult and unique problem, without analytic descriptions to readily relate these. Our approach addresses this problem in two steps: in the first we constrain the beam optics optimization studies by setting engineering limits on solenoid parameters; in the second we have developed a numerical optimization routine to find the best configuration given a desired field profile, in terms of cost and engineering complexity. The following paper reviews this approach and key features, and presents optimization results on the latest optics solution.

New developments in the design of the muon production target area of a multi-TeV muon collider

J. Manczak, L. Bottura, D. Calzolari, M. Calviani, S. Candido, R. Franqueira Ximenes, A.Lechner, G. Lerner, A. Portone, C. Rogers

As the International Muon Collider Collaboration advances the conceptual design for a multi-TeV muon collider facility, new technical constraints continue to arise in the muon production stage, where a high-power proton beam interacts with a target. Achieving the required muon bunch intensity may necessitate increasing the primary beam power up to 4 MW. Consequently, the shielding design must address sustained radiation exposure, particularly on critical components such as superconducting solenoids, which generate strong magnetic fields essential for capturing both pions and decay muons. Additionally, the portion of the proton beam that passes through the target without undergoing inelastic interaction leads to a very high power density in the chicane area and an intense ionising dose on the insulation material of the normal-conducting chicane magnets, which are used to separate the muon component. A robust method to safely extract these spent protons is crucial. This study presents the latest results from FLUKA Monte Carlo simulations, modelling the radiation load on solenoids and the extraction channel across varying beam power and target designs.

A Muon Beam Facility at CERN to Demonstrate Muon Ionisation Cooling.

R. Losito, D. Schulte, R. Taylor, P.B. Jurj, C. Rogers, L.K. Krzempek, L. Rossi, M. Statera, D. Giove, A. Grudiev, C. Barbagallo, L. Bottura, S.S. Fabbri, C. Bracco, C. Ahdida, D. Lucchesi, N. Pastrone, J. Osborne, T. A. Bud, D. Zuliani, G. Scarantino, R. Kamath

The International Muon Collider Collaboration (IMCC) has been formed following the 2020 European Strategy for Particle Physics Update, with the goal of studying the feasibility of a muon collider at a centre of mass energy of around 10 TeV. One of the most challenging sections of a muon collider is the initial cooling before acceleration, due to the necessity to apply intense magnetic and electric fields to reduce the 6D emittance of the muon beam by 5 orders of magnitude in a very short time, to cope with the limited lifetime of muons (2.2 µs at rest). The IMCC proposes to build a Demonstrator to prove that all the involved technologies (RF, magnets, absorbers, beam instrumentation) can be built at the required specifications, and integrated in order to limit the length of the cooling sections to an acceptable value. Several options are being considered in different laboratories within the collaboration. This paper describes a possible implementation at CERN, in the existing TT7 tunnel.

Magnet R&D for the Muon Collider: Proposed R&D Plans

L. Bottura, B. Bordini, S. Fabbri, M. Statera, F. Boattini, S. Mariotto, B. Caiffi, S. Gourlay

The muon collider represents a transformative approach in particle physics, offering a pathway to achieve high energy and luminosity with reduced environmental impact compared to other collider technologies. Central to its feasibility is the development of advanced magnet systems capable of supporting the stringent requirements of muon production, acceleration, and collision. The key targets for magnet R&D include achieving field levels up to 40 T, magnets with stored energies up to 300 MJ, managing heat loads from muon decay at the level of several W/m, and ensuring radiation resistance well above 50 MGy. Given such extraordinary challenges, research presently focuses on integrating high-temperature superconductors (HTS), tailored for efficient cooling at cryogenic temperature, and striving for compact magnets to reduce the capital expenditure. In the past years we have progressed in the conceptual design, and in some cases we have initiated engineering design, as well as materials and small-size coil testing. This has allowed to outline an R&D plan that we describe in this paper. The proposal plan involves staged milestones, includes the development of small- and full-scale magnet prototypes, up to the validation under collider-relevant conditions.

Transient finite-element simulations of fast-ramping normal-conducting magnets for a 10TeV muon collider

Dominik Moll, Laura A.M. D'Angelo, Herbert De Gersem, Fulvio Boattini, Luca Bottura, Marco Breschi

Ongoing conceptual studies for a 10TeV muon collider identified rapid cycling synchrotrons as major engineering challenge. Due to the muon's short lifetime of only 2.2µs at rest, normal-conducting bending magnets with field rise rates of well beyond 1kT/s are indispensable to support accordingly fast acceleration cycles. Energies of 100MJ will be interchanged between magnets and capacitor banks within few milliseconds. Accurate models of the magnets are thus required to evaluate and optimize the overall system performance. The non-uniform temperature distribution in the magnet strongly affects material properties like the electrical conductivity of copper and must therefore be considered in the electromagnetic field problem posed by Maxwell's equations. This contribution presents recent advancements in addressing this multi-physical problem by using problem-specific finite-element tools allowing to describe the inherently transient behavior. The ferromagnetic yoke is accurately resolved by using a novel combination of a Bergqvist hysteresis and a homogenized eddy current model. Finally, different magnet design concepts are compared in terms of material costs, magnetic energy, losses, field quality and temperature buildup.

MISSED DEADLINE ~~**Design, Integration and Technology R&D of a Muon Ionisation Cooling Cell.**~~

~~L. Rossi, R. Losito, D. Giove, M. Statera, D. Schulte, C. Rogers, A. Grudiev, C. Barbagallo, L. Bottura, S.S. Fabbri, G. Scarantino,… more EU and US colleagues~~

~~The International Muon Collider Collaboration (IMCC) was established following the 2020 European Strategy for Particle Physics Update, with the goal of investigating the feasibility of a muon collider with a center-of-mass energy of approximately 10 TeV. The initial muon cooling section, prior to acceleration, is a critical component, as it necessitates the application of intense solenoidal magnetic fields overlapping with high radio frequency (RF) electric fields. This process aims to reduce the 6D emittance of the muon beam by five orders of magnitude in a very short time to accommodate the limited lifetime of muons (2.2 µs at rest). Building on the previous US-led Muon Accelerator Program (MAP), the IMCC team has developed a series of very high field (20-30 T peak), medium bore (100-1000 mm) high-temperature superconducting (HTS) solenoids, along with RF cavities that have gradients exceeding 30 MV/m at 352/704 MHz. Following several iterations, the first complete cooling cell has been fully designed, integrating various components, including magnets with a 20 K cooling circuit, RF cavities with power couplers and windows, and solid absorbers in a dispersive field. This integration has been accomplished with a satisfactory assembly procedure. Numerous research and development (R&D) and technology validation steps are currently underway in various laboratories, contributing to the ongoing optimization of beam cooling performance.~~

MT-29: International Conference on Magnet Technology 2025 (Boston, July 1-6 2025)

Experimental Study on Delamination Induced by Electromagnetic Forces in REBCO Tapes.

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This study investigates the delamination behavior of REBCO coated conductors (CCs) using the electromagnetic delamination strength (EDS) method. Unlike the mechanical delamination strength (MDS), which relates stress to structural failure, EDS focuses on the irreversible threshold at which critical current degradation occurs. This distinction is particularly important for high-field magnet applications, such as fusion magnets and particle accelerators, where REBCO CCs are increasingly utilized for their exceptional superconducting properties. However, conductors in these applications are subjected to substantial Lorentz forces, driven in part by the interaction between screening currents and the magnetic field.
The inherent weakness of REBCO coated conductors (CCs) lies in their multilayer structure, particularly the adhesion between the superconducting layer and the buffer layers. To investigate the degradation of the critical current (Ic), a custom-designed sample holder was developed, aided by numerical analyses to minimize hoop stress components and isolate the radial stresses responsible for delamination. Experiments were performed on 4 mm-wide commercial samples from various manufacturers, using magnetic fields up to 19 T and currents up to 2 kA. The relative orientation of the magnetic field and current generated an average transverse tension of up to 10 MPa. Measurements conducted at 77 K and 4.2 K were complemented by inductive mapping of the local critical current density (Jc) before and after testing, as well as SEM/EDX analyses, providing detailed insights into damage distribution and underlying mechanisms. Forensic analyses revealed compositional changes in specific regions, highlighting simultaneous quench events and localized delamination, which predominantly occurred at the tape edges. To investigate the influence of the current density profile within the superconducting layer, experiments were conducted under varying magnetic fields and temperatures. Furthermore, as 4 mm-wide tapes are fabricated by mechanical or laser slitting from 12 mm-wide tapes, the effect of the slitting process on delamination was also analyzed.
These findings offer critical insights for magnet design, identifying the conditions that cause irreversible degradation of superconducting properties and informing strategies to mitigate such effects.

A comprehensive framework for the mechanical analysis of Ultra High Field REBCO Solenoids
Authors

G. Vernassa, B. Bordini, L. Bottura, H. Felice, C. Senatore, M. Rusinowicz, R. Babouche, C. Lucas, S.S. Joao, A. Raktus, D. Irbe, J. M. Bergheau and G. Kermouche.

The need for strong steady state magnetic fields, of 40 T and above, raises several new challenges in the design of superconducting magnets. Rare-earth barium copper oxide (REBCO) coated conductors (CCs) are nowadays the strongest candidates for this type of applications, yet the layered structure of these materials carries along the major mechanical challenges. Recent tests of ultra-high field (UHF) REBCO magnets have demonstrated the capabilities of these conductors of operating at fields up to 45.5 T, but they also evidenced some critical multi-scale dynamic effects, where crack patterns and delaminated areas in the REBCO phase influence the electrodynamics and quench behavior of the magnet.
In this contribution, we report on an encompassing multi-scale approach for the mechanical analyses of REBCO UHF solenoids; a paradigm that has been proposed in the context of the R&D studies for a 40+ T no/partial-insulation (NI/PI) solenoid for the Muon Collider. The goal of this approach is to estimate the stress/strain state inside a superconductor when employed for UHF applications. We investigate here the mechanical challenges based on material characterization campaigns and modeling efforts developed synergistically at coherent scales.
Initially, as a steppingstone, we focus on mechanical properties of REBCO layers' materials, presenting a measurement campaign at the micro-scale which provided with reliable constitutive laws for any further mechanical studies. We then address the issue of screening currents induced stresses/strains (SCIS) in connection with measurements of the delamination strength of REBCO CCs under Lorentz force. Finally, we move to examining the mechanical loads in the case of quenches in the windings. The evolution of the force density field and consequent stress fields are treated in a statistical manner, highlighting trends and extreme case scenarios.
In conclusion, for each of the mechanical load step mentioned above, we propose a set of design criteria to be used in the design of UHF solenoids.

Update on the Preliminary Electromagnetic and Mechanical Design of the Block-Coil Dipole for the Muon Collider Ring

Luca Alfonso1, Andrea Bersani1, Luca Bottura2, Barbara Caiffi1, Stefania Farinon1, Francesco Mariani3,4, Samuele Mariotto3,5, Riccardo Musenich1, Daniel Novelli1,4, Alessandra Pampaloni1,4, and Tiina Salmi6 on behalf of IMCC

Within the framework of the International Muon Collider Collaboration (IMCC), a feasibility study is underway to develop the proposed 10 km collider ring, aimed at achieving a center-of-mass energy of 10 TeV. The stringent requirements to maximize luminosity and shield decay products of muons - characterized by only 2.2 μs lifetime at rest - necessitate the design of compact, high-field, and large aperture superconducting magnets. These ambitious specifications present substantial technological challenges from both physical and engineering perspectives, pointing the importance of using ReBCO high-temperature superconductors (HTS) as the primary conductor material. These operating conditions call for the development and exploration of advanced methodologies to address multiple aspects of the system's design and operation. Key considerations include cooling strategies, quench protection mechanisms, AC losses mitigation, mechanical structure integrity, and the integration of effective internal shielding. This paper presents a preliminary 2D analysis of dipoles in a block-coil configuration, featuring an innovative stacked cable orientation and a novel end-winding concept. An updated electromagnetic design with a bore field of 16 T in a 140 mm aperture diameter is introduced, accompanied by an analytical estimation of hysteretic losses, accounting for transport current effects. Additionally, a preliminary mechanical design is provided using finite element analysis (FEM) via ANSYS software, employing a stress-management strategy to address the high Lorentz forces.

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Updates on the Conceptual Design Study of the Magnets for the Muon Collider Storage Rin

B. Caiffi, L. Alfonso, A. Bersani, L. Bottura, S. Farinon, F. Mariani, S. Mariotto, D. Novelli, A. Pampaloni, T. Salmi

The Muon Collider represents an exciting proposal for a post-LHC accelerator, capable of exploring higher-energy regions with greater power consumption efficiency compared to hadronic alternatives, while avoiding synchrotron radiation limitations inherent in electron colliders.
This contribution will focus on the magnets for the Muon Collider storage ring. These magnets pose an unprecedented technological challenge: high magnetic fields are required to ensure the compactness of the ring, maximizing the number of muon beam passes through the interaction region and thereby increasing luminosity. Additionally, large apertures are essential to accommodate an adequate shielding system that keeps the thermal and nuclear loads induced by the beam within acceptable limits. Furthermore, minimizing straight sections is critical to avoid the radioactive hazard posed by collimated neutrino beams, necessitating the use of combined-function magnets (dipole + quadrupole and dipole + sextupole). The interaction region also presents extreme conditions that demand the development of magnets beyond the current state of the art.
In this contribution, we will discuss the progress in the feasibility study of magnets for both the arc and the interaction region of the Muon Collider storage ring. Performance limits will be analyzed for dipoles, quadrupoles and combined function magnets, taking into consideration constraints on mechanical stresses, margin on the load line, ease of the protection system and cost, assuming both LTS (Nb_3Sn) and HTS (ReBCO) materials.
Finally, the most up-to-date conceptual designs of the arc dipole will be presented, comparing the strengths and challenges of the cos-theta and block coils layouts in terms of achieving of electromagnetic requirements, mechanical structure feasibility, and windability This analysis will provide valuable insights into the development of advanced magnet technologies required for the Muon Collider.

Magnet R&D Plans for the Muon Collider

B. Bordini, B. Auchmann, F. Boattini, L. Bottura, B. Caiffi, L. Cooley, S. Fabbri, S. Gourlay, T. Nakamoto, S. Mariotto, S. Prestemon, M. Statera

The Muon Collider (MC) embodies a groundbreaking concept in circular colliders for high-energy physics, offering a unique pathway to achieve unprecedented energy and luminosity of the colliding partons while significantly reducing environmental impact compared to conventional collider technologies. A critical aspect of its feasibility lies in the development of cutting-edge superconducting magnet systems capable of meeting the demanding requirements of muon production, acceleration, and collision.
Key research and development (R&D) objectives include achieving magnetic field strengths of up to 40 T (in solenoids), managing stored energies exceeding 300 MJ in a single magnet (solenoid), mitigating heat loads from muon decay at levels of several W/m, and ensuring radiation resistance exceeding 50 MGy. Overcoming these extraordinary challenges requires the innovative integration of high-temperature superconductor (HTS) technology, optimized for efficient operation at cryogenic temperatures up to 20 K, as well as the pursuit of compact designs to reduce capital expenditure.
In recent years, the International Muon Collider Collaboration (IMCC), hosted at CERN, has made significant progress in both the conceptual and, in some cases, the engineering design of these systems. This includes advancements in materials development, small-scale coil testing, and the establishment of a comprehensive R&D roadmap. This paper outlines a detailed plan with staged milestones, focusing on the development and testing of small- and full-scale magnet prototypes, ultimately culminating in their validation under collider-relevant conditions. This systematic approach aims to advance the technological readiness of magnet systems, bringing the realization of the Muon Collider closer to reality.

Update on the Electromagnetic and Mechanical Design of a Cosθ Dipole for the Muon Collider Study

Francesco Mariani1,2, Luca Alfonso3, Andrea Bersani3, Luca Bottura4, Barbara Caiffi3, Samuele Mariotto1,5, Daniel Novelli2,3, Stefania Farinon3, Alessandra Pampaloni3, Lucio Rossi1,5, Fellow, IEEE, Tiina Salmi6, Stefano Sorti1,5

Within the framework of the International Muon Collider Collaboration (IMCC), researchers are involved in a feasibility study to develop high-temperature superconducting (HTS) magnets for the proposed 10 km collider ring, designed to reach a 10 TeV center-of-mass energy. Due to the short lifetime of muons of only 2.2 µs, the machine must minimize the acceleration time of the particles allowing them to collide before they decay. To optimize the machine cost and maximize the collider luminosity, the superconducting dipoles of the collider ring must be compact and generate high steady-state magnetic field. In addition, they must feature large apertures to assure enough space for the insertion of a shielding structure needful to preserve superconducting coil from interacting with products of muons decays. These demanding specifications pose significant technological challenges for the dipole magnets design, both in terms of physics and engineering.
In this contribution we update the 2D cosϴ electromagnetic and mechanical design of the main collider dipoles. Since the coil design requires the use of REBCO tapes (whose magnetization effect in field quality and losses is not negligible), an analytical code has been written in MATLAB to evaluate the electromagnetic performances considering non-uniform current distribution inside REBCO tapes according with Brandt model. Validation study of the code - by comparing the results with finite element method (FEM) simulations - is also presented in this work. This includes a comparison of computational time between the analytical and FEM method, to better appreciate the advantages of the two calculation methods and their accuracies.

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Young scientist plenary - The role of High Temperature Superconductors for a 10 TeV Muon Collider

S. Mariotto, C. Accettura, L. Alfonso, L. Balconi, A. Bersani, B. Bordini, L. Bottura, B. Caiffi, S. Fabbri, S. Farinon, T. Maiello, F. Mariani, D. Novelli, A. Pampaloni, L. Rossi, T. Salmi, G. Scarantino, M. Statera, M. Sorbi, S. Sorti, G. Vernassa

The international particle physics community, among different options for the development of future high-energy particle colliders and fundamental interactions exploration, considers Muon Colliders (MC) as a great 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 set up, following the recommendations of the European Strategy for Particle Physics (ESPP), to produce a conceptual design of 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) result the enabling 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 increment magnet performances 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 to overcome the current energy frontier.

Performance limits of combined function magnets for a Muon Collider

Daniel Novelli, Luca Alfonso, Andrea Bersani, Luca Bottura, Barbara Caiffi, Stefania Farinon, Francesco Mariani, Samuele Mariotto, Alessandra Pampaloni, Tiina Salmi, on behalf of IMCC

An International Muon Collider Collaboration (IMCC) has been formed following the recommendation of the Updated European Strategy for Particle Physics (ESPPU) to study the feasibility of a 10 TeV muon collider within a compact 10 km ring. This machine combines the precision of lepton colliders with the energy reach and discovery potential of hadron colliders, overcoming synchrotron radiation limitations affecting electron-positron machines. However, the short muon lifetime (2.2 μs at rest) presents several challenges in the development of magnets, RF systems, targets, shielding, and cooling. One of the main concerns is the flux of neutrinos originated by muon decay in the collider, which calls for the need of minimizing straight sections. This constraint makes conventional FoDo cells unsuitable, necessitating the development of combined function magnets that integrate bending and focusing/defocusing or chromaticity correction functions. To address these challenges, magnets capable of combining a dipole field with either a quadrupole field (B1+B2) or a sextupole field (B1+B3) are currently under study. This work extends the Aperture-Field (A-B) plot methodology, previously applied to single dipoles or quadrupoles, to dipole-quadrupole combined function magnets, delineating feasible designs based on aperture, field strength, mechanical stress, quench protection, and cost. Using a Python-ANSYS tool, optimized configurations were simulated under the sector coil approximation, focusing on ReBCO coils operating at 4.5K, 10K, and 20K, providing Dipole Field – Quadrupole Gradient (B-G) plots that illustrate the design space, highlighting the technological limits and feasibility of different dipole and quadrupole combinations.

A "20 T at 20 K" Model Coil for the Muon Collider Target Decay and Capture Solenoid

Proposed Authors (to be defined !) : L. Bottura (placeholder)

The Muon Collider (MC) is one of the options under study as the next step for high-energy physics beyond the Large Hadron Collider. The magnets for a MC, largely based on high-temperature superconductors (HTS), bear some of the most pressing technology challenges and will require intense development and demonstration in the next years. The "target decay and capture solenoid", a high field solenoid hosting the muon beam production target, is one of these challenges. In the present baseline, the solenoid is 18 m long, produces a peak field of 20 T in a large bore of 1.4 m, it is designed to operate at 20 K, and has a stored energy in excess of 1 GJ. We have designed it based on a HTS, force-flow cooled, high-current conductor. Such performance is well beyond present state-of-the-art. This is why we are proposing to build and test a model coil that aims at increasing the technology readiness level, giving enough confidence that the whole system can be built and operated. Beyond its direct application to the Muon Collider, this development aligns with demands from other scientific fields, such as high-field physics, and societal applications, including fusion energy. In this paper we set the requirements on the model coil geometry and performance. We then describe the conceptual design of a 20 T model coil operated at 20 K, its initial engineering and analysis, and propose a construction and test plan.

EUCAS-2025: European Conference on Applied Superconductivity (Porto, 21-25 September 2025)

Exploring combined dipole-quadrupole and dipole-sextupole magnets for a Muon Collider

Daniel Novelli, Luca Alfonso, Andrea Bersani, Luca Bottura, Barbara Caiffi, Stefania Farinon, Francesco Mariani, Samuele Mariotto, Alessandra Pampaloni, Tiina Salmi, on behalf of IMCC

Over the past few years, interest in a Muon Collider as a potential post-LHC machine has grown significantly. By colliding muons, it is possible to achieve both precision and high energy, overcoming the limitations imposed by synchrotron radiation in lepton colliders using electrons and positrons. However, the very short muons lifetime at rest (2.2 μs) requires high beam intensity and very fast acceleration rates limiting the collider ring dimensions to maximize the luminosity. These limitations lead to several challenges in the design of the superconducting magnets, required to generate high magnetic fields in large apertures to enable shielding from radiation caused by muon decay. This work explores the design of combined function magnets, both dipole-quadrupole and dipole-sextupole, which are essential to address the neutrino flux issue in the straight sections by bending the particles during both focusing/defocusing or chromaticity correction stages. The superconducting material selected for these magnets is ReBCO, a High Temperature Superconductor (HTS), with operating temperatures ranging from 4.5K to 20K. Various configurations of combined function magnets are studied and simulated using FEM (Finite Element Method) through Python code interfaced with Ansys software, employing the sector coil approximation.

Preliminary Electromagnetic and Mechanical Analysis of the Block-Coil Dipole Configuration for the Muon Collider Arc Ring

Luca Alfonso1, Andrea Bersani1, Luca Bottura2, Barbara Caiffi1, Stefania Farinon1, Francesco Mariani3,4, Samuele Mariotto3,5, Riccardo Musenich1, Daniel Novelli1,4, Alessandra Pampaloni1,4, and Tiina Salmi6 endorsed by the IMCC

In line with the European Strategy for Particle Physics, the International Muon Collider Collaboration (IMCC) was established to develop an innovative 10 km collider ring with a center-of-mass energy of 10 TeV, advancing the exploration of fundamental particles and their interactions. The short muon lifetime (2.2 µs at rest) poses significant challenges, including the need for rapid beam production, acceleration, and precise collision. These conditions require cutting-edge solutions, particularly for the collider ring arc magnets. ReBCO high-temperature superconductors (HTS) have been identified as the best superconducting technology to achieve the required performances of compact, high-field, large-aperture magnets essential to maximize luminosity and incorporate internal shielding for muon decay products. This paper presents a preliminary 2D electromagnetic and mechanical study of block-coil dipoles with an innovative stacked cable configuration and a new conceptual idea of ends windings. An updated electromagnetic design achieving a bore field of 16 T is introduced, alongside an analytical estimation of hysteretic losses in the superconducting layers, considering the effects of transport current. Additionally, an initial mechanical analysis using the ANSYS finite element method (FEM) is reported incorporating a stress-management strategy through the use of cases around the coils to mitigate the high Lorentz forces.

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Update on the Electromagnetic and Mechanical Design of a cosθ Dipole for the Muon Collider

Francesco Mariani1,2, Luca Alfonso3, Andrea Bersani3, Luca Bottura4, Barbara Caiffi3, Samuele Mariotto1,5, Daniel Novelli2,3, Stefania Farinon3, Alessandra Pampaloni3, Lucio Rossi1,5, Fellow, IEEE, Tiina Salmi6, Stefano Sorti1,5

Within the International Muon Collider Collaboration (IMCC), researchers are conducting a feasibility study to develop a 10 km collider ring designed to achieve a center-of-mass energy of 10 TeV. Since muons have a short lifetime of only 2.2 µs at rest, the accelerator must rapidly increase their energy to enable collisions before decay occurs. To optimize costs and maximize collider luminosity, the superconducting dipoles must be compact, generate high steady-state magnetic fields, and have large apertures to accommodate shielding structures that protect the superconducting coils from muon decay products. These stringent requirements pose significant technological challenges in dipole magnet design from both a physics and engineering perspective.
This contribution presents an update on the 2D cos-theta electromagnetic and mechanical design of the collider's main dipoles. The coil design is based on REBCO tapes, whose magnetization effects influence field quality and losses. To account for these effects in the 2D electromagnetic design, an analytical code has been developed in MATLAB to evaluate overall performances, considering the non-uniform current distribution in REBCO tapes according to the Brandt model. In addition, a comparison between this code and finite element method (FEM) simulations is presented for different coil configurations and magnet performances to highlight the benefits and limitations of each method in terms of precision and efficiency. The study provides a detailed analysis of the magnetization effects on the field quality and margin performances of REBCO-based cos-theta dipoles, offering information for further coil layout optimization. The results contribute to the ongoing

development of HTS high-field magnets for the muon collider impacting on the different design choice of the magnet cross-section and superconducting coil expected performances.

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Design Optimization of the S5 Cooling Cell Demonstrator Solenoids for the Muon Collider

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The muon collider is a promising candidate for future multi-TeV lepton colliders, with the possibility for high luminosity and reaching center-of-mass energies of 10 TeV or more. Achieving this luminosity requires a high-brightness muon beam obtained through ionization cooling in the 6D cooling sections. Consequently, cooling performance is critical for collider efficiency.
To demonstrate that the technology can be developed, built and reliably operated in conditions relevant for a muon collider, the International Muon Collider Collaboration (IMCC) has recently started a Muon Cooling Demonstrator programme.
The cooling cells are complex mechanical assemblies consisting of high field, large radius superconducting solenoids, absorbers and high gradient RF cavities, all tightly integrated. Among the different types of cooling cells, the S5-type has been selected as the candidate demonstrator cell. The solenoids are based on high temperature superconductors (HTS) in a non-insulated layout, operated at 20 K. These magnets pose multiple challenges: they need to deliver a precise magnetic field profile with an on-axis field swing of ± 7.3 T, with compact integration, subjected to strong axial forces, and high coil stresses. Under these requirements, a design optimization strategy is therefore needed.
In this work, we present a custom design optimization tool to identify the best magnet configuration under specific operational constraints. The results of single-objective optimization have been compared with the Pareto optimal solutions from a multi-objective approach. Among the competing optimization targets, we considered the minimum axial forces, conductor volume, adequate margins and coil thermal stability. A transient 1D thermal model is employed to evaluate the coil thermal stability and is integrated into the optimization routine. Finally, the resulting optimal configuration has been evaluated with commercial FEM software, completing the analysis with a mechanical evaluation. The proposed design of the demonstrator magnets will be included in the next cell integration studies.

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Mechanical design of a ReBCO non/metal-insulated 40 T solenoid for the Muon Collider

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In the framework of the design studies of a Muon Collider, the development of Ultra-High-Field (UHF) magnets is a key challenge, crucial for the final cooling stage. CERN has introduced a conceptual design for a 40 T solenoid featuring compact pancake coils, aiming to achieve the required high magnetic field and operating current density (~600 A/mm^2).
Due to the extreme Lorentz forces acting on the winding, the mechanical design of the magnet is a major issue. In particular, the strong anisotropy and low mechanical strength of ReBCO tapes add further complexity. To address these issues, this study focuses on the optimization of the assembly sequence to ensure radial shrink fitting of the coil, partly compensating Lorentz forces.
Specifically, we propose a two-step pre-compression strategy by two coaxial cylindrical shells, optimizing both their materials and the geometry to improve the mechanical performance of the solenoid.

A detailed finite element analysis (FEA) is performed, incorporating nonlinear material properties, plasticity effects, and geometric considerations. Furthermore, the influence of mechanical tolerances on the overall stress distribution is analysed, to optimize the fabrication and assembly process and ensure reproducibility. This study also presents an experimental campaign aimed at assessing the mechanical response of the coil under compression. Dedicated compression tests were performed, and their results were benchmarked against numerical simulations to validate the material constitutive models and the FEA.
By combining numerical simulations with experimental validation, this study provides a detailed analysis of the mechanical behavior of a high-field solenoid under pre-compression.
The findings contribute to improving the mechanical robustness of the magnet and provide useful insights for future developments in the context of UHF magnets for Muon Collider magnets and other applications.

Advancing the Development of a Compact 40 T ReBCO Solenoid for the Muon Collider

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The International Muon Collider Collaboration (IMCC) continues to advance the conceptual design study of a Muon Collider (MC), with a key focus on the development of its magnet systems. Among these, the Ultra-High-Field (UHF) solenoids required for the final cooling stage remain a major technological challenge. CERN has been leading efforts in this area, particularly with the conceptual design of a fully superconducting 40 T solenoid based on ReBCO tapes. This magnet, characterized by a 50 mm free bore, 1% field homogeneity over a 0.5 m length, and a compact design featuring stacked Non/Metal-Insulated (N/M-I) single pancakes, is designed to operate at 4.2 K under significant mechanical radial precompression.
This paper provides an update on the ongoing R&D activities supporting the realization of this ambitious project. We present the first experimental results from the mechanical and electro-mechanical characterization of pancake coils produced at CERN via both hot and cold winding techniques. The mechanical behavior of these coils under different precompression strategies is examined, shedding light on their structural integrity and feasibility for high-field operation. Additionally, we discuss recent electromechanical simulations that investigate the impact of magnetization effects on the mechanical behavior of the 40 T solenoid, with implications for stress management and long-term performance. Further progress in solenoid manufacturing technologies, including advancements in tooling and assembly methods, is also reviewed.

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How experimental micromechanics can help in the design of High Temperature Superconducting magnets

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The need for strong steady magnetic fields, above 40 T, raises several new challenges in the design of superconducting magnets. As a start, the field requested exceeds the limitations of the consolidated LTS technologies, leading us to the use of HTS technology. Besides the difficulty of making HTS magnets, the challenges at ultra-high field are found in the structural mechanics, driven by electromagnetic forces, and quench protection, due to the high stored energy density. ReBCO, the leading candidate for ultra-high field magnets, is produced in the form of thin tapes, consisting of multiple layers of different materials with very diverse nature and properties. Understanding the elastic and plastic behavior of these materials is crucial for both the magnet design process and advancing technological development to meet end-product requirements. However, the small size of HTS makes it impractical to employ macroscopic mechanical tests for characterizing the required mechanical properties at the right scale. In this paper we show how nanomechanical testing can help to address this issue. More specifically, elasticity, plasticity and toughness of REBCO materials are measured at the scale of the tape’s constituents at room temperature and at cryogenic temperature (120 K). The paper concludes by highlighting the main results of our initial test and the forthcoming developments in the field of nanomechanical testing to aid in the design of HTS superconductors.

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A Dynamic Energy-Based Hysteresis Model for Pulsed-Operated Fast-Ramping Magnets

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Due to the strongly nonlinear behavior of ferromagnetic cores, the numerical analysis of fast-ramping magnets is highly cumbersome and, therefore, in practice overly simplified by means of anhysteretic material descriptions and a posteriori loss formulae. This paper establishes a new dynamic ferromagnetic model combining a preconditioned energy-based hysteresis description and an eddy-current model in time-domain. The model was successfully employed in the analysis of a normal-conducting bending magnet and succeeded to precisely calculate the losses and the time-lag between current excitation and air-gap field.