PROCEEDINGS OF SCIENCE

Muon Collider Progress

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This paper presents recent progress and prospects for the Muon Collider as a next-generation collider facility following the High Luminosity LHC program. With capabilities for high-energy muon collisions, the Muon Collider opens the door to a wide range of physics opportunities, particularly in Higgs boson studies and beyond. A overview of the current status of the facility is presented focusing on the recent progress obtained by the International Muon Collider Collaboration. The main challenges, and the future technological developments are discussed.

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1. Introduction

The Muon Collider (MuC) offers a unique potential for high-energy physics by allowing collisions at very high center-of-mass energies with relatively low synchrotron radiation losses. This feature enables precise measurements of Standard Model parameters, allowing for high-precision determination of Higgs boson couplings [1] and opens new possibility in the searches for new physic like for example high-mass Z' bosons [2]. The International Muon Collider Collaboration (IMCC), leveraging on the results provided by the Muon Accelerator Program (MAP), is studying the feasibility of producing high intense muon beams, accelerate and collide them at a center-of-mass of 10 TeV. The revived interest in the MuC is clearly visible on the publications *Dream Machine*[3] and *US particle physicists want to build a muon collider — Europe should pitch in*[4] and it is supported by the experimental results obtained by the MICE collaboration that demonstrate a significant reduction in the transverse emittance of muon beams by ionization cooling [5].

The design of the MuC facility would be much easier if the muon had a longer lifetime. The production, cooling, acceleration, and collision of muon beams must be completed within approximately $2.2 \cdot \gamma$ μs where γ is the Lorentz time dilatation factor, varying across the different stages. Another consequence of muon decay is the production of high-energy electrons and positrons, these particles can impact the performance of machine elements if not adequately protected and compromise the detector's usability if not properly shielded. A Machine-Detector-Interface capable of mitigating the effects of the beam-induced background has been designed [6]. This design includes two cone-shaped tungsten shielding structures. The detector performance with this interaction region (IR) configuration has been evaluated, demonstrating the excellent physics discovery potential of muon collisions [1, 7–10]. This contribution presents the progress of the facility focusing on selected aspects of the machine.

2. Muon Collider Facility

Designs for a MuC facility operating at center-of-mass energies of 1.5 and 3 TeV have been developed by MAP, while more recently, the IMCC has proposed a complex for delivering muon collisions at $\sqrt{s}$ = 10 TeV. Figure 1 illustrates its main components: the muon injector, the accelerator and the collider rings. The basic structure of the facility remains consistent across different center-of-mass energies, though the specific requirements and performance vary. Here, the $\sqrt{s}$ = 10 TeV requirements and recent achievements are briefly summarized [11, 12].

2.1 Muon Injector

Muon production begins with high-intensity (a few MW) 5 GeV proton beams striking a target to produce pions, which then decay into muons. An accumulator and a compressor ring are proposed to create extremely high-intensity bunches with lengths of just a few nanoseconds.

The target is immersed in about 20 T solenoidal field to produce intense pion bunches. The high beam power and the short proton pulse length create challenging conditions for the target, necessitating active cooling to counteract the heating from the proton beam. Mechanical issues that could lead to target failure are being investigated for various materials. Operating a high-

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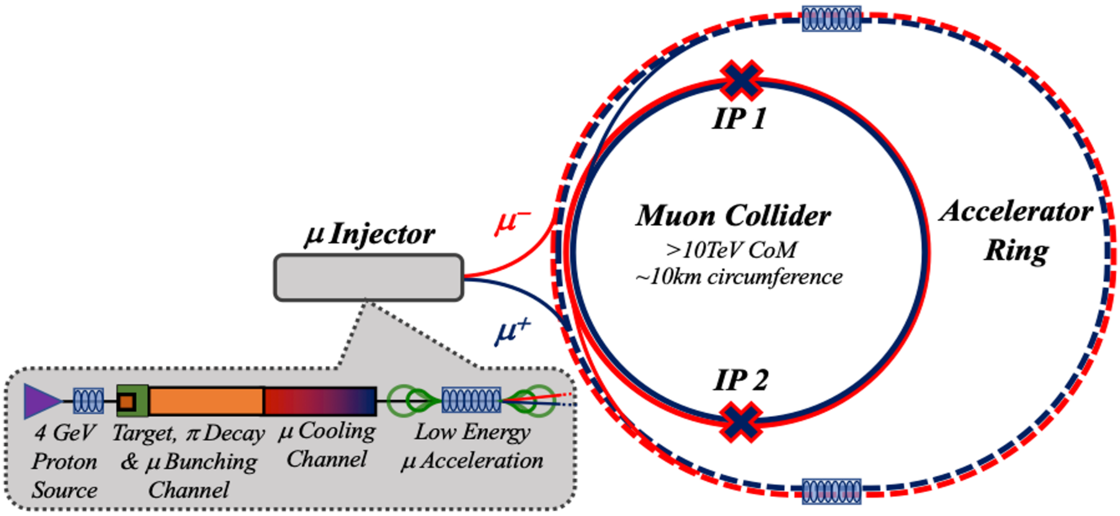

Figure 1: Sketch of the MuC facility. The main elements, the muon injector and the accelerator and collider rings are represented.

field solenoid in the target region, especially in the presence of intense radiation, has not yet been achieved in practice. This is one of the areas where a dedicated R&D is planned.

After the target, a combination of chicane lines and absorbers is used to capture the beam and remove impurities. A charge selection system then splits the beam into separate positive and negative muon lines in preparation for the cooling process.

2.2 Muon cooling and first stage of acceleration

Beam cooling techniques used for stable or semi-stable particles are ineffective for muon beams due to their short lifetime. Additionally, a significant phase space reduction is required, given the muon production process, to achieve high luminosity in the collider. The ionization cooling, a relatively novel technique, is proposed in the MuC facility. The basic element is the cooling cell. The conceptual design, shown in Figure 2, is constituted by RF structure, dark red rectangles, surrounded by superconducting solenoid, yellow rectangles, and an absorber material, red triangles. The muons beams pass through a material with low atomic number to minimize the multiple scattering, and lose momentum in the direction transverse to the their motion. They are then re-accelerated in RF cavities. Longitudinal cooling can be achieved by exploiting correlations between energy and energy loss under the assumption that the RF-cavities restore the energy lost in the material. The concept of ionization cooling has been demonstrated by the MICE experiment [5], though substantial R&D is still required to confirm the expected performance. In fact, the MuC cooling system will need multiple types of cooling cells to accommodate the evolving beam characteristics after each cooling step. A systematic design of the cells is being pursued by IMCC [13] together with the proposal of testing facilities.

The muon beams exiting the cooling system have low energy, making rapid acceleration essential to maintain high intensity. The system proposed by IMCC consists of a linear pre-accelerator followed by two *Dogbone* recirculating linacs as shown in Figure 3. The latest IMCC

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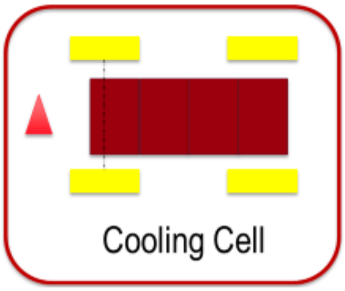

Figure 2: Sketch of the basic structure of the cooling cell.

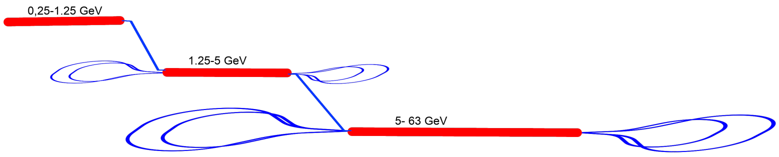

Figure 3: Possible schema of the rapid acceleration complex.

developments propose that acceleration begins after final cooling at 255 MeV and continues up to 63 GeV, at which point the beam is injected into a first rapid cycling synchrotron. The start-to-end design and the simulation of this complex is one of the key areas currently being designed inside the collaboration.

3. Accelerator and Collider rings

3.1 High energy acceleration

Beam energies of the order of several TeV can be reached using a chain of rapid cycling synchrotrons (RCS) with a repetition rate of 5 Hz. As shown in Figure 4, this configuration, initially proposed by MAP, includes a normal conducting RCS, (RCS1), that increases the energy to 0.3 TeV followed by a hybrid RCS, (RCS2), that pushes the energy to 0.75 TeV. The hybrid RCS design currently features strong fixed-field superconducting magnets interleaved with normal conducting magnets. These two stages can be housed in the same ring. To reach beam energies of 5 TeV, two additional RCS stages, RCS3 and RCS4, are planned with RCS3 reaching up to 1.5 TeV. Recent progress includes the initial design of RCS2 and the determination of the required number of RF cavities in each RCS to maintain longitudinal emittance within the necessary tolerance.

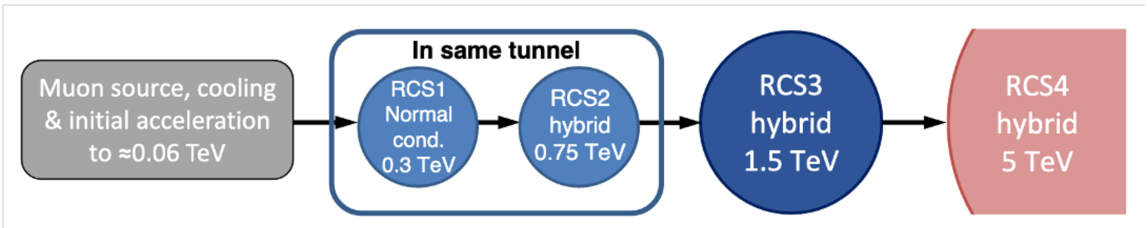

Figure 4: Schema of the high energy acceleration.

3.2 Collider

The collider ring should be kept as short as possible to maximize the luminosity. A collider with a center-of-mass energy of 3 TeV requires 10 T dipole magnets, while for $\sqrt{s}$ = 10 TeV, 16 T dipole magnets are necessary. This will require vigorous R&D efforts, as the maximum

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magnetic field achieved for this type of magnet so far is around 14 T. The IR at $\sqrt{s}$ = 10 TeV is very challenging. The requirement of a small beta-function results in a significant chromaticity that needs to be compensated [14], while short bunches are needed to avoid degradation of the beta-function. IMCC is dedicating significant efforts to designing this high energy collider ring, though even an ideal machine is still not available. For the European Strategy of Particle Physics Update (ESPPU) an IR configuration was finalized to generate beam-induced background for detector performance studies [6] although this configuration is far from optimal. The straight section housing the detector is kept minimal to reduce neutrino flux and minimize the dose levels where these neutrinos reach Earth's surface. However, to maintain these doses at negligible levels, additional strategies are being proposed by IMCC [12].

4. Steps toward a muon collider

The IMCC is working toward having a muon collider facility ready to take data by the end of the High Luminosity LHC (HL-LHC) era. This goal can be achieved if sufficient resources are allocated to the R&D program, which includes among others, the development of high-field magnets, RF systems, target materials and structures, as well as shielding solutions for both the detector and machine elements. Beside the R&D activities, the IMCC aims to the construction of a medium-size facility, usually referred as "demonstrator". The primary goal of this facility is to demonstrate that the emittance of a muon beam can be reduced to the required levels using a series of ionization cooling cells, as described in section 2.2. Additionally, the demonstrator will serve as a platform to test prototypes developed by the R&D activities, including the already mentioned high-field magnets, RF cavities in magnetic fields, materials for absorbers and targets, and muon beam instrumentation. Depending on the resources dedicated to the project, the re-acceleration of cooled muon beams could make physics measurements possible. For instance, the nuSTORM [15] community proposes to measure ν_μ and ν_e cross sections on material relevant for long-baseline experiments and to search for exotic processes. These neutrino beams could be generated from the decays of muons of the demonstrator beams.

5. Conclusions

The MuC presents a compelling physics and technology case, supported by a committed international community. Significant progress in simulation studies on key components of the facility in recent years has strengthened confidence in the MuC as a viable option for the next collider facility after the HL-LHC. Future efforts will focus on optimizing the design of critical components to meet the luminosity goals essential for groundbreaking physics discoveries. If adequate resources are made available, an intensive R&D program will be pursued, including the design and construction of the "demonstrator" facility.

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