PROCEEDINGS OF SCIENCE

Status of the International Muon Collider Complex Study at 10 TeV

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A circular muon collider, due to strong suppression of synchrotron radiation (muons are about 207 times heavier than electrons), can provide high energy (multi-TeV) collisions using fundamental (point-like) particles improving that way the energy frontiers of lepton-antilepton machines. A unique feature of muon colliders, is the significant increase of the luminosity per beam power with beam energy. Muon colliders have been studied in the past by several initiatives. Recently, a new International Muon Collider Collaboration (IMCC) was formed and and is working mainly on the development of a 10 TeV center of mass energy muon collider complex. Such a machine is expected to require less power than the CLIC at 3 TeV and to provide a physics reach similar to the 100 TeV proton version of FCC with a more compact collider ring. A muon accelerator complex is expected to be a cost effective facility provided numerous technical challenges can be overcome. These challenges are mainly driven by the short lifetime of muons and among the crucial ones are the need for rapid cooling and acceleration of the beams with power and cost efficient solutions, the use of high field magnets, the minimisation of the beam induced background and to keep the maximum radiation doses for people due to neutrinos recaching the Earth surface at negligible levels. The different stages of the muon acceleration chain and some of the main studies on the 10 TeV version will be present.

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1. Introduction

Particle accelerators capable to perform high-precision measurements offer the possibility to understand the behaviour of known particles and the potential discovery of subtle indications of previously unknown physics. Complementary to this, the high-energy colliders have the capacity to discover unknown particles. Typically, these two approaches are associated with separate machines: one dedicated to precise measurements, often involving electron-positron (e^-e^+) collisions, and the other geared towards high-energy investigations, typically employing proton-proton (pp) collisions. Nevertheless, a Muon Collider (MC) offers a unique opportunity to combine the advantages of both precision measurements and high-energy studies in a single machine representing a significant advancement in productive exploration of fundamental interactions. The main source of the following document is the detailed description of the muon collider project presented in [1].

Addressing the challenges of generating high-luminosity muon collisions at a center-of-mass energy of 10 TeV is the focus of the recently formed International Muon Collider Collaboration (IMCC) [2]. This collaboration builds upon the knowledge gained from earlier studies, most notably the Muon Accelerator Program (MAP) [3], which established the groundwork for the muon accelerator complex.

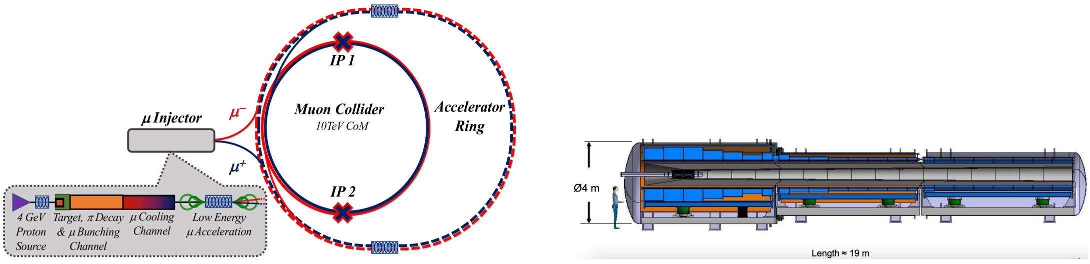
2. 10 TeV muon accelerator complex

A schematic overview of the IMCC accelerator complex is shown in Fig. 1a. The first step is a high power (a few MW) proton drive beam, consisting of one or several very short high-intensity proton bunches arriving simultaneously onto a target for the production of pions. These pions are guided through a decay channel where the resulting muons are collected by a bunching and phase rotator system to form a series of muon bunches. Several 6D and transverse ionisation cooling stages follows for the reduction of the longitudinal and transverse emittance of the beam using a sequence of absorbers and radiofrequency (RF) cavities that are placed in high solenoidal fields. Interleaved with the cooling stages the bunches are merged forming a high intensity single μ^+ and single μ^- bunches. Once the required emittances are reached, the two bunches are accelerated to collision energy (5 TeV) through a system of Re-Circulating Linacs (RCL) and Rapid Cycling Sychrotron (RCS). As a last step, the bunches are injected into the collider ring for luminosity production. There are wide margins for the optimisation of the exact energy stages of the acceleration system, taking also into account the possible exploitation of the intermediate-energies muon colliders like the 3 TeV centre of mass energy initially studies by MAP. An overview of the progress for the different sections of the 10 TeV option will be discussed in the following sections.

2.1 Proton driver and muon capture

The required proton drive beam powers of typically 2 MW and energies between 5 and 15 GeV are in line with ones of existing and planned facilities for the generation of neutrons and/or neutrinos. Specific requirements for the muon collider are a low repetition rate of 5 Hz and the need for short bunches with rms lengths of 1 to 3 ns.

The process begins with the creation of H^- ions in an ion source, followed by their acceleration through a radiofrequency quadrupole and a series of drift-tube linacs. Further acceleration occurs



(a) **(b)**

Figure 1: Conceptual scheme (a) of the muon collider complex and (b) of the target area utilizing HTS magnets.

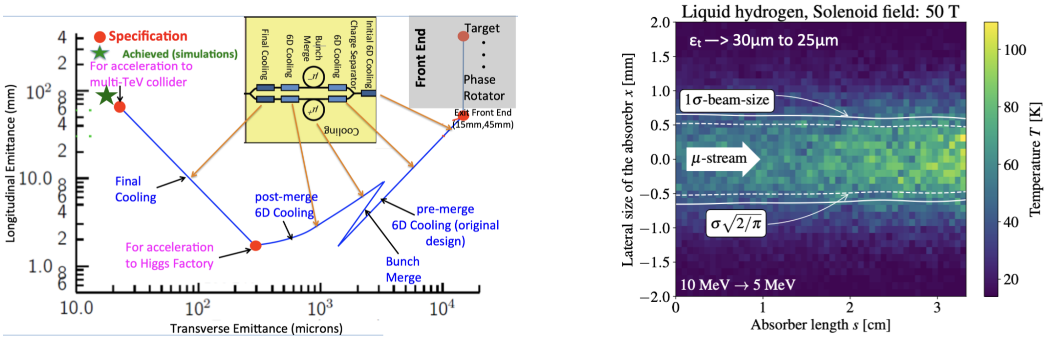
within a linear accelerator using standard RF cavities, before the ions are injected into a ring using charge-exchange injection and phase space painting. The technology selection for the MC proton driver hinges on effectively addressing key considerations like the careful management of heat deposition within the injection foil (located in the accumulator ring), managing limitations on beam intensity due to space charge effects, and ensuring the successful compression of the proton bunch.

Once the proton bunches are formed and accelerated, they are driven into collision with a target located in a solenoidal magnetic field 15-20 T. Within this magnetic field, muons, pions, kaons, and other secondary particles are generated. The pions and kaons decay into muons that are captured by the solenoid field across a wide range of momenta. The layout of a recent study on the target area utilizing HTS magnets is shown in Fig. 1b. The magnetic field is smoothly reduced along the beam line, preserving like that the relativistic magnetic moment. The beam leaving the target area has a large longitudinal and transverse emittance while the undesirable particles accompanying the muons will be removed in the beam cleaning system (solenoidal chicane) further down strim. After leaving the target area, the muon are arranged into a series of 21 bunches with equal energy suitable for ionization cooling.

2.2 Muon cooling

In this section, the train of 21 $\mu^+\mu^-$ bunches are cooled end merged into single $\mu^+\mu^-$ bunches. To achieve the desired level of luminosity, it becomes imperative to shrink the phase space volume of the muon beam. Conventional cooling methods often operate on timescales that are not compatible with the muon's natural lifespan therefore a relatively innovative approach, ionization cooling [4, 5], is proposed for reducing the phase space volume of the muon beam.

In muon ionization cooling, muons are directed through a material (absorber) and RF cavities located in solenoidal fields. Like that their transverse and longitudinal momentum are reduced due to elastic scattering. Re-acceleration of the muons restores only the longitudinal momentum resulting in transverse cooling. Longitudinal cooling [6] is obtained by generating dispersion and wedge shaped absorbers at the expense of transverse cooling. In order to minimize the beam blow-up due to Coulomb scattering the absorber material has a low atomic number and the solenoidal fields used is 10s of Tesla strong. The expected emittance evolution along the different steps of the beam cooling, 6D cooling before and after the beam merging and the final transverse cooling, is shown in Fig. 2a. The final cooling aims at reducing the transverse emittances to levels suitable for



(a) (b)

Figure 2: In (a) the transverse and longitudinal emittance evolution in the muon cooling channels and in (b) the large temperatures developed at the end of the final cooling channels indicating the need for an alternative material.

a collider in a channel with maximum solenoidal fields and without longitudinal cooling leading to an increase of the longitudinal emittance. Numerous optimization studies are ongoing for all the cooling stages. Latest highlights are, the performance improvement of the final cooling channels, green asterisk in Fig. 2a and the finding that new material (like gaseous hydrogen with adjusted gas pressures) at the final cooling stage is needed due to the development of high temperature Fig. 2b.

2.3 Acceleration

Acceleration to collision energies it planned using a series of linacs as well as recirculating linacs and a series of pulsed synchrotrons (rapid cycling synchrotron) as can be seen in Fig. 3a.

This rapid acceleration is particularly critical during the initial phases when the muon beam has not undergone sufficient time dilation. However, beyond a few GeV, the implementation of such a linac could become cost-prohibitive therefore, to maximize the utilization of the radiofrequency (RF) system, a strategy involving recirculating linacs (RCL) is adopted. As we reach higher energy levels, the implementation of Rapid Cycling Synchrotron (RCS) is foreseen, thanks to the increased number of recirculations through each cavity. For the 10 TeV version four RCS systems are planed to be used. The muon's limited lifetime imposes the need for fast-ramping magnet systems that will be one of the most important cost and power driver parameter. For that reason quasi-linear ramping, Fig. 3b, is studied showing sizeable decrease of the RF peak power and the magnet powering costs. To sustain a substantial average dipole field, the design of the higher energy rings incorporates a combination of pulsed dipoles and superconducting fixed field dipoles. In this arrangement, it is essential to take precautions to ensure that the beam's excursion within the fixed dipoles remains within the prescribed aperture, and that deviations in the path length do not reach a magnitude that would cause the beam to lose synchronization with the RF cavities.

2.4 Collider ring

For the collider ring a series of special designs should be developed in order to reach the performance requirements. To achieve the highest possible luminosity, the circumference must be as small as possible (10 km) therefore, high field dipoles are considered (14-16 T). Additionally, very

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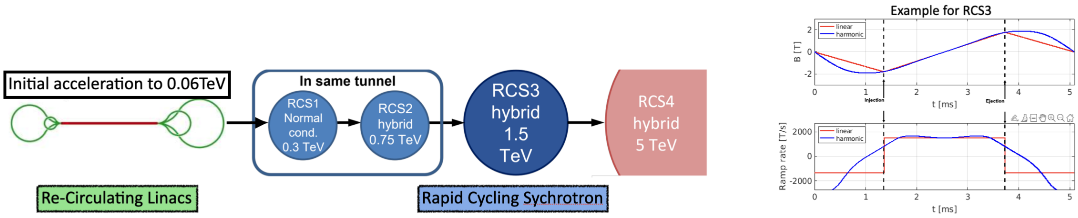

(a) **(b)**

Figure 3: (a) acceleration to collision energies and (b) the quasi-linear magnets ramping.

small beta-functions (1.5 mm) at the collision point are a necessity leading however to substantial linear and non-linear chromatic aberrations that have to be effectively addressed by special lattice designs right after the final focusing quads Fig. 4a. Also, a short bunch length is required to minimize the "hourglass effect" but leading to a large momentum spread enhancing chromatic effects. The momentum compaction, that is controlled in the arcs, must be kept to values very close to zero.

Based on the beam stability studies Fiq. 4b, the required beam radius can be significantly reduced with the used of Cu making it comparable with the aperture defined by the current optics version. An important issue that should be addressed is the radiation generated by muon decays. The decay products generate unwanted beam induced background that can potentially be mitigated by special optics design of the final focusing section Fig 4c and the use of nozzles aiming at intercepting as much as possible the resulting showers. Neutrinos from muon decays are generated within a narrow cone in direction tangential to the collider ring. To ensure that radiation levels caused by neutrinos reaching Earth's surface (or rather showers from neutrinos interacting shortly before) remain negligible, mitigation measures as the use of combined function magnets (to limit the duration with the neutrino radiation cones pointing in the same direction) and vertical periodic deformations of the machine sketched in Fig. 4d are planned.

3. Conclusion

Muon colliders offer an exceptional pathway to achieve high-energy collisions, facilitating groundbreaking discovery searches and precision measurements that advance our comprehension of fundamental physics principles while remaining reasonable of costs and power consumption. This perspective has triggered the formation of an international collaboration the IMCC, uniting efforts to refine design concepts and conduct performance evaluations for such a facility. The central objective of this endeavour is to assess the feasibility of a 10 TeV com muon collider, obtain a consistent design of the complex from the drive beam generation up the to collider and detectors and define further developments necessary.

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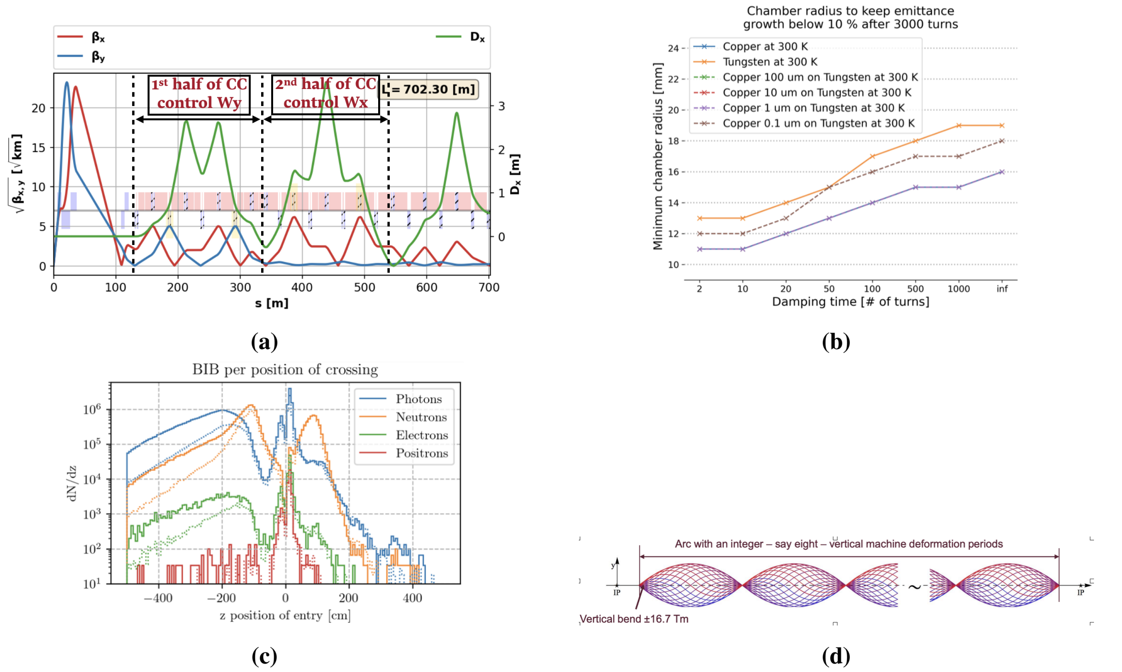

Figure 4: (a) the final focusing quads followed by the chromatic correction section and the matching section, (b) the beam radius requirement for beam stability based on impedance studies, (c) the beam induced background for different final focusing versions (solid and dashed line) and (d) the planned vertical wobbling of the arc lattice.

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