III.4.8 Muon collider

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Recently the muon collider has been recognised as an important option to be considered for the future of particle physics. It is part of the European Accelerator R&D Roadmap developed in 2021 and its study was approved by the CERN Council. Also interest is rising in the Americas and in Asia, for example demonstrated by the Snowmass process in the USA. This section will give an introduction into the muon collider concept and the identified challenges. It will also describe the R&D progress and plans.

III.4.8.1 Introduction

Circular muon colliders have the potential to reach centre-of-mass energies in the multi-TeV range with high luminosity [1, 2]. The concept has been developed in the past by the MAP collaboration mainly in the US [3]. Experimental verifications have also been carried out in the UK by the MICE collaboration [4] and an alternative muon production scheme (LEMMA) has been studied mainly by INFN [5].

The last Update of the European Strategy for Particle Physics [6] recommended to explore a muon collider. CERN Council charged the European Large National Laboratories Directors Group (LDG) [7] to develop an Accelerator R&D Roadmap with a work progamme and to follow its implementation. The LDG initated the International Muon Collider Collaboration (IMCC), hosted by CERN. An increasing number of partner institutes are contributing to the IMCC and the European Union is co-funding a Design Study. The US community expressed strong interest both to participate to the muon collider R&D but also to potentially host such a project. Several white papers where submitted [8–11] to the Snowmass strategy process. The subsequent Particle Physics Project Prioritization Panel (P5) recommended to explore a muon collider as the potential next flagship project in the US and to join the IMCC. Currently (2024), the US community is organising itself to secure resources together with the funding agencies. The current resources are not yet sufficient to fully implement the Roadmap programme, but the increasing support is promising.

The IMCC studies a 10 TeV option, and also explore lower and higher energy options, e.g. a 3 TeV option as a potential step toward 10 TeV. An excellent overview of the muon collider physics case, the detector and the machine can be found in [1].

III.4.8.2 Why Muons?

High-energy lepton colliders combine cutting-edge discovery potential with precision measurements [8, 13]. Because leptons are point-like particles in contrast to protons, they can achieve comparable physics at lower centre-of-mass energies. The relative physics reach depends on the channels considered but a 10 TeV lepton collider would be roughly comparable to a 100 TeV proton-proton collider.

Based on physics considerations, initial integrated luminosity targets have been defined for lepton colliders, namely 1, 10 and 20 ab^{-1} at 3, 10 and 14 TeV, respectively. The increase with the square of the collision energy compensates the decrease of the s-channel cross sections with energy for a constant rate of relevant physics events.

Electron-positron colliders face important limitations at high collision energies. Circular colliders suffer from the strong emission of synchrotron radiation that increases with the fourth power of the particle energy. Linear colliders avoid this limitation but they require that the beam be accelerated to full energy in a single passage of the linacs and they can collide the bunches only once.

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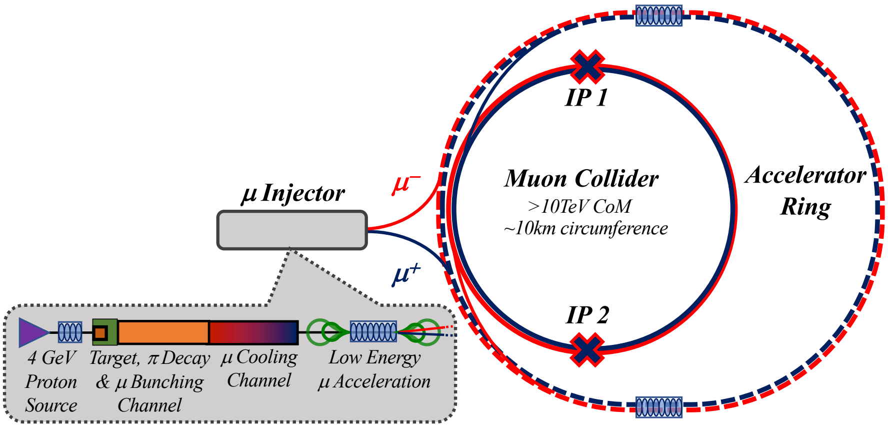

Fig. III.4.1: A conceptual scheme of the muon collider, courtesy M. Palmer.

Muons are leptons, like electrons and positrons, but with mass about 200 times larger. The synchrotron radiation scales inversely with the fourth power of the particle mass. Muons beam of many TeV can therefore be accelerated and collided in rings.

Muons however have one important drawback. Their lifetime is finite and rather short, $\tau = 2.2\,\mu\mathrm{s}$ at rest. Fortunately, the lifetime increases with beam energy, in proportion to the relativistic factor γ. At 5 TeV the lifetime reaches $\tau\gamma \approx 104\ \mathrm{ms}$. The muon collider thus has to produce the muons and then rapidly accelerate and collide them. If it were not for the short lifetime a muon collider would have been realised long time ago.

III.4.8.3 The concept in a nutshell

MAP developed the concept shown in Fig. III.4.1. The proton complex produces a short, high-intensity proton pulse that hits the target and produces pions. The charged pions will rapidly almost exclusively decay into muons. The decay channel guides the pions and collects the produced muons into a bunching and phase-rotator system to form a muon beam. Several cooling stages then reduce the longitudinal and transverse emittance of the beam using a sequence of absorbers and RF cavities in a high magnetic field. A system of a linac and two recirculating linacs accelerate the beams to 60 GeV followed by two or three high-energy accelerator rings to reach 1.5 TeV. In the 10 TeV collider an additional ring from 1.5 to 5 TeV follows. These rings can be either fast-pulsed synchrotrons or FFA (Fixed Field Alternating gradient) accelerators. Finally the beams are injected at full energy into the collider ring. Here, they will circulate to produce luminosity until they are decayed; alternatively they can be extracted once the beam current is strongly reduced. The exact energy stages of the acceleration system have to be developed.

Figure III.4.2 compares the luminosity of CLIC and a muon collider [12], based on MAP parameters [3], as a function of centre-of-mass energy. The luminosities are normalised to the beam power and show the unique feature of the muon collider that its luminosity production efficiency can inrease with energy. The figure also compares the footprint of several colliders to a 10 TeV muon collider. The relative compactness of the muon collider compared to other approaches is expected to also lead to a reduced cost. The very similar size of the largest muon ring and the LHC makes it interesting to explore if the LHC tunnel can be reused.

III.4.8.4 Goal of the study

The goal of the study is to assess and develop the concept to a level that allows informed decisions to be taken after the next update of the European Strategy for Particle Physics and similar processes in other regions about the role of the muon collider in the future of particle physics. Based on the study outcome

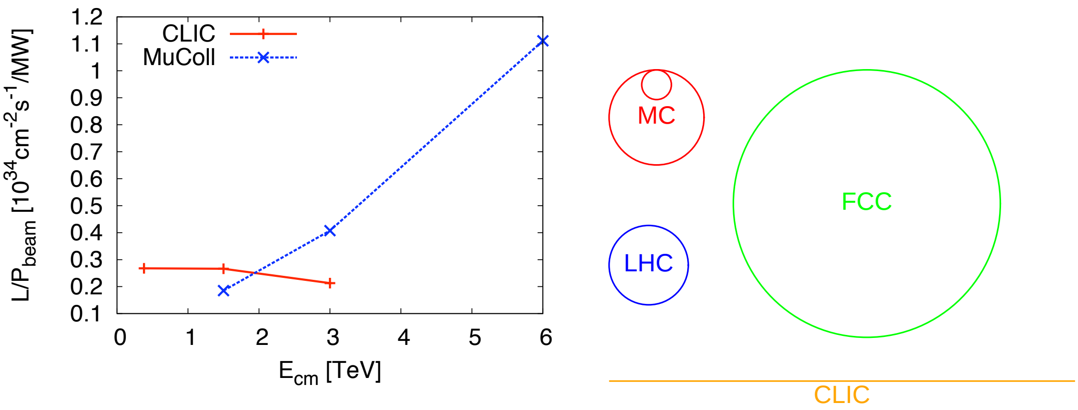

Fig. III.4.2: Left: Comparison of CLIC and a muon collider (MuColl) luminosities normalised to the beam power and as a function of the centre-of-mass energy. Right: The scaled dimensions of the collider and final accelerator ring of a 10 TeV muon collider (MC) compared to other colliders.

Table III.4.1: Tentative target parameters for a muon collider at different energies based on the MAP design. These values are only to give a first, rough indication. The study is developing coherent parameter sets of its own.

Parameter	Symbol	unit			
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	10^{34} cm^{-2}s^{-1}	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5
Transverse emittance	ϵ	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP betafunction	β	mm	5	1.5	1.07
IP beam size	σ	µm	3	0.9	0.63

and strategic decisions, a conceptual design and demonstration programme could then be launched.

Currently, the limit of the energy reach has not been identified. The study focuses on a 10 TeV design with an integrated luminosity goal of $10\ \mathrm{ab}^{-1}$. This goal is expected to provide a good balance between an excellent physics case and affordable cost, power consumption and risk. Once a robust design has been established at 10 TeV other, higher energies will be explored.

A potential initial energy stage of 3 TeV with an integrated luminosity of $1\ \mathrm{ab}^{-1}$ is also considered and would address an important physics case [10]. This initial stage might cost around half as much as the 10 TeV option, and can be upgraded to 10 TeV or beyond by adding an accelerator ring and building a new collider ring (maybe the accelerator ring of 3 TeV could be used for this). Only the 4.5 km-long 3 TeV collider ring would not be reused in this case. This stage could potentially start colliding beams before 2050—depending on the strategic decisions and requiring an important increase in resources.

Based on the MAP design corresponding tentative target parameter sets have been defined for the collider, see Table III.4.1. They would achieve the integrated luminosities within five years. Practical consideration make it likely that each energy stage should operate longer, which provides some margin to reach the goals. The parameters are the basis to identify the key issues and assess how the different subsystems can achieve them; they will be updated based on the study results.

III.4.8.5 Status and key challenges

The collaboration and the muon beam panel assessed the muon collider challenges and concluded that the concept is less mature than linear colliders and that important challenges have to be addressed. However, no insurmountable obstacles have been identified.

Past work has demonstrated several key MuC technologies and concepts, and gives confidence that the concept is viable. Component designs have been developed that can cool the initially diffuse beam and accelerate it to multi-TeV energy on a time scale compatible with the muon lifetime. However, a fully integrated design has yet to be developed and further development and demonstration of technology is required. In order to enable the next European Strategy for Particle Physics Update (ESPPU), the next Particle Physics Project Prioritisation Process (P5) and other strategy processes to judge the scientific justification of a full Conceptual Design Report (CDR) and demonstration programme, the design and potential performance of the facility must be developed in the next few years.

The Roadmap identifies a set of key studies that have to be addressed in the coming years. A workplan with resource estimates is defined, including the critical areas:

- The **physics potential** has to be further explored; 10 TeV is uncharted territory. This is beyond the scope of this paper.
- The **environmental impact** must be minimised and at least one **potential site** for the collider identified.
- The impact of **beam-induced background** in the detector might limit the physics reach and has to be minimised.
- The muon **acceleration and collision** systems become more demanding at higher energies and are the most important cost and power consumption drivers. The concept and technologies have to be deloped beyond what MAP has considered.
- The muon **production and cooling** system are challenging novel systems and call for development and optimisation beyond the MAP designs.

The work on all issues has started following the priorities and resource availability.

III.4.8.6 Conclusion

The muon collider promises a sustainable path towards very high energy. Potential intermediate stages may provide important physics results early, on timescales more adapted to a human career, and provide the important motivation for scientists and engineers that is the driver of the technological progress. Muon collider technology must overcome several significant challenges to reach a level of maturity similar to linear colliders. An increased level of R&D effort is justified at the current time, because the muon collider promises an alternative path toward high-energy, high-luminosity lepton collisions that extends beyond the expected reach of linear colliders. Supporting technologies such as high-power proton drivers, high-field solenoids and high-gradient RF cavities have, in the last decade, approached the level required to deliver the requisite luminosity. The partners of the growing IMCC are actively addressing these challenges, with the support of the European Union and in particular also growing contributions from the US following the P5 recommendation.

Aknowledgement

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