PROCEEDINGS OF SCIENCE

The muon collider progress

Daniel Schulte[a,*]

[a] *CERN,*
Geneva, Switzerland

E-mail: daniel.schulte@cern.ch

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 approved by Council. Also interest is rising in the Amerikas and in Asia, for example demonstrated by the ongoing Snowmass process. The paper will give an introduction into the muon collider concept and the identified challenges. It will also describe the R&D progress and plans.

41rst International Conference on High Energy physics - ICHEP2022
July 6 - July 13, 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)060

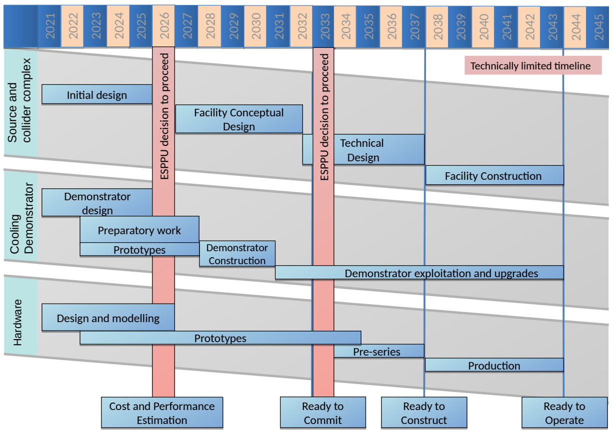

Figure 1: Tentative, technically limited schedule for the muon collider.

1. Introduction

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

Following the recommendation of the last Update of the European Strategy for Particle Physics[5] an international collaboration has been initiated by the European Large National Laboratories Directors Group (LDG)[7], hosted by CERN.

Following a request by CERN Council, guided by the LDG, and with the help of the global community, the collaboration assessed the muon collider challenges and devised a Roadmap toward a muon collider. This includes a detailed workprogramme for the next five years and estimates of the required reources. The collaboration also submitted white papers[8–11] to the ongoing strategy process in the US and a proposal for an EU cofunded Design Study.

Following the presentation of the Roadmap, CERN Council asked for an implementation plan. The muon collider collaboration envisages to study a 10 TeV option, and also explore lower and higher energy options, e.g. a 3 TeV option as a step toward 10 TeV. Based on physics considerations, initial integrated luminosity targets have been defined, namely 1, 10 and 20 ab^{-1} for 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. The potential of muon colliders to improve the luminosities to beam power ratio at high energies is one of main benefits of the concept.

2. 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 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 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.

An option with an initial energy stage of 3 TeV and an integrated luminosity of 1 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 in the mid 2040s - depending on the strategic decisions. This also requires that sufficient funding is available already during the design phase and that all challenges can be successfully addressed with no delays.

A technically limited schedule for such a fast implementation is shown in figure 1. It is very ambitious and requires a noticible effort to start now and an important ramp-up of resources in a few years. But at this moment, no insurmountable obstacle has been identified that would prevent realising it and potentially starting commissioning before 2045.

3. 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.

4. Work Programme

The goal of the workprogramme is to deliver three reports:

- a **Project Evaluation Report** that assesses the muon collider potential as input to the next ESPPU and other strategy processes;
- an **R&D Plan** that describes a path towards the collider;
- an **Interim Report** by the end of 2023 that documents progress and allows the wider community to update their view of the concept and to give feedback to the collaboration.

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The Roadmap identifies a set of key studies that have to be addressed in the coming years, namely:

- 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.

A comprehensive set of workpackages has been developed to address these challenges sufficiently to allow informed decisions for the next round of strategy processes. The workpackages include the development of the essential accelerator concepts based on realistic functional component specifications and beam studies to support that the performance targets can be reached. Other workpackages address the key technologies, in particular the high-field solenoides and the collider ring magnets, the fast-ramping magnet system of the accelerator, the RF systems across the complex and the target systems. In addition, the design of a muon cooling module is included as well as the concept of a demonstrator facility that includes muon production and cooling.

The design effort should be supported by a limited experimental programme:

- component tests for the unique fast-ramping magnet system and its powering, to demonstrate sufficient muon energy reach with appropriate cost and power efficiency;
- construction of models for the superconducting solenoids of the muon cooling complex;
- construction of a test stand to measure the performance of the normal conducting muon cooling cavities in high field;
- test of components for the mechanical neutrino flux mitigation system and its alignment;
- tests of materials for the target of the muon production complex.

Currently the collaboration seeks to identify the resources to implement the workprogramme, starting from the highest priority items.

To kickstart this process a EU Design Study has been proposed and will address a part of the programme for the muon collider. It will provide resources from the EU, the UK and Switzerland that allow the partner institutes to leverage additional resources. The workpackages cover the physics requirements, the proton complex, the muon production and cooling, the high-energy complex, the RF systems, the magnet systems and the design of a muon cooling module.

5. Demonstration Programme

After the initial study phase a conceptual design phase and technology development programme will follow. A facility to produce and cool a muon beam will be the core and will allow the integrated performance of the systems to be tested. Different sites for the facility will be explored. A particular advantage of a site is obviously the existance of a proton complex that can produce the beam for the target.

Sites of interest are for example FNAL and ESS. One potential site exists on land that is already owned by CERN but is located outside of the currently fenced site. The beam from the PS could feed the target and would produce a muon bunch charge only a factor of a few below that of the real facility. The muon beam would then be cleaned and could be reduced in emittance by collimation to be passed through a number of cooling cells that are similar to the most challenging final 6D cooling cells. It appears possible to combine this facility with other facilities such as for example NuStorm since the infrastructure up to and including the target are similar. This part represents about half the cost of NuStorm.

The early development of muon cooling cell modules is key to ensure that this most complex and novel system can be tested before small-scale production is launched for the test facility. The above mentioned RF test stand to verify and improve the cavity performance would be an important stepping stone toward this goal.

The demonstration programme also will contain the development of different components such as high-field solenoids, efficient RF power sources and high-field dipoles as well as other magnets.

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 the human life span, 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 muon collider is based on novel concepts and important challenges have to be faced to make it a reality. The Accelerator R&D Roadmap that has been developed in 2021 provides a comprehensive workprogramme for the global community to achieve this goal and serves as an excellent basis for the collaboration. We hope to be able to globally join forces to open a road to exciting physics.

7. Aknowledgement

The author would like to thank MAP and MICE collaborations and the members of the forming muon collider collaboration as well as the Muon Beam Panel and the conveners and participants of the community meetings. Mark Palmer's knowlege of the MAP study has been instrumental and Nadia Pastrone and the Muon Collider Review Group reinitiated the interest in the concept. The authors wishes to acknowledge the support from the European Union's Horizon 2020 Re- search and Innovation programme under Grant Agreement No 101004730.

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