LDG Muon Collider report December 2023

Daniel Schulte and Steinar Stapnes, CERN

January 15, 2024

1 Introduction

The International Muon Collider Collaboration (IMCC) was initiated in 2020 following the recommendations of the European Strategy for Particle Physics (ESPP). The Muon Collider Study (MuC) covers the accelerator complex, detectors and physics for a future muon collider. In 2023 European Commission support was obtained for a Design Study of a muon collider (MuCol). This project started 1.3.2023, with work-packages aligned with the overall Muon Collider Studies. After summarizing the structure of the IMCC and the studies, this document covers the recent project development with a focus on the accelerator, however referring frequently to documents and publications of key studies for the detector performance and physics potential. CERN acts as host for the International Muon Collider Collaboration and coordinator of the MuCol design study.

1.1 Motivation for a muon collider

High-energy lepton colliders combine cutting edge discovery potential with precision measurements. Because leptons are point-like particles in contrast to protons, they can achieve comparable physics at lower centre-of-mass energies [1, 2]. The relative physics reach depends on the channels considered but a 10 to 14 TeV lepton collider would be comparable or complementary in many aspects to a 100 TeV proton-proton collider. Based on physics considerations, initial integrated luminosity targets were defined, namely 1, 10 and 20 ab^{-1} for 3, 10 and 14 TeV, respectively. The current study concentrate on a 3 TeV configuration and a 10 TeV configuration.

In terms of footprint, costs and power consumption a muon collider is potentially very favourable. The schematic layout of the muon collider is shown in figure 1-left. Concerning the luminosity performance for lepton colliders figure 1-right compares the luminosities of CLIC and a muon collider [3] based on the US Muon Accelerator Programme (MAP) parameters [4], as a function of centre-of-mass energy. The luminosities are normalised to the beam power. The increase with the square of the collision energy compensates for the decrease of the s-channel cross sections with energy. The potential of muon colliders to improve the luminosities to beam power ratio at high energies is one of main benefits of the concept.

1.2 Main goals of the Muon Collider Study

The muon collider collaboration, the muon beam panel of the Laboratory Directors Group (LDG) and the Snowmass process in the US assessed the muon collider challenges and concluded that the

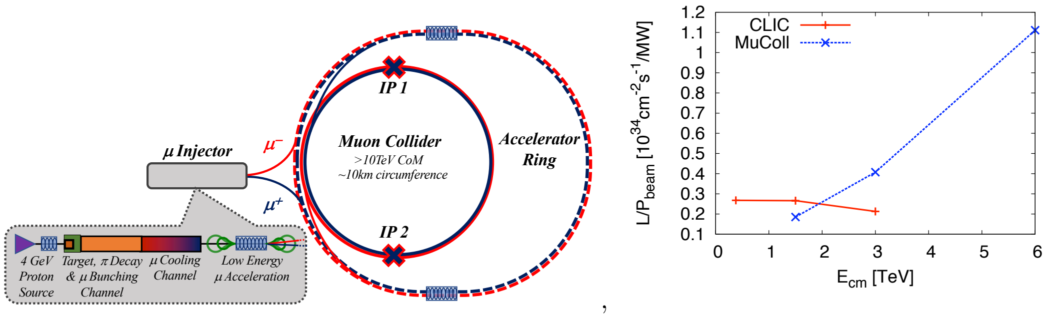

Figure 1: Left: A conceptual scheme of the muon collider, courtesy M. Palmer. Right: Comparison of CLIC and a muon collider luminosities normalised to the beam power and as a function of the centre-of-mass energy.

concept is less mature than linear colliders and that important challenges have to be addressed. However, no insurmountable obstacles were identified. Past work has demonstrated several key MuC technologies and concepts, and gives confidence that the overall concept is viable. Component designs and technologies 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. The LDG roadmap report [5] identifies a set of key studies that have to be addressed in the coming years to prepare the grounds for a Conceptual Design Report (CDR) and demonstrator programme for a muon collider, 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 detector studies are not covered in this paper.
- 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 developed 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 muon collider collaboration aims to perform these studies in time for the next Update of the European Strategy for Particle Physics. Three main deliverables are foreseen:

- a Project Evaluation Report that assesses the muon collider potential;
- an R&D Plan that describes a path towards the collider;
- an Interim Report early 2024 that documents progress and allows the wider community to be updated on the concept and to give feedback to the collaboration.

As mentioned the muon collider collaboration envisages to study the 10 TeV option, and also explore lower and higher energy options, e.g. a 3 TeV option as a step toward 10 TeV. The details of the required work and the required resources are detailed in the LDG roadmap report [5]. While important initial resources have been available, additional resources have recently become available via an EU co-funded design study that started in March 2023. This has also allowed to secure corresponding resources from key partners. However, the current total is not yet sufficient to fully achieve the goals above and additional resources are being sough across the collaboration.

2 Building the Muon Collider Collaboration

A Memorandum of Cooperation (MoC) for the IMCC has been drawn up and the collaboration is rapidly growing. The formal structure of the collaboration consists of the following main bodies:

- International Collaboration Board (ICB): The ICB role is to provide a forum for participants to examine ongoing activities, assure appropriate, well directed use of contributions and ensure a balanced portfolio of engagements. The chair of the ICB is elected by its members (simple majority). The ICB consists of one representative of each participating institute that has signed the MoC. The ICB has been active since October 2022.
- Steering Board (SB): The SB oversees the execution of the Muon Collider Study by assessing the progress, resource usage and providing guidance. The SB reports to the LDG in Europe and to similar regional supervising organisations in other regions as required. The SG is active and operational since Spring 2023.
- International Advisory Committee (IAC): The mandate of the International Advisory Committee is to review the scientific and technical progress of the Study. This body is in the process of being set up.
- Coordination Committee (CC): The CC performs the overall coordination and execution of the Muon Collider Study. It is chaired by the Study Leader. This body consists of experts across the main working areas of the collaboration and is very active. It provides the daily guidance of the study.

The Study Leader is proposed by the host organization, and endorsed by the ICB. The Study Leader was appointed in 2022 and has led the work to build up the collaboration and activities since then.

3 The accelerator studies and key challenges

MAP developed the muon collider concept shown in figure 1 above. The proton complex produces a short, high-intensity proton pulse that hits the target and produces pions. 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 one or more high-energy accelerator rings; e.g. one to 300 GeV and one to 1.5 TeV. In the 10 TeV collider an additional ring from 1.5 to 5 TeV follows. 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 following subsections provide more information on the main technical challenges for the muon collider.

3.1 Environmental Impact

The compact footprint, limited cost and power consumption are intrinsic features that motivate the muon collider study in the first place. Radiation protection measures will ensure a negligible impact of the facility on the environment, similar to the LHC. Particular attention will be paid to the neutrino flux that is produced by the decays of the muons in the collider and that exits the ground far from the collider [6].

3.2 Machine-Detector Interface

Studies to optimise the masking system that mitigates the impact of muon decays close to the interaction point (about 200,000 per bunch crossing and metre at 3 TeV) have started, based on MAP designs at 1.5 TeV and 3 TeV [7]. Considerations on the design of a similar system for higher energies are starting.

3.3 Muon Production

A proton beam power of around 2 MW at 5 Hz is used for muon production. Designs for proton facilities with similar or larger power exist. The main proton complex challenge arises from the combination of the protons into short, high-charge bunches. The key challenge for the high-power target is the survival of the target itself under the shock waves of the incoming beam pulses and the temperature gradients to remove the deposited heat. The target is immersed into a 20 T solenoid field.

3.4 Muon Cooling

Muon ionisation cooling increases the muon beam brightness by repeatedly slowing it in absorbers and re-accelerating it in RF cavities; both inside of strong solenoid fields to keep the beam focused. This principle has been demonstrated in MICE [8]. A factor two improvement of the transverse emittance in the final cooling will allow to reach the emittance goal. The cooling concept is based on close integration of high-gradient normal conducting RF with the high-field solenoids.

A facility to test the cavities in high magnetic fields is mandatory to validate the muon collider performance predictions. Since the previous setups in the US do no longer exist, the design and construction of a new test stand is a key goal.

3.5 Muon Acceleration

Most of the acceleration will be performed by a sequence of pulsed synchrotrons; an alternative use of FFAs is also considered. The synchrotrons can be based on a hybrid design where the fast-ramping magnets are interleaved with static superconducting ones. The pulsed synchrotrons face challenges in terms of optics design, the magnet systems and the RF system. Field ramp rates between 300 T/s in the largest and 10 kT/s in the smallest ring are currently foreseen. The latter requires normal-conducting magnets while for the former also superferric or HTS magnets can also be considered. Finally, the large stored energy in the magnets (in total in the range of O(100MJ)) requires demanding power converters with very efficient recovery of the energy of each pulse for the subsequent one.

3.6 Collider Ring

The collider ring requires a small beta-function at the collision point, resulting in significant chromaticity that needs to be compensated. It also needs to maintain a short bunch. A solution for 3 TeV has been developed by the MAP study and successfully addresses the challenges. A design of 10 TeV is more challenging and one of the key ongoing efforts. High-energy electrons and positrons that arise from muon decay and strike the collider ring magnets can cause radiation damage and unwanted heat load. This can be mitigated with sufficient tungsten shielding.

3.7 The MuCol EU design study

IMCC successfully applied for an EU cofunded design study (named MuCol). The project started 1.3.2023. The total co-funding of MuCol amounts to 3 MEUR, provided by the European Commission, the UK and Switzerland. In the design study, CERN only receives limited contributions for administrative support and travel, but has, in support of the successful Design Study bid, increased its contribution to the muon collider study.

The design study is fully integrated in the overall muon collaboration. The technical meetings and leaders are in common and governance and management will also be synchronised. The organisation is shown in figure 2. Important activities in the collaboration, directly supported by the MuCol work-packages listed below, are:

- **Physics and Detector Requirements** provides the link to the physics and detector studies.Based on feedback from the physics community, it will provide feedback and guidance to the accelerator design.
- **The Proton Complex** addresses the key challenge of the accumulation of the protons in very high-charge bunches, by addressing in details the proton complex design, and provides the basic parameters of the complex and the characteristics of the beam impacting on the production target.
- **The Muon Production and Cooling** addresses the production of the muons by the proton beam hitting a target and the subsequent cooling, including some of the specific technologies, such as for the production target and the absorbers that reduce the beam phase space volume.
- **The High-energy Complex** studyies the acceleration and collision complex of the muons.
- **Radio Frequency Systems** addresses the Radio Frequency (RF) systems of the muon cooling ensuring coherence in frequency choice and synchronization among the various stages. It contributes to sustainability studies by its work on high efficiency RF Power sources.
- **Magnet Systems** will establish a complete inventory of the necessary magnets to optimize and standardise the design, and address the most critical ones. In particular it focuses on the solenoids of the muon production and cooling, which are specific to the muon collider, and the fast-ramping magnet system, which have ambitious requirements on power flow and power efficiency and limits the energy reach of the collider.
- **Cooling Cell Integration** addresses the design of the muon cooling cell, which is a unique and novel design and that faces integration challenges.

4 Demonstration Programme

After the initial study phase described above a conceptual design phase and technology development programme will follow. Demonstrator facilities, world-wide, for various aspects of the muon collider challenges will be considered and evaluated already in the coming years planning such a next phase. The possibilities of using such facilities for physics and/or more general technology developments will be important part of the discussions. One key element is a facility to produce and cool a muon beam that will allow the integrated performance of the systems to be tested. Laboratories with intense proton-beams are natural candidates for hosting such a facility. The overall demonstration

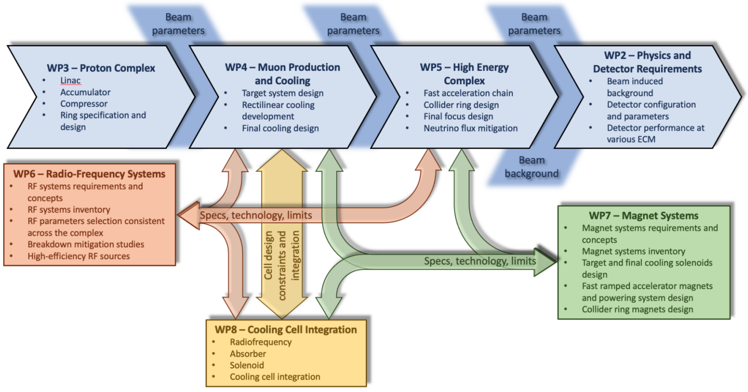

Figure 2: The MuCol workpackages and their interactions.

programme also will contain development of different components such as high-field solenoids, efficient RF power sources and high-field dipoles as well as other magnets. The preparation of the demonstrator programme will become a focus of the IMCC after the completion of the Interim Report and the US P5 process.

5 Recent achievements - 2023

During the 2023 the Muon Collider study has moved forward on several fronts. The mains points are summarizes in the following paragraphs.

The collaboration has grown to more than 60 institutes. The Steering Board has been set up and is operative. A publication and speaker committee (PSC) has been set up and is active.

The US groups are very active and in leading roles, e.g. in the Coordination Committee and the Publications and Speakers Committee, even though in several cases the formal MoC signatures awaits the P5 outcome. A bid has been made by the US groups concerning their muon collider planning, in good communication with the IMCC leadership.

The MuCol project has successfully started up, well aligned with the IMCC overall progress, and the first deliverables have successfully been completed.

A parameter summary have been collected and published (an example of a MuCol milestone), to ensure that technical teams work with a common consistent parameter set.

An interim report, as advertise above, is being prepared with the goal of having a complete draft by the end of 2023. It will be reviewed, improved and published January-March 2024.

The site studies currently focus on ensuring minimal environmental impact. In particular, the goal is to mitigate the neutrino flux to have a negligible impact on the environment, similar to the LHC. Detailed studies have estimated this impact. A mechanical system is being developed that mitigates neutrino flux from the arcs. The current goal is to mitigate the flux in the direction of the prolongation of the experimental insertions by careful choice of site and orientation of the collider ring. A program has been develop by the civil engineering experts that allows to model the underground orientation. A first possible orientation has been identified for an implementation at CERN where the experimental insertions point to the mediterranean on one side and to an uninhabited are in the Jura on the other side. More detailed studies to verify the site are planned and further options will be searched. At a later stage the reuse of existing infrastructure will be studied. In particular, the size of the first and the last accelerator rings are temptingly close to the size of the SPS and the LHC, respectively. Fermilab has earlier made significant studies related to hosting a muon collider at its site.

The magnet programme has been reviewed by a review committee during the IMCC annual meeting in June. The experts concluded that the different HTS solenoids that are required in the muon production and cooling complex can be expected to be mature in about 15 years. The same is true for the fast-ramping and the superconducting accelerator magnets. For the collider ring magnets with a performance that corresponds to the current 3 TeV stage can be ready at the same timescale. They would be based on Nb_3Sn and have dipole field of about 11 T. The timescale required to develop more performant HTS or hybrid magnets is still under discussion and requires further study.

The detector design has been derived from the CLIC detector design and a masking system from the MAP studies has been included. The initial detector studies focused on 1.5 and 3 TeV. The decay of the circulating muon beams generates beam-induced background (BiB) in the detector. The masks and the detector technology mitigates the impact of this on the physics. The masks limit the number of background particles reaching the detector. The tracking devices use timing and directional information to remove hits that are produced by background. The work has started to develop a 10 TeV detector. This is unprecedented for lepton detectors and requires careful consideration of the different design choices. Background studies for this energy have started. It should be noticed that while the energy of the lost beam particles increases the number of particles lost per unit length and bunch crossing is decreasing. Sofar no strong increase in BiB has been identified. The radiation in the detector components is calculated to be similar to the level in HL-LHC.

A technically limited, success-oriented schedule is being developed by the collaboration and will be delivered to the next ESPP update. The current strategy is to establish a timeline where the project design and components are technically mature before 2040, to be able to construct and start physics operation before 2050. Three main technologies have been identified to be critical for this timescale:

- The muon cooling technology. In particular the development and tests of cooling modules that tightly integrate normal-conducting RF systems and superconducting solenoids as well as the other components, such as absorbers, vacuum and instrumentation. And similarly importantly the construction of a demonstrator facility to test these modules with beam.
- The superconducting magnets of the muon production and cooling systems, and also the collider ring.
- The detector technologies.

The studies for the items on the critical path have not concluded at this moment. However, it appears very likely that the cooling technology and the detector can be mature within 15 years to a degree that is sufficient for the target timeline. The magnet technology would be ready for the muon production and cooling, but for the collider ring one might have to accept 11 T dipoles at this timescale.

The planning for the demonstrator is starting. Of particular importance will be to ensure that an infrastructure to test RF cavities in high magnetic field is constructed early. The previous test infrastructure in the US does not exist any longer; but it will be important to test the systems before installation in the demonstrator.

Staging is being considered to address the schedule considerations. Several staging options are being studied:

- Energy staging: The first phase would be at a lower energy, e.g. with 3 TeV. This would require a budget well below the one for the 10 TeV collider. The magnets in the 3 TeV design actually are consistent with the 11 T dipoles and the performance in our target parameters for 3 TeV could be met. At a later stage an additional accelerator ring and a new collider ring will be constructed with the improved technology. Only the 4.5 km-long collider ring of the first stage would not be reused in this scenario.
- Luminosity staging: The collider ring can be constructed with 11 T magnets. This requires the full budget already for the first phase and reaches full energy. The luminosity would be reduced by a factor of a few due to the larger collider circumference and the lower performance of the quadrupoles in the interaction region. At a later stage the interaction region magnets can be replaced with new ones using better technology, similar to HL-LHC. This would reduce the luminosity loss to a factor 1.5 from the arcs.

At this moment it appears premature to decide between the staging options. Physics advances, also from HL-LHC, technology advances, in particular for the collider ring magnets, and the availability of resources will be prime ingredients in the choices.

6 Conclusions

The muon collider is based on novel concepts and important technological and systems challenges have to be faced to make it a reality. Key technologies such as high-power proton drivers, high-field solenoids and high-gradient RF cavities have, in the last decade, approached the level needed to deliver the required performances and luminosity.

An international muon collider collaboration, currently hosted by CERN, has been formed. A successful EU Design Study bid has been made. With involvement of the global community a concise set of work-packages has been developed for the LDG accelerator R&D roadmap. The programme provides an excellent basis for the global collaboration and planning of future work towards a multi-TeV muon collider. The project continues to make important progress with a growing collaboration enthusiastically supporting it.

References

[1] C. Aimé *et al.*, "Muon Collider Physics Summary", arXiv:2203.07256

[2] H. Al Ali *et al.*, "The Muon Smasher's Guide", arXiv 2103.14043 (2021)

[3] M. Boscolo, J.-P. Delahaye, M. Palmer, "The future prospects of muon colliders and neutrino factories", arXiv:1808.01858.

[4] `https://map.fnal.gov/`

[5] European Large National Laboratories Directors Group (LDG), "Accelerator Roadmap", arXiv:2201.07895

[6] B. King, "Neutrino Radiation Challenges and Propsoed Solutions for Many-TeV Muon COlliders", BNL - 67408, 2000.

[7] F. Collamati *et al.*, "A flexible tool for Beam Induced Background Simulations at a Muon Collider", ICHEP2020, 2021.

[8] M. Bogomilov, R. Tsenov, G. Vankova-Kirilova *et al.* "Demonstration of cooling by the Muon Ionization Cooling Experiment", Nature 578, 53–59 (2020), https://doi.org/10.1038/s41586-020-1958-9