ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB017

THE INTERNATIONAL MUON COLLIDER COLLABORATION

D. Schulte*, CERN, Geneva, Switzerland
for the Muon Collider Collaboration

Abstract

A muon collider offers a unique opportunity for high-energy, high-luminosity lepton collisions and could push the frontiers of particle physics by providing excellent discovery reach with excellent precision. A scheme has been developed by the MAP collaboration [1]. The updated European Strategy for Particle Physics recommended the development of an Accelerator R&D Roadmap for Europe and the CERN Council has charged the Laboratory Directors Group (LDG) to develop it. LDG has initiated panels to provide input including one on the use of muon beams, in particular in view of a high-energy, high luminosity muon collider. Also initiated by LDG, a new international collaboration, is forming [2] to develop a muon collider design and address the associated challenges, which are mainly due to the limited muon lifetime. The focus is on two energy ranges, around 3 TeV and above 10 TeV. Ambitious magnets, RF systems, targets and shielding are key for the design.

INTRODUCTION

Circular muon colliders have the potential to reach centre-of-mass energies in the multi-TeV range with high luminosity [3]. The muon collider concept has been developed in the past by the MAP collaboration mainly in the US [1]. 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].

Following the recommendation of the recent Update of the European Strategy for Particle Physics [6] a collaboration has been initiated by the European Large National Laboratories Directors Group [7]. In the framework of the muon collider collaboration we envisage to study different options, in particular one with a centre-of-mass energy of 3 TeV and one with 10 TeV or more.

MAP developed the concept shown in Fig. 1. 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. These rings can be either fast-pulsed synchrotrons or FFAs. 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. The above numbers are based on the MAP design and tentative goals for the accelerator rings.

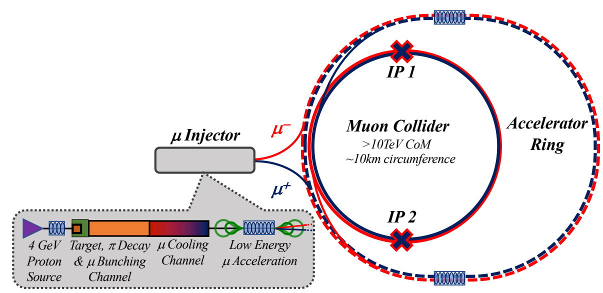

Figure 1: A conceptual scheme of the muon collider.

LEMMA is an alternative scheme to produce a muon beam with a very small emittance. An injector complex produces a high-current positron beam. The positrons impact a target with an energy of 45 GeV, sufficient to produce muon pairs by annihilating with the electrons of the target. This scheme can produce small emittance muon beams. However, it is difficult to achieve a high muon beam current and hence competative luminosity. Novel ideas are required to overcome this limitation.

MOTIVATION

High-energy lepton colliders combine cutting edge discovery potential with precision measurements. the energy reach of circular electron-positron colliders is limited by synchrotron radiation. Linear colliders in contrast need to accelerate the beam in a single passage and collide it only once. CLIC, the highest energy lepton collider proposed during the update of the European Strategy for Particle Physics, is not fundamentally limited to 3 TeV. But collider cost and length scale approximately linearly with energy and power consumption roughly linearly with luminosity.

The large muon mass suppresses synchrotron radiation and enables to use circular accelerator and collider rings. This reduces the required RF voltage and provides repeated collisions. However, the short muon lifetime of $\tau = 2.2$ μs limits the number of turns in the accelerator and collider.

Figure 2 compares the luminosity of CLIC and a muon collider, based on MAP parameters [1], as a function of centre-of-mass energy. The luminosities are normalised to the beam power.

* daniel.schulte@cern.ch

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB017

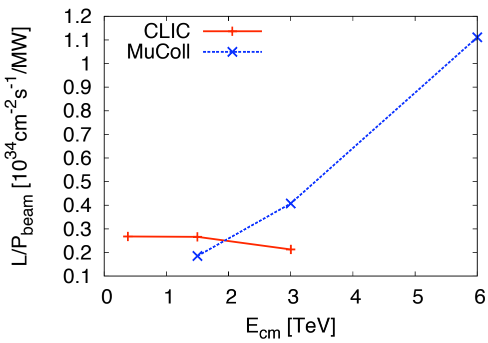

Figure 2: Comparison of CLIC and a muon collider luminosities normalised to the beam power and as a function of the centre-of-mass energy.

GOAL OF THE COLLABORATION

The International Muon Collider (MC) Study aims to establish whether a muon collider is feasible and, if so, to develop the concept and technology to a level of maturity that allows committing to its construction. It will also assess the physics reach. This full conceptual design is expected to demand a very important effort. In particular, the technology challenges motivate further R&D, prototype construction and performance demonstrations.

A tentative, technically limited, schedule is shown in Fig. 3. In the first period, in time for the next European Strategy for Particle Physics Update, the study aims to establish whether the investment into a full CDR and the required R&D programme is scientifically justified. It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers. It will also identify an R&D path to demonstrate the feasibility of the collider and support its performance claims and to develop a full CDR for the collider and its experiments.

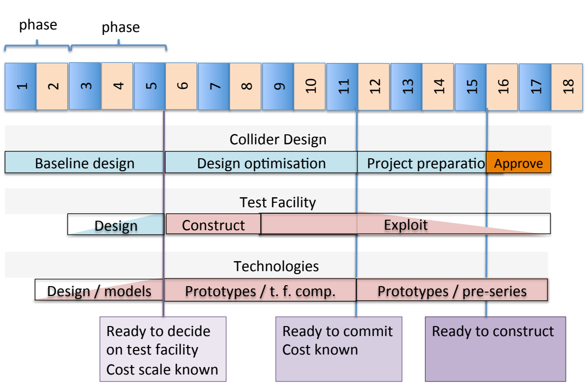

Figure 3: Tentative, technically limited schedule for the muon collider.

Depending on the European Strategy Update, the design can be optimised in the next stage and a demonstration programme can be implemented. The latter contains one or more test facilities as well as the development and testing of individual components and potentially dedicated beam tests. The resulting conceptual design would allow judge if one can technically commit to the collider. In this case a technical design phase will follow to prepare the approval and ultimate implementation of the collider.

In particular, the MC Study will focus on the high-energy frontier and consider options with a centre-of-mass energy of 3 TeV and of 10 TeV or more. Potential synergies with other projects shall be explored and collaborations formed where beneficial to the MC Study.

TARGET PARAMETERS

Initial targets for the integrated luminosities have been defined, namely 1, 10 and 20 ab^{-1} for 3, 10 and 14 TeV, respectively. They compensate the decrease of the s-channel cross sections with energy with the corresponding increase in luminosity.

Based on the MAP design corresponding target parameter sets have been defined for the collider, see Table 1. They would achieve the integrated luminosities within five years and are the basis to identify the key issues; the addition of budgets to account for beam quality degradation and operational considerations has to be made once detailed studies are available.

All parameter sets assume the same muon source. They further assume that the longitudinal emittance can be preserved during the acceleration and that the bunch in the collider ring can be shortened at higher energies allowing for a smaller beta-function. The design of the technical components, such as the final focus quadrupoles, to achieve this goal are a key to the muon collider study.

KEY CHALLENGES

Main challenges that have to be addressed in the exploratory phase are:

- The physics potential; 10 TeV is uncharted territory.
- The high neutrino flux and its impact on the site, which requires mitigation strategies for the highest energies.
- The impact of beam induced background on the detector and physics as it might limit the physics reach.
- The collider ring and acceleration after muon cooling can limit the energy reach and are key to cost and power consumption. The collider ring impacts neutrino flux and Machine detector Interface (MDI).
- The production and preservation of a high-quality muon beam. This luminosity performance depends strongly on the muon production and cooling as well as the beam acceleration and collider ring. Currently, the muon source is the same for all energies.

The collaboration has started to address these key challenges. A tentative concept to address the neutrino flux has been developed and is discussed below.

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 meter at 3 TeV) have started, based on MAP designs at 1.5 TeV and 3 TeV [8].

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB017

Table 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 will develop coherent parameter sets of its own.

Parameter	**Symbol**	**Unit**			
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	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	m	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	m	3	0.9	0.63

Considerations on the design of a similar system for high energies is starting.

First studies on the high-energy part of the collider also started with the aim to identify the bottlenecks. In particular the collider ring design also is important for the neutrino flux and MDI studies. For a pulsed synchrotron as muon accelerator, fast-ramping magnets largely determine the ring size. Normal-conducting magnets can be ramped quickly to about 2 T. A strong development programme could advanve field speed and field amplitude of fast-ramping HTS magnets. Efficient recovery of the energy in the magnetic fields, which is much larger than the total kinetic energy of the beam, is essential to limit the power consumption of the synchrotron. The alternative solution of an FFA requires complex high-field magnets. Efficient and cost effective RF that can deal with the high bunch charge is also important. In addition the collider ring requires high-field, large-aperture superconducting magnets.

The principle of muon beam ionisation cooling has been demonstrated in MICE [4]. Also important effort has been invested by MAP into the design of the cooling system for the collider. However, further optimisation of the cooling complex is important. A factor two improvement of the transverse emittance in the final cooling will allow to reach the emittance goal. In particular, very high field in the solenoids are important for the final cooling stage as they can reduce the emittance. More compact cooling systems will improve the muon survival rate. The high demonstrated RF gradients are the key to achieve this. Engineering designs that integrate the components as closely as possible are an important step toward the collider and call for a demonstration.

A summary of important issues can be found in [3, 9] and a list of relevant key technolgies in [10].

NEUTRINO RADIATION

The muon decay produces two neutrinos in very forward direction leading to a high flux of neutrinos. Passing through the ground they have a small likelyhood to produce showers just before or after leaving the ground. Two main sources of neutrinos exist: the arcs, producing a ring of flux around the collider and the insertions, which produce a more complex pattern with locally higher flux.

We aim to limit the flux from the arcs to a level that requires no legal approval procedure. Using formulae from [11], one finds that in a 200 m deep tunnel, a 3 TeV collider would require no mitigation, while a 10 TeV would approach the legal limit. Deforming the beamline vertically with remote movers avoids the very narrow flux cones and brings the level below the approval limit, consistent with radiation levels of LHC. Such a system will be developed and its impact on the beam will be studied and more precise radiation calculations will be performed. This expands a previous proposal to move the beam within the magnet aperture [12].

The flux from the insertions will be mitigated by either acquiring the land or by using a similar scheme as for the arcs. Studies of the flux pattern produced by the experimental insertions started [13].

CONCLUSION

The muon collider is based on novel concepts and important challenges have to be faced to make it a reality. However, the collider promises a unique option for high-energy, high-luminosity lepton collisions. In Europe, the Roadmap for Accelerator R&D is being developed and an expert panel is assessing the muon collider needs. In the US the Snowmass Process is about to restart and raising interest in the muon collider has been shown. An international collaboration is forming and already started to address the key R&D.

AKNOWLEDGEMENT

The author would like to thank MAP and MICE collaborations and the members of the forming muon collider collaboration. 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.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB017

REFERENCES

[1] Muon Accelerator Program (MAP), https://map.fnal.gov/.

[2] Muon Collider Collaboration, http://muoncollider.web.cern.ch

[3] J. P. Delahaye *et al.*, "Muon Colliders", 2019. arXiv:1901.06150

[4] MICE collaboration, "Demonstration of cooling by the Muon Ionization Cooling Experiment", *Nature*, vol. 578, pp. 53–59, 2020. doi:10.1038/s41586-020-1958-9

[5] D. Alesini, "Positron driven muon source for a muon collider", 2019. arXiv:1905.05747v2

[6] The European Strategy Group,"Deliberation document on the 2020 Update of the European Strategy for Particle Physics", CERN, Geneva, Switzerland, Rep. CERN-ESU-014, 2020.

[7] European Large National Laboratories Directors Group (LDG), "Minutes", presented at the Lab Directors Group meeting, Geneva, Switzerland, Jul. 2020.

[8] F. Collamati *et al.*, "A flexible tool for Beam Induced Background Simulations at a Muon Collider", in *Proc. 40th International Conference on High Energy physics (ICHEP2020)*, Prague, Czech republic, Jul.-Aug. 2021, pp. 1-6. doi:10.22323/1.390.0684

[9] M. Boscolo, J.-P. Delahaye, and M. Palmer, "The future prospects of muon colliders and neutrino factories", 2019. arXiv:1808.01858

[10] D. Schulte *et al.*, "Prospects on Muon Colliders", in *Proc. 40th International Conference on High Energy physics (ICHEP2020)*, Prague, Czech republic, Jul.-Aug. 2021, pp. 1-6. doi:10.22323/1.390.0703

[11] B. J. King, "Neutrino Radiation Challenges and Proposed Solutions for Many-TeV Muon COlliders", Brookhaven National Lab. (BNL), Upton, NY, USA, Rep. BNL-67408, May 2000.

[12] N. V. Mokhovy, and A. Van Ginneken, "Neutrino Induced Radiation at Muon Colliders", in Proc. 17th Particle Accelerator Conf. (PAC'97), Vancouver, Canada, May 1997, pp. 3074-3076. doi:10.1109/PAC.1999.792184

[13] C. Carli, private communication.