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THE MUON COLLIDER

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Abstract

Muon colliders are considered nowadays in the landscape of future lepton colliders. Since the MAP project in USA, an important effort is being made in Europe with support from the international community to identify the neccesary R&D to advance towards a Conceptual Design Report in the next years. The paper will review the status of the technologies and accelerator designs and will present the R&D plans.

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 recent Update of the European Strategy for Particle Physics [5] an international collaboration [6] has been initiated by the European Large National Laboratories Directors Group (LDG) [7]. 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. Following the presentation of the Roadmap, CERN Council asked for an implementation plan. 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.

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.

THE CONCEPT

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

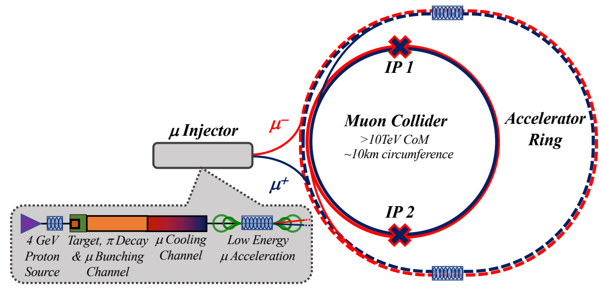

Figure 1: A conceptual scheme of the muon collider, courtesy M. Palmer.

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.

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 [8, 12]. 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 to 14 TeV lepton collider would be comparable to a 100 TeV proton-proton collider.

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 linear 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 the use of circular accelerator and collider rings. This reduces the required RF voltage and provides repeated collisions. However, the short muon lifetime of $\tau = 2.2$ s at rest (about $\tau\gamma \approx 104$ ms at 5 TeV) limits the number of turns in the accelerator and collider.

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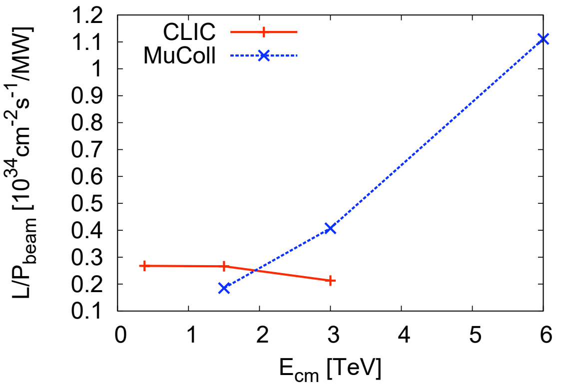

Figure 2: Comparison of CLIC and a muon collider luminosities normalised to the beam power and as a function of the centre-of-mass energy.

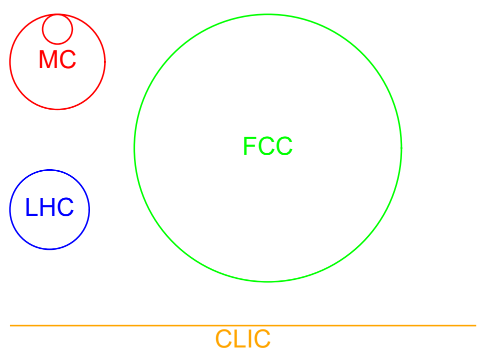

Figure 3: The scaled dimensions of the collider and final accelerator ring of a 10 TeV muon collider compared to other colliders.

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.

Figure 2 compares the luminosity of CLIC and a muon collider [13], based on MAP parameters [2], as a function of centre-of-mass energy. The luminosities are normalised to the beam power.

Figure 3 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.

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

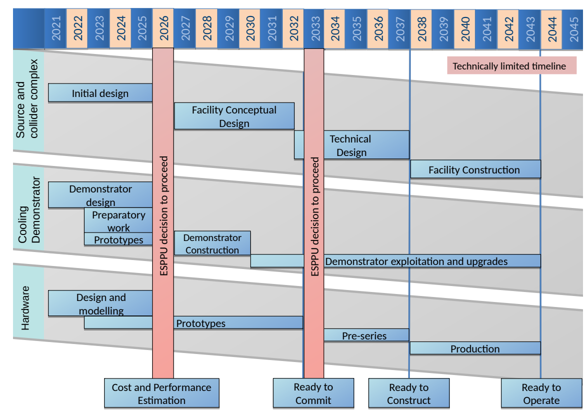

Figure 4: Tentative, technically limited schedule for the muon collider.

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 4. It is very ambitious and requires a noticeable 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.

Based on the MAP design corresponding tentative 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; they will be updated based on the study results.

All parameter sets assume the same muon source and that the emittances can be preserved during the acceleration.

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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

Furthermore they assume 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, e.g. the final focus quadrupoles, to achieve this goal are a key to the muon collider study.

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, 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 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.

ENVIRONMENTAL IMPACT

The compact footprint, limited cost and power consumption are intrinsic features that motivate the muon collider study in the first place. The key cost and power drivers will be addressed as a part of the overall design optimisation.

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 [14]. A proposed solution is a mechanical system that will disperse the neutrino flux by periodically deforming the collider ring arcs vertically with remote movers; this is an extention of a previous proposal that moves the beam [15]. The system ensures that the impact of the neutrino flux on the environment remains negligible and an order of magnitude below the goal of the MAP study, even for a 14 TeV collider placed 200 m underground. The study will address the mechanical aspects of the solution and its impact on beam operation.

A dedicated effort, supported by civil engineers, beam scientists, FLUKA and radiation experts is ongoing to assess and mitigate the impact of the insertions on the neutrino flux.

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 [16].

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These studies indicate that the background conditions are acceptable [11]. Considerations on the design of a similar system for higher energies are starting.

MUON PRODUCTION

A proton beam power of around 2 MW at 5 Hz is used for muon production; this is much less power than foreseen in MAP. 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 MERIT experiment [17] demonstrated that a liquid mercury target can sustain larger power; however safety considerations may not allow to use this proposed solution. The now reduced power allows to consider the use of a solid target in addition to a liquid metal or a fluidized tungsten target. First simulations of a graphite target are promising.

The target is imersed into a 20 T solenoid field, either produced by a single HTS solenoid or by a LTS solenoid with around 15 T and a inserted resistive solenoid to boost the field to 20 T. Tungsten shielding protects the superconducting solenoids from unwanted particles produced by the proton beam impacting the target. Past studies of a higher power 4 MW mercury-based target, showed that a 1.2 m radius of the solenoid provides enough space to reach peak powers in the coil of less than 0.1 mW/g, which corresponds to O(1 MGy) per year [18]. FCC-hh assumes that the magnet insulation can withstand an accumulated dose of 30 MGy [19]. This solenoid is very demanding and resembles in cost and stored energy the central solenoid of ITER.

MUON COOLING

Muon ionisation cooling increases the muon beam brightness by repeatedly slowing it in absorbers and reaccelerating it in RF cavities; both inside of strong solenoid fields to keep the beam focused. This is key to achieve high luminosity. This principle has been demonstrated in MICE [3]. 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. In particular, a factor two improvement of the transverse emittance in the final cooling will allow to reach the emittance goal.

The cooling complex consist of a sequence of different systems, the inital cooling, the first 6D cooling, the bunch merge—which increases beam intensity and emittance by combining a few bunches, the second 6D cooling and the final cooling. The whole chain is optimised for large acceptance in longitudinal and transverse emittance at the beginning and then gradually reduces the acceptance as the beam emittance is reduced.

The 6D cooling reduces longitudinal and transverse emittance. It is based on close integration of high-gradient normal conducting RF with the high-field solenoids that provide the strong focusing at the absorbers. The optics design and the technological components of the system are demanding; in addition, the integration of the components into a most compact cell is challenging but essential for muon survival.

The final cooling combines very strong solenoids combined with low beam energy to reduce the transverse emittance at the cost of letting the longitudinal emittance grow. Low frequency RF cavities or induction linacs will accelerate the beam in regions of relatively lower magnetic field. The solenoids around the absorbers have to provide the fields to minimise the transverse emittance. We strive to increase the field well beyond the already obtained 32 T. The absorber and their entrance and exit windows will have a significant energy deposition from the dense muon beam at the end of the cooling and need to be designed for robustness.

The solenoid field in the RF cavities guide electrons that are emitted at one location of the cavity surface to another location on the opposing wall and leads to localised heating that can result in breakdown and cavity damage. Operation of copper cavities is 3 T magnetic field showed a maximum usable gradient of only 10 MV/m. Three approaches to overcome this obstacle are known:

- Lower-Z materials, e.g. beryllium, limits the energy loss density.
- High-pressure hydrogen gas in the cavity limits the electron energy gain by colliding them with gas molecules.
- Very short RF pulses can limit the heat load in the cavity.

The first two techniques have been experimentally verified in MUCOOL with a field of about 3 T (limited by the solenoid). They yielded a gradient of 50 MV/m in a beryllium cavity under vacuum and 65 MV/m in a molybdenum cavity with hydrogen [20, 21].

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; however resources need to be found.

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. At injection the fast-ramping magnets have the full field strength but with a sign to bend the beam outwards compensating in part the bending provided by the superconducting magnets. As the beam energy increases the magnets are ramped down and then up to add to the superconducting magnets. This scheme halves the length of ramping magnets. The pulsed synchrotrons face challenges in terms of optics design, the magnet systems and the RF system.

The lattice design has to minimise the impact of the change of orbit with energy and ensure that the beam quality

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is preserved. Currently, the preferred solution for the RF systems is to integrate them in as many locations as possible around the ring. The possibility to integrate the RF in the arc cells and to compensate dispersion effects will thus be explored.

The ring will only accelerate one positive and one negative muon bunch at a time. However, the charge of the bunches is ten times the charge of an HL-LHC bunch and the bunches need to become very short at high energies. As a consequence the wakefield effects in the accelerating cavities can become very important and could lead to significant emittance increase in the longitudinal plane. Simulation studies have started to develop the longitudinal design of the acceleration complex.

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. It is planned to develop concepts for the magnets starting from those developed by MAP.

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. A first concept is being developed and will be optimised for performance, cost and power consumption in close integration with a starting design of the magnets. The most critical components will be assessed experimentally for performence.

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 that successfully addressed 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; a successful design has been developed at 3 TeV. First studies at 10 TeV indicate that the effect is comparable to 3 TeV, since the power per unit length of the particle loss remains similar. The shielding requires a substantial aperture in the superconducting magnets. The limit for the dipole field is thus given by the maximum stress that the conductor can withstand rather than by the maximum field that it can support. Novel concepts such as stress-managed coils will allow this challenge to be addressed.

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. One promising 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 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 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.

CONCLUSION

The muon collider promises a sustainable path towards very high energy. Potential intermedidate 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. A new muon collider collaboration, currently hosted by CERN, is forming. Initiated by the CERN Council and with involvement of the global community a concise set of workpackages has been developed for the Accelerator R&D Roadmap. These workpackages provide an excellent basis for the global collaboration and can provide important input to the ongoing US Snowmass Process and to strategic decisions in other regions. We hope to be able to globally join forces to open a road to exciting physics.

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