1 Motivation

Muon colliders can in principle reach the highest lepton collision energies with the required luminosity for affordable cost and power consumption. This allows unprecedented exploration in direct searches of new heavy states and high-precision tests of Standard Model phenomena. The required luminosity increase with the square of the energy can in principle be provided with a constant beam current, i.e. with an only linear increase in the beam power with energy.

The full physics potential at high energies remains to be quantified. But first explorations are encouraging. For example, the number of produced Higgs bosons will allow to measure its couplings to fermions and bosons with an unprecedented precision. Moreover, a collider with a centre-of-mass energy in the range of $\sqrt{s} \approx 10$ TeV or above and with a luminosity of the order of $10^{35} cm^{-2} s^{-1}$ will have a very high double and triple Higgs-boson production rate, which will allow to directly measure the parameters of trilinear and quadrilinear self-couplings, enabling the precise determination of the Higgs boson potential.

An important concern is the impact of the high background level induced by the muon beam decays. This has to be studied in detail, including potential mitigation methods. A recent exploratory study is encouraging and demonstrated that the measurement of $\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ process is feasible in this harsh environment, with a precision on $\sigma(\nu\nu H) \cdot BR(H \to b\bar{b})$ at the level of less than 1% at $\sqrt{s} = 3$ TeV, competitive to other proposed machines.

2 Proposed Plan

Important progress has been made on the concept of such a collider and on individual hardware components but further development and innovation is required to bring the technology to a maturity level that allows reliable predictions of the performance, cost, power consumption and risk.

We propose to form a collaboration and develop a muon collider design in the range of 3 TeV centre-of-mass energy and a luminosity of $\mathcal{L} = 1.8 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ and explore a potential second stage, tentatively at 14 TeV and $\mathcal{L} = 4 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. Lower energy stages might be considered if they have not been covered by other projects in due time.

Given the current level of maturity, the proton-driven muon source would be the baseline and the positron-driven source would be developed as the option that could have a lower beam current and mitigate radiation limitations at higher energies from muon beam decays.

The technically limited plan foresees a four year period to establish a baseline design, which allows to evaluate the risk and cost scale of the project and defines the required test facility or facilities as a basis for further decisions. This would be followed by six years of construction and operation of the facility and the optimisation of the collider design. The results of this phase will allow to decide on committing to the project in which case a technical design could be developed in the following four years.

3 Choice of Stages and Parameters

In addition to the technical challenges, two main limitations exist for the energy reach of the muon collider. The first is given by the cost and site requirements. Therefore an optimisation for cost and footprint is instrumental and has to be an important consideration during the design phase. The second limitation is given by the ability to achieve the required luminosity with an affordable power consumption and cost.

The level of luminosity required for different energy reach and purposes may vary. The current baseline is to aim for: $\mathcal{L} \approx (\frac{\sqrt{s}}{10\mathrm{TeV}})^2 \cdot 2 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

The muon collider could be implemented in energy stages to limit the cost and risk of each stage, while still providing excellent physics. The choice of stages will also depend on future findings of the HL-LHC and other relevant colliders.

To get started, first considerations yielded the following tentative conclusions that will be reviewed as the work progresses:

- The design effort should focus on an initial energy stage at 3 TeV with a luminosity of 1.8×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This matches the maximum energy of CLIC and is a good point to compare the merits of the approaches. This energy also appears consistent with the use of the LHC tunnel for the muon accelerator, the optimum collider ring circumference would be smaller.
- A second stage will be explored at higher energies, i.e. tentatively 14 TeV with a luminosity of 4×10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ where the discovery potential supersedes any other future collider evaluated at the moment.
- A dedicated design effort for a muon collider at lower energies (below 3 TeV) is feasible, but requires dedicated additional studies. Currently, no studies are foreseen but this will have to be reviewed as the progress and choices of other projects become clearer.

4 Key Technologies and Test Facilities

Successful implementation of a muon collider is based on a wide range of cutting edge technologies. In particular, key technologies are:

- High field, robust and cost-effective superconducting magnets for the muon production, cooling, acceleration and collision. High-temperature superconductors would be an ideal option.
- High-gradient and robust normal-conducting RF to minimise muon losses during cooling.

- Fast ramping normal conducting, superferric or superconducting magnets that can be used in a rapid cycling synchrotron to accelerate the muons.
- Efficient, high-gradient superconducting RF to minimise power consumption and muon losses during acceleration.
- Efficient cryogenics systems to minimise the power consumption of the superconducting components and minimise the impact of beam losses.
- Robust materials for muon cooling and also collimation and machine protection.
- Advanced detector concepts and technologies to deal with the background induced by the muon beams.
- Other accelerator technologies including high-performance, compact vacuum systems to minimise magnet aperture and cost as well as fast, robust, high-resolution instrumentation.

Laboratories in Europe and world-wide have important expertise in these areas and could further develop these technologies to enable a muon collider and push its performance reach. The formation of a collaboration to initiate and coordinate a development programme appears essential. In the first phase of the programme, the development of the baseline, this effort would largely draw on the experience while in later stages it will focus more on prototyping.

At least one test facility will be required to develop the muon collider concept to address the most critical challenges. The production of a high quality muon beam will be key and most likely the lion share of this effort. The collaboration will have to develop the experimental beam programme and its implementation drawing on the expertise of the contributing laboratories.

5 Reuse of Existing Infrastructures

The reuse of existing CERN infrastructure can have a significant impact on the cost and risk of a muon collider. Hence, the potential to use and modify the existing proton installations and related infrastructure should be investigated as well as the reuse of existing buildings, tunnels and services.

The muon source requires an important proton beam current, and one can consider upgrading the existing proton infrastructure to meet the requirements. Other equipment could be used for the new complex, e.g. existing cooling plants could potentially be used for the accelerator and collider rings.

The main reuse of tunnels is for the accelerator and for the collider ring. The latter should be as small as possible to maximise luminosity. The former will be longer and has less stringent requirements on the length. It is therefore expected to profit more from existing tunnels. Tentative estimates indicate that the LHC tunnel might be adapted to house the accelerator ring for a 3 TeV collider, while a purpose-built, smaller collider ring would be preferred for this option.

An important consideration for the tunnels is the neutrino radiation. It can come from the arcs or more important from the straight insertions. Civil engineering studies should identify the locations of highest radiation. It may be possible to improve the situation by acquiring the surface sites corresponding to the highest radiation. A detailed study should be performed of the potential mitigation of the radiation from the straights by a special optics design. One can envisage to bend the beam in the vertical plane using alternating sets of dipoles to produce a wave-like orbit. This can dilute the radiation. More advanced concepts should be considered.

6 Luminosity Considerations

The maximum luminosity of a muon collider is proportional to

$$\mathcal{L} \propto \frac{\tau\gamma}{C}\frac{N^2}{\sigma^2}f_r \tag{1}$$

Here, τ is the muon lifetime, γ their relativistic factor at collision energy, C the circumference of the collider ring, N the initial bunch charge in the collider ring, σ the transverse beam size assuming round beams and f_r the rate of injecting fresh bunches.

The ratio of lifetime at collision energy $\tau\gamma$ and collider ring circumference C is proportional to the average number of collisions that a muon has before it decays. It is simply proportional to the average magnetic bending field $\langle B\rangle$ in the collider ring. The muon energy does not enter because both the muon lifetime and the bending radius scale linearly with energy, compensating each other. The product of the transverse beam sizes σ^2 is given by $\sqrt{\epsilon_x\epsilon_y}\beta/\gamma$. Here, $\epsilon_{x,y}$ are the normalised transverse emittances and one assumes the same beta function β in both planes. Further one can assume $\beta \propto \sigma_z$. This assumes that the focusing system is not limited because of technical reasons. The bunch length σ_z is given by the relative energy acceptance of the collider ring δ and the longitudinal emittance ϵ_L as $\sigma_z \propto \epsilon_L/(\gamma\delta)$. Again one assumes that one can indeed achieve this bunch length. Hence neglecting potential technical limitations, the luminosity is proportional to

$$\mathcal{L} \propto \langle B\rangle \frac{N}{\sqrt{\epsilon_x\epsilon_y}\epsilon_L}\gamma^2\delta I \tag{2}$$

Here, I is the injected beam current Nf_r.

It will be instrumental to address several challenges that can limit the luminosity.

- Generation of high-charge and dense muon beams. The muon phase space should be as dense as possible from the very beginning. In MAP this is achieved by cooling the beam after production. In LEMMA the beam is generated with a small emittance in the first place.

- Phase space density increase. In principle, one can consider further cooling stages at higher energies but this appears very difficult. In particular in the LEMMA scheme it might be possible to increase the phase space factor $N/\sqrt{\epsilon_x\epsilon_y}$ by combining bunches in the transverse plane. This would in the limit lead to a scaling for n combinations as $nN/\sqrt{n\epsilon_x\epsilon_y}$.
- Preservation of the emittance during acceleration and collision is critical. Many detrimental effects need to be considered including single particle and collective effects. The latter includes beam loading and transverse instabilities.
- Minimising beam loss. During the transport muons will decay, which in turn reduces the phase space density. Rapid acceleration thus maximises the luminosity and calls for high gradients.
- Achieving the bunch length. During the acceleration the bunch length must be reduced to the small value in the collider ring. This will have to be done gradually to avoid larger energy spreads during acceleration. Optics and RF design will be instrumental to achieve this in the presence of imperfections. With higher energies smaller final bunch lengths are required scaling as $\sigma_{x,y} \propto 1/\gamma$.
- Achieving the small collision beta function. The focusing system at the collision point needs to achieve the small beta fuction. At higher energies the focusing becomes increasingly difficult as the stiffer beam requires more integrated quadrupole strength and the collision beta function decreases as $\beta \propto 1/\gamma$ to take advantage of the shorter bunches.
- Maximising the number of beam collisions. This is achieved with high magnetic field $\langle B \rangle$ in the collider to minimise its circumference.
- Maximising the beam current. Important limitations will arise from radiation and power consumption considerations. It therefore seems preferable to optimise the other factors for luminosity.

The different potential limitations also can impact each other. For example consider the case where the collision beta function would be limited by the beam size in the focusing magnets to a value above the optimum. In this case a reduction of the transverse emittance increases the luminosity not only directly because it reduces the beam size for the same beta function. It would also increase the luminosity because it decreases also the beam size in the focusing magnets which would allow to reduce the beta function at the collision point in proportion to the decrease of the emittance, resulting in $\mathcal{L} \propto 1/\epsilon^2$ for this specific case.

7 Collider Complex Design

The baseline collider design will use protons for muon production, i.e. follow the MAP scheme. It will consist of a number of subsystems that need to be

Parameter	Symbol	unit						
Centre-of-mass energy	E_{cm}	TeV	3	3	10	10	14	14
Luminosity	$\mathcal{L}$	$10^{35}\text{cm}^{-2}\text{s}^{-1}$	1.8	1.8	20	20	40	40
Collider tunnel length	C_{coll}	km	4.5	26.7	10	26.7	14	26.7
Average field	$\langle B \rangle$	T	7	1.2	10.5	3.9	10.5	5.5
Muons/bunch	N	10^{12}	2.2	2.2	1.8	1.8	1.8	1.8
Repetition rate	f_r	Hz	5	29	5	12	5	9
Beam power	P_{coll}	MW	5.3	32	14.4	35	20	37
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5	7.5	7.5	7.5
Transverse emittance	ϵ	μm	25	25	25	25	25	25
IP bunch length	σ_z	mm	5	5	1.5	1.5	1.07	1.07
IP beta function	β	mm	5	5	1.5	1.5	1.07	1.07
IP beam size	σ	μm	3	3	0.9	0.9	0.63	0.63

Table 1: Tentative target parameters for a muon collider at different energies. These values would be further developed and modified during the studies. The second column of each energy corresponds to using the LHC tunnel for the collider.

designed:

- A proton driver will provide the beam into the production target.
- In the muon source the protons produce pions in the target, which decay into muons that are captured.
- In the stages of the cooling system the muons are cooled and compressed into bunches.
- In the accelerator complex they are then accelerated to collision energy.
- in the collider ring they finally produce luminosity.

Development and innovation of special technologies will be the key.

7.1 Target Parameters

The tentative target parameters are shown in Table 1. They are based on the parameters developed by the MAP study. The bunch charges are modified, increased by 10% at 3 TeV and decreased by 10% at the higher energies to account for the muons lost during acceleration. The repetition rate is adjusted to achieve the luminosity target. The parameters are consistent with a scenario where the higher energy parameters correspond to a second stage added to the 3 TeV stage. The acceleration stage would have to deliver an average acceleration gradient of about 1 MV/m and 1.25 MV/m for the 10 TeV and 14 TeV case, respectively.

7.2 Proton Driver Complex Design

A concept of the proton driver has to be developed that can achieve the required dense, high-charge bunches. In particular, the reuse and improvement of existing infrastructures is of importance.

In addition, the proton driver that could be made available at reasonable cost for a test facility is a key for the experimental programme.

7.3 Muon Source Design

The muon source consists of the proton beam target that produces pions and the system that captures the muons from the pion decays. The target has to be very robust to withstand the shocks from the proton beam pulses and the capture system has to maximise the capture rate of useful muons.

A total proton beam power in the order of some MW will be required in the target posing a radiation hazard downstream. This load exceeds the value in the HL-LHC and the experiments of FCC-hh but is similar to the maximum load in the FCC-hh collimation system.

7.4 Cooling System Design

The muon phase space density has a direct impact on the luminosity per beam current and is one of key performance parameters. Pushing for the highest phase space density is important.

In the MAP study a baseline cooling system has been devised. It consists of three stages. In the first stage the muon beam is cooled sufficiently that it can be compressed into a single bunch in the merging system. In the second stage, the muons are further cooled in the transverse and the longitudinal plane to a minimum. In the final cooling stage the transverse emittance is further reduced at the cost of an increase in the longitudinal.

The cooling system designed for MAP does not fully reach the emittance target. An improved system has to be designed, also taking the achieved hardware performances and potential improvements into account. Further, improved designs such as parametric cooling need to be studied.

7.5 Accelerator Complex Design

The muon beam has to be accelerated with high effective gradient, taking into account the filling factor, to minimise the decay of muons. If the beam is accelerated from E_1 to E_2 with an effective voltage G the number of muons decreases as

$$N_2 = N_1 \left(\frac{E_2}{E_1}\right)^{-\frac{m_\mu c^2}{\tau c G}} \tag{3}$$

For example accelerating from 1.5 to 7 TeV with 1 MV/m (i.e. 20 MV/cavities and 5% filling factor) would reduce the muon current by 22%. Hence the gradient should remain in the MV/m range. For cost reasons the integrated voltage needs to remain limited. Therefore the accelerator complex might consist of different stages. The first rapidly accelerates the muon to an intermediate energy while the final one accelerates to the full energy. An approach could be to use a linac, followed by a recirculating linac, followed by a ring.

Different options can be considered for the accelerator ring:

- An FFAG. This ring has constant magnetic fields but can transport beams within a wide range of energies due to its optics design.

- A Rapid Cycling Synchrotron. In this solution the magnets in the ring would be ramped up rapidly to follow the increasing beam energy. Typically this ramping has to be done in the millisecond range. One can consider a mixture of high-field static and fast ramping magnets, see figure1. At injection, the fast ramping magnets would be powered to bend the beam in opposite direction to the high field magnets. Their field would then be ramped down and up again with the other sign to add to the static magnets as the beam energy increases.

Also a recirculating linac can be considered for the final stage but might only allow for a few turns, which requires an important RF voltage and consequently high cost. These options have to be developed to a sufficient level to chose a baseline.

In all of the rings the integration of the RF is important. The high muon bunch charge can lead to large single bunch wakefield effects in the accelerating RF and other beamline components, both in the longitudinal and in the transverse plane. The longitudinal wakefield can impact the ability to achieve the required very short bunch length for the collision, which is instrumental to reach the luminosity target.

7.5.1 Parameter Considerations

One idea is to use a fast ramping synchrotron with interleaved superconducting and normal-conducting magnets. The superconducting magnets bend the beam inwards, while the normal-conducting ones bend it to the outside at injection. Their field is then ramped down while the beam energy increases and further ramped to the opposite sign up so that at the top energy both magnet types bend the beam inwards.

In this scenario, the integrated length of fast ramping magnets is a function of the beam energy gain ΔE and the magnetic field of the ramping magnets B_{ramp}:

$$L_{ramp} \approx 10.472\ \mathrm{km} \frac{\Delta E}{\mathrm{TeV}} \frac{\mathrm{T}}{B_{ramp}} \tag{4}$$

To accelerate a beam from 0.3 to 1.5 TeV one needs about 6283 m of 2 T magnets.

The energy inside of the magnet aperture that has to be extracted and injected into the magnets to ramp the field down and up with the other sign rcs-dipole.pdf

Figure 1: Schematic of the mixture of fast-ramping and superconducting static dipoles in the RCS.

can be estimated as

$$W_{ramp} \approx 4.167 \text{ GJ/m}^2 \frac{\Delta E}{\text{TeV}} \frac{B_{ramp}}{\text{T}} HV \tag{5}$$

Here, H and V are the width and height of the gap, respectively. For $H = 80$ mm, $V = 40$ mm, $B_{ramp} = 2$ T and an acceleration of $\Delta E = 1.5$ TeV this yields 40 MJ.

The amount of superconducting magnets depends both on the injection energy and the final energy

$$L_{super} \approx 10.472 \text{ km} \frac{E_{out} + E_{in}}{\text{TeV}} \frac{\text{T}}{B_{super}} \tag{6}$$

For the above acceleration to 1.5 TeV, one needs about 2356 m of 8 T bends. This would be a total of 8639 m of dipoles and 10.8 km of arcs if one has a filling factor of 80%, similar to LHC.

With 20 MV/m RF and a filling factor of 65% in the straights one would need roughly 2000 m with a total voltage of 26.1 GV. The total ring length would then be 12.8 km. Some additional length is required for injection and extraction, maybe of the order of several hundred metres. Assuming a total of 1000 m for this, the circumference would be 13.8 km and 87% of the muons would survive the acceleration during the 46 turns. The magnets would have to be ramped from -2 to 2 T within 2.1 ms, corresponding to an ambitious rate of 1900 T/s. the power flow during the ramp would be 38 GW.

A ring to accelerate the beam from 1.5 to 7 TeV would need 28.9 km of 2 T ramping magnets and 13.8 km of 8 T dipoles for a total arc length of 54.4 km with 80% filling factor. Using 6 km of RF and 2 km for injection and extraction would lead to a total of 62.4 km with a voltage of 78 GV and a survival of 82.3% of the muons, consistent with the tentative proposed parameters. The beam would have to circulate about 70 times and the ramping speed would be about 14.6 ms.

This ring would be 2.4 times longer than the LHC and about 2/3 of the FCC tunnel. The total length of single aperture 8 T magnets would be 60% of the length of the twin-aperture LHC magnets. The RF would correspond to 30% of the ILC main linac RF. The cost of the fast-ramping magnets and their powering system would be an important cost factor, which remains to be determined.

The size of this ring could be reduced either by higher field magnets and better filling factors or by staging the acceleration and using two rings in the same tunnel, where the second accelerates from the extraction energy of the first on-wards.

Higher-field magnets and better filling factors would reduce the circumference. As an example one can consider 90% arc filling factor, with integration of the focusing in the dipoles, 16 T field of for the static magnets and 4 T for the ramping ones, which might be achievable with superconducting magnets. This would reduce the arc length to about 22 km. With 2.75 km of RF and 1 km of injection and extraction the ring circumference would 25.75 km and have the same muon survival rate and a reduced integrated voltage of 35.75 GV. Such a ring could be integrated in the LHC tunnel provided the radiation effects can be solved. The insertions for injection and extraction could not exceed 500 m each in this case and the RF would have to be distributed over 6 insertions. In the arcs a filling factor of 88% would be sufficient.

An example of a two-stage approach would use 16 T and 2 T dipoles with 90% arc filling factor. The first ring would accelerate from 1.5 to 4.6 TeV and the second from 4.6 to 7 TeV. The first would have 4 km superconducting and 16.3 km ramping dipoles and the second 7.6 km and 12.6 km, respectively. Both would have 3000 m of RF. In this scenario one can consider to use the same RF for both energy stages, which would reduce the cost and increase the efficiency.

The total integrated field of the superconducting dipoles would be 25% more than in the collider ring and 1/6 of the FCC-hh. The RF would be about 36 GVm about 15% of the ILC value.

7.6 Collider Ring Design

The integrated design of the collider is important for the achievable luminosity. In addition to the arcs it has to contain the injection system, the experimental insertions, some beam dumping system and some RF to compensate synchrotron radiation at very high energies. Also instrumentation and as required beam cleaning need to be integrated.

7.6.1 Parameter Considerations

The collider ring circumference should be minimal to obtain maximum luminosity per beam power. The main component are the bending magnets. The total length bending dipoles is about

$$L_{bend} \approx 21 \text{ km} \frac{\text{T}}{\text{B}} \frac{\text{E}}{\text{TeV}} \tag{7}$$

For the to this length one has to add the experimental insertions, the injection and extraction system as well as some RF and diagnostics section. An example design for a 3 TeV collider has been presented in [**?**] using dipoles of up to 10 T. The circumference is slightly less than the target of 4.5 km.

In the collider ring two main scenarios of longitudinal dynamics can be considered. Either the motion is reduced such that the length of the injected bunch is not changing significantly over the lifetime of the beam. Or one uses enough RF to control the synchrotron motion.

To reduce the longitudinal motion sufficiently to avoid bunch lengthening during the collisions, even with no synchrotron motion one has to fulfill

$$\alpha_c \ll \frac{\epsilon_L m_\mu c^2}{\sigma_\delta^2 E^2 \tau c} \tag{8}$$

This corresponds to 5.4×10^{-6} at 1.5 TeV and 2.5×10^{-7} at 7 TeV beam energy. In order to take advantage of a reduced longitudinal emittance the momentum compaction has to be scaled with the square of the emittance.

If one considers the beam to perform synchrotron motion in the collider one can relate the bunch length and the energy spread via the RF and ring parameters.

$$\sigma_z = \sigma_\delta \sqrt{\frac{E\alpha_c \lambda_{RF} C}{U 2\pi}} \tag{9}$$

Here, λ_{RF} is the RF wavelength, $U = eV \cos\phi_S$ is the bucket-forming voltage and α_c in the momentum compaction factor. The required RF voltage can be calculated as

$$U = \sigma_\delta^2 \frac{E\alpha_c \lambda_{RF} C}{2\pi\sigma_z^2} \tag{10}$$

This can be expressed as

$$U = \frac{\sigma_\delta^4}{\epsilon_L^2} \frac{E^4 \alpha_c \lambda_{RF} (\mathrm{Tm/GeV})}{0.3\langle B\rangle} \tag{11}$$

For a magnetic dipole field averaged around the ring of $B = 10.5$ T we have $C \approx 2$ km/TeV. The bunch length scales as $\sigma_z \approx \epsilon_L/(\sigma_\delta E) \approx 7.5/E$ mmTeV.

....$\sigma_z \approx \epsilon_L/E \approx 7.5/E$ mmTeV. .....

For illustration one can assume 1 GHz RF and $\alpha = 10^{-5}$. This yields about 86 MV of voltage for a 1.5 TeV beam and 40 GV for 7 TeV beams. Even assuming 20 MV/m it is clear that for the latter an important part of the ring (with a length of 14 km) has to be filled with RF.

Evidently, the voltage can be reduced by increasing the RF frequency. One thus has to aim for the highest frequency that is still able to handle the beam loading and is consistent with acceptable wake fields. Decreasing the momentum compaction factor also reduces the voltage by slowing down the synchrotron oscillations. If one can reduce it enough, the longitudinal motion becomes negligible over the lifetime of the muons and one could use the RF voltage only to compensate synchrotron radiation losses of the beam, which are small. One can also note that in order to take advantage of a reduced longitudinal emittance a quadratic increase of the voltage is required.

7.6.2 Experimental Insertion Lattice Design

The experimental insertion is instrumental in achieving the high luminosity per beam power. In particular the increase of this ratio with increasing collision energy is a result of the decreasing beta functions, which makes the lattice design increasingly difficult; at 14 TeV centre-of-mass energy a beta function of 1 mm is the target in both planes. The focusing quadrupoles triplet also can impact the background condition significantly and has to deal with a significant flux from beam loss.

7.6.3 Arc Lattice and Integrated Design

The arc lattice has to minimise the collider circumference to maximise the luminosity. The optics design must maintain the very short bunch length in order to allow for the small collision beta functions.

7.7 Combined Accelerator and Collider Ring Design

A specific option that is worthwhile studying is the combination of the collider ring and the last stage of acceleration. This will likely compromise the luminosity performance and enhance the complexity but could reduce the cost. In this scenario, the collider ring would contain a number of fast ramping dipole magnets, similar to the option of the fast ramping cyclotron solution for the accelerator ring. This would simplify the accelerator chain but makes the design of the collider ring more challenging. Specific issues that need to be addressed are:

- How are the experimental insertions handled during the ramp-up? The focusing magnets cannot be ramped at sufficient speed. So one has either to design a system with a mixture of static and fast ramping magnets or some bypass that avoids the collision lattice.
- The RF system and the transition from fast ramping to stable collision has to be understood.
- The fast ramping magnets are challenging, this is the same as for the rapid cycling synchrotron as the main accelerator.

It could also be considered to use a FFAG design for the collider ring.

7.8 Integrated Collider Model

7.8.1 Simulation tool development

The muon collider will require a number of specialised tools. The beam dynamics differs both from the single pass in linear colliders and from the very high number of passes in circular colliders. The limited number of turns in the muon collider has to be taken into account in a number of cases. Examples are the particle loss due to beam-beam effects and the impact of wakefields on the beam. Also the continues reduction of the muon beam current needs to be considered.

7.8.2 Collider Model

A start-to-end model of the collider will be instrumental to ensure that the beam parameters are consistent in the design and allow to optimise the performance.

7.8.3 Collective Effects

The charge of the muon bunch and the phase space density are high, which is essential to achieve the luminosity target. Collective effects will limit the achievable charge and density and need to be studied across the whole complex. In order to maximise the luminosity one actually must push toward the limits set by collective effects. Tools will need to be developed to analyse the collective effects. An example of a potential limitation are the beam-beam effects in the collider ring that could lead to beam loss and emittance growth. In particular if one can increase the bunch charge or reduce the transverse emittance the effects will increase.

7.9 Radiation Consideration

The radiation effects in the different parts of the machine have to be explored and evaluated and mitigation methods have to be developed. Particular issues are the radiation in all of the the accelerator systems from the proton target to the collider ring, the detector background caused by decaying muons in the collider ring and the radiation emitted outside of the complex.

7.9.1 Parameter Considerations

The importance of radiation hazard due to highly collimated intense neutrino beams is known since many years. It has already been studied in an analytic way and with MARS15 simulations, as reported for instance in Refs. .. Concerns come from the dose at the point where the neutrino beam reaches the earth surface, far away from the production point. The dose shall be well below the recommended annual dose limit for public, presently at 1mSv/year. A goal of 0.1 mSv/year is assumed here. The neutrino beam spread is roughly given by $1/\gamma$ of the parent muon. At 1 TeV, $1/\gamma = 1.10^{-4}$, resulting in a 100 m spot at a distance of 100 km from the production point. Despite the very small cross section, products from neutrino interactions are concentrated in a small cone, thus delivering a sizable dose. When considering a real collider, part of the neutrinos will be produced by muons decaying in the arcs, part in the straight sections. The level and distribution of dose is different in the two situations. In an ideal ring, with no straight sections, the neutrino products will reach the Earth surface along a ring concentric to the collider, at a distance that (for a flat Earth) is roughly proportional to $1/D^2$, were D is the depth at which the collider is situated. The dose from a ring scales approximately with E_μ^3, E_μ being the muon energy: deposited energy scales with E_μ, the spot size with $1/E_\mu$ neutrino cross section again with E_μ. Products from straight sections emerge on a spot-like area, and straight sections dose scales approximately with E_μ^4 due to an additional $1/\gamma$ factor. Dose can be mitigated by proper design limiting straight sections, beam wobbling, beam focusing/defocusing.

A first estimate uses formulae derived in [?] to find a general expression for the radiation D_{gap} from a gap of length L between two dipoles with a constant field B:

$$D_{gap} \approx 0.41 \text{ mSv} \frac{N f_r T_{operate}}{10^{20}} \left(\frac{E}{\text{TeV}}\right)^3 \frac{\text{m}}{d} \frac{\langle B \rangle}{\text{T}} \left(\frac{\text{T}}{B} + \frac{L}{0.7 \text{ m}}\right) \tag{12}$$

The formula is also valid for long straights and gaps of zero length. The radiation dose can be normalised to the accumulated luminosity

$$\int \mathcal{L} dt \propto \int dt \langle B \rangle \frac{N}{\sqrt{\epsilon_x \epsilon_y} \epsilon_L} \gamma^2 \delta N f_r \tag{13}$$

One obtains

$$\frac{D_{gap}}{\int \mathcal{L} dt} \approx aE \left(\frac{\text{T}}{B} + \frac{L}{0.7 \text{ m}}\right) \frac{1}{d} \frac{\epsilon \epsilon_L}{N} \frac{1}{\sigma_\delta} \tag{14}$$

with $a \approx 4 \times 10^{-4}$ mSv/(ab^{-1}eV^{2}m). *Here will follow some more discussion of the radiation at different energies.*

The neutrinos from the decay have an angle with respect to the muon axis in the order of $1/\gamma$. In order to limit the neutrino flux in any direction, one has to minimise the maximum path length $\Delta s = s_2 - s_1$ over which the muon trajectory is bent be $2/\gamma$, which requires

$$\int_{s_1}^{s_2} B ds = 0.7 \text{ Tm} \tag{15}$$

More detailed shower modelling will allow to refine this criterion. For the magnet design of the arcs one has to minimise gaps between dipoles. It appears best to use combined function magnets to provide the focusing or to introduce of an additional dipole field in quadrupoles and sextupoles. A gap of 0.2 m between two hard-edged 16 T dipole fields is in terms of maximum radiation equivalent to a longer section of about 2.9 T dipole field.

For the 14 TeV parameters, the radiation from the arcs is 0.8 mSv/year, assuming the beam parameters from the table, a magnetic field of $B = 16$ T and gaps of $L = 0.2$ m as well as a depth of $d = 500$ m and and integrated luminosity of 4 ab^{-1}. This requires additional measures to reach acceptable levels. A 10 TeV collider would have only 0.3 mSv/year, mainly because the luminosity target is halved. A 3 TeV collider would have only 6.5 μSv/year and could still meet the gaol with a tunnel depth of slightly more than 30 m.

Here will follow some more discussion of the radiation at different energies.

The decaying muons produce one electron and positron each with an average energy of about one third of the beam energy. The collider complex has to be able to withstand the associated radiation and heat load.

In the collider ring the power loss can be estimated by

$$W_{loss} \approx N f_r \frac{E}{3} \tag{16}$$

Using the 14 TeV parameters one finds a power of about 6.7 MW combining both beams or 480 W/m. For the 3 TeV parameters the loads are a total of

1.76 MW and 390 W/m. The solutions investigated by the MAP study have been to either use large-aperture magnets and place shielding inside or to use an open mid-plane design that allows the electrons and positrons to escape from the magnet.

In an accelerator with average gradient g that accelerate from E_0 to E_f the total energy W_{total} deposited can be estimated as

$$W_{loss} \approx \frac{N_f E_f - N_0 E_0}{3} \frac{m_\mu c^2}{c\tau e G - m_\mu c^2} \tag{17}$$

Using $E_0 = 1.5$ TeV, $E_f = 7$ TeV, $N_0 = 2.2 \times 10^{12}$, $N_f = 1.8 \times 10^{12}$, $f_r = 5$ Hz and $G = 1.0$ MV/m one finds about 930 kW of power lost for both beams. In an LHC-size tunnel this would correspond to 35 W/m, somewhat above the load produced by one FCC-hh beam. However, the energy is lost in form of high-energy particles, therefore the shielding strategy used in FCC-hh cannot be applied but has to be improved.

.... A reasonable goal is to limit the radiation outside of the collider complex to 0.1 mSv/year. The integration time over which the radiation can be averaged has to be determined. In the following we tentatively assume one year. ... It should be noted that detailed simulation indicate that the radiation is higher since the radiation is more concentrated in the centre of the cone than towards the edges. The relative changes of the radiation with luminosity, energy and other parameters should remain unchanged. Only the ralative contribution of a gap or straight will also be modified since the horizontal extension of the cone is relevant in thus case.

7.9.2 Radiation simulation and evaluation

Simulation studies of the radiation in the different parts of the machine are the basis for an evaluation of their importance. This will have to combine a wide range of topics, including material, radiation safety and simulation expertise.

Full simulation of the neutrino-induced radiation hazard has already been carried out for a variety of idealized situations. These studies confirmed that eq. 10 *put ref to label* can be used as a rough first order approximation in order to guide the collider design. They also assessed that the energy scaling contained (in a somewhat hidden way) in eq. 10 is conservative, while the overall normalization is slightly optimistic. It has to be underlined that eq 10, as well as most of the simulations performed in xx and yy (our pre-print and Nikolai), assume perfectly **parallel** muon beams on plane orbits. Fist investigations do also show that the actual parameters of the beam, and possible variation of the orbit plane, might be a powerful tool for the reduction of the neutrino hazard. Therefore, simulations of the neutrino hazard will be repeated on the basis of realistic muon trajectories as soon as possible, and results will be the basis for further iteration among beam and simulation experts. These simulations will also take into account the local orography: a careful choice of the ring location and/or the direction of the straight sections should be envisaged when possible.

Besides neutrino hazard to general public, all other radiation issues, such as radiation damage to the machine components, activation of the soil and water in proximity of the ring, will be addressed as soon as a preliminary design is available.

7.9.3 Mitigation techniques

Different mitigation techniques have to be developed. This includes specific beamline designs to minimise the radiation, robust design of components and others.

7.10 Machine Detector Interface studies

In a multi-TeV muon collider, the effects of backgrounds created by decays from the muon beam in the collider ring must be evaluated in detail. Muon decay products can contaminate the Interaction Region (IR) from a distance that varies with the beam energy. In fact, the distance from the last focusing magnet of the accelerator to the interaction point is a design driver both for the machine and the detector. Previous studies [**?**, **?**, **?**], have shown that two cone-shaped tungsten shields can be used to protect the IR and the detector from the extremely high flux of beam background particles. Nevertheless, the flux of background particles arriving to the detector is still too high to operate successfully a detector.

7.11 Parameters and Layout

The overall concept of the collider and its key parameters have to be developed and optimised taking into account the limits of the different sub-systems and the trade-offs between them.

8 Technology

A number of specific technologies need to be developed as an integral part of the design process.

8.1 Cooling Module Design

The integrated design of the 6D cooling module and construction of a model are the key to the muon collider test programme. This combines the key expertise in a single team that has to closely work together, including magnets, RF, targets, safety, cryogenics, vacuum, beam dynamics and others.

8.2 Superconducting Magnet Design

Across the whole complex, high-performance superconducting magnets are essential to reach the muon collider performance target. The most advanced technologies will be required to maximise the magnet field and provide the essential operation margin in an environment with significant radiation. A design of the complex has to be developed so the individual requirements for the magnets are not all known. Based on the previous US study and basic considerations one can however identify the most likely needs.

Both, conventional niobium-titanium and cutting edge niobium-tin magnets could be used. However, novel magnets based on high temperature superconducting technology would offer particular advantages. They can provide

- Higher fields. This can increase the collider luminosity. Higher fields in the collider ring allow for more collisions. Higher fields in the muon source and cooling can increase the beam phase space density. Also the accelerator complex can profit from higher fields.

- Higher operating temperature. A higher operating temperature can increase the power efficiency of the collider by simplifying the cooling system. It may also allow to make designs more compact as the cryostats could be simplified.

- Higher robustness. HTS magnets can have a higher operation margin. This allows for a more robust design and would be helpful in mitigating issues caused by beam losses due to the muon decays.

The optimum balancing of the different advantages will be an important part of the design process and require a close loop of accelerator and magnet experts.

An important number of magnets need to designed, some of them are particularly important. These include the following.

Target Magnet System The magnet system for the target and capturing section plays a key role in the ability to produce high charge muon beams.

Cooling solenoids The muon cooling system is based on the use of high-field solenoids to strongly focus the beam. Higher fields will improve the cooling performance by more strongly focusing the beam. These solenoids need to be closely integrated with the RF systems and the cooling targets, which requires a fully integrated design also including the cooling systems.

Cooling bends The cooling system also needs bends to keep the longitudinal emittance under control.

Other cooling system magnets Other cooling options can be considered, for example parametric cooling. The basic idea is to generate a set of beam waists with very small beta functions, since the transverse equilibrium emittance is proportional to the average beta function over the cooling target.

Collider dipoles The luminosity is directly proportional to the field that can be achieved in the collider ring dipoles. In order to minimise the radiation also the distance with no bending between the dipoles must be minimised. This requires to integrate the focusing in the dipoles and to aim for field free regions between dipoles of the order of a few centimetres.

Experimental insertion magnets The quadrupoles to focus the beam into the experiments need to combine large field gradient, large aperture and robustness against radiation. The muon collider can in principle achieve an increasing luminosity per beam power because at higher energies the bunch length can be shortened inversely proportional to the energy $\sigma_z \propto 1/E$ and one can reduce the collision beta function in proportion $\beta^* \propto \sigma_z \propto 1/E$. This in turn will increase the beta functions in the final focus system.

If the final focusing layout would remain constant, this would imply that the beam size in the focusing element would not change with energy. The geometric emittance would decrease with energy as $1/E$ and the beta function in the triples would increase with $1/\beta^* \propto E$. Thus the beam size in the triplets would remain constant. However an increase in the field gradient proportional to the beam energy would be required. For a constant technology this translates into a requirement to reduce the aperture inversely proportional to the beam energy which is in conflict with the constant beam size. The solution is to increase the length of the triplets.

As an illustrative example, one can start from a lower energy solution and one could consider to increase all lengths, including L^*, and the magnet aperture in proportion to E. This will provide both the focusing strength and aperture required in the magnets. However the size of the magnets would be quite large. A scaling which keeps L^* shorter is expected to be more beneficial.

Accelerator dipoles Different accelerator concepts are considered and have different requirements for the magnets. A FFAG would require high-field magnets. In the case of a vertical FFAG, specific magnet designs would be required. A rapid cycling synchrotron might require a combination of high-field superconducting and fast-ramping magnets. They might need to be integrated over very short distances to minimise the impact of the ramp on the beam.

Other magnets Other magnets, such as steering magnets, will also be required.

8.3 Fast ramping magnet systems

The rapid cycling synchrotron solution for the accelerator ring requires fast ramping magnets and efficient powering systems that can recover the stored energy in the magnet with high efficiency. Likely these magnets need also to be integrated with superconducting static magnets. This system is expected to be key to the collider power consumption and overall cost.

8.4 RF Design

A particular challenge for the RF systems in the muon collider is to achieve a high RF to beam efficiency while keeping negative effects of the beam loading at bay. The RF systems also are crucial for the bunch length control in the whole complex. Particularly important systems are:

Muon cooling RF Very high gradient RF is used in the muon cooling system and it has to be able to deal with the radiation from decaying and lost muons and should be able to work in a high magnetic field. This favours normal conducting RF. Pushing the gradient while avoiding breakdown is instrumental to minimise the emittance as rapidly as possible. The cavities preferably are gas-filled and will have to be able to operate in a very high magnetic field to maximise the cooling efficiency. The high muon bunch charge will also lead to important beam loading effects. The RF, magnet and targets have to be highly integrated posing a particular challenge.

Muon acceleration RF After the cooling the muons have to be accelerated rapidly to minimise the beam loss. The layout of the system has to be determined but it is likely to consist of a linac followed by a recirculating linac and finally an accelerator ring in order to balance cost, efficiency and performance. The RF can give rise to important collective effects, ranging from beam loading to transverse instabilities. The degradation of the longitudinal and transverse emittance has to be limited to the minimum to achieve high luminosity. This will be a driving factor of the RF design.

Muon collider ring RF At high energies the muons will loose energy due to synchrotron radiation. Some RF system is therefore required in the collider ring.

8.5 Transfer System Design

The transfer systems will require space in the adjacent accelerator systems. These straights are important sources of radiation and are important for machine protection. The transfer systems are also important for the overall collider layout.

A specific transfer system that should be explored is a bunch combiner for the LEMMA scheme. It appears possible to improve the luminosity by combining muon bunches in the transverse plane. This will increase the transverse emittance in proportion to the square root of the number of combined bunches but the charge linearly, which improves the relevant phase space density. A technical solution for the combination of bunches needs to be studied and the actual size of the final phase space has to be evaluated. This might yield an improvement of the luminosity by an order of magnitude. It might be possible to find an application of such a system also in the design based on the proton source.

8.6 Beam cleaning systems

The needs for beam cleaning have to be established. This requires estimating the formation of halo and tails and considering the machine protection needs. Based on these studies a beam cleaning system has to be developed, which will be particularly challenging since the muons are difficult to collimate due to their ability to deeply penetrate into matter.

8.7 Instrumentation considerations

Instrumentation will be important for the collider performance. It has to be adapted to the special environment, which demands rapid measurements over a limited number of turns and with potential background from muon decays. An exploratory study of the key challenges would be essential to better define the scope of the required work.

8.8 Cryogenics

The important loss of beam due to muon decay will require efficient cooling of superconducting magnets and RF systems. The tight integration of superconducting and normal conducting systems in the muon cooling and accelerating systems poses additional challenges.

8.9 Vacuum systems

The vacuum system has to provide good vacuum quality in the presence of beam loss and has to help to minimise the power losses into the magnet. Its aperture is critical both for the beam, since it limits the aperture can drive collective effects, and the magnets. It therefor can drive the performance and the cost of the project.

8.10 Machine robustness

The decay of the muons during the cooling, acceleration and collision lead to important losses in all parts of the collider. the impact on the different components needs to be evaluated and mitigation methods such as shielding of the critical components need to be devised. Also collimation of the beam might be considered but is complicated by the large penetration depth of the muons in matter. Novel approaches will therefore have to be considered such as the use of crystals.

8.11 Beam-beam Effect Mitigation

The luminosity of the collider is proportional to the transverse beam density at the collision point

$$\mathcal{L} \propto \frac{N}{\sqrt{\epsilon_x \epsilon_y}} \tag{18}$$

This parameter is directly proportional to the beam-beam tune shift. A detailed study of the acceptable value has to be carried out, previous studies indicate that an increase by about a factor two might be acceptable. Concepts to mitigate the beam-beam effects will have to be developed in order to allow for a significant increase in acceptable tune shift.

9 Site and Infrastructure

9.1 Site studies

The site choice is not only important for the project cost but also for the luminosity that can be achieved at higher energies. This has to cover the options to reuse existing tunnels but also the possibility to construct a new collider tunnel that allows to reach high energies. The civil engineering is potentially also an important part of the overall cost and has to be considered early on.

9.2 Infrastructure studies

An important infrastructure already exists at CERN. This includes existing accelerators as well as for example cryogenics plants and power stations. Important new infrastructure will be required and can have important implications for the project cost and power consumption.

10 Lemma Scheme

The Low Emittance Muon Accelerator (LEMMA) concept [5, 6, 7] is based on μ production from a 45 GeV e^+ beam annihilating with the electrons of a target close to threshold ($\sqrt{s} \approx 0.212$ GeV) for $\mu^+\mu^-$ pair creation, thus generating μ beams with low enough transverse emittance for a high energy collider. This should provide a muon pair boost for post-production capture and emittance minimization, drastically reducing the source transverse emittance and, coupled with a collider nano-beam scheme, should reach the required luminosity with a much lower bunch intensity. The initial design foresaw an e^+ storage ring with an internal production target. The main problem of this scheme was the low production cross section not allowing an efficient muon production by a single positron bunch passage in the target, requiring many passages with the consequence of a too high energy density deposition in the target, and the building of low energy tails in the positron bunch due to the passage through the target that introduces too high positron losses. The work later carried out clarified that the proposed layout was suffering for technology limits, among others the achievable positron sources fluxes and the storage rings design, as far as the energy acceptance was concerned. A main revision of the baseline scheme was performed to propose an alternative design, presently under study, to identify the challenges within reach of the existing technology, and those requiring further innovation. In the new scheme the e^+ bunches are extracted to impinge on multiple targets in a dedicated straight section. Muons are then collected in two Accumulation Rings (AR) and stored until the μ bunch has a suitable number of particles. This scheme could release the impact of the average power on the targets and also reduce the number of e^+ needed from the source.

10.1 Layout of the complex

In order to have a reliable μ production scheme, precise requirements on the muon source chain timing have been set. The complete μ production cycle should be $\sim$410 μsec, of the order of the particle lifetime (467 μsec) at 22.5 GeV, thus reducing the intrinsic beam losses with respect to the accumulated μ intensity. After one production cycle, μ bunches must be immediately accelerated to increase their lifetime and reduce losses. Moreover, one complete cycle must accommodate enough time for the e^+ production and damping, in the main Positron Ring (PR) or in a dedicated Damping Ring (DR). Damping time must be compatible with a reasonable amount of synchrotron power emitted, ranging from 10 msec in a 5 GeV DR to 80 msec in a 45 GeV PR. This time is needed even in case it is possible to recuperate the e^+ bunches "spent" in the μ production which, after interacting with the targets, are strongly affected and have a degraded 6D emittance. It is evident that the impact of the μ production on the e^+ bunches should be minimized to allow for generating the maximum amount of μ for a single e^+ bunch passage, for this the study of different type of targets is in progress. Once an e^+ bunch has interacted with the targets and has been "spent", it is mandatory to have a "fresh" e^+ bunch for the μ accumulation cycle. Furthermore, the different systems composing the μ source complex must not show unrealistic performances, taking into account the state-of-the-art of the existing technology and the possibility to have a future R&D program to fulfill the required parameters. A detailed description of the design can be found in [8]. The main components of the preliminary layout are the following:

- e^+ Source (PS) at 300 MeV plus 5 GeV Linac,
- 5 GeV Damping Ring (DR),
- SC Linac or Energy Recovery Linac (ERL) to accelerate to 45 GeV, and decelerate to 5 GeV after μ production,
- 45 GeV Positron Ring (PR) to accumulate 1000 bunches needed for μ production,
- delay loops to synchronize e^+ and μ bunches,
- one or more Interaction Regions (IR) with targets for the μ production,
- 2 Accumulation Rings (AR) where μ are stored until the μ bunch has a suitable number of particles,

- a chicane and compressor Linac, if needed, to re-inject the "spent" e^+ in the PR,
- "embedded" e^+ source, for the production of the e^+ needed to restore the design e^+ beam current.

The PS and the first Linac have to produce and inject 1000 bunches of $5x10^{11}$ e^+/bunch in the DR, which stores 3.8 A e^+ and has a short (∼10 msec) cooling time thanks to damping wigglers. After the cooling, the e^+ beam is extracted from the DR, accelerated in a SC Linac or ERL to 45 GeV and injected in the PR in 10 msec, with a pulsed current of the injector Linac of 8 mA. In the meantime, the PS can continue to top-up the DR. Once 1000 bunches are stored in the PR, they are extracted to collide with the targets in the TL for μ production. This process can take 410 μsec. After μ production, degraded e^+ bunches are sent back to the PR with a reduced injection efficiency, estimated to 70% due to the high energy spread generated in the targets interactions. With a slow extraction (∼20 msec) the "spent" e^+ bunches are slowly extracted from the PR, decelerated to 5 GeV in the SC Linac, and sent back to the DR. At the same time the produced μ bunches are extracted and accelerated to the final collider energy in a separate accelerators chain. In the following 30 msec the DR provides for cooling of both the e^+ produced by the PS and those coming back from the PR. The cycle is then repeated at 20 Hz. Since the PR is not circulating any beam during the DR cooling phase, the synchrotron radiation emission duty cycle is reduced, decreasing also the total synchrotron power budget.

Studies are in progress to verify if the injection efficiency of the "spent" positron beam in the 45 GeV PR ring, and its damping process, can be good enough to keep such beam circulating, damped and be ready for interaction again. In this case only the fraction of positrons lost in the beam transport line and in the injection process will need to be provided by the main positron source, so decreasing its required performances.

Each sub-system will need a dedicated analysis to define the different parameter correlations and to provide a final baseline scheme maximizing the expected luminosity in the collider, the main path for the LEMMA proposal being to produce low emittance muon bunches with the maximum number of muons per bunch.

10.2 LEMMA future R&D

To increase the muon beams quality, and consequently the final luminosity, in the proposed scheme different proposals are conceivable if a solid R&D program could demonstrate their technical feasibility. Improvements in the technical solution could enhance not only each system performances, but in some case the global efficiency of the full muon source complex. We will briefly summarize hereafter the main possible directions for the R&D programs, their correlation with the source parameters and their functional relationship with the final luminosity.

10.2.1 Targets

Targets are a common topic for both the positron production and the muon production. As already mentioned one of the most important parameter to increase the muon bunch population is the possibility to produce the maximum number of μ^+ μ^- pairs in a single positron bunch passage, up to the limit of its energy and energy spread deterioration that fix the limit to the use of a "fresh" bunch. To maximize this parameter, Be and C targets were considered since, thanks to their low Z, they present a lower Z(Z+1) dependent bremsstrahlung effect. At present the scheme takes into account that an integrated $0.3X_0$ target thickness is suitable for a single positron bunch passage. The need to maintain a low PEDD (Peak Energy Density Deposition), average energy deposition, and temperature, to ensure target durability and efficiency, as well as to maximise the number of produced particles, is a key R&D topic. The determination of the damage and fusion thresholds, thermo-mechanical stresses, and the evaluation of technical designs for heating evacuation and PEDD remedies need material studies and experimental test. A prototype of a rotational target, both a single thick target or an ensemble of close thin targets, with an amorphous and a granular amorphous material should be built and tested. A very important development would be the use of liquid Hydrogen (H2) targets that, mixed with the multi-IP lines, would improve the integrated thickness reducing the number of passages and so increasing the ration of "fresh" bunches/passages.

This would have a linear dependence on the muon per bunch number, and so a quadratic increase of the final luminosity. Taking into account a simple scaling with Z we can expect a factor 15 in increase of the luminosity with H2 targets. Crystal targets should be also considered as a solution for muons recombination and post-production cooling.

10.2.2 Positron Sources

One of the main limit in the source repetition frequency is the physical constraint imposed by the e^+ source given by the required e^+ flux, the required cooling and the thermo-mechanical stress on the target. In this framework a very interesting development is represented by the use of rotating target as already conceived for the ILC. Different schemes at a f_{rep} of 50-100 Hz should be implemented in case that high technology targets and high efficiency e^+ source should deliver e^+ rate higher than 10^{16} e^+/sec. This has to take into account also the possibility to develop immersed large acceptance e^+ capture systems at 1 GHz, with very high peak B Field in the AMD (20 T in the MAPS scheme) and in the capture solenoid. A very large energy acceptance of the DR will also increase the efficiency of the e^+ source.

An increase in the efficiency of the e^+ source, and consequently of the repetition rate of a factor 5-10, will have a linear dependence on the luminosity.

10.2.3 Positron Ring

In this scheme one of the imposed limit is given by the achievable current in the PR. This is mainly due to the beam instabilities and to the synchrotron power budget. A possibility would be to reduce the PR energy, so drastically reducing the emitted power, and then to accelerate and decelerate the e^+ beam respectively before and after the e^+ production in a push pull configuration. To implement this scheme, it is necessary to develop high gradient accelerating systems that can work at a very high value of the pulse current, typically 250 mA, in the 410 μsec allowed for the muon production cycle.

This could increase the ring current of a factor 3-4, so increasing the number of available "fresh" bunches. In this case we could have more passages to produce the muons, so increasing the number of muons per bunch, with a quadratic effect on the luminosity.

10.2.4 High field magnets

The need to focus 45 GeV positrons and 22.5 GeV muons together in a short low β function IR calls for high gradient, large aperture and compact quadrupoles. The design of the IR as well as the multi-targets muon production line will require also an efficient 3-beams separation design, aiming at minimising particle losses, with high field, large aperture dipoles.

10.2.5 Target tests at DAΦNE

A test of the DAΦNE positron beam impinging on a target will allow for benchmarking the simulations of target materials and released power with a real case. Beam lifetime, high currents and beam dynamics studies will help to identify issues and finalise the scheme design. Vacuum tests of different targets will be also possible.

10.2.6 Muon Cooling

The LEMMA scheme, despite of the low production cross section, introduces two main advantages in the source: a reduced emittance at the production and a higher production energy resulting in a longer muon lifetime. So, also if the former suggests the possibility to avoid a cooling phase, the second allow for enough time to introduce also a moderate cooling mechanism to further reduce the production emittance. Different evaluations were done in the past for the cooling efficiency given by stochastic cooling, optical stochastic cooling, crystal cooling.

A full evaluation of these mechanisms associated to high energy, low emittance and bunch current, to produce long lifetime muon bunches, should be done and R&D programs proposed, targeting an emittance reduction of 1-2 order of magnitude, that will linearly impact the final peak luminosity.

10.2.7 Muon Recombination for higher luminosity

Due to the quadratic dependence of the luminosity on the bunch population, testing muon bunches recombination techniques, that can increase the number of particle per bunch without been drastically affected by the consequent emittance increase, could be envisaged. Different techniques, considering both transverse and longitudinal recombination, have already been proposed in the framework of the MAP program. In the framework of the LEMMA activity a new hypothesis is under study: the possible recombination of different muon bunches by injection in a curved crystal. Combining the channeling angle with the volume reflection it should be possible to merge two different bunches with a relative emittance increase, mainly in the distribution tail. The efficiency of this process should be optimized by an extensive R&D program.

11 Test Facility Design

An important part of the test facility will be the muon cooling system and the heart of this system will be the cooling module that combines target, magnet and RF. In the preparation phase for the test facility the development of a test model or prototype is key. This will allow to gain experience in the optimisation the components and their most effective integration. The development of the cooling module model is an important part of this work as it develops the key component of a test facility.

12 Initial Steps

A conceptual design of the different collider sub-systems, such as cooling, acceleration and collider ring will enable to judge the cost, power consumption and risk of such a project. However, in a first stage, one can explore a number of specific points in order to be able identify the bottlenecks, cost and power consumption drivers as well as highest risk factors. This allows to better judge the promises and weaknesses of a muon collider and will allow prioritise the design and technology work. These specific points include the following:

- A conceptual design of the muon source. The muon collider performance depends strongly on the beam phase space; aiming for the smallest emittance while maintaining high bunch charges is thus critical. Key for this is an integrated design of the different subsystems to maximise the phase space density of the produced beam, namely
  - the initial muon cooling system,
  - the muon bunch merging system,
  - the second 6-D muon cooling system,
  - the final muon cooling system.

In addition alternative options have to be studied. This includes

  - The LEMMA source, which could dramatically reduce the emittance.
  - Alternative cooling options or additional means as for example parametric cooling.

  Also the muon production has to be explored as this provides important input to the above studies. This includes:

  - The proton driver system in particular in view of the reuse of existing infrastructure, equipment and accelerators.
  - The muon production system. In particular the proton target, the efficient capture of the produced muons and radiation effects have to considered.

- Development of a cooling cell model for the test facility. This requires integration of normal conducting RF, superconducting solenoids, cryogenics and targets. Also the use of thin windows and safety concerns would need to be addressed. After a first exploration, a conceptual design needs to be developed. In the longer run, it appears important to build and test a cell before the start of construction for the test facility. A beam test would be preferable but one would have to explore the use of protons or electrons for this purpose.

- A conceptual design of the collider ring and its focusing into the collision point. This system is essential in order to profit from the potential improvements of the muon source. Particular points are

  - The beam delivery system that produces the very small beta functions.
  - The collider ring with large energy acceptance, dynamic aperture and low impedance.
  - The systems to mitigate beam-beam effects in order to allow for the use of small-emittance beams.

- Conceptual design of the collider ring magnets with the focus on robustness against beam loss, high field and minimal field-free distance to the next magnet. The focusing magnets around the experiments are equally key. In the longer run, it may be required to have some hardware tests to validate the magnet end design and for special design such as open midplane.

- Studies of the radiation effects across the whole complex. This includes the impact of the radiation on the site and on the components. This also should include an study of mitigation methods such as orbit variations of the colliding beams and special optics to mitigate the radiation from the straights.

- Integrated beam dynamics to ensure consistent parameters in the complex. In particular an exploration is required of the collective effects that limit the parameters space and the potential mitigation. As an example the current parameters in the collider ring are consistent with acceptable losses due to beam-beam effects but past studies showed that they cannot be pushed much further without generating beam loss. Mitigation of this should be possible. Space charge and wakefield effects might limit the bunch charge at other locations.

- Exploratory site studies to identify the possibility to optimise the use of existing tunnels and to mitigate radiation issues. Also the possibility to implement a new collider tunnel is of great importance.

- Exploration and conceptual design of the machine detector interface. This is essential to identify and mitigate limitations for the collider performance resulting from muon decays.

- An exploration and later conceptual design of the accelerating system. This system has to maintain the beam quality from the source to the collider ring and is important for a consistent machine design. It is likely the most important cost driver and choices between different options have to be made, for example between a rapid cycling synchrotron or an FFAG as the last stage of the acceleration. It might be possible to combine the last accelerator ring with the collider ring compromising the performance but potentially reducing the cost.

- Exploration and later development of the fast-ramping magnet system including the powering. This is one of the main cost and power consumption items if one choses a rapid cycling synchrotron. Therefore some experiments to determine and improve the technological limits will be required. A normal-conducting option appears easier but a superconducting option might significantly redcue the length of the accelerator ring and make an integration of the accelerator and collider ring easier.

- Exploration and later conceptual design of the superconducting magnets for the acceleration complex. This may include magnets for a rapid cycling synchrotron and for an alternative FFAG.

- Exploration and later conceptual design of the superconducting RF systems for the acceleration complex. This may pose challenges in terms of efficiency and beam quality.

- An exploration of the challenges for the technologies used for the collider. For example, cryogenics and instrumentation will face important challenges due to the important beam losses and the resulting high radiation and heat loads, which might require special developments. Also other parts of the collider, such as the beam transfer systems may turn out to be technically challenging and could limit the performance.

- An exploration of alternatives and novel approaches in order to improve the collider performance. This includes the LEMMA approach for the source. Other options might also be considered, e.g. the painting of the neutrino beam by wiggling the muon beam.

As the first exploratory studies yield conclusions a more refined work programme can be defined focusing on the key design drivers.

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