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 $\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$ process is feasible in this harsh environment, with a precision on $\sigma(\nu\nu H) \cdot BR(H \rightarrow b\bar{b})$ 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 $\mathcal{L} = 1.8 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ and explore a potential second stage, tentatively at 14 TeV and $\mathcal{L} = 4 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$. 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 relevent colliders.

To get starget, 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 superseedes 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 normalconducting, 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 vaccum 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 indispensible. 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 instrastructure 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 consideratons

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 betafunction 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 beamloading 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 betafunction. The focusing system at the collision point needs to achieve the small betafuction. At higher energies the focusing becomes increasingly difficult as the stiffer beam requires more integrated quadrupole strength and the collision betafunction 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 betafunction would be limited by the beamsize 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 betafunction. It would also increase the luminosity because it decreases also the beam size in the focusing magnets which would allow to reduce the betafunction 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 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 sytem 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 global target parameters for 3 TeV could be based on the proposal at the Muon Meeting. They would have significant uncertainties. A set of more detailed tentative parameter tables for the different subsystems could be developed using ad hoc assumptions and some results from MAP. The 10 to 14 TeV parameters suffer from a too high radiation if they are based on the MAP parameters choices.

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 a 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 synchroton. In this solution the magnets in the ring would be ramped up rapidly to follow the increasing beam energy. Typicaly this ramping has to be done in the millisecond range. One can consider a mixture of high-field static and fast ramping magnets. 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 consquently high cost. These options have to be developed to a suffient 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.

7.6 Collider Ring Design

The integrated design of the collider is important for the achieveable 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 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 betafunctions, which makes the lattice design increasingly difficult; at 14 TeV centre-of-mass energy a beta-function of 1mm is the target in both planes. The triplet also can impact the background condition significantly and has to deal with a significant flux from beam loss.

7.6.2 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 betafunctions.

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 mangets 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 achieveable 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 i nthe 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 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.

7.9.2 Mitigation techniques

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

7.10 Machine Detector Interface studies

The machine detector interface needs to be considered. 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. The machine induced background in the detector is very high and needs careful study and development of mitigation methods to ensure that the physics goals are not compromised.

7.11 Parameters and Layout

The overall concept of the collider and its key paramters have to be developed and optimised taking into account the limits of the different sub-systems and the tradeoffs 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 expertises 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 environnement 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 betafunctions, since the transverse equilibrium emittance is proportional to the average betafunction 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 betafunction in proportion $\beta^* \propto \sigma_z \propto 1/E$. This in turn will increase the betafunctions 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 betafunction 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 correctors, will also be required.

8.3 Fast ramping magnet systems

The rapid cycling synchrotron solution for the accelerator ring requires fast ramping magnets and efficent 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 muoncollider is to achieve a high RF to beam efficiency while keeping negative effects of the beamloading 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 beamloading effects. The RF, magnet and targets have to be highly integrated posing a particular challange.

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 beamloading 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 imrpovement 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

Instrumentaion will be important for the collider performance. It has to be adapted to the special environnement, wich 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 accelratign 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

$$\mathcal{L} \propto \frac{N}{\sqrt{\epsilon_x \epsilon_y}} \tag{4}$$

This parameter is directly proportional to the beam-beam tuneshift. 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 tuneshift.

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

to be detailed

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 inital 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 betafunctions.
  - 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.