Muon Beam Community Meeting Summary

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In Europe, the CERN Council has charged the Laboratory Directors Group (LDG) to develop the Accelerator R&D Roadmap for the next decade before the end of 2021. This Roadmap will consider different funding scenarios and contain deliverables and demonstrators. Council is expected to decide on the Roadmap by the end of the year. As a consequence the Roadmap will define the R&D for the next decade. In this frame a Muon Beam Panel has been created by the LDG. In order to prepare the Roadmap three community meetings have been planned. The first community meeting took place on May 20th and 21st

The muon beam panel of the LDG called a community meeting on 20th and 21st May 2021[1]. Nine working groups were formed. The working groups were charged to identify the R&D that has to be carried out before the next European Strategy Update to scientifically justify the investment into a full CDR for the muon collider and the corresponding demonstration programme. This included R&D to develop a baseline collider concept, well-supported performance expectations and an assessment of the associated key risks, cost and power drivers. Further, the working groups were charged to identify the main components of an experimental demonstration programme together with the corresponding preparatory work. The working groups were asked to propose realistic but ambitious targets for the performance goals of the different collider systems and consider what could be assumed for the demonstration programme, i.e. in one or more test facilities starting in 2026, as well what could be anticipated to be available in 2035-2040 for a first collider stage and in 2050 for an energy upgrade.

The nine working groups and their conveners were:
RF: Alexej Grudiev, Jean-Pierre Delahaye, Akira Yamamoto, Derun Li.
Magnets: Lionel Quettier, Soren Prestemon, Sasha Zlobin.
High-energy complex: Antoine Chance, J. Scott Berg, Eliana Gianfelice-Wendt, Angeles Faus-Golfe, Alex Bogacz, Shinji Machida, Christian Carli.
Muon production and cooling: Chris Rogers, Diktys Stratakis, Chris Densham, Marco Calviani, Katsuya Yonehara.
Proton complex: Simone Gilardoni and Frank Gerigk.
Beam Dynamics: Elias Metral, Rob Ryne, Tor Raubenheimer.
Radiation protection and other technologies: Roberto Losito, Claudia Ahdida, Vladimir Shiltsev, Philippe Lebrun, Mike Seidel.
MDI: Donatella Lucchesi, Nicolai Mokhov, Christian Carli, Nadia Pastrone.
Synergy: Kenneth Long.

Each working group assembled input from experts. The working groups provided summaries which are gathered in this document.

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1 https://indico.cern.ch/event/1030726/

Muon collider RF working group: Summary of challenges.

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J.P. Delahaye, A. Grudiev, D. Li, A. Yamamoto

Muon capture and cooling

RF system parameters and challenges:

- Complex **normal conducting RF (NRF)** system, and many of the cavities need to be independently powered and controlled at many different frequencies in the ranges from 20 to 650 MHz. Majority of the cavities operate at two main frequencies: 325 and 650 MHz at high gradients in a strong magnetic field at multi-Tesla magnitude.
- **Low frequency (large cavity):** **325 - 650 MHz,**
- **High gradient:** **25 - 30 MV/m,**
- **Strong magnetic field:** **5 - 10 T**
- **High peak current before bunch merge:** 3.6E12 μ @325MHz => **187 A**
- **Large bunch charge after bunch merge:** 7.3E12 μ => **1168nC**
- **Large beam aperture/window:**
- **High level of beam losses and decay radiation**
- **Technology is far from being mature**. The closest example is a positron capture RF cavity: high frequency, high gradient, but not in so strong magnetic field.

Critical issues and R&D on NRF:

- **Gap** between **performance** of the prototype and the test cavities achieved so far must be closed. Based on the nominal parameters from the Muon Cooling WG: frequency, gradient, B-field, aperture and on the existing (and future) test results, design, build and test prototype cavities for the muon cooling test facility.
- **Achievable high gradient** in a **strong magnetic field** requires continuous R&D on: alternative materials, gas versus vacuum, operation temperatures, pulse shapes and other new ideas. This requires a dedicated test stand on a time scale before the muon cooling test facility.
- **RF power source**: Existing commercial RF power sources are by design operate at lower peak power but higher average power than what is needed for muon collider. This is driven by current applications. A new design of the RF power source targeting muon collider parameters (higher peak power, lower duty factor) and high efficiency must be pursuit.
- **Engineering design and integration:** RF, SC magnet, cryogenics, etc.
- Safety, maintenance and etc. associated with using Beryllium materials on cavity walls and beam windows.
- **Collective effects**: beam loading, single and multi-bunch must be addressed.

Accelerators and collider

RF system parameters and challenges:

- Super conducting RF (SRF) system for **high efficiency** and **highest acceleration rate** to minimize the muon decay losses on the way to very high energies: ~10TeV
- **Large bunch charge in the linacs:** 3.6E12 μ => **576nC**
- **Large bunch charge in the rings:** 2.2E12 μ => **352nC**
- **Short bunch length in the collider: 1.5 mm**
- **Highest possible gradient**
- **Power efficiency**
- **High energy gain per turn in the rings**
- **High level of radiation**
- **Stray magnetic field**

Critical issues and R&D on SRF:

- **Design of the RF system** including: acceleration, longitudinal beam dynamics, wakefields, bunch length and energy spread control must be done to provide specification for RF cavity design.
- **High gradient at low frequency multi cell cavities**: 325, 650 MHz with seeking for common SRF cavity frequency beneficially applicable to various project with saving synergy.
- **Technology** choice: Bulk vs Coating; Different materials: Nb, Nb3Sn, HTS, …
- Cavity **type(shape)** for high gradient and low loss factor.
- **Pulsed operation**. **Lorenz force** detuning and High-Q resonance control in pulsed mode.
- **RF power sources**: pulsed, high peak power, high efficiency.
- Tolerance to external (stray) **magnetic** fields. Common motivation with HTS beam-screen under 16 T or more for the FCC-hh
- Tolerance to the radiation and beam loss.
- Power couplers

Collider magnets summary

The muon collider will require several different types of superconducting magnets, with have different requirements (geometry, field level, size and aperture, energization mode…) to answer to physics goals in each area. The First Muon Community Meeting hold on 20 May and 21 has been a very good opportunity to clarify physics needs, magnets requirements, and to initiate discussions on R&D topics that have to be carried out before the next ESSU-PP. The main conclusion is that magnets are critical in the target/front end, cooling, acceleration, and collider ring areas, and that they will have to be operated in a high radiation environment, with high radiation loads.

Target area and Front end

In the target area a large-aperture high-field solenoid is needed. The most promising option is based on a hybrid configuration, composed of a 5 T resistive magnet, inserted inside an outer superconducting solenoid. The central field of SC solenoid should be between 15T to 20T—with the inner diameter of superconducting coils up to 1.2 m to provide a sufficient space for the resistive section and central shieling bore. A strong effort will be needed to optimize the design. Given the field level, the outer superconducting magnet will probably combine NbTi and Nb_3Sn coils. The design will have to address several challenges, especially the high radiation loads and the large magnetic forces. A balance will have to be founded between field level, operating temperature, magnetic forces, stray field shielding… Some experience with detector solenoids, ITER central solenoid and on-going projects of high-field solenoid at NHMFL and in Europe may be used. A specific R&D may be needed to develop reinforced superconductors. Given their current level of maturity, it does not seem reasonable to use high temperature superconductors for this magnet. Finally, experimental studies shall be planned to validate how the magnet cooling design can withstand the very high heat deposition.

Cooling area

In this area, high-field large-aperture solenoids and several configurations with normal RF cavities inside or in-between are considered. The level of field in majority of magnets allows using Nb3Sn superconductor. In the final cooling stage very high field solenoids will be needed. The field should be higher than 30 T, and the inner aperture diameter should be 50 mm for the final cooling. These solenoids will require using hybrid coils with HTS and LTS sections. These are very ambitious parameters, that will lead to very high mechanical forces. In addition, the magnet will be exposed to very high radiation loads. One will have to use high temperature superconductors that will require an ambitious R&D program to increase by far their existing performances, as well as prototypes to validate manufacturing techniques, quench protection, and mechanical stresses management.

Acceleration

In this area, physics needs rapid cycled magnets able to generate +/- 1.8T @ 400Hz. Given this field level and this frequency, a strong effort is needed to develop new power converters and high efficiency power supplies, as well as to manage the high AC losses generated inside the magnet in addition to the heat power deposition. R&D should be carried out to develop low losses conductors and magnet structures. The magnet protection may also require some specific development due to the stored energy, again, especially in case HTS would be used. Finally, a strong effort is needed to assess aging and fatigue of superconductors and other structural materials exposed to high radiation, and mechanical cycling.

Collider ring and IRs

The baseline 3 TeV collider needs high gradient quadrupoles (up to 250 T/m) and high field dipole magnets (up to 8 T) with large apertures (from 80 mm to 180 mm) in IRs and combined function 150 mm aperture magnets with dipole field up to 10 T and gradient up to 85 T in the arc. Larger energy machines will require even larger apertures to accommodate thicker absorbers. The maximum field in magnet coils reach ~17 T that is the practical limit for the Nb_3Sn magnets. Using hybrid HTS/LTS coils to increase the operating field and margin and curved magnets may be also considered. In any case, the two main technical challenges are related to the large mechanical forces in magnet coils and to the magnet protection from radiation. To control the mechanical stresses in brittle Nb_3Sn and HTS coils stress management approach has been proposed and being experimentally studied by the USMDP. Magnet radiation protection will be provided by thick Tungsten absorbers in magnet apertures and by masks in between magnets. For now, objectives of demonstrators have still to be discussed.

MDI

The detector is based on a CLIC-like solenoid of 3.6T detector with a free bore diameter of 6.9m. While the design is ambitious in terms of size and field, there are no major stoppers identified. The design is based on proven manufacturing, cooling and protection technics and the main challenge will be the development of an aluminium-stabilized NbTi conductor, as there is currently no supplier able to do it.

Summary of the challenges for the High Energy Complex Working Group

The proposed studies and refined designs of the HEC aim at ensuring feasibility and keep the cost (acceleration efficiency) within reasonable limits. The achievable luminosity and thus the physics reach of the complex depend also on the collider design. The HEC has to handle many challenges (neutrino hazard, magnet protection, energy efficiency…). The HEC WG identified and prioritized 14 R&D items:

Criticality 1 (high):

1) High gradient and quality factor RF cavities and efficient power supplies and couplers.
2) Short cycling magnets with efficient, reproducible and stable power supplies.
3) Parametric model of the HEC.
4) Global Lattice design of the full HEC, including “s2e” simulations
5) Radiation mitigation by moving (mechanical wobbling) the beam/magnets / alternative optics in the collider.
6) Radiation mitigation in the arcs.
7) Tolerance and feasibility studies (magnets: multipole errors, power stability, misalignments,… ; wobbling impact; and so on)

Criticality 2 (medium):

8) FFAs as an alternative to pulsed synchrotrons.
9) Longitudinal and transverse beam dynamics studies in the HEC.
10) Development of adapted simulation tools.
11) Machine tuning with combined magnets (independency of dipole/quad field variation)

Criticality 3 (low):

12) Optimize the design of the linac and RLA.
13) Build a synergy around FFAs (spallation sources for instance)
14) Usefulness of sextupoles (non-linear elements) in pulsed synchrotrons.

Each item listed above is important because:

1) Higher gradient enables to reduce the acceleration time and to increase the muon survival. Efficient cavities enable to reduce the operating cost.

2) One of the cost drivers is the efficiency of the power supplies and magnets of the RCS. Any improvement will dramatically reduce the operating cost. The reproducibility and stability of the power supplies are important because the acceleration is so fast that feedback systems will be difficult to use.

3) Most of the acceleration rings are conceptual. Before going to the lattice design, we should put together the different scaling rules to identify a set of parameters for a baseline, coherent with the different constraints (magnets and RF cavities, impedance models, power consumption,). Longitudinal and transverse beam dynamics are also a key point to preserve the emittance during the process.

4) Lattice for the whole HEC are mandatory for detailed beam dynamics studies and for a thorough tolerance analysis. The different lattices should be stored on the CERN repository to share them with the community. The collider has already a lattice from MAP and new lattice studies are ongoing with a racetrack configuration. The insertions (injection, interaction regions, RF sections) should be integrated in the full lattice. How to mitigate nonlinear effects in the collider is to study with open questions like nonlinear effects of momentum compaction or chromaticity correction.

5) Neutrino hazard is a strong limitation for the machine performance. Three options are under study: 1) mechanically moving magnets. 2) Slow varying horizontal dipole fields introducing vertical orbit wobbling. 3) Lattice with skew quadrupoles with vertically shift (fixed) which produces horizontal fields. The mechanical option needs a demonstrator to test the stability and reproducibility.

6) Muons continuously decay in the machine. Estimating the impact of these losses requires updating and harmonizing the radiation tools and FLUKA models for the interaction region and the arcs. The compatibility with vacuum and cryogenics operations is to be checked. The option using open mid-plane dipoles is to be checked.

7) They are an input to validate the different technological choices like the power supplies or the field quality. For instance, in the RCS, the required field quality enables to validate if HTS pulsed magnets can be used. The multipole errors and misalignments in the collider can limit its performances. The full remote alignment system is to validate with a test bench.

8) At lower energies, driving the magnets requires very rapid ramp rates. An alternative is FFAs, using DC fields. The vertical excursion FFA (vFFA) is a new concept, not yet demonstrated on a machine, with unique coupled optics and a great importance of field maps. Theoretical and numerical developments are to pursue. The next step requires to get a realistic design and to check the feasibility of the parameters.

9) The peak current is very high making beam loading, coherent wakefield effects and beam-breakup instabilities are potential issues in the RLA, limiting the number of passes in the RLA. We should deeply study these phenomena. The collider operation is close to the isochronous condition in order to keep a reasonable RF voltage, which means that there will be no help from a high synchrotron tune for beam instabilities. The significance of the single-particle effects (working point, beating,…) vs. the short muon lifetime are also to be assessed.

10) We need to fully understand and simulate several mechanisms in the HEC. That required developing: non-standard acceleration schemes; tools to study collective effects for vFFA for instance; handling muon losses and new collimation schemes.

11) The current way to mitigate the neutrino flux from the arcs is to use combined functions magnets. The operation requires independently tuning the different multipole components. A scaled prototype should validate this functionality.

12) The linac design enables to optimize the capture and compression of the beam after the cooling. Entire design of a low energy acceleration complex (linac + RLA) is strongly driven by the achievable degree of the longitudinal and transverse cooling) e.g. choice of the RF frequency, cavity phasing profile etc. The linac and RLA can benefit from the RF developments for intense beams. The choice of the final energy of the RLA will depend on the cost optimization and on the stability in the RCS or FFA rings.

13) The interest of the FFA is beyond the muon collider. It can have a great interest for small synchrotrons or for spallation sources. Building an enlarged community using this kind of optics can help in funding a demonstrator.

14) In an ordinary synchrotron, the chromaticity correction mitigates the head-tail instabilities. The usefulness of the sextupoles in the operating regime is to be checked. A lattice with no sextupoles enables to get a higher dipole packing fraction and avoid feed-down since the beam will likely move in the sextupoles during the ramp.

Muon Production and Cooling – Summary of Challenges

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Muon Production and Cooling System – MAP Design

The current muon production and cooling system is based on the design generated by the Muon Accelerator Programme (MAP). Multi-MW protons incident onto a target immersed in a 15-20 T field produce pions. Liquid mercury was considered as a target option. The pions are captured in a field which tapers down to 2 T. The pions decay in the field taper and through the initial chicane. Particles outside the momentum acceptance of the front-end system are removed by means of a chicane. Low energy protons, which would give rise to significant activation in the downstream cooling section, are removed from the beam by a Beryllium plug. The remaining muons and a significant electron population are transported through a longitudinal drift, buncher and energy-phase rotation system to yield a train of bunches at 325 MHz.

The bunched muon beam is first cooled in the “HFoFo” that is capable of cooling both signs of muons, followed by the charge separator, the sign-specific rectilinear cooling system, bunch merger, and another set of rectilinear cooling of the single bunches. A final section of transverse-only cooling provides the low transverse emittances required for the high luminosity muon collider.

The challenges in developing the muon production and cooling system can be divided into three levels: those challenges that are critical to deliver a self-consistent and practicable design; challenges that are essential to deliver a good performance estimate; and issues that may have an impact on the eventual system performance.

Critical Challenges

The MAP scheme has explored conceptual production, capture and cooling across the emittance space required for a muon collider and shown a feasible way forwards for a design. However no self-consistent baseline or coherent engineering assessment exists. The delivery of a single self-consistent baseline is an essential step in the delivery of the cooling channel. In particular, the following elements are in need of particular attention.

- A self-consistent baseline for cooling before the merge should be established. Appropriate hand-off points in emittance space should be found between the dual-sign HFoFo, charge separator, multi-bunch rectilinear cooler, bunch merger, single bunch rectilinear cooler, and final transverse cooler, including reoptimisation of the existing cooling designs where necessary.
- The final cooling system is an important performance driver for the entire facility. Assessment and optimisation of the available final cooling systems is necessary. Consideration should be taken of the possible application of high field solenoids for a transverse cooling channel, as well as alternate schemes such as more rectilinear cooling, parametric ionisation cooling and reverse emittance exchange.
- A preliminary physics and engineering study of the target solenoid system, including study of the magnetic forces, stray field management and required shielding materials is necessary, taking into account both heat load on the cryogenic systems and radiation damage to the superconducting assembly.
- Selection of appropriate target material considering existing regulatory frameworks is required. The MAP mercury target is not expected to be compliant with European regulations nor with the reliability required by the muon collider. Consideration of materials should include light material such as graphite, a granular packed bed, fluidised tungsten targets and heavy liquid metals (HLM). Systems for appropriate management of the residual

proton beam and associated radiation around the target area require study in light of the modified target.

- In light of the above challenges, a combined physics and engineering study may find a more conventional magnetic horn to have a higher integrated performance than the current baseline solenoid. This should be examined,
- including consideration of capturing reverse focused alternately charged pions in addition to the forward focused pions.

In order to meet these challenges, it is essential that codes and appropriate computing resources are maintained and available.

A demonstrator facility is essential to provide:

- Demonstration of six-dimensional cooling and reacceleration, at an appropriate emittance point so as to demonstrate cooling potential over a broad range of cooling channels; and.
- Demonstration of the muon production target system with appropriate scaling of beam conditions suitable for a muon collider, to validate design choices for shock and thermal loading and superconducting material performance in an appropriate radiation environment.

Challenges to Deliver a Realistic Performance Assessment

In order to assess the ultimate performance of the muon collider facility, the following challenges must be met.

- A more thorough study of the requirements for radiation management in the target area, including concepts for management of thermal and radiation load on material in the target itself and surrounding shielding and magnets.
- Further study of the target systems, early integration studies including concepts for remote handling and radiation protection issues of the entire facility, focusing in the area up to the end of the chicane.
- Re-optimisation of the target chicane and preliminary consideration of radiation load and relevant shielding is necessary.
- A study of the current and near-term availability of magnet systems both for final cooling and rectilinear cooling. In light of this, an assessment of the possible performance of the cooling system.
- A study of the availability of RF gradient in the context of high magnetic fields, and the relevant performance impact of the cooling system.
- Optimisation of lattices to improve transmission, paying particular attention to matching between components.
- Preliminary studies on the charge separation system have been performed. A more thorough design that enables proper evaluation of transmission and emittance budget is necessary.
- The bunch merge system uses a set of RF cavities comprising a number of harmonics of 325 MHz that are not found elsewhere in the bunch system, as well as a unique pulsed magnet. Engineering studies are required to determine the availability of components and their suitability for inclusion in this lattice.
- Consideration of critical engineering issues, such as requirements for force management between adjacent magnets, beam windows, cryogenic needs for magnets in close proximity to warm RF cavities and allocation of space for appropriate alignment systems and diagnostics. Assessment of the impact on performance.

Challenges to Deliver a Robust Performance Assessment

In order to demonstrate that the performance assessment is robust, further studies on potential technical issues must be addressed.

- Study of material physics processes in the cooling systems. Impact that mis-estimate of the material physics processes may have on the cooling systems, in the light of the material physics modelling and experimental evidence.
- Study of collective effects. Conventional collective effects should be studied, such as space charge and beam loading. Exotic effects such as wakefields in materials and effect of absorber heating on the cooling performance.
- Study of the required alignment, tolerances and methods for their correction should be performed.
- Early civil engineering, radiological and licensing studies of the target complex, in order to assess showstoppers or any critical or challenging aspect, resulting from the target complex systems integration study.
- Investigate the need and possibility to perform an experimental validation of understanding of high intensity effects, for example by using a high-intensity proton source with appropriate scaling for differing energy loss in the absorbers.

Proton driver summary

The proton driver scheme for the muon collider foresees a high-power Linac with an energy of few GeV and an accumulator and compressor working at fixed energy .

Alternative schemes, like using an FFA to replace the two rings, has been proposed as an option.

The proton-on-target repetition rate should be down to 5 Hz, with a baseline delivered power of 2 MW but with possibly of reaching 4 MW.

Strategy to assess the feasibility of a multi-MW proton driver

Different facilities have been operated for many years delivering MW on target during regular operation. In particular, SNS and the J-PARC RCS are operating at and beyond 1 MW with high operational efficiencies. While the proton time structure and bunch length is not exactly what is needed for the muon collider, and the power is below the desired 2 MW, the beam power is close to the requirement and the primary proton energy range is not too far away from the one that would maximise the secondary pion production, i.e. 5-10 GeV. These differences however do not put in question the fact that their successful operation is indicating the proton driver of the muon collider as feasible.

In fact, for example, studies for the J-PARC RCS are progressing to investigate the performances up to 3 MW, where the only evident limitation comes from the direct space-charge tune spread at injection energy. This, however, could be solved by increasing the injection energy.

The ESS Linac, as the PIP-II at FNAL, will also provide MW class beams to their users in the near future. In this case, the muon collider proton driver could clearly profit from the technological developments introduce by these facilities.

Some consideration on proton repetition rate

Existing examples of proton sources either in operation or studied as proton driver are designed with high repetition rates as:

- SC-Linac+accumulator+compressor (PDAC) at high repetition rate – 50/75 Hz
- J-PARC – 25 Hz
- SNS – 60 Hz

This will imply high repetition rates on target or the need of a bunch recombination scheme to mimic low repetition rates, down to 5 Hz, of bunches once delivered on target.

In this view, an FFA-based proton driver could constitute a valuable alternative to more conventional schemes. The FFA could in fact serve as accumulator and compressor thanks to its very large momentum acceptance by design.

Questions to be answered:

- *Is the p-driver for the muon collider well within reach?*
  No evident showstoppers in building a proton driver conforming to the requirements of the muon collider could be identified during the presentations and the discussions.

- *Can we extrapolate from existing proton sources?*
  Existing neutron spallation sources like SNS in Oak-Ridge are already operating beyond 1 MW (1.4 MW), whereas the RCS at J-PARC is running at 1 MW with studies ongoing to reach 3 MW and a test at equivalent power of 1.5 MW

- *Which kind of challenges we could expect?*
  Besides operational challenges, the main concern is the missing operational experience in creating so intense bunches for few-ns bunch length. In this sense, synergies could be found in the studies for short pulse neutron sources.

- Which kind of R&D studies are missing to bring us to a reliable multi-MW proton source for collider operation?
  - Refer to the next section.

Subject discussed as candidates for R&D/Studies

Different topics have been discussed, in the view of their importance, with the intent of determining: if the existing technologies are already adequate for the realization of the proton driver; if significant developments are required; or if there are major limitations that might become fundamental showstoppers.

Namely:

- Optimization of RF efficiency: No technical showstoppers could be identified.

  - HE-klystrons are already being developed at CERN but they would need continued effort and should enable sizeable wall-plug-power savings. R&D should be put on that.

  - Long pulses are better for power efficiency because less power is “wasted” for “filling” and “emptying” the cavities.

- Klystron power converters: no technical showstoppers.

    - High efficiency klystrons typically use reduced voltage, which simplifies a lot the power converter

- H^- ion sources: Low repetition-rate, long-pulse and high-current H^- source will need significant R&D effort

- Uncontrolled H^- stripping: Magnetic stripping of H and intra-beam stripping of H^- are nowadays understood and should pose no limitations.

- H^- injection in accumulators: two existing technologies, foil stripping and laser stripping, should pose no significant limitations.

    - Lifetime and injection hardware activation might become a limiting factor
    - SNS predicts limit for the foil at 5 MW

- Beam stabilities in the compressor/accumulators: studies should be resumed with the latest beam dynamics computational tools, some investigations done in the past are now more than 15 years ago. Better understanding of many limitations improved, like space-charge, electron-cloud, impedance-driven instabilities.
  Losses and halo formation should be also considered.

Observation on timescale towards Multi-MW operation.

Operational experience from existing proton sources shows that a few years are necessary to reach the nominal power-on-target. This should be considered while planning the collider start-up.

Conclusions

No fundamental showstoppers could be identified in the realization of a proton driver delivering 2 or 4 MW on target.

Based on experience in the design, construction and operation of existing proton sources, the technologies and the power ramp-up are challenging but can be solved by continued commissioning effort and gradual improvements (e.g. as done at SNS to ramp up the power). Technical and physics related challenges are there, but solutions have been found.

H^- sources and the accumulator - compressor rings are the most critical items that need an immediate and prolonged R&D effort.

FFA-based alternative solution should be explored.

Summary of the challenges for the Beam Dynamics Working Group

Even if everything needs to be done quickly with muons (due to the short lifetime), many issues can happen with high bunch charges and high impedances (which is the case here with the many RF stations all along the muon collider chain) and many aspects need to be carefully studied. The BD-WG identified and prioritized 12 R&D items (many thanks to all participants, MAP experts, Daniel and Mark):

Criticality 1 (high):

1) New beam dynamics regime during acceleration
2) Opposite sign bunches – beam crossing and wakes
3) Design of the full chain (acceleration in particular)
4) Radiation mitigation by moving the beam / magnets in the collider
5) Collective instabilities during ionization cooling

Criticality 2 (medium):

6) FFAs as an alternative to pulsed synchrotrons
7) Longitudinal and transverse beam dynamics studies in the collider
8) Development of simulation tools

Criticality 3 (low):

9) Halo formation and beam losses in the Proton Driver
10) Check of all cooling studies with a second code
11) Are sextupoles needed in pulsed synchrotrons?
12) Impedance models

1) is important because the longitudinal and transverse emittances need to be preserved to reach the required collider's luminosity and control the orbit. The issue is that we need to handle 2 high-charge bunches, one of μ^+ and one of μ^-, with a lot of RF (which means a strong longitudinal focusing and a high impedance) and we need to be fast: this is a unique regime for collective dynamics, and the consequences for beam stability and operation (e.g., phase shifting to compensate potential well distortion) need to be understood.
2) is important because both signs of muons are accelerated simultaneously in the rings. There will be 2 beam-beam collision points with wakes in the cavities, which will vary depending on where the cavities are in the ring (cavities must be distributed in several uniformly-spaced stations in the ring). The impact of these collective effects should be understood.
3) is important because right now most of the acceleration designs are conceptual, with few details available. We should start to put together detailed designs and agree on a set of baseline accelerator parameters, which is essential for refined studies (lattices for all stages, from past studies or to be developed/optimized, which should be stored in the versioning CERN repository; RF frequencies; etc.). A particular emphasis should be placed on the longitudinal dynamics since preservation of longitudinal emittance is critical but the transverse plane should not be overlooked.
4) is important as this might be needed to reach acceptable levels of radiation, which is a fundamental aspect of the study. All the consequences for the beam dynamics need to be carefully analysed.
5) is important because such mechanism could jeopardize the generation of high brightness muon beams through ionization cooling. The knowledge of collective instabilities that could arise from the interaction of the beam with electromagnetic wake fields propagating in

matter (absorbers, gas-filled RF cavities, etc.) as well as with the pair of charges generated by ionization is practically non-existing.

6) is important because particularly at lower energies, driving the magnets requires very rapid ramp rates. The challenges associated with this may drive us towards alternatives, in particular FFAs. For example, the vFFA is a relatively new concept with unique coupled optics and a great importance of fringe fields, no machine was constructed yet and there are no dedicated tools to study collective effects.

7) is important because we need to operate the collider close to the isochronous condition in order to use a reasonable RF voltage, which means that there will be no help from a high synchrotron tune for beam instabilities (both longitudinal and transverse). The significance of the single-particle effects (resonances, working point, β-beating, …) vs. the short muon lifetime need also to be assessed.

8) is important because we need to have a detailed understanding of the many challenging mechanisms and new regimes: the collective beam-matter interactions need to be studied; non-standard acceleration schemes need to be developed; tools to study collective effects for vFFA for instance need to be developed; what about the study of the muon losses (we cannot collimate because muons go through everything and the issue is the decay products…)? Etc.

9) is important because the more protons (and therefore the more muons we create), the easier it is afterwards. The issue is that we need a high (few MW) beam power, with a short (1-2 ns) bunch length and in particular a low (5 Hz) repetition rate.

10) is important because cooling it the key ingredient for a muon collider, and therefore it has to be fully understood and optimized. One should not rely on only 1 code (ICOOL, for which the most complete simulation studies were made) and use G4BL and/or G4MICE to check all the past results (e.g. ICOOL does not do hadronic interactions).

11) is important because in an ordinary synchrotron, it would be important to correct the chromaticity to mitigate the head-tail instabilities. Is that needed in our operating regime? It would be preferable to avoid sextupoles to maintain a high dipole packing fraction and avoid feed-down since the beam will likely have to move in the sextupoles during the ramp.

12) is important because building a realistic impedance model of a machine is a necessary step to be able to evaluate the machine performance limitations, identify the main contributors in case an impedance reduction is required, and study the interaction with other mechanisms such as optics nonlinearities, transverse damper, noise, space charge, electron cloud, beam-beam (in a collider) … It requires time and resources, with many interactions with the equipment groups and here the impedance of many machines need be built. However, the impedance from RF and the resistive-wall impedance dominate the cooling and the acceleration stages and therefore, there, it could be quickly done.

Radiation Protection Challenges

Neutrino Radiation

The main radiation protection challenge of a muon collider is the neutrino radiation emitted by the collider ring and its impact outside the complex. The neutrino radiation arises from the muon decays that produce a neutrino radiation disk emitted out tangentially from the collider ring with radiation hot spots created by straight sections of the collider. Neutrinos are so penetrating that even the earth between the facility and the very distant places where the neutrino radiation disc emerges on the surface is not sufficient to reduce the neutrino flux considerably, which makes the radiation hazard challenging. The exposure comes from secondary particles produced by deep inelastic scattering of the neutrinos in the upstream earth. Several past studies have generically addressed the potential neutrino doses showing a substantial neutrino-induced dose at far distances from the collider, particularly from straight sections. At the same time, the studies have proposed several possible mitigation methods and have shown the need for a more reliable dose estimation. An optimized and refined dose model is needed in particular for reducing individual effective doses to members of the public to about 10 μSv or less – a constraint below which the optimisation requirement is considered as fulfilled and public acceptance can be expected.

The following two main R&D items were identified to tackle the given neutrino radiation challenge.

R&D item – Refined dose model

A refined dose model for a reliable and precise estimation of neutrino-induced doses outside the complex shall be developed and used for a collider ring optimization to minimise the dosimetric impact on the public.

Such a dose model shall be based on the stipulated collider parameters. For the well-defined operational modes and scenarios, including accidents, the neutrino source term shall be defined and optimized. The optimization shall cover the optics design of the collider ring insertions, in particular the final focus, the RF section, as well as the injection and extraction. Further mitigation methods such as orbit oscillations could be investigated. Additional refinement and optimization shall also assess civil engineering challenges, for instance the depth and inclination of the collider ring layout. A surface map showing the regions impacted by the neutrino radiation shall be established.

The given dose model shall allow for a full path assessment between the source and the impact locations. In addition, it shall be used for evaluating the fluence spectra of the secondary particles produced by the neutrino interactions needed to design suitable monitoring instrumentation.

In addition, a sensitivity analysis for the model parameters, for example alignment, optics, material properties, etc., shall be performed. The underlying simulation models and codes shall be validated as well.

The representative person from the public shall be finally identified for which the final dose assessments in planned as well as potential exposure situations will be carried out to demonstrate the facility compliance with the radiation protection regulations in force.

R&D item – Mitigation by movers (“mechanical wobbling magnets”)

One solution to mitigate neutrino-induced hazard from a muon collider would be to move the beam line components to change the beam direction by deforming the beamline in the vertical plane (vertical bending with 1% of main field). These very low frequency movements of components (on a weekly basis) would cover an amplitude of 15 cm, considering an opening angle of ± 1 mrad, 14 TeV in a 200m deep tunnel comparable to the LHC case.

3 key issues were identified:

- K1: The development of large stroke / high resolution movers to perform “safe” remote displacements
- K2: The development of a remote alignment solution to monitor and control the position of components for circular collider for large amplitude displacements
- K3: The study of the accuracy / necessity needed to develop a solution to determine in a continuous way the absolute position of components underground with respect to the surface.

Concerning K1 and K2, a brief look at the state of the art concerning remote alignment of synchrotrons shows that only a very few numbers of synchrotron use remote alignment, on short ranges (maximum 0.5 mm, within sub-micrometric resolution). At CERN, the Full Remote Alignment System (FRAS) will be implemented in 2025 on HL-LHC components over more than 200 m on each side of the ATLAS and CMS collision points to perform a remote adjustment of the components within ±2.5 mm (over a motorized stroke of ± 5 mm). We are far from the 15 cm of amplitude requested. First, a more complete study of the state of the art in other labs should be performed, while establishing in parallel a list of requirements / hypotheses for the solutions to be developed. Second, a study of different options should be carried out, before developing specific solutions and their prototypes. Third, the prototypes should be fully qualified. On top of this, specific points should be addressed like the impact of such a mitigation solution on the cryogenic system, vacuum, and other tunnel systems.

Concerning K3, the absolute position of the accelerator components will have to be known w.r.t. the surface, within an accuracy to be studied. Therefore, an important number of geodetic studies and simulations should be undertaken. In an accelerator like the LHC, the absolute position of the underground components is known during their initial alignment: each component is aligned with respect to the underground geodetic network, determined w.r.t. surface geodetic reference network. Then, during the whole operation of the machine, it is only the relative alignment of components over sliding windows of hundreds of meters that matters: the machine and its shape can drift w.r.t. their initial position and shape. This should not be the case of the muon collider and solutions to transfer in a permanent and continuous way the surface geodetic network to the underground geodetic network should be developed to have an accurate definition of the areas where the neutrinos beams will reach the Earth surface. Then, solutions to store all these underground positions and the corresponding impacts on the surface will have to be developed under a GIS platform.

MDI Summary

The physics goals of a Muon Collider can only be achieved with a self-consistent design of the collider ring, interaction region (IR), high-field SC magnets, Machine Detector Interface (MDI) and detector. At a muon collider the role of MDI is unique, due to muon beams decay products interacting with the machine components tens of meters from the Interaction Point (IP), generating high fluxes of beam induced background (BIB) on the detector.

BIB composition, distribution, rates and arrival time may vary at different beam energies and are strongly related to IR design optimization. The ultimate goal of MDI design is to suppress by several orders of magnitude the BIB rates reaching the detector volume. At the moment, this is achieved by adding absorber shielding around the beampipe region impacting on the detector acceptance and performance.

The most recent studies are based on MAP IR design and optimized MDI at 1.5 TeV [1], as benchmark, and they are summarized in [2] and references therein.
The present absorber solution, proposed by MAP is a twofold cone shaped tungsten “nozzle” with the vertex close to the IP.

To face the need to prepare for specific MDI designs and study the detector constraints, tuned at different energies in the center of mass, the main recent achievement was the implementation of a flexible framework able to read the lattice and optics code optimized at each energy with traditional code like MAD-X, importing the beam line geometry in FLUKA [3]. Over the past ten years, the simulation tools have been extensively used and benchmarked for beam loss studies in the LHC [4], which indicates the predictive ability of radiation field studies for a high-energy collider environment. This FLUKA implementation also allows comparison of results with the pioneering MARS15 studies [5], thus building further confidence in the background rates. With the new tool it is possible to identify the origin and the sources of the BIB and therefore one can act on the IR active and passive elements to minimize the particles’ fluxes on the detector and go toward a second order MDI optimization. Ambitious IR focusing magnet design defines IP parameters and detector size.

To demonstrate the full physics potential required to scientifically justify the investment into a full CDR for a facility with centre of mass energy up to 10+ TeV demands dedicated efforts to optimize the MDI and detector design simultaneously to the IR configuration while aiming at the highest instantaneous luminosity.
Dedicated studies and optimization are needed for the forward region, covered at 1.5 TeV by the tungsten polyethylene-borated nozzle, to evaluate if it could be instrumented to extend detector acceptance.

For the 10+ TeV, we need to study the BIB in detail only when we will have a possible viable IR design. Extrapolating from the current IR and the current BIB is highly challenging, since the processes we have to deal with are not only non-linear, but also hard to predict.

In the following the current work plan is described including the MDI activities shared with other working groups.

MDI Studies done - ongoing

- first proof of BIB mitigation by several order of magnitude at detector volume and IR optimization by MARS15 [1]
- framework to import lattice and optics in FLUKA ready to study any energy

MDI next steps

- shielding absorber optimization including IR design for BIB mitigation at 3 TeV
- identify a strategy to attempt a first absorber design at 10+ TeV, identifying challenges and potential solutions to address these challenges

MDI plans – next 4-5 years

- define and optimize BIB generation tools at each different energy
- explore new ideas for detector shielding to optimize acceptance and efficiency at 3 TeV and then at 10+ TeV
- study of detector magnet at 10 TeV to investigate possible interferences with optics in the IR

Activities shared with other working groups

<u>Accelerator, Magnets and RF design</u>

Activities in progress

- dedicated efforts on the lattice and IR design starting from MAP 3 TeV lattice
- tune a well consistent collider lattice at 3 TeV

Planned activities

- optimize lattice and IR design at 3 TeV up to several tens of meters from IP
- start to design a feasible lattice and IR optimized design at 10+ TeV

  ⇒ The requirement to reduce β^* for higher energies poses strong challenges

<u>Physics and Detector</u>

Major progress has been made recently in understanding physics reach and detector specifications for a Muon Collider detector. More details can be found in [6].

Activities in progress

- full detector with improved tracker and calorimeter capabilities studies at 1.5 TeV with FLUKA/ILCsoft/Geant4 full simulation under final optimization
- optimize detector design and performances with defined physics benchmarks, also exploiting new detector technologies
- detector and on detector read-out technologies and reconstruction tools are key items to improve detector and physics performances in presence of BIB (on-detector logic, timing, granularity, DAQ and back-end data processing)

  <u>⇒ strong links with the on-going work by Physics&Detector Group and the ECFA Detector R&D Roadmap</u>

Planned activities

- optimize detector/reconstruction performances at 3 TeV
- first experiment design and plan R&D for new technologies for 10 TeV

Neutrino induced dose

The maximum radiation dose due to neutrinos generated in the straight section between the focusing structures around the IP are reduced by the divergence of the beam, widening the opening of the effective neutrino radiation cone. Several mitigation strategies were proposed in [7] and we do not therefore consider it as an insurmountable challenge. However, further studies are needed to finalize the mitigation strategy and the projected doses.

[1] Y. I. Alexahin, et al., Phys. Rev. ST Accel. Beams 14, 061001 – 2 June 2011
[2] F.Collamati, et al., https://arxiv.org/abs/2105.09116
[3] A. Mereghetti, et al., WEPPD071, IPAC2012 .
[4] A. Lechner et al., Phys. Rev. ST Accel. Beams 22, 071003, 2019
[5] N.V. Mokhov, S.I. Striganov, Physics Procedia 37 (2012) 2015-2022
[6] Physics and Detector Workshop, https://indico.cern.ch/event/1037447/timetable/
[7] N.V. Mokhov and A. VanGinneken, *J.Nucl.Sci.Tech.* 37 (2000) sup1, 172-179

Synergies:

- 1st community meeting explored synergies in:
  - **nuSTORM/ENUBET:**
    - Well rehearsed for this group; synergies from "source to storage ring"
  - **PSI programme:**
    - HIMB, "frictional cooling", solenoid transport
  - **ISIS programme:**
    - Intensity upgrade, especially preparation of ISIS II
  - **FNAL programme:**
    - Intensity upgrades for PIP II era; especially:
      - mu2e target
      - PRISM: target/capture, solenoidal muon transport, FFA ring + injection/extraction
- In preparation for 2nd community meeting:
  - **Need to meet with Asian colleagues to explore, e.g., COMET/PRISM programme**

Synergies for documentation:

- Propose:
  - **Short review of ambitions for evolution of muon-based programme**
  - **Review of synergies:**
    - Likely, key synergies are in the, nuSTORM (ENUBET) & mu2e/COMET/PRISM programmes
    - Identification of places where performance benefit could be derived from adoption of techniques under development for muon collider
  - **Summary of potential for incremental "roll out"**

Demonstrator

Motivation:

A beam test facility is key to demonstrate items of critical importance for the MC luminosity, namely, the 6D cooling and integrated engineering of the cooling cells.

Beam Intensity

10% of the Collider beam intensity is appropriate to test the chosen cooling scheme and the associated components. Consequently, 10^{13} ppp is the requirement for the Demonstrator.

Cooling for the demonstrator

Several schemes are being studied by the community. The community agreed that priority for the studies should be given to a low transverse emittance (<few 100 micrometers) rectilinear scheme. The most challenging requirement is the time spread, that should remain below 100 psec.

As a second option, a high emittance scheme (e.g. HFOFO) should be studied. In this case the transverse emittance is of the order of 10 mm, and the time spread required a few nsec.

Other options that are considered not yet mature are the final cooling (low emittance, 10 nsec time spread), the Cooling ring and the PIC cooling, which both have the potential to be less expensive, but the concepts are not mature yet.

Target/Production solenoid

To demonstrate the efficiency of the cooling channel the relevant parameter is the number of protons per pulse, while average power of the beam can be much lower. For this reason, a demonstrator can be built with average beam power in the order between 10 kW to 100 kW which is not sufficient to test all the limits of a target station that should operate at up to 4 MW, although interesting information can be drawn. The facility will be the first step towards having a fully understood engineering of the target/production solenoid assembly, that is important since muon production will be as efficient as the integration of the target into the solenoid.

The facility can adopt conventional graphite as target material, or other well-established technology in order not to induce any risk on the main goal, which should be to test the cooling efficiency. For the solenoid as well, one can use conservative parameters, as the goal of the facility in this respect will be to benchmark the simulations on critical aspects of the design, rather than final performances.

For this reason, a parallel R&D programme on items such as target and solenoid with offline tests should accompany the facility but can be somehow decoupled from it.

Siting

At present, CERN seems the best option to host the facility given the variety of beams available, and the availability of previous studies (eg. NuStorm, PS2, BDF, CENF) for target and beam facilities on which the study team can leverage to reduce the resources needed for a study. In particular, previous studies give confidence that there are no showstoppers to run at average power of up to

100 kW. In addition, if the facility is constructed at the right depth and with the appropriate solutions (geomembranes, appropriate size, concrete with reduced permeability to tritium), there seem to be no evident showstopper to upgrade it later to a higher power facility, even 4 MW. Finally, the facility could be built in a location compatible to receive beam from the PS initially, and from an HP-SPL as studied in the past, followed by an accumulator and bunch compressor. For the reasons above, it is recommended to pursue the study of a siting in the vicinity of TT10 and the BA1 facility of the SPS, where one could get > 10^{13} ppp with a time spread of 4÷7 nsec, or a smaller intensity (10^{11} ppp) at close to 1 nsec. Such a facility could demonstrate a full 6D cooling scheme.

ESS could host a complementary proposal, based on the Initial Cooling Experiment proposed by C. Rubbia, that could then evolve to a Higgs factory provided the upgrade to 5 MW under study at ESS is approved. Even without the high power upgrade however, a detailed study and demonstration of a full 3D cooling scheme can be demonstrated in such a facility.