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Muon Colliders and their future R&D

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Muons offer a unique opportunity to build a compact high-energy electroweak collider at the 10 TeV scale. It will be a paradigm-shifting tool for particle physics representing the first collider to combine the high-energy reach of a proton collider and the high precision of an electron-positron collider. The International Muon Collider Collaboration (IMCC) has made significant progress in developing a 10 TeV centre-of-mass facility, including the proton driver, target, front-end, cooling, low and high energy acceleration, and a 10 km collider ring with two detectors. The muon collider design is sufficiently mature that R&D is now essential to guide the technological limits of simulations of the accelerator complex. A 10 year R&D plan has been proposed which would focus on developing detector technology, muon cooling technology and the superconducting magnet prototyping. This would enable a first muon collider stage with a start of operation around 2050. It could thus be the next flagship project in Europe. This talk highlights the overall design of the muon collider, the contributions made by the IMCC in recent years, and the aims of the proposed R&D plan.

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1. Introduction

The muon collider is a proposed particle accelerator which will produce, cool, accelerate and collide muon beams. Studies have determined that this concept has no technological barriers, yet Research and Development (R&D) is necessary to determine the engineering limits to constrain the developing designs of the facility.

This report will explain the engaging physics concepts behind *why* we should collide muons, and a commentary on *who* is preparing for this facility. It will present the latest status of the accelerator complex which explains the process of *how* we would collide muons. In particular, *what* technology developments are necessary for each system of the accelerator complex. There will be some consideration of *when* and *where* such a complex may be built.

1.1 Why should we collide muons?

Muons are fundamental particles, ensuring a complete transfer of energy upon collision, whereas composite particles such as hadrons provide only a fraction of their energy upon collision. With respect to energy reach and discovery potential, this means a 10 TeV $\mu^+ - \mu^-$ collision could be roughly equivalent to a 100 TeV $p^+ - p^+$ collision in physics reach [1].

Muons have a mass of 105.66 MeV, which is 200 times more than the electron mass of 0.511 MeV, ensuring a reduced emittance of synchrotron radiation compared to electron colliders. For a same-energy, same-radius collider, the loss in energy from synchrotron radiation is $\Delta E \propto \frac{E^4}{m^4 r}$, equivalent to a factor of 6×10^{-10} less energy lost per turn [2]. Whilst synchrotron radiation emission has the benefit of emittance reduction due to damping, it also requires a recompensation of energy loss, which is unsustainable for high energy electron colliders.

The muon collider has unique advantages as a Vector Boson Fusion (VBF) factory. VBF occurs at centre-of-mass energies $\sqrt{s} \gg M_X$ where the cross-section grows logarithmically as $\sigma \approx \ln(s/M_X^2)$ [2], where M_X is the mass of the vector boson. At these energies, the muon beam PDF includes relatively massless gauge bosons, which radiate like photons. This is an ideal environment for electroweak studies in particular.

1.2 Who works on colliding muons?

The muon collider concept was first considered in the late 1960s [3] but was not developed further until the late 1990s. Since then the idea has been developed through the Neutrino Factory and Muon Collider Collaboration [4], the Muon Acceleration Programme (MAP) [5], which developed a 3 TeV complex design, and now the International Muon Collider Collaboration [6], which is developing a 10 TeV complex design.

The International Muon Collider Collaboration (IMCC) formed in 2022 following the European Strategy for Particle Physics Update (ESPPU) and the ESPPU Accelerator R&D Roadmap. The IMCC is supported by the EU Horizon project MuCol. The muon collider has gained further support in the US from Snowmass 2021 and the Particle Physics Project Prioritisation Panel (P5) which submitted its final report in 2024. The muon collider community comprises over 60 partner institutes drawn from all regions. In particular, the challenges of a muon collider has attracted a large early career researcher community [7] with over 200 attendees at dedicated ECR events.

2. How would we collide muons?

Figure 1 shows the accelerator complex of the muon collider. There are three main challenges to a muon collider:

1. The muons must be produced; most commonly with a high intensity MW **proton** beam incident on a **target** to produce pions which decay to muons. Muons are collected and bunched in the **front-end**. The resulting beam is large, and requires significant cooling in phase-space volume prior to collision.
2. The muons decay; this is a natural time-constraint on the methods used to prepare the beam for collision. For example, the **cooling** of the large beam-size must be done quickly; only ionization cooling is a fast enough process. A significant series of **acceleration** chains is required to reach the target center-of-mass collision energy. LINACS and recirculating linear accelerators deliver high average gradient for the muons at low energy. At higher energy rapid cycling synchrotrons are used, featuring rapid-ramping magnets and multiple RF stations within each ring.
   The beam collides at two interaction points within a dedicated **collider** ring. Muon decays causes a pile-up of high-energy electrons and neutrinos, causing short-range and long-range radiation effects for the detector and surrounding environment.
3. The high intensity beam provides unique **collective effects** across all regions of the complex. Space-charge, beam-loading, impedance, inter-beam scattering and beam-beam effects cause perturbations which will impact the design of the facility. Simulation codes for each system will need to account for these effects, considering these unique beam optics environments.

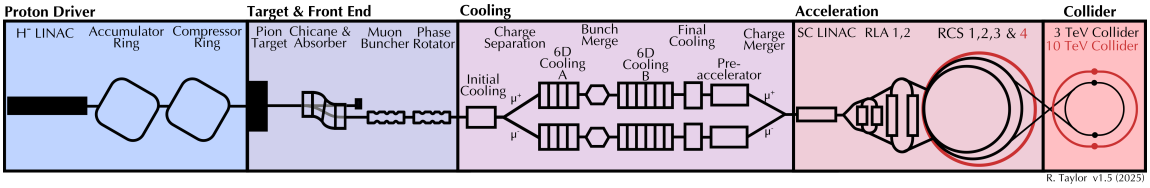

Figure 1: Muon Collider schematic showing each stage of the greenfield design

The collider would not be constructed all in one go, but via a modular path with either a 3 TeV energy stage or incremental luminosity staging prior to the ultimate goal of 10 TeV and 20×10^{34} cm^{-1} s^{-2} luminosity. The luminosity $\mathcal{L}$ of the colliding beams for a muon collider is determined by the following formula [8]:

$$\mathcal{L} = \frac{\gamma^2 \tau_0 c}{2C_{\text{coll}}} \frac{N^2}{4\pi\varepsilon_\perp \beta^*} f_r F_{hg} H_D \tag{1}$$

The baseline has a collider circumference C_{coll} of 11.4 km, with 14 T arc peak field. The muon intensity per beam is expected to be N =1.8×10^{12}. These beams have a transverse emittance $\varepsilon_\perp$ =25 µm and will collide with β^* =1.5 mm focusing at a f_r =5 Hz repetition rate. γ is the relativistic gamma from the 5 TeV beams, and τ_0 is the muon rest lifetime of 2.2 µs. F_{hg} is the hourglass factor where F_{hg} = 0.76 when $\beta^* = \sigma_z$. H_D is a focusing factor from beam-beam interactions. The following subsections will detail the design status of each acceleration system and further R&D required.

2.1 Proton Driver

Overview: The main challenge of the proton driver is to deliver a highly compressed, high intensity proton beam. The proton driver is comprised of a LINAC to accelerate to 5 GeV, an accumulator ring that forms a 5×10^{14} protons into a single bunch, and a compressor ring that compresses the beam into a 2 ns pulse that is sent to the target. The repetition rate of this system is 5 Hz and average beam power is 2 MW. If higher muon charge is required, an alternative design has been developed that can provide a 4 MW proton pulse to target. Due to space-charge constraints, this high power option requires an additional proton acceleration stage to 10 GeV energy. Lattice designs have been produced for the accumulator and compressor rings for both parameter sets [9].
R&D: Future proton driver R&D can be performed in situ at other high-intensity proton facilities. This work has synergies with large-aperture H- sources, and laser-assisted charge extraction injection. The muon collider is a good opportunity to explore the limitations of high-intensity compression schemes with high space-charge.

2.2 Target and Front-End

Overview: The target must accept an impact of 400 kJ per pulse at a 5 Hz rate. A graphite target has been designed and optimized for maximum pion yield [9]. To reach higher power, up to 4 MW, alternative design schemes have been considered, using liquid lead and fluidised tungsten. Existing R&D has been performed using a liquid mercury target [10].
R&D: To capture the produced pions, a series of high-aperture (1400 mm), 20 T HTS solenoids are required. Successful studies of the radiation loads on these magnets guides the required shielding within this region. Given the large-bore high-field magnets within a radioactive environment, the R&D path required for the target-area is highly synergistic with fusion magnet development.
The front-end RF will also require significant development, due to the long spread of the beam and the significant rotation required to capture the full yield of the beam. Beam loading of the front-end cavities will induce similar difficulties as in cooling.

2.3 Cooling

Overview: Cooling reduces the volume occupied by the beam in transverse (x, p_x, y, p_y) and longitudinal (z, p_z) phase-space. In ionisation cooling the muon beam is passed through low-Z energy absorbers and then reaccelerated in RF cavities, giving the beam a net reduction in p_x and p_y distributions. Liquid hydrogen or lithium hydride absorbers have been demonstrated as suitable absorbers. Longitudinal cooling is possible by introducing a dipole, and inserting a wedge-shaped absorber such that the higher momentum particles traverse through more material. All absorbers and RF cavities are placed within solenoidal fields to ensure constant tight focusing and to avoid emittance growth. A compact lattice is used to provide sufficient focusing, but the lattice is challenging to model, design and construct. There has been significant progress in the benchmarking of cooling tools, designs of lattices and the initial studies of collective effects, particular beam loading and space charge. At the end of the cooling complex the beam leaves with 5 MeV energy, so a pre-acceleration system is envisioned which restores the energy to relativistic energies of 250 MeV. The R&D needs have different approaches for the two main cooling stages.
6D R&D: 6D cooling requires many solenoids ranging from 2.6–18 T, with a range of apertures

from 800–60 mm. The RF cavities must be operable in high gradients, up to 30 MV/m in strong solenoidal fields, as high as 10 T. The importance of demonstrating integrated cooling technologies is clear, and plans for such a facility are expressed in subsection 3.

Final Cooling R&D: For the final cooling, maximum focusing is essential to reduce the equilibrium emittance. For this reason, absorbers are contained within a 40 T solenoid. Whilst this is a large field, apertures at this point can be as small as 30 mm. Work is ongoing to study the forces within the magnet, required mechanical bracing, and quench protection measures. The RF cavities are challenging due to their particularly low frequencies, below 100 MHz. The smaller beam size and lower beam energy in final cooling results in significant energy deposition. This can cause localised high pressures within the liquid hydrogen absorbers if not mitigated. The final few stages would use hydrogen vapour. Further cryogenic studies are required to model this system in more detail.

2.4 Acceleration

The accelerator brings the muon beam from 250 MeV to its collision energy of 1.5 TeV or 5 TeV. For reasonable transmission per system, rapid acceleration is required, and the limits of dipole field ramping means that the input-to-output energy of a synchrotron is limited to around 2 – 5. For this reason, the low-energy system uses LINAC and recirculating LINAC technologies, until reaching the target energy of 62.5 GeV (half of the Higgs mass). After this, the high-energy acceleration system is made of four synchrotrons with either normal conducting magnets or a hybrid of pulsed normal and static superconducting magnets. The transmission of each ring is directly proportional to the RF cavity power.

R&D: Ramp rates up to 3.3 kT/s are required in the normal conducting dipoles ramping from −1.8 T to 1.8 T. Power converters which would need to ensure good energy recovery of the 200 MJ of energy stored in the magnets. The RF cavities are based on 1.3 GHz TESLA cavities [11].

2.5 Collider

Overview: The dedicated collider ring has three distinct regions: The arcs, where the dipoles bend using a 14 T field, the chromaticity compensation region, and the two interaction regions where the beam is prepared for collision at two detectors. Lattices are under study with 1.5 mm β^*, which is the target, and 5 mm with the full 0.1 % energy acceptance. Progress has been made in evaluating radiation loss due to muon decays, at 500 W m^{-1}, and magnet shielding has been evaluated for this head load, as well as the corresponding impedance. Additional studies on machine imperfections and alignment are required.

R&D: R&D will define the available superconducting technology for the collider magnets. The considered technologies are LTS with 16 cm diameter and 11 T at 4.5 K or HTS with 14 cm diameter and 14 T at 20 K. The interaction region demands higher fields, so would require a HTS final focusing quadrupole with 14 cm diameter, 300 T m^{-1} at 4.5 K. 10 TeV Collider magnet R&D is time-constraining technology for a 2050 muon collider, shown by the magnet timeline in Figure 2.

2.5.1 Radiation

Overview: Radiation shielding has been studied in detail for the target – where it would impact the capture solenoids, and for the collider – where shielding equipment from secondary decay products

is required. In the collider, neutron showers are studied from the arcs, from the interconnect within the arcs, and from the straight sections of the interaction points. This is to ensure a neglitable impact at the surface. A geoprofiler tool has been developed for detailed modelling of the collider orientation in known soil and rock samples.

R&D: A mover system has been envisioned which would dilute neutrino beams arising from muon decay, and subsequent neutron showers. Significant development would be required for a jack which can reach 1 mrad with 0.004 mrad tolerance, at a rate compatible with the collider repetition rate.

2.5.2 Detectors

Overview: Two detector designs are in progress, called MUSIC (Muon Smasher for Interesting Collisions) [12] and MAIA (Muon Accelerator Instrumented Apparatus) [13]. Both of these are based on CLIC detector technology, and differ primarily in the arrangement of the detector solenoid.

R&D: Both detectors require a tungsten nozzle configuration as shielding for the muon decay products that may otherwise enter the detector cavern. The detector instrumentation places strong demands on the timing and spacial resolutions which are compatible with filtering out this beam-induced background (BIB).

3. What technology developments are necessary to collide muons?

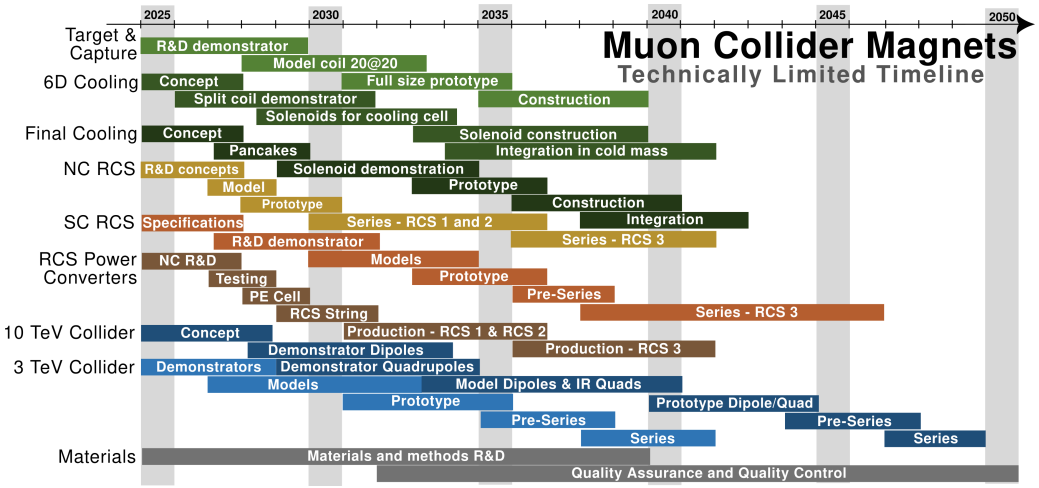

Figure 2: Magnet timelines and milestones for each technology

The above sections detailed the key areas of development necessary for each section. The R&D deliverables required for the muon collider can be split into three categories:

Magnets: The unique beam dynamics at each stage demands a wide range of magnet technologies, including high-field solenoids, rapid-ramping NC dipoles and HTS final-focusing quadrupoles. Each magnet set would have development, prototyping and series stages, as anticipated in Figure 2.

RF cavities: Likewise the variety of RF cavities is high. The front-end and cooling demand a wide range of low-frequency cavities at the highest gradients possible operable within high field solenoids. The RCS currently anticipate over 4000 superconducting RF cavities.

Muon Cooling Demonstration: The 6D cooling lattice is made of ≈740 cooling cells. Each cell consists of an RF pillbox cavity, surrounding solenoidal coils, dipole magnet and a wedge absorber integrated into a small space. It is important to study the limits of available cavity gradient within these solenoids [14]. The IMCC R&D programme intends to produce a facility made of ≈30 cooling cells tested in a beam environment. This requires testing individual cooling cells, then cryo-modules of five combined cooling cells. A demonstrator sited at CERN's CTF3 building has been proposed. The Proton Synchrotron could provide an intense 14 GeV proton beam pulse of 10 ns length that would yield a suitable muon pulse. FLUKA studies of the resulting target, pion decay line and muon selection chicane have been performed. Civil engineering studies have examined the hall, klystron gallery and connections. The facility timeline is shown in Figure 3.

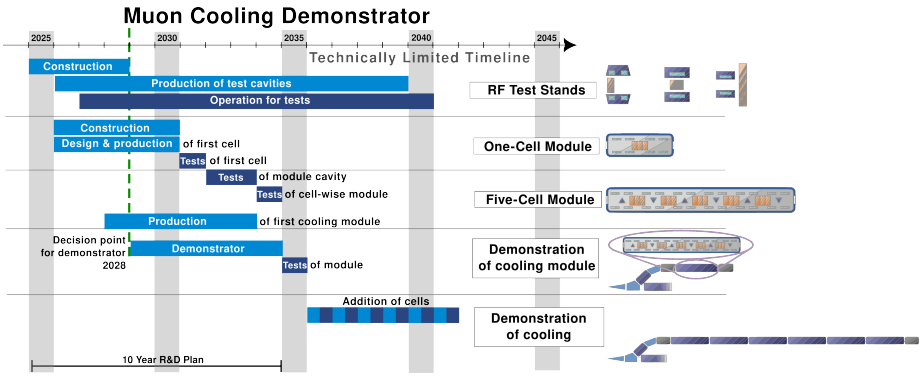

Figure 3: Timeline for construction of a muon cooling demonstrator

4. Where might we collide muons?

In order to enable studies to begin, a baseline design for the muon collider was made based on a greenfield site. Sites at CERN and Fermilab have received detailed consideration. The **CERN** design uses LINAC4 and the postulated Superconducting Proton Linac (SPL) as a 5 GeV proton driver. Target, cooling and low-energy acceleration are located at the Prevessin site. Three RCS are located within the SPS and LHC tunnels, to reach 7.6 TeV. The muon production system, collider ring and some beam transfers would require new tunnels but other parts of the facility would use existing tunnel infrastructure. The collider has been positioned such that both detector sites are on CERN land, and the direction of the interaction regions are favourable for the trajectory of the neutrino beams. The **Fermilab** siting would benefit from the PIP-II upgrade plan as the proton driver. Two RCS would fit within the existing Tevatron tunnel. RCS3 is designed to fit within Fermilab campus borders and reaches 1.5 TeV. RCS4 circumference is sufficient to reach 5 TeV.

5. Conclusion

The muon collider excels as a vector boson fusion factory, and features an exceptionally strong high energy physics case, with a unique programme in electroweak searches. Whilst the acceleration complex features many unique systems with different beam dynamics requirements, no technological barriers have been identified. A 10 year R&D programme has been proposed with a broad scope of magnet and RF technologies, focusing on a muon cooling demonstrator facility. Every year there is increasing confidence that the muon collider can provide a unique, sustainable path to the future of high energy physics. The growing momentum needs to ramp up globally in order to achieve this ambitious programme.

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