REFINED DESIGN OF THE FRONT-END COMPLEX FOR A MUON COOLING DEMONSTRATOR AT CERN

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Abstract

The muon collider has great potential for enabling high-luminosity multi-TeV lepton–antilepton collisions provided low-emittance, high-intensity muon beams can be produced. Ionization cooling is the proposed technique to achieve the required muon beam emittance. The International Muon Collider Collaboration aims to demonstrate the integration and reliable operation of a 6D ionization cooling system, including RF acceleration in strong magnetic fields. This study advances the design of the muon production and transport systems for a Muon Cooling Demonstrator implemented in the CERN CTF3 building. Building on previous work, the design is extended to the beam-preparation section and the matching of the transport line into the cooling channel. The target–horn model has been further developed and now incorporates a forced-convection helium cooling system, providing a more mature and realistic representation. An extended FLUKA model of the target area is used to assess and optimise shielding requirements.

MUON COOLING DEMONSTRATOR

A central challenge on the path towards a muon collider is the production of low-emittance, high-intensity muon beams, which requires efficient and compact 6D ionization cooling systems. The Muon Ionization Cooling Experiment (MICE) demonstrated transverse emittance reduction in high-emittance muon beams passing through a single, non-accelerating ionization cooling cell [1, 2]. Building on this proof-of-principle, the muon cooling demonstrator is an essential component of the muon collider R&D programme. Its aim is to demonstrate the successful integration of the cooling hardware (high-field solenoids, absorbers, dipoles, and high-gradient radiofrequency (RF) cavities), its operation with beam, and the achieement of the required beam-physics performance. To realise these objectives in a controlled and progressive manner, the programme follows a staged approach: starting with RF test stands to characterise the achievable gradients in high-field solenoids, then advancing to one-cell and multi-cell modules, and ultimately culminating in the operation of a complete cooling line with beam [3, 4].

A conceptual layout of the Muon Cooling Demonstrator is shown in Fig. 1. The muon beam is produced through the decay of pions resulting from the interaction of protons with a target. The pions emerging from the target are captured using a magnetic horn and collected into a quadrupole-based decay channel. At the end of this channel, a momentum-selecting chicane delivers the resulting muon beam into a beam preparation system (BPS), where the beam emittance is tuned through collimation and the beam is rotated and bunched in the longitudinal phase space using RF cavities. The prepared beam is then matched into the cooling channel.

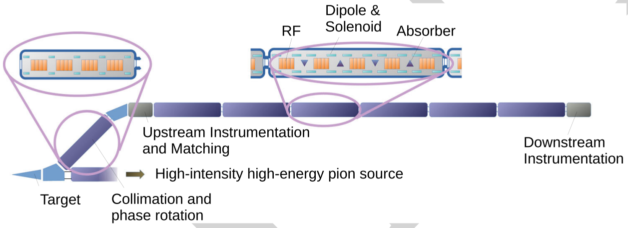

Figure 1: Conceptual schematic of the Muon Cooling Demonstrator [5].

Candidate sites at CERN, Fermilab, and other laboratories have been identified. At CERN, two siting options making use of existing infrastructure—the TT7 tunnel and the CTF3 building—have been studied in detail, including lattice design, engineering integration, and cost estimation. Both configurations would operate with a low-power proton beam (≤ 10 kW) from the CERN PS. The CTF3 option (Fig. 2) requires substantially less civil engineering, making it a cost-effective solution that can support all stages of the programme. A similar site study has also been approved at Fermilab. This paper presents recent progress on the front-end design, with particular emphasis on the target system, the beam preparation and matching sections of the muon transport line, and a preliminary radiation protection study for the CTF3 target area layout.

TARGET SYSTEM

The pion production system is based on a cylindrical graphite rod placed within a magnetic horn, a configuration motivated by the maturity and widespread use of such systems in proton-driven meson production. To further develop the target system and assess the pion capture yield with a more realistic design, a target cooling system based on forced helium convection has been added to the existing baseline FLUKA [6] model [7]. The cooling system is based on a double-walled titanium vessel, similar to that proposed for the Muon Collider target [8]. A schematic and a view of

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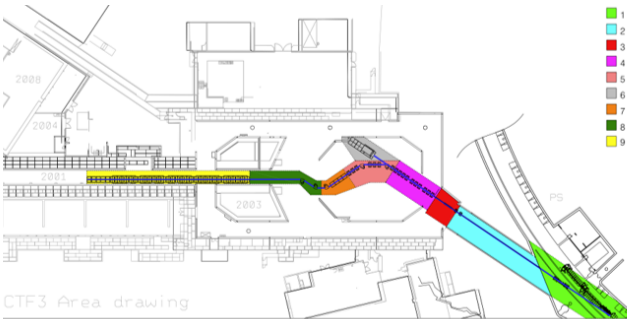

Figure 2: Proposed layout of the muon cooling demonstrator at the CTF3 site. Beam extracted from the PS (bottom right of the figure). Layout sections defined as follows: Proton extraction (light green), Proton Transfer line (cyan), Target area (red), pion decay channel (magenta), magnetic chicane (peach), proton and pion dump (grey), beam preparation system (orange), matching section (dark green), cooling cell channel (yellow).

the FLUKA model of the target and cooling vessel assembly are shown in Fig. 3.

The model view shows the limited available radial space between the graphite target and the inner conductor of the horn (14 mm), which is used to accommodate the vessel. A scan of the internal horn conductor radius revealed that relaxing its value from 20 mm to 30 mm decreases the pion yield by ~ 60%, from 7.9×10^{-4} $^{+}$/ POT to 3.2×10^{-4} $^{+}$/ POT. Due to this strong sensitivity, the baseline horn geometry was kept unchanged, and the cooling assembly was designed to fit within the available radial envelope. Including the cooling assembly with a vessel thickness of 1 mm, the pion yield is 6.9×10^{-4} $^{+}$/ POT, with the thermo-mechanical robustness of the vessel design currently under investigation.

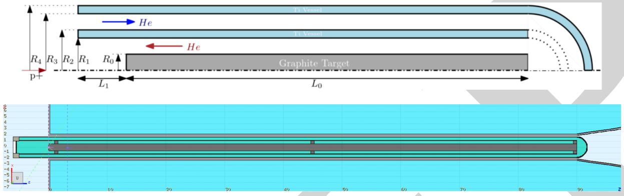

Figure 3: (top) Conceptual schematic target and cooling vessel assembly and (bottom) view of its implementation in the FLUKA model of the target system.

BEAM PREPARATION SYSTEM

Muons originating from a proton-driven target system occupy a large volume in phase space and a bunch length of 5-10 ns, which do not satisfy the transverse emittance ($\varepsilon_\perp \sim 2.5$ mm) and bunch length ($\mathcal{O}(100$ ps)) required by the cooling channel beam dynamics. The beam preparation system performs transverse collimation and longitudinal phase-space rotation to transform the muon distribution into a beam suitable for injection into the cooling system.

The preparation system is integrated into the final segment of the chicane (orange section in Fig. 2), and it consists of a series of solenoids that focus the beam transversely, collimators for transverse clipping, and high-gradient RF cavities to rotate the beam in the phase-energy space. A dipole followed by another collimator is used for momentum collimation.

The most restrictive physical aperture in the BPS is set by the iris of the RF cavities, assumed to be ~ 80 mm in radius for 704 MHz cavities. To ensure high transmission and avoid excessive collimation, the solenoids must provide sufficient focusing to keep the beam envelope well within all apertures, in particular in the RF cavities. For a beam with $\varepsilon_\perp \sim 2.5$ mm, this requires $\beta_\perp \lesssim 1$ m. For example, at $\beta_\perp \approx 0.8$ m, the RF cavity iris radius corresponds to $\sim 2.5\,\sigma_{RMS}$ of the beam. The lattice has been designed to follow a solenoid spacing of 1 m, consistent with the cooling channel, enabling the use of the same RF structures between consecutive solenoids. Figure 4 shows the magnetic field and transverse betatron function profiles corresponding to a lattice of five alternating polarity solenoids. The peak field is ~ 4 T, and a $\beta_\perp < 1$ m is achieved throughout the system. The optimisation of the momentum collimation section is ongoing.

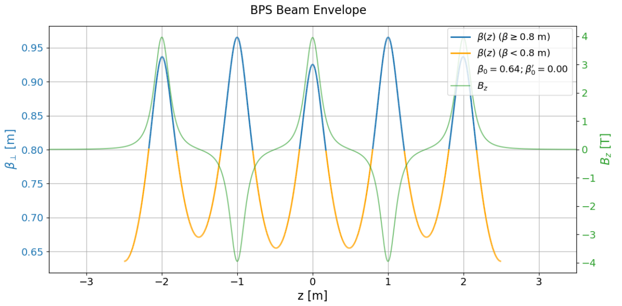

Figure 4: (green) Longitudinal magnetic field and (blue/yellow) transverse betatron function profiles within the BPS region. Yellow indicates the regions where $\beta_\perp < 0.8$ m, suitable for the placement of RF cavities.

MATCHING SECTION

The matching section provides the transition between the beam preparation system and the cooling channel, ensuring that the beam is tuned the specifications of the cooling lattice beam dynamics. This involves matching the transverse optics (Twiss parameters), the orbit and dispersion. In addition to beam optics, the matching section must also address magnetic force management. The cooling channel is composed of modular solenoidal structures (each containing and supporting four coils) designed to balance the forces internally. However, at the ends of the channel, the breaking field symmetry results in a net axial force on the end modules. Due to the long fringe fields of the solenoids, the matching section—located in close proximity and itself solenoidal—will inevitably interact magnetically with the upstream end of the cooling channel. As a result, the field configuration in the matching section influences both the beam optics and the force balance at the upstream end of the cooling channel. Thus, the matching section fulfils a dual role: providing the required optical matching while also contributing to the management of residual magnetic forces.

A beam optics matching framework has been developed that accounts for magnetic forces acting on the lattice coils. Multiple solutions have been identified. Figure 5 shows one representative solution in which a beam with $\beta_\perp = 1$ m and $\alpha_\perp = 0$ is matched to $\beta_\perp = 0.13$ m and $\alpha_\perp = 0$ at the location of the first absorber of a short cooling channel (at $z = -1.5$ m in the figure). The matching is achieved using a pair of four-coil magnetic structures identical to those of the cooling channel, together with an additional matching coil. These elements provide an adiabatic reduction of the magnetic field, which helps distribute the axial forces between them. The successful matching is reflected in the periodic optics observed in the cooling lattice.

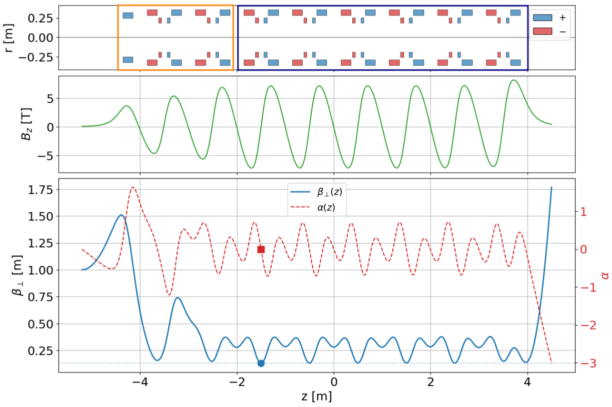

Figure 5: (top) Cross sections of the coils in the matching (orange box) and cooling lattices (blue box), with coil polarities colour coded; (center) Lattice magnetic field; (bottom) Beam optics, (blue) $\beta_\perp$ and (red) $\alpha_\perp$, through the lattice.

In the absence of the matching section, a net axial force of 4.8 MN would be exerted on the first cooling channel 4-coil structure. With the inclusion of the matching lattice, this force is redistributed approximately evenly across the first matching coil and the two matching magnetic structures (1.4, 1.5, and 1.8 MN, respectively), while the residual force on the first cooling channel module is reduced to 0.18 MN.

RADIATION PROTECTION

A radiation protection (RP) study of the CTF3 demonstrator target area has been carried out to estimate the required shielding configuration, materials, and volumes, and to highlight constraints on the beamline layout and civil engineering implications, such as modifications to the existing building, additional shielding structures, or excavation requirements.

A FLUKA model has been developed based on the baseline target and beamline design and the existing CTF3 infrastructure. The model includes the target and horn, the beamline up to the exit of the chicane, and a replica of the AD beam dump. The surrounding environment is described with increased geometric fidelity in the vicinity of the target area. Layered shielding configurations composed of cast iron (GG20) and concrete have been implemented around the target, beamline, and dump.

Figure 6 shows a top view of the FLUKA model and the simulated ambient dose equivalent rate distribution. The simulations assume an average proton beam power of approximately 1.5 kW, corresponding to 10^{13} protons per pulse at 14 GeV and a repetition rate of $(1/15.6)$ Hz. Neutrons are found to be the dominant contributors to the radiation field. With the current shielding configuration, dose rates at the building boundary are of the order of 2–4 µSv/h, approaching the target level of < 2.5 µSv/h. The AD dump is effective, although further optimisation of its geometry may be required to address develop shielding solutions for high-energy muons. Further design of the building roof and shielding sarcophagus is required, that will prevent neutrons escaping vertically. More work is required to mitigate any soil activation, which depends on the assumed operational scenarios, as well as to assess radiation loads on beamline components.

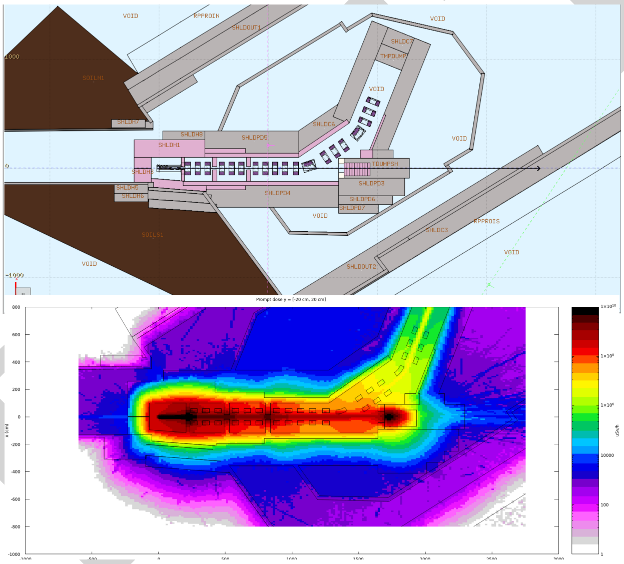

Figure 6: (top) X-Z view of the target area FLUKA model; (bottom) Ambient dose equivalent rate, averaged vertically over the range of [-20, 20] cm around the beam axis.

CONCLUSION

This work presents a refined front-end design for a Muon Cooling Demonstrator at CERN, incorporating more realistic models of the target and beam preparation, a new matching lattice design and radiation protection study. The target–horn system includes a vessel for helium cooling of the target, while the beam preparation solenoid lattice meets the required transverse focusing constraints for efficient transmission. A key new element is the matching section, which serves to match the muon beam into the cooling channel while reducing axial forces on the first cooling cell. Initial RP studies indicate that shielding requirements are broadly achievable within the existing infrastructure, with further optimisation ongoing. Future work will focus on optimising the longitudinal beam preparation at the BPS level and integrating all elements into a full start-to-end simulation of the front-end complex.

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