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COOLING DEMONSTRATOR TARGET AND PION CAPTURE STUDY

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Abstract

The muon collider has great potential to facilitate multi-TeV lepton-antilepton collisions. Reaching a suitably high luminosity requires low-emittance high-intensity muon beams. Ionization cooling is the technique proposed to reduce the emittance of muon beams. The Muon Ionization Cooling Experiment (MICE) has demonstrated transverse emittance reduction through ionization cooling by passing the beams with relatively large emittance through a single absorber, without acceleration. The international Muon Collider Collaboration aims to demonstrate 6-D ionization cooling at low emittance using beam acceleration. Two siting options are currently considered for a Cooling Demonstrator facility at CERN, with proton-driven pion production facilitated by the Proton Synchrotron (PS) or the Super Proton Synchrotron (SPS). In this work, we use FLUKA-based Monte Carlo simulations to optimize the number of pions produced in the proton-target interactions and subsequently captured by a magnetic horn-based system. We explore the feasibility of different target and capture system designs for 14, 26 and 100 GeV proton beam energies.

MUON COOLING DEMONSTRATOR

The Muon Ionization Cooling Experiment demonstrated transverse ionization cooling of muon beams [1, 2]. MICE measured the reduction of transverse emittance of muon beams with relatively large emittance that passed through a single cooling cell and were not subject to acceleration. The work presented in this paper is concerned with the muon production system of a Muon Cooling Demonstrator, a facility designed to demonstrate the 6-D ionization cooling principle at lower emittances by subjecting the muon beams to acceleration across multiple cooling cells [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 can be captured using a magnetic horn-based system or a solenoid channel. Downstream of the target and capture complex, the resulting muon pulse is prepared for cooling in a beam preparation system. The beam emittance is reduced to the desired input values through collimation and the beam is rotated in the longitudinal phase space using high-gradient radiofrequency (RF) cavities. The prepared beam is then matched into the muon cooling system, a sequence of cells containing wedge absorbers for ionization cooling, high-field solenoids for tight focussing at the absorbers, low-field dipoles to induce dispersion, and RF cavities for acceleration.

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Facility Siting and Proton Beam Power Options

Two siting options at CERN are currently under consideration, and discussions with other laboratories are in progress. The first option explores the feasibility of a small scale Cooling Demonstrator within the Intersection Storage Ring (ISR) complex on the CERN Meyrin site. The facility would be located in the TT7 extraction line, which is close to the surface level, and would use the proton beam from the PS. The proton beam power would be limited to 10 kW for radiation safety concerns due to the proximity to the surface level and surrounding buildings. In order to achieve greater bunch intensity within the beam power limit, a lower PS proton beam energy of 14 GeV has been proposed. The study of pion production and capture using a 14 GeV PS proton beam is the main focus of this work.

In the second option, the facility would be situated in a bespoke cavern complex 40 m underground, at the same depth as the SPS. It would be placed adjacent to the TT10 line which is used to deliver the PS beam to the SPS. In a first phase, the full power of the 26 GeV PS beam could be exploited (80 kW), followed by a potential upgrade using 100 GeV protons from the SPS. A conceptual 3-D layout of this dedicated facility is shown in Fig. 2.

TARGET AND PION CAPTURE CONCEPT

The pion production system for a low power Muon Cooling Demonstrator situated in the CERN TT7 extraction line is currently conceived as a cylindrical graphite rod placed within a magnetic horn. The choice of target material and pion capture system is motivated by the relative maturity of these technologies and their extensive use in experiments that rely on proton-driven pion/meson production.

PROTON BEAM ENERGY

The feasibility of using 14 GeV protons for pion production was analysed. In this study, a comparison with two other proton energies of interest available at CERN, 26 GeV and 100 GeV, was made. The chosen figure of merit is the pion yield normalized to the number of protons on target (POT). FLUKA [5] was used to simulate the proton-target interaction and to track the resulting pions through the magnetic field of the horn. The particle position and momentum were recorded at a virtual plane placed at the downstream end of the horn.

In assessing the pion yields, it was assumed that only pions with a single particle emittance smaller than a 2 mm rad transverse acceptance produce useful muons. In addition, only pions with momenta in the 270 – 330 MeV/c range were

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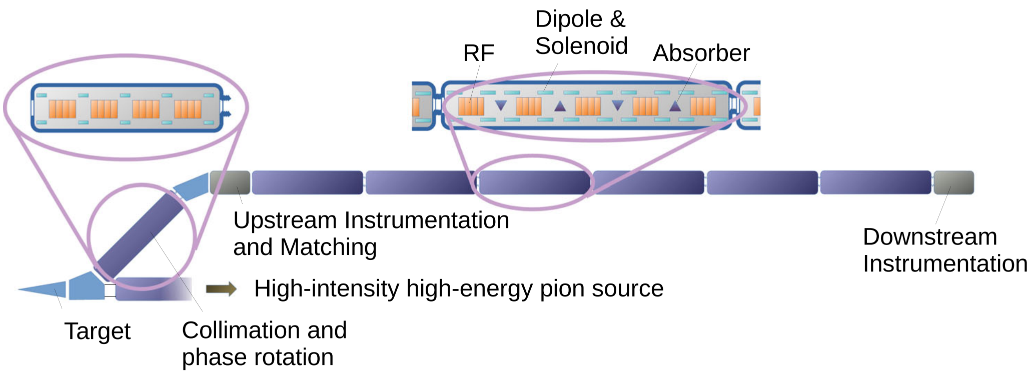

Figure 1: Conceptual schematic of the Muon Cooling Demonstrator [3].

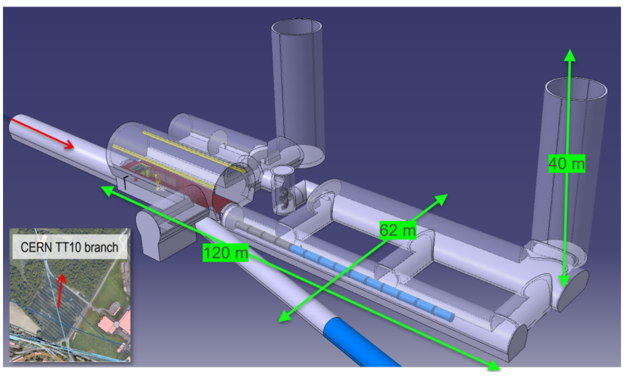

Figure 2: TT10 3-D facility concept [6].

considered. These pions would produce a muon beam in which the muons that are backward-going in the pion rest frame have momenta in the 200 ± 10 MeV/c, which is the operating momentum window of the Demonstrator. In this study, the graphite rod was 80 cm long with a radius of 0.63 cm. The proton beam size (1 σ) used across all energies was 2.67 mm. The horn inner conductor profile had a straight section along the length of the target, followed by a 1.4 m-long parabolic-shaped opening downstream of the target. The horn current was set at 220 kA. The pion yields at the target surface and horn exit are shown in Table 1.

Table 1: Yield of Pions with 270–330 MeV/c Momenta

E_p [GeV]	14	26	100
At target [1/POT]	0.07	0.09	0.16
At horn exit [10^{-2}/POT]	0.79	1.05	2.07
At horn exit (2 mm rad) [10^{-4}/POT]	2.80	4.27	7.53
Energy normalized [10^{-5}/POT/GeV]	2.00	1.64	0.75

The absolute pion yields scale with the proton beam energy, as expected. The yield decrease observed when the 2 mm rad transverse acceptance cut is applied highlights the challenge of capturing low-emittance, low-energy pion beams. This can be improved by appropriately optimizing the target and horn parameters. The absolute yields for all three proton energies are within the same order of magnitude. This indicates that, provided a sufficient muon beam intensity is achieved at the cooling channel, 14 GeV protons may be used. In addition, the 14 GeV proton beam produces the largest energy-normalized pion yield, which may be advantageous for the low beam power scenario.

TARGET PARAMETRIC SCAN ANALYSIS

Having concluded that a 14 GeV proton beam could be used for pion production in the low beam power option, a parametric scan of the graphite target was conducted. The yield of the pions captured by the horn was studied as a function of the target radius to beam size ratio, the proton beam size and the target length. For all three scans, the horn parameters were the same as in the proton beam energy study above.

Two pion momentum windows were considered in these studies: 270 – 330 MeV/c and 210 – 330 MeV/c. In the second option, a momentum window twice as large was chosen to enhance the pion yield. However, a pion beam with momenta in this range will produce 200 ± 10 MeV/c muons that will have a larger angular spread which is expected to cause an increase transmission losses. Only pions within the 2 mm rad transverse acceptance are included in the yield calculation. The pion yields for the three parametric scans are shown in Fig. 3.

For the target radius scan, the proton beam size was set at 2.67 mm and the target length was 80 cm. The results indicate optimum performance is achieved when the ratio between the target radius and proton beam size is ~ 2.5 – 3. A ratio of 3 was set for the other two scans.

The proton beam size was varied between 1 – 5 mm while using an 80 cm-long target with a radius three times the beam size. A clear trend which indicates a preference for smaller proton beam sizes is observed.

The target length was varied between 70 – 100 cm while using a beam size of 2 mm and target radius of 6 mm. The observed trend is not significant, with a modest preference to a length of ~ 85 – 90 cm. Given the relatively large target length, further study is required to understand the impact of variations in the proton beam size as it traverses the target.

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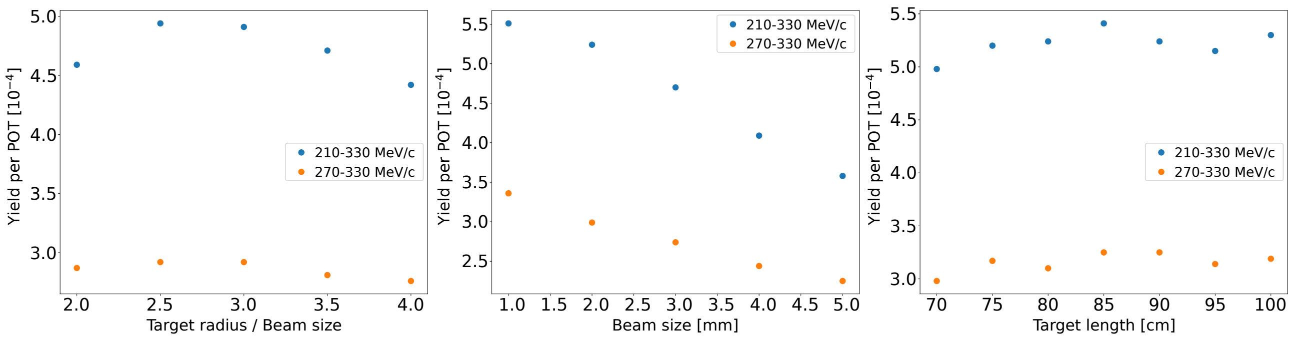

Figure 3: Target parametric scans - pion yield.

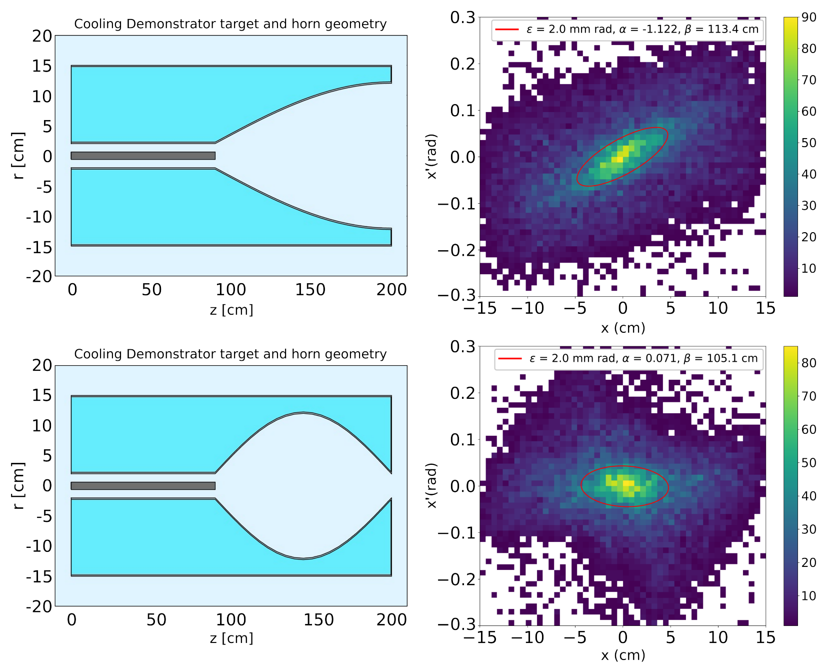

Figure 4: (left) Horn conductor profiles and (right) the respective $x - x'$ phase space of the captured pions. (top) Parabolic, (bottom) ellipsoidal.

MAGNETIC HORN CONCEPT

In the last stage of this work, various horn geometries were explored. All horn models were designed to have an inner conductor profile radius of 2 cm along the length of the target. This section of the horn acts as a collector which imparts a transverse kick to the pions shortly after they leave the target volume and before they gain a large radial excursion. Downstream of the target section, three horn inner conductor profiles were studied: conical, parabolic and ellipsoidal.

Figure 4 shows one parabolic and one ellipsoidal horn and the respective $x - x'$ phase spaces of the captured pions. The red ellipse indicates the 2 mm rad transverse acceptance cut. Initial parametric scans varying the downstream section of the inner conductor profile indicate an optimum pion yield of 7.9×10^{-4} π^+/POT using the parabolic horn shown at the top of Fig. 4. While the best yields achieved with an ellipsoidal horn were ~ 15% lower, this geometry is of interest as it can produce pion beams with upright beam ellipses which may be easier to match and transport.

CONCLUSION

Two CERN siting options are currently being considered for a Muon Cooling Demonstrator. This paper show that a 14 GeV proton beam from the CERN PS may be used for pion production in a low power (10 kW) scenario. Parametric scans of the target, proton beam, and horn resulted into a first-pass design of the pion production system. Future work will involve a multi-parameter optimization of the whole system and may explore multi-horn or solenoid channel capture solutions if a higher pion yield is required.

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