FERMILAB-CONF-16-238-AD

THE MICE DEMONSTRATION OF MUON IONIZATION COOLING

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Abstract

Muon beams of low emittance provide the basis for the intense, well-characterised neutrino beams necessary to elucidate the physics of flavour at the Neutrino Factory and to provide lepton-antilepton collisions up to several TeV at the Muon Collider. The international Muon Ionization Cooling Experiment (MICE) will demonstrate muon ionization cooling, the technique proposed to reduce the phase-space volume occupied by the muon beam at such facilities. In an ionization-cooling channel, the muon beam traverses a material (the absorber) loosing energy, which is replaced using RF cavities. The combined effect is to reduce the transverse emittance of the beam (transverse cooling). The configuration of MICE required to deliver the demonstration of ionization cooling is being prepared in parallel to the execution of a programme designed to measure the cooling properties of liquid-hydrogen and lithium hydride. The design of the cooling-demonstration experiment will be presented together with a summary of the performance of each of its components and the cooling performance of the experiment.

INTRODUCTION

Stored muon beams have been proposed as the source of neutrinos at the Neutrino Factory and as the means to deliver multi-TeV lepton-antilepton collisions at the Muon Collider [1]. In such facilities the tertiary muon beam occupies a large volume in phase space. To optimise the muon intensity while maintaining a suitably small aperture in the muon-acceleration systems requires that the muon-beam phase space is reduced (cooled) prior to acceleration. The short muon lifetime makes traditional cooling techniques unacceptably inefficient when applied to muon beams. Ionization cooling, in which the muon beam is passed through material (the absorber) and is subsequently accelerated, is the technique by which it is proposed to cool the beam [2, 3]. This technique has never been demonstrated experimentally, and such a demonstration is believed to be essential to the development of future muon accelerators.

A full demonstration of transverse ionisation cooling is the goal of the MICE collaboration and can be considered in two parts:

- A study of the properties that determine the cooling performance of the lattice and,
- Demonstration of transverse emittance reduction with longitudinal re-acceleration.

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Cooling performance depends on the initial emittance-momentum of the beam, the absorber material and the transverse betatron function $\beta_\perp$ at the absorber, and is studied in MICE Step IV [4]. In this stage the muon beam, focused by superconducting solenoids, interacts with the absorber (either liquid hydrogen or lithium hydride), however no re-accelerating is performed.

BUILDING BLOCKS OF THE DEMONSTRATION OF IONIZATION COOLING EXPERIMENT

The configuration that will be used for the demonstration of ionisation cooling is shown in Fig. 1. It contains two single 201 MHz cavities, one primary (65 mm) LiH absorber, and two secondary (32.5 mm) LiH secondary ("screening") absorbers. The central lithium-hydride (LiH) absorber is sandwiched between two superconducting "focus-coil" (FC) modules. The emittance is measured upstream and downstream of the cooling channel using solenoidal spectrometers. Further instrumentation upstream and downstream of the magnetic channel serves to select a pure sample of muons passing through the channel and to measure the phase at which each muon passes through the RF cavities. The spectrometer solenoids (SSs) house high-precision scintillating-fibre tracking detectors (trackers) [5] in a uniform field of 4 T. The trackers will be used to reconstruct the trajectories of individual muons at the entrance and exit of the cooling channel.

LATTICE DESIGN

Design Parameters

The lattice has been optimised to maximise the reduction in transverse emittance using the primary and secondary LiH absorbers. This is obtained by matching the betatron function to a small value in the central absorber while minimising its maximum values in the FC modules, which helps to reduce the influence of non-linear effects. In this configuration, it is also possible to keep a relatively small betatron function at the position of the secondary absorbers keeping an acceptable beam size at the position of the cavities. The parameters of the lattice are presented in Tab. 1.

In addition, the phase advance of the cooling cell has been carefully chosen to minimize the chromatic effect due to the large momentum spread of the beam, which leads to a chromatic mismatch at the primary absorber and in the Downstream Spectrometer. This reduces the measurable cooling by a chromatic decoherence, which results from

Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy

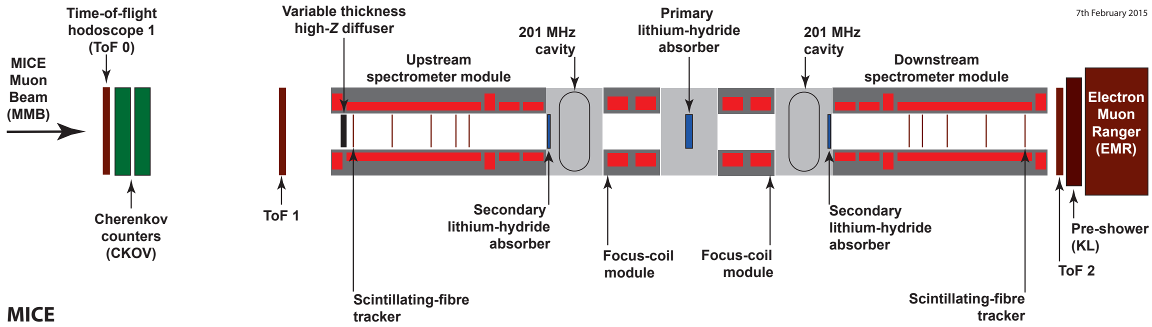

Figure 1: Layout of the lattice configuration for the MICE Cooling Demonstration.

Table 1: Design Parameters of the DEMO Lattice

Parameter	Value
$L_{SS\rightarrow FC}$ (mm)	2607.5
$L_{FC\rightarrow FC}$ (mm)	1678.8
$L_{RFmodule\rightarrow FC}$ (mm)	784.0
RF Gradient (MV/m)	10.3
No. RF cavities	2
No. primary absorbers	1
No. secondary absorbers	2

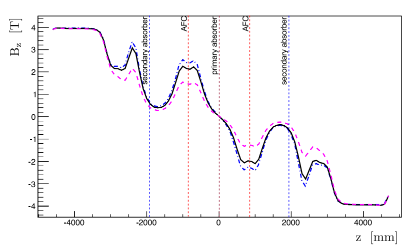

Figure 2: B_z on-axis for the DEMO lattice design for 200 MeV/c (solid black line), for 140 MeV/c (dashed purple line) and for 240 MeV/c (mixed blue line).

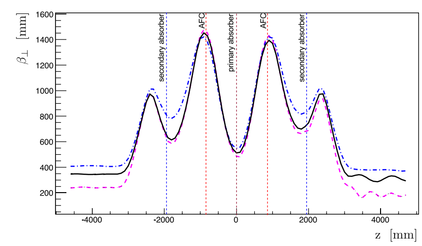

Figure 3: $\beta_\perp$ for 200 MeV/c (solid black line), for 140 MeV/c (dashed purple line) and for 240 MeV/c (mixed blue line) in the DEMO lattice.

Table 2: General Parameters of the Initial Beam in the Different Simulations

Parameter	Value
Particle ID	muon μ^+
Number of particles	10000
Central energy (140 MeV/c conf.) [MeV]	175.4
Central energy (200 MeV/c conf.) [MeV]	228.0
Central energy (240 MeV/c conf.) [MeV]	262.2
rms momentum spread	4%

a superposition of beam evolutions with different betatron frequencies for different momenta.

The resulting solenoidal magnetic field on axis is shown in Fig. 2 for the three planned settings (140 MeV/c, 200 MeV/c and 240 MeV/c). Vertical lines locate the positions of the centre of the FC modules (red), the primary absorber (burgundy) and the secondary absorbers (blue). The configuration shown powers the downstream FC and SS modules in the opposite sense to the upstream FC and SS so that the field changes sign at the absorber. This is a desirable feature for studying the cancellation of canonical angular momentum through the lattice.

Optics Parameters

The betatron functions shown in Fig. 3 are matched for different initial momentum beams. In all cases, the Courant Snyder parameter $\alpha = 0$ and the value of the beta-function in each Tracker are met for the central momentum to match the constant magnetic field region, and a small beta waist in the central absorber is achieved. This matching takes into account the change in energy of the muons as they pass through the cooling cell by adjusting currents in the upstream and downstream FCs and in the matching coils in the SSs independently while maintaining the field in the tracking volumes at 4 T.

PERFORMANCE IN SIMULATIONS

Simulations to evaluate the performance of the lattice have been performed using the official simulation and reconstruction software of MICE called MAUS (MICE Analysis User Framework). Parameters of the initial beam used for the different simulations are summarized in Tab. 2

The transmission of the lattice represents the proportion of muons that remain after scraping and cuts have been accounted for. Table 3 lists the acceptance criteria required by all analyses presented here, which exclude muons that do not appear within the active region of the trackers and limit particles to positive muons only (as muons may decay).

Table 3: Acceptance Criteria for Analysis

Parameter	Muon accepted
Radius at upstream tracker (mm)	≤ 150.0
Radius at downstream tracker (mm)	≤ 150.0
Charge	+
PDG particle ID	|13|

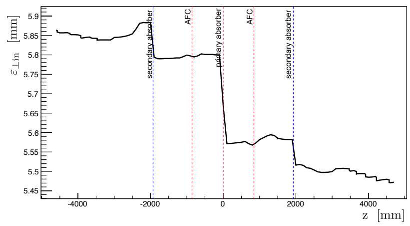

Figure 4: Emittance reduction of an initial ε = 6 mm beam for the DEMO lattice in the 200 MeV/c configuration.

The reduction in transverse emittance, with acceleration, is shown in Figures 4, 5 and 6 in the 200 MeV/c, 140 MeV/c and 240 MeV/c configuration, respectively, for the same initial geometrical emittance. The beam is subject to non-linear effects in regions of high $\beta_\perp$, which causes limited emittance growth. Nonetheless, a measurable reduction in emittance can be observed between the upstream and downstream trackers ($z \approx \pm 3500$ mm) in all cases, achieving 5.8%, 8.1% and 3.0% in the 200 MeV/c, 140 MeV/c and 240 MeV/c configuration, respectively.

Figure 7 shows the fractional change in emittance with respect to the input emittance in the 200 MeV/c configuration.

CONCLUSION

The MICE collaboration is now on track to deliver its demonstration of ionization cooling by 2018. The equipment necessary to mount the experiment is either in hand, the superconducting magnets and instrumentation, or at an advanced stage of preparation, for example the single-cavity modules. The cooling-demonstration configuration has been shown to deliver the performance required for the detailed study of the ionization-cooling technique.

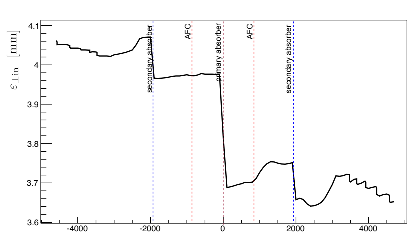

Figure 5: Emittance reduction of an initial ε = 4.2 mm beam for the DEMO lattice in the 140 MeV/c configuration.

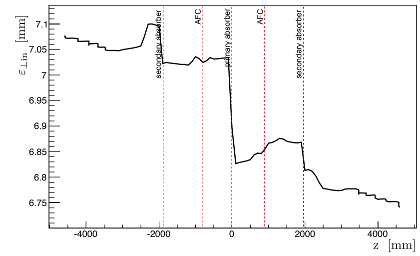

Figure 6: Emittance reduction of a ε = 7.2 mm beam for the DEMO lattice in the 240 MeV/c configuration.

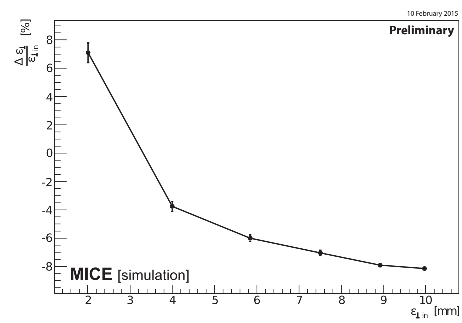

Figure 7: Fractional change in emittance as a function of initial emittance for the DEMO lattice in the 200 MeV/c configuration.

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ISBN 978-3-95450-147-2