MICE Demonstration of 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 at energies of up to several TeV at the Muon Collider. The International Muon Ionization Cooling Experiment (MICE) will demonstrate ionization cooling, the technique by which it is proposed to reduce the phase-space volume occupied by the muon beam at such facilities. In an ionization- cooling channel, the muon beam passes through a material (the absorber) in which it loses energy. The energy lost is then replaced using RF cavities. The combined effect of energy loss and re-acceleration is to reduce the transverse emittance of the beam (transverse cooling). A major revision of the scope of the MICE project was carried out over the summer of 2014. The revised project plan, which has received the formal endorsement of the international MICE Project Board and the international MICE Funding Agency Committee, will deliver a demonstration of ionization cooling. The design of the cooling demonstration experiment will be described together with the cooling performance of the revised configuration.

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 muon beam is produced from the decay of pions produced by a high-power proton beam hitting a target. The tertiary muon beam occupies a large volume in phase space. To optimise the muon yield while maintaining a suitably small aperture in the muon-acceleration systems requires that the muon-beam phase space be 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 subsequently accelerated, is the technique by which it is proposed to cool the beam [2, 3].

A full demonstration of ionisation cooling can be considered in two parts:

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

Cooling performance depends on the initial beam emittance, momentum, absorber material and $\beta_{\perp}$ at the absorber which is studied in MICE Step IV [4]. Once material properties have been fully characterised at Step IV, sustainable ionisation cooling must be demonstrated. This requires restoring the energy lost by the muons passing through the absorber in RF cavities. The experimental configuration with which the MICE collaboration will study ionization cooling has been revised in the light of the recommendations of the US Particle Physics Projects Prioritization Panel and subsequent national and international reviews of the project. This process culminated in November 2014 when the project was formally rebaselined to deliver the configuration presented in this paper. The schedule for the rebaselined project shows that the initial demonstration of ionization cooling will be performed by the end of US fiscal year 2017, while preserving MICE measurements at Step IV [4]. This paper describes the lattice configuration adopted for the MICE demonstration of ionization cooling and presents its performance.

LATTICE CONFIGURATION

The so-called "DEMO" lattice that will be used for the demonstration of ionization cooling is shown in Fig. 1. It consists of two single RF cavities, one primary (65 mm) LiH absorber, and two secondary (32.5 mm) LiH secondary absorbers. The cooling cell is formed of the central lithium-hydride (LiH) absorber sandwiched between two focus-coil (AFC) modules. The emittance is measured upstream and downstream of the cooling channel by 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 layout of the experiment has been optimised to maximise the reduction in transverse emittance using the primary (central) and secondary LiH absorbers, while keeping minimum the non-linear effects. With this configuration, a small betatron function at the position of the primary absorber can be achieved together with an acceptable beam size at the position of the 201 MHz cavities. The phase advance of the cooling cell has been chosen between two half integer resonances to minimize the chromatic effects due to the large momentum spread of the beam, leading to strong non-linearities. The spectrometer solenoids (SSs) house high-precision scintillating-fibre tracking detectors (trackers) [5] in a uniform field of

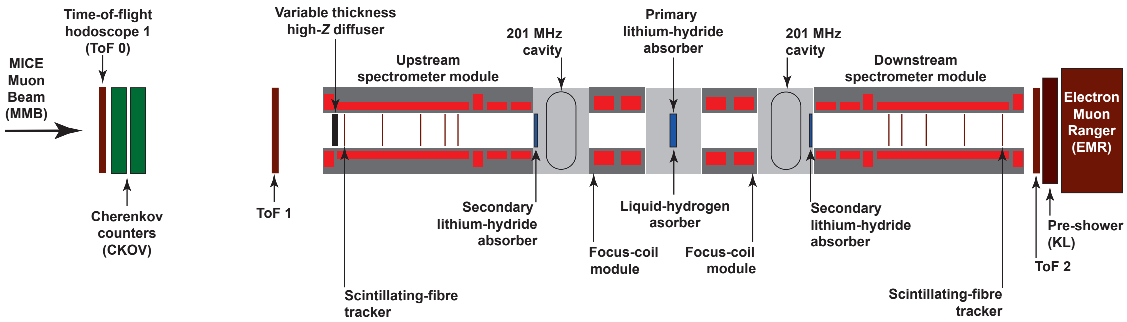

FIG. 1: Layout of the lattice configuration for the MICE Cooling Demonstration (DEMO lattice).

TABLE I: Design parameters of the DEMO lattice.

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

4T. The trackers will be used to reconstruct the trajectories of individual muons before and after they pass through the cooling cell. The reconstructed tracks will be combined with the information from the instrumentation upstream and downstream of the channel to measure the muon beam emittance with a precision of 0.1%.

The parameters of the lattice are presented in Tab. I. Bellows around each cavity module have been added in order to allow easy cavity module inspection.

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 AFC modules (red), the primary absorber (burgundy) and the secondary absorbers (blue). In the "[+ + − −]" configuration shown, the downstream AFC and SS modules are powered in the opposite sense to the upstream AFC and SS so that the field changes sign at the absorber. This is a desirable feature for studying the cancellation of

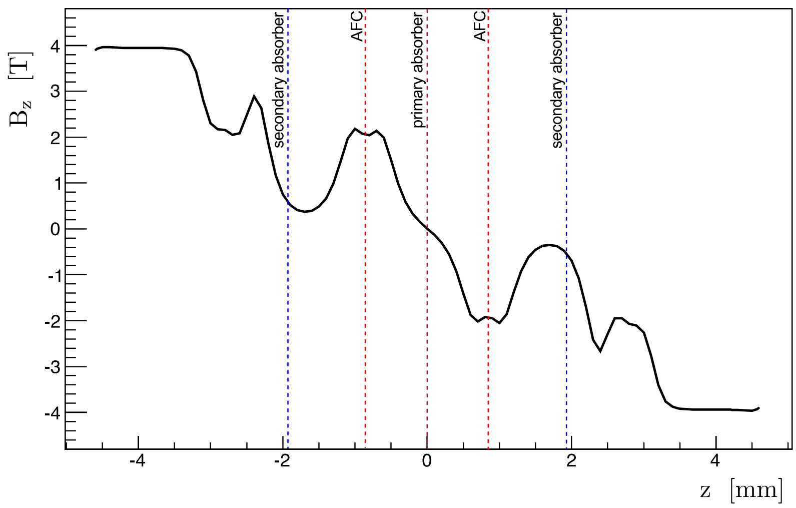

FIG. 2: B_z on-axis in $[++--]$ polarity for the DEMO lattice design for 200 MeV/c configuration.

canonical angular momentum through the lattice.

Secondary absorbers

The secondary LiH absorbers (SAs) are introduced between the cavities and trackers in order to minimise the exposure of trackers to dark-current electrons originating from the RF cavities. Such electrons produce correlated background to the muon tracks in the trackers.

The SAs also increase the net transverse cooling effect. The positions for SAs were carefully selected as a compromise between the requirement of a small value of beta at absorbers and the ability to remove the absorbers remotely to allow studies of the bare magnetic lattice.

Radiation shutters

Retractable, lead radiation shutters will be installed on rails between SSs and the RF modules to protect the trackers against dark-current induced radiation during cavity conditioning. The SAs will be mounted on a rail system and will be located between the cavities and the lead shutters. Both mechanisms will be moved using linear Piezo-electric motors that operate in vacuum and in magnetic field.

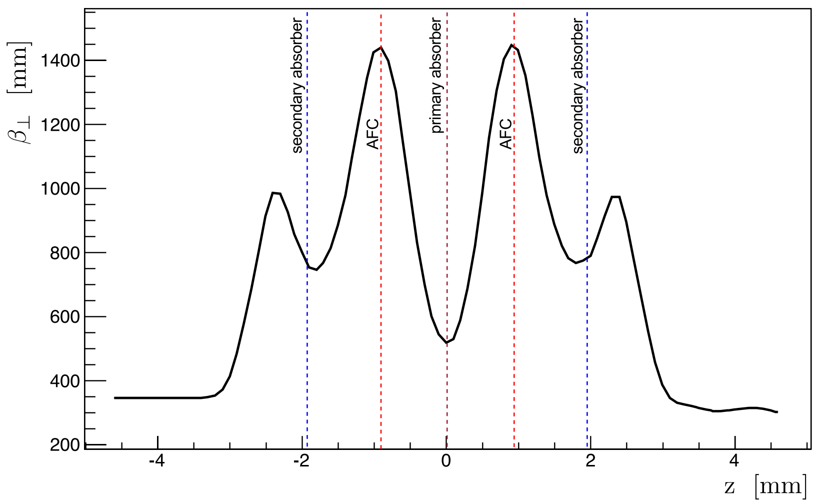

FIG. 3: $\beta_\perp$ for 200 MeV/c configuration in the DEMO lattice.

TABLE II: Beta-function values at relevant positions for an initial beam at 200 MeV/c in the DEMO lattice design.

Parameter	Value
$\beta_\perp$ at primary absorber (mm)	520
$\beta_\perp$ at secondary absorbers (mm)	780
β_{max} at AFC (mm)	1450

Optics parameters

The betatron function evolution shown in Fig. 3 is matched for an initial 200 MeV/c beam. The Courant Snyder parameters in each Tracker are matched to the constant 4 T solenoidal field 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. Beta values at relevant positions are summarised in Tab. II.

TABLE III: General parameters of the initial beam in the different simulations

Parameter	Value
Particle	muon μ^+
Number of particles	10000
Longitudinal position [mm]	-4612.1
Central energy [MeV]	228.0
Gaussian transverse distribution	
$\alpha_\perp$	0
$\beta_\perp$ [mm]	339.0
Gaussian longitudinal distribution	
Longitudinal emittance [mm]	20
Longitudinal β [mm]	11
Longitudinal α	-0.7

COOLING PERFORMANCE

MAUS code

Simulation to evaluate the performance of the lattice has been done using the official simulation and reconstruction software of MICE called MAUS (MICE Analysis User Framework). In addition to simulation, MAUS also provides a framework for any subsequent data analysis. MAUS is used for both offline analysis and also to provide fast real-time detector reconstruction and data visualization during MICE running.

MAUS is written in Python (primarily for top level code provided to the user) and C++ (lower level code used for performance). GEANT4 is used to support simulation by providing beam propagation and detector responses, ROOT is used for data visualization and as a data storage format.

Tracking and analysis

Tracking has been done for different configurations. Parameters of the initial beam used for the different simulations are summarized in Table III.

TABLE IV: Acceptance criteria for analysis.

Parameter	Muon accepted
Radius at upstream tracker (mm)	≤ 150.0
Radius at downstream tracker (mm)	≤ 150.0
Particle	muon μ^+

Table IV 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).

A muon passing through two 32.5 mm secondary LiH absorbers and one 65 mm primary LiH absorber would lose $\langle \Delta E \rangle = 18.9$ MeV. Including losses in the SciFi trackers and windows, this increases to 24.3 MeV. The RF gradient achievable in two cavities is insufficient to replace the energy lost in the absorber, therefore a comparison of beam energy with and without RF is required. With RF an energy deficit of $\langle \Delta E \rangle = 19$ MeV would be observed. This measurable difference would confirm that, were more RF cavities or higher RF gradient available, the transverse emittance reduction would be sustainable.

200 MeV/c configuration performance

Energy is lost in the upstream tracker and first secondary absorber before being partially restored in the first RF cavity ($z \approx -1600$ mm). Further energy is lost in the primary absorber, partially restored in the second RF cavity, and then lost in the final secondary absorber. The reduction in transverse emittance, with RF, is shown in Figure 4. The beam is subject to non-linear effects in regions of high $\beta_\perp$, which causes limited emittance growth. Nonetheless, a reduction in emittance is observed between the upstream and downstream trackers ($z \approx \pm 3500$ mm). The DEMO lattice achieves a reduction of ≈ 5.6 %.

Figure 5 shows the fractional change in emittance with respect to the initial emittance.

SUMMARY

The MICE collaboration is now on track to deliver its demonstration of ionization cooling by 2017. The demonstration will be performed using lithium-hydride absorbers and with

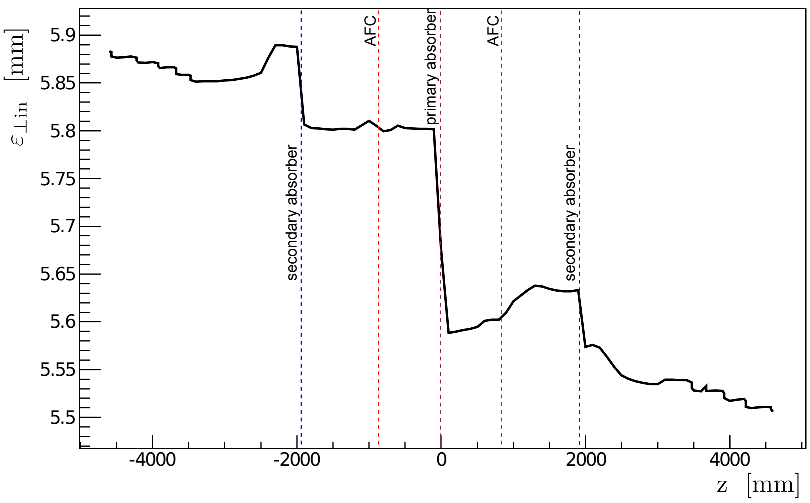

FIG. 4: Emittance reduction of an initial $\varepsilon = 6$ mm beam for the DEMO lattice design in the 200 MeV/c configuration.

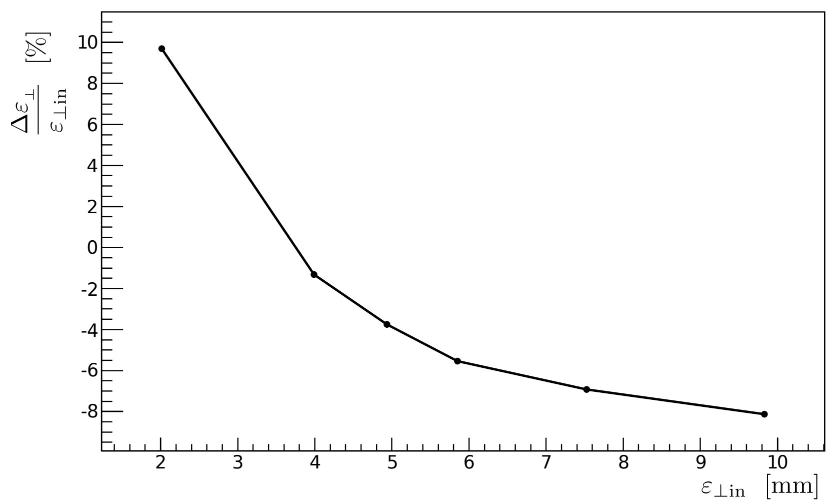

FIG. 5: Fractional change in emittance as a function of initial emittance for the DEMO lattice design in the 200 MeV/c configuration.

acceleration provided by two single, 201 MHz, cavity modules. The equipment necessary to mount the experiment is either in hand like the superconducting magnets and instrumentation or at an advanced stage of preparation such as the single-cavity modules. The DEMO configuration has been shown to deliver the performance required for the detailed study of the ionization-cooling technique.

The demonstration of ionization cooling that MICE will provide is essential for the provision of the intense, well characterised muon beams required to elucidate the physics of flavour at the Neutrino Factory or to deliver multi-TeV lepton-antilepton collisions at the Muon Collider. The successful completion of the MICE programme will therefore herald the establishment of a new technique for particle physics.

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