MICE DEMONSTRATION OF IONIZATION COOLING*

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Abstract

The goal of the international Muon Ionization Cooling Experiment (MICE) is to demonstrate transverse emittance reduction of a muon beam through use of absorber materials, RF cavities, and focusing solenoids. Low emittance muon beams are basic to Neutrino Factory and Muon Collider studies. In summer 2014, following the P5 report, a revised project plan for MICE was approved with a cooling lattice consisting of one central (primary) and two secondary LiH absorbers for energy loss, two 201 MHz RF cavities for beam re-acceleration, two solenoidal spectrometers for emittance measurement, and two focus coils to focus the muon beam. The superconducting magnets, absorbers and detectors necessary for the final stage of the experiment are already in hand and a 201 MHz prototype RF cavity module is under test at Fermilab's MuCool Test Area. We describe the muon ionization cooling concept, the redesigned cooling lattice of the MICE Demonstration of Ionization Cooling, and the cooling performance of the redesigned lattice.

INTRODUCTION

Stored low emittance muon beams lay the foundation for intense, well-parameterized neutrino beams at the Neutrino Factory and high-luminosity Muon Colliders [1]. Typical muon beams produced at the front ends of these facilities have an emittance range of 15-20 π·mm·rad. The desired muon beam emittance range at the Neutrino Factory is 2-5 π·mm·rad [2]. The Muon Collider needs further cooling with a desired transverse emittance of 0.025 π·mm·rad and longitudinal emittance of 72 π·mm·rad [3]. In order to produce a muon beam at such facilities, a high power proton beam collides and interacts with a target to produce pions, which in turn decay to muons. Such muon beams occupy a large phase space volume and in order to optimize muon yield, fit the beam into small apertures, and achieve the required luminosity, one would need to reduce the phase space volume occupied by the beam [4]. Given the muon's large mass and short lifetime, the traditional cooling techniques—synchrotron radiation and stochastic or electron cooling—are inefficient in cooling the muon beam.

Taking advantage of the muon's long interaction length, ionization cooling is suitable (and is the only feasible technique) for reducing the muon beam emittance in a time comparable to the muon lifetime [5].

In order to accomplish sustainable ionization cooling, the muon beam transverse and longitudinal momenta must be reduced via energy loss in an absorber material, with its longitudinal momentum subsequently restored in RF cavities. The rate of change of the normalized transverse emittance is

$$\frac{d\varepsilon_{in}}{ds} \cong -\frac{\varepsilon_{in}}{\beta^2 E_\mu}\left\langle \frac{dE}{ds} \right\rangle + \frac{\beta_\perp (13.6\text{MeV})^2}{2\beta^3 E_\mu m_\mu X_0}. \qquad (1)$$

where βc, E_μ, and m_μ are the muon velocity, energy, and mass, dE/ds the energy loss rate through ionization, X_0 the absorber radiation length, and $\beta_\perp$ the transverse beta function at the absorber. The first term in Eq. 1 describes cooling via energy loss and the second term heating due to multiple Coulomb scattering. When the heating term and the cooling term are equal, the cooling channel is said to be at "equilibrium emittance". Setting $\frac{d\varepsilon_{in}}{ds}$ equal to zero yields

$$\varepsilon_{in} \cong \frac{\beta_\perp (13.6\text{MeV})^2}{X_0 2\beta m_\mu}\left\langle \frac{dE}{ds} \right\rangle^{-1}. \qquad (2)$$

A smaller equilibrium emittance leads to a more effective emittance reduction which from Eq. 2 can be achieved by minimizing $\beta_\perp$ and maximizing X_0 and dE/ds [2]. Experimentally, use of a solenoid focusing channel leads to small transverse betatron functions, and use of low-Z absorber materials such as LiH (lithium hydride) leads to large radiation length and energy loss. The muons passing through low-Z absorber material lose energy due to electromagnetic interactions with the atomic electrons of the material and in general for the cooling effect to dominate, the low-Z materials are placed in strong focusing fields [2]. The MICE cooling lattice components make use of the muon ionization cooling concept, and they are described in the following section.

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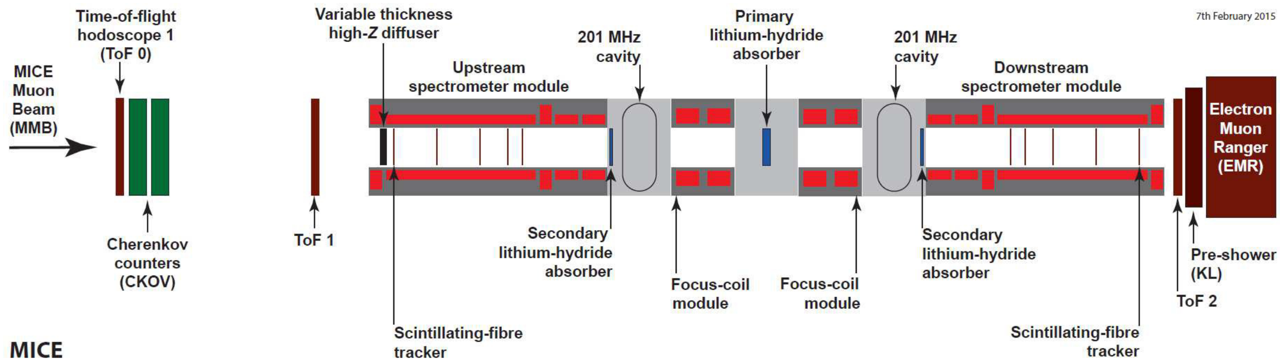

Fig 1: Schematic diagram of the final MICE cooling demonstration step.

MICE COOLING LATTICE

The revised lattice design of the Ionization Cooling Demonstration Step of MICE (shown in Fig. 1) is set to demonstrate sustainable muon cooling with reacceleration. The experiment will be operational in 2017.

The Ionization Cooling Demonstration step makes use of one central and two secondary LiH absorbers interspersed with superconducting focus coils. The two focus coils are designed to reduce multiple Coulomb scattering by providing a small beta waist at the location of the absorbers. The focus coils have two modes of operation, "solenoid" and "flip". The purpose of the flip mode of operation is to control the accumulation of canonical angular momentum in the cooling lattice [2]. The secondary LiH absorbers are located between the RF cavities and the scintillating fiber trackers, upstream and downstream of the central absorber, and they contribute to the net reduction in transverse cooling. The secondary absorbers also screen the scintillating fiber trackers from RF cavity x-rays. The scintillating fiber trackers inside the spectrometer solenoid modules reconstruct the muon beam tracks and along with the other MICE detectors reconstruct and measure the emittance to about 0.1% accuracy [4].

The upstream and downstream spectrometer solenoids are each made of five superconducting coils. The three central coils of the spectrometer solenoids are responsible for producing a uniform 4 T magnetic field at the locations of the five scintillating fibre tracker stations. The other two superconducting coils are responsible for matching the beam entering and leaving the cooling lattice. The upstream spectrometer solenoid has a high-*Z* diffuser which controls the initial muon beam emittance before entry to the cooling channel [2]. The cooling lattice also has two 201 MHz RF cavities each with a peak RF gradient of around 10 MV/m for restoring the beam's lost longitudinal momentum [6]. In the section that follows, the results of the Monte Carlo simulation studies and the analysis of the cooling performance of the redesigned lattice are presented.

COOLING LATTICE PERFORMANCE

In the MICE cooling lattice design studies, a realistic input muon beam is simulated using the MICE Analysis User Software, MAUS. The role of MAUS is to model the particle trajectories and electronics response in MICE, reconstruct the particle tracks either from MC or data electronics signals, and provide the framework for accelerator physics analysis [7].

The transverse betatron function evolution along the MICE cooling lattice is shown in Fig. 2. In order to elucidate the cell performance over a range of momenta, Fig. 2 displays the transverse beta function for varying momentum values of 140 MeV/c, 200 MeV/c, and 240 MeV/c, while keeping the initial beam emittance at a constant value of 6 $\pi\cdot$mm$\cdot$rad. As expected, the transverse beta function is focused at the location of the central LiH absorber due to the focus coils, while a large beam size is observed at the locations of the RF cavities. The beta values at $z \sim \pm 4000$ mm reflect respectively the upstream and downstream uniform 4 T regions of the cooling lattice at the locations of the two scintillating fiber trackers. With smaller beta values at the location of the absorbers, one would get a more effective emittance reduction [2].

Figure 3 displays the transverse emittance evolution along the MICE cooling channel. Due to nonlinear effects in high transverse beta regions, emittance growth is observed at the RF cavity locations. However, there is an overall emittance reduction of 5.6% between the upstream and the downstream trackers [2].

Figure 4 displays the fractional change in emittance versus the input emittance. Larger input emittance leads to better overall beam emittance reduction.

Figure 5 displays the muon transmission versus initial emittance. The smaller the input emittance in Fig. 3, the higher the muon beam transmission in the cooling lattice and even at large input emittance values, we have a high transmission of muons of ~90%.

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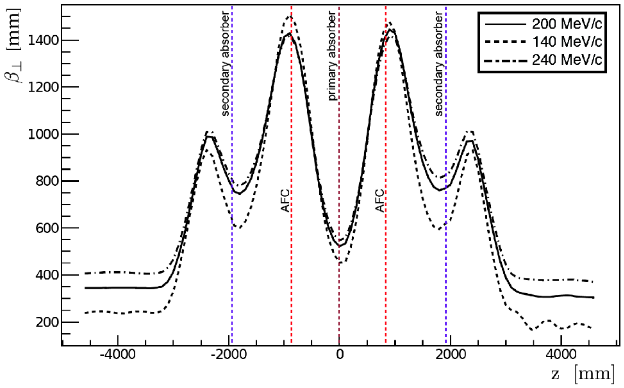

Fig 2: Evolution of the transverse betatron function along the redesigned cooling channel of MICE.

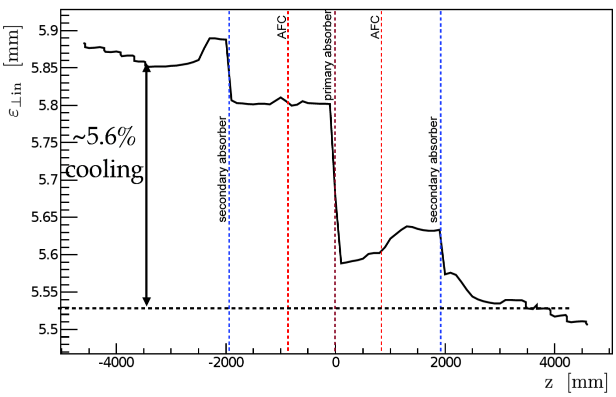

Fig 3: Evolution of 4D transverse emittance along the redesigned cooling channel of MICE for 200 MeV/c muon beam.

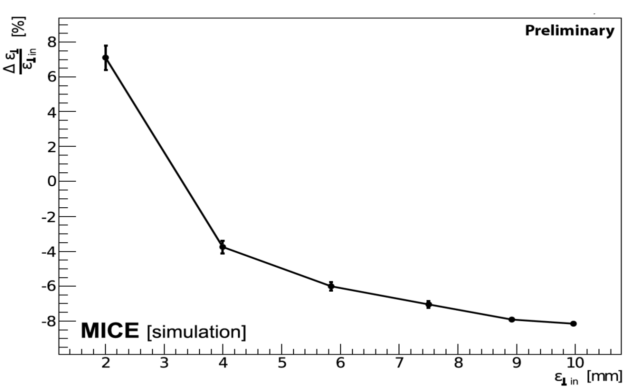

Fig 4: Fractional change in normalized 4D emittance vs. input beam emittance for 200 MeV/c muon beam; error bars represent estimated reconstructed measurement errors.

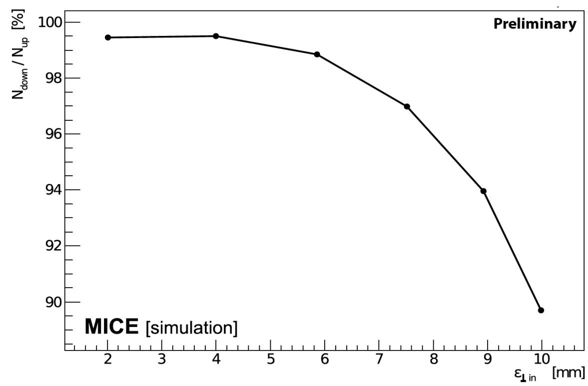

Fig 5: Muon beam transmission vs. input beam emittance for 200 MeV/c muon beam.

CONCLUSION

MICE is scheduled to demonstrate ionization cooling with reacceleration with a redesigned lattice, consisting of three lithium-hydride absorbers, two 201 MHz RF cavity modules, and two solenoidal focus coils. The required instrumentation for the MICE Demonstration of Ionization Cooling is either in hand or at an advanced stage of preparation and the redesigned cooling lattice shows excellent cooling. Demonstration of ionization cooling in MICE sets the basis for high luminosity and intense muon beams at the Neutrino Factory and the Muon Collider. As a result, a successful completion of MICE is an essential step to establishing a new technique in particle physics and accelerator physics.

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