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THE 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 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 by September 2017. In the revised configuration a central lithium-hydride absorber provides the cooling effect. The magnetic lattice is provided by the two superconducting focus coils and acceleration is provided by two 201 MHz single-cavity modules. The phase space of the muons entering and leaving the cooling cell will be measured by two solenoidal spectrometers. All the superconducting magnets for the ionization cooling demonstration are available at the Rutherford Appleton Laboratory and the first single-cavity prototype is under test in the MuCool Test Area at Fermilab. The design of the cooling demonstration experiment will be described together with a summary of the performance of each of its components. The cooling performance of the revised configuration will also be presented.

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 in the bombardment of a target by a high-power proton beam. 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].

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 [4] 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 Fig 1. The cooling cell is formed of a central lithium-hydride (LiH) absorber sandwiched between two "focus-coil" (FC) modules. Acceleration is provided by two 201 MHz cavities. 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 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 [5] scheduled in 2015.

This paper describes the novel lattice configuration adopted for the MICE demonstration of ionization cooling and presents its performance.

LATTICE FOR COOLING DEMONSTRATION

The lattice that will be used for the demonstration of ionization cooling is shown in Fig. 1. The lattice has been optimised to maximise the reduction in transverse emittance using the primary (central) and secondary LiH absorbers. 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 spectrometer solenoids (SSs) house high-precision scintillating-fibre

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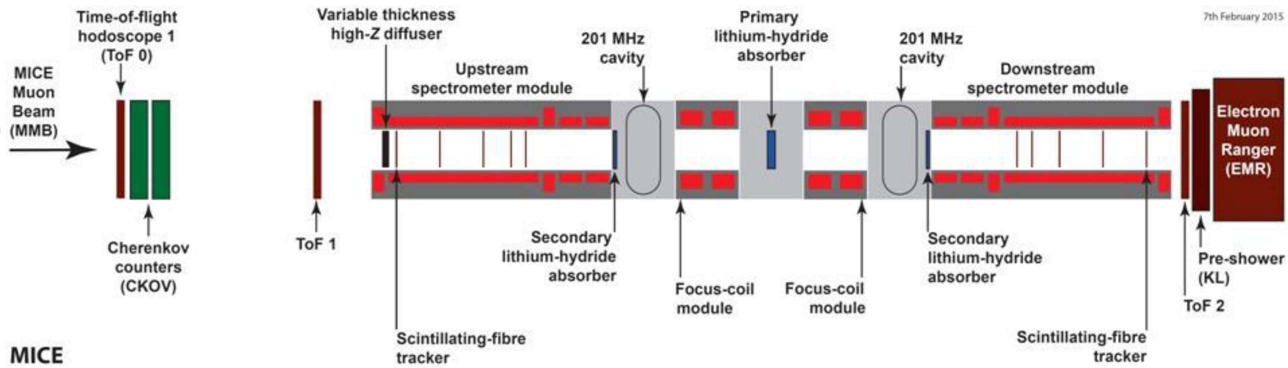

Figure 1: Layout of the novel lattice configuration for the MICE Cooling Demonstration.

tracking detectors (trackers) [6] in a uniform field of 4 T. 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 secondary LiH absorbers (SAs) will be 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.

The betatron function shown in Fig. 2 is matched such that the Twiss parameter α=0 in each Tracker is met 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.

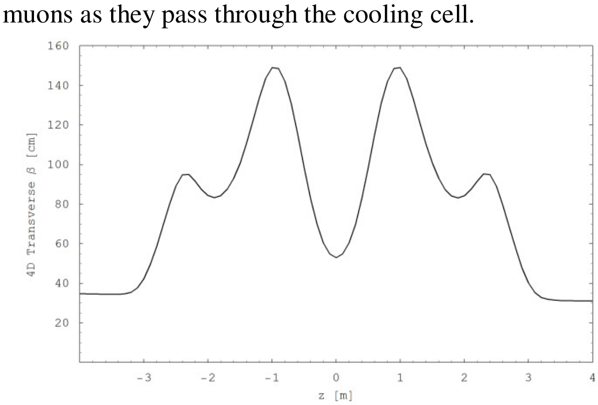

Figure 2: 4D betatron function evolution in the novel lattice designed for MICE Cooling Demonstration.

This is achieved 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. The resulting solenoidal magnetic field on axis is shown in Fig. 3. Selected design parameters of the baseline lattice are summarised in Table 1.

Table 1: Selected Parameters of Lattice for MICE Cooling Demonstration

Parameter	Value
RF frequency (MHz)	201
Number of RF cavities	2
Peak RF gradient (MV/m)	10.3
Number of main (secondary) LiH absorbers	1(2)
β⊥ at main (secondary) LiH absorber(s) (cm)	~53(85)
Main (secondary) absorber thickness (mm)	65(32.5)

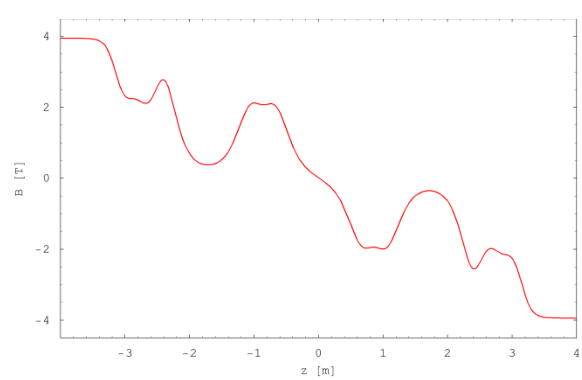

Figure 3: Solenoidal magnetic field on axis in the novel lattice designed for MICE Cooling Demonstration.

COOLING PERFORMANCE

The optical design of the lattice was evaluated with Monte Carlo simulations using MAUS (MICE Analysis User Software). The simulation uses realistic input muon-beam phase space distributions and includes the effect of realistic magnetic and RF fields. The full material budget seen by the muon beam (absorbers, apertures, windows,

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He gas, detector planes) is also simulated. The baseline lattice performs very well in these simulations yielding a measurable spectrum of cooling as shown in Fig. 4, while keeping the high transmission of muons through the cooling cell (see Fig. 5).

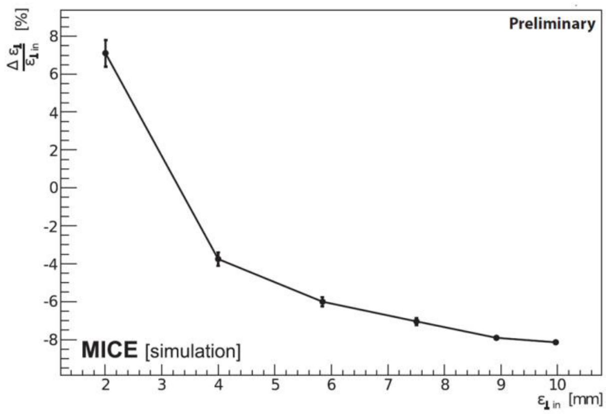

Figure 4: Change in muon beam normalised 4D emittance versus initial input emittance expected using the configuration adopted for the demonstration of ionization cooling.

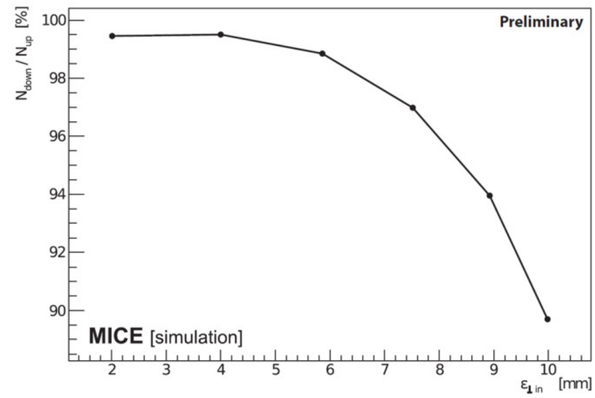

Figure 5: Transmission of the ionization-cooling demonstration lattice as function of the input beam emittance.

RADIATION SHUTTER AND SECONDARY ABSORBER

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 similar to that which will be used for lead shutters 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 magnetic field. The design of both the radiation shutter and the movable SA inside the vacuum chamber is shown in Fig. 6.

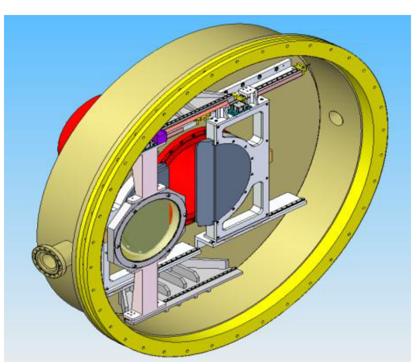

Figure 6: Design of the movable frame for the SA (front) and the lead radiation shutter (back). The half discs of lead shutter (grey) can be seen together with the rails inside the MICE vacuum chamber (yellow).

CONCLUSION AND FUTURE PLANS

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 acceleration provided by two single, 201 MHz, cavity modules[7]. The equipment necessary to mount the experiment is either in hand (the superconducting magnets and instrumentation) or at an advanced stage of preparation (the single-cavity modules). The novel revised 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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