LAYOUT OF 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 multi-TeV lepton-antilepton collisions 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 was prepared in parallel to the execution of a programme designed to measure the cooling properties of liquid-hydrogen and lithium hydride (Step IV). The design will be presented together with a summary of the projected 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 (an absorber) and subsequently accelerated, is the technique by which it is proposed to cool the beam [2, 3]. A factor of 10^5 in 6D muon cooling has been achieved in simulation with a 970 meter long channel [4], however 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 ionization cooling is the goal of the MICE collaboration. The current form of the experiment, MICE Step IV, is providing the data required to study the material properties of typical absorber materials (lithium hydride and liquid hydrogen) and the behaviour of muon beams in complex solenoidal fields [5]. The addition of an accleration stage however, is essential for the demonstration of ionization cooling.

Cooling performance depends on the initial emittance and momentum of the beam, the absorber material and the transverse betatron function, $\beta_\perp$, at the absorber. Ionization cooling is optimised when the betatron function is at a minimum through the absorber, and the initial emittance is large. Additionally, the beam momentum must be selected to optimise ionization energy losses, whilst the material must be chosen to induce the smallest emittance growth due to the effect of multiple coulomb scattering.

DESIGN AND DEVELOPMENT

Physical Layout

The configuration that will be used for the demonstration of ionization cooling is shown in Fig. 1. It contains two single 201 MHz cavities, one primary (65 mm) lithium-hydride (LiH) absorber, and two secondary (32.5 mm) LiH "screening" absorbers. The central LiH absorber is sandwiched between two superconducting "focus-coil" (FC) modules. The beam enters and exits the cooling cell through two spectrometer solenoid (SS) modules

The emittance is measured upstream and downstream of the cooling channel using the MICE Scintillating Fibre trackers, placed within a uniform 4 T solenoid field [6]. Further instrumentation upstream and downstream of the cooling channel serves to provide particle identification and additional event selection information [7], through the use of calorimetry and time-of-flight measurements.

Magnetic Design

The lattice has been designed to maximise the measurable reduction in transverse emittance. This is achieved by matching the betatron function to a minimum at the central absorber, whilst moderating the maximum value within the FC modules. This reduces the influence of non-linear effects and permits secondary absorbers to be installed close to the secondary minima to: (a) further enhance the cooling effect and (b) shield the trackers from possible RF dark current-induced noise.

The phase advance of the cooling cell was 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. The measurable cooling is decreased due to chromatic decoherence, which results from a superposition of beam evolutions with different betatron frequencies for different momenta.

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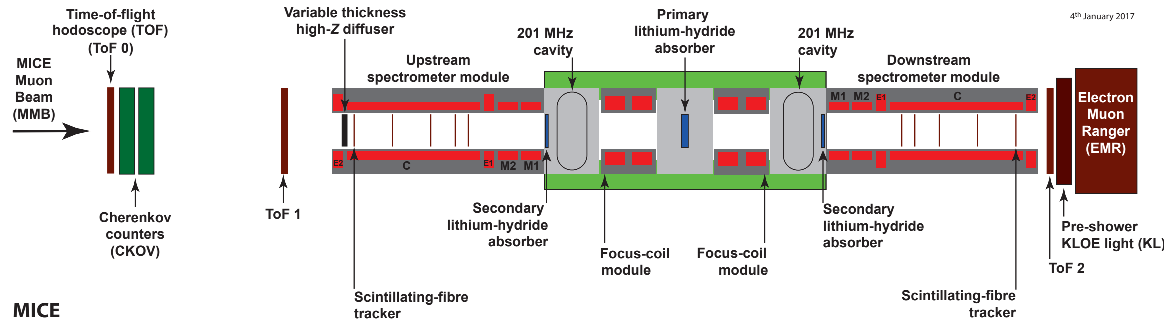

Figure 1: Layout of the lattice configuration for the cooling demonstration. The red rectangles represent the solenoids. The individual coils in the spectrometer solenoids are labelled E1, C, E2, M1 and M2. The ovals represent the RF cavities and the blue rectangles the absorbers. The various detectors (time-of-flight hodoscopes, Cerenkov counters, scintillating-fibre trackers, KLOE Light (KL) calorimeter, electron muon ranger) used to characterise the beam are also represented. The green-shaded box indicates the cooling cell.

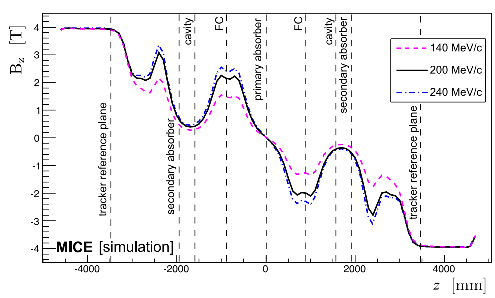

Figure 2: Longitudinal magnetic field strength through the length of the cooling channel for the 200 MeV/c (solid black line), 140 MeV/c (dashed purple line) and 240 MeV/c (mixed blue line) settings. The position of key components are indicated by the vertical lines.

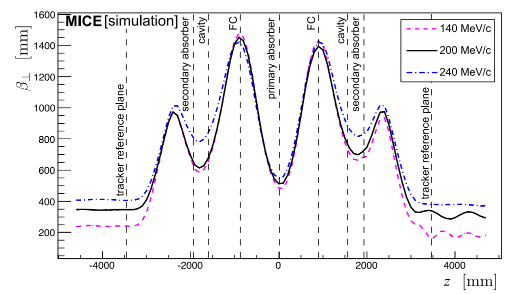

Figure 3: Transverse betatron function through the length of the cooling channel for the 200 MeV/c (solid black line), 140 MeV/c (dashed purple line) and 240 MeV/c (mixed blue line) settings. The position of key components are indicated by the vertical lines.

The resulting on axis magnetic field strength 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 key components within the cooling channel. The downstream FC and SS modules are powered in the opposite sense to the upstream FC and SS modules so that the field changes sign at the primary absorber. This is a desirable feature for studying the cancellation of canonical angular momentum through the lattice.

Optical Layout

The betatron functions shown in Fig. 3 are matched for different initial momentum beams. In all cases, the Courant Snyder parameter α was matched to zero within the tracking volume, and a minimum value of beta in the central absorber was achieved. The matching procedure takes into account the change in momentum of the beam as it traverses the cooling channel by adjusting the currents in the FC and SS matching coils whilst maintaining a uniform 4 T field within the tracking volume.

PERFORMANCE

The performance of the lattice has been evaluated using Monte Carlo simulations using the official simulation and reconstruction software of the MICE Collaboration: the MICE Analysis and User Software (MAUS [8]). Each of the 3 momenta (140, 200 and 240 MeV/c) beams were initially simulated as matched within the upstream spectrometer and allowed to propagate through to the KL and EMR detectors. A range of emittances from 2 to 12 mm were selected to probe the measurement space available to the lattice. Figure 4 shows the emittance behaviour for a 200 MeV/c muon beam, simulated with an initial emittance of 6 mm.

The effects of the absorbers are clearly recognisable as distinct drops in the emittance. In general, good behaviour of the emittance is maintained through the solenoidal fields, with some small non-linear effects, due to the high focussing strength of the SS match coils. During the matching, the non-linear effects were balanced against the requirement for strong focussing through the absorbers, hence some non-linear emittance growth was expected.

Figure 5 shows the fractional change in emittance between the upstream and downstream tracker reference planes, for

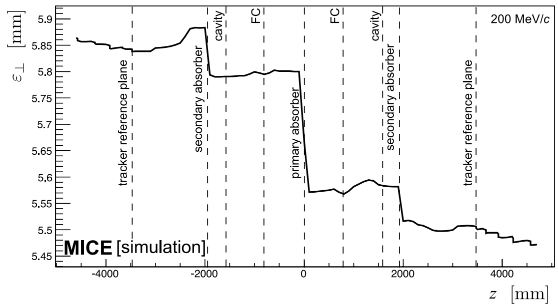

Figure 4: Evolution of the transverse emittance for a transmitted 6 mm beam, with central momentum 200 MeV/c (RMS spread 4.0%). The position of key components are indicated by the vertical lines.

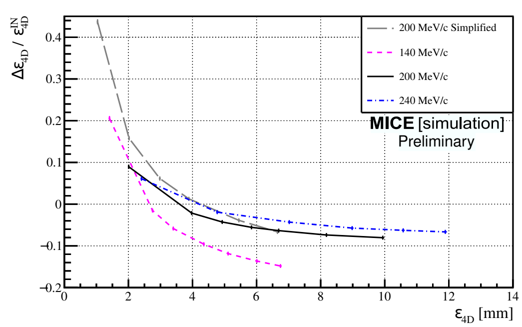

Figure 5: The fractional change in transverse emittance for each transmitted beam as simulated for each emittance of the three momentum settings. The 200 MeV/c setting for the simplified design is also included for comparison.

particles that were transmitted successfully. A statistically significant effect of transverse cooling is measurable for all three momenta, and across a range of initial emittances. The transmission of each beam is over 95% for all but the largest initial emittances.

SIMPLIFIED DESIGN

In order to mitigate issues arising from the damaged M1 coil of the downstream SS module, a simplified layout has also been considered. The design removes the downstream spectrometer module leaving a drift space following the second RF cavity.

Figure 6 depicts the layout of the downstream section of the cooling cell. The SS module has been removed and replaced with a bespoke 3-station tracking detector in the zero-field region. In this configuration the downstream emittance is calculable using a combination of a straight line track fit in the tracker and a total momentum reconstruction using the EMR detector.

There are several benefits of this design, predominantly the low cost. No repairs are required to the downstream SS; the cooling channel fits entirely within the existing magnetic return yoke, negating the need for an extension; and the only

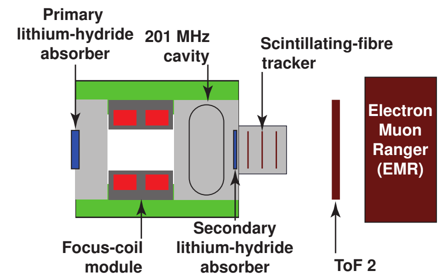

Figure 6: Layout of the downstream components of the simplified design. The spectrometer solenoid has been replaced by a 3-station tracker and the KL detector has been removed to improve the momentum resolution.

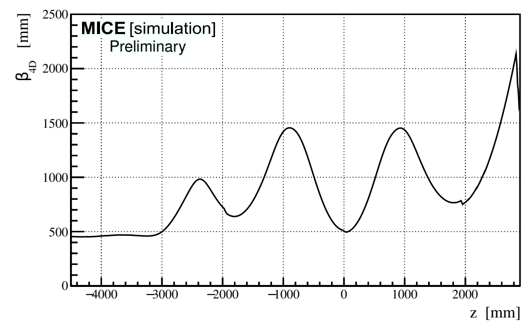

Figure 7: Evolution of the transverse betatron function for the 200 MeV/c setting in the simplified lattice. Significant growth can be seen, following the secondary absorber at z = 2000mm, due to the lack of magnetic fields.

new piece of equipment is the 3-station tracker module, for which all the components are already in hand.

Due to the lack of focussing into the downstream detectors, the optics becomes limited by the aperture of the 3-station tracker. Figure 7 demonstrates the growth of the betatron function due the drift space. Only a subset of emittances can therefore be successfully transmitted through the cooling channel, however cooling can still be measured with high precision for a range of momenta and emittances. In contrast to the original design however, the transmission is reduced for initial emittances, $\varepsilon > 5$mm.

CONCLUSION

The MICE collaboration has presented a design that is capable of demonstrating ionization cooling and measuring the effect to a high precision, across a range of parameters. The equipment is either in hand, or at an advanced stage of preparation, and the experimental performance has been studied in detail. An additional design for a simplified configuration has also been considered as a way to mitigate risk and cost if required.

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