PROCEEDINGS OF SCIENCE

Normalized Transverse Emittance Reduction via Ionization Cooling in MICE 'Flip Mode'

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Low emittance muon beams are central to the development of a Muon Collider and can significantly enhance the performance of a Neutrino Factory. The international Muon Ionization Cooling Experiment (MICE) has recorded several million individual muon tracks passing through a liquid hydrogen or a lithium hydride absorber and has demonstrated the ionization cooling of muon beams. Previous analysis used a restricted data set, and the beam matching was not perfect. In this analysis, beam sampling routines were employed to account for imperfections in beam matching at the entrance into the cooling channel and enable an improvement of the cooling measurement. A study of the normalized transverse emittance change in the MICE cooling channel set up in a flipped polarity magnetic field configuration is presented. Additionally, the evolution of the canonical angular momentum across the absorber is shown and the characteristics of the cooling effect are discussed.

**** The 22nd International Workshop on Neutrinos from Accelerators (NuFact2021) ****
**** 6-11 Sep 2021 ****
**** Cagliari, Italy ****

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PoS(NuFact2021)114

1. Introduction

Muons are considered excellent beam particles for collider applications, their relatively large mass means synchrotron radiation is suppressed, which allows compact rings to be used for beam acceleration and storage. A 10-14 TeV Muon Collider has a physics reach comparable with 100 TeV proton-proton collider, with a footprint compatible with existing laboratories [1].

Over the years a very significant effort has been devoted to demonstrate the feasibility of a Muon Collider. It is proposed to send protons on a target to produce pions which decay into muons. The resulting muon beam has a very large initial emittance and energy spread, which requires significant beam cooling to achieve a sufficient luminosity. Due to the shortness of the muon lifetime the only cooling technique fast enough to be applicable to the muon beams is ionization cooling [2–4], where muons are passing through an absorber material immersed in a strongly focusing lattice losing total momentum via ionization and subsequently recovering the longitudinal component of momentum via RF re-acceleration. The ionization cooling of muons has been demonstrated for the first time experimentally by the Muon Ionization Cooling Experiment (MICE) at RAL [5] studying the change in distribution of single particle transverse amplitudes.

In this paper, after describing the MICE experiment, preliminary results of an alternative analysis based on a study of the normalized transverse emittance change in the MICE cooling channel set up in a flipped polarity magnetic field configuration is presented, together with the evolution of the canonical angular momentum across the absorber.

2. MICE Experiment

The MICE experiment used a muon beam produced at a titanium target dipped in the edge of the proton beam in the ISIS synchrotron at RAL [6]. Pions produced at the target were captured in a beam line consisting of quadrupoles, dipoles and a decay solenoid, where the muon beam was formed and transported to the MICE cooling channel [7]. The MICE cooling channel consisted of twelve superconducting solenoids subdivided into three magnet modules. The central Focus Coil module contained the absorber. Two coils, which could be operated with the same or opposite polarity, provided strong beam focusing required to achieve ionization cooling. Two identical Spectrometer Solenoids, placed anti-symmetrically upstream and downstream of the Focus Coil, were made out of five coils each. Three were grouped together to provide the uniform magnetic field for the tracker detectors [8], and two others were used to perform beam matching into and out of the Focus Coil module. At the entrance to the upstream Spectrometer Solenoid module a variable thickness brass and tungsten diffuser was placed, which allowed the incident beam emittance to be varied. The MICE beam line was instrumented with several sub-detectors both upstream and downstream of the absorber [9, 10]. The Time Of Flight (TOF) detectors together with threshold Cherenkov counters (Ckov A and Ckov B) were used for particle velocity measurements. Two scintillating fibre trackers (TKU and TKD) measured particle position and momentum before and after passing the absorber module. Downstream of the cooling channel an additional TOF station, a mixed lead and scintillator pre-shower detector (KL), and a totally active scintillator calorimeter, the Electron Muon Ranger (EMR), were used to cross-validate the measurements of upstream detectors and identify electrons from the muon decay. The MICE detector system was designed to measure particle position, momentum, velocity, energy and particle ID on a particle-by-particle basis, which was essential to perform the world's first single particle emittance measurement [11]. The schematic of the MICE apparatus with its subsystems is shown in figure 1(upper part).

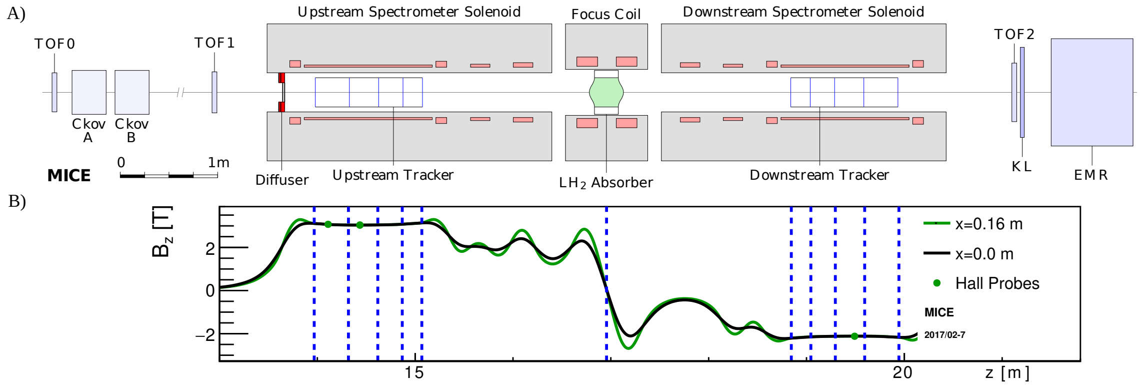

Figure 1: Upper part: schematic of the MICE apparatus with its subsystems. Lower part: the calculated magnetic field, B_z[T], in the flip mode. The modelled field is shown on the beam axis and 160 mm from the axis in the horizontal plane. The readings of Hall probes, situated 160 mm from the beam axis, are also shown. Dashed vertical lines indicate the position of the tracker stations and absorber.

3. MICE Analysis

The main goal of the MICE experiment is to demonstrate ionization cooling of muons using low-Z absorbers, which minimises the heating effect from the multiple Coulomb scattering. In particular, liquid hydrogen ('Full LH_2') and lithium hydride ('LiH') absorbers were tested. For comparison, data were also taken with the evacuated LH_2 absorber ('Empty LH_2') and with the absorber module completely removed ('No Absorber'). MICE was operated in two main magnetic configurations: in the solenoid mode, where the polarity of the magnetic field was positive upstream and downstream of the Focus Coil module, and in the flip mode, with the polarity changing across the Focus Coil as shown in figure 1 (lower part). The analysis described here concerns the emittance change in the flip mode configuration.

After selecting the sample within the momentum window of 135-145 MeV/c, events were required to pass the quality test for the track reconstruction in both trackers [12] and be fully contained in the fiducial volume. Monte Carlo simulations were extensively used to test the performance of the MICE cooling channel, and to study the resolution and efficiency of detectors. The main variable of interest for the demonstration of ionization cooling is the root-mean-square normalized transverse 4D emittance. In the absence of cooling and heating effects it is an approximately conserved quantity during motion of the beam along the magnetic lattice.

Beams were sampled from parent ensembles with nominal input emittances of 4, 6 and 10 mm and nominal input momentum of 140 MeV/c. Applying a rejection sampling technique to the parent distribution reconstructed in the upstream tracker allows one to vary the input emittance of the beams considered in this analysis, and improve the beam matching to the upstream tracker and the absorber. This analysis demonstrates that, for beams with input emittances in the 1.5 - 6.5 mm range, the absolute change in emittance induced by the LiH or LH_2 absorbers is negative for large

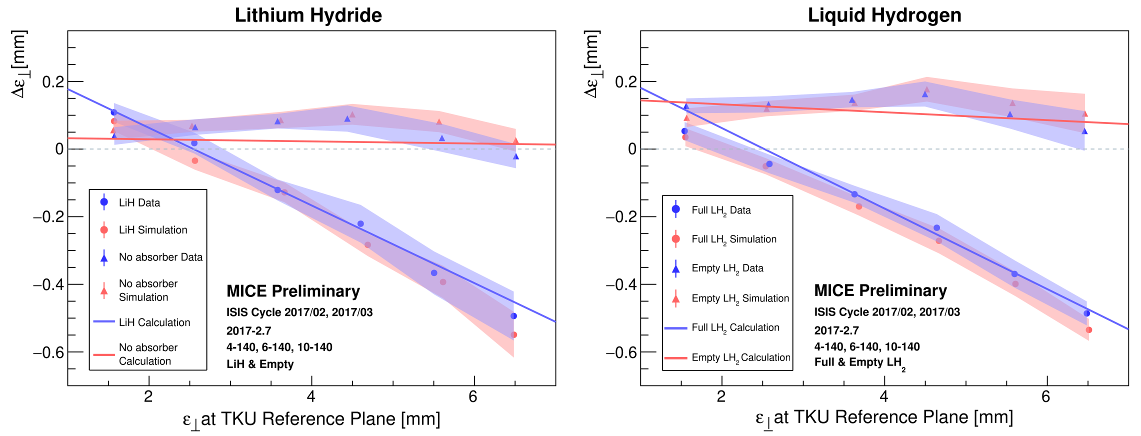

Figure 2: Emittance change between upstream and downstream tracker reference planes as a function of beam emittance at the upstream tracker. Comparisons between (left) 'LiH' and 'No absorber' data, and (right) 'Full LH_2' and 'Empty LH_2' data indicate cooling in the presence of an ionizing material of the absorbers. The error bars represent the values of statistical errors.

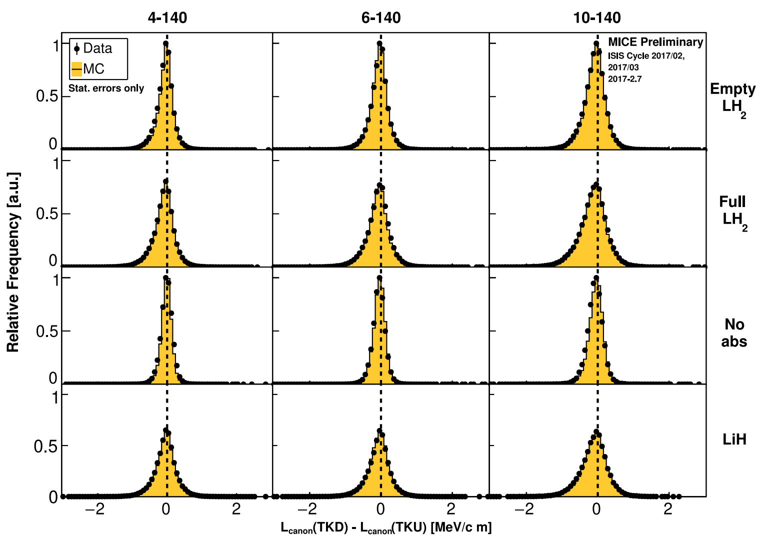

Figure 3: Comparison of (black circles) reconstructed data and (yellow fill) reconstructed simulation of canonical angular momentum change distributions, for the (left) 4, (middle) 6 and (right) 10 mm beams, in the four different absorber settings.

emittances and positive for low emittances. This approach allows a measurement of the equilibrium emittance, where heating due to multiple Coulomb scattering balances cooling due to ionization, yielding the net zero change. This clear sign of the ionization cooling is shown in figure 2. The 'No absorber' case shows slight heating due to optical aberrations, while the 'Empty LH_2' one shows additional heating, which can be explained by the presence of the aluminium windows of the LH_2 absorber module.

The distributions of canonical angular momentum change between the upstream and downstream trackers are shown in figure 3. No net shift in the mean of the distributions occurs between the empty and absorber cases, as expected for a flipped field configuration. In contrast, data taken in the solenoid mode show an increase in this quantity [13]. Similar behaviour is observed in data and simulation. The systematic effects are currently under study and are not accounted for here.

4. Conclusions

MICE demonstrated experimentally the principle of ionization cooling for muon beams [5] opening the route for the development of future muon accelerators like the Neutrino Factory or a Muon Collider. The quantitative analysis of the beam emittance by applying the beam sampling in 'Flip Mode' confirms the cooling effect and verifies the cooling theory. Evolution of canonical angular momentum in 'Flip Mode' seems consistent with zero, as predicted by theory.

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