PROCEEDINGS OF SCIENCE

Muon Ionization Cooling Demonstration by Normalized Transverse Emittance Reduction 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) was designed to demonstrate and study the cooling of muon beams. Several million individual muon tracks have been recorded passing through a liquid hydrogen or a lithium hydride absorber. 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 performance measurement. A study of the change in normalized transverse emittance in a flipped polarity magnetic field configuration is presented in this paper and the characteristics of the cooling effect are discussed.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

[1]For the MICE collaboration.

[2]The work described here was made possible by grants from Department of Energy and National Science Foundation (USA), the Istituto Nazionale di Fisica Nucleare (Italy), the Science and Technology Facilities Council (UK), the European Community under the European Commission Framework Programme 7 (AIDA project, grant agreement no. 262025, TIARA project, grant agreement no. 261905, and EuCARD), the Japan Society for the Promotion of Science and the Swiss National Science Foundation, in the framework of the SCOPES programme. We gratefully acknowledge all sources of support. We are grateful to the support given to us by the staff of the STFC Rutherford Appleton and Daresbury Laboratories and the Cockroft Institute. We acknowledge the use of Grid computing resources deployed and operated by GridPP in the UK, http://www.gridpp.ac.uk/.

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PoS(ICHEP2020)711

1. The Muon Ionization Cooling Experiment (MICE)

Maximizing the beam intensity and maintaining a suitably small aperture in future facilities like a Neutrino Factory or a Muon Collider, require that the muon beam phase space volume be reduced (cooled) prior to acceleration. Ionization cooling, in which the muon beam is passed through a low-Z absorber and subsequently accelerated, is the only viable technique to cool the beam. The MICE collaboration published the first demonstration of muon ionization cooling [1].

In MICE, an upstream beamline [2] captures pions produced from proton interactions on a titanium target [3], allows the pions to decay into muons and transports the resulting muons into a cooling channel (CC). The cooling channel (figure 1 A) consists of 12 superconducting solenoid coils, symmetrically placed up and downstream of an absorber module which would be configured depending on the beam momentum and required betatron function at the absorber. Particle identification detectors (PID) [4], placed up and downstream of the CC, are used to reject events in which pions enter the CC or electrons (decayed muons) exit the CC. The scintillating fiber trackers [5][6] measure the trajectories from which momenta are computed for each muon before and after passing through the absorber. A range of absobers were used during data collection, including a 65 mm lithium hydride disk (*LiH*) and a 22 l liquid hydrogen vessel ($Full\ LH_2$), while an empty drift space (*No absorber*) and the empty vessel ($Empty\ LH_2$) were used as controls. Data presented here were taken with the CC in a flipped polarity magnetic field configuration, to prevent the build-up of canonical angular momentum at the absorber. The solenoidal field strength evolution across the CC is shown in figure 1 B.

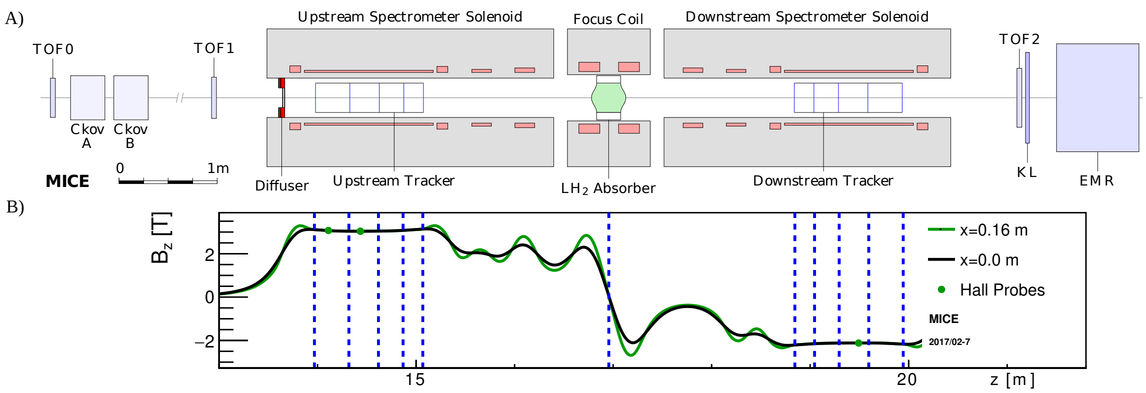

Figure 1: Schematic layout of the MICE cooling channel (A). Magnet coils are shown in red, the absorber in green and the various detetectors are individually marked. The modelled on-axis magnetic field along the length of the cooling channel is shown in B (black line).

2. Emittance

In this analysis, the effect of the absorber module on the 4-dimensional normalized transverse emittance is studied. The beam emittance, a measure of the beam phase space volume, is calculated as follows

$$\varepsilon_{\perp} = \frac{1}{m_{\mu}c}\sqrt[4]{|\Sigma|}\,, \tag{1}$$

where Σ is the 4-dimensional covariance matrix and m_{μ} is the muon mass.

3. Analysis

A set of cuts is applied to the individually reconstructed muon tracks, to remove electron and pion impurities and select events with adequate reconstruction quality. The time of flight recorded upstream of the CC is required to be consistent with a muon with momentum as measured in the upstream tracker (135 - 145 MeV/c selection window) for each track. Each event is required to have a single, well-reconstructed track in both tracking detectors (χ^2/NDF < 8) and fully contained within the fiducial volume. All the events that are successfully reconstructed and pass all the cuts are combined to form the parent sample.

A beam selection procedure based on a rejection sampling algorithm is applied to the parent beam at the upstream reference plane (the tracker plane closest to the absorber), to match the optics of the studied sampled beam to the cooling channel. As a result, the betatron function at the absorber is reduced, hence suppressing the heating effect due to multiple Coulomb scattering. Additionally, the selection procedure provides the flexibility of sampling beams with a range of input emittances.

Figure 2 shows the absolute change in emittance induced by the absorber module, for beams with input emittances in the $\sim$ 1.5 - 5 mm range. The beams are sampled from parent ensembles with nominal input emittance of 6 mm and nominal input momentum of 140 MeV/c. A correction is applied to the data, to account for detector resolution effects. The *LiH* and $Full\ LH_2$ cases demonstrate emittance reduction. This is a clear signal of ionization cooling, a direct consequence of the presence of an absorber material in the cooling channel. In both cases, the cooling effect increases linearly with initial emittance, as expected. The control cases show no cooling effects - the $Empty\ LH_2$ data show slight heating due to muon scattering in the vessel's aluminium windows.

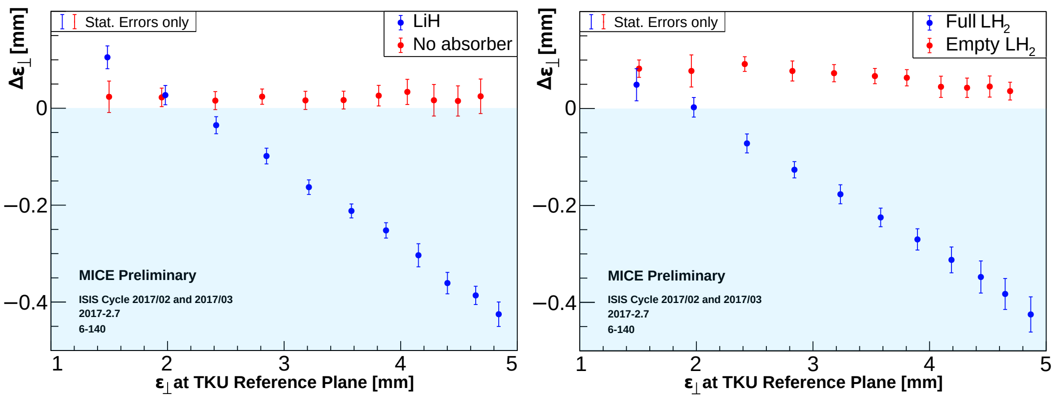

Figure 2: Absolute emittance change between upstream and downstream tracker reference planes as function of beam emittance at the upstream tracker (TKU). Comparisons between (left) *LiH* and *No absorber* data and (right) $Full\ LH_2$ and $Empty\ LH_2$ data indicate cooling in the presence of an ionizing material.

4. Summary

The preliminary MICE results shown in this work give a clear signal of ionization cooling in the presence of lithium hydride and liquid hydrogen absorbers. Ongoing efforts are focused on a comparison with simulation and understanding the systematic effects. Furthermore, the analysis will be applied on a variety of datasets, to study the cooling effect variation with input variables other than emittance, such as momentum and betatron function.

References

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