ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-S701

MUON IONIZATION COOLING EXPERIMENT: RESULTS AND PROSPECTS

D. Maletic†, Institute of Physics Belgrade, University of Belgrade, Belgrade, Serbia
C. T. Rogers, Rutherford Appleton Laboratory, Didcot, United Kingdom
on behalf of the MICE collaboration

Abstract

A high-energy muon collider could be the most powerful and cost-effective collider approach in the multi-TeV regime, and a neutrino source based on decay of an intense muon beam would be ideal for measurement of neutrino oscillation parameters. Muon beams may be created through the decay of pions produced in the interaction of a proton beam with a target. The muons are subsequently accelerated and injected into a storage ring where they decay producing a beam of neutrinos, or collide with counter-rotating antimuons. Cooling of the muon beam would enable more muons to be accelerated resulting in a more intense neutrino source and higher collider luminosity. Ionization cooling is the novel technique by which it is proposed to cool the beam. The Muon Ionization Cooling Experiment collaboration has constructed a section of an ionization cooling cell and used it to provide the first demonstration of ionization cooling. Here the observation of ionization cooling is described. The cooling performance is studied for a variety of beam and magnetic field configurations. The outlook for an experiment to measure muon ionization cooling in all six phase-space dimensions as part of the demonstrator facility being considered by the interna-tional Muon Collider collaboration will also be discussed.

INTRODUCTION

Muons are considered excellent beam particles for a collider applications due to their unique properties. Entire muon energy, being fundamental particle, is available for production of secondary particles. The design of such Muon collider is strongly influenced by radiative effects. The large muon mass also offers an increased coupling to Higgs boson compared to electron. Muon colliders can thus employ rings of small circumference for acceleration and collisions, reducing facility footprints and construction and operating costs. Production of high quality muon beams is challenging. Muon beam production starts by sending the high power proton beam to the target, where pions are produced subsequently decaying into muons. This way muons emerge as a tertiary beam with a very large initial emittance and energy spread, which requires a significant beam cooling in order to be able to achieve a sufficient luminosity in the collider applications. Due to the shortness of the muon lifetime the only cooling technique fast enough to be applicable to the muon beams is ionization cooling [1–3]. In muon ionization cooling, muons are passed through energy-absorbing material where the transverse and longitudinal momentum is reduced, reducing the normalised beam emittance and cooling the beam. Multiple Coulomb scattering from atomic nuclei induces an increase in transverse momentum and heats the beam. By focussing the beam tightly onto the absorber and using materials having low atomic number the heating effect may be suppressed, resulting in overall cooling. The ionization cooling of muons has been demonstrated for the first time experimentally by Muon Ionization Cooling Experiment (MICE) at RAL [4].

† maletic@ipb.ac.rs

EXPERIMENT

The Muon Ionization Cooling Experiment (MICE) was designed, most importantly, to demonstrate the ionization cooling principle and amplitude non-conservation. Other components of the MICE program were to demonstrate high acceptance and tight focussing solenoid lattice, then to demonstrate the integration of liquid hydrogen and lithium hydride absorbers, and also to precisely measure the absorber material properties (dE/dx and multiple scattering distributions) that determine the performance of ionization cooling. MICE was approved in 2003 at RAL. After an extended design, construction, installation, and commissioning process, MICE recorded a substantial dataset (3.5 × 10^8 events) in 2016-17 with one absorber and no RF cavities. MICE collaboration grouped over 100 scientists from 30 institutions in 10 countries.

A schematic of MICE is shown in Fig. 1. Pions arising from protons striking a target in the fringe of the ISIS synchrotron proton beam were guided to the cooling apparatus by quadrupoles, dipoles and a solenoid. Momentum of the resultant beam was selected by the dipoles. A variable thickness diffuser at the upstream end of the cooling channel served to scatter the beam enabling choice of incident emittance. The beam was passed into a solenoid focussing channel. Spectrometer Solenoid modules were placed upstream and downstream of a Focus Coil module within which the absorber was placed providing a tight focus in both transverse planes suitable for ionization cooling. Liquid hydrogen and lithium hydride absorbers were used. Particles passed through a pair of Time-of-Flight (TOF) detectors, which were used to estimate the particle velocity. Scintillating fibre trackers upstream and downstream of the experiment in fields of up to 4 T enabled characterisation of particles' position and momentum before and after passing through the cooling section. By comparing the momentum measured in the trackers and the velocity measured in the TOFs, the particle species was identified and pion and electron impurities rejected. Muons were passed through the experiment one-by-one and an ensemble of muons was accumulated. The experiment was modelled using Geant4-based simulation [5].

ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-S701

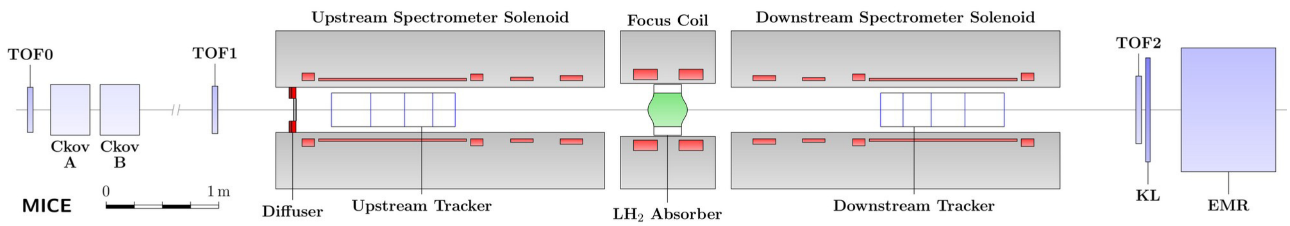

Figure 1: A schematic of MICE. Muons are incident from the left.

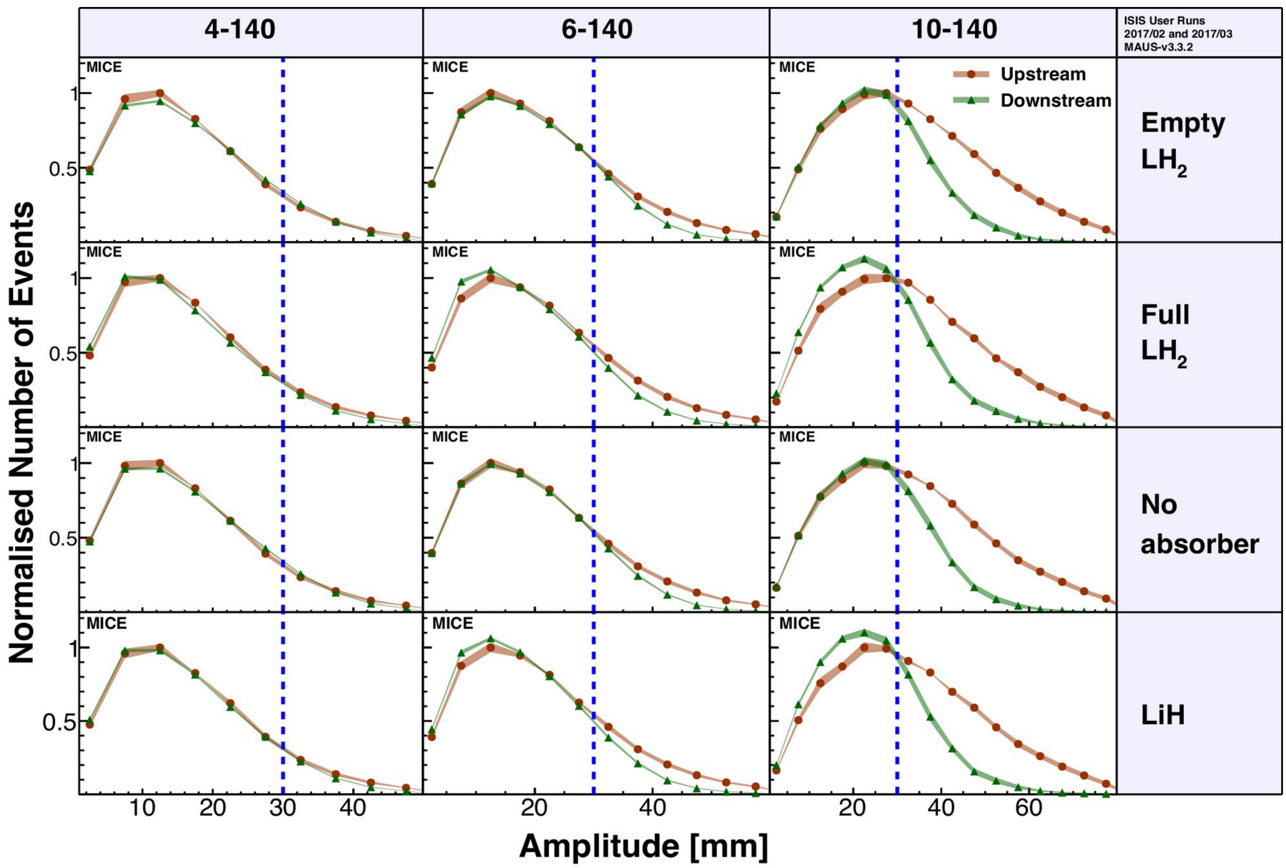

Figure 2: The amplitude distribution of the muon beam upstream and downstream of the absorber for a number of different configurations.

RESULTS

Transverse amplitude distributions were found by counting the number of muons sitting within hyper-ellipsoids of varying sizes in four dimensional phase space upstream and downstream. Enhancement in the number of particles at low amplitude when passing through the absorber was indicative of an increase in the number of muons in the beam core i.e. cooling. A decrease in the number of particles at high amplitude was indicative of either migration towards the beam core or scraping.

The amplitude distributions are shown in Fig. 2 [4]. Results are shown for beams having nominal momentum of 140 MeV/c and incident RMS emittances of 4, 6 and 10 mm (4-140, 6-140 and 10-140 respectively). Beam was passed through the liquid hydrogen vessel both in an empty (Empty LH2) and full (Full LH2) configuration. The beam was also passed through the experiment with No absorber and the lithium hydride (LiH) absorber. In the Empty LH2 and No absorber configuration, the core of the beam was observed to have the same number of particles both upstream and downstream of the absorber. The tail of the distribution was observed to be depleted above about 30 mm amplitude and this was attributed to beam scraping on the beam pipe leading to beam loss.

In the Full LH2 and LiH case, there was a significant enhancement in the number of muons downstream of the absorber in the beam core. This enhancement was the signal for cooling: the beam core density has increased. The ratios of the amplitude distributions are shown in Fig. 3 together with the simulated cooling performance. Where the number of muons has increased, the ratio is more than 1. Where the number of muons has decreased, the ratio is less than 1. A clear signal for the enhancement in core density is observed for settings where an absorber was installed. The simulated cooling performance shows good agreement with the measured data [5].

ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-S701

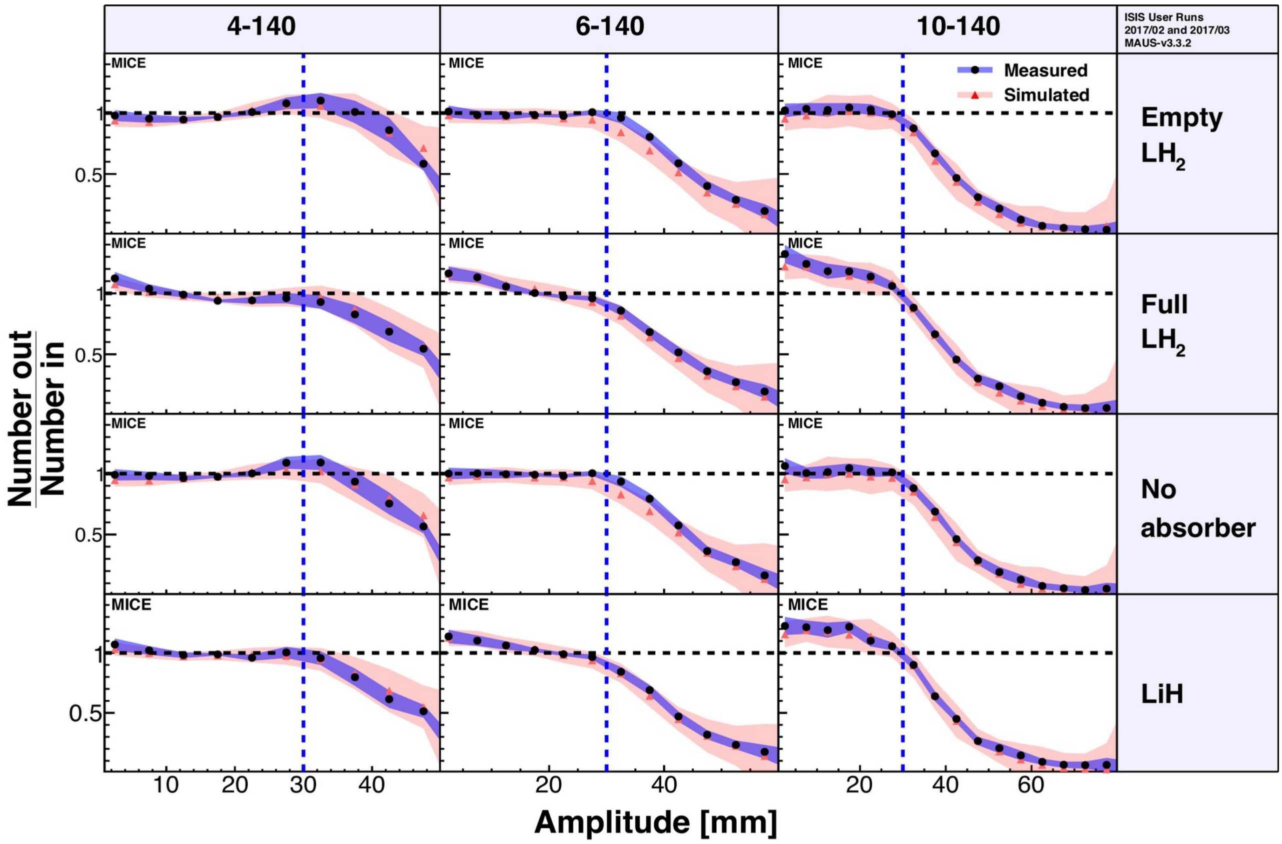

Figure 3: The ratio of downstream to upstream amplitudes. A ratio greater than 1 indicates an increase in particle density.

PROSPECTS AND CONCLUSIONS

The MICE Collaboration has recorded a substantial dataset with which to demonstrate muon ionization cooling and is well on its way to accomplishing its goals. Clear evidence of transverse ionization cooling has been presented. The analysis of MICE data continues.

Further settings are being explored having different momenta and different focussing properties. In particular, results including a lattice operating in solenoid mode and results showing RMS emittance are under study and are presented in [6] and [7]. Studies are in progress for a follow-up experiment. Designs are under study for lattices with enhanced cooling at lower emittances, including RF. In particular, by including a dipole in the lattice arrangement, a modest position-energy correlation may be introduced into the beam (dispersion). By passing the beam through an appropriately aligned wedge-shaped absorber, higher energy particles will experience greater energy loss leading to exchange of emittance from longitudinal to transverse. Together with the transverse cooling described here, so-called ‘6D’ cooling may be achieved. Studies of a muon source are underway. Using the proposed nuSTORM beam as a muon source is one particularly interesting proposal, described in [8]. The Muon Ionization Cooling Experiment has demonstrated conclusively the reduction of normalised emittance by ionization cooling. Analysis of data for a number of different beam conditions is ongoing. Design work to pursue a follow-up experiment is ongoing.

REFERENCES

[1] A. Skrinsky and V. Parkhomchuk, *Sov. J. Part. Nucl.* 12, 223, 1981.

[2] D. Neuffer, *Conf. Proc.* C 830811, 481, 1983.

[3] D. Neuffer, *Part. Accel.* 14, 75, 1983.

[4] M. Bogomilov, MICE collaboration, ”Demonstration of cooling by the Muon Ionization Cooling Experiment”, *Nature* 578, 53–59, 2020.

[5] C. T. Rogers, “Muon Ionization Cooling Experiment: Results & Prospects”, in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 4528-4530. doi:10.18429/JACoW-IPAC2021-FRXB05

[6] T. W. Lord, “Transverse Emittance Change and Canonical Angular Momentum Growth in MICE ‘Solenoid Mode’ with Muon Ionization Cooling”, in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 3289-3292. doi:10.18429/JACoW-IPAC2021-WEPAB277

[7] P. B. Jurj, “Normalized Transverse Emittance Reduction via Ionization Cooling in MICE ’Flip Mode’”, in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 474-477. doi:10.18429/JACoW-IPAC2021-MOPAB134

[8] C. T. Rogers, N. Gall, J.-B. Lagrange, and J. Pasternak, “nuSTORM Accelerator Challenges and Opportunities”, in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 4104-4106. doi:10.18429/JACoW-IPAC2021-THPAB175