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MUON IONIZATION COOLING EXPERIMENT: RESULTS & PROSPECTS*

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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 constructed a section of an ionization cooling channel 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 muon ionization cooling demonstrations is discussed.

THE NEED FOR MUON COOLING

The muon collider has potential to explore physics at the highest energy scale on a footprint that is small compared to existing and proposed collider facilities. This is because unlike protons, muons are fundamental particles so the entire muon energy is available for production of secondary particles, rather than being spread among constituent quarks. Production of synchrotron radiation is suppressed by the high muon mass so muons may be accelerated to high energy in ring accelerators, unlike in electron-positron colliders.

Production of high quality muon beams is challenging. Pions are produced by firing protons onto a target. The pions decay to muons, but the resultant beam has high emittance. In order to reach suitable luminosity, the muon emittance must be reduced on a time scale that is compatible with the muon lifetime. Ionization cooling is the only technique that has been identified that can be used to cool muons to provide a beam suitable for a muon collider.

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 MUON IONIZATION COOLING EXPERIMENT

The Muon Ionization Cooling Experiment (MICE) was designed to demonstrate the ionization cooling principle. 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 ionisation 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 over several hours. A number of configurations were studied having different incident momenta and emittances. Absorbers were changed every few weeks. The apparatus was observed to be exceptionally stable over this time. The experiment was modelled using a bespoke Geant4-based simulation.

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 [1]. Results are shown for beams having nominal momentum of

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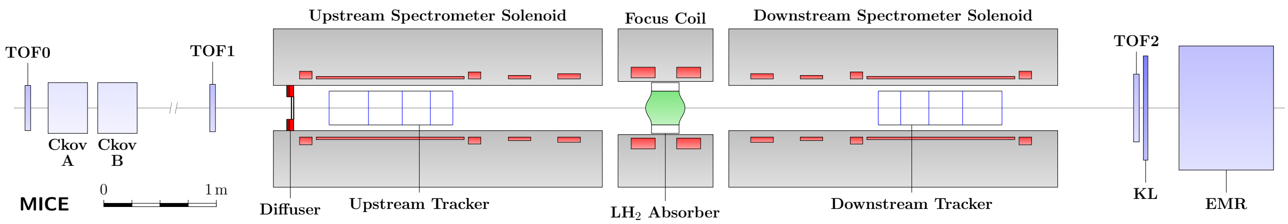

Figure 1: A schematic of MICE. Muons are incident from the left.

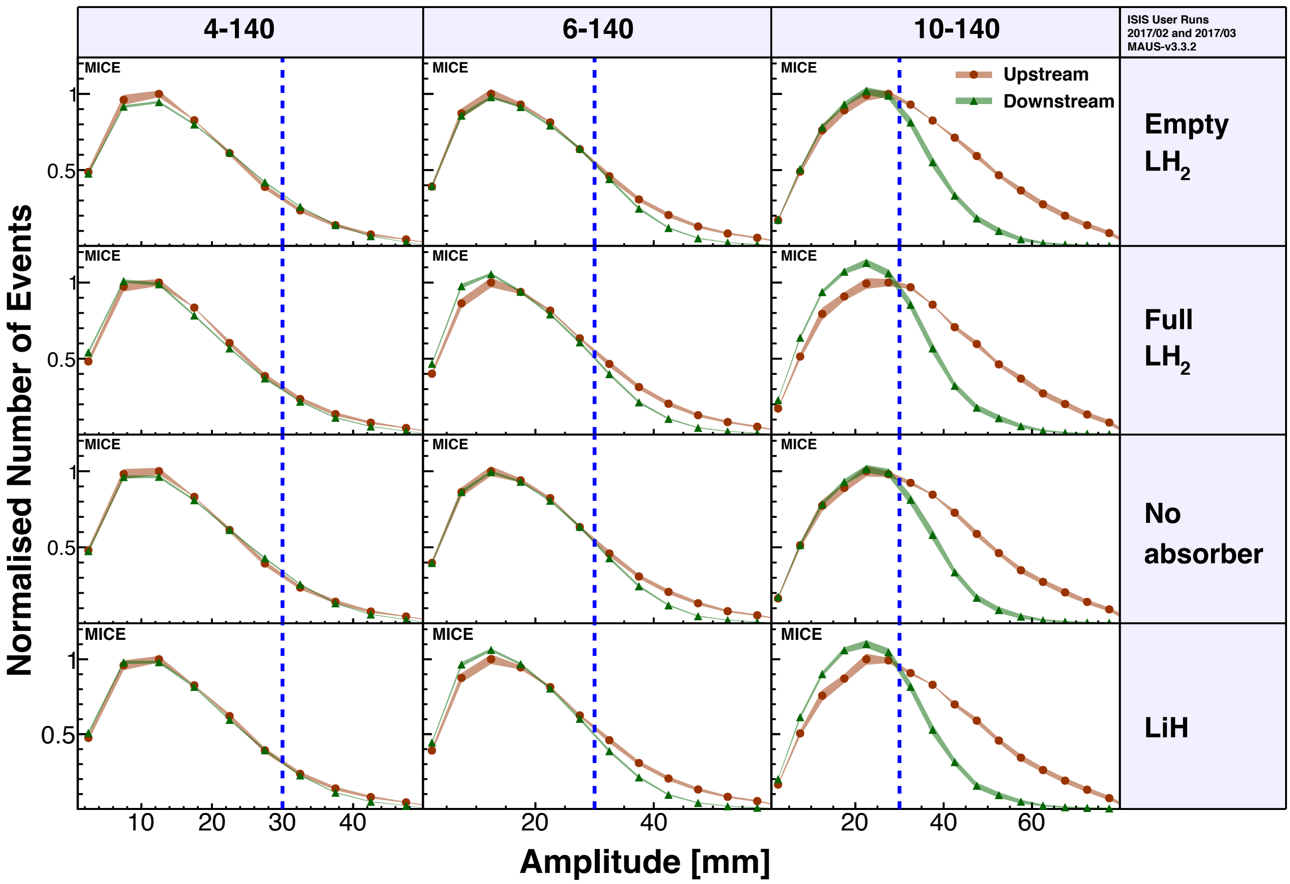

Figure 2: The amplitude distribution of the muon beam upstream and downstream of the absorber for a number of different configurations.

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.

PROSPECTS

The analysis of MICE data continues. Further settings are being explored having different momenta and different

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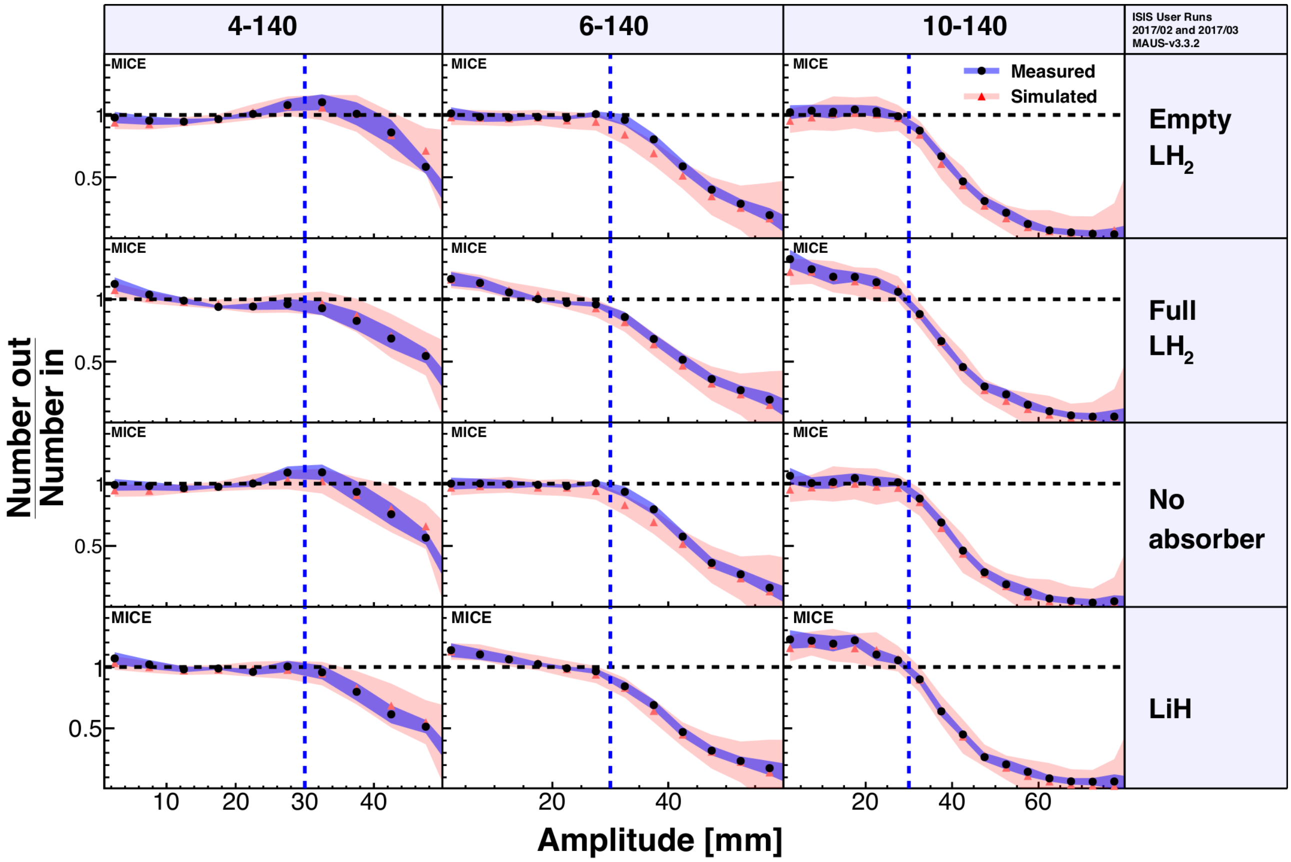

Figure 3: The ratio of downstream to upstream amplitudes. A ratio greater than 1 indicates an increase in particle density.

focussing properties. In particular, results including a lattice operating in solenoid mode and results showing RMS emittance are under study and are presented in [2] and [3].

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 [4].

CONCLUSIONS

The Muon Ionisation Cooling Experiment has demonstrated conclusively the reduction of normalised emittance by ionisation cooling. Analysis of data for a number of different beam conditions is ongoing. Design work to pursue a follow-up experiment is ongoing.

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