First Demonstration of Ionization Cooling by the Muon Ionization Cooling Experiment

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Muon colliders have the potential to carry the search for new phenomena to energies well beyond the reach of the LHC in the same or smaller footprint. Muon beams may be created through the decay of pions produced in the interaction of a proton beam with a target. To produce a high-brightness beam from such a source requires that the beam be cooled. 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 cooling performance is related to the performance of a possible future muon collider facility.

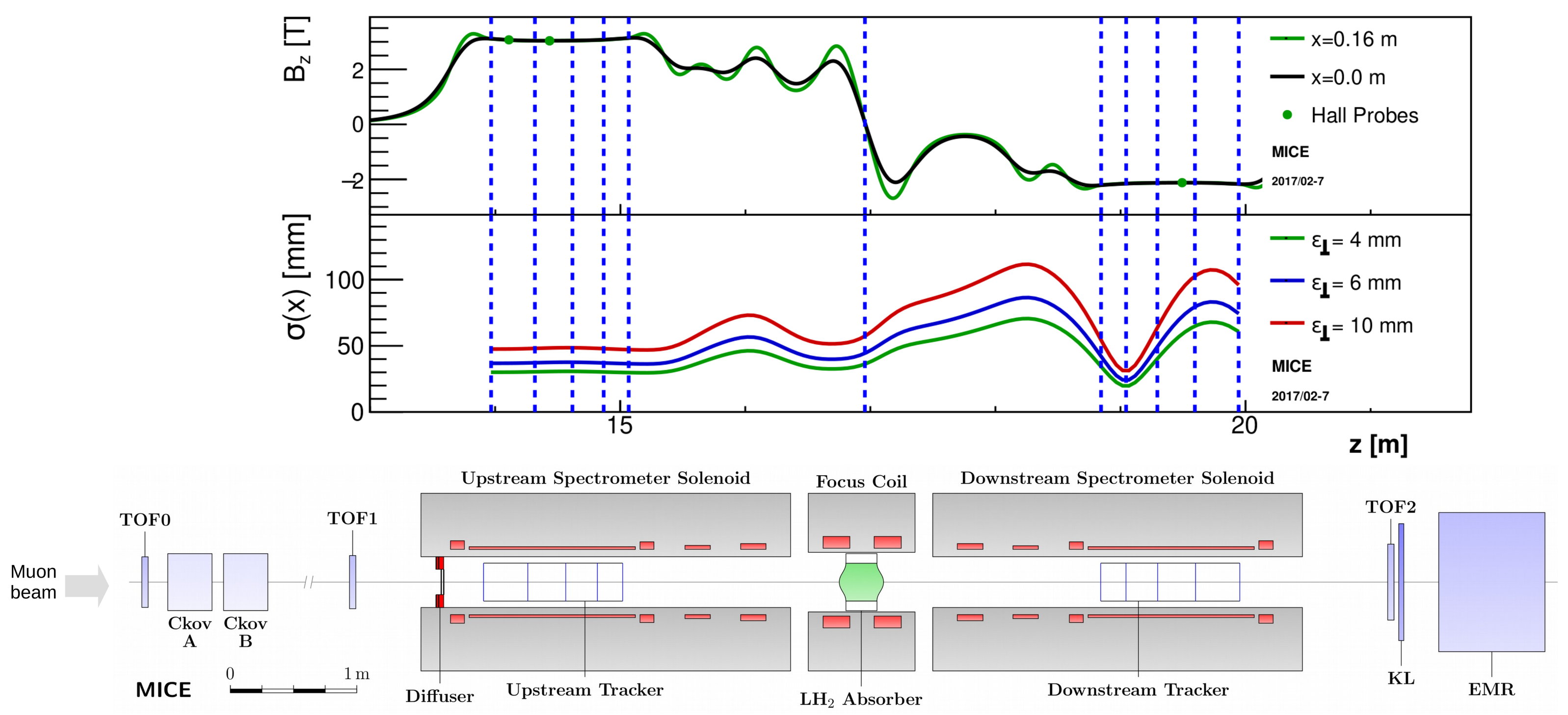
Muons as a Source of Neutrinos

Artificial neutrino beams are typically made from a decaying beam of pions. The resulting neutrino beams are challenging to characterise. Neutrinos from the decay of an accelerated, stored muon beam can be characterised more easily resulting in excellent sensitivity to neutrino oscillation parameters. A facility that produces neutrinos in this way is known as a Neutrino Factory.

Muons are produced using a proton beam striking a target to produce a secondary beam comprising many particle species including pions, kaons and muons. The pions and kaons decay to produce additional muons, which must be captured on a time scale compatible with the muon lifetime. In order to efficiently accelerate a high current of muons, it is beneficial to increase the brightness of the muon beam. Most designs achieve this using a technique known as Ionization Cooling.

In ionization cooling a suitably prepared beam is passed through an appropriate material. Momentum is lost through ionization. Radio-frequency cavities restore momentum only along the beam direction. This results in a reduction in the overall position and momentum spread of the beam, known as the beam phase space volume, and a concomitant increase in brightness.

The international Muon Ionization Cooling Experiment (MICE) collaboration has constructed a section of cooling channel and demonstrated transverse ionization cooling for the first time.



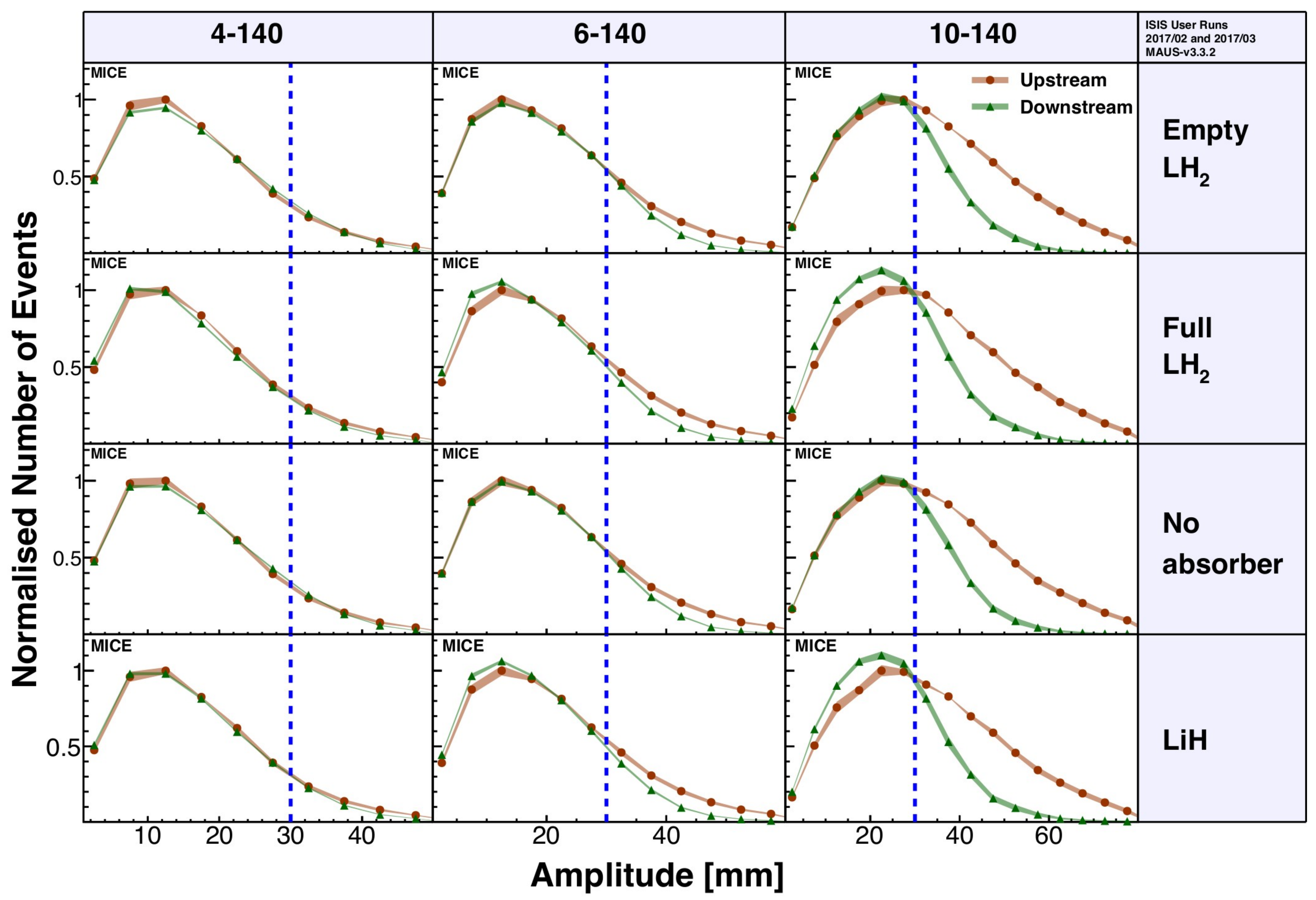
MICE Apparatus

A transfer line brought a beam to the cooling apparatus. Tight focussing was achieved using 12 superconducting solenoids contained in three warm-bore modules. Spectrometer solenoid modules provided uniform fields of up to 4 T for momentum measurement as well as two "matching" coils to match the beam to the central pair of closely space "focus" coils. The focus coils were designed to enable peak on-axis fields of 3.5 T. The field configuration and nominal beam size is shown in fig. 1.

Liquid hydrogen and lithium hydride absorbers created energy loss that generated the ionization cooling effect. Low Z materials, having a long radiation length relative to the rate of energy loss, enhanced the cooling effect. A tight focus near the absorber and large acceptance contributed to the good cooling performance.

Upstream of the cooling apparatus, two time-of-flight (TOF) detectors measured the particle velocity. A complementary velocity measurement was made upstream by threshold Cherenkov counters. Scintillating fibre trackers, positioned in the uniform-field region of each of the two spectrometer solenoids, measured the particle position and momentum upstream and downstream of the absorber. Downstream, an additional TOF detector, a mixed lead-scintillator pre-shower detector and a totally active scintillator calorimeter, the Electron–Muon Ranger, identified electrons produced by muon decay.

This enabled reconstruction of the full phase space, including the angular momentum introduced by the solenoids and species of each particle entering and leaving the cooling channel.



Measurement of Particle Amplitude

The data presented here were taken using beams with a nominal momentum of 140 MeV/c and a nominal normalized RMS emittance in the upstream tracking volume of 4 mm, 6 mm and 10 mm; these settings are denoted as '4–140', '6–140' and '10–140', respectively. Beams with a higher emittance have more muons at high amplitudes and occupy a larger region in phase space. For each beam setting, two samples were considered for the analysis. The 'upstream sample' contained particles identified as muons by the upstream TOF detectors and tracker, for which the muon trajectory reconstructed in the upstream tracker was fully contained in the fiducial volume and for which the reconstructed momentum fell within the range 135 MeV/c to 145 MeV/c (which is considerably higher than the momentum resolution of the tracker, 2 MeV/c). The 'downstream sample' was the subset of the upstream sample for which the reconstructed muons were fully contained in the fiducial volume of the downstream tracker.

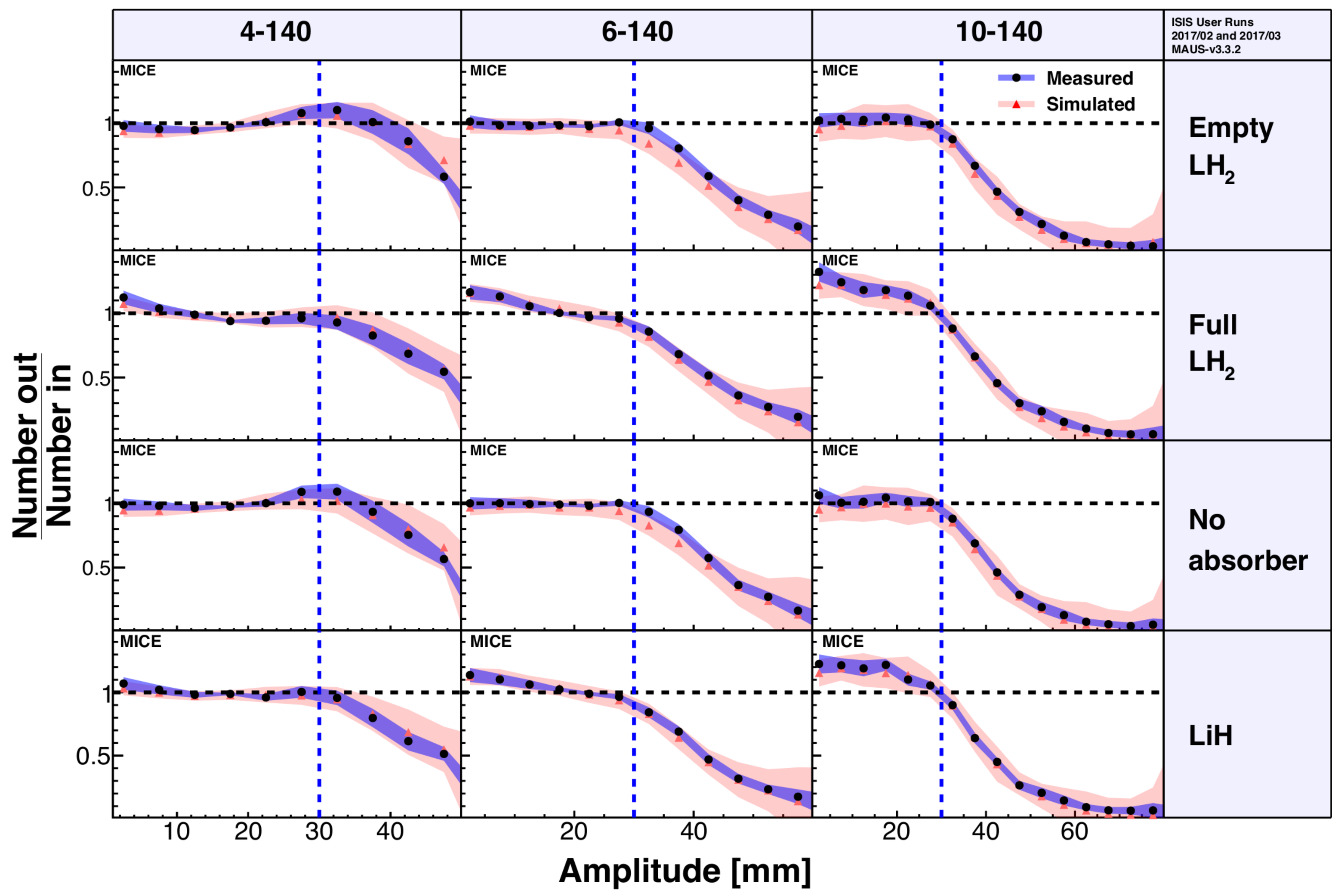
The amplitude distribution of the beam upstream and downstream of the absorber is shown in fig. 2. Amplitude is a phase-space normalised estimator of distance from the beam core.

The behaviour of the beam at low amplitude is the key result of this study. For the 'No absorber' and 'Empty LH 2 ' configurations, the number of events with low amplitude in the downstream sample is similar to that observed in the upstream sample. For the 6–140 and 10–140 configurations for both the 'Full LH 2 ' and the 'LiH' samples, the number of events with low amplitude is considerably larger in the downstream sample than in the upstream sample. This indicates an increase in the number of particles in the beam core when an absorber is installed, which is expected if ionization cooling takes place. This effect can occur only because energy loss is a non-conservative process.

Amplitude Ratio

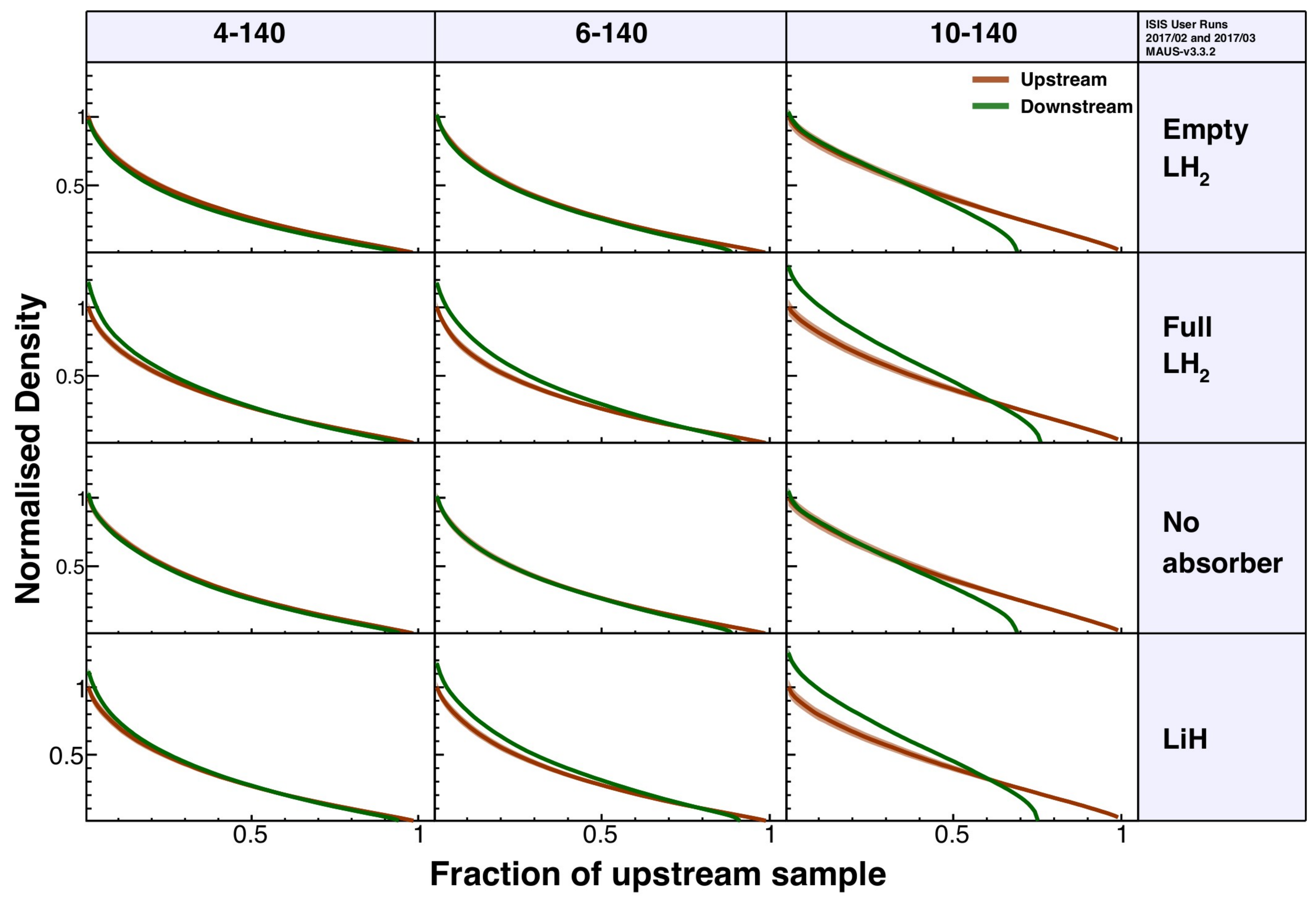
The cooling effect can also be seen by looking at the ratio of downstream to upstream amplitudes, as shown in fig. 3. In the "no absorber" and "empty absorber" cases, the ratios are consistent with 1 for amplitudes less than 30 mm confirming the conservation of amplitude in this region. Above 30 mm the amplitude drops below unity, indicating that at high amplitude there are fewer muons downstream. This can also be observed in the distributions shown in fig. 2. This is because some muons strike the beam pipe or are outside the fiducial volume of the downstream tracker.

For the 6-140 and 10-140 datasets, the addition of liquid-hydrogen or lithium hydride absorber material causes the ratios to rise above unity for the low-amplitude particles that correspond to the beam core. This indicates ionization cooling.



Density

The MICE collaboration has directly measured the beam density, estimated using the k-Nearest Neighbour method. Phase space density is an invariant of a symplectic system. An increase in phase-space density is also an unequivocal demonstration of cooling. The density quantile distribution is shown in fig. 4. For the "no absorber" and "empty lH2" cases, the downstream density in the highest-density regions is indistinguishable from the upstream density. In the presence of an absorber, beams with larger nominal emittance show an increase in core density a signal for ionization cooling.



Conclusions

The MICE collaboration has unequivocally demonstrated ionization cooling of muons for the first time. The collaboration has built and operated a section of a solenoidal cooling channel and demonstrated the ionization cooling of muons using both liquid hydrogen and lithium hydride absorbers. The results are well described by simulations. This demonstration of ionization cooling is an important advance in the development of high-brightness muon beams, which may be used as a source for a well-characterised and high energy neutrino beam.