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CHARACTERISATION OF COOLING IN THE MUON IONIZATION COOLING EXPERIMENT

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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 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 results of the further analysis of the data are presented, including studies in different magnet configurations and with more detailed understanding of the detector systematic uncertainty.

THE NEED FOR MUON COOLING

The muon collider is an excellent prospect for the energy frontier [1], because:

- synchrotron radiation is suppressed due to the high muon mass, compared to electrons;
- muon recirculation through the detector leads to high luminosity, compared to linear colliders;
- muons are fundamental so have a much improved physics reach compared to protons at the same energy.

These characteristics can be used to make a collider that is:

- energy efficient;
- cost efficient; and
- compact.

Muons are produced by firing protons onto a pion production target, yielding a beam having large emittance. Achievement of high luminosity requires several orders of magnitude reduction in beam emittance. Muon ionization cooling [2] is the technique proposed to deliver this.

Muon ionization cooling may also be beneficial for a muon-based neutrino source [3]. In this case, muon cooling would enable more muons to be accelerated in a smaller aperture, improving the facility efficiency and performance.

Muon ionization cooling has been demonstrated by the Muon Ionization Cooling Experiment (MICE) [4]. Here we outline the current status of the data analysis.

EXPERIMENTAL APPARATUS

MICE was constructed at the Rutherford Appleton Laboratory in the UK [5]. A target was inserted into the proton synchrotron as the protons reached peak energy. Pions created in the target were transported through a series of focusing quadrupoles, momentum-selection dipoles, and a pion-decay solenoid which enabled selection of muon beams having different momentum, rate and pion contamination. A remotely operable beam diffuser just before the main cooling system enabled generation of different beam emittances. Samples were generated by accumulating particle-by-particle measurements.

Incident particles passed through a TOF station (TOF0), a pair of threshold Cherenkov counters and a further TOF station (TOF1), as shown in Fig. 1. The particle velocity was calculated by measuring the time-of-flight between TOF0 and TOF1. The rate was kept low enough that individual particles were reconstructed. As the transfer line had a relatively narrow momentum acceptance, pion and electron impurities could be rejected by studying the particle time-of-flight.

Scintillating fibre trackers upstream and downstream of the cooling apparatus, immersed in solenoid fields of several T, enabled measurement of the position and momentum of particles. Particles took a helical trajectory in the solenoid. The positions of the particles were measured in 5 stations in each tracker, enabling characterisation of the helix and hence inference of the particle momentum.

Several solenoid coils between the two trackers enabled focusing of the beam onto an absorber. In this paper lithium hydride (LiH) and liquid hydrogen absorbers are considered as well as the empty hydrogen absorber vessel and the case where no absorber was installed at all.

CONFIGURATIONS

Two solenoid configurations are studied here, with and without a polarity reversal at the absorber. When the solenoid polarity is not reversed at the absorber (‘solenoid’ mode), the beam develops canonical angular momentum as it passes through the absorber material. In a long channel this can be detrimental to the cooling performance. When the solenoid polarity is reversed at the absorber (‘flip’ mode), the coils near the absorber act in opposition so that higher

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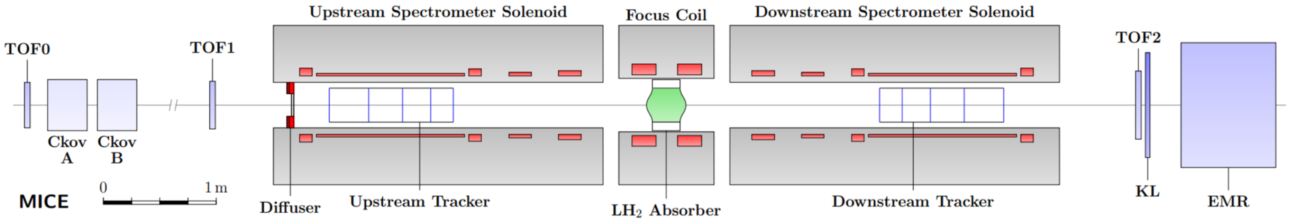

Figure 1: Schematic of the MICE experiment. Particles were incident from the left.

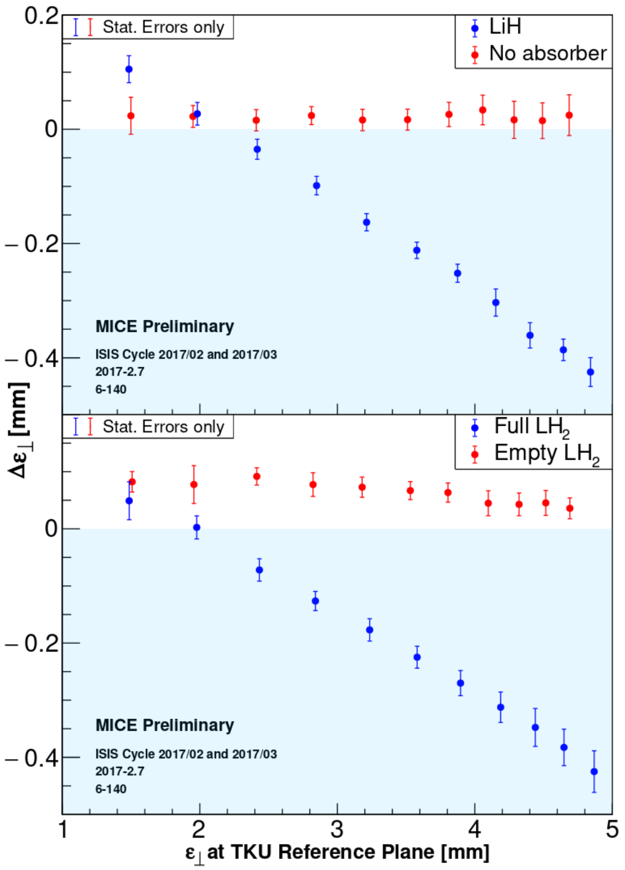

Figure 2: RMS emittance change for beam samples in the 'flip' configuration having different absorbers installed and different event selections.

currents are required to generate the same field. This can make the magnets more technically demanding.

Both configurations were operated by MICE and demonstrated excellent performance. When an absorber was installed, large-emittance beams had significant emittance reduction. At lower emittance multiple Coulomb scattering tended to spoil the ionization cooling effect leading to lower emittance reduction. At the lowest emittances, multiple Coulomb scattering dominated over ionization cooling leading to beam heating. This was as expected.

FLIP MODE PERFORMANCE

The change in RMS beam emittance in flip mode is shown in Fig. 2 for different absorbers. Samples of particles having different emittances were selected and examined. When an empty absorber was installed the beam was slightly heated by the presence of thin hydrogen containment windows which, being made of aluminium, tended to induce scattering more strongly than the hydrogen. Even with no absorber installed at all, some heating was observed due to optical aberrations.

Because MICE measured individual particles, it was possible to examine the behaviour of the beam core independently from the rest of the beam (Fig. 3). An increase in the number of particles having low amplitude was observed for beams having high nominal emittance when the absorber was installed. This is indicative of cooling. When no absorber was present or the emittance was low enough that scattering was dominant, there was a decrease in the number particles at low amplitude. This was indicative of heating.

SOLENOID MODE PERFORMANCE

Cooling was also observed in solenoid mode, comparable to that measured in flip mode (Fig. 4). For a beam having 10 and 6 mm nominal emittance, the number of muons in the core of the beam increased downstream which was the signal for cooling to have taken place.

For a beam having 4 mm nominal emittance, no significant emittance change occurred in the core of the beam. For a 3 mm beam significant heating was observed. In part this was caused by the absorber, however the 3 mm beam was not well matched to the beam line leading to an additional optical heating effect.

OUTLOOK

Further analysis of the data is ongoing. Focus is now shifting to the preparation of a new Demonstrator for muon ionization cooling. This would build on the MICE results by demonstrating reduction in both longitudinal and transverse emittance, over a longer section of beam line, leading to greater cooling, including the demonstration of reacceleration and including cooling to lower beam emittances. This would build confidence in the ionization cooling technique enabling development of a muon collider.

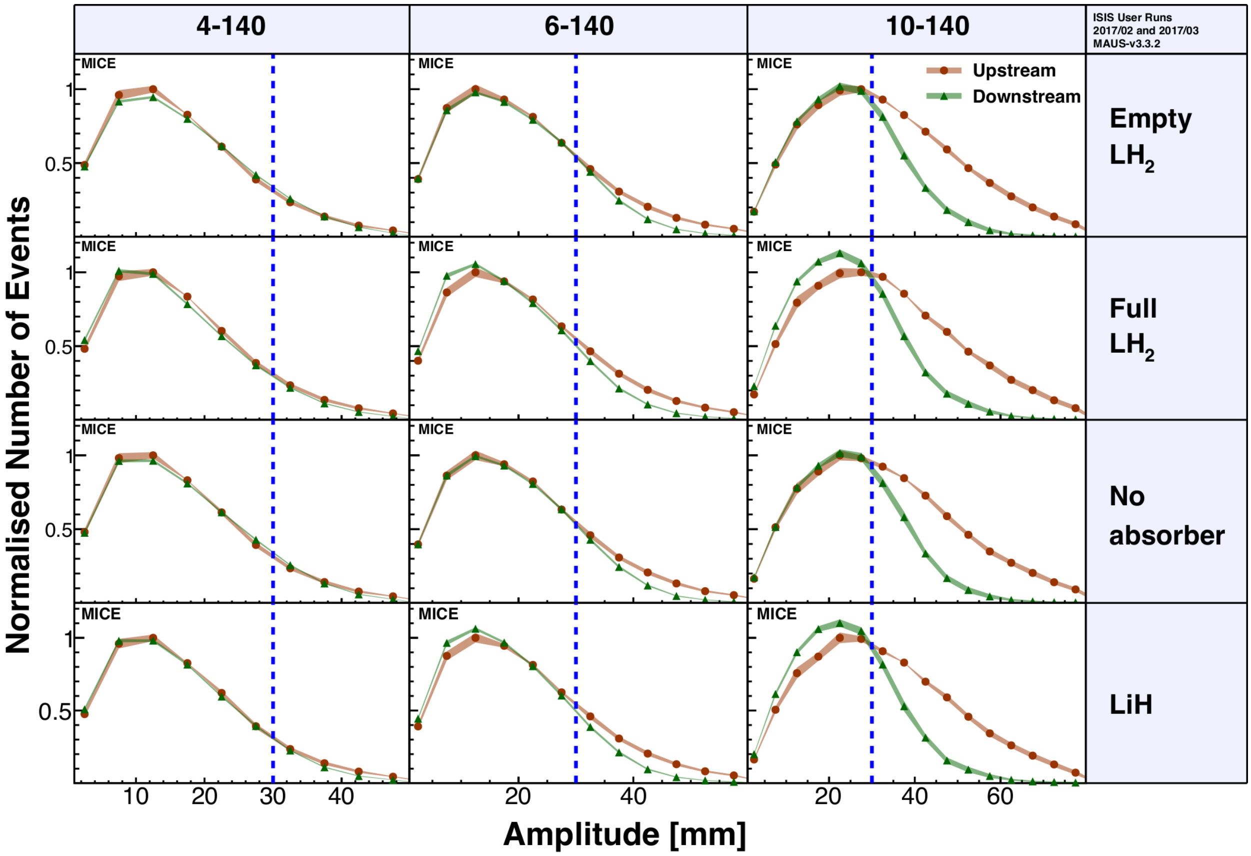

Figure 3: Distribution of particle amplitudes in ‘flip’ mode. An increase of low amplitude particles downstream (green) compared to upstream (orange) indicates cooling.

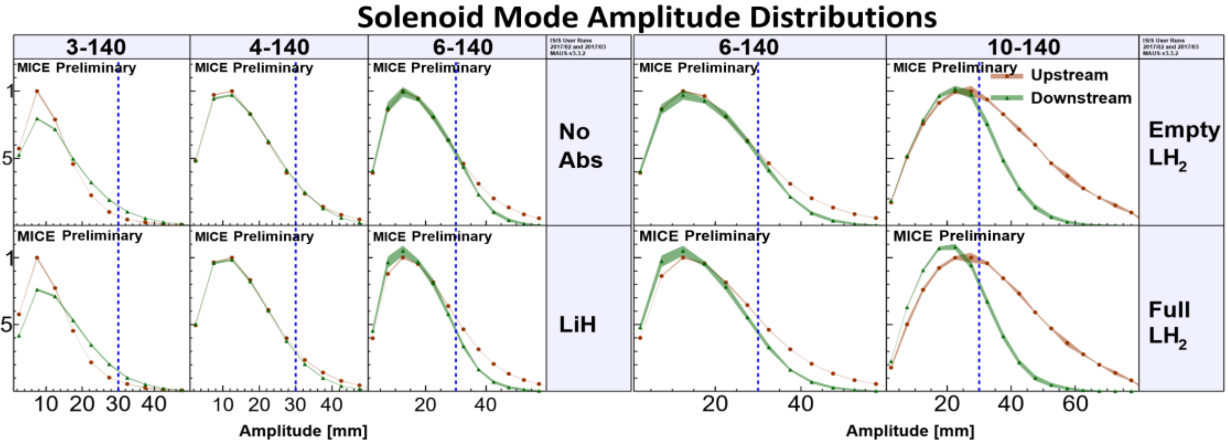

Figure 4: Distribution of particle amplitudes in ‘solenoid’ mode. An increase of low amplitude particles downstream (green) compared to upstream (orange) indicates cooling.

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