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Study of Ionization Cooling With the MICE Experiment

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Ionization Cooling

The international Muon Ionization Cooling Experiment (MICE) will demonstrate the ionization cooling of muons for the first time; Ionization cooling is the only known technique that can provide high brightness muon beams suitable for applications such as a Neutrino Factory or Muon Collider.

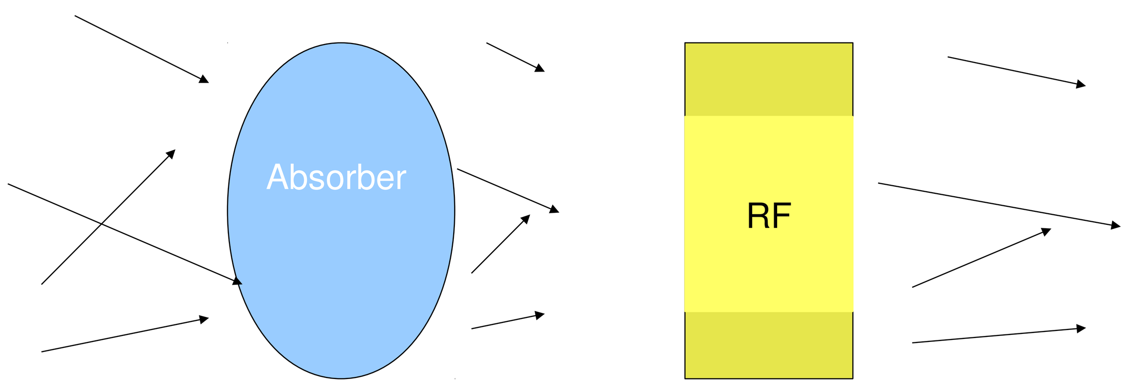

Fig. 1: The principle of ionisation cooling.

In ionization cooling, a beam is passed through an absorber. The transverse and longitudinal momentum of the particles is lost due to ionization of atomic electrons. This yields a reduction in normalized emittance. Multiple Coulomb scattering from atoms causes increase in angular divergence of the beam, and hence emittance growth. The beam can be accelerated in RF cavities, replacing the lost longitudinal momentum, yielding a reduction in geometric emittance.

The MICE Apparatus

MICE Step IV consists of a transfer line to bring particles from the ISIS synchrotron at Rutherford Appleton Laboratory to the experiment. A schematic of the apparatus is shown in fig. 2.

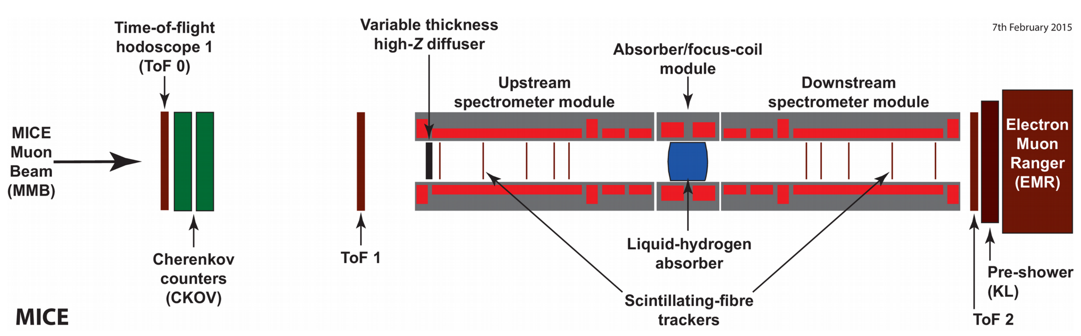

Fig. 2: The MICE apparatus.

The apparatus to reduce beam emittance consists of a section of a solenoid focussing ionization cooling cell. Detectors, placed upstream and downstream of the emittance reduction apparatus, measure the momentum, position and species of particles entering and leaving the cooling channel, enabling the measurement of change in normalized beam emittance of the ensemble.

Up to around 100 particles are observed per second. MICE accumulates data in runs, each run consisting of a single experimental configuration and lasting of order hours.

MICE has taken data over thousands of runs, with many different configurations. The total integrated triggers since 2015 is shown in fig. 3. The data analysis shown here uses only a small subset of the available data for two configurations.

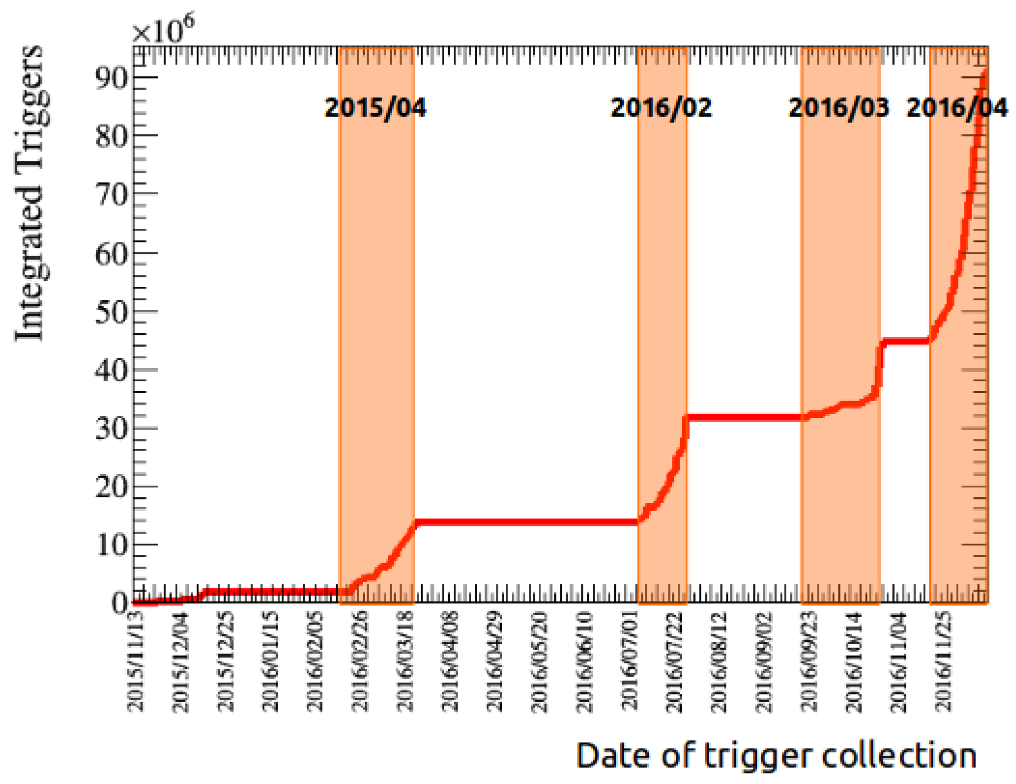

Fig.3: Integrated number of triggers since 2015.

Design Optics

The optics of the lattice, and the momentum and emittance of the incoming particles can all be varied. The magnetic fields and optics arrangement for the data reported in this paper are shown in fig. 4.

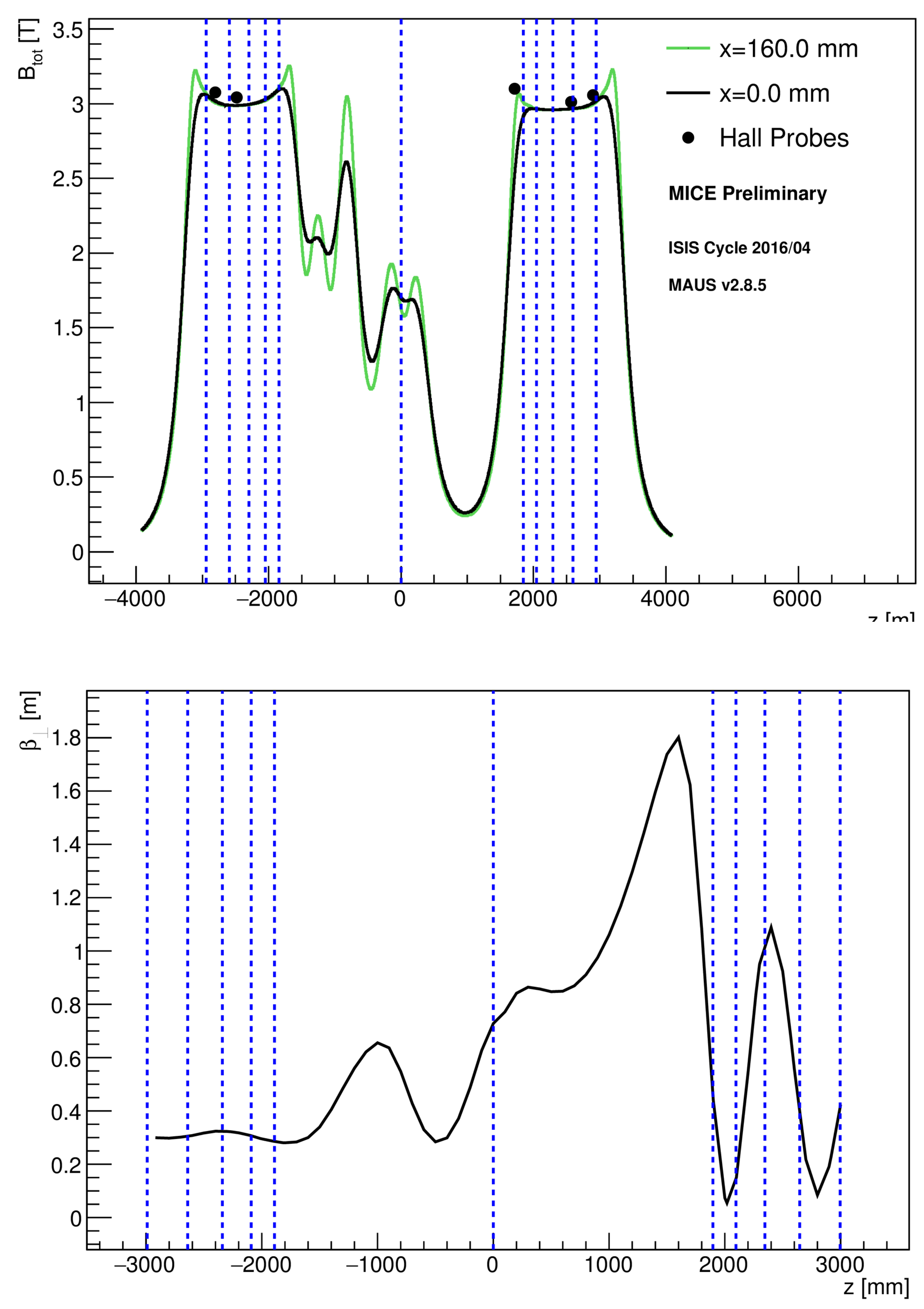

Fig. 4: (top) Total magnetic field strength and (bottom) design optical beta function in the MICE cooling channel.

Event Selection

As MICE measures each particle event individually, it is possible to select a particle ensemble from the collection of measured tracks. This enables the study of the effect of momentum spread and transverse beam parameters on the cooling. In this analysis, muons have been selected with:

- momentum in the range 135 to 145 MeV/c;
- time-of-flight between TOF0 and TOF1 consistent with muons in this momentum range;
- a single, good quality track formed in the upstream diagnostics.

Data

MICE has measured the distribution of amplitude upstream and downstream of the absorber. The 4D amplitude of a particle with phase space vector $\underline{u}$ = (x, p_x, y, p_y) is given by

$$A_\perp = \varepsilon_n \underline{u}^T \underline{\underline{V}}^{-1} \underline{u}$$

where $\underline{\underline{V}}$ is the covariance matrix of $\underline{u}$ and ε_n is the normalised 4D emittance.

The change in the amplitude distribution is shown in fig. 5. Muons are seen to move to higher amplitude for the 3-140 setting, where the beam is below equilibrium emittance and heating is expected. Muons sampled from the 6-140 setting are seen to stay with roughly the same amplitude, as the beam is at the equilibrium emittance. There is some dilution due to scraping at high amplitude.

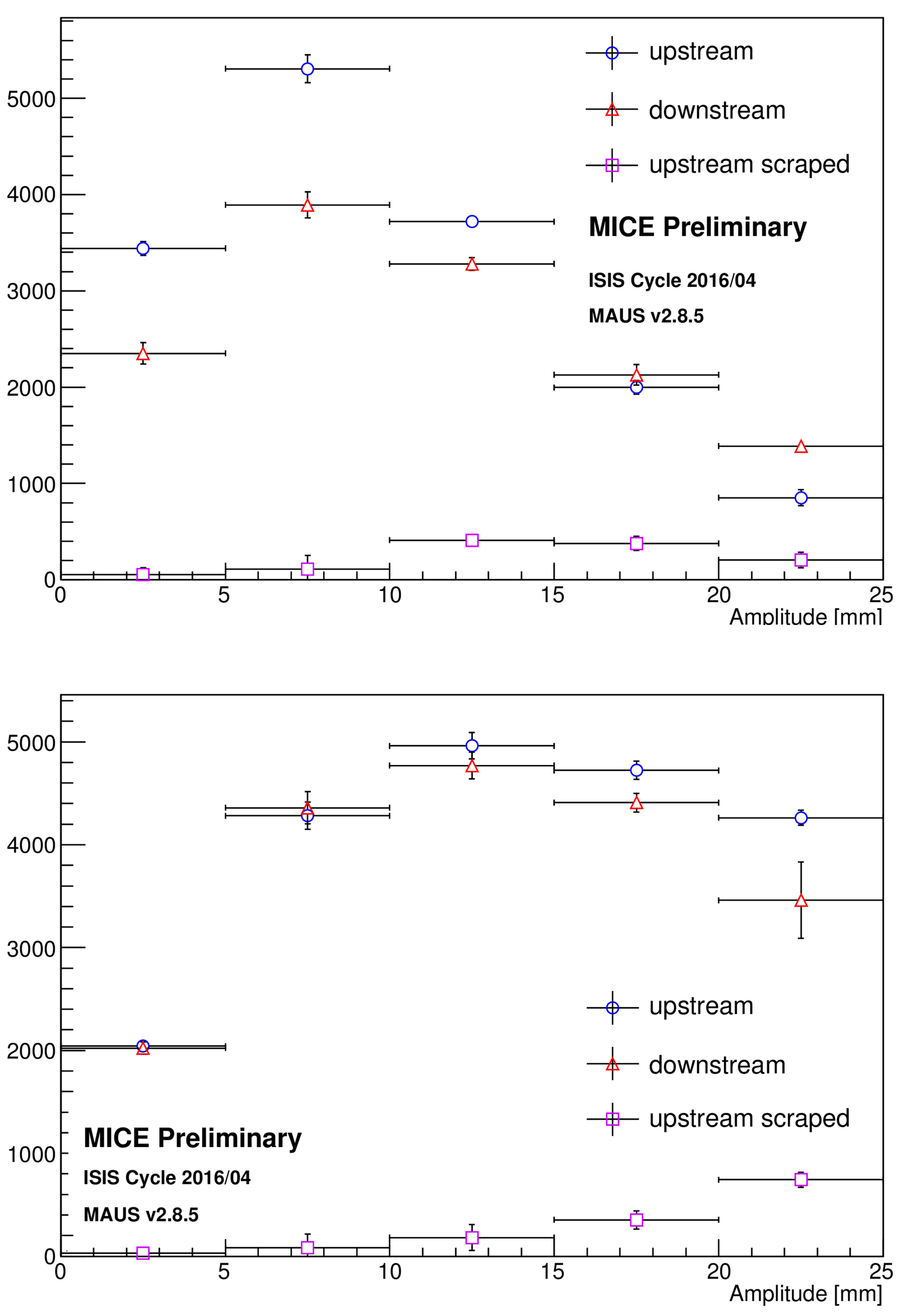

Fig. 5: Emittance evolution for the (top) 3-140 setting and (bottom) the 6-140 setting.

Plans

MICE continues to reduce the systematic uncertainties associated with the data. Analysis of the full data sample over a wide range of initial configurations, including larger initial emittances, is underway. Simulation and preliminary analysis indicates the collaboration will achieve improved uncertainties.

Data taking will continue through 2017 with liquid hydrogen absorbers in a number of configurations. A pair of RF cavities have been constructed. The collaboration seeks to upgrade the existing equipment to demonstrate energy recovery along with emittance reduction..