Recent results from the study of emittance evolution in MICE

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The Muon Ionization Cooling Experiment (MICE) has measured the change in emittance due to ionization energy loss. Large aperture solenoid magnets were used to focus muons through Lithium-hydride, liquid hydrogen and empty absorbers. Diagnostic devices were placed upstream and downstream of the absorber, enabling the phase-space coordinates of individual muons to be reconstructed. By observing the properties of ensembles of muons, the evolution of the beam emittance was studied. The phase-space was analysed using single particle amplitude distributions and shows a clear increase in the core density of the beam, a direct effect of ionization cooling.

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1. Muon Ionization Cooling Experiment

The International Muon Ionization Cooling Experiment (MICE) [1], aims to demonstrate ionization cooling so that it may be exploited in future cooling-channel designs [2, 3, 4]. The MICE experiment produces pions using a titanium target, dipped into the beam halo of the 800MeV ISIS proton synchrotron [5]. The emitted pions are captured and allowed to decay, such that the produced muons may by focussed and transported to the cooling channel. Twelve superconducting coils arranged in 3 cryostats were used to transport the beam through a central absorber chamber. Three different absorbers were used: liquid hydrogen, lithium hydride (LiH) and a plastic wedge-shaped absorber. Performance of the wedge-shaped absorber is not reported in this paper. The upstream and downstream ensembles were reconstructed particle-by-particle using a scintillating fibre tracker [6, 7], such that the effect of the absorber could be investigated.

2. Ionization Cooling

Ionization cooling that involves focussing the beam through a "cooling" material (the absorber), in order to reduce normalised transverse emittance. The absorber material isotropically reduces the beam momentum through the process of ionization energy losses. Low-Z materials and strong focussing fields are favoured in order to mitigate the effects of multiple Coulomb scattering.

The cooling equation (eq. 2.1) describes the evolution of normalised transverse emittance, $\varepsilon_\perp$, of a beam with betatron function, $\beta_\perp$, and energy, E, through a material with radiation length, X_0,

$$\frac{d\varepsilon_\perp}{dx} = -\frac{\varepsilon_\perp}{\beta^2 E}\left\langle\frac{dE}{dx}\right\rangle + \frac{\beta_\perp(13.6\text{MeV/c})^2}{2\beta^3 E m_\mu X_0}, \tag{2.1}$$

where m_μ is the muon mass, β is the relativistic velocity of the beam and x is the thickness of the absorber. In order to understand the evolution of the beam on a particle-by-particle basis, single particle amplitudes were calculated to demonstrate the migration of muons into (cooling) and out of (heating) the beam core. An amplitude, A, is calculated as, $A = \varepsilon_\perp \mathbf{x} \boldsymbol{\Sigma}^{-1} \mathbf{x}$, where $\mathbf{x} = (x, p_x, y, p_y)$ is the individual muon phase-space vector relative to the beam centroid, and $\boldsymbol{\Sigma}$ is the covariance matrix of the current ensemble, with RMS emittance, $\varepsilon_\perp$. In order to prevent tail events from biasing the orientation of the core, events with larger amplitudes are iteratively removed from the calculation of the covariance matrix.

3. Particle Selection

Each event was required to contain precisely one muon throughout the entire experiment. Events with additional reconstructed tracks were rejected. Each muon was then required to pass a Time-of-Flight (ToF) [8] cut on entry to the cooling channel and momentum selection (135-145 MeV/c) within the upstream tracker. The momentum and ToF measurements were required to be consistent with the muon mass. Goodness of fit tests ensure that each track was well fitted upstream and downstream, reducing the possibility of noise contamination and misidentification.

A loose momentum selection was applied to the downstream tracker to ensure that poorly recon-structed tracks were removed. The event selection was primarily performed on the upstream sam-ple. Cuts applied to the downstream sample were only made to ensure that the transmitted muons were well reconstructed. This ensures that we do not preferentially select muons that have migrated towards the beam core.

4. Results

The upstream and downstream samples were analysed independently. The amplitude distribu-tions for each sample were calculated and summed such that the ratio of the cumulative distributions could be calculated. This is shown in figure 1 for the three absorber settings and two nominal emit-tance settings. The excess in the lowest bins demonstrates the migration of particles towards lower amplitudes, which is only achieved if a fraction of the beam has been cooled. Additionally the lowest transmission is noted to be 94% in the 10mm settings, as seen as the value in the final bin. A Monte Carlo simulation was developed which reproduces the performance of the experiment to
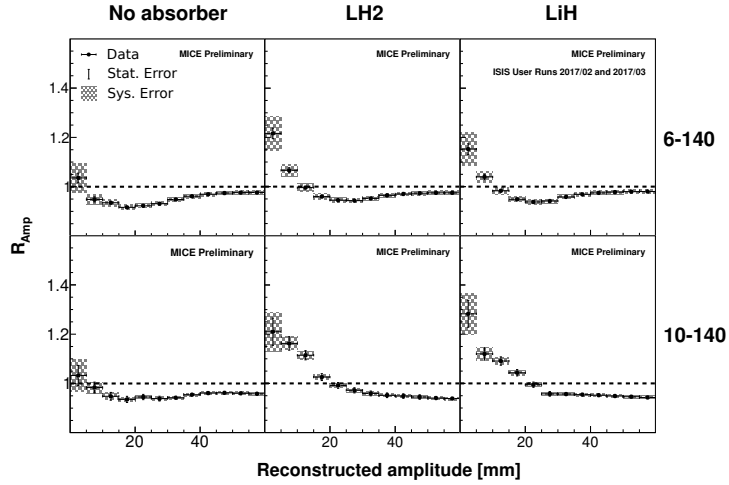

Figure 1: The ratio between the upstream and downstream cumulative amplitude distributions.

high precision. This was used to estimate the systematic uncertainties by varying the known pa-rameters and evaluating the effect on the final amplitude distributions. Systematic corrections were calculated for each bin in amplitude to account for the evaluated residuals. The uncertainty of the correction was included as the systematic error bar.

5. Conclusion

Data were taken within the MICE cooling channel in order to reconstruct the transverse phase-space upstream and downstream of an absorber. The migration in single particle amplitudes can be seen to demonstrate a clear increase in the core density, a signal which is only present due to ionization cooling. This is seen in two materials, LiH and liquid hydrogen, with the empty absorber producing no statistically significant change. Systematic uncertainties have been calcu-lated for each bin in amplitude using a Monte Carlo simulation that is in good agreement with the reconstructed data.

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