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Emittance measurement in the Muon Ionization Cooling Experiment

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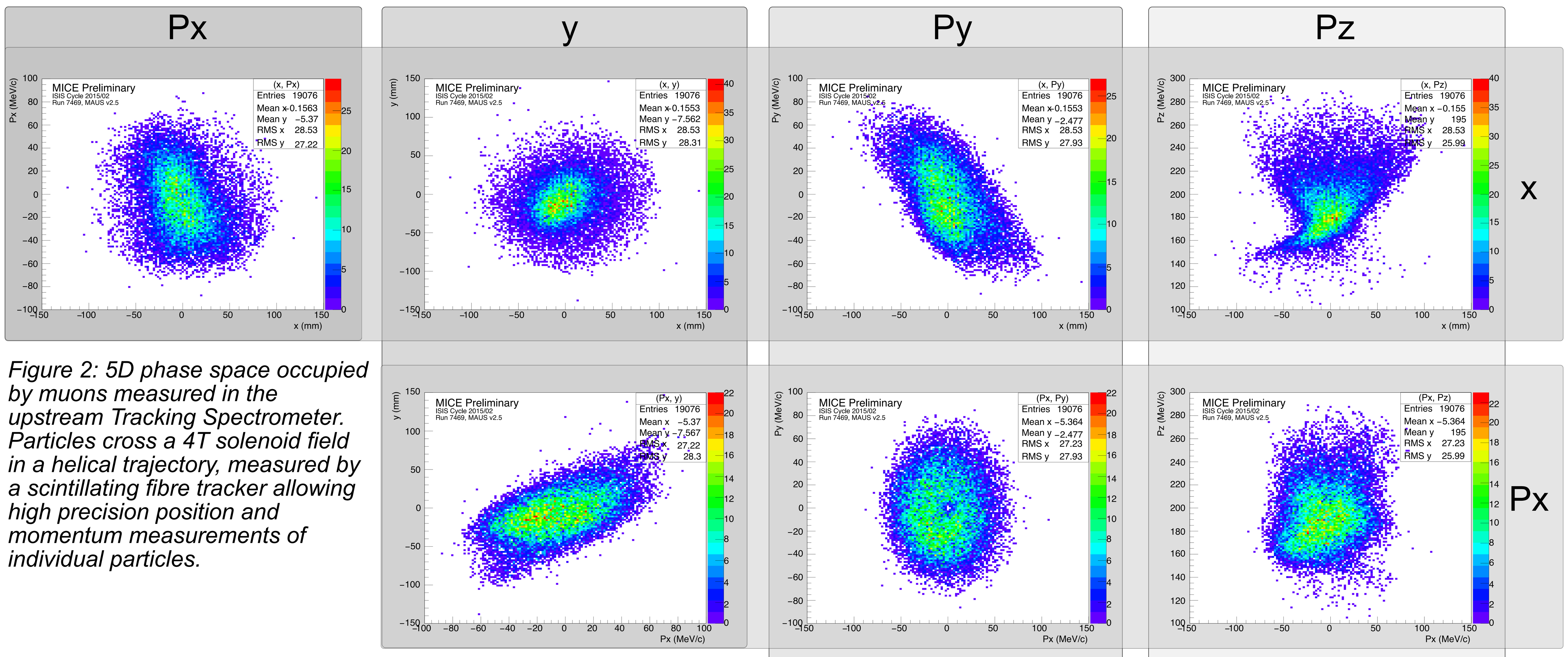
The Muon Ionization Cooling Experiment (MICE) collaboration will demonstrate the feasibility of ionization cooling, a technique to produce a small emittance muon beam for a future neutrino factory and/or muon collider. The emittance is measured on a particle-by-particle basis. Measurements are made before and after the cooling cell using a high precision scintillating-fibre tracker in a solenoidal field. A pure muon beam is selected using a particle identification (PID) system that can efficiently reject pions and electrons.

The emittance of a muon beam has been measured particle-by-particle for the first time using a tracking system. The analysis techniques required for this precision measurement are presented.



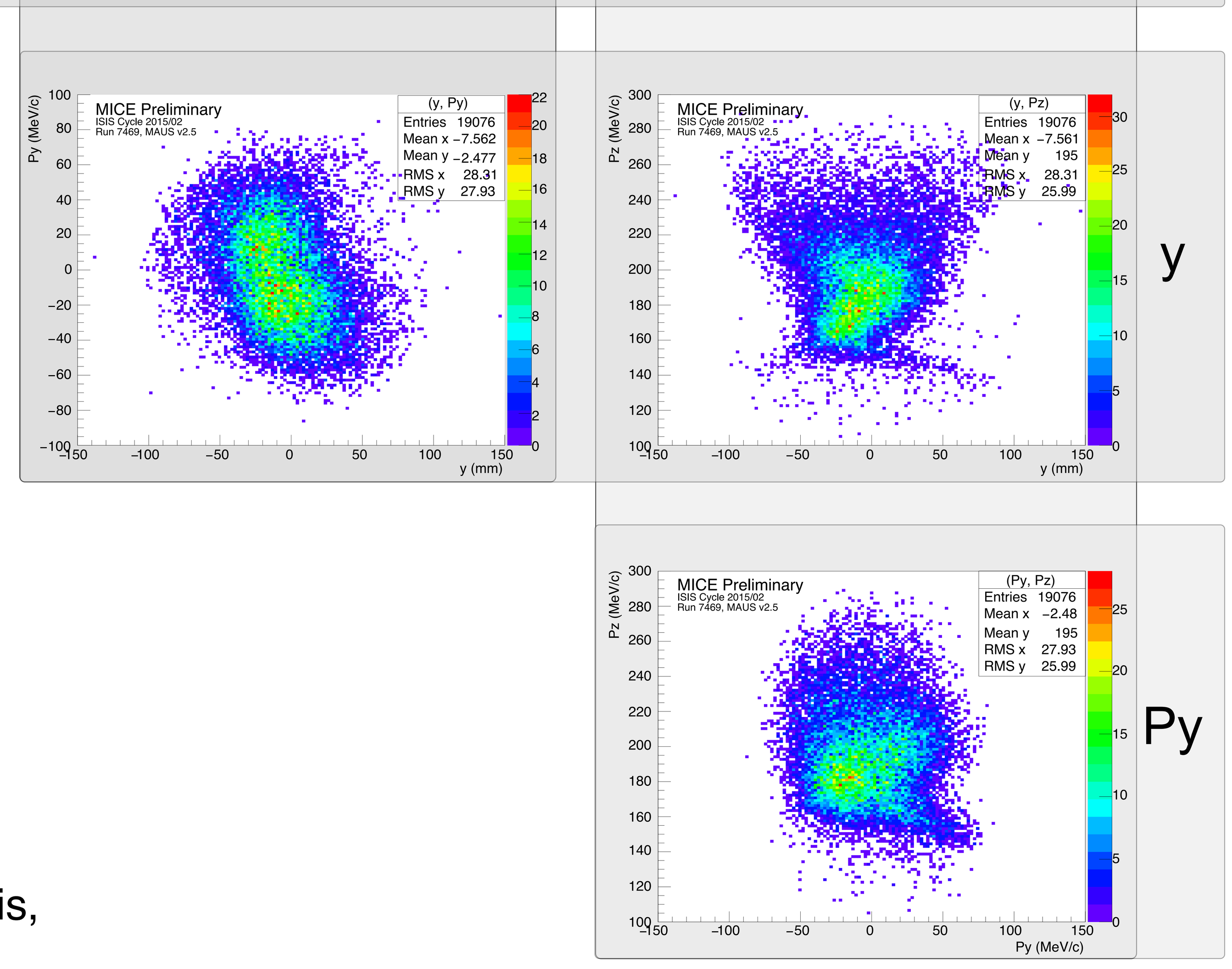


Figure 2: 5D phase space occupied by muons measured in the upstream Tracking Spectrometer. Particles cross a 4T solenoid field in a helical trajectory, measured by a scintillating fibre tracker allowing high precision position and momentum measurements of individual particles.

The need for MICE

When produced, muon beams have a large emittance that must be reduced for cost-efficient acceleration. The short muon lifetime prevents the use of existing techniques.

Ionization cooling is the only technique that can act within the muon lifetime. The Muon Ionization Cooling Experiment (MICE) [1], at the Rutherford Appleton Laboratory, UK, will demonstrate that ionization cooling is a viable method of reducing the phase space volume occupied by a muon beam.

Ionization Cooling

Particles cross a low-*Z* absorber and lose energy by ionization (dE/dx). Their divergence is increased by Multiple Coulomb Scattering, which is minimised through a careful choice of absorber. RF restores lost momentum only in the longitudinal direction. An overall reduction in transverse phase space is achieved.

Ionization cooling depends on:
- Absorber material (LiH or liquid hydrogen)
- Initial momentum (140--240 MeV/c)
- Initial emittance (3--10 mm)
- Solenoid optics (3--4 T solenoid fields)

MICE is shown in Figure 1. Emittance is measured particle-by-particle before and after a low-Z absorber and compared. The cooling channel can be run in a variety of magnetic configurations with different absorbers to understand their impact on emittance reduction.

Emittance Measurement

The position and momentum of each muon that crosses the upstream scintillating fibre tracking detector was measured, the first particle-by-particle measurement of transverse normalised emittance and phase space. The 5D phase space occupied by muons from the MICE Muon Beam is shown in Figure 2. Correlations and dispersion are clearly visible.

MICE measures emittance in the transverse plane. The phase space covariance of the particle sample is defined by,

$$\Sigma_{4D} = \begin{pmatrix} \sigma_{x.x} & \sigma_{x.Px} & \sigma_{x.y} & \sigma_{x.Py} \\ .. & \sigma_{PxPx} & \sigma_{Px.y} & \sigma_{Px.Py} \\ .. & .. & \sigma_{y.y} & \sigma_{y.Py} \\ .. & .. & .. & \sigma_{Py.Py} \end{pmatrix},$$

where the covariance between variables is,

$$\sigma_{a.b} = \langle ab\rangle - \langle a\rangle\langle b\rangle,$$

and the transverse normalised emittance of the sample is,

$$\epsilon_N = \frac{1}{\mu_{mass}} \sqrt[4]{\det|\Sigma_{4D}|}.$$

Figure 3 shows the transverse normalised emittance of the beam in 8 MeV longitudinal momentum slices through the beam sample. The emittance is approximately flat with longitudinal momentum. Errors are dominated by the statistical uncertainty.

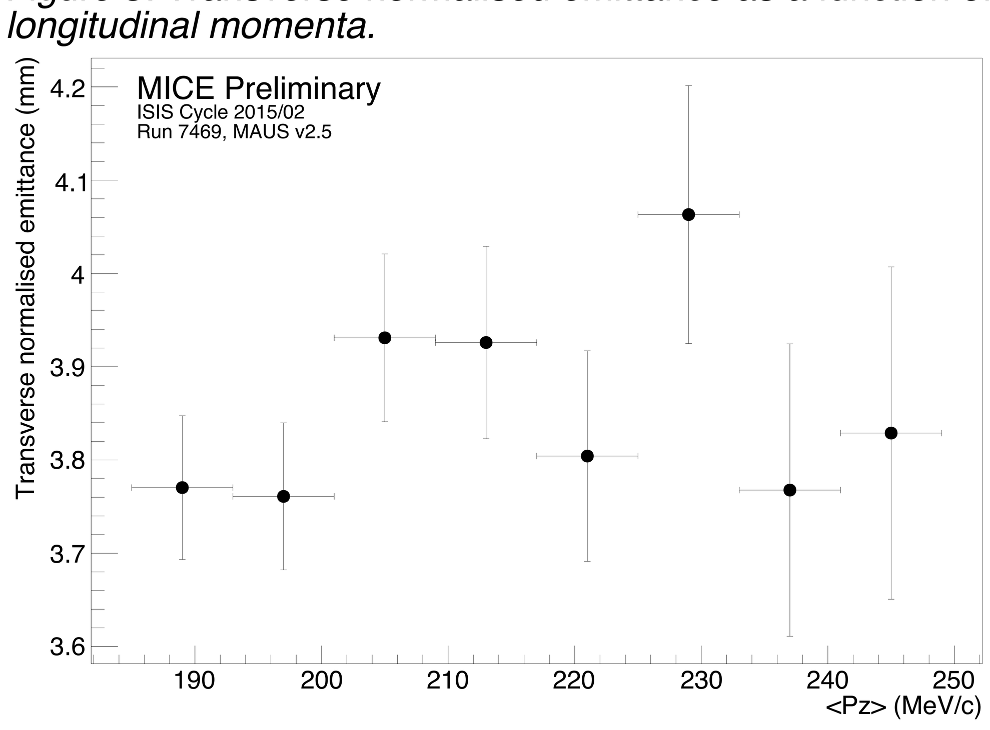
Alternative Analyses

Non-linear terms in beam dynamics can affect emittance-reduction measurements. An alternative technique uses Kernal Density Estimation (KDE) to determine the underlying probability density function of the beam. KDE is under study as a method of calculating the increase in phase space density of particles after crossing an absorber [2]. Simulations of the density increase after 65mm of LiH absorber are shown in Figure 4.

Conclusions

Transverse normalised emittance has been measured for the first time in MICE on a particle-by-particle basis using a high-precision scintillating fibre tracker. This demonstrates the method by which MICE will measure the input and output emittance of the cooling cell. Alternative methods, less sensitive to non-linear effects, are also being studied.

Figure 3: Transverse normalised emittance as a function of longitudinal momenta.



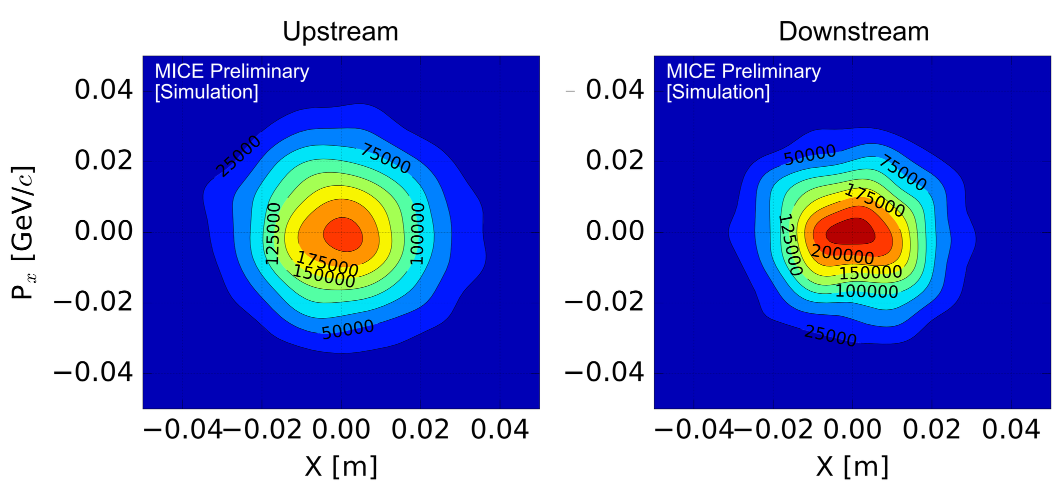
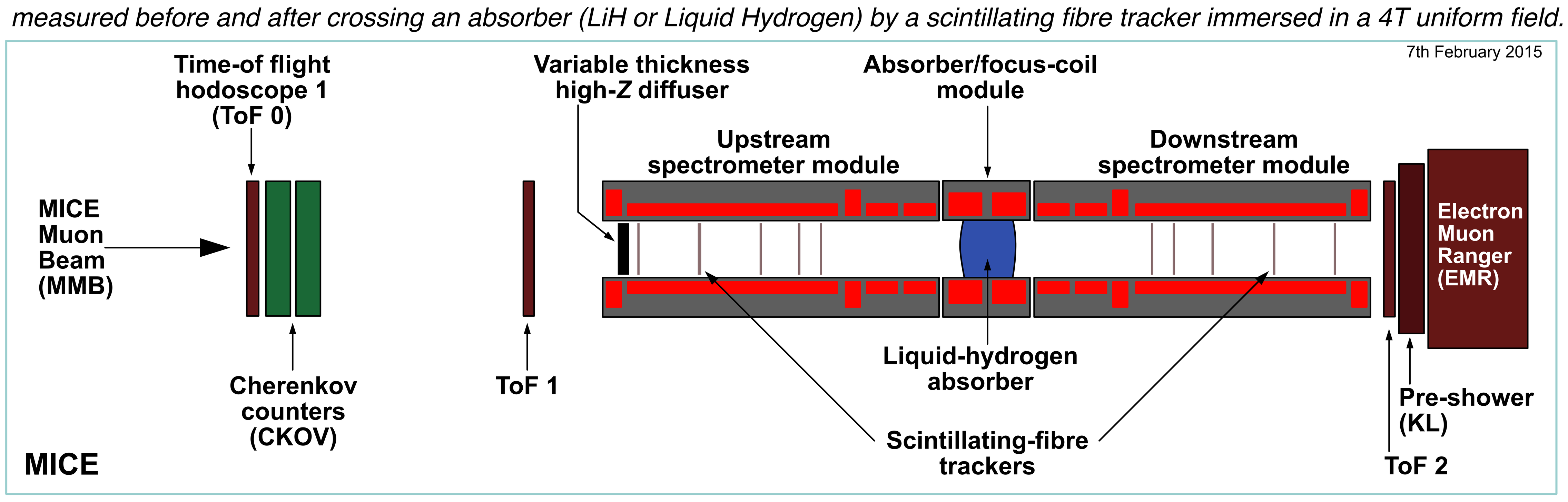


Figure 4: Simulated (x, Px) phase space contours before (left) and after (right) passing through a 65mm LiH absorber. An increase in density at the beam centre indicates emittance reduction [2].

Figure 1: Muons are transported through PID detectors to the cooling channel. The position and momenta of individual muons are measured before and after crossing an absorber (LiH or Liquid Hydrogen) by a scintillating fibre tracker immersed in a 4T uniform field.



Acknowledgements

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[2] Simulated Measurements of Cooling in Muon Ionization Cooling Experiment, *T. A. Mohayai, C. Rogers, P. Snopok,* IPAC 2016 Proceedings, TUPMY011