The use of timing detectors for beam characterization at the Muon Ionization Cooling Experiment

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Abstract
The Muon Ionization Cooling Experiment is designed to demonstrate the operation of a module of a cooling channel by observing individual particles of a beam with the properties found in a Neutrino Factory. It incorporates timing detectors with a resolution of 50 picoseconds whose primary purpose is particle identification. Their other uses in beam characterization, specifically the measurement of momentum, transverse and longitudinal beam emittance, and the phase of the muons in the RF cavities are described.

1 The analysis philosophy of the MICE experiment

The MICE Ionization Cooling demonstration combines three crucial elements: a fully engineered module of the cooling channel, treated as a 'black box'; spectrometers which measure initial and final phase space distributions, and; muon beams with the properties found in Neutrino Factory designs. While no beam line currently offers the required luminosity, if the position, momentum, and RF phase of individual muons is measured, appropriate beams may be assembled offline.

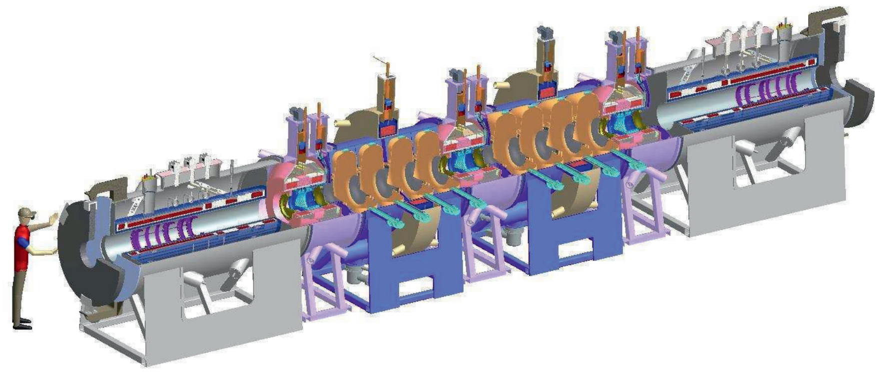

Fig. 1: The MICE cooling channel lattice element, and the upstream and downstream spectrometers.

Although the spectrometers provide measurements of transverse position and momentum, and p_z, separate timing detectors are employed to recreate the longitudinal phase space, as MICE must demonstrate the transverse cooling of a beam with the appropriate longitudinal properties. Upstream (t, p_z) is therefore be reconstructed in order to create RF buckets of suitable longitudinal emittance, with the correlation between longitudinal momentum and transverse amplitude which develops naturally in a solenoidal lattice. [**?**] These measurements will also allow the growth and exchange of longitudinal emittance to be monitored.

In order to measure time in the cooling channel, individual muon trajectories must be calculated between the timing detectors and the spectrometer and RF cavities. As a result of scattering in the emittance generating lead degrader, and the difficulty of reconstructing low amplitude particles' p_z in the spectrometer, a phase space measurement by the two upstream timing detectors is useful. Separated by a quadrupole triplet and 8 m of air, the upstream timing detectors provide a measurement of the angles $x' = dx/dz$ and $y' = dy/dz$, dependent on measurements of x and y, p_z, and the transfer matrix M. The calculation of p_z and (x', y') is an iterative process best suited to a Kalman filter.

2 Phase space reconstruction by the timing detectors

The two time of flight detectors (TOFs) are located in the muon beam line upstream of the MICE cooling channel. A Cherenkov detector is immediately downstream of TOF0, followed a number of metres later by a triplet of quadrupoles, as illustrated in Fig. **??**. The TOFs are designed to acheive a resolution of 50 ps per station.

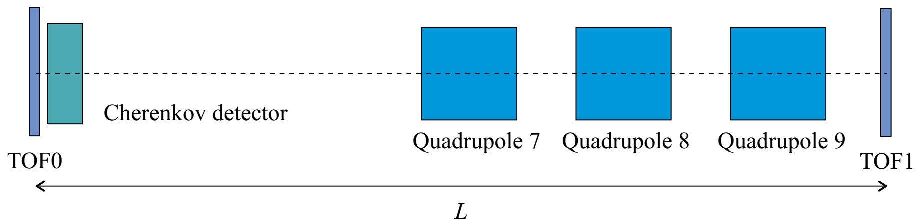

Fig. 2: Schematic of the beam line between TOF0 and TOF1. $L \approx 8$ m.

If a particle's time of flight t and path length s between two planes are known, its momentum p may be calculated via $p/E = s/t$, assuming p to be constant. The resolution on p is given by

$$\frac{\sigma_p}{p} = \frac{E^2}{m_0^2}\sqrt{\left(\frac{\sigma_t}{t}\right)^2 + \left(\frac{\sigma_s}{s}\right)^2}. \tag{1}$$

Consider first the approximation that the path length is the geometrical distance L between the TOFs. The TOFs will measure the time of flight of a muon with $p = 260$ MeV/c to be $t = 28.7$ ns with a fractional error of $\sigma_t/t = 0.24\%$. The momentum will be measured with $\sigma_p = 4.5$ MeV/c. The error increases with momentum, and is smaller for the more massive pion.

The approximation that path length equals L leads to an underestimate of p. Measurement bias is given by

$$\frac{\Delta p}{p} = \frac{E^2}{m_0^2}\left(\frac{\Delta s}{s} - \frac{\Delta t}{t}\right). \tag{2}$$

Therefore if a 260 MeV/c muon's path length is underestimated by 10 mm, the momentum will be underestimated by 2.3 MeV/c. Similarly, if the time of flight is miscalibrated by 10 ps, the momentum measurement will by wrong by 0.64 MeV/c.

Path length bias may be eliminated by tracking the particles between TOF0 and TOF1. The method is iterative and involves making increasingly good estimates of momentum, based on increasingly good estimates of path length. The result of applying this procedure to a Monte Carlo simulation of a $\epsilon_{\mathrm{n}} =$ 6 mm muon beam with $p_z = 200$ MeV/c in the centre of the absorbers is shown in Fig. **??**. The black line includes all detector effects; the red line shows the resolution which would be achieved if the detectors had perfect timing resolution.

Finally, when the momentum is known, the transfer matrix between TOF0 and TOF1 may be calculated, and the angles (x'_0, x'_1) are implied by the positions (x_0, x_1):

$$\begin{pmatrix} x'_0 \\ x'_1 \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix}.$$

In addition to providing pre-degrader phase space measurements for use in extrapolating time downstream to the cooling channel, this method is currently being used to characterize the emittance generated by the MICE muon beam line at the ISIS proton synchrotron at the Rutherford Appleton Laboratory.

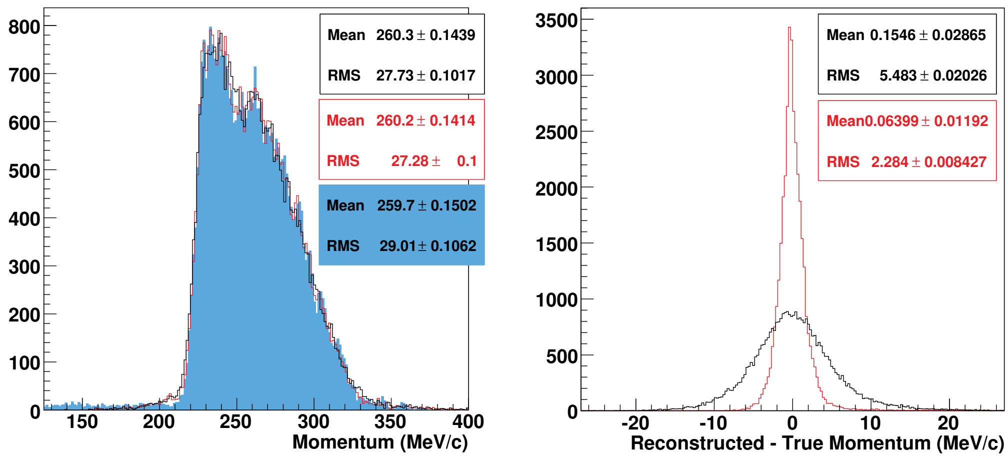

Fig. 3: A comparison of the reconstructed and true momenta before TOF1.

3 Conclusion

The 50 ps timing detectors upstream of the MICE cooling channel allow the measurement of muon momentum with a resolution of the order of 5.5 MeV/c. This measurement is currently being used to characterize the muon beam line, and will eventually be used to select beams with the appropriate longitudinal phase space structure in the demonstration of Ionization Cooling.

References

[1] The MICE Technical Reference Document, The MICE collaboration, `http://mice.iit.edu`.

[2] Feasibility Study-II of a Muon-Based Neutrino Source, ed., S.Ozaki, R.Palmer, M.Zisman, and J.Gallardo, BNL-52623 (2001).