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High Precision Measurement of Muon Beam Emittance Reduction in MICE

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MICE as a Neutrino Factory Component

Muon ionization cooling, an essential ingredient of a neutrino factory, will be demonstrated for the first time by the Muon Ionisation Cooling Experiment (MICE). The central part of MICE consists of a short section of a Neutrino Factory cooling channel (Figure 1). The emittance reduction achieved in this experiment is between 10% and 15%.

In order to extrapolate the performance of a full cooling channel from these measurements, it is desirable for MICE to achieve an emittance measurement accuracy of 10^{-3} absolute. To date, beam emittance has never been measured with such a precision. We present constraints on the spectrometers and the error reduction method that is necessary to achieve the 10^{-3} level of accuracy.

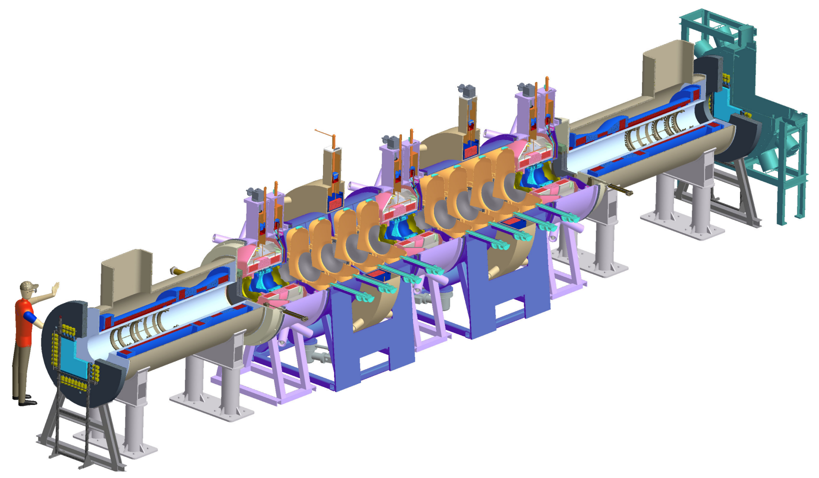

Figure 1: Engineering drawing of the MICE experiment, which is 15 m long and 3 m high.

Emittance Resolution of MICE

In MICE, single muons will be passed through the cooling cell particle-by-particle. Each muon's position in phase space will be measured upstream and downstream of the cooling cell using scintillating fibre trackers (SciFi) and time-of-flight stations. A bunch will be composed from up to 10^6 individual muons.

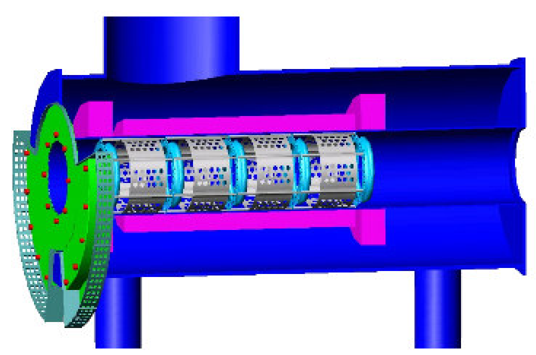

Figure 2: Visualisation of the MICE SciFi Tracker.

A Neutrino Factory cooling channel consists of a number of cells in series. Hence to predict the change in emittance for a typical Neutrino Factory cooling channel to of order 10%, it is necessary to measure the change in emittance for a single cell to 1% and the absolute emittance to approximately 0.1%.

Required SciFi Resolution

The bias due to predictable measurement errors, such as multiple scattering and detector granularity, can be corrected statistically by the following method. If one assumes a distribution in one single variable u, the effect of a measurement error δu with an rms $\sigma(\delta u)$ on the rms width $\sigma(u)$ of the distribution (which is what enters the emittance calculation) is to widen it by an addition in quadrature:

$$\sigma(u_i^{meas}) = \sigma(u_i^{true})\left(1 + \frac{\sigma^2(\delta u_i)}{2\sigma^2(u_i^{true})}\right)$$

In this one dimensional case, a simple subtraction in quadrature of the measurement can be performed. An uncertainty of 10% on the measurement error itself will result in an uncertainty of 10^{-3} on the derived emittance if the measurement error is less than 14% of the width of the distribution (which we chose to be the width at equilibrium emittance).

This requirement was achieved on Monte Carlo simulation for all phase space variables measured by the MICE scintillating fibre tracker. The Monte Carlo simulation was based on inputs (point resolution, efficiency, light yield, percentage of dead channels) from the first MICE-tracker prototype. Similar tests of resolution for the time-of-flight system are planned for the end of 2005.

In Figure 3 we show the distributions in dx and dp_x.

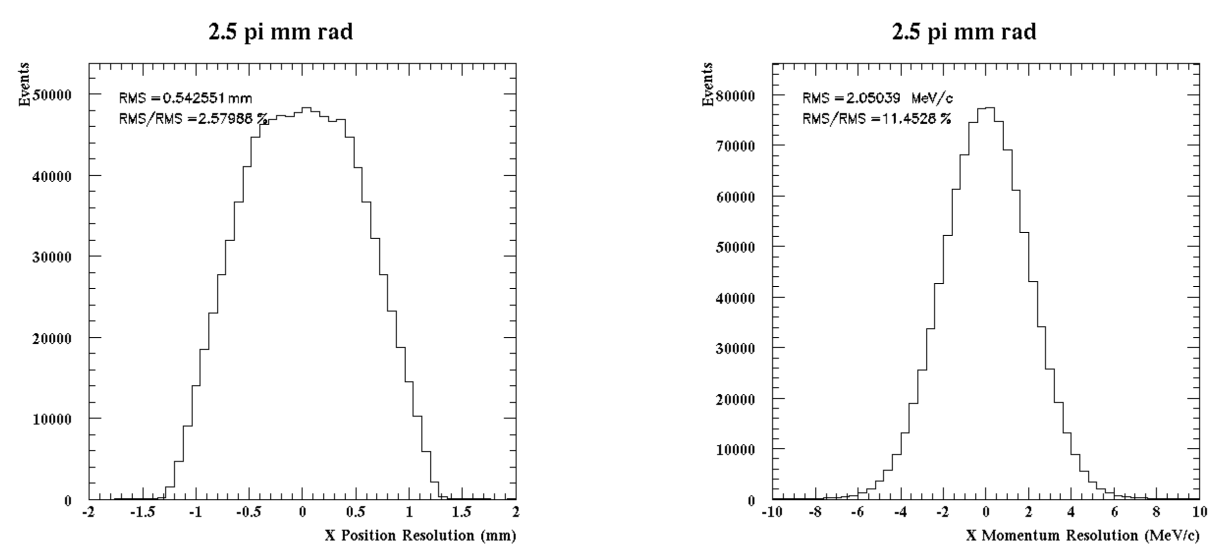

Figure 3: The distribution in δx and δp_x for the SciFi tracker.

Emittance Bias Correction

For the multi-dimensional case, the emittance is obtained by the formula

$$\varepsilon_n = \frac{1}{m_\mu}\sqrt{V}$$

Where ***V*** is the bunch covariance matrix in some phase space. It is possible to devise a general method to calculate the offset due to detector resolution for a particle-by-particle experiment. The measured value of some phase space variable is related to the true value by $u^{meas}=u^{true}+\delta u$ such that the true covariance is related to the measured covariance by

$$\sigma^2(u_i^{true}, u_j^{true}) = \sigma^2(u_j^{meas}, u_j^{meas}) - \\ -\sigma^2(\delta u_i, \delta u_j) - \sigma^2(u_i^{true}, \delta u_j) - \sigma^2(\delta u_i, u_j^{true})$$

Hence the true covariance matrix is related to the measured covariance matrix by

$$V^{true} = V^{meas} - R^T - R - C$$

and by calculating **R** and **C** we can remove the emittance offset. We show the offset emittance and the emittance with the offset removed in Figure 4. We see that the emittance can be measured to the required accuracy of 10^{-3} by the MICE experiment, assuming we have a good knowledge of the error in the tracker.

Hence we have seen that MICE can be used as a means to measure the emittance of a particle beam to an unprecedented accuracy, and to predict the cooling efficiency of a full Neutrino Factory cooling channel.

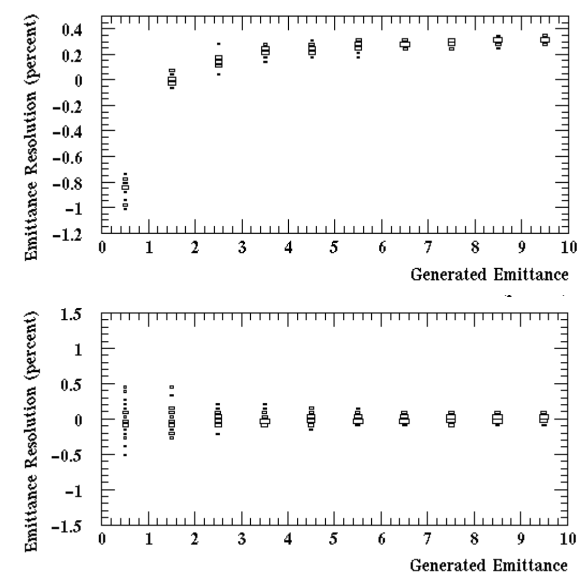

Figure 4: The uncorrected and corrected emittance for the upstream SciFi tracker.