MICE STEP I: FIRST MEASUREMENT OF EMITTANCE WITH PARTICLE PHYSICS DETECTORS

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Abstract

The muon ionization cooling experiment (MICE) is a strategic R&D project intending to demonstrate the only practical solution to prepare high brilliance beams necessary for a neutrino factory or muon colliders. MICE is under development at the Rutherford Appleton Laboratory (UK). It comprises a dedicated beam line to generate a range of input emittance and momentum, with time-of-flight and Cherenkov detectors to ensure a pure muon beam. The emittance of the incoming beam is measured in the upstream magnetic spectrometer with a scintillating fiber tracker. A cooling cell will then follow, alternating energy loss in liquid hydrogen absorbers and RF acceleration. A second spectrometer identical to the first and a second muon identification system measure the outgoing emittance. In the 2010 run the beam and most detectors have been fully commissioned and a first measurement of the emittance of a beam with particle physics (time-of-flight) detectors has been performed. The analysis of these data is presented here. The next steps of more precise measurements, of emittance and emittance reduction (cooling), that will follow in 2011 and later, are also outlined.

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) collaboration is building a lattice cell of the cooling channel [1] of Neutrino Factory of Neutrino Factory Feasibility Study-II [2] at a muon beam line at the ISIS proton accelerator at the Rutherford Appleton Laboratory in the UK. In order to demonstrate cooling over a range of emittances and momenta, the beam line must generate several matched beams with different optical parameters at TOF1.

The normalized root mean square (RMS) emittance in 6 dimensions is defined as

$$\epsilon_{rms} = \frac{1}{m_\mu}\sqrt{|V|},$$

$|V|$ is the determinant of the 6×6 covariance matrix of the phase space vector $\vec{U} = (\vec{x}, \vec{p})$, where $\vec{x} = (x, y, t)$ and $\vec{p} = (p_x, p_y, E)$. All these 6 variables will be measured in spectrometers before and after cooling cell on a particle-by-particle basis and then bunched to up to 10^6 particles for emittance calculation. The beam before colling channel can be measured by timing detectors. Data from TOF0 and T0F1 were used already to analyze the performance of the existing MICE muon beam line.

Technique

Data from timing detectors TOF0 and T0F1 are used to analyze the performance of the MICE muon beam line (Figure 1). Both detectors are composed of two orthogonally oriented planes of scintillator slabs read out at each end by photomultiplier tubes, and measure time. with resolution st = 50 ps [3]. Particle species is determined by measuring the time of flight between TOF0 and TOF1. Longitudinal momentum may then be reconstructed using an iterative method.

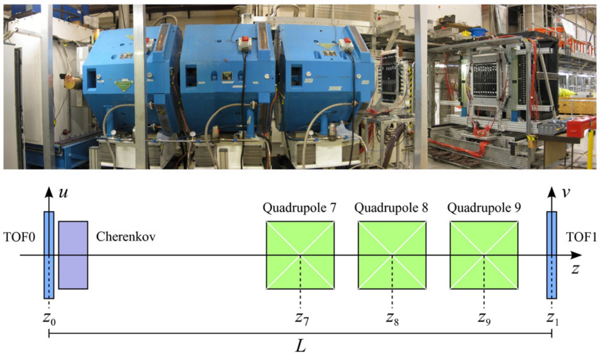

Figure 1: The MICE time of flight system.

The average momentum between the TOFs is given by

$$p(s,t) = \frac{m_0 s/t}{\sqrt{1 - s^2/(ct)^2}},$$

where the path length $s = L + \delta$ is reconstructed by tracking (Figure 2) the particle's trace-space vectors $(x, dx/dz)$ and $(y, dt/dz)$ through the beam line, and integrating the path length through each section. The initial trace space vector at TOF0 can be transported to TOF1 by a transfer matrix $(x_1, x'_1) = M(x_0, x'_0)$ defined by quadrupole parameters. Since the TOFs provide a measurement of (x_0, x_1) and that det M = 1 for linear transformation, it is possible to find the angles $x' = dx/dz$ and $y' = dy/dz$ needed for path length calculation:

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

A set of beam line optics configurations have been generated and corresponding beam parameter measured by TOF system. All variables measured in data have been compared with simulation.

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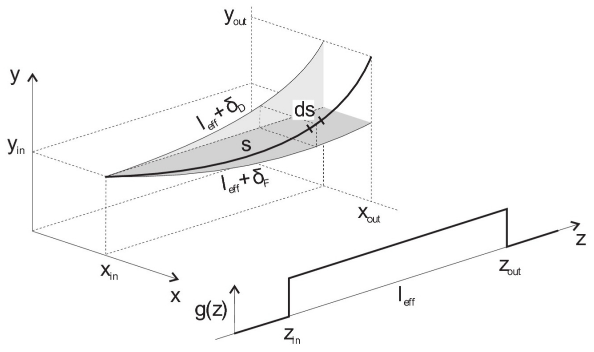


Figure 2: Particle reconstruction technique.

MEASURED OPTICAL BEAM PARAMETERS

A sample time of flight spectrum for a base line μ^- beam is shown in Figure 3. An electron peak is clearly distinguishable at 25.7 ns. As the electrons have E∼m, this is used to calibrate the time of flight of the muons. The broad peak at 28.3 ns is mainly made up of muons. This is borne out by the Monte Carlo simulation results plotted on the same graph, which indicate a pion contamination ¡ 1%. The simulated beams were generated by G4Beamline, a beam line simulation program which models particle interactions in matter in detail [4].

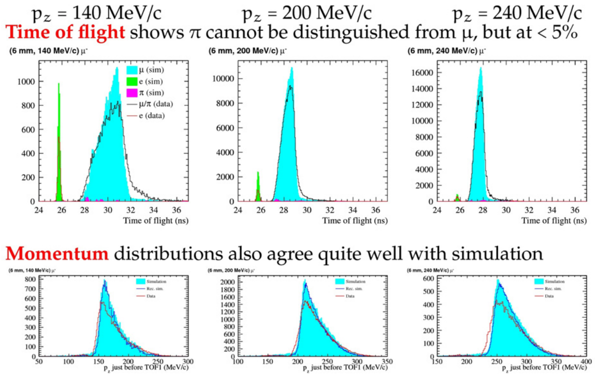
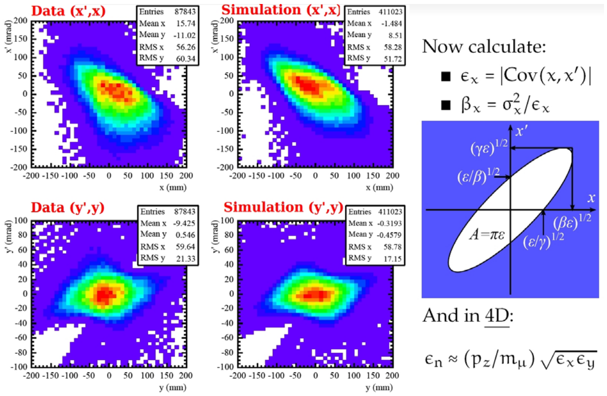


Figure 3: A comparison of the simulation and data.(top) The time of flight between TOF0 and TOF1. (bottom) The longitudinal momentum at TOF1.

The discrepancy between data and reconstructed simulation at the low-p_z edge is ascribed to model sensitivity to the size of the magnet apertures given the significant horizontal dispersion, and the fast variation in M(p_z) at low momenta. This anomaly is not a concern for MICE as this portion of the momentum spectrum is not optimized for transmission in the subsequent cooling channel.

The distribution of the baseline beam in trace space thereby deduced is shown in Figure 4. The transverse trace space distribution of the base line beam is reconstructed with resolution ∼10 mrad arising from the position resolution and the effects of multiple scattering in equal part. The orientation of the trace ellipse varies as a function of p_z, resulting in the visible skew. The reconstruction procedure is shown to skew the true distribution predominantly in the fringes of the distribution, where nonlinear effects are not negligible.



Now calculate:

- $\epsilon_x = |\mathrm{Cov}(x, x')|$
- $\beta_x = \sigma_x^2/\epsilon_x$

And in 4D:

$\epsilon_n \approx (p_z/m_\mu)\sqrt{\epsilon_x\epsilon_y}$

Figure 4: The reconstructed transverse trace space of the baseline beam at TOF1.

As the beam size in a plane is uniquely determined by the emittance and betatron function, contours of constant beam size are drawn in Figure 5. In both horizontal and vertical phase space, we note that all beams have RMS beam sizes between 5 and 7 cm. This illustrates further that this beam line is dominated by scraping in the quadrupoles, as demonstrated in simulations, where ∼60% of muons are scraped in quadrupole 7. As a result of the constancy of σ_x and σ_y, the betatron function is determined by the emittance to first order. Trends may also be observed in polarity and momentum. In both planes, μ^+ beams tend to have a higher emittance than μ^- beams. This is a result of the inclusion of a proton absorber in the μ^+ beams which heats the beams slightly. We also observe that low-p_z beams have a higher emittance. This is because the focusing strength of a quadrupole is proportional to 1/p_z. As the 140 MeV/c beams are focused more powerfully by the magnets, they have a higher amplitude acceptance, and therefore a higher emittance.

Beams designed to have every combination of ϵ_n = (3, 6, 10) mm upstream of the first liquid hydrogen absorber, and p_z = (140, 200, 240) MeV/c in the center of each absorber. Muon beams of both polarities were generated and key optics parameter measured at TOF1. The transverse normalized emittance is related to the measured values of ϵ_x and ϵ_y as $\epsilon_n \approx (p_z/m)\sqrt{\epsilon_x\epsilon_y}$. The emittance of the incoming beam, measured by TOF0, TOF1 is much smaller than that of the beam that will go through the cooling channel. In order to generate the desired large emittance the beam goes through a high Z diffuser of adjustable thickness situated inside the first solenoid (Figure 6).

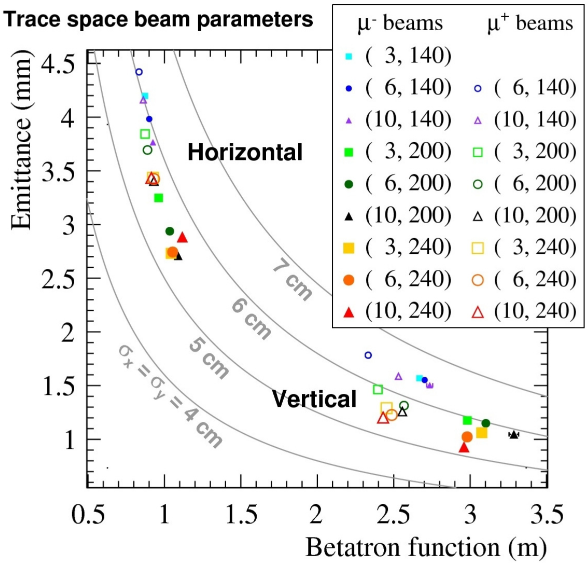


Figure 5: The betatron function and RMS trace emittance for all of the matched beams in both the horizontal and vertical planes, as measured just before the TOF1 detector.

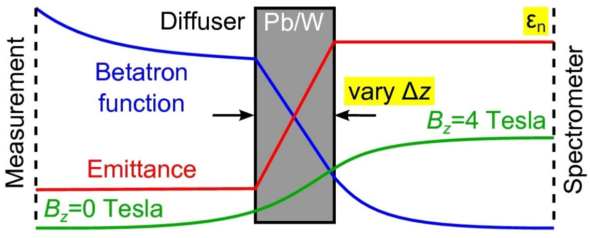


Figure 6: Diffuser matching.

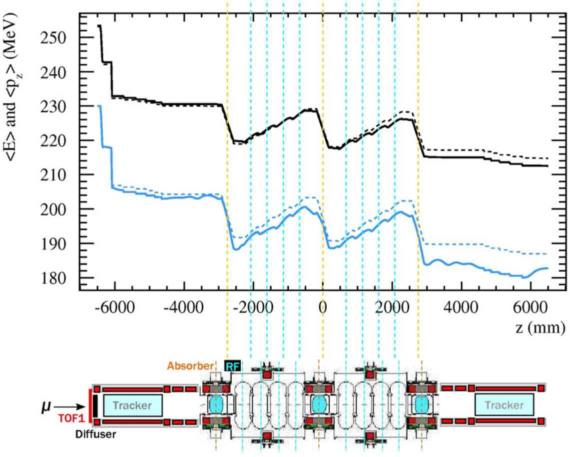


Figure 7: Measured beam simulation.

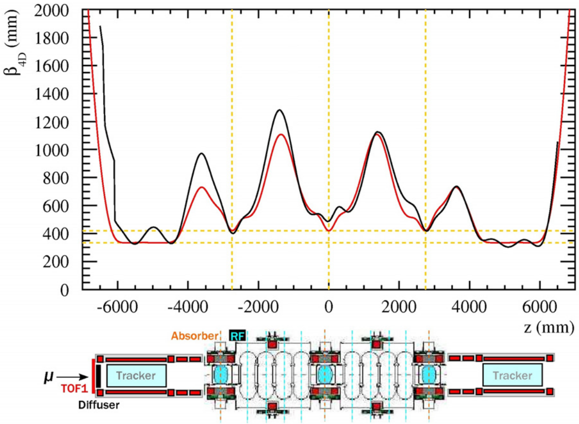


Figure 8: Beam envelope.

SIMULATION OF THE MEASURED BEAM

A beam, starting at TOF1, with the transverse distributions characteristic of the measured beam was simulated in full MICE cooling channel. The simulated beam was generated according to the measured covariance matrix of the four transverse phase space coordinates and therefore had the emittance and optical parameters of the real beam (Figure 7). Dashed line is the reference particle traveling along the axis.

The evolution of the transverse beta function along the MICE cooling channel of the real beam has been also simulated (Figure 8). The optics of the beam are seen to be similar to the ideal optics (red line) derived from a numerical solution to betatron equation:

$$2\beta_\perp\beta_\perp'' - (\beta_\perp')^2 + 4\beta_\perp^2\kappa^2 - 4 = 0$$

where κ is the focusing strength.

Figure 9 shows the evolution of the emittance of the simulated real beam. The emittance of the simulated real beam is slightly higher than the nominal 6 mm but decreases as expected at the absorbers. The initial overinflation of the emittance to 8 instead of 6 mm may be corrected by the use of a thinner lead diffuser disc. Despite no transverse selection or re-weighting having taken place, the optics of the beam behave tolerably well and the simulated real beam is seen to be cooled. It is anticipated that only a small re-weighting of the measured beam will be required.

CONCLUSIONS

The MICE collaboration intends to use beams with central momenta ranging from 140 MeV/c to 240 MeV/c, and normalized emittances between 3 and 10 mm. Several beams designed to have appropriate optical parameters were generated in a successful data taking campaign in 2010. Timing detectors of ~50 ps resolution confirm the generation of beams dominated by muons at the required momenta.

Distributions of the trace space vectors of individual muons have been reconstructed for the various beams, and promising agreement is observed with Geant4 simulations.

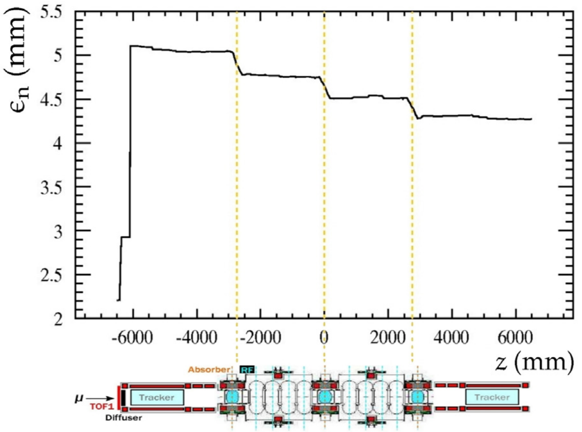


Figure 9: The baseline beam distribution measured in 2010 evolved through the final MICE lattice.

The evolution through MICE of the optical parameters of a measured baseline beam has then been simulated; the beam is relatively well matched, and tuning magnet currents and diffuser thickness should be sufficient to generate a well matched beam.

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