Measuring Muon Beam Emittance in MICE Step IV

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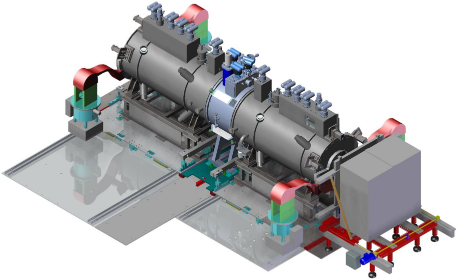
MICE Step IV

Aiming to demonstrate Muon Ionisation Cooling to 10%
Measured to 0.1% absolute precision



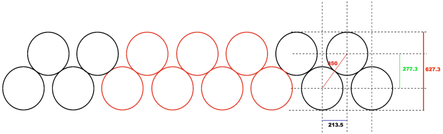
The SciFi Trackers provide our measurement power.
This study asumes only Tracker data.

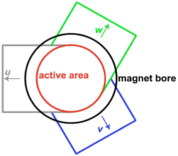
For Steps IV & V Global Reconstruction improves our PID and overall measurement accuracy

The SciFi Trackers

Each solenoid has 1 Tracker, with 5 Stations, each with 3 Planes.

Each plane is a layer of scintillating fibres, rotated 120 ° to their neighbours.

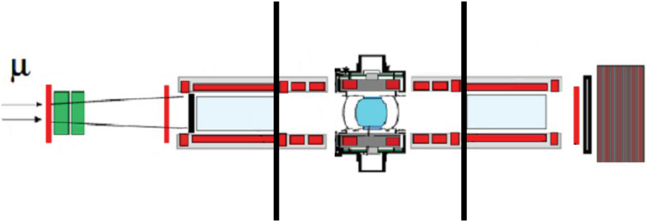




The Emittance Measurement

Each of the 3 planes in each Tracker station is individually analysed in the Kalman fitting algorithm - using the seeds provided by pattern recognition algorithms.

Officially the Trackers reconstruct the emittance at a point *just* inside the first plane for each Tracker.



Goals

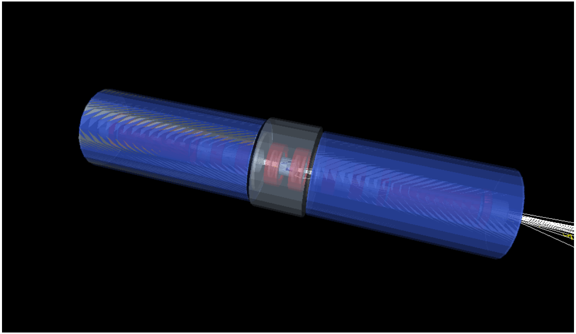
We were tasked with:

1. Using our own, specific software (MAUS) to simulate the cooling channel in Step IV
2. Estimating the effects of a reduced current FC on the cooling performance
3. Investigating the emittance measurements of pure and reconstructed Monte Carlo data
4. Predicting the measurable cooling effect for the MICE Step IV cooling channel

The Beamline

Simple Step IV cooling channel simulated.
SS1, SS2, AFC

PID and Calorimetry not yet included.



The Beam

Input beam assumed to be idealised in intial simulations:

Profile	Gaussian
Transverse Emittance	6πmm
Transverse Beta Function	333mm
Momentum	200MeV/c (0.0001 MeV/c RMS)
Start	Within upstream solenoid (-2900mm)
Content	100% Positive Muons

Plans to include G4Beamline simulated distributions later in the year.

Cuts

Cuts were applied to both Monte Carlo and Reconstructed datasets, to ensure good data integrity and to simplify the analysis.

They include:

Monte Carlo Cuts:

- Hit aperture cut: r $<$ 189mm (Width of the Tracker module)
- PID selection: Only Positive Muons (PID $=$ -13)

Reconstruction Cuts:

- Transverse Momentum: Pt $<$ 150 MeV/c
- Longitudinal Momentum: Pl $<$ 300 MeV/c
- p-value of the Kalmna track fit must be better than 5%

Cuts

To ensure that we can perform Covariance matrix corrections, we must be able to match Monte Carlo to Reconstructed tracks. The easiest way to do so is to simplify the dataset - So impose the following conditions:

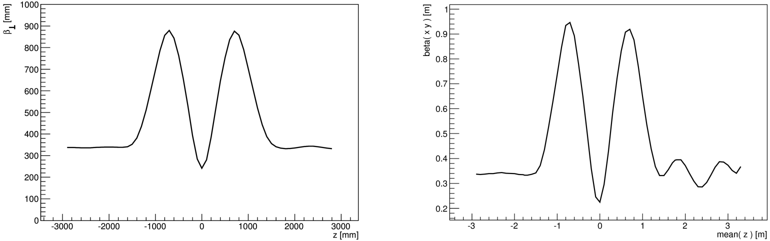
1. Only "Helical Tracks". We cannot produce p_T measurements with "Straight Tracks".
2. Tracks must be present in both upstream and downstream Trackers, for both Monte Carlo and Reconstruction.
3. No evidence of decays can be found (e.g. extra track points, missing track points, etc).

To pass as a "Helical Track" in software, pattern recognition must be able to reconstruct the helix with a low enough χ-squared value to pass a cut.

Beam Optics

The Beta Function for the MICE Beamline with Nominal FC Current

Left: As derived from transfer matrices
Right: As simulated in MAUS including Energy Losses and Straggling



Note the presence of Tracker planes and various windows increases the RMS P_z from zero to approx 3 MeV/c.

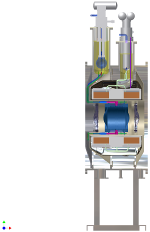
The AFC

The Focus Coil training didn't quite go as planned. FC#2 is currently returned to sender and FC#1's training fell a little short.

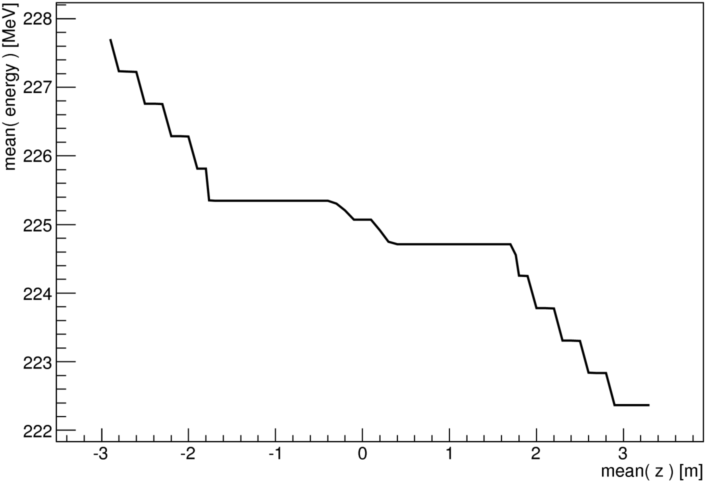
- Reached full design current in solenoid mode (114A)
- Only just reached the baseline (200 MeV/c) current in flip mode (188A)

If we use it in step 4 - what could we 'safely' run at?

First estimate: assume *approximate*
derrating of 11%
(thanks to John Cobb)
Approx 167A

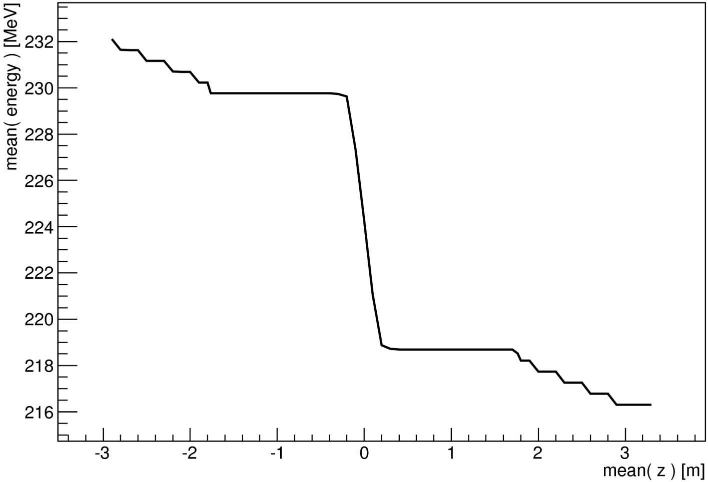


Reduced Current Beamline - No Absorber



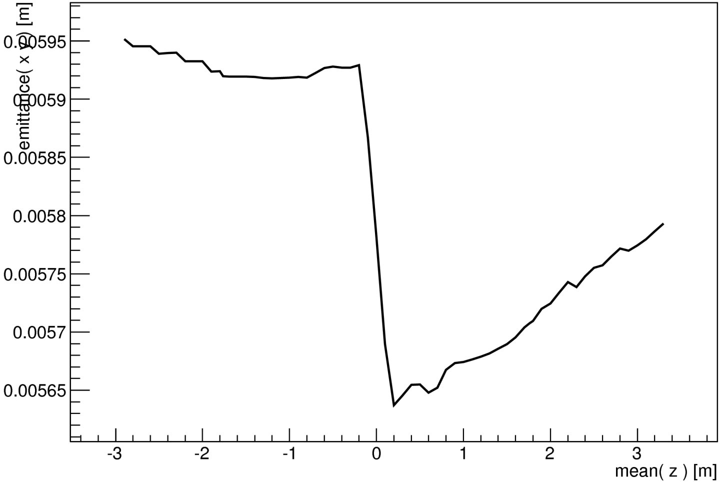
Mean Bunch Energy

Reduced Current Beamline - LH2



Mean Bunch Energy

Reduced Current Beamline - LH2



Bunch Emittance

Raw Emittance Calculations

Parameter	Monte Carlo	Reconstructed	Deviation
Emittance Upstream	5.885 mm	5.887 mm	0.03%
Emittance Downstream	5.655 mm	5.658 mm	0.05%
Beta Upstream	337.5 mm	336.0 mm	-0.4%
Beta Downstream	491.0 mm	481.4 mm	-1.9%
Number Upstream	16737	16737	0.0%
Number Downstream	16737	16737	0.0%

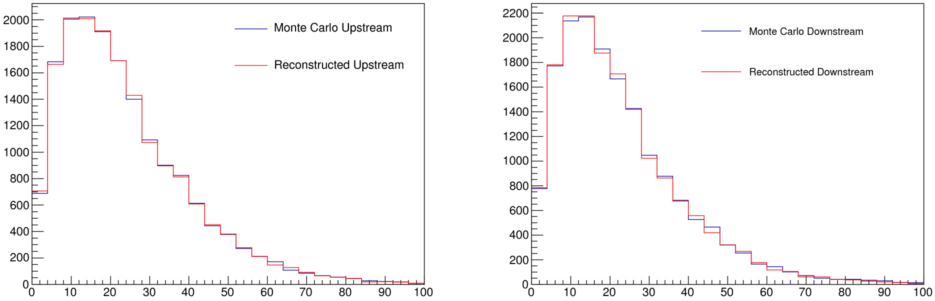
These numbers are in agreement with previous simulations.
Very encouraging results!

This demonstrates Monte Carlo cooling of 3.9%.

Still an asymmetry between upstream and downstream results to look into.

Single Particle Amplitudes

Comparisons between Reconstruction and Monte Carlo



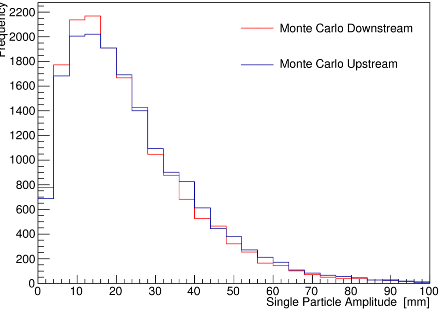
Upstream

Downstream

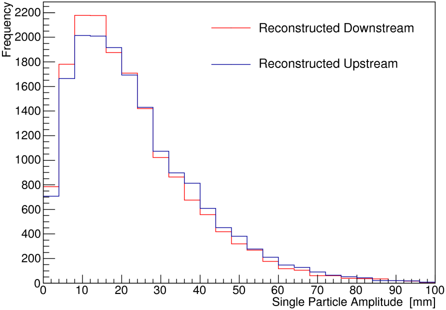
For idealised situation Mean Amplitude = 4 × Emittance.
This holds!

Single Particle Amplitudes

Comparisons between Upstream and Downstream



Monte Carlo



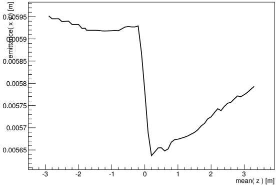
Reconstruction

More statistics required to enhance these plots

Downstream Optics

There is a rise in Emittance, upstream of the downstream reference plane.

Possibly the Beta Function or possibly a non-linear effect . . . [MuCool Theory Note: 288 - *Behaviour of Kinematic Invariants of Beams with Large Energy Spread*]



If it is the Beta Function:

- Turn off Energy Straggling and Energy Spread
- Rematch the downstream channel (Past the absorber)
- Reset Match Coil currents accordingly

This has been done “by eye” with promising results - however we still need to use some software!

Covariance Matrix Corrections

For 6D phase space (x,x',y,y',z,z') we have a 6×6 covariance matrix V with components:

$$V_{ij} = \mathrm{cov}(u_i, u_j)$$

Now the Normalised, RMS, 4D emittance is given simply by:

$$\epsilon = \frac{\sqrt[4]{|V_{4\mathrm{D}}|}}{m_\mu}$$

But if there are errors in our measurements (m), of (δ) compared to the actual value (u), our covariance matrix has some corrections. . .

$$m_i = u_i + \delta_i$$

Covariance Matrix Corrections

$$\begin{aligned} V_{ij} &= \mathrm{cov}(m_i, m_j) \\ &= < u_i u_j > - < u_i >< u_j > + < u_i \delta_j > - < u_i >< \delta_j > \\ &\quad + < \delta_i u_j > - < \delta_i >< u_j > + < \delta_i \delta_j > - < \delta_i >< \delta_j > \end{aligned}$$

We can rewrite this as:

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

Holds perfectly for the Upstream Tracker.
Holds to 0.02% for the Downstream Tracker.

(This is due to a small bug involving the placement of a reference plane)
This is to be fixed in the reconstruction - but we know what it is!

Conclusions

- We have a full Tracker reconstruction including Kalman fitting and Covariance matrix corrections that works!
- Good agreement between Monte Carlo and Reconstruction - within the expectations of prior studies
- Beam optics still to be improved - but asymmetric matching coils have shown promising results (Coming soon!)
- A small bug exists with the placement of the downstream reference plane - to be fixed.
- Analysis code will be made available. Started talking with Chris Rogers about improvements.

We are confident that we are on a good path.

Future Plans

We're not done yet:

- Implement G4Beamline generated beams
- Use the full MICE Geometry from the CDB
- A more detailed optics study with asymmetric match coil currents
- Write/check the documentation - including a MICE Note
- A simulated physics run using a predetermined covariance matrix
- Repeat all datasets with solenoid mode

We expect huge progress at the next CM in Rome!