# Measuring Muon Beam Emittance in MICE Step IV

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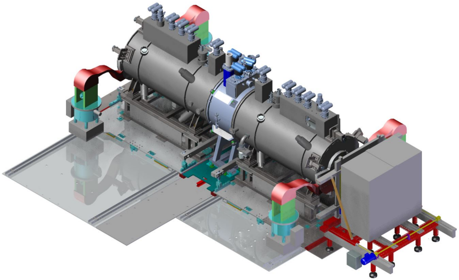
# MICE Step IV

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

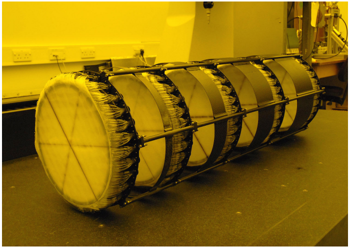


The SciFi Trackers provide our measurement power.
This study asumes only tracker data.

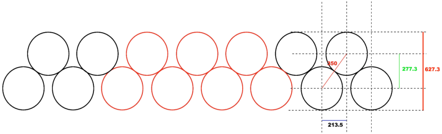
For Steps IV & V Global Reconstruction improves our PID and overall measurement accuracy

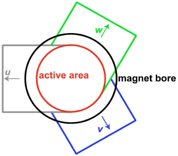
# The SciFi Trackers

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.

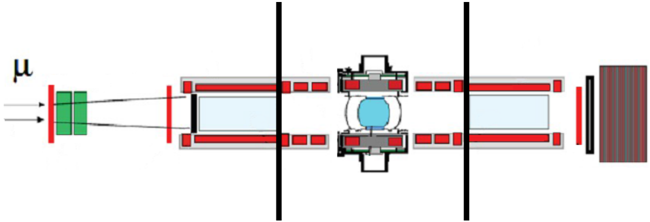


# The Emittance Measurement

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

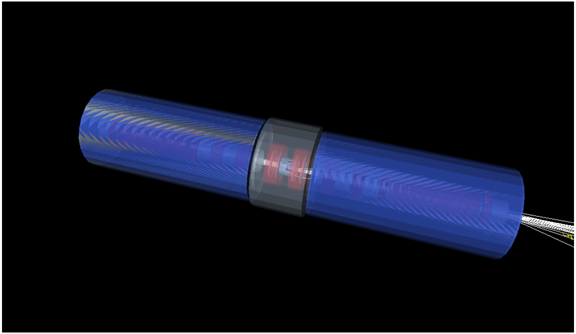
We were tasked with:

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 | $6\pi$mm |
| Transverse Beta Function | 333mm |
| Momentum | 200MeV/c (5MeV/c RMS) |
| Start | Within upstream solenoid |
| 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, including:

Monte Carlo Cuts:

- Hit aperture cut: r $<$ 189mm
- PID selection: Only Positive Muons (PID = -13)

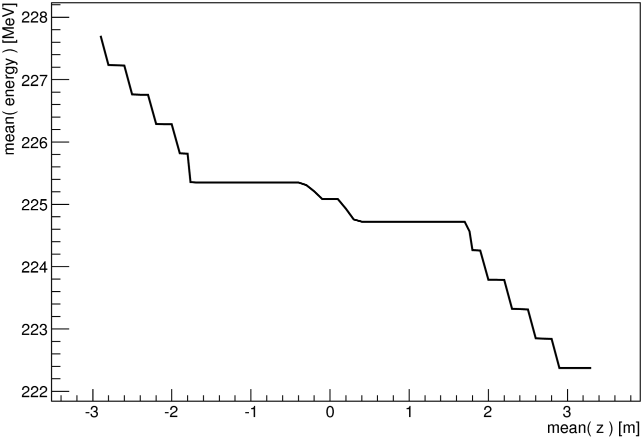
Reconstruction Cuts:

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

Joint Cuts:

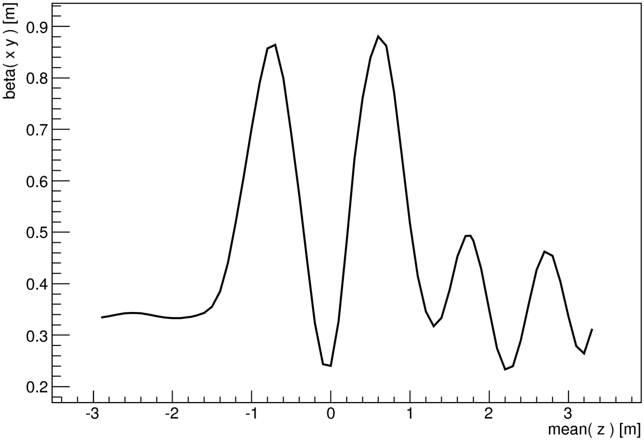
- Require tracks in both up- and down-stream trackers
- Must be a helical track - No fitted straight tracks!
- Must be a simple event - No decays!

# Nominal Beamline - No Absorber



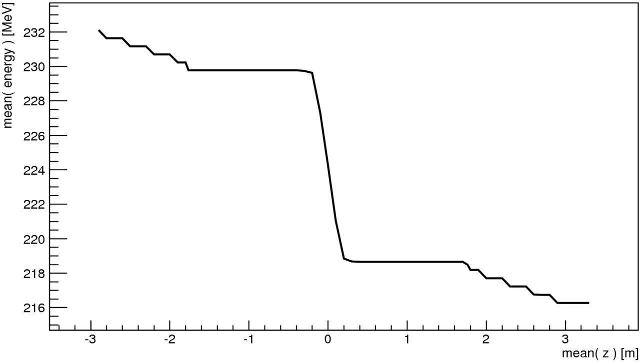

Mean Bunch Energy

# Nominal Beamline - No Absorber




Beta Function

# Nominal Beamline - LH2




Mean Bunch Energy

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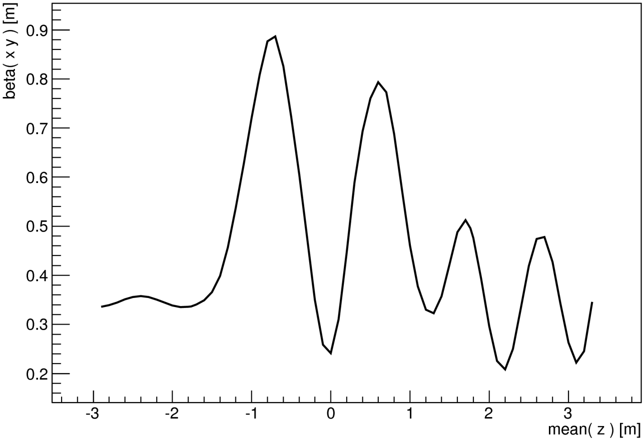
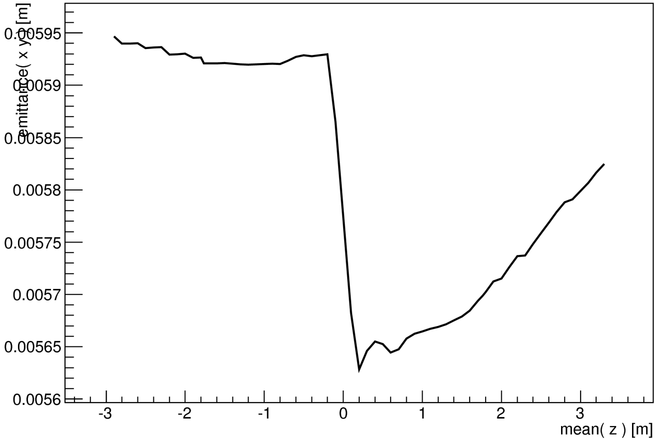



Beta Function

# Nominal Beamline - LH2




Emittance

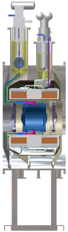
# The AFC

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.

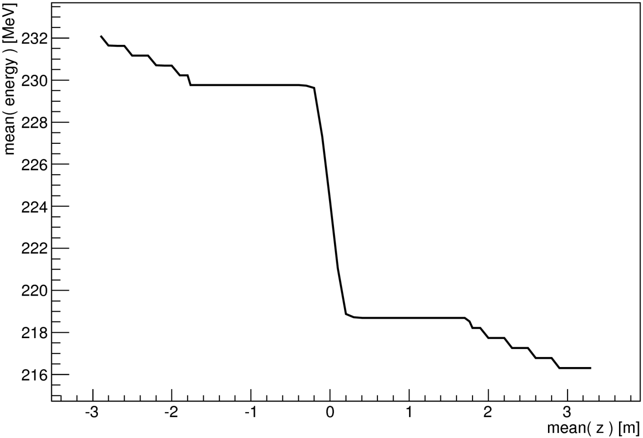
- Reached full design current in solenoid mode (114A)
- Only just reached the baseline (200 MeV/c) current in flip mode (188A)

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

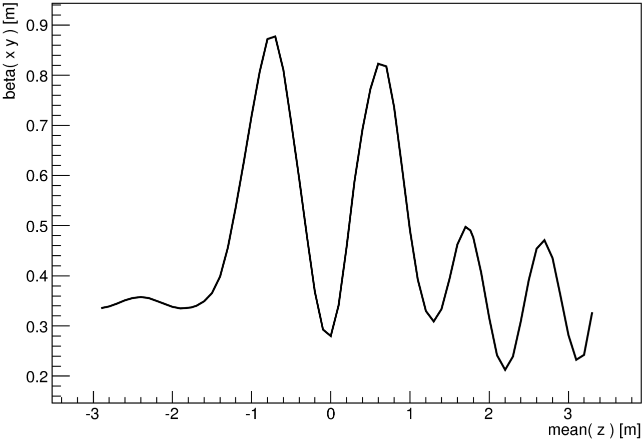


# Reduced Current - LH2



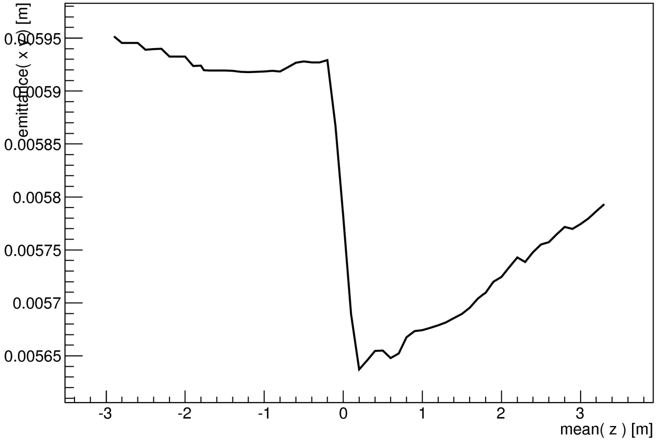

Mean Bunch Energy

# Reduced Current - LH2




Beta Function

# Reduced Current - LH2




Emittance

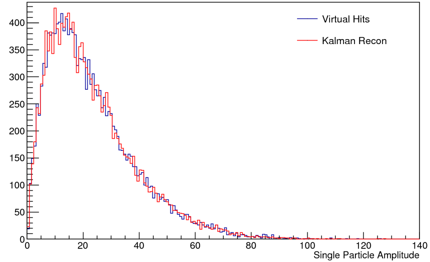
# Raw Emittance Calculations

| Parameter | Virtual | 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% |

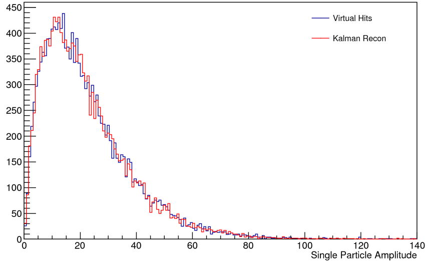
These numbers are in agreement with previous simulations.
Very encouraging results!

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

# Single Particle Amplitudes




Upstream




Downstream

For idealised situation Mean Amplitude $= 4 \times$ Emittance.

This holds!

# Covariance Matrix

For 6D phase space $(x, x', y, y', z, z')$ we have a $6 \times 6$ 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 $(\delta)$ 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 Upstream tracker.
Holds $\approx$ 0.6% for Downstream tracker
*(This is due to a reference plane being in the wrong place!)*

With a slight adjustment we get better than 0.02% at present

# Conclusions

- We have a full tracker reconstruction including Kalman fitting and Covariance matrix corrections that works!
- Good agreement between Monte Carlo and Reconstruction
- 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.

We are confident that we are on a good path.

# Future Plans

- 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

We expect huge progress at the next CM in Rome!