# The MICE Measurement Programme:

# Concepts and Practicalities

C. T. Rogers,
ASTeC Intense Beams Group
Rutherford Appleton Laboratory

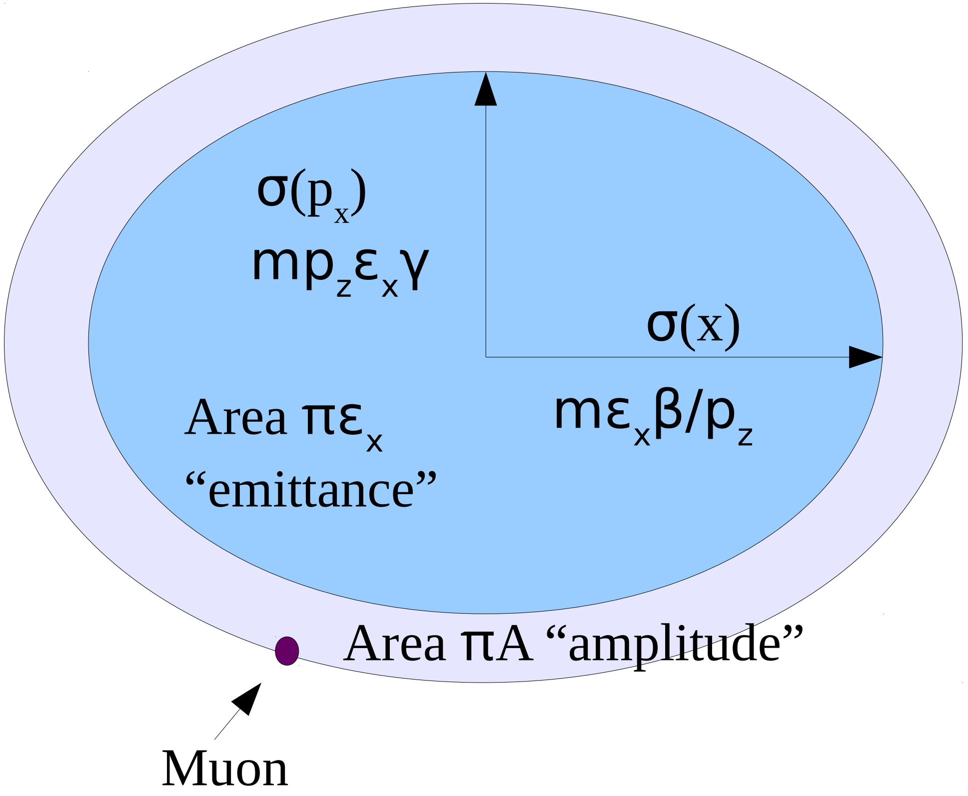
# Aims of MICE

- At Step IV MICE will:
  - Measure material properties of liquid hydrogen and lithium hydride that determine ionization cooling performance
  - Observe transverse normalised emittance reduction
- At the demonstration of ionization cooling MICE will:
  - Observe transverse emittance reduction with re-acceleration
  - Observe longitudinal emittance evolution
  - Observe angular momentum evolution
- How does MICE achieve those goals?
- How does MICE achieve the required precision?

# MICE Data Taking Programme

- Commission hardware
- Particle-based commissioning:
  - Validation of diagnostics with field off
  - Particle-based alignment of detectors with field off
  - Validation of diagnostics with field on
  - Particle-based alignment of magnets with field on
    - Compare with field mapping performed offline
  - Particle-based measurement of RF voltage and phase
    - When RF is installed
  - Input distribution tuning
  - Check distribution propagation through the lattice
- Optics and momentum scans with/without absorber
  - Material physics measurement (at Step IV)
  - Emittance reduction measurements under various conditions

# 2D Emittance



$\sigma(p_x)$

$mp_z\varepsilon_x\gamma$

$\sigma(x)$

$m\varepsilon_x\beta/p_z$

Area $\pi\varepsilon_x$ "emittance"

Area $\pi A$ "amplitude"

Muon

- Normalised 2D RMS emittance (in horizontal phase space):

$$\varepsilon_x = \frac{\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle x p_x\rangle^2}}{m}$$

- MICE is a solenoid lattice
  - Coupling between transverse planes

# Transverse emittance

- MICE typically uses RMS 4D emittance for analysis

$$\varepsilon_N = \frac{\sqrt[4]{|\mathbf{V}|}}{m}$$

  - $\boldsymbol{V}$ is the matrix of transverse covariances with elements

$$v_{ij} = \frac{1}{n}\sum(u_i u_j) - \frac{1}{n}\sum(u_i)\frac{1}{n}\sum(u_j)$$

  - Where $u_i$ are elements from the phase space vector $\underline{u}$

$$\underline{u} = (x, p_x, y, p_y)$$

  - Proportional to volume of a 4D hyperellipsoid
- Single particle amplitude is also a useful quantity

$$A = \varepsilon_N\, \underline{u}^T \mathbf{V}^{-1} \underline{u}$$

  - Sum of transverse “actions” of linear Hamiltonian
- Emittance is conserved in linear approximation
  - Solenoids are inherently non-linear, even without fringe fields

# Optical functions

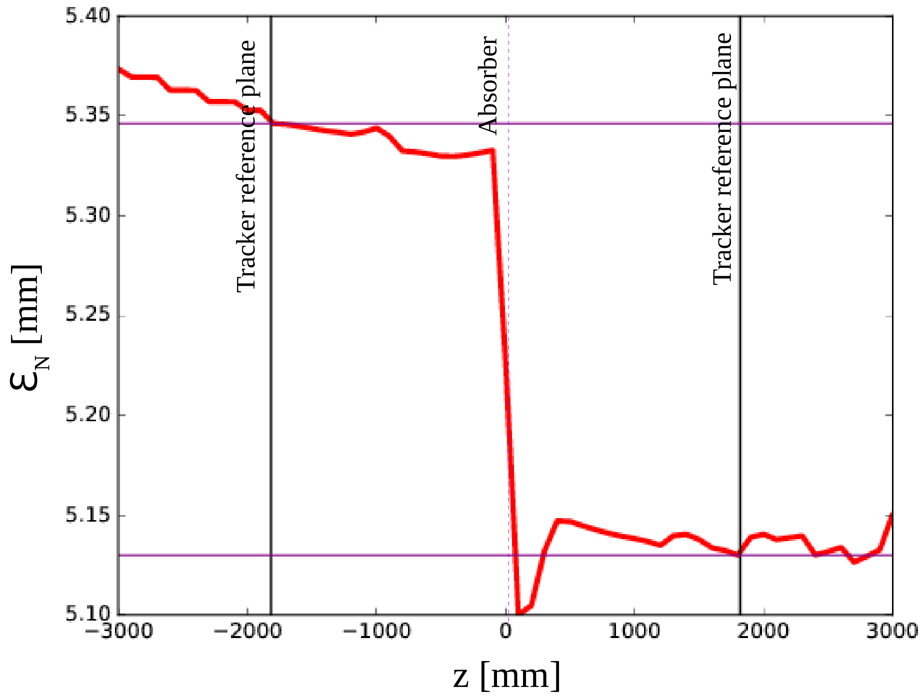
- MICE requires a cylindrically symmetric beam
  - Symmetric focussing in x and y
  - Results in a single transverse optical function
- Beam optical functions are defined by

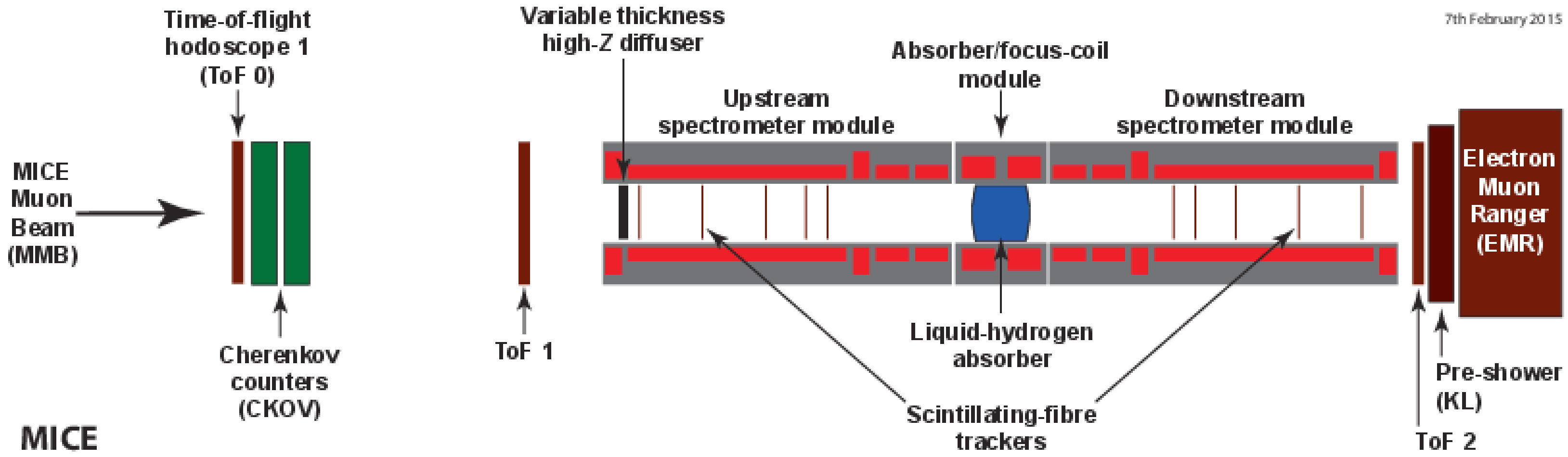
$$\beta_{4D} = \frac{p_z\left(\langle x^2\rangle + \langle y^2\rangle\right)}{2\varepsilon m c}$$

$$\alpha_{4D} = \frac{-\left(\langle x p_x\rangle + \langle y p_y\rangle\right)}{2\varepsilon m c}$$

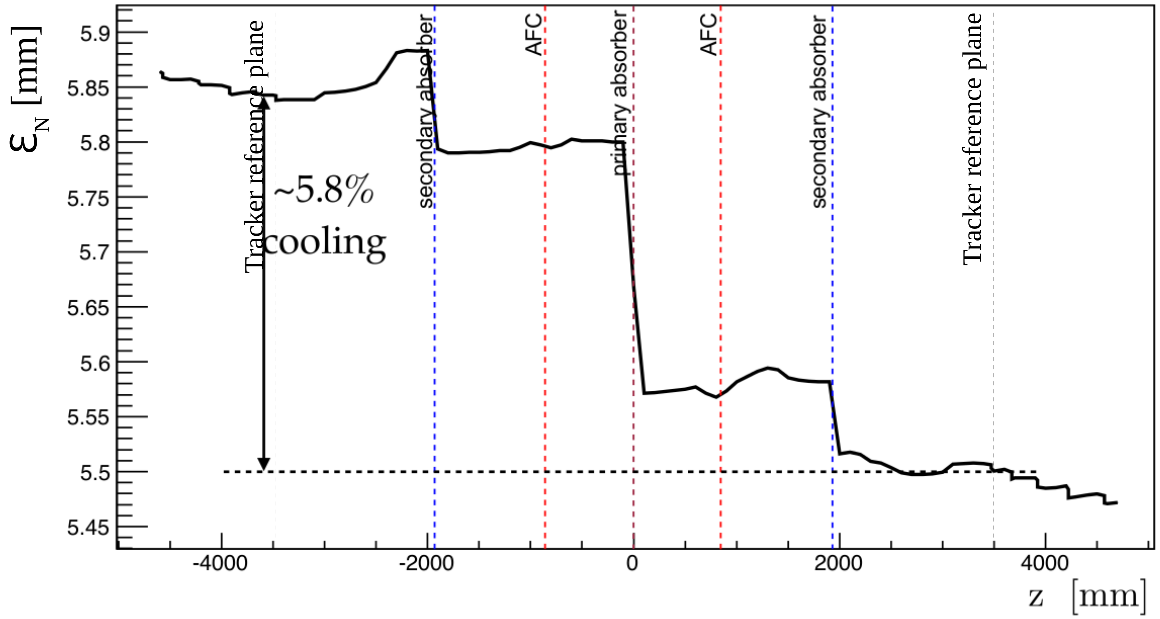
$$\gamma_{4D} = \frac{\langle p_x^2\rangle + \langle p_y^2\rangle}{2 p_z \varepsilon m c}$$

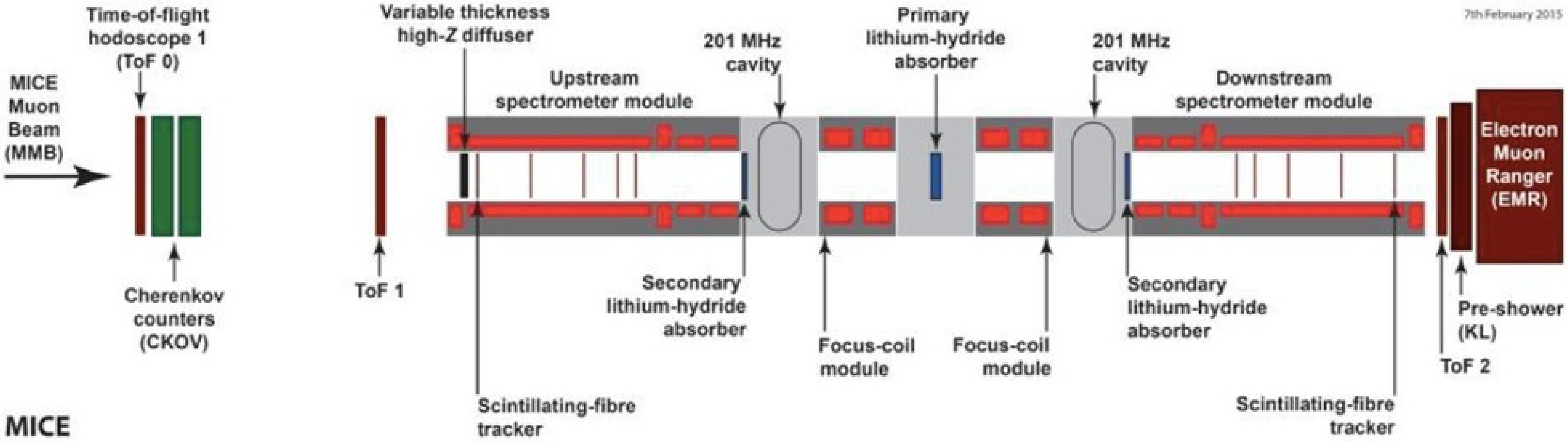
# Emittance Reduction at Step IV





# Demonstration of Ionisation Cooling




7th February 2015

MICE Muon Beam (MMB)

Time-of-flight hodoscope 1 (ToF 0)

Cherenkov counters (CKOV)

ToF 1

Variable thickness high-*Z* diffuser

Scintillating-fibre tracker

Upstream spectrometer module

Secondary lithium-hydride absorber

201 MHz cavity

Focus-coil module

Primary lithium-hydride absorber

Focus-coil module

201 MHz cavity

Secondary lithium-hydride absorber

Downstream spectrometer module

Scintillating-fibre tracker

ToF 2

Pre-shower (KL)

Electron Muon Ranger (EMR)

MICE

# Emittance Reduction in MICE

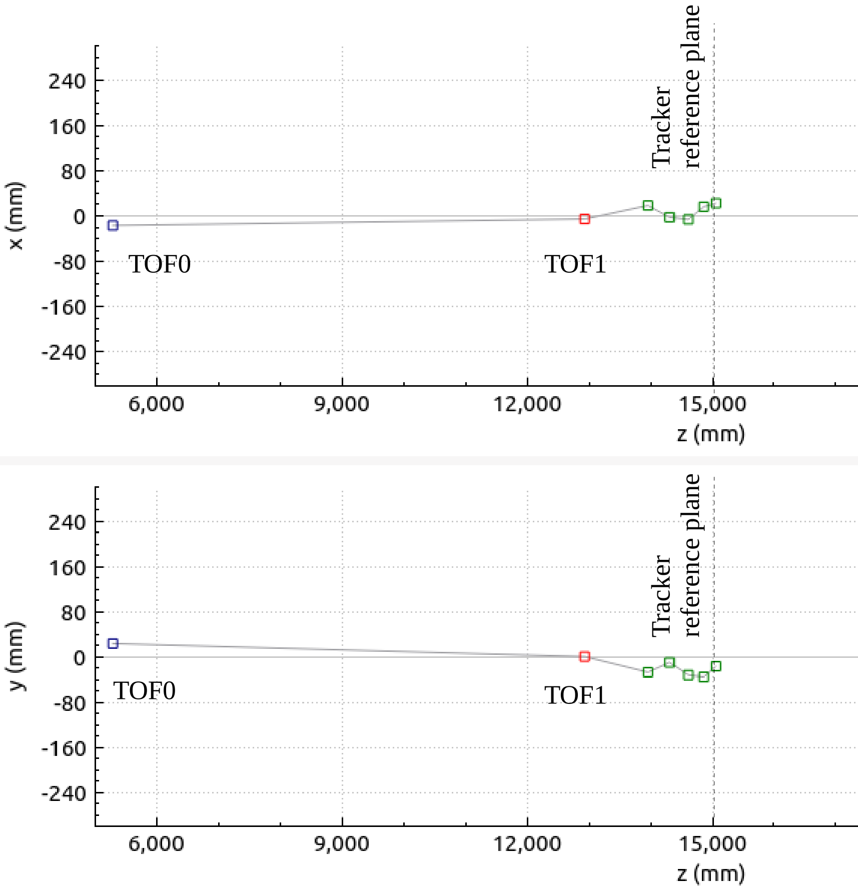
- Emittance reduction in a cell is approximately

$$\frac{d\varepsilon_{4D}}{dz} \approx \frac{-1}{\beta_{rel}^2 E}\left\langle \frac{dE}{dz} \right\rangle + \frac{1}{2m}\frac{13.6^2}{L_R}\frac{\beta_{4D}}{\beta_{rel}^3 E}$$

  - $L_R$ is the material radiation length;
  - $\langle dE/dz \rangle$ is mean energy loss per unit length
- MICE makes an emittance reduction of a few per cent
  - Demonstrated precision is important
  - Correlations are important → measure particle-by-particle
- MICE seeks to measure the *change* in emittance with 1 % precision

# MICE is a Single Particle Experiment

- 10-100 particles enter MICE on each dip of the target
  - Target dips at 0.78 Hz
- Particle phase space vector is measured for each particle
  - At the “tracker reference plane”
- Pion and electron impurities are rejected
- Muons are selected upstream of the cooling channel to:
  - Reduce the momentum spread
  - Ensure a matched profile in phase space
  - Ensure an appropriate phase profile if RF is running



# Particle Accumulation

- Individual particle trajectories are accumulated into an ensemble
  - High precision measurement requires 100,000 good muons
- Distribution parameters are calculated upstream and downstream of the channel
  - Calculate the covariance matrix
  - Measure 4D transverse emittance

# Particle Measurements

- Particles are measured upstream and downstream at tracker reference planes (TRPs)
  - Scintillating Fibre Tracker (SciFi) measures ($x$, $p_x$, $y$, $p_y$, $p_z$)
  - Time-of-Flight (TOF) measurement is used to calculate RF phase
- Particle identification is performed by a number of detectors
  - TOF compared to SciFi to deduce mass
  - Threshold cerenkov detector (ckov)
  - KL (KLOE Lite) – sampling calorimeter
  - EMR (Electron Muon Ranger) – electron shower compared with muon track

# Sources of Uncertainty

- Sources of uncertainty in making an emittance change measurement
  - Statistical uncertainty owing to finite sample size
  - Detector resolution and inefficiency
  - Misidentification of particles

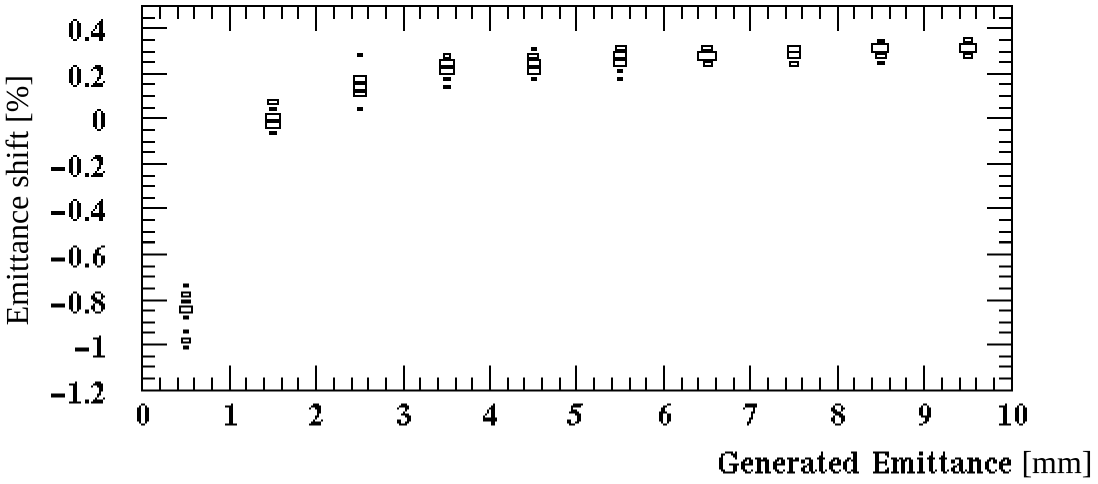
# Statistical Uncertainty

- Emittance evolution is deterministic in the absence of stochastic processes
  - e.g. in the absence of multiple Coulomb scattering
- Statistical uncertainty is driven by stochastic processes in material
  - i.e. Multiple Coulomb scattering
  - Uncertainty given by

$$\sigma_f = \sqrt{\frac{1}{2n}\left(\frac{\sigma_s^2}{\sigma_{px}^2}\right)}$$

- Leads to a required sample size of
  - ~ 60,000 muons at Step IV
  - ~ 80,000 muons in the demonstration of ionisation cooling

# Effect of Detector Resolution



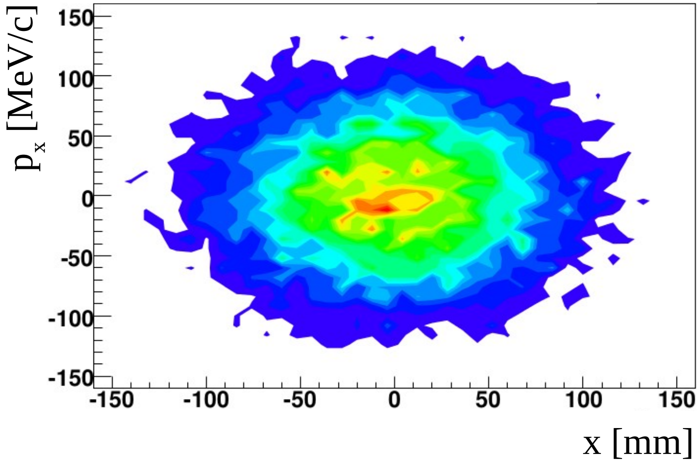
- Detector resolution introduces a systematic shift in emittance
  - Measured distribution is approximately convolution of true distribution and errors
  - Correlations between true distributions and errors also contribute
- Measure detector resolutions to make a correction

# Particle identification

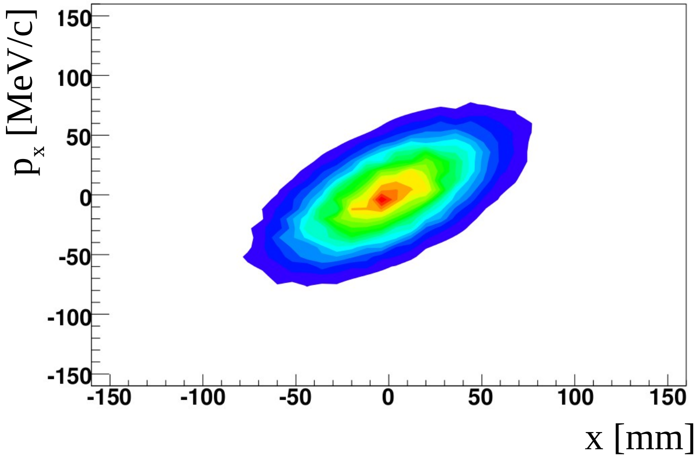
- Effect of misidentification depends on the misreconstructed event's amplitude
- Pions identified as muons upstream
  - Pions undergo nuclear processes in the absorber
  - Pions likely to decay (transmission loss or emittance growth)
- Electrons identified as muons upstream
  - Electrons scatter more in the absorber
  - Electrons likely to be identified as muon decay downstream
- Muons identified as non-muons upstream
  - May reduce statistics
- Electrons downstream
  - Electrons from muon decay likely have larger emittance
  - Electrons from RF background may also contribute

# Beam Sampling

- Beam line does not give MICE the desired distributions
  - Momentum spread is too large
  - Uncorrected dispersion
- Three algorithms for sampling the beam
  - Cut-based
    - Cuts on amplitude and momentum
  - Phase Space Tesselation
    - Calculate phase space volume on a particle-by-particle basis
    - Apply statistical weights to enhance underdense regions
  - Moment/Multipole-based weighting
    - Apply statistical weights to generate a desired set of beam moments
- Weighting is performed upstream only



Unweighted – no correlation

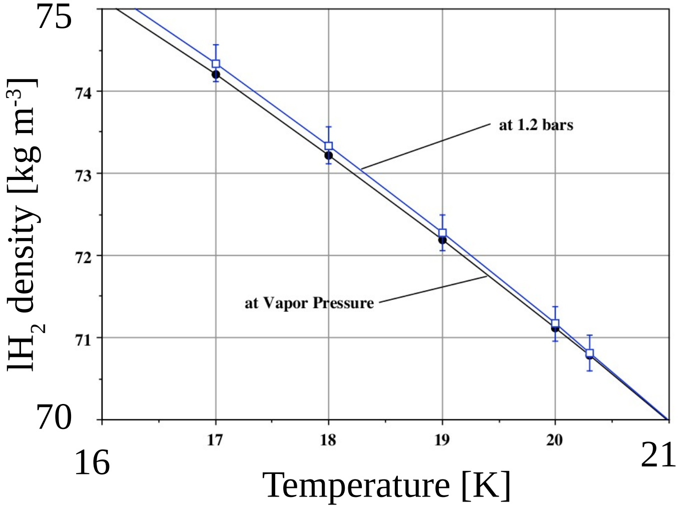


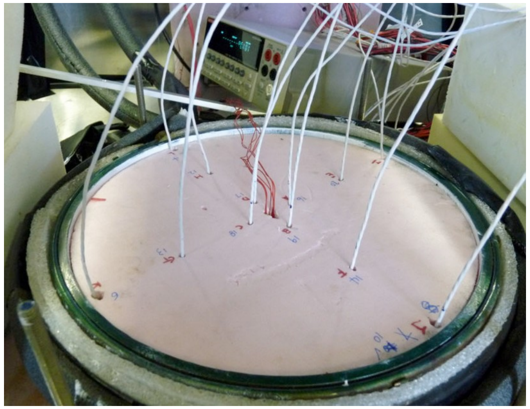
Weighted to induce correlation

# Magnetic Fields

- MICE will measure emittance change with high precision
- MICE will seek to compare emittance change with simulation
  - Poor knowledge of magnetic field can introduce a systematic error in the simulated performance
- Several approaches to deal with this effect
  - Magnetic field produced by the MICE magnets has been assessed by a detailed mapping
  - Beam-based measurement of the magnetic fields has begun
  - OPERA magnetic model of the cooling channel has been produced

# Absorber





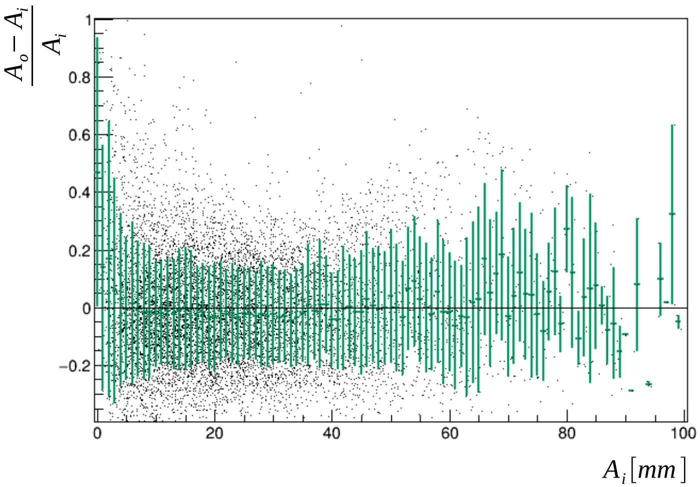
- As with the magnetic fields, so with the absorber
  - Poor knowledge of absorber can introduce a systematic error in the simulated performance
- Lithium hydride absorber has undergone detailed chemical and dimensional analysis
- Liquid hydrogen absorber material budget controlled by
  - Precise temperature control
  - Careful measurement of window thickness
  - FEA to predict deformation of the window under load

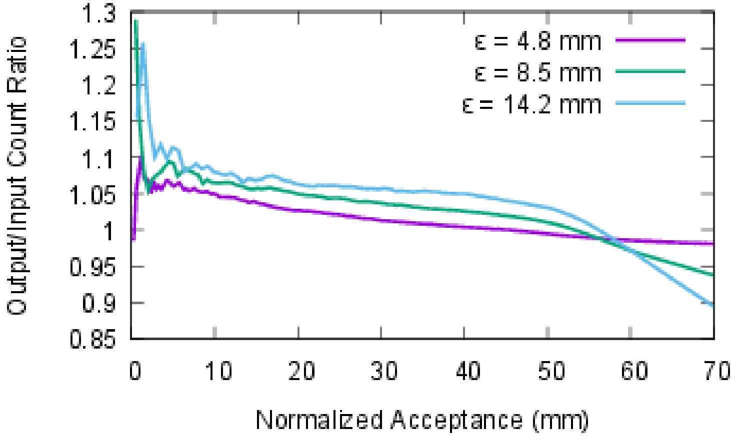
# Alternatives - particle amplitude

- RMS emittance reduction is our baseline measurement
  - Well understood by (muon) accelerator community
  - Sensitive to effects on beam tail
  - Scraping reduces RMS emittance (but is not cooling!)
- An alternative approach is to use single particle amplitude

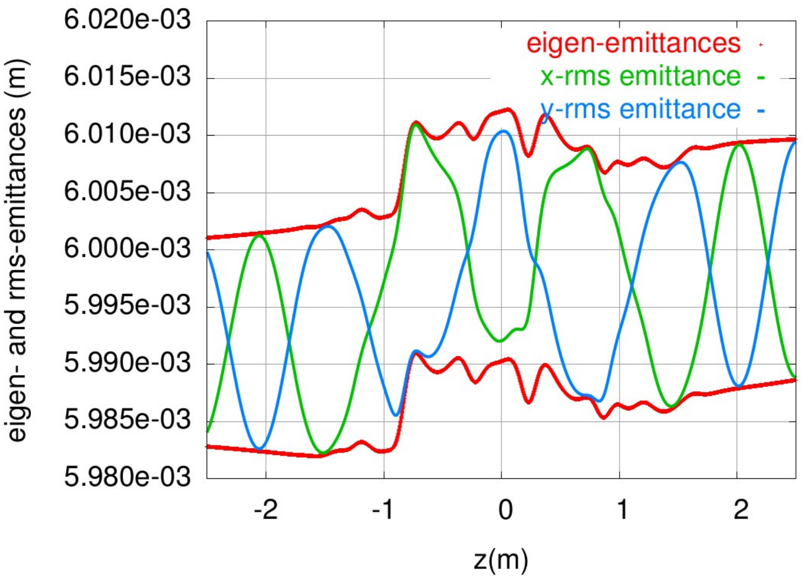
$$A = \varepsilon_N \underline{u}^T \boldsymbol{V}^{-1} \underline{u}$$

- ***V*** can be measured using a subsample of the beam
  - e.g. beam core where optics are linear
  - $\varepsilon_N$ is emittance of ***V***
- ***V*** can be assumed based on knowledge of the field map



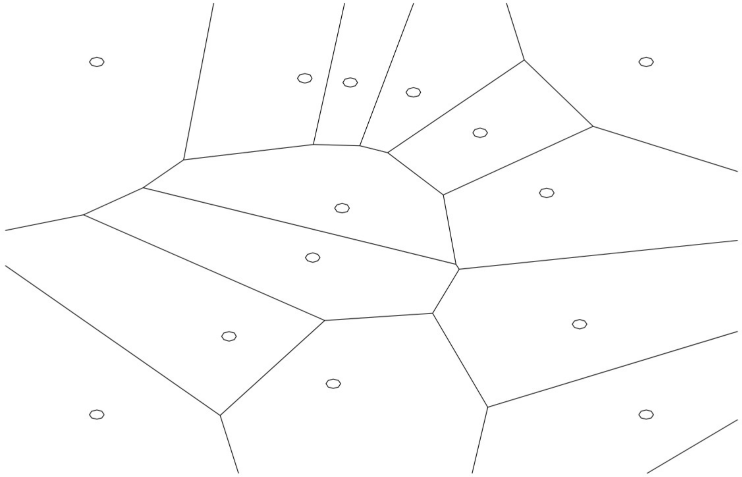


# Alternatives - eigenemittance



- Given the transfer matrix **M**, can deduce transformation to uncoupled 2D eigenspaces
  - **M** can be assumed based on knowledge of the field map
  - **M** can be measured based on particle trajectories
- Demonstrates different behaviour of the solenoid and flip modes
  - Flip → field flips from +ve to -ve on absorber
  - Solenoid → field is +ve throughout the lattice

# Alternatives – phase space volume



- Can calculate the exact phase space volume occupied by the beam
  - Mesh the beam particles
  - Divide phase space occupied by the beam into 4D simplices
  - Calculate the phase space volume occupied by the beam
  - Direct measurement of violation of Liouville's theorem
- But
  - May need high statistics to get good measurement of volume
  - Limited by detector resolution

# Conclusion

- Precision is achieved by careful evaluation of sources of uncertainty
  - Redundancy in detector systems enables precise measurement of detector-induced uncertainty
  - Enables detailed characterisation of the lattice
- Leads to a high precision measurement of emittance