Transverse phase-space measurements in the Muon Ionization Cooling Experiment

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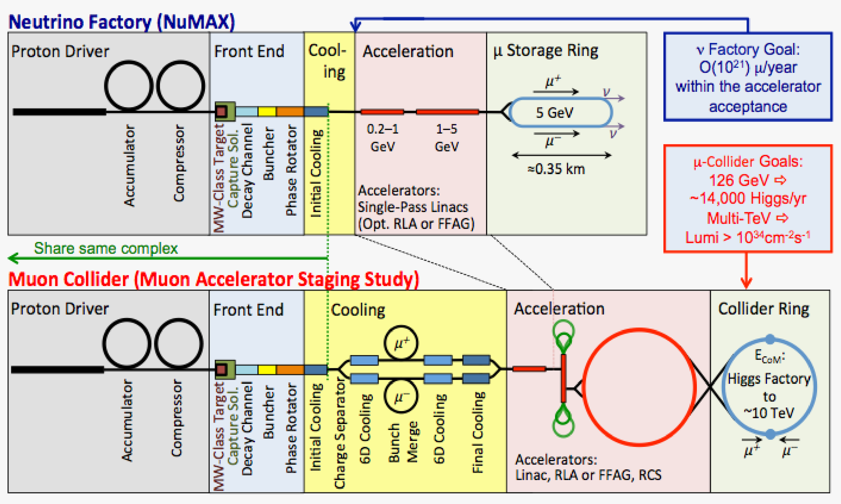
on behalf of the MICE Collaboration

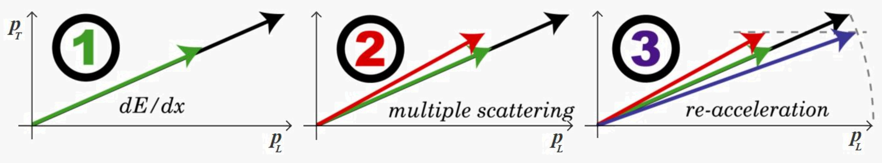
1. Muon Ionization Cooling Experiment (MICE)

• Motivation



Ionization cooling provides the **only practical solution** to prepare high brightness beams necessary for a **Neutrino Factory** or **Muon Collider** because it is the only method fast enough to cool the beam on a time-scale of the muon lifetime

• Ionization Cooling



1. Energy loss by ionization (dE/dx reduces both p_L and p_T)
2. Heating from multiple scattering
3. p_L restored by RF cavities

$$\frac{d\varepsilon_N}{dz} = \underbrace{-\frac{\varepsilon_N}{\beta^2 E_\mu}\left|\frac{dE_\mu}{dz}\right|}_{\text{cooling}} + \underbrace{\frac{\beta_\perp (13.6\,\mathrm{MeV}/c)^2}{2\beta^3 E_\mu m_\mu X_0}}_{\text{heating}}$$

→ Equilibrium emittance means *cooling = heating*

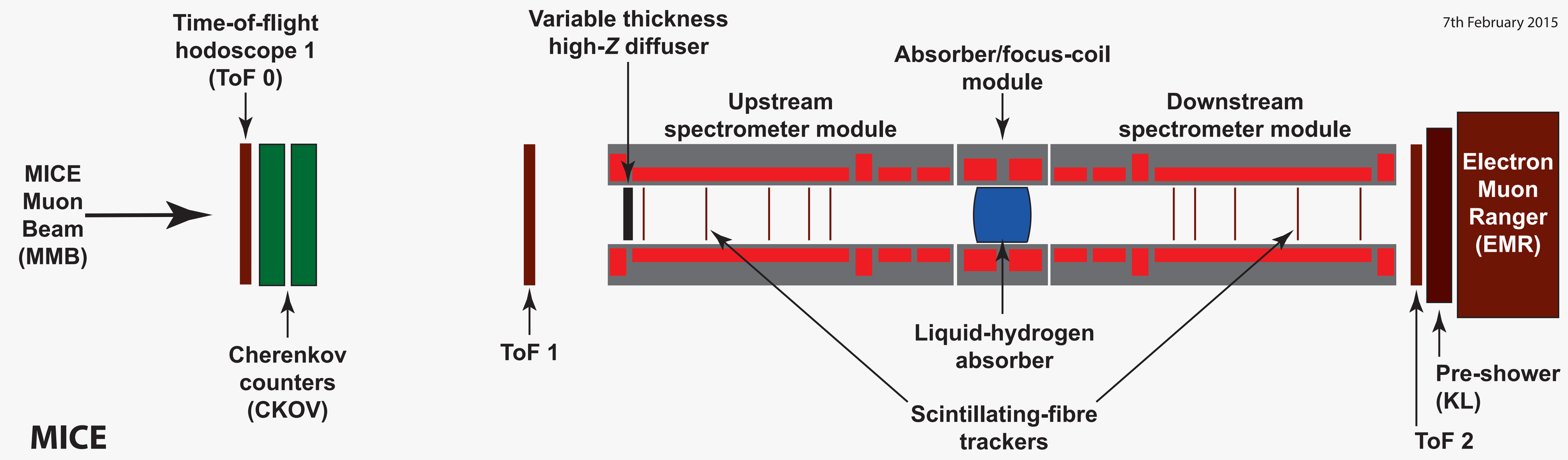
→ To maximize cooling, one must use a material with **low-Z** placed at a position where $\beta_\perp$ **has a minimum**.

• MICE

- MICE is a **key R&D** towards Neutrino Factory and Muon Collider
  → Design, build, commission and operate a realistic section of a cooling channel
- MICE collaboration: Bulgaria, China, Italy, Japan, Netherlands, Serbia, Switzerland, UK, USA: ∼80 collaborators

• Goals

- Measure **cooling performance** in a variety of modes of operation and beam conditions
  → LiH or LH_2 absorber
  → 140–240 MeV/c central momentum
  → 3–10 mm input emittance
- Achieve an absolute normalized transverse emittance measurement resolution of 0.1 %

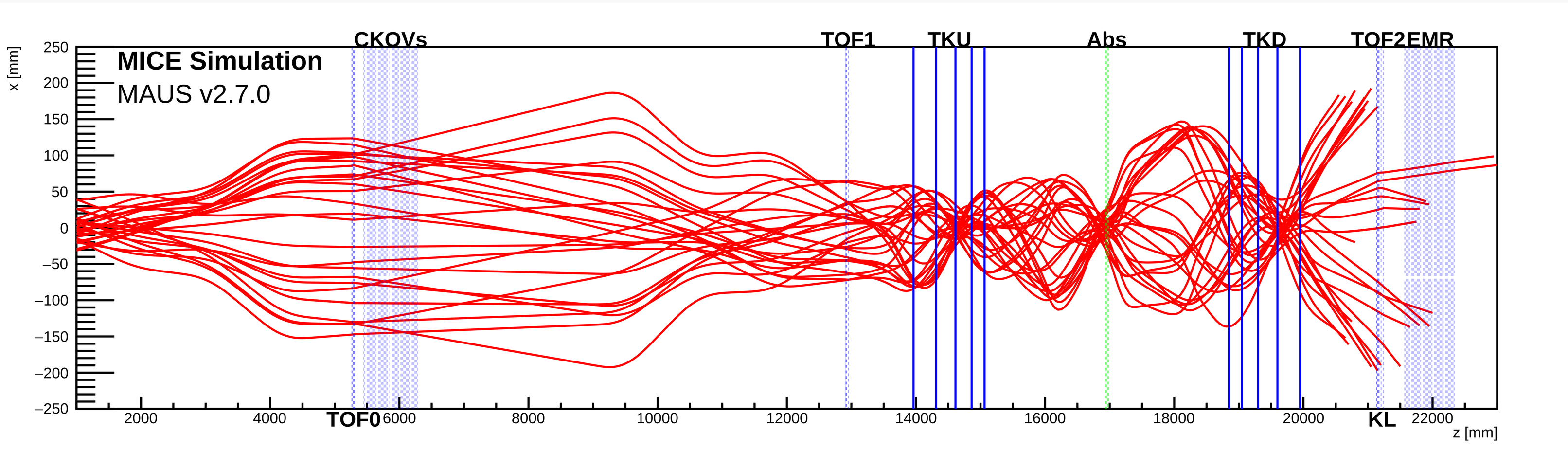


2. Single particle experiment

- Muons are measured **one-by-one** (f ∼200 Hz)
- Tracks are **accumulated** into a statistical ensemble
- **Scintillating fibre trackers**

$$\rightarrow \begin{cases} \sigma_x, \sigma_y \sim 347\,\mu\mathrm{m} \\ \sigma_{p_T} \sim 1.264\,\mathrm{MeV}/c \\ \sigma_{p_L} \sim 3.974\,\mathrm{MeV}/c \end{cases}$$

- Robust **particle identification**:
  → TOFs, CKOVs, KL, EMR



3. First direct measurement of emittance with the trackers

• Data sample

The data sample represented here was recorded in October 2015

- 4 T field in the upstream tracker
- 19076 good muon tracks individually measured in 70 minutes

• Emittance

MICE has measured emittance in the transverse space. The transverse phase-space covariance matrix reads

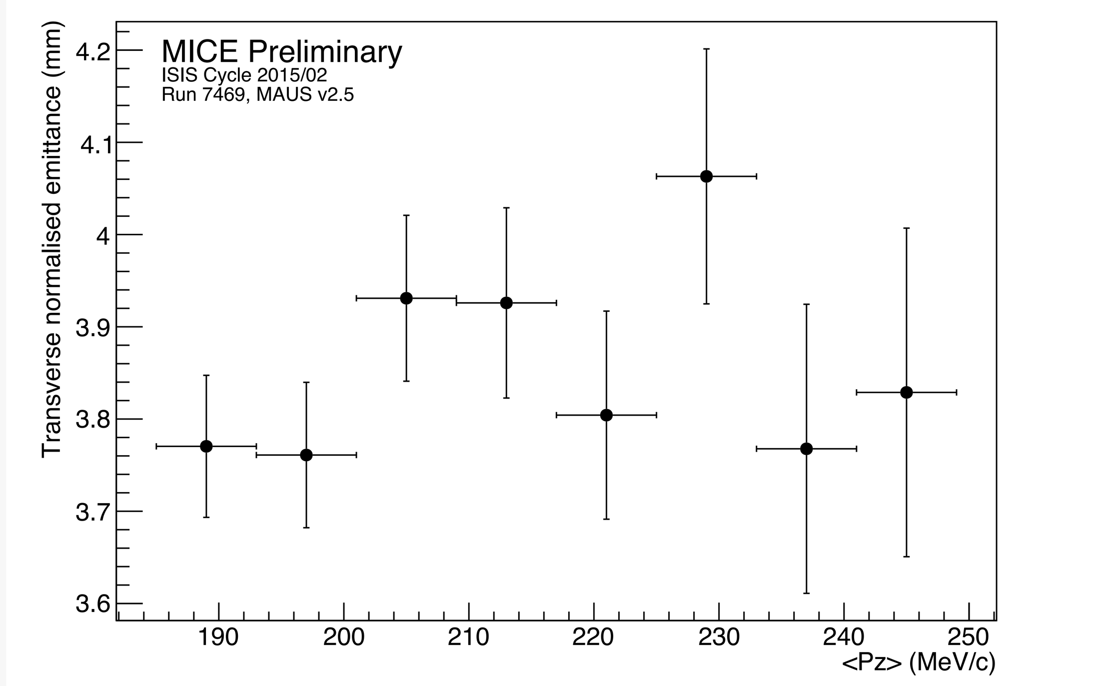
$$\Sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xp_x} & \sigma_{xy} & \sigma_{xp_y} \\ \sigma_{p_x x} & \sigma_{p_x p_x} & \sigma_{p_x y} & \sigma_{p_x p_y} \\ \sigma_{yx} & \sigma_{yp_x} & \sigma_{yy} & \sigma_{yp_y} \\ \sigma_{p_y x} & \sigma_{p_y p_x} & \sigma_{p_y y} & \sigma_{p_y p_y} \end{pmatrix}. \quad (3)$$

4D transverse normalised emittance:

$$\epsilon_n = \frac{1}{m_\mu}\sqrt[4]{\det\Sigma}. \quad (4)$$

The estimator $\hat{\Sigma}$ is a Wishart matrix whose determinant has a statistical uncertainty of

$$\sqrt{1/(2N)}\det\hat{\Sigma}. \quad (5)$$



→ To be published, under internal review

4. Transverse phase-space volume reduction in MICE Step IV

• Challenges

MICE is poised to measure transverse phase-space volume reduction but faces challenges due to the loss of one of its magnets:

- Lower transmission through the cooling channel
- Nonlinearities in the beam downstream of the absorber

• Transmission

A cooling channel with partial transmission discriminatingly loses particles that were scattered (heated) in the absorber, introducing artificial cooling. Two ways to tackle it:

- **Select** a beam upstream that has ∼100 % transmission
- Study a fraction of the beam that is **not affected by the tails**

• Nonlinearities

Nonlinear beam transport results in distortion and filamentation of the beam.

This introduces a bias on phase-space volume measurement using emittance. Alternatives:

- Study a fraction of the beam that has a **linear behaviour**
- Use **non-parametric density estimation** techniques to calculate probability contour volumes in phase-space

• Single-particle amplitude

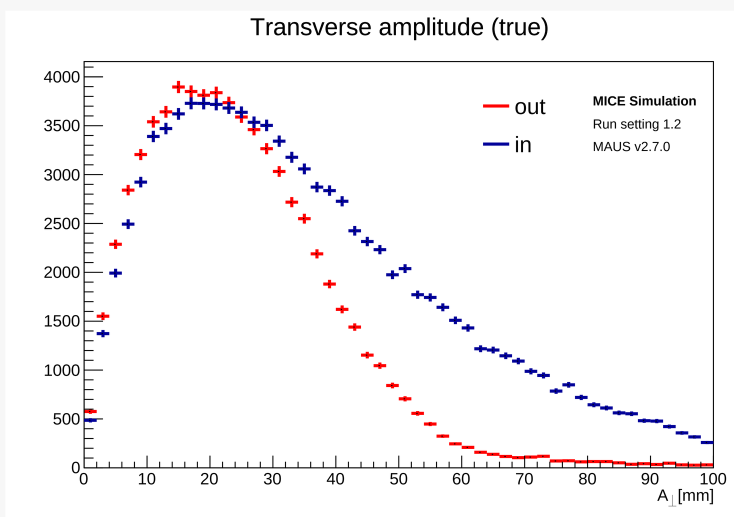
Transverse amplitude:

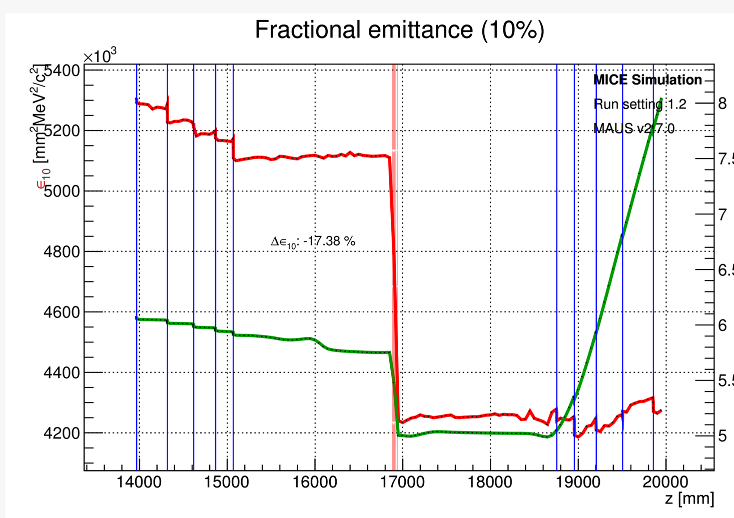
$$A_\perp = \epsilon_n u^T \Sigma^{-1} u \sim \epsilon_n \chi^2_4, \quad (1)$$

with u the centred phase-space vector, i.e. the **degree** at which a particle is **removed** from the core distribution.

Assuming a Gaussian distribution, the 4D RMS ellipse encloses 9 % of the beam particles. The volume of the corresponding contour, V_n, **can be related to normalised emittance** through

$$\epsilon_n = \sqrt{\frac{2V_n}{\pi^2 m_\mu^2}} \quad (2)$$

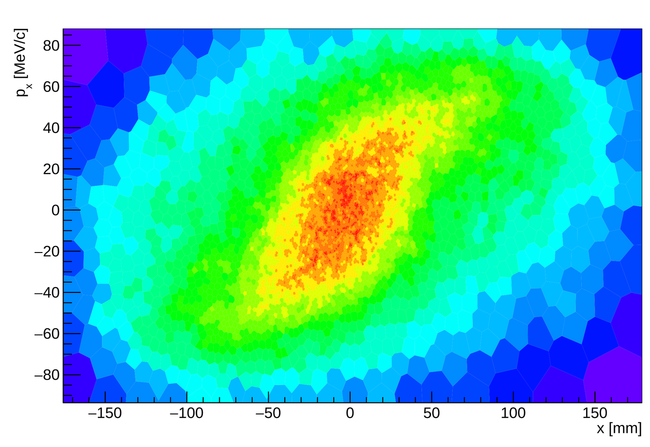




• Voronoi tessellation

Tessellating the space allows to estimate **local phase-space density** for each region

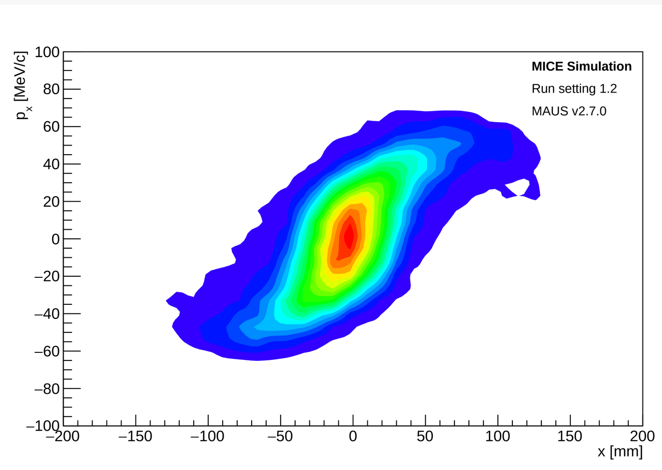
Cooling translates in an **increased amount of small** Voronoi regions



• Alternative density estimators

Many additional non-parametric density estimators exist and are under study to deal with beam nonlinearities

- Optimal binning (here)
- k Nearest Neighbours
- LRD, DFTE, PBATDE, . . .



5. Conclusions

- The **emittance** of a muon beam was measured **particle-by-particle** in MICE for the first time with its trackers
- **Cooling data** has been taken for the LiH absorber and is being analysed right now
- MICE is poised to observe **transverse phase-space volume reduction** in its current Step IV configuration

http://mice.iit.edu