Measurement of phase space density evolution in the Muon Ionization Cooling Experiment

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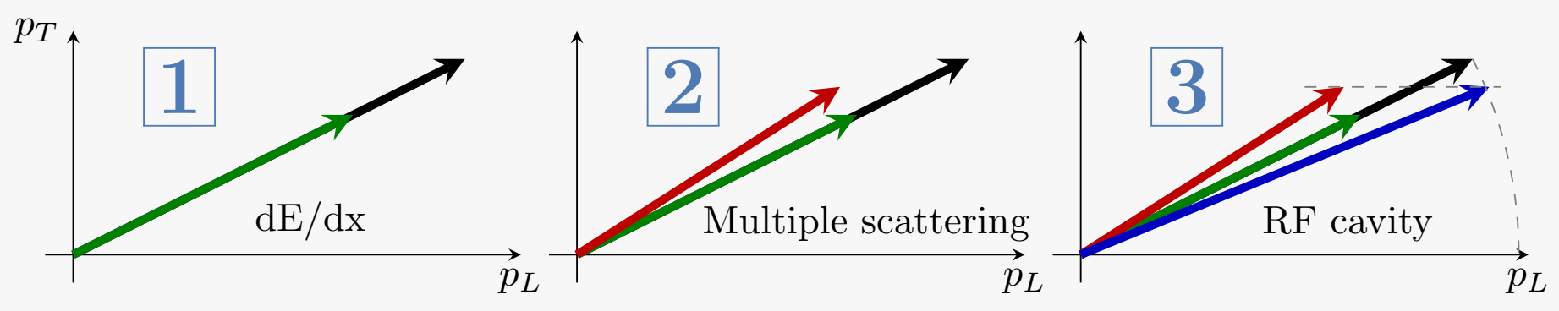
Muon Ionization Cooling Experiment (MICE)

http://mice.iit.edu

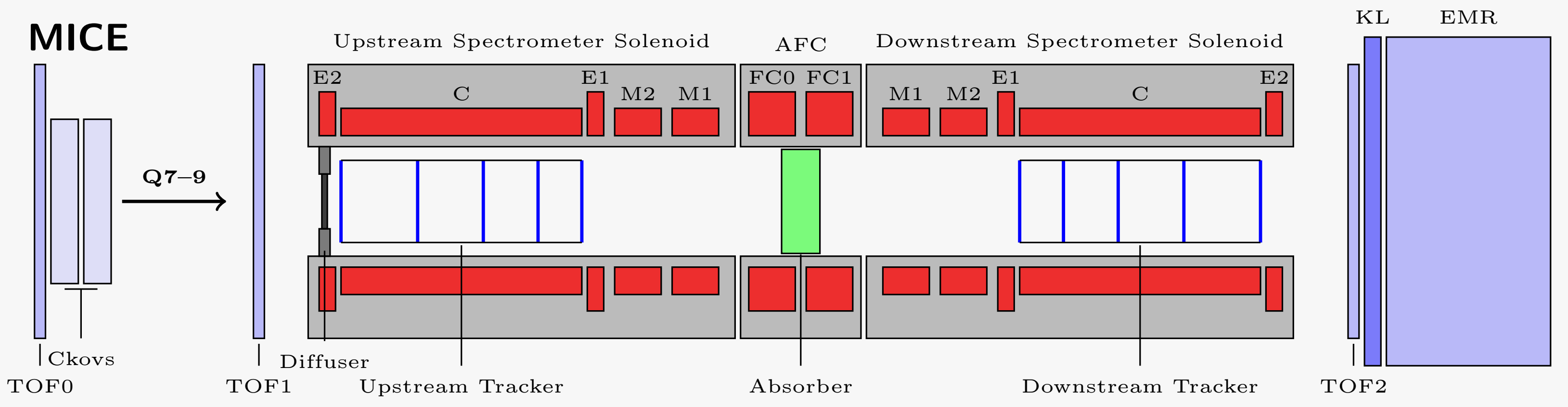
Ionization cooling

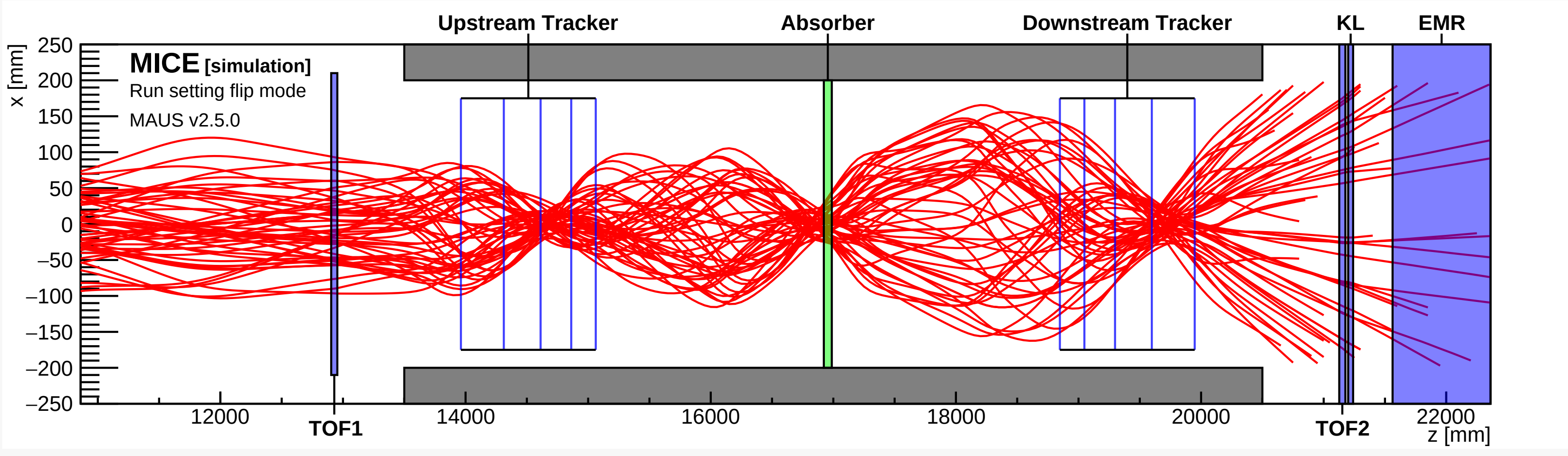
Ionization cooling is the only practical solution to prepare high brightness muon beams necessary for a Neutrino Factory or Muon Collider.



1. Ionization energy loss (reduces both p_L and p_T) concurrent with
2. Heating from multiple scattering.
3. p_L restored by RF cavities.

To maximize cooling, one must use a low-Z material positioned where the beam is tightly focused.





Experiment

MICE will measure the phase space density evolution of muon beams under a variety of configurations:

- LiH or LH_2 absorber
- 140–240 MeV/c momentum
- 3–10 mm input emittance

Single particle experiment:

1. Muons tracked one by one (200/s)
2. Accumulated in an ensemble

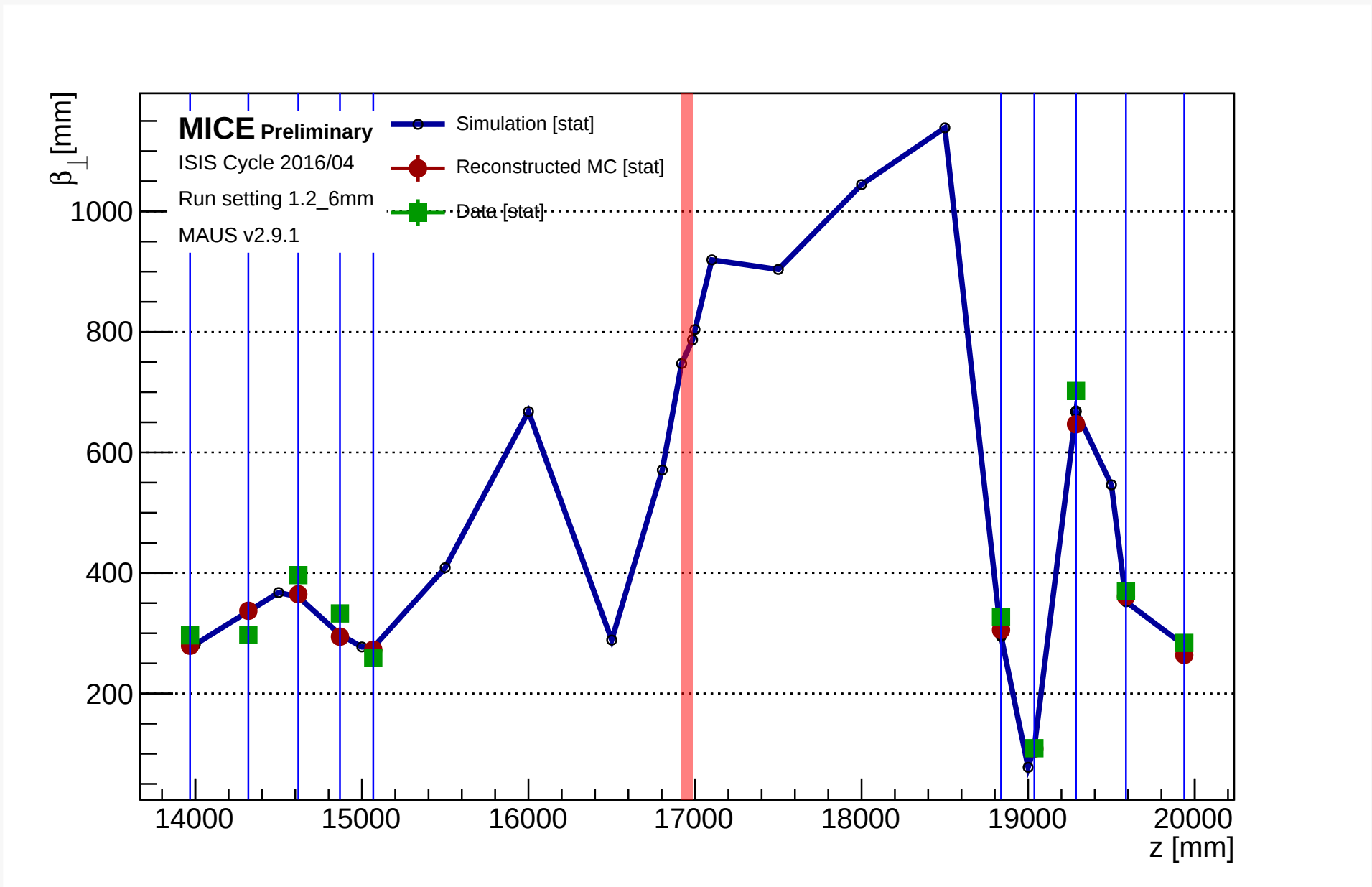
Tracking by scintillating fibre trackers embedded in 3 T solenoid field.

Robust particle identification provided by time-of-flight detectors, Cherenkov threshold counters and calorimeters.

Muon beam under consideration

Analysis performed on a simulation that faithfully reproduces a magnetic channel used during the Dec. 2016 data-taking cycle, with M1 and M2 off in the downstream spectrometer.

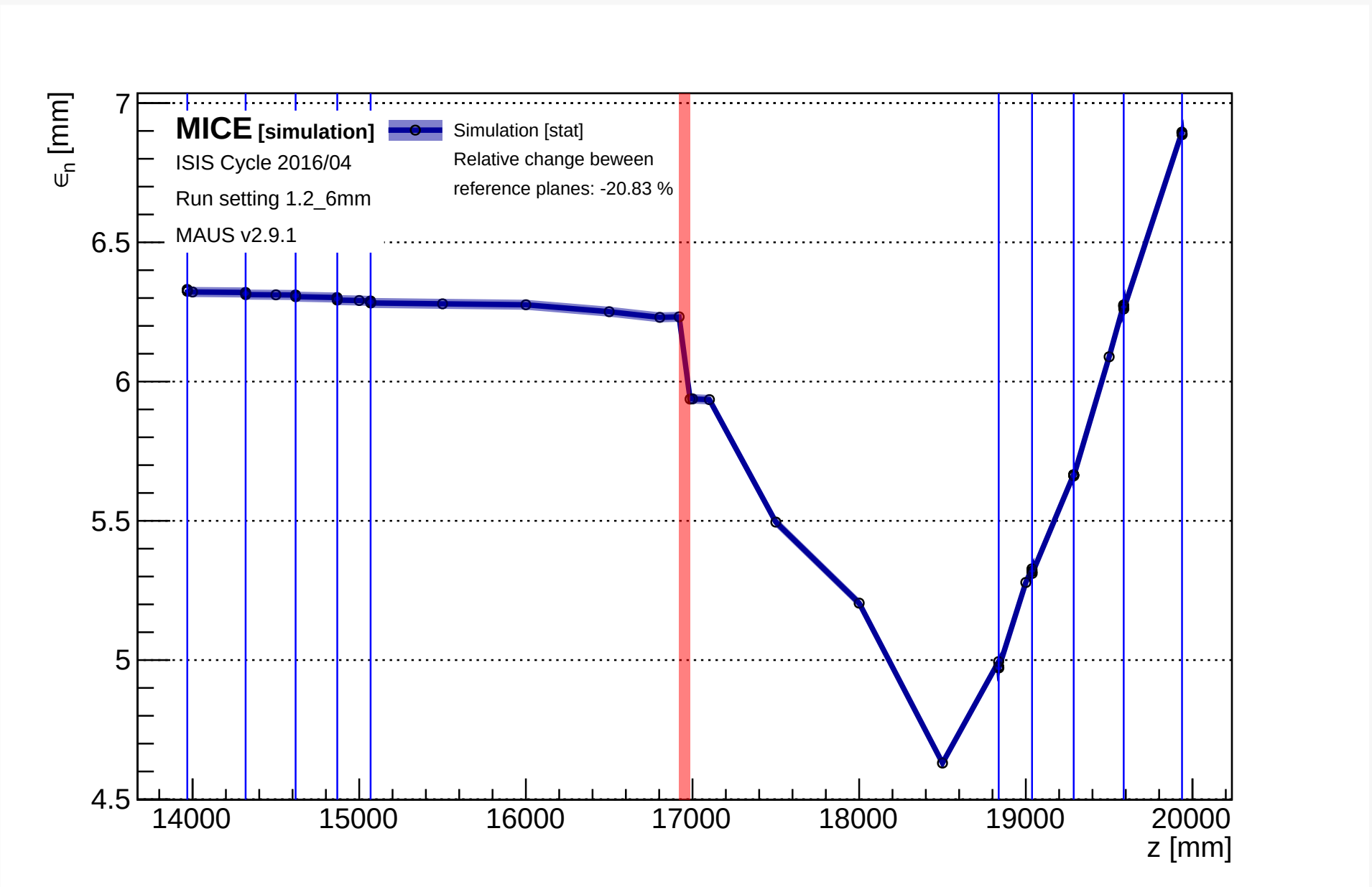
Run characteristics: $\sim$ 6 mm input emittance, 140 MeV/c central momentum, LiH absorber.



Transverse RMS emittance, defined as

$$\epsilon_\perp = \frac{1}{m_\mu}|\Sigma_\perp|^{\frac{1}{4}},$$

with $\Sigma_\perp$ the covariance matrix, is a poor proxy in low-transmission, nonlinear beams.

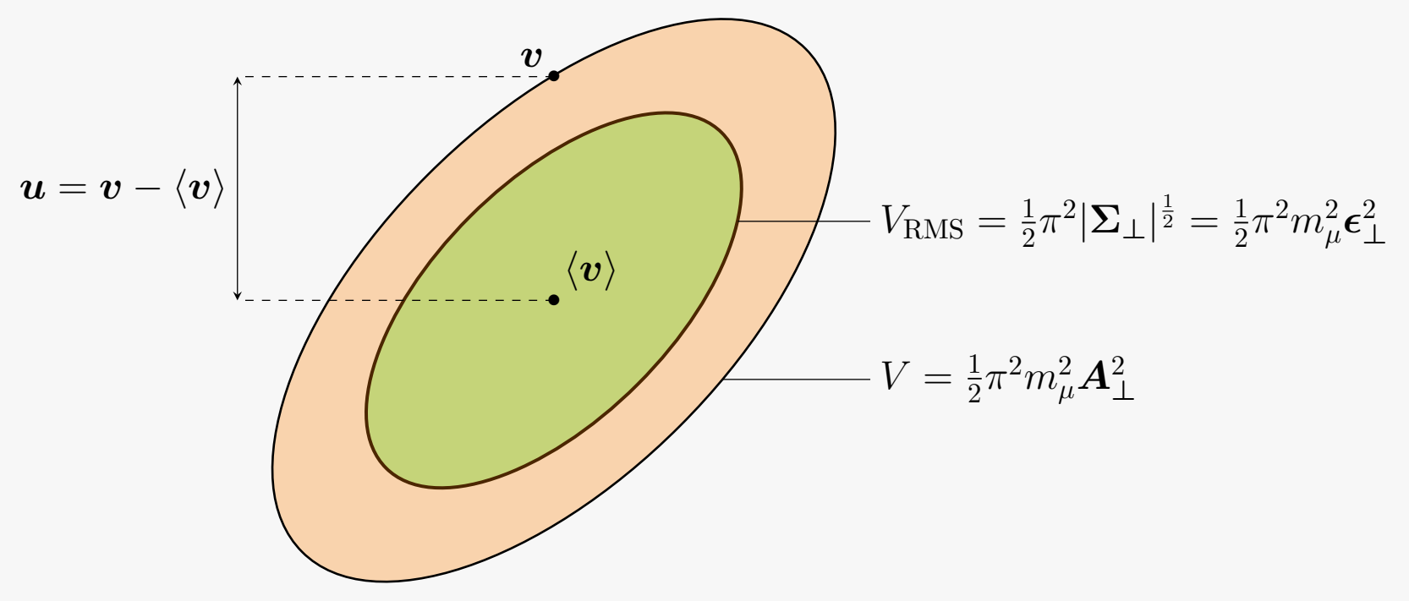


Phase space density evolution

Single-particle amplitude defined as:

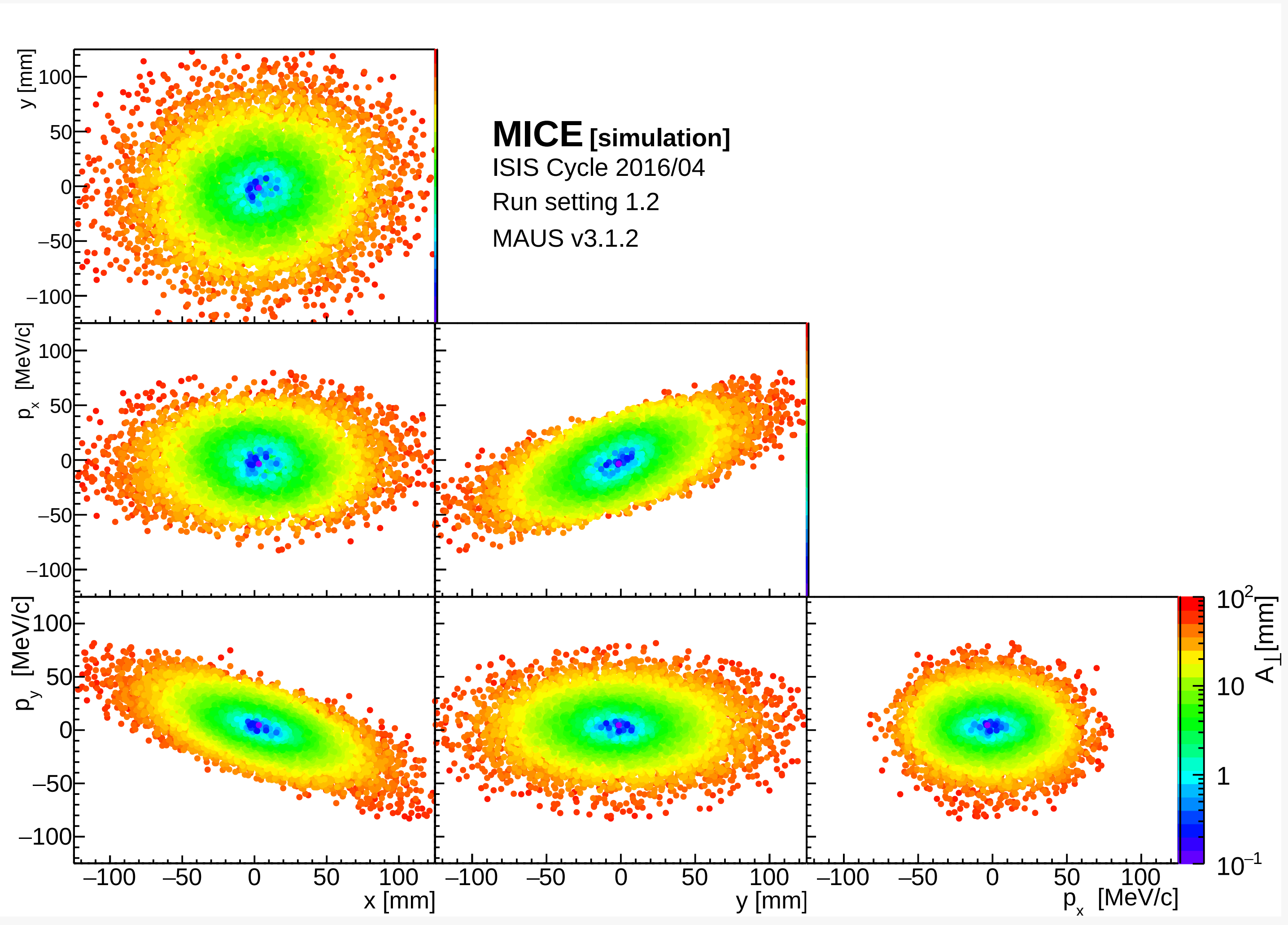
$$A_\perp = \epsilon_\perp \mathbf{u}^T \Sigma_\perp^{-1} \mathbf{u},$$

with $\mathbf{v} = (x, p_x, y, p_y)$ the transverse phase space vector and $\mathbf{u} = \mathbf{v} - \langle \mathbf{v} \rangle$.



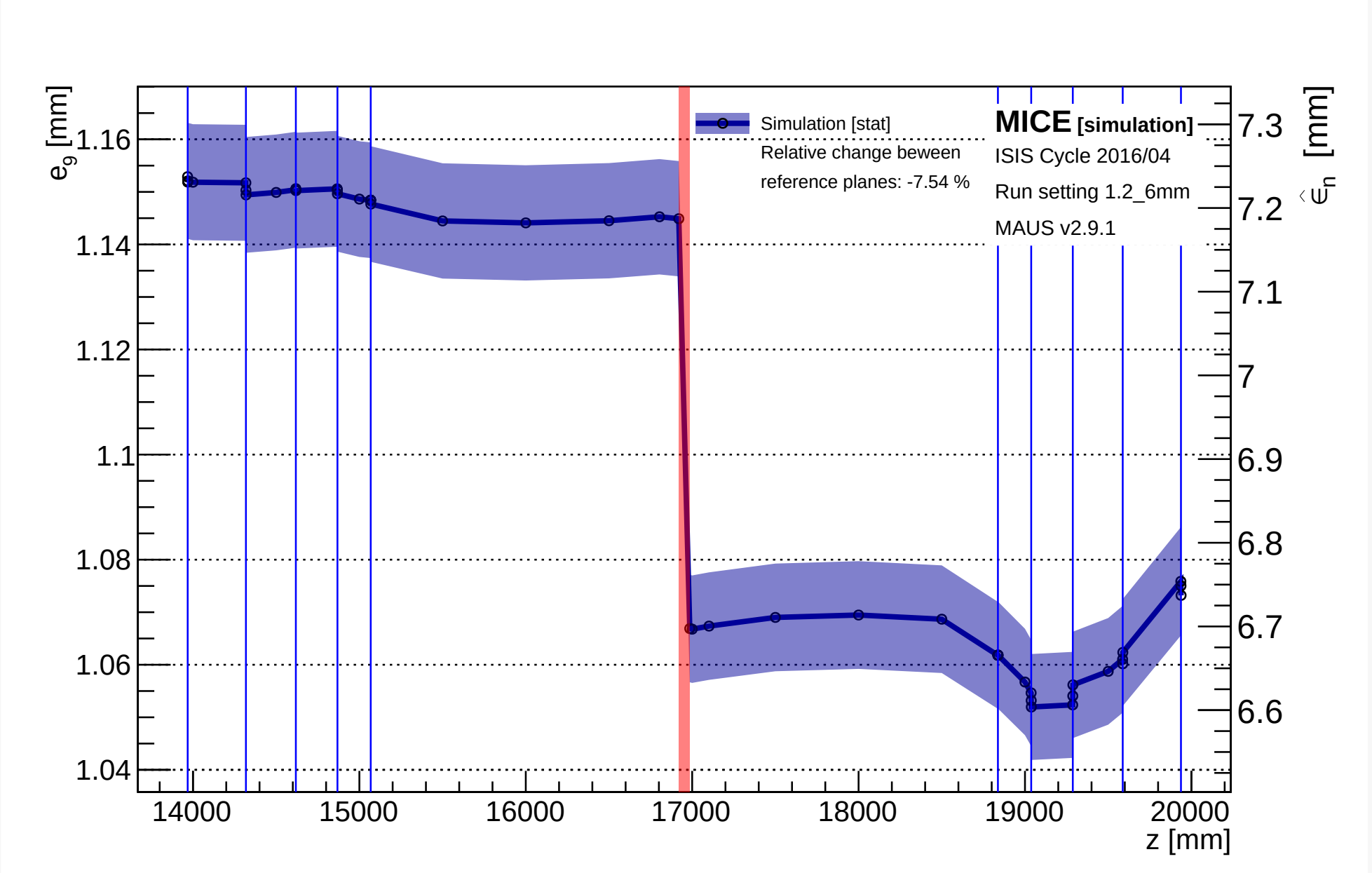
→ High amplitude particles iteratively removed from sample to select beam core

→ Increase in core density is an unequivocal cooling signal



The α-subemittance, e_α, defined as the emittance of the core fraction α of the beam, verifies

$$\frac{e_\alpha^{out} - e_\alpha^{in}}{e_\alpha^{in}} = \frac{\epsilon_\perp^{out} - \epsilon_\perp^{in}}{\epsilon_\perp^{in}}.$$



Nonparametric density estimation

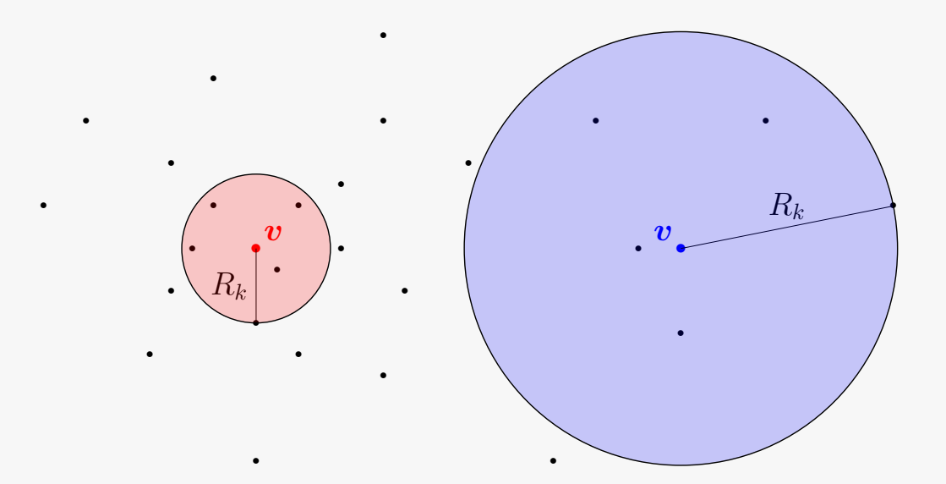
Nonparametric density estimation removes the need for any prior assumption about the underlying probability distributions.

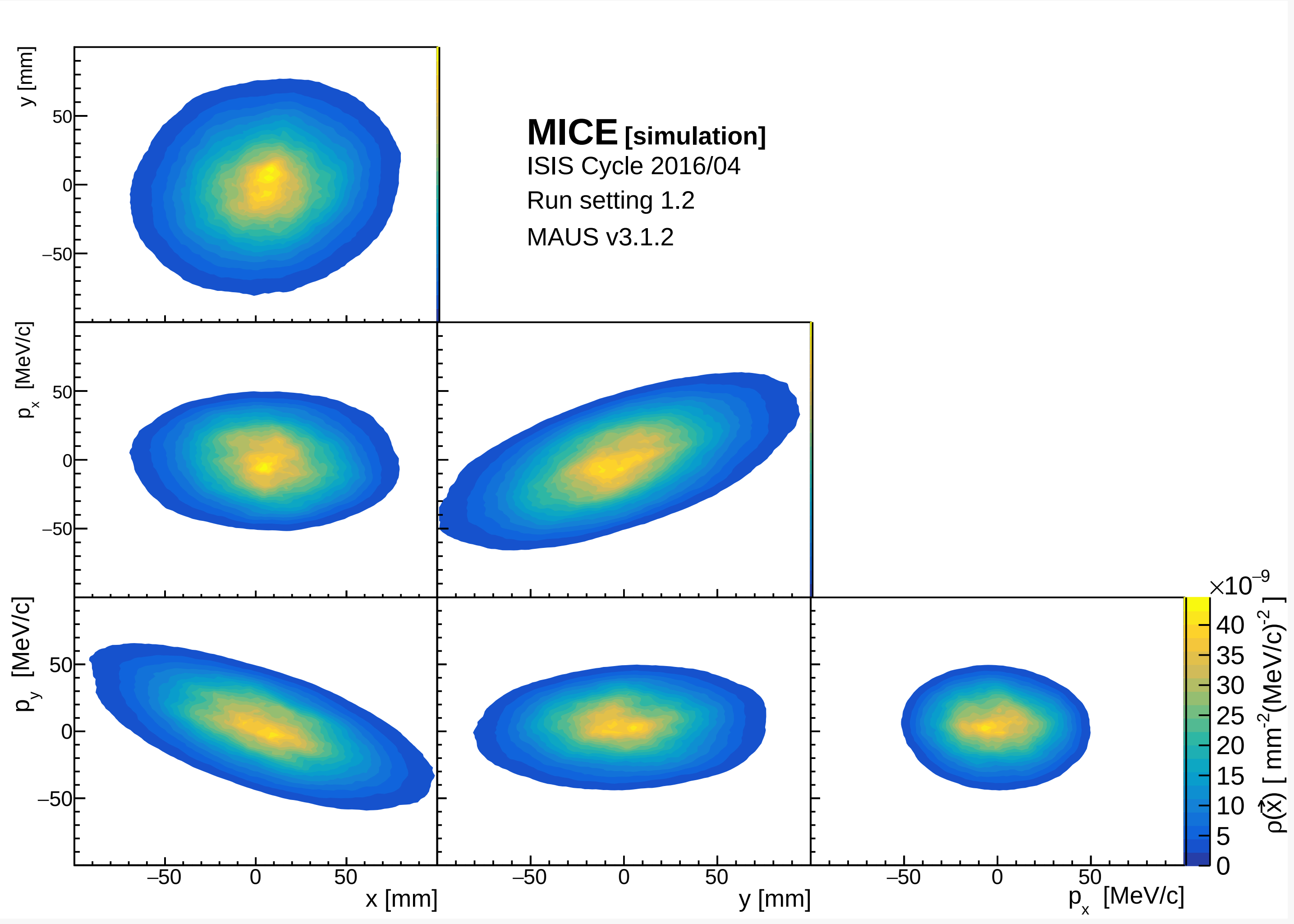
The k Nearest Neighbour method is the most efficient and robust technique in 4D:

1. Find the k points closest to $\mathbf{v}$
2. Evaluate distance, R_k, to farthest point
3. Local density reads

$$\rho(\mathbf{v}) = \frac{k}{nV_k} = \frac{2k}{n\pi^2 R_k^4},$$

with V_k the volume of the ball of radius R_k.





The α-emittance, ϵ_α, is defined as the volume of the α-contour of the beam probability density function and verifies

$$\frac{\Delta\epsilon_\alpha}{\epsilon_\alpha^{in}} = \frac{\Delta\epsilon_\perp^2}{(\epsilon_\perp^{in})^2} \simeq 2\frac{\Delta\epsilon_\perp}{\epsilon_\perp^{in}}.$$