Emittance Evolution in MICE: the Muon Ionization Cooling Experiment

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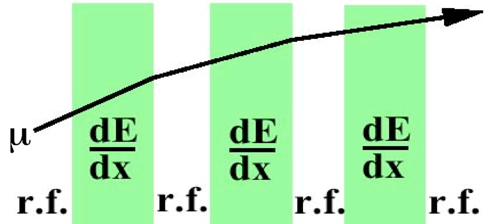
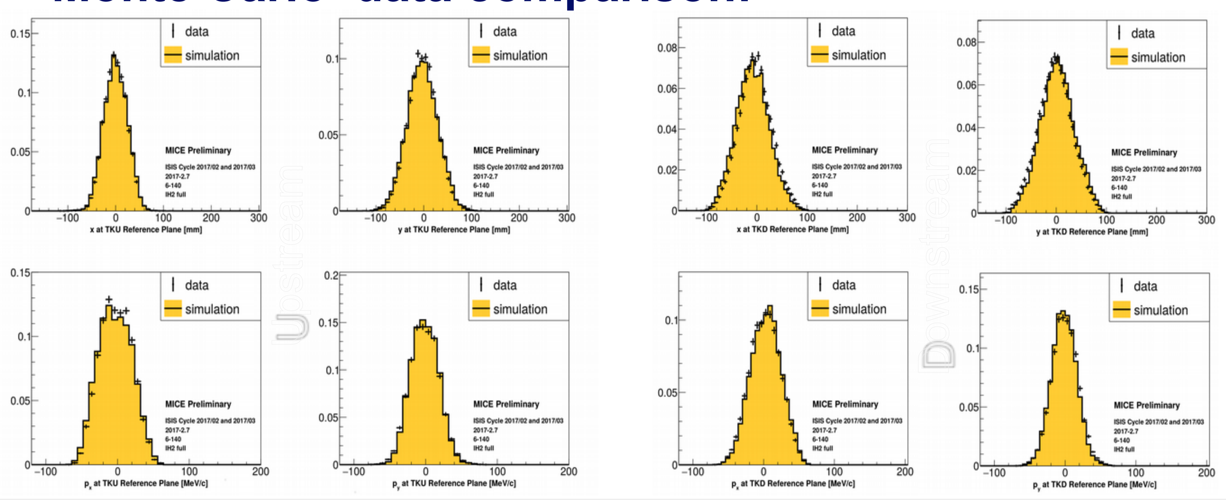
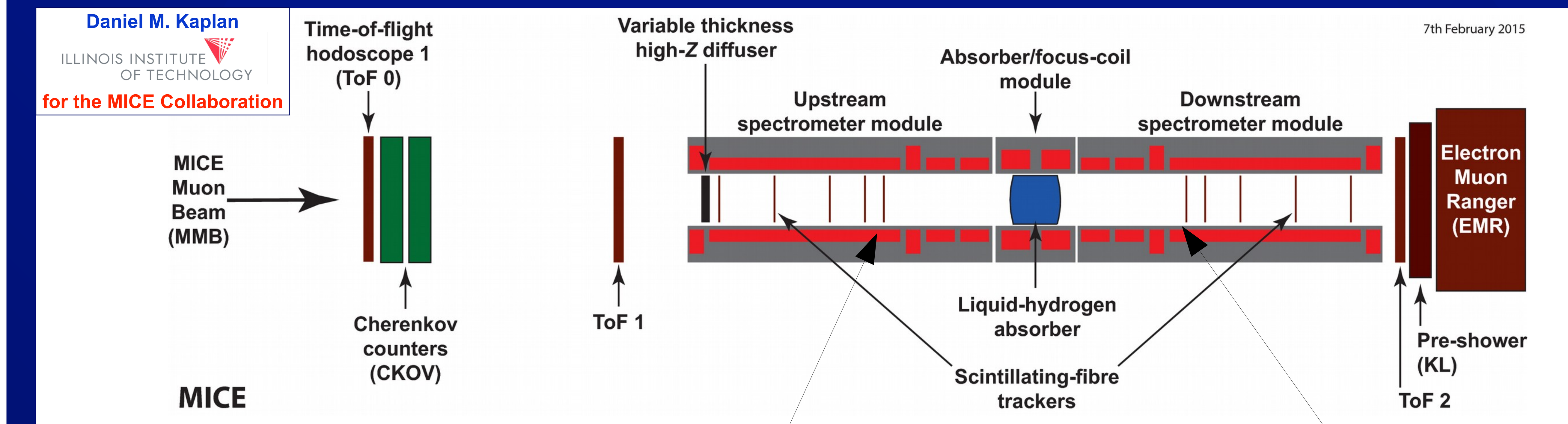
Ionization Cooling



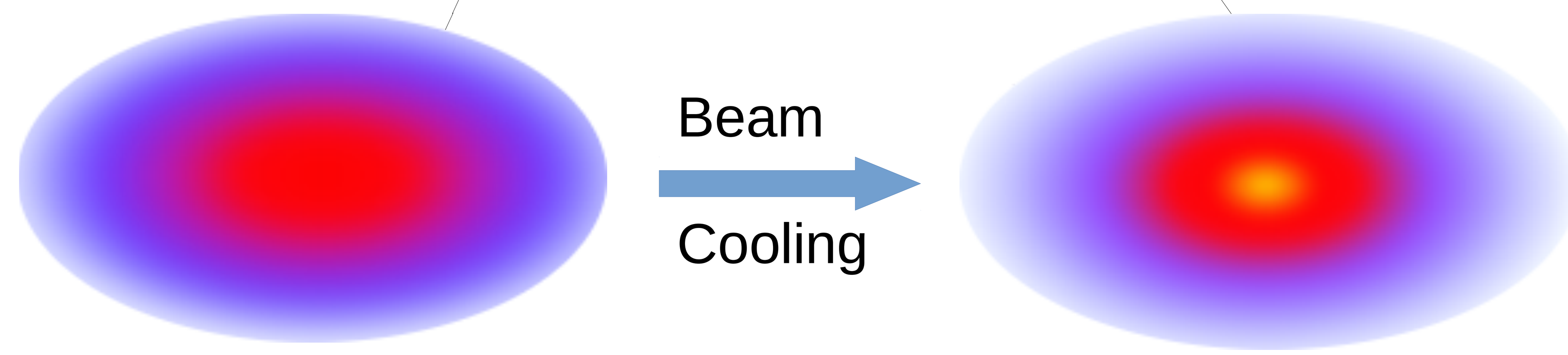
G.I. Budker & A.N. Skrinsky, Sov. Phys. Usp. **21**, 277 (1978)
A.N. Skrinsky & V.V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981)
D. Neuffer, Part. Acc. **14**, 75 (1983)

- Energy loss in liquid hydrogen or LiH
  - muons lose both transverse and longitudinal momentum
- Acceleration in radio-frequency (RF) cavity:
  - restores *only* longitudinal momentum
- Result: transverse cooling
  - competition between dE/dx cooling & MCS heating
- MICE measures individual muons crossing:
  - empty absorber
  - 35 cm LH_2
  - 65 mm LiH disk
- Muons measured before and after absorber in a uniform 3 T magnetic field
- Beam emittance change in absorber measured by comparing upstream and downstream muon phase space volumes
- Monte Carlo–data comparison:



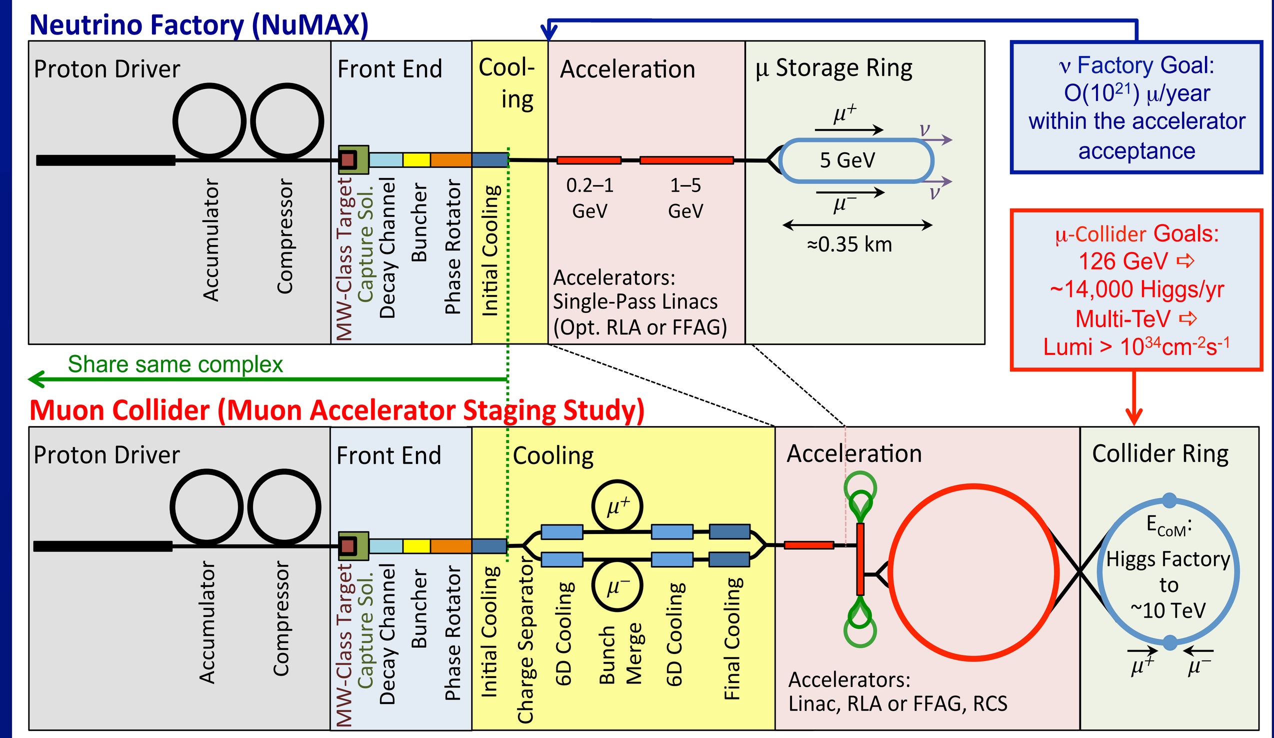


Beam cooling causes migration of particles (in beam phase space) towards beam core



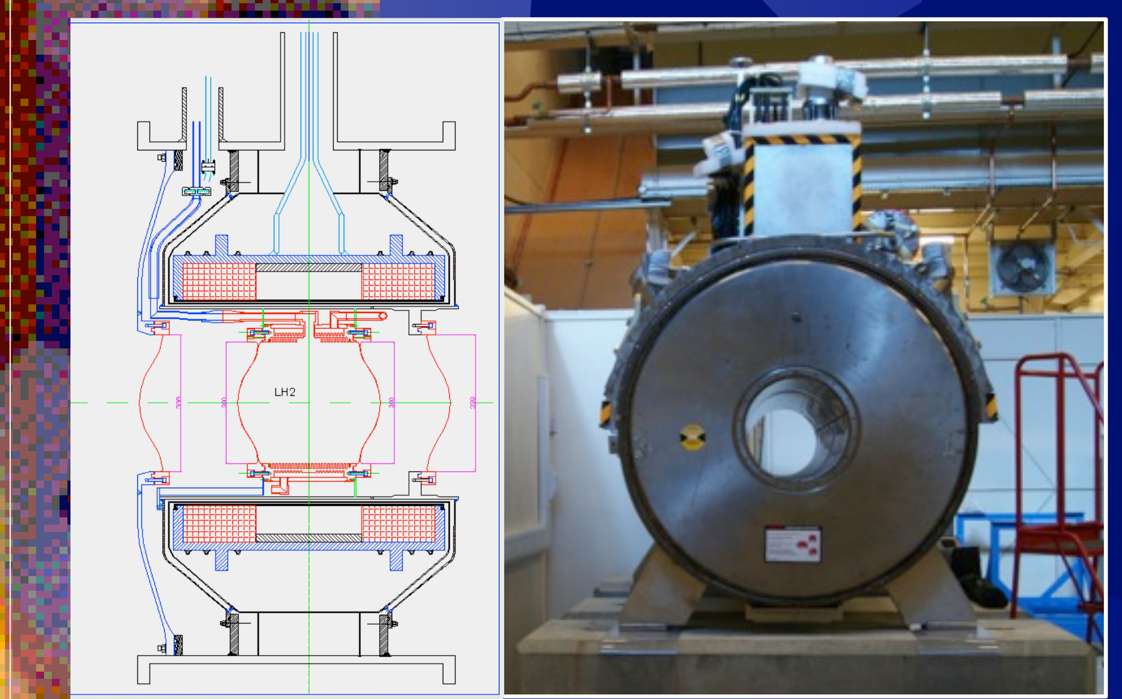
Abstract: The provision of intense stored muon beams would allow the properties of neutrinos to be measured precisely and provide a route to multi-TeV lepton-antilepton collisions. The short muon lifetime makes it impossible to employ traditional cooling techniques while maintaining the muon-beam intensity. Ionization cooling, a process in which the muon beam is passed through a series of low-Z absorbers followed by accelerating RF cavities, is the proposed cooling technique. The international Muon Ionization Cooling Experiment (MICE) collaboration has performed, at Rutherford Appleton Laboratory (UK), an initial demonstration of the ionization cooling principle, by measuring the effect of low-Z absorber materials on a muon beam. Data taken in 2016 and 2017 are currently being analyzed. Initial results are presented.

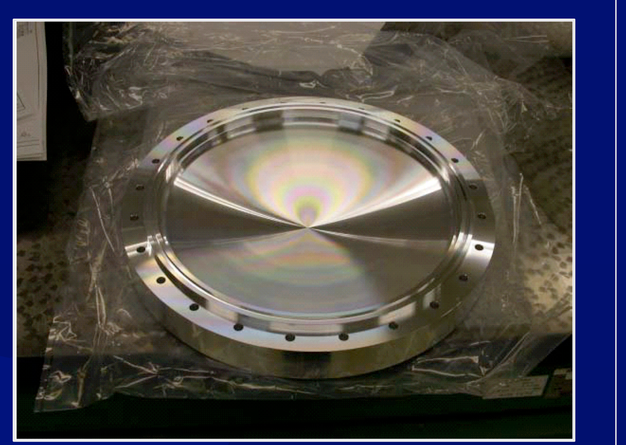
Future Stored-Muon Accelerator Facilities

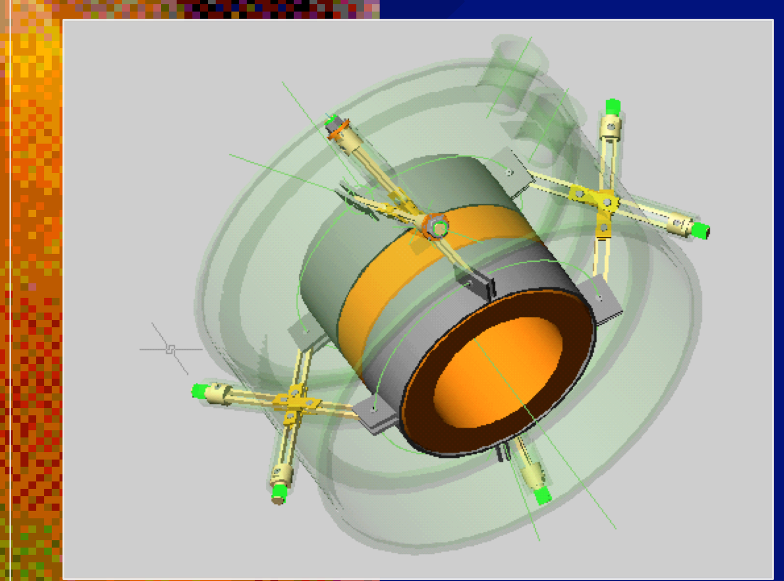


- Neutrino Factory
  - World's most sensitive neutrino-oscillation experiment
    - ultra-clean ν_μ appearance in ν_e beam
  - Physics reach increases with neutrino flux
  - High flux requires cooled muon beam
    - emittance reduction by factor ~10
- Muon Collider:
  - CM energy up to ~10 TeV
  - Luminosity > 10^{34} cm^{-2}s^{-1}
  - High luminosity requires cold muon beams
    - emittance reduction by factor ~10^6

Liquid-hydrogen absorber & focus-coil assembly

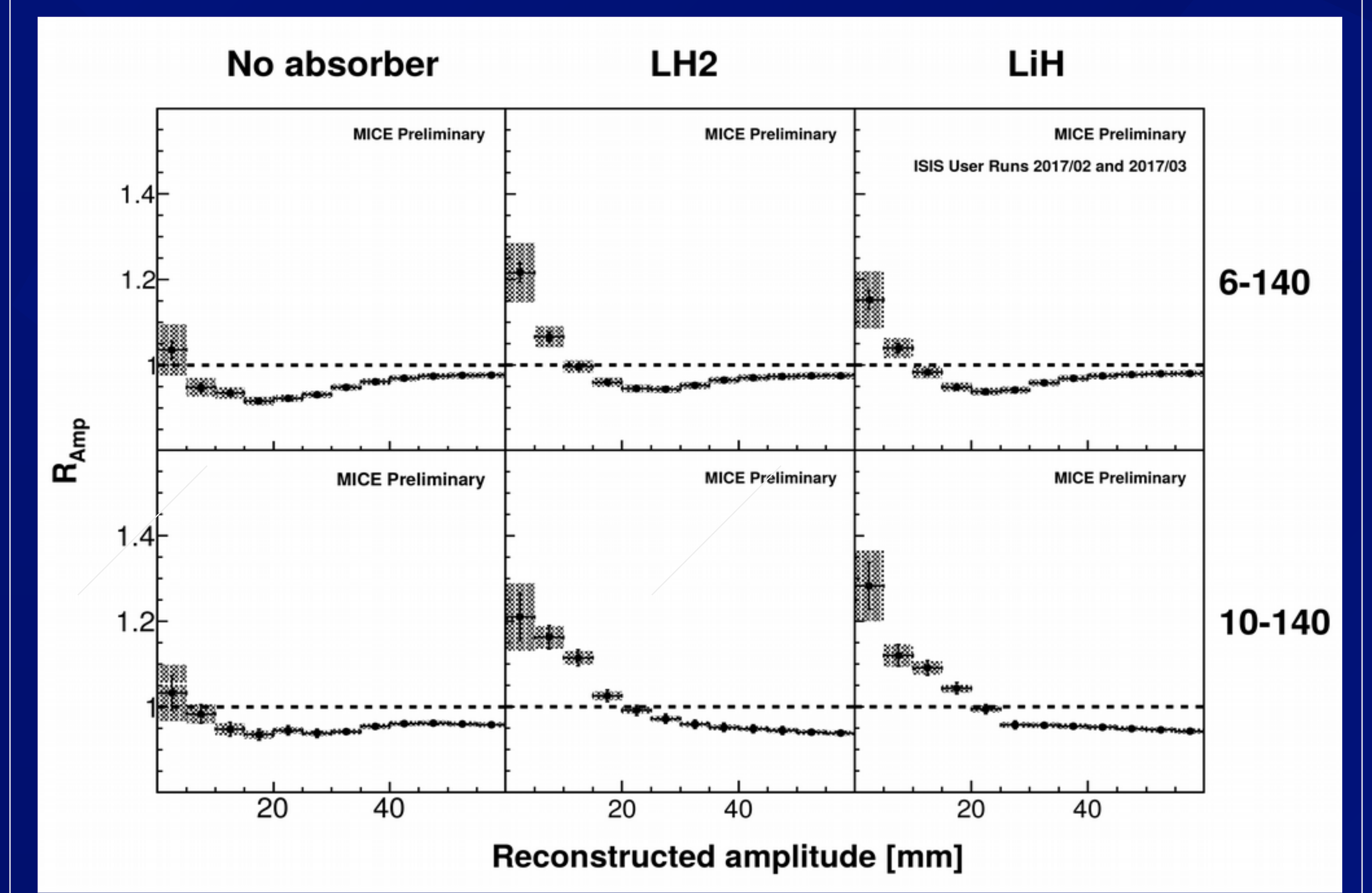






- Liquid-hydrogen absorber:
  (Japan, USA)
  - Large ionization energy-loss rate (cooling)
  - Low multiple scattering (heating)
  - First prototype built and bench-tested
- Focus-coil assembly:
  (UK)
  - Superconducting magnets: Two coils; up to 5 Tesla

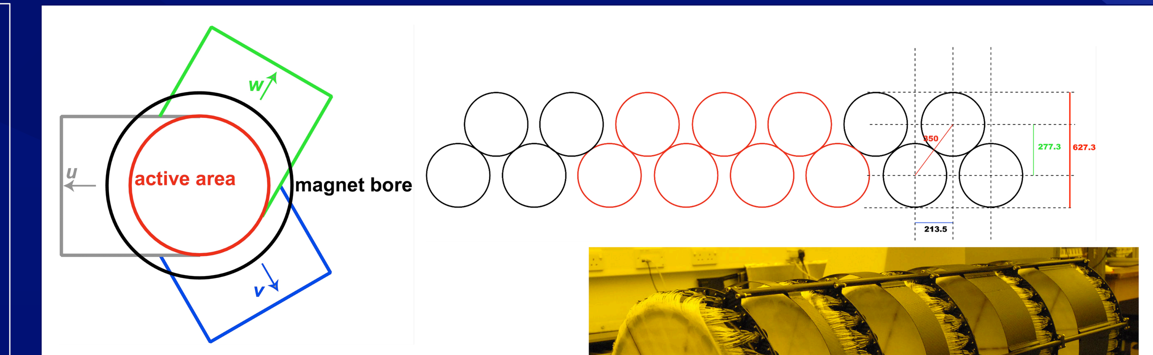
Initial Cooling Results

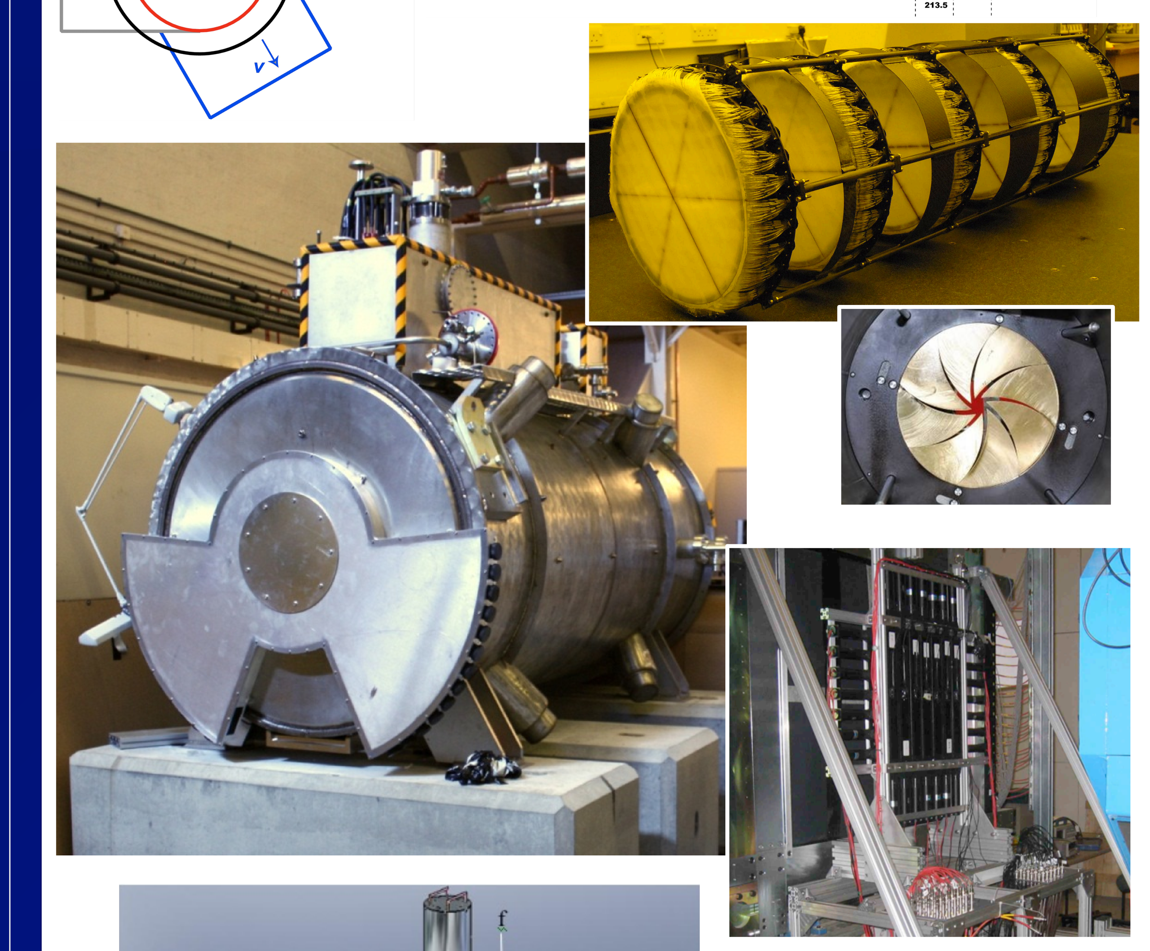


The ratio of the downstream to upstream cumulative amplitudes for two input beam configurations with nominal momenta of 140 MeV/c and nominal emittance of 6 (top) and 10 (bottom) mm. Cooling is observed where R_{Amp} > 1, showing migration of muons from high to low amplitude.

Beam size expressed as 4-D transverse, normalized emittance
$\varepsilon_{4D,N} = \sqrt[4]{|\det\Sigma_\perp|} / m_\mu$
$\Sigma_\perp$= covariance matrix of muon ensemble in (x,y,p_x,p_y) space
Amplitude $A_\perp = \varepsilon_N\, \mathbf{\Delta_\mu}^T\, \Sigma_\perp\, \mathbf{\Delta_\mu}$
$\mathbf{\Delta_\mu} = (\mathbf{v} - \langle\mathbf{v}\rangle)$ distance of muon from beam center

Instrumentation





- Particle identification:
  (EU, USA)
  - Upstream: π/μ separation
    - Cherenkov, time-of-flight (TOF)
  - Downstream: e/μ separation
    - TOF, calorimeter, e/μ Ranger
- Muon momentum measurement:
  (UK, USA, Japan)
  - Five-station planar scintillating-fiber trackers
    - in 3 T superconducting solenoids
  - 350 μm fibers, three stereo views
  - Cryogenic solid-state photodetectors (VLPCs)
- Emittance resolution: 0.1%