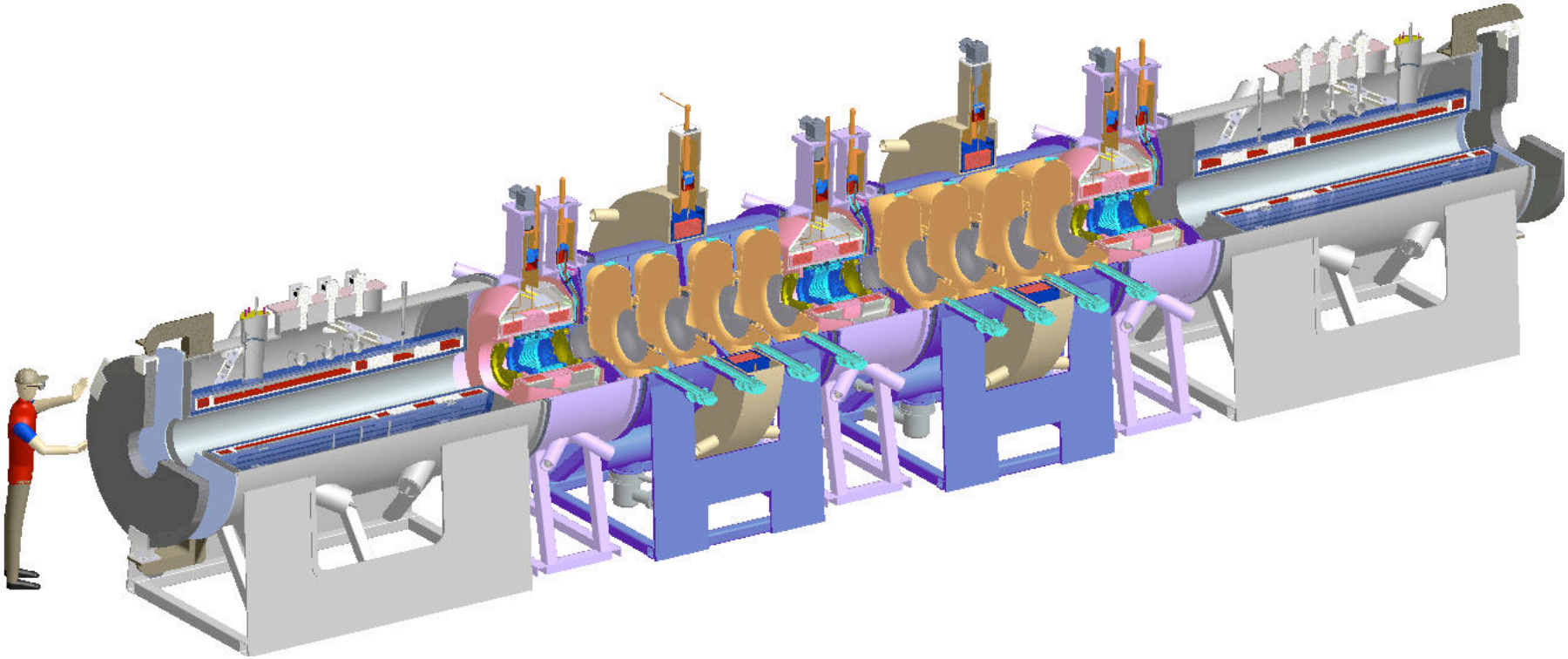
The Muon Ionization Cooling Experiment



- Introduction and Motivation
- Emittance Cooling
- Emittance Measurement
- Status and Schedule
- Summary

Terry Hart for the MICE collaboration,
Illinois Institute of Technology,
April 22, 2006,
2006 American Physical Society April Meeting

Introduction - Description

- Muon Ionization Cooling Experiment (MICE): international accelerator R&D project designed to demonstrate muon cooling.

- MICE is being built at Rutherford Appleton Laboratory (RAL) using muon beam generated from ISIS.

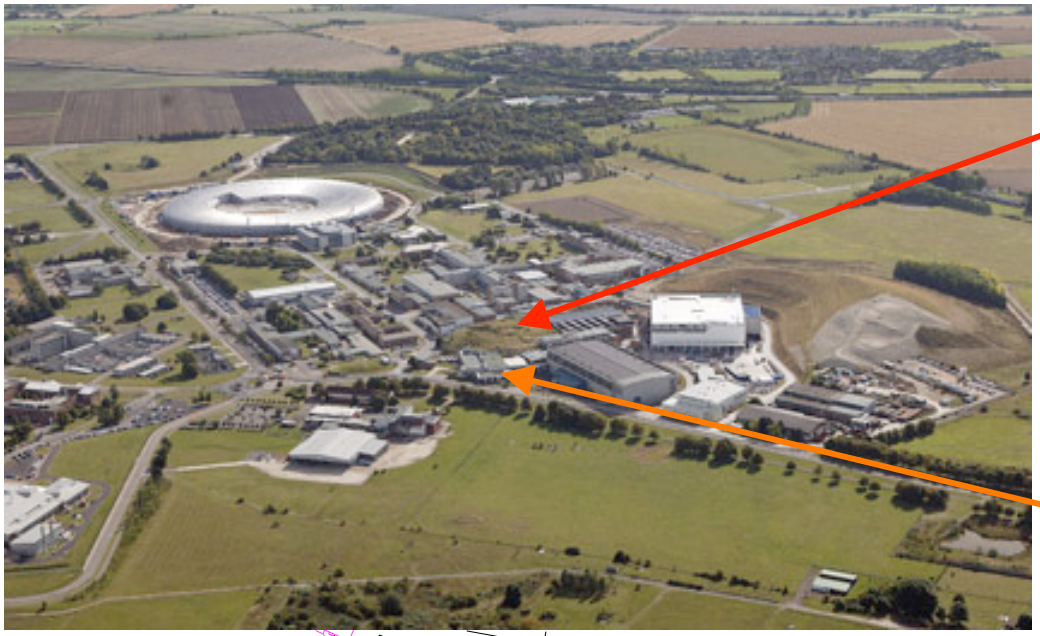
- One muon cooling lattice cell with detectors measuring muon beam emittance before and after cooling.

Introduction - Motivation

- Muon ionization cooling necessary for future facilities including Neutrino Factory and Muon Collider

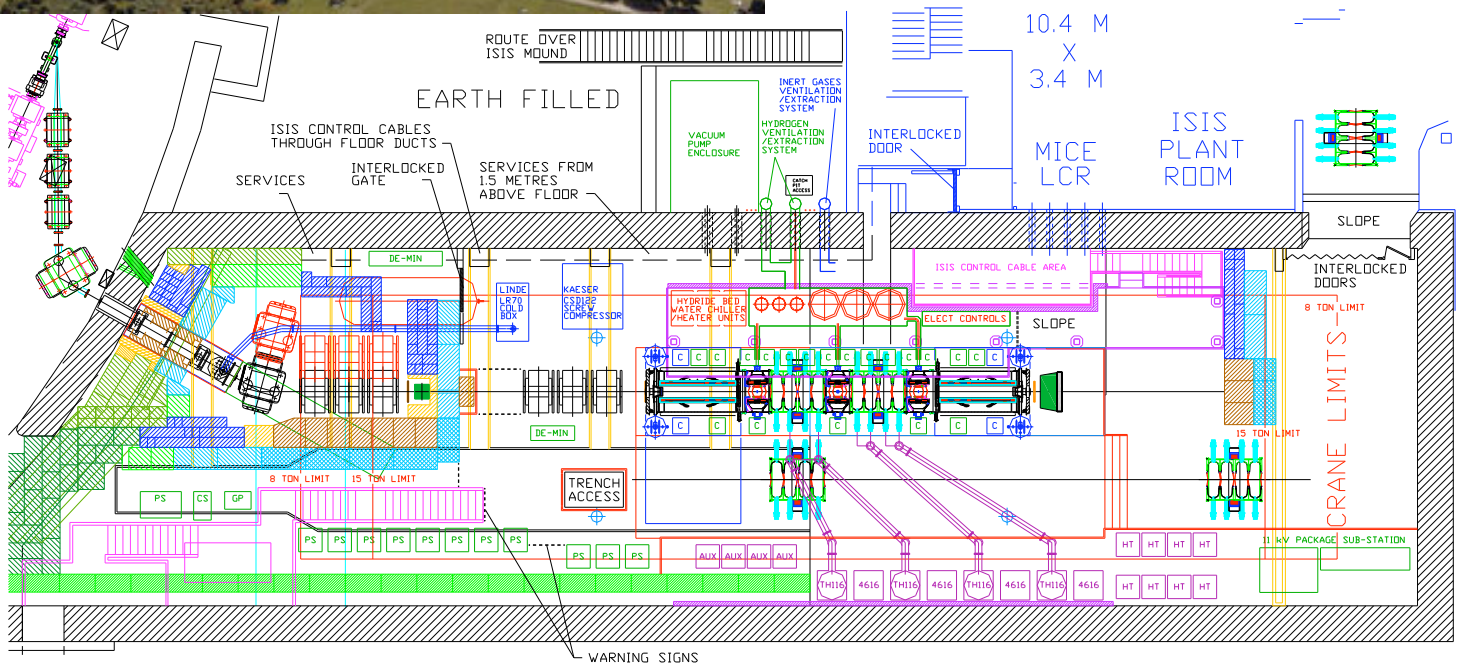
- MICE's primary goals
  - Demonstrate ability to design, engineer, and build section of a cooling channel providing desired performance for neutrino factory
  - Place cooling channel section in muon beam and measure performance including validating simulation predictions

MICE at RAL



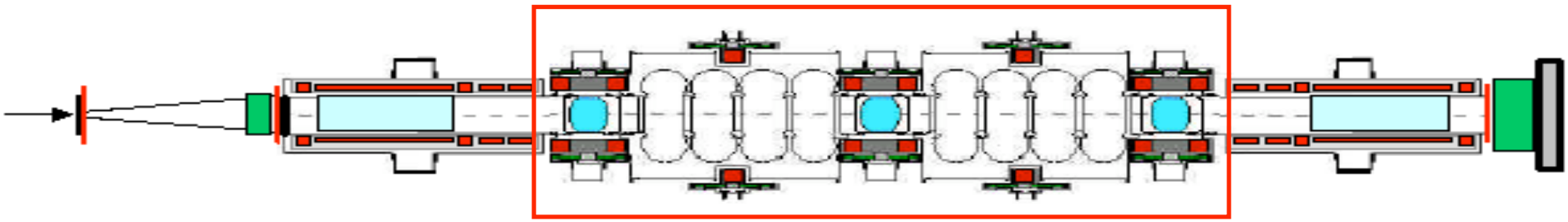
ISIS accelerator

MICE experimental hall



Muon Beam Emittance

Emittance: Measure of spreads of particle positions and momenta with respect to ideal muon path.



Cooling channel

Measure 6 kinematic parameters for <u>each particle</u> before and after cooling channel.

$$(x, y, t, x', y', t') \qquad x' = \frac{dx}{dz} = \frac{p_x}{p_z}, \quad y' = \frac{dy}{dz} = \frac{p_y}{p_z}, \quad t' = \frac{dt}{dz} = \frac{E}{p_z}$$

Form covariance matrices

$$M = \begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xt} & \sigma_{xx'} & \sigma_{xy'} & \sigma_{xt'} \\ \cdots & \sigma_y^2 & \cdots & \cdots & \cdots & \sigma_{yt'} \\ \cdots & \cdots & \sigma_t^2 & \cdots & \cdots & \sigma_{tt'} \\ \cdots & \cdots & \cdots & \sigma_{x'}^2 & \cdots & \sigma_{x't'} \\ \cdots & \cdots & \cdots & \cdots & \sigma_{y'}^2 & \sigma_{y't'} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \sigma_{t'}^2 \end{pmatrix}$$

Calculate emittances

$$\epsilon^{6D} = \sqrt{\det(M_{xytx'y't'})}$$

$$\epsilon^{4D} = \sqrt{\det(M_{xyx'y'})}$$

$$\epsilon^{2D} = \sqrt{\det(M_{xx'})}$$

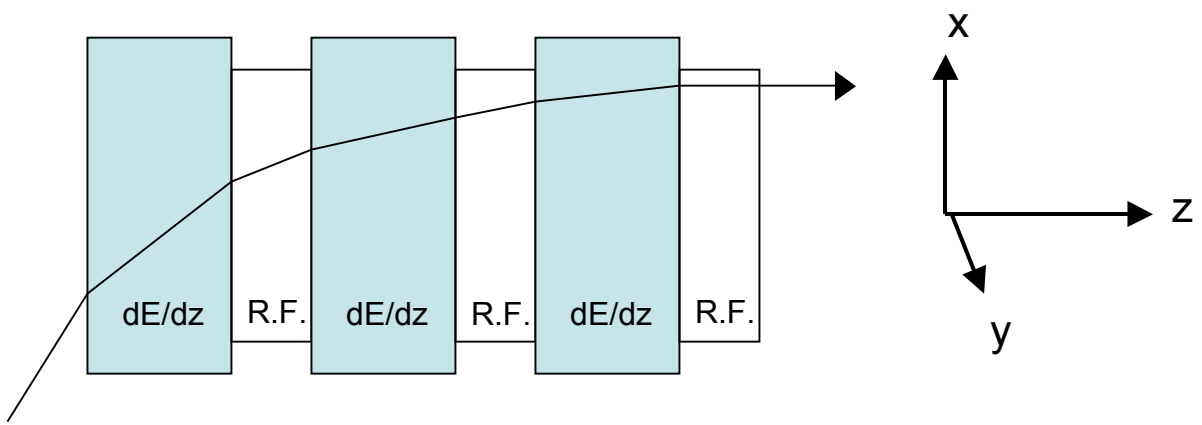
Compare ϵ^{in} with ϵ^{out}

Cooling Description

- Muons need to be cooled quickly due to 2.2 μs lifetime.

- Cooling done through alternate
  - Ionization reducing p_x, p_y, p_z.
  - RF cavities restoring p_z.

- Repetition of energy loss and longitudinal (along z) energy gain reduces $p_{x,y}$/ p_z and thus transverse emittance.



Cooling Description

- Rate of change of normalized emittance along beam direction:

$$\frac{d\varepsilon_N}{dz} = -\frac{1}{\beta^2}\left|\frac{dE_\mu}{dz}\right|\frac{\varepsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

Cooling term Heating term

$\varepsilon_N = (\beta\gamma)\,\varepsilon_x$ for 2D emittance

- Setting $d\varepsilon_N/dz$ equal to zero ⇒

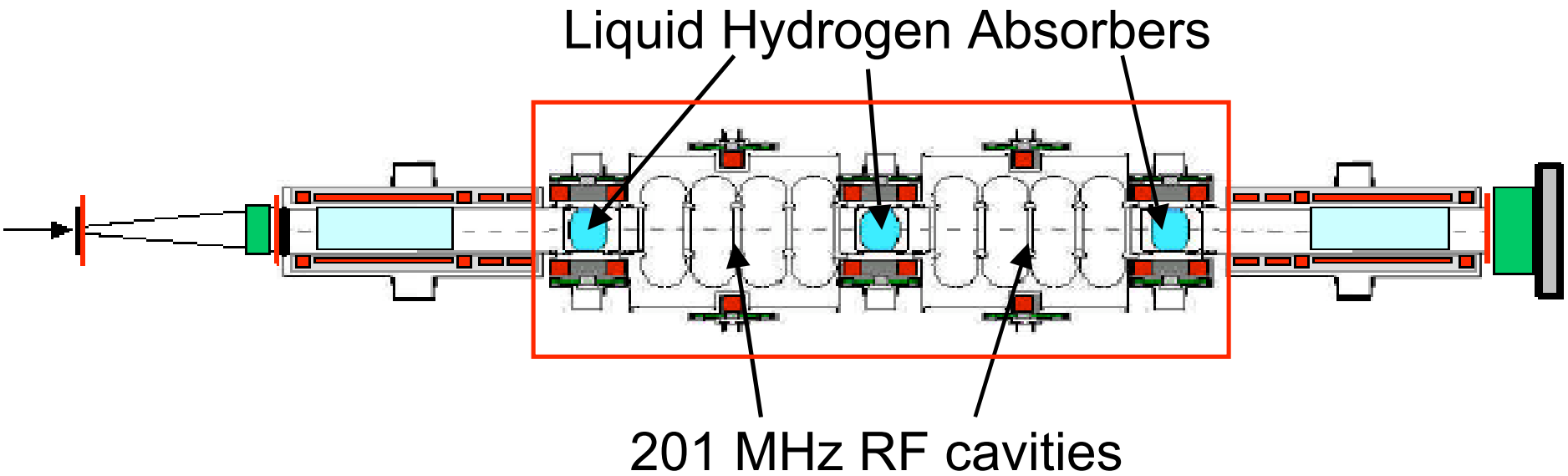
$$\varepsilon_{N,equil.} = \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta m_\mu X_0\left|\frac{dE_\mu}{dz}\right|}$$

- z is coordinate along muon beamline.
- ε_N is normalized emittance.
- X_0 is radiation length of material muon is passing through.
- E_μ and m_μ are muon energy and mass.
- β is v/c.
- $\beta_\perp$ is optical beta function (= $\beta\varepsilon_{xy}^2/\varepsilon$ where ε_{xy}^2 is transverse size of muon beam).

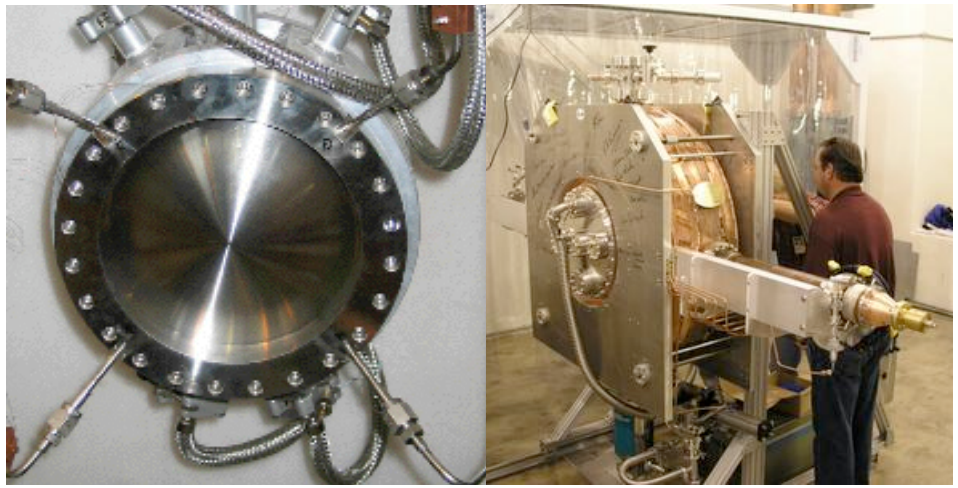
- Small emittance is achieved through low $\beta_\perp$, large X_0, and large dE_μ/dz.

Strong magnetic focusing and H_2 absorber best meet these criteria.

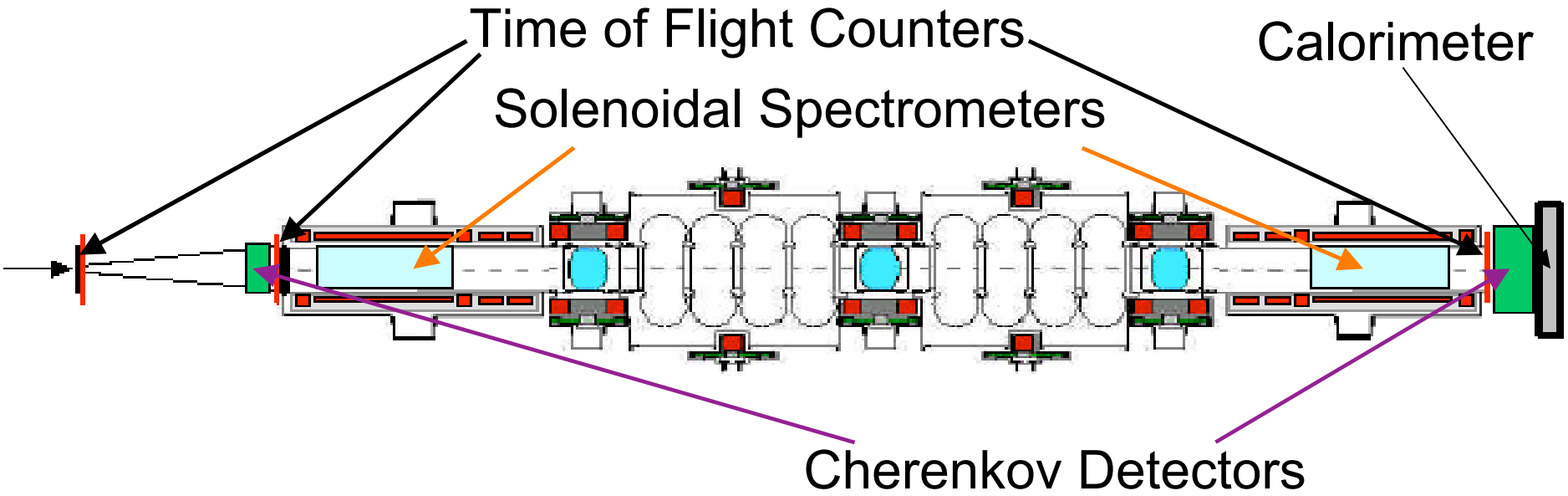
Muon Cooling Cell



- Liquid hydrogen (LH_2) absorbers reduce muon momenta.
  - Large ionization energy loss rate
  - Low scattering
- RF cavities restore lost p_z.
  - 8 MV/m accelerator gradient
  - 4 tesla axial magnetic field

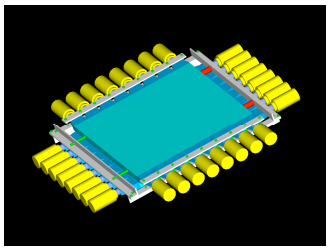


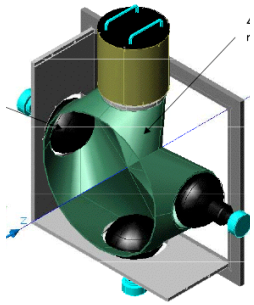
Muon Emittance Measurement

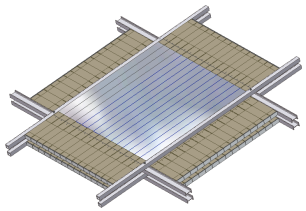


- Spectrometers measure initial and final muon momenta and positions which determine intial and final beam emittances.

- Muon beam contamination
  - Pions for incoming beam
  - Electrons for outgoing beam

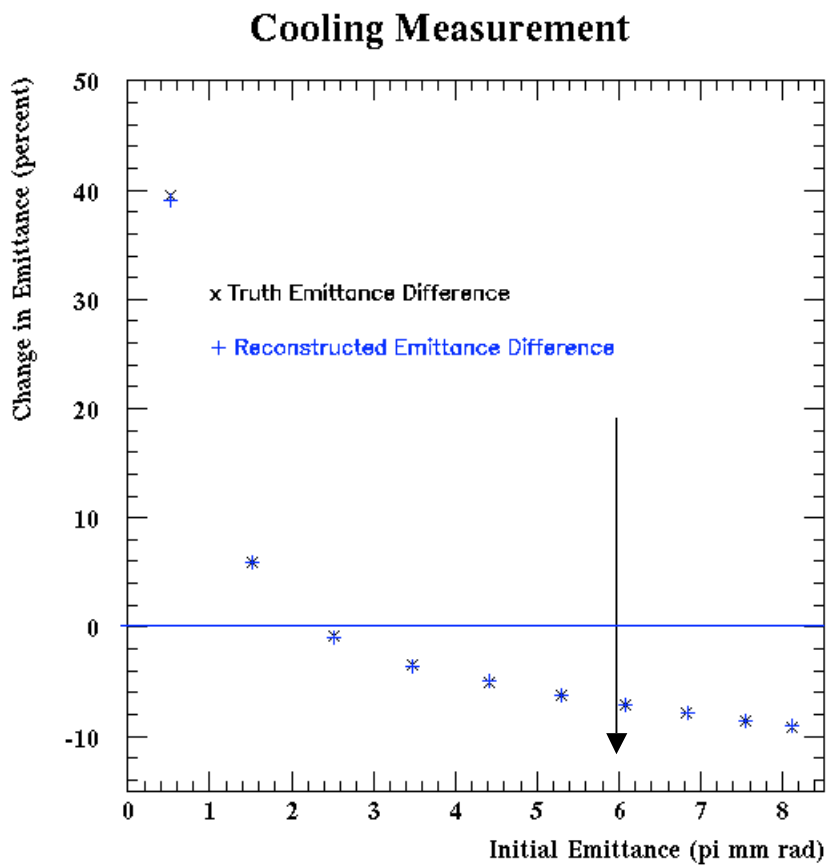


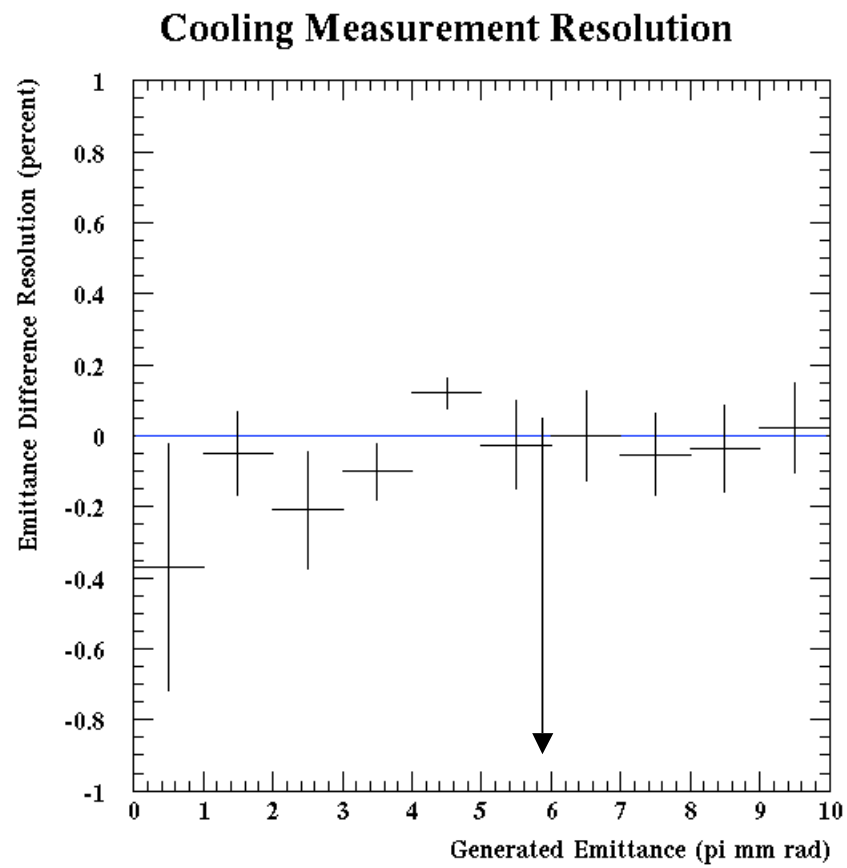




- Particle identification determined through
  - Time measurements (time of flight counters and Cherenkov detectors)
  - Energy measurements (calorimeter)

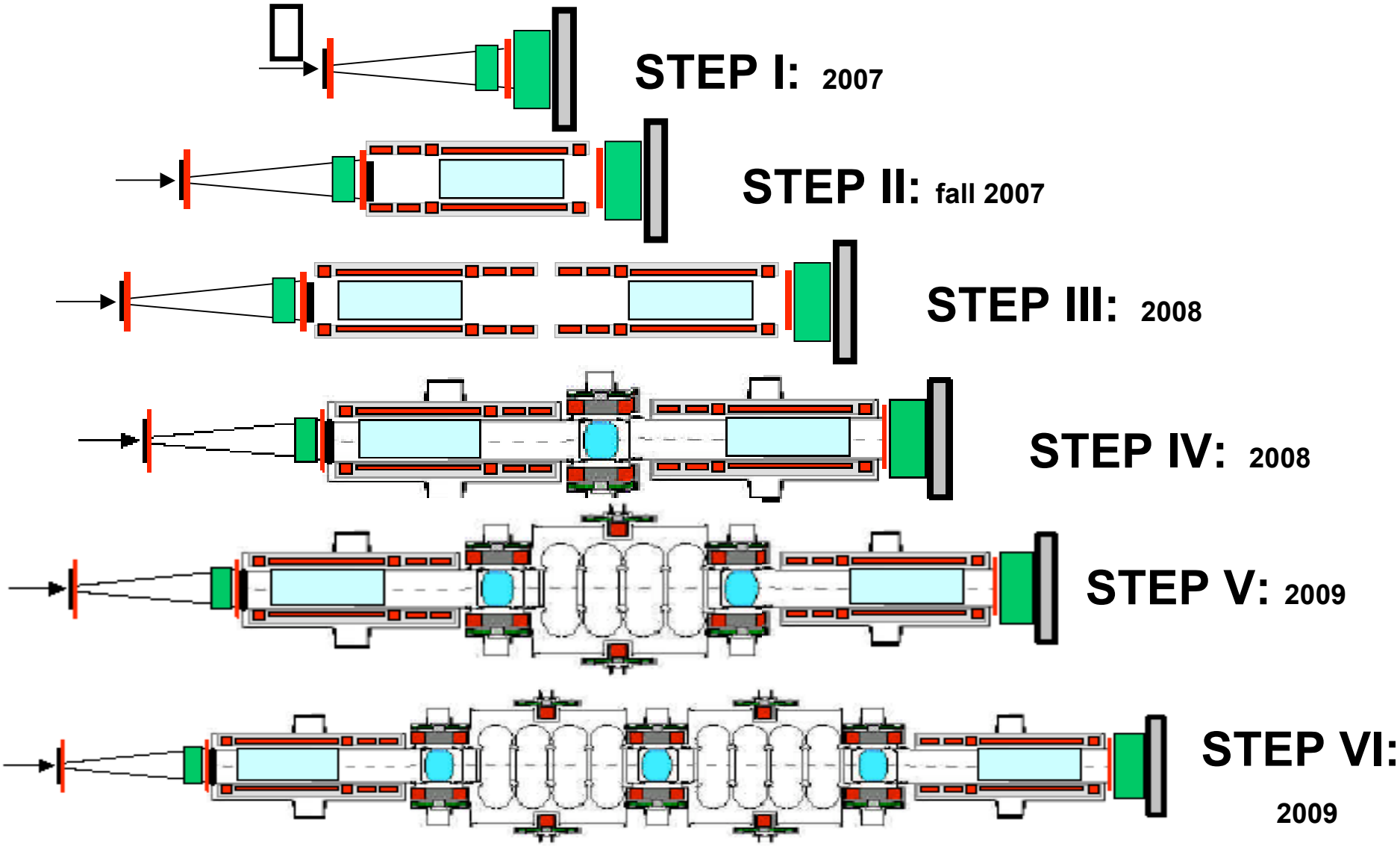
G4MICE Simulations





- GEANT4-based simulations of emittance change (left) and resolution (right) as function of input emittance
- MICE will test how closely simulations match measurements.

MICE Schedule



Summary and Outlook

- Progress on many fronts all over the world.
  - Tracker in USA, UK, and Japan
  - Time of Flight, Cherenkov detectors, and calorimeter in USA and Europe
  - RF cavity R&D in USA (Yagmur Torun's MuCOOL talk)
  - LH_2 absorber R&D in USA and Japan

- First ISIS beam for MICE expected in Fall, 2007.

- Goal: Full emittance cooling measurements with variety of modes and beam conditions in 2009.