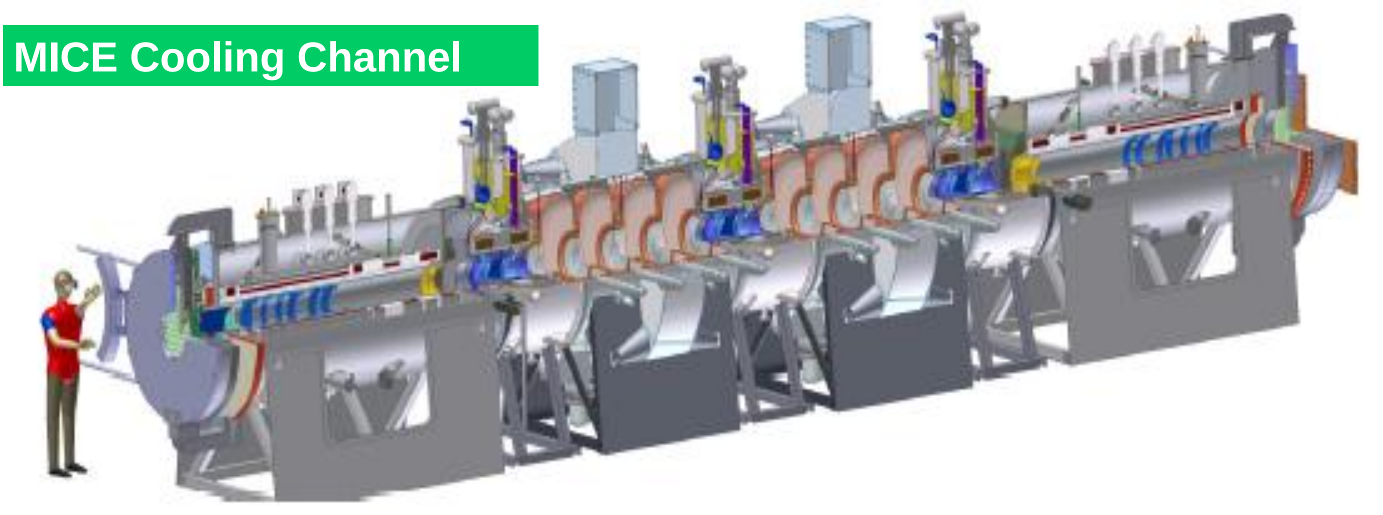
MICE Status



Linda R. Coney

UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

DPF July 27, 2009

Outline

- Introduction
- Neutrino Factory
- What is MICE?
  - Why build it?
- MICE Status
- Conclusions

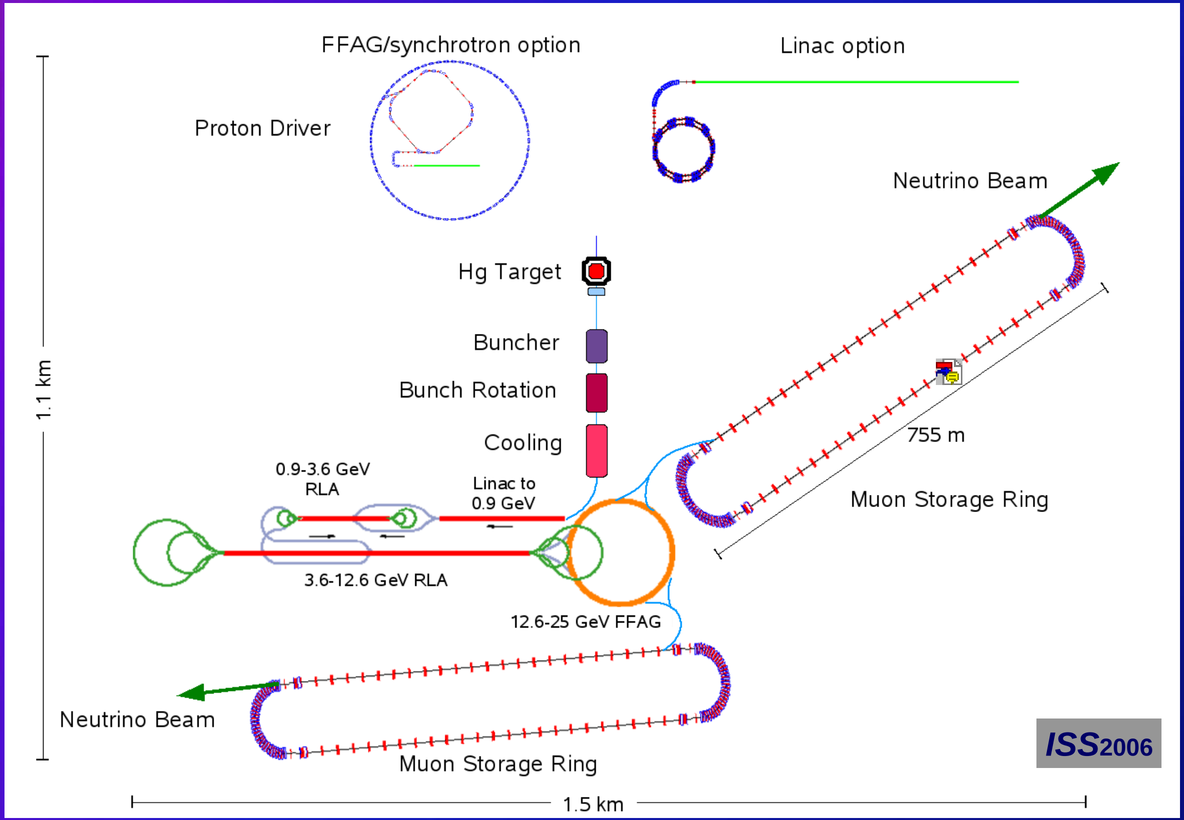
Future Neutrino Beams

- Neutrino oscillations have been observed
  - Neutrinos have mass and they mix – leads to great interest in neutrino physics
- What’s next?
  - Develop detailed understanding of the properties of neutrinos to understand the physics of flavor.

- Neutrino Factory: Create an intense beam of neutrinos from the decay of a stored muon beam:
  - Beam composition known precisely
  - Energy spectrum known and tuneable
  - Flux of neutrinos determined from muon current in storage ring
  - Produce beams of neutrinos 1000 times more intense than conventional beams
  - A wide variety of possible oscillation channels can be studied.
  - Conventional neutrino physics can be done close to the Factory with vastly increased statistics.

Neutrino Factory Accelerator Facility

Baseline out of International Scoping Study



- **Proton Driver**
  - 4 MW, 2 ns bunch
- **Target, Capture, Drift ($\pi \rightarrow \mu$) & Phase Rotation**
  - Hg Jet
  - 200 MHz train
- **Cooling**
  - 30 πmm ($\perp$)
  - 150 πmm (L)
- **Acceleration**
  - 103 MeV → 25 GeV
- **Decay rings**
  - 7500 km L
  - 4000 km L
    - Baseline is race-track design

ISS Accelerator WG report: RAL-2007-023

The Neutrino Factory

Well-understood neutrino source:

μ Decay Ring:

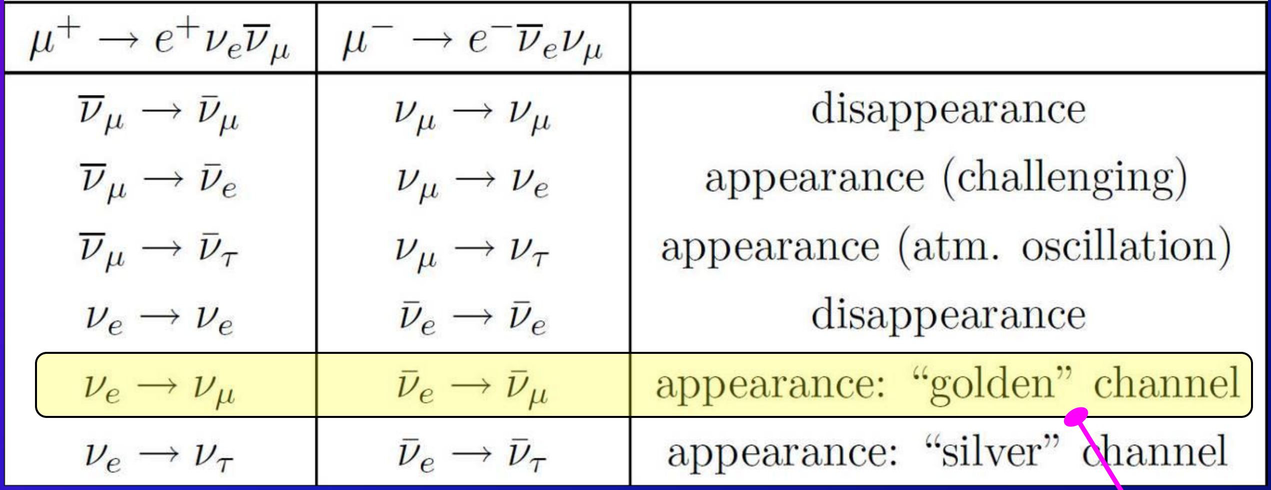
$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

S. Geer, Phys. Rev. **D57** (1998) 6989

- **Flavor content fully known**
- **"*Absolute*" Flux Determination is possible**
  - Beam current, polarization, Near Detector semi & purely leptonic event rates
- **Tremendous control of systematic uncertainties with well designed near detector(s)**

Neutrino Factory – μ Decay Rings



$\mu^+ \to e^+\nu_e\overline{\nu}_\mu$	$\mu^- \to e^-\overline{\nu}_e\nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

- 'Reference' Neutrino Factory:
  - $\geq 10^{21}$ useful decays/yr; exposure '5 plus 5' years
- Two baselines (≈7500 km & ≈4000 km)
  - 50 kT magnetised iron detector (MIND) with MINOS performance – Golden Channel Detector
  - Backgrounds (for golden channel):
    - Sign of μ mis-ID'd
    - Charm decays
  - $E_{res} \sim 0.15 * E_\nu$

"Golden" → Sign of μ observed in detector opposite to that stored in decay ring

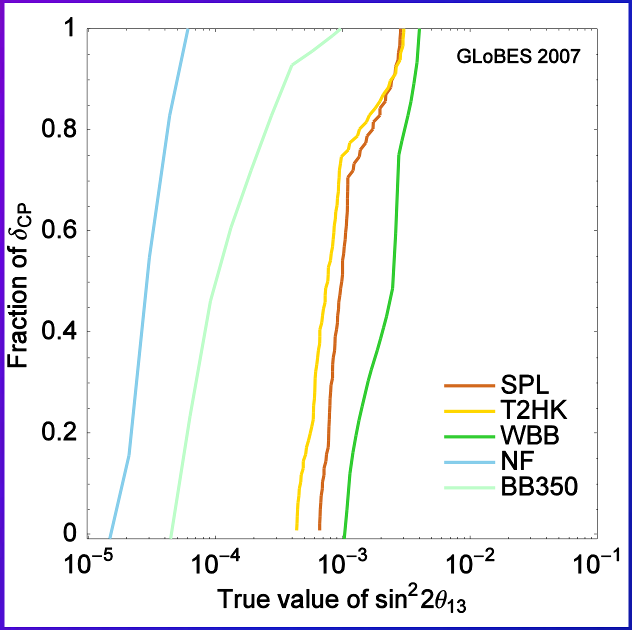
$\mu^+ \to \nu_e \Rightarrow \nu_\mu n \to \mu^- p$

International Scoping Study – Physics Reach

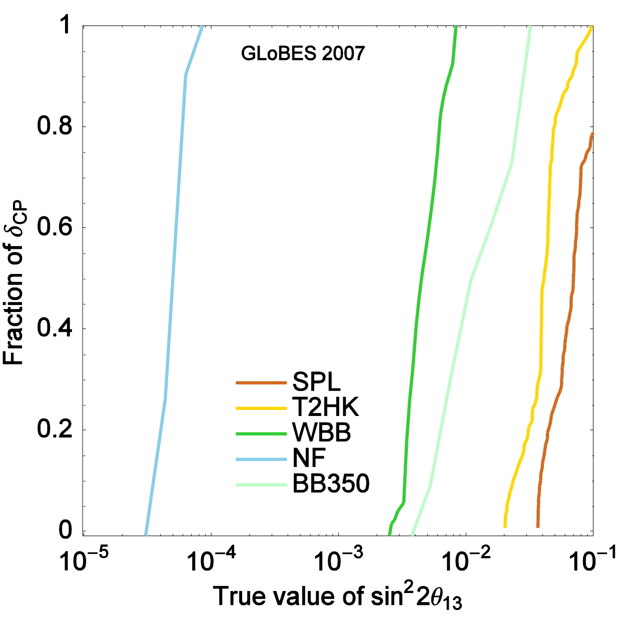
3σ contours shown

ISS Physics Group Report: arXiv:0710.4947v2

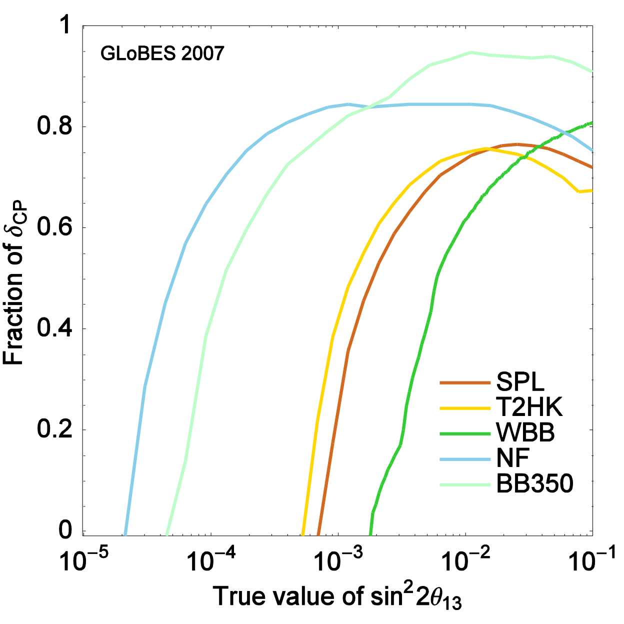
$\sin^2 2\theta_{13}$



Hierarchy



δ *CP*

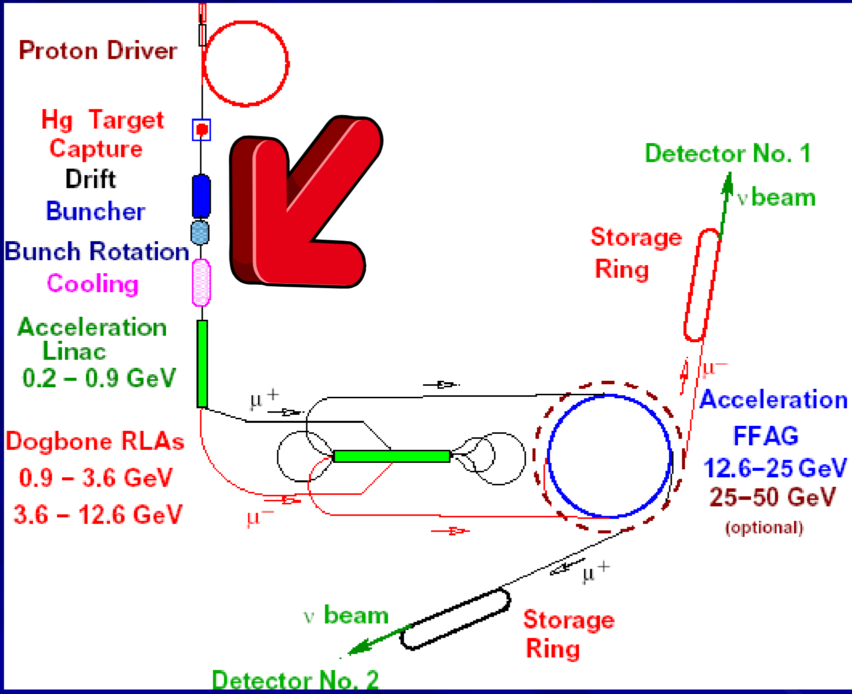


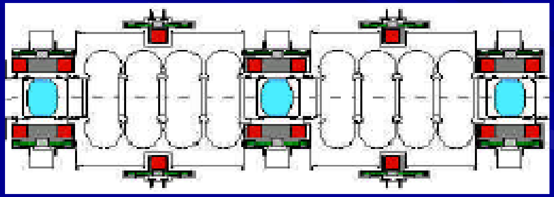
SPL: 4MW, 1MT H_2OC, 130 km BL
T2HK: 4 MW, 1MT H_2OC, 295 km BL
WBB: 2MW, 1MT H_2OC, 1300 km BL

NF: 4MW, 100KT MIND, 4000 & 7500 BL
BB350: γ=350, 1MT H_2OC, 730 km BL

Neutrino Factory R&D

- Challenges:
  - High intensity proton source
  - Complex target
  - Want to accelerate muon beam
    - Stem from decay of pions
    - Large phase space
      - → ie. High emittance
      - → need to cool (shrink) beam
- What do we need?
  - **MICE**
    - **Proof of ionization cooling**
    - **~20% cost of Neutrino Factory**
  - Detector designs
  - Targetry studies
  - RF in magnetic field studies





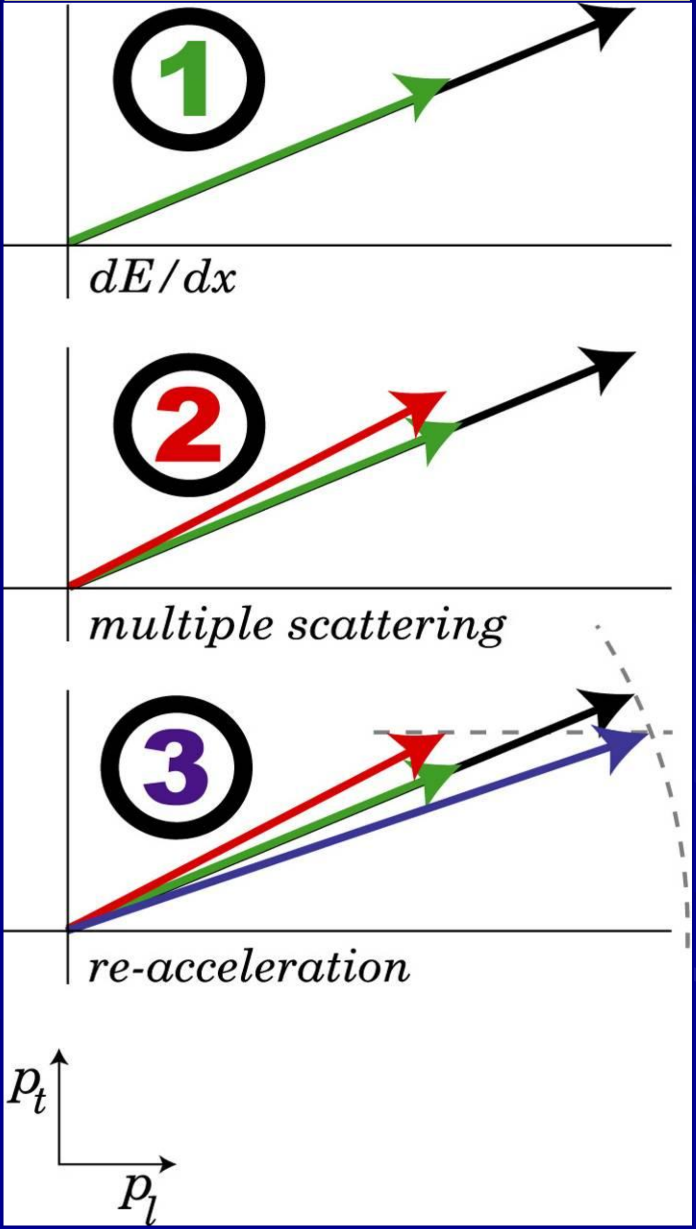
Muon Cooling

- Muons captured from pion decay form a beam with a large size and divergence.
- In order to accelerate this beam, it is necessary to shrink the beam (cooling).
- Conventional beam cooling techniques require a relatively long amount of time (compared to the 2 μs life-time of a muon)
- A new solution is required…

Ionisation Cooling

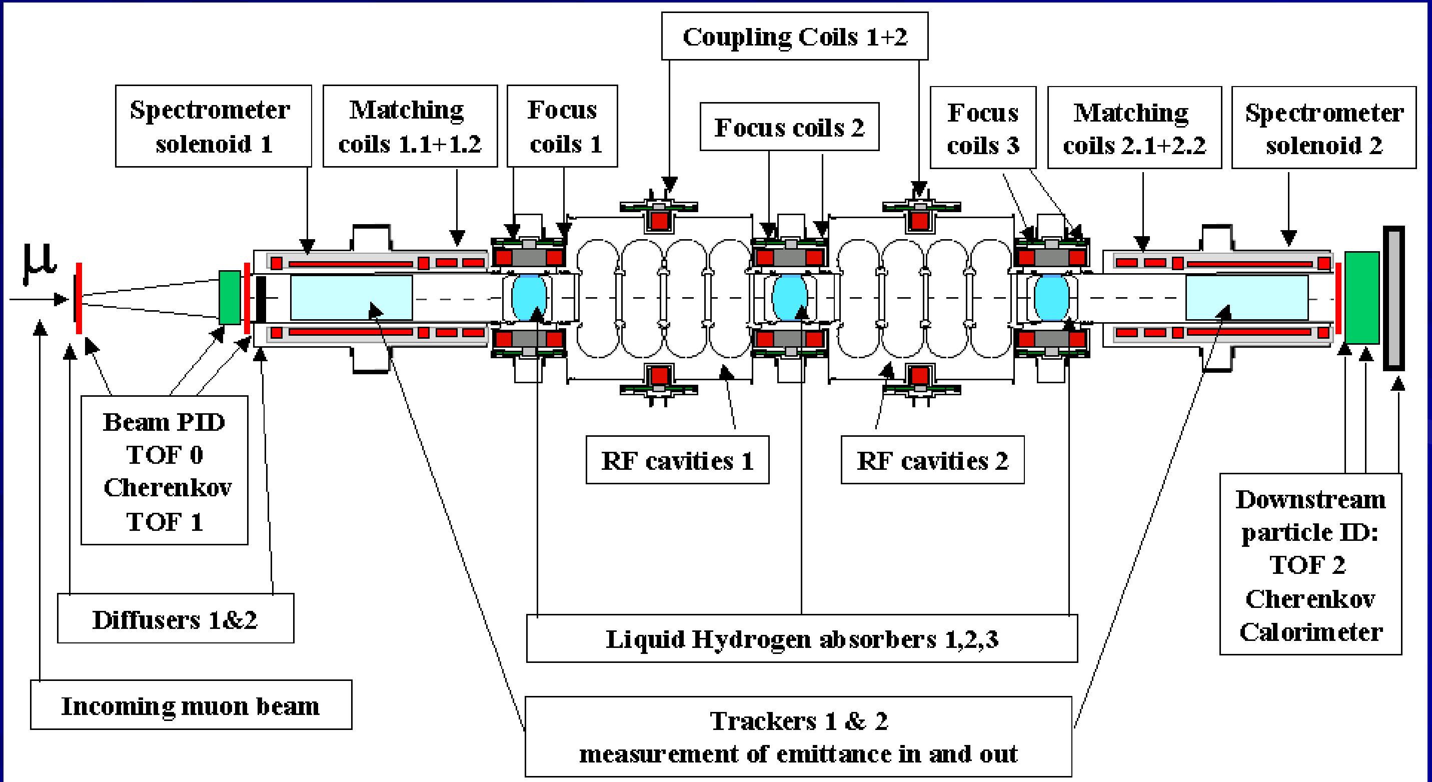
1. **Beam passes through absorber and loses energy/momentum.**
2. **Multiple scattering will result in a change in the angle of the particle, but not the total momentum**
3. **Re-acceleration with an RF cavity restores the longitudinal momentum, but not the transverse component: transverse cooling!**

Principle



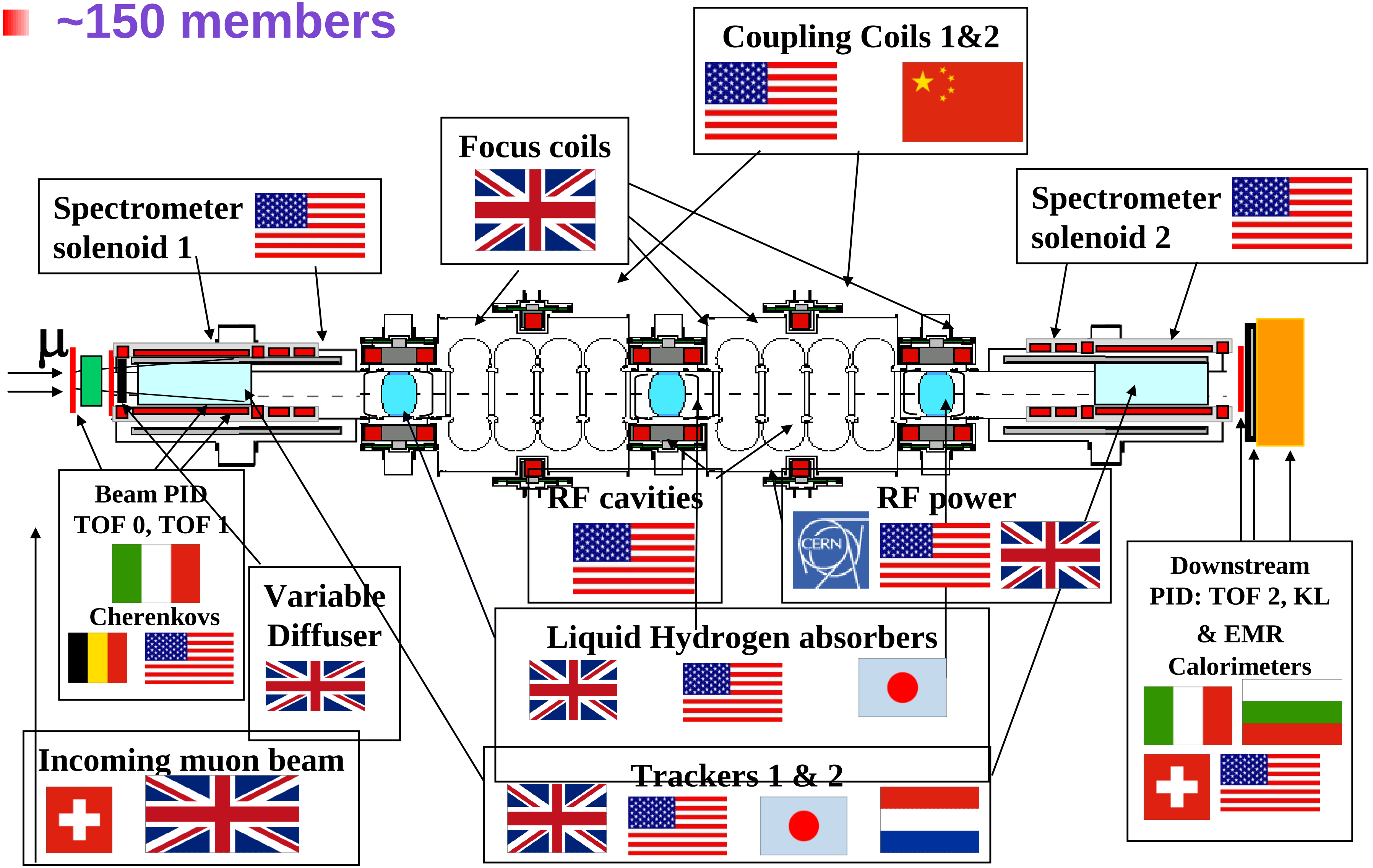
MICE

- Goals:
  - To build and operate a realistic section of a cooling channel, as might be used in a Neutrino Factory.
  - To measure the muon into and out of the cooling channel and measure a 10% reduction in emittance of the beam with a precision of 1%, and experimentally demonstrate ionization cooling
  - 140-240 MeV/c muon beam tuneable from 2-10 π mm-rad transverse emittance



MICE Collaboration

- ~150 members



Coupling Coils 1&2

Focus coils

Spectrometer solenoid 1

Spectrometer solenoid 2

RF cavities

RF power

Beam PID
TOF 0, TOF 1

Cherenkovs

Variable Diffuser

Liquid Hydrogen absorbers

Downstream
PID: TOF 2, KL
& EMR
Calorimeters

Incoming muon beam

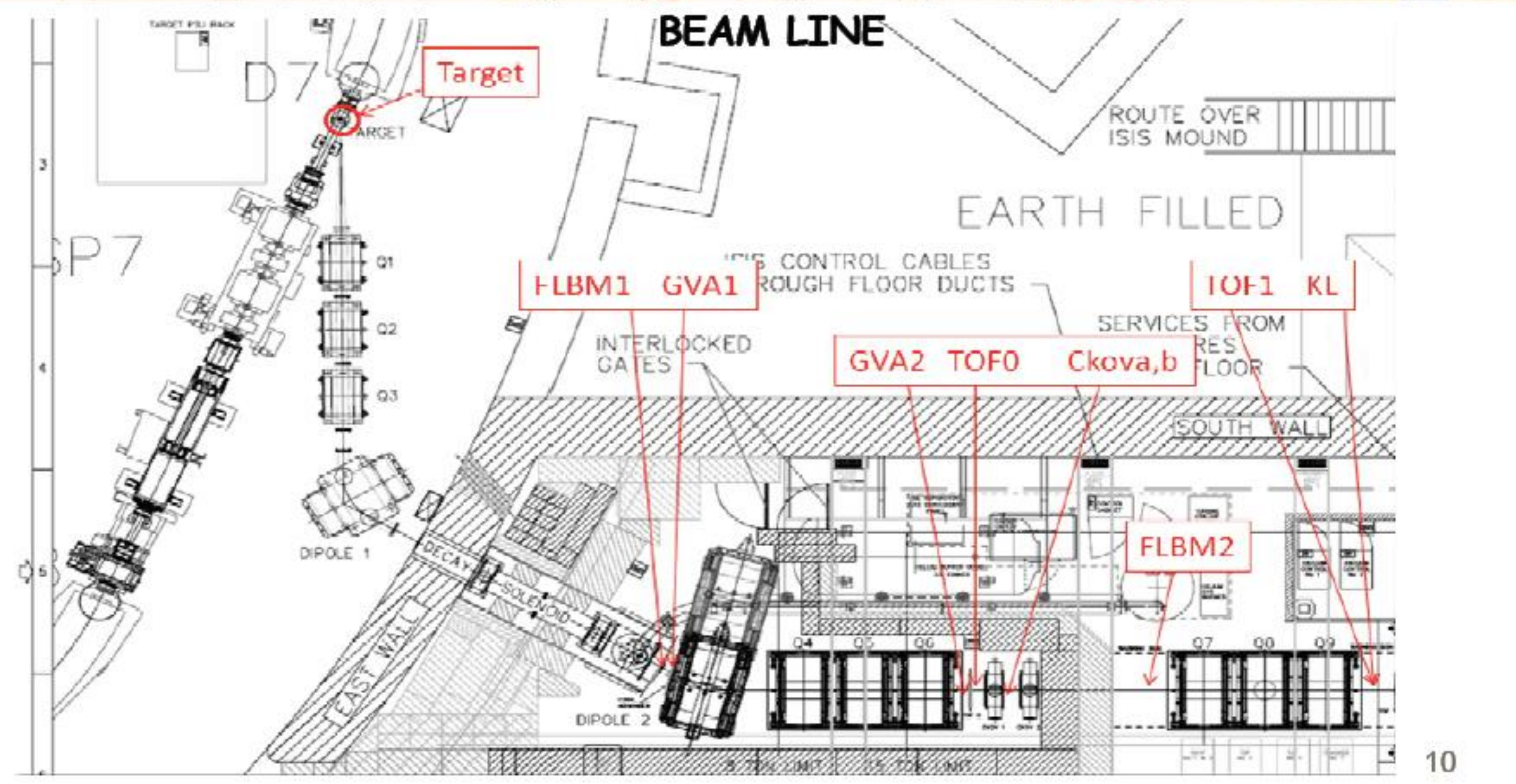
Trackers 1 & 2

MICE Beamline

- ISIS 800 MeV proton synchrotron at RAL
- First beam March 2008

- Titanium target
- Pions captured by quadrupole triplet and momentum selected by dipole
- Followed by 5T superconducting decay solenoid (5 m long) contain π and decay muons
- Second dipole momentum select muons

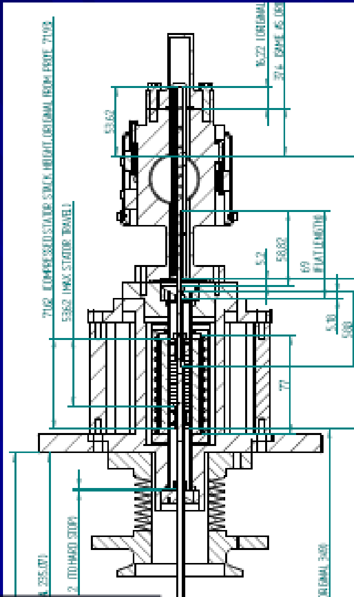
MICE Beamline

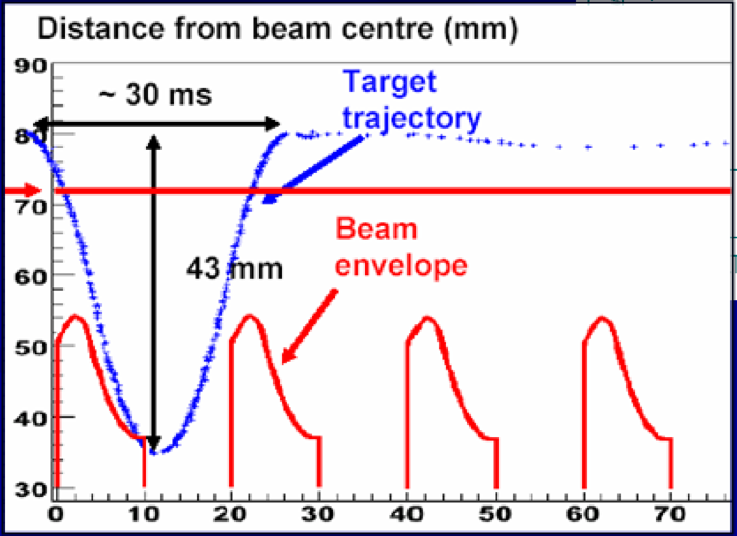


MICE Target

- Titanium target (UK) dipped into ISIS beam at end of 20 ms beam cycle at ~0.4 Hz
  - Only dips once every 50 ISIS cycles
- Original target ran 190K dips into beam
- **Target failure December 2008**
  - Tip melted, shorter but no lost material
  - shaft bent 10°
  - Target jammed due to alignment collar which came loose

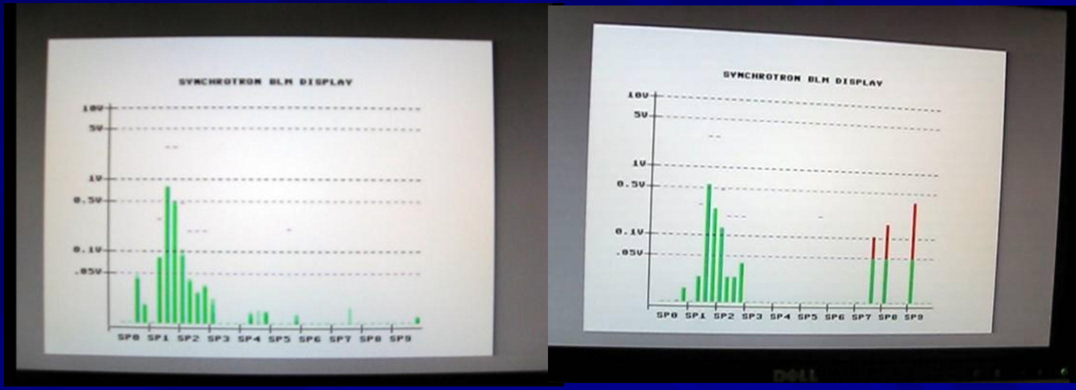
- **Redesign/re-engineered**
  - Simplified - Circular shaft
  - No alignment collar
  - Installation during late August ISIS shutdown
- **Understand target operation**
  - Beam loss
  - Dip depth and timing
  - How affect ISIS
  - How many particles in MICE



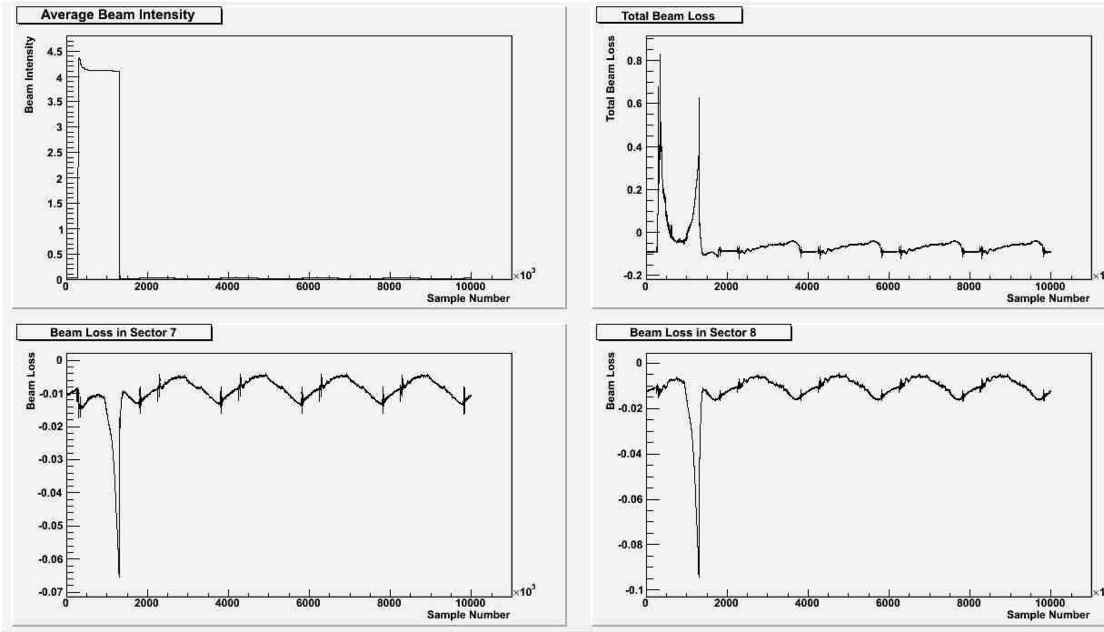


Target Operation Data

- Live ISIS Beam Loss plots into MICE control room
  - Took data to study beam losses in ISIS as function of MICE target operation

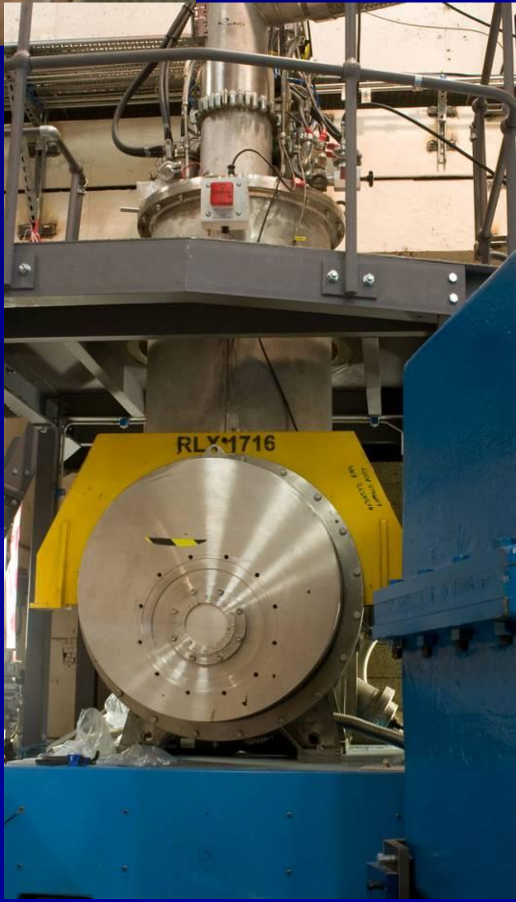


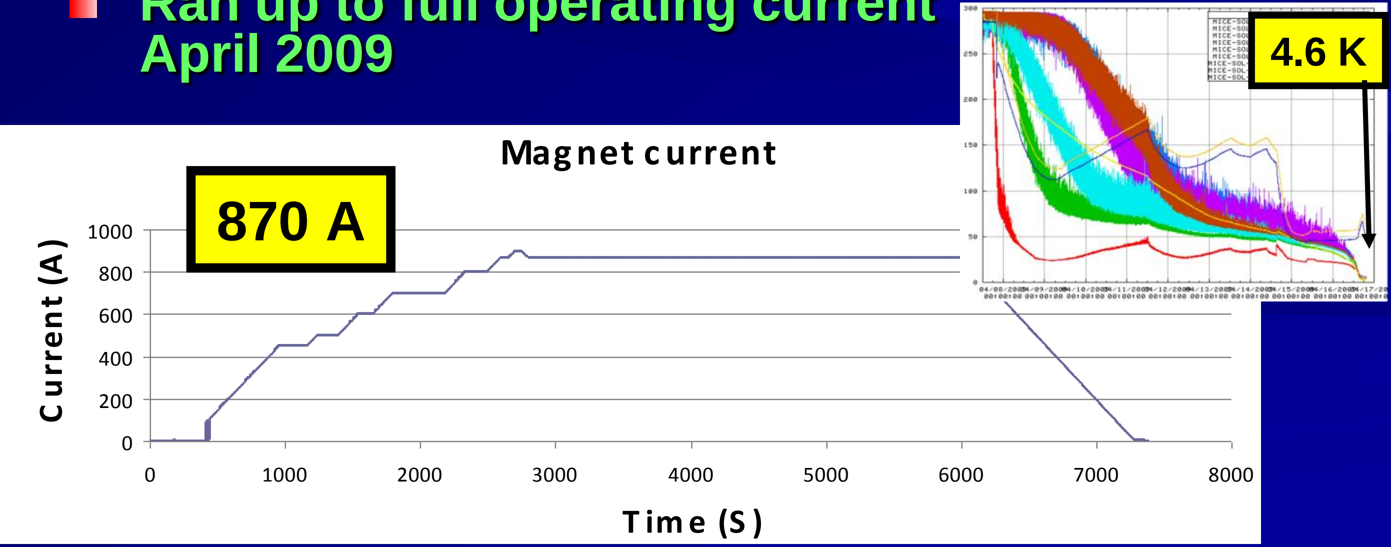
- Target DAQ info is available in MICE control room
  - ISIS beam intensity, Total Beam Loss, Sector 7, Sector 8



Decay Solenoid

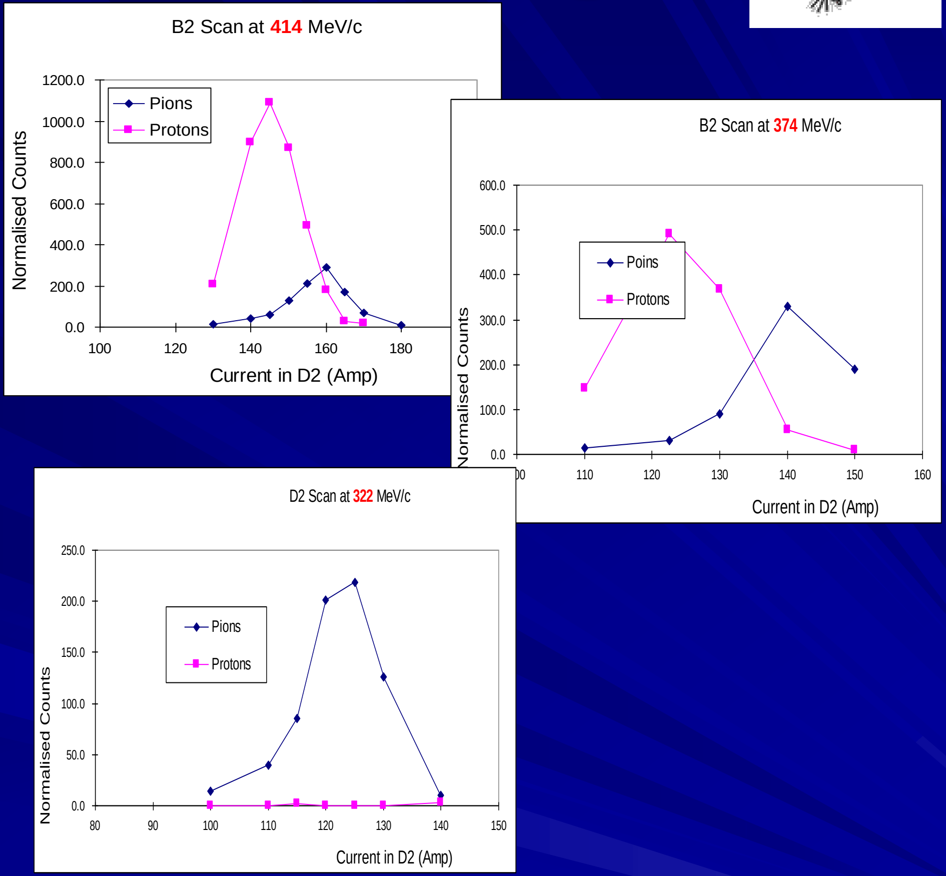
- 5T superconducting solenoid (PSI)
- Problems:
  - Quench at ~300A
  - Quench protector trips
- Solutions:
  - Missing multi-layer insulation caused quenches → installed Mar/April
  - Bad wire caused glitches in QP system → Fixed
- Cooled down
- Ran up to full operating current April 2009

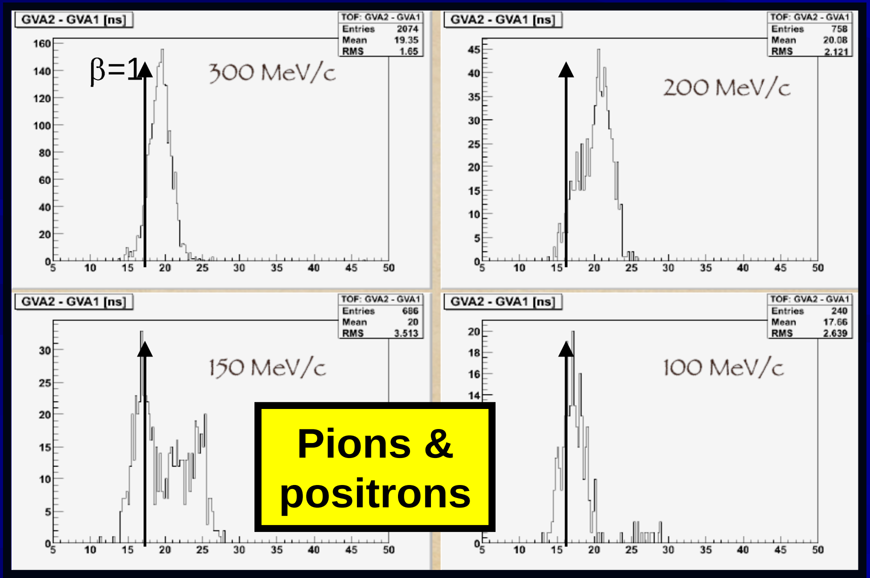




Beamline Commissioning

- Method:
  - Start with 480 MeV/c proton momentum at D1
  - Tune Q1,Q2,Q3 to maximize particle rate in counter
  - Scan 2nd dipole magnet at proton momentum
  - measure pion and proton production rates



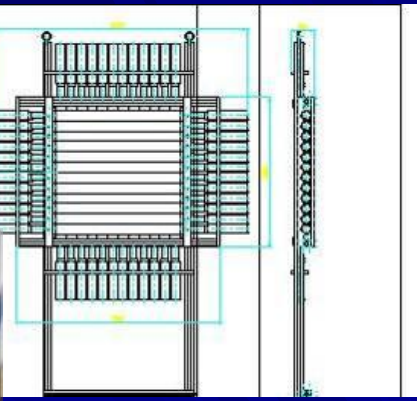


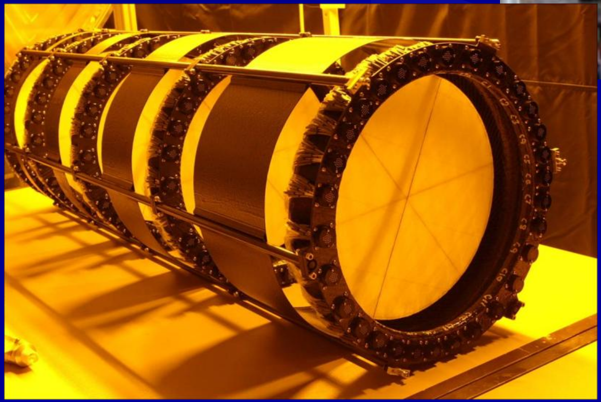
Pions & positrons

- Start with 300 MeV/c beam
- Reduced field gradually until 100 MeV/c
- Only electrons remain in beam

MICE Detectors

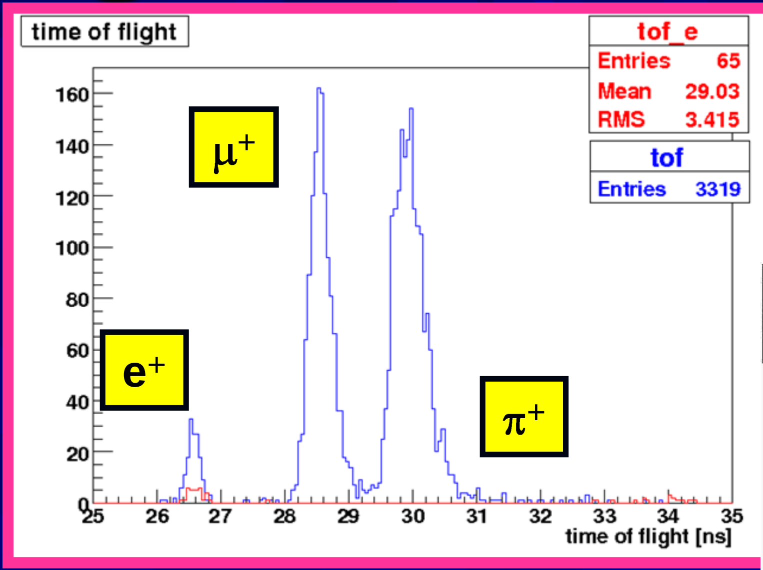
- **Particle identification: TOF, CKOV, Calorimeter**
  - Upstream
    - Time of Flight TOF0 + TOF1 (Italy)
    - 2 Aerogel threshold Cherenkov detectors (US,Belgium)
    - ➔ π/μ separation up to 360 MeV/c
    - ➔ Beam purity better than 99.9%
  - Downstream
    - TOF2
    - Calorimeter (Italy,Geneva,FNAL)
      - Kloe-like (KL) Lead-scintillating fiber sandwich layer
      - Electron-Muon Ranger (EMR)
        - $1m^3$ block extruded scintillator bars
        - Also measure muon momentum
    - ➔ μ/e separation
- **Particle tracking**
  - Scintillating Fiber trackers
  - Measure position and reconstruct momentum

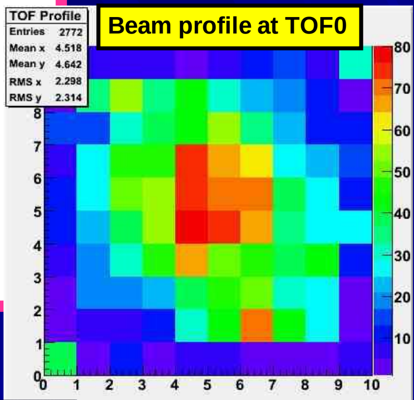




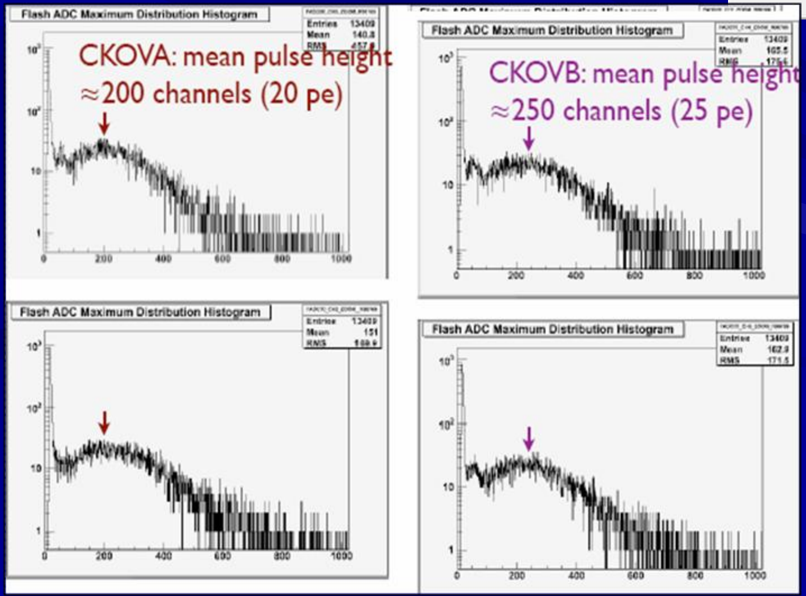
Commissioning PID Detectors

- **TOF**
  - 2 planes of 1 inch orthogonal scintillator slabs in x and y
  - Timing resolution determined to be ~60 ps
  - Time of flight for nominal 300 MeV/c pion beam





- **CKOV**
  - Took data in MICE beamline
  - Typical light spectrum from single PMT
  - Muon tagging efficiency 98%

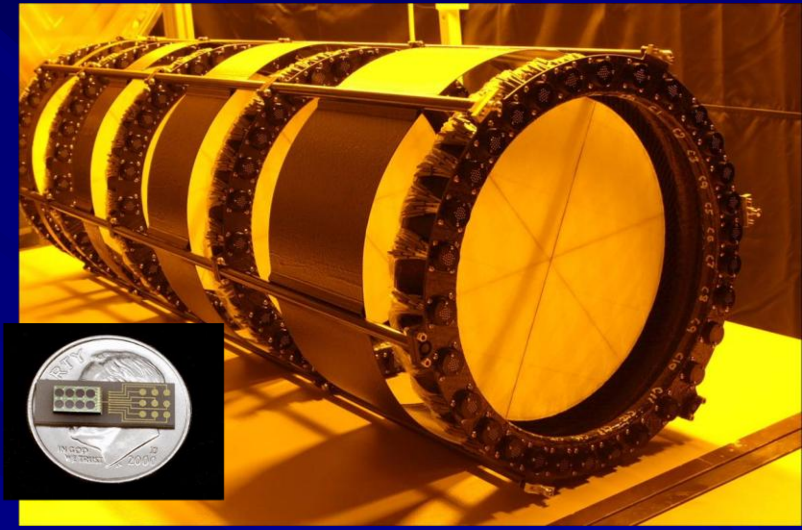


CKOVA: mean pulse height ≈200 channels (20 pe)

CKOVB: mean pulse height ≈250 channels (25 pe)

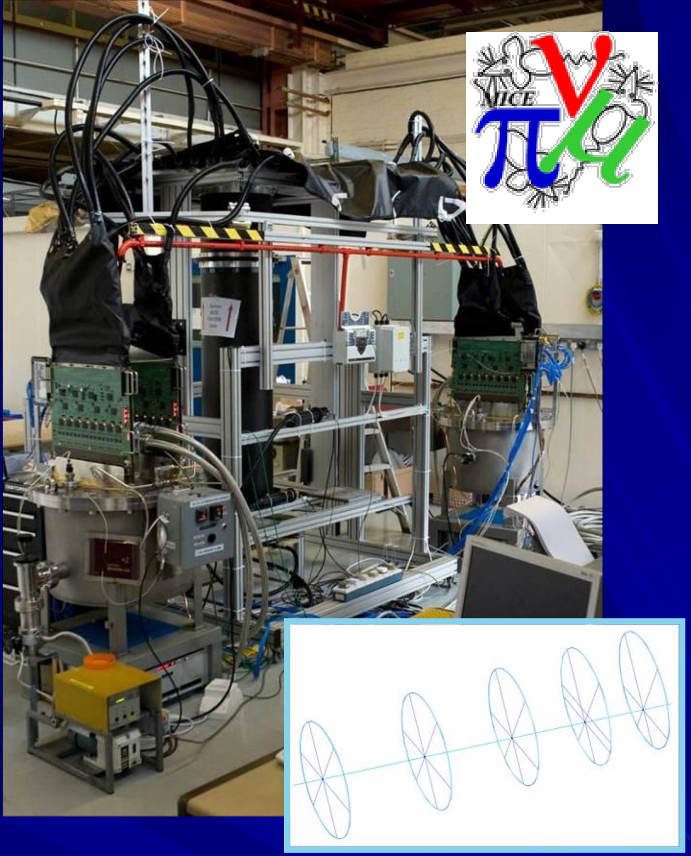
MICE Tracker

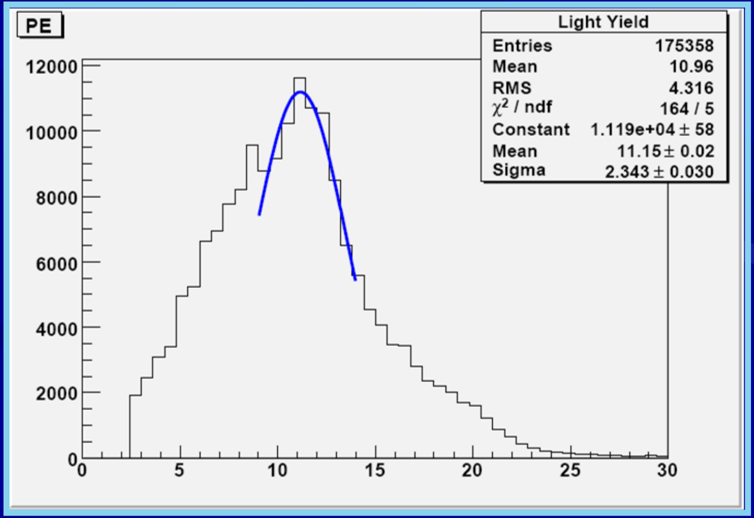
- **Scintillating fiber tracker (UK,US)**
  - Reduce transverse emittance by 10%
  - Trackers need to measure this reduction to 0.1% precision
  - Determine x,x’,y,y’ and momentum
  - High resolution needed
- Design
  - 350 μm scintillating fiber doublet layers
  - Active area has diameter of 30 cm
  - 5 measurement stations with 3 planes each
- Inside 4 T solenoid magnet (US) ~1m long with 5 SC coils



Spectrometer Status

- **Trackers**
  - Both trackers completed
  - Cosmic ray test Tracker1
  - Design goals met:
    - Light yield goal of 10.5 PE → measured 11 PE
    - Measured resolution consistent with goal of 430 mm
    - Efficiency – less than 1/1000 dead channels (< 0.1%)
  - Tracker2 now taking cosmic ray data
- **Magnets**
  - First spectrometer solenoid built
  - Cooldown followed by magnet performance tests
  - Then ship to FNAL for field measurements
  - Second follows 3 months later





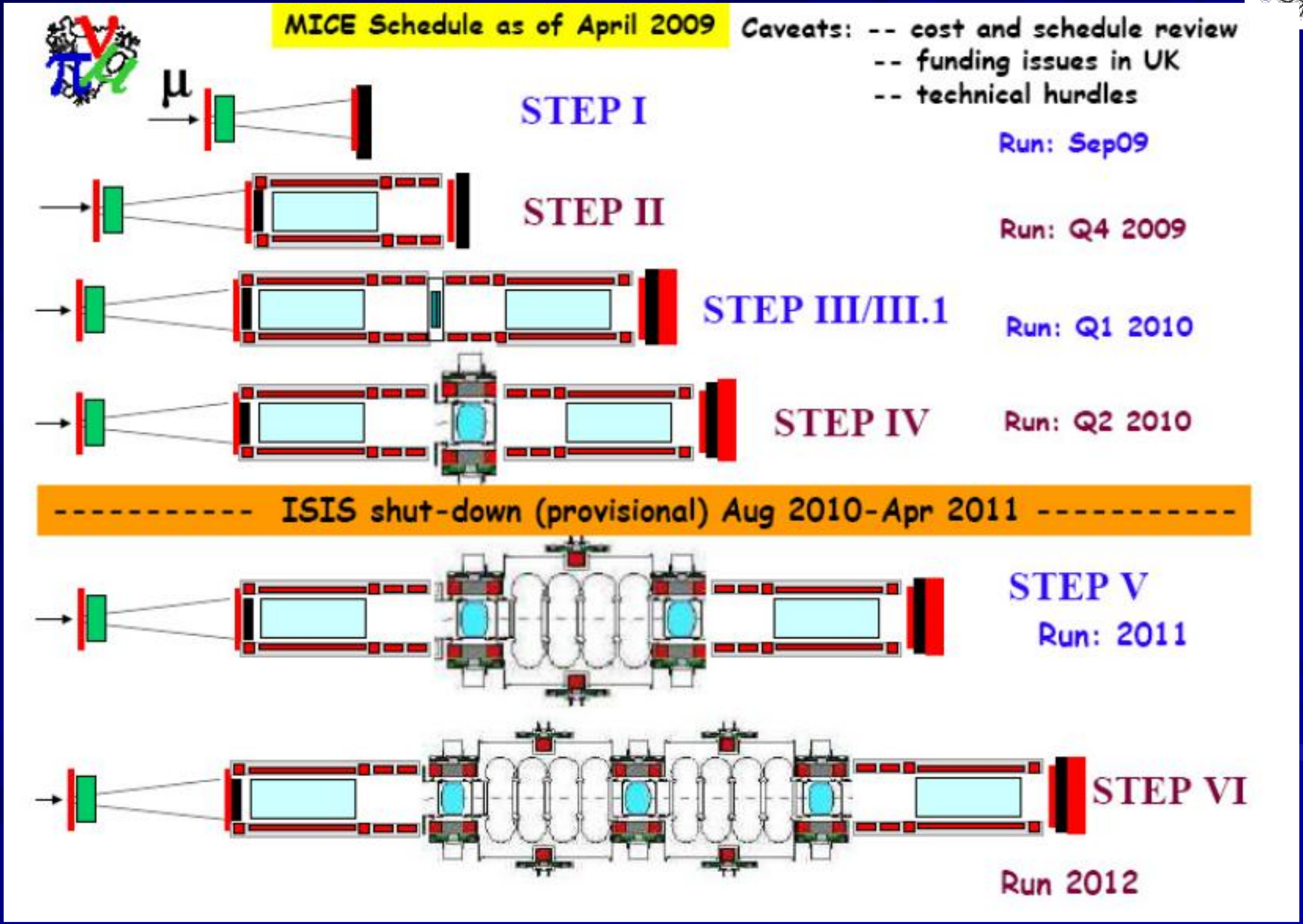
Cooling Channel

- Liquid hydrogen absorbers (Japan) alternating with normal conducting 201 MHz RF cavities
  - First absorber fabricated at KEK
  - Test soon with LH_2
- LH2 absorbers inside absorber-focus-coil (AFC) module (UK) with superconducting coils to provide strong focus at absorber
  - Delivery expected Feb 2010 first AFC module
- RF cavities (US) inside Coupling Coil modules (China)
  - Challenges due to operation inside magnetic field

RF Module

- RF Cavities
  - LBNL responsible for design and fabrication of cavities
  - Copper procured for first 5 cavities
  - Formed into half shells – delivery end 2009
- RF Coupling Coils
  - Final design of RFCC modules done
  - Harbin Institute of Technology responsible for design and fabrication of coupling coils
  - LBNL responsible for RF cavity integration with coils
  - Fabrication underway – first unit delivery summer 2010
- RF power
  - ~1MW in 1ms pulse at 1 Hz per cavity
  - 4 sets of amplifiers (LBNL,CERN) being refurbished at Daresbury Lab (UK)
  - First test summer 2009

The MICE Schedule



MICE Schedule as of April 2009

Caveats: -- cost and schedule review
-- funding issues in UK
-- technical hurdles

STEP I
Run: Sep09

STEP II
Run: Q4 2009

STEP III/III.1
Run: Q1 2010

STEP IV
Run: Q2 2010

----------- ISIS shut-down (provisional) Aug 2010-Apr 2011 -----------

STEP V
Run: 2011

STEP VI
Run 2012

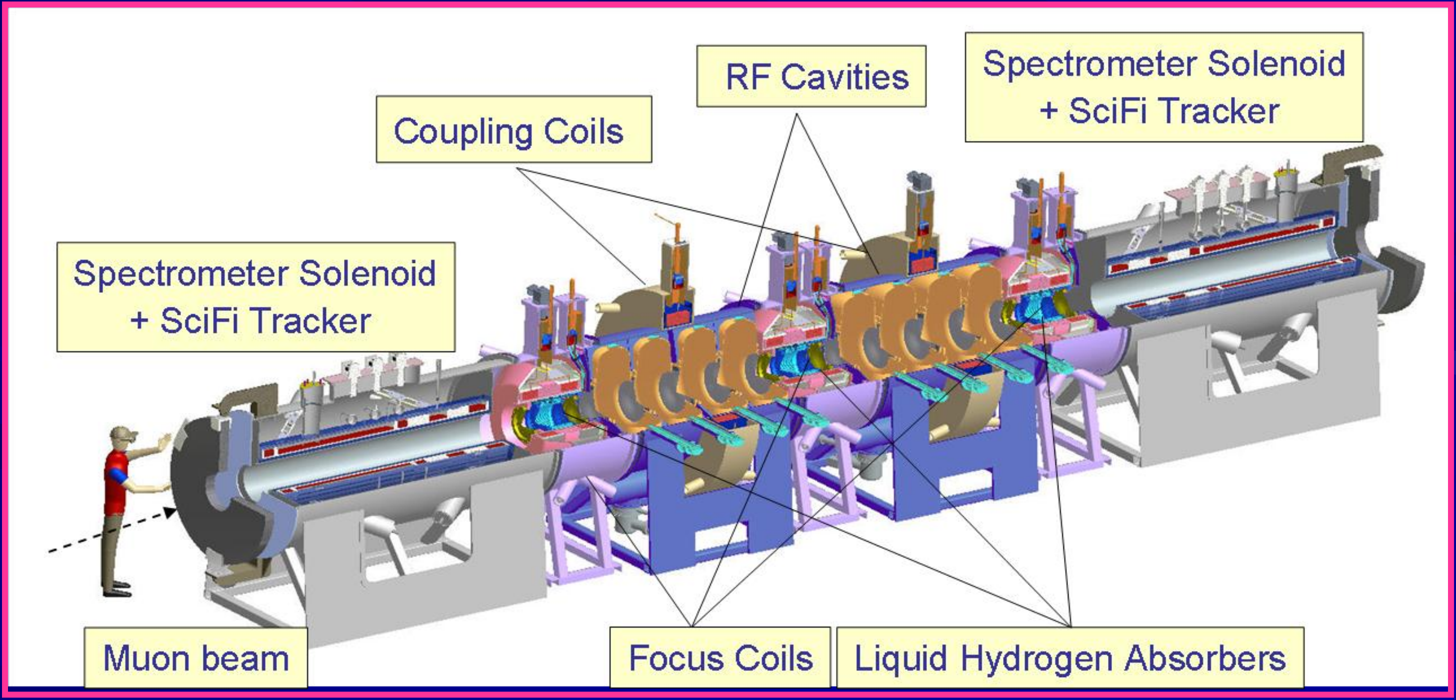
- Experiment designed to grow with each step providing important information

MICE Status

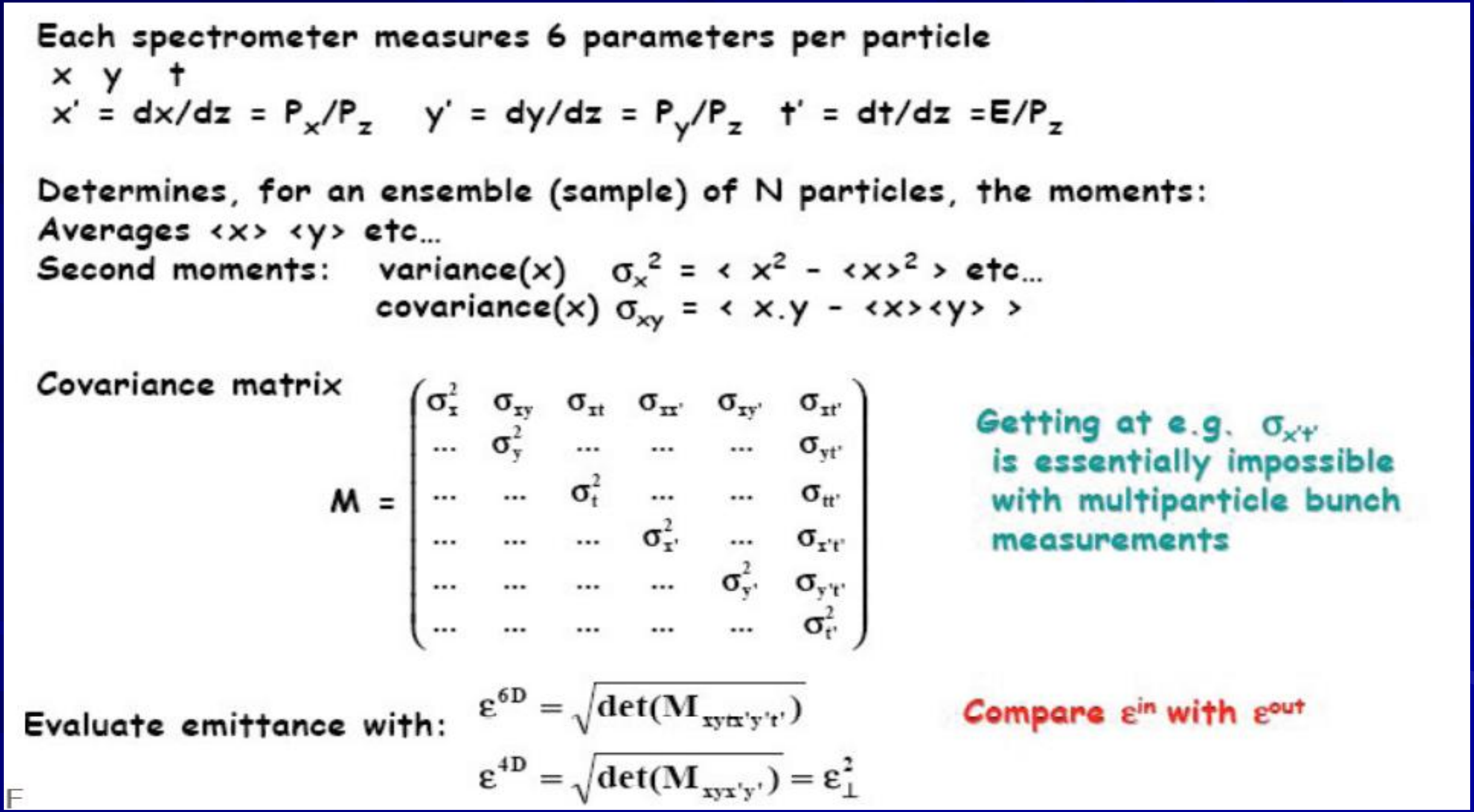
- **Beamline in place and commissioning begun**
  - **Decay solenoid working**
  - **Hall infrastructure nearly done for Steps I-III**
- **Detectors**
  - **PID detectors in place and working well**
  - **Trackers**
    - **Tracker1 performing well**
    - **Tracker2 taking cosmic ray data now**
- **First emittance measurement late 2009**
- **First cooling 2010**

Conclusions

- A neutrino factory would provide excellent opportunities to study neutrino physics in detail.
- Neutrino Factory R&D is under way and covers aspects of the machine from front end through acceleration.
- MICE results will provide critical input on the feasibility of muon beam cooling and will inform future Neutrino Factory designs.



Emittance



Each spectrometer measures 6 parameters per particle

$x \quad y \quad t$

$x' = dx/dz = P_x/P_z \quad y' = dy/dz = P_y/P_z \quad t' = dt/dz = E/P_z$

Determines, for an ensemble (sample) of N particles, the moments:

Averages $\langle x \rangle$ $\langle y \rangle$ etc...

Second moments: variance(x) $\sigma_x^2 = \langle x^2 - \langle x \rangle^2 \rangle$ etc...

covariance(x) $\sigma_{xy} = \langle x.y - \langle x \rangle \langle y \rangle \rangle$

Covariance matrix

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

Getting at e.g. $\sigma_{x't'}$ is essentially impossible with multiparticle bunch measurements

Evaluate emittance with:

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

$$\varepsilon^{4D} = \sqrt{\det(M_{xyx'y'})} = \varepsilon_\perp^2$$

Compare ε^{in} with ε^{out}

Ionization Cooling

- Ionization cooling:
  - Ionization gives cooling term, multiple scattering gives a heating term

$$\frac{d\varepsilon}{dz} \approx -\frac{\varepsilon}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2m\beta^3}\frac{(13.6\,MeV)^2}{E_\mu X_0}$$

  - Ionization per density is proportional to Z, multiple scattering is inversely proportional to X_0 thus prop to Z(Z+1)
  - Thus, best cooling achieved with low Z: hydrogen, lithium hydride (LiH)
- Definition of emittance:
  - V_{ij} is covariance matrix of phase space:

Need to perform single particle experiment to measure ε with full correlations

$$V_{ij} = \begin{bmatrix} \beta_\perp / p_z & -\alpha_\perp & 0 & -(\beta_\perp\kappa - \mathcal{L}) \\ -\alpha_\perp & p_z\gamma_\perp & +(\beta_\perp\kappa - \mathcal{L}) & 0 \\ 0 & +(\beta_\perp\kappa - \mathcal{L}) & \beta_\perp / p_z & -\alpha_\perp \\ -(\beta_\perp\kappa - \mathcal{L}) & 0 & -\alpha_\perp & p_z\gamma_\perp \end{bmatrix}$$

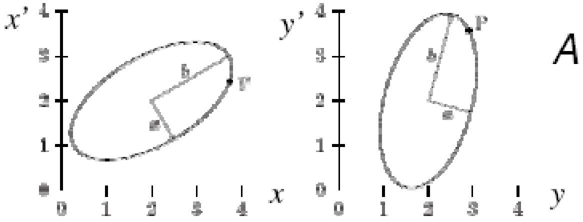
$\alpha_\perp, \beta_\perp, \gamma_\perp$ = Twiss parameters

$$\mathcal{L} \approx \frac{\langle L_{canon} \rangle}{2m_\mu c\varepsilon_N}$$

κ = radius of curvature

Emittance: area of 4D ellipse ($x, x' \equiv p_x/p_z$, $y, y' \equiv p_y/p_z$)

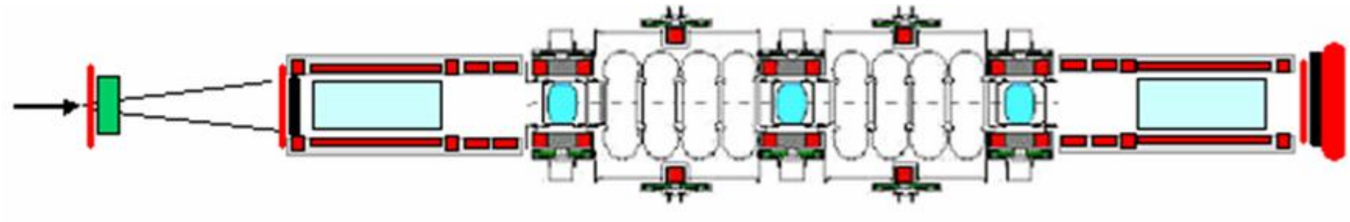
$$\varepsilon_{4D} = \frac{1}{m_\mu c}\sqrt[4]{|V_{ij}|}$$

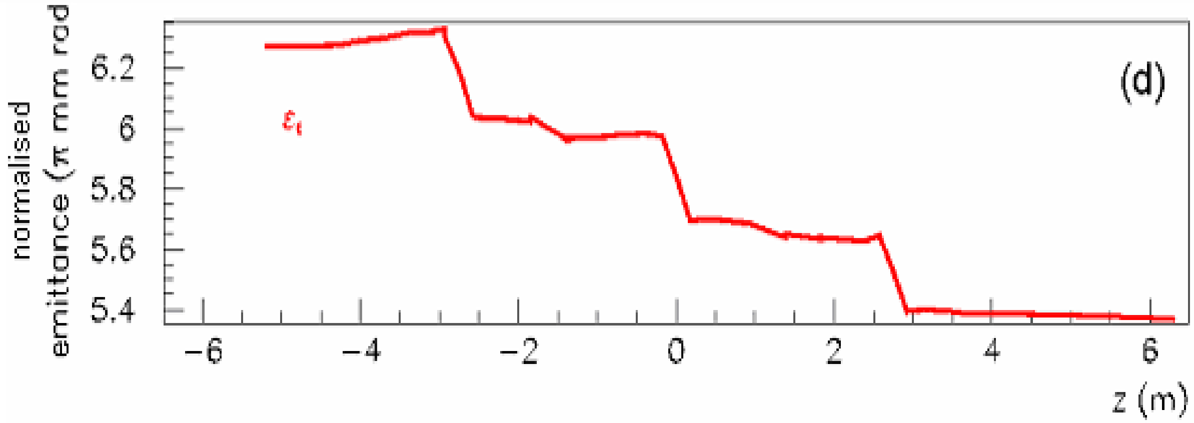


$$A = \pi\sqrt{|V|}$$

7

EXPECTED PERFORMANCE





Change in emittance at absorber $\Delta\varepsilon / \varepsilon = -(\Delta p/p)(1-\varepsilon_0/\varepsilon)$

5% momentum loss in each absorber ➔ 15% cooling for large ε beam

Equilibrium emittance for H_2 $\varepsilon_0 \sim 2.5\ (\pi)$ mm-radians
(acceptance of accelerators in NF 15 – 30 (π) mm-radians)

➔ *Measure $\Delta\varepsilon$ to 1%*

PID Detectors: TOF & CKOV

- TOF
  - 2 planes of 1 inch orthogonal scintillator slabs in x and y
  - Read out by fast PMT
  - used to identify protons, pions, electrons and especially muons
- CKOV
  - Threshold, aerogel
  - Used to ID electrons

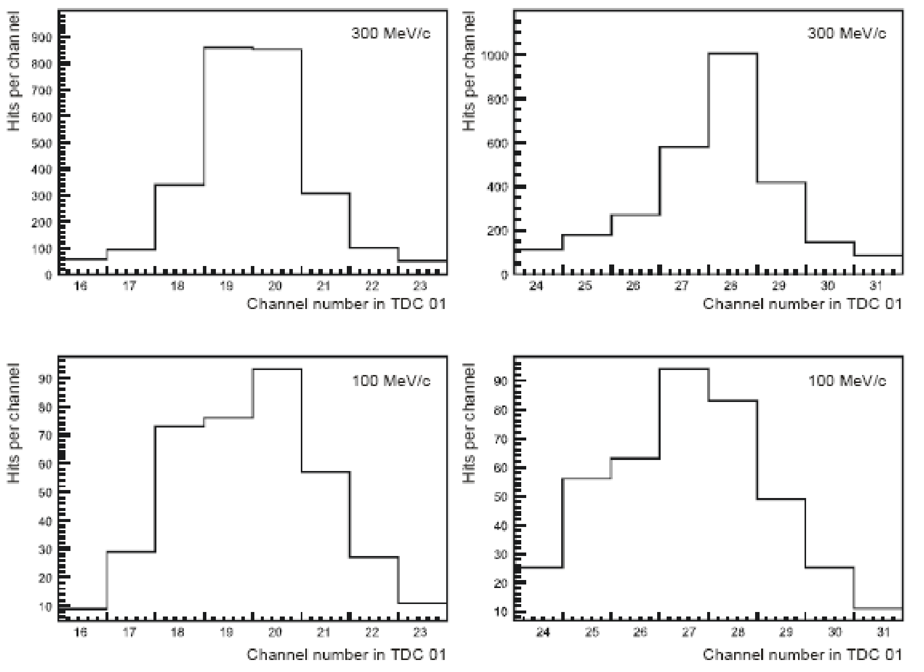


Figure 1: Vertical (left) and horizontal (right) profiles in TOF0 obtained from online monitoring histogram at 300 MeV/c (top) and 100 MeV/c (bottom). The beam can be considered as centred at both momenta.

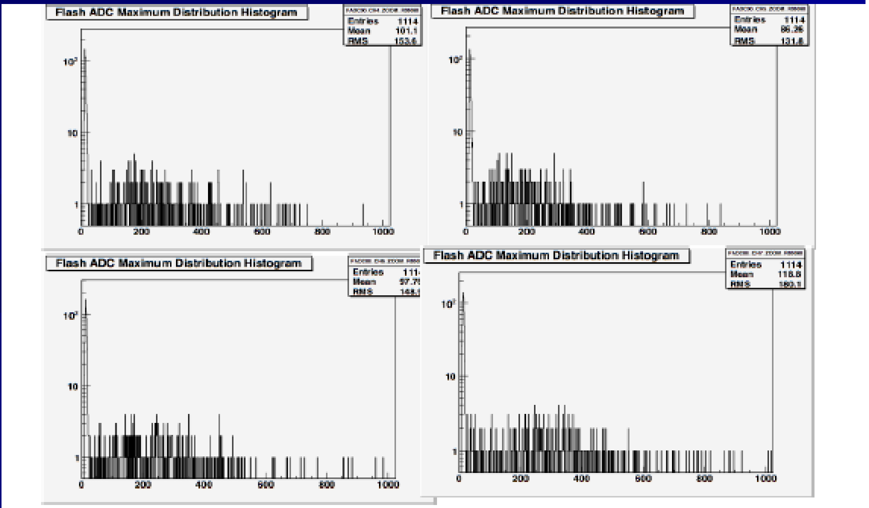
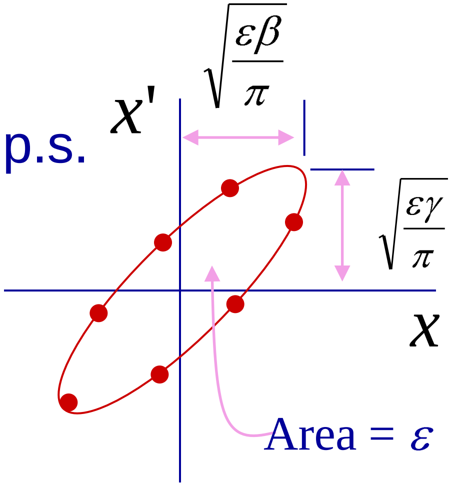


Figure 3: Amplitude histograms from the Cherekov counters. Top four histograms correspond to CKOVa. Bottom four histograms correspond to CKOVb.

Tracker2 Readout System

- Two cryostats
  - Each powered by new Wiener power supply
- Each cryostat has 2 VLPC cassettes
- Each VLPC cassette has 2 AFE IIt boards
  - → total of 8 AFE boards
- In rack:
  - 9 VLSB modules: 1 master to control timing and 8 slaves (one for each AFE board)
  - 1553 module: controls AFE initialization, bias voltage controls, temp controls, data taking
  - Fanout: sends correct timing signal to all AFE boards
- Goals:
  - characterize VLPC cassettes
  - get everything working correctly together in layout to be used at RAL

COOLING



- Accelerators have limited acceptance in phase space
- Muon beams from pion decay occupy large volume of p.s.
  - wide σ_x ~ 10 cm
  - divergent σ_θ ~ 150+ mr
  - *i.e.* have large normalised *emittance, ε_n*

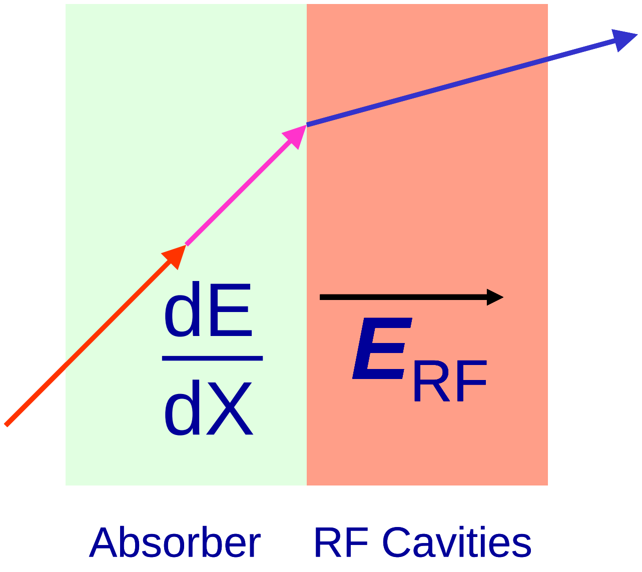
In 2D $$\varepsilon_n = \frac{1}{m_\mu c}(\sigma_x^2\sigma_{p_x}^2 - \sigma_{xp_x}^2)^{\frac{1}{2}} \rightarrow \beta\gamma\sigma_x\sigma_\vartheta$$ at a focus

- ε_n ~ 15 – 20 (π) mm-rad initially
- *Cooling* = reduce emittance ➔ 2 – 10 x number of μ into accelerator
  - Highly advantageous for a NF & essential for muon collider
- Finite muon lifetime ➔ conventional cooling (e.g. stochastic) too slow
- *Ionisation cooling* the only practical possibility

IONISATION COOLING

- Pass muons of ~200 MeV/*c* through
  - *absorbers* ➔ reduce p_t and p_l
  - RF replaces p_l

  ➔ *beam 'cooled'*



- Emittance decreases exponentially:

$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t \;\; 0.014\ \text{GeV}^{\;2}}{2\beta^3 E m_\mu X_0}$$

- *<dE/dX>* *versus* scattering (X_0)

➔ *low Z absorber material*

➔ *tight focus* (*low β function*)

- Figure of Merit = X_0*<dE/dX>*

➔ *H_2 is best absorber material*

	Z	FoM	Rel. 4D cooling
H	1	252.6	1.000
He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024