The International Muon Ionization Cooling Experiment

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Overview

- Motivation for building a Neutrino Factory
- Introduction to Ionization cooling
- The MICE experiment
  - The Magnetic Lattice
  - The Hydrogen Absorbers
  - The RF System
  - The Instrumentation
- MICE at RAL
- Status of MICE

Motivation for a Neutrino Factory

- Recent results from Super-K and SNO provide exciting evidence for neutrino oscillations
- A neutrino factory would provide a high intensity, high energy beam of muon and electron type neutrinos with very low backgrounds.
- Potential for a non-oscillation physics program

Physics at a Neutrino Factory Complex

Long baseline -

Neutrino oscillations: precision measurements of mixing parameters, matter effects, CP violation!

Short baseline -

High brilliance neutrino beams, nuclear effects, polarized structure functions, charm factory

High intensity proton source -

Unstable isotope beams and other synergies with nuclear physics

High brilliance muon beams -

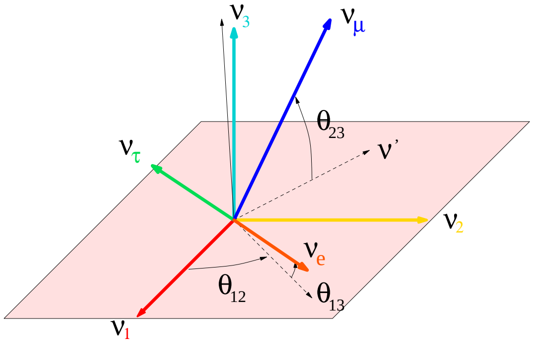
Rare muon decays, muonic atoms, ...

R & D -

First step towards a muon collider: s-channel Higgs and Susy Higgs production, high precision/resolution E_{cm} for new particle studies

Physics at a Neutrino Factory Complex II

Most fundamental particle physics discovery of the decade: *Neutrinos have mass and mix!*



As in the quark sector, there are three mixing angles and a phase to measure,

but

the pattern of angles is very different,

CKM Matrix
(almost diagonal)
$\theta_{12} \cong 12.8°$
$\theta_{23} \cong 2.2°$
$\theta_{13} \cong 0.4°$

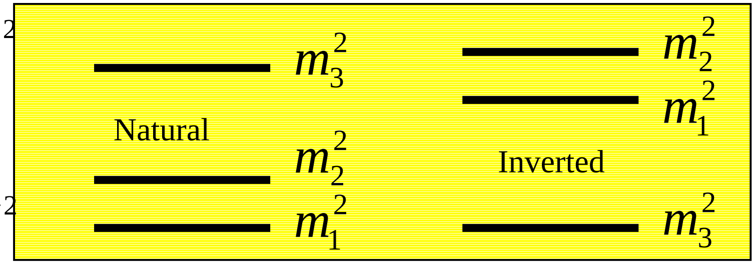
MNS Matrix (LMA)
(heavily mixed)
$\theta_{12} \cong 20\text{-}45°$
$\theta_{23} \cong 35\text{-}45°$
$\theta_{13} < 10°$

and

$$\left|\Delta m^2_{32}\right| \approx 3\times10^{-3}\,\text{eV}^2$$

the mass hierarchy needs to be resolved.

$$\left|\Delta m^2_{21}\right| < O\left(10^{-4}\right)\text{eV}^2$$



Oscillation Physics

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

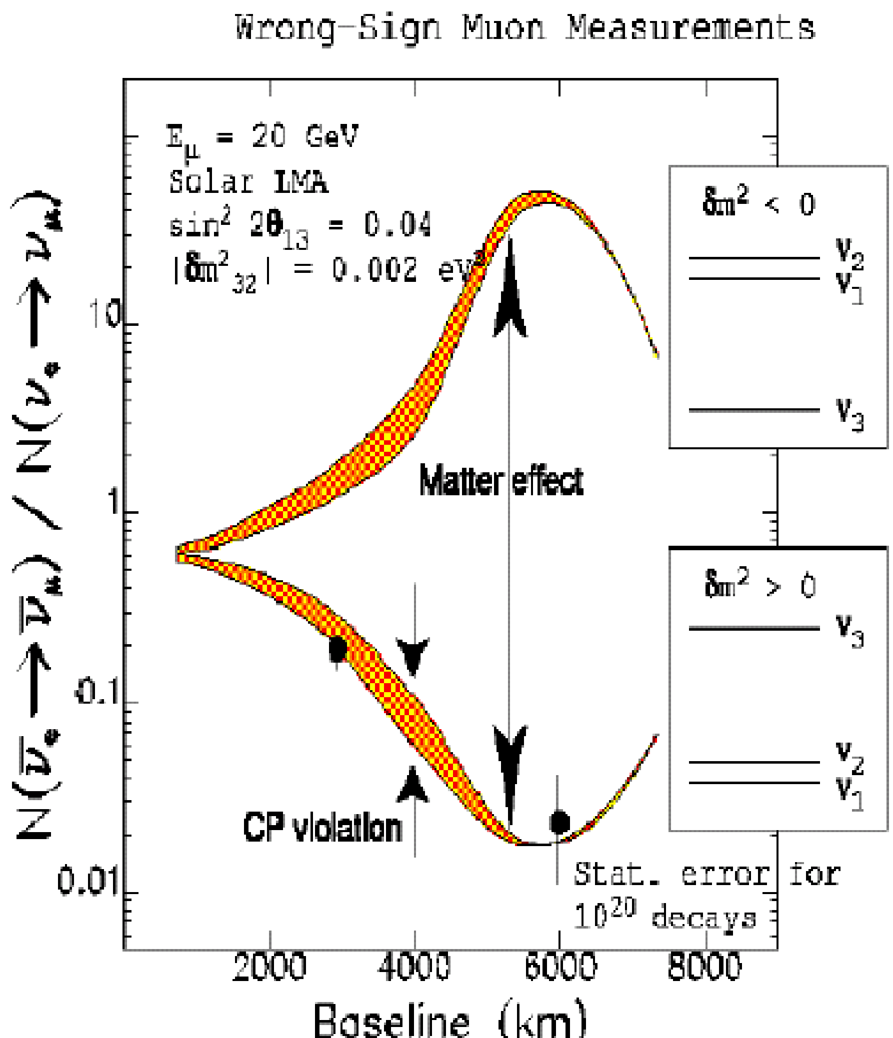
The MNS Matrix

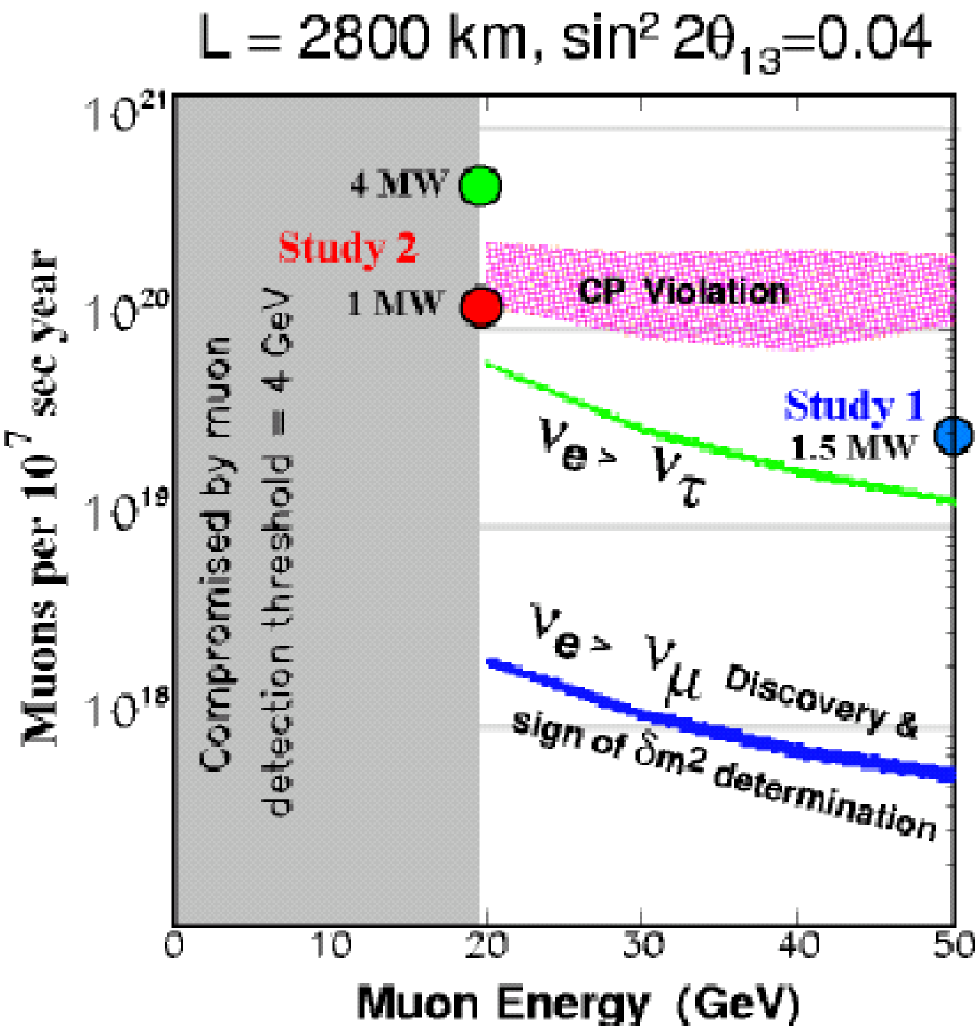
Neutrino Factory Oscillation Physics Program:

1) Determine all $P(\nu_{\mu,e} \rightarrow \nu_x)$ to high precision
2) Determine the pattern of neutrino masses
3) Confirm MSW
4) Extract all of the mixing angles
5) Study CP violation in the lepton sector

Mass Hierarchy and CP Phase

Comparing $\nu_e \rightarrow \nu_\mu, \bar{\nu}_e \rightarrow \bar{\nu}_\mu$ gives both sgn(Δm^2_{32}) and CP phase:

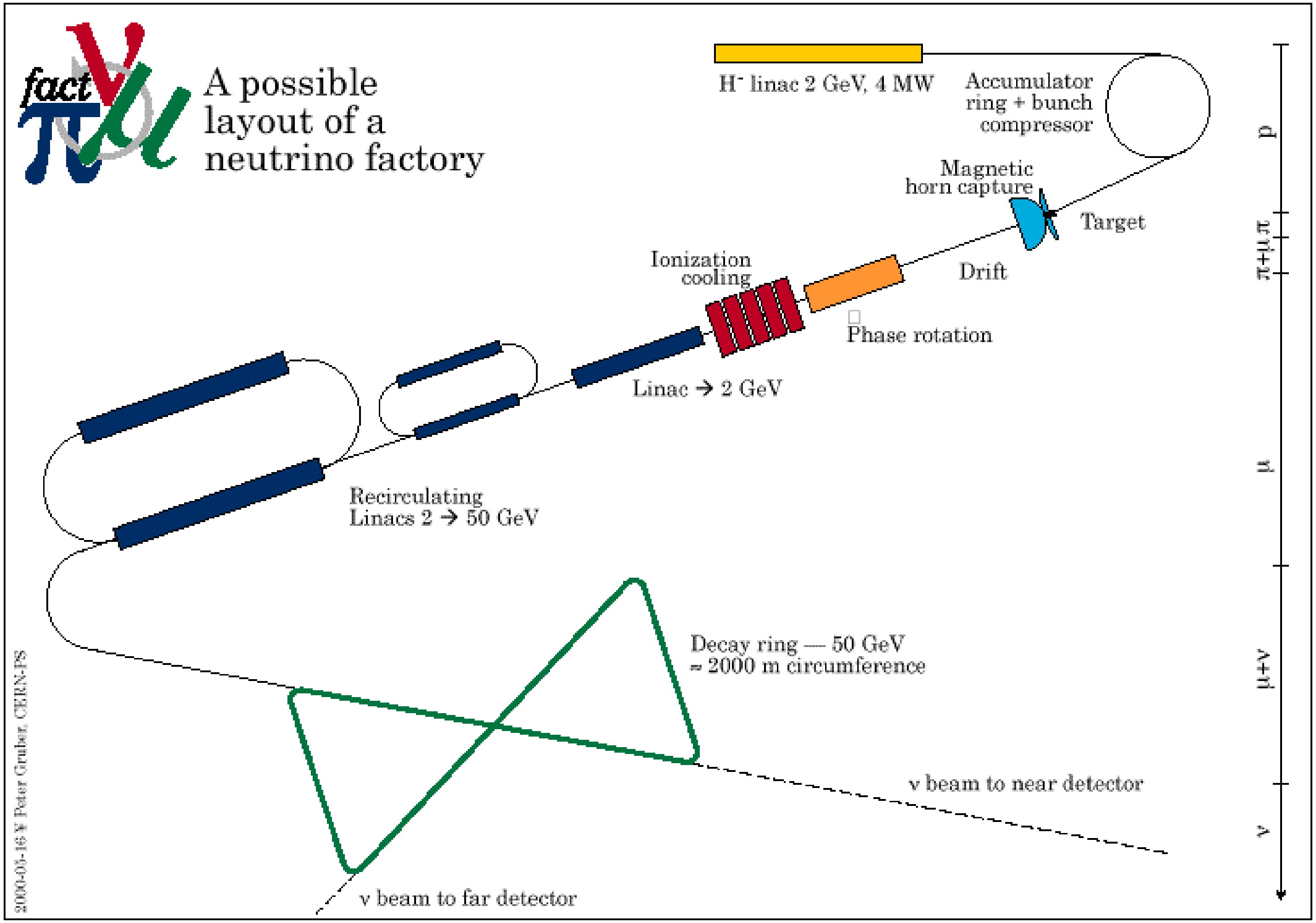




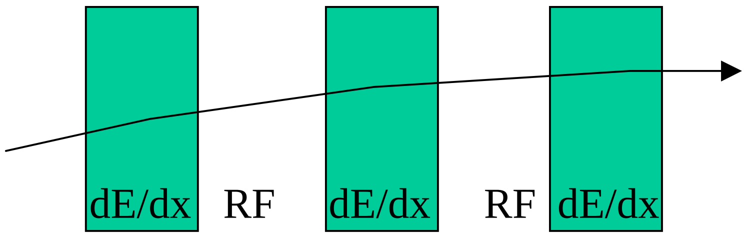
Neutrino Factory Parameters

- Beam Energy - up to 50 GeV
- Beam Intensity - 10^{19} to 10^{21} muon decays per year
- Baseline to Experiments - 500 to 8000 km (two long baseline experiments can be accommodated)

Neutrino Factory Overview



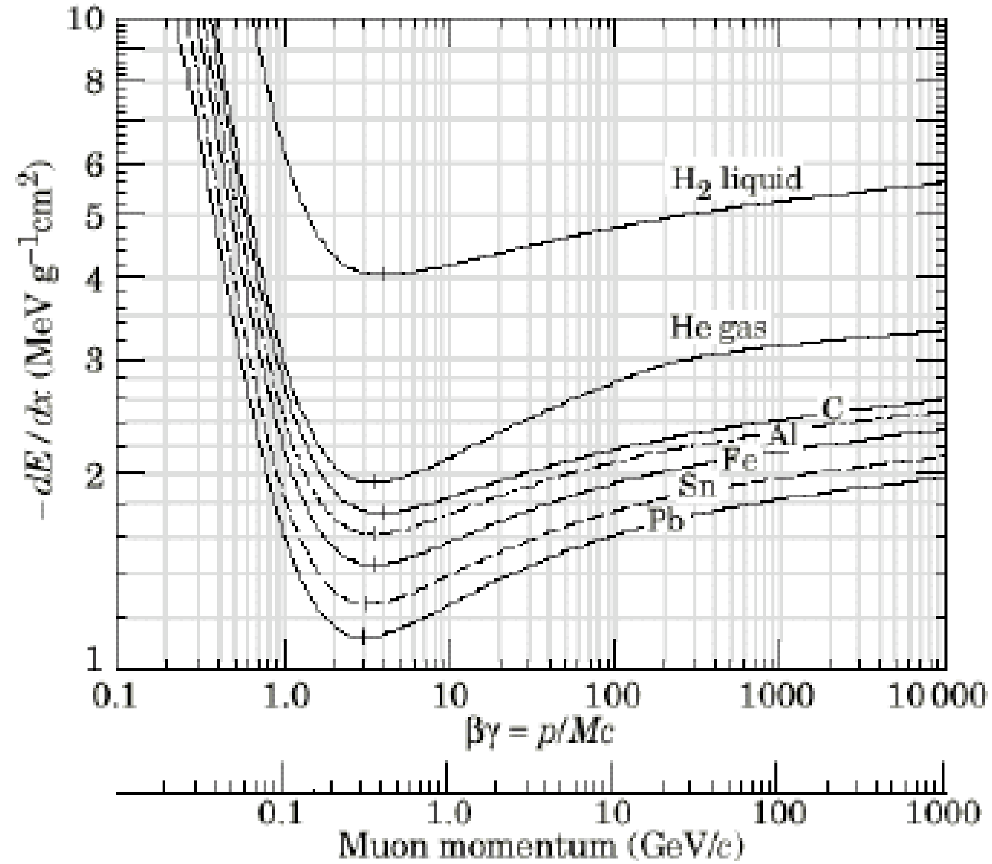
Ionization Cooling: Background



Absorbers remove total momentum,
RF restores longitudinal momentum

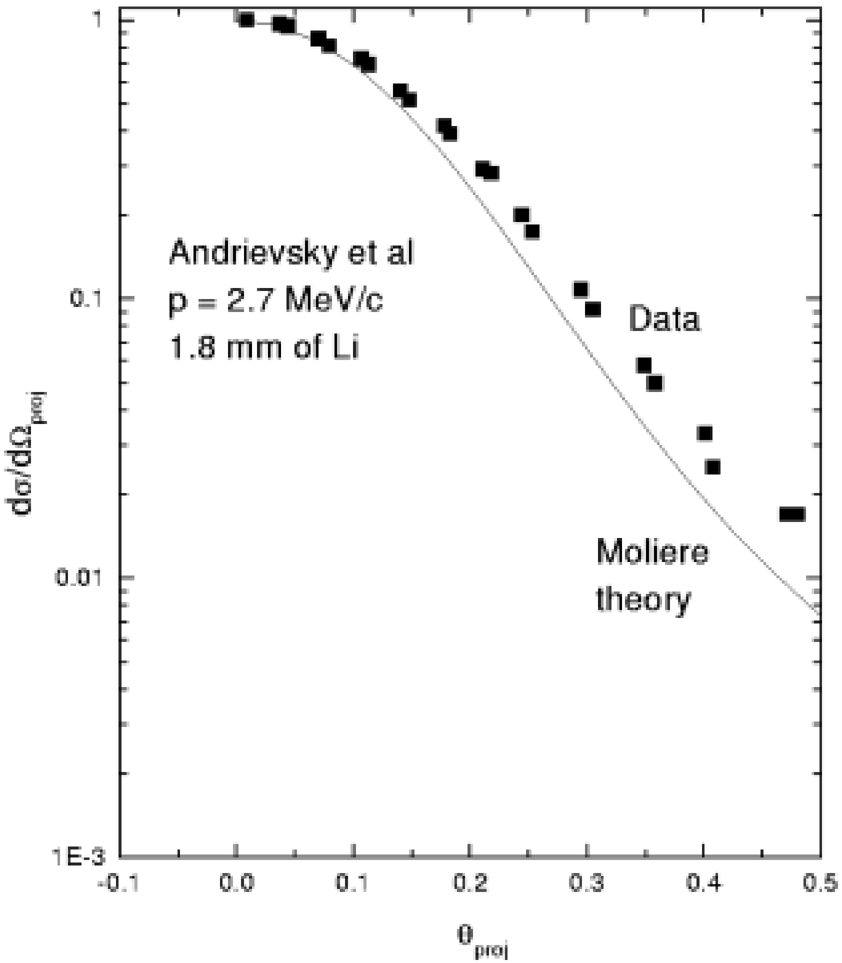
$$\frac{d\varepsilon_n}{ds} \approx -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}$$

Approximation of the cooling relation



In principle ionization cooling should work, but in practice it is subtle and complicated

Multiple Scattering



$$P(\theta) = \frac{1}{\sqrt{2\pi}\theta_0} \exp\left(\frac{-\theta^2}{2\theta_0{}^2}\right) d\theta$$

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta cp} z \sqrt{x/X_0}\left[1 + 0.038 \ln\left(x/X_0\right)\right]$$

- Coulomb scattering
- Dominated by scattering from the nucleus
- Several models, all with an approximately Gaussian core, all are small angle approximations

Muon Ionization Cooling Experiment (MICE)

The aims are to:

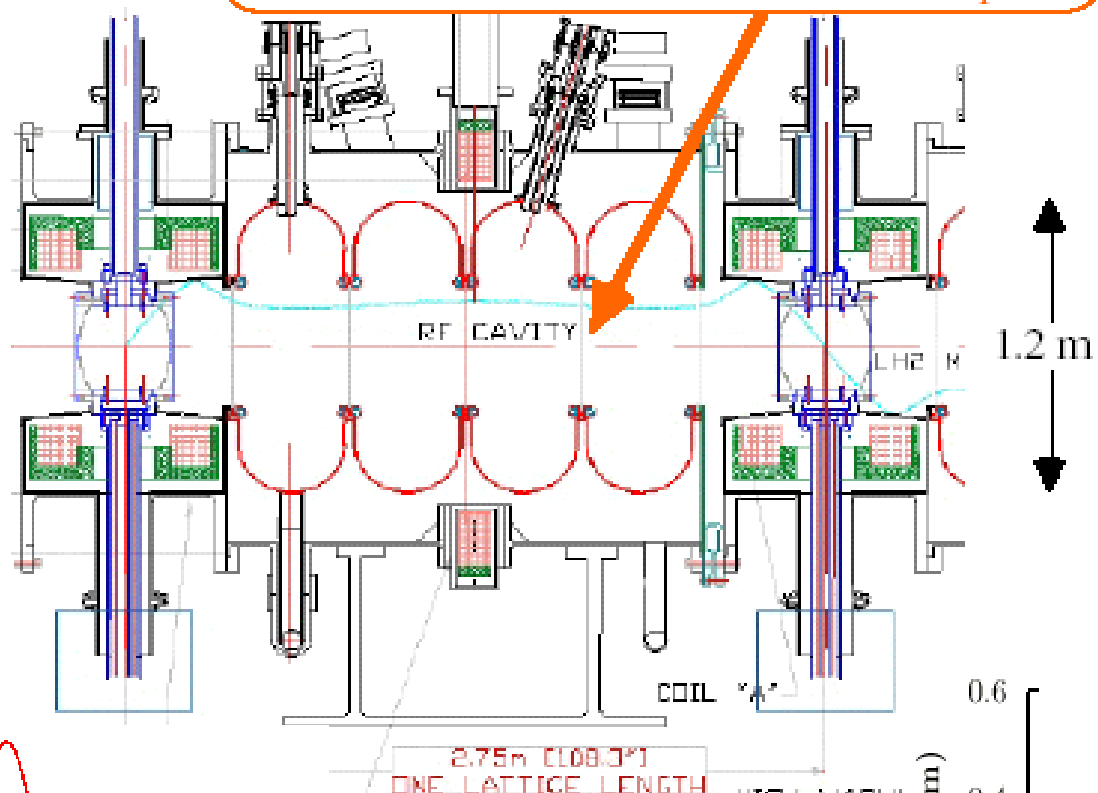
- Engineer the components of a cooling channel
- Demonstrate cooling
- Compare cooling calculations/simulations with experiment (transmission, equilibrium emittance, etc.)

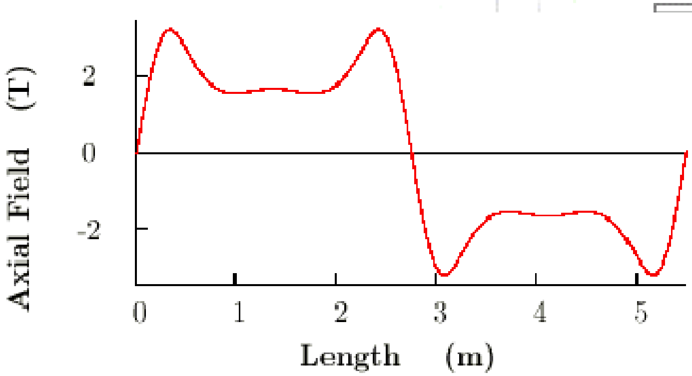
Strategy

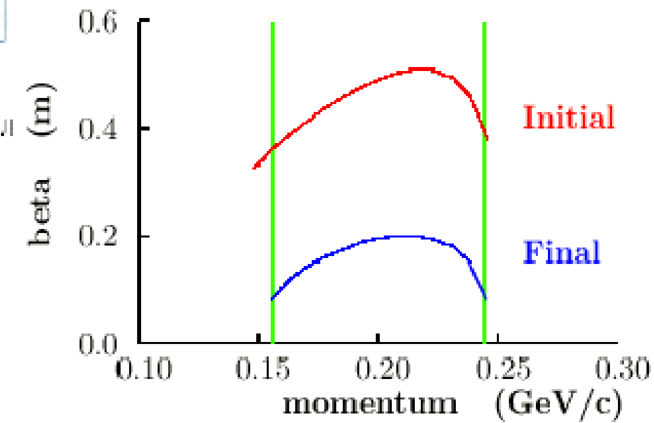
- Build a piece of a cooling channel (three absorbers and two RF sections) and operate it
- Send single particles through the apparatus and measure the incoming and outgoing momenta
- Reconstruct a beam from a large number of single particles

Tapered-SFOFO Cooling Lattice

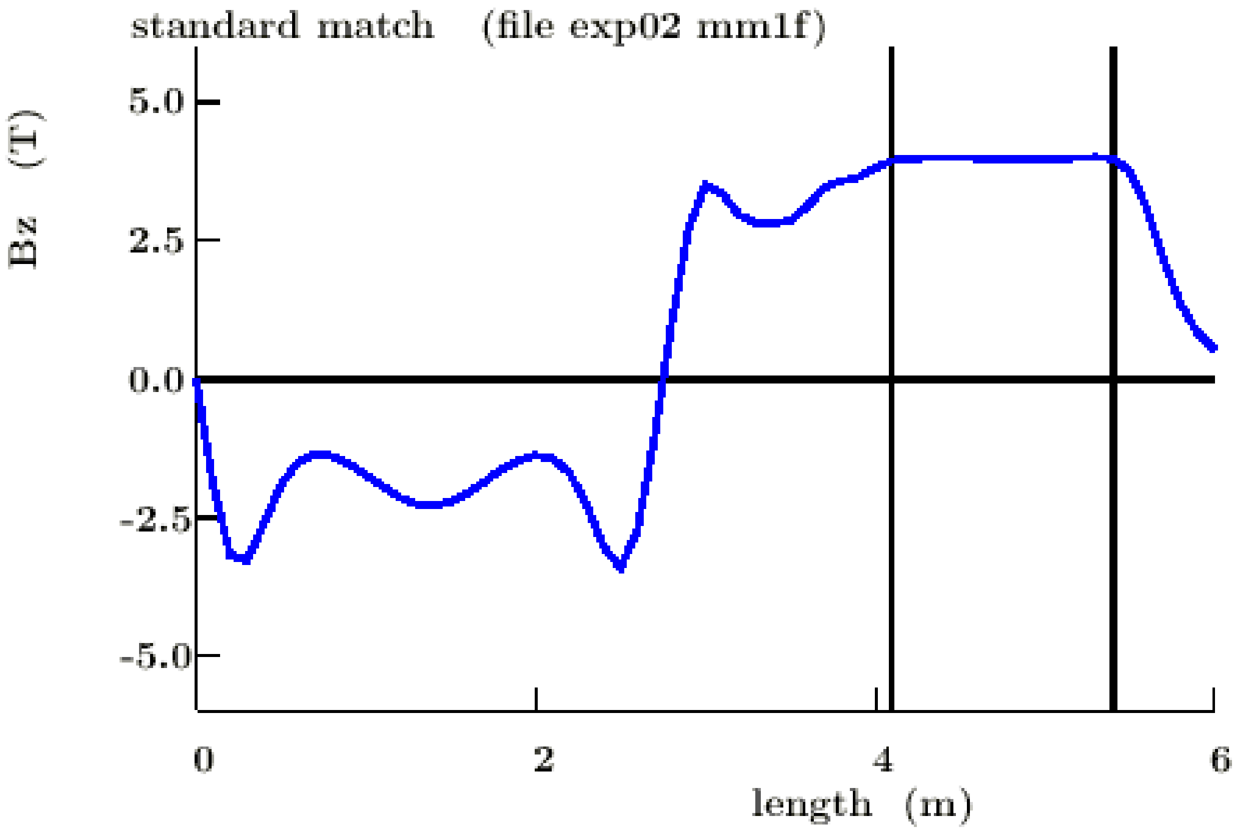
Cavities have thin (≈0.5–1-mm) stepped
Be windows to reduce surf. fields and RF power







MICE Magnetic Field Profile

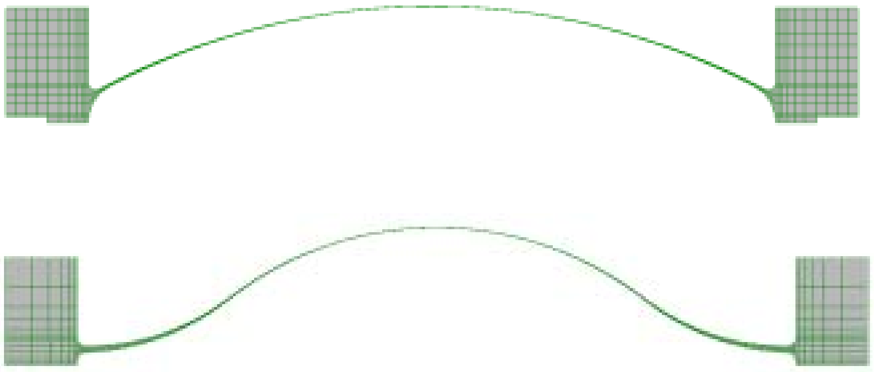


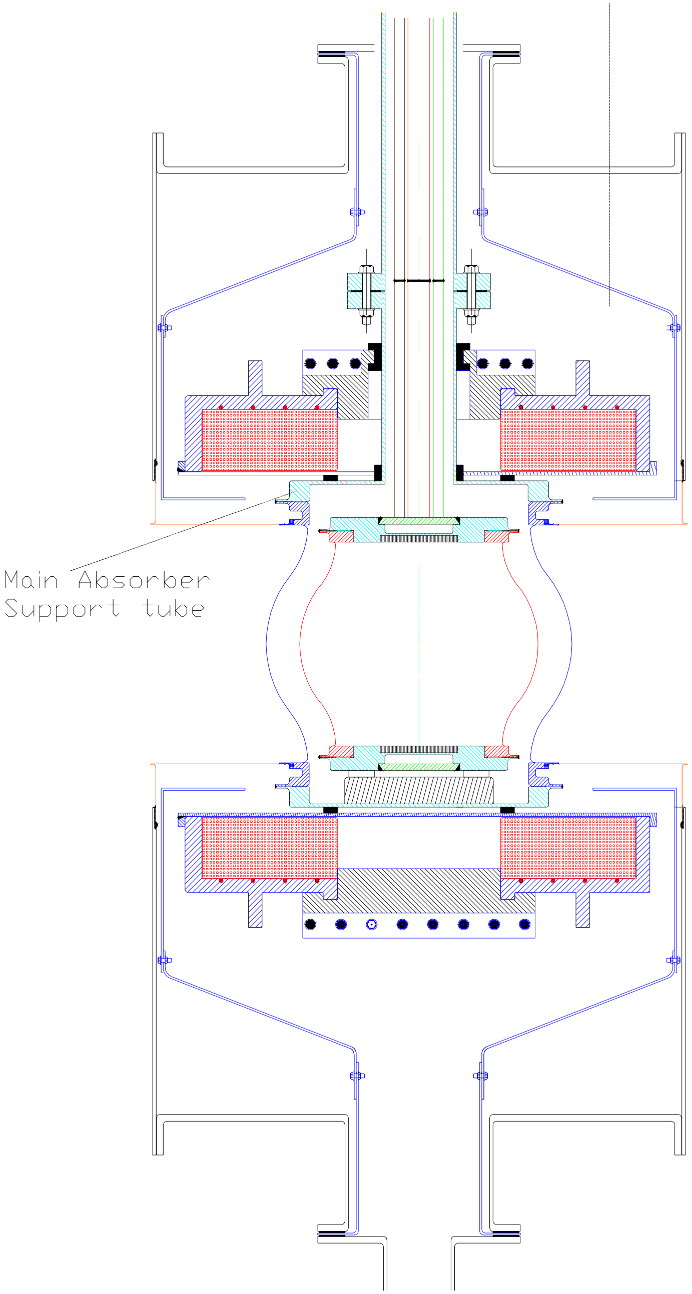
RF System

- Uses 200 MHz for large longitudinal acceptance
- RF is pulsed because it is operating in a high magnetic field
- Tapered four cell cavities with Be windows give performance similar to a Pillbox cavity
- Design gradient of about 15 MV/m is challenging at 200 MHz

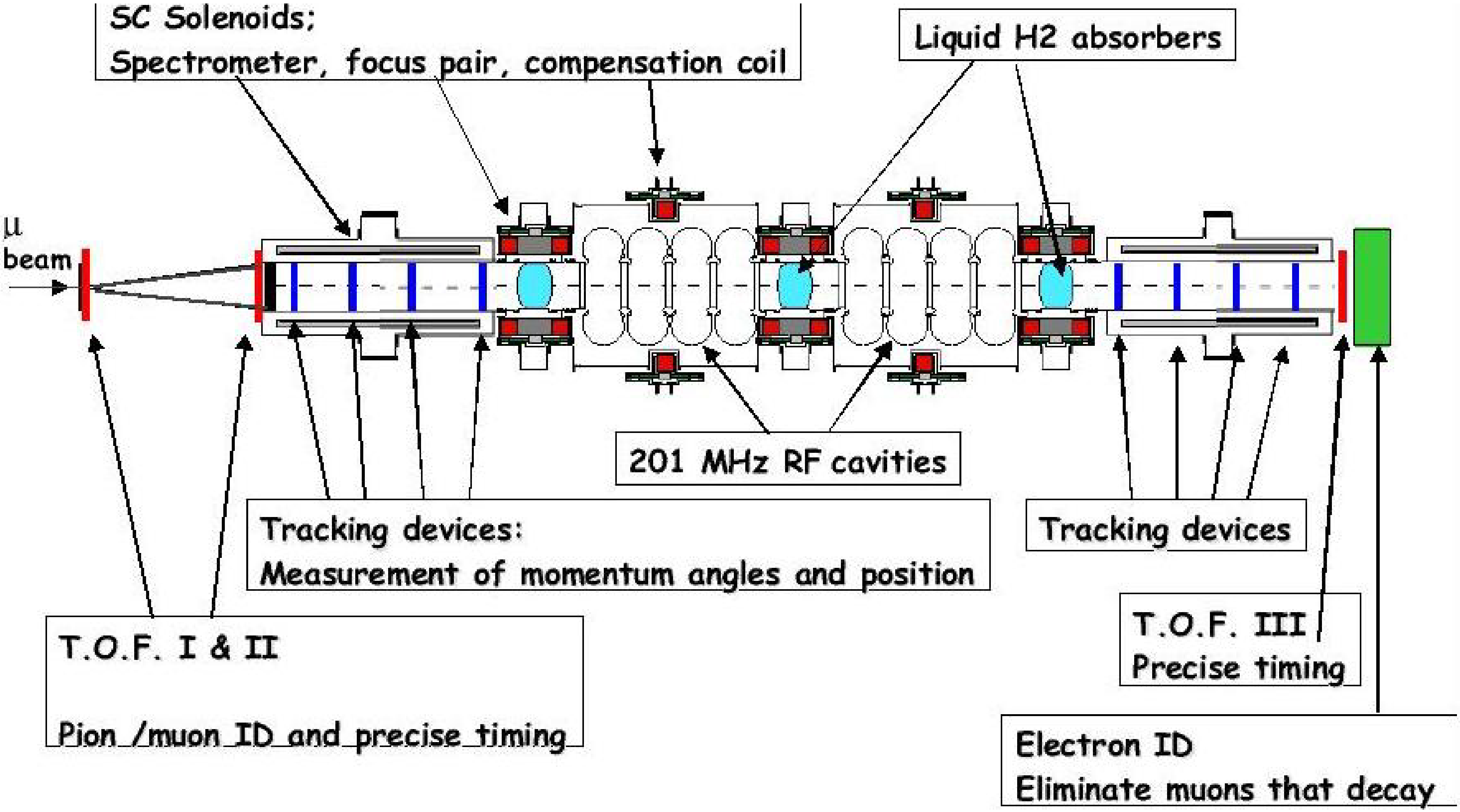
Hydrogen Absorber

- Challenge is to contain the hydrogen with a minimum of material
- Two flow models – convective flow and forced flow
- Being developed by a collaboration of Osaka University, KEK, ICAR (IIT, NIU, Chicago, FNAL)





MICE Experimental Apparatus

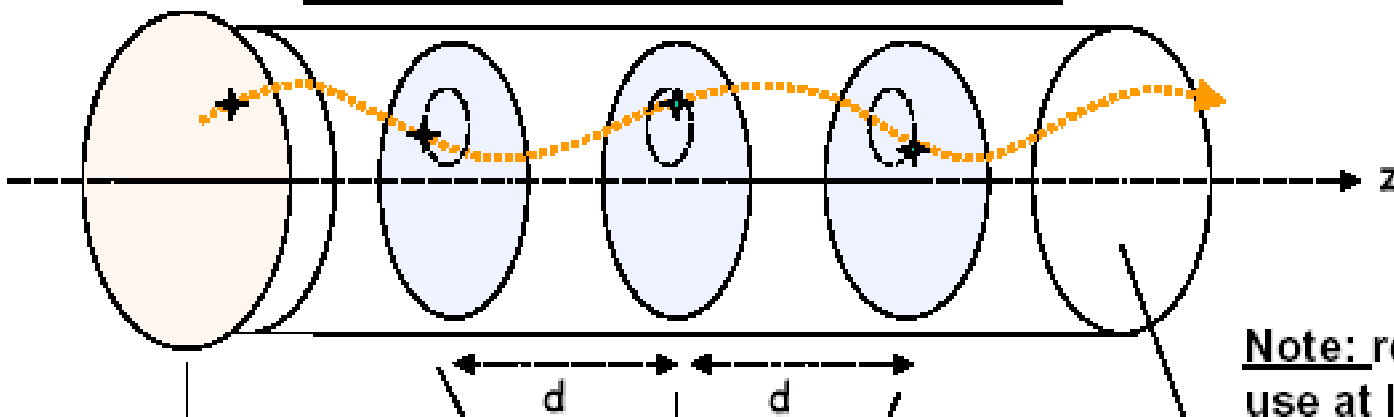


Emittance Measurement

(P. Janot)

Need to determine, for each muon, x,y,t, and x',y',t' (=p_x/p_z, p_y/p_z, E/p_z) at entrance and exit of the cooling channel:

Solenoid, B = 5 T, R = 15 cm, L > 3d (to keep B uniform on the plates)



Note: real set-up will use at least 4 plates for redundancy

T.O.F.
Measure t
With $\sigma_t \sim 70$ ps

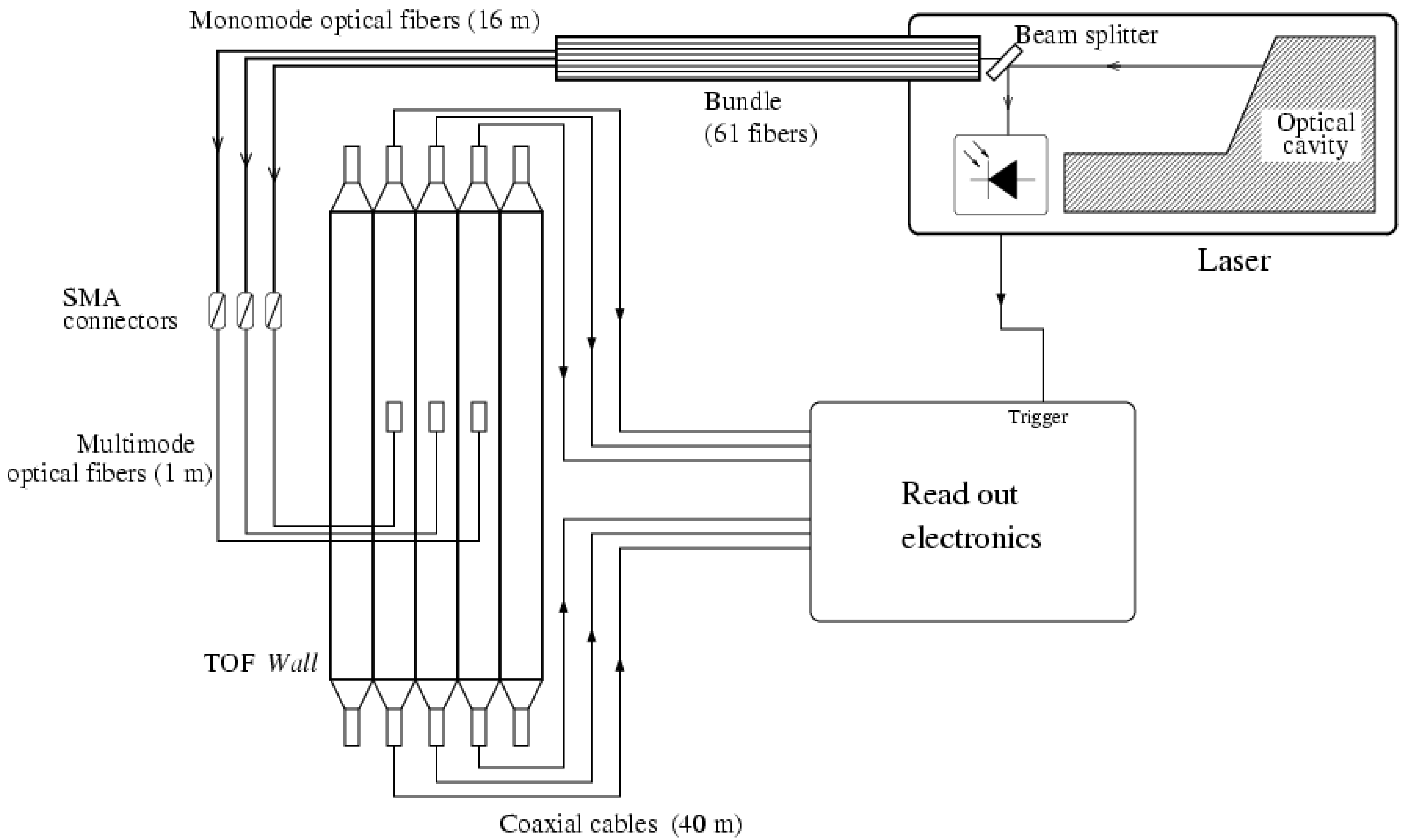
Three plates of, e.g., three layers of sc. fibres (diameter 0.5 mm)
Measure x_1, y_1, x_2, y_2, x_3, y_3 with precision 0.5mm/√12

Extrapolate x, y, t, p_x, p_y, p_z, at entrance of the channel. Make it symmetric at exit.

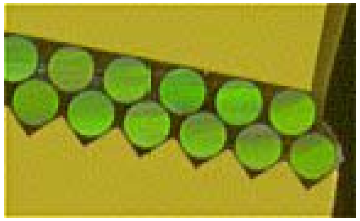
Instrumentation

- TOF – Timing (σ=50 ns) for RF phase measurement and upstream π/μ
- Cerenkov – Threshold counter for downstream e/μ separation
- Electromagnetic Calorimeter – alternate downstream particle ID
- Tracking – Measures particle position and momentum

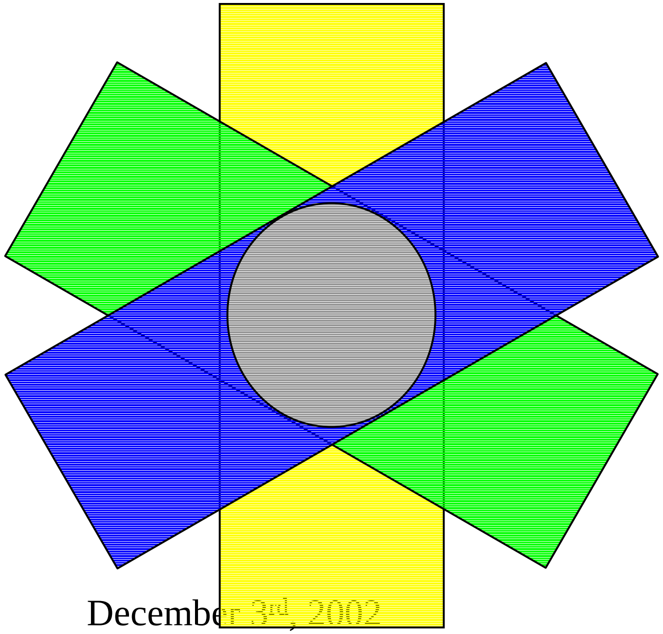
TOF Calibration System



Fiber Tracker Layout



(A. Bross)

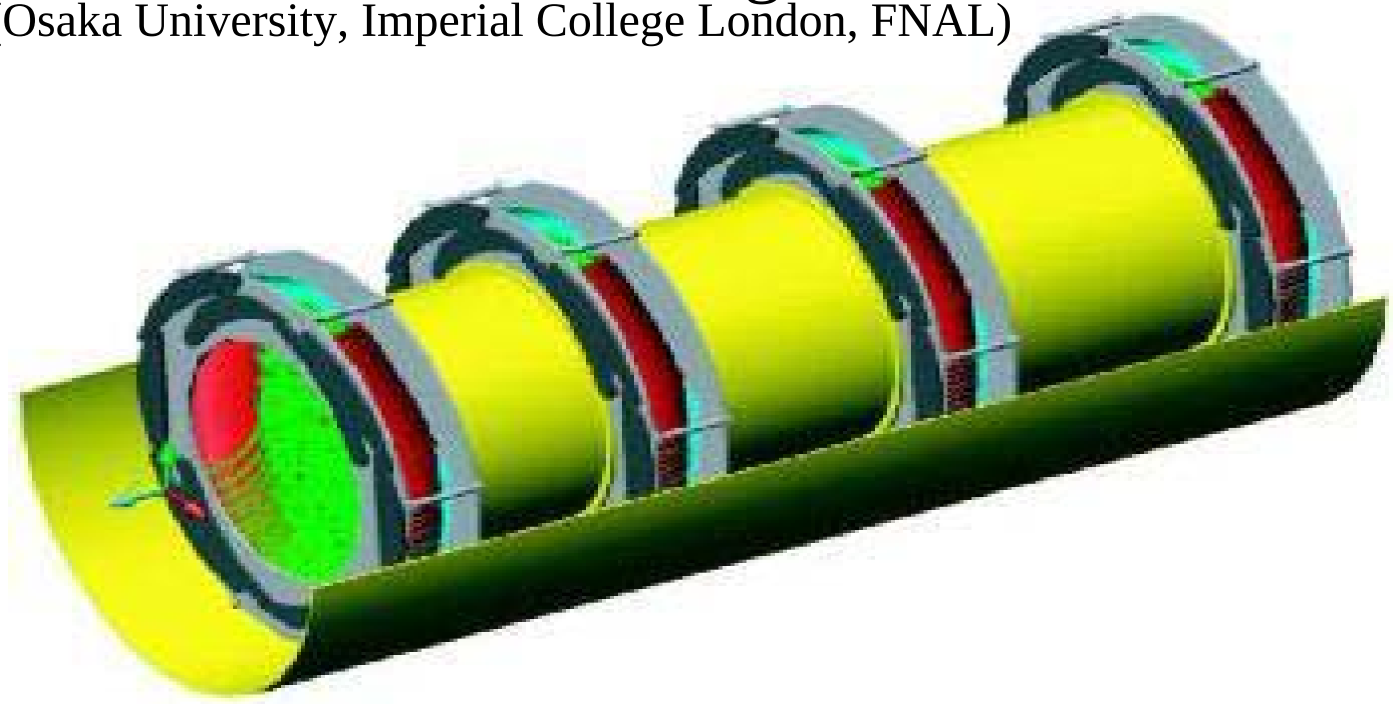


- Layout based on 0.35 mm or 0.50 mm round doubly clad fibers with a doublet layer structure
- Three layers of doublets crossed at 120º provide an active area of 30 cm diameter
- There are a total of 4286 (3000) fibers per detector plane
- 0.3% (0.4%) X_0 per plane with a resolution of about 40 μm (extrapolated from the measured resolution in D0)
- Two trackers of four stations each have been simulated in a 5T constant solenoidal field

Tracking

The baseline design is a scintillating fiber tracker based on the D0 design

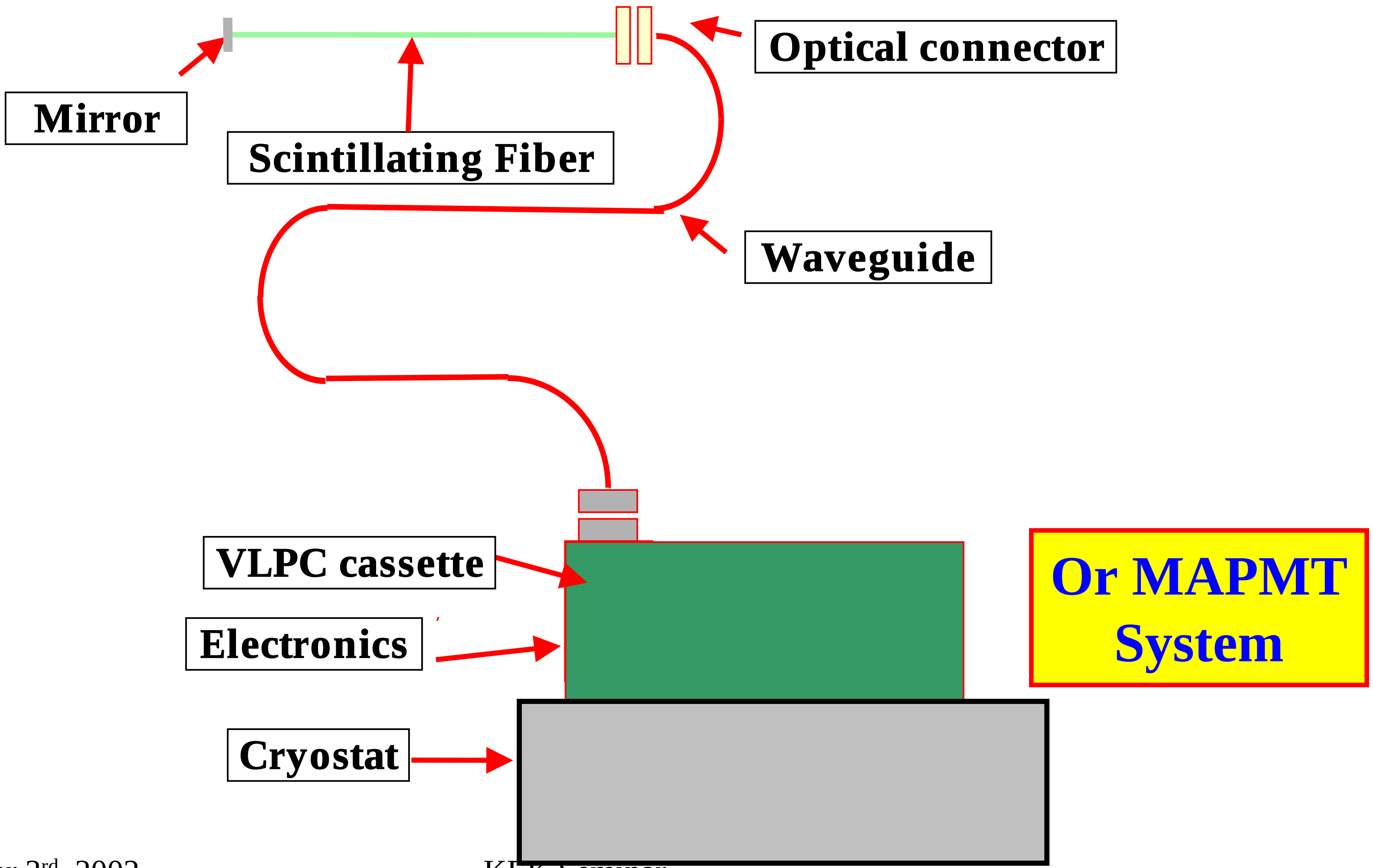
(Osaka University, Imperial College London, FNAL)



An alternative design based on a TPC with GEM amplification and strip readout is being studied

Readout Schematic

(A. Bross)

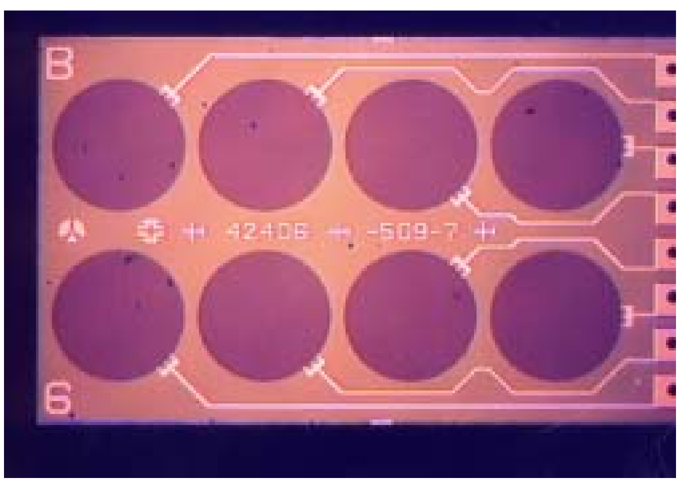


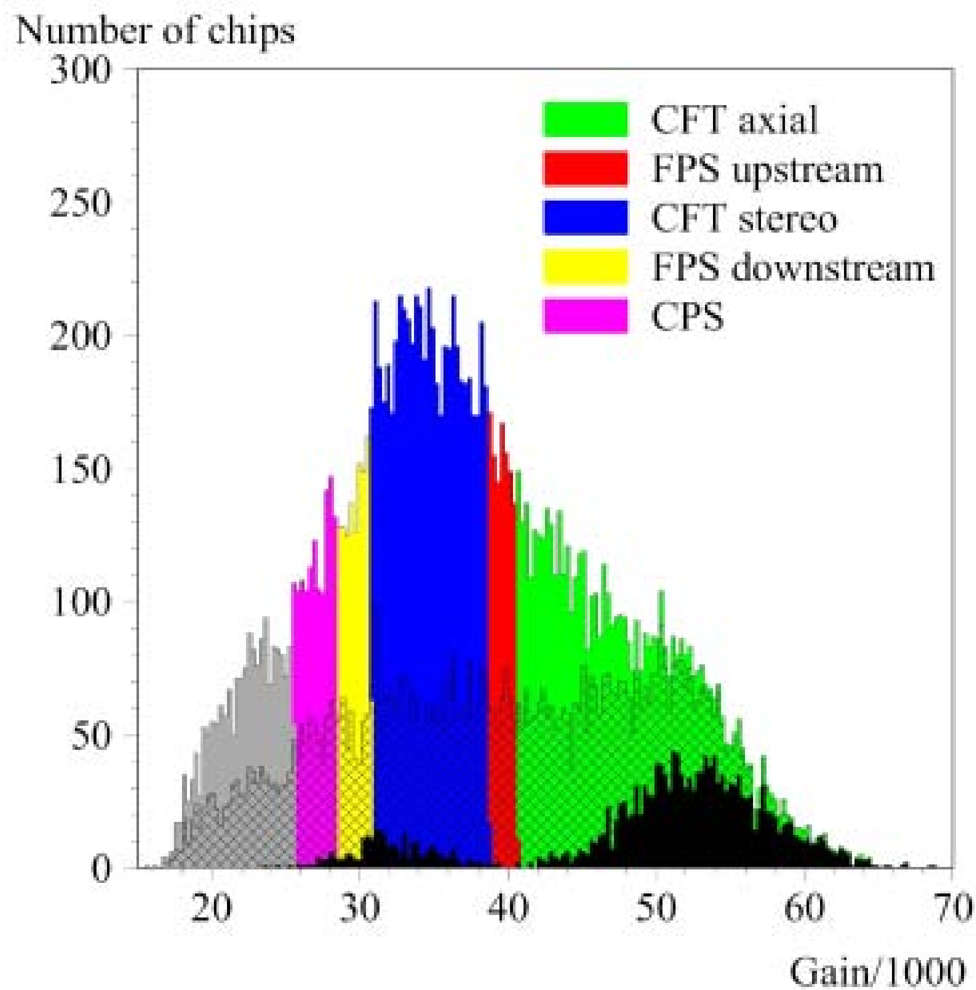
MA-PMT Readout

- A well understood and reliable technology
- Front-end electronics could be based on ASD/AMT system
- Pixel based PMT (Hamamatsu R5900 series)
- Need to optimize fiber thickness so that we have sufficient light yield
- Need to shield from magnetic fields

VLPC
(A. Bross)

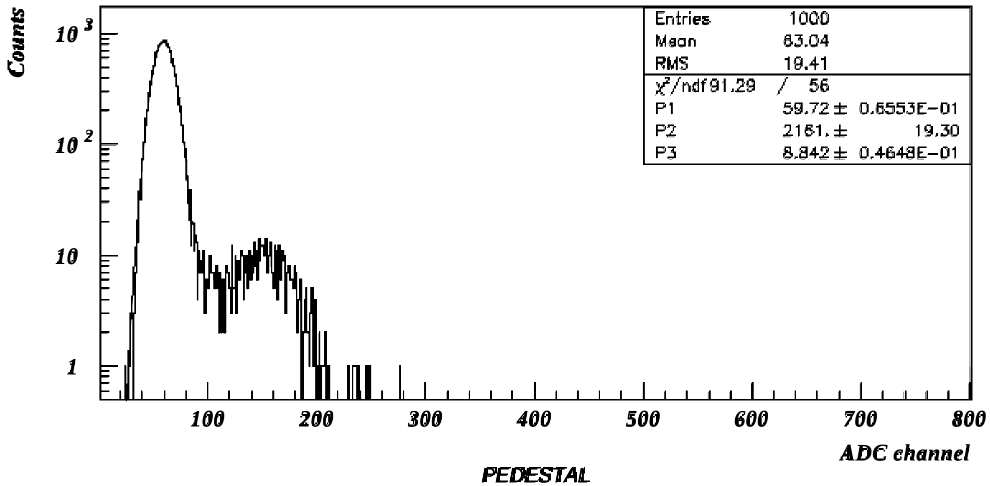
- VLPC (Visible Light Photon Counter)
  - Cryogenic APD operating @ 9K
- Characterization/test/sort Cassette Assignment
  - As shown

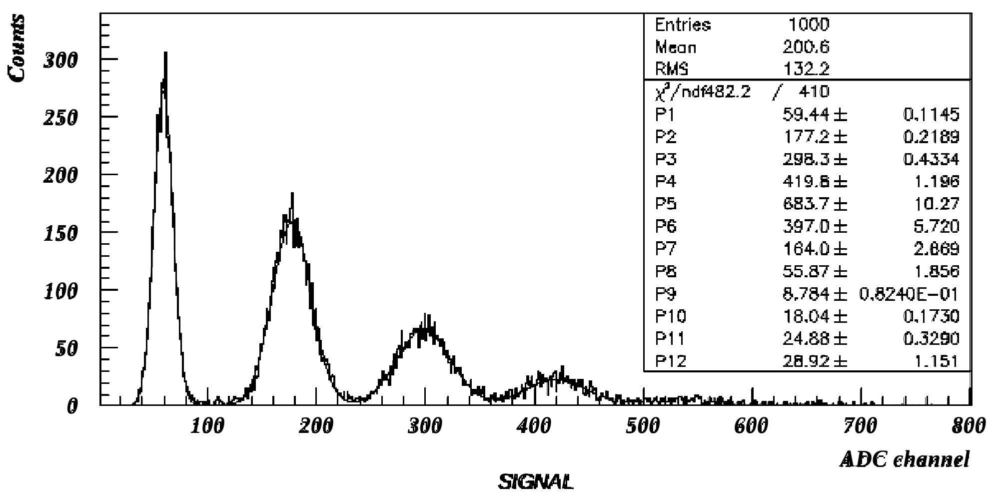




VLPC Performance

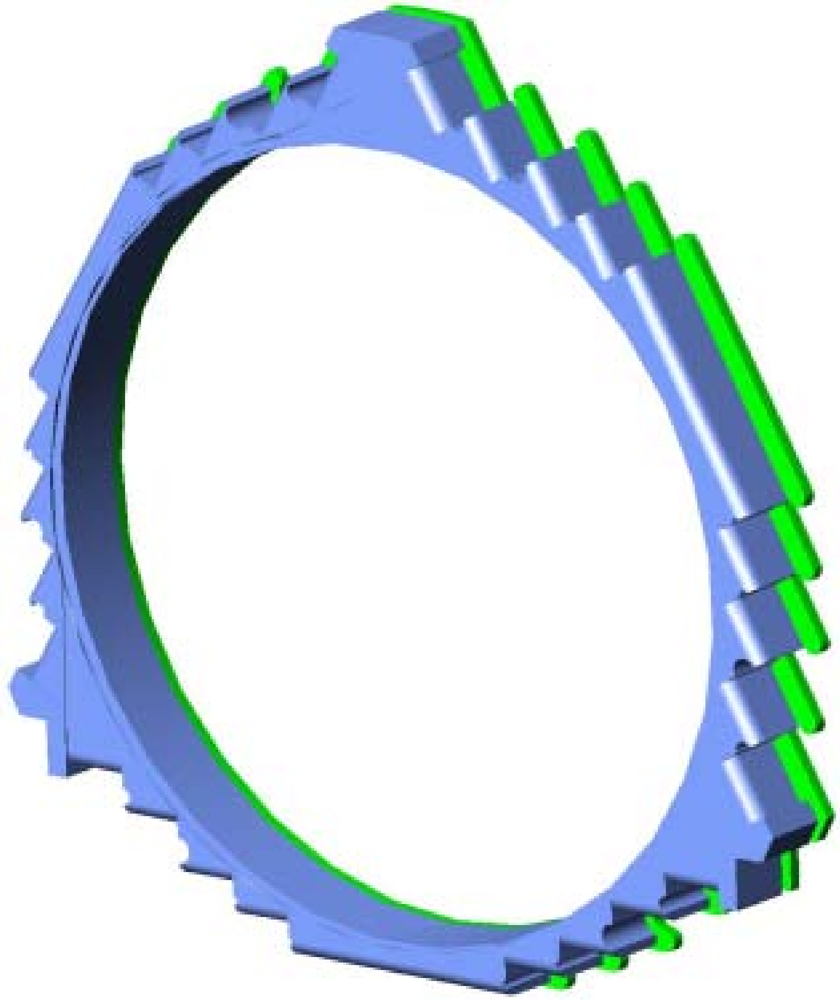
(A. Bross)

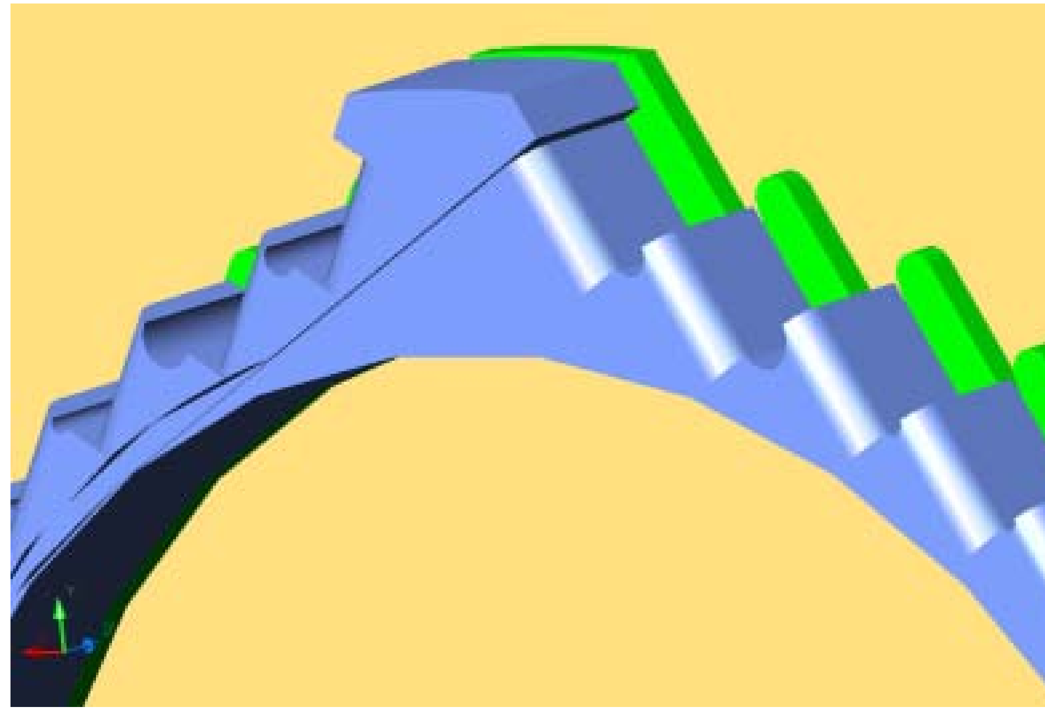




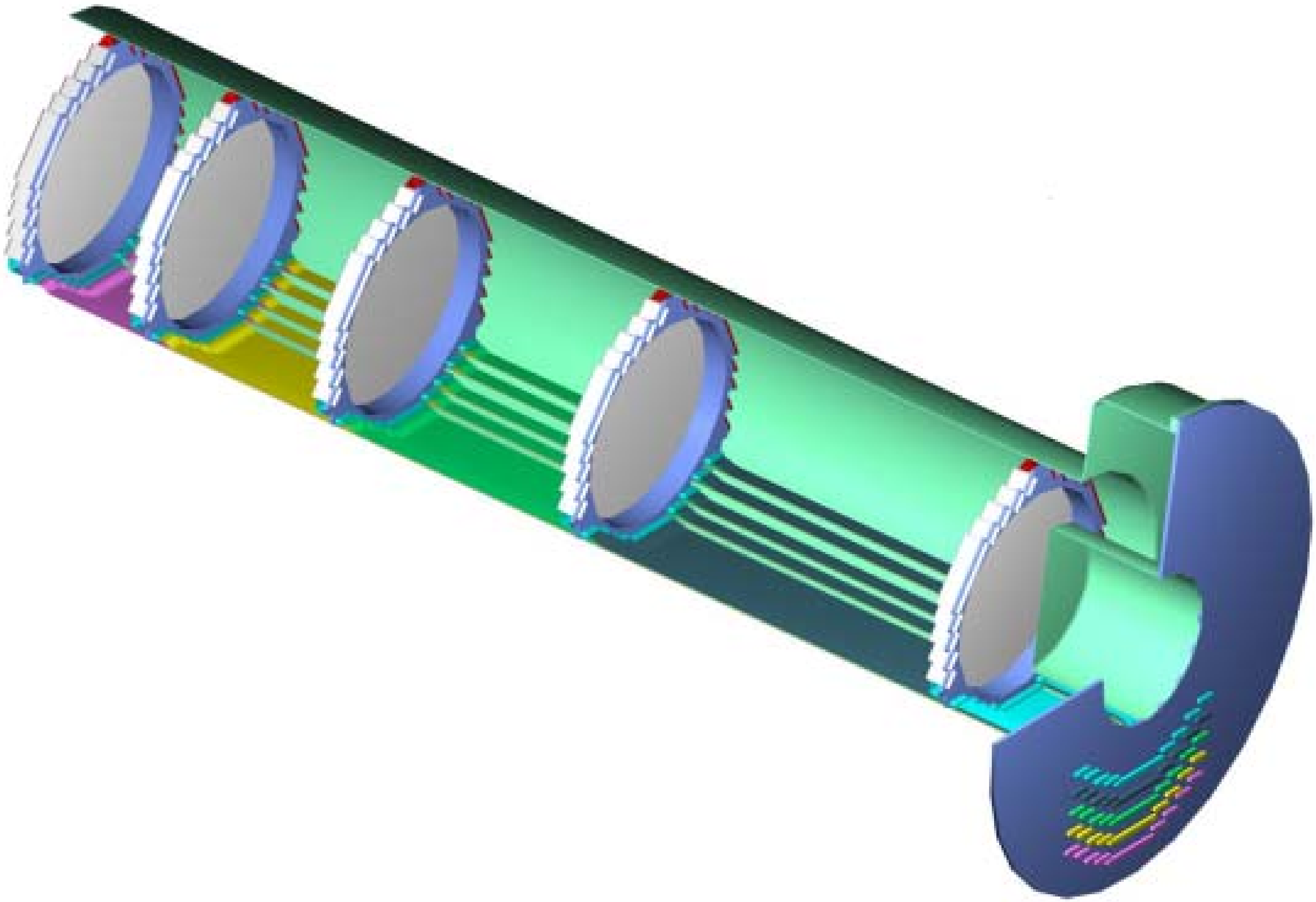
- VLPC → HISTE VI
  - High QE ≈ 80%
  - Low noise <$5X10^4$ Hz (@≈1.0 pe)
  - High Rate capability
    - >40 MHz
  - High production yield
    - □ ≈ 70%
      (vs. 27% projected)

SciFi Tracker Station

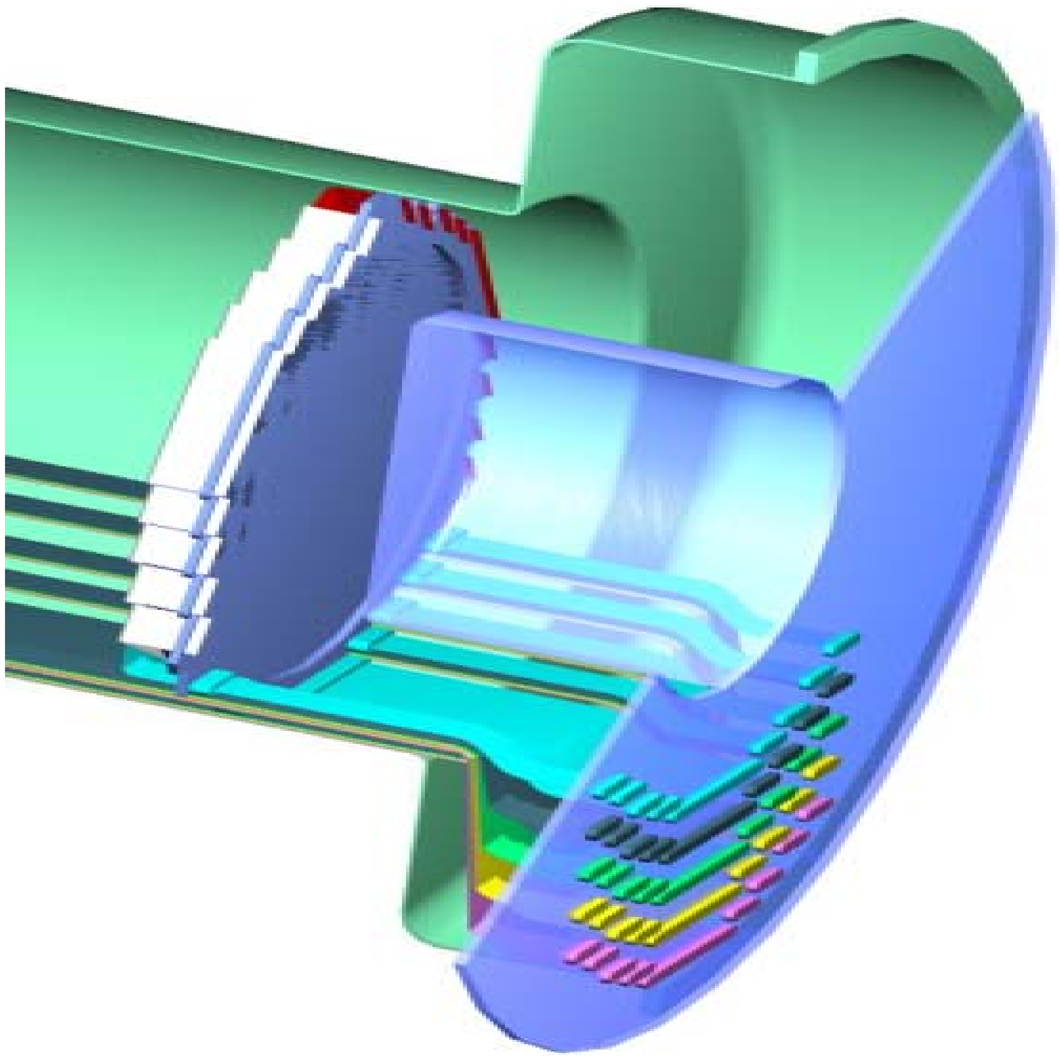




Five Station Tracker Layout

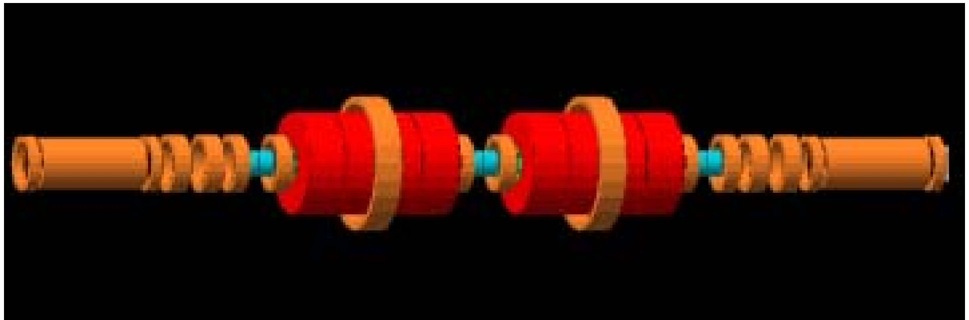


Endplate Detail



MICE Simulation

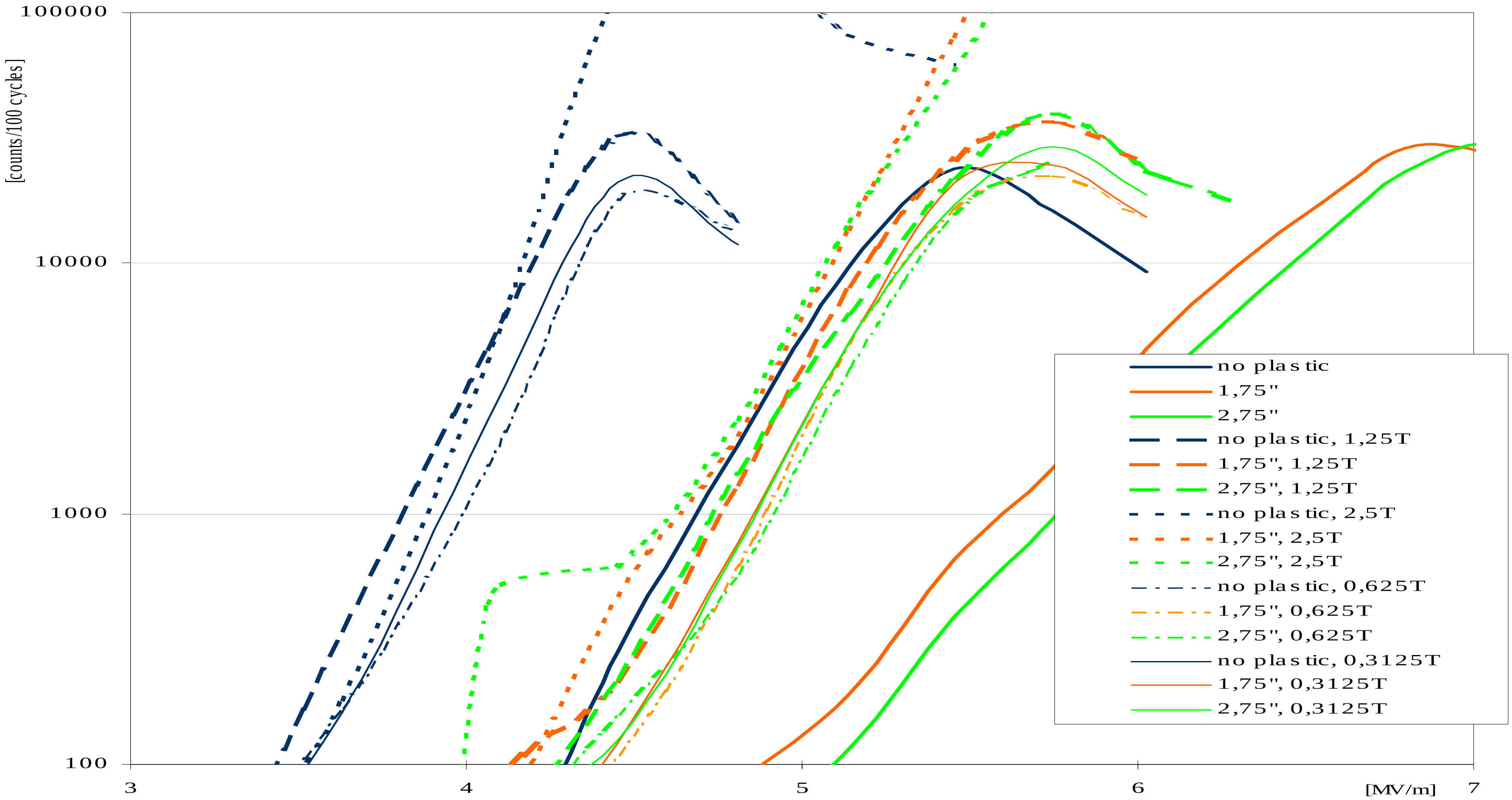
- Complete cooling channel lattice, including Pb blocks, absorbers, vessels, magnet coils, RF cavities, windows of correct shape, position and number in GEANT4.
- BeamTools (a Fermilab package) used to make magnet field maps from thin current sheets and time dependant electric fields in RF cavities.
- Beam Simulation includes contamination, dp/p...
- RF induced background simulation
- Relevant physics (dE/dx, multiple scattering, etc)



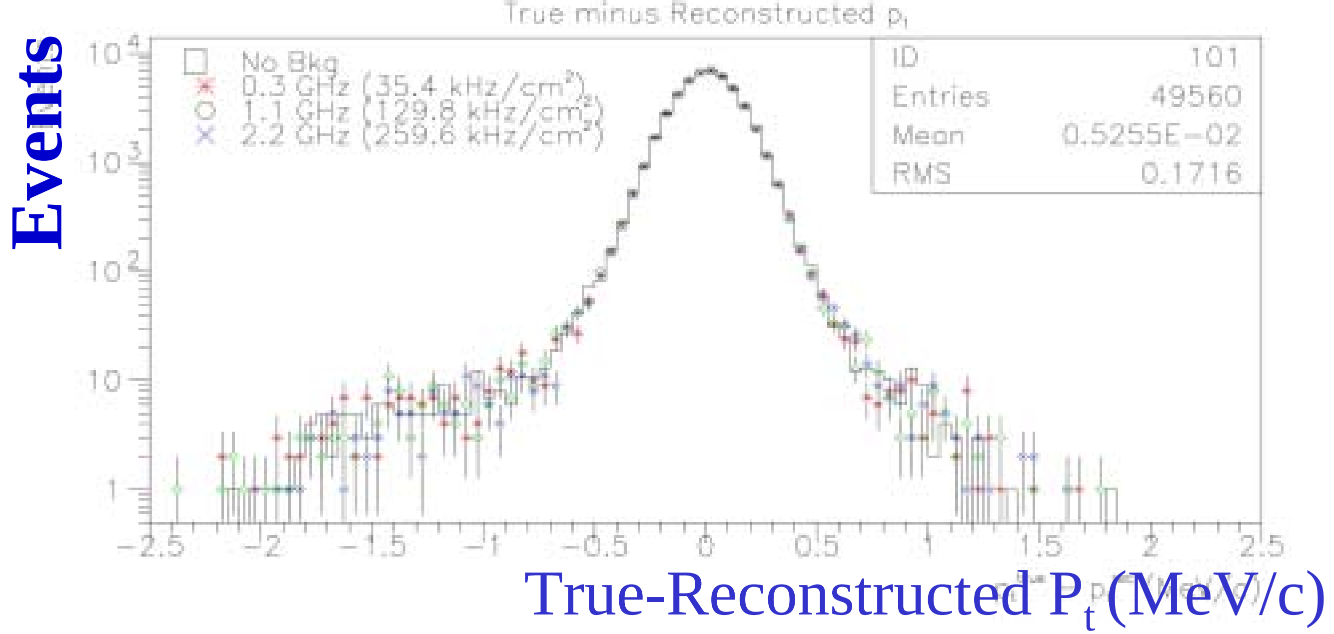
Source of Background in MICE

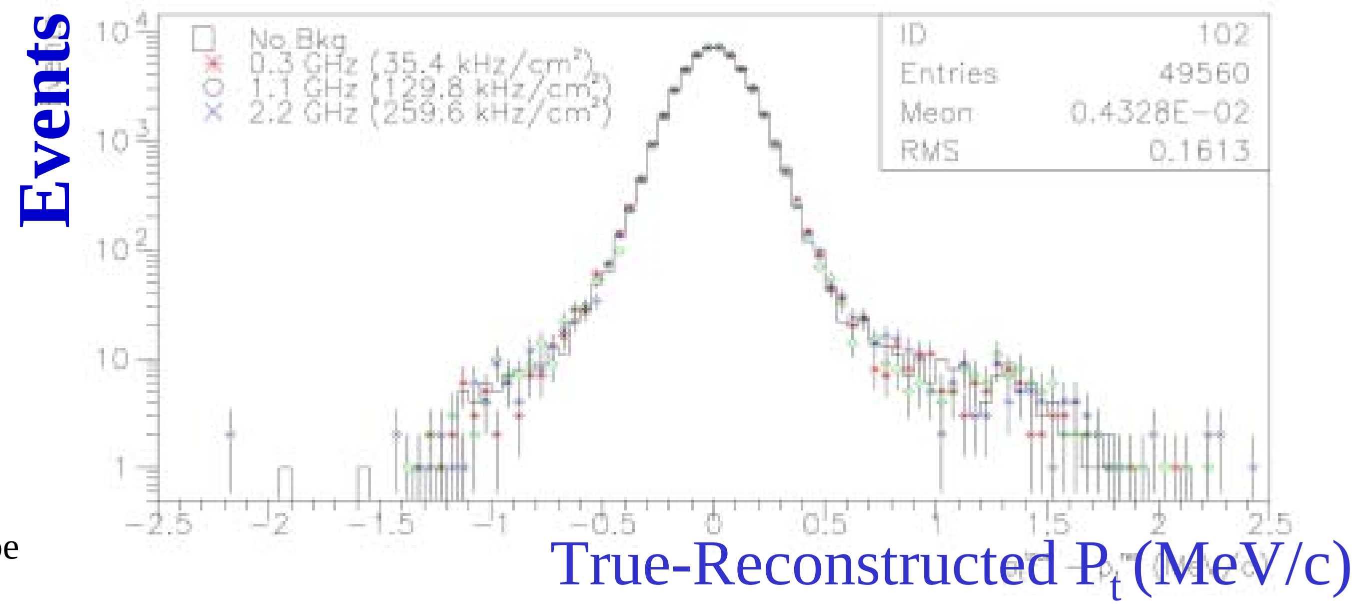
- The dominant source of background in MICE is radiation from the RF cavities
- This radiation is produced by field emission of electrons from the cavities followed by acceleration of the emitted electrons
- The electrons also produce photons when they strike material
- Hits from these backgrounds can mimic muon hits and the rate is potentially very large
- This is being studied at Lab G with 801 MHz cavities

X-ray Background

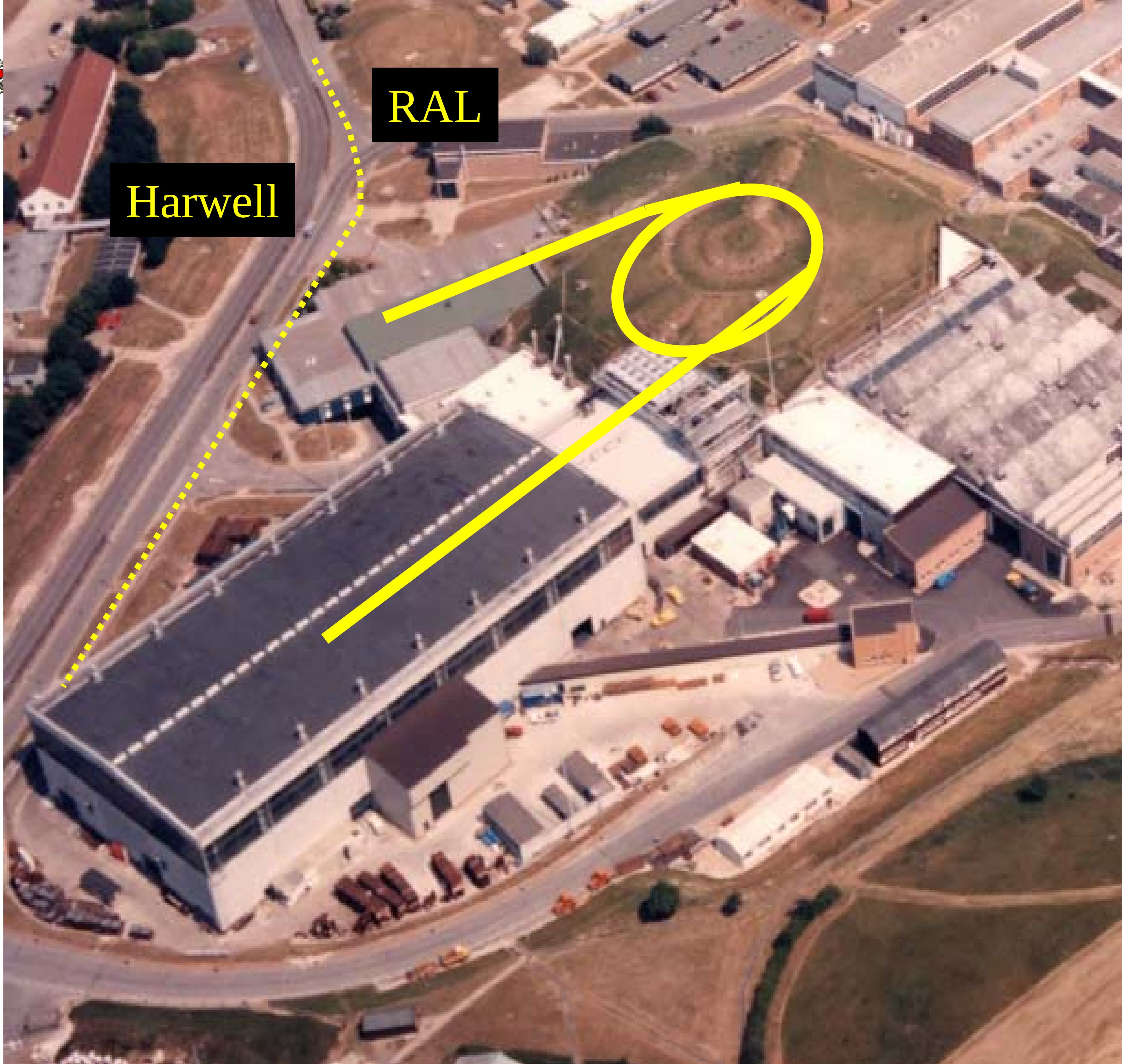


Transverse Momentum Resolution

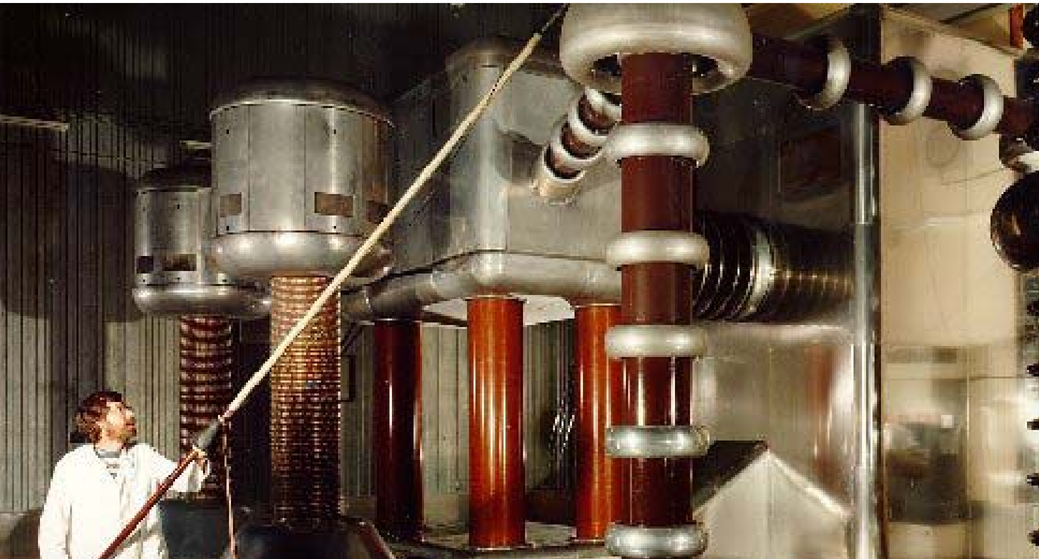


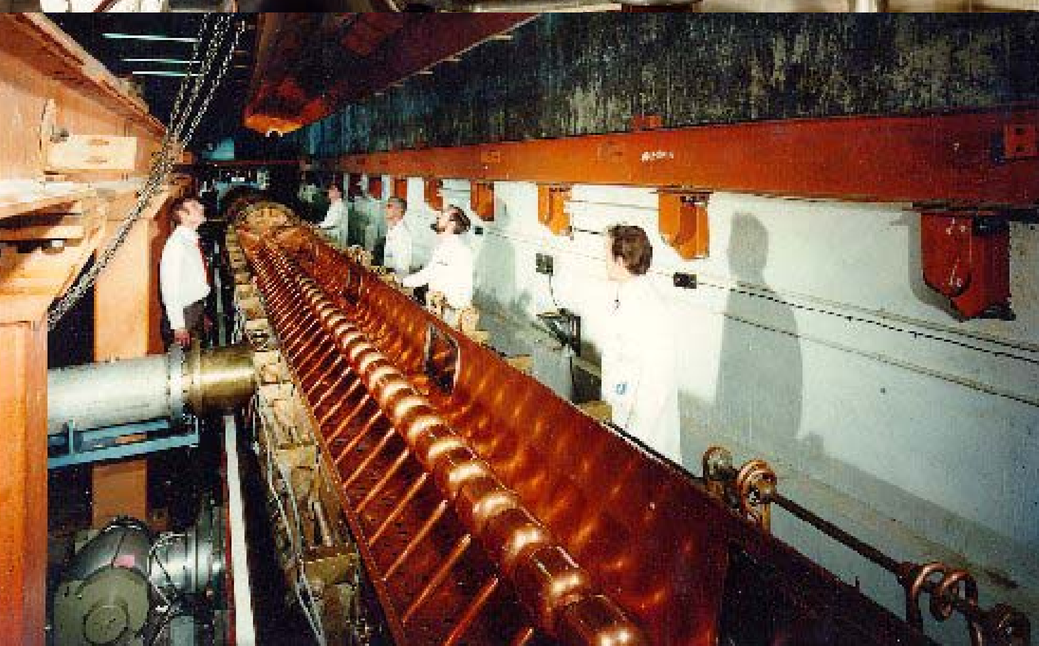


ISIS



ISIS Complex





ISIS Internal Target

Performance Requirements

(P. Drumm)

Momentum Range:

Muons: 170 – 390 MeV/c

(Pions: < 700 MeV/c backwards decay)

dp/p ~ 10%

Purity:

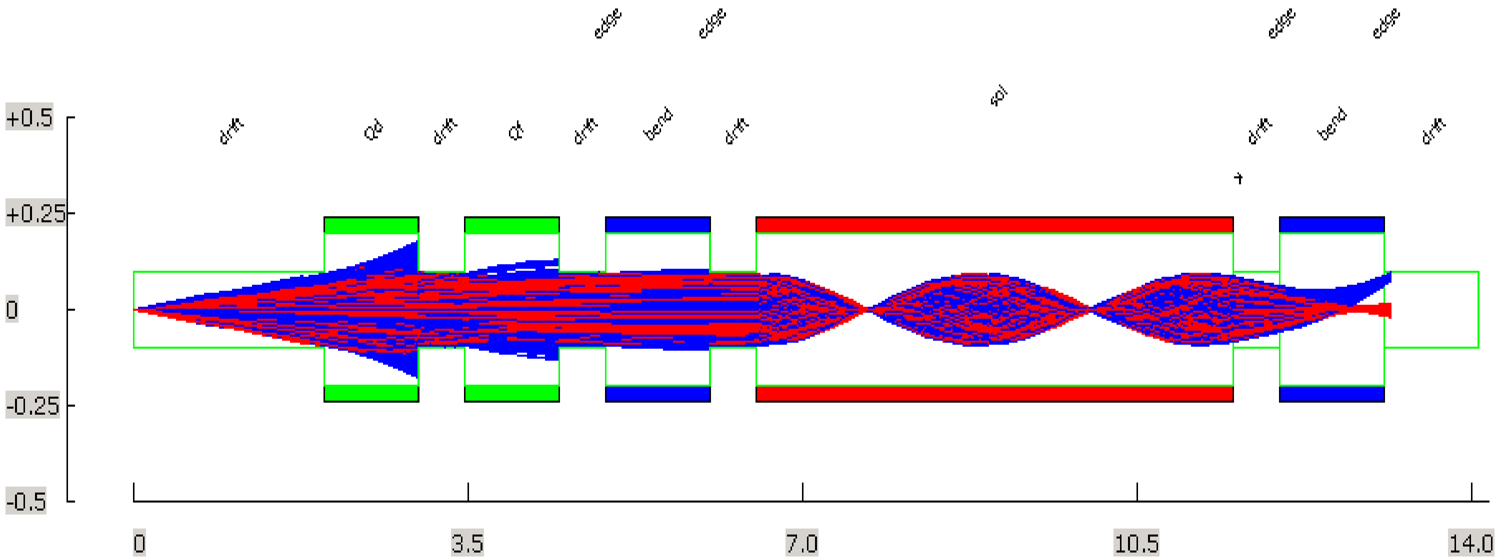
Clean ⇨ R(μ) » R(π) | R(p)

Rates:

Few muons per μs

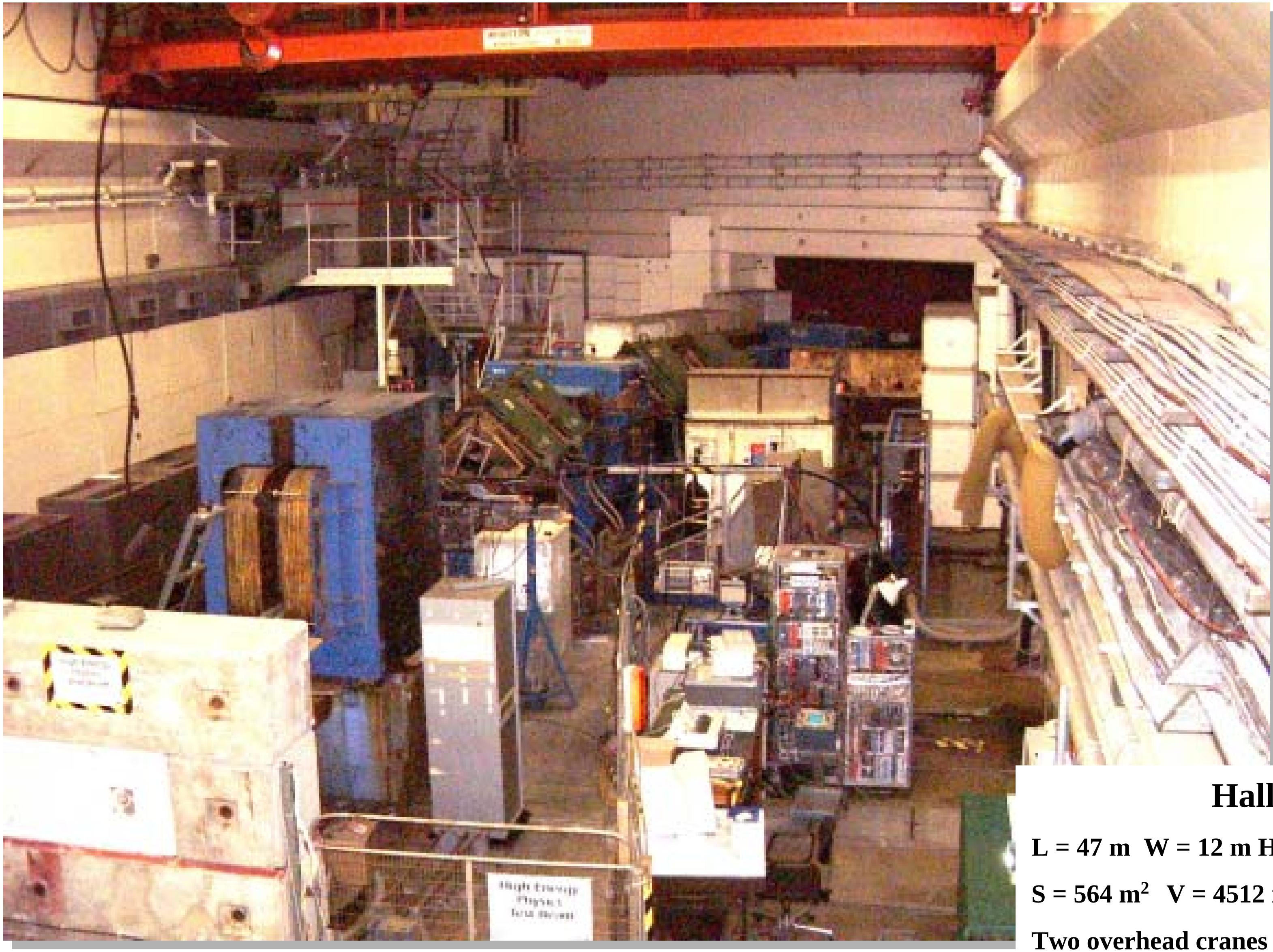
Proton/Pion Transport

(P. Drumm)



10% Δp/p

Experimental Hall



Hall:

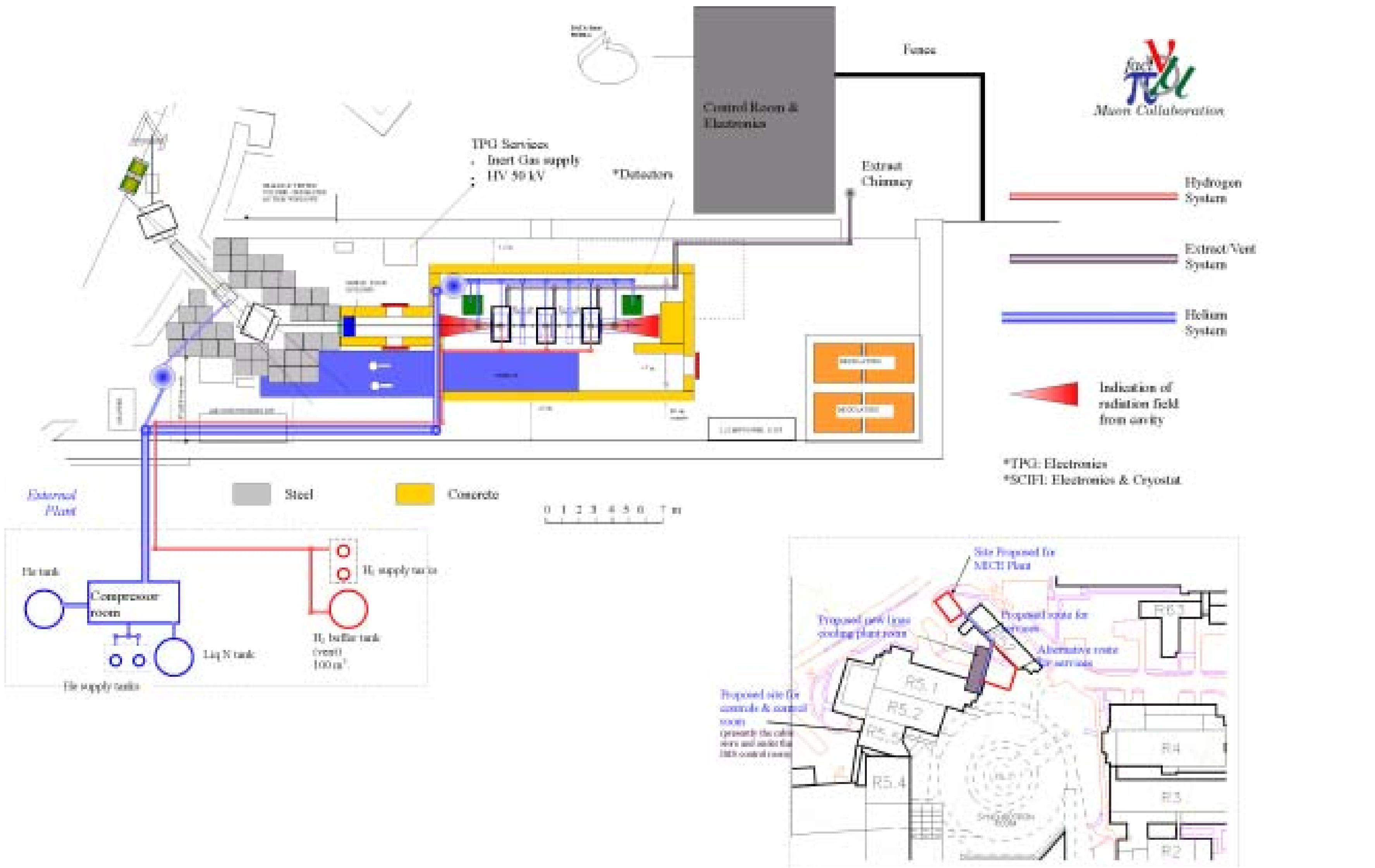
L = 47 m W = 12 m H = 8 m

S = 564 m^2 V = 4512 m^3

Two overhead cranes (8 tonnes each)

MICE Layout

(I. Ivaniouchenkov)



Status of MICE

- A prototype fiber tracker is being tested in beam at KEK
- A letter of intent was submitted to the Rutherford Appleton laboratory in the UK and this resulted in a request for a proposal
- The proposal is being prepared and will be submitted on December 15th
- Design and simulation of the experiment is continuing…