The MICE Experiment

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Outline

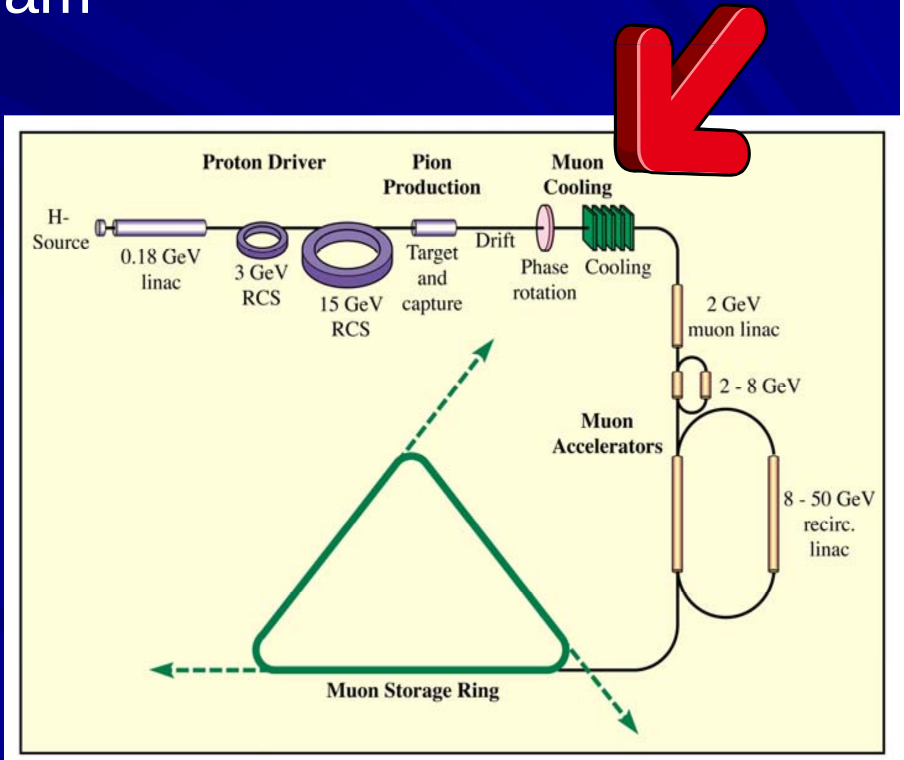
- Introduction
- What is MICE?
  - Beamline
  - What we have now
  - What we will have in time
- Diagnostics for MICE
  - Detectors
    - TOF
    - Tracker
    - CKOV
- Conclusions

Future Neutrino Beams:
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

- 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**
  - Detector designs



Neutrino Factory at RAL

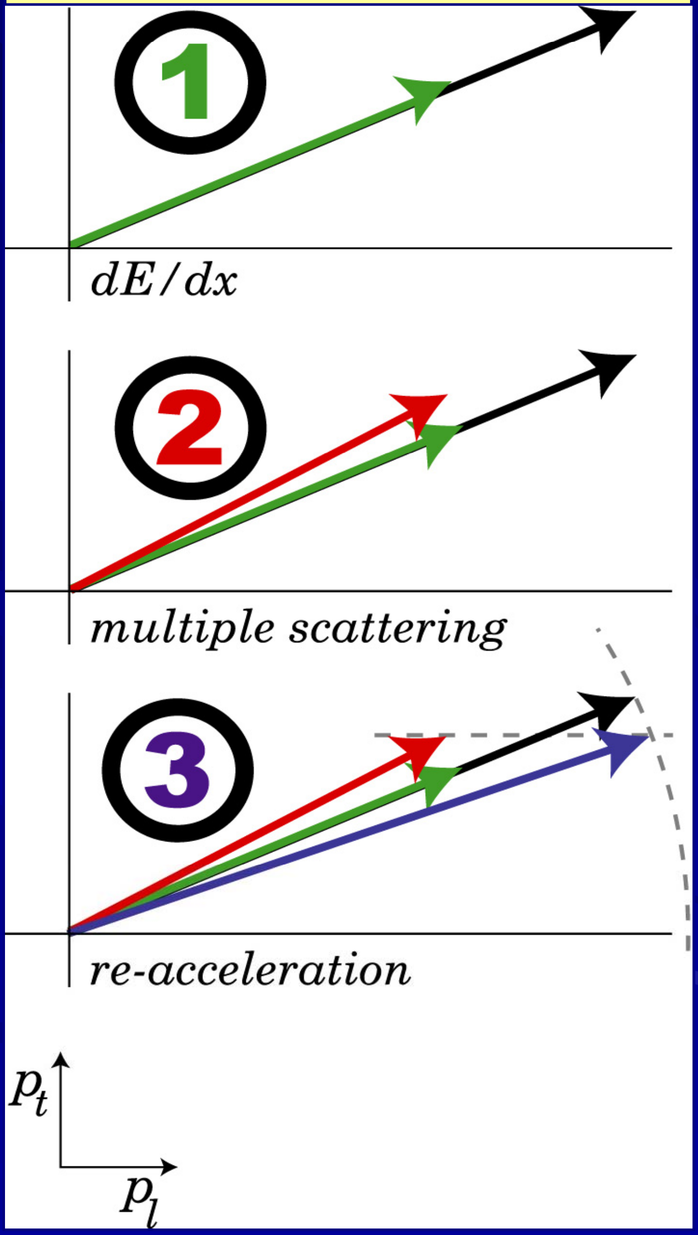
Muon Cooling

- **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

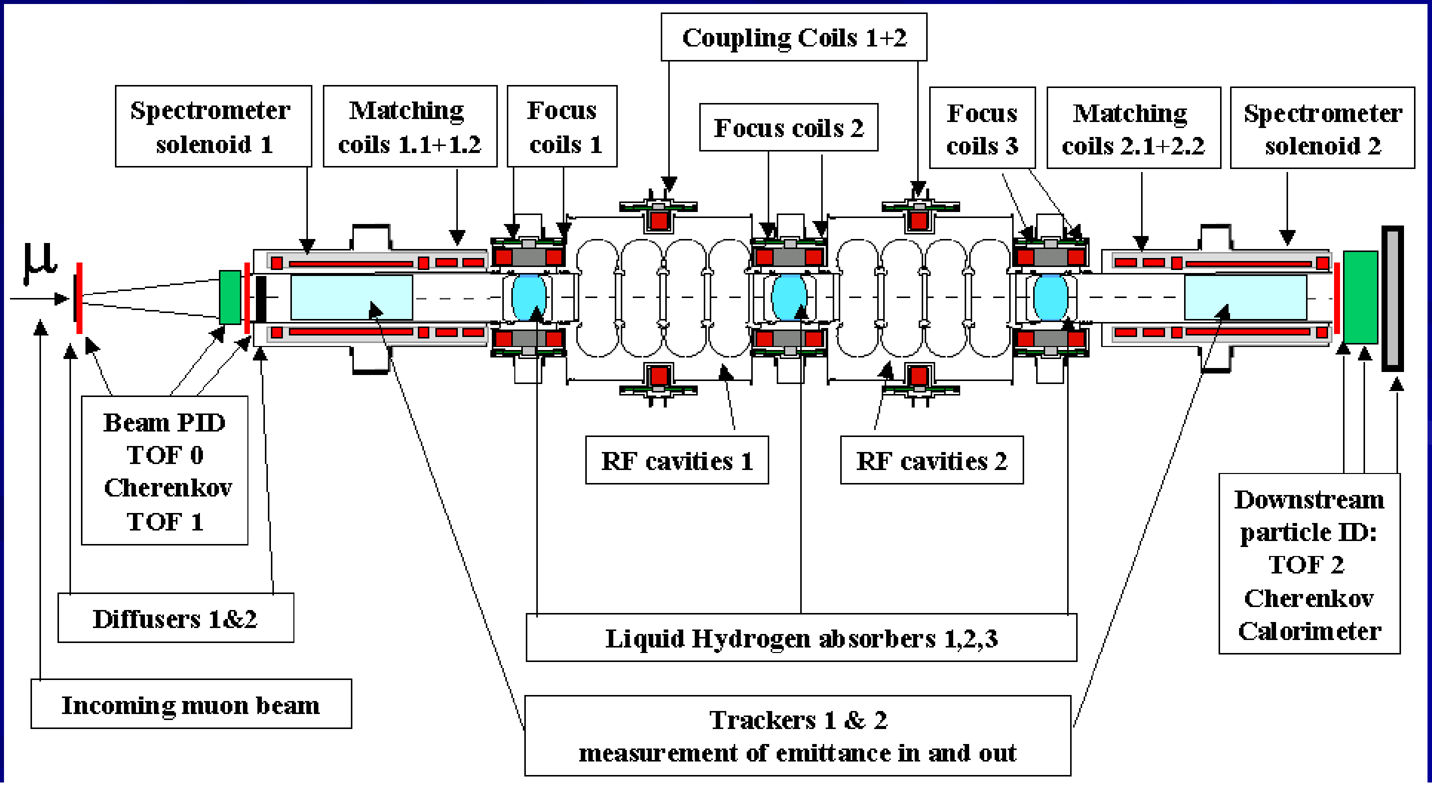
1. **Beam passes through absorber and loses energy/momentum.**
2. **Multiple scattering will result in a change in the angle of the particle, but not the total momentum**
3. **Re-acceleration with an RF cavity restores the longitudinal momentum, but not the transverse component: transverse cooling!**

Principle

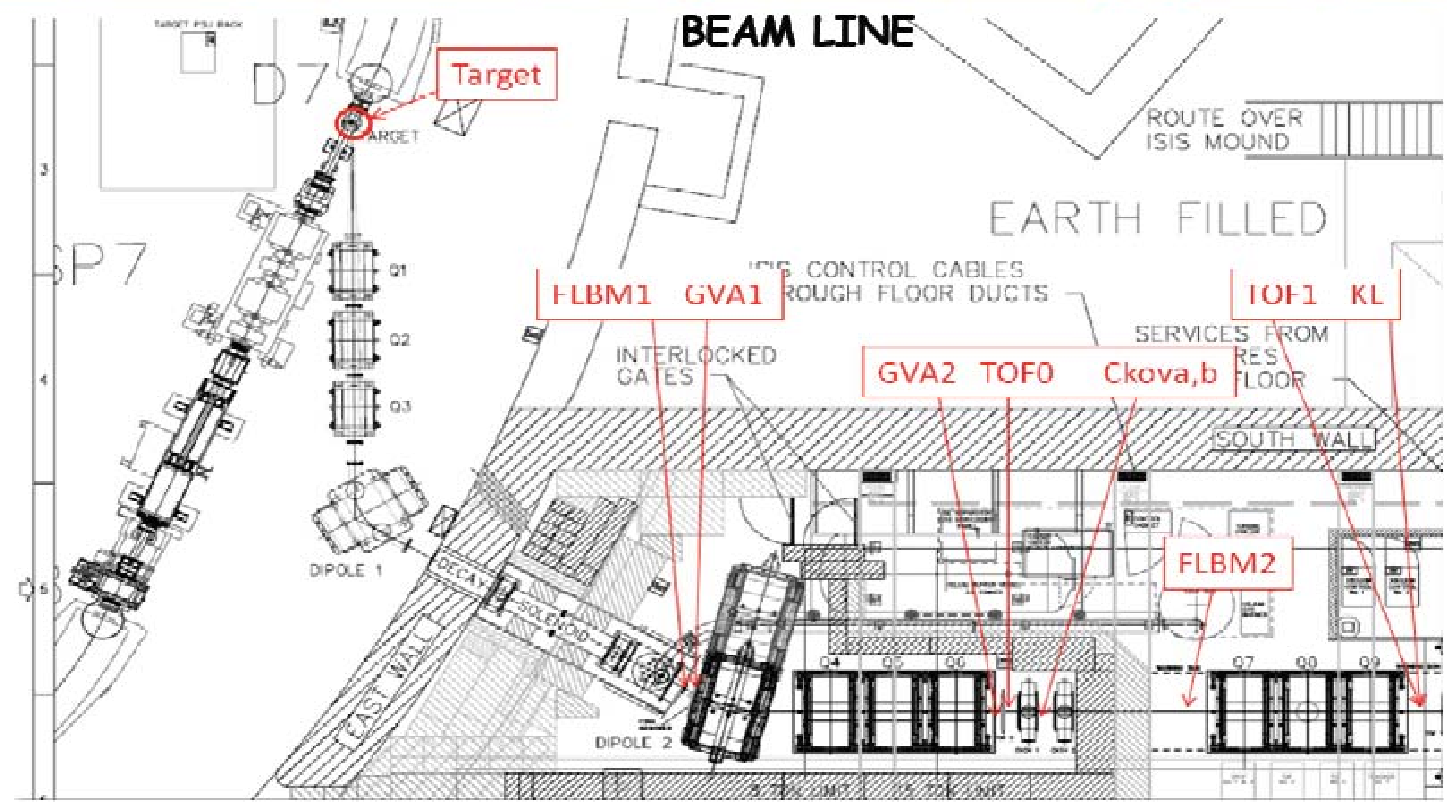


MICE

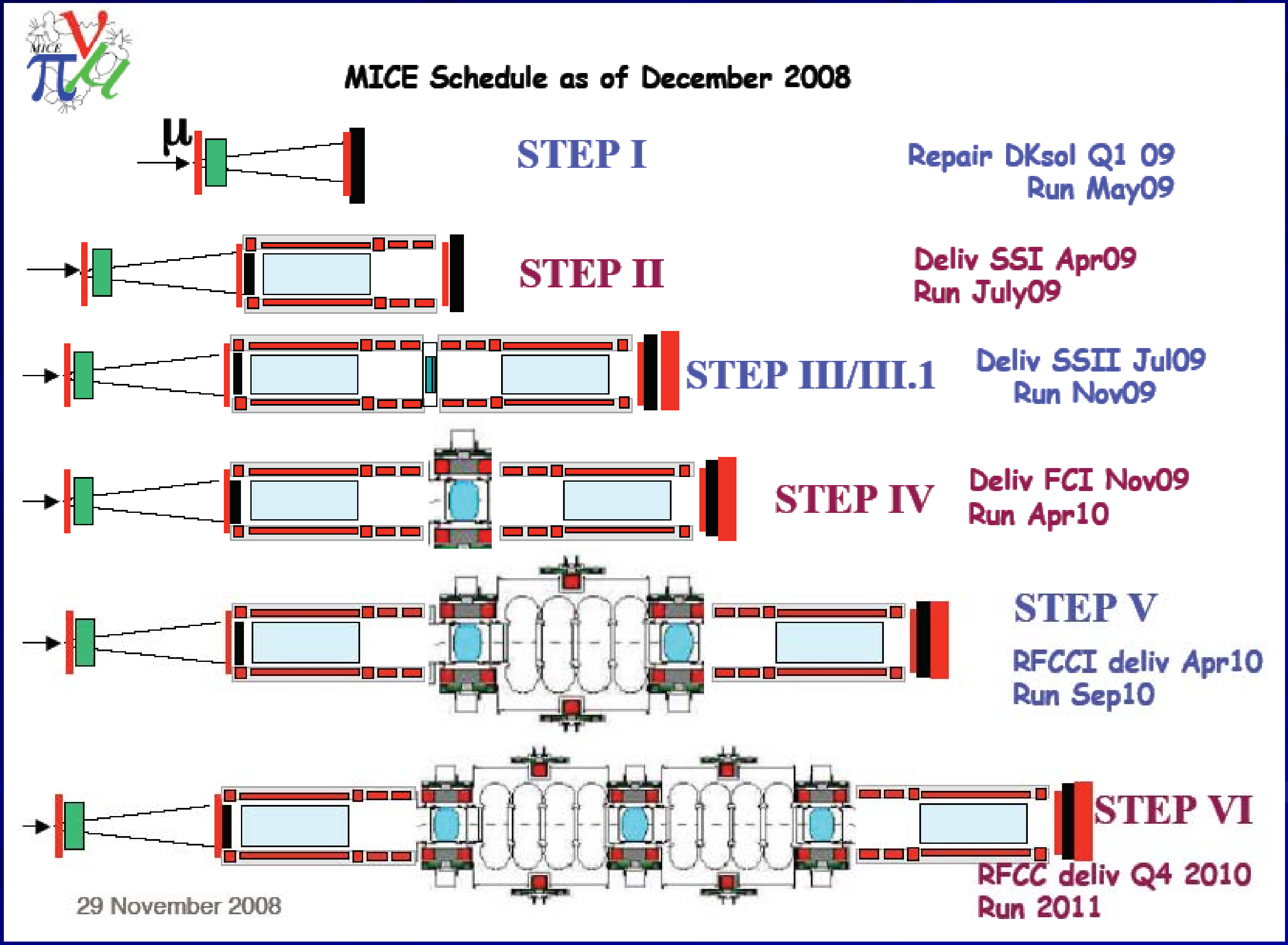
- Goals:
  - To build and operate a realistic section of a cooling channel, as might be used in a Neutrino Factory.
  - To measure the muon into and out of the cooling channel and measure a 10% reduction in emittance of the beam with a precision of 0.1%, and experimentally demonstrate ionization cooling



MICE: Current Status



The MICE Stages



MICE Schedule as of December 2008

STEP I

Repair DKsol Q1 09
Run May09

STEP II

Deliv SSI Apr09
Run July09

STEP III/III.1

Deliv SSII Jul09
Run Nov09

STEP IV

Deliv FCI Nov09
Run Apr10

STEP V

RFCCI deliv Apr10
Run Sep10

STEP VI

RFCC deliv Q4 2010
Run 2011

29 November 2008

- Experiment designed to grow with each step providing important information

MICE Diagnostics

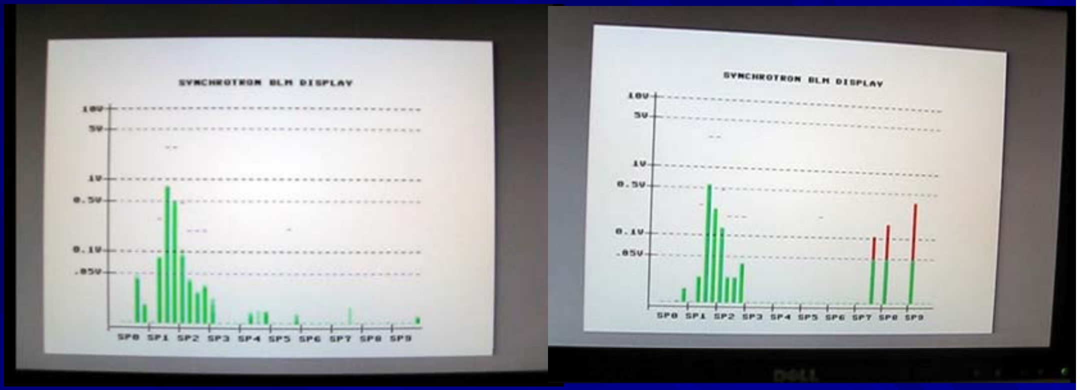
- Use a combination of “traditional” diagnostics and detectors from particle physics
  - Traditional
    - Beam losses from ISIS
  - Detectors from particle physics
    - TOF
    - CKOV
    - Tracker
    - Calorimeter

Traditional Diagnostics

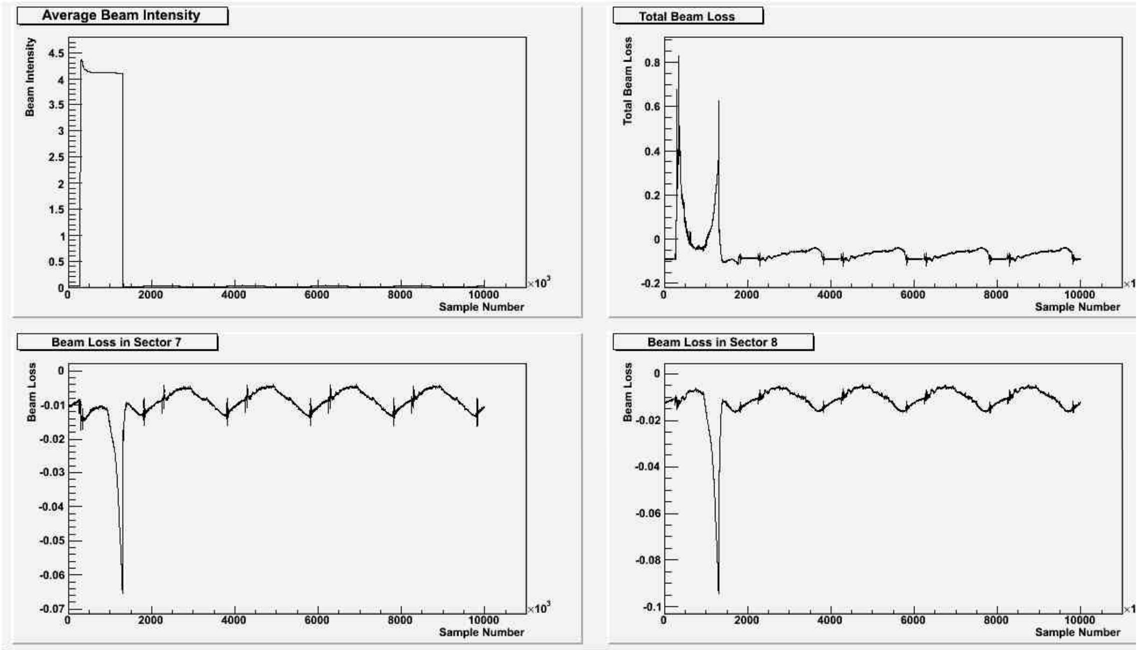
- Need to know what target is doing
  - Beam losses
  - Target depth
  - Target dip timing
  - Are we affecting ISIS?
  - How many particles are we getting down our beamline?

Target Information

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

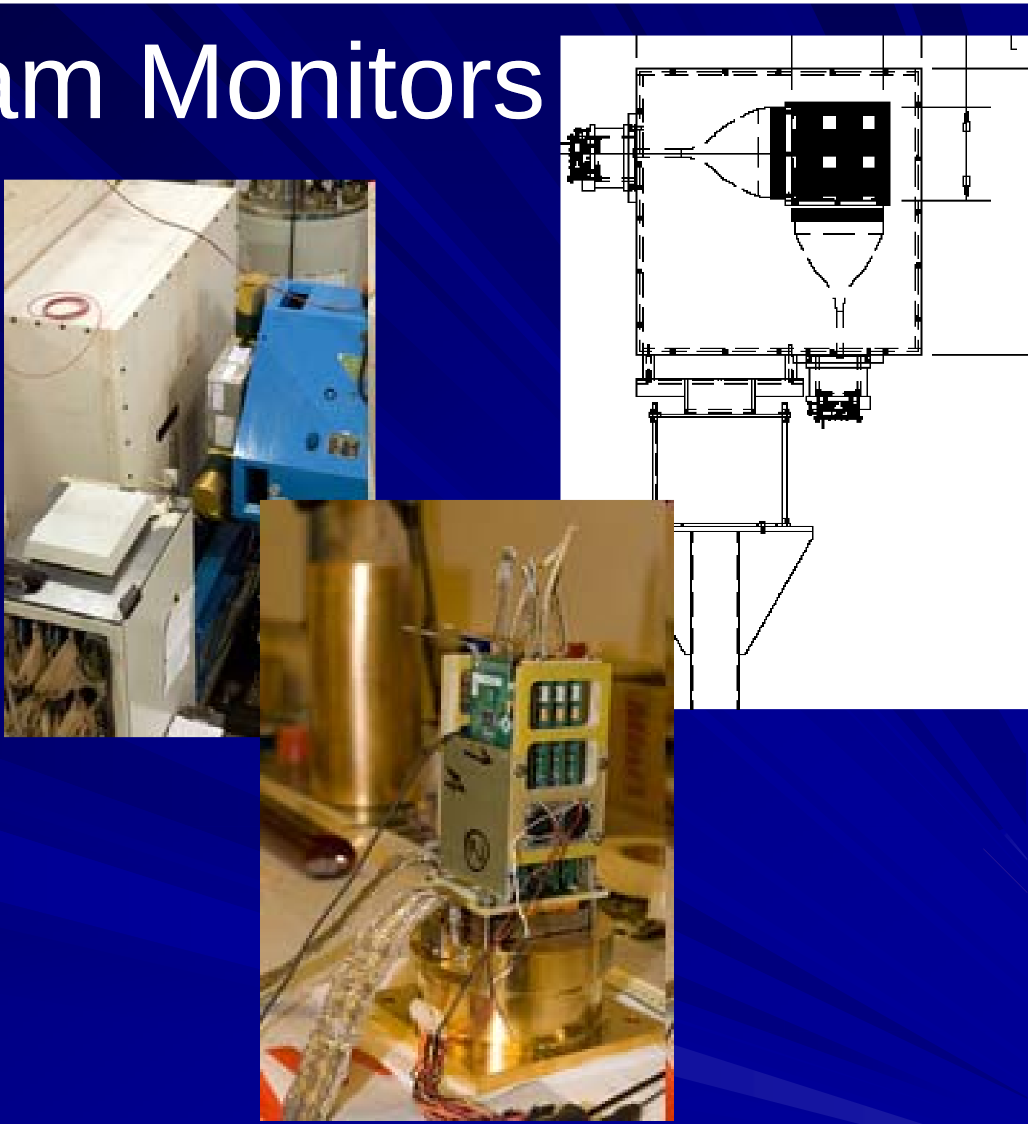


- **New Target DAQ info into MLCR**
  - ISIS beam intensity, Total Beam Loss, Sector 7, Sector 8



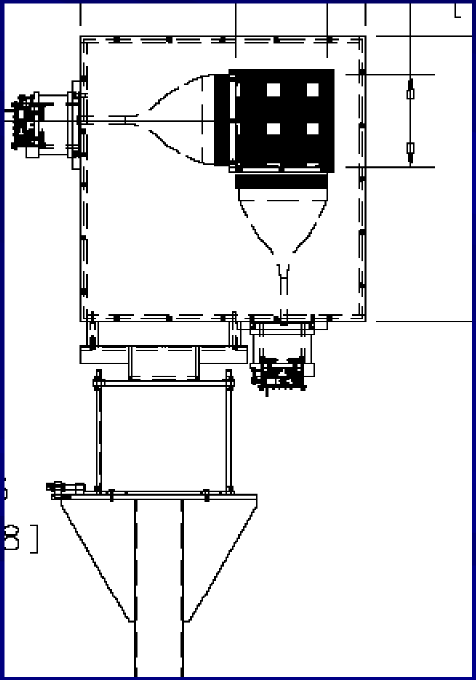
FNAL Beam Monitors

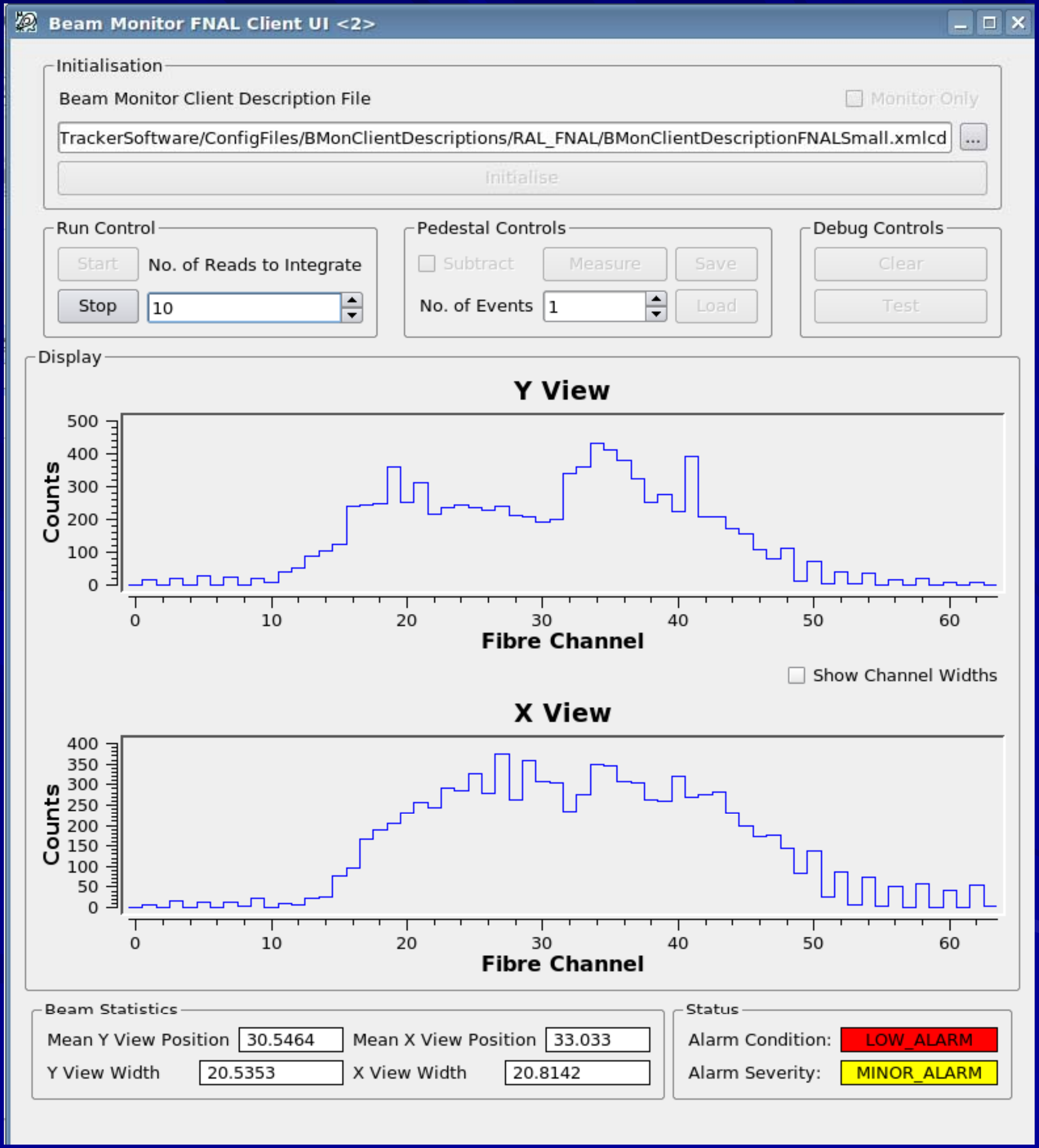
- Two beam profile monitors installed in the MICE beamline
- Scintillating fiber detectors made of 0.9 mm diameter fibers in doublet planes with a 1.08 mm pitch and read out with Burle multi-anode PMTs.
- The active area of the two detectors covers 20x20 cm and 45x45 cm with doublets in both x and y giving a two dimensional profile of the MICE beam.



FNAL Beam Monitors

- Two dimensional beam profile information





Beam Monitor FNAL Client UI <2>

Beam Monitor Client Description File ☐ Monitor Only

TrackerSoftware/ConfigFiles/BMonClientDescriptions/RAL_FNAL/BMonClientDescriptionFNALSmall.xmlcd

No. of Reads to Integrate: 10

☐ Subtract

No. of Events: 1

☐ Show Channel Widths

Mean Y View Position: 30.5464

Mean X View Position: 33.033

Y View Width: 20.5353

X View Width: 20.8142

Alarm Condition: LOW_ALARM

Alarm Severity: MINOR_ALARM

MICE Diagnostics: Particle Physics Detectors

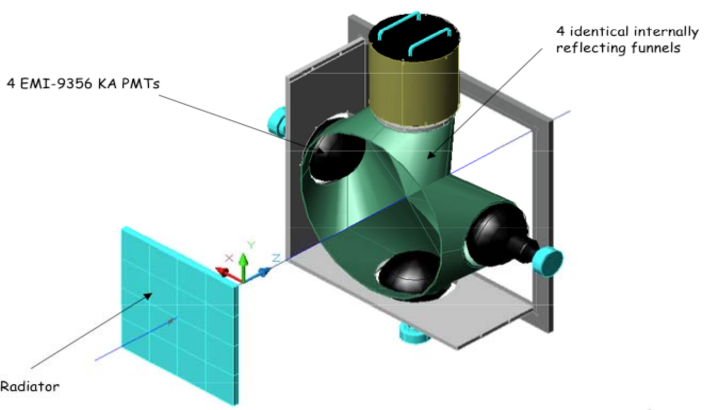
- Particle identification
  - TOF
  - CKOV
  - Calorimeter
- Particle tracking
  - Scintillating Fiber trackers
  - Measure position and reconstruct momentum

PID DETECTORS

Upstream

- Time of Flight TOF0 + TOF1
- Aerogel Cerenkov

➔ π/μ separation

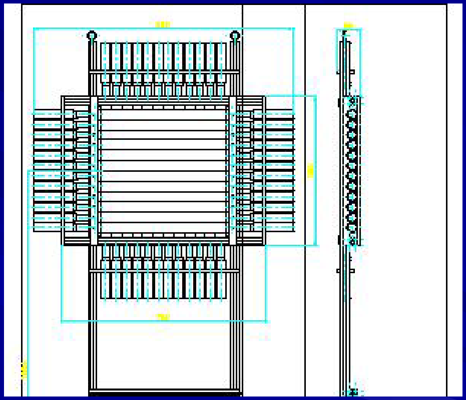


Upstream C’kov

Downstream

- TOF2 + Calorimeter

➔ μ / e separation



TOF & Calorimeter components

Up + Downstream TOFs

➔ RF phase of muons (50ps timing)

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

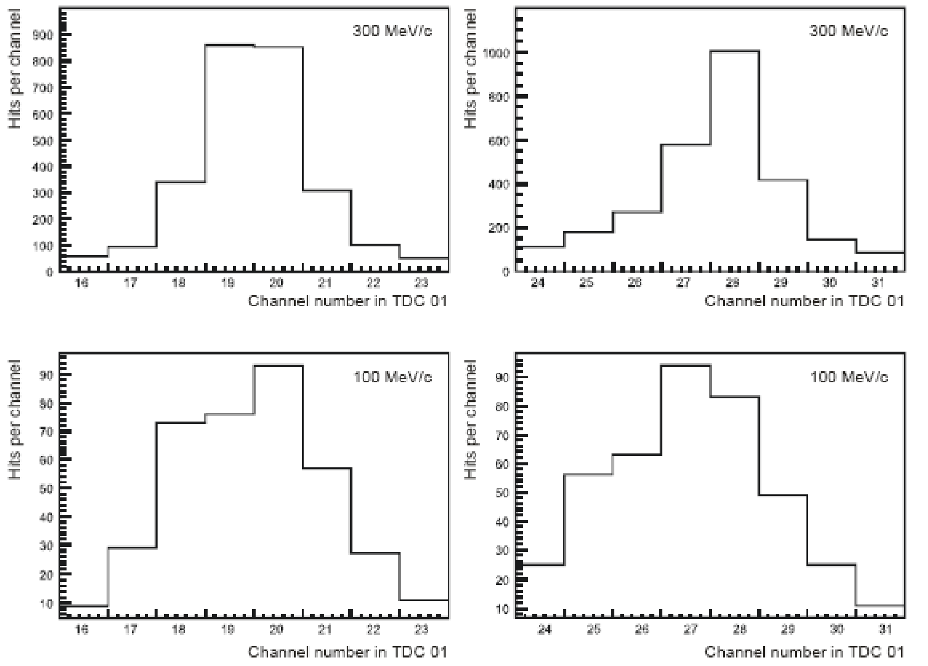


Figure 1: Vertical (left) and horizontal (right) profiles in TOF0 obtained from online monitoring histogram at 300 MeV/c (top) and 100 MeV/c (bottom). The beam can be considered as centred at both momenta.

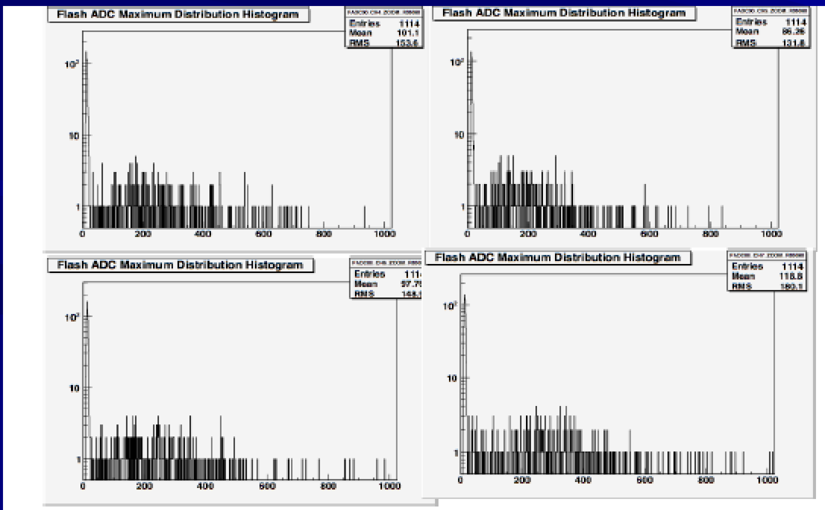


Figure 3: Amplitude histograms from the Cherekov counters. Top four histograms correspond to CKOVa. Bottom four histograms correspond to CKOVb.

PID Detectors: TOF

- TOF
  - 2 planes of 1 inch orthogonal scintillator slabs in x and y
  - Read out by fast PMT

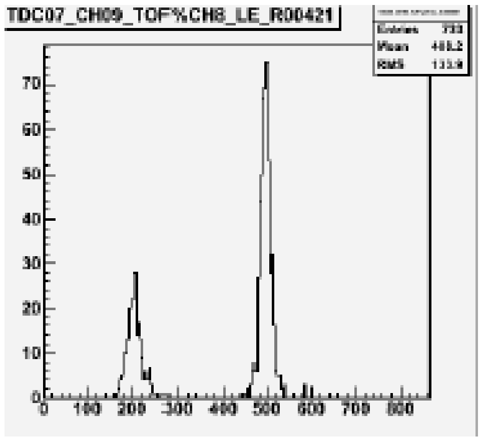
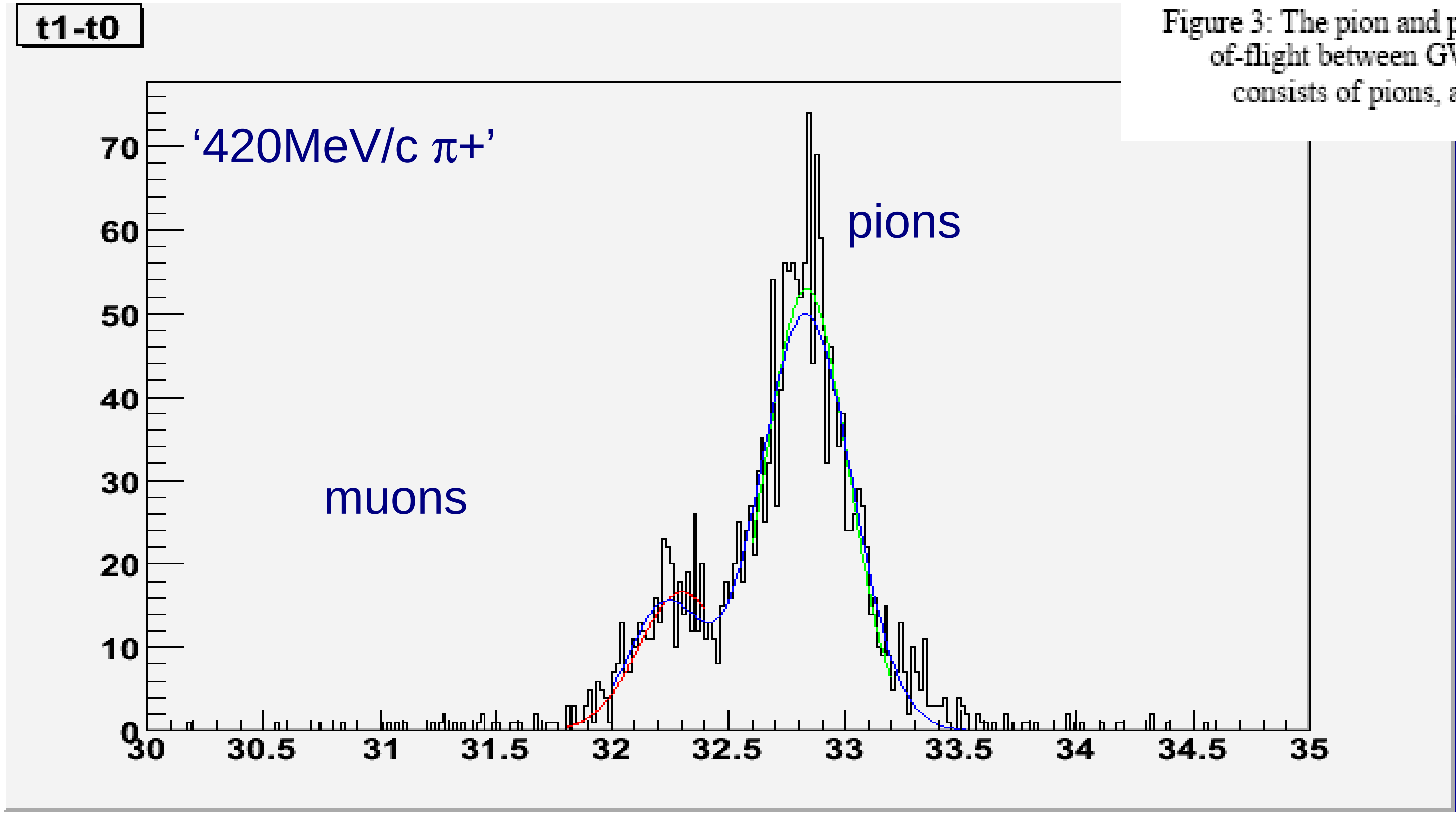
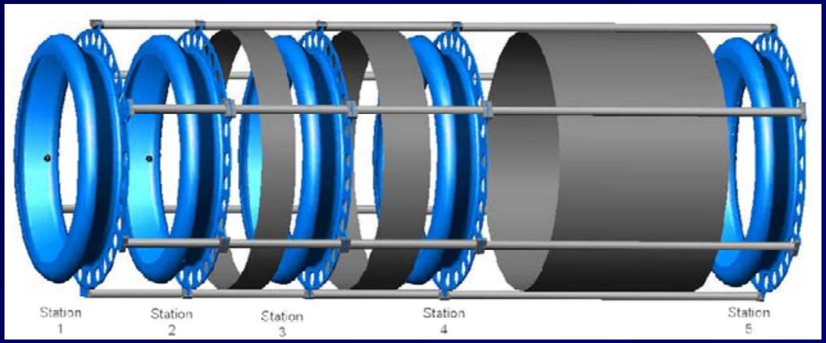


Figure 3: The pion and proton separated through the time-of-flight between GVA1 and GVA2. The left peak consists of pions, and the right peak of protons

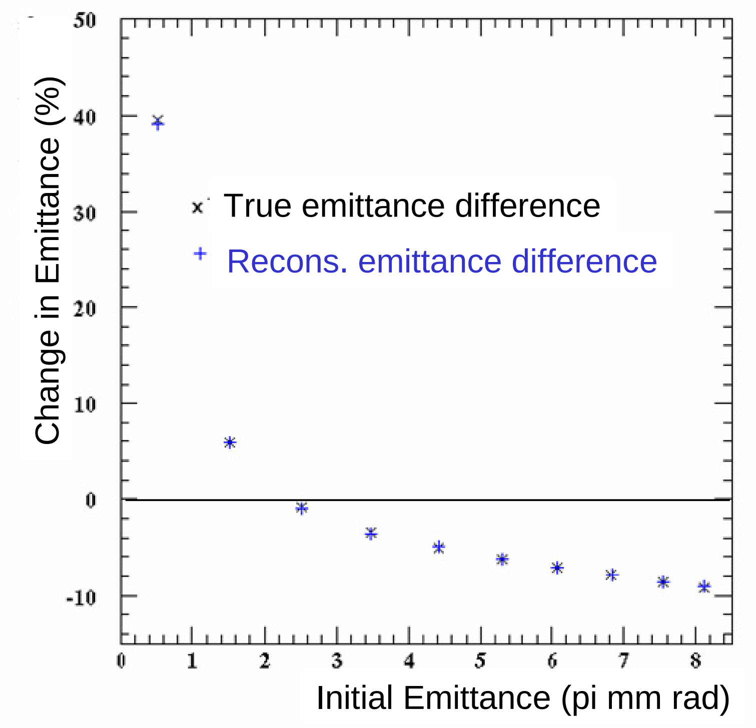


SCI-FI TRACKER



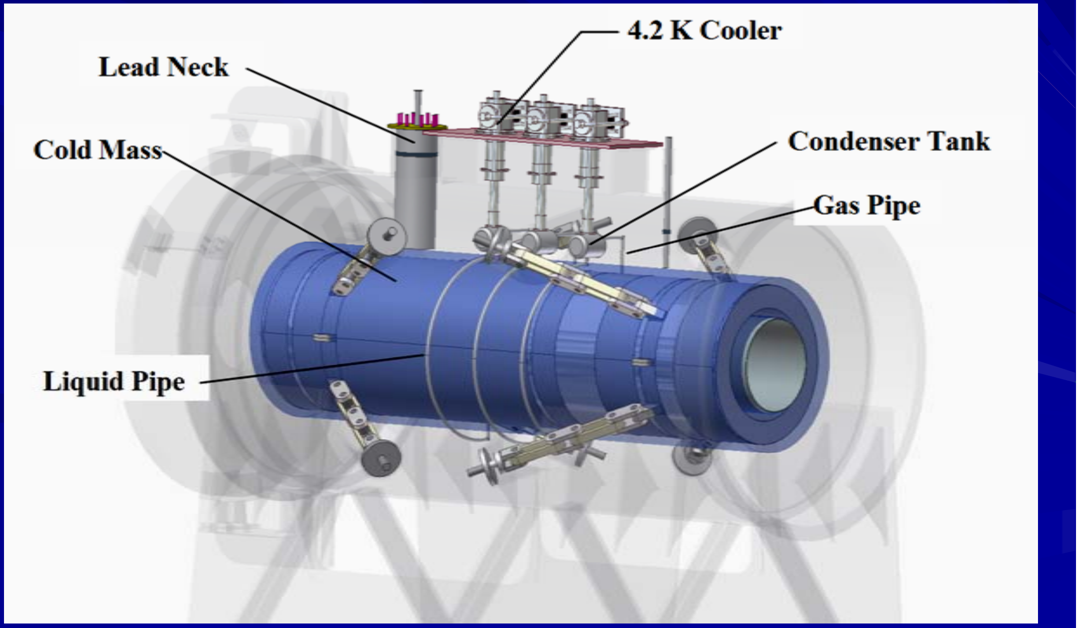
Low mass Sci-Fi tracker inside solenoid

5 planes x 3 views
350 micron fibres + VLPC readout
Cosmic ray tests with trackers
Light yield ~10pe
Data used as input to simulations



MICE Tracker

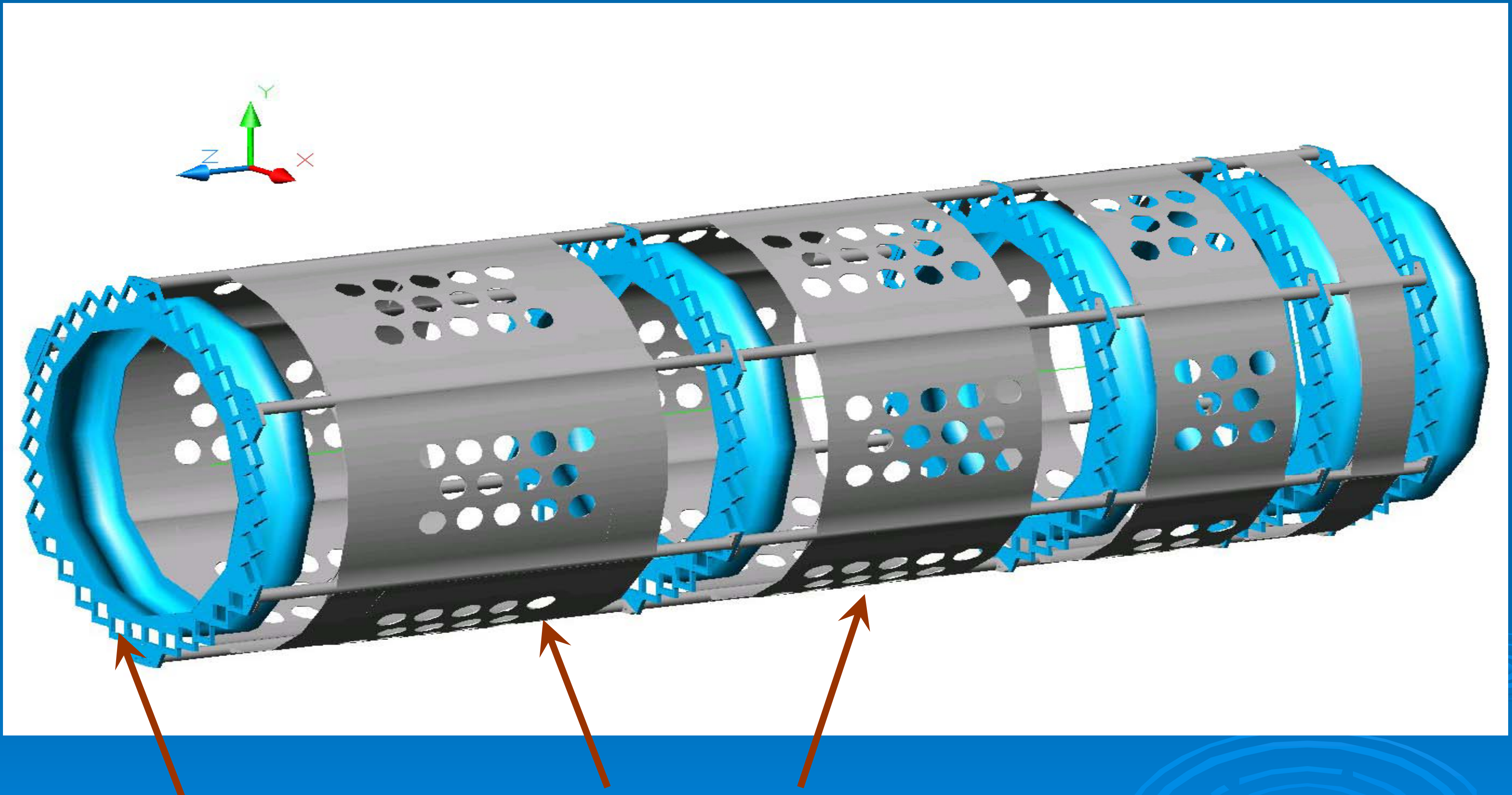
- Scintillating fiber tracker
  - Reduce transverse emittance by 10%
  - Trackers need to measure this reduction to 0.1% precision
  - High resolution on order of 1 fiber needed
- Sits inside 4 T solenoid magnet ~1m long with 5 SC coils



MICE Tracker

- MICE requires two identical trackers to measure each muon individually as it enters and exits the cooling channel.
- Tracker needs to safely operate next to the liquid Hydrogen absorbers and in the presence of the strong background (RF and X-rays/conversions) from the RF cavities.
- Solution: Scintillating Fibres readout with Visible Light Photon Counters (VLPCs).

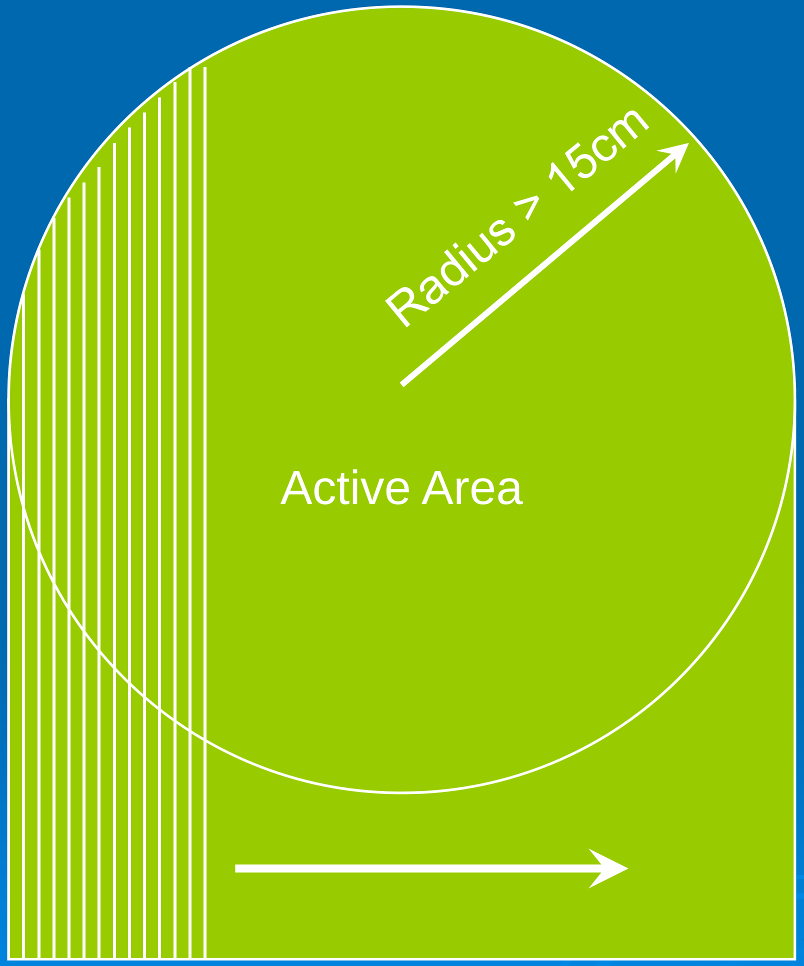
A MICE Tracker

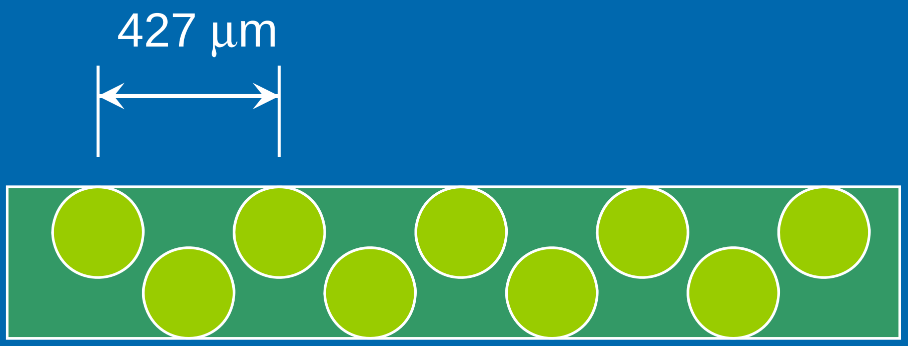


A “Station”

Carbon Fibre Support

Fibre Plane (Doublet/Ribbon)

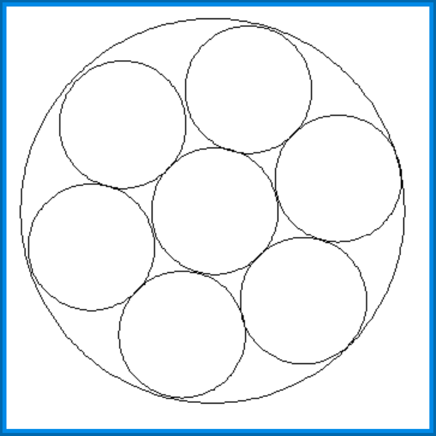


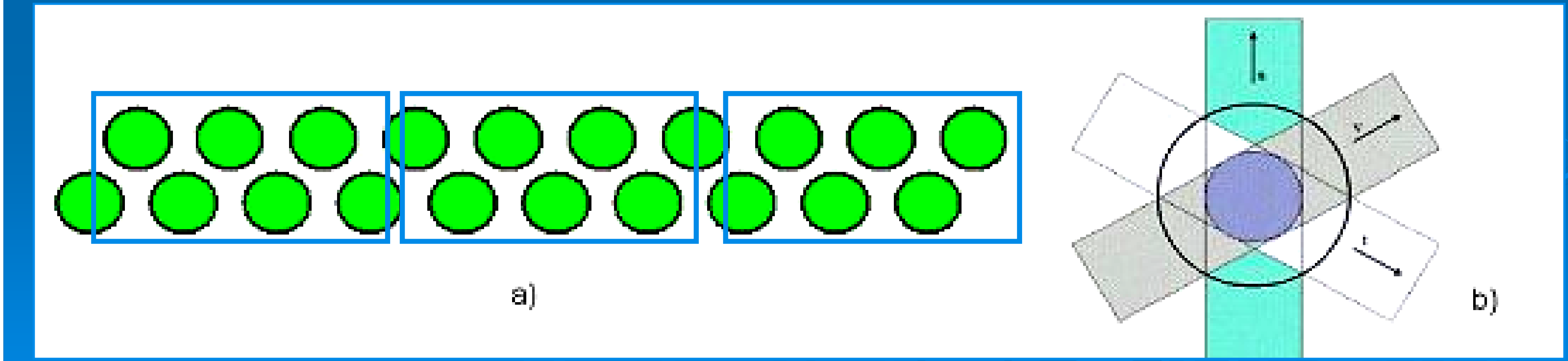


- 350 µm scintillating fibres are arranged in two overlapping rows to form a sheet of fibre.
- Active area has a diameter of 30 cm.
- Small fibre minimises radiation length in direction of muon passage.

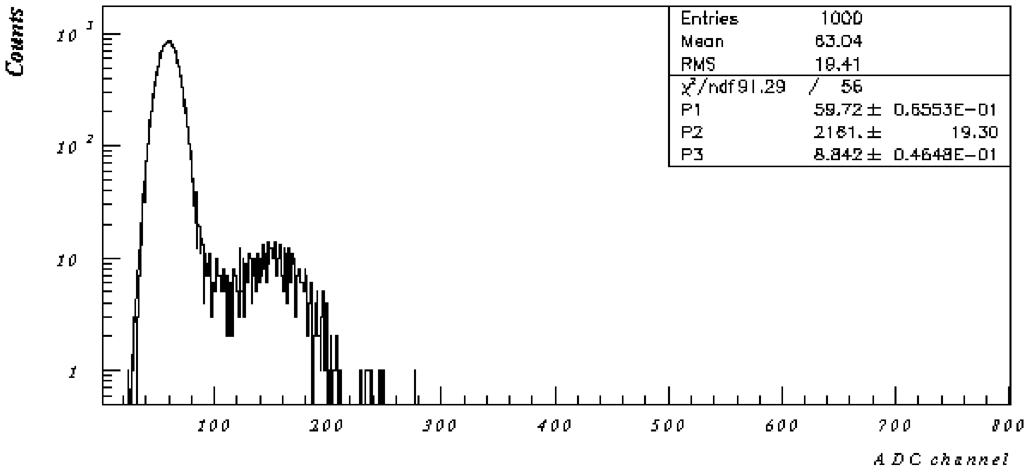
Tracker Design

- Each tracker has five measurement stations
- A station consists of 3 planes
- Each plane has over 1400 fibres.
- Light from groups of seven neighbouring fibres are read out on a single VLPC channel.

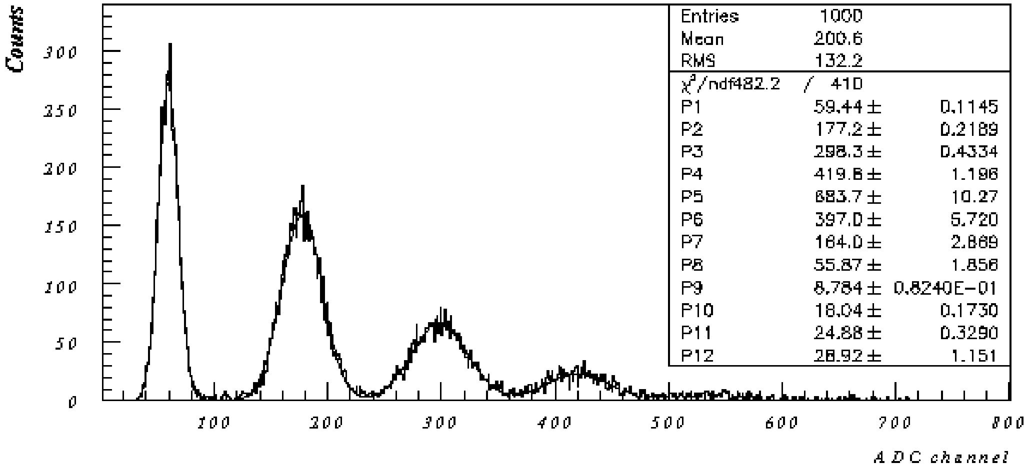




VLPCs

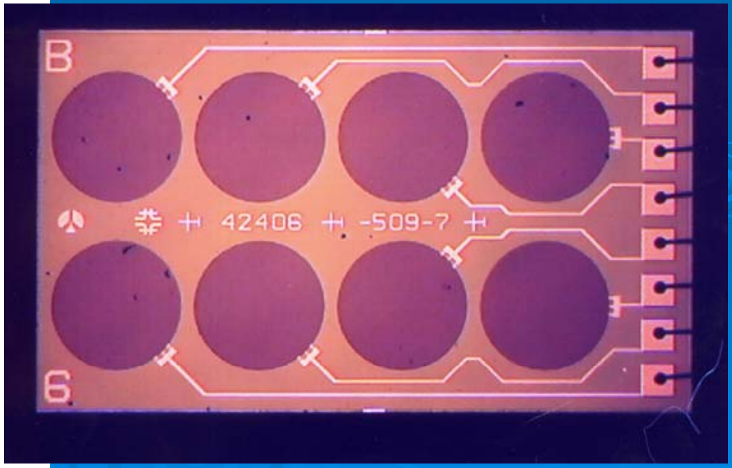


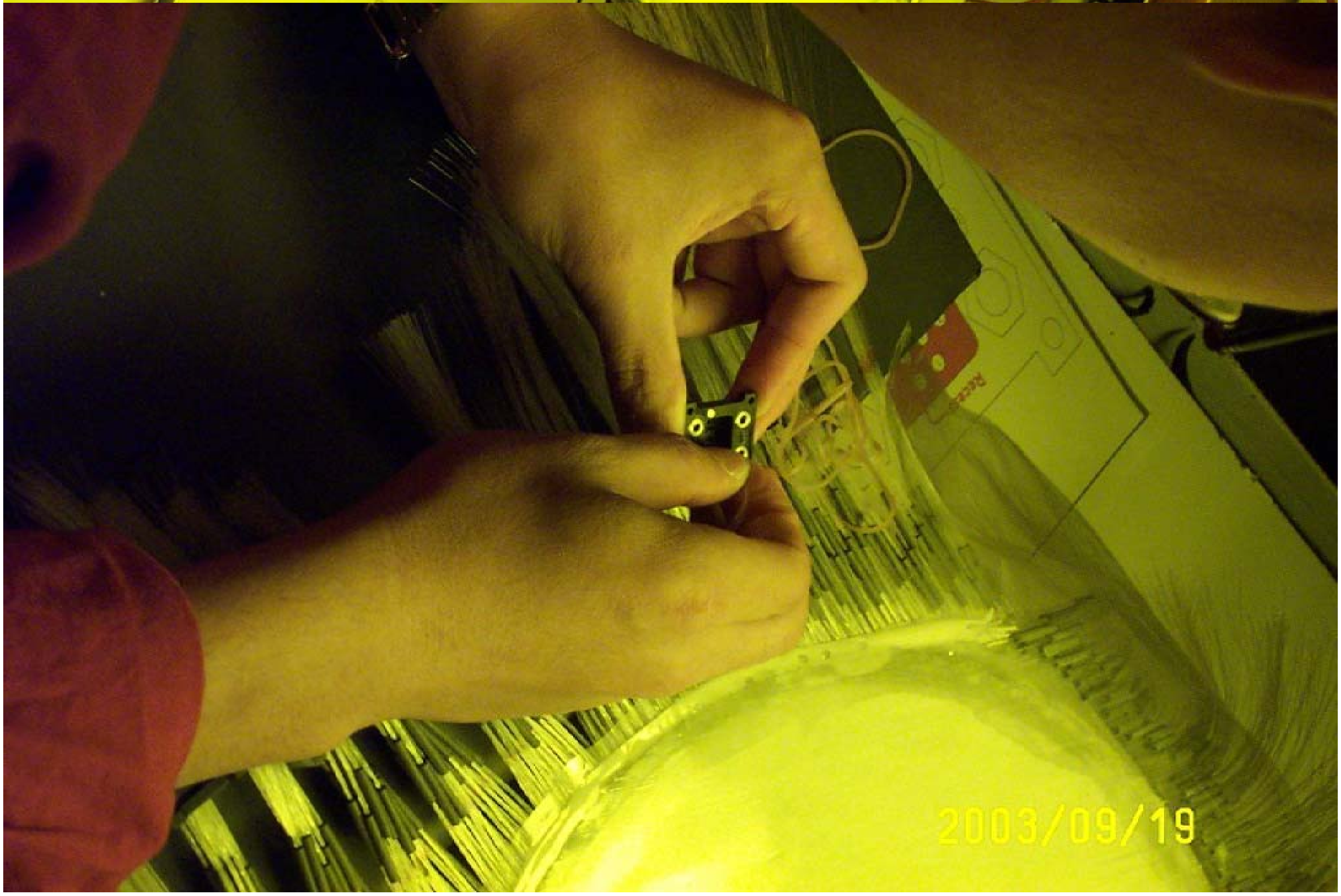
PEDESTAL



SIGNAL

- Operate at 9K
- High QE
- Low noise
- High rate




2003/09/19

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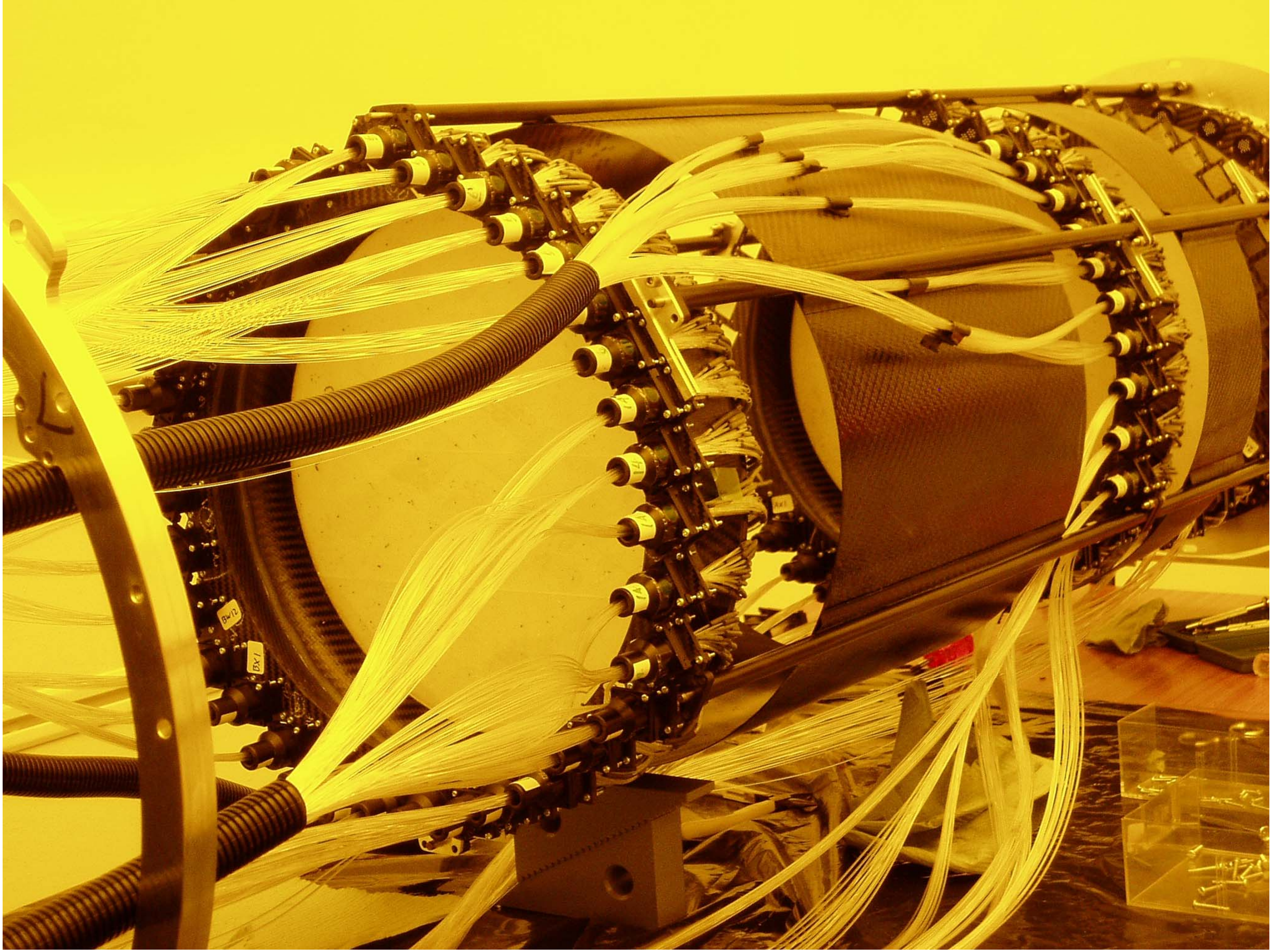
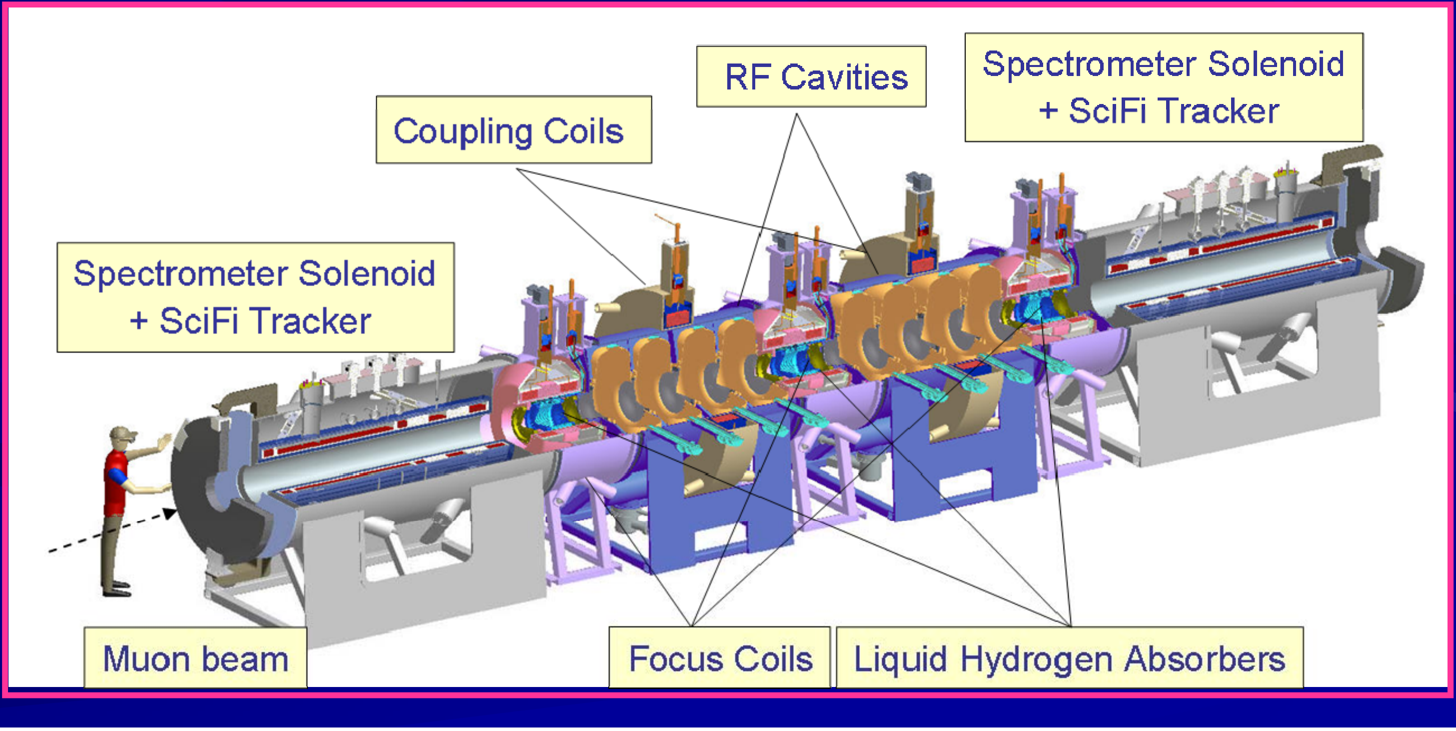

BW12
BX1
Ax1

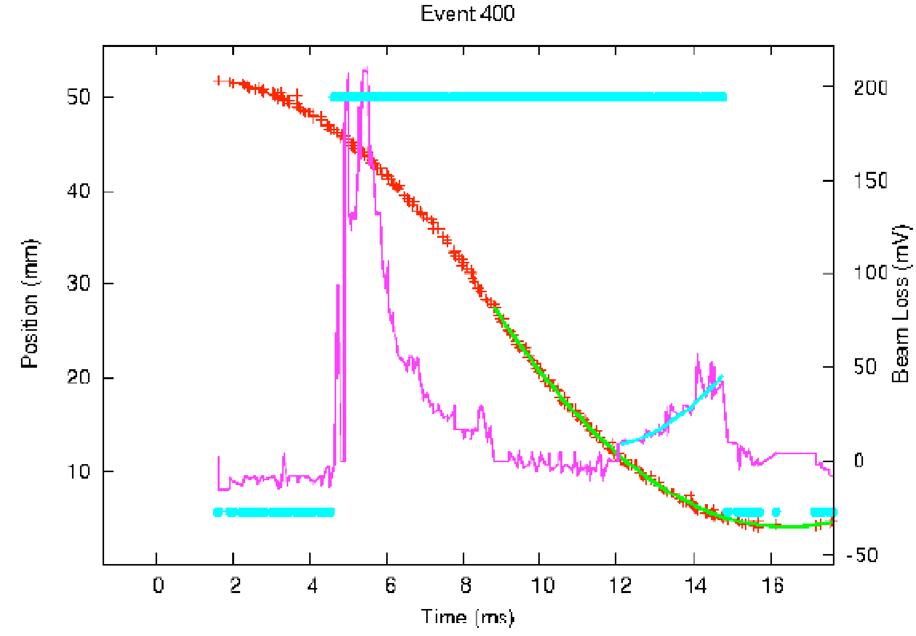
Prototype Performance

- Most probable light yield: 10.0 ~ 10.5 P.E.
  - Expectation based on D0 experience ~10
- Resolution: 442 ± 4 (stat) ± 27 (syst) μm
  - Expectation from fibre geometry: 424 – 465 μm (single fibre bunch or two fibre bunch)
- Single Plane Efficiency: (99.7 ± 0.2)%
  - Poisson expectation for 10 P.E. signal 99.7%
- Dead channels: 0.2% (two channels)
  - 0.25% assumed in G4MICE simulation based on D0 experience

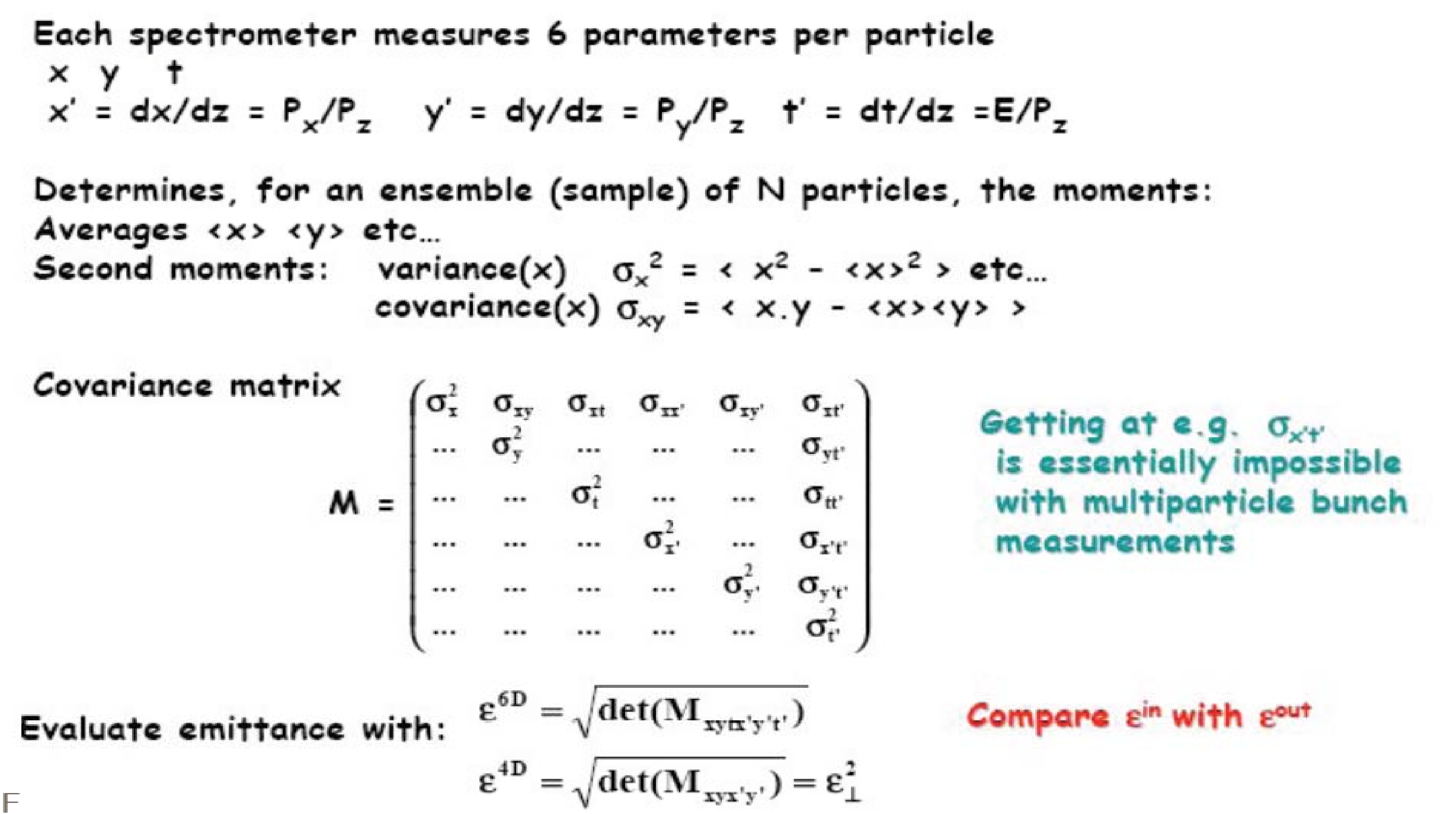
Conclusions

- Many different types of detectors used to understand the experiment
- Come see what we've got in person!




Event 400
Position (mm)
Beam Loss (mV)
Time (ms)
50
40
30
20
10
200
150
100
50
0
-50
0
2
4
6
8
10
12
14
16

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:

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

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

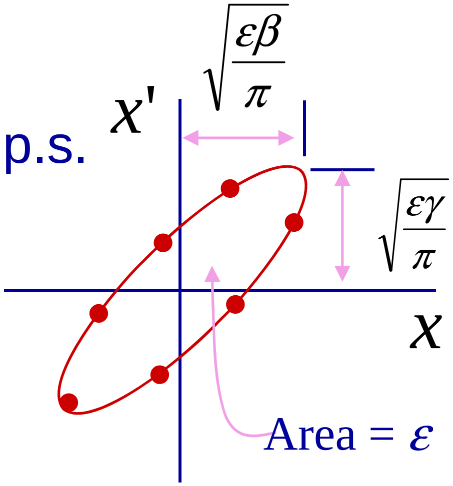
Compare ε^{in} with ε^{out}

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:

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

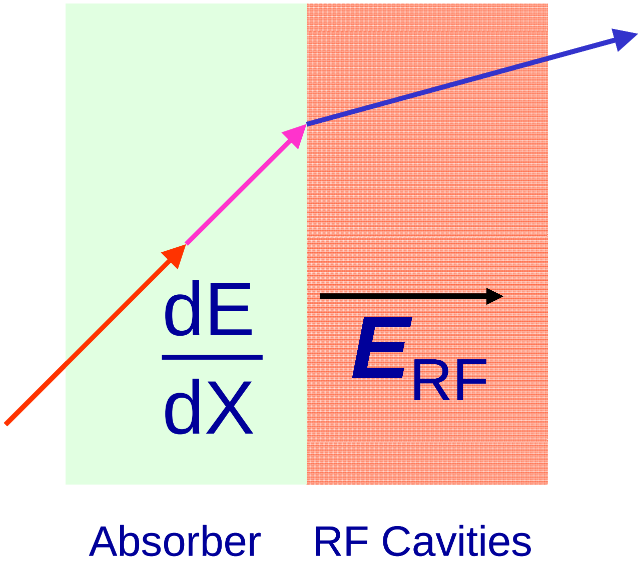
- *<dE/dX>* *versus* scattering (X_0)

➔ *low Z absorber material*

➔ *tight focus* (*low β function*)

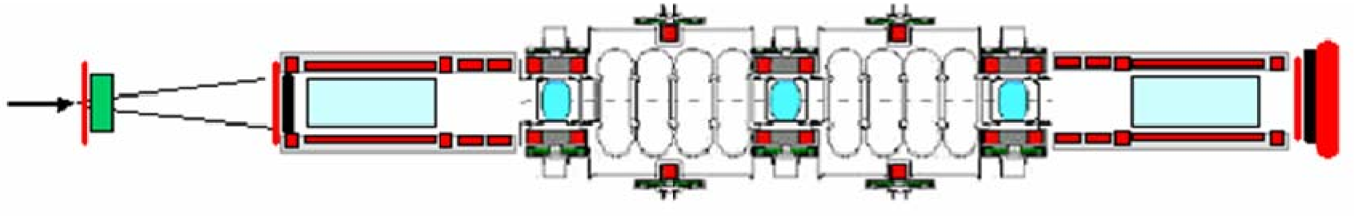
- Figure of Merit = X_0*<dE/dX>*

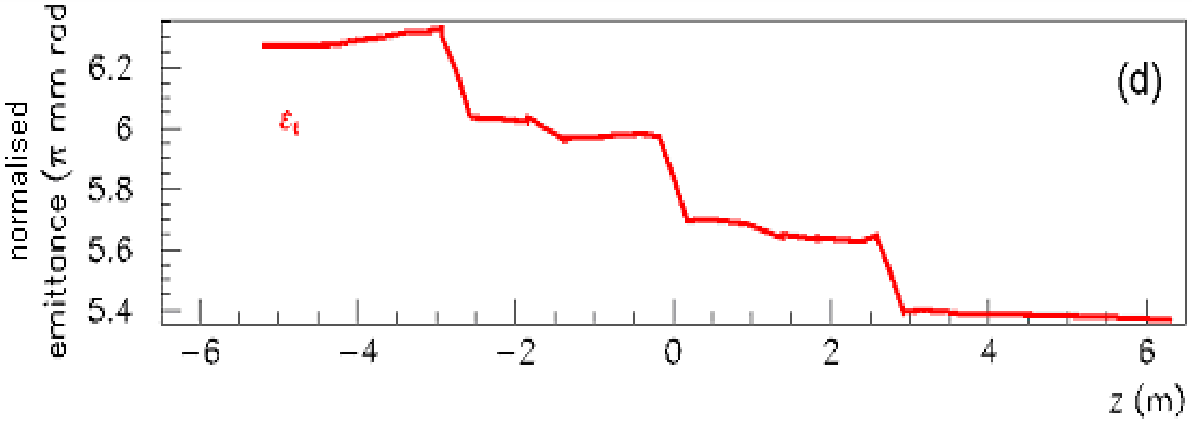
➔ *H_2 is best absorber material*



	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**

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%*