MICE STATUS REPORT

MICE Collaboration

M. Bonesini

INFN, Sezione di Milano Bicocca

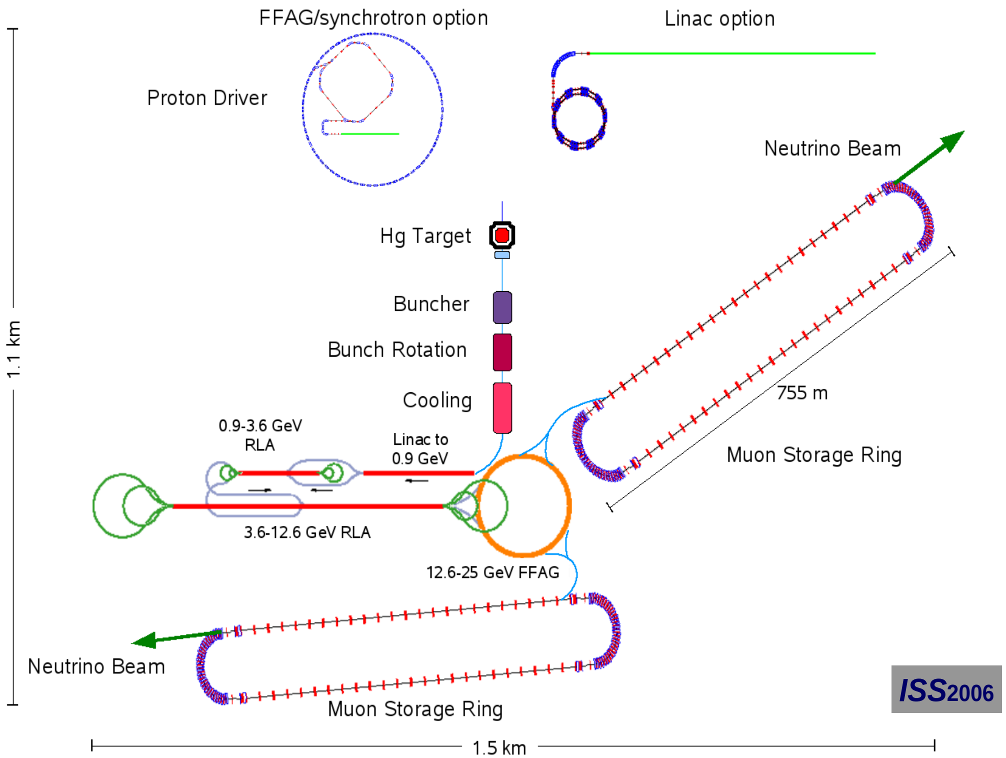
Milano Italy

Outline

- Introduction: towards a Neutrino Factory
- The MICE cooling experiment
- MICE beamline
- The MICE Cooling channel
- The MICE spectrometers
  - MICE trackers
  - MICE PID instrumentation
    - Upstream PID detectors
    - Downstream electron muon calo (EMC)
    - The TOF system
- Conclusions

Neutrino Factory

International Scoping Study baseline

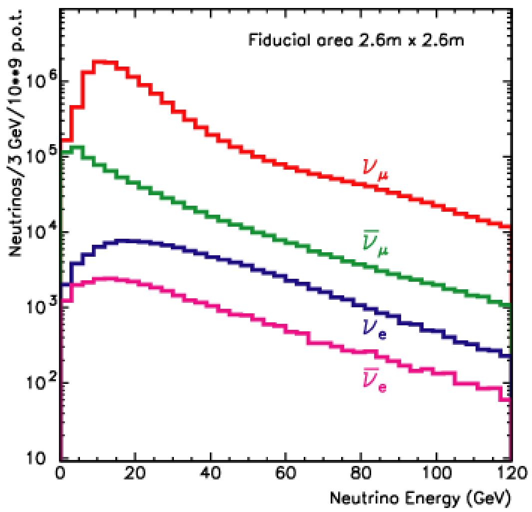


- Proton Drive (4 MW, 2 ns bunch)
- Target, Capture, Drift (π→μ) & Phase Rotation
  - Hg Jet
  - 200 MHz train
- Cooling
  - 30 πmm (⊥)
  - 150 πmm (L)
- Acceleration
  - 103 MeV → 25 GeV
- Decay rings (baseline is race-track design):
  - 7500 km L
  - 4000 km L

ISS Accelerator WG report: RAL-2007-023

ν beams: conventional and nufact beams

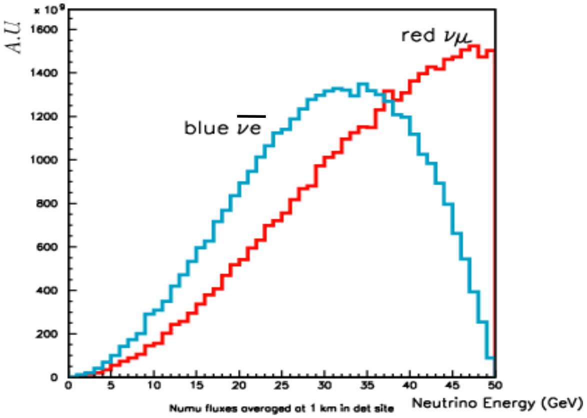
WANF (conventional ν beam at SPS)



- **Problem in conventional ν beams: a lot of minority components (beam understanding)**
- **Following muon collider studies, accelerated muons are ALSO an intense source of "high energy" ν**

$$\mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e \qquad \mu^+ \rightarrow e^+ \overline{\nu}_\mu \nu_e$$

Nufact beam



- **Crucial features:**
  - **high intensity (x 100 conventional beams)**
  - **known beam composition (50% ν_μ 50% ν_e)**
  - **Possibility to have an intense ν_e beam**
- **Essential detector capabilities:**

detect μ and determine their sign

Neutrino Factory: physics channels

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	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 ($\approx$7500 km & $\approx$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" $\to$ Sign of μ observed in detector opposite to that stored in decay ring

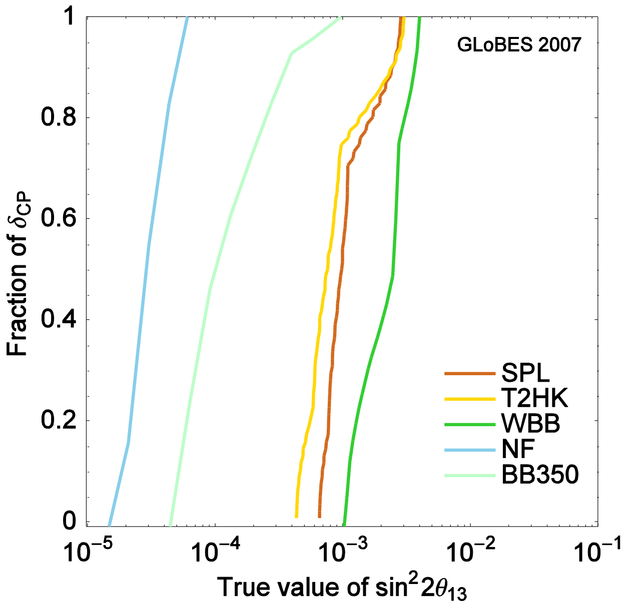
$\mu^+ \to \nu_e \;\; -> \nu_\mu n \to \mu^- p$

IDS Study - Physics Reach

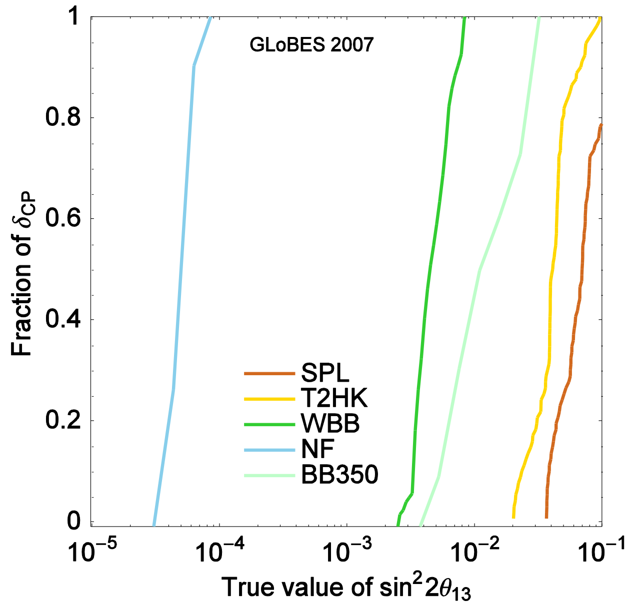
3σ contours shown

ISS Physics Group Report: arXiv:0710.4947v2

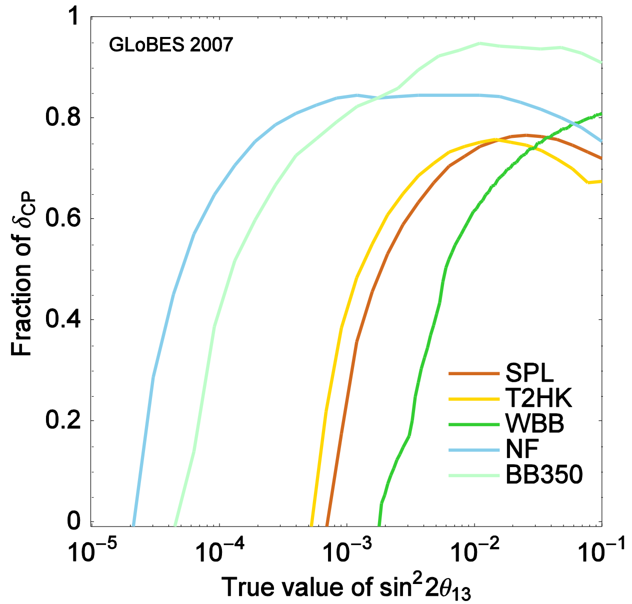
$\sin^2 2\theta_{13}$



Hierarchy



δ *CP*

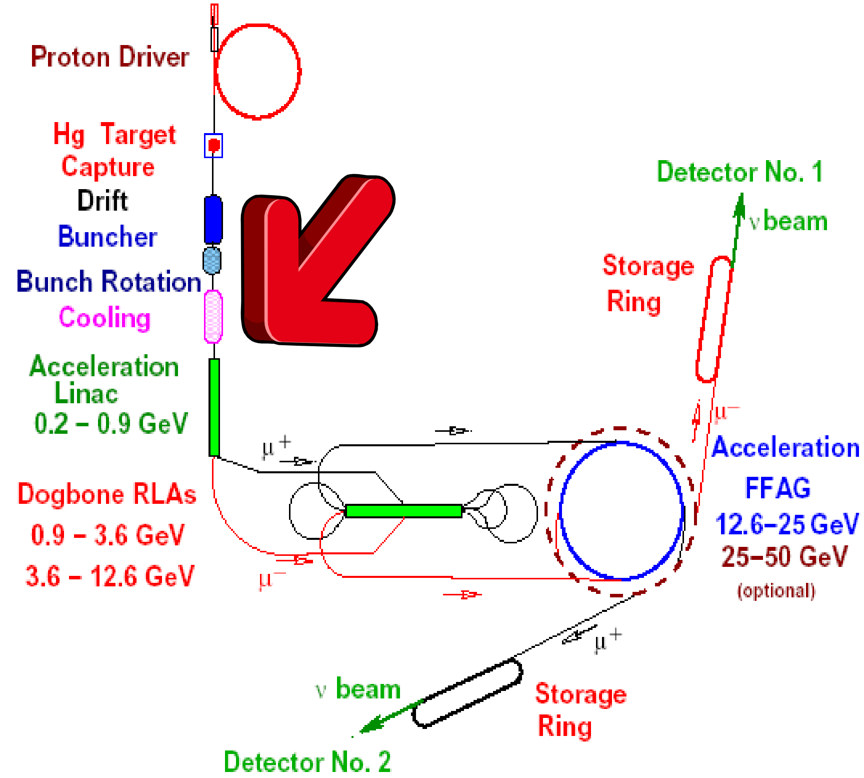


SPL: 4MW, 1MT H_2OC, 130 km BL
T2HK: 4 MW, 1MT H_2OC, 295 km BL
WBB: 2MW, 1MT H_2OC, 1300 km BL

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

Neutrino Factory R&D

- High power (MW) proton driver
- Target and collection (HARP/MERIT)
  - Maximize π^+ and π^- production
  - Sustain high power (MW driver)
  - Optimize pion capture
- Muon cooling (MICE)
  - Reduce $\mu+/\mu-$ phase space to capture as many muons as possible in an accelerator
- Muon acceleration
  - Has to be fast, because muons are short-lived ! (RLA, FFAG, …)

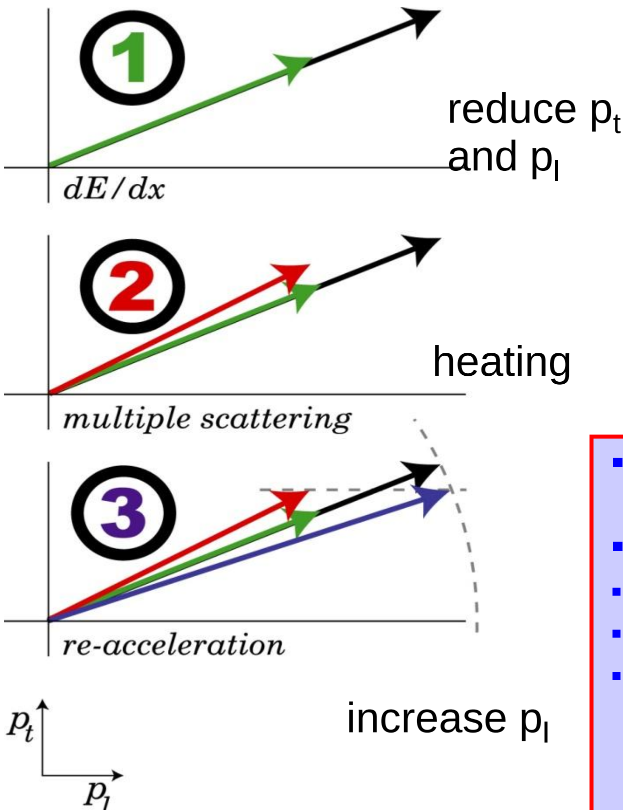


Muon ionization cooling

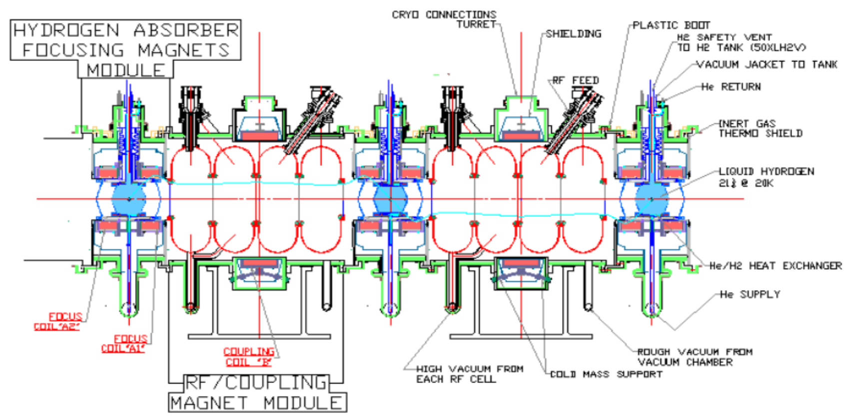
Stochastic cooling is too slow.

A novel method for $\mu+$ <u>and</u> $\mu-$ is needed: **ionization cooling**

principle

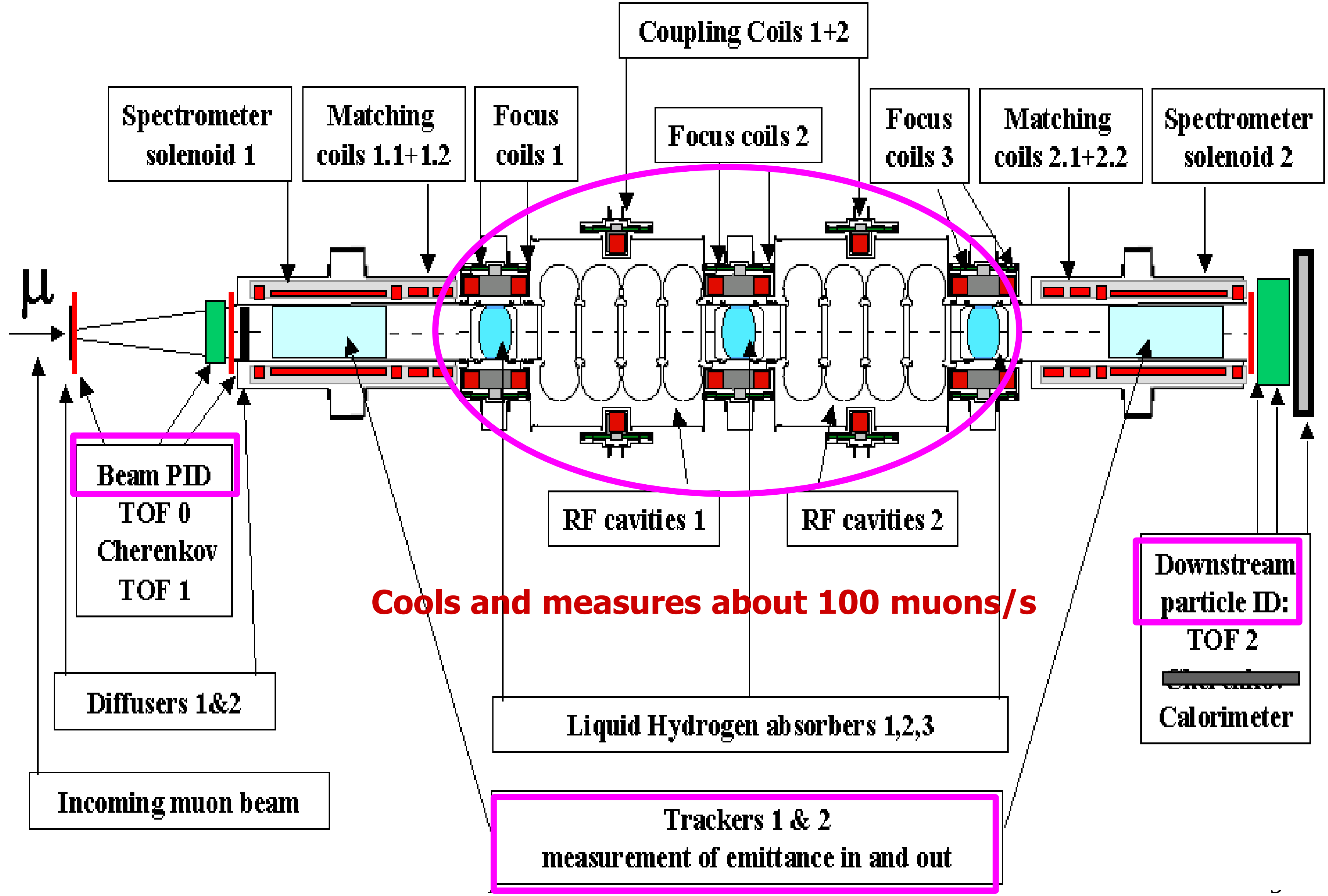


reality (simplified)

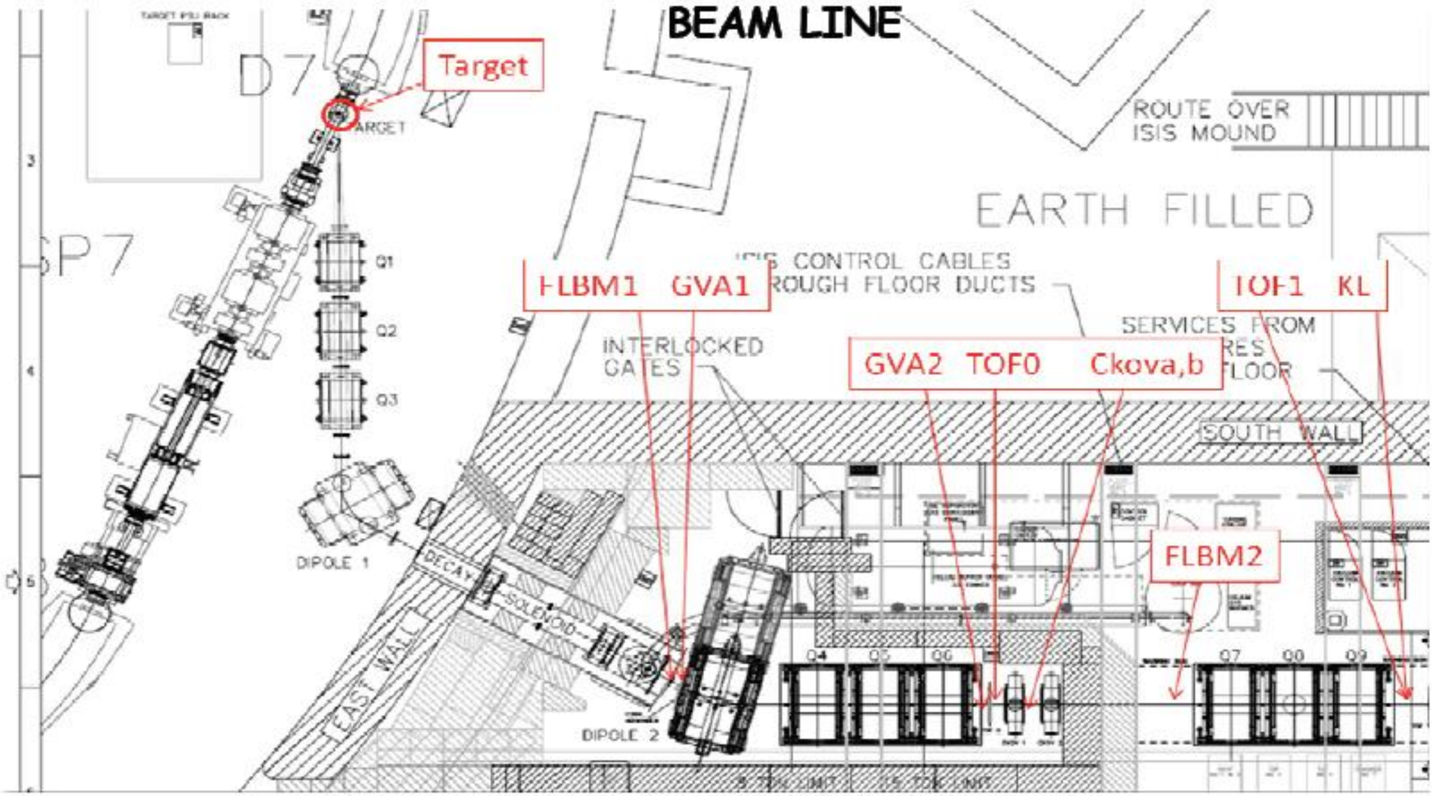


- Build a section of cooling channel long enough to provide measurable cooling (10%) and short enough to be affordable and flexible
- Wish to measure this change to 1%
- Requires measurement of emittance of beams into and out of cooling channel to 0.1% !
- Cannot be done with conventional beam monitoring device
- Instead perform a single particle experiment:
  - High precision measurement of each track (x,y,z,px,py,pz,t,E)
  - Build up a virtual bunch offline
  - Analyse effect of cooling channel on many different bunches
  - Study cooling channels parameters over a range of initial beam momenta and emittances

MICE setup: cooling + diagnostics



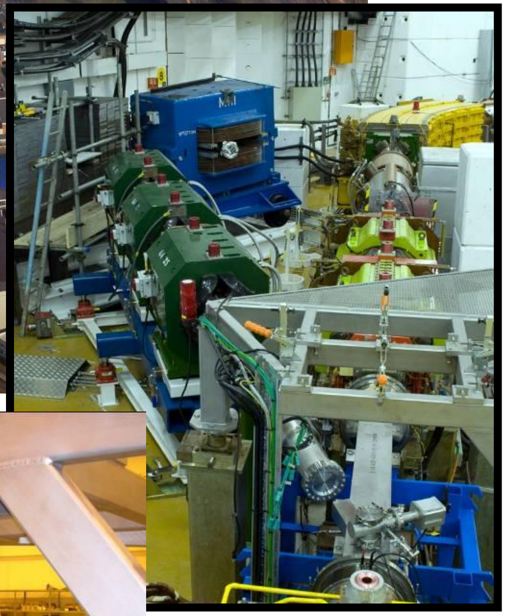
MICE installation status (2009)



- Target
- Beamline
- PID detectors

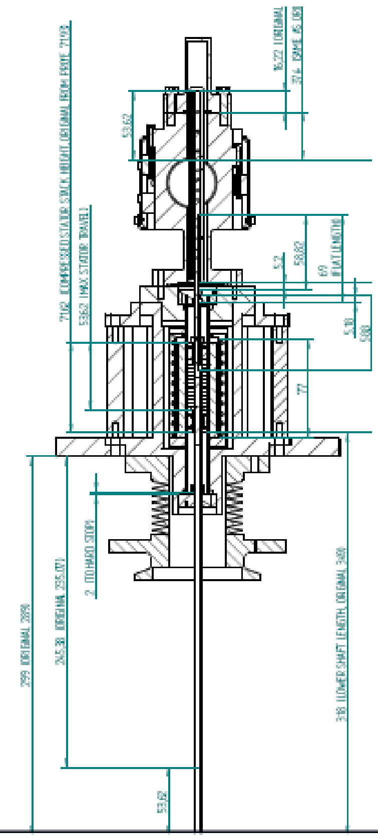
MICE Beamline

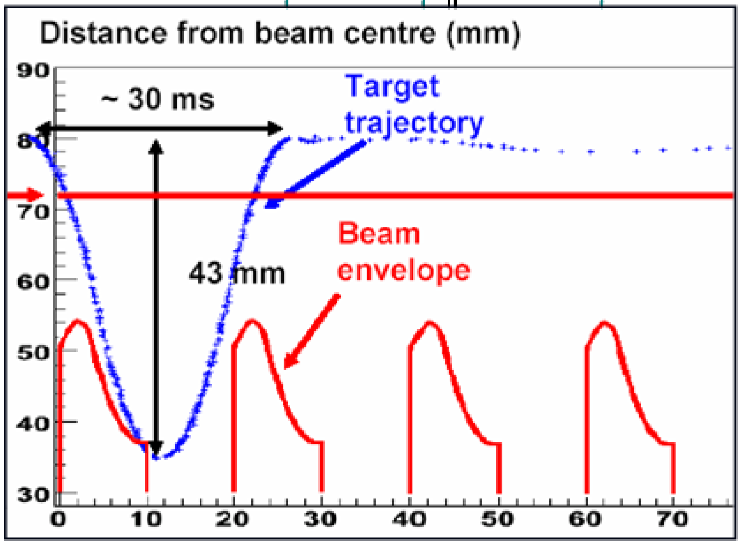
- ISIS 800 MeV proton synchrotron at RAL
- Titanium target, grazing ISIS beam
- π captured by quad triplet and momentum selected by dipole
- Followed by 5T decay superconducting solenoid (5 m long): contain π and decay μ
- Second dipole momentum select muons



MICE Target

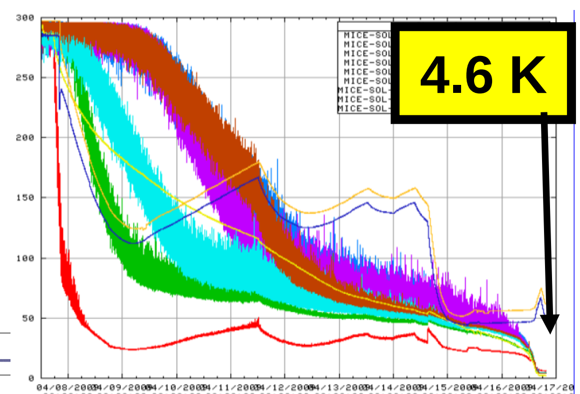
- Titanium target (UK) dipped into ISIS beam at end of 20 ms beam cycle at ~0.4 Hz
- This requires fine control of the position of the target as well as high acceleration (~80 g)
- Original target ran 190K dips into beam, but failed december 2008 (Tip melted)
- *A simplified design is being constructed*
- Understand target operation
  - Beam loss
  - Dip depth and timing
  - How affect ISIS
  - Number of particles in MICE beamline

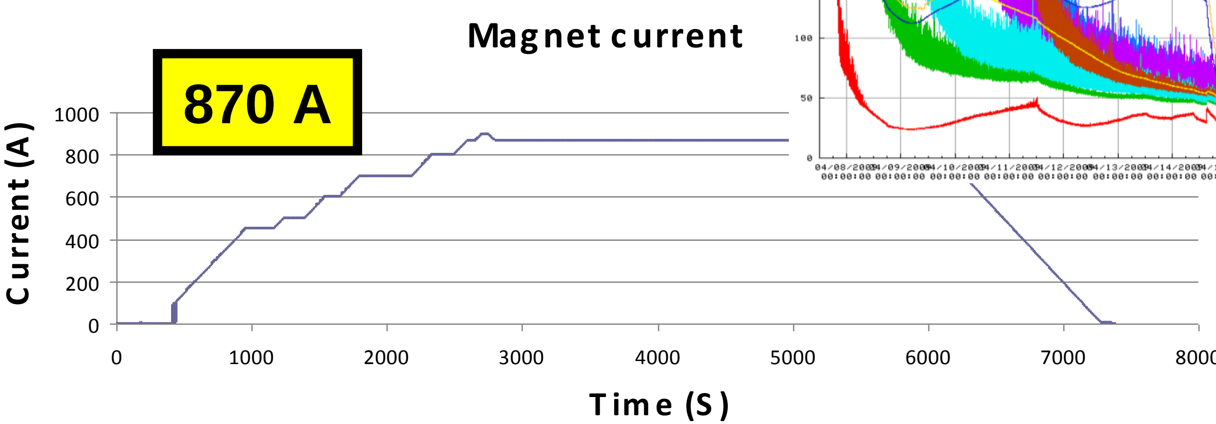




Decay Solenoid

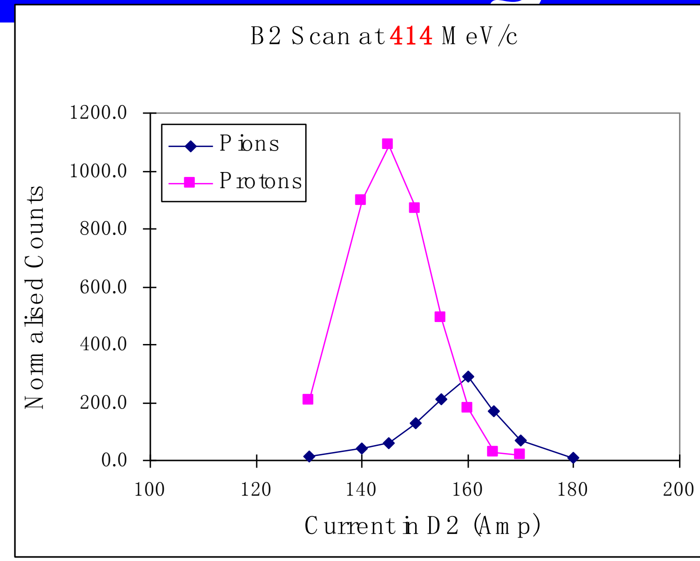
- 5T superconducting solenoid (PSI)
- Problem:
  - Quenched at ~290A (870 A is required for normal running at 5 T)
- Solution:
  - Missing multi-layer insulation caused quenches → installed March/April
- Cooled down
- Ran up to full operating current April 2009

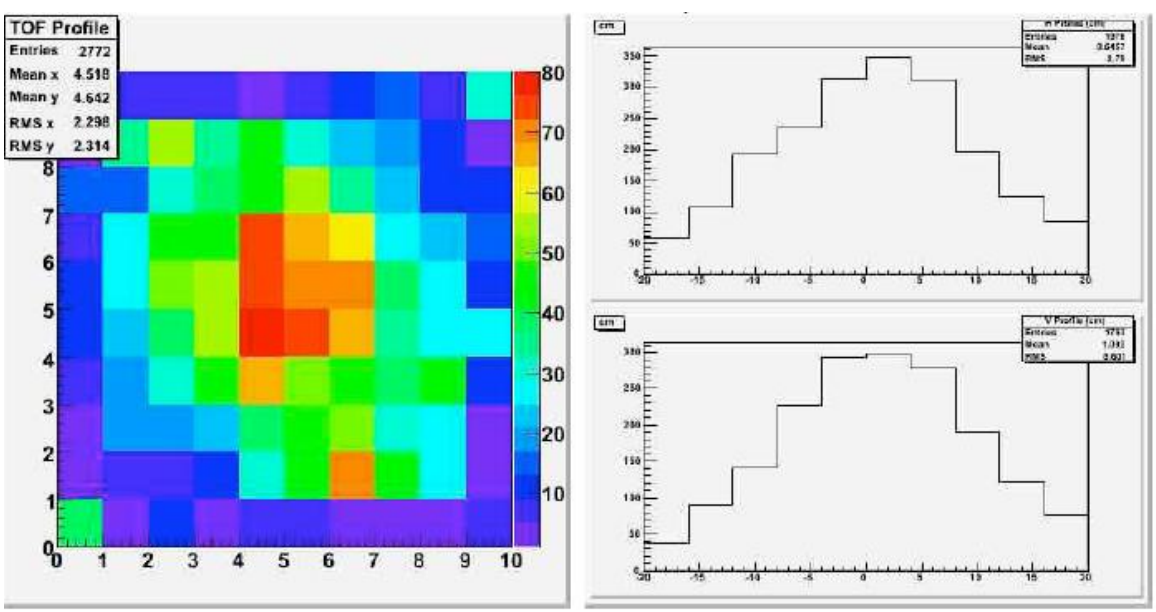




Beamline Commissioning

- The beamline has been operated over a range of momenta, producing positrons, pions and protons
- TOF0 and KL detectors have been used to record beam profiles
- Time of flight have been used to identify pions and protons





300 MeV/c pion beam profile in TOF0. Left : 2D beam profile

MICE cooling channel

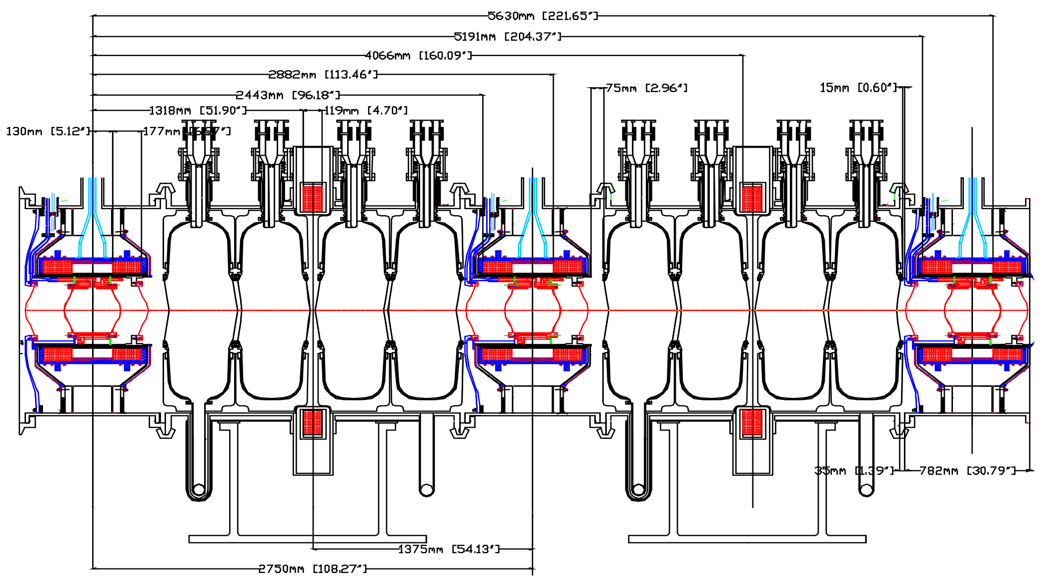
- $$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}$$

Minimize heating term:

•Absorber with large X_0

•SC solenoid focusing for small β_T

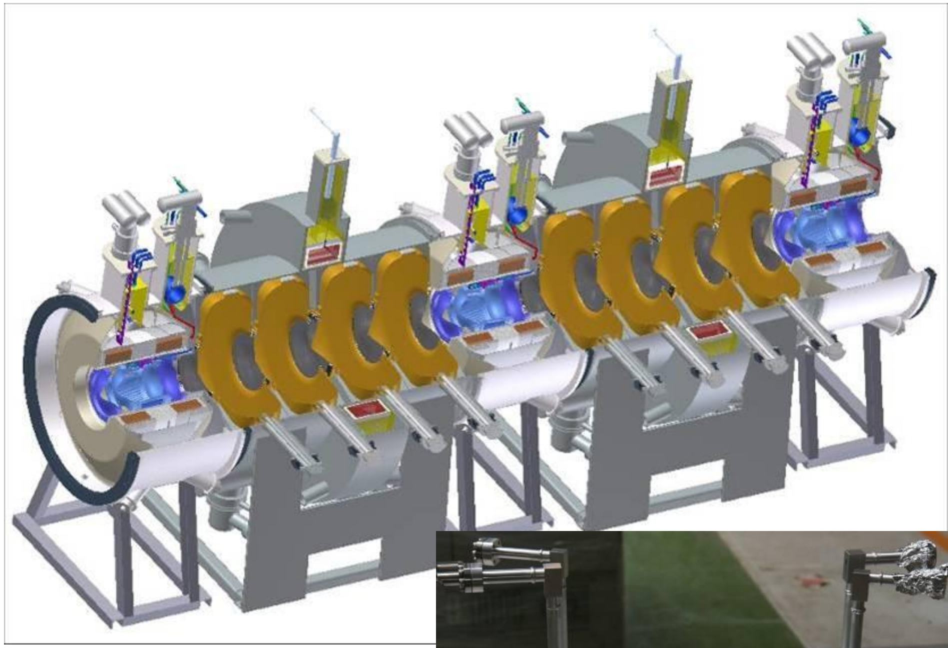
- High gradient reacceleration
  - 10% reduction of muon emittance for 200 MeV muons requires ~20MV RF
- Challenge: integration of these elements in the most compact and economic way

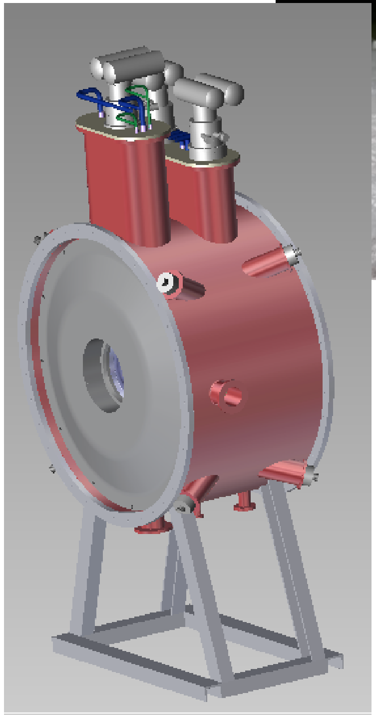


- 3 Liquid Hydrogen absorbers
- 8 cavities 201MHz RFs, 8MV/m
- 5T SC solenoids

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



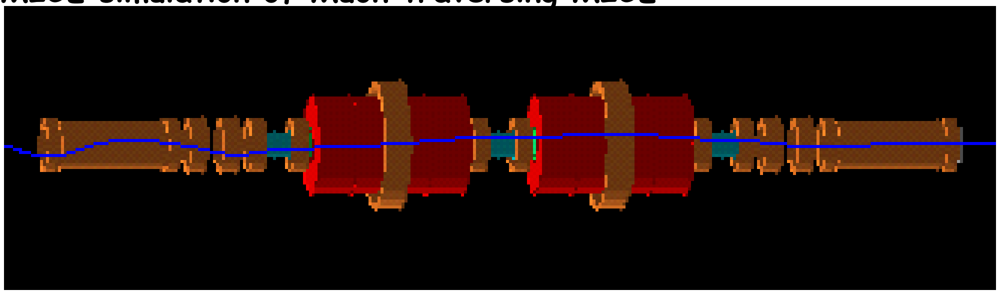


RF Module

- 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

Muon Emittance measurement

G4MICE simulation of Muon traversing MICE



Each spectrometer measures 6 parameters per particle
x y t $x' = dx/dz = P_x/P_z$ $y' = dy/dz = P_y/P_z$ $t' = dt/dz = E/P_z$

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

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

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}

Spectrometer syst. requirements

1. must be sure particles considered are muons throughout
   a) reject incoming e, p, π
   => TOF 2 stations 10 m flight with 70 ps resolution
   b) reject outgoing e => EMR Calorimeter

=>

2. measure 6 particle parameters
   i.e. $x, y, t, p_x/p_z, p_y/p_z, E/p_z$

3. measure widths and correlations …
   resolution in all parameters must be better than 10% of width at equilibrium emittance (correction less than 1%)
   $\sigma^2_{meas} = \sigma^2_{true} + \sigma^2_{res} = \sigma^2_{true} [1 + (\sigma_{res} / \sigma_{true})^2]$ (n.b. these are r.m.s.!)

4. robust against noise from RF cavities

Statistical precision

10^5 muons $\rightarrow \Delta(\varepsilon^{out} / \varepsilon^{in}) = 10^{-3}$ in ~ 1 hour

Systematics!!!!

MICE Detectors

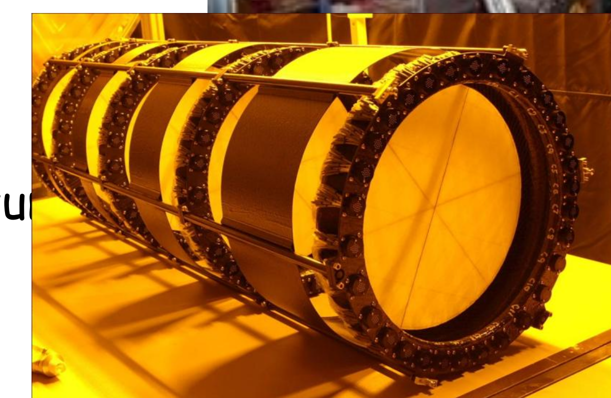
- Particle identification: TOF, CKOV, Calorimeter
  - Upstream
    - Time of Flight TOF0 + TOF1
    - 2 Aerogel threshold Cherenkov detectors

    ➔ π/μ separation up to 360 MeV/c

    ➔ Beam purity better than 99.9%
  - Downstream
    - TOF2
    - EMC Calorimeter
      - Kloe-like (KL) Lead-scintillating fiber sandwich layer (built)
      - Electron-Muon Ranger (EMR) (to be built)
        - » $1m^3$ block extruded scintillator bars
        - » Also measure muon momentum

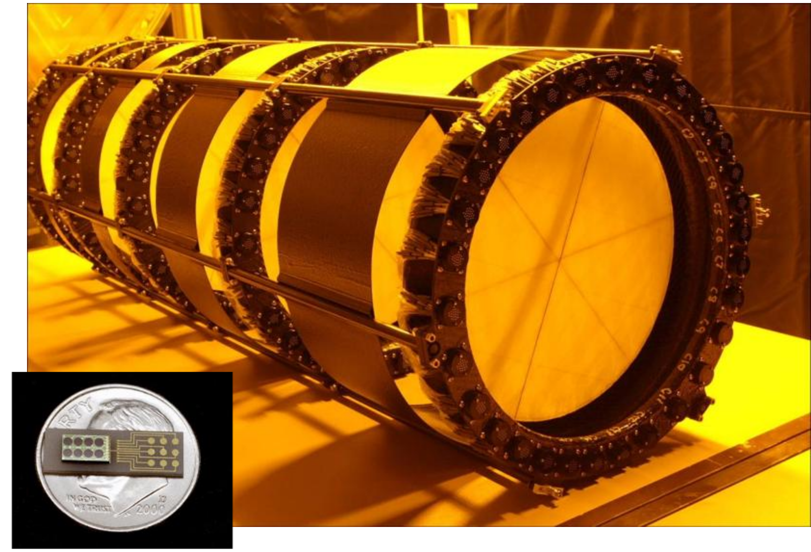
    ➔ μ/e separation

- Particle tracking
  - Scintillating Fiber trackers
  - Measure position and reconstruct momentu

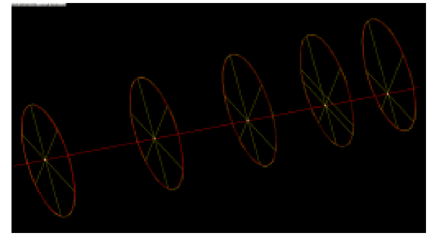


MICE Tracker

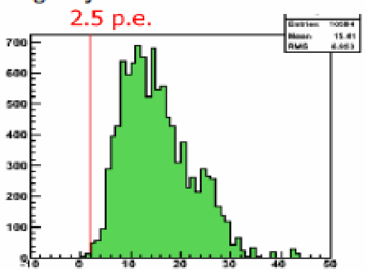
- **Scintillating fiber trackers**
  - Reduce transverse emittance by 10%
  - Trackers need to measure this reduction to 0.1% precision
  - Determine x,x′,y,y′ and momentum
  - High resolution on order of 1 fiber needed
- **Design**
  - 350 μm scintillating fiber doublet layers
  - Active area has diameter of 30 cm
  - 5 measurement stations with 3 planes each



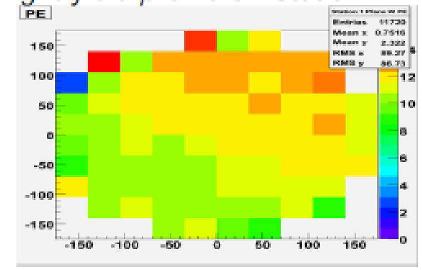
G4MICE event display



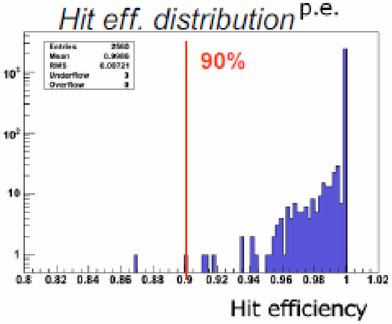
Light-yield distribution



Light-yield profile on Station

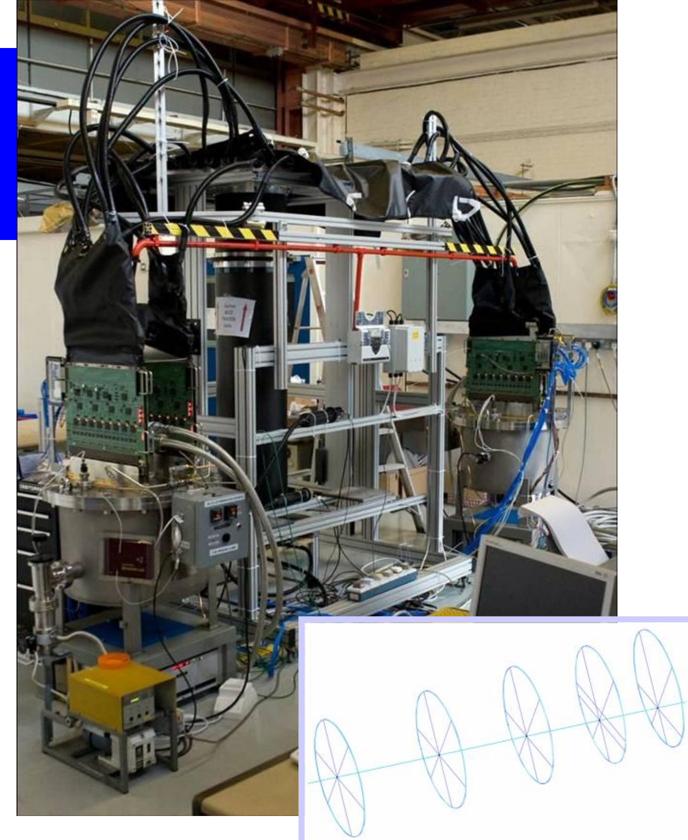


Hit eff. distribution



Spectrometer Status

- **Trackers**
  - Both trackers completed
  - Cosmic ray test of tracker1 at RAL:
    - Light yield measured 11 PE
    - Measured resolution consistent with goal of 430 μm
    - Efficiency – 99% hit efficiencies
  - **First to be installed in beam inside 4 T solenoid magnet (US) ~1m long with 5 SC coils**
- **Magnets**
  - First spectrometer solenoid built
  - Undergoing cooldown followed by magnet performance tests
  - Then ship to FNAL for field measurements
  - Second will follow later



PID apparatus: overview

MICE Particle ID Important to insure high muon purity for muon cooling measurement.

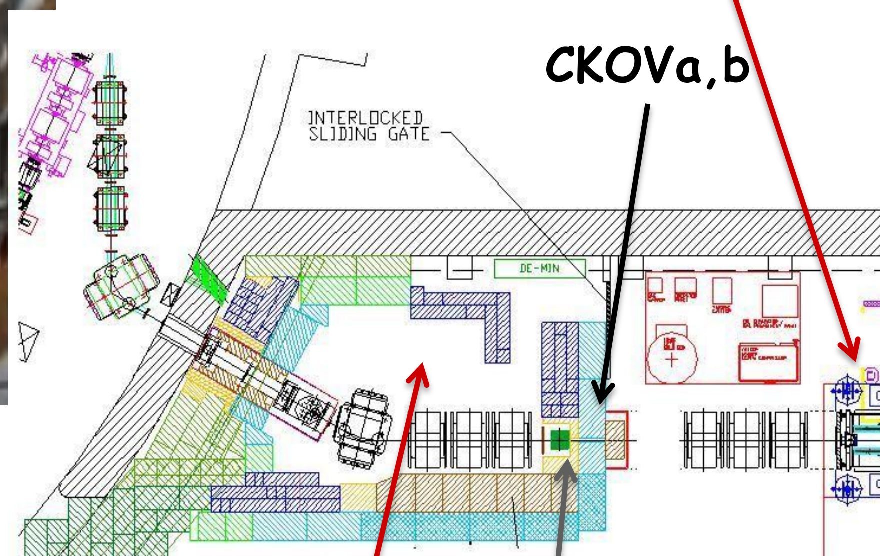
- Upstream:
  - TOF0,1 X/Y hodoscope with 10m path, 70 ps resolution
  - 2 Aereogel threshold Cherenkov detectors (n=1.07 and n=1.12)
  - $\pi/\mu/e$ separation at better than 1% at 230 MeV/c
- Downstream:
  - 0.5% of μ s decay in flight: need electron rejection at 10^{-3} to avoid bias on emittance reduction measurement
  - TOF2 X/Y hodoscope
  - EMC Calorimeter for MIP vs E.M. Shower (KL (built) + EMR (in future))

The upstream part (inside DSA)

MICE Beamline
Phase1/2 Startup

TOF1,KL

CKOVa,b



TOF0

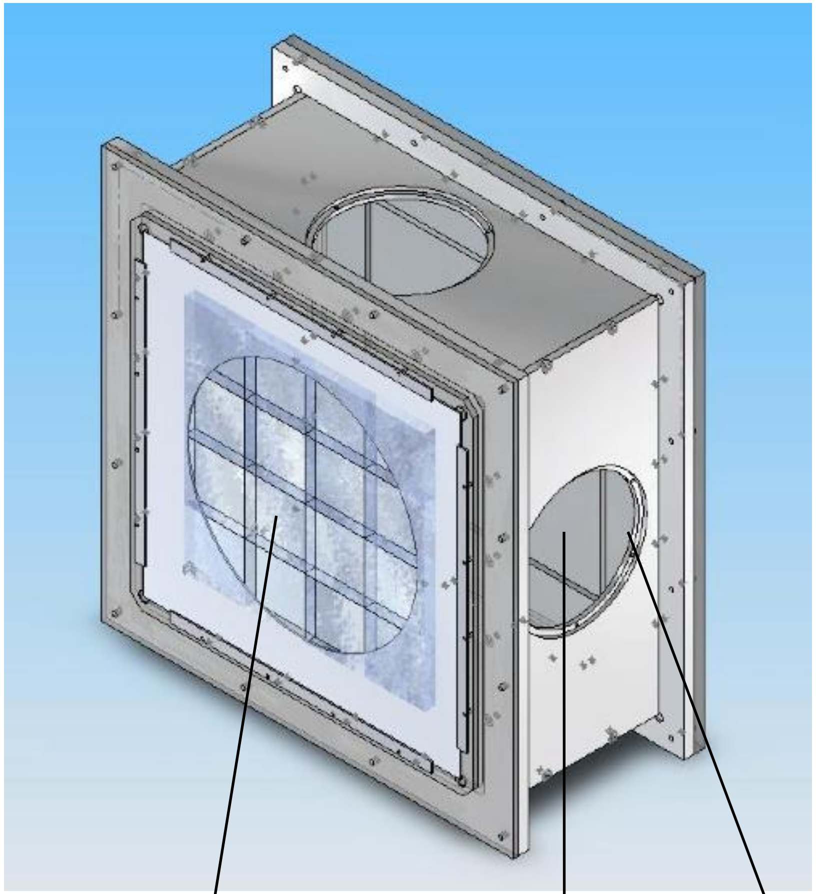
DSA

TOF0

Ckov counters

Upstream : CKOVa/CKOVb

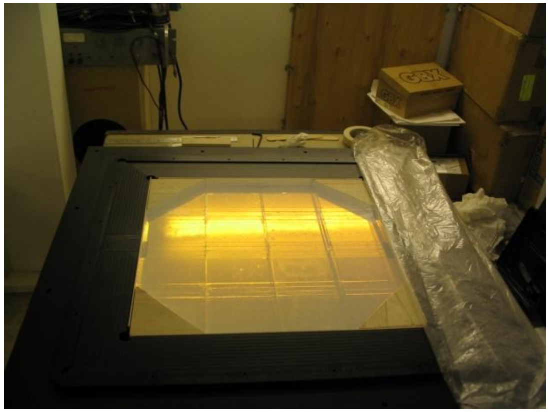
Aerogel box



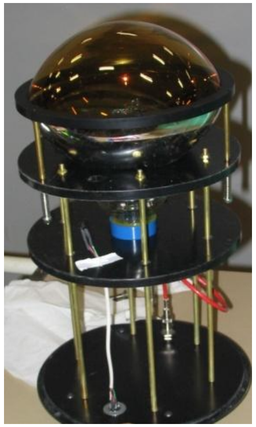
radiator

Reflector Panels
(not shown)

8" PMT port

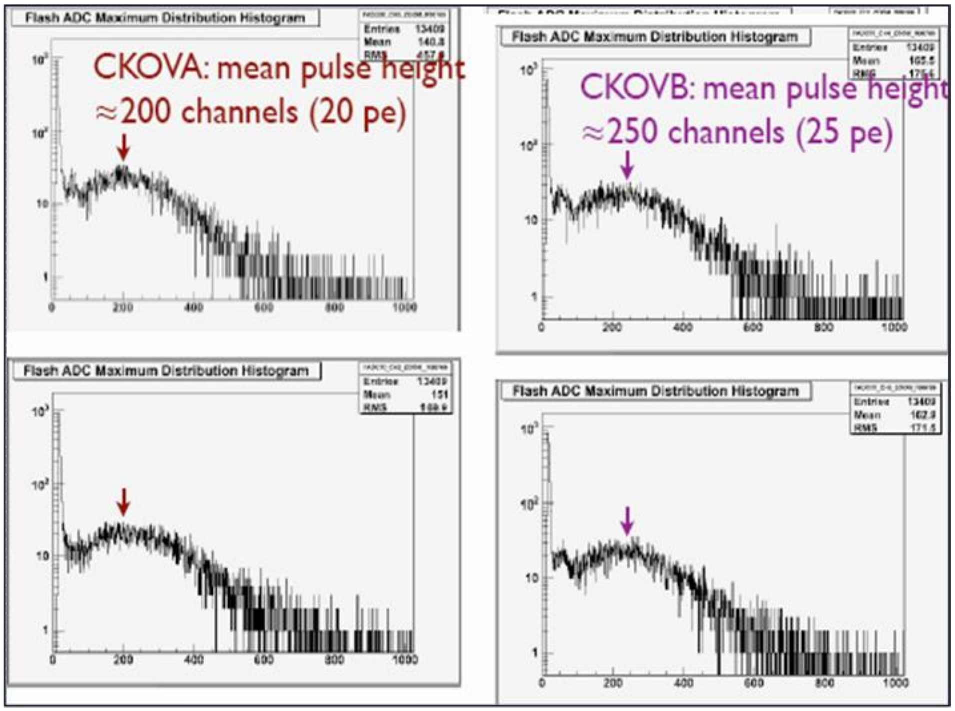


Aerogel radiator compartment



CKOV PMTs
(from CHOOZ)

Performances in beam of CKOVa,b

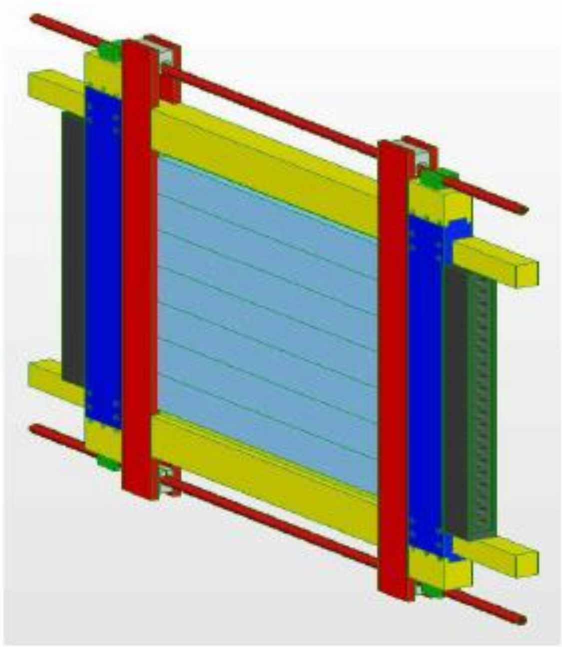


- ❑ Took data in MICE beamline
- ❑ Typical light spectrum from single PMT
- ❑ Muon tagging efficiency 98%

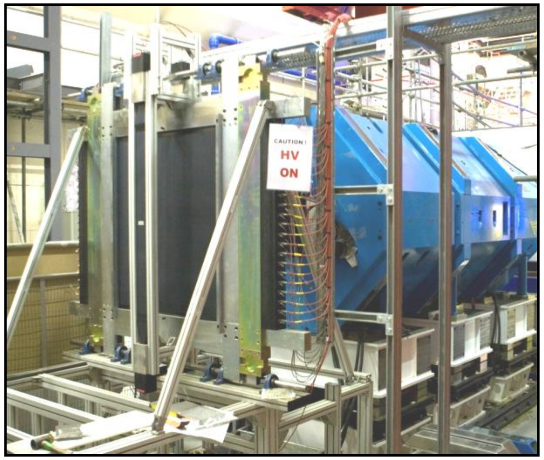
The downstream calorimeter electron-muon calorimeter (EMC)

- EMC is not primarily intended for energy measurements
- It's main role is to provide e/μ separation
- In MICE proposal this was provided by a CKOV counter + an em calorimeter (KL)
- Now it will be provided by KL + a sandwich calorimeter (EMR to be constructed)
- KL (KLOE-light) is a fiber spaghetti calorimeter with a design similar to the KLOE one
- EMR is a fully active calorimeter (10 layers) with increasing thickness

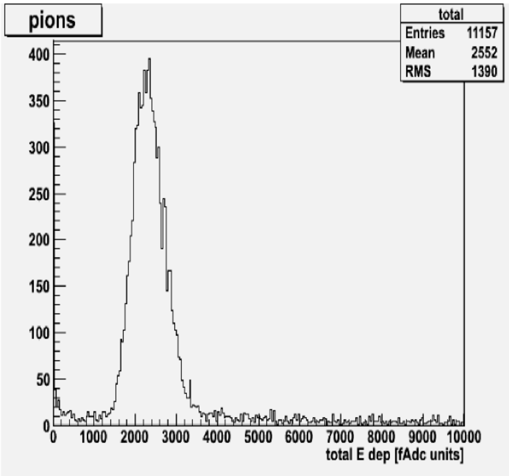
KL assembly



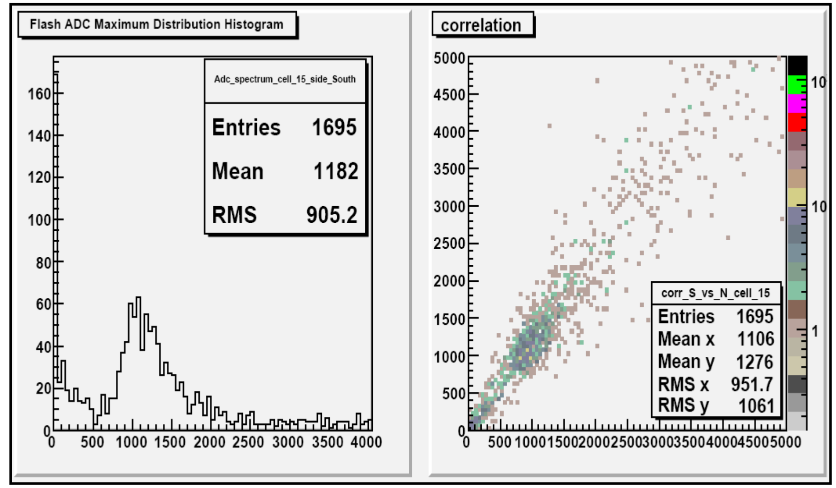
Installation in temporary position after Q9 at RAL



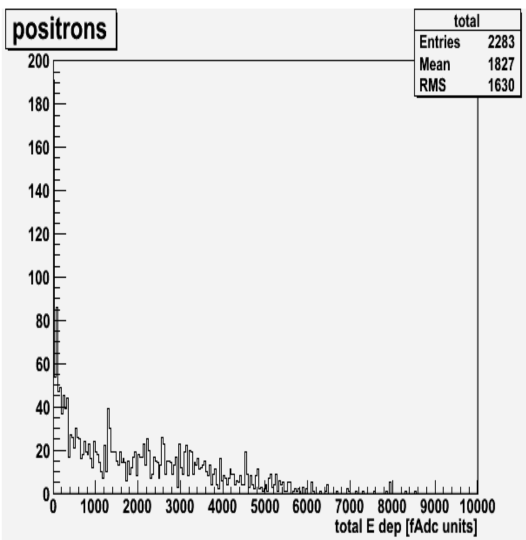
KL performances in beam



KL response to 300 MeV/c π beam

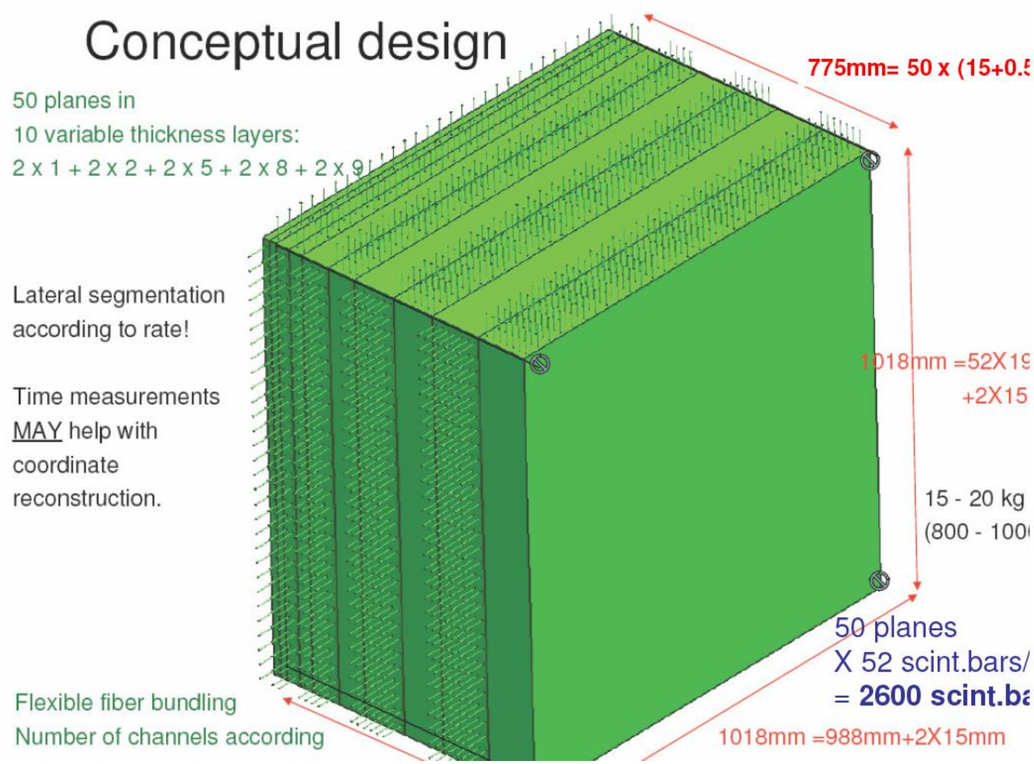


The typical MIP distribution and the correlation left-right of the photomultiplier signals with cosmics.



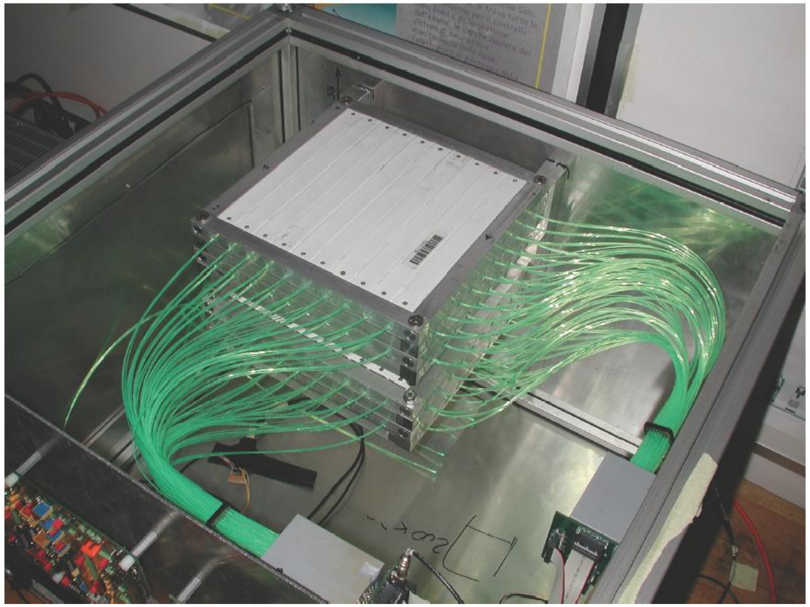
KL response to 100MeV e^+ beam

PID system upgrade: the EMR Calorimeter



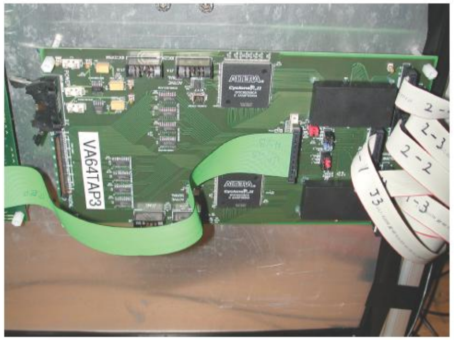
- **70 cm of fully active scintillator, highly segmented**
- **Light colleted by WLS fibers, read by Multi-anode PMTs**
- **Track Properties:**
  - **Muons show tracks;**
  - **Electrons converted in EM showers in KL show scattered hits**
- **dE/dx along Z**
  - **Muons have constant dE/dX up to the Bragg peak**
  - **Electrons have large fluctuations in Energy loss which tends to decrease with Z**

Full prototype mounted



Front-end electronics

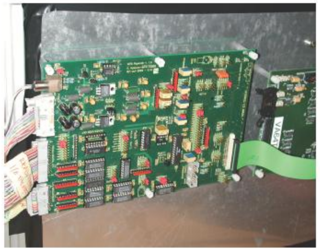
Read-out based on 2 board: the FEE and the repeater which transfer the information from the FEE to the VME crate.



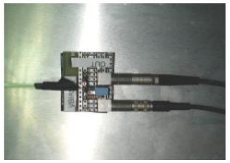
The IDEAS integrated circuit used (VA series) has 2 working mode:

- Threshold detection
- Peak sampling (Sample and Hold)

In threshold mode an FPGA is used to reduce the amount of information sent to the repeater.
In Peak Sampling mode the peak amplitude of all the channels are read sequentially.



Read-out with 1 SiPM also tested



Cosmic rays setup

- External scintillator trigger
- 4 silicon strips external tracker (2 “x” and 2 “y” measurements of each cosmic ray)
- SW prototype in horizontal position
- ~10^5 events acquired

A test is on-going at CERN with high energy electrons!

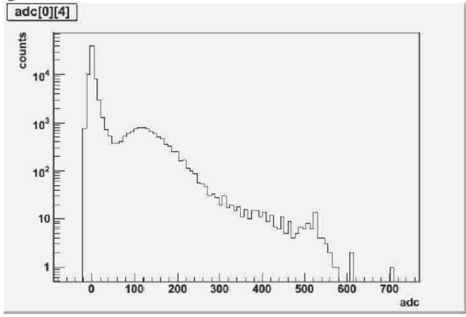
Preliminary Results

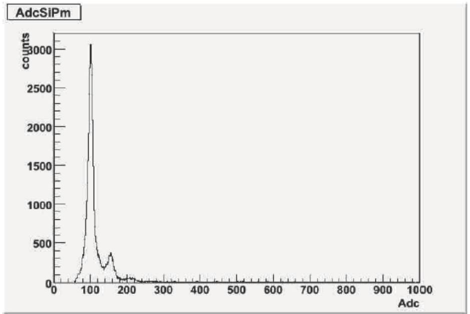
- Big number of photoelectrons in PM
- SiPM also an option (but maybe too early)

0: threshold at 60
*: threshold at 30

```
event: 35
---------0-        ----0-----
---------0-        --*0------
----------0        --0-------
----------0        -00-------
```

EP X layers Y layers





TOF system requirements

- Exp trigger, upstream/downstream PID and measure of t vs RF
- Work in a harsh environment (high incoming particle rate, high fringe fields from solenoids, X rays from converted e^-)

with good timing performances (σ_t~50 ps) → Some points to look to have high resolution TOFs

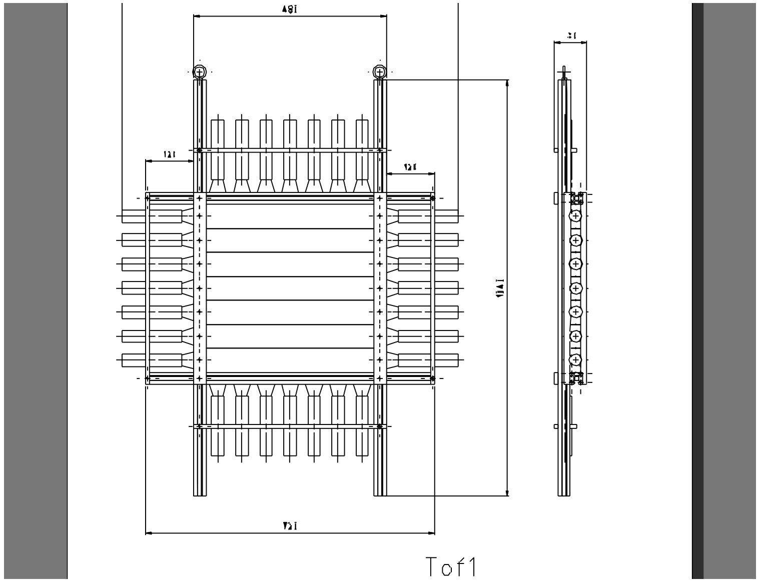
Tof resolution can be expressed as:

$$\sigma_t = \sqrt{\frac{\sigma^2_{scint} + \sigma^2_{PMT} + \sigma^2_{pl}}{N_{pe}} + \sigma^2_{elec}}$$

- σ_{pl} **dominated by geometrical dimensions ~√(L/Npe)**
- σ_{scint} ~ **50-60 ps (mainly connected with produced number of γ's fast and scintillator characteristics, such as risetime)**
- σ_{PMT} **PMT TTS (typically 150-300 ps)** **+**

- **HARSH Environment (shielding from B, RF noise, high particle rate)**

TOF design



- "conventional" X/Y scintillator structure with readout at both ends, to provide redundancy & intercalibration with inc. μ
- problem: choice of PMTs for high incident particle rate (1 MHz) and solenoid B fringe field ($B_{//}$ ~ 200-300 G, B_{perp} ~ 1K G)

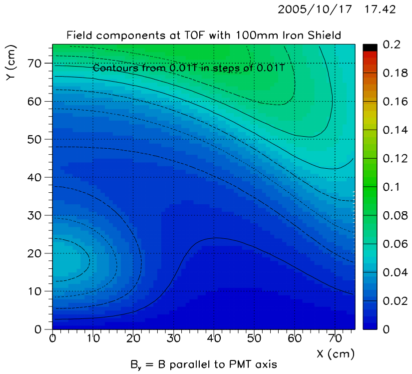


Figure 4: $B_{\parallel}$ at the position of TOF2 with the 100 mm iron shield.

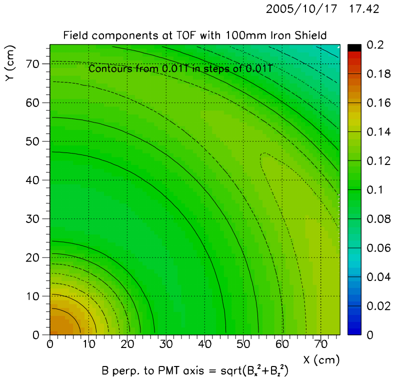
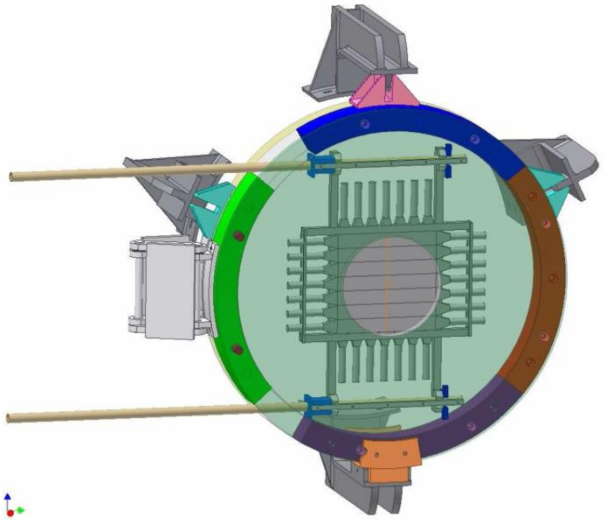
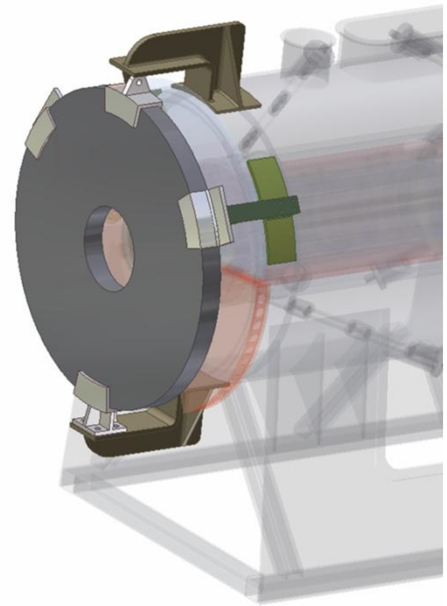
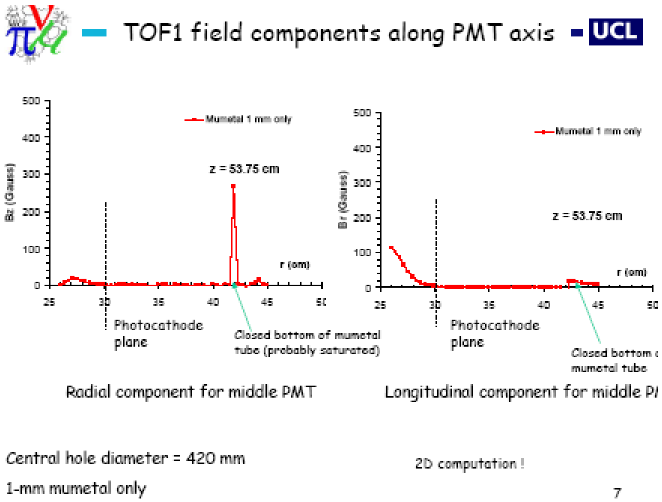


Figure 5: $B_{\perp}$ at the position of TOF2 with the 100 mm iron shield.

Magnetic field shielding

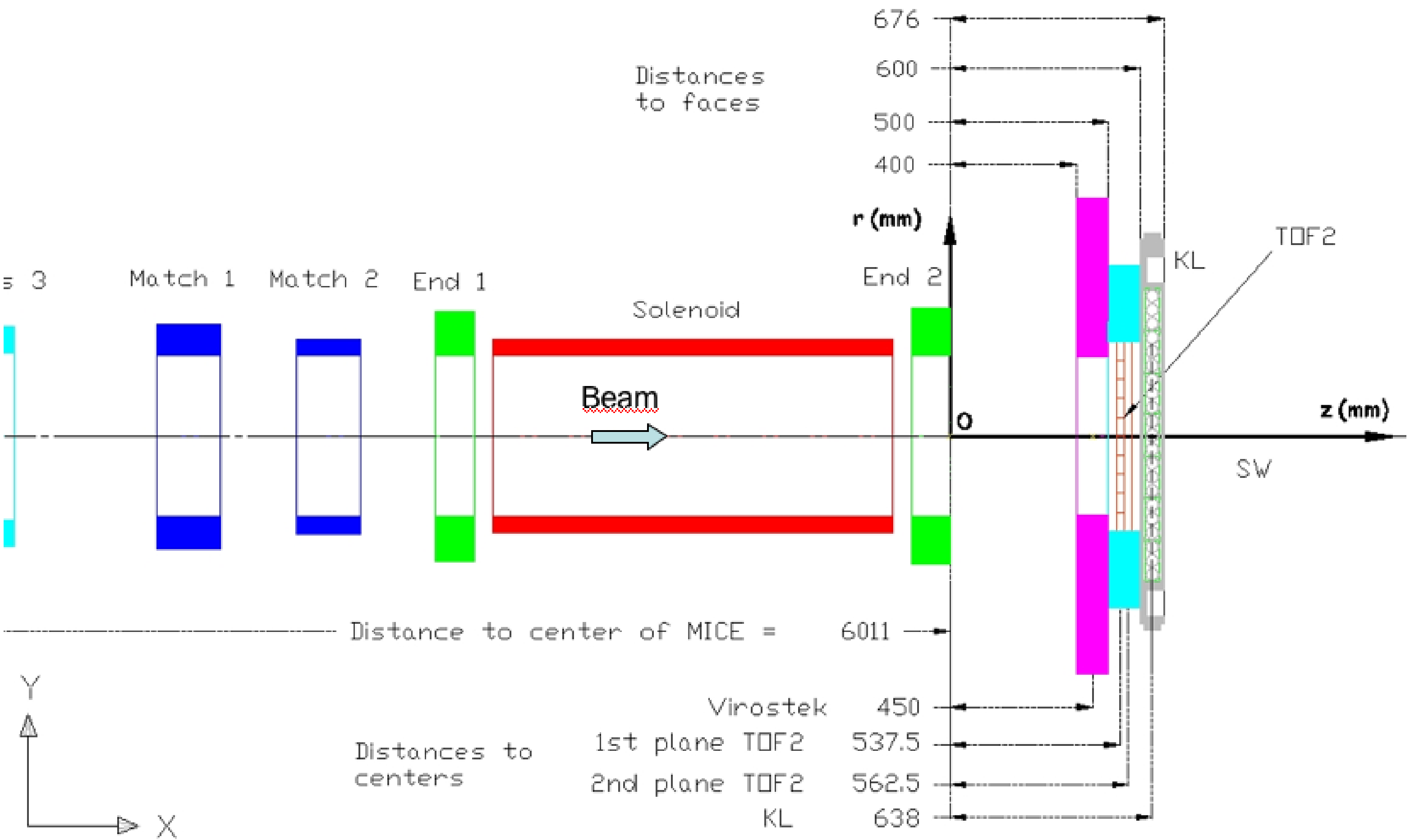




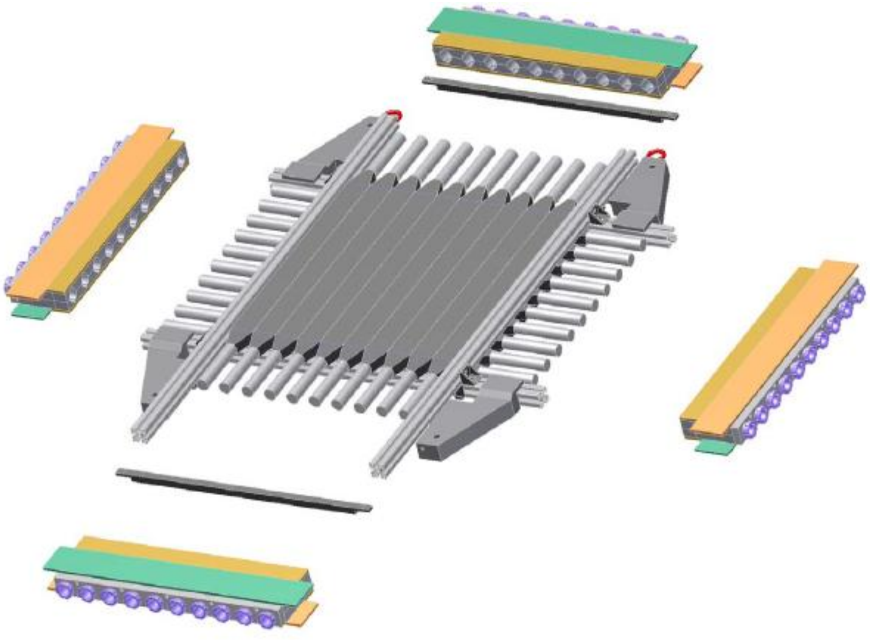


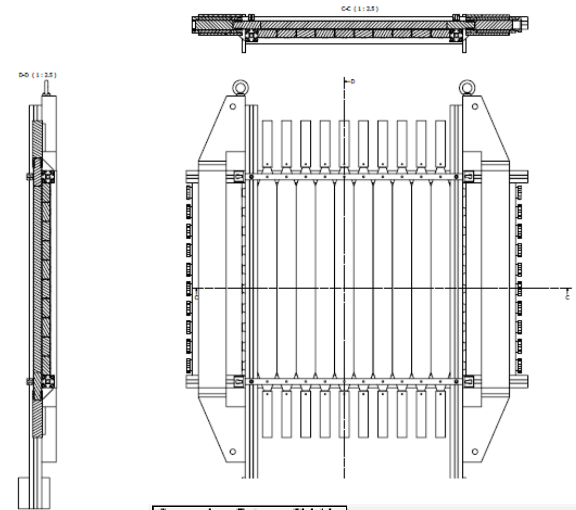
With an external cage B field is reduced to tolerable levels for conventional R4198 PMTs (solution adopted for TOF1)

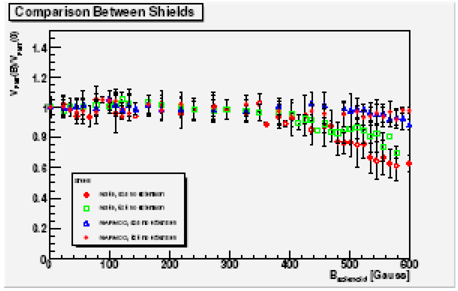
Downstream PID Layout

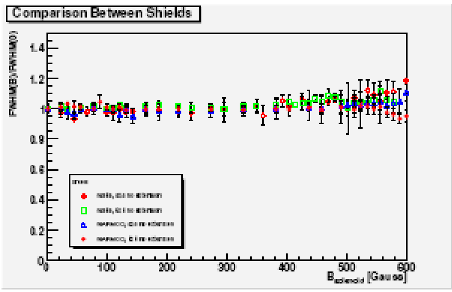


TOF2 Local Shielding



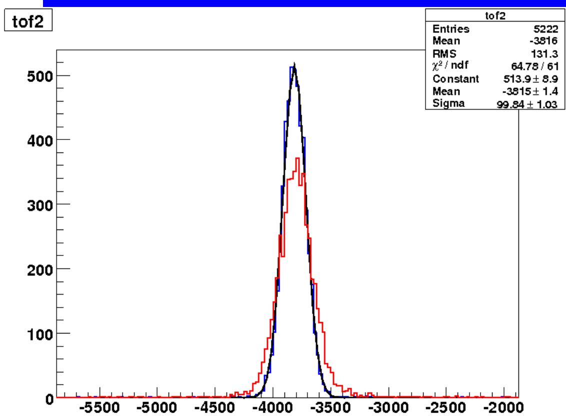




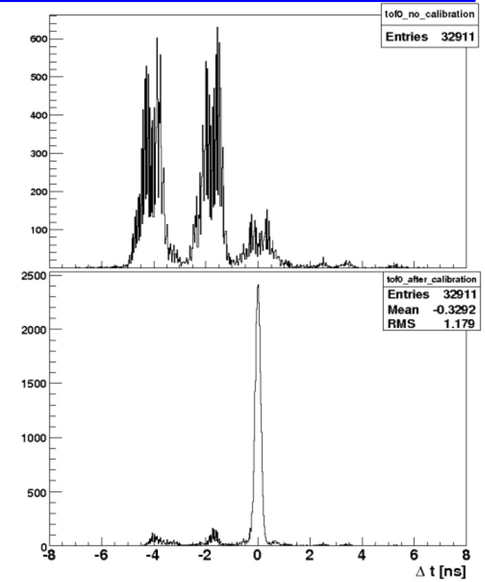


- for TOF2 **massive box ARMCO local shielding (D0-like)** solution
- PMT studies show solution is adequate..

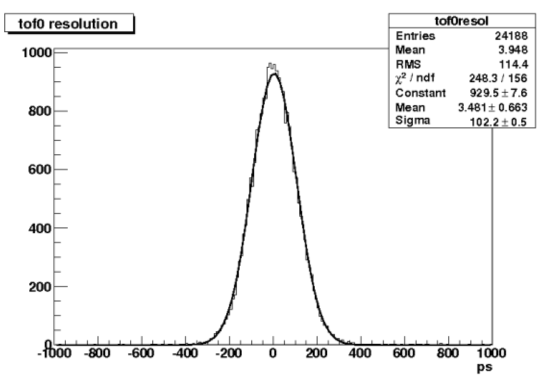
First results in beam for TOF0-TOF1

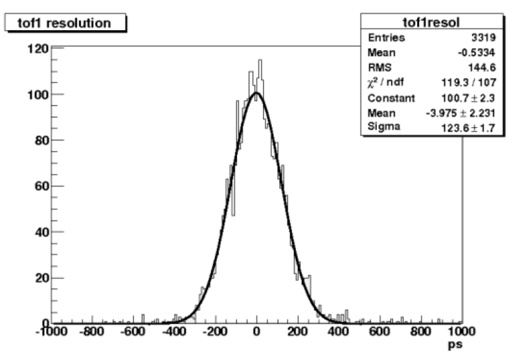


After time-walk correction
+ time calibration

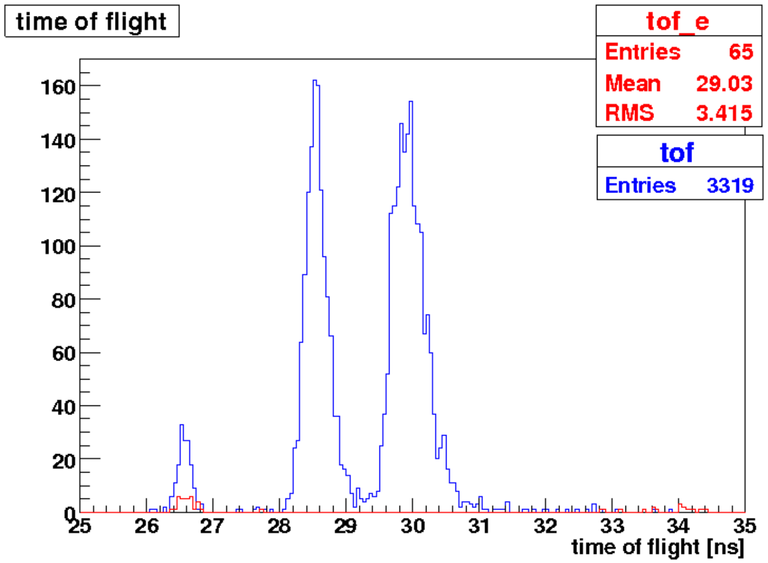


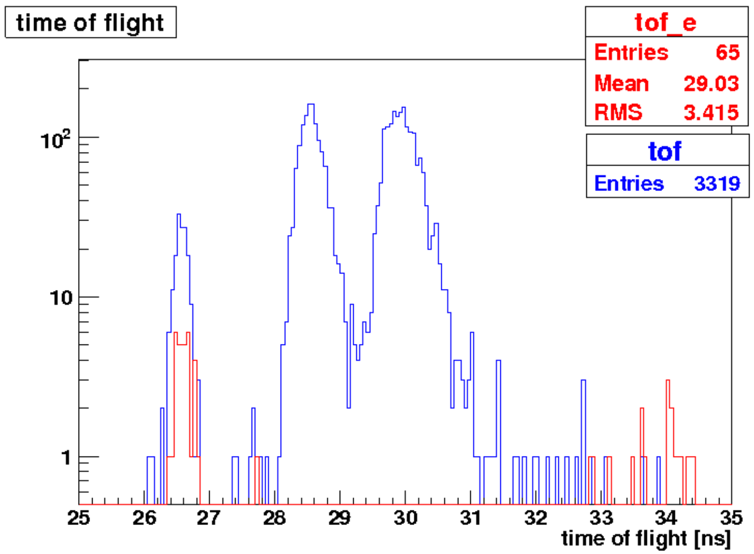
The time difference between the vertical and horizontal slabs in the same station can be used also to measure the time resolution obtained after the calibration. The resolution on the difference in the calibrated pixels in TOF0 (TOF1) is ~ 102 (124) ps. This translates into ~ 51 (62) ps resolution for the full detector with crossed horizontal and vertical planes





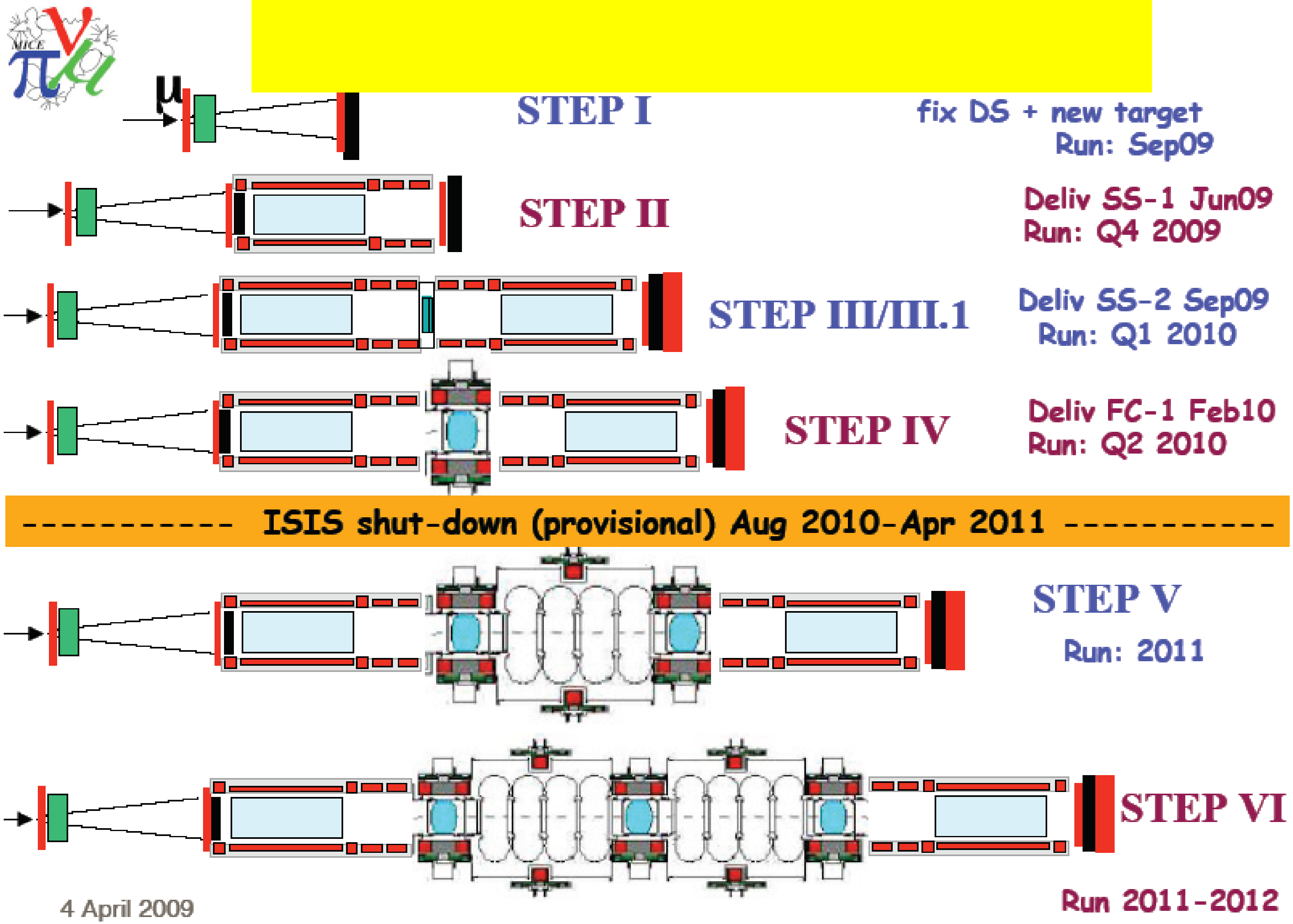
Time of flight spectrum





- **Time of flight between TOF0 and TOF1 for the so called positron (red) and pion (blue) beams**
- The first peak which is present in both distributions is considered as the **time of flight** of the positrons and is used to determine the absolute value of the time in TOF1.. A natural interpretation of the other two peaks in the time of flight spectrum from the so called **pion beam** is that they are due to forward flying muons from pion decay and pions themselves , but the calculated time of flight of nominal 300 MeV/c pions is ~ 29.4 ns instead of ~ 30.0 ns, where the third peak maximum is positioned.
- This difference may be partly explained by the energy loss inside the TOF0 and the two upstream Cerenkovs, that amounts to ~ 17 MeV.

The MICE Schedule



- Experiment designed to grow with each step providing important information

Conclusions

- Beamline in place and commissioning begun
- Decay solenoid working
- PID detectors (TOF0,TOF1,CKoV, KL) in place and working well
- Tracker1 performing well and ready for installation when first tracking solenoid will arrive
- First emittance measurement Fall 2009
- First cooling 2010