MICE Overview, Status, and Facility

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Muon Accelerator Program Review
Fermilab, August 24, 2010

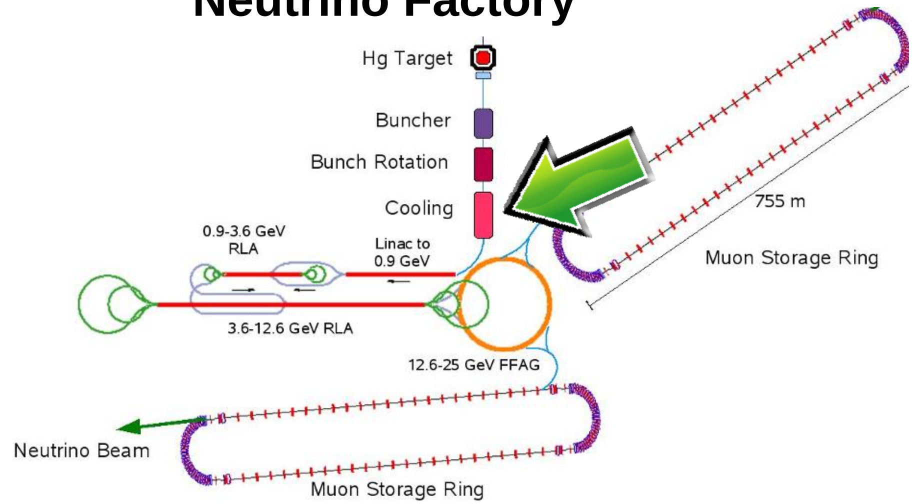
Outline

- ***Motivation***
- ***MICE Schedule***
- ***MICE Description***
- ***Step I Results***
- ***Cooling Channel Status***
- ***Conclusions***

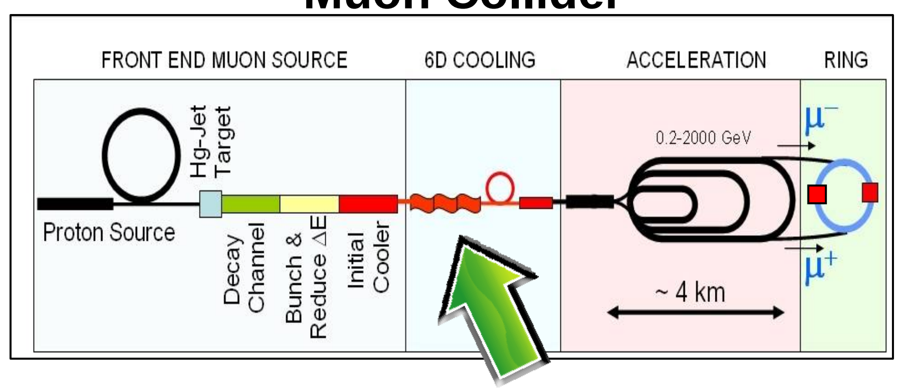
NF & MC R&D

- ***Challenges:***
  - ***High intensity proton source***
  - ***Complex target***
  - ***Want to accelerate muon beam***
    - ***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***
  - ***Target studies (MERIT)***
  - ***RF in magnetic field studies (MUCOOL)***

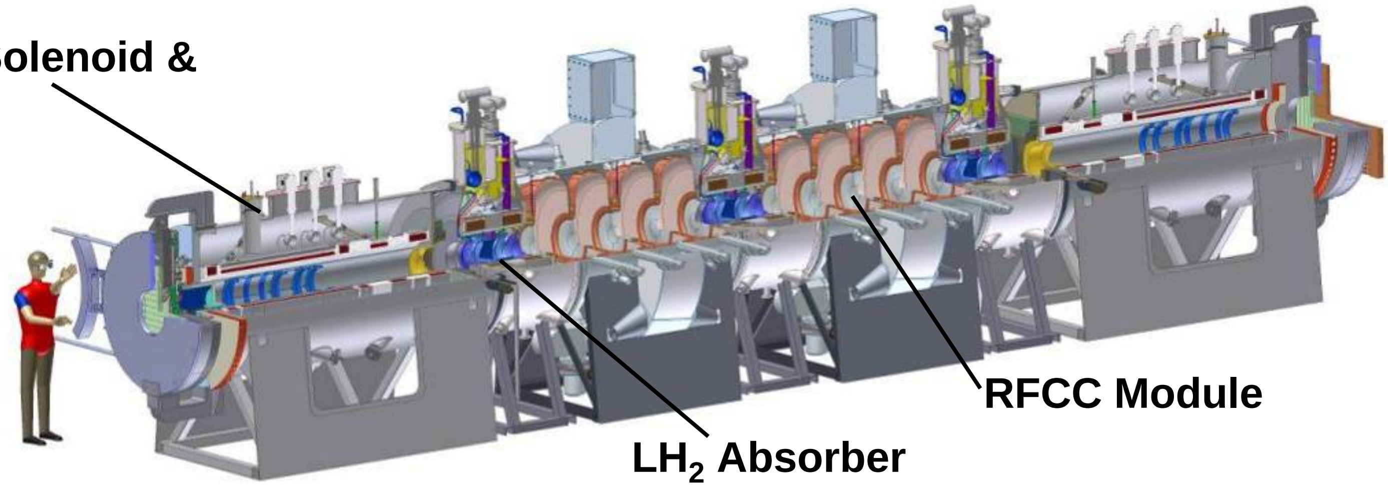
Neutrino Factory



Muon Collider



MICE:
Muon Ionization Cooling Experiment



- **MICE:**
  - Design, build, commission and operate a realistic section of cooling channel
  - Measure its performance in a variety of modes of operation and beam conditions …

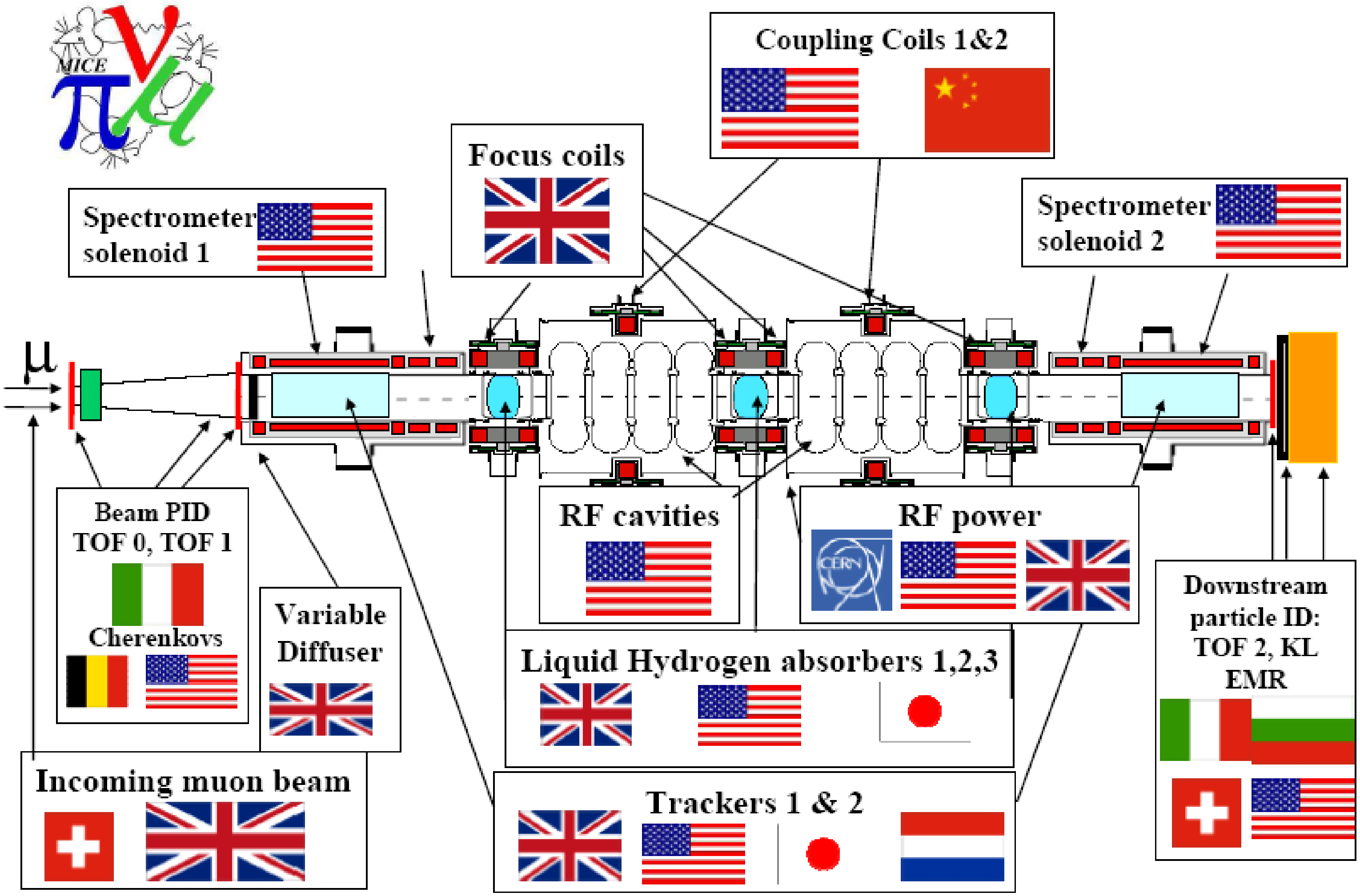
  … results will be used to optimize Neutrino Factory & Muon Collider designs

MICE: Design

- ***MICE designed to produce a 10% cooling effect on the muon beam***
- ***Uses particle detectors to measure cooling effect to ~1%***
- ***Measurements will be done with muon beams having momentum of 140 MeV/c – 240 MeV/c***
- **Method:**
  - **Create beam of muons**
  - **Identify muons and reject background**
  - **Measure single particle parameters x, p_x, y, p_y, p_z**
  - **Cool muons in absorber**
  - **Restore longitudinal momentum component with RF cavities**
  - **Identify outgoing particles to reject electrons from muon decay**

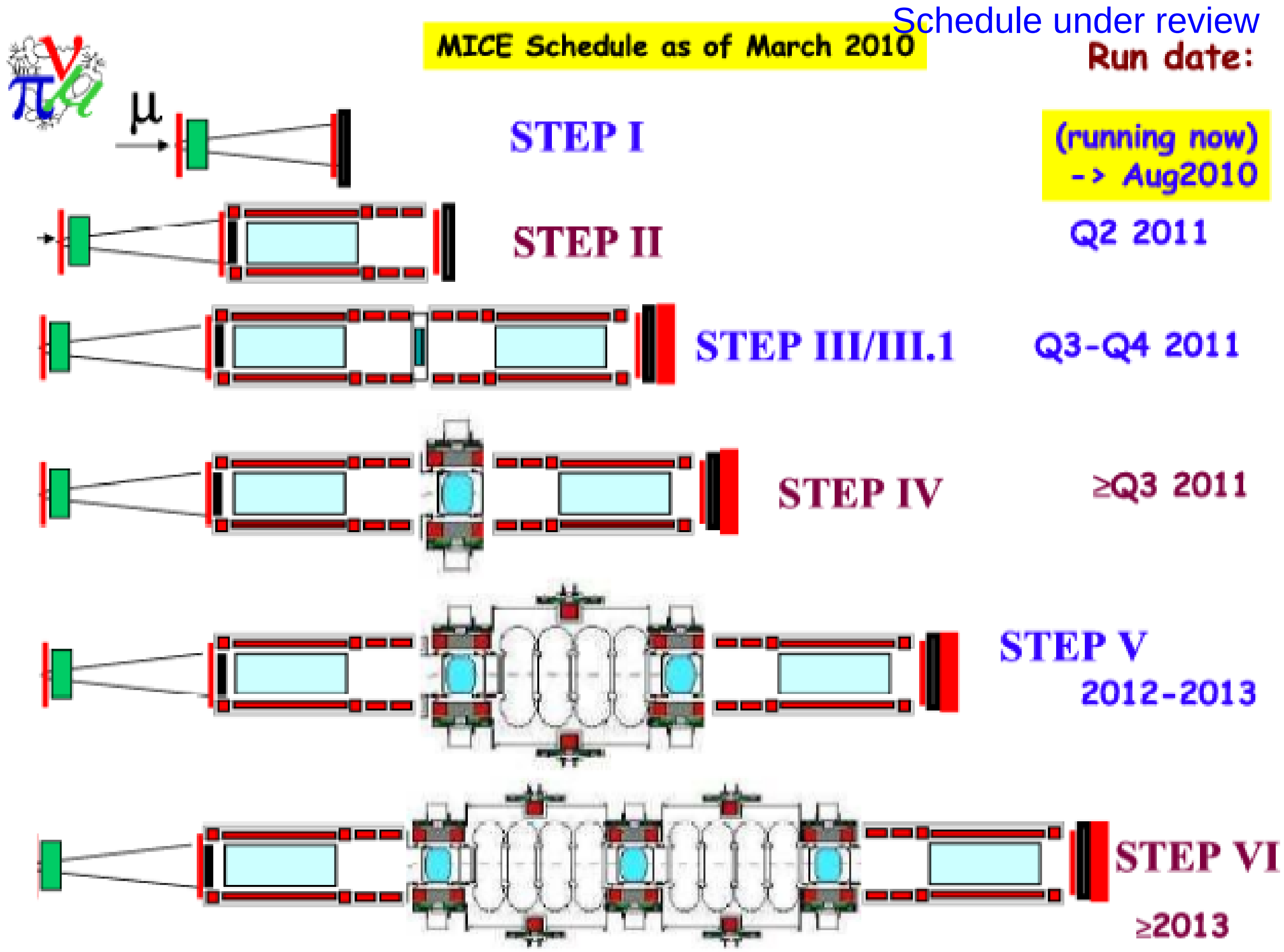
MICE: MAP Involvement

- ***MAP institutions contributing to all aspects of MICE***



MICE Schedule

- ***Proceeding in stages***



Commission beam line & detectors

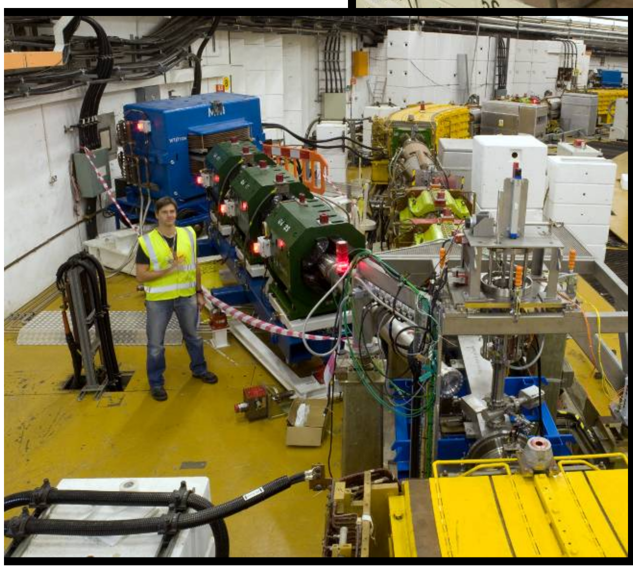
Precisely measure incoming emittance & compare trackers

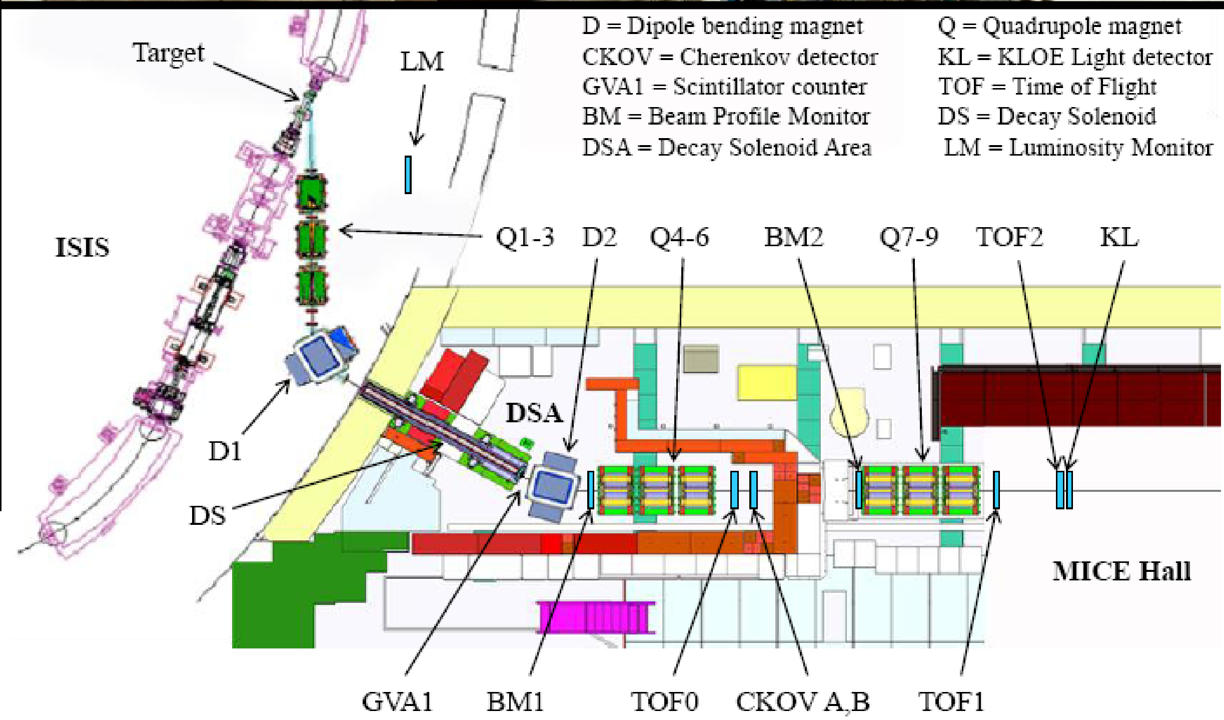
Precisely measure muon cooling

Test sustainable cooling

Ultimate MICE goal: operate full cooling channel

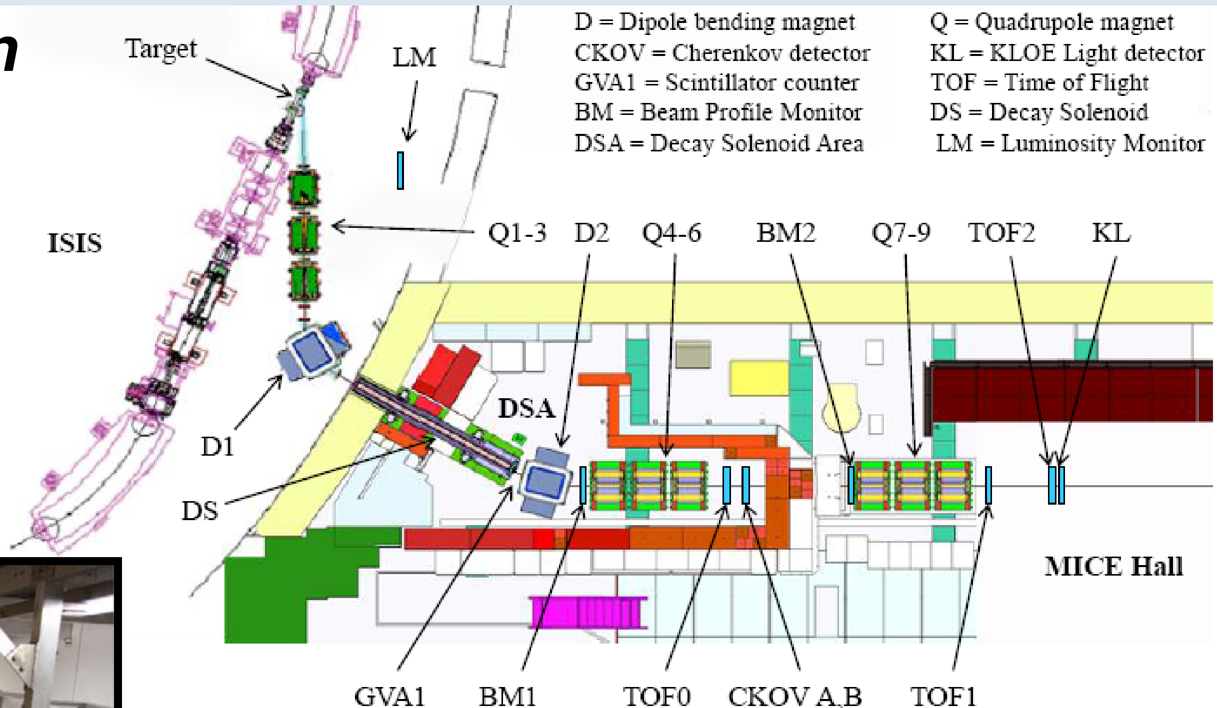
MICE Beam Line





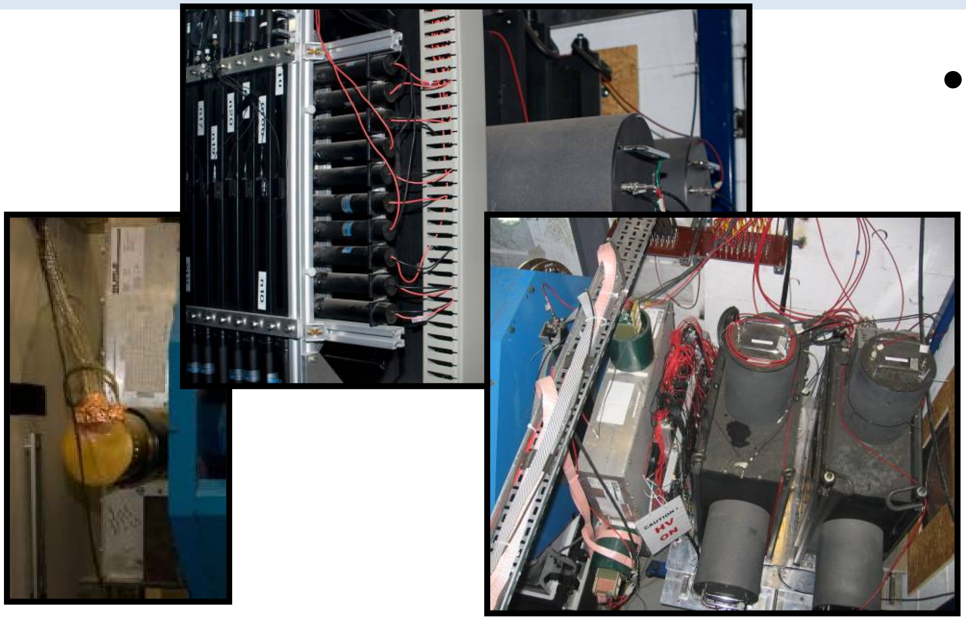
MICE Beam Line

- ***ISIS 800 MeV proton synchrotron at RAL***
- ***Titanium target***
- ***Quad Triplet***
  - *Captures pions*
- ***First Dipole***
  - *Selects pion momentum*



- ***Superconducting Decay Solenoid***
  - *Contains π and decay muons*
  - *5 T, 5 m long*
- ***Second dipole***
  - *Selects muon momentum*
- ***Two Quad Triplets follow for transport***

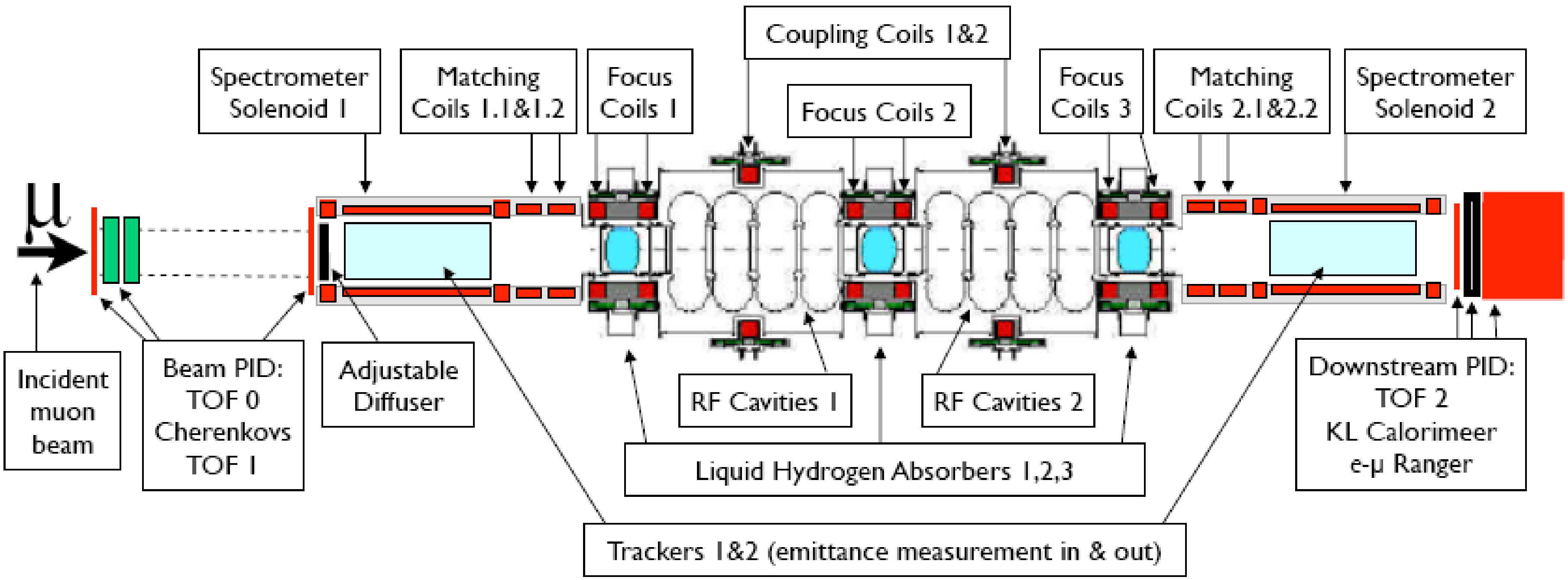
Description: Particle Identification Detectors



- ***Upstream PID:***
  discriminate p, π, μ
  - ***Beam Profile Monitors (FNAL)***
  - ***Threshold Cerenkov (UMiss/Belgium)***
  - ***Time of Flight – TOF0 & TOF1 (Italy/Bulgaria)***

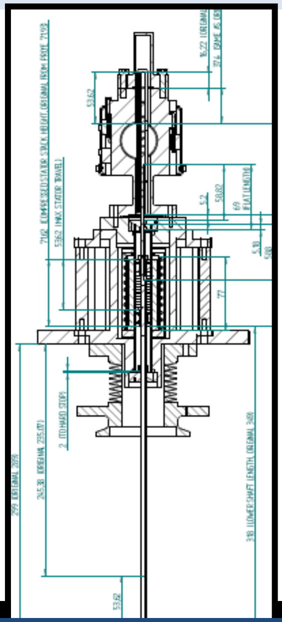
- ***Downstream PID:***
  reject decay electrons
  - ***Time of Flight – TOF2 (Italy/Bulgaria)***
  - ***Kloe-Light Calorimeter – KL (Italy)***
  - ***Electron-Muon Ranger – EMR (UGeneva)***

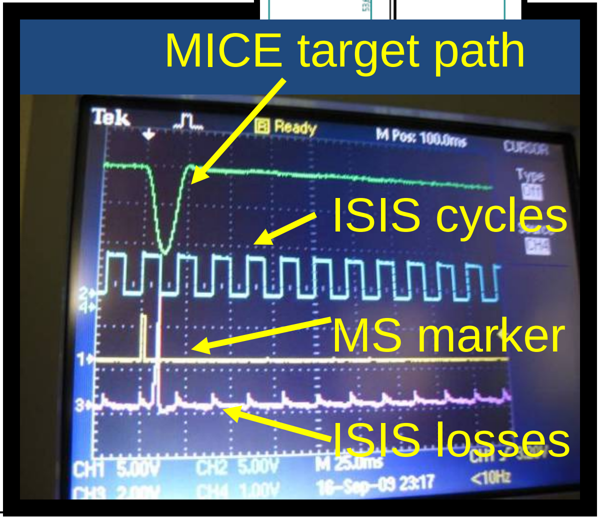
Description: Cooling Channel



Status: Target

- ***MICE target installed in ISIS August 2009 (UK)***
  - ***Run at base rate & 50 Hz (Normal User Run)***
- ***Target is working beautifully***
- ***Target stability checked every 10,000 pulses***
  - ***Process to monitor target behavior agreed upon with ISIS***
  - ***Target timing monitored***
- ***Target Operation:***
  - ***570,000 pulses to date in ISIS***
  - ***Offline target ran 2.15 M actuations***
- ***Need online & offline working targets***
  - ***T3 under construction***
  - ***Two target system fall 2010***



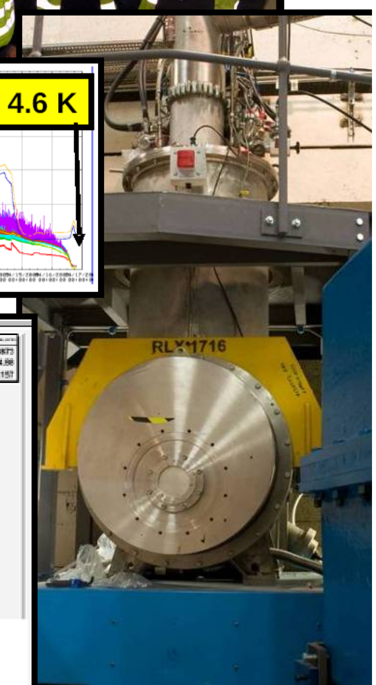


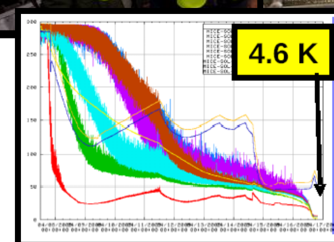
Status: Beam Line

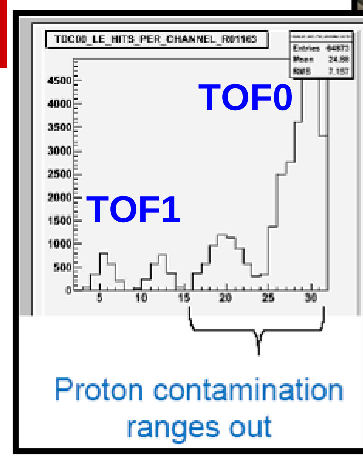
- ***Conventional Magnets***
  - *All operational and working well*
  - *Current reliably stable during User Run*
- ***Decay Solenoid (PSI/RAL)***
  - *5 T superconducting solenoid magnet*
  - *Increases downstream particle flux by factor of ~5*

Decay Solenoid cold, stable, and operational for entire User Run June – August 2010

- ***Proton Absorber installed downstream of Decay Solenoid***
  - *15, 29, 49, 54mm*
  - *Successfully eliminated proton contamination in positive μ beams*







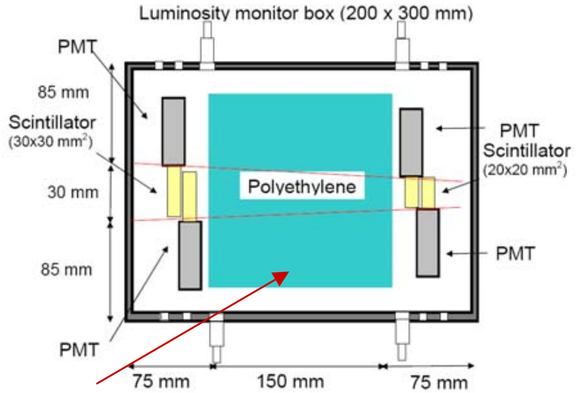
Step I: Running

- ***Goals***
  - ***Commission and calibrate beam line detectors***
    - ***Luminosity Monitor***
    - ***TOF0, TOF1, TOF2, CKOVs, KL***
    - ***FNAL beam profile monitors***
  - ***Commission beam line magnets***
  - ***Take data for each point in ε-p matrix***
    - ***MICE beam designed to be tunable***
    - ***Understand beam parameters for each configuration***
  - ***Compare data to simulation of beam line***
  - ***Prepare for Steps with cooling***
- ***Method***
  - ***Dedicated data-taking run from June 22 – August 12***
  - ***Special Machine Physics study periods***

Step I: Luminosity Monitor Commissioning

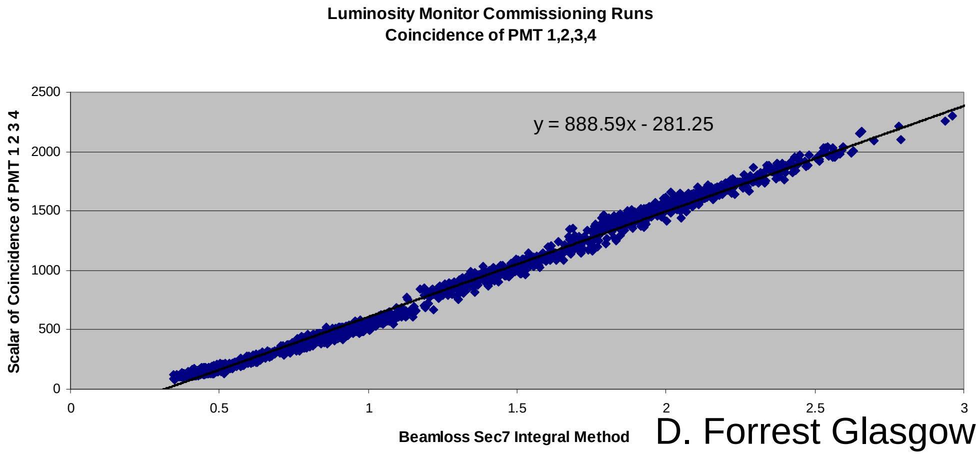
- ***Determines particle rate close to target***
- ***Extract protons on target as function of depth***
  - *independent of beam loss monitors.*
- ***Installed in the ISIS vault & commissioned (Glasgow)***
  - *Coincidence between 4 scintillators with plastic filter to reduce low energy protons*
  - *Data scales well with beam loss*

Working well with info available online during running



Cuts off: protons ~500 MeV/c;

pions ~150 MeV/c

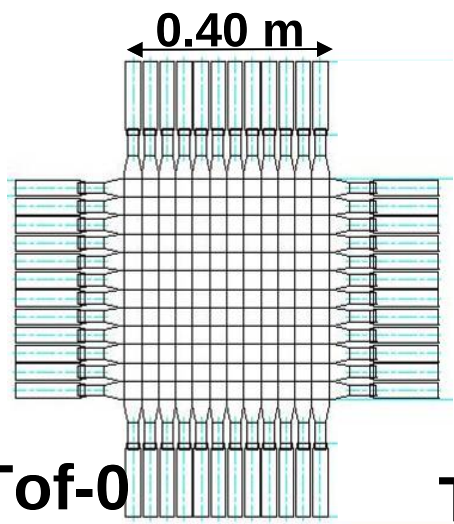


D. Forrest Glasgow

Step I:
TOF Detector Commissioning

- ***TOF0, TOF1, TOF2 are in beam line***
- ***Two planes of 1 inch orthogonal scintillator slabs in x and y***
  - ***Timing information & beam profile data***
  - ***2D grid provides spatial information***

- ***Essential in beam line commissioning***

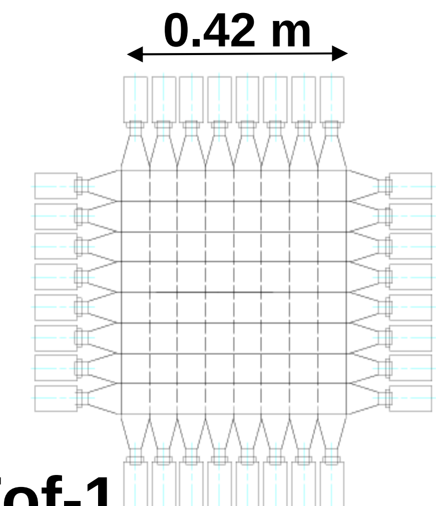


Tof-0

10 x 4cm scintillator bars

σ_x = 1.15 cm

σ_t = 50 ps

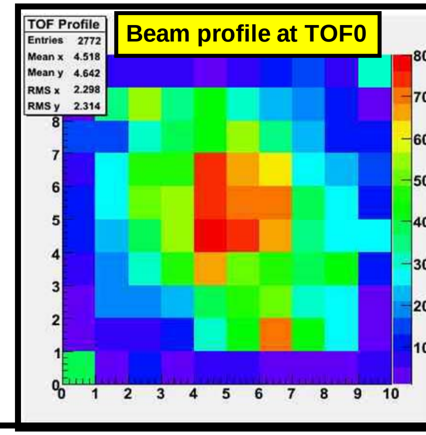


Tof-1

7 x 6cm scintillator bars

σ_x = 1.73 cm

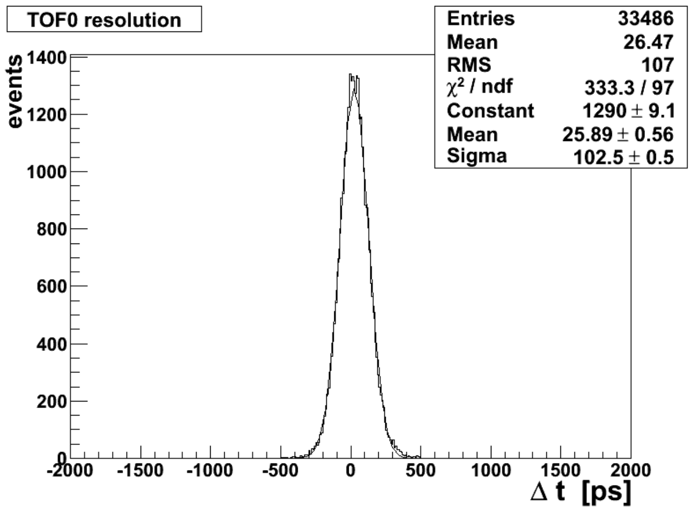
σ_t = 50 ps

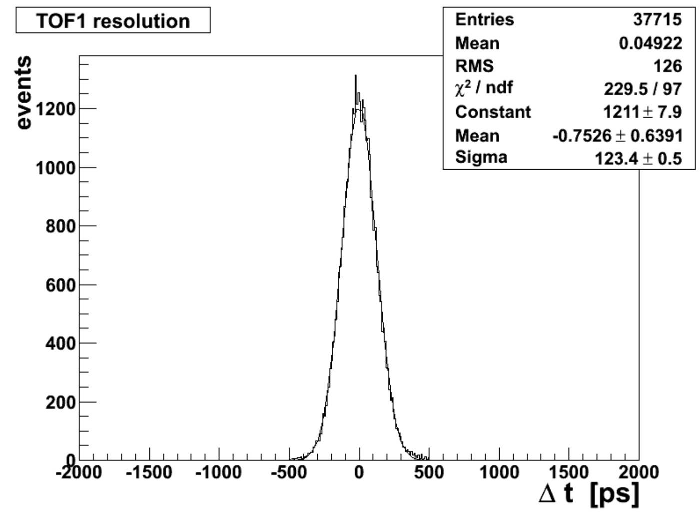


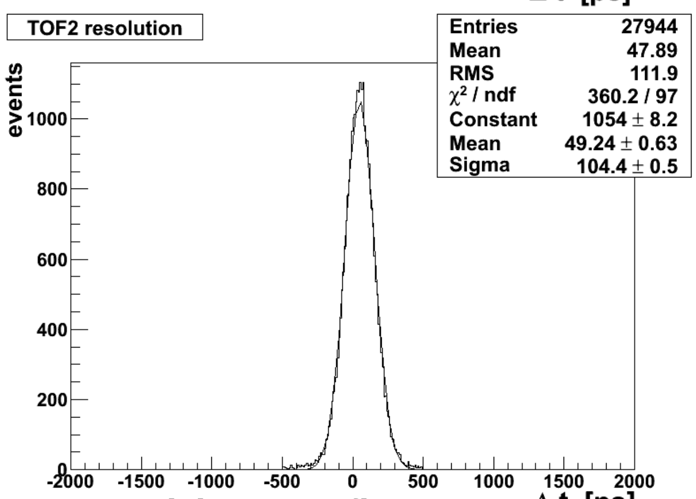
TOF Detectors Used to Calculate Beam Optics Parameters

- ***Define good muon sample with timing***
- ***Find muon (x,y) from TOF0 & TOF1 spatial information***

Step I: TOF Detector Commissioning







Y.Karadzhov USofia

- ***Time resolution after calibration:***
- ***TOF0 – 51ps***
- ***TOF1 – 62ps***
- ***TOF2 – 52ps***
- ***Resolution meets design goals for TOFs***

Step I Running: Data Summary

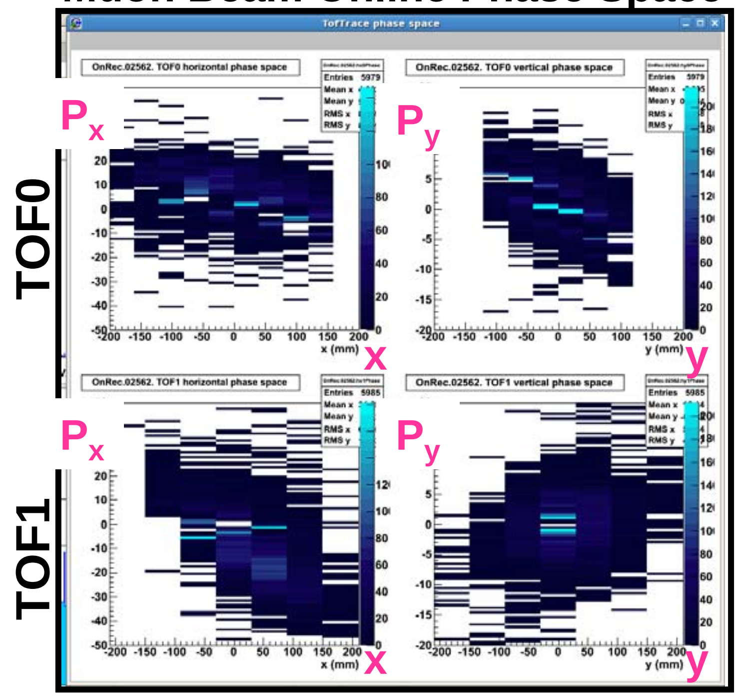
- ***Record amount of data taken this summer***
  - ***Over 335,000 dips of target into ISIS***
  - ***Over 13,000,000 particle triggers***

- ***Emittance-momentum matrix scan***
- ***Beam line studies:***
  - ***Quad scans***
  - ***Dipole scans***
  - ***DS scan***
  - ***Neutrals***

- ***Online tuning of beam with online reconstruction using beam optics parameters***

- ***Reference run each day***
  - ***400 pulses 6-200 (ε-p)***
- ***Target test run each day***
- ***All hardware found to be stable***

Muon Beam Online Phase Space



Step I Goal:
Fill in ε-p matrix data

P (MeV/c)

εN (mm rad)

(3-140)	(3-200)	(3-240)
(6-140)	(6-200)	(6-240)
(10-140)	(10-200)	(10-240)

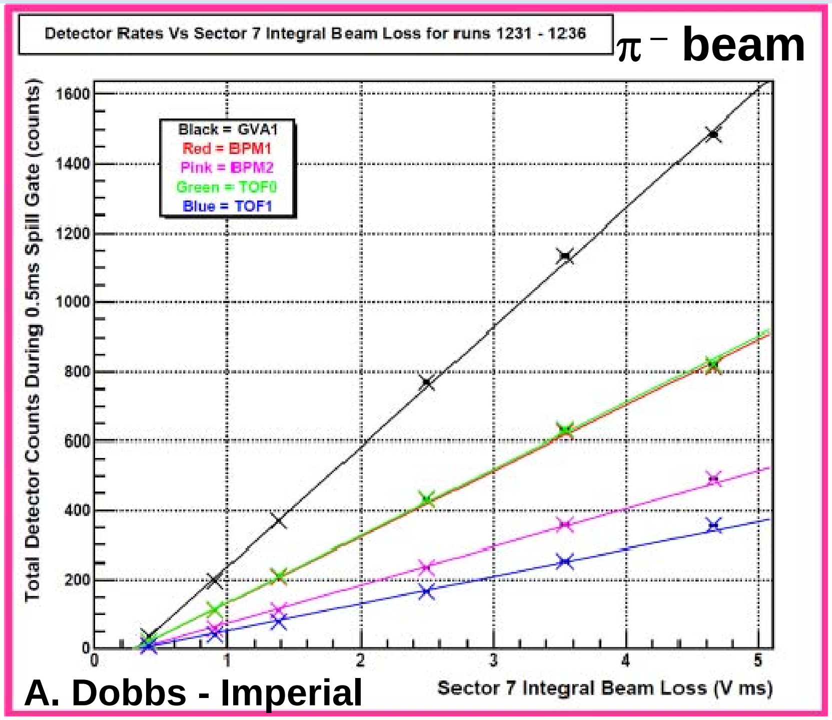
- Finding the element (3,240) means finding BL settings that produce MICE optics at the upstream end of the diffuser for a beam of 3 mm rad at P=240 MeV/c

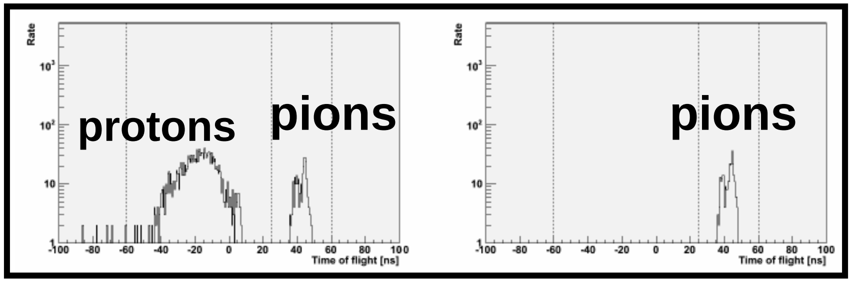
- The element (10,200) is the BL optics producing a MICE beam with 10 mm rad at P=200 MeV/c

If this pair is our goal: how do we get it?

Step I: Beam Studies

- ***Particle Rate vs Losses***
  - *Goal of ~500 muons/spill*
  - *Systematically study particle rates in MICE vs ISIS beam loss*
  - *Initially used pion optics (plot to right)*
    - *recently μ beam*
  - *Linear relationship over beam loss range of ~500 mV – 4700 mV*
  - *Up to 10 V running!*
- ***Target operation studies***
- ***Proton absorber***
  - *Time-of-flight between GVA1 & TOF0*
    - *See protons and pions*
    - *Dashed lines → cuts used for PID*
  - *Determined absorber setting for each beam line in ε-p matrix*
  - *Proton absorber works*

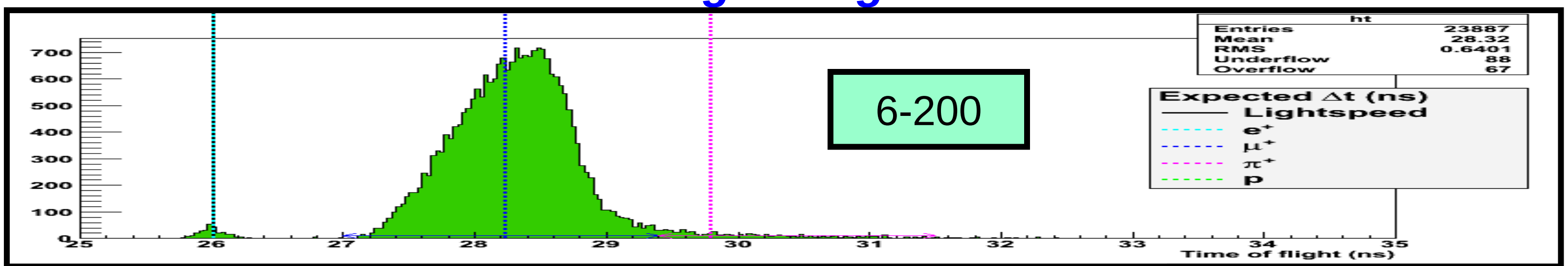




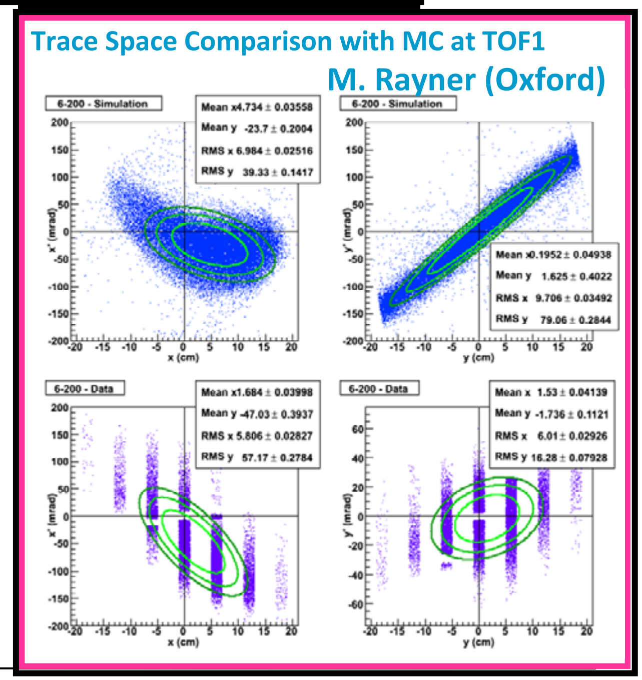
Raw Time of Flight

Step I: Beam Studies

- ***First emittance measurement using TOF detectors***
  - ***Good muons selected using timing information***



  - ***Use TOF0 & TOF1 as (x,y) stations***
  - ***Initial path length assumed given beam line transfer matrix***
  - ***Each particle tracked through Q789***
  - ***Momentum estimated***
  - ***Infer x', y' → (x,x') (y,y')***
  - ***Phase space parameters calculated***
  - ***Iterated until true position/momentum known for each muon***
  - ***Compared to MC – reasonable agreement***

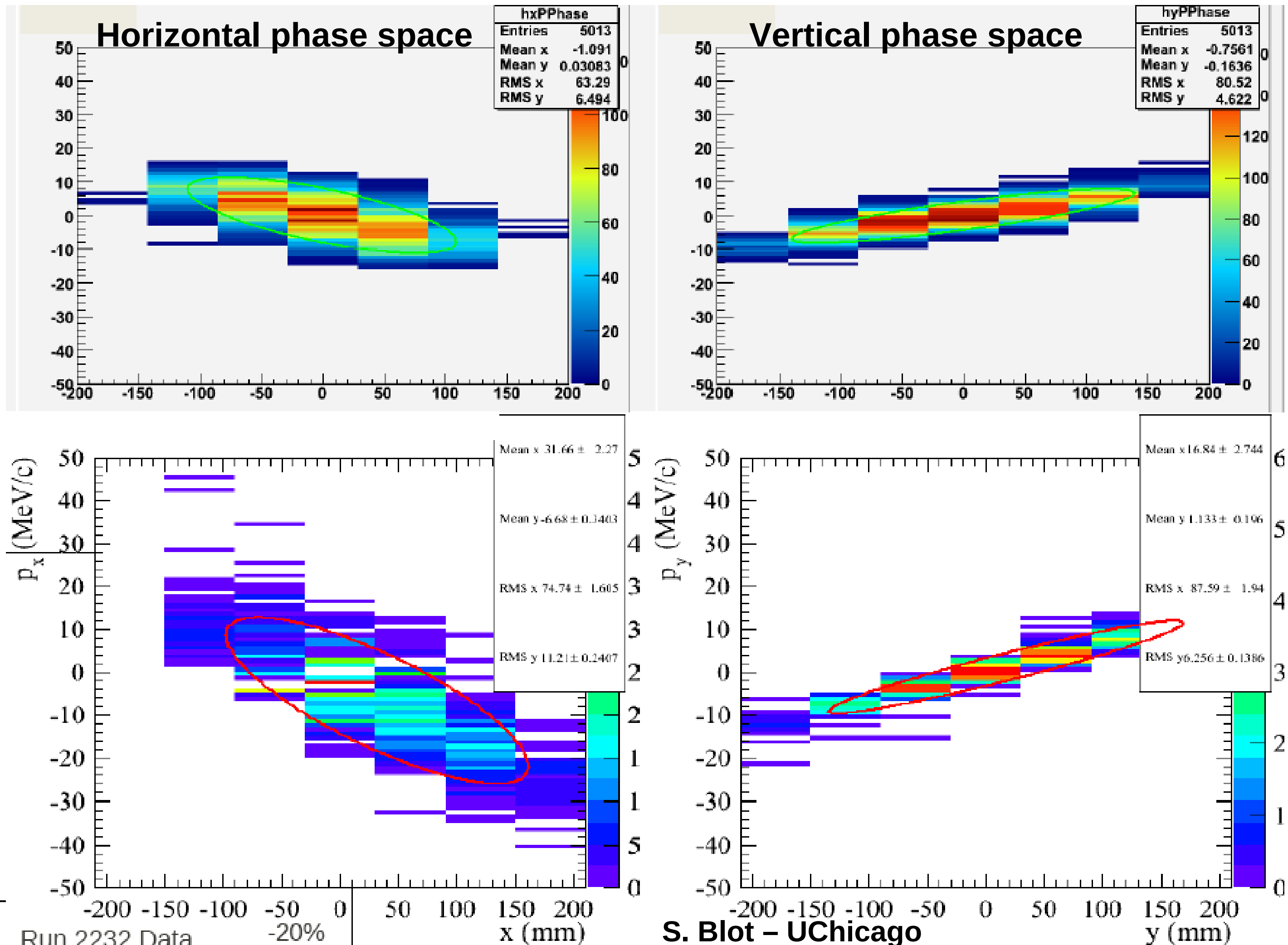


Step I: Data vs MC Comparison

- ***Analyzing recent data***
- ***Quad scan (Q789) with 6-200 data – Q789 current at -20% of nominal***

MC

Data



S. Blot – UChicago
M. Apollonio - Imperial

Step I: Results

- ***Goals***
  - ✓ – ***Commission and calibrate beam line detectors***
    - *Luminosity Monitor*
    - *TOF0, TOF1, TOF2, CKOVs, KL*
    - *FNAL beam profile monitors*
  - ✓ – ***Commission beam line magnets***
  - ✓ – ***Take data for each point in ε-p matrix***
    - *MICE beam designed to be tuneable*
    - *Understand beam parameters for each configuration*
  - ✓ – ***Compare data to simulation of beam line***
  - ✓ – ***Prepare for Steps with cooling***

- ***Muon Beams Produced Routinely***
  - ***Run at high beam losses (2-3V)***
  - ***Produces ~50 μ^+/~8 μ^- per target dip (every ~3 sec)***
  - ***Reached a maximum of 10V losses recently***

MICE Schedule: Beyond Step I

Schedule under review

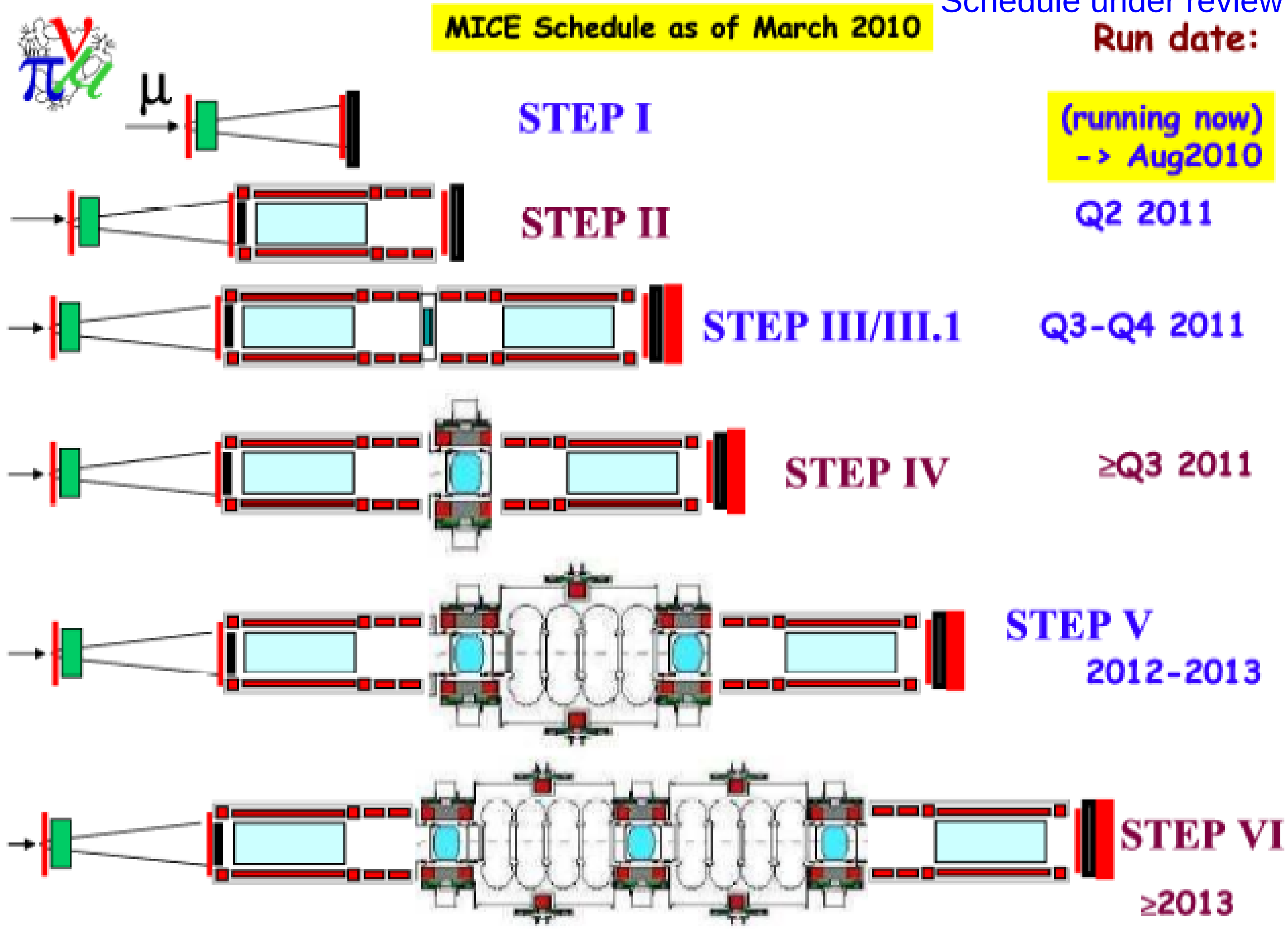
Commission beam line & detectors

Precisely measure incoming emittance & compare trackers

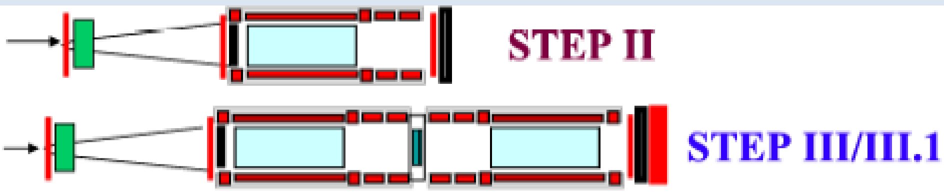
Precisely measure muon cooling

Test sustainable cooling

Ultimate MICE goal: operate full cooling channel

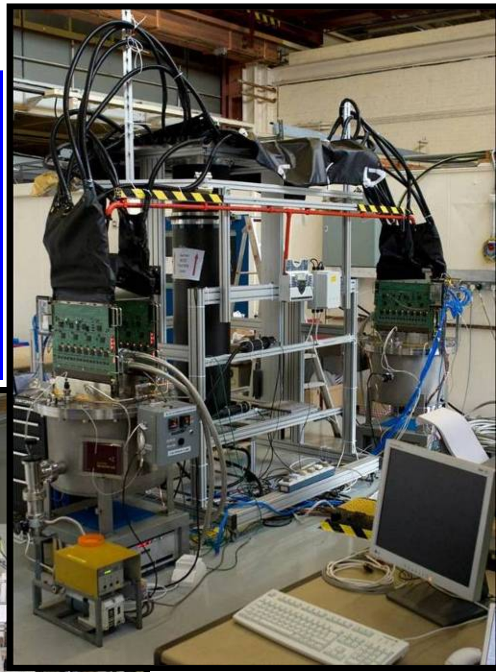


Status: Cooling Channel Components

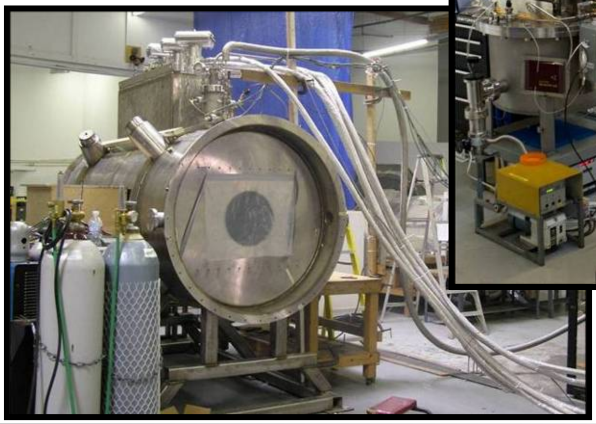


- ***Steps II/III, and beyond, require spectrometers for precise emittance measurements***

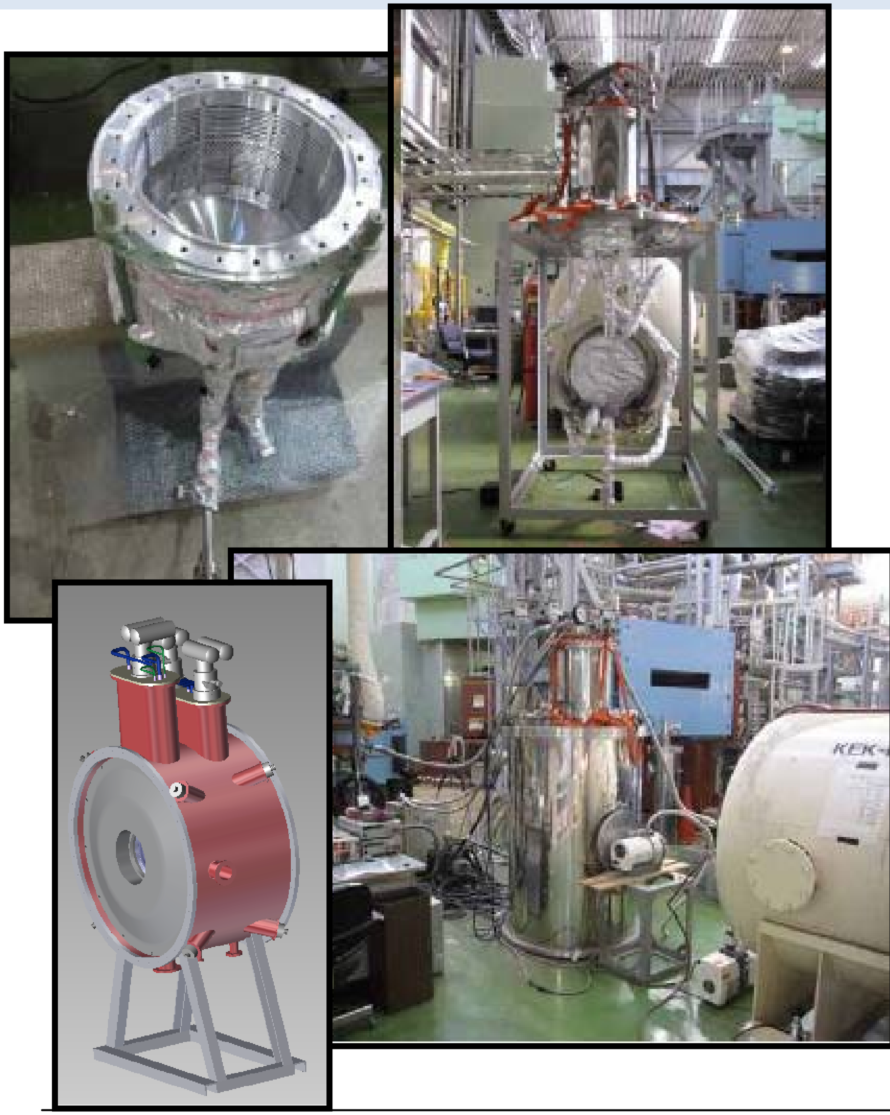
- ***Tracker** (US, UK, Japan)*
  - *Both trackers ready and tested with cosmic rays*
  - *Resolution, Light Yield & Efficiency all exceed design goals*
  - *NIM paper submission In progress*



- ***Spectrometer Solenoids** (US)*
  - *Trackers sit inside solenoids*
  - *4 T superconducting*
  - *5 coils: 1 main tracker coil*
    - *2 end coils, 2 matching coils*
  - *See talk by S. Virostek*



Description: Absorber - AFC



- ***Absorber-Focusing Coil – AFC***
  - ***LH_2 absorbers inside Absorber-Focus-Coil (AFC) module with superconducting coils to provide strong focus for muon cooling***
  - ***3 modules by Step VI***
- ***LH2 Absorber (KEK)***
  - ***20.7 liters LH2***
  - ***LiH absorber will also be tested***
  - ***35 cm long on beam axis***
  - ***15 cm radius***
- ***Focusing Coils (UK)***
  - ***2 coils***
  - ***26.3 cm inner radius***
  - ***4 T in solenoid mode***

Status: Cooling Channel Components

- ***Step IV requires absorber for first cooling measurements***

- ***Absorber 1 tested at KEK***
  - ***Interface with Absorber Focus Coil***

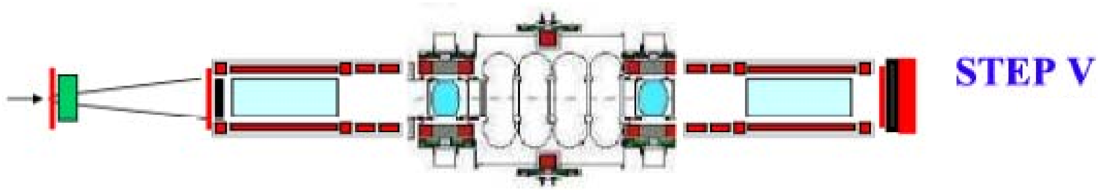
- ***First LH_2 absorber to RAL end 2010***

- ***Second LH_2 absorber being made in Tsukuba***
  - ***Cooling test to follow***

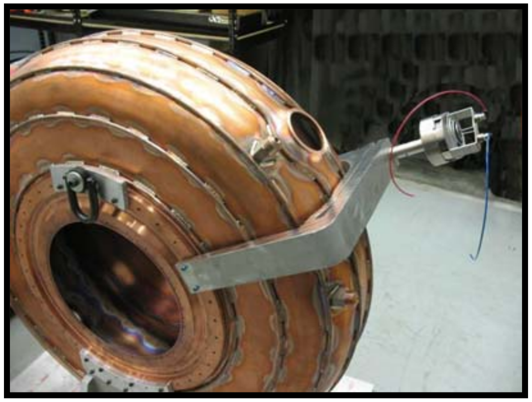
- ***Absorber Focus Coils***
  - ***Construction in UK beginning***
  - ***Test program under development***
  - ***First magnet to RAL Jan 2011 – second in May***

- ***Solid absorbers***
  - ***LiH disk in production***
  - ***LiH wedges in production (2 x 45°)***
    - ***Test emittance exchange – See talk by P. Snopok***

Status: Cooling Channel Components



- *Step V requires RFCC module for replenishing longitudinal component of momentum*
- ***RF Cavities***
  - ***Provides magnetic field to guide muons through cooling cell***
  - ***Restore longitudinal momentum after absorbers***
  - ***Production and measurement proceeding well***
    - ***See talk by D. Li***
- ***RF Coupling Coils***
  - ***Fabrication in progress***
    - ***See talk by S. Virostek***
- ***First RFCC module at RAL Oct 2012***

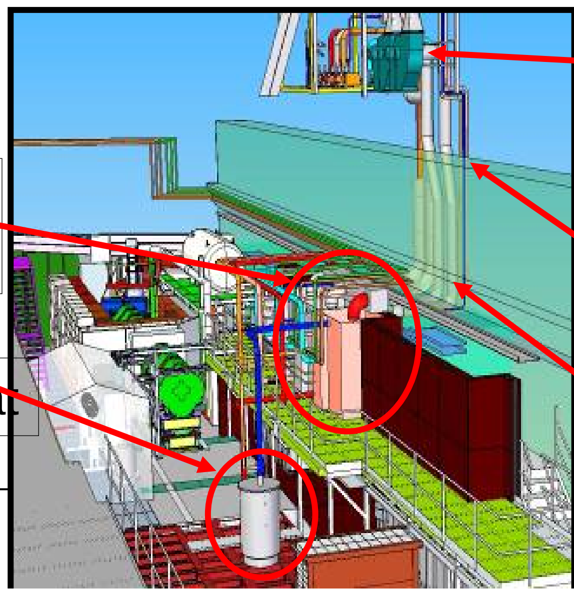


MICE: Preparation for Next Steps

- ***Infrastructure projects have been reordered to take into account delay in spectrometer solenoids***
  - ***Advance work on LH2 infrastructure***
    - ***Vent system, Civil engineering, Pipe/valve & gas panel work***
    - ***Control & safety engineering***
  - ***RF power work (UK, UMiss - NSF)***
    - ***Design of waveguide/power/cooling infrastructure, placement of amplifiers***
    - ***Waveguide infrastructure***
    - ***Specification and procurement of hardware***
  - ***RF amplifiers (LBNL, CERN)***
    - ***2 being reconditioned at Daresbury – one complete – second waiting***
    - ***Very large (4m tall, 1 ton) and must fit four in confined space in MICE Hall***

Gas Panel Enclosures

Test Cryostat



Fans

Relief lines

Ventilation ducts

MICE: Conclusions

- ***Muons routinely observed at MICE***
- ***Beam line and associated detectors fully operational***
- ***Step I data-taking complete!***
- ***Data analysis under way***

- ***Absorber and RF cavities near delivery***
- ***Infrastructure complete for Step II, III***

- ***Spectrometer solenoid – plan for completion in place***
- ***Infrastructure projects reordered – preparing for cooling steps***
- ***Focusing coil – fabrication in progress***
- ***Coupling coil – fabrication in progress***

Backup Slides

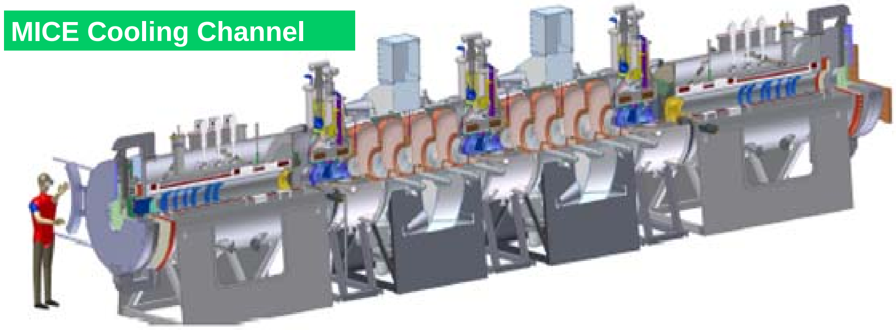
MICE Motivation

- ***Ionization cooling is the only good option:***
  - *Muon lifetime is short ~2 μs*
  - *Cannot use stochastic cooling – slow, iterative process*
  - *Here muons pass through absorber material followed by RF cavities*
  - *Lose transverse and longitudinal momentum in absorber*
  - *Restore longitudinal with RF →reduction in transverse emittance*
  - *Competition between cooling (dE/dx) and heating (multiple scattering)*
- ***Optimal results with:***
  - *Low Z, large X_0 material*
  - *Tightly focused beam*
  - *H_2 most promising absorber material*

- ***Simple premise; however, the reality is not simple***
  ⇨ need a test

MICE Overview

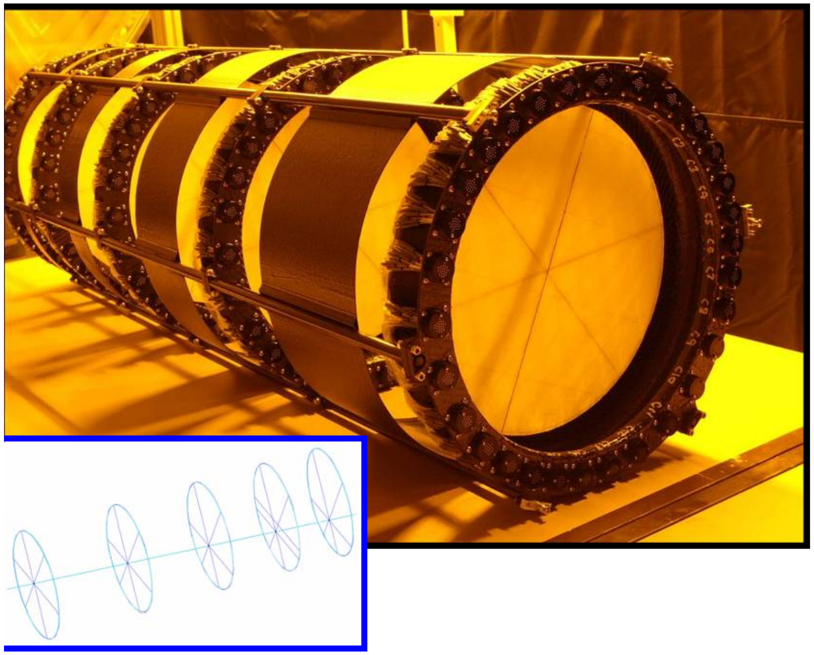
- ***Beam line – create tuneable beam of muons***
- ***Particle ID – tag and time muons (TOF) and measure E,P (EMR)***
- ***Spectrometers – measure muon x,y,x',y' and P_z for each particle***
- ***Absorber – LH2 or LiH – cooling***
- ***RF – reestablish longitudinal p_z***



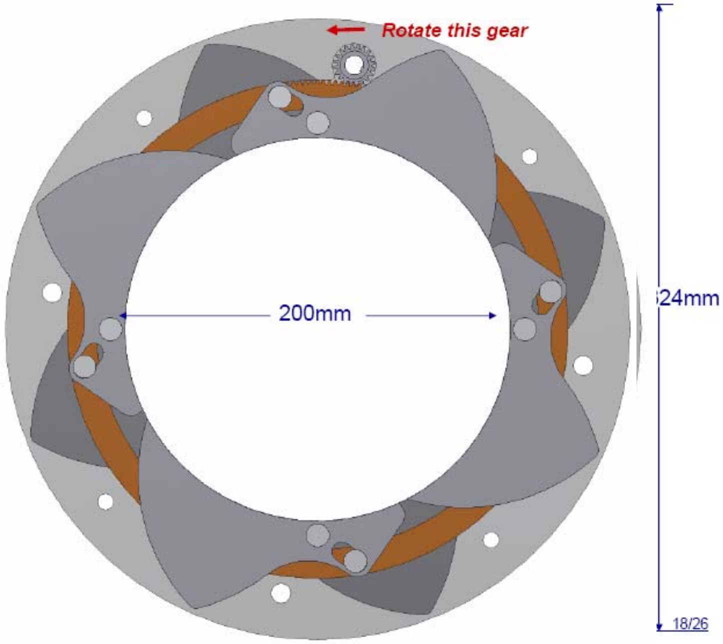
MICE Description

- ***Located at the ISIS 800 MeV proton synchrotron at Rutherford Appleton Laboratory***

Description: Trackers & Diffuser



- ***Trackers before/after cooling channel (UK, US, Japan)***
  - ***Inside 4 T solenoid magnet (US)***
  - ***Measures x, x', y, y', P_z***
  - ***5 stations/tracker, 3 planes/station (U/V/W)***
  - ***350 μm scintillating fiber doublet layers***
- ***Performance: Design Goals Met***
  - ***Light yield goal of 10 PE → measured 11.2 & 10.7 PE***
  - ***Measured track residual 650 μm with 470 μm point resolution***
  - ***Efficiency 99.8% and 99.6% (<0.2% dead ch)***



- ***Diffuser (Oxford)***
  - ***Enable study of cooling over a range of emittance***
  - ***Integral part of Step II & beyond***
  - ***At upstream end of tracker 1***
  - ***4 stacked variable thickness disks***
  - ***New camera iris design***

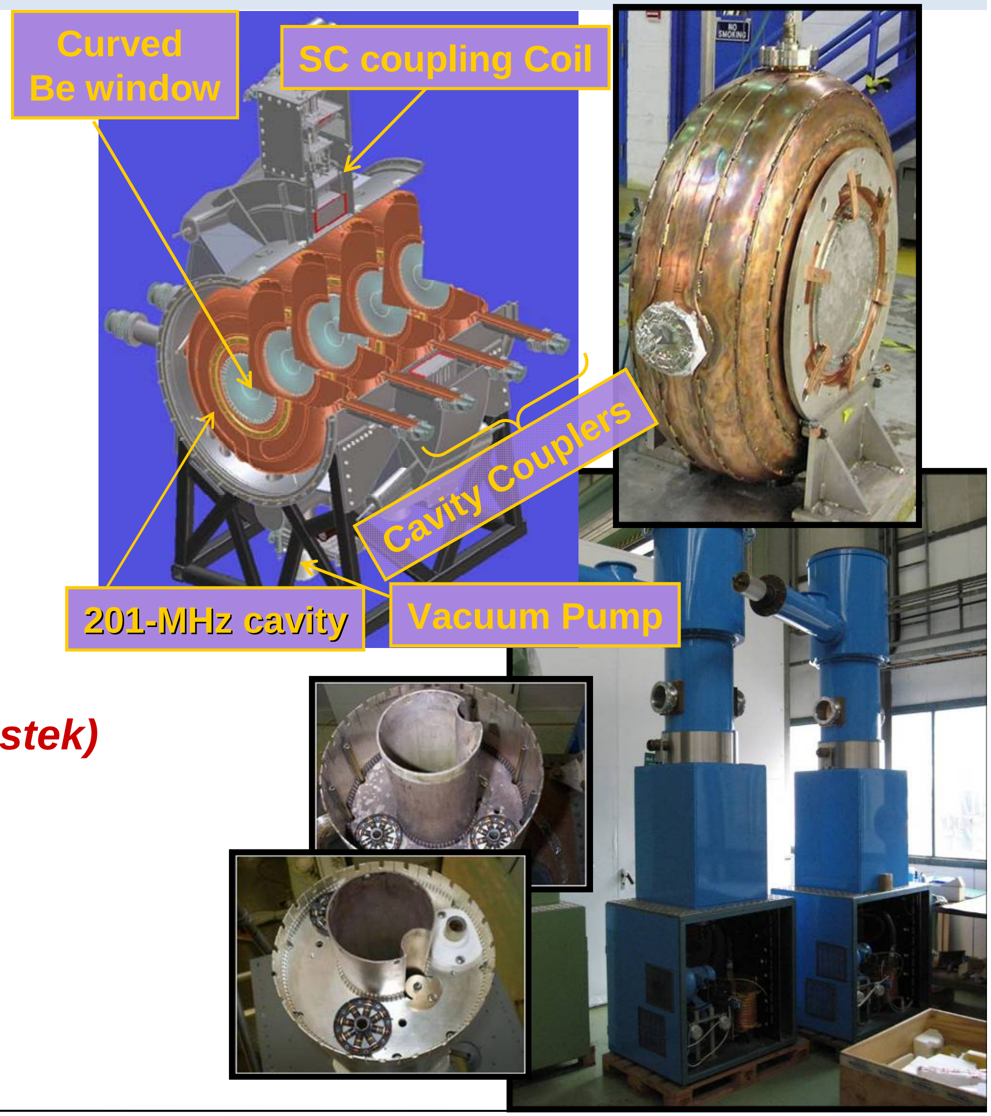
Description: RF - RFCC

- ***RF Coupling Coil – RFCC***
  - ***Provides magnetic field to guide muons through cooling cell***
  - ***Restore longitudinal momentum after absorbers***

- ***RF Cavities (LBNL)*** ***(See talk by D. Li)***
  - ***4 cavities/module***
  - ***Normal conducting 201.25 MHz***
  - ***8 MV/m***
  - ***Curved Be windows (UMiss – NSF)***

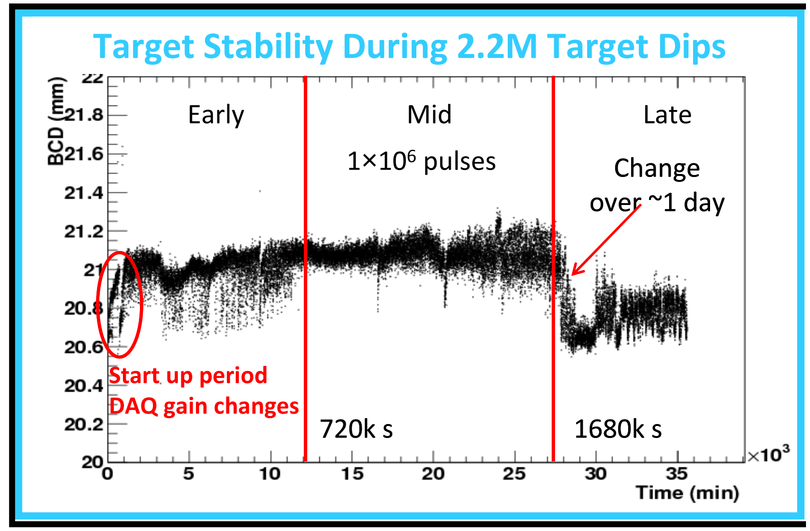
- ***Coupling Coil (China/LBNL)***
  - ***Single coil***
  - ***7.8 T*** ***(See talk by S. Virostek)***
  - ***Cooled by cryocoolers***

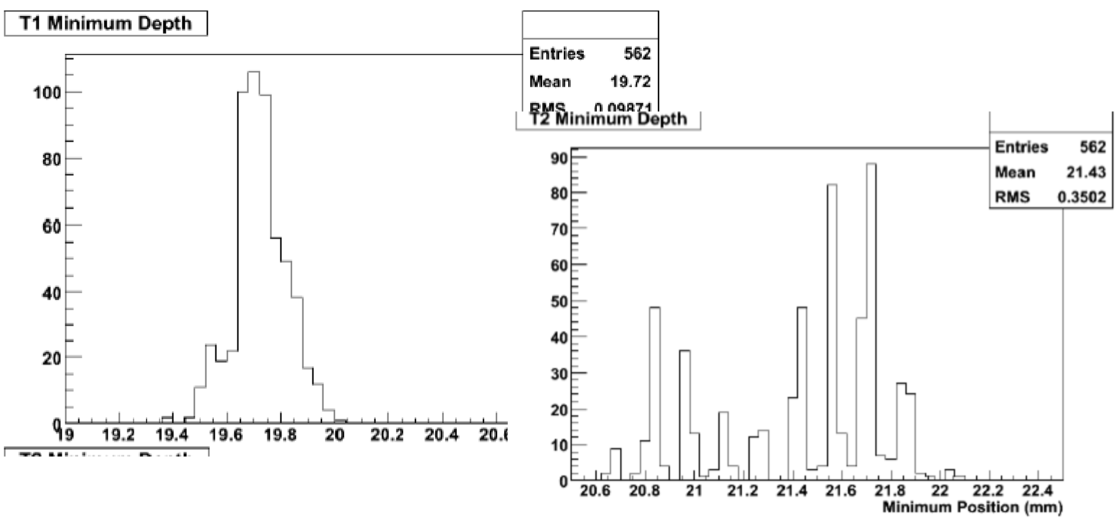
- ***RF power***
  - ***~1MW in 1ms pulse at 1HZ/cavity***
  - ***4 sets of amplifiers (LBNL,CERN) being refurbished at Daresbury Lab (UK, UMiss – NSF)***

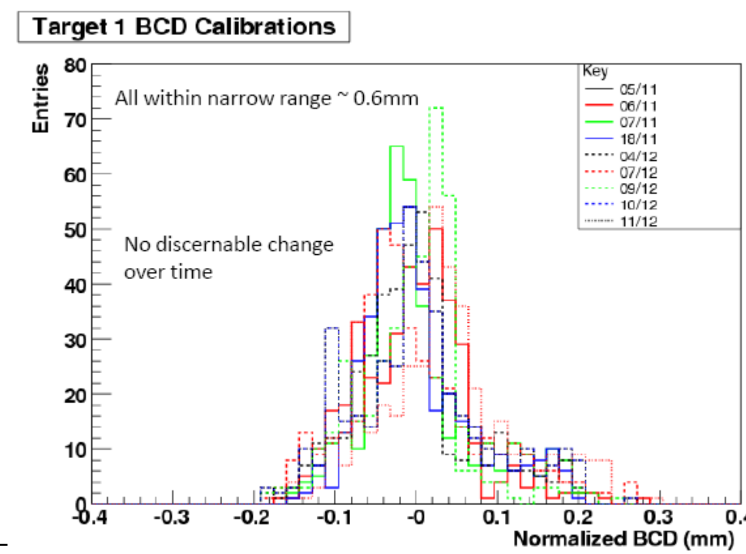


Status: Target Monitoring

- ***Target stability checked every 10,000 pulses***
  - *Study Beam Center Distance (BCD) to monitor target stability*
- ***Clear difference between BCD distribution for functioning target and failing target***
  - *Failing target has much broader spread*
  - *T2 distribution 3-4 times as broad*





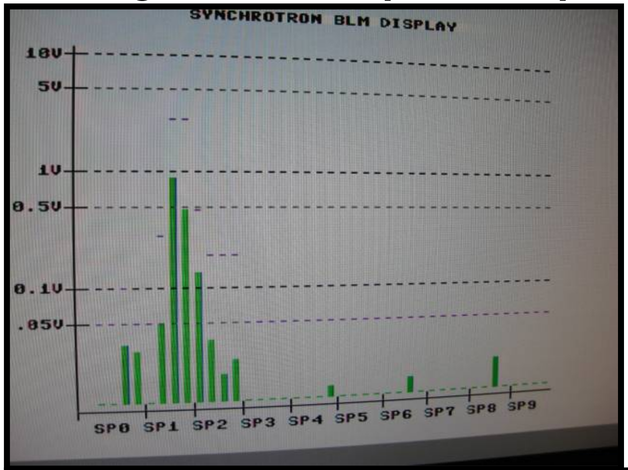


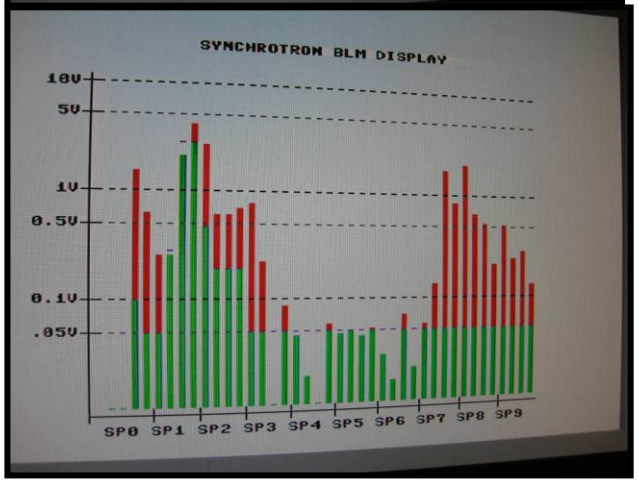
- ***Target BCD very stable – 2.2M pulses!***

Status: Target Studies

- ***Target Operation Studies:***
  - *Search for ideal timing with respect to ISIS cycle*
    - *Also a function of target depth*
  - *ISIS Beam loss vs particle rate study*
    - *Increase target depth, producing ISIS beam loss of 0.1, 0.5, 1, 2, 3, 4, 5, 6, 8, 10 V*
    - *In 2008, maximum ISIS beam loss 50 mV*
  - *Found edge of beam at injection → need to avoid injection of next pulse*
  - *Study different accelerations*
- ***ISIS machine study: beam bump at MICE target***

Normal BLMs around ISIS with MICE target inactive (Sector 7)

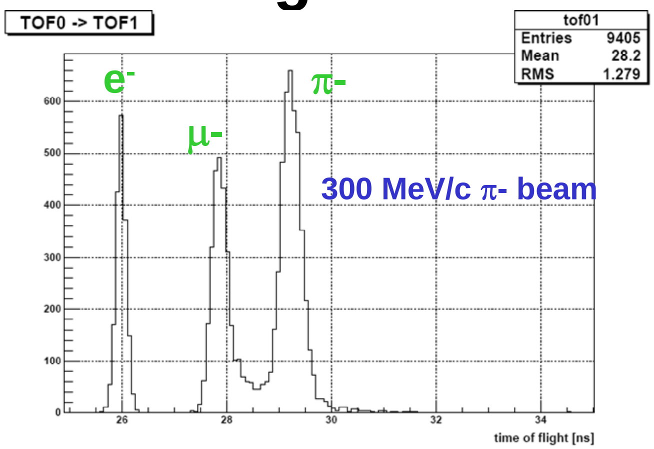


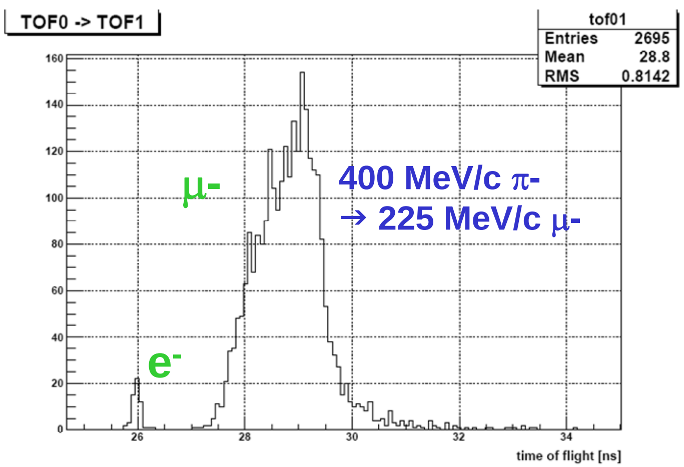


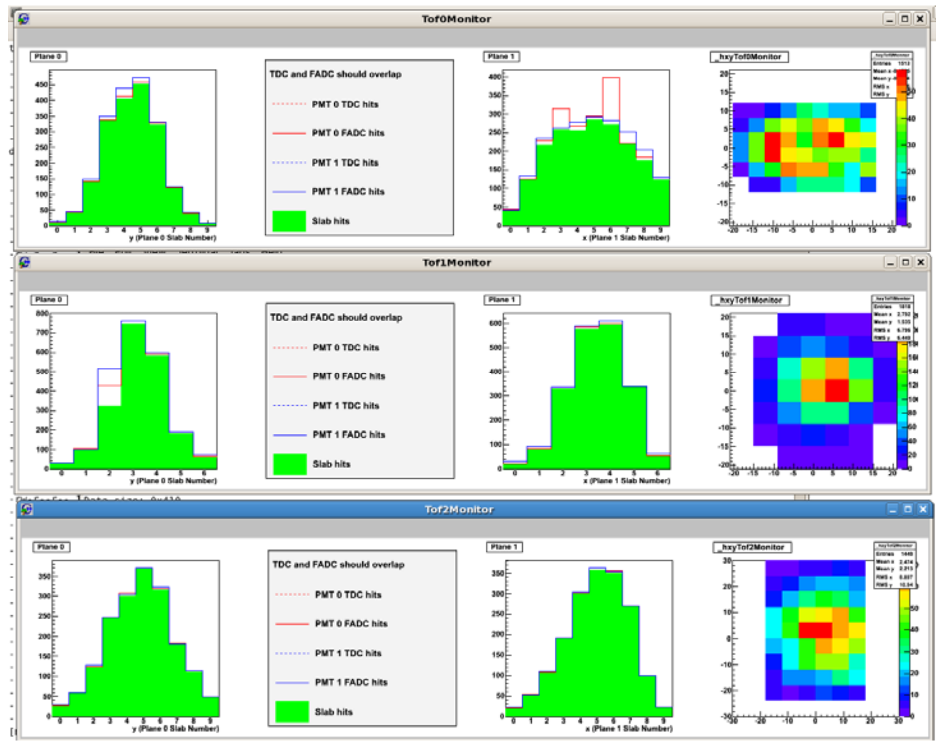
Target operating at 2V beamloss

Step I: TOF Detector Commissioning

- **Time-of-flight distributions for different beam line configurations**



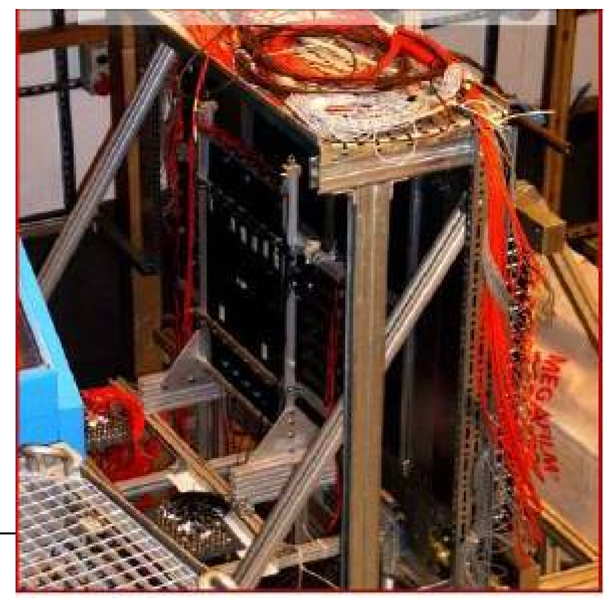


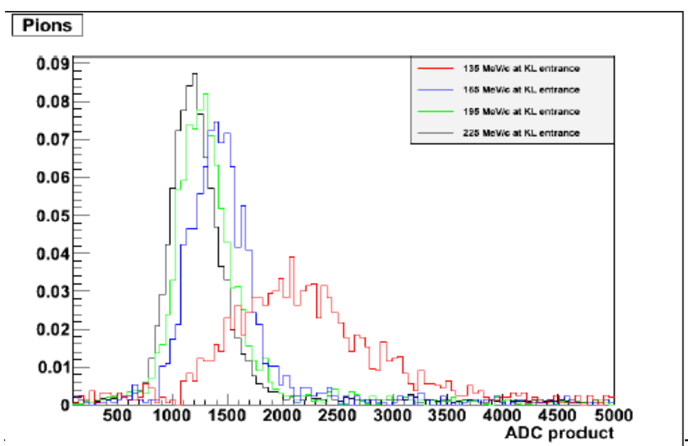


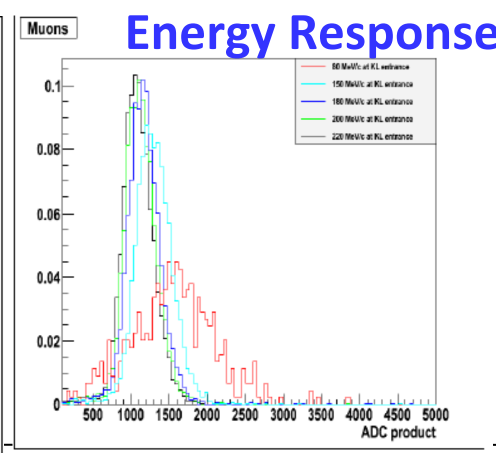
- **TOF Monitor – y, x, combined distributions for TOFs**
  - **TOF0 (top); TOF1 (middle); TOF2 (bottom)**
  - **Online reconstructed μ beam data**

Step I: KL Detector Commissioning

- ***KL lead/scintillating fiber calorimeter module***
  - ***Calibration in progress***
  - ***Electrons:***
    - ***240 MeV/c at target → 50% release energy in KL tag counter***
    - ***360 MeV/c at target → 80% release energy in KL tag counter***
  - ***Muons with 220 MeV/c at target reach EMR***
  - ***Muons with 170 MeV/c at target will die in KL (< 80 MeV/c at KL)***







Step I Running: ε-p Matrix Scan

- **Several different optics**
- **M0 and M1 correspond to different ways to obtain the right distribution in phase-space after the diffuser according to G4Beamline**

- ***Main Goal: Comparison Data/Simulation***

	140 MeV/c	200 MeV/c	240 MeV/c
3 mm rad	M0	M0	M0
6 mm rad	M0 & M1	M0 & M1	M0 & M1
10 mm rad	M0 & M1	M0 & M1	M0 & M1

Negative polarity

	140		200		240	
	M0	M1	M0	M1	M0	M1
3	39,434		57,763		57,361	
6	52,440	45,284	61,652	50,522	39,417	45,942
10	42,490	53,006	50,446	27,814	43,870	45,212

Tables show number of triggers recorded in TOF1 for each beam line configuration in the ε-p matrix during July User Run

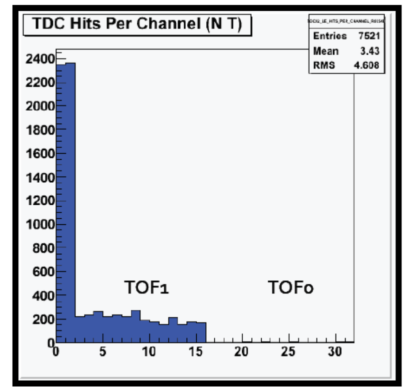
Positive polarity

	140		200		240	
	M0	M1	M0	M1	M0	M1
3	80,160		171,600		236,630	
6	104,040	103,042	302,897	225,200	120,911	77,177
10	85,090	98,460	120,000	80,000	105,172	68,576

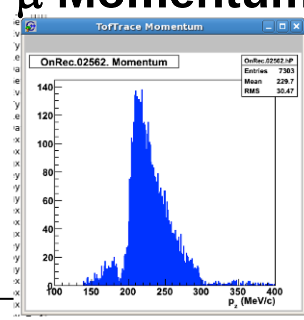
Step I Running: Beam Line Studies

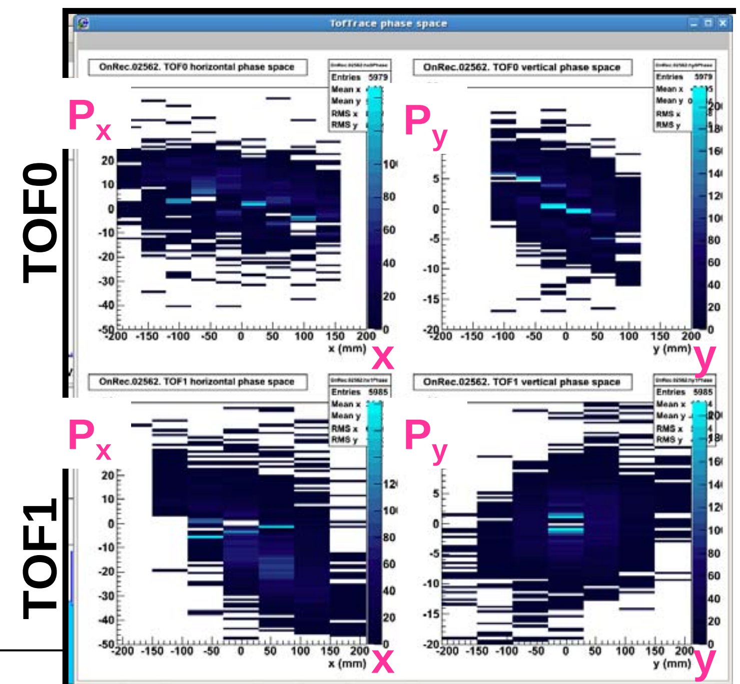
- ***Beam line studies:***
  - ***Neutrals***
    - ***Observe neutrals causing trigger in TOF1***
    - ***Even with all magnets off***
    - ***Only when dip target and beam stop lowered – scales with beam loss***
  - ***Dipole scans***
    - ***D2 kept constant – selects same momentum as for negatives without proton absorber***
    - ***Proton absorber does not affect trigger rate***
  - ***Quad scans***
    - ***Check beam line alignment***
      - ***We observe offset in Y in TOF1***
      - ***Being investigated***
    - ***Characterize effect of each magnet***
  - ***DS scan***
  - ***Online Optimization***
    - ***Muon PID w/TOFs***
    - ***Momentum***
    - ***Phase space plots***

Neutrals in MICE



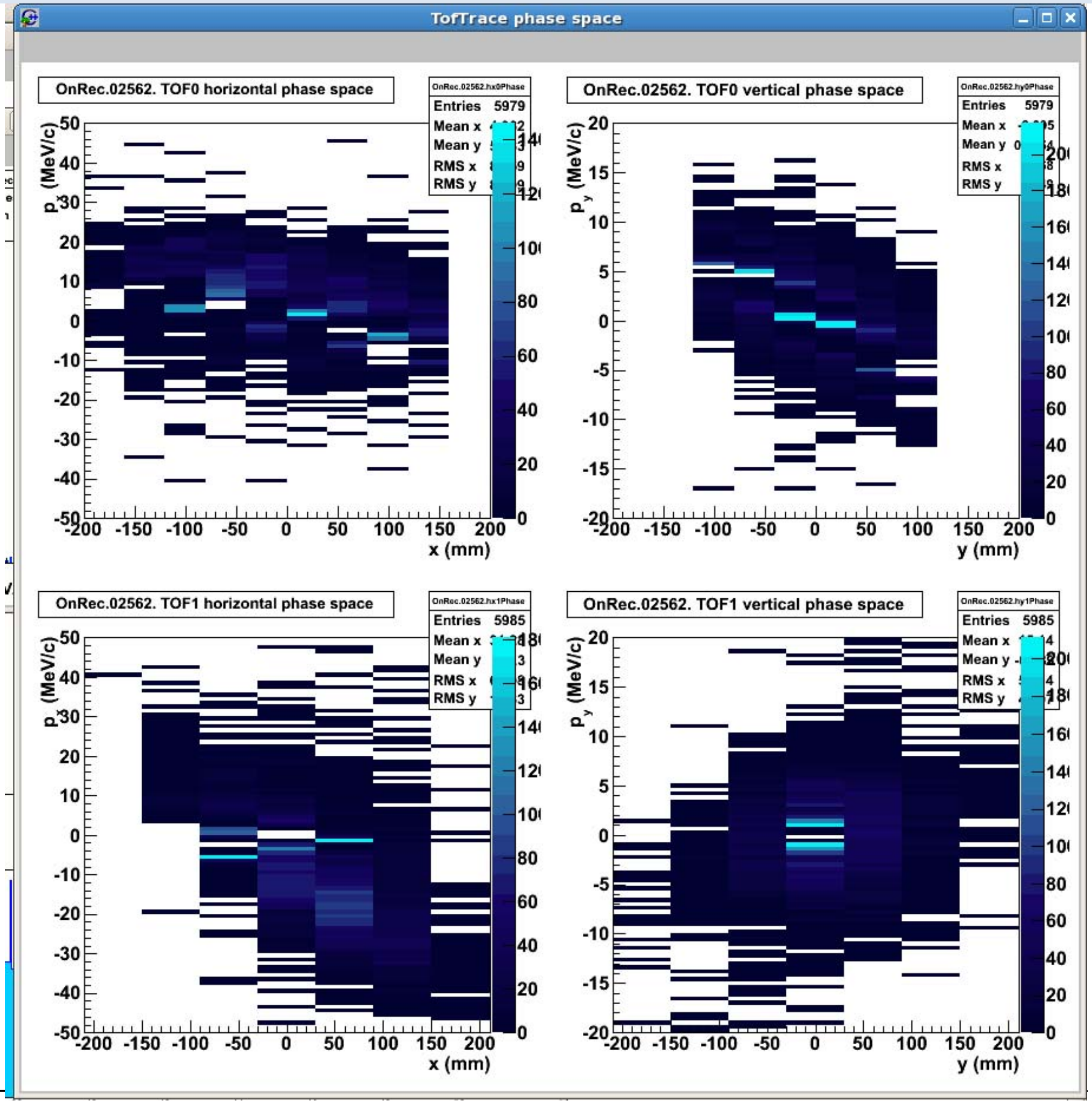
μ Momentum





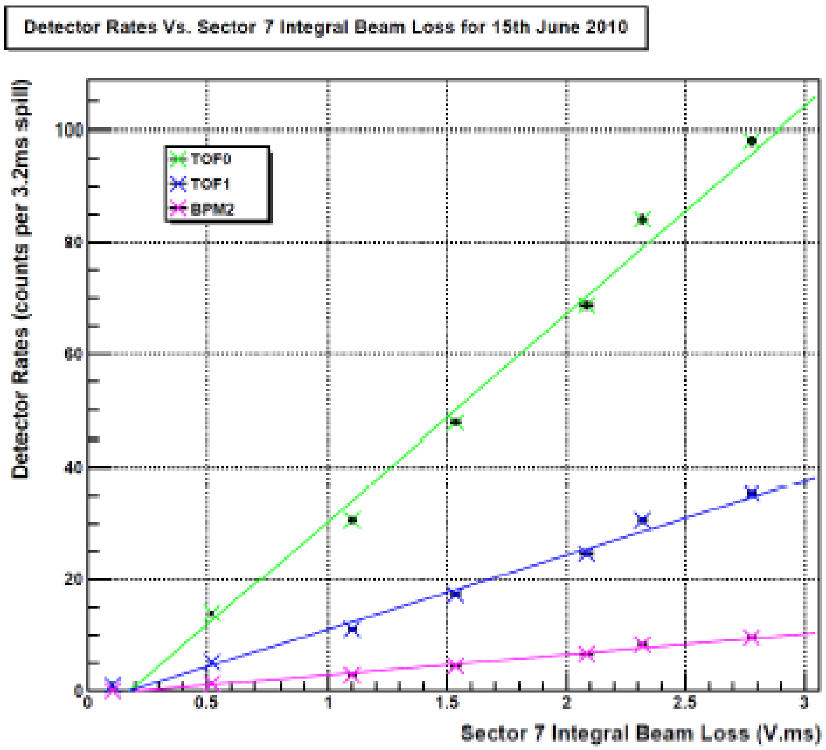
Step I Running: Online Reconstruction

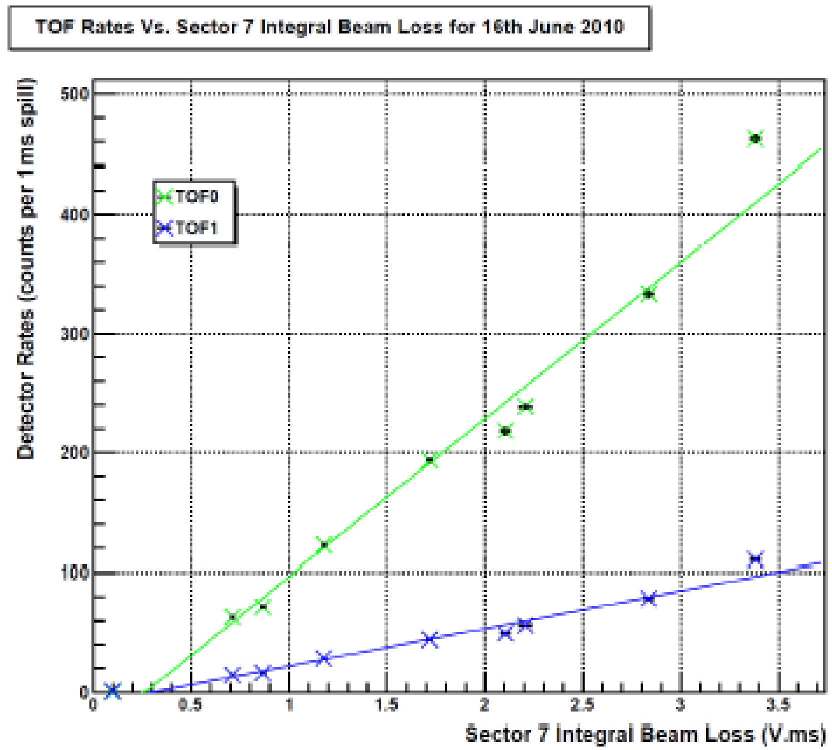
- ***Phase Space Plots Using TOFs (x, P_x) (y, P_y)***
  - ***TOF0 (top plots)***
  - ***TOF1 (bottom plots)***



Beam Studies: Particle Rate

- Muon beam particle rate v losses





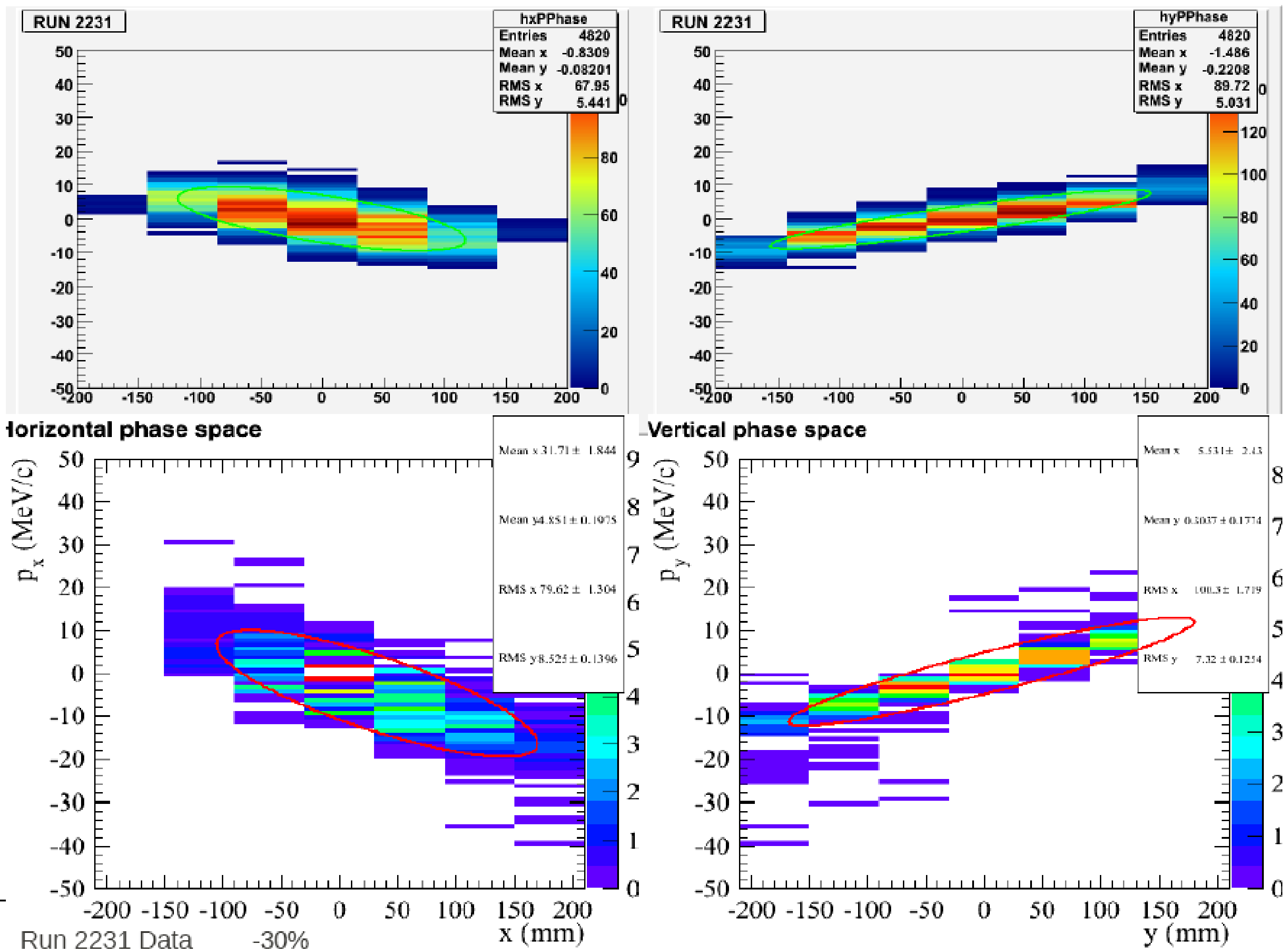
So at 2V beam loss observe ~ 8 TOF1 hits per 1ms spill for –ve
50 TOF1 hits per 1ms spill for +ve

Step I: Data vs MC Comparison

- ***Analyzing recent data***
- ***Quad scan (Q789) with 6-200 data – Q789 -30%***

MC

Data



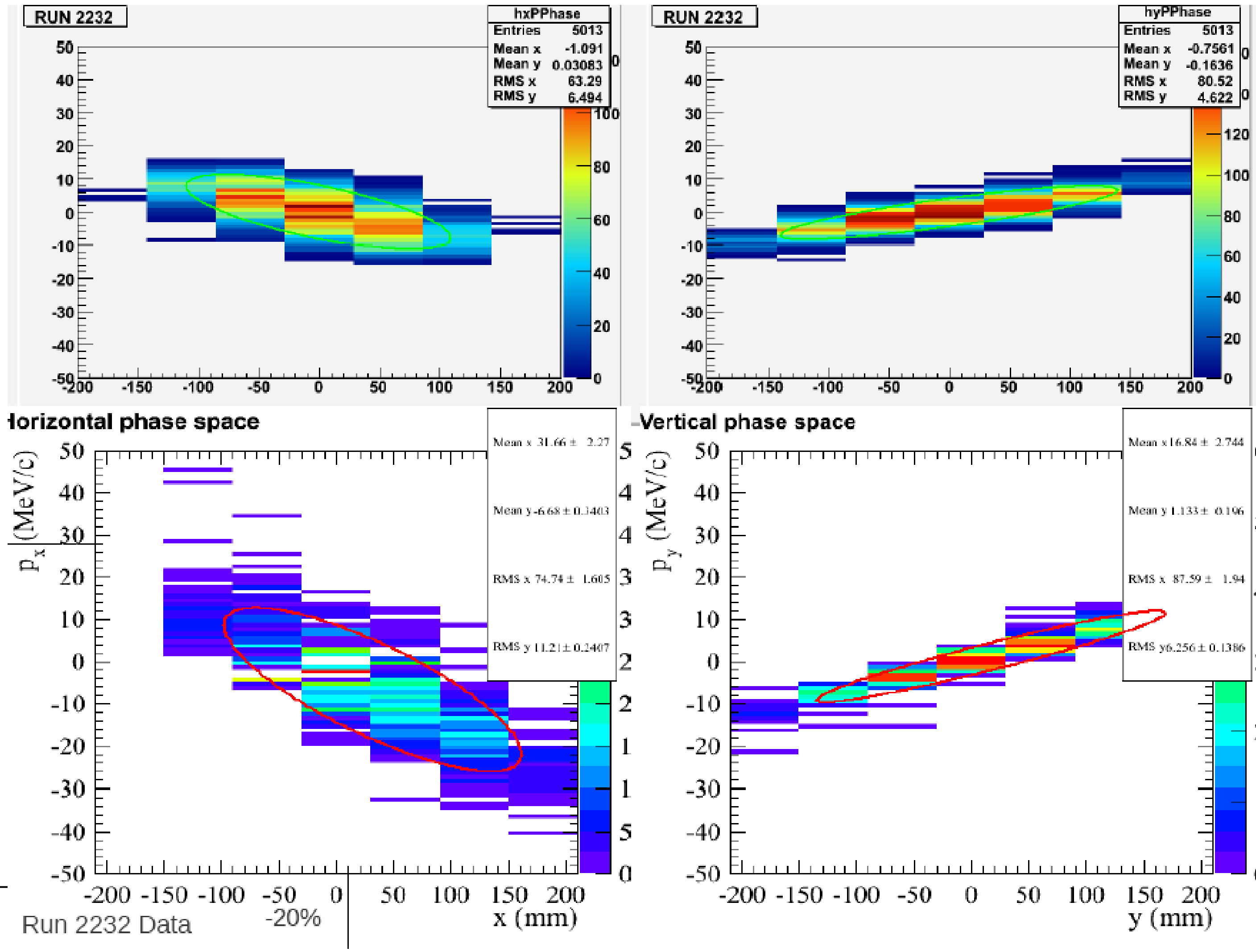
Run 2231 Data -30%

Step I: Data vs MC Comparison

- ***Analyzing recent data***
- ***Quad scan (Q789) with 6-200 data – Q789 -20%***

MC

Data

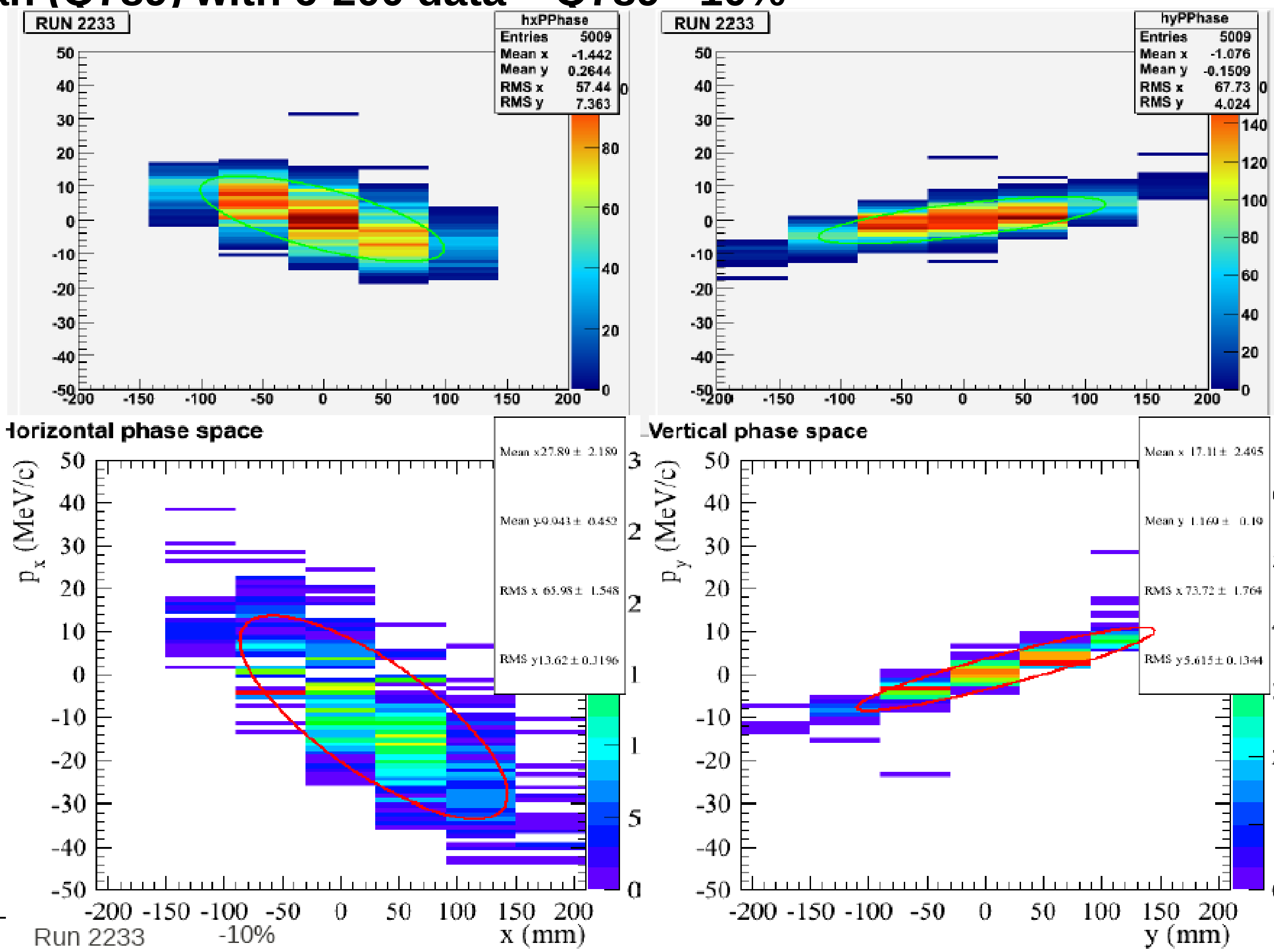


Step I: Data vs MC Comparison

- **Analyzing recent data**
- **Quad scan (Q789) with 6-200 data – Q789 -10%**

MC

Data

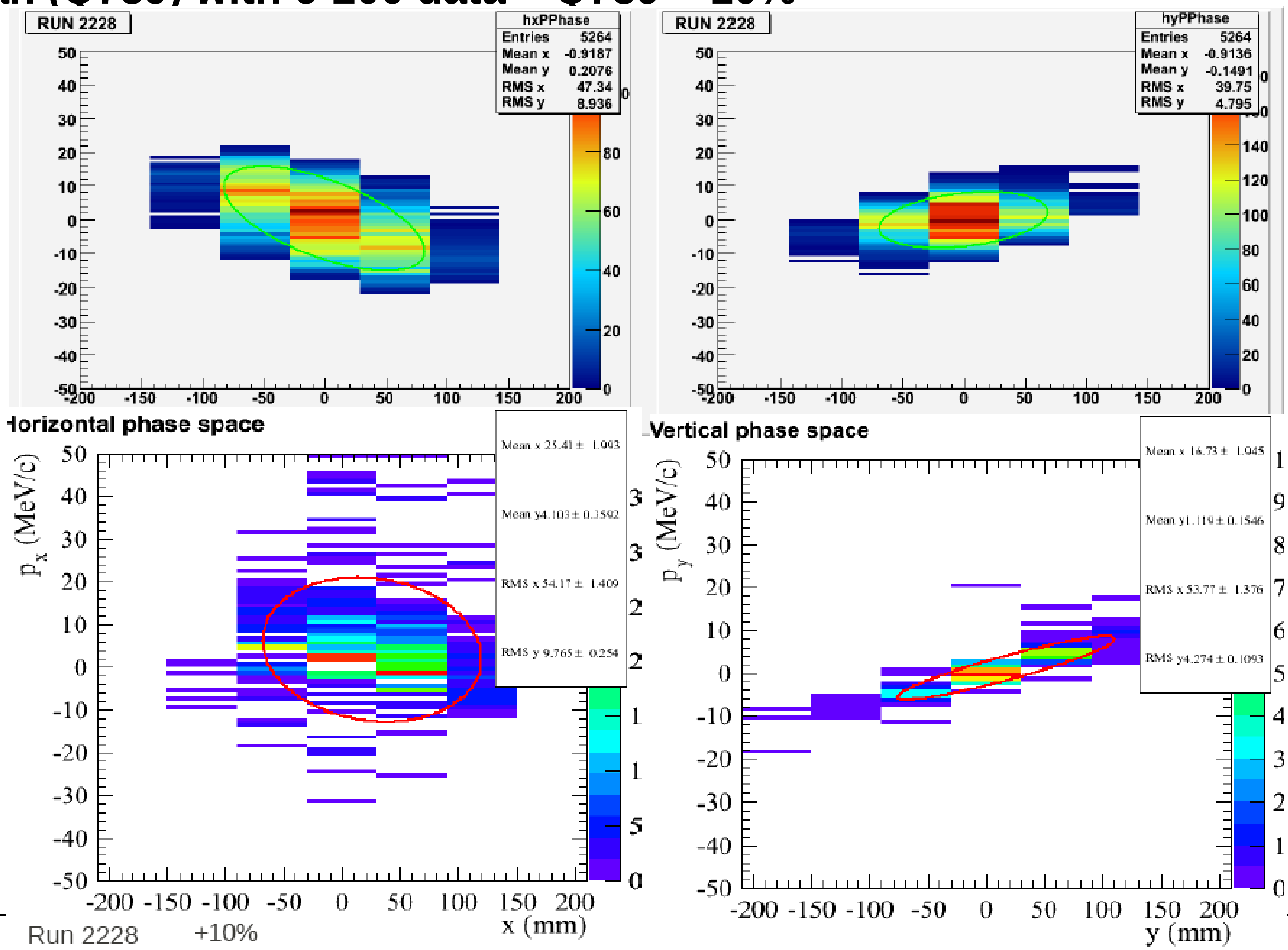


Step I: Data vs MC Comparison

- **Analyzing recent data**
- **Quad scan (Q789) with 6-200 data – Q789 +10%**

MC

Data



Step I: Data vs MC Comparison

- **Analyzing recent data**
- **Quad scan (Q789) with 6-200 data – Q789 +30%**

MC

Data