Totally Active Scintillator Calorimeter

for the Muon Ionization Cooling Experiment

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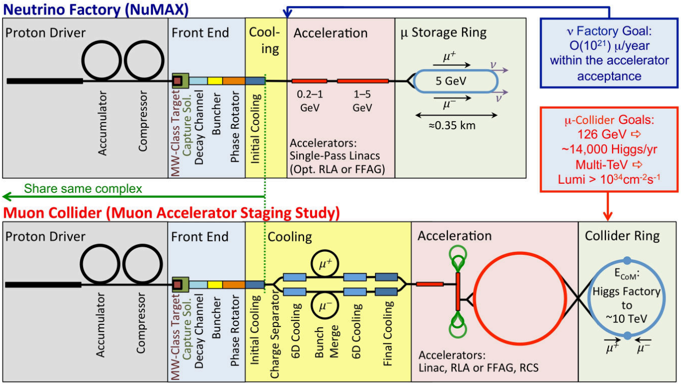
Table of Contents

Ultimate Goal

A Neutrino Factory based on muon storage ring is the ultimate tool for studies of neutrino physics. It is also a step towards a muon collider.



Ionization cooling has never been demonstrated in practice but has been shown by simulation and design studies to be an essential factor both for the performance and for the cost of a Neutrino Factory or Muon Collider.

Ionization Cooling: Principle

The principle of ionization cooling relies on the cooling rate formula, expressing the emittance variation in a medium with thickness X ($g \cdot cm^2$) due to ionization(cooling) and multiple scattering(heating):

$$\frac{d\epsilon_n}{dX} = -\frac{\epsilon_n}{\beta^2 E_\mu}\left\langle \frac{dE_\mu}{dX} \right\rangle + \frac{\beta_t (0.014GeV)^2}{2\beta^3 E_\mu m_\mu X_0}$$

where ϵ_n is the normalized 4D emittance of the beam, β_t is the betatron function, and β is the velocity of the particle. The ideal cooling channel should produce the lowest possible emittance:

$$\epsilon_{eq} = \frac{\beta_t (0.014GeV)^2}{2\beta m_\mu X_0}\left\langle \frac{dE_\mu}{dX} \right\rangle^{-1}$$

Hence, the goal is to minimize the β_t and maximize $X_0 \langle \frac{dE_\mu}{dX} \rangle$. Therefore liquid hydrogen has been chosen for the first realization of a cooling channel.

Ionizatoin Cooling: Concept

Due to the short muon lifetime (2.2 μs), ionization cooling must be used. The cooling of the transverse phase-space coordinates of a muon beam can be accomplished by passing it through a light energy-absorbing material and an accelerating structure, both embedded within a focusing magnetic lattice. Longitudinal and transverse momentum are lost in the absorber while the RF-cavities restore only the longitudinal component.

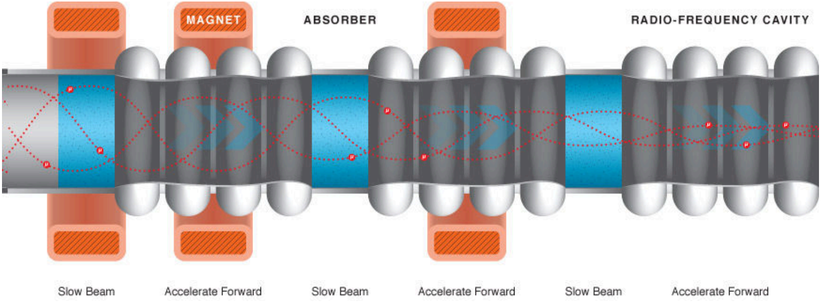
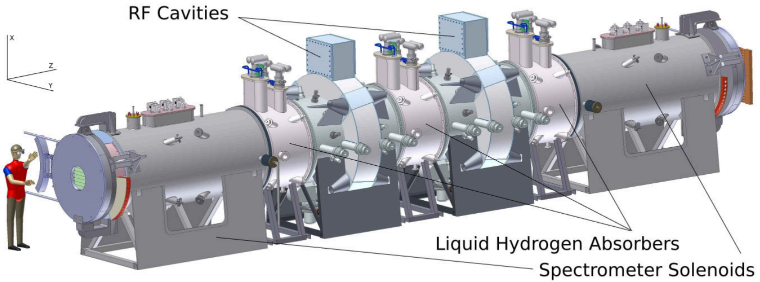


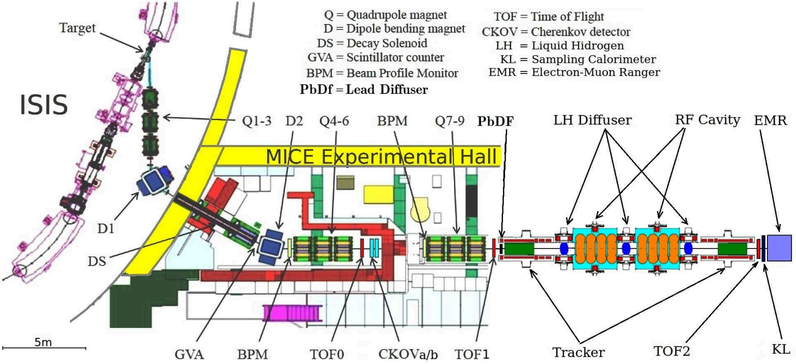
Table of Contents

Muon Ionization Cooling Experiment (MICE)

The Muon Ionization Cooling Experiment (MICE) aims to construct a cooling cell with all the equipment necessary to measure the emittance of a muon beam before and after this cell based on single particle measurements and achieve 10% cooling of 200 MeV/c muons. The cooling cell will be sandwiched between two identical trackers inside 4T superconducting solenoids, complemented by upstream and downstream particle detectors.

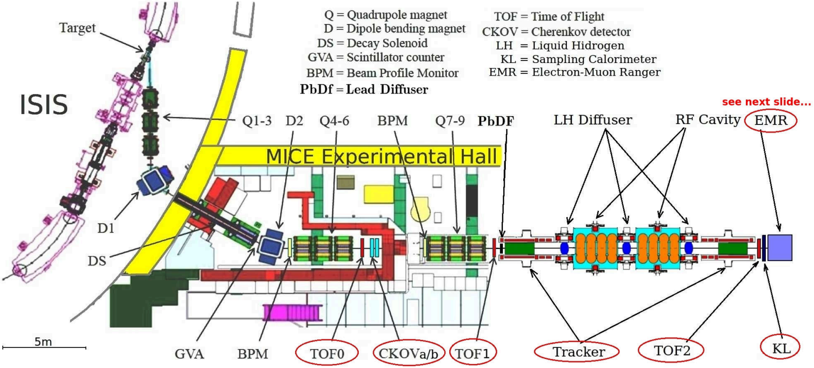


MICE Beamline and Cooling Channel



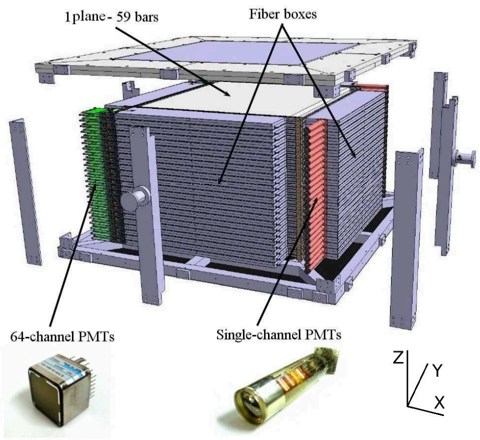
- MICE is designed to produce a 10% cooling effect on the muon beam
- measurement of muon cooling effect to $\sim$1% precision
- different detector technologies are employed
- 100-400 MeV/c $e^{\pm}$,$\mu^{\pm}$,$\pi^{\pm}$ beams are used

MICE Beamline Instrumentation



- TOF - particle identification, trigger and timing
- CKOV - muon/pion/electron separation at high momentum
- Tracker - particle momentum measurement
- KL - electron pre-shower

Electron-Muon Ranger (EMR)



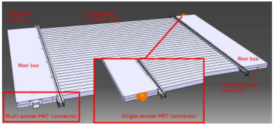
A Fully active scintillator tracker-calorimeter located at the very end of the cooling channel. It stops electrons / muons / pions with momentum below 150 / 300 / 350 MeV/c, records muon/pion decays and give very distinct particle identification signatures.

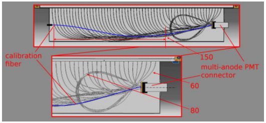
- 1 m^3 of active volume
- 48 planes made of 59 triangular scintillator bars with glued 1.2 mm wavelength shifting fibers
- light is collected by single-anode PMT on one side of a plane and by 64-channel PMTs - on the other: 3120 channels in total

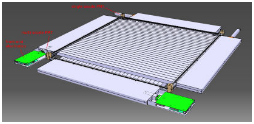
- the granularity of the detector allows for the individual track reconstruction
- muons/pion decay products can be reconstructed as well
- the detector help to reach high precision of the emittance measurements

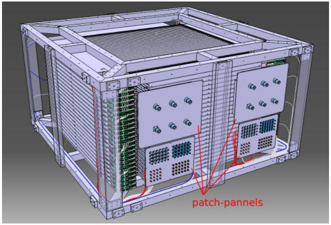
Table of Contents

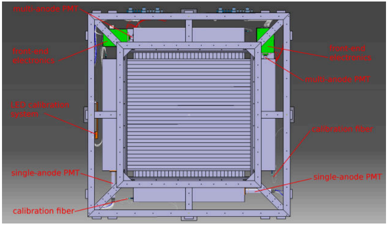
Overall Detector Design









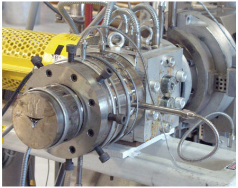


- 48 intersecting planes form 24 modules which allow for measurement of X-Y coordinate of a track, Z coordinate is given by a plane position
- readout electronics is housed inside the support frame and located next to the PMTs to minimize analog signal distortions, digital signals from 64-ch. PMTs and analog signal from 1-ch. PMTs are sent from the front-end boards outside the detector enclosure

Scintillator Bars

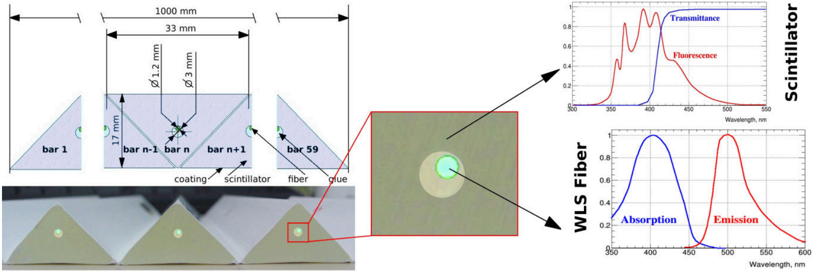
- scintillator bars have been produced at extrusion facility at Fermilab (also produced scintillators of different shapes for large scale experiments MINOS, Minerva, T2K-ND280 etc.)





- made of polystyrene pellets (Dow Styron 663 W) as base and 1% PPO(scintillator, 2,5-diphenyloxazole, $C_{15}H_{11}NO$) as primary and 0.03% POPOP(wavelength shifter, 1,4-di-(5-phenyl-2-oxazolyl)-benzene, $C_{24}H_{16}N_2O$) as secondary fluor
- each bar is coated with TiO_2 reflector in order to increase light collection by a wavelength shifting fiber inserted and glued inside the scintillator
- light output of the scintillator is around 17 photo-electrons (measured by PMT with 25% quantum efficiency)

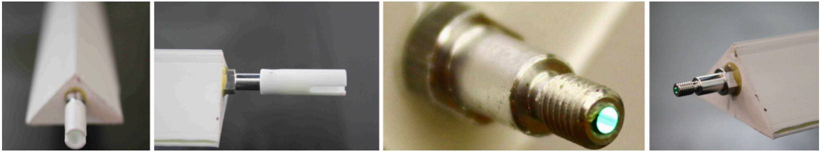
Scintillator Bars, Fibers



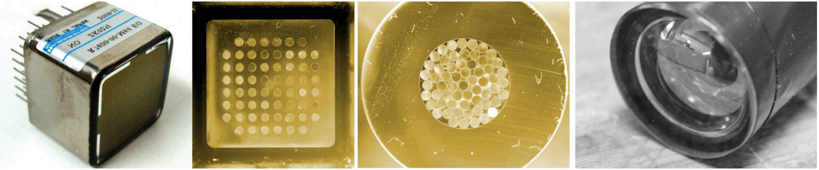
- the scintillator bars are 110 cm long, 1.7 cm high and 3.3 cm wide with 3 mm hole along a bar for a wavelength shifting (WLS) fibers
- fluorescence spectrum of the scintillator matches to absorption spectrum of the WLS fiber that re-emits green light to which PMTs are most sensitive
- WLS fiber characteristics:
  - made by Saint-Gobain Crystals
  - double cladding: 1.2 mm
  - core material: polystyrene with acrylic cladding
  - numerical aperture: 0.58
  - trapping efficiency: 3.5%.

Scintillator Bars, Fibers, PMT Connectors

- each bar is equipped with two custom-made connectors to which clear fibers (1.5mm multi-cladding light guide produced by Kuraray) are coupled
- each fiber end is polished with the help of special polishing machine with 4 different diamond-based polishing papers (last one is 1μm grade)



- a bundler of 60 clear fibers glued into PMT connectors of two types: one for 64-ch. PMT, another for 1-ch. PMT; and polished

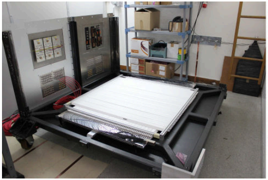
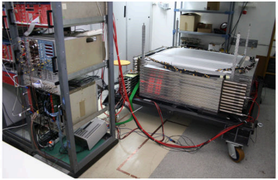
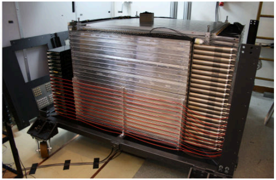


- no crimping is used fix the fibers, only glue, to avoid any damage to fibers

Table of Contents

Plane Assembly

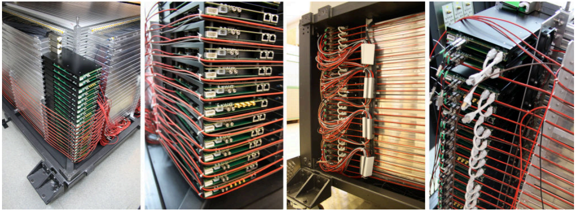
- numerous quality tests have been implemented in order to insure that all the bars and fibers are of good quality
- all electronics components (front-end boards, PMTs, cables) were tested individually before final assembly
- construction was split into several steps:
  1. gluing bars with WLS fibers (+ optical quality test, dedicated test bench)
  2. gluing clear fiber bundles
  3. polishing fiber connectors (+ optical quality test, dedicated test bench)
  4. assembling planes (+ optical quality test, dedicated test bench)
  5. assembling front-end electronics
- planes assembly was completed within 6 months

- as a result: no dead channels on bar/fiber/connectors level
- 3 (out of 3120) dead channel on electronics level

Front-End Electronics

- 64-ch. PMT front-end electronics:

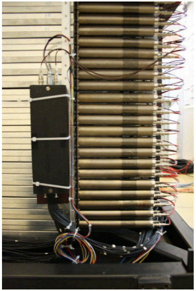
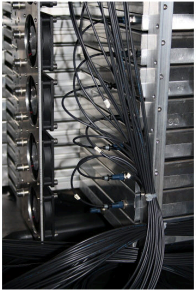
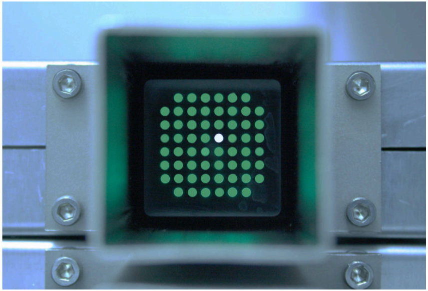


- 1-ch. PMT front-end electronics (voltage dividers only):

- cooling fans are place in front of the boards in insure efficient air exchange

PMT Calibration System

- LED calibration system is setup inside the detector enclosure
- LED driver box connected to 100 fibers going to each PMT

- it is used to verify PMT alignment, cross-talk and to monitor PMT stability

Fully Assembled Detector

- cabling, control rack, detector light-tight enclosure:

- detector patch panels:

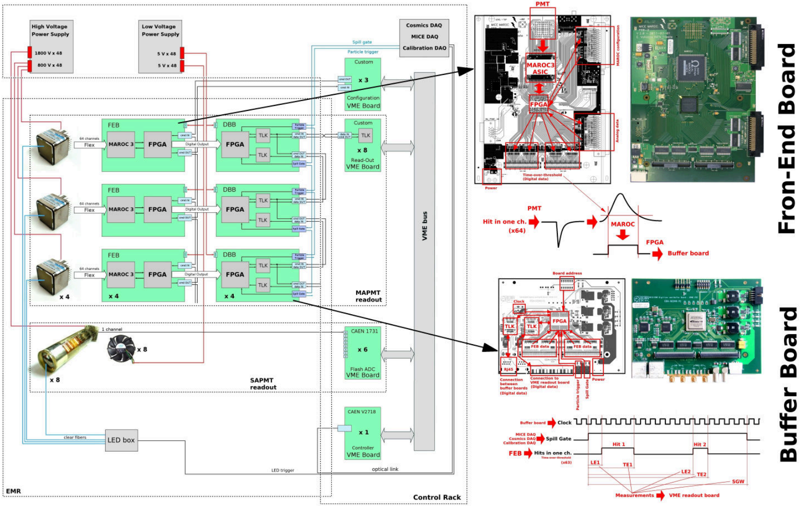
Detector Installation in MICE Hall

- the detector was positioned at the end of MICE beamline (September 2013):

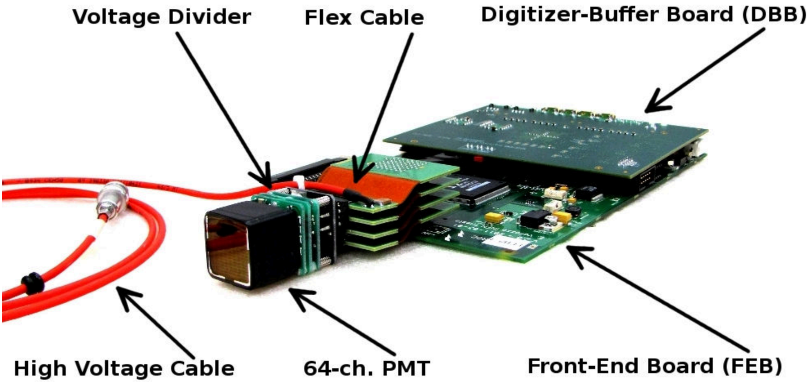
- control rack was temporarily installed next to the detector:

Table of Contents

EMR Electronics Layout



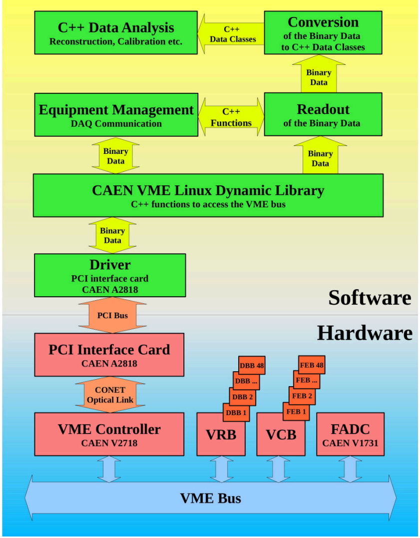
EMR Front-End Boards



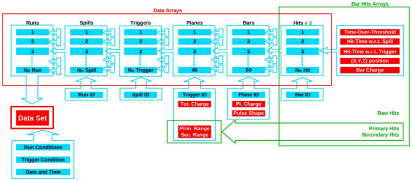
The Front-End Board (FEB) is designed to readout the 64-ch. PMT. It hosts a MAROC ASIC that amplifies, discriminates and shapes all input signals. Pulse height information can be extracted at low rate (during calibration with cosmics). Time over threshold information is directed to a piggy-back buffer board.

The Digitizer-Buffer Board (DBB) receives signals from FEB and stores them in buffer memory. MICE beam is made of 1ms spills every second. Every spill is composed of hundreds of particles. All interactions of these particles are stored in DBB and transferred to PC at the end of a spill.

EMR DAQ Hardware and Software



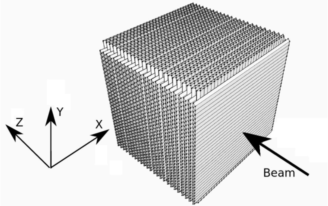
The detector front-end electronics is controlled via VME readout boards and based on CAEN VME interface. Binary data is saved into dedicated C++ data structure:

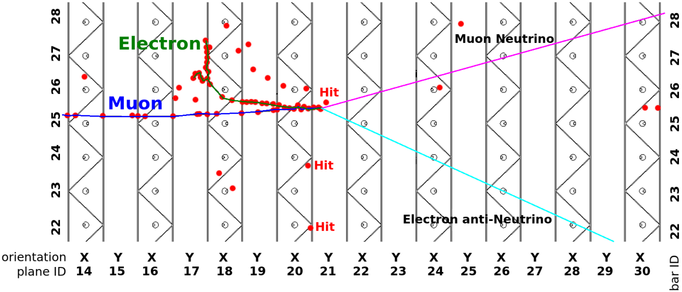


The EMR can work either as a standalone detector (cosmis, calibration) or as a part of the MICE (beam data taking). The EMR DAQ software allow for both operational modes with no modifications to the codes when switching from one to another. When operated within MICE, the readout code is enabled inside the MICE DAQ software, while in the standalone mode the rest of the experiment is disabled.

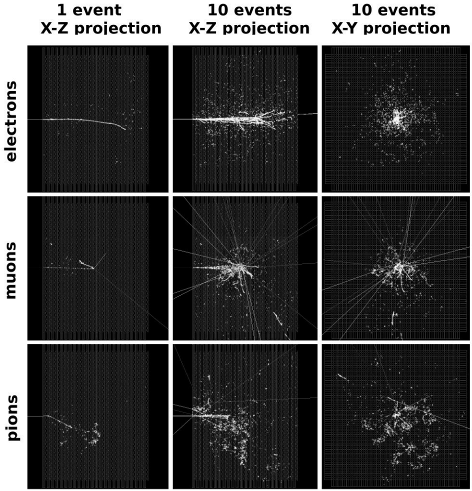
Table of Contents

Geant4 Simulation: Typical Event Display

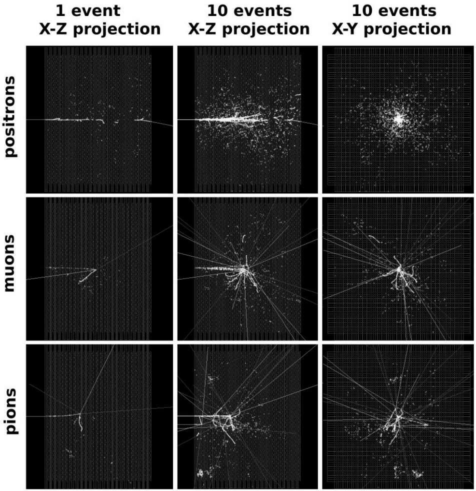




Geant4 Simulation: Negative Particles Event Displays

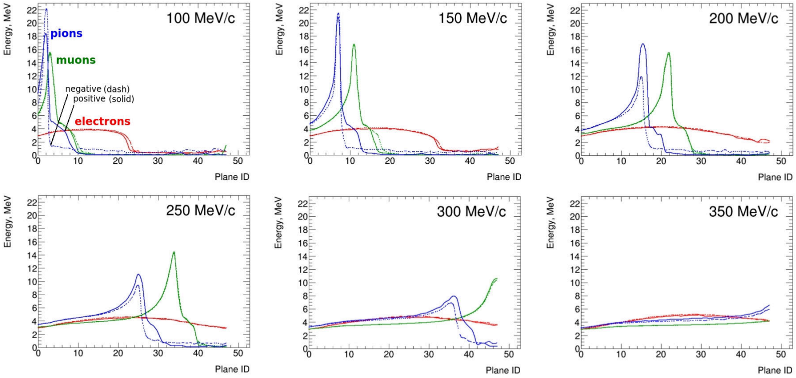


Geant4 Simulation: Positive Particles Event Displays

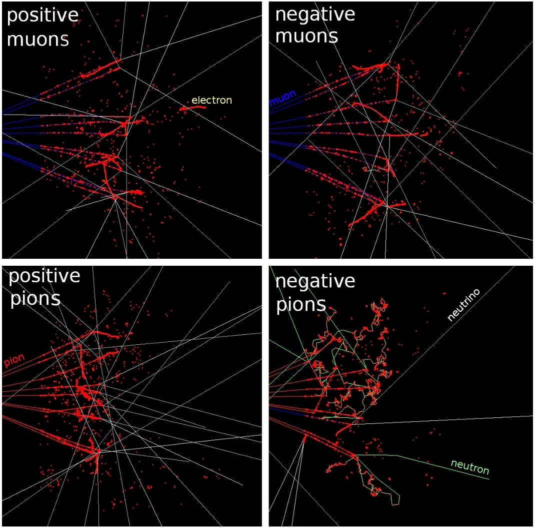


Geant4 Simulation: Muon/Pion Bragg Peaks

- muons/pions with momentum below 300/350 MeV/s stop in the detector
- Bragg peaks are clearly visible where muons/pions stop
- no difference between positive and negative electrons/muons
- significant difference between positive end negative pions due to nuclear capture



Geant4 Simulation: Muon/Pion Nuclear Capture



Geant4 Simulation: Shower Shapes

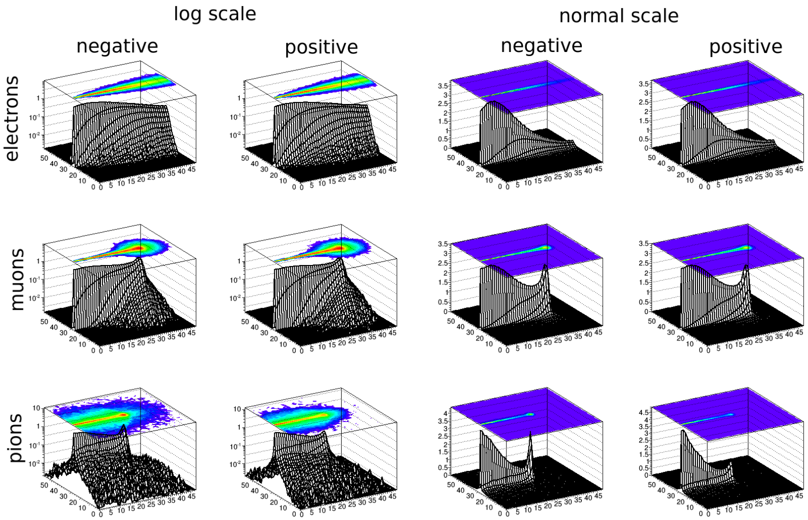
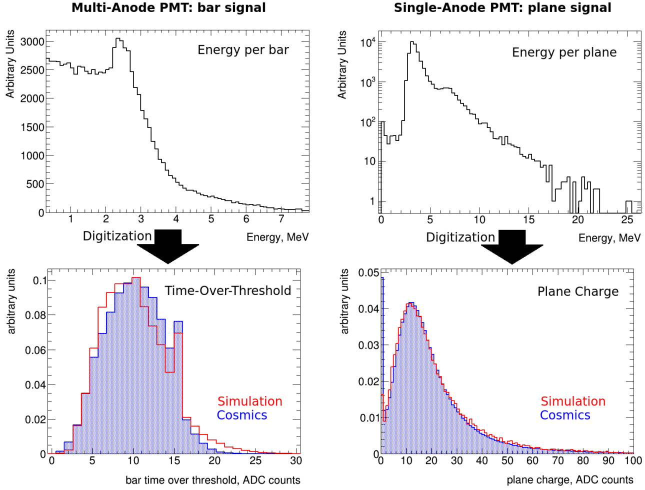


Table of Contents

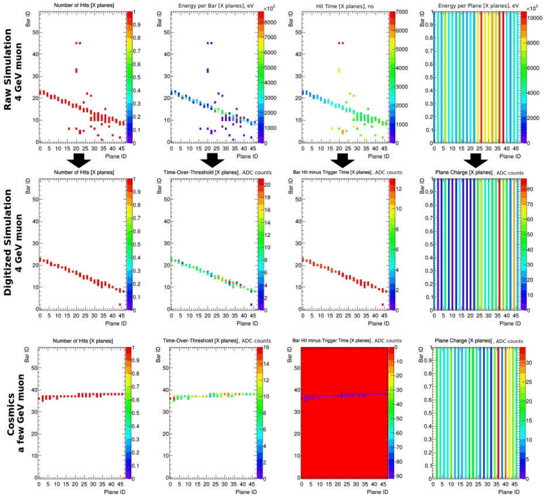
Monte Carlo Digitization Validation

4 GeV muons from simulation VS cosmics muons

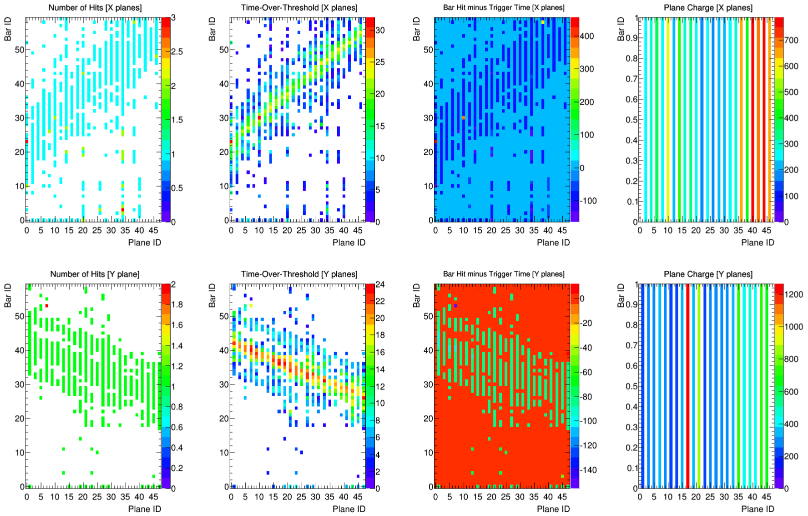


Monte Carlo Digitization Validation

4 GeV muons from simulation VS cosmics muons



High Energy Cosmic Rays



High Energy Cosmic Rays

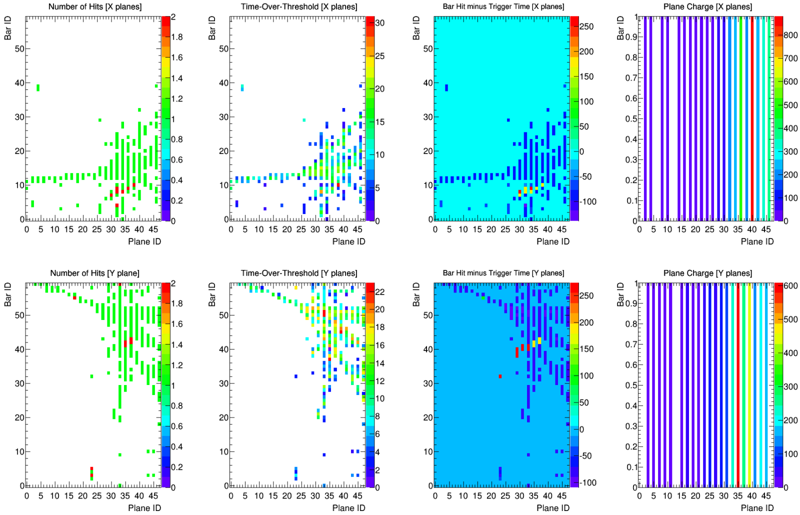
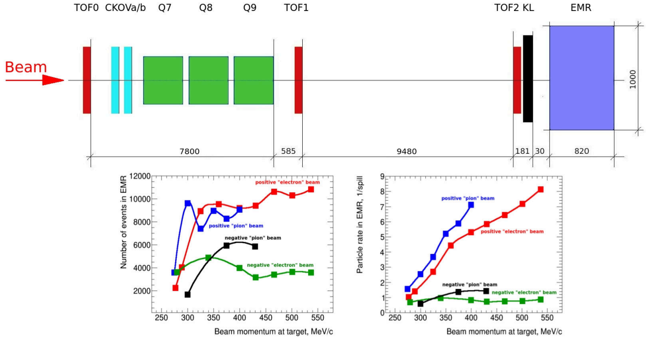


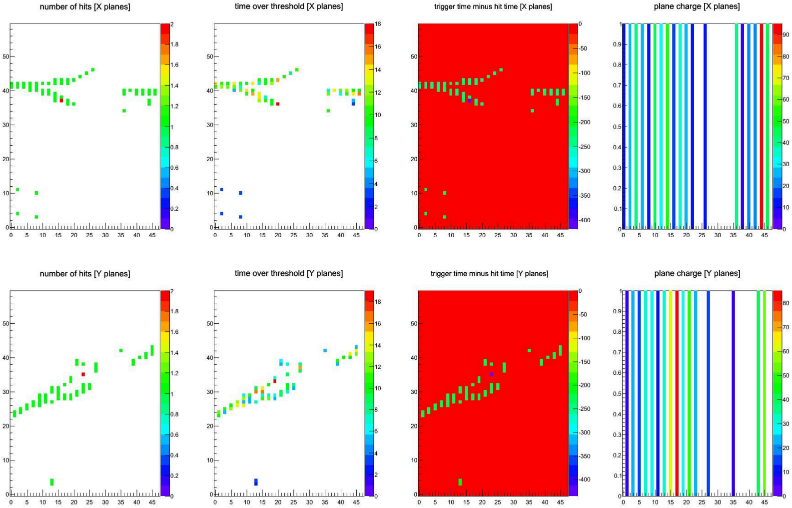
Table of Contents

MICE Beam Data

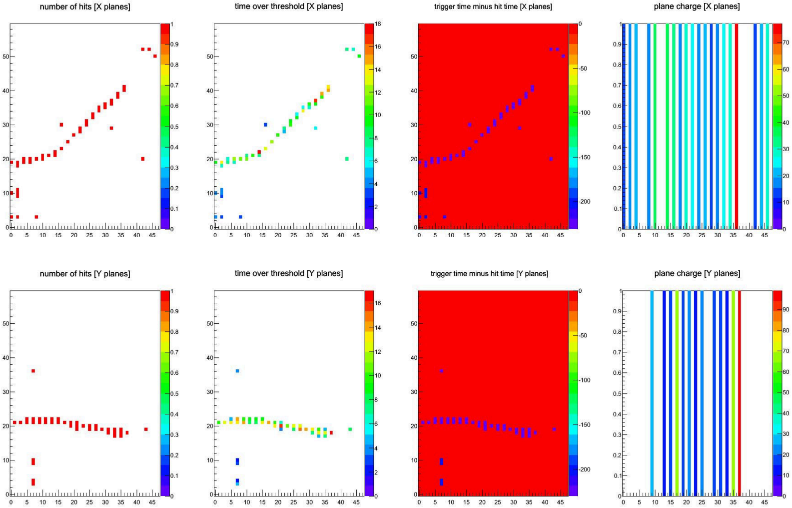


- during one month the detector was exposed to the MICE beam
- the beam was composed of e, μ, π with momenta from 250 to 550 MeV/c
- spill period is 1 sec. and there are from 1 to 8 particles per spill
- particle type and momentum is identified by TOF detectors
- for each particle the following is measured in the EMR:
  1. range of primary (muon/pion) and secondary (electron) tracks
  2. total charge

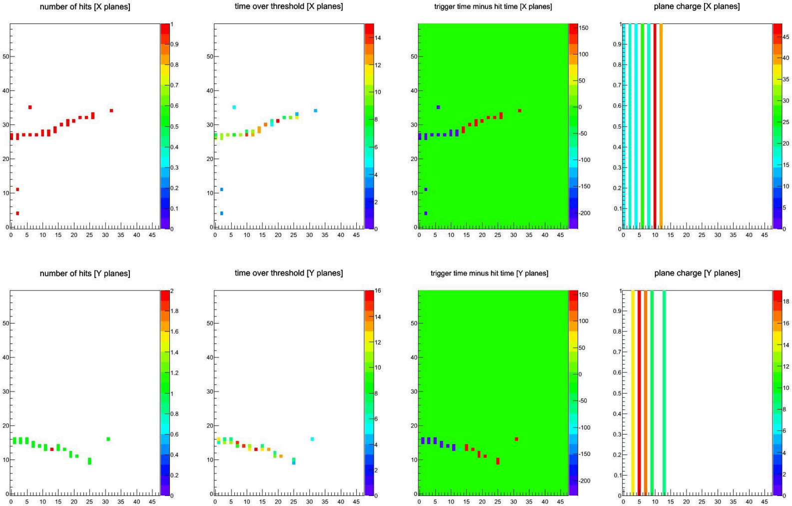
MICE beam particles: electron



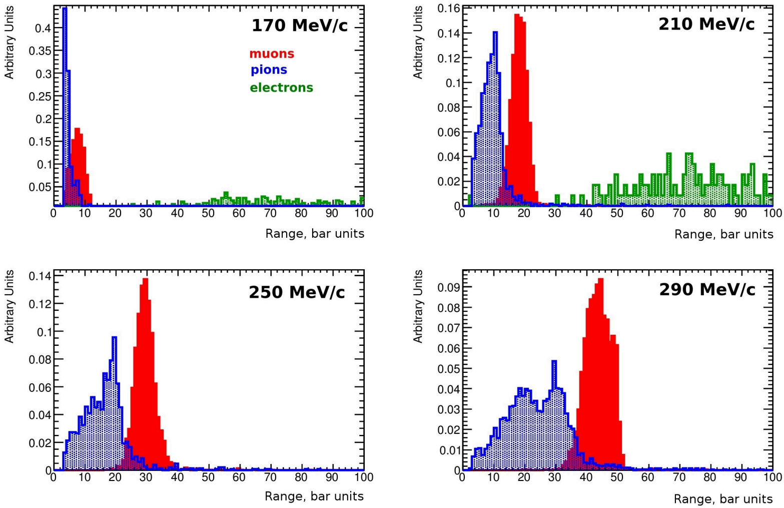
MICE beam particles: electron



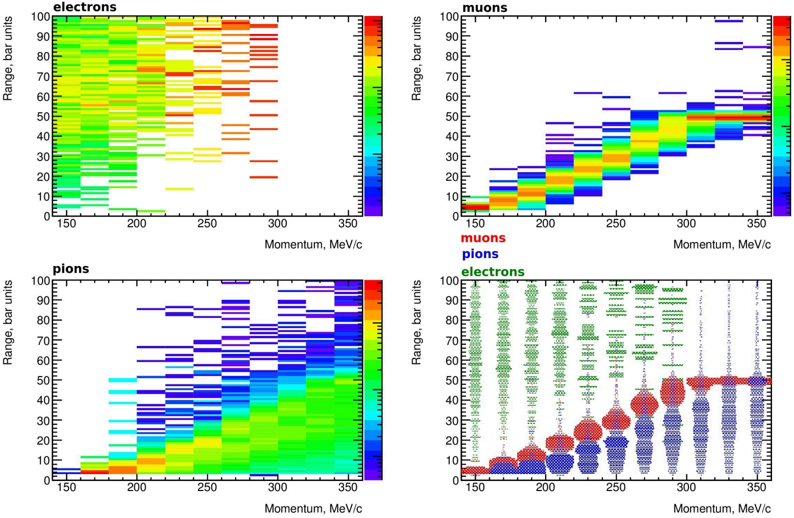
MICE beam particles: muon/pion decay



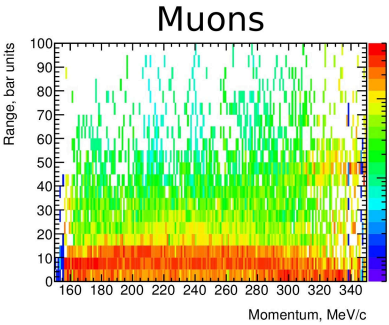
Range of Primary Particles

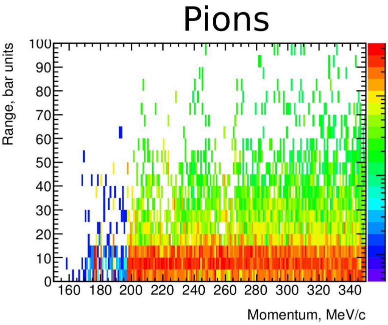


Range of Primary Particles: Scatter Plots

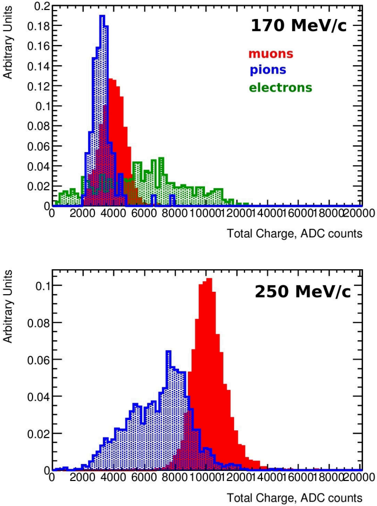


Range of Secondary Particles: Scatter Plots

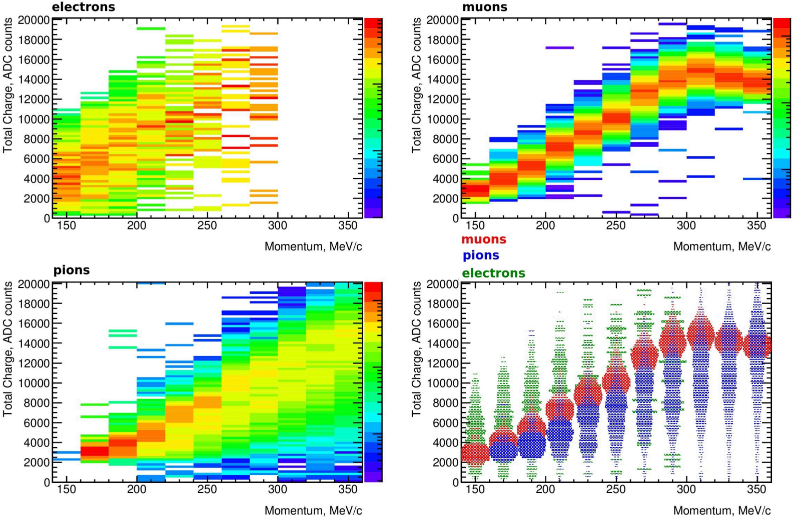




Total Reconstructed Charge



Total Reconstructed Charge: Scatter Plots



Summary

- The EMR project was initiated in 2008. Only in 2010 after major revision and overhaul the actual construction began and after four years it was completed and successfully commissioned in MICE.
- Beam tests revealed an exceptional behavior of the detector.
- It will be used as part of the MICE beam instrumentation and provide valuable data that will allow for the precise measurement of physical quantities required to prove the possibility of the muon ionization cooling.

Thank you for your attention!