Totally Active Scintillator Calorimeter

for the Muon Ionization Cooling Experiment

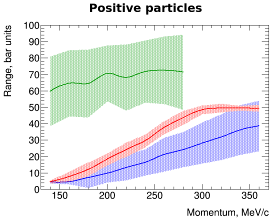
Ruslan Asfandiyarov

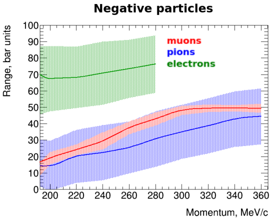
University of Geneva (DPNC)
Switzerland

MICE Collaboration Meeting
Oxford
July 25-28, 2014

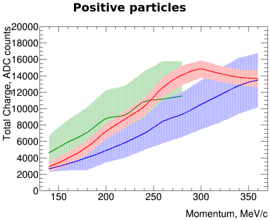
Ultimate Plots

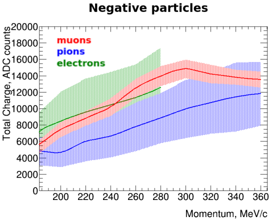
Reconstructed range as a function of TOF12 momentum





Reconstructed total charge as a function of TOF12 momentum



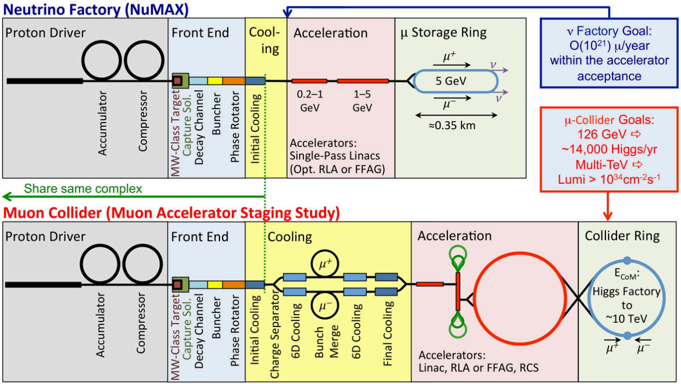


EMR Paper Outline

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):

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

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:

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

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.

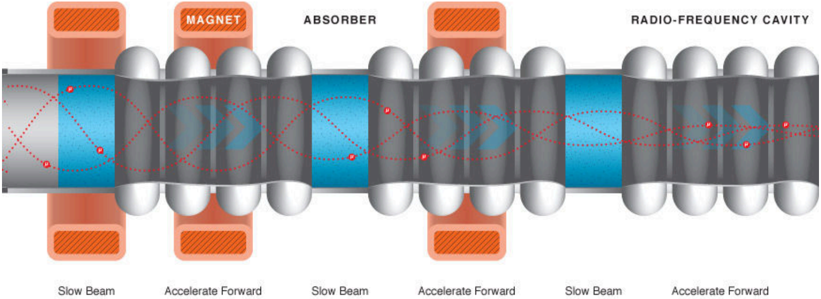
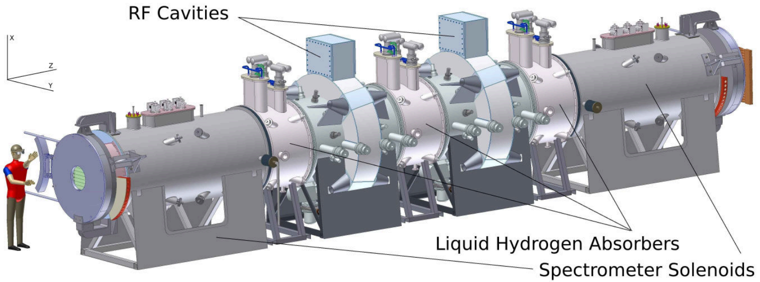


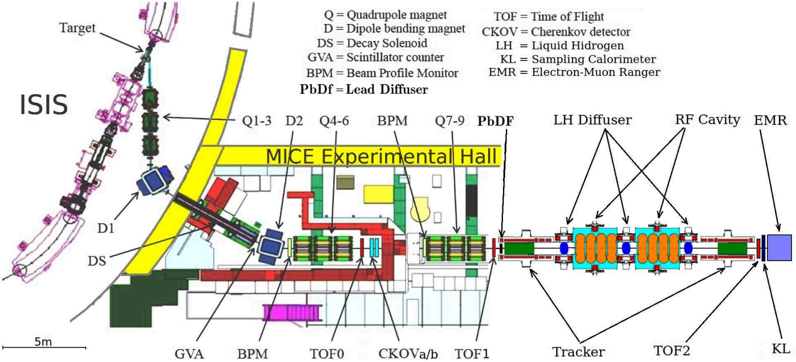
Table of Contents

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.

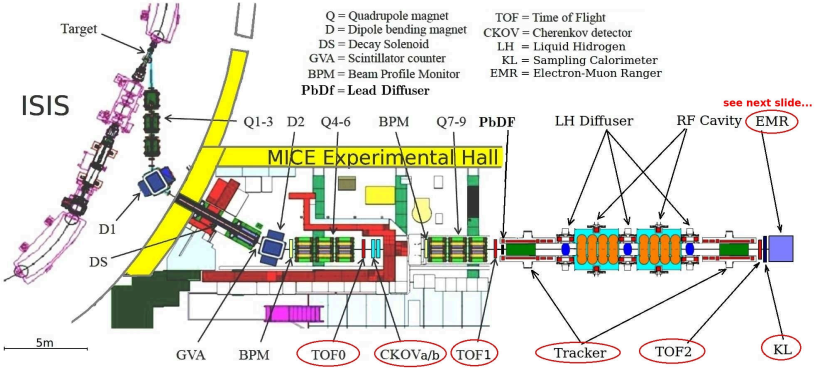


MICE Beamline and Cooling Channel



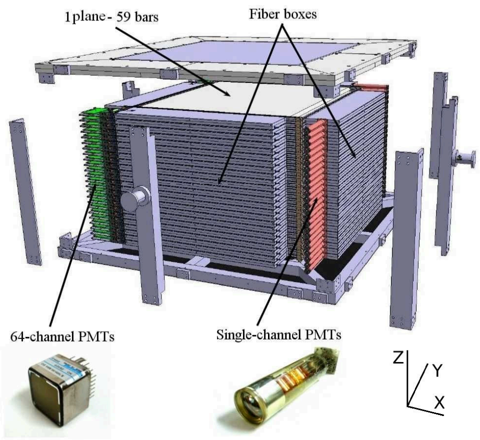
- MICE is designed to produce a 10% cooling effect on the muon beam
- measurement of muon cooling effect to $\sim$1% precision
- different detector technologies are employed
- 100-400 MeV/c $e^{\pm}$,$\mu^{\pm}$,$\pi^{\pm}$ beams are used

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)



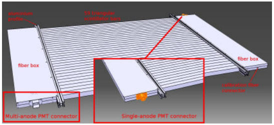
A Fully active scintillator tracker-calorimeter located at the very end of the cooling channel. It stops electrons / muons / pions with momentum below 150 / 300 / 350 MeV/c, records muon/pion decays and give very distinct particle identification signatures.

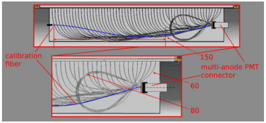
- 1 m^3 of active volume
- 48 planes made of 59 triangular scintillator bars with glued 1.2 mm wavelength shifting fibers
- light is collected by single-anode PMT on one side of a plane and by 64-channel PMTs - on the other: 3120 channels in total

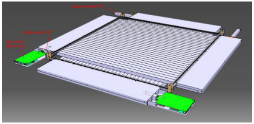
- the granularity of the detector allows for the individual track reconstruction
- muons/pion decay products can be reconstructed as well
- the detector help to reach high precision of the emittance measurements

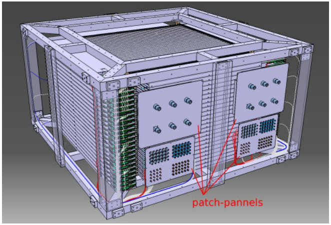
Table of Contents

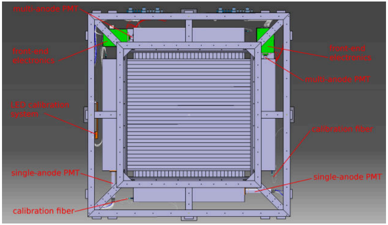
Overall Detector Design









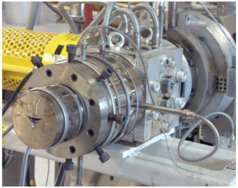


- 48 intersecting planes form 24 modules which allow for measurement of X-Y coordinate of a track, Z coordinate is given by a plane position
- readout electronics is housed inside the support frame and located next to the PMTs to minimize analog signal distortions, digital signals from 64-ch. PMTs and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

Scintillator Bars

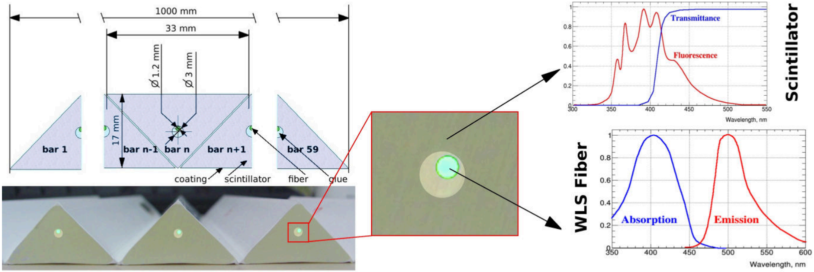
- scintillator bars have been produced at extrusion facility at Fermilab (also produced scintillators of different shapes for large scale experiments MINOS, Minerva, T2K-ND280 etc.)





- 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)

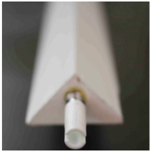
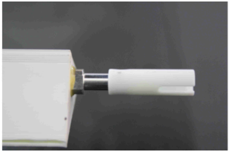
Scintillator Bars, Fibers

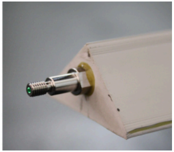


- the scintillator bars are 110 cm long, 1.7 cm high and 3.3 cm wide with 3 mm hole along a bar for a wavelength shifting (WLS) fibers
- fluorescence spectrum of the scintillator matches to absorption spectrum of the WLS fiber that re-emits green light to which PMTs are most sensitive
- WLS fiber characteristics: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

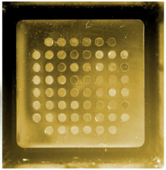
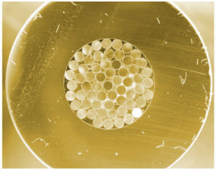
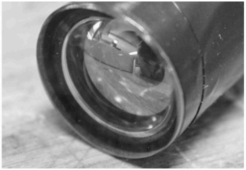
Scintillator Bars, Fibers, PMT Connectors

- 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

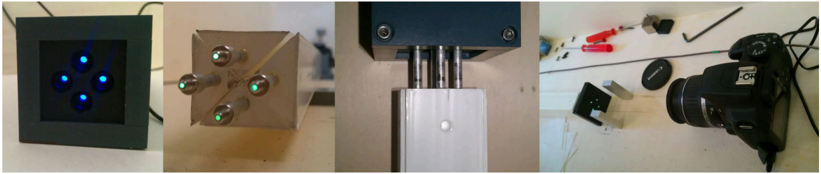
Assembly

- 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

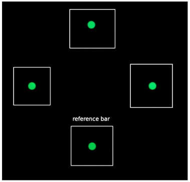
- as a result: no dead channels on bar/fiber/connectors level
- 3 (out of 3120) dead channel on electronics level

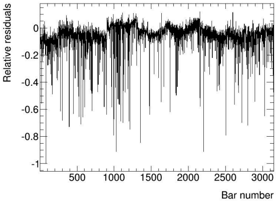
Quality tests of Scintillator Bars

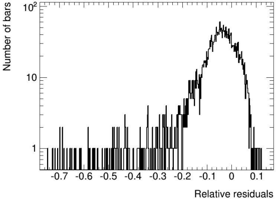
- 3150 bars were tested
- light intensity of each bar was measured using LED/camera setup



- only bars with a relative intensity above -0.15 were accepted



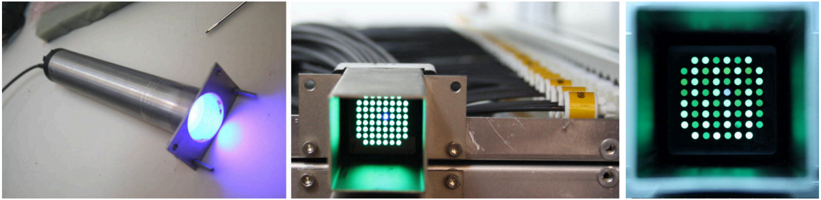




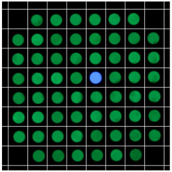
- 305 bars (9.7%) did not pass the quality test and were rejected

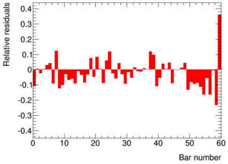
Quality tests of Planes

- once assembled each planes was tested using LED/camera setup
- an image of MAPMT fiber connector was used to estimate light intensity of each channel



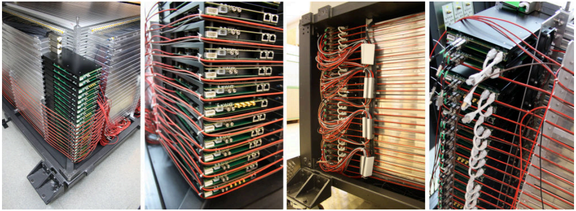
- an image of MAPMT fiber connector was used to estimate light intensity of each channel → no dead channels were found





Front-End Electronics

- 64-ch. PMT front-end electronics:

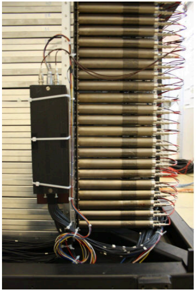
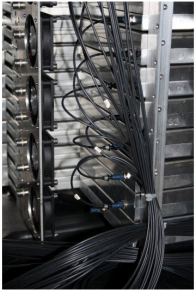
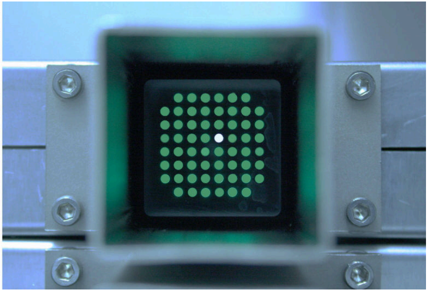


- 1-ch. PMT front-end electronics (voltage dividers only):

- 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

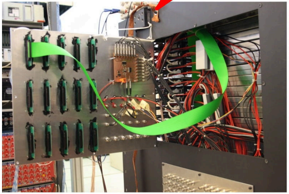
Fully Assembled Detector

detector patch panels

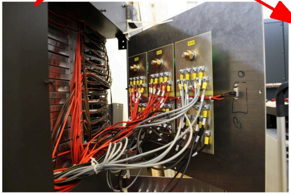
Cables between detector and the control rack:

- **48 SAPMT signal**
- **32 MAPMT signal**
- **96 High Voltage**
- **6 Low Voltage high current**
- **15 FEB configuration and analog signal**
- **6 spare High Voltage**
- **6 Low Voltage low current**
- **12 spare signal**

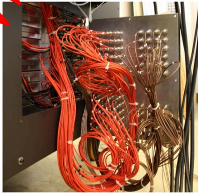
All cables between the detector and the control rack are 15 meters long (but practically can be up to few hundred meters)



FEB configuraton
FEB Analog signal
Auxiliary IN/OUT



Low Voltage power for FEB and DBB



High Voltage
SAPMT signal
MAPMT signal

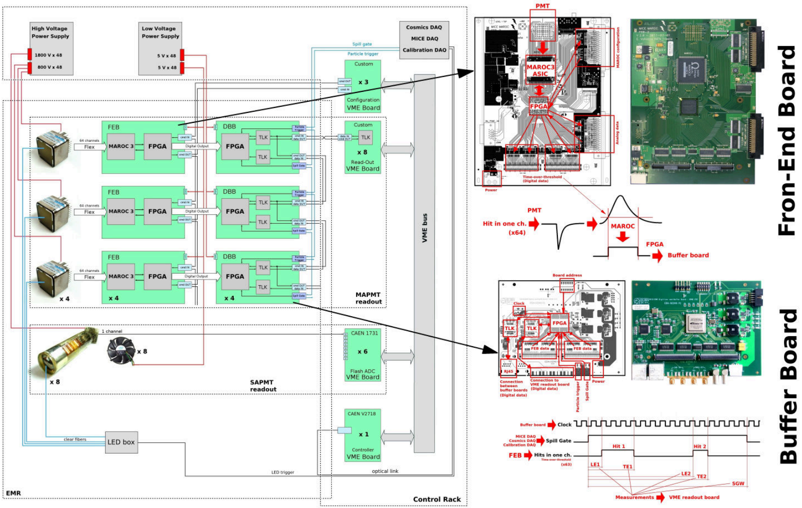
Detector Installation in MICE Hall

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

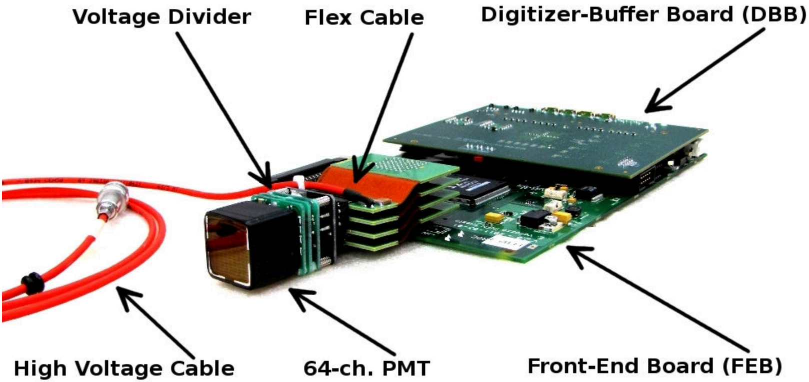
- control rack was temporarily installed next to the detector:

Table of Contents

EMR Electronics Layout



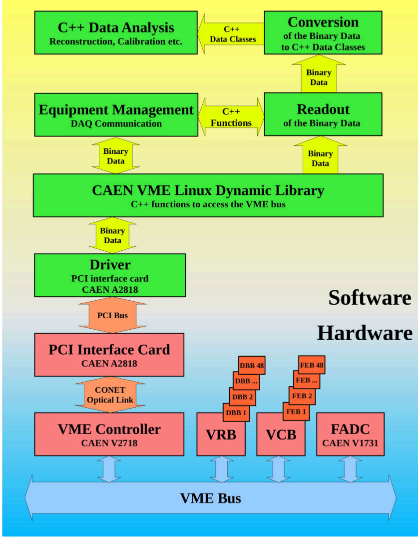
EMR Front-End Boards



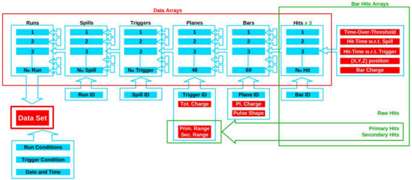
The Front-End Board (FEB) is designed to readout the 64-ch. PMT. It hosts a MAROC ASIC that amplifies, discriminates and shapes all input signals. Pulse height information can be extracted at low rate (during calibration with cosmics). Time over threshold information is directed to a piggy-back buffer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



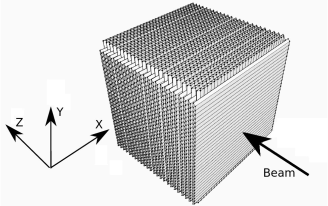
The detector front-end electronics is controlled via VME readout boards and based on CAEN VME interface. Binary data is saved into dedicated C++ data structure:

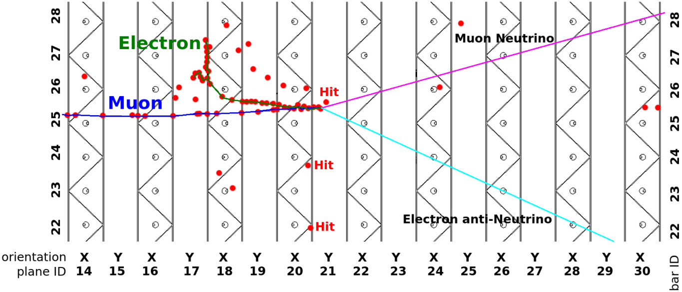


The EMR can work either as a standalone detector (cosmis, calibration) or as a part of the MICE (beam data taking). The EMR DAQ software allow for both operational modes with no modifications to the codes when switching from one to another. When operated within MICE, the readout code is enabled inside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

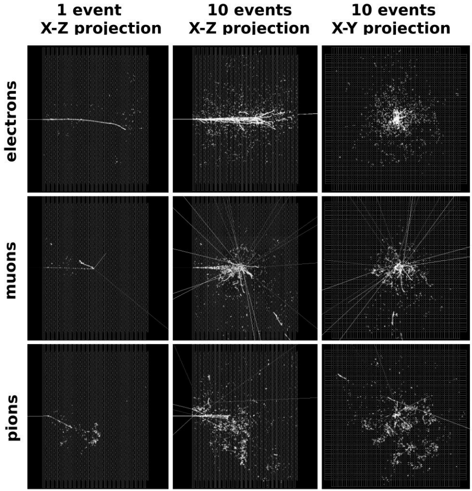
Table of Contents

Geant4 Simulation: Typical Event Display

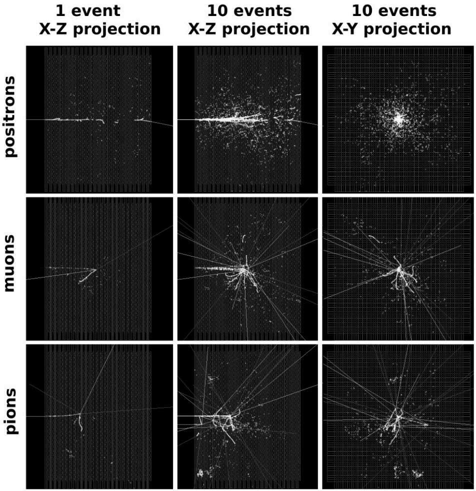




Geant4 Simulation: Negative Particles Event Displays

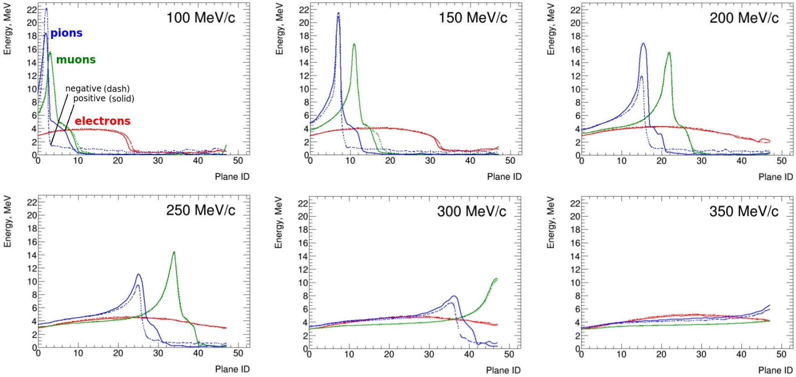


Geant4 Simulation: Positive Particles Event Displays

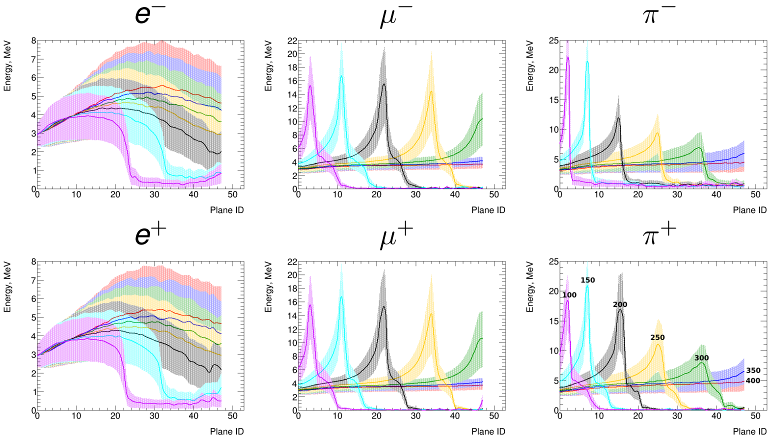


Geant4 Simulation: Muon/Pion Bragg Curves

- muons/pions with momentum below 300/350 MeV/s stop in the detector
- Bragg peaks are clearly visible where muons/pions stop



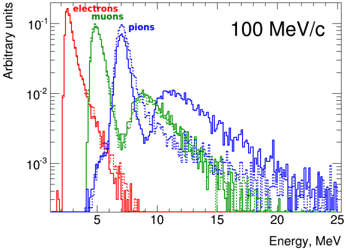
Geant4 Simulation: RMS of Muon/Pion Bragg Curves

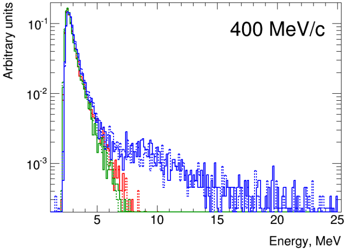


- no difference between positive and negative electrons/muons
- significant difference between positive end negative pions due to nuclear capture

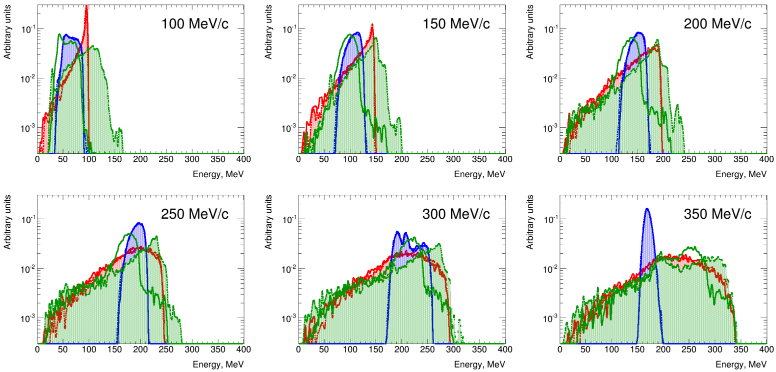
Geant4 Simulation: Energy Loss in the 1^{st} Plane

- significant difference in energy loss at low momenta
- at high momenta energy loss is around 3.5 MeV per plane



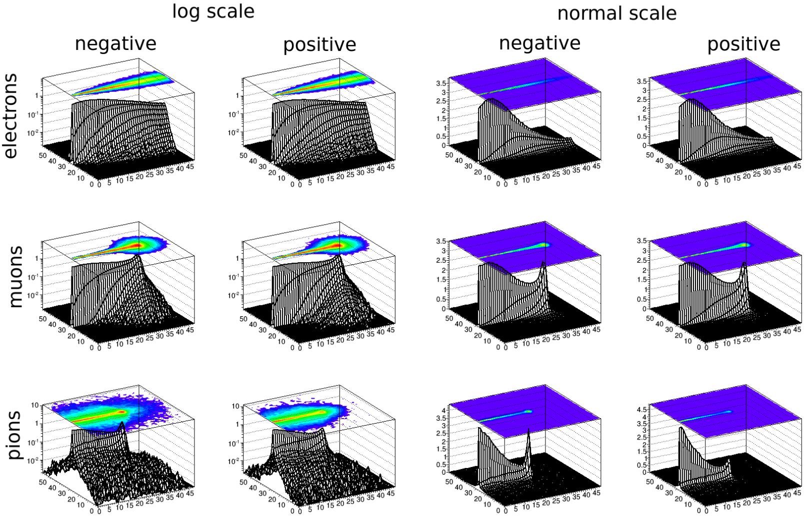


Geant4 Simulation: Total Energy Loss



- energy resolution is quite limited
- nevertheless it has strong discriminating power

Geant4 Simulation: Shower Shapes



Geant4 Simulation: Muon/Pion Nuclear Capture

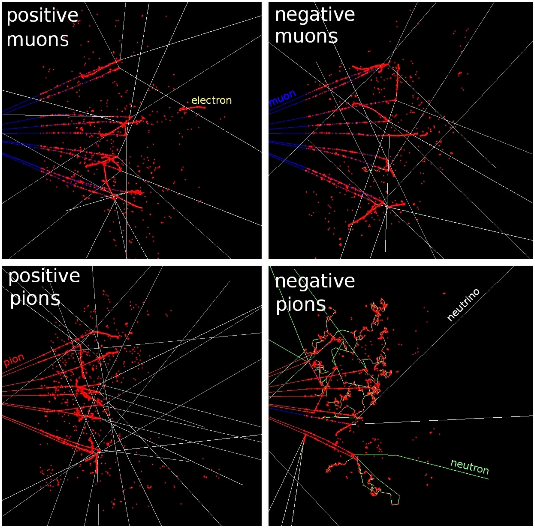
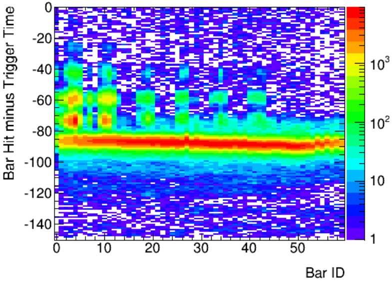
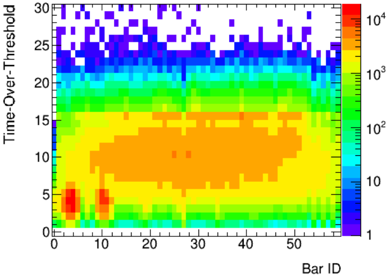


Table of Contents

Timing Analysis: Noise rejection

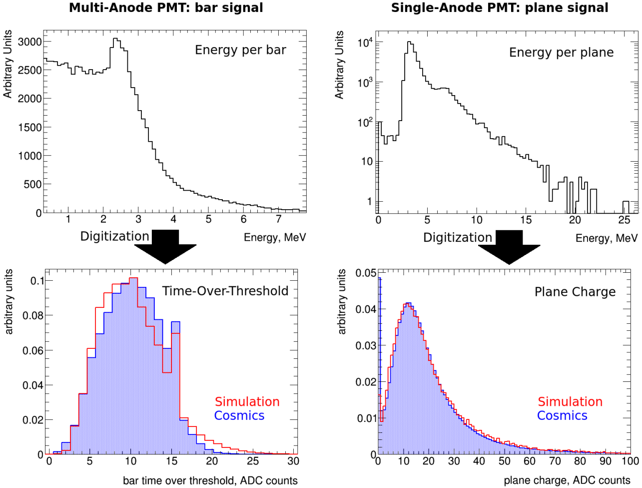




- the noise hits are not only grouped in time but also they appear in certain channels and typically they have time-over-threshold value around 4 ADC counts
- hits that come between 80 and 100 ADC units before a trigger are coming from real cosmics signals while hits between 80 and 35 before a trigger are associated to electronics noise

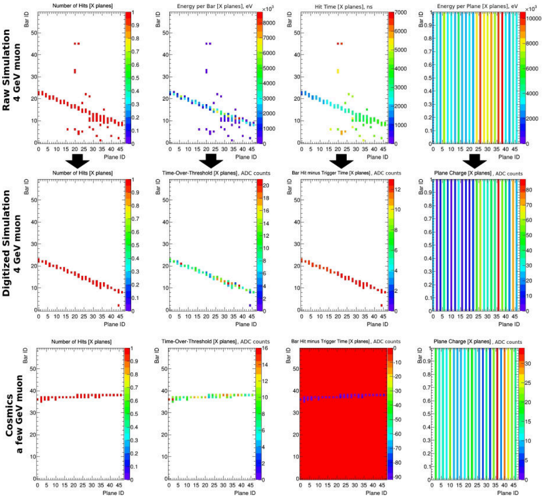
Monte Carlo Digitization Validation

4 GeV muons from simulation VS cosmics muons

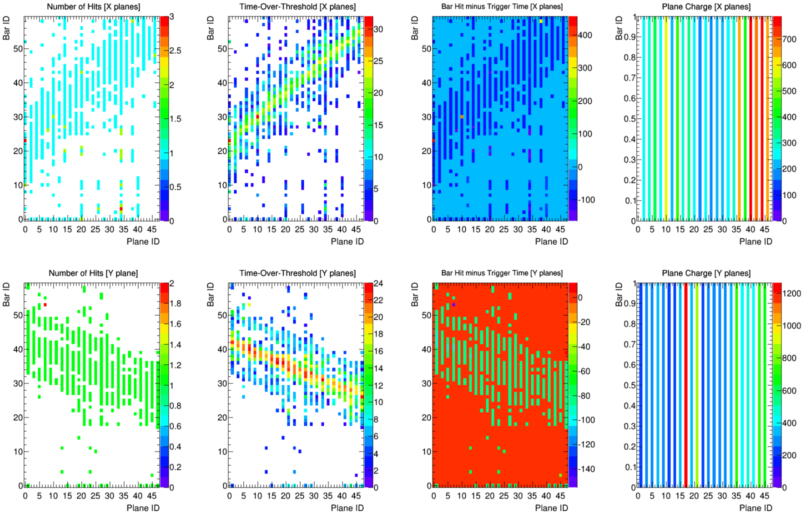


Monte Carlo Digitization Validation

4 GeV muons from simulation VS cosmics muons



High Energy Cosmic Rays



High Energy Cosmic Rays

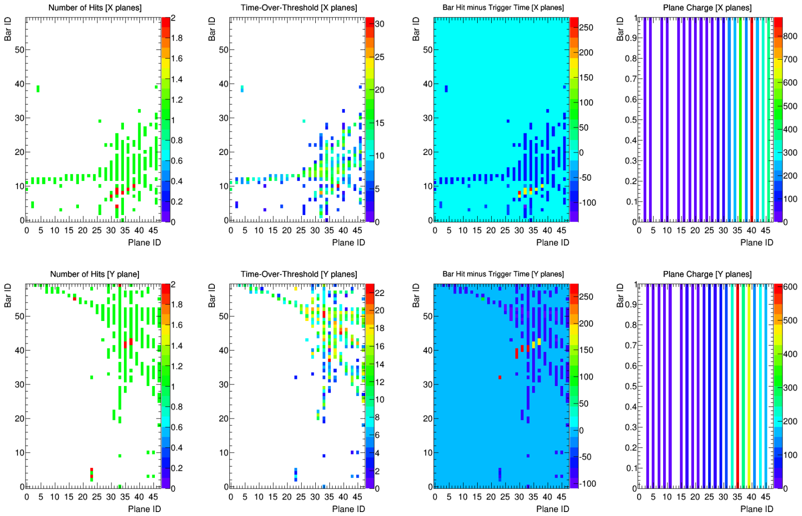
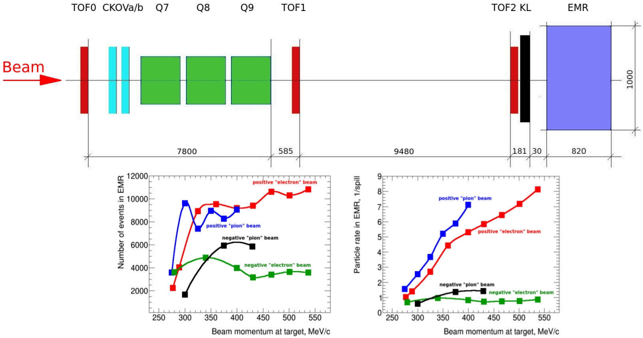


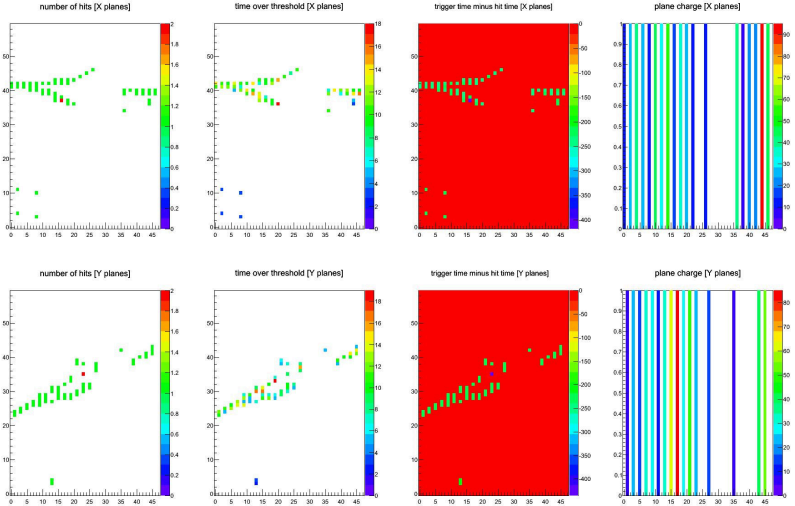
Table of Contents

MICE Beam Data

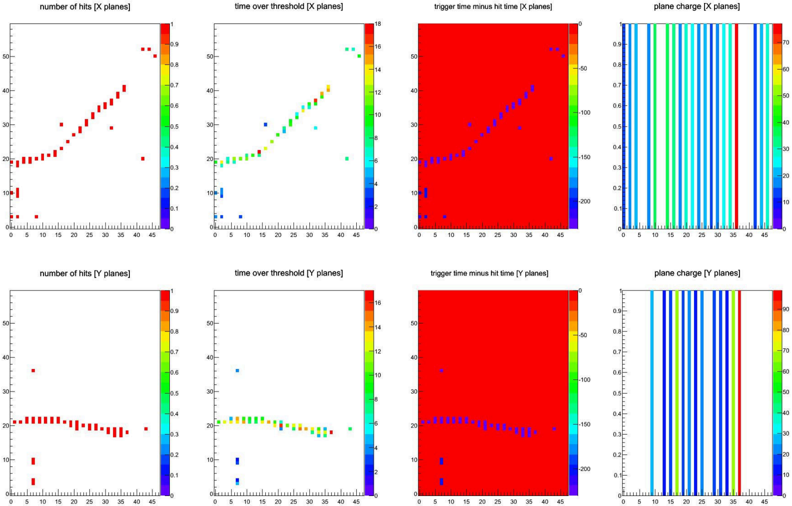


- during one month the detector was exposed to the MICE beam
- the beam was composed of e, μ, π with momenta from 250 to 550 MeV/c
- spill period is 1 sec. and there are from 1 to 8 particles per spill
- particle type and momentum is identified by TOF detectors
- for each particle the following is measured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

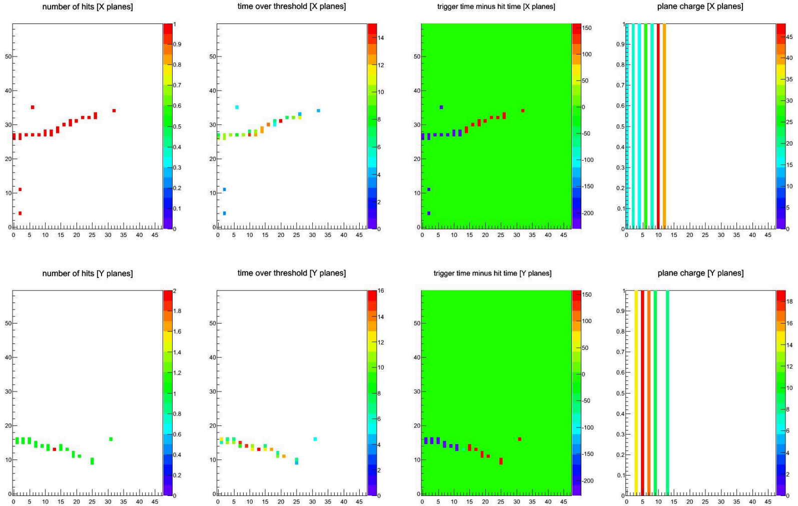
MICE beam particles: electron



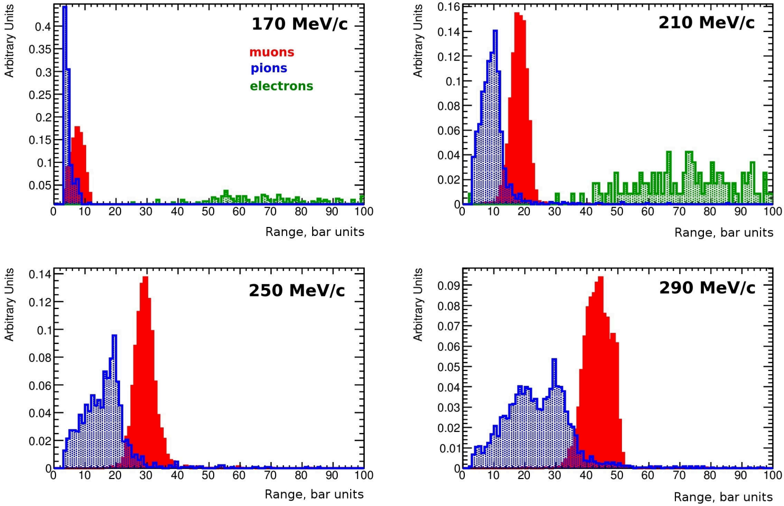
MICE beam particles: electron



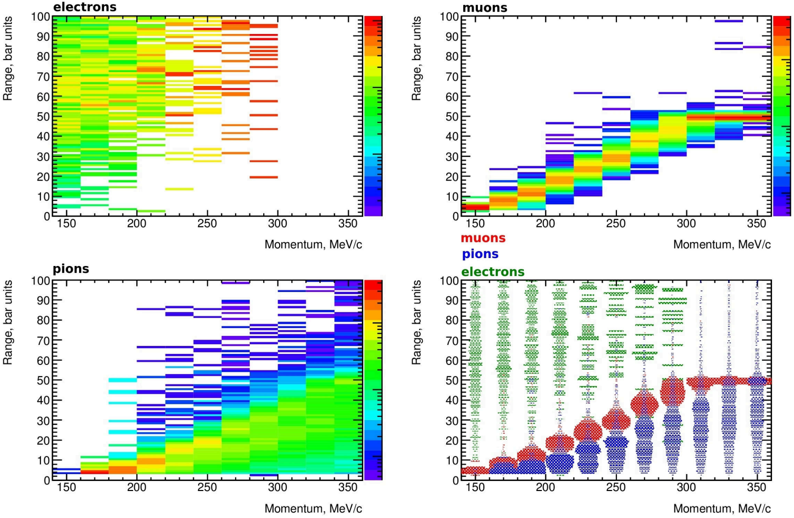
MICE beam particles: muon/pion decay



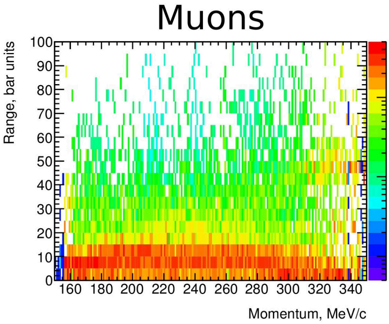
Range of Primary Particles

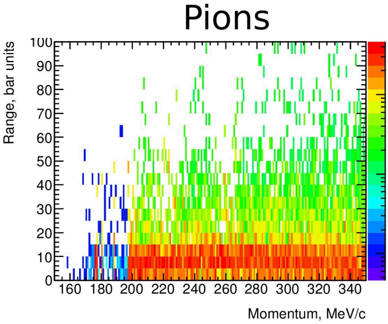


Range of Primary Particles: Scatter Plots

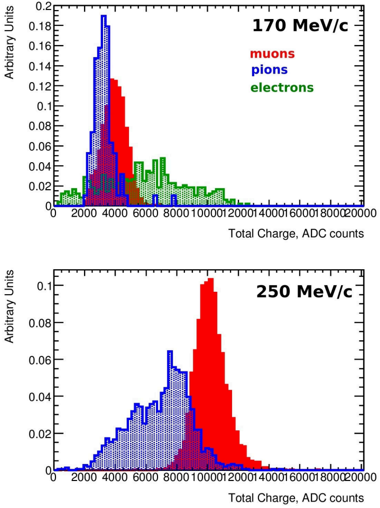


Range of Secondary Particles: Scatter Plots

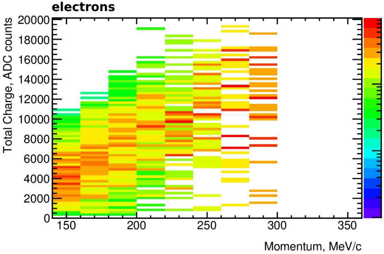


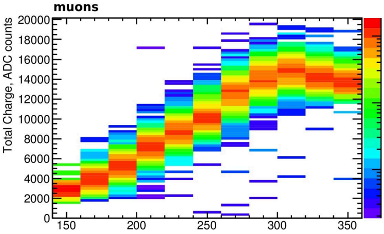


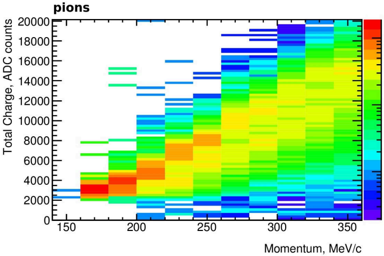
Total Reconstructed Charge

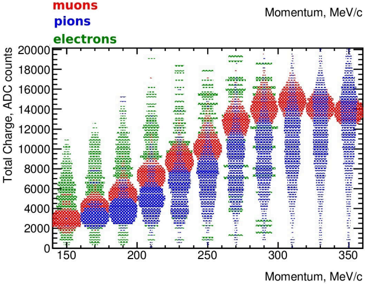


Total Reconstructed Charge: Scatter Plots



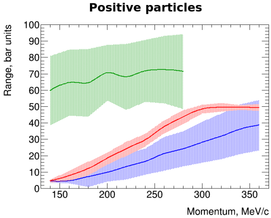


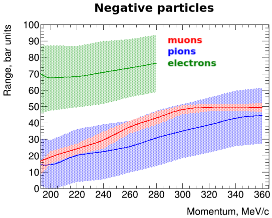




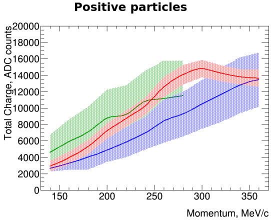
Ultimate Plots

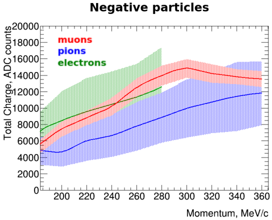
Reconstructed range as a function of TOF12 momentum





Reconstructed total charge as a function of TOF12 momentum





Summary

- the main objective of the beam tests was to commission the detector and to verify its functionality, namely its ability to measure the range of particles and clearly separate electrons from muons
- electrons, muons and pions produce substantially different signal
- separation between electrons and muons can be established with high efficiency
- the detector was not tuned and optimized; there are plenty of hardware parameters that significantly affect the performance of the detectors: configuration of the ASIC of the front-end board, high voltage of the PMTs, parameters of the readout/buffer boards; these parameters were set to the most reasonable values but they were never optimized; nevertheless, the detector showed excellent performance
- tracks can be clearly reconstructed and identified as being muons, electrons or pions; muon or pion decay products can be identified and matched to its originating particles; a presence of the decay electron is one of the powerful discriminating signatures; a Bragg peak at the end of muon and pion tracks mark the place where a particle stops and, therefore, helps to measure the range; it's shown that the range can be used to infer particle's momentum
- the detector has been characterized qualitatively, quantitative characterization was outside the scope of this analysis
- a draft of the paper outlined here will be ready by mid-August

Thank you for your attention!