PARTICLE IDENTIFICATION DEVICES IN MICE

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Abstract

The international Muon Ionization Cooling Experiment (MICE) is being built at the Rutherford Appleton Laboratory (RAL). It will carry out a systematic investigation of ionization cooling of a muon beam. This is one of the major technological steps needed in the development of a muon collider and a neutrino factory based on muon decays in a storage ring. MICE will use particle detectors to measure the cooling effect with high precision, achieving an absolute accuracy on the measurement of emittance of 0.1% or better. A PID system based on three Time-of-Flight stations, two Aerogel Cerenkov detectors, a KLOE-like calorimeter in combination with Electron-Muon Ranger calorimeter has been constructed in order to keep beam contamination (e, π) well below 1%. The MICE time-of-flight system will measure timing with a resolution better than 70 ps per plane, in a harsh environment due to high particle rates, fringe magnetic fields and electron backgrounds from RF dark current. The aim of this paper is to give a quick overview of the particle identification system in MICE.

OVERVIEW

The physics program at a neutrino factory is very rich and includes long-baseline ν oscillations, short-baseline ν physics and slow muon physics [1]. The performance of a Neutrino Factory depends not only on its clean beam composition ($50\%\nu_e, 50\%\overline{\nu}_\mu$ for the $\mu^+ \mapsto \overline{\nu}_\mu \nu_e e^+$ case), but also on the available beam intensity. The cooling of muons (accounting for $\sim 20\%$ of the final costs of the factory) is thus compulsory, increasing the performance up to a factor 10 [2], [3], [4], [5].

The process of ionization cooling of the transverse phase-space coordinates of a muon beam was proposed more than 20 years ago by A.N. Skrinsky [6]. Essentially it can be accomplished by passing it through an energy-absorbing material and an accelerating structure, both embedded within a focusing magnetic lattice. Both longitudinal and transverse momentum are lost in the absorber while the RF-cavities restore only the longitudinal component. The Muon Ionization Cooling Experiment (MICE) [7], [8], [9] at Rutherford-Appleton Lab is the first test of the ionization cooling concept for muon beams in the approximate momentum range 140 to 240 MeV/c. A minimum ionizing muon beam will be transversely cooled by stages of -dE/dx in LH_2 absorbers and longitudinal energy restoration in a series of 201 MHz RF cavities; (Figure 1) The 6D emittance reduction is measured before and after the cooling stage by tracking individual muons through the system. To establish muon cooling the in-flight muon beam is positively identified by three time-of-flight (TOF) stations [10], by two threshold Cherenkovs (CKOVs), and by a low energy ranging electron-muon calorimeter (KL/EMR) near the beam exit.

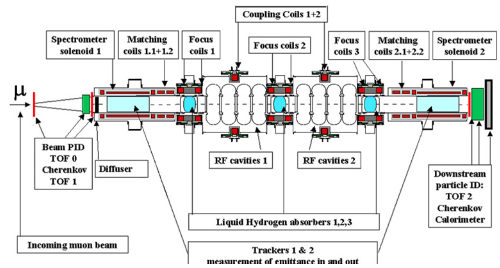

Figure 1: MICE Spectrometer Layout.

TIME OF FLIGHT DETECTORS

Three time-of-flight (TOF) stations are positioned in the MICE channel at the beginning (TOF0), midway(TOF1), and near the rear(TOF2). Each station is approximately 50cm $\times$ 50cm in active cross section and spaced apart by a $\approx$10 m flight path. The TOF stations are used in establishing a precision particle trigger which can be synchronized to within $\leq 70ps$ of the RF cavity phase of the experiment. The TOF 0/1/2 stations consist of 10/7/10 X-counter and 10/7/10 Y-counter arrays constructed of BC404/420 scintillator bar with dual R4998 PMT (TOF0) readout (Fig. 2). The HV dividers have been modified for high rate performance ($\approx$2 MHz). The dual photomultiplier (PMT) readout gives typically σ_t=50-60 ps intrinsic timing resolution for each bar assembly. The bars are 2.5 cm thick, optimizing between light collection and energy loss. The transit time and associated dispersion, σ_{tt}, of the signal through the PMT, cable delay, and the discriminating electronics is not known and are measured measured for each channel by a calibration procedure which can use particle beam and/or cosmics. Leading edge discriminators have been adopted for the timing measurements. This introduces a dependence of the discrimination crossing time, "time-walk", with its associated dispersion σ_{tw}. To calculate the time-walk correction the difference of the time measured by the

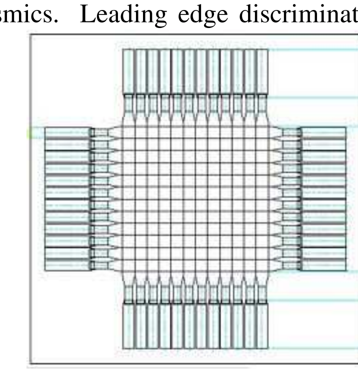

Figure 2: X/Y planes for TOF0 station. Each bar assembly is 4 cm wide.

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PMTs and a reference time is measured for a series of data, and a correction function is applied offline. The projected time-of-flight resolution between 2 stations is given by

$$\Delta t_{12} = \sqrt{2(\sigma_t/\sqrt{2})^2 + \sigma_{tt}^2 + \sigma_{tw}^2} \leq 75\,ps \qquad (1)$$

The TOF data acquisition utilizes three TDC boards (CAEN V1290). The digital values recorded by the TDCs correspond to the absolute time since the last reset of each TDC board. A ”particle trigger” signal is generated by hardware logic units in the data acquisition (DAQ) racks. It is given by the first dual coincidence of the PMTs connected to the same TOF0 bar unit. The first channel of each TDC board receives a copy of a particle trigger signal and this signal is used as a reference for all the PMT signals of the TOF stations. In the fall of 2008, components of the TOF0 and TOF1 stations were commissioned in the MICE beamline. For a set of pion runs, with time-walk corrections applied, the intrinsic detector resolutions were measured to be in the 55 ps to 65 ps range, very close to design specification. These intrinsic timing distributions are shown in Figure 3 and Figure 4. The time-of-flight distribution for the nominal 300 MeV/c pion tune is shown in Figure 5, displaying a good separation between positrons, muons, and pions in the beam at this early stage of analysis.

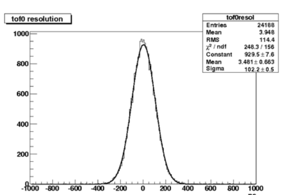

Figure 3: TOF0 detector's intrinsic timing.

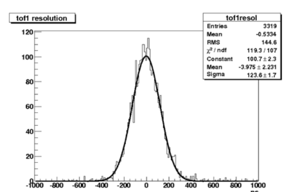

Figure 4: TOF1 detector's intrinsic timing.

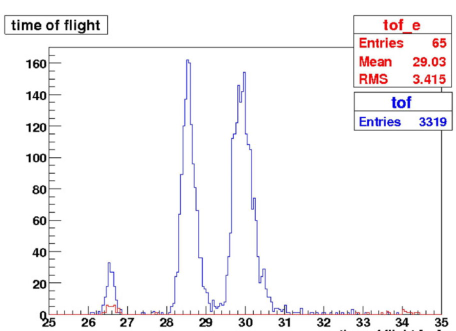

Figure 5: TOF1-TOF0 timing of e^+, μ^+, π^+ in nominal 300 MeV/c π^+ beam.

AEROGEL CHERENKOV COUNTERS

It is not possible to select a single material as Cerenkov radiator that is sensitive to muons and blind to pions over the entire range. To overcome this, high density aerogel Cherenkov radiators were selected, [11], with indexes of refraction and muon threshold momenta of n=1.07 (p^{μ}_{th}=278 MeV/c) and n=1.12 (p^{μ}_{th}=220 MeV/c). Each counter consists of a 2.3 cm thick aerogel radiator sealed behind a thin UV-transmitting window. The Cherenkov light is collected by four 8 inch 9354KB Electron Tubes PMTs. The PMT dividers have been designed to operate at $\leq$ 5 MHz beam rate with transistorized last dynode stages. The charge is collect in a 500 MHz flash ADC (CAEN V1721 500MS/s FADC) in the DAQ rack. A model of the aerogel Cherenkov detector with open PMT ports is shown in Figure 6.

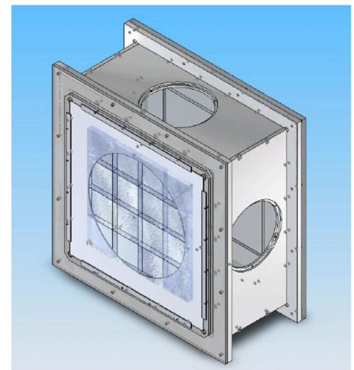

Figure 6: Model sketch of aerogel Cherenkov detector.

The saturation (β=1) photoelectron calibration for particles is found in 100 MeV/c positron runs. A typical PMT spectrum is shown in Figure 7. We collect between 20 and 25 photoelectrons in the aerogel counters. This yield gives sufficient photostatistics for a good muon tagging efficiency of 98% at low pion misidentification rate ($\leq 10^{-3}$) over the 220-360 MeV/c momentum range.

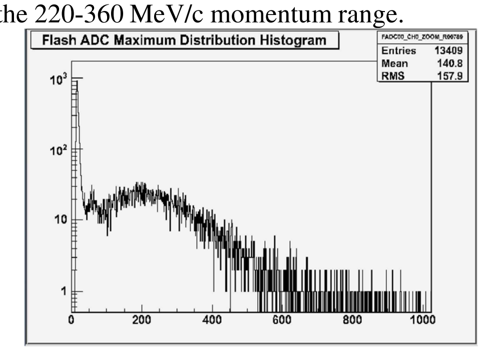

Figure 7: Typical light spectrum from single CKOV PMT, about 5-6 p.e. per channel $\times$ 4 .

KLOE LIGHT + ELECTRON-MUON RANGER

The downstream calorimeter (EMCAL) is a Pb-scintillating fiber calorimeter (KL), of the KLOE type [12], [13], with 1-mm diameter blue scintillating fibers glued between 0.3 mm thick grooved lead plates followed by a Electron-Muon Ranger (EMR), made of higly segmented 70 cm long fully active scintilators. The combination of both detectors will provide the final clean muon tag veto $\mu^+ \rightarrow e^+\overline{\nu_e}\nu_\mu$ decays at the 10^{-2} level. EMCAL system offers adequate energy resolution to perform muon and electron identification in the momentum range of interest for MICE.

KL The KL preshower calorimeter is constructed of 0.3mm grooved Pb with BF12 scintillating fiber inlay in a KLOE-type layout. The original KLOE design represents 2.5 X_0 in depth, a 4 cm thick active depth. It has an energy resolution for electrons of $\Delta E/E(GeV = 7\%/\sqrt{(E(GeV))}$, and timing resolution of Δ_t = 70 ps / $\sqrt{E}$. The KL was commissioned in fall 2008 MICE run. Below we show a scan with 300 MeV/c pion beam into the calorimeter. The ionizing response shown in Figure 8 was nominally what is expected. Further calibrating exposures to electron beam are planned for fall 2009.

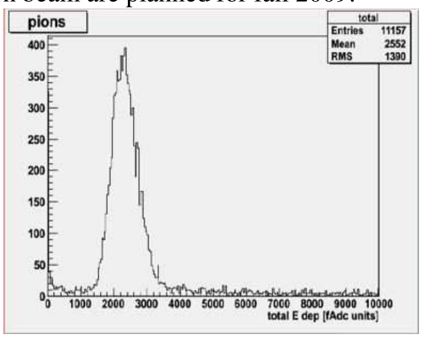

Figure 8: KL response to 300 MeV/c pion beam. The horizontal scale is in ADC channels.

EMR The EMR is currently under construction for MICE and utilizes a MINERνA-like design [14]. It will consist of 40 layers of 59 extruded scintillator bars with a triangular shape (Figure 9). Each bar is interfaced with a multianode PMT through WLS fibers (4 with a diameter of 0.8 mm); in total there will be 32 64-channel PMTs (Hamamatsu, H7645B) and 2 256-channel PMTs (Hamamatsu, H9500) to obtain an indication on the charge deposit in each layer, the analog signal of each PMT dynode will be digitized with a CAEN V1731; this will require 3 digitizers for the whole detector. With the foreseen electronics it is not possible to obtain the analog information of every bar without introducing dead time. The front-end electronics will allow to obtain a digital information for every bar, that is the time when the bar signal is over threshold. The system will not work in self triggering mode; the trigger will be given by an external detector (e.g. TOF0) or by the machine itself (the so-called "MICE spill gate") Simulations show that MICE can achieve a longitudinal momentum resolution of $\sigma_{P_z} \approx 4$ MeV/c for muons under 270 MeV/c, which range out in the calorimeter. See Figure 10. The error of this momentum is complementary to the MICE tracker measurement.

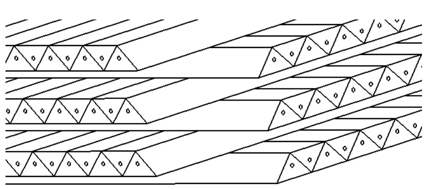

Figure 9: Sketch of MINERνA-like EMR calorimeter design to be used in MICE.

CONCLUSIONS

Muon cooling is necessary for building a neutrino factory. MICE, The Muon Ionization Cooling Experiment, based at RAL, UK will try to achieve a transversal cooling of a muon beam in the range 140 to 240 MeV/c. To reduce the systematics in the measurement of the cooling effect, a combination of PID detectors was designed and manufactured. Two Time-of-Flight detectors, two Aerogel Cerenkov detectors and a KLOE-like calorimeter were already installed and commissioned along the MICE beamline. Third Time-of-Flight detector as well as the second part of the EMCAL system - the Electron-Muon Ranger will be installed in the next year.

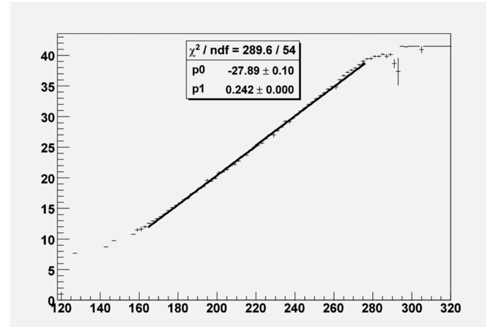

Figure 10: Muon range simulation in the EMR. $\sum E$ vs Layer # is plotted. The horizontal axis is in MeV/c. Muons above $\tilde{2}70$ MeV/c will range through.

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