The Particle Identification System for the MICE Beamline Characterization

Antonio de Bari[1]

Sezione INFN Pavia
Dipartimento di Fisica, Università di Pavia, Pavia

Abstract

The International Muon Ionization Cooling Experiment (MICE) will carry out a systematic investigation of ionization cooling of a muon beam, for the future Neutrino Factory and the Muon Collider. As the emittance measurement will be done on a particle-by-particle basis, a sophisticated beam instrumentation is needed to measure both particle coordinates and timing vs RF in a harsh environment due to high particle rates, fringe magnetic fields and RF backgrounds. A PID system, based on three x/y time-of-flight stations (with resolutions around 50 ps), two Aerogel Cerenkov counters and a KLOE-like calorimeter (KL) has been constructed and has allowed the commissioning of the MICE muon beamline. PID detector performances will be shown and their use for a preliminary estimate of the beamline emittance and the MICE muon beam pion contamination will be illustrated.

Keywords: Ionization cooling, muon beams, neutrino factory, particle detectors
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1. Introduction

The proposed neutrino factory [1, 2] is a muon storage ring with long straight sections, where decaying muons produce collimated neutrino beams of high intensity and well defined composition, with no uncertainties in the spectrum and flux from hadronic production [3]. The cooling of muons will increase the neutrino factory performance and reduce the muon beam emittance up to a factor 2.4 (as described in reference [4] with a cooling section 75 m long) [2]. A neutrino factory will be the most efficient tool to probe the neutrino sector and observe CP violation in leptons.

The MICE experiment [5] at RAL aims at a systematic study of a section of the cooling channel of the proposed US Study 2 [6], attaining a 10% effect for a 6π·mm rad beam. The 5.5 m long cooling section consists of three liquid hydrogen absorbers and eight 201 MHz RF cavities encircled by lattice solenoids. As conventional emittance measurement techniques, based on profile monitors, reach barely a $\sim$ 10% precision, a novel method based on single particle measurements has been proposed. For each particle x, y, t, p_x, p_y, E coordinates are measured. In this way, the input and output beam emittances may be determined with a precision up to 0.1%, that allows a sensible extrapolation of the results to the full cooling channel. The experiment will be done in several steps, of which the first one (STEP I) is the characterization of the beamline [7].

[1]On behalf of the MICE collaboration

[2]by contrast, cooling requirements for a muon collider are much more demanding, requiring cooling factors up to 10^6

2. The MICE beamline and its instrumentation

The secondary muon beam from ISIS (140-240 MeV/c central momentum, tunable between $3 - 10\pi\cdot$ mm rad input emittance) enters the MICE cooling section after a Pb diffuser of adjustable thickness (see figure 1 for details). Muons originate from π decay inside a 5 m long superconducting (SC) solenoid upstream of the first particle identification (PID) detectors. A sketch of the present MICE beamline, with detectors installed for STEP I, is shown in figure 2.

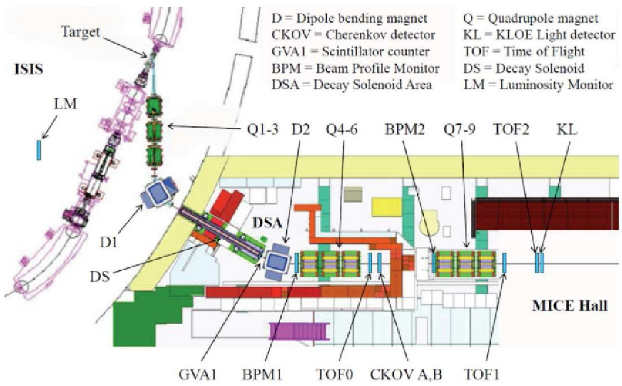

Figure 2: Sketch of the present MICE beamline, with installed detectors for STEPI.

The driving design criteria for MICE beamline detectors are robustness, in particular of the trackers, to sustain the severe background conditions near the RF cavities and redundancy in PID in order to keep beam contaminations (e, π) well below 1% and reduce systematics on the emittance measurements.

PID is obtained upstream of the first tracking solenoid by two

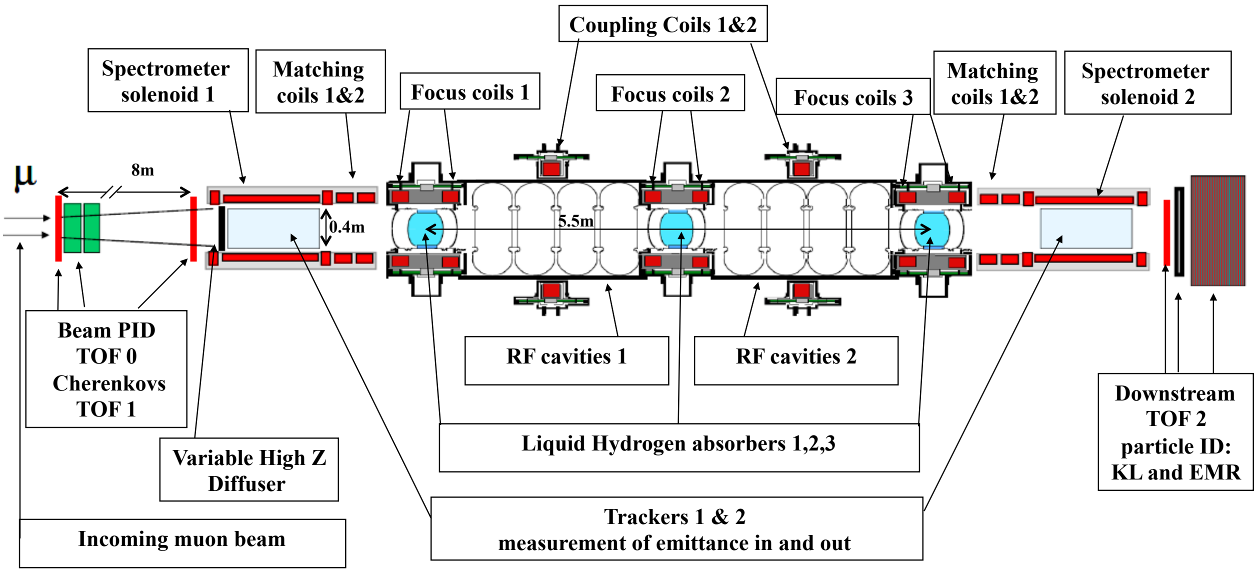

Figure 1: View of the MICE experiment at RAL. The muon beam from ISIS enters from the left. The cooling channel is put between two magnetic spectrometers and two TOF stations (TOF1 and TOF2) to measure particle parameters.

	$P^{th}\mu$(MeV/c)	$P^{th}\pi$(MeV/c)
Aerogel 1.12	210	277
Aerogel 1.07	278	367

Table 1: Aerogel refractive index and momentum thresholds for Ckova/Ckovb

TOF stations (TOF0/TOF1) [8] and two threshold Cerenkov counters (CKOVa/CKOVb) [9].

Each of the two Cherenkov counters employs a different high density aerogel, one with a refractive index equal to 1.12 and the other 1.07. These two counters were chosen with momentum thresholds to provide π/μ separation up to 365 MeV/c (see Table 1). Four 8 inch EMI 9356KB PMTs collect the Cherenkov light in each counter. A very fast sampling digitizer, a CAEN V1731 (1 GS/s maximum sampling rate), is directly connected to the PMTs through a coaxial cable, due to high particle rate [7].

One inch thick slab of fast plastic scintillator is the base structure of which all TOF stations are built. Bicron BC-420 scintillator was used for TOF0, BC-404 was used for TOF1 and TOF2. Each station consists of two planes of slabs with x and y orientation: TOF0(1,2) is made of 10(7,10)X and 10(7,10)Y arrays. The active areas of TOF0, TOF1 and TOF2 are 40x40 cm^2, 42x42 cm^2 and 60x60 cm^2, respectively. The scintillation light coming out of the two opposite ends of each slab is read by a Hamamatsu R4998 fast photomultiplier. Each PMT signal is

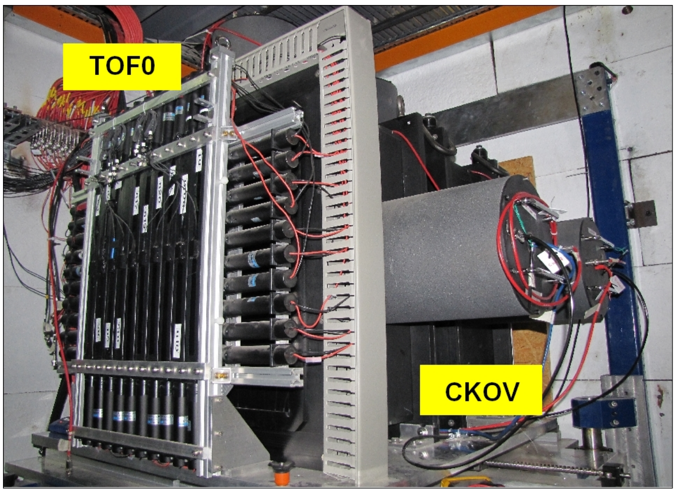

Figure 3: TOF0 and CKOV.

sent to a splitter. One part of the signal reaches a leading-edge LeCroy 4415 discriminator followed by a CAEN V1290 TDC. The other part of the signal is sent to RC shaper, followed by a sampling digitiser CAEN V1724 FADC (100 MS/s maximum sampling rate) [8].

All TOF detectors are used to determine the time coordinate (t) in the measurement of the emittance. After time-walk corrections and calibration with impinging beam particles [8], the

TOF detector timing resolution can be measured by using the time difference Δt_{xy} between the vertical and horizontal slabs in the same station (see the left panel of figure 4 for an example). The obtained resolution on the difference $\sigma_{xy} \sim 100$ ps translates into ~ 50 ps time resolution for a full TOF detector with crossed x/y slabs.

Downstream the PID is obtained via an additional TOF station (TOF2) and a calorimeter (EMCAL), made of two separate detectors (KL and EMR), to separate muons from decay electrons and undecayed pions.

KL acts as an active pre-shower to tag electrons from muon decay. KL is a lighter version of a KLOE-type sampling calorimeter and it is composed of extruded Pb foils in which scintillator fibers are placed in a volume ratio Scintillator/Pb ~ 2/1. Bicron BCF-12 is the employed fiber: it scintillates in the blue and has a diameter of 1 mm. The active volume of KL is 93x4x93 cm^3 and it is divided in seven modules. Each module is made of 3 cells, for a total of 21 cells and 42 readout channels (one at each end of each cell). The light is collected by Hamamatsu R1355 PMTs fed by E2624-11 voltage dividers wich provide differencial output pulses on twisted pair cables. The PMT signal is sent to a shaper wich matches the sampling rate of a flash ADC. The flash ADCs are the same used for the TOF stations: 14 bit CAEN V1724 [7].

Electron-Muon Ranger determines precisely the muon momentum by range measurement. EMR is an active scintillating calorimeter and tracking detector for low energy muons and electrons. It consists of 48 planes made up of 59 scintillating bars per plane. The planes are installed perpendicular to each other in an x-y arrangement and should deliver 1 m^2 active region. Using optical fibers, one side of each plane is connected to a 64 channels PMT, a Hamamatsu R6427. On the other side, the light is sent to a single channel PMT, a Philips XP 2972, to be read out by a CAEN V1731 Flash ADC. The former electronic branch is used for timing purposes while the last to recover the total energy deposited in each plane. EMR is still under construction [10].

3. The MICE beamline characterization

The characterization of the MICE beamline has been done mainly with the TOF detectors. The middle and right panels of figure 4 shows, as an example, the distribution of the time-of-flight between TOF0 and TOF1 for a high emittance muon ($\pi \to \mu$) beam and a low emittance "calibration" beam. The first peak which is present in both distributions is considered as the time-of-flight of the positrons and is used to determine the absolute value of the time in TOF1. A natural interpretation of the other two peaks is that they are due to forward flying muons from pion decay and pions themselves.

Due to a delay in the delivery of the tracking solenoids, in MICE STEPI, the beam emittance was preliminary measured with the TOF system only, using it to derive also the x, y, x', y' information for each particle and measuring p_z from the time-of-flight between TOF0 and TOF1.

Once the initial and final x, y particle coordinates are measured, the muon track through the present MICE channel (including the two Cherenkov counters, drift spaces and the last Q7, Q8, Q9 quadruplet of the STEPI MICE beamline) is estimated as $(u_1, u_1') = \mathbf{M}(p_z) \cdot (u_0, u_0')$, with $\mathbf{M}(p_z)$ transfer matrix and $u = x$ or y. The muon momentum p_z is initially estimated via the formula: $p_z = E \cdot (s/\Delta t)$, with s track length and Δt time-of-flight between TOF0 and TOF1. With a separation of ~ 7.7 m between TOF0 and TOF1, p_z may be measured with a resolution $\sigma_{p_z} = (E^2/m^2)\sigma_t/t$. For the the MICE baseline beam, with $\epsilon = 6\pi$ mm and $p_z = 200$ MeV/c, this corresponds to about 1%, giving a comparable resolution on the transfer matrix $\mathbf{M}$. An iterative procedure, based on the transfer matrix, is then used to recompute s and p_z. This procedure correct a track length bias (~ 5 MeV/c) on p_z reducing it to less than 1 MeV/c.

At this point x', y' are evaluated from the initial and final muon positions. The horizontal and vertical trace space distributions (x, x') and (y, y') are then plotted and the transverse emittances ϵ_x and ϵ_y may be computed, giving an estimation of the normalized emittance via the formula: $\epsilon_N \simeq (p_z/m)\sqrt{\epsilon_x \cdot \epsilon_y}$. Figure 4 shows the trace plots for the MICE μ^- baseline beam, with $\epsilon = 6\pi$ mm and $p_z = 200$ MeV/c, for both experimental data and MC simulation. Even if the agreement is not perfect, the beam occupies the desired regions in the trace space. All beams show an RMS beam size of the order of 5-7 cm. The method allows to reconstruct beam emittances at a few per-cent level.

4. Conclusions

The fist step of MICE, corresponding to characterize the incoming muon beam, has been accomplished. Detector performances are compatible with requirements and a preliminary measure of emittance, with TOF only, has been realized.

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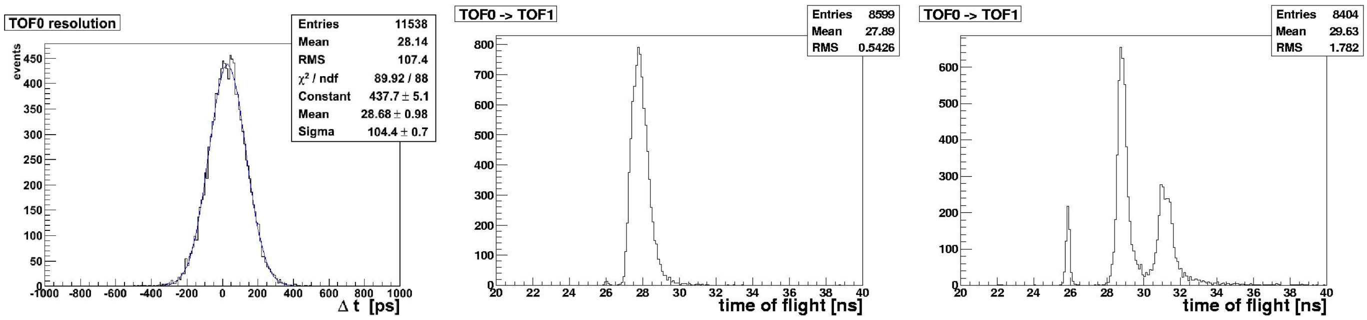

Figure 4: Left panel: time difference Δt_{xy} between vertical and horizontal slabs in TOF0. Middle and left panels: time of flight between TOF0 and TOF1 for a muon beam and a calibration beam.

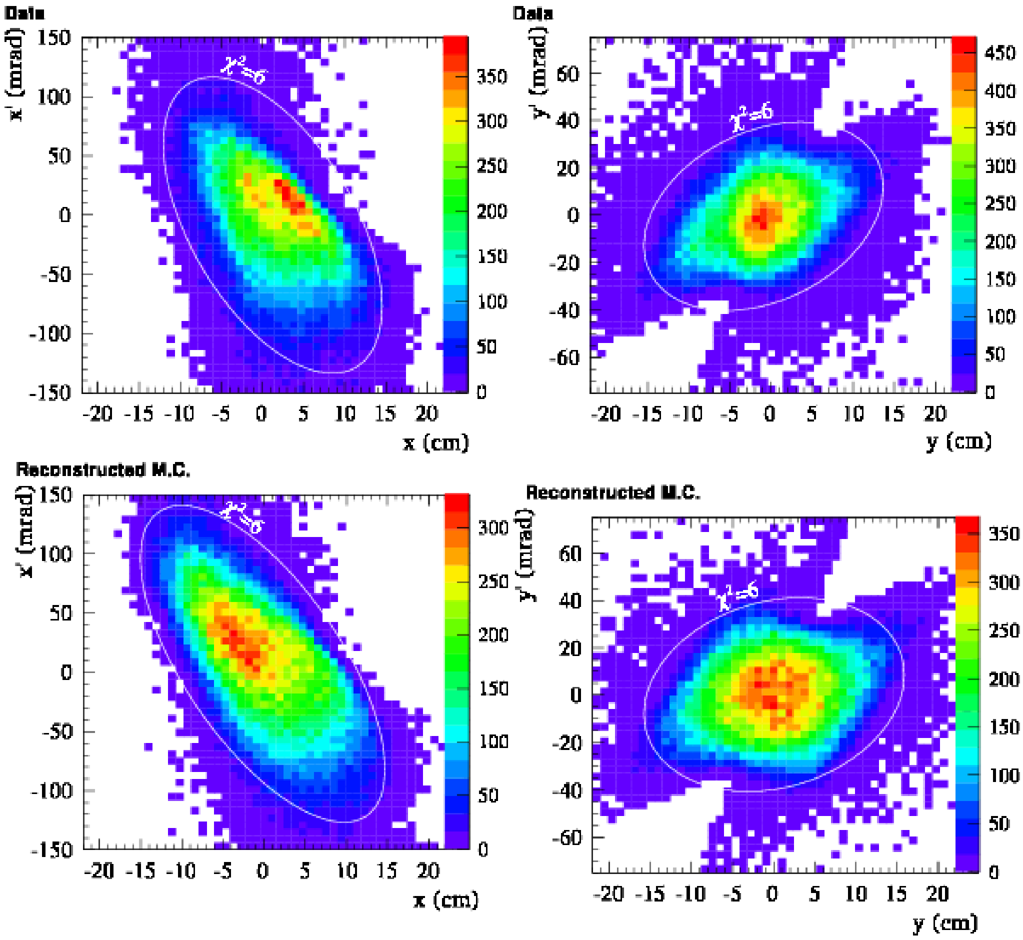

Figure 5: Reconstructed data (top) and simulation (bottom) horizontal (x) and vertical (y) trace plots at TOF1 for the baseline MICE μ^- beam $\epsilon = 6\pi$ mm and $p_z = 200$ MeV/c.