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The MICE beamline instrumentation for a precise emittance measurement

MAURIZIO BONESINI*
Sezione INFN Milano Bicocca
E-mail: maurizio.bonesini@mib.infn.it
(on behalf of the MICE Collaboration)

The international Muon Ionization Cooling Experiment (MICE) will perform a systematic investigation of ionization cooling of a muon beam. The demonstration comprises one cell of the neutrino factory cooling channel. As the emittance measurement will be done on a particle-by-particle basis, sophisticated beam instrumentation is needed to measure particle coordinates and timing vs RF. A PID system has been constructed and installed at RAL, in order to keep beam contamination (e,π) well below 1%. The muon beamline has been characterized, obtaining μ^+ rates up to ~ 30 good muons per ISIS spill.

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*Speaker.

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The MICE experiment [1] at RAL aims at a systematic study of a section of the cooling channel of the proposed US Study 2 design for a neutrino factory [2], attaining a $\sim 10\%$ 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

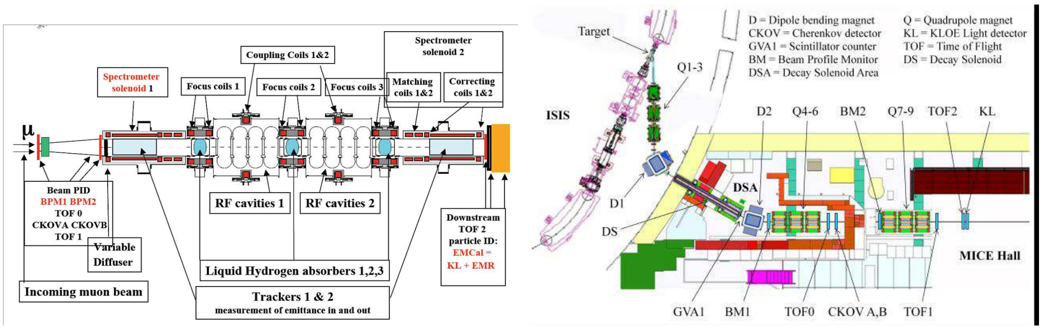

Figure 1: Right: view of the MICE experiment at RAL. The muon beam from ISIS enters from the left. The cooling channel is put between two magnetic spectrometers and two TOF stations (TOF1 and TOF2) to measure particle parameters. Left: sketch of the present beamline for STEP I. Only installed detectors are shown.

techniques reach barely a $\sim 10\%$ precision, a novel method based on single particle measurements has been used. Particles are measured before and after the cooling section by two magnetic spectrometers complemented by TOF detectors. For each particle x,y,t,p_x,p_y, E coordinates are measured. In this way, for an ensemble of N ($\sim 10^6$) particles, the input and output 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 six steps, of which the first one (STEP I) is the characterization of the beamline.

1. THE MICE DETECTOR SYSTEM

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 the left panel of figure 1 for details). Muons originate from π decay inside a 5 m long SC solenoid upstream of the first PID detectors.

PID is obtained upstream of the first tracking solenoid by two TOF stations (TOF0/TOF1) [3] and two threshold Cerenkov counters (CKOVa/CKOVb) [4], that will provide π/μ separation up to 365 MeV/c. A sketch of the present MICE beamline is shown in the right panel of figure 1. Downstream the PID is obtained via an additional TOF station (TOF2) and a calorimeter (EMCAL), to separate muons from decay electrons and undecayed pions. TOF detectors are used to determine the time coordinate (t) in the measurement of the emittance.

All the TOF stations share a common design based on fast 1" scintillator counters along the x/y directions (to increase measurement redundancy) read at both edges by conventional R4998 Hamamatsu photomultipliers [1]. TOF0 planes cover a 40×40 cm^2 active area and TOF1 and TOF2

[1] 1" linear focussed PMTs, typical gain $G \sim 5.7\times 10^6$ at B=0 Gauss, risetime 0.7 ns, TTS $\sim$ 160ps

cover respectively a 42×42 cm^2 and 60×60 cm^2 active area. The counter width is 4 cm in TOF0 and 6 cm in the following ones. The TOF stations must sustain a high incoming particle rate (up to 1.5 MHz for TOF0). R4998 PMT rate capabilities were tested in the laboratory with a dedicated setup based on a fast laser. The rate capability was increased by the use of an active base.

The PMT signals, after a splitter, are sent to a fast CAEN V1290 TDC, following a Lecroy 4415 leading edge discriminator, for time measurements and are digitized by a CAEN V1724 FADC [2] to give the pulse height for the time-walk correction.

The downstream calorimeter (EMCAL) is not intended to be used for energy measurement: its main goal is to provide separation between μ and decay electrons. In addition it should be able to separate μ from π. It consists of a Pb-scintillating fiber calorimeter (KL), of the KLOE type [5], with 1-mm diameter blue scintillating fibers glued between 0.3 mm thick grooved lead plates followed by an electron-muon ranger (EMR), made of a $\sim 1m^3$ fully sensitive segmented scintillator block.

The PID detectors have been installed in steps in the MICE Hall at RAL in 2008 and 2009. They have performances compatible with requirements. After time-walk corrections and the calibration procedure with impinging beam particles (see reference [3] for details), 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-hand panel of figure 2). The obtained resolution on the difference is $\sigma_{xy} \sim 100$ ps for TOF0 and TOF2, $\sigma_{xy} \sim 120$ ps for TOF2 [3]. Resolutions are compatible in the TOF0 detector (4 cm wide slabs) and the TOF2 detector (6 cm wide slabs), showing that path length fluctuations effects are negligible. A hint on the intrinsic stability of TOF detectors is shown in the right-hand panel of figure 2. The transverse impact position of a particle on a TOF

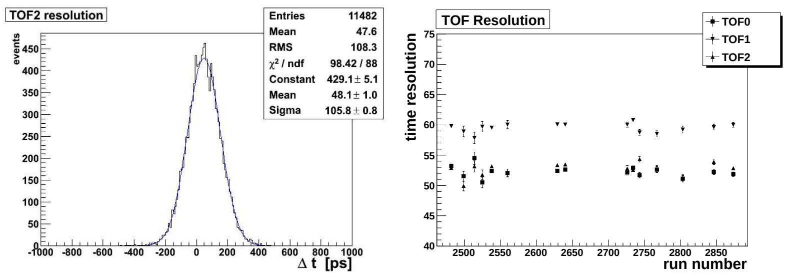

Figure 2: Left panel: time difference Δt_{xy} between vertical and horizontal slabs in TOF2; right panel: stability of the time resolution vs run number (the elapsed time is about one month). Trigger is on TOF1.

station may be reconstructed from the difference of the PMT's time measurement at the ends of a scintillation counter with a resolution better than 1 cm.

2. BEAMLINE CHARACTERISATION

The beamline has been characterized mainly by the use of the TOF system. Figure 3 shows, as an example, the distribution of the time-of-flight between TOF0 and TOF2 for a high emittance

[2] the same ADC is used also for the KL calorimeter readout

[3] This translates into $\sim 50(60)ps$ resolution for the full TOF0/TOF2 (TOF1) detector with crossed horizontal and vertical slabs. The worse resolution of TOF1 is probably due to the poorer quality of the PMTs used.

muon ($\pi \to \mu$) beam, that will be used to demonstrate μ cooling, 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 TOF2. A natural interpretation of the other two peaks is that they are due to forward flying μ from π decay and π themselves.

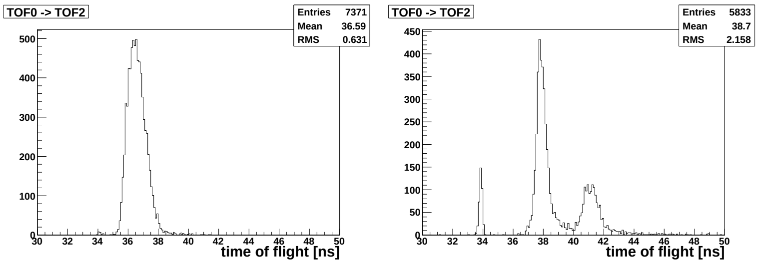

Figure 3: Time of flight between TOF0 and TOF2 for the muon and calibration beams.

Using TOF identification, it was possible to determine the muon rate for the $\pi \to \mu$ beam as a function of target dip into the ISIS beam (measured as beam loss in $V \cdot ms$). This is shown in figure 4. Up to 30 (6) good muons were obtained for the positive (negative) beam with a pion background of $\sim 3-5\%$ ($\sim 1\%$) as preliminarily estimated by MC simulations.

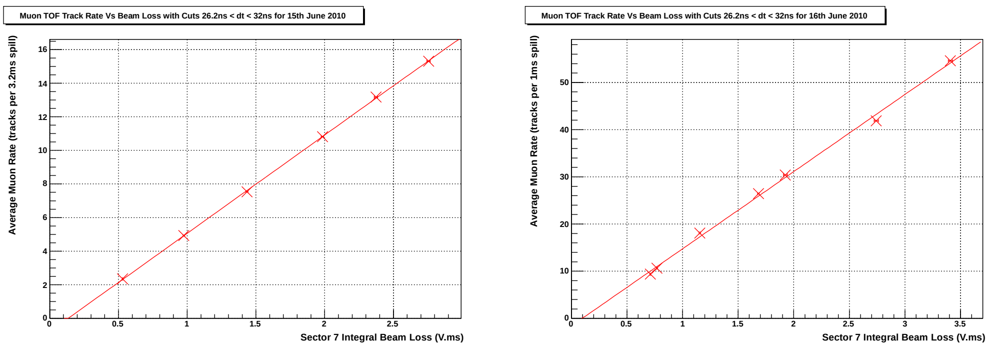

Figure 4: Average muon TOF track rate per spill as a function of induced ISIS beam loss for a negative $\pi \to \mu$ beam, with a 3.2 ms spill gate (left), and for a positive $\pi \to \mu$ beam, with a 1 ms spill gate (right).

The TOF detectors alone have also been used for a preliminary estimate of the emittance in the MICE beam, see [6] for more details.

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