PARTICLE PRODUCTION IN THE MICE BEAM LINE*

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Abstract

The MICE experiment aims at demonstrating that the performances of the muon ionization technique are compatible with the requirements of the neutrino factory and the muon collider. The experiment is running at the Rutherford-Appleton Laboratory in the UK using the ISIS proton beam on a dynamic target as a muon source. New target system and muon beam line have been designed, built and installed during the last two years. In parallel, particle identification detectors needed for the experiment were installed and commissioned. This paper describes how we made use of Time of Flight detectors and aerogel Cherenkov counters to characterize the content of the MICE beam between 100 and 480 MeV/c.

INTRODUCTION

The MICE experiment [1] is part of the R&D programme towards a neutrino factory broadly considered as the most precise option to probe neutrino physics in the future. In a neutrino factory an intense neutrino beam is produced from a high energy muon storage ring.

The cooling of muon beam is essentially unexplored and is a major source of uncertainty on the cost and construction time of a neutrino factory. MICE has been designed to demonstrate that it is possible to engineer, build and operate safely and reliably a realistic section of linear muon ionization cooling channel similar to the one proposed in the US Feasibility Studies [2].

The experiment consists in placing one cell of a solenoidal cooling channel lattice in between two spectrometers measuring precisely the emittance of upstream and downstream beams. Such a setup allows direct measurement of the cooling performances in various operation modes and muon beam conditions. Moreover, detailed comparison with simulations will also provide a validated design tool for future optimization of a Neutrino Factory acceleration scheme.

MICE GENERAL LAYOUT

MICE is hosted at the Rutherford Appleton Laboratory (RAL), Oxfordshire, UK. A completely new muon beam line is under construction on the ISIS proton synchrotron (800 MeV, 200 μA). The beam line components are shown on Figure 1 and detailed in [3]. A short description is given below.

The Target System

A dedicated target system has been designed [4] to dip a Ti target into the halo of the beam in the few milliseconds preceding the extraction of the primary protons with the constraint that it must be completely out of the way when the injection of the next ISIS bunch starts. The required acceleration of 80*g* m/s^2 has been achieved with a target attached to a diamond-like carbon coated shaft driven by induction coils.

Pion Collection and decay

The pions produced by the collision of the protons on the target and the scattered protons are captured by a triplet of quadrupoles, followed by a dipole selecting the upstream momentum P_{up}. The pions then decay in a 5 m long, 12 cm bore, supra-conducting solenoid normally working at 5 T. Unfortunately, technical problems with the helium cooling system prevented us from turning the decay solenoid on, causing a dramatic reduction of the number of muons obtainable downstream.

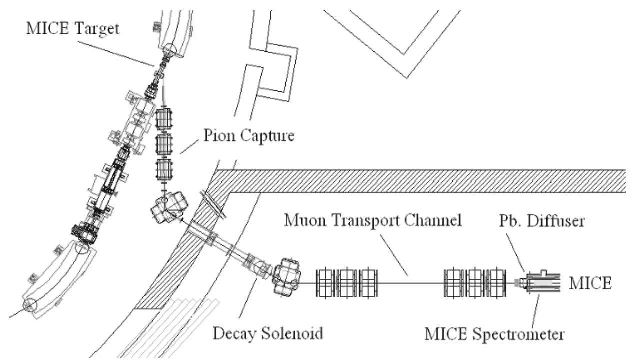

Figure 1: Schematic of the MICE beam line at ISIS, Rutherford Appleton Laboratory, UK.

Beam optics

After the decay solenoid, a second dipole selects downstream momentum P_d. Muons from pion decay have a momentum between ~$P_{up}/2$ (muons decaying backward) and ~ P_{up} (forward muons). Setting $P_d = P_{up}/2$ ensures a very large reduction of the pion content in the muon beam. Two additional triplets of quadrupoles allow efficient beam transport to the experiment. The entire beam line is designed for muon beam central momentum ranging between 140 MeV/c and 240 MeV/c with up to 500 muons traversing the apparatus per target actuation.

Detectors

MICE uses experimental particle physics techniques for the measurement of the single particle emittance of each muon traversing the cooling channel. Particle identification detectors (PID) are also necessary to separate muons from residual pions and decay electrons. The installation of the MICE components is schedules in six consecutives steps. The first step, consisting in the installation of the target and beam line magnets [5] together with the major particle identification detectors [6], has been performed in 2008. In order to commission these detectors, temporary instrumentation was installed in the beam line. Two 20x20 cm square organic

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scintillators coupled to 2" Photo-Multiplier Tubes (PMT) named GVA1 and GVA2 were placed respectively just after the decay solenoid and in between the two downstream triplets. Two out of the three Time of Flight Stations, namely TOF0 and TOF1, have been installed respectively after GVA1 and after the last triplet. Each station is a hodoscope made of 10 (TOF0) or 7 (TOF1) scintillator bars, read by PMTs at both ends, arranged in 2 perpendicular planes X and Y. This design optimizes both spatial and time resolution performances and simplifies the calibration procedure.

Two Aerogel Cherenkov Counters, with different index of refraction (1.12 and 1.07), were installed behind TOF0. They allow muon/pion/electron identification upstream. A 4 cm layer of electromagnetic calorimeter made of scintillating fibers interleaved with grooved lead sheets was also installed but it was not used for this analysis.

EXPERIMENTAL METHOD

The aim of this measurement was to understand and quantify the particle production at the MICE target, the capture process in the upstream triplets and the transport in the mice beam line. It was also used to define standard settings for the magnets providing optimized beam at different momenta. With the Decay Solenoid turned off, the expected muon rate is too low for the commissioning and the calibration of the detectors. Pions and protons beams had to be used instead. The current in the second magnet D2 was therefore set in order to have $P_d = P_{up}$. The resulting beam is a mixture of protons, pions, electrons and muons in proportions depending on the selected momentum. We have used the time of flight technique to identify the different particles in the beam. In early runs only GVA1 and GVA2 counters were installed. The time resolution was good enough to separate protons from pions up to the maximum momentum of 480 MeV/c (Figure 2).

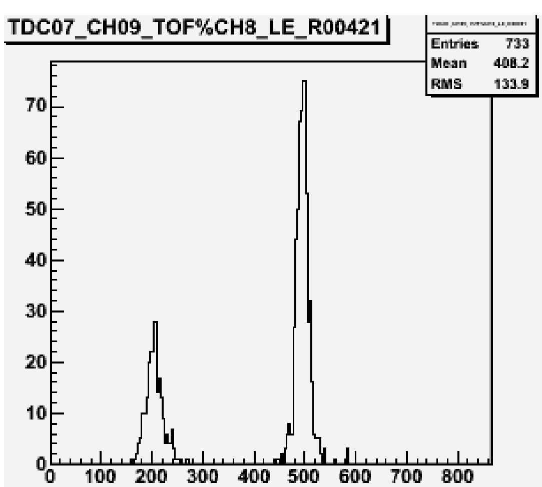

Figure 2: The first spectrum of the time of flight between GVA1 and GVA2 as it's available from the MICE online monitoring.

In later runs, the TOF stations were installed, allowing a better time resolution. However they had to be calibrated with particles of well known velocity. In order to reduce the systematic errors due to the estimation of the velocity of the particles, we searched for settings producing a pure positron beam. Indeed, positrons have a velocity very close to *c* at all the momenta considered (≥100 MeV)/c. With the positron beam, we were able to calibrate the time of flight stations and the obtained resolution was good enough to separate muons from pions.

Proton and Pion Content

Protons and Pions have different energy losses in the material along the beam line (e.g. the GVA counters, the vacuum pipe window and the Beam Profile Monitors). Therefore, they have different momenta when they arrive at D2. Moreover, below 320 MeV/c the protons are expected range out and to be stopped before D2.

For this measurement we had to turn the downstream quadrupoles OFF because they were not yet aligned. We started with a selected momentum at D1 equal to 480 MeV/c and a setting at D2 corresponding to the momentum of the protons after their travel through the upstream beam line. Then we tuned the upstream triplet in order to maximize the rate in GVA2. Eventually, we scanned the current in the second dipole D2 for different current in D1 corresponding to proton momentums equal to 414 MeV/c, 374 MeV/c and 322 MeV/c. Figure 3 shows a typical result at 414 MeV/c. At 374 MeV/c, the proton content is strongly reduced both in absolute and relative terms. At 322 MeV/c no more protons are observed while the absolute rate for pions is only reduced by a few tens of percent.

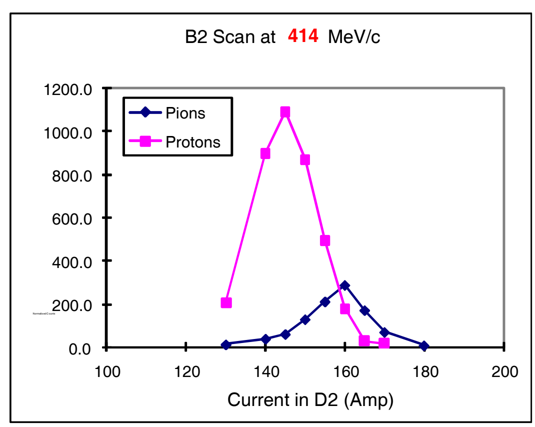

Figure 3: Relative protons and pions rate as a function of the current in the second dipole (D2) for a momentum selected in D1 equal to 414 MeV/c.

Positron and Muon Content

Starting from a 300 MeV/c pion beam defined following the method above, we reduced the fields until the momentum selected corresponds to 100 MeV/c.

At this momentum only positrons can travel through the beam line.

The GVA1 and GVA2 counters have barely enough resolution to separate electrons from pions. However, at 100 MeV/c the time of flight of the pions differs from the positrons' one by more than 13 ns. By looking at the evolution of time of flight spectra between 300 and 100 MeV/c we observed a pion peak gradually appearing and separating from the positron peak. The pion peak then disappears nearly completely at 100 MeV/c asexpected from the pion range at this momentum.

The Cherenkov counters confirm that the beam at 100 MeV/c is dominated by particles with a velocity above Cherenkov threshold. These can only be positrons.

Later, the positron beam defined by this method was used to calibrate the time of flight between the TOF stations. After this calibration, we had a closer look at the composition of the beam at 300 MeV/c. The time of flight spectrum is shown on Figure 4. Even though it was referred to as a pion beam, it appears clearly that the positron content is not negligible and, more surprisingly, that a significant part of the beam is made of muons. The shift between muon and pion peaks corresponds to the difference in time of flight at 300 MeV/c, indicating that they are mainly coming from forward pion decay in the upstream segment of the beam line. More refined analysis, including detailed simulation is in progress.

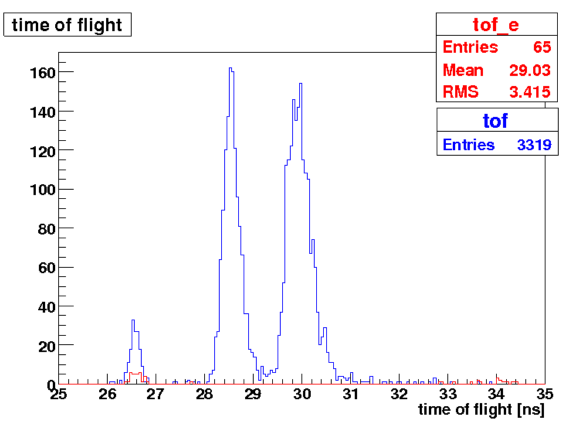

Figure 4: Time of Flight spectrum between TOF0 and TOF1 after calibration and time walk corrections. The red spectrum is obtained with the positron beam at 100 MeV/c. It is used to fix the horizontal scale. The blue spectrum is obtained at 300 MeV/c. The positron, muon and pion components are clearly separated.

SIMULATION

A full simulation of the MICE experiment has been implemented based on GEANT4. The same software framework, called G4MICE, is also used for data analysis. It allows simulation and reconstruction of all steps of MICE. It can also be used for transport optimization using a simplified version of ICOOL.

The upstream beam line is currently simulated by an independent code, also based on GEANT4, but more

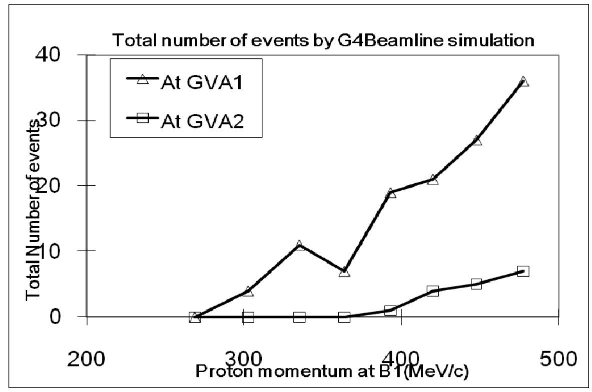

Figure 5: Relative number of expected proton counts in GVA1 and GVA2 counters as a function of the proton momentum at the entrance of the first dipole.

oriented toward beam line optimization. It is called G4beamline and it is using Turtle for optimizations. This code has been used to produce the graph shown on Figure 5, confirming the observed behavior of the number of protons reaching GVA1 and GVA2 counters as a function of momentum.

CONCLUSION AND DISCUSSION

Using temporary simple scintillator counters, we have measured relative proton and pion content in the MICE beam line at ~320 MeV/c, 375 and 415 MeV/c.

As expected, proton rate drops drastically when decreasing momentum and disappears at ~320 MeV/c. With this particular layout of detectors, a good setting was established at ~320 MeV/c for producing a pure positive pion beam for further studies.

A positron beam at 100 MeV/c was also established by time of flight measurement confirmed by the Cherenkov counters. This beam was used to calibrate the Time of Flight between the two first MICE TOF stations. A time of flight resolution of about 70 ps was obtained and was sufficient to demonstrate the presence of significant muon content in the beam at 300 MeV/c, albeit the the absence of the field in the decay solenoid.

Only a small subset of the data has been analyzed yet and more refined analysis is under way.

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