The MICE Muon Beam Line

Marco Apollonio, for the MICE collaboration

High Energy Physics Group, Department of Physics, Imperial College London SW7 2AZ, UK

Abstract.
In the Muon Ionization Cooling Experiment (MICE) at RAL[1], muons are produced and transported in a dedicated beam line connecting the production point (target) to the cooling channel. We discuss the main features of the beamline, meant to provide muons with momenta between 140 MeV/c and 240 MeV/c and emittances up to 10 mm rad, which is accomplished by means of a diffuser. Matching procedures to the MICE cooling channel are also described. In summer 2010 we performed an intense data taking campaign to finalize the calibration of the MICE Particle Identification (PID) detectors and the understanding of the beam line, which completes the STEPI phase of MICE. We highlight the main results from these data.

Keywords: Ionization Cooling, Muon Beam, Transfer Lines, MICE
PACS: 29.20.-c

INTRODUCTION

Ionization Cooling is a key element of future machines, like the Neutrino Factory or, in a longer term perspective, the Muon Collider. In both cases some phase space compression (*cooling*) is needed prior to muon acceleration. This technique exploits the energy loss by ionization in a material, the dominant form of interaction for muons. The first realization of this idea, that dates back to several decades, is happening now at RAL. In MICE a cooling cell for the neutrino factory will be sandwiched between two identical trackers, providing a measurement of kinematic parameters and hence the emittance before and after the cell. Upstream and downstream PID detectors will complete the scheme ensuring a very high rejection of background, mainly due to electrons from decaying muons. Fig. 1 shows a top view of the MICE beam line.

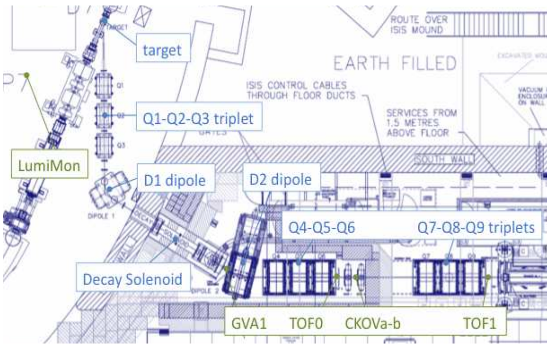

FIGURE 1. Top view of the MICE Beam Line. Magnets (blue text) and instrumentation (green) are highlighted.

[1] The Rutherford Appleton Laboratory, Chilton, Didcot (UK)

In order to test the cooling channel, a beam of muons must be produced and transported towards the aforementioned appartus: this function is provided by the MICE Muon Beam Line. This can be subdivided into three parts: a) an upstream section, where pions from hadronic interactions of protons are generated, b) a decay section, meant to collect the muons from pion decays and c) a downstream section transporting the muons towards MICE. Opposite sign beams can be produced by inverting magnet polarities.

UPSTREAM PION PRODUCTION

An oscillating titanium tube dipping into the ISIS synchrotron proton beam is used to produce pions. Dip depth and timing with respect to the ISIS beam cycle determine the secondary production rate [1]. A first triplet of quadrupoles (Q1-Q2-Q3) is placed close to the target insertion point, optimizing pion capture. This is followed by a dipole (D1) selecting the pion momentum around 410 MeV/c and directing a fraction of the initial beam towards the Decay Solenoid (DS) upstream bore (12 cm diameter). We checked the working point of the upstream section by measuring the pion rate as a function of the first triplet current. A scintillator counter (GVA1) placed after the decay solenoid monitors the rate due to charged particles. Fig. 2-right shows the variation of particle rate as a function of the first triplet excitation. The coloured bands represent rates with the associated statistical errors. All the counts in the GVA1 detector are normalized with respect to a reference optics. Data are represented by a red band. Two simulations are displayed too, which depend on the effective length of the quadrupoles introduced in the model. The green band refers to the nominal L_{eff} = 853.4 mm from the original specifications

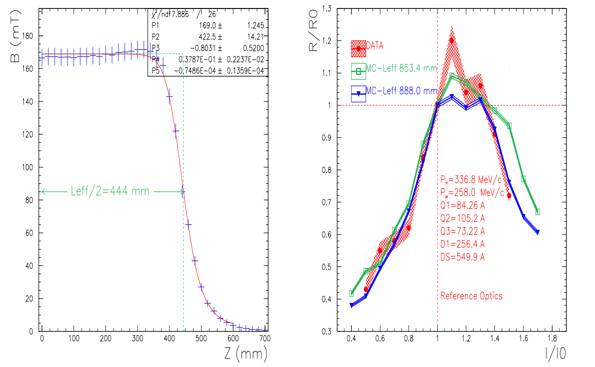

FIGURE 2. Left: measurement of Q1 effective length. Right: rate of charged particles recorded in the GVA1 scintillator. Data (red band) is compared to simulation with an effective length of 854 mm from the nominal specifications (green band) and of 888 mm, from the measurement described in the text (blue band).

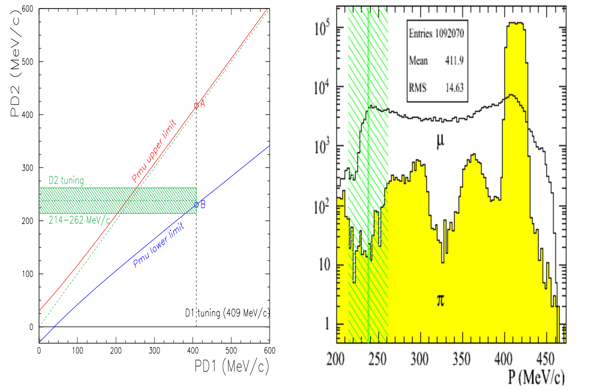

FIGURE 3. Working principle of the MICE Beam Line: (left) the red and blue lines are the kinematic limits of the spectrum for muons produced in pion decays. By tuning D2 to the backward going muon peak an almost pion-free sample is produced. (Right) simulation showing pion and muon spectra at the end of the decay solenoid. Only high momentum pions survive. The green band shows the acceptance of D2, when tuned to the backward-going muon peak.

of the magnets, showing a non satisfactory behaviour for high currents. In January 2010 a measurement of the quadrupole effective length was performed by sliding a hall probe into Q1 along the beam line vacuum pipe (Fig. 2-left). By fitting the measured values to an Enge function $h(s) = h_0 \cdot [1 + exp(c_0 + c_1 s + c_2 s^2)]^{-1}$ $(s = z - z_0)$[2] a new value for L_{eff} = 888.0 mm is found. The results of the simulation with this new parameter are represented by the blue band in Fig. 2-right. While we still observe a disagreement between data and simulation at I/I0=1.1, we note a better agreement on the right tail of the curve. We conclude that an increase in the first triplet current of about 15% does not influence secondary collection, however it sets the system on a more stable working point.

MUON PRODUCTION AND TRANSPORT

The beam line is optimized to capture muons from pion decays inside a super conducting solenoid (length=5 m, B_z^{MAX}=5 T). At its exit, a second dipole (D2) is tuned to select muons with a momentum about 1/2 of the original pion sample. This *backward going* muon selection is particularly effective in obtaining a pure sample, as illustrated in Fig. 3. On the left the interplay between the two dipoles is shown: the abscissa represent the pion momentum as selected in D1 with the blue and red lines showing the kinematic limits in momentum for pion decay muons. If, *e.g.*, pion momentum is selected to be 409 MeV/c, the muon momentum spectrum lies between 230 and 410 MeV/c. The plot on the right shows how D2 tuned around 240 MeV/c captures mostly muons with a less than 2% fraction of residual pions accepted within a ± 10% momentum bite. For calibration purposes the line can also be tuned to transport particles with the same momentum bite both in the upstream and downstream section. These two beam line modes are summarized in Fig. 4 where the distribution of times of flight reflects the particle content of the beam line in the two cases.

(ε_N, P) MATRIX

Ionization Cooling will be tested for a variety of initial momenta and emittances of the muon beam, ideally covering every configuration used in a Neutrino Factory. A practical approach to sample this (ε_N, p) space consists in its discretization, which produces a matrix of 9 elements (see Table 1). Each of these points corresponds to an optics for MICE which requires a matching of the beam line at the entrance of the MICE channel where a layer of material (diffuser) produces the correct emittance inflation. For each of the 9 matrix elements the Twiss parameters at the upstream face of the diffuser, the momentum and the diffuser thickness are given. The optimization of the downstream section of the beamline proceeds then in two steps: a) we simply scale the central optics [3] to the momenta given in Tab. 1, b) we tune the last 6 quadrupoles in order to produce the right Twiss parameters at the diffuser. Step (a) produces a so called M0-matrix of optics, step (b) generates the properly matched M1-matrix (see [4] for details). During summer 2010 runs have been taken covering the M0 nine points and six points of the M1 matrix.

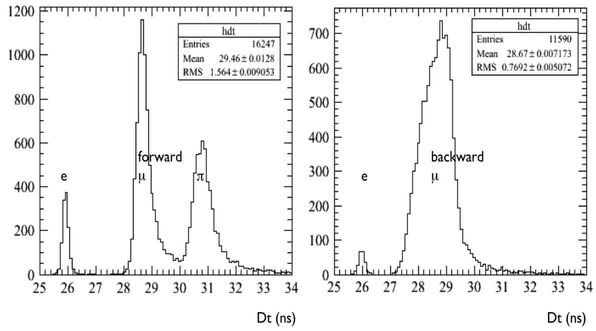

FIGURE 4. Time of flight distributions for two modes of beam line operation. (Left) single momentum mode with three particle species (e, mu, pi). (Right) dual momentum mode: only muons are effectively transported (with a tiny electron fraction easily cut off).

TABLE 1. (ε_N, p_z) matrix for the MICE programme. Each square represents an optics and contains the Twiss parameters at the upstream face of the diffuser for a matched configuration with the cooling channel (dark grey). Diffuser thickness (for lead) and momentum at its upstream edge are also shown (pale grey).

		p_z (MeV/c)		
		140	200	240
ε_N (mm·rad)	3	t=0.0 mm	t=0.0 mm	t=0.0 mm
		P_{dif}=151	P_{dif}=207	P_{dif}=245
		α=0.2	α=0.1	α=0.1
		β=56 cm	β=36 cm	β=42 cm
	6	t=5.0 mm	t=7.5 mm	t=7.5 mm
		P_{dif}=148	P_{dif}=215	P_{dif}=256
		α=0.3	α=0.2	α=0.2
		β=113 cm	β=78 cm	β=80 cm
	10	t=10.0 mm	t=15.5 mm	t=15.5 mm
		P_{dif}=164	P_{dif}=229	P_{dif}=267
		α=0.6	α=0.4	α=0.3
		β=198 cm	β=131 cm	β=129 cm

DATA TAKING CAMPAIGN

MICE Step I phase consists in the commissioning of the beam line including the understanding of its lattice and the characterization of the detectors located along the line itself. While some early work of detector commissioning dates back to the end of 2009, most of the beam line measurements have been achieved in an extensive data taking campaign from June 19^{th} to August 12^{th} 2010. During this period we operated the beam line in a variety of configurations, measuring the basic properties of the beam and also testing the performance of our acquisition and monitoring system.

Thanks to their high time accuracy (50 ps per station) and segmented structure (few cm size per space point), TOF0 and TOF1 detectors are used to determine the basic beam parameters: position, size, phase space and momentum as described in [5]. Measured quantities are presently compared with our simulation in order to assess our ability at reproducing the beam line. Muon track reconstruction rate has been measured for both beam polarities for all the nine elements of the (ε_N,p) matrix. Values reported on Tab. 2 are normalized to the integrated beam losses as recorded by ISIS sector 7 beam loss monitors [1].

TABLE 2. Muon track rates for two opposite polarities in the MICE beam line. Counts are normalized to the V.ms units used to characterize the target depth. Errors are mainly due to the time of flight cuts used to define a muon (see Fig. 4).

M0		μ^- rate *			μ^+ rate		
		P_z †(MeV/c)			P_z (MeV/c)		
		140	200	240	140	200	240
ε_N ** (mm·rad)	3	4.1 ±0.2	6.3 ±0.2	4.9 ±0.2	16.8 ±1.8	33.1 ±3.2	33.0 ±2.6
	6	4.1 ±0.4	4.8 ±0.2	4.5 ±0.2	17.8 ±1.8	31.0 ±2.0	31.7 ±2.0
	10	4.6 ±0.2	5.4 ±0.2	4.4 ±0.1	21.6 ±2.2	34.0 ±2.5	26.1 ±1.5

* reconstructed muon tracks/(Vms)/(3.2 ms spill)
† momentum referred to MICE central absorber position
** emittance referred to 1^{st} spectrometer

CONCLUSIONS

Analysis of the data taken during the summer 2010 campaign is under way. Comparison with montecarlo predictions will allow to understand the beam and tune the simulation to produce new optics.

ACKNOWLEDGMENTS

We acknowledge and thank the MICE collaboration, the ISIS division at RAL and the Merit group for their invaluable help. This work was supported by the Science and Technology Facilities Council (UK).

REFERENCES

1. A. Dobbs *et al.*, “The MICE Muon Beam: Status and Progress ”, proceedings of IPAC2010, Kyoto.
2. H. A. Enge, “Effect of Extended Fringing Fields on Ion-Focusing Properties of Deflecting Magnets”, Rev. Sci. Instrum. 35, 278 (1964).
3. K. Tilley *et al.*, “Design and Expected Performance of the Muon Beam Line for the Muon Ionization Cooling Experiment”, proceedings of EPAC2006, Edinburgh.
4. M. Apollonio, M. A. Rayner, “Optimization of the MICE Muon Beam Line”, proceedings of IPAC2010, Kyoto.
5. M. A. Rayner, “The performance of the MICE beam line”,these proceedings.