OPTIMIZATION OF THE MICE MUON BEAM LINE

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Abstract

In the Muon Ionization Cooling Experiment (MICE) [1] at RAL muons are produced and transported in a dedicated beam line connecting the production point (target) to the diffuser, a mechanism inside the first spectrometer solenoid designed to inflate the initial normalized emittance up to 10 mm rad in a controlled fashion. In order to match the incoming muons to the downstream experiment, covering all the possible values of the emittance-momentum matrix, an optimization procedure has been devised which is based upon a genetic algorithm coupled to the tracking code G4Beamline. Details of beam line tuning and initial measurements are discussed.

THE MICE BEAM LINE

The beam line can be logically split into two main parts. The *Upstream Section* collects the pions produced in the interactions of the ISIS proton beam with the MICE target and transports them inside a vacuum tight pipe towards a 5T decay solenoid after a first momentum selection by a dipole. The *Downstream Section* captures the muons from pion decays inside the solenoid and transports them to the diffuser. A general layout of the beam line is displayed in Fig. 1. The beam line is complemented by a series of detectors used to count the particle rate (GVA1), monitor the beam profile (BPM 1,2) and determine the nature of the particle (TOF0,1,2 and Cherenkov a,b). Particular emphasis will be given here to GVA1 and TOF0,1 for the role they have in the present analysis.

OPTIMIZATION OF THE CHANNEL

Upstream Section

This section is constituted by one quadrupole triplet (Q1-Q2-Q3) and one dipole (D1). Pions captured in the first triplet proceed towards the first dipole where their momentum is selected, with a typical value of about 450 MeV/c. The dipole deflects the central momentum beam by 60 degrees steering the beam to the 12 cm bore of the decay solenoid. The purpose of this optimization is to increase the number of pions collected inside the solenoid where muons generated from pion decays are transported to the downstream section. One obvious way to reach this goal is by increasing the target dip depth into the ISIS proton beam. This subject is reported in [2] together with the implications on ISIS beam losses. In the present paper only the optical tuning of the beam line is investigated. Studies

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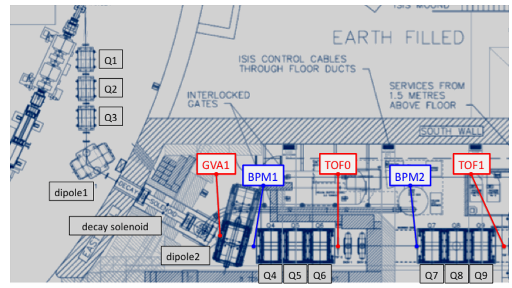

Figure 1: Top view of the MICE beam line showing the locations of the detectors used to monitor the beam.

conducted at the end of 2009 during a data-taking campaign show that the optics used was nearly at the optimal configuration while an overall 10 to 20 % increase in the triplet current would increase the rate by few percentage points. This small correction sets the working point in a more stable region. Results are summarized in Fig. 2.

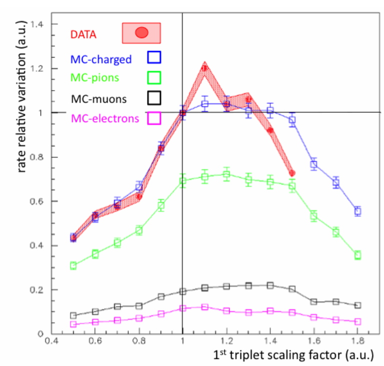

Figure 2: Relative change in charged particle rate as a function of the currents in the first quadrupole triplet. Data from the GVA1 scintillator (red band) overlap well with the total charged particle Monte Carlo predictions (blue line) made up of pions (green), muons (black) and electrons (pink).

Downstream Section

The most important scope for optimization of the beam line is in the downstream section where we aim to increase the muon rate and determine the optics to match the cooling channel. The goal of MICE is studying ionization cooling in a variety of emittances and momenta by sampling the (ϵ_N, P_z) space. This discretization produces a "matrix" represented in Table 1 [3]. For every chosen emittance and momentum inside the cooling channel, the goal is to match the beam line optics to the values reported in that table. The

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 and momentum at its upstream edge are also shown (pale grey).

ϵ_N (mm·rad)		P_z (MeV/c) 140	200	240
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

natural emittance of the muon beam from pion decays is a combination of the scraping and inflation through material encountered by the beam. According to initial beam line studies this value should be about 3 mm rad (normalized emittance). Lead discs of different thickness will be used to generate higher emittances. For every thickness a momentum at the diffuser upstream face is determined as well as the optics for the beam. Momentum tuning is accomplished by acting on the second dipole (D2) set to capture the backscattered muons from pion decays, which strongly reduces the fraction of unwanted pions in the beam. Once the momentum is defined we use the last set of quadrupoles (Q4-Q5-Q6 and Q7-Q8-Q9) to tune the optics of the beam line. The code G4Beamline [4] has been adopted to track the particles through air and detector material and realistically take into account effects of scraping due to the large size of the beam. A script launches the simulation, calculates the Twiss parameters at the diffuser entrance, changes the quadrupole gradients, and, following the prescriptions of a genetic algorithm, iterates the procedure until a good fit for the target parameters is reached [3]. With this tool we determined a first matrix for the MICE programme.

FIRST RESULTS

The completion of the (ϵ_N, P_z) matrix via a simulation code is a necessary (but not sufficient) condition to proceed with the MICE programme and a validation based on real data is desirable. The Time of Flight counters equip us with a tool to investigate the main properties of the beam, namely its momentum, emittance and Twiss parameters. During the winter of 2009 we had the first chance to take some measurements and give a first estimate of the aforementioned quantities.

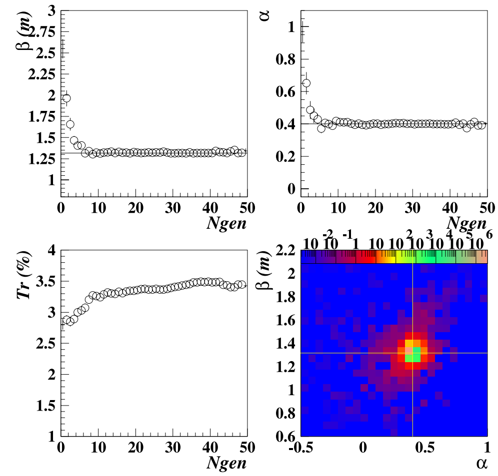

Figure 3: Downstream beam line optimization with a genetic algorithm for the (ϵ_N=10 mm rad, P_z=200 MeV/c) element of the matrix (see Table 1). $\beta_\perp$ and $\alpha_\perp$ Twiss parameters reach their target value after less than 15 iterations. Transmission stabilizes at around 3.5 %.

TOF0 and TOF1

Timing detectors TOF0,1 have recently been calibrated to a level approaching their design specification of 50 ps resolution [5]. As shown in Fig. 1, they are separated by L=8 m and a quadrupole triplet, and are located immediately prior to the diffuser. A simple calculation $P/E = L/t$ allows a momentum measurement with resolution $\sigma_P/P = (E^2/m_0^2)\sigma_t/t$, where t is the time of flight, measured typically with a resolution of 70 ps.

This momentum measurement may be used to estimate the transfer map $M(P)$ between TOF0 and TOF1. Noting that the TOFs provide a measurement of (x_0, x_1), and that by Liouville's theorem $\det M = 1$, it is possible to solve for the angles:

$$\begin{pmatrix} x_0' \\ x_1' \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix}. \quad (1)$$

Using TOF0,1 in tandem in this manner, one may directly measure time, and estimate momentum and position in trace space at either upstream station. The method may be refined by iteratively reconstructing the muon's position in phase space at TOF0, tracking its path length s to TOF1, and using the superior momentum measurement obtained from $P/E = s/t$ to more accurately estimate $M(P)$ [6]. This iteration removes a path length bias of a few MeV/c from the measurement of P_z.

The results of one such trace space reconstruction are shown in Fig. 4, which shows a comparison between Monte Carlo [7] and data of horizontal and vertical trace space at TOF1. The discrete structure of the trace space reconstructed from data is the result of the coarse measurement of position by the timing detector not designed for this purpose. Emittance, and optical parameters may be directly

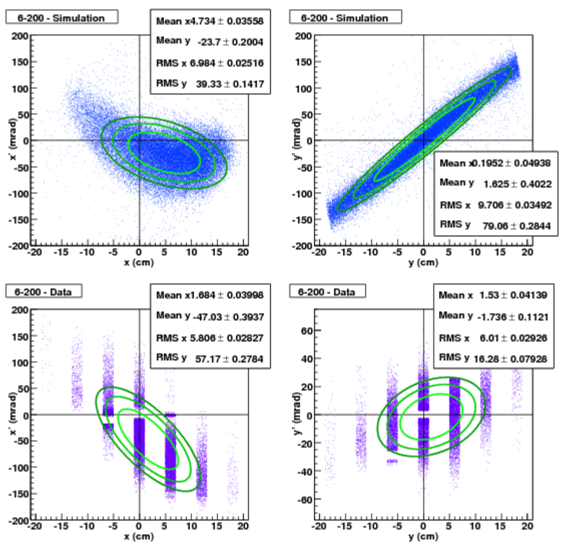

Figure 4: Comparison of trace space in simulation and reconstructed from data in December 2009 using the TOF0,1 detectors. Values refer to the upstream face of TOF1.

estimated from the covariance matrix of the reconstructed distribution in phase space; 1, 2, and 3σ RMS trace ellipses have been marked on the distributions in the figure.

Demonstrating the Momentum Emittance Matrix

Fig. 4 shows a good agreement in the trend for the two fitted distributions, however we also notice discrepancies between data and simulations that can be attributed to several reasons: (A) the spatial accuracy in TOF0,1 stations is not particularly high, (B) the Monte Carlo description of the beam line is not completely accurate. Point (A) cannot be improved any further, since the TOF counters where not designed for this task. A more precise measurement of the beam parameters is meant to be achieved with the installation of the MICE tracker-spectrometer. About point (B), a detailed comparison between the Monte Carlo and the beam line parameters still needs to be carried out. However the importance of this analysis is in the first determination of the muon beam emittance as summarized in Table 2. While we still need to develop the analysis to quote an error, we are pleased to confirm that the measured emittance of the beam is around 3.5 mm rad, a value close to the assumption made during the design of the system. An

Table 2: Beam properties measured at TOF1-upstream for two possible MICE optics.

optics (ϵ, P)	$\langle P_z \rangle$ (MeV/c)	ϵ_N (mm rad)
(6,200)	258.6	3.48
(6,140)	212.8	3.07

extrapolation of this result to the diffuser is reported in Table 3 for the (6,200) optics, where some relevant figures are highlighted (grey cells), namely the Twiss parameters $\alpha_\perp$

Table 3: Emittance and Twiss parameters at the diffuser upstream (US) and downstream (DS) faces for the (6,200) matrix element.

	ϵ_N (mm rad)	$\beta_\perp$ (cm)	$\alpha_\perp$
US-diff	4.16	113.0	0.25
DS-diff	7.98	54.7	0.13

and $\beta_\perp$ at the *upstream* face of the diffuser and the emittance at the *downstream* face. Albeit very preliminary, we notice how these values are not so unreasonably far from the desired figures from Table 1.

CONCLUSIONS

The optimization of the MICE muon beam line is the conclusive part of its commissioning. While on the upstream π-line we basically aim to increase the particle rate, the downstream μ-line should match the optics of the experiment and produce the required emittance inside MICE. A first emittance matrix has been produced and a preliminary set of measurement performed on two of its configurations. Preliminary results show that the emittance of the beam is close to the design value. Extrapolated figures for the Twiss parameters to the diffuser interface are encouraging. We are looking forward to a new campaign of mesurements and a thorough test of the (ϵ_N, P_z) matrix during the incoming summer (June to August 2010).

ACKNOWLEDGMENTS

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REFERENCES

[1] D. M. Kaplan, K. Long. "MICE: The International Muon Ionisation Cooling Experiment", arXiv:0707.1915v1 [physics.acc-ph].

[2] A. Dobbs *et al.*, "The MICE Muon Beam: Status and Progress", IPAC10, Kyoto, these proceedings.

[3] M. Apollonio, "Emittance Generation in MICE", proceedings of the 23rd Particle Accel. Conf. (PAC09), Vancouver.

[4] T. Roberts, "A Swiss Army Knife for Geant4, optimized for simulating beam lines", in `http://www.muonsinc.com/tiki-index.php`.

[5] Y. Karadzhov *et al.*, Nucl. Instr. and Meth. in Phys. Res. **A615** (2010).

[6] M. Rayner, "Muon Beam Emittance Measurement with TOF Detectors", talk at MICE Collaboration Meeting 26 (2010), `http://cm26.ucr.edu/`.

[7] M. Ellis, "MICE Software Design and Physics Performance", proceedings of the 10th ICATPP conference, (2007), Como.