EMITTANCE GENERATION IN MICE

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Abstract

The Muon Ionisation Cooling Experiment (MICE) at RAL will be the first apparatus to study muon cooling at high precision. Muons are produced along a transport beamline in a super-conducting solenoid via pion decay. The final beam emittance is generated by tuning the quadrupoles for beam size matching. The beam angular divergence is matched in a variable-thickness diffuser, which is a re-entrant mechanism inside the first solenoid, automatically changeable in few minutes from 0 to $4X_0$. The initial normalized emittance of the beam (few mm rad) will be inflated up to 10 mm rad in order to cover the (ϵ_N,P) matrix required by the experiment. Details of beamline tuning are presented.

INTRODUCTION

The MICE beamline can be sub-divided into five main elements:

- target and pion production,
- pion focussing and transport,
- muon production,
- muon steering,
- interface with MICE and emittance generation.

Protons with 800 MeV kinetic energy from the ISIS synchrotron impinge on a titanium blade [1] generating secondary pions by hadron production. A first quadrupole triplet and a dipole focus and steer these particles towards a super-conducting decay solenoid where they decay into the final muons. These are transported by a dipole and two quadruple triplets, completing the transport beamline towards the experiment [2]. The emittance from the beamline is dominated by the muon production mechanism while MICE requires a variable normalized emittance (up to 10 mm rad) for a variety of beam momenta (coverage in the(ϵ_N, P) space). The interface between the beamline and the MICE experiment is ensured by a diffuser, a lead disc used to artificially inflate the emittance of the beam by multiple scattering while providing a matched configuration with the upstream optics. The beamline and its connection to MICE are illustrated in Fig. 1.

OPTICAL MATCHING REQUIREMENTS

The matching condition inside the spectrometer solenoids ($\beta \cdot \kappa$=1, where κ[m^{-1}]=0.15$\cdot B$[T]$/P_z$[GeV/c]) defines the optics we need to reach. Propagation of the β_{4D} function back to the diffuser and through it, keeping into account the multiple scattering effects, determine the Twiss parameters on its upstream face, which have been calculated for every (ϵ_N, P) configuration required by MICE [3] and are reported in table 1. The goal of the tuning procedure is reproducing these values.

Table 1: Downstream emittances and Twiss parameters at the upstream face of the diffuser as a function of the diffuser thickness for empty and full absorber configurations and for different initial upstream momenta.

MICE Step VI: empty [full] absorbers				
t (mm)	P (MeV/c)	ϵ_{N2} (mm rad)	α_1	β_1 (cm)
1.5	142 [151]	2.9 [3.0]	0.3 [0.2]	53.9 [55.7]
5.0	148 [156]	6.1 [6.0]	0.7 [0.3]	113.1 [112.7]
10.0	156 [164]	10.8 [10.6]	1.2 [0.6]	200.7 [197.8]
0.0	200 [207]	2.6 [2.7]	0.1 [0.1]	34.3 [36.4]
7.5	211 [218]	6.0 [6.0]	0.2 [0.2]	78.0 [78.2]
15.5	222 [229]	10.1 [10.0]	0.4 [0.4]	131.7 [130.8]
0.0	240 [245]	3.5 [3.5]	0.06 [0.1]	40.8 [41.8]
7.5	250 [256]	6.9 [6.8]	0.14 [0.2]	79.6 [80.6]
15.5	262 [267]	11.0 [10.9]	0.25 [0.3]	128.2 [129.4]

MATCHING PROCEDURE

A *reference beamline* optics for MICE has been released since 2006 which corresponds to a central momentum of 207 MeV/c (past the diffuser) and a final transverse emittance of 6 mm rad [2].

Completion of the (ϵ_N,P) matrix requires a fast matching procedure capable of determining the optimal quadrupole currents. In this approach we consider the upstream part of the beamline (pion production to decay solenoid) as set and only tune the last two quadrupole triplets, Q_{4-5-6} and Q_{7-8-9}, to match $(\alpha,\beta)_{4D}$ at one or more positions along the beamline. In this study transmission is monitored but not included in the optimisation.

In the MICE beamline downstream section muons travel through matter, namely air or materials constituting the MICE Particle Identification (PId) detectors ($TOF_{0,1}$ and Čerenkov$_{a,b}$), and the beam radius is of the order of few cm. In order to model realistically these effects the code Decay-TURTLE [4] has been chosen, which tracks particles through the magnets and computes energy loss and multiple scattering effects.

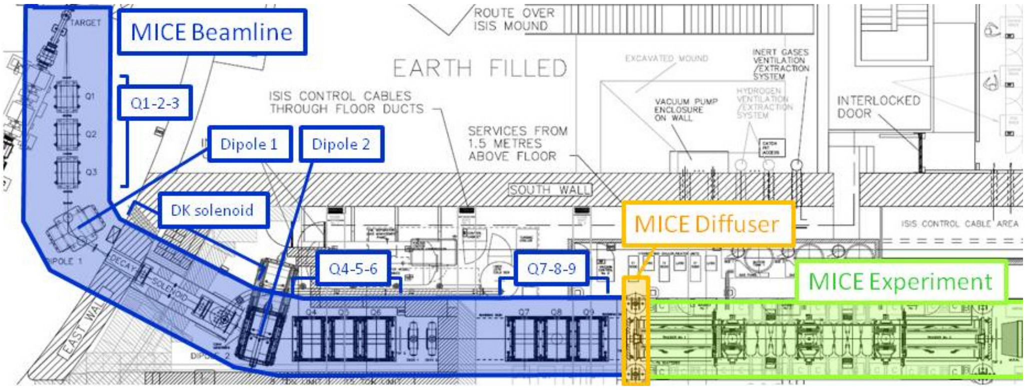

Figure 1: top view of the MICE beamline, marked in blue: clearly visible the quadrupole triplets (Q_{1-2-3}, Q_{4-5-6}, Q_{7-8-9}) and the two dipoles use to steer and select the beam momentum. The super-conducting solenoid is located between them . The green area highlights the MICE experiment, while the orange box shows the position of the diffuser.

Twiss parameters are calculated from the covariance matrix of the beam at a certain position along the line.

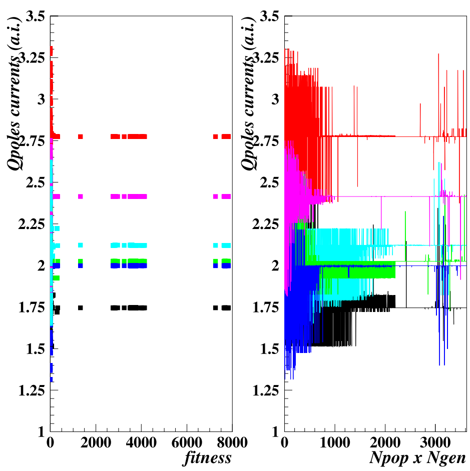

Figure 2: (left) quadrupole currents for the last two triplets as a function of the Fitness defined in eq. (1): higher values of fitness correspond to a better matching of the beamline. (right) evolution of the quadrupole currents through the number of generations: after an inital erratic behaviour currents assume stable values.This case is for a beamline with ϵ_N=10mm rad, P=207 MeV/c and t_{diff}=15.5 mm.

The PIKAIA [5] Genetic Algorithm (GA) has been chosen to optimise the values of the last six quadrupoles. While other optimisation procedures are suitable for this case, a GA is appealing for the non linear nature of the problem and the high correlation among the parameters. In the naming convention of GA's the genotype for our case is a sequence of six genes, each of which represents the current of a quadrupole. Every genotype determines a distinct optics for the beamline or a phenotype: from the Twiss parameters evaluated in one or more Z positions along the beamline a function can be calculated which defines the degree of fitness for a specific individual. The algorithm exchanges sequences of genes between pairs of individuals, creating new genotypes, discarding the cases with lower fitness and keeping those with higher ones, which eventually are the solution sought. The fitness function for our case is:

$$F^{-1}_{fitness} = \sum_{i=1}^{N} \left(\frac{\beta_i - \beta_{0i}}{\sigma_\beta} \right)^2 + \left(\frac{\alpha_i - \alpha_{0i}}{\sigma_\alpha} \right)^2 \quad (1)$$

where the suffix i denotes a position along the line, and 0 refers to the goal value for the optimisation.

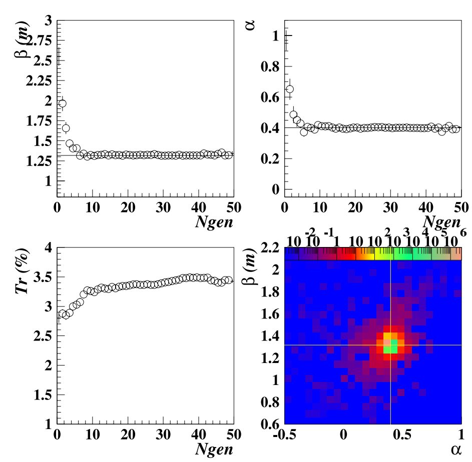

Figure 3: optimisation for the case ϵ_N=10 mm rad, P=207 MeV/c and t_{diff}=15.5 mm. Upper plots: (left) β evolution and (right) α evolution as a function of number of generations. The horizontal lines are the goal values. Lower plots: (left) transmission through the beamline as a function of number of generations. (right) β versus α computed values weighted by the fitness function of a phenotype. Brighter colors correspond to solutions with higher fitness: the lines highlight the desired matching values.

As a first test we match the beamline for the case (ϵ_N=10 mm rad, P=207 MeV/c and t_{diff}=15.5 mm).The results of the optimisation are summarized in Fig. 2 and 3.

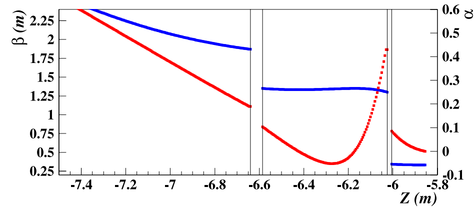

Figure 4: evolution of beta (blue) and alpha (red) functions from inside the MICE spectrometer solenoid (Z=-5500 mm) towards TOF_1 (upstream face at Z=-6585 mm). Distances refer to the nominal centre of MICE. Vertical lines show TOF_1 and Diffuser position and thickness.

Likewise a match of the case ϵ_N=6 mm rad, P=207 MeV/c and t_{diff}=7.5 mm is performed which produces very similar results. In both cases optimisation seems to reach a stable and satisfying solution with a transmission fairly constant around 3%. However one might want to consider effects of underconstraining the two constraint equations during optimisation, when one searches for six parameters. This could lead to a non well defined family of solutions, possibly generating dependency on the initial parameters. A stronger request on the final optics can be done by imposing values of (α_0,β_0) on multiple positions. An example is given when considering the case for a diffuser of 15.5 mm thickness (sixth row in table 1). In Fig. 4 the optical functions are back-propagated from the spectrometer solenoid to TOF_1 passing through the diffuser. This defines three pairs of (α_0,β_0) as given in table 2. The result

Table 2: Twiss parameters (α,β) for three positions along the beamline: upstream and downstream face of TOF_1 and upstream face of the diffuser. Momentum and diffuser thickness are 207 MeV/c and 15.5 mm (see tab. 1).

$t_{Diffuser}$=15.5 mm					
α^{US}_{TOF}	β^{US}_{TOF} (cm)	α^{DS}_{TOF}	β^{DS}_{TOF} (cm)	α^{US}_{Dif}	β^{US}_{Dif} (cm)
0.19	186.7	0.10	135.0	0.40	131.0

for an optimisation with three constraint points is shown on Fig. 5. The horizontal lines shown in the upper pictures represent the target values for (α,β) with the following color convention: black for the upstream face of the diffuser, red for the downstream face and green for the upstream face of TOF_1. It can be noticed how convergence of the Twiss parameters towards the chosen values is not so good, determining a lower fitness with respect to the single constraint case and a transmission reduced by nearly 50%. We believe this approach deserves further studies to be better understood, in particular a thorough check of the optical functions in the TOF_1 region and a careful study of the scraping effects of the magnets on the beam should be carried out.

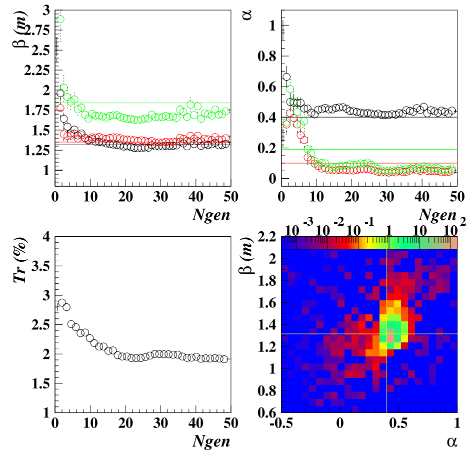

Figure 5: Same as Fig. 3 with an optics constraint in three points along the beamline (see text for color code convention). The horizontal lines represent the target values for α and β at the upstream diffuser face.

CONCLUSIONS AND FUTURE WORK

Generating the correct emittance inside MICE requires a proper matching of the optics from the beamline. The use of a Genetic Algorithm associated to a particle tracking code is described which looks promising for our purposes: in both of the studied cases the code reaches a solution in a reasonable time: 2.5 hours for an initial population of 70000 muons. The procedure is flexible enough to allow for multiple constraints on the optics. The natural progression of this work is the completion of the (ϵ_N,P) matrix as required in the MICE program: verification of the performance with high definition tracking codes (*e.g.* G4Beamline [6]) is also envisaged as a development of the present study.

REFERENCES

[1] C.N.Booth *et al.*, "Design and Operational Experience of the MICE Target", 11th European Particle Accelerator Conference (EPAC 08), Genoa, Italy, 23-27 Jun 2008, pp WEPP110.

[2] K. Tilley *et al.*, "Design and expected performance of the muon beamline for the Muon Ionisation Cooling Experiment",European Particle Accelerator Conference (EPAC 06), Edinburgh, Scotland, 26-30 Jun 2006.

[3] M.Apollonio *et al.*, "The MICE Diffuser system", 11th European Particle Accelerator Conference (EPAC 08), Genoa, Italy, 23-27 Jun 2008, pp WEPP108.

[4] D. C. Carey, K. L. Brown, Ch. Iselin, "Decay Turtle", SLAC-246, UC-28 (I/A) .

[5] P. Charbonneau, B. Knapp "A User's Guide to PIKAIA 1.0 ", NCAR/TN-418+IA, December 1995, National Centre for Atmospheric Research, Boulder, Colorado (http://www.hao.ucar.edu/Public/models/pikaia/pikaia.html).

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