MICE STEP IV OPTICS WITHOUT THE M1 COIL IN SSD*

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on behalf of the MICE collaboration

Abstract

The international Muon Ionization Cooling Experiment (MICE) will demonstrate ionization cooling, the only technique that, given the short muon lifetime, can reduce the phase-space volume occupied by a muon beam quickly enough. MICE will demonstrate cooling in two steps. In the first one, Step IV, MICE will study the multiple Coulomb scattering in liquid hydrogen (LH2) and lithium hydride (LiH). A focus coil module will provide focussing on the absorber. The transverse emittance will be measured upstream and downstream of the absorber in two spectrometer solenoids (SS). Magnetic fields generated by two match coils in the SSs allow the beam to be matched into a flat-field regions in which the tracking detectors are installed. An incident in September 2015 rendered matching coil #1 (M1D) of the downstream spectrometer inoperable. A new Step IV lattice without M1D and its optimization via a Genetic Algorithm (GA) will be described in this paper.

INTRODUCTION

A stored muon beam is capable of producing a high intensity, precisely known, flavor-pure neutrino beam, and can provide a source for a multi-TeV muon collider [1–3]. The muon beam is generated from pion decay, where the pion beam is produced by bombarding a target with a high-power proton beam. Muons generated in this way occupy a large phase space volume, which is hard to accept using traditional accelerator components. In order to increase the acceptance, the beam must be cooled before acceleration. Because of the short lifetime of muons, traditional cooling methods do not suffice. Ionization cooling, in which all components of the muon momentum are reduced when the beam passes through an absorber and, subsequently, the longitudinal momentum is restored [4]. The dependence of the normalized transverse emittance of a muon beam passing through a medium is given by:

$$\frac{d\epsilon_n}{ds} \approx -\frac{1}{\beta^2}\frac{\epsilon_n}{E_\mu}\left\langle\frac{dE}{ds}\right\rangle + \frac{1}{\beta^3}\frac{\beta_\perp(0.014\mathrm{GeV})^2}{2E_\mu m_\mu X_0} \tag{1}$$

where ϵ_n is the normalized transverse emittance, $\beta = v/c$, E_μ the energy in GeV, $\beta_\perp$ the transverse Courant-Snyder betatron function, m_μ the muon mass in GeV/c^2, and X_0 the radiation length of the material. MICE [5] will be the first experiment to demonstrate the reduction of the transverse phase space volume of a muon beam at a momentum useful for neutrino factory and muon collider applications.

Step IV of MICE will make detailed measurements of multiple Coulomb scattering and energy loss of muons in the absorber materials over a range of momenta from 140 to 240 MeV/c. The collaboration also seeks to measure transverse normalized emittance reduction in a number of lattice configurations [6]. The schematic drawing of MICE Step IV is shown in Figure 1. The phase space volume of the beam is measured in the upstream and downstream spectrometer solenoids (SSU and SSD) using scintillating-fiber (Sci-fi) trackers. Time-of-flight (TOF) detectors upstream of SSU and downstream of SSD are used for particle identification. There are twelve coils in the channel. Three coils, E-C-E, in each of the SS provide constant fields for the trackers; two coils, M1 and M2, in each of the SS provide matching into the focus coil (FC) module, and two coils in the FC module provide a final focus onto the absorber. MICE Step IV will operate in both flip and solenoid modes, where the direction of longitudinal magnetic field, B_z, flips across the absorber in flip mode and stays the same in solenoid mode. M1D failed during an incident in September 2015. Under this condition, the lattice needs to be redefined to provide an optimal environment for emittance reduction and measurement.

Most of the coil currents can be used as individual parameters to tune the beamline. This paper discusses the application of a Genetic Algorithm (GA) on multi-parameter lattice optimization based directly on multi-particle tracking in G4Beamline (G4BL) [7].

SETUP FOR BEAM SIMULATION

Simulation of a muon beam in the MICE cooling channel involves not only particle tracking in the magnetic field, but also particle decay and particle-material interactions. Therefore, G4BL with Message Passing Interface (MPI) capabilities running on the computing clusters at the National Energy Research Scientific Computing center (NERSC) was chosen to perform fast simulation of variants of the Step IV configuration. The MICE collaboration has also developed a complex Geant4 based program, MAUS [8], which includes a more detailed geometry of all the elements in the channel and therefore simulates the muon beam in the channel more realistically, and will be used as a final check of the optimized lattice configuration obtained from the G4BL analysis.

In the simulation setups, the nominal (with all coils operational) 200 MeV/c flip mode configuration was compared between the two codes. In both cases, multiparticle tracking was started with a matched beam with P_z = 200 MeV/c and ϵ_n = 6 mm, for which the transverse beta functions are calculated by $\beta_\perp = 1/\kappa$, where $\kappa = 0.15B_z[T]/p_z[GeV/c]\ m^{-1}$ [9]. A LH2 absorber with 35 cm length and 25 cm radius was used. The visualization of the cooling channel is shown in Figure 2, where the coils are shown in white and muon tracks

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* Work supported by Fermilab, Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

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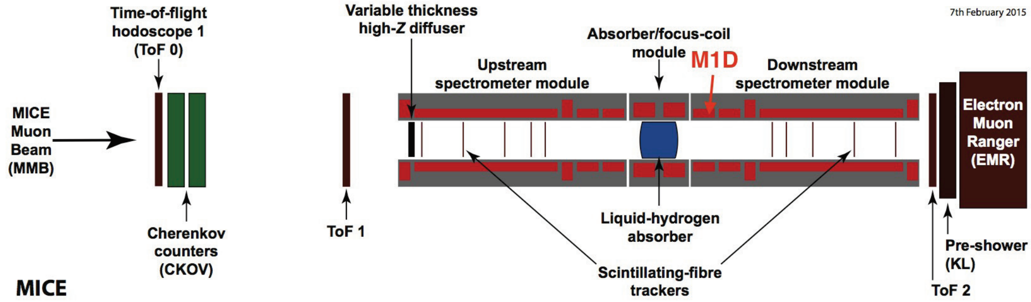

Figure 1: The schematic drawing of the MICE Step IV beamline configuration. The black cross marks the position of M1D, which will stay powered off during Step IV due to a failure in Sep. 2015.

are shown in blue. The coil currents and corresponding current density of the nominal Step IV lattice are summarized in Table 1. The RMS transverse ϵ_n, calculated from the tracked beam, are consistent in both simulation codes within error. G4BL was selected as the tracking program in the GA optimizations because of its superior speed.

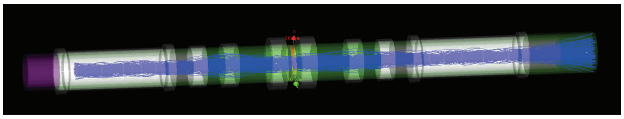

Figure 2: The visualization of multi-particle tracking of MICE Step IV nominal 200 MeV/c flip mode configuration in G4BL

Table 1: The Nominal Coil Current Density and Corresponding Current of MICE Step IV

	Current Density (A/mm^2)	Current (A)
End Coil 2	135.18	228.97
Center Coil	152.44	264.82
End Coil 1	127.37	255.50
Match Coil 2	137.13	288.27
Match Coil 1	118.56	254.05
Focus Coil	113.95	204.52
Flip at downstream	Sign Flip	Sign Flip

SETUP FOR THE GA

With a beam that is large in both transverse phase space and momentum spread, designing the Step IV lattice without M1D purely from the linear optics usually does not guarantee good transmission and a measurable emittance reduction at the same time. Therefore, the lattice design was performed directly based on the multi-particle tracking through the channel. Due to system limitations, there are 6 tunable coil current, among the 12 coils.

The Genetic Algorithm has been applied in many accelerator fields, including muon facilities [10]. The algorithm is capable of testing a wide range in parameter space to propose new generations of individual solutions that have a high probability of surpassing the older generation. In this study, the same GA module as described in [10], written in Python, was used on NERSC. The 6 genes (variables) x_1 to x_6 in this optimization are summarized in Table 2.

Table 2: The Current of Each Coil, Eontrolled by 6 Variables x_1 to x_6 in the Optimization.

	Current (A)		Current (A) solenoid	Current (A) flip
E2U	$253.23\times x_1$	FCD	x_4	$-x_4$
CU	$277.98\times x_1$	M1D	0	0
E1U	$246.2\times x_1$	M2D	x_5	x_5
M2U	x_2	E1D	$246.2\times x_6$	$246.2\times x_6$
M1U	x_3	CD	$277.98\times x_6$	$277.98\times x_6$
FCU	x_4	E2D	$253.23\times x_6$	$253.23\times x_6$

In each of the generations a number of individual lattice designs are proposed and tested. For each lattice, an initial beam with corresponding p_z and ϵ_n is generated based on the axial B_z at the beginning of the tracking, $z = -3000$ mm. After the tracking is done, the lattice is then examined by evaluating an objective function, $F = T^2\left[(\epsilon_{ref,u} - \epsilon_{ref,d})/\epsilon_{ref,u} + (\epsilon_{end,u} - \epsilon_{end,d})/\epsilon_{end,u}\right]$, where T is the transmission, ϵ is the normalized transverse emittance, ref means the reference planes at 1800 mm upstream and downstream of the absorber center, and end means the ∓ 3000 mm from the absorber center where the first and last SciFi planes are located. This objective function can guarantee a good transmission while searching for emittance reduction not only between the reference planes, but also between the upstream and downstream tracker stations. Designs that result in less than 90% transmission will be disfavored and eventually removed.

OPTIMIZATION RESULTS AND CONCLUSIONS

The above algorithm was applied to look for the optimized lattice design for both flip and solenoid modes at 140, 200 and 240 MeV/c. The optimized beta functions and normalized emittance versus the longitudinal coordinate z for flip mode at 200 MeV/c are plotted in Figure 3 as an example.

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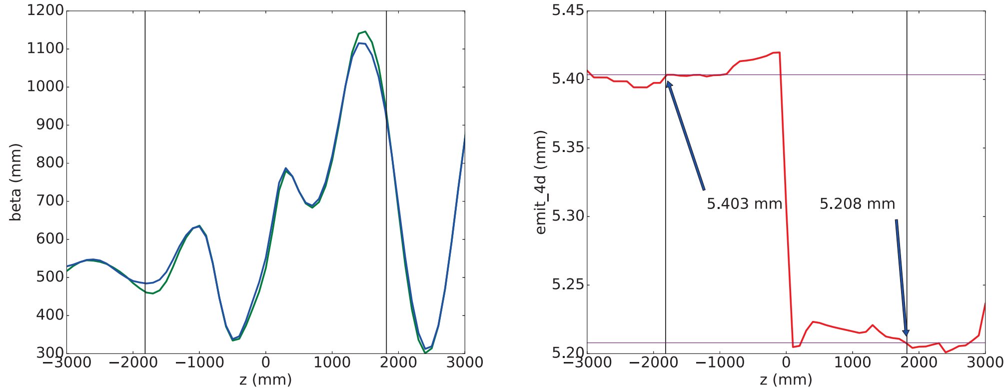

Figure 3: The betatron function (β_x in blue and β_y in green) and normalized emittance versus the longitudinal coordinate z for 200 MeV/c flip mode. Only the "good muons" (ones that can survive to TOF2) are included in the emittance calculation. The two vertical lines mark the locations of the two reference planes. The transmission in this case is 93% and the ϵ_n reduction is 3.7%.

Table 3: The Optimum Variable Values Found by the GA for Each Scenario

variable	flip, 140	flip, 200	flip, 240	sol, 140	sol, 200	sol, 240
x_1	0.64	0.63	0.80	0.75	0.72	0.89
x_2	116.40	231.91	251.62	241.14	219.81	222.69
x_3	133.01	268.11	150.98	225.42	162.66	146.06
x_4	181.21	184.73	126.80	53.52	55.95	64.09
x_5	-205.95	-234.35	-244.00	147.05	205.66	161.48
x_6	-0.71	-0.51	-0.70	0.51	0.51	0.70
$\Delta\epsilon/\epsilon_i$	-7.7%	-3.7%	-2.2%	-2.2%	-2.8%	-2.3%
T	93%	93%	90%	91%	92%	90%

The values of $x_1 ... x_6$ and optimization results are summarized in Table 3.

For all the configurations without M1D, solutions were found to yield at least 90% transmission through the channel, with an emittance reduction of several percent. The optimization results indicate that MICE Step IV is capable of demonstrating normalized transverse emittance reduction through the cooling channel, even with the one non-functioning coil.

ACKNOWLEDGMENT

The authors thank Dr. Pavel Snopok for providing original G4BL files, Dr. Chris Rogers for providing magnet settings, Dr. Alan Bross, Dr. David Neuffer and MICE collaborators for their support from numerous discussions. This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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