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# The Physics Program of MICE Step IV

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**Abstract**

The Muon Ionization Cooling Experiment (MICE) is progressing towards a demonstration of the cooling technology required for the Neutrino Factory and the Muon Collider. MICE Step IV will allow the cooling properties of liquid hydrogen and lithium hydride to be studied in detail and provide the first opportunity to observe the reduction of normalized transverse emittance using ionization cooling. Absorbers sited within a superconducting focus-coil magnet will cause the muon beam to lose energy. The muon-beam phase space upstream and downstream of the absorber/focus-coil module will be measured using two solenoidal spectrometers. After a brief summary of the status of the experiment, the physics program of Step IV is described.

*Keywords:* Muon Ionization Cooling Experiment, Step IV, Emittance Reduction, Absorber Study, Beam Matching

## 1. Introduction

The goal of the International Muon Ionization Cooling Experiment (MICE) is to demonstrate, for the first time, sustainable 4D emittance reduction (cooling) of a beam of muons incident upon a series of absorbing materials. MICE has been designed to operate over a range of momenta from 140MeV/c to 240MeV/c with a momentum spread of 20MeV/c and an initial emittance range of 3-10$\pi$mm-rad.

the MICE collaboration is motivated by the desire to develop a technique for producing intense well collimated muon beams for future high energy facilities. These facilities include the Neutrino Factory, which is the ultimate tool for long baseline studies of neutrino oscillations, and the Muon Collider, a multi-TeV lepton anti-lepton collider. Ionization cooling provides the only technique that can achieve such emittance reductions within the short time frame of the muon lifetime.

MICE is being constructed in a stepwise fashion with the intention of developing an understanding of the sources of systematic errors as its development proceeds. Step I was completed in 2012, with the commissioning of the Particle Identification (PID) beamline detectors and characterization of the beam. Step IV introduces the spectrometer solenoids which house the scintillating fiber trackers along with the absorber material and focusing coil module. This step measures the properties of the $LH_2$ and LiH absorbers that produce emittance reduction. The final configuration after Step IV will demonstrate that longitudinal momentum can be restored and produce the first experimental evidence for ionization cooling (see Figure 1).

MICE is being built at the Rutherford Appleton Laboratory (RAL) in southern Oxfordshire, UK. The ISIS synchrotron is used as the proton source. The MICE beam is created by dipping a titanium target into the ISIS beam and collecting the resulting pion shower in a series of quadrupole magnets. Momentum selection is preformed by two bending dipole magnets. A decay solenoid, located between the dipole magnets, increases the pion path length allowing time for the pions to decay to muons[1]. Tbe input beam emittance can be set by an iris diffuser.

The MICE beamline instrumentation consists of a

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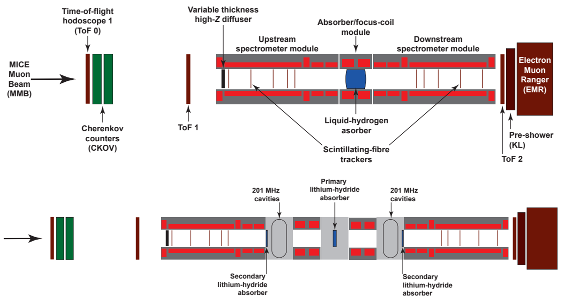


Figure 1: The Step IV configuration (top) and the final MICE configuration (bottom). The Step IV physics program will study the physical properties of the absorbing materials, and the final configuration will demonstrate ionization emittance cooling.

suite of PID detectors. The upstream detectors include two time of flight (TOF) dectors and two Cherenkov detectors. While the downstream detectors include a single TOF, a KLOE light detector, and the electron muon ranger. These detectors allow for identification of single muons entering the experiment and detecting particle decays after leaving the the cooling channel.

## 2. Step IV Measurement Program

The rate of change of the normalized emittance is approximated as:

$$\frac{d\epsilon_\perp}{ds} \approx \frac{-\epsilon_\perp}{\beta^2 E}\langle\frac{dE}{dz}\rangle + \frac{\beta_\perp(14MeV)^2}{2\beta^3 E m_\mu X_0}, \quad (1)$$

where $\epsilon_n$ is the normalized transverse emittance, $\beta_\perp$ is the optical transverse beta function, $X_0$ is the radiation length and $\beta$E is the momentum. The first term of equation 1 represents emittance reduction from ionization cooling while the second term is heating due to multiple scattering. In Step IV this relation will be used to study the properties of the absorbers in MICE.

### *2.1. Emittance*

Emittance describes the phase space occupied by a beam. Step IV will demonstrate transverse emittance reduction. Emittance is determined from an ensemble of single particle measurements from evaluation of the covariance matrix as follows[2]:

$$\epsilon_D = \frac{1}{m_\mu}\sqrt[D]{|\mathbf{V}_{(u)}|}\,; \quad (2)$$

where the elements of the covariance matrix are given by:

$$\mathbf{V}_{i,j} = \frac{1}{N}\sum_{k=1}^{N}(x_{ik}-\mu_i)(x_{jk}-\mu_j)\,. \quad (3)$$

Here the vector $u_k$ is of the form $(\mathbf{x},\mathbf{p})$, N is the total number of events recorded, D is the phase space dimension (generally either 4 or 6), and $\mu_i$ is the mean value of the $i^{th}$ value of $u$.

Measurements of these quantities are carried out by a pair of scintillating fiber trackers located upstream and downstream of the absorber. The trackers are housed in spectrometer solenoids that produce a uniform magnetic field, allowing for precision measurements of position and momentum. Each tracker consists of five tracking stations of three planes, each plane comprised of a doublet layer of scintillating fibers (Figure 2). The fibers are then ganged into groups of seven and read out by Visible Light Photon Counters (VLPC)[3].

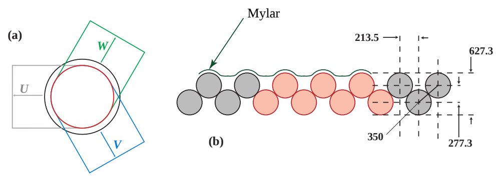


Figure 2: (a) Arrangement of the three scintillating fiber planes ($u$, $v$, and $w$) in a tracker station, from a beam's eye view. The colored lines indicate the direction fibers run in each plane, while the overlap area in red is the active area. (b) Placement of individual fibers in a doublet layer. The mylar is a thin sheet of plastic that separates each plane.

Space-point positions are analyzed by a simple pattern recognition algorithm to group the space-points into particle tracks which are then processed by a Kalman filter algorithm to take into account offsets due to multiple scattering[4]. Reconstruction shows good agreement with Monte Carlo (MC) truth results (Figure 3).

### *2.2. Beam Matching and Absorber Study*

Equation 1 provides the blueprint for how the MICE absorbers should behave. Step IV will run in three different configurations, with $LH_2$, LiH, and with no absorbing material. Matching predicted transverse emittance reduction for both absorbing materials over the emittances and momenta given in Table 1 will provide validation of the basic tenant of ionization cooling. Setting of the beam emittance will be done with the beamline diffuser and momentum selection will be carried out by the dipole magnets.

In making this measurement corrections need to be applied in the beam optics between the upstream and

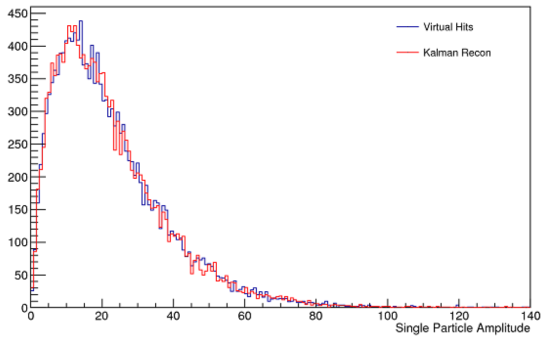


Figure 3: MC truth single particle amplitude plotted against Kalman reconstructed MC amplitude for the downstream tracker. Single particle amplitude corresponds to four times the emittance[5].

downstream sections. Transversing the absorbing material will introduce a mismatch in the optics, as the r.m.s. beam size is a constant in a thin absorber. The relation between the beam size ($\sigma$), $\epsilon_n$, and $\beta_\perp$ is given by[6]:

$$\sigma_n^2 = \beta_\perp \epsilon_n \tag{4}$$

so that comparing the input beam size against the output gives:

$$\beta_{out} = \frac{\beta_{in}\epsilon_{in}}{\epsilon_{out}} \tag{5}$$

$\beta_\perp$ corresponds to the transverse width of the beam, and as such, reducing the output emittance will increase the width of the beam. This may prevent particle propagation through the MICE channel. To deal with this a pair of matching coils in both the spectrometer solenoids will be a adjusted to maximize beam transport, with baseline figures coming from simulation. Step IV specifications are for a matched beam of $\beta_\perp$ = 43cm at the center of the absorber[7].

## 3. Conclusions

The Step IV tracker/solenoid and the absorber/focusing coil modules have been delivered to RAL. Installation and commissioning of these modules is proceeding on schedule. Additionally, the software needed to run, monitor, and analyze the experiment are showing good results against live tests and Monte Carlo.

MICE Step IV is on schedule to begin taking data in 2015. The measurements will demonstrate transverse emittance reduction and provide the understanding required to proceed with the final configuration and demonstration of ionization emittance cooling.

MICE Step IV Run Conditions

| | |
|---|---|
| Momentum | 140 MeV/c<br>200 MeV/c<br>240 MeV/c |
| Emittance | 3 mm<br>6 mm<br>10 mm |
| $LH_2$ Absorber | $X_0$ = 63.04 g/cm$^{-2}$<br>dE/dX = 4.103 MeVg$^{-1}$cm$^2$<br>$\Delta$z = 35 cm |
| LiH Absorber | $X_0$ = 79.62 g/cm$^{-2}$<br>dE/dX = 1.897 MeVg$^{-1}$cm$^2$<br>$\Delta$z = 6.3 cm |

Table 1: Step IV will run with both absorbers, and no absorber, at each momentum and emittance setting.

## 4. Acknowledgment

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