STATUS OF MICE STEP IV *

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Abstract

Muon beams of low emittance provide the basis for the intense, well characterised neutrino beams of the Neutrino Factory and for lepton-antilepton collisions at energies of up to several TeV at a Muon Collider. The international Muon Ionization Cooling Experiment (MICE) will demonstrate ionization cooling–the technique by which it is proposed to reduce the phase-space volume occupied by the muon beam. MICE is being constructed in a series of Steps. The configuration currently in operation at the Rutherford Appleton Laboratory is optimised for the study the properties of liquid hydrogen and lithium hydride that affect cooling. The plans for data taking in the present configuration will be described together with a summary of the status of preparation of the experimental configuration by which MICE will demonstration the principle of ionization cooling.

MOTIVATION

The decays ($\mu^- \to e^- \nu_\mu \overline{\nu}_e$ and $\mu^+ \to e^+ \overline{\nu}_\mu \nu_e$) of stored muons in a high intensity Neutrino Factory produce a narrow beam of fully characterized neutrinos. The neutrinos are ideal for the study of the "Golden" oscillation channels [1] ($\nu_e \to \nu_\mu$ and $\overline{\nu}_e \to \overline{\nu}_\mu$) where the sign of the detected muon is opposite to that in the storage ring and for the "Platinum" oscillation channels [1] ($\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$). Furthermore with 10^{21} useful muon decays per year, this uniquely clean source of neutrinos would enable the study of CP violation in the lepton sector, thus providing the best chance of its discovery [2–4]. For example, the precision with which the CP phase δ can be measured at the IDS Neutrino Factory [1], in comparison to other future facilities, is shown in Fig. 1.

Muons for a neutrino factory or for a muon collider [5, 6] are produced as tertiary particles ($p+N \to \pi + X$ with subsequent decay $\pi \to \mu\nu$), and hence have too large an inherent emittance (beam volume in the 6D position and momentum phase space) for a cost-effective accelerator. They must therefore be "cooled" to reduce the beam spread both transversely and longitudinally[1]. Due to the short muon lifetime, the only feasible technique to cool muons, which has as yet only been studied in simulations, is ionization cooling. The international **M**uon **I**onization **C**ooling **E**xperiment (MICE), at the ISIS accelerator at Rutherford Appleton Laboratory (UK), will demonstrate the viability of muon ionization cooling with a variety of beam optics, muon momenta (140–240 MeV/c), and input emittances.

MICE is a precision experiment which will measure a ~5% reduction in beam emittance with a measurement precision of better than 0.1 mm-rad. Thus, it is imperative that the systematic errors be minimized and well understood. For this reason, as well as budget constraints, MICE is staged such that the parameters of the beam, detectors, tracking, and cooling channel components are studied in detail in each step. At present, MICE is in the final stages of commissioning its tracking solenoids and cooling channel and has begun collecting data to perform muon scattering measurements on Xe, liquid hydrogen (LH_2), and LiH. We will study the cooling effect of these absorbers for a variety of optics settings. For historic reasons this stage is named Step IV. In its final configuration, MICE will include RF cavities to partially restore the muon longitudinal momentum and thus demonstrate sustainable ionization cooling.

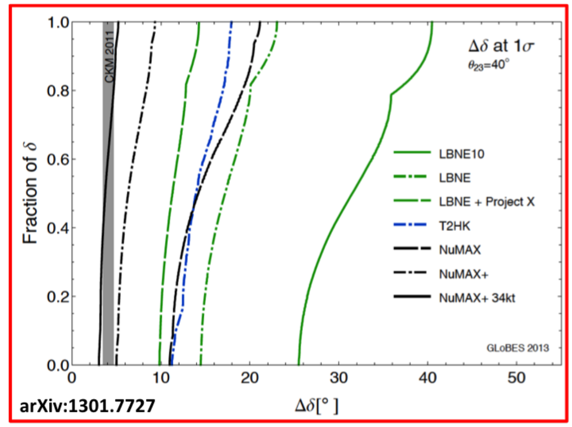

Figure 1: Comparison of 1σ measurement precision of CP violating phase δ for different facilities.

Normalized beam emittance is given by $\varepsilon_{i,n} = \sigma_{r_i}\sigma_{p_i}/(mc)$, where σ_{r_i} and σ_{p_i} are the i^{th} component of the RMS spatial and momentum spreads, respectively, and mc is the product of the particle mass and speed of light [5, 7]. The normalized emittance accounts for the energy dependence of the beam, since a higher energy beam has smaller geomtrical emittance.

In ionization cooling, the muons lose energy traversing a low-Z absorber and have the longitudinal component of momentum restored in accelerating cavities, all while being focused in a magnetic lattice. In traversing the absorber, muons lose momentum in all directions—"cooling"—while Coulomb scattering increases emittance—"heating". The rate of change of ε_n thus has both a cooling term and a heating term when traversing a path length s:

$$\frac{d\varepsilon_n}{ds} \approx -\frac{1}{\beta^2}\left\langle\left|\frac{dE_\mu}{ds}\right|\right\rangle\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp(13.6\,\mathrm{MeV/c})^2}{2E_\mu m_\mu X_0}. \quad (1)$$

Here βc is the muon velocity, $\langle dE_\mu/ds\rangle$ is the average rate of energy loss, E_μ and m_μ are the muon energy and mass, $\beta_\perp$ is the transverse betatron function (focal length) evaluated at the absorber, and X_0 is the radiation length of the absorber

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[1] Only transverse cooling is required for a neutrino factory

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material. Note that heating is reduced by strong focusing in the absorber (low $\beta_\perp$) and by use of a low-Z absorber to increase X_0.

MICE DESCRIPTION

To perform the cooling measurement, MICE must: 1) create a muon beam, 2) identify the muons and reject other particles, 3) measure the muon's position and momentum prior to cooling, 4) tightly focus the muons and cool them in a low-Z absorber, 5) restore the longitudinal component of momentum in RF cavities, 6) re-measure the muon's position and momentum after cooling, and 7) identify muons–reject those events in which the muon decayed.

MICE is a single particle experiment, i.e., we measure the individual muons using particle physics techniques, and combine the individual measurements to form an ensemble used in the emittance measurements. The normalized root mean squared emittance, ε_n, is determined from the evaluation of the covariance matrix [8]:

$$\varepsilon_n = \frac{1}{m_\mu}\sqrt{|\mathbf{V}|} \quad \text{with matrix elements}$$

$$\mathbf{V}_{i,j} = \frac{1}{N}\sum_{k=1}^{N}(u_{i,k}-\mu_i)(u_{j,k}-\mu_j) \qquad (2)$$

for an ensemble of N measurements and using the vector $\vec{u} = (\vec{x}, \vec{p})$, where we measure $\vec{x} = (x, y, t)$ and $\vec{p} = (p_x, p_y, E)$, and μ_i is the mean value of u_i. The measured cooling effect is then the difference between the initial and final measured normalized emittances.

Figure 2 shows a schematic of the MICE configuration. The muon beam is created using a titanium target that is dipped at ~1 Hz with acceleration ~90g into the ISIS synchrotron beam during the last 3 ms of the ISIS acceleration cycle. The pions produced in the collision are transported to the MICE Hall and momentum selected using conventional quadrupole triplet (Q1-3) and dipole (D1) magnets. Following D1 is the superconducting Decay Solenoid (DS) which strongly focuses the pions while increasing their path length, thus increasing the total muon flux by an order of magnitude compared to a conventional quadrupole channel. Following the DS, muons are momentum selected and transported to the cooling channel with a dipole (D2) and quad triplets (Q4-6 & Q7-9). Results of the characterization of the MICE muon beamline can be found in [9, 10].

Particle Identification (PID) on the incoming beam is performed with two threshold Cherenkov counters and two time-of-flight scintillator hodoscopes (ToF0 & ToF1) up and downstream of the last quadrupole triplet, as seen in Fig. 2. These detectors serve to identify muons and reject other particles. Muons which decay in the channel are rejected using the last ToF plane (ToF2), the KLOE-light calorimeter (KL), and the electron-muon ranger [11] (EMR) downstream of the cooling channel. Data have been collected with all detectors. The ToF detectors were calibrated to have time resolutions of 55 ps, 53 ps, 52 ps for ToF0, ToF1, ToF2, respectively [12, 13]. The ToF system is also used as the trigger

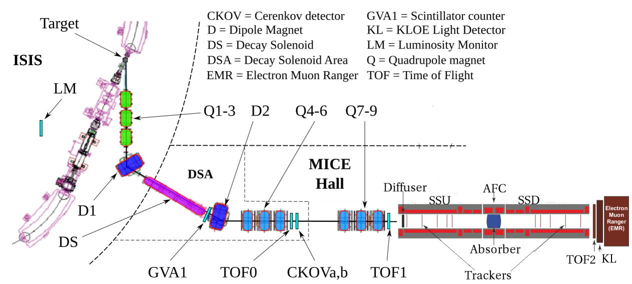

Figure 2: Plan view of MICE Step IV configuration, beginning from the target in ISIS.

for the experiment. The beamline and detectors were characterized in the first stage of MICE which was completed in 2011; further details can be found in [10, 12].

MICE STEP IV

The MICE channel for Step IV consists of an "Absorber/Focus Coil" module (AFC) sandwiched between two identical Tracking Spectrometers, as shown in Fig. 2.

Each Tracking Spectrometer solenoid (SSU & SSD) cryostat is 2.9 m in length with a 40 cm warm bore and has 5 Nb–Ti superconducting coils wound on a single 6061–$T6$ Al mandrel. The longest, ~1.3 m, coil is flanked on either side with trim coils to provide a uniform 4 T field in the tracking region; the remaining two coils, closest to the AFC, serve to match the beam optics to the cooling channel. Both magnets were built and trained to 102% of the maximum operating currents at the manufacturer Wang, NMR, Livermore, California, U.S.A. [14]. Each tracker is built of 5-planes, 3-120° stereo-view scintillating fibers with 1,400 350 μm fibers/plane and is positioned coaxially inside the uniform field. Readout of the trackers is performed with visible light photon counters (VLPC) and DØ AFEIIt electronics [15, 16]. The tracking spectrometers are used to measure muon trajectories and momenta, thus providing the inputs to Eq. 2 for the emittance measurements.

The Focus Coil (FC) (the "FC" part of the AFC) is also a superconducting solenoidal magnet with 2 Nb–Ti coils wound on a single 6061 – $T6$ Al mandrel. The coils can be operated with fields parallel or anti-parallel and provide strong focusing (small $\beta_\perp$ in Eq. 1) of the muons in the absorber, which is positioned co-axially and longitudinally in the warm bore of the coils. The magnet for Step IV has been trained to ~1% above full current in both modes. The absorbers being studied in Step IV are Xe, LH_2, and LiH. The cryogenic system for the H_2 liquification is installed and has been tested using a dewar, and the absorber body is awaiting installation for final commissioning this summer.

The MICE channel magnets are all built without a magnetic return yoke and thus produce large stray fields which would adversely affect the operation of some of the local electronics. To mitigate this problem, a soft iron shell, known as the Partial Return Yoke (PRY), has been manufactured to provide a return path for the magnetic flux; the field outside the PRY is less than 5 Gauss.

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Figure 3: Upstream view of the MICE channel.

Figure 3 is a photograph of the MICE channel as seen from the upstream end of SSU. The "butterfly wings" at the upstream end houses the tracker waveguides. Within the beam hole is the diffuser. The grey walls on either side are the PRY.

STEP IV PHYSICS PROGRAM

During the Step IV stage of MICE, we will measure multiple scattering, energy loss, and emittance reduction in a variety of materials for different input momenta and emittances. Multiple scattering measurements have been made with Xe and LiH, and the Xe data are presently being prepared for publication.

Due to a loss of one of the match coils in SSD during commissioning, alternate optics are being studied [17] and the quench protection systems for SSU and SSD are being made more robust. Once complete, the final commissioning of the string of magnets, SSU-FC-SSD, will be performed and energy loss measurements will resume as well as measurements of emittance reduction.

CONCLUSIONS

MICE, at Step IV, will measure the properties of LH_2 and LiH that affect the performance of an ionization-cooling channel. The Step IV configuration will also be used to study the dependence of the ionization-cooling effect on the optics of the channel and the momentum and emittance of the input beam. Step IV construction is complete and the final commissioning will start in June of 2016. Muon scattering measurements on Xe and LiH have been performed and the Xe data results are in preparation for publication.

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