STATUS, RECENT RESULTS AND PROSPECTS OF THE INTERNATIONAL MUON IONIZATION COOLING EXPERIMENT

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Abstract

Muon accelerators have been proposed as a means to produce intense, high energy muon beams for particle physics. Designs call for beam cooling to provide suitable beams. Existing cooling schemes cannot operate on time scales that are competitive with the muon lifetime. Ionisation cooling has been proposed as a means to achieve sufficient cooling, but it has never been demonstrated practically. In the Muon Ionisation Cooling Experiment (MICE), based at the Rutherford Appleton Laboratory (RAL), ionisation cooling will be demonstrated. MICE Step IV is currently in progress and will be completed in 2016. Muons are brought onto an absorber, resulting in a reduction of momentum and hence reduction of normalised transverse emittance. The full Demonstration of Ionisation Cooling will take place in 2017. An extra magnet module and RF cavities will be installed, as in a cell of a cooling channel. This will enable the demonstration of reduction of emittance and subsequent re-acceleration, both critical components for a realistic ionisation cooling channel.

COOLING FOR MUON ACCELERATORS

Muon accelerators have been proposed as a source for high energy neutrino beams, at the Neutrino Factory, as a source of Higgs particles in a Higgs factory and as a multi-TeV lepton collider for searches for higher energy phenomena [1, 2].

Muons are created by firing an intense beam of protons onto a high power target. Pions are produced which are captured in high field solenoids where they decay to muons. The resultant muon beam has large emittance.

In order to provide sufficient muons within the acceptance of the Neutrino Factory acceleration system, it is desirable to cool the muon beam prior to acceleration. In order to reach luminosities appropriate for a Muon Collider it is essential to cool the muon beam.

Muon cooling is performed by ionisation cooling [3–5]. This is the only technique that is competitive with the 2.2 μs muon life time. Particles are passed through an absorber where the momentum of the muons is reduced in transverse and longitudinal directions, then passed through an RF cavity where momentum is restored only in the longitudinal direction, resulting in a reduction in beam emittance.

Multiple scattering produces random momentum kicks that tend to degrade the cooling effect or even heat the beam. Low-Z materials like liquid hydrogen or lithium hydride give less multiple scattering for a given energy loss, so these are considered as absorber materials. A tight focus means that the beam has relatively high transverse momentum, so that the multiple scatters are less significant.

Muon cooling has never been demonstrated before. The Muon Ioniation Cooling Experiment (MICE) collaboration is building a section of a cooling channel in order to demonstrate the technique [6].

THE MICE PROGRAM

The MICE program is planned to operate in several installation steps [7]. Step IV is now fully installed and the equipment is being commissioned. Installation of the final step, known as the Demonstration of Ionisation Cooling, will begin in mid-2016. Schematics of Step IV and the Demonstration of Ionisation Cooling are shown in Fig. 1.

In Step IV the full diagnostics system has been installed together with a single absorber system. In this configuration MICE will study the material physics properties of the MICE absorbers and measure transverse normalised emittance reduction .

In the Demonstration of Ionisation Cooling, a cooling cell will be installed including RF equipment. This will enable the measurement of ionisation cooling with reacceleration.

In order to accommodate the characteristics of muon beams, MICE has a number of features which make it a unique accelerator physics experiment. These features are outlined below.

High resolution particle-by-particle diagnostics

MICE is similar to a small section of a much longer cooling channel, so will produce a cooling effect of only a few percent. In order to measure such a cooling effect with high precision, a high resolution detector system has been designed.

MICE will measure individual particles' position, momentum and time with respect to the RF pulse once RF is installed [8]. This enables the collaboration to make a full correlated measurement of the beam upstream and downstream of the cooling equipment.

MICE can also reject beam impurities such as undecayed pions and electrons from muon decay on a particle-by-particle basis.

The position and momentum of particles are measured using two scintillating fibre trackers upstream and downstream of the cooling region. Three 50 ps time-of-flight counters (TOFs) provide time measurement and velocity measurement. Comparison of velocity and momentum enables measurement of particle mass. Cherenkov threshold counters (Ckov), the KL pre-shower and Electron Muon Ranger (EMR) calorimeter provide additional

ISBN 978-3-95450-174-8

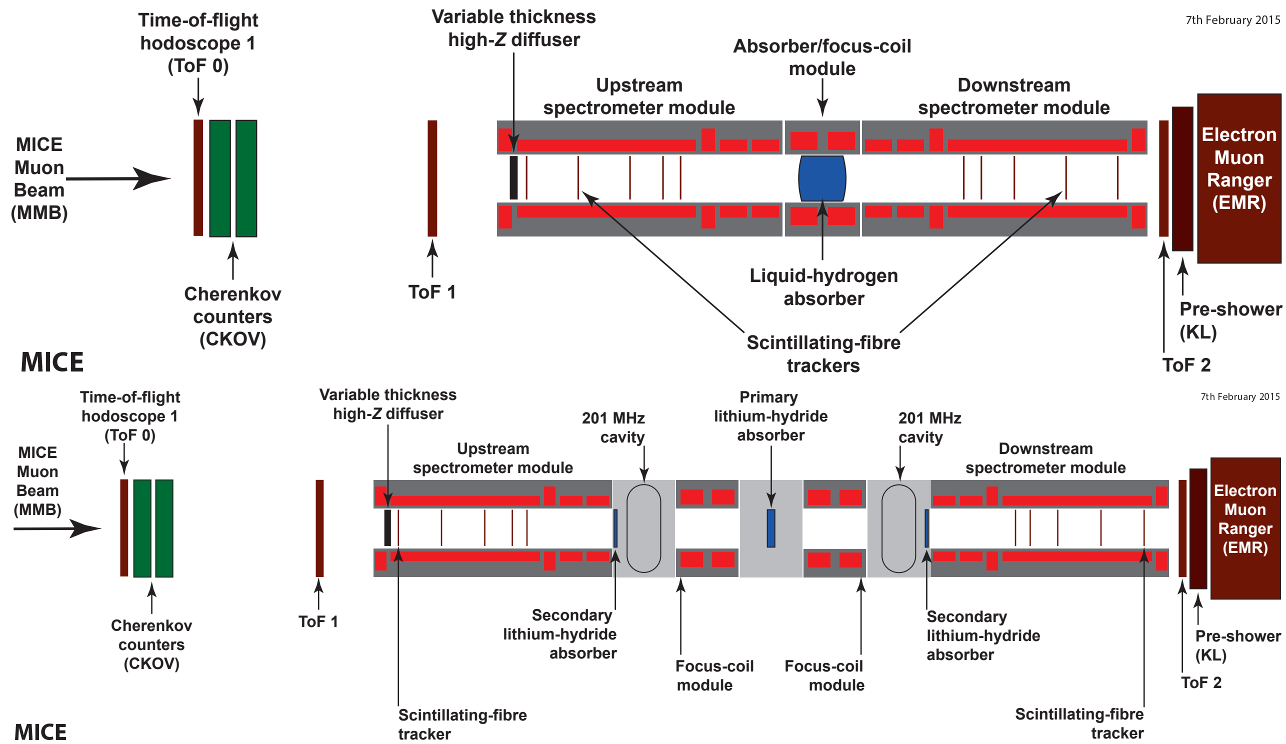

Figure 1: Schematic of the MICE cooling channel at Step IV (top) and for the full demonstration of ionisation cooling (bottom).

particle identification.

High Aperture Superconducting Solenoids

At Step IV MICE has three superconducting solenoid assemblies: two 5-coil Spectrometer Solenoids (SSU and SSD) and one 2-coil Focus Coil module (FC). SSU and SSD provide a uniform 4 T field which is necessary for reconstruction of particle momentum in the tracker. Match coils provide matching to the final focus enabling independent selection of β and β'. FC can operate with the coils having the same polarity (solenoid mode) or opposite polarite (flip mode). In the Demonstration of Ionisation Cooling an additional Focus Coil module will be installed.

The bore aperture of the magnets is more than 200 mm radius and the magnets are closely packed at Step IV, resulting in magnetic coupling between adjacent modules.

Liquid Hydrogen and Lithium Hydride Absorbers

At Step IV, energy loss is provided by either liquid hydrogen or lithium hydride absorbers. Both will be operated separately. During the Demonstration of Ionisation Cooling, only lithium hydride absorbers will be operated.

The liquid hydrogen absorbers present 350 mm thickness of liquid hydrogen on the beam axis. The hydrogen is encapsulated in a pair aluminium windows of 150 micron thickness. An additional pair of windows protect the rest of the experiment in the case of a burst of the main windows. The windows are curved, enabling a thinner construction. This results in less scattering.

The lithium hydride absorber is a 65 mm thickness disk of lithium-6 enriched lithium hydride.

COMMISSIONING STATUS OF THE MICE MAGNETS

The Step IV magnet assemblies have all been tested and trained to design currents during the construction phase of the project. They have been transported to the MICE hall and were installed on the beam line in 2014. A partial return yoke was installed around the MICE magnets in 2015 so that stray fields from the MICE magnets do not impinge on nearby equipment. The magnets have been cooled down and all magnets have been successfully powered.

- SSU has been fully trained to production current. SSU awaits a soak test before it can be considered fully commissioned.
- SSD has been trained to near production currents. During one of the training cycles the low temperature lead to Match Coil 1 of SSD failed, making the coil inoperable at Step IV. MICE has designed a new baseline optics to accommodate the failed coil.
- FC has been cooled and powered with a 114 A current, followed by a 20 hour soak test at 120 A, demonstrating the full range of operational currents with the coils in solenoid mode. Tests in flip mode will follow.

ISBN 978-3-95450-174-8

Once the individual coil assemblies have been shown to power correctly, the entire line will be powered together. Adjacent magnets are coupled. This may result in a requirement for combined training of coils in the presence of the field of neighbouring coils. Additionally, simulations indicate that a quench in one coil will quench the line. A combined quench protection system has been designed and will be tested with all the magnets in combination.

COMMISSIONING STATUS OF THE MICE DIAGNOSTICS

The MICE diagnostics is now commissioned and operational.

Scintillating Fibre Trackers

The MICE scintillating fibre trackers consist of planes of fibres laid across the beam pipe. Three planes are arranged into a station, adjacent planes rotated through 120 degrees, providing a measurement of the position of particles at each station. Five stations make up each tracker. By fitting the expected helical trajectory to the observed space points, MICE determines the momentum of each particle. Combined with the position measurement and time measurement at the TOFs, MICE is able to reconstruct the full phase space of particles in the beam.

The MICE scintillating fibre trackers were installed in the MICE spectrometers prior to their move to the Hall. The cabling was completed during April and a series of calibration runs were performed using a pulser trigger and light provided by a set of LEDs in the magnet bore. Subsequently a muon beam was passed through the trackers and the tracker readout was synchronised with the other detector readouts. The tracker efficiency has been measured using this beam and found to meet specification. Final numbers await a full analysis.

Particle Identification Detectors

The EMR is a totally active scintillator detector at the downstream end of MICE. Muons that pass into the detector are stopped. Particle identification is achieved by examining the characteristics of energy deposition in the detector.

The EMR was commissioned in 2013 and shown to achieve a good rejection of electrons from muon decays. Several features of the energy deposited by electron showers and muons were used to characterise these different particle species. Analysis has shown 99.6% of muons tagged as muons while 95% of electrons are tagged as electrons. The MICE muon beam has on a small electron impurity, and so the EMR should enable good rejection of electrons.

The Ckov, KL and TOF detectors have been installed and operational for many years and continue to function reliably.

Beam Based Alignment

The MICE beam has been used to validate individual detector reconstruction and to provide a global alignment of the diagnostics with each other. The beam based alignment of the diagnostics validates the surveyed alignment.

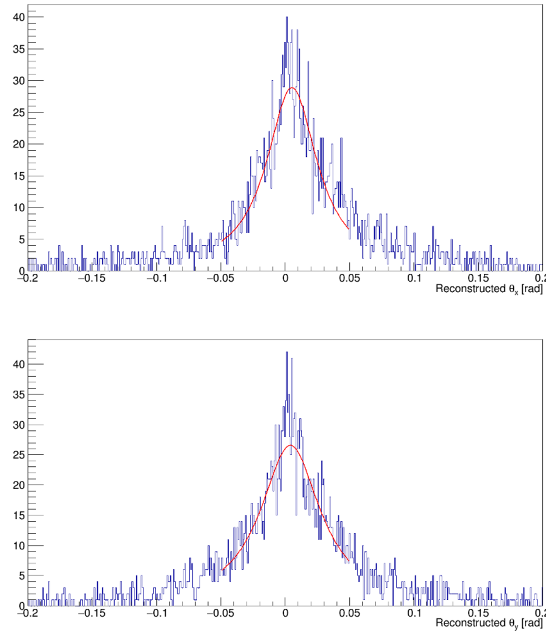

Figure 2: Angular distribution of axis of helices, fitted to tracker station hits in the tracker region.

The tracking detectors have been aligned with respect to one another by means of propagating straight tracks from one detector to the other in the absence of fields in the magnets. By performing the analysis track by track, effects that are dependent on momentum or other phase space variables can be neglected. Analysis indicates alignments in line with expectations from survey and other measurements.

A similar procedure has been used to align the other detectors. For these detectors, the position resolution is insufficient to be competitive with the survey and the measurement merely validates the survey. All of the detector positions have been found to be consistent with the survey except for TOF0, where the analysis of the alignment has not yet been completed.

Reconstruction has been performed in the MICE trackers in order to measure the alignment of the trackers to the solenoids. Space points were projected onto a single $x - y$ plane and a cycloid was fitted, enabling a calculation of the estimated track tilt for each track. By calculating the distribution peak, the tracker tilt was found with respect to the solenoid axis.

The distribution of angles for a set of reconstructed tracks is shown in Fig. 2. The spectrometer solenoids were running in a pre-commissioning state in a reduced field of 1.46 T. A 4 T field will be used when the trackers are fully commissioned. The measurement is expected to have a significant systematic error that has yet to be calculated. Alignments were found to be of order mrad, which is compatible with the survey and field measurements.

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PLANS FOR STEP IV

The beam-based alignment of the cooling channel will continue. Measurement of magnet alignment will be performed by projecting tracks from the upstream tracker to the downstream tracker and comparing with simulation.

The beam will be passed through the cooling channel without an absorber and the optical properties of the beamline will be checked. Absorbers will be placed in the beamline and the transported emittance with and without the absorber will be measured.

DEMONSTRATION OF IONISATION COOLING

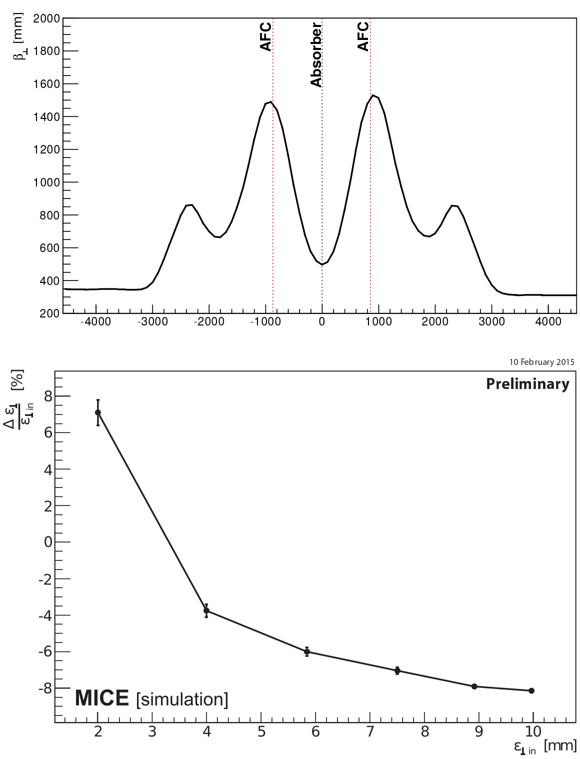

Figure 3: (Top) optical β function and (Bottom) simulated emittance reduction as a function of input emittance in the full demonstration lattice.

A revised lattice for the Demonstration of Ionisation Cooling has been devised in the light of experience from the Step IV construction phase [11]. This step reuses the existing Step IV hardware, with the addition of two 200 MHz RF cavities and an additional Focus Coil module that has already been constructed and operated successfully.

The lattice has a focus at the central point of the two Focus Coil modules, where the primary lithium hydride absorber sits. Additional secondary absorbers sit at the outer edge of the lattice. These secondary absorbers serve to shield the tracking detectors from the RF cavities and to provide additional cooling. The simulated optical function is shown in Fig. 3.

The 430 mm long RF cavities will operate at around 10 MV/m and 201.25 MHz. The gradient is enhanced by beryllium windows on the axis which helps to keep the electric field more axial to the beamline. The energy recovered by the RF cavities will be less than the energy lost by the beam in the absorbers, but should be sufficient to show the principle of energy recovery.

The performance of the lattice is shown in Fig. 3. The equilibrium emittance is expected to be around 3 mm while transverse emittance reduction around 7% is expected for higher emittance beams.

Construction of the Demonstration of Ionisation Cooling will begin in the summer of 2016, following the end of Step IV operations. First beam is expected in 2017.

CONCLUSIONS

Muon accelerators have the potential to make definitive measurements of neutrino oscillations at the Neutrino Factory, and to serve as either a Higgs factory or a discovery machine in a Muon Collider.

Ionisation cooling is the critical enabling technique for muon accelerators. MICE is intended to demonstrate muon ionisation cooling for the first time.

MICE Step IV is in the final stages of commissioning for data taking late in 2015 or early in 2016. The MICE Demonstration of Ionisation Cooling is in the final design stage, with most of the major design components on site at RAL.

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ISBN 978-3-95450-174-8