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PROGRESS TOWARDS COMPLETION OF THE MICE DEMONSTRATION OF MUON IONIZATION COOLING*

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Abstract

The Muon Ionization Cooling Experiment (MICE) at the Rutherford Appleton Laboratory aims to demonstrate ≈ 10% ionization cooling of a muon beam, by its interaction with low-Z absorber materials followed by restoration of longitudinal momentum in RF linacs. MICE Step V will provide the flexibility for a thorough exploration and characterization of the performance of ionization cooling. Step V will include four RF cavities to provide 8 MV/m gradient in a strong magnetic field. This entails an RF drive system to deliver 2 MW, 1 ms pulses of 201 MHz frequency at 1 Hz repetition rate, the distribution network to deliver 1 MW to each cavity with correct RF phasing, diagnostics to determine the gradient and the muon transit phase, and development of the large diameter magnets required in order to keep the muons focused through the linacs. Progress towards the completion of Step V is described.

INTRODUCTION

The international Muon Ionization Cooling Experiment is designed to demonstrate for the first time that emittance reduction of a muon beam can be achieved via ionization cooling [1]. Muon cooling is an essential technique for any future facility based on intense muon beams, such as a Neutrino Factory, the ultimate tool for studying leptonic CP violation, or a Muon Collider, a potential route to multi-TeV lepton–anti-lepton collisions.

Due to the short muon lifetime, traditional beam cooling techniques cannot be applied to muons. Ionization cooling involves first reducing beam momentum in all directions (both transverse and longitudinal) via ionisation energy loss, by passing the beam through a low-Z material. Lost momentum is then restored in only the longitudinal direction using radio frequency (RF) cavities.

Repeated application of this procedure leads to a progressive reduction in the beam divergence, which can be combined with alternating gradient focusing to reduce the beam cross section, for an overall reduction in emittance. Eventually an equilibrium emittance is reached where the cooling effect becomes balanced by an opposing beam heating effect due to multiple scattering. This is described by Eqn. 1, where the first term on the right hand side represents the cooling effect, and the second term the heating effect:

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

Here $d\epsilon_n/ds$ is the rate of change of normalized-emittance within the absorber; βc, E_μ, and m_μ the muon velocity, energy, and mass; $\beta_\perp$ the lattice betatron function at the absorber; and L_R the radiation length of the absorber material.

The goal of MICE is to demonstrate a ≈ 10% reduction in the emittance of muon beams of various emittances and momenta, with the reduction being measured to within 1% precision (an overall emittance measurement precision of 0.1%). This is to be achieved by using a low intensity muon beam, with each muon being measured individually by an upstream and downstream high precision scintillating fibre tracker, each of which is contained within a 4 T superconducting spectrometer solenoid.

MICE STEPS

MICE is based at the Rutherford Appleton Laboratory (RAL), in the UK. MICE is a staged experiment, built and run in discrete steps. Originally six steps were envisaged for the MICE programme, but over time this has evolved and compacted into only three, whilst maintaining the original naming convention. These are shown in Fig. 1.

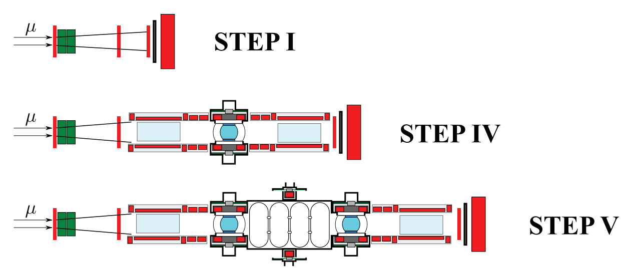

Figure 1: The MICE programme of staged contruction and running. Step I (completed in 2013) consists of the muon beamline and particle identification. Step IV (first running expected in 2015) adds the spectrometers solenoids, trackers and first absorber focus coil module. Step V (first running expected in 2018) adds an RF coupling coil module and second absorber focus coil module.

Step I consists of the muon beamline, employing the 800 MeV ISIS synchrotron as a proton driver, and various particle identification (PID) detectors. These include

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three time-of-flight (TOF) detectors, two aerogel threshold Cherenkov detectors for pion–muon discrimination, and a calorimeter consisting of a thin 'KLOE-light' (KL) lead/scintillating-fibre section backed by a segmented plastic-scintillator electron–muon ranger (EMR). Results from Step I are published in [2, 3], describing the characterisation of the beamline, and the development of a novel emittance measurement technique achieved using the time-of-flight detectors. A diagram of the Step I beamline (which will also apply to the subsequent steps with additions as described below) is shown in Fig. 2.

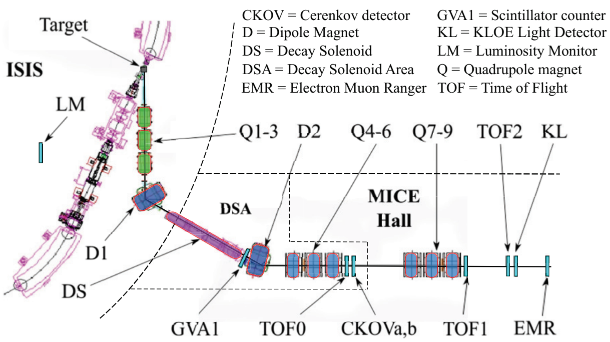

Figure 2: The MICE Muon Beamline, showing the beamline magnets and PID detectors. The far left shows part of the ISIS accelerator which serves as a proton driver, with a titanium target used to generate pions by intercepting the circulating proton beam.

Construction of the next stage, known as Step IV, is well advanced [4] and data taking is due to begin in 2015. Step IV will involve the addition of two spectrometers, consisting of both the solenoids (manufactured by Wang NMR Inc, USA) and their embedded trackers, and the first absorber focus coil (AFC) module, to the beamline. Step IV will demonstrate ionization cooling, but not full *sustainable cooling*, which requires longitudinal reacceleration. Various absorber materials, including LH_2 and LiH, will be used. The possibility also exists for a test of transverse–longitudinal emittance exchange using a wedge absorber design (allowing the cooling effect to migrate from the transverse direction to the longitudinal, an essential requirement for a Muon Collider).

Following Step IV, MICE will move to its final stage, Step V, which is discussed in the sections below.

STEP V

Overview

Step V of MICE will add an RF cavity–coupling coil (RFCC) module and a second AFC module, making up half of a full lattice cell of the Neutrino Factory Feasibility Study II (FS-II) [5] cooling channel.[1] This will then represent a full demonstration of sustainable ionisation cooling, including replacement of momentum in the longitudinal direction. The Step V cooling channel design is shown Fig. 3. Delivery of Step V is expected in 2017, with an expected completion date of 2018.

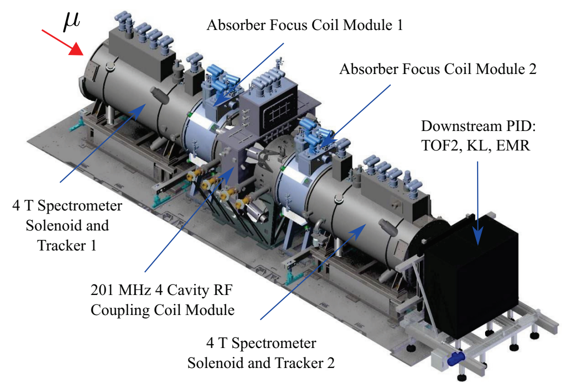

Figure 3: The MICE Step V Cooling Channel sandwiched by the up- and downstream spectrometers.

Absorber Focus Coil Modules

The absorber focus coil modules have been built by Tesla Engineering Ltd, UK. The AFCs integrate an absorber module used to hold the various media MICE will use to provide ionisation energy loss, together with two superconducting coils to provide beam focusing. The absorber modules use a modular design which allows different absorber choices to be swapped in and out as required. The presence of two focus coils per absorber allows running in two distinct modes, *solenoid mode* where both fields are aligned, and *flip mode* where the fields oppose.

Both AFC modules (shown in Fig. 4) have now been delivered to RAL by Tesla. AFC 1 has been trained to just above the baseline current in flip mode, and to its full design current in solenoid mode, and is the baseline choice for the Step IV module. A liquid hydrogen absorber body has also been successfully inserted into the bore. AFC 2 remains in the commissioning stages, and will be introduced at Step V.

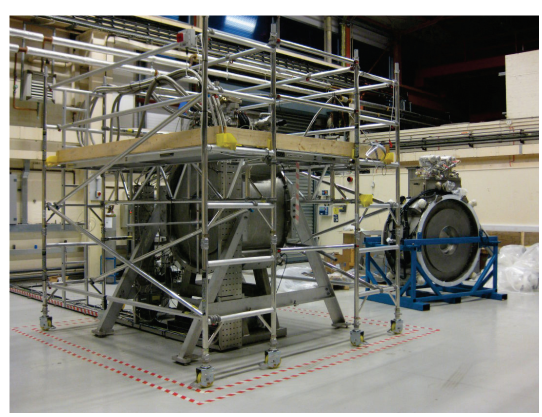

Figure 4: The two AFC modules at RAL. Different absorber materials may be used interchangeably.

[1] The full lattice cell (known as Step VI) offers a greater variety of lattice configurations. However, the Step V configuration will allow the essential demonstration of ionisation cooling with re-acceleration to be achieved. Since the additional cost and time required to implement Step VI is large a pragmatic decision has been taken to implement half a lattice cell, the Step V configuration, and study its performance in detail.

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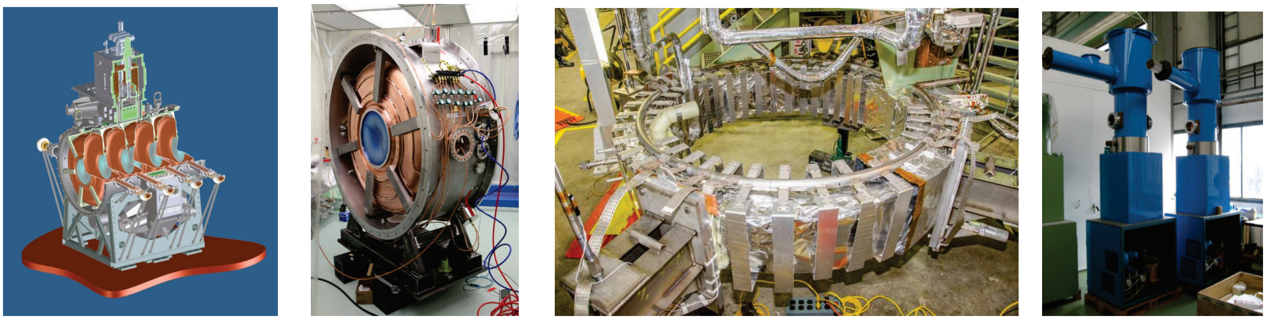

Figure 5: *Left*: Cutaway CAD drawing of the four cavity RFCC module. *Centre-left*: A MICE 201 MHz RF cavity. *Centre-right*: CC cold mass under test at Fermilab. *Right*: Two 201 MHz RF power supplies undergoing refurbishment at Daresbury Laboratory.

RF Coupling Coil Module

The RFCC module houses four RF cavities and a large-diameter superconducting 'coupling-coil' (CC) solenoid, illustrated in Fig. 5.

The MICE specification calls for an 8 MV/m gradient RF field. This gradient will be excited by pulses (from two 2 MW RF power amplifiers) of ≈1 ms duration, 201.25 MHz frequency at a 1 Hz repetition rate delivered to four normal conducting copper cavities ($Q \approx 50000$). The power distribution network will deliver 1 MW to each cavity with RF phasing selected for the desired muon momentum, as well as diagnostics to determine the gradient and the muon transit phase. These components are being developed and tested at Daresbury Laboratory (DL), RAL, Lawrence Berkeley National Laboratory (LBNL), Fermi National Accelerator Laboratory (FNAL) and Strathclyde University.

The high gradient RF field delivered by the cavities, together with the high magnetic field present, leads to issues of RF breakdown on the cavity surfaces. This continues to be studied at the Fermilab MuCool Test Area (MTA) [6], and, besides the cooling measurement, the practicalities of operating high gradient RF in the presence of large magnetic field will be a key learning output of Step V.

All the RF cavities have been fabricated by LBNL, and the first is being prepared for testing at the MTA [7]. The Coupling Coil cold mass has also been built, by Qi Huan Co., Beijing, China, for the Harbin Institute of Technology; it has been successfully tested at the Fermilab Solenoid Test Facility [8] and its cryostat is in fabrication at LBNL. The RF power system is being modernised at DL [9], with ≈2 MW output power capability having been recently demonstrated from the first amplifier chain.

CONCLUSION

MICE is on schedule to deliver Step V in 2018. That will conclude the approved programme of experimental demonstrations of muon ionization cooling at RAL, demonstrating a new technology for the accelerator physics community, and will lay the groundwork for a possible stored muon beam neutrino factory. There has been some consideration of a follow-on test: a realistic demonstration of six-dimensional muon ionization cooling, as needed for a future muon collider. Whether such a test will be needed, and, if so, where it might be performed, remain, at present, open questions.

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