PROGRESS TOWARDS THE COMPLETION OF THE MICE APPARATUS

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Abstract

MICE aims to demonstrate 10% ionisation cooling of a synthesised beam of muons by its interaction with low Z absorber materials followed by restoration of translational momentum in RF linacs. Extensions to the apparatus required to achieve Step IV, including the first absorber cell, of either liq. H_2 or LiH, and the two particle tracking spectrometers shall be described. Two very large superconducting spectrometer solenoids and one focus coil solenoid will provide a magnetic field of up to 4 T in the volume of the two trackers and the absorber cell respectively. The development, testing and integration of these challenging components will be reported. Progress towards Steps V & VI will be presented: tests of the RF cavities to demonstrate the required 8 MV/m gradient in a strong magnetic field; the RF drive system to deliver 2 MW, 1ms pulses of 201 MHz frequency at a PRF of 1 Hz; the distribution network to deliver 1 MW to each cavity with correct RF phasing; diagnostics to determine the gradient and transit phase of the muons and the development of the very large diameter magnets required for the accelerators.

INTRODUCTION

The Muon Ionisation Cooling Experiment (MICE), Fig. 1, is being created to demonstrate that ionising interactions with low Z 'absorber' materials, specifically LiH and Liq. H_2, followed by re-acceleration can reduce the emittance of a muon beam in the momentum range of 140-240 MeV/c [1]. Future muon accelerators would have a 'front end' with a repeating lattice of such devices to reduce the emittance to the level demanded by the application. In MICE, the muon beam is formed by the decay of pions generated by the impact between a fraction of the high power proton beam in the ISIS synchrotron and a dynamically inserted target [2]. The experiment aims to measure a 10% reduction in emittance to 1% accuracy in a set up consisting of 3 'absorber' and 2 RF acceleration cells, see Fig 1.

MICE is being conducted in stages, referred to as 'steps'. Step I is complete and the apparatus is now being prepared for the imminent Step IV measurements (which incorporate Steps II and III) and finally Step VI where sustainable cooling will be tested. The staging is illustrated in Fig 2.

EXPERIMENTAL APPROACH

To measure emittance to the required levels, MICE uses a single particle technique, where the behaviour of a real beam will be reconstructed from precision measurements of the behaviour of individual particles. The muons are first momentum selected by the magnets in the transport system from the ISIS synchrotron hall into the MICE hall. The particle species is identified to select the muons for analysis using a range of detectors: time of flight (ToF); threshold Cherenkovs and sampling calorimeter [3]. These have been used in Step I to analyse the constitution of the beam and to perform, using a novel technique, preliminary measurements of the emittance.

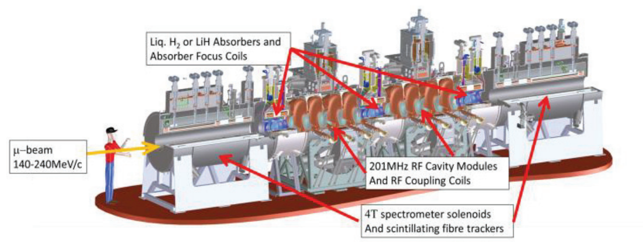

Figure 1: The MICE Step VI Cooling channel.

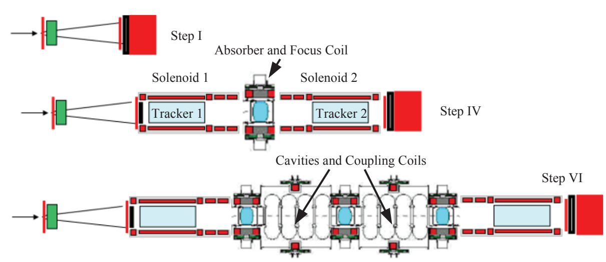

Figure 2: The MICE phased construction project.

In Step IV, the first studies will be undertaken of the effect of transporting the muons through the absorbers [4]. This requires the addition of the first absorber cell and absorber focus coil, along with a much augmented suite of detectors, specifically a pair of scintillating fibre trackers [5] to provide precision phase space measurements of each muon at the entrance and exit of the absorber cell. The measurements will be compared to predictions and simulations of the ionisation cooling process. Enhanced particle identification will be enabled by the electron muon ranger (EMR) detector which will stop all particles and identify muons by the distribution of their energy deposition. Step VI adds two further absorber units, the three absorber cells bracketing a pair of RF accelerators to restore the electron translational momentum. The 8 individual cavities are separated by beryllium windows and are driven by 4 high power 201MHz amplifier chains, with 1MW delivered to each cavity. This will allow a study of the cooling process in an energy sustaining system. An option remains to perform a 'Step V' experiment as an intermediate stage, which would use four RF cavities (i.e. one linac module) sandwiched by 2 absorber cells.

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STEP IV

The apparatus required for Step IV has been making good progress. Both tracking spectrometers have been completed, and the first spectrometer solenoid has been commissioned by LBNL with the second being prepared for test. The first absorber focus coil module (AFC) is also being tested at RAL.

Figure 3: The first spectrometer solenoid training (foreground) whilst the second completes assembly.

Spectrometer System

The scintillating fibre trackers have been completed, and tested using cosmic rays and are now awaiting installation in the solenoids at RAL. Their role is to track the trajectory of particles through the strong magnetic field (4 T) provided by the spectrometer solenoids, hence measuring the phase space footprint of the beam. These exceptionally large superconducting solenoids, which also provide regions of matching magnetic field into the absorber magnet system, are nearing completion at LBNL, Fig 3. The first coil has been fully trained to above the required operational magnetic field, whilst the second is completing assembly and will be tested shortly. As these magnets near completion the performance of the trackers is being re-checked and verified.

Absorber System

The absorbers will comprise either solid LiH, in various configurations, or Liq H_2 cells. The unusual hydrogen handling system has been tested and the liquid absorber chambers have been built, whilst the solid absorbers have been fabricated and will be transported to RAL shortly. A special, large diameter, 4T magnet coil known as the focus coil provides continuity of the guiding magnetic field across the absorber cell. A special feature of these coils is their ability to operate in either solenoid mode, or through having two axial separated windings, in reverse mode, allowing the entire cooling channel to be immersed in either a solenoidal or a periodic magnetic field (in this mode, in Step VI, adjacent accelerators would be in reversed magnetic bias). The first of the focus coils has been commissioned in solenoid mode and is currently being trained in reversing (or 'flip') mode.

STEP VI

The key additional features which will be added to the apparatus for Step VI are the accelerator modules, their 201MHz cavities, four 2MW, driving RF amplifier chains and their associated 'coupling' coils, comprising the two Radio Frequency and Coupling Coil modules (RFCC's). The MICE magnetic field, required to control the relatively disordered particle streams, must co-exist with a strong RF acceleration gradient of 8 MV/m. This poses significant issues for the cavities due to the reduced tolerance of most components to high electric fields in strong B-fields.

Coupling Coils and Cavities

The coupling coils are the largest diameter superconducting windings in the system. These are being constructed by LBNL and the Harbin Institute of Technology in China. The cold masses have been subjected to pressure and vacuum tests and the first one has been shipped to FNAL where it will be tested in a large cryostat whilst its own, more compact, cryostat is built, Fig. 4(a) and (b).

RF Linac Cavities

The RF linac modules Fig 4(c) are being developed by LBNL, FNAL, the Illinois Institute of Technology and the University of Mississippi. Each linac module is formed from four cavities placed directly one after the other, in a single external assembly. The RF cavities are 201 MHz, room temperature, copper cavities (see Fig. 5) with large central beryllium windows for the beam [5]. Each cavity is fed from two 4" co-axial couplers mounted equatorially. A power of 1 MW to each cavity gives a gradient of 8 MV/m. The experiment is expected to operate at a repetition frequency of 1 Hz with 1ms duration pulses. Each cavity will receive an average power of ~1 kW.

The RF cavities are electro-polished after fabrication and are then plastically deformed to bring them close to their desired final frequency. Each cavity is surrounded by a tuning system, Fig. 5, formed by a set of forks driven by an actuator system, this will interface with the Low Level RF (LLRF) control and maintain the cavity resonance by dynamical elastic deformation.

The first cavity has been completed and shipped by LBNL to FNAL where a single cavity test stand has been built in the MuCool Test Area (MTA). This single cavity test cell, illustrated in Fig. 5, will allow the development of experience in the assembly and handling protocols for the four cavity linac modules, and it will allow the first testing of a MICE cavity. The impact of the magnetic field will also be tested at the MTA, initially with a fringe magnetic field and ultimately in the plateau field of the first RFCC when it becomes available.

RF Drive System

The RF cavities will be driven by four separate amplifier chains, one for each adjacent pair of cavities, being developed at Daresbury Laboratory. The amplifiers must deliver 2 MW of peak power in 1 ms pulses at a rate of 1 Hz to provide the energy for the cavities [6,7]. An oscillator provides the input signal to a solid state power

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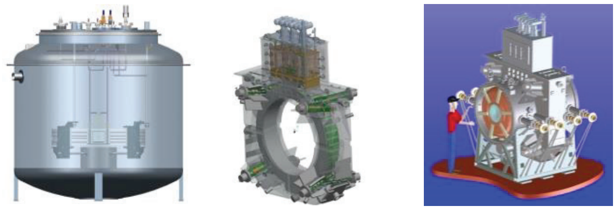

Figure 4: (a) FNAL test configuration for coupling coils, (b) final RFCC cryostat and (c) the RF module and coil.

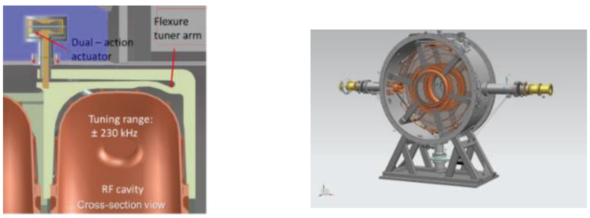

Figure 5: Cavity section showing tuning arm system, and view of the single cavity test stand at the MTA.

amplifier which boosts the power to ~4 kW. This signal drives a tetrode valve amplifier, a Burle 4616 which in turn raises the power to 250 kW. The signal from this amplifier provides the AC grid modulation for a Thales 116 triode valve system that delivers the required 2 MW.

The required 250 kW has been produced by tetrodes running at a bias voltage of 15 kV, whilst the triode amplifier has demonstrated 1.2 MW at 32 kV. Tests are underway to take this up to the final required level of 2 MW. One triode amplifier and two tetrode amplifiers are fully operational, whilst work is advanced on the second triode amplifier. The first amplifier will soon move to the Rutherford Appleton Laboratory, where assembly and operation of the amplifier behind the magnetic shield wall, Fig. 6, to protect the valves from the strong magnetic field, will be demonstrated.

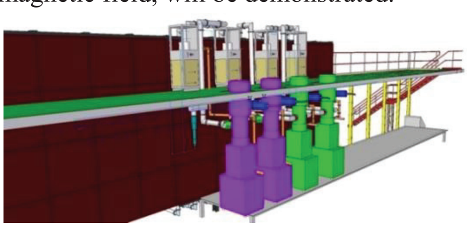

Figure 6: RF Amplifier chain, final installation plan.

Distribution Network

The RF distribution network conveys the signal from the four amplifiers to the eight cavities, over the magnetic shield wall, Fig. 5 and under the floor in the foreground of Fig. 1 to reach the 16 input couplers. At the output from the amplifiers, the signal is split into eight 6” coaxial lines, one for each of the cavities. These signals are then split again to 4” lines, each carrying half a megawatt of peak power to the cavity couplers. The cavities will present a strong reflection during the initial ‘charge cycle’ and during this time the peak line voltage will double. The line will be pressurised to boost its peak power capability, whilst LLRF control will provide a slow ramp in the drive power. This will ensure that the line voltage does not exceed the rating during the pulse.

The system has a fixed phase between adjacent pairs of cavities, optimised for the central muon momentum for the MICE project. The phase between the cavity pairs will be tuned dynamically by the LLRF for the selected momentum range. The gradient is only marginally affected by fixing the phase across pairs of cavities.

LLRF and Diagnostics

The LLRF system is being designed at Daresbury Laboratory, exploiting the LLRF 4 architecture proposed by LBNL. The system will provide at least 1% amplitude regulation and 0.5° in phase. Moreover it will provide for a ramp on the input drive signal, moderating the amplitude of the standing wave below the rated peak capability of the lines. The LLRF will monitor the signal levels at key points in the system. Should these fall out of specification, the LLRF will be able to shutdown the system and report the fault condition that caused the trip.

MICE does not have a prebunched, high fluence beam, but instead will analyse the behaviour of a virtual beam by selection and analysis of many individually tracked particles, randomly distributed in time. It therefore needs to be able to select particles on the basis of the phase of the RF radiation they will experience in the cavities. The analysis of the initial and final momenta for each ‘bunch’ will yield the actual field experienced by that group. It will be necessary to know the RF phase for each grouping to below the 50 ps resolution of the TOF detectors to prevent degradation of the resolution of the data. Since the cavity frequency is known accurately, it is proposed that we need only satisfy the Nyquist criterion on the bandwidth of the feedback system to record the signal. This will greatly mitigate the data acquisition.

SUMMARY

The apparatus for Step IV of the MICE project is nearing completion, with the testing of the large focus and spectrometer magnet systems underway, Step IV will be operational in 2014. The Step VI apparatus, target date 2018, is also being developed, with the testing of the RF cavities and the driving amplifier chains progressing, and construction of the coupling coils underway.

ACKNOWLEDGEMENTS

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REFERENCES

[1] D. Kaplan, MOAM2HA01, these proceedings
[2] C.N. Booth et al, J. Inst. 8 (2013) P03006.
[3] M. Bogomilov et al, J. Inst. 7 (2012) P05009.
[4] V.J. Blackmore, WEPPO17, COOL’13, (2013).
[5] M. Ellis et al, Nucl. Inst. & Methods A 659 (2011) p136
[6] D. Li et al, EPAC’06, 2006, TUPCH148, p. 1367 (2006).
[7] J. Orrett et al, EPAC’08, 2008, MOPD028, p. 508 (2008)
[8] A. Moss et al., EPAC’08, 2008, MOPP099, p. 787 (2008)

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