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THE RF SYSTEM FOR THE INTERNATIONAL MUON IONISATION COOLING EXPERIMENT

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on behalf of the MICE Collaboration,
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Abstract

The International Muon Ionisation Cooling Experiment (MICE) is designed to demonstrate the effectiveness of ionisation cooling to reduce the phase space footprint of a charged particle beam, principally to allow the subsequent acceleration of muons for next generation colliders and/or neutrino factories. The experiment (and indeed any subsequent accelerator cooling channel based on the same principles) poses certain unusual requirements on its RF system, whilst the precision measurement of the ionisation cooling process demands special diagnostics. This paper shall outline the key features of the RF system, including the low level RF control, the power amplifier chain, distribution network, cavities, tuners and couplers, many parts of which are required to operate in a high magnetic field environment. The RF diagnostics which, in conjunction with the other MICE diagnostics, shall allow detailed knowledge of the amplitude and phase of the acceleration field during the transit of each individual muon will also be discussed.

I. INTRODUCTION

The Muon Ionisation Cooling Experiment (MICE), Fig. 1 is being created to demonstrate that ionising interactions with low Z 'absorber' materials, specifically liquid hydrogen or Lithium Hydride, followed by acceleration in RF cavities can decrease the emittance of a muon beam in the momentum range of 140-240 MeV/c by 10%. 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. The muons are produced by decay of pions formed by the interaction of an intense and moderately energetic proton beam with a target. In the case of MICE, a fraction of the beam in the ISIS synchrotron is periodically intercepted by a dynamically inserted target [1,2].

The MICE experiment has several unusual features from an RF perspective. Firstly, in order to control the relatively disordered particle streams, and to control the cooling process, one must immerse the experiment in a strong magnetic field. This magnetic field 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. Secondly, the MICE experiment has a relatively low fluence of muons, the rate being sufficiently low that it is possible for the diagnostic suite to record data for each individual particle transiting the system. By analysing the properties of every muon as it transits the cooling cell, and comparing this as a benchmark to simulation software, it will be possible to predict the impact of the cooling process on a realistic, high fluence beam. This however means that the muons are randomly distributed in time with a broad transverse phase space as they approach the cooling channel. As the effectiveness of the cooling process vitally depends on the muons being accelerated in the RF cavities, only some particles will be in the correct relative phase range for this process to take place. The experiment needs therefore a measurement which allows it to sort the muons by the RF phase they will experience.

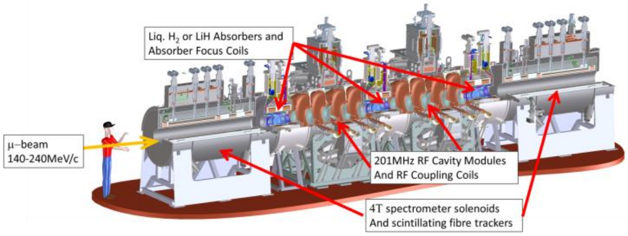

Figure 1 The MICE Cooling Channel

II. COOLING CHANNEL

Muons are produced in a pion decay region between the target in the ISIS synchrotron hall and the MICE hall itself, beyond the left end of the cooling channel shown in Fig. 1 [3]. In this region the particles are momentum selected by dipole magnets and directed into a sequence of detectors designed to identify the type of particle and to select only the muon data for analysis. Time of flight detectors provide high resolution (~50 ps) timestamps on the muon events at 3 points in the line (2 are at either end of the structure in Fig. 1), whilst two fibre trackers [4] provide precise measurements of the momentum and spatial distribution of the particles at the entrance and exit of the cooling channel. Fig. 1 illustrates the general layout of the complete MICE Step VI experiment, where between these two sets of diagnostics there are three cells containing the absorber material, and two banks of 4 RF cavities. The particle spectrometers are surrounded by large solenoids, whilst each absorber cell has a separate ‘focus coil’ consisting of two windings which can either be driven in the same direction or in opposite directions. A large diameter coil, called the Radio Frequency Coupling Coil (RFCC) surrounds each bank of cavities.

A. RF Lin-Ac Cavities

The development of the RF linac modules is being led by the US team members, principally by LBL , FNAL, Univ. of Mississippi and the Illinois Institute of Technology. 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. 2) with large central beryllium windows for the beam [6]. Each cavity is fed from two 4” co-axial couplers mounted equatorially. A power of 1 MW to each cavity (500 kW on each coupler) gives rise to a gradient of some 8 MV/m. As the beam is extremely tenuous, there is no loading of the cavity fields by the beam and all the energy delivered to the cavity is dissipated in the walls of the cavity. The experiment is expected to operate at a repetition frequency of 1 Hz with pulses 1ms in duration. Each cavity will receive an average power of ~1 kW.

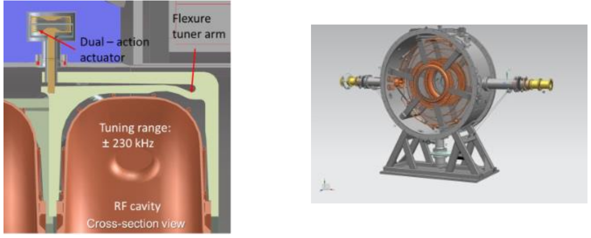

Figure 2 Cavity section showing tuning arm system, and view of the single cavity test stand at the MTA [5].

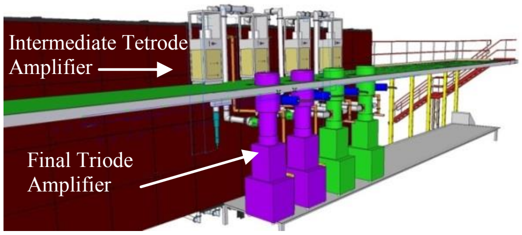

Figure 3 RF Amplifier chain, final installation plan.

The RF cavities are electropolished after fabrication and are then slightly plastically deformed to bring them close to their desired final frequency. Each cavity is surrounded by a tuning system, Fig. 2 formed by a set of forks driven by an actuator system that will interface with the Low Level RF (LLRF) control, this ensures that any spectral shift in the cavity resonance, due perhaps to temperature variations, will be corrected by additional, dynamical elastic deformation.

The status of the linac system is that the first cavity has been completed and shipped by LBL to FNAL where a single cavity test stand has been built in the Muon Test Area (MTA). This single cavity test cell, illustrated in Fig. 2 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. One special feature of the MICE project is that the cavities must operate in a strong magnetic field. This will also be tested in the MTA, initially with a fringe magnetic field and ultimately in the plateau field of the first RFCC when it becomes available.

B. RF Drive System

The RF cavities will be driven by four separate amplifier chains, one for each adjacent pair of cavities, as illustrated in Fig. 3. Each amplifier chain must deliver 2 MW of peak power in 1 ms pulses at a rate of 1 Hz to provide the energy for the cavities [7,8]. The RF amplifier chain is being developed at Daresbury Laboratory with participation of RAL, Strathclyde University and Imperial College. A master oscillator provides the input signal to a solid state power amplifier which boosts the power to ~2-4 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 amplifies the signal to 2 MW.

A sophisticated power supply system has been built for each amplifier consisting of large capacitors and their associated charging power supplies which set the valve bias voltage and grid/cathode switches to allow the amplifier chain to be pulsed as required. Crowbar circuits have been integrated into the power supply with current sensors on the high tension (HT) circuits to sense arc surges. Any such surge triggers the crowbar and latches the supply off until the cause can be resolved, protecting the RF valves from damage..

An amplifier commissioning and proving facility has been built at Daresbury lab., allowing testing of amplifiers independently of the experimental and construction activity at RAL. The prototype amplifier system has been successfully commissioned showing that the required 250 kW can be developed by the tetrode amplifier running at a bias voltage of 15 kV, whilst the triode final stage amplifier has demonstrated 2.06 MW at a bias voltage of 34 kV. The prototype amplifier chain has been installed and operated at the MICE hall to the limits of the available loads (500kW).

At this time, one triode amplifier and two tetrode amplifiers have demonstrated the required performance, whilst work is advanced on two more tetrode amplifiers and three further triode amplifiers.

C. Distribution Network

The RF distribution network has been designed by Daresbury Laboratory and procured through the University of Mississippi. It must convey the signal from the four amplifiers to the eight cavities, over the magnetic shield wall, Fig. 3 and immediately 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 in 90^o, 3 dB hybrid couplers to 4” lines, each carrying half a megawatt of peak power to the cavity couplers, threaded through the floor support struts. A key issue is that the cavities will present a strong reflection during the initial ‘charge cycle’ and during this time the line will have to deal with a doubling of the line voltage at the antinodes of the standing wave. This effect will in fact follow all the way back through the distribution system. The line will be pressurised with dry nitrogen to boost its peak power capability, whilst using the LLRF feed forward control feature to programme in a slow ramp in the drive power. This will ensure that the superposition of the input and output signals does not exceed the line rating at any time during the pulse.

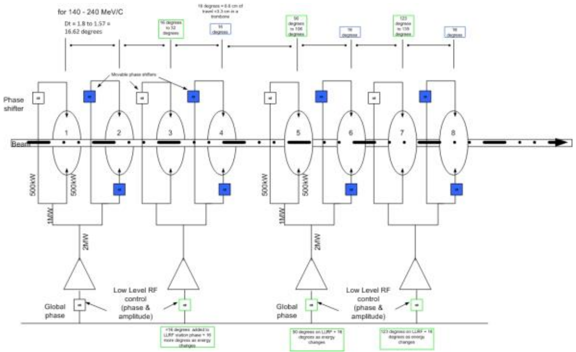

Figure 4 RF Distribution network, general layout.

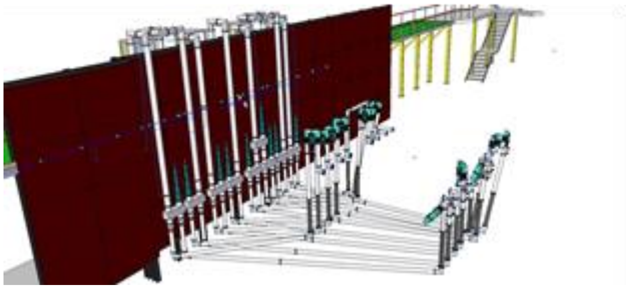

Figure 5 3D CAD Model of RF Distribution network

The general layout of the distribution network is illustrated in Fig. 4. Electronic phase control will be provided by the LLRF system between each amplifier chain to tune the accelerator for the selected muon momentum range. However since each amplifier feeds a pair of cavities, it is not possible to provide fast phase control between these cavity pairs. In fact it turns out that phase control between these elements is not vital. If the phase between these pairs of cavities is tuned to the global central momentum for the entire MICE experiment then the difference in the gradient experienced by the early or late arrival of the highest and least energetic particles is in fact negligibly small. This eliminates the need to provide high power dynamic phase shifters. The phase shifting hardware indicated in the diagram exists purely to eliminate assembly errors. Figure 5 illustrates the routing of the waveguides showing how the space between the screen wall and the cooling channel is kept relatively free from obstructions for service access to the components of the channel.

D. LLRF and Diagnostics

The LLRF system is being designed at Daresbury, exploiting the LLRF 4 architecture proposed by LBL. The system will provide at least 1% amplitude regulation and 0.5^o in phase. Moreover it will provide for a pre-programmed ramp on the input drive signal, moderating the strength of the standing wave patterns below the rated peak capability of the lines. The LLRF boards will also perform a monitoring function for the entire system, measuring the forward and reverse signal levels at key points in the system. Should these fall out of specification, the LLRF will be able to shut down the system and report the fault condition that caused the trip.

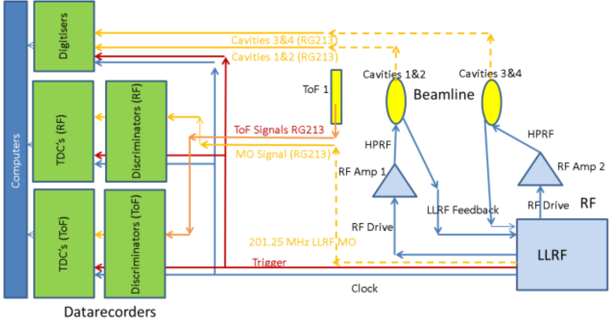

Figure 6 Proposed diagnostic system for Muon-RF phase determination

As noted previously, MICE operates not on a prebunched, high fluence beam, but on the principle that it can form a virtual beam by analysis of many individually tracked particles. To do this however it is essential to be able to understand the phase of RF radiation experienced by each particle in the accelerator cavities. This poses an unusual diagnostic problem. In fact it is not vital to know the absolute phase of RF for each muon, but instead to be able to bundle together muons which will have experienced the same initial RF interaction. The analysis of the initial and final momenta for each ‘group’ will yield the actual field experienced by this group. The key difficulty however is that it will be necessary to know the RF phase for each grouping to below the 50 ps resolution of the TOF detectors in order to prevent degradation of the resolution of the data. As the LLRF will force the phase of the cavities to well beyond this accuracy, it is necessary to monitor the phase of only one of these. Normally to determine the phase of a sinusoidal signal it should be necessary to digitise it at the Nyquist rate, which would generate a great deal of data. It is also difficult to pre-trigger the data acquisition system since the event data would come late. However since we know the cavity frequency (the Q is 44,000) very accurately, and indeed since the feedback loop will constrain the bandwidth even more tightly than the cavity, we need only satisfy the Nyquist condition on this much smaller rate to record the signal. This will mitigate the data acquisition. Work is under way at Strathclyde to test the reconstruction of a realistic, imperfect sinusoidal waveform from such subsampled data, whilst both Strathclyde and Sheffield are investigating systems based on TDC data recorders to timestamp a fraction of the zero crossings of the RF waveform. With this information contrasted against the timestamp provided by the TOF detectors, it should be possible to use the axial momentum data from the tracker detector [4] and computer projections to determine the transit phase of the muons. Figure 6 shows the general arrangement for a system which can provide this relative timing information.

III. SUMMARY

The RF system for the MICE project is being developed at four laboratories in the UK and US, with involvement from Universities in each country. The first cavity tests and the high power RF driver tests are expected this year. The RF system will be required for MICE Step V (two absorbers and one accelerator) and Step VI (three absorbers and two linacs) with expected dates of 2018 and 2020 respectively.

IV. ACKNOWLEDGMENTS

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