PROCEEDINGS OF SCIENCE

The Progress on the MICE RF System

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The Muon Ionisation Cooling Experiment (MICE) aims to demonstrate ionisation cooling with re-acceleration by reducing the emittance of muon beams with momenta in the range of 140-240 MeV/c. MICE will also demonstrate the viability of the technologies needed for the front end of future muon colliders or neutrino factories. As each emittance measurement is essentially a ‘single particle’ measurement and the muon arrival times are randomly distributed, a system is required with the capability to detect each muon and relate the time of its transit through the cavity to the RF phase of the accelerating field. This is an unusual requirement which demands a novel combined particle and RF instrument.

This paper outlines the main parts of the drive system - the low level RF (LLRF) control system, the amplifier chain and its distribution network - and reports on their current state of development. In addition, the RF diagnostic system is described which will provide information on the amplitude and phase of the field within the cavity during the individual muon transits.

16th International Workshop on Neutrino Factories and Future Neutrino Beam Facilities
25 -30 August, 2014
University of Glasgow, United Kingdom

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PoS(NUFACT2014)124

1. Introduction

Muon accelerators have applications in high energy physics experiments; storage rings containing energetic muon beams are viewed as potential sources for neutrino beams in a Neutrino Factory [1][2][3] whilst muon-based high energy lepton-anti-lepton colliders [4][5] can enable high precision measurements at very high energy. Muon beams are formed by the decay of pions resulting from the interaction of a very intense proton beam with a target and have large emittance. For either application, the phase space footprint of the muon beam would have to be reduced from its natural condition to allow efficient acceleration to high energy. This would be accomplished by 'cooling' the beam before acceleration and storage.

There are several different approaches to cooling that can be used to reduce the emittance of a beam, however most of these methods are unsuitable for use with a beam comprised of muons due to the short lifetime of the particles. The average lifetime of a muon at rest is 2.2 μs and most methods of cooling require longer than this to achieve the desired emittance. This leaves ionisation cooling, which can perform the cooling process within this short time period. Ionisation cooling is included in the proposed designs for the Neutrino Factory and the Muon Collider.

Ionisation cooling is achieved by passing a muon beam through an absorber material which causes an ionisation energy loss. This reduces the normalised emittance of the beam. The momentum of the muons is reduced by ionising the atoms in the material; this energy loss reduces both the transverse and longitudinal momenta of the beam. The particles are then reaccelerated by an RF cavity, which restores the longitudinal momentum without restoring the transverse. Equation 1, below, is used to describe ionisation cooling and is made up of two main terms; the first term on the right hand side describes the cooling effect (the reduction in emittance per unit length). The second term shows the effect due to multiple scattering (heating effect).

$$\frac{d\varepsilon_n}{dx} \approx \frac{-\varepsilon_n}{\beta^2 E_\mu}\left\langle\frac{dE}{dx}\right\rangle + \frac{\beta_t\left(14\,MeV/c\right)^2}{2\beta^3 E_\mu m_\mu X_0} \qquad (1)$$

where ε_n is the normalised emittance, β_t is one of the Twiss parameters and X_0 is the radiation length. When the cooling and heating effect reach an equilibrium state, the beam emittance can be described as

$$\varepsilon_{eq} \approx \frac{\beta_t(14MeV/c)^2}{2\beta m_\mu X_0}\left|\left\langle\frac{dE}{dx}\right\rangle\right|^{-1} \qquad (2)$$

where $\beta = v_\mu / c$ is the beam's normalised velocity, E_μ is the energy of the muons, x is the distance traversed and m_μ is the rest mass. $\left|\langle\frac{dE}{dx}\rangle\right|$ is the magnitude of the energy loss of the beam. The lowest possible emittance will be produced when β_t is minimised (met when there is strong focussing at the absorber) and $\left|\langle\frac{dE}{dx}\rangle\right|.X_0$ is maximised. The longitudinal energy lost passing through the absorber cell must be replaced by RF acceleration since sustained cooling in subsequent cells depends on maintaining the energy of the particles in the range where the cooling term dominates the heating term.

MICE is currently under construction to test ionisation cooling experimentally. The present apparatus is designed to measure the emittance change in a muon beam as it transits an absorber cell (absorber materials will include liquid hydrogen and lithium hydride- LiH); this is referred to as MICE STEP IV (figure 1). This requires an extensive suite of beam diagnostics including particle identification detectors, momentum spectrometers (one upstream and the other downstream from the absorber) and three time of flight detectors which precisely time stamp the particles as they transit through the experiment.

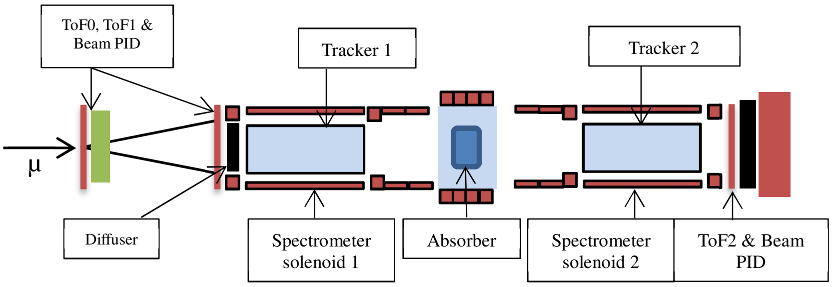

Figure 1. MICE Step IV schematic layout

To demonstrate ionisation cooling with reacceleration, MICE will ultimately consist of 1 primary LiH absorber between 2 RF accelerating cavities which are bracketed by thinner LiH absorbers, primarily to protect the diagnostic equipment from electrons emitted from the RF cavities (figure 2). The experiment will measure the effectiveness of the cooling process as a function of the RF gradient whilst demonstrating the technology required to build a front end for the neutrino factory.

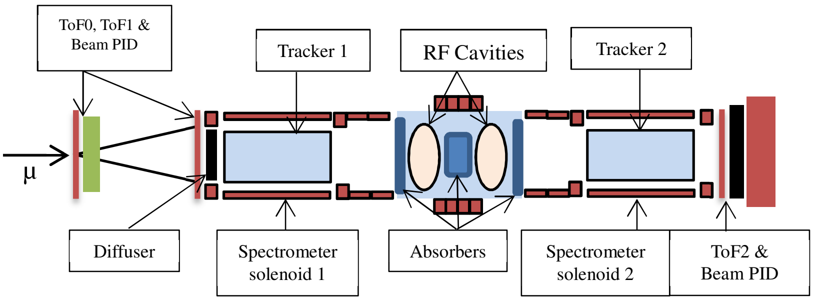

Figure 2. Schematic of MICE Demonstration of Ionisation Cooling with Re-acceleration

2. High Power Radio Frequency Drivers

The amplifier chain that will be used to excite the cavities is currently under development at Daresbury Lab with participation from RAL, Imperial College and the Universities of Strathclyde and Mississippi. Each chain is required to deliver 2 MW of peak power to drive one cavity [6] [7].

Each chain is comprised of an oscillator which provides the input to a 4 kW solid state power amplifier. This, in turn, drives a Burle/Photonis 4616 tetrode amplifier which raises the power to 250 kW. The RF output from the tetrode drives a Thales 116 triode amplifier which outputs 2 MW. The power is split by a 3 dB quadrature hybrid coupler which delivers 1 MW to each input port; each cavity will be excited with 2 couplers fed by 4” coaxial line. This chain has a duty cycle of 1 ms at 1 Hz which results in an average power per cavity of ~ 2 kW [8].

One amplifier chain has been tested at Daresbury and the required 2 MW power level was observed; the details are recorded in Table 1 (below). The amplifier was installed and tested at RAL and has subsequently returned to Daresbury for further testing and incorporation of the automation system.

Output RF Power	2.06 MW
Bias Voltage	34 kV
Forward current (average)	129 A
Gain	10.8 dB
Efficiency	0.46
Return loss	-12.5 dB

Table 1. TH116 Triode Performance data

3. Low Level RF Control System

The LLRF system will be developed at Daresbury based on the system that was implemented on ALICE [9], using the LLRF4 system first developed by L. Doolittle (LBNL) [10]. The LLRF will provide control and stabilisation of the cavity signal to within 1% in amplitude and 0.5° in phase and will control the ramp of the amplifiers to prevent overloading of the RF high power co-axial lines due to the initial reflection of the signal back from the cavity during the fill process [11]. A demonstration of this ramp functionality has been built and tested at 1.3 GHz.

The LLRF will also allow programmable phase control between different amplifier chains and hence enable tuning of the accelerator for the central momentum required for any desired experiment. The LLRF will be used to monitor the input/output at specific points in the power distribution network and will have the ability to cut power to the amplifier systems if these are out of specification.

4. Power Distribution Network

Output from each high power amplifier is coupled into a single $6\,{}^{1}/_{8}$” co-axial line. Power is then split using $6\,{}^{1}/_{8}$” hybrid couplers. The co-axial line diameter is finally reduced to match the $4\,{}^{1}/_{16}$” diameter of the cavity couplers with each line carrying 1 MW (figure 3). The LLRF system provides phase control between the different amplifier chains to allow tuning of the RF system to accommodate operation over a range of muon momenta. Line trimmers will be used to adjust the line lengths after installation. The co-axial lines will be pressurised to enhance their peak power handling capability.

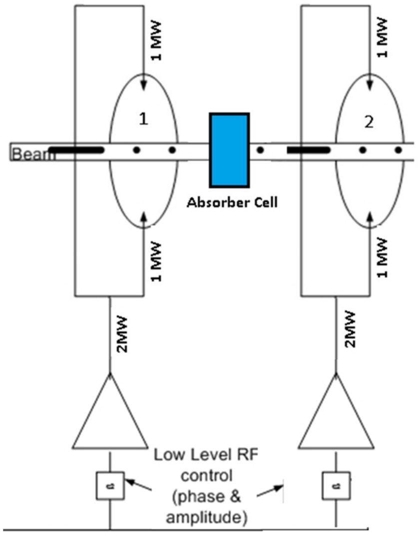

Figure 3. Schematic of the High Power distribution network

5. RF Diagnostics

MICE will perform individual particle measurements. Three Time of Flight (ToF) detectors will be used to indicate when a particle enters the experimental channel with a resolution of ~ 50 ps. The Tracker diagnostic will provide accurate position and momentum data to determine the muon trajectory within the experiment. The phase of the RF inside the cavity must be correlated with the ToF event so that the accelerating gradient experienced may be determined. The aim is to be able to select particles by the RF phase that they experience; muons which were optimally accelerated can then be analysed statistically to understand the effectiveness of the cooling.

In order to understand what electric field the muon experienced it is necessary to sample the RF signal inside the cavity. The experiment runs at 1 Hz with an RF pulse length of 1 ms, if the cavity is sampled at 2 GSa/s, a rate that comfortably satisfies the Nyquist condition for this case [12], then the amount of data that would be generated would be significant (~2 MB/s). This data would then have to be transferred from the capture digitiser into storage before the next pulse of the experiment, a relatively demanding task. However, as the linewidth is limited by the cavity Q (linewidth <5 kHz), one may accurately reproduce the signal with a much lower sample rate.

If the signal within the cavity is subsampled in this manner, then the amount of data one must transfer in the short period of time between pulses is enormously reduced. This has the added advantage of reducing the amount of storage required for the raw experimental data.

The testing of this undersampling method is currently underway and uses the digital signal processing (DSP) principle which states that signal reconstruction using the 'low resolution' data in the spectral domain can effectively simulate an increased sampling rate in the time domain. This has been shown to work for signals generated numerically and captured via an oscilloscope and is being tested on cavity signals provided from the high power cavity tests currently underway at FNAL. Shown in figure 4 is a comparison of a high resolution (5 GSa/s) cavity trace obtained from the cavity tests at FNAL (blue) and the signal after subsampling at a rate of 20 MSa/s and subsequent Fourier domain reconstruction (red). It can be seen that the amplitudes vary slightly between the plots; however the phase of the reconstruction shows good agreement with the original cavity signal. Work is continuing to increase the accuracy of the process and to test sensitivity to the signal properties.

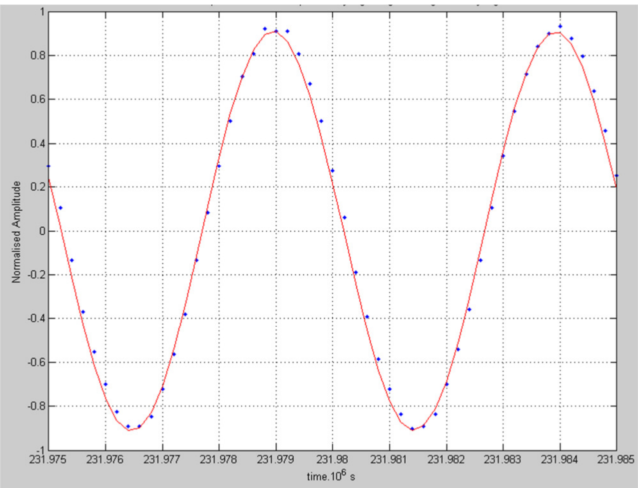

Figure 4. Comparison of sample obtained from cavity at 5 Gsa/s (blue) and reconstruction of subsampled trace (red)

6. Conclusions

To demonstrate ionisation cooling with re-acceleration, the MICE experiment requires the operation of two 201.25 MHz, 10.3 MV/m cavities to compensate for the energy loss as the particles traverse a LiH absorber. Each of these cavities will be excited by a 2 MW RF amplifier chain. The first amplifier and a prototype cavity have been tested and have exceeded the required performance levels. The RF distribution network has been designed to deliver 1 MW to each input coupler of the cavity.

A diagnostic to determine the RF phase of the cavities at an arbitrary point in time based on a DSP Fourier domain reconstruction of an 'undersampled' waveform is being developed. This diagnostic, linked to the ToF particle detectors and momentum spectrometers, will be used to identify those particles experiencing optimum acceleration. Analysis of the trajectories of these selected muons will determine the emittance reduction of the beam.

7. Acknowledgements

The research leading to these results has received funding from the UK STFC, the US DoE, the US National Science Foundation and the European Commission under the FP7-INFRASTRUCTURES-2010-1/INFRA-2010-2.2.11 project TIARA (CNI-PP), Grant agreement no 261905.

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