THE DESIGN AND IMPLEMENTATION OF THE RADIATION MONITORS FOR THE PROTECTION OF THE MICE TRACKER DETECTORS*

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Abstract

A radiation monitor will be required for the Muon Ionisation Cooling experiment (MICE) beyond Step IV, when the RF cavities are installed. The role of the radiation monitors will be to protect the particle tracking detectors (Trackers) from dangerous levels of RF dark currents and the associated photon fluxes that could potentially be produced in the RF cavities. If such levels of radiation should occur the radiation monitor will ensure that the radiation shields (shutters) are closed thereby protecting the Tracker modules. The radiation monitor will be positioned on these radiation shields and will monitor x-rays, gamma-rays and electrons up to a few MeV. It is expected that the spectrum will peak at very low energies, since the peak voltage across the cavities is 8 MV/m and so the maximum energy that an electron could gain is 12 MeV (maximally accelerated from all four RF cavities). The design, positioning and expected sensitivity of the radiation monitors will be described here along with their readout and inclusion into the MICE interlocking systems. The schedule for the work and progress so far will also be presented.

INTRODUCTION

The Muon Ionisation Cooling Experiment (MICE), under development at the Rutherford Appleton Laboratory (UK), aims to demonstrate ionisation cooling for the first time. Ionisation cooling is the process of reducing the beam emittance (phase space) while maintaining the longitudinal momentum of the beam. As the muon lifetime is relatively short, traditional beam cooling techniques which reduce emittance cannot be used and ionisation cooling is the only practical solution to preparing high brilliance muon beams for use in the Neutrino Factory or Muon Collider.

The MICE experiment shown in Figure 1 [1] will pass a muon beam through a low-Z material, called an absorber, where the muons lose both longitudinal and transverse momentum through ionisation energy loss (cooling). The lost longitudinal momentum is then restored using accelerating RF cavities that follow the absorber. The result is a net reduction in transverse momentum spread with constant longitudinal momentum. Along with this cooling, however, there is a heating effect produced as a result of multiple scattering through the system, therefore, the net cooling is a balance between these two effects. This is described in Eq. 1, where the first term on the right hand side represents the cooling effect and the second term the heating effect:

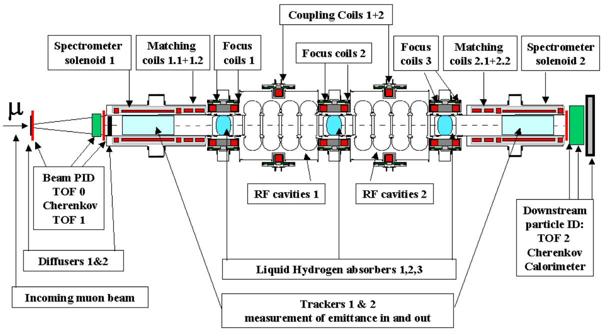

Figure 1: Schematic of the International Muon Ionisation Cooling Experiment (MICE), with the beam entering from the left.

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

$\frac{d\epsilon_n}{ds}$ is the rate of change of normalised-emittance within the absorber; β, E_μ and m_μ the muon velocity, energy, and mass respectively; $\beta_\perp$ is the lattice betatron function at the absorber; and L_R is the radiation length of the absorber material.

MICE aims to achieve a 10% reduction in muon beam emittance and to measure it with an accuracy of 0.1%. To do this each muon will be measured individually by an upstream and downstream high precision scintillating fibre tracking detector (Tracker). The Trackers are contained within super-conducting spectrometer solenoids which produce a 4 T field. The muon beamline has been commissioned and the beams have been shown by direct measurement with MICE particle detectors to be adequate for cooling measurements, the beam was experimentally studied paying particular attention to the rate, particle composition and emittance; the Trackers are built and fully tested.

MICE STAGES

MICE will be built in three main stages as shown in Figure 2.

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[1] This shows the MICE Step VI design including two RF cavities and three absorbers, which represents a full Neutrino factory lattice cell. 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, at present MICE is reviewing whether the time and cost of Step VI is commensurate with the extra information it provides.

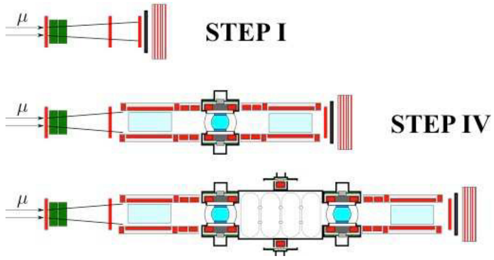

Figure 2: The stages of the MICE Experiment.

Step I commissioned the beamline and tested the beam particle rate, particle identification and performed some emittance measurements [1, 2]. The setup included the full beamline instrumentation and several particle identification (PID) detectors. It was completed in 2013.

Step IV is currently in the advanced stages of construction and commissioning [3]. It will test the full system but without RF cavities to re-accelerate the beam (and will have only one absorber). Step IV will demonstrate ionisation cooling but without beam re-acceleration which means it will not be sustainable cooling. Data taking is on target to begin in 2015.

Step V will include the RF cavities and an additional absorber module and will represent half of a full lattice cell of the Neutrino Factory Feasibility Study II (FS-II) [4] cooling channel. The Step V configuration will allow the essential demonstration of ionisation cooling with re-acceleration to be achieved. Construction of Step V is scheduled for completion in 2017. The radiation monitors and shielding become essential at Step V to protect against potentially dangerous levels of radiation that could be produced in the RF cavities and may damage the Trackers.

RADIATION MONITOR

Purpose

The RF Cavity Modules are four, 0.43 m, normal conducting 201 MHz copper RF cavities within a super-conducting solenoidal coupling coil. They are designed to operate at a high field gradient of 8 MV/m making the cavities susceptible to field emission of electrons which are accelerated by the RF fields. Radiation shields have been designed and built to shield the Tracker detectors which sit on either side of the RF cavities from any such radiation. Ensuring that the radiation shields are closed until safe conditions have been achieved is the job of the the radiation monitor. Technical drawings of the radiation shield to which the monitor (not shown) will attach can be seen in Figure 3. Figure 4 is a photograph of the end of the super-conducting spectrometer solenoid showing the bore (in which the Tracker sits) which is protected by the shield.

Design

The radiation monitor will sit on the radiation shield and monitor x-rays, gamma-rays and electrons of a few MeV—since the maximum energy that an electron/photon can theoretically have ~12 MeV from the four RF cavities, yet we see from simulation that it is likely that the spectrum will peak at much lower energies. A treatment of the simulation work for this study see can be seen elsewhere in these proceedings [5]. The readout will be monitored in the control room and so adequate cabling and electronics readout systems must be designed. The radiation monitors are currently in the design phase.

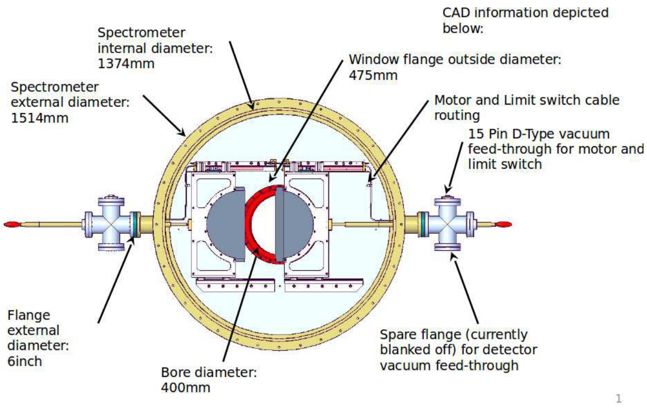

Figure 3: Technical drawing showing the radiation shield and its assembly. The red circle is the bore of the magnet where the Tracker detector sits. The two dark grey cylinders are the two halves of the shield itself that splits open, exposing the Tracker and allowing the beam through. The white is the mechanism that moves the shields.

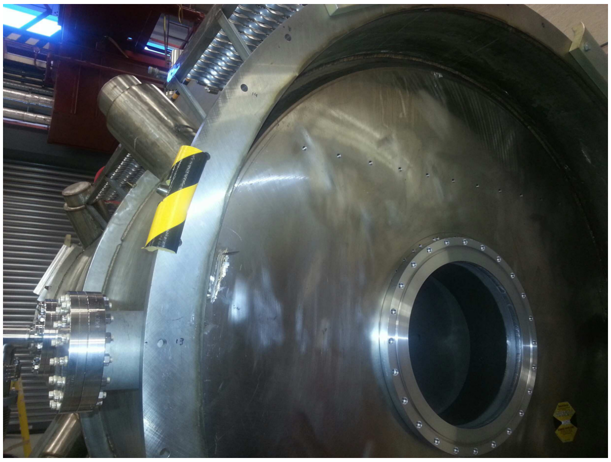

Figure 4: Photograph showing the upstream super-conducting spectrometer solenoid and its bore (in which the Tracker sits) which must be shielded.

Detectors Silicon detectors can be used for detecting, counting and determining the energy of charged particles. The energy resolution of the detector is significantly affected by its capacitance, which is in turn dependent on the active area. Implanted and diffused silicon surface barrier type detectors are available; implanted silicon detectors perform better within the range of parameters where they are appropriate, but there is a broader range of device parameters available from the silicon surface barrier type detectors (SSBDs) and so they are chosen.

The majority of SSBDs are partially depleted (active counting depth within the silicon) while the 'B' type which we will use, is fully depleted meaning that apart from thin surface layers the full thickness of the silicon is actively detecting. Partially depleted detectors are closed at the back as the intention is that all particles incident on the front of the detector will be absorbed by the depletion layer and certainly will not be expected to pass through the detector completely. In the case of fully depleted detectors it is expected that at least some of the particles will be energetic enough to pass through. In these cases a second detector can be placed behind the first.

As it is likely that the spectrum will peak at very low energies, the radiation monitors are designed to have a pair of thin sensors, sensitive to the high rate of low energy photons/electrons and a thicker pair sensitive to higher energy, lower flux. These detectors can be used in a vacuum, they have an operating temperature of $^{+}25 -^{-} 30^{\circ}C$ and a guaranteed maximum resolution for alpha and beta test counts in tens of KeV. The thicker 2000 micron detectors will have better conversion capability and be sensitive to high energy x-rays while the thinner smaller sensors will be sensitive to the lower energy end of the spectrum. The active areas of the detectors are 50-450 mm^2 and the max resolution for alpha and betas is 18 and 13 KeV respectively for the thin and 26 and 21 KeV respectively for the thick detector.

Positioning

The radiation monitors must be positioned on the radiation shields such that they are: perpendicular to the beam, do not infringe on the beam, stay clear of the aperture and give a clear picture of the radiation "cross-section". Ideally also the amplifier should be away from high levels of radiation and magnetic field, i.e. outside the vessel and special consideration is given to the signal/noise ratio, that can be affected by long cable lengths.

There are currently two designs for the detector positioning on the radiation shields—shown in Figure 5. A decision will be made between them shortly based on the outcome of further simulation and recent changes to final MICE design.

Readout

The monitor will be read out using a local pre-amplifier sitting close to the detector and mounted in the vacuum (9-12 V, the selection of the pre-amp is matched to the capacitance of the detector). Cables then run from the pre-amplifier to the amplifier and MICE control room and final readout is tied in with interlocking system to ensure minimum response time for radiation monitors to override shield opening.

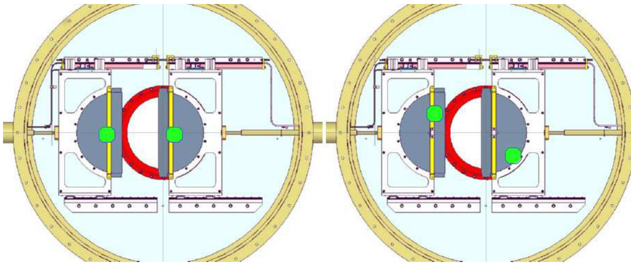

Figure 5: Possible positions of the two pairs of radiation monitors in green (not to scale). Both layouts meet the criteria well, with the rightmost design allowing a greater cross-sectional area to be sampled, but a more complex cabling system must be used. The coaxial cables that connect to the detectors can be connected to the white frame and fed out via the four way flanges. The pre-amplifiers can be mounted inside the vessel (beige outer ring) inside the vacuum.

CONCLUSIONS

The MICE experiment aims to reduce the emittance of a muon beam by 10% and to measure it with an accuracy of 0.1% using a pair of Tracker detectors. The Trackers will be positioned either side of an RF module of four RF cavities with a high field gradient of 8 MV/m. These RF cavities could produce dangerous levels of RF dark currents and associated photon fluxes which could potentially be dangerous to the Trackers. The radiation monitors are essential to ensure that the radiation shields are closed should such levels of radiation occur.

Much of the design work for the radiation monitors is well advanced and the choice of detector and electronics chain will be finalised in the next few months. The system will be built, installed and tested prior to Step V construction completion in 2017.

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