ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRI003

SIMULATING THE PRODUCTION AND EFFECTS OF DARK CURRENTS IN MICE STEPS V AND VI*

C. Hunt†, J. Pasternak, M. A. Uchida, Imperial College London, UK
for the MICE collaboration

Abstract

The completion of the international Muon Ionisation Cooling Experiment (MICE) Step V will involve the construction, commissioning and use of RF cavity and Coupling Coil (RFCC) Modules. The RFCCs consist of 4 RF cavities and a solenoid magnet, and are expected to act as a source of potentially damaging electrons (dark currents) and X-rays. Ongoing work to create a high-statistics simulation of the dark current production, within RF cavities, is described. Current results predict the energy and angular spectra of emitted electrons for an RFCC, and include particle tracking, realistic field maps and ionisation energy losses in cavity windows. Individual electron emitters, parametrised by the Fowler-Nordheim equation, are used and are user-definable, allowing potential worst-case scenarios to be simulated and upper/lower limits for the total dark current to be estimated. These data are being used within the MICE Analysis and User Software (MAUS) to estimate the potential detector backgrounds and the damage that may be inflicted upon the scintillating fibre trackers.

INTRODUCTION

The International Muon Ionisation Cooling Experiment (MICE), aims to demonstrate ionisation cooling such that similar technologies may be exploited in future cooling-channel designs. Ionisation cooling is currently the only technology fast enough to cool a muon beam within the short muon lifetime, hence it is currently of great interest to future muon beam experiments. The design of MICE Step VI is based on the cooling cell from the channel described in the Neutrino Factory Feasibility Study [1]. Due to recent rescoping, the experiment will reach its conclusion with Step V - one half of the cooling cell - rather than the originally intended Step VI.

Ionisation cooling is a two stage process, firstly the beam is passed through an absorbing material to isotropically reduce the beam momentum, and secondly the beam is re-accelerated in the longitudinal direction only, in order to restore the lost longitudinal momentum. For MICE Step V liquid hydrogen is the primary cooling material due to its high rate of energy loss and very low levels of multiple scattering. The re-acceleration is provided by four RF cavities in a single RF cavity and Coupling Coil module (RFCC).

This process may then be repeated, combined with strong focussing, to provide a progressive and significant reduction in beam emittance. Alternating the magnetic field lattice reduces the build up of angular momentum and improves the cooling. Hence, the Absorber Focus Coil modules (AFCs) in MICE are designed to be operated with their two solenoid magnets either in parallel operation - solenoid mode, or in an anti-parallel operation - flip mode.

* Work supported by the (UK) Science and Technology Facilities Council and the (US) Dept. of Energy and National Science Foundation
† christopher.hunt08@imperial.ac.uk

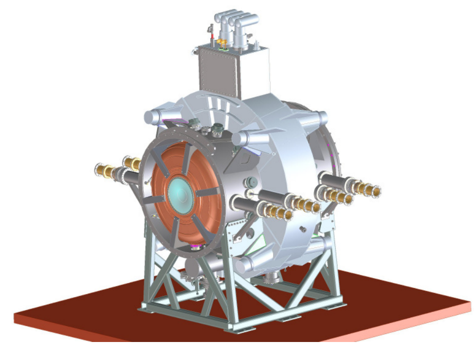

Figure 1: Rendering of the RFCC designed for MICE Step V. The copper cavities are visible in brown with the beryllium windows in the centre. The RF couplers can be seen protruding from the module.

To verify the beam cooling, multiple detectors are under construction [2], the Scintillating Fibre (SciFi) Trackers being vital in order to make the emittance measurements.

MICE Step V

MICE Step V is due to be commissioned during 2018 and is composed of upstream and downstream spectrometer solenoids, housing the two SciFi Trackers, between which are the two AFCs and the RFCC.

MICE RF Cavities are constructed as a set of four, contained within a super conducting, solenoid Coupling Coil, shown in Fig. 1. The cavities are normal conducting 201 MHz copper cavities, designed to be operated at a peak, on-axis accelerating gradient of 8 MV/m. This high field gradient makes the cavities very susceptible to the field emission phenomena, in which electrons are pulled from the surface of the metal and accelerated by the RF fields.

SciFi Trackers are the core detectors for MICE, designed to be capable of reconstructing beam emittance to a precision of 0.1%. They use 5 stations, each with 3 planes of scintillating fibres, to measure muon tracks and extrapolate the particle momentum vector. The scintillating fibres are extremely sensitive to damage and degradation from high energy electrons and X-rays. It is important, therefore, to be able to predict any unwanted exposure that the stations will experience and protect against it.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRI003

Field Emissions

This is the process whereby electrons are emitted from the surface of a metal due to strong perpendicular electric fields. Fowler and Nordheim [3] derived a formula for the electron current density, emitted from a metal surface, due to a strong electric field (equation 1):

$$j(E) = \frac{A\beta^2 E^2}{\phi} e^{-B\frac{\phi^{3/2}}{\beta E}} ; \tag{1}$$

where A and B are constants, ϕ is the work function, E is the perpendicular electric field strength and β is the enhancement factor. The constants take the values: $A = 1.54 \times 10^{-6}$ (eV)AV^{-2}, $B = 6.83 \times 10^9$ Vm^{-1}(eV)$^{-3/2}$ if we take ϕ in eV and the other variables in SI units.

METHOD

The Field Emission Simulator (FES) consists of a 3D particle tracking simulation, supporting field map modelling and accurate cavity descriptions, with Fowler-Nordheim emitter sites, each modelled by equation 1. The emitters are randomly distributed across the surface of the cavities (Fig. 2), with randomly generated enhancement factors; such that the approximate distribution described in [4] can be reproduced. It is currently assumed that with a large number of emitters, covering a wide range of enhancement factors, specific issues with the modelling of single emitters will be of less significance to the results. Comparisons with data are as yet required to validate this assumption and provide improvements to the current configuration. A realistic RFCC geometry has been simulated, comprising of four cavities, each with beryllium windows. The cavities are simulated with realistic RF field maps and an overlaid Coupling Coil field map to complete the simplified RFCC geometry. An example event display can be seen in Fig. 3.

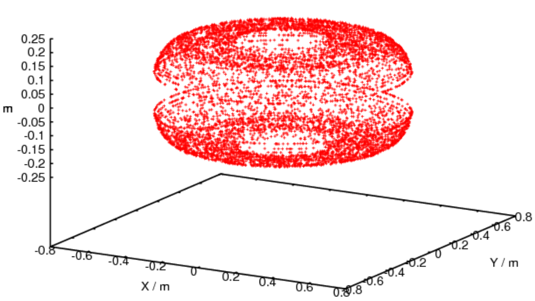

Figure 2: Distribution of Fowler-Nordheim emitters across the inside surface of a single MICE RF cavity (not show), as used in FES.

The simulation was run for four RF cycles, in time steps of 10^{-11} seconds. On each time step, each emitter simulates some emission of electrons as described by equation 1 with its own, unique enhancement factor. The electrons are then propagated through the geometry and recorded when either (a) they interact with a cavity, resulting in the emission of bremsstrahlung X-rays, or (b) they escape through an outer window of the RFCC and enter the rest of the beamline. At present FES does not have the capability to simulate the production of X-rays through bremsstrahlung.

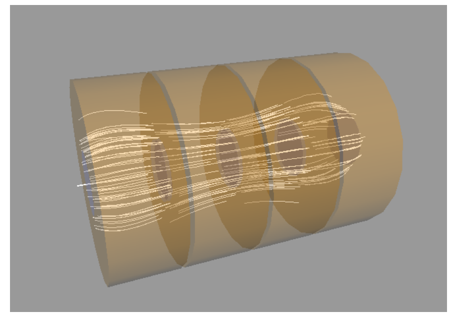

Figure 3: A rendering of the RFCC as simulated by FES. The RF cavities are shown approximated to cylinders in orange, and some example electron tracks are shown in white.

RESULTS

Direct FES Analyses

Figure 4 describes the energy spectrum of electrons that propagate through an outer window and were emitted from the RFCC. These electrons may cause problems for the SciFi Trackers, should they propagate that far. Figure 5 shows the energy spectrum of dark current electrons that didn't make it through the RFCC and instead were deposited into the side of an RF cavity or a beryllium window. This spectrum would feed the spectrum of emitted bremsstrahlung X-rays.

A more in-depth analysis of these results revealed that the individual structures, seen in the spectra, can each be related to a type of electron path within the RFCC. The number of cavities crossed, and whether the electron reverses direction are the main factors that produce the complex structures.

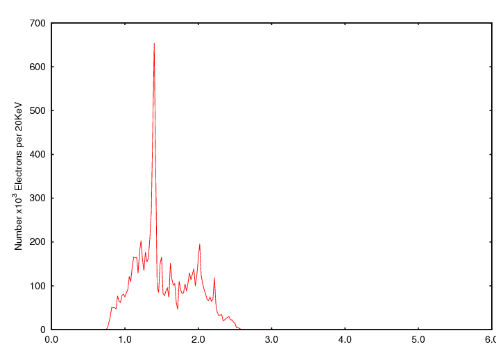

Figure 4: Energy spectrum for all dark current electrons emitted from the simulated RFCC in FES. These electrons will be propagated through the MICE beam line following their emission from the RFCC.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRI003

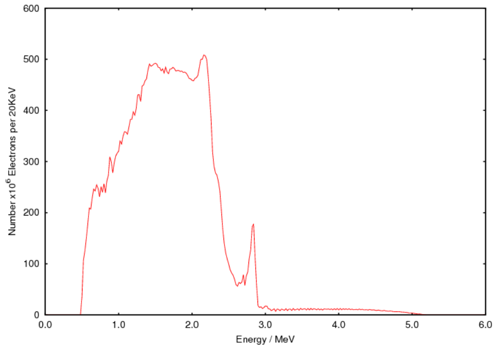

Figure 5: Energy spectrum for all dark current electrons that interact with an RF cavity. This spectrum will drive the X-ray spectrum produced from the RFCC during operation.

Cavity Heating Studies

A recent addition to the analysis library included with FES is the ability to map the density of electron-cavity interactions for a given geometry (Fig. 6). This component is currently still being developed and is designed to predict the localised cavity temperature increases due to the impacts. It is possible that a high rate of electron-cavity interactions can heat the local area and cause vaporisation of the copper, thereby facilitating a cavity breakdown.

Although this feature is still being developed it can already be shown that the addition of a solenoid field greatly increases the density of interactions around the iris of the window.

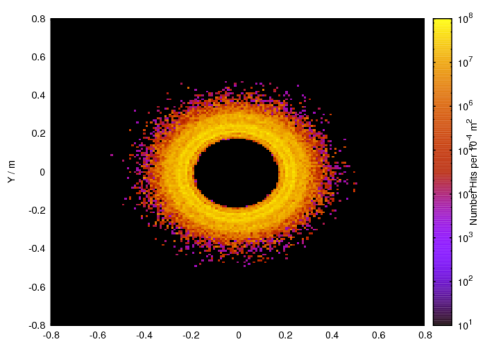

Figure 6: A cross section of the simulated RFCC showing the density of electron-cavity interactions for all cavities.

Integration with MAUS

Additional modules have been constructed for the MICE Analysis and User Software (MAUS) that can import the data produced by FES and simulate the entire MICE cooling-channel around it. This would allow realistic dark currents to be produced and simulated in parallel with the muon beam in order to determine the effect, if any, on the muon track reconstruction in the trackers and other detectors. Figure 7 shows the initial tests of this development using only the central part of the MICE beamline for Step V - one RFCC and two AFCs. This test was done with no absorber, as this is likely to be the configuration which is most damaging to the SciFi Trackers. It can be seen that operating the AFCs in flip-mode essentially stops the propagation of dark currents any further through the beamline. Solenoid-mode however, appears much more dangerous to the beamline and will require further study.

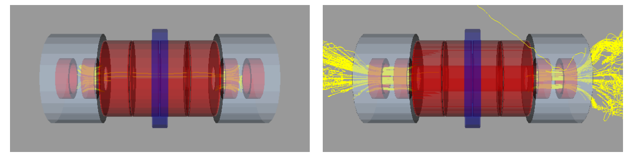

Figure 7: A comparison of the FES-simulated dark current electrons in the central part of the MICE beamline. Cavities are shown in red, the Coupling Coil in blue. The AFC focus coils were simulated in flip mode (LEFT) and solenoid mode (RIGHT). No absorbers t were simulated in this geometry.

CONCLUSIONS AND OUTLOOK

The results shown so far indicate that FES behaves correctly. The verification of these results, however is still to be performed. Upcoming experiments at the Fermilab MTA are expected to provide some comparable data to help tune and validate the simulation results.

The first application of the simulation is to help design a pair of radiation monitors [5], that will measure the dark current and X-ray flux close to the beamline. This allows the amount of exposure, experienced by the trackers, to be monitored by the control room and for steps to be taken to shield against it.

There are several improvements currently planned for FES including a space charge simulation, a cavity heating model and an improved interface with MAUS. Additionally, a cavity breakdown study is anticipated to conclude the project. This would involve trying to predict the parameters that may cause an RF cavity to undergo breakdown events, by using knowledge of simulated, localised cavity heating and multipacting events.

REFERENCES

[1] S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo, “Feasability study-II of a muon based neutrino source,” tech. rep., BNL-52623, 2001.

[2] D. Orestano, “The detector system of the MICE experiment,” *Nucl. Inst. Phys. A*, vol. 617, pp. 45 – 47, 2010.

[3] R. H. Fowler and L. Nordheim, “Electron emission in intense electric fields,” *Proc. R. Soc. Lond.*, no. 119, 1928.

[4] A. Moretti *et al.*, “Effects of high solenoidal magnetic fields on rf accelerating cavities,” *Phys. Rev. ST - Accelerators and Beams*, vol. 8, 2005.

[5] M. A. Uchida, C. Hunt, and J. Pasternak, “The design and implementation of the radiation monitors for the protection of the mice tracker detectors,” in *IPAC Conf. Proc.*, 2014.