AN INVESTIGATION INTO THE BEHAVIOUR OF RESIDUAL GAS IONISATION PROFILE MONITORS IN THE ISIS EXTRACTED BEAMLINE

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Abstract

Non-destructive beam profile measurements at the ISIS neutron source are performed using Multi-Channel Profile Monitors (MCPMs). These use residual gas ionisation within the beam pipe, with the ions being guided to an array of 40 Channeltron electron multipliers by a high voltage drift field.

Non-uniform transverse electric fields within these monitors are caused by the drift field and the beam's space charge. Longitudinally, a saddle point located between the drift field plate and the opposing compensating field plate introduces extra complexity into the ion motion. To allow for detailed studies of this behaviour, an MCPM has been placed in Extracted Proton Beamline 1 (EPB1) where the beam is well defined. Simulations of the profiles obtained by this monitor are performed using machine measurements, CST EM Studio and a simple C++ particle tracking code.

This paper describes the process used to simulate MCPM profiles along with a comparison of simulated and measured results. Trajectories of detected ions from their creation to the Channeltrons are discussed, together with a study of Channeltron detection characteristics carried out in the ISIS diagnostics laboratory vacuum tank.

INTRODUCTION

ISIS is a spallation neutron and muon source based at the Rutherford Appleton Laboratory in the UK. The facility consists of a 70 MeV H^- linear accelerator, an 800 MeV proton synchrotron and two EPBs, which transport the accelerated protons to two target stations (TS1 & TS2). The synchrotron operates at a repetition rate of 50 Hz, with four out of every five proton pulses being delivered to TS1 at a rate of 40 Hz and the remaining pulses being delivered to TS2 at a rate of 10 Hz.

Non-destructive profile measurements at ISIS are performed with residual gas ionisation monitors. These utilise the interaction between the proton beam and molecules of the residual gas within the monitor's volume, which creates electron-ion pairs. A drift field, typically of 15 kV, is applied across the monitor to guide the created ions towards an array of detectors. As the level of ionisation at any point within the monitor is directly proportional to the beam intensity at that location [1], a 1D beam profile can be constructed by comparing the quantities of ions arriving at each detector in the array.

Over the past decade, the ISIS design of ionisation profile monitor has undergone multiple stages of evolution to improve both the acquisition speed and accuracy of the measured profiles [2]. The monitors consist of two high voltage electrodes, placed on opposing sides of the monitor to ensure there is no overall influence on the beam trajectory, as shown in Fig. 1. The primary electrode applies a drift field which drives residual gas ions towards a 240 mm wide array of 40 Channeltron electron multipliers. This part of the monitor is referred to as the MCPM, and uses the 4800 series Channeltrons manufactured by Photonis [3], arranged with a regular spacing of 6 mm between each Channeltron centre. The compensating electrode drives ions towards a single, larger 4700 series Channeltron which is connected to a linear motor. This single channel monitor (SCPM) is scanned across the beam aperture and used to calibrate the gains of each of the MCPM Channeltrons, as described in [2].

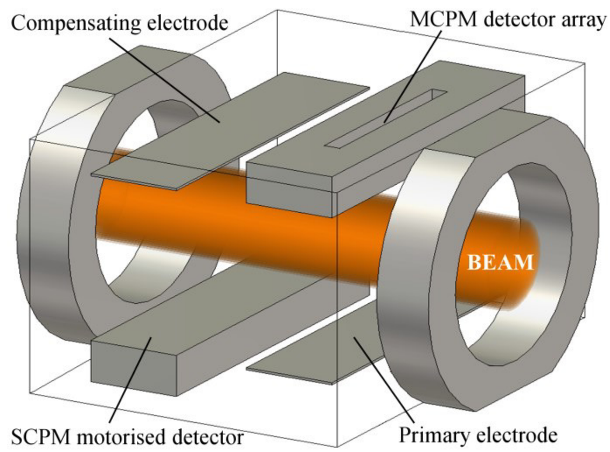

Figure 1: The layout of an ISIS profile monitor.

MEASUREMENT ERRORS

In order to understand high intensity loss mechanisms in the synchrotron and to establish good beam models, it is essential that accurate profile measurements can be taken both quickly and non-destructively.

Accurate measurements depend on the created residual gas ions travelling directly towards the detectors without undergoing any additional transverse motion. For example, in a horizontal profile monitor the ideal ion trajectory is a direct vertical path between the creation and detection points, resulting in an accurate horizontal measurement. However, both the shape of the drift field generated by the electrodes and the effect of the beam's space charge field cause additional transverse ion motion, introducing a broadening effect into the profile measurement (Fig. 2). Furthermore, a saddle point in the electric field exists in the centre of the monitor, created by the interaction between the primary and compensating electrodes.

A profile correction scheme has been developed from previous studies [4] to account for the effects of the drift field and space charge on measurements. Previous investigations have yielded good results when this correction is applied to the monitors located in the synchrotron [5, 6].

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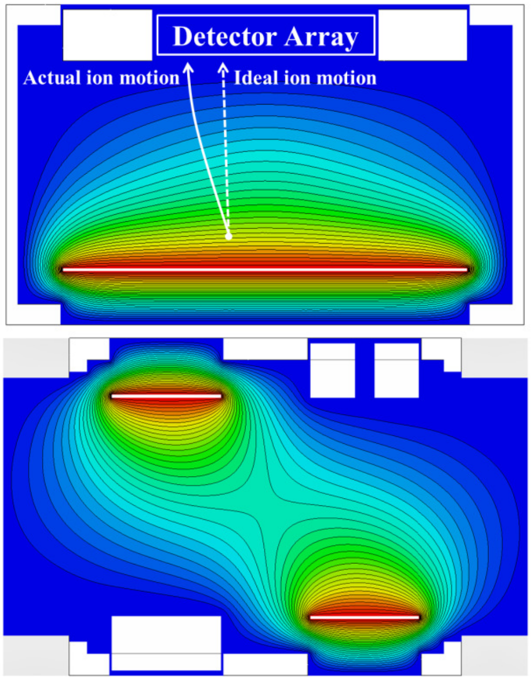

Figure 2: Non-uniform electrostatic potential distributions within the MCPM: transverse (top) and longitudinal (bottom), showing the central saddle point.

To perform a thorough benchmarking of the synchrotron profile monitors and the correction scheme, a monitor was relocated to EPB1, where the beam is well defined due to a large number of diagnostics. The monitor was placed in close proximity to a pair of secondary emission grid profile monitors (known as 'harp' monitors) as shown in Fig. 3. These allow accurate but destructive profile measurements to be taken, something not possible in the synchrotron, providing a reliable and direct comparison for the corrected MCPM measurements.

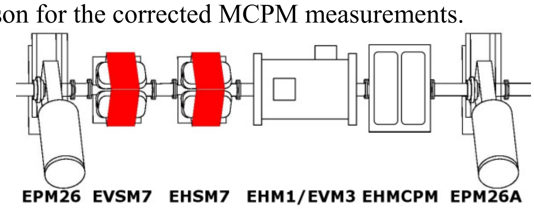

Figure 3: Schematic of the EPB1 layout surrounding the MCPM. EPM26 and EPM26A are harp monitors and EHM1/EVM3 is a dual plane position monitor.

Initial results showed that, unlike the monitors placed in the synchrotron, the EPB1 MCPM measured broader profiles than expected, with corrected profiles remaining wider than those measured by the nearby harp monitors. As a result, to better understand the internal behaviour of the monitor a detailed simulation process has been developed to calculate both the ion trajectories within the MCPM and the associated beam profile measurement.

SIMULATION MODEL

To calculate the monitor's internal electric fields, a 3D model of the monitor geometry is used, created with the finite element modelling software CST EM Studio [7]. The beam's space charge field is modelled using twenty-five concentric elliptic charge distributions of increasing radii, placed within the monitor to represent the beam (as shown in Fig. 1). The total charge within the monitor is calculated from the beam intensity and is arranged to represent an elliptic distribution within the beam. The drift field voltage is applied to the electrodes as an electrostatic potential. During routine operation this is set to 15 kV but can be varied between 0 – 30 kV. The software then calculates a 3D matrix of electric field values within the monitor, which is exported with a resolution of 2 mm in each plane. To approximate a time dependent space charge in the ion tracking phase, a second electric field is calculated with the beam removed from the model.

Calculation of the ion trajectories within the monitor is carried out using a custom written C++ ion tracking code. A uniform distribution of stationary ions is generated within the beam's volume and these are then tracked through the electric fields calculated by CST. The kinematic equations of motion are used to calculate the change in each ion's position and velocity in time steps of 1 ns. As there is no magnetic field within the monitor, the acceleration of each ion within a time step is calculated from the Lorentz force applied by the local electric field as shown in Eq. (1). The equations of motion are solved with a second order Euler method, which is considered to be sufficiently accurate given the small time step size.

$$F_{\mathrm{LORENTZ}} = q(\vec{E} + \vec{v} \times \vec{B}), \quad \vec{B} \equiv 0$$
$$\therefore\ F_x = qE_x = ma_x \tag{1}$$

To account for the space charge effect disappearing once the beam leaves the monitor, the electric field values used by the tracker are swapped for the beam-independent field after 200 ns of motion have been simulated. While in reality there are two separate 100 ns bunches travelling through EPB1, these are approximated to a single, longer bunch in the simulation for simplicity. It should be noted that this time dependence is only applied in simulations of the EPB1 profile monitor. Models of synchrotron profile monitors instead use an electrostatic approximation of the average charge within the monitor during operation.

Due to the size of the monitor the 2 mm resolution of the electric field matrices is considered adequate and no interpolation is performed on the values. The simulation runs until every ion has either reached the detectors or moved outside of the tracking region. If an ion travels into a Channeltron, its final time step is calculated precisely (i.e. to less than 1 ns) and the final step of motion is recalculated, giving the precise location at which it is detected.

An IDL [8] code is used to post process the ion trajectories and generate the simulated profile measurement. The positions at which the ions reach the Channeltron detector array are split into 6 mm bins, each corresponding to a Channeltron location, and a histogram is plotted to represent the MCPM profile measurement. An elliptic weighting is applied to each ion based on its initial position, to compensate for the use of a uniform initial distribution in the tracking code. A further weighting can be applied to model the detection efficiency of the Channeltrons, as discussed in the detector characterisation section.

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BENCHMARKING MEASUREMENTS

To verify the simulation model, profile measurements were recorded in EPB1 at multiple beam intensities from both the MCPM and the adjacent harp monitors. When combined with the measured intensities, these harp measurements ensured that the beam passing through the MCPM was well defined, with known positions and 95% widths in both planes. This beam definition was subsequently used as an input throughout the simulation procedure, meaning the results could be directly compared with the profiles measured by the MCPM.

Once agreement between simulation and measurement had been observed, the behaviour and dominant sources of error in the monitor were studied in more detail, as described below.

SIMULATION RESULTS

The simulation produces results that match closely with associated machine measurements, particularly when a low intensity beam is used. Figure 4a) demonstrates this, showing a close agreement between simulation and measurements taken at 10% of standard operating intensity. Variation between the 95% widths of the simulated and measured profiles is less than 1.5 mm, a satisfactory result when considering that the monitor itself has a resolution of 6 mm.

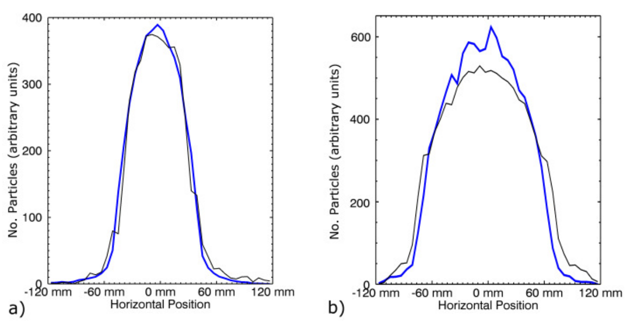

Figure 4: Comparisons of simulated (blue) and measured (black) MCPM profiles in EPB1, taken at a) low intensity operation and b) standard operating intensity.

Simulations at higher intensities show greater variation when compared with measurements (Fig. 4b). While the overall shape of the profile remains a good match, the 95% widths differ by 15 mm at standard operating intensity, with the levels of profile broadening observed in the EPB not being reproduced by the simulation.

This result is in line with the previously mentioned benchmarking measurements of the profile correction scheme, which found increased levels of broadening in the EPB1 monitor compared with profiles measured in the synchrotron. As simulated profiles agree with measurements across all intensities in the synchrotron, studies are currently underway to identify the source of this behaviour in the EPB.

Ion Trajectories

The complexity of the ion motion within the monitor can be seen in Figs. 5 and 6, which show the trajectories of ions that reach the Channeltrons and therefore form the profile measurement. The effect of the saddle point can be seen, causing extra ions from the monitor's centre to reach the detectors, many via indirect paths. Approximately 20% of the detected ions are created in this saddle point region, causing further broadening of the profile in addition to the drift field and space charge effects.

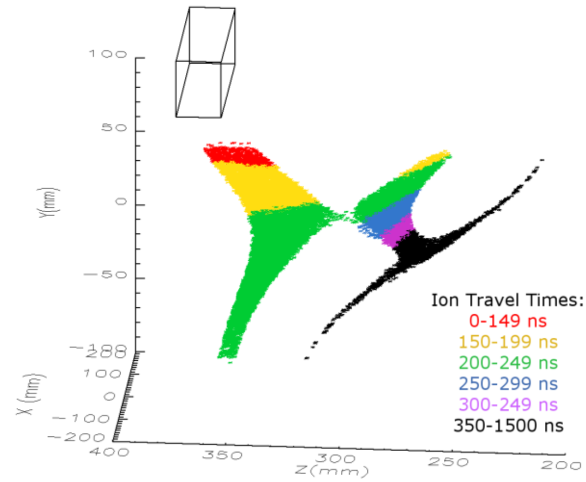

Figure 5: Initial positions of ions that travel into the detector array. The different colours denote the time of flight from creation to detection. The position of the MCPM detector array is shown as a black box.

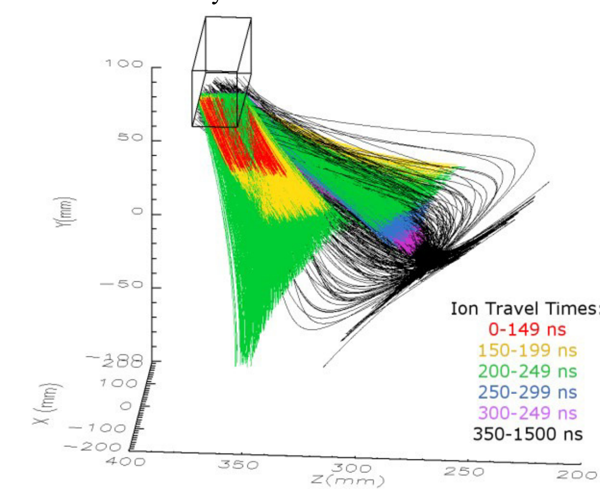

Figure 6: Trajectories of ions that reach the detectors, shown in the longitudinal plane.

Due to the irregular trajectories taken by many of the ions travelling towards the detectors from the saddle point, their angles of incidence upon entering the Channeltrons are significantly higher than those of other detected ions. Figure 7 shows that this angle can be used to separate the detected ions into two distinct groups, a result which has important implications. Firstly, as many of the ions arriving at sharper angles have taken indirect trajectories, they are undesirable in the profile measurement as they contribute to the artificial broadening. Consequently any future modification to the MCPM housing that can prevent these ions reaching the detector would improve the overall performance of the monitor. Secondly, the scale of variation in angles means that the Channel-

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tron detection efficiency at different angles must be characterised and included in the simulation.

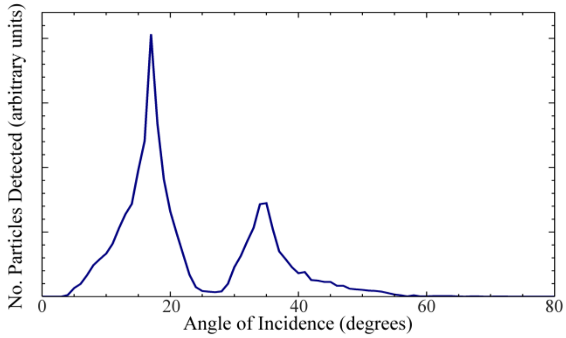

Figure 7: Longitudinal angles of incidence at which ions enter the detector.

DETECTOR CHARACTERISATION

Detailed data on the angular acceptances of the Channeltrons used in the monitor is not available from Photonis. As a result, a miniature test assembly was built containing a single 4700 series Channeltron and an array of four 4800 series Channeltrons, with both sets of detectors placed inside housings of identical geometries to those used in the full monitor. The test assembly was then fixed to a rotatable plate within a vacuum tank and an ion gun was used to test the response of the Channeltrons at different angles. The majority of the residual gas within EPB1 is water vapour, meaning the dominant residual gas ion species are of hydrogen and oxygen. The IDL code was used to calculate the kinetic energies of these species as they reach the detectors, with the majority arriving at energies of 4-4.5 keV. To match these conditions as closely as possible the vacuum tank ion gun was set up to produce 4 keV helium ions.

The assembly was rotated to vary the incident angle of the ion beam and the Channeltron current measurements were used to calculate their detection efficiencies. The results presented in Fig. 8 show the significant efficiency variations observed in both types of Channeltron within the range of angles seen in the simulation results. Furthermore the different models of Channeltron exhibited very different behaviours, a result that was unexpected.

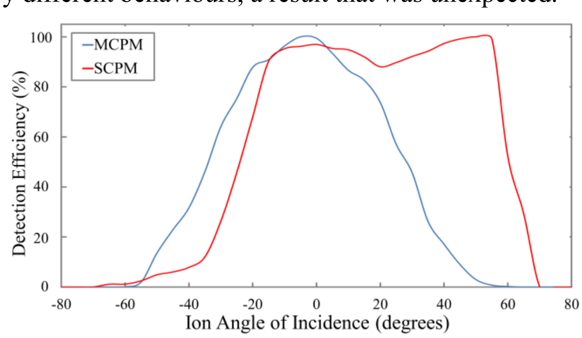

Figure 8: Variation in Channeltron detection efficiency with ion angle of incidence. The MCPM contains 4800 series Channeltrons while the SCPM uses a 4700 series.

The results from the MCPM Channeltrons were used to generate an extra weighting for the simulated profile measurement during the post processing stage. This will be applied during future studies, with saddle point ions generating roughly half the current of those created directly below the detector array. The levels of variation observed and the asymmetrical results obtained from the SCPM Channeltron highlight the importance of considering the performance of the detectors in detail as part of the simulation process.

CONCLUSIONS AND FUTURE WORK

Simulations of the ISIS MCPMs have been carried out and compared against well-defined benchmarking measurements performed in EPB1. Close agreement between simulated and measured profiles has been achieved at low beam intensities, allowing for more detailed modelling of ion behaviour and error mechanisms within the monitor. The properties of the Channeltrons have been measured as a function of incident angle and the results will be used to enhance the accuracy of future simulations.

Modifications for future iterations of the profile monitors will be tested using the Channeltron test assembly. Adjustments to the detector housing with the aim of preventing detection of ions arriving at angles of incidence larger than 25 degrees will be targeted, to remove the effect of the ions created near the monitor's saddle point.

Future studies are planned to provide alternative data for benchmarking the simulation and studying the monitor's behaviour. A fast acting amplifier will be used to measure the time structure of ions arriving at the Channeltrons. Measurements will also be taken with the compensating field deactivated, removing the saddle point from the monitor and reducing the time spread of detected ions.

The simulation's time dependent electric field approximation will be improved to accurately model the proton bunch structure within EPB1, which contains two 100 ns bunches with a separation of 225 ns. The smaller timescales involved suggest this simulation component will have a larger effect on results than at present.

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