ANALYSIS OF MEASUREMENT ERRORS IN RESIDUAL GAS IONISATION PROFILE MONITORS IN A HIGH INTENSITY PROTON BEAM

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Abstract

ISIS is the pulsed neutron and muon source based at the Rutherford Appleton Laboratory in the UK. Operation is centred on a loss-limited 50 Hz proton synchrotron which accelerates $\sim 3 \times 10^{13}$ protons per pulse from 70 MeV to 800 MeV, corresponding to a mean beam power of 0.2 MW. Beam profile measurements are a key component of both ISIS operational running and R&D beam studies. Understanding and quantifying limitations in these monitors is essential, and has become more important as work to optimise and study the beam in more detail has progressed. This paper presents 3D field and ion trajectory modelling of the ISIS residual gas ionisation profile monitors, including the effects of non-uniformity in longitudinal and transverse drift fields, and beam space charge. The simulation model allows comparison between the input beam profile and that deduced from ion currents. The resulting behaviour is summarised along with corrections and errors.

INTRODUCTION

The ISIS synchrotron, with a circumference of 163 m, accumulates a proton beam over approximately 130 turns using charge-exchange injection. During acceleration the beam separates into two bunches. At injection, and particularly during bunching, transverse space charge levels are high with peak incoherent tune shifts of ~ -0.4 in both planes. Space charge levels remain significant until the beam is extracted from the synchrotron. ISIS has successfully employed five Residual Gas Ionisation (RGI) profile monitors for many years, but with higher intensity operations required for the Second Target Station project, and related high intensity beam studies, a detailed analysis of the measurement errors has been required.

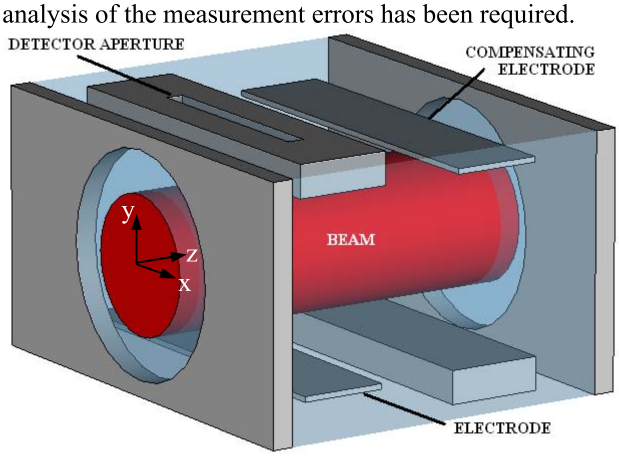

Figure 1: RGI profile monitor geometry

DESCRIPTION OF MONITOR

The ISIS RGI profile monitors consist of two high voltage electrodes and detector housings mounted in the monitor body and two circular apertures for beam passage, see Figure 1. One electrode creates the required drift field for the ions created by beam interaction; the second compensates for the first electrode's influence on the beam trajectory. The nominal applied electrode voltage is 15 kV. The electrostatic potential is shown in Figure 2.

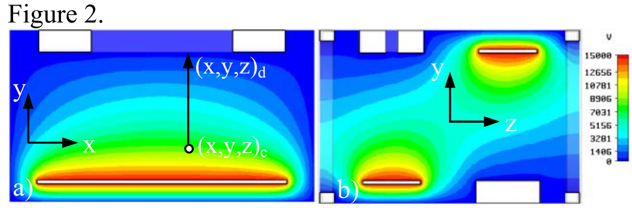

Figure 2: a) Transverse and b) longitudinal electrostatic potential distributions

The RGI profile monitors operate by guiding and detecting ions produced when the passing proton beam interacts with the residual gas within the accelerator vacuum vessel. The number of ions detected is taken to be proportional to the local beam intensity [1]. Accurate profiles rely on linear ion trajectories, perpendicular to the detector, from ion creation in the beam to detection i.e. a horizontal profile monitor with ions produced at $(x, y, z)_c$ should detect those ions at $(x, y, z)_d$ (see Figure 2a). Two effects which prevent this ideal path are studied: distortion due to the beam's space charge field and non-uniformity in the high voltage drift field produced by the RGI profile monitor.

SIMULATION

Detailed dimensions from technical drawings of the profile monitor were used to create a geometrical model in CST Studio Suite [2]. The electrostatic field solver in EM Studio was used to calculate the electrostatic field generated by the combination of proton beam and drift electrode at varying voltages. Limitations in the flexibility of CST software and the need for detailed and accurate ion trajectories motivated development of a separate optimised ion tracking code. The tracker assumes the beam self field is static during the profile measurement. A grid of ion starting positions was created to match simple beam density distributions (uniform, elliptic or parabolic). These were tracked through the field map extracted from CST and the trajectories filtered to leave only those that entered the detector aperture.

SPACE CHARGE EFFECTS

Width Variation with Drift Voltage

Ions, rather than electrons, are guided by the drift field to the detector, but are also deflected away from the beam centre by the proton beam's space charge field. The effect of drift field strength on 90 % beam widths has been studied [3, 4] and a simple theoretical model produced [5]:

$$w_{m,90\,\%} = w_{t,90\,\%} + \frac{K_{90\,\%}}{V_D} \tag{1}$$

where $w_{m,\,90\,\%}$ and $w_{t,\,90\,\%}$ are the measured and true 90 % beam widths; $K_{90\,\%}$ is a constant proportional to the space charge force and thus related to the beam intensity and energy; V_D is the applied drift voltage. 2D simulations have shown that the true width in (1) has a significant dependence upon the non-uniformity in the electrode drift field [3], which is discussed below.

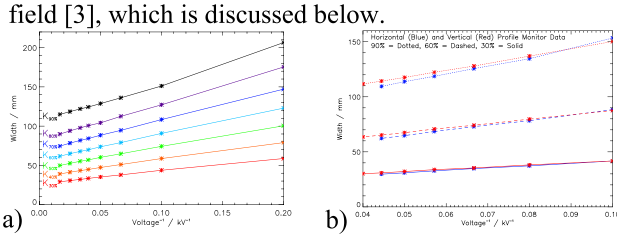

Figure 3: a) Simulated and b) experimental results for beam widths versus 1 / V_D for different percentage widths

3D simulations from this study have confirmed the relationship between the detected 90 % width and the applied drift voltage and extended it to all percentage widths (Figure 3a). This behaviour has also been demonstrated experimentally (Figure 3b).

K_p Variation with Percentage Width

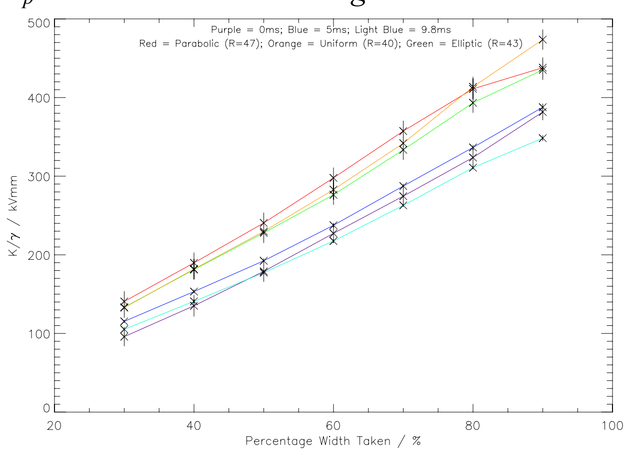

Figure 4: Experimental results of K_p / γ (γ= relativistic factor) versus percentage width, p, alongside simulation results of K_p versus p

A relationship was expected between the normalised or percentage width measured, p, and K_p. Experimental data showed this to be the case and it was found to be approximately linear ($K_p \propto p$) for the whole ISIS cycle (Figure 4). Using the experimental data it was possible to derive the absolute width of the beam, assuming a particular density distribution, and input this into the model. Uniform, parabolic and elliptic density distributions matched in this way produced space charge correction factors that were very similar to experimental data. In particular, parabolic and elliptic simulations produced linear functions of space charge correction with percentage width, with gradients that closely matched experiment, also shown in Figure 4.

K_p Variation with Beam Energy

On measuring K_p experimentally for a given percentage width, it was found to vary with time through the ISIS cycle, and hence with beam energy. Figure 5 shows that the variation of space charge correction is linear with γ. This is understood as a consequence of the linear variation in space charge electric field with γ, with respect to the stationary ion's rest frame.

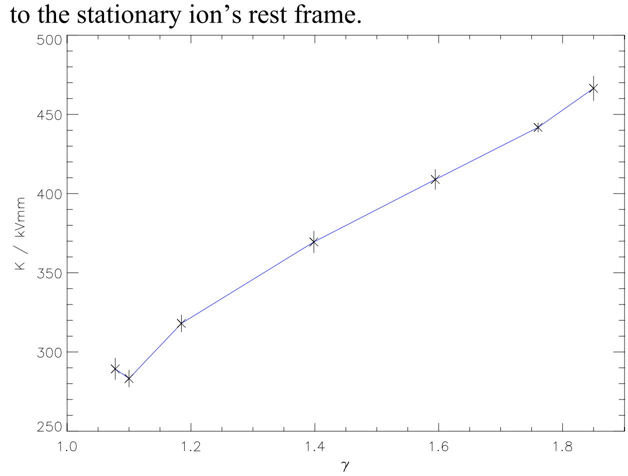

Figure 5: Example of K_p variation with the relativistic factor γ

NON-UNIFORM DRIFT FIELD EFFECTS

Drift Field Correction

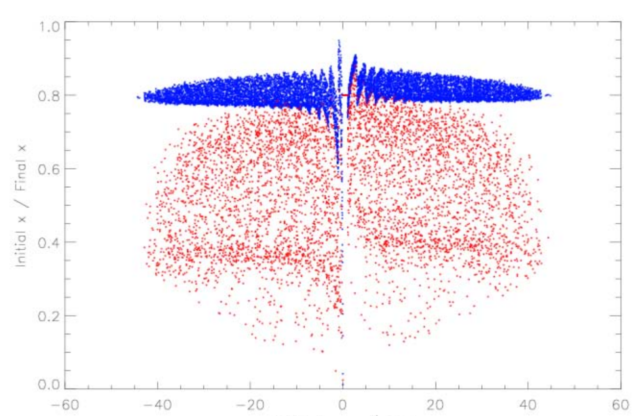

Figure 6: Ratio of created to detected x co-ordinates (x_c / x_d) versus the created x position (x_c). Z co-ordinates are split at 170 mm (< 170 mm, blue; > 170 mm, red)

The simulation allows the freedom to turn the space charge of the beam off and give a detailed picture of the effect non-uniformity in the drift field has on ion motion. For each density distribution a simple scaling correction with respect to the monitor centre was calculated to correct the distorted profile width. Overall the drift field scaling correction was constant (± 6 %) for all density distributions and percentage widths. Figure 6 shows how the ion's x co-ordinate changes from creation to detection (x_c to x_d), moving further away from the centre of the monitor.

Ion Motion

As shown in Figure 2, the drift field is non-uniform in both transverse and longitudinal directions. The drift field causes complicated ion motion away from the centre of the monitor. Examples of this complicated motion are shown in Figure 7. The dominant effect on the measured profiles is to increase their widths.

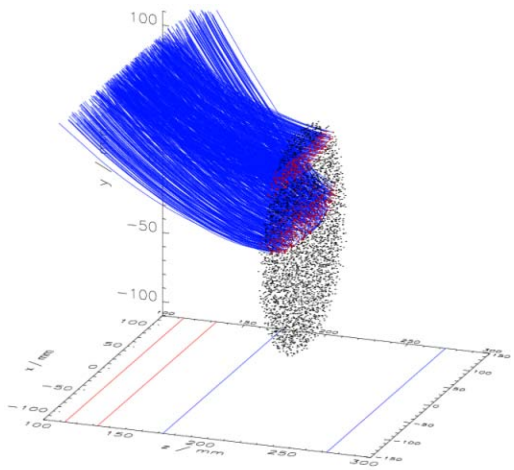

Figure 7: An example 2D slice of initial ion positions (black) and those that enter the detector (red) complete with their tracks (blue). (Red lines = detector aperture projection; blue lines = electrode edges)

LONGITUDINAL EFFECTS

The longitudinal field has a complex impact on the measured profile of the beam. A uniform drift field would give profile information about a flat slice of the beam directly between the detector and high voltage electrode. The compensating electrode draws this slice into a complicated 3D chevron. It also produces a second set of ion paths, increasing the absolute number of ions entering the detector for centred beams (up to ~ 20 %). Ions produced on the saddle in the electrostatic potential between the two electrodes (see Figure 2b) move on unstable oscillatory trajectories.

Ion drift time to the detector was found to be spread over a range from 0 to over 350 ns (bunch length = 100 ns). The ions originating at the potential saddle take the longest to enter the detector with the nominal electrode voltage of 15 kV.

CONCLUSIONS & FUTURE WORK

3D simulations confirm that both non-uniform drift fields and space charge play a significant role in beam profile measurement within RGI profile monitors. A new correction model is suggested:

$$w_{m,\,p} = \zeta_D w_{t,\,p} + \frac{\zeta_{SC} p \gamma}{V_D} \qquad (2)$$

where $w_{m\,,p}$ and $w_{t,\,p}$ are the measured and true widths at a given percentage, p; ζ_D is constant for the monitor; $\zeta_{SC}\,(= K_p\,/\,p)$ is constant for a given intensity, varying slightly with beam density distribution. Energy, and hence γ, dependence is explicitly stated.

Provisional correction schemes using simulated and experimental data (Figure 8, [6]) have yielded promising results. The correction algorithm reduces the measured width by 35 – 60 %. This produces a 90% width good to ± 10 mm on centred beams.

New high voltage towers are currently being commissioned to allow electrode voltages up to 60 kV. This will reduce ion drift time for the majority of ions to less than 100 ns, making the assumption of static beam fields more accurate. Further study into the complicated ion dynamics from creation through to detection may be required.

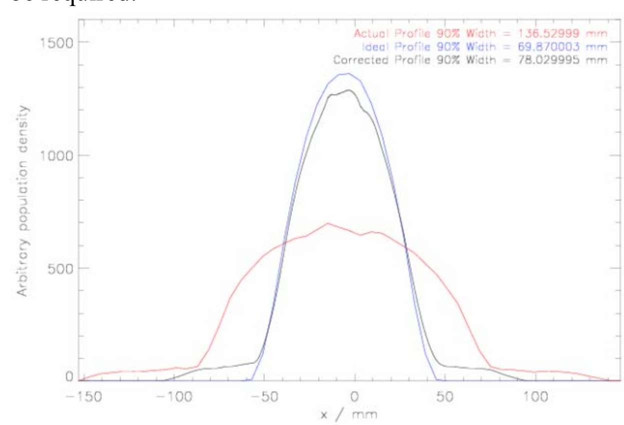

Figure 8: Comparison of simulated profiles produced with uniform E-field (blue), realistic field (red) and the corrected profile (green)

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