INJECTION OPTIMISATION ON THE ISIS SYNCHROTRON

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Abstract

The ISIS Facility at the Rutherford Appleton Laboratory in the UK produces intense neutron and muon beams for condensed matter research. It is based on a 50 Hz proton synchrotron which, as the commissioning of a new dual harmonic RF system concludes, will accelerate up to 3.75×10^{13} protons per pulse from 70 to 800 MeV, delivering a mean beam power of 0.24 MW.

The multi-turn charge-exchange injection process strongly affects transverse beam distributions, space charge forces and thus beam loss, which ultimately limits operational intensity. Optimising injection is therefore a key consideration for present and future upgrades.

This paper summarises injection studies including 2D space-charge simulations of the ISIS injection process using the ORBIT code [1]. Comparisons of simulation results with measurements for a range of beam intensities are presented and an assessment is made of a correlated painting scheme in contrast to the usual anti-correlated configuration. Previous simulation work has suggested this may result in a more uniform beam distribution in vertical phase space [2].

ISIS INJECTION

The ISIS injection system is based on H^- charge exchange injection through a 0.25 µm aluminium oxide foil at 70.4 MeV. The foil is mounted in the middle of four dipole magnets which remove un-stripped beam. The bump collapses after injection to limit foil recirculation. A schematic of the injection elements is shown in Figure 1.

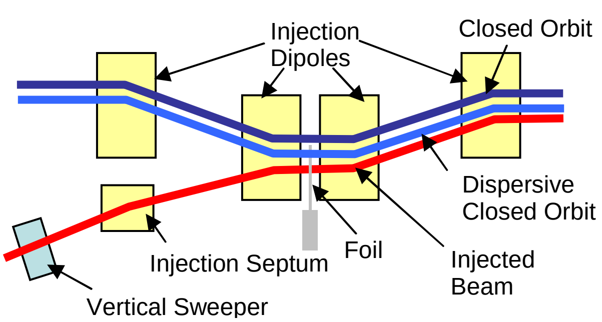

Figure 1: Schematic layout of ISIS injection system.

ISIS operates on a 50 Hz sinusoidal main dipole field. Injection begins 0.4 ms before field minimum, lasting ~ 200 µs (137 turns) during which protons are accumulated in the synchrotron. The beam is painted transversely to reduce space charge forces. Vertical painting is achieved with a programmable dipole upstream of the foil. Horizontal painting makes use of the moving dispersive closed orbit generated by an energy mismatch between the constant injection energy and the changing synchronous energy in the ring.

CHOPPED BEAM STUDIES

The ISIS injection beamline incorporates an electrostatic beam 'chopper' to produce very short (down to 100 ns) beam pulses for diagnostic studies of the synchrotron using the AC-coupled position monitors [3].

Key parameters studied in this work are the closed orbit and relative betatron amplitude variation during the injection period. These values determine the transverse painting of the injected beam.

A theoretical function for the beam position on each turn can be derived [4]. Performing a least-squares fit of the measured positions to this function allows the closed orbit and relative betatron amplitudes to be calculated. These parameters are measured through the injection period by scanning the beam chopper trigger.

Simulations of chopped beam motion have been performed with the ORBIT tracking code. Transverse beam positions are recorded using 'momentNodes'. The simulated positions undergo the same post-processing as the measured positions. The position, angle and energy of the injected beam were varied to match the ORBIT model to the measured data. Generally good agreement is observed between measured and calculated values. The best-matched results are shown in Figure 2.

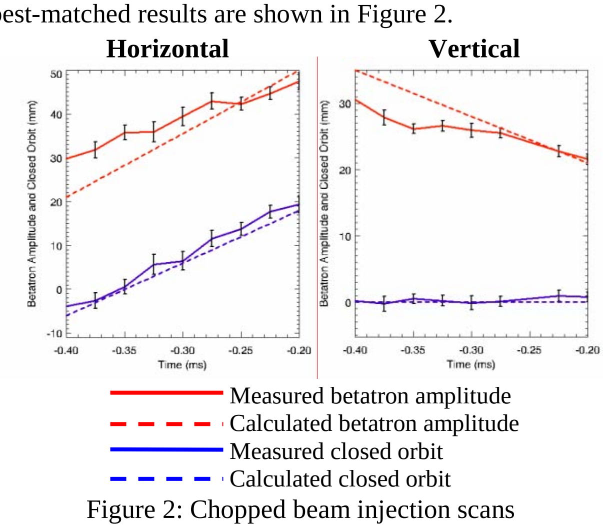

Figure 2: Chopped beam injection scans

HORIZONTAL BEAM PROFILE

The ISIS synchrotron contains five residual gas ionisation transverse profile monitors to non-destructively measure the beam during trapping and acceleration. The monitors use a single channel electron multiplier which is scanned across the beam and records a signal proportional to the beam intensity at 5 mm steps. The resultant profile is an average over several thousand acceleration cycles whereas the ORBIT profiles show particle positions on a single turn.

Horizontal beam profiles were measured at two intensities, 2.5×10^{13} protons per pulse (ppp) and 2.5×10^{12} ppp, with the same injection configuration.

Simulations of the full injection process, i.e. from -0.4 to 0 ms, were performed with 10^5 macroparticles experiencing 630 transverse space charge kicks per turn, equivalent to 146 per horizontal betatron oscillation, 164 per vertical betatron oscillation. A 128 × 128 grid was used to generate transverse distributions to be compared to measured data. No magnet errors or chromatic effects were included.

Figure 3 shows horizontal beam profiles at three stages of injection, labelled relative to the main magnetic field minimum at 0 ms. Thus, -0.3 ms is mid-way through injection, -0.2 ms is the end of injection and by -0.1 ms the injected beam has made a further 65 turns of the synchrotron.

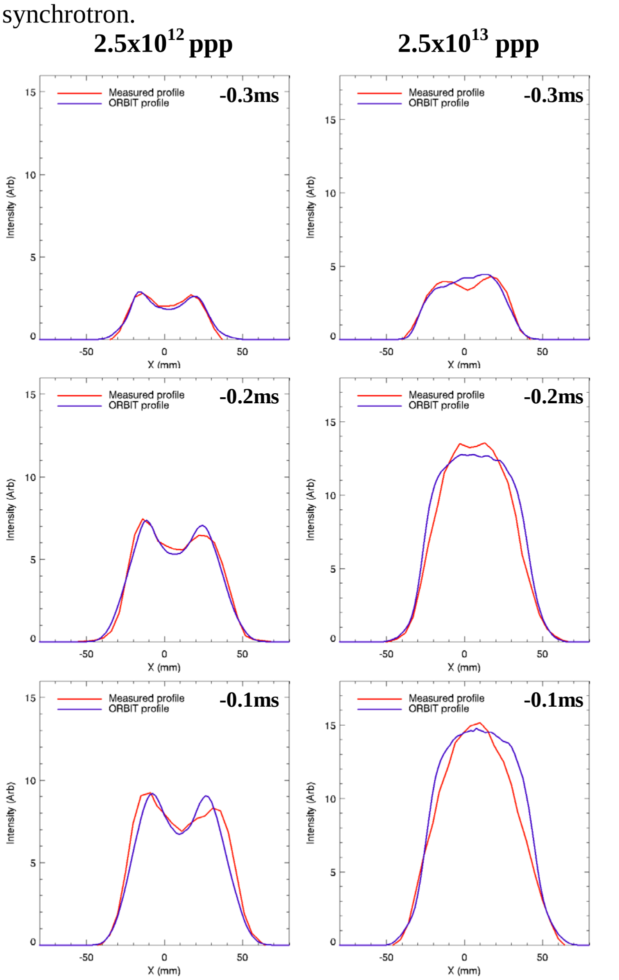

Figure 3: Measured (red) and simulated (blue) horizontal beam profiles

The measured profiles have been corrected for monitor drift field errors and the 2.5×10^{13} ppp profiles at $t \geq -0.2$ ms have been corrected for space charge broadening [5]. The simulated profiles have been scaled such that the area under the profile matches that of the measured profile. The vertical axis is of an arbitrary scale fixed for each measurement. The beam centres have been adjusted to match the measured value since closed orbit errors have not been included in the simulations.

The agreement is good for both intensities. The lower intensity profiles show the beam painted with a hollow centre. This is due to an initial offset between the dispersive orbit and the injection position. At higher intensity the hollow is filled in by the larger space charge forces resulting in little change to the total profile width.

A Root-Sum-of-Squares (RSS) error, normalised to the measured profile size (Eq. 1), was used as a measure of the error between the simulated and measured profiles.

$$Y_{error} = \frac{\sqrt{\sum_i \left(y_i^{\exp} - y_i^{calc}\right)^2}}{\sum_i y_i^{\exp}} \tag{1}$$

This value averaged 4.1% for the horizontal measurements.

VERTICAL BEAM PROFILE

The deflection through the dipole sweeper is non-zero at the end of injection to create a hollow beam. This is observed with a low intensity beam in the vertical profiles shown in Figure 4.

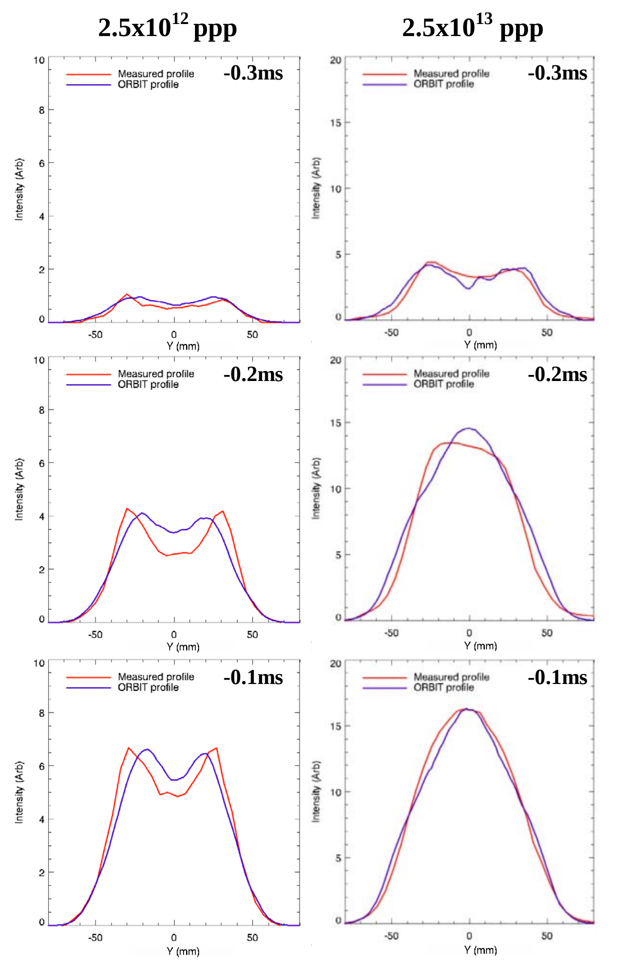

Figure 4: Measured (red) and simulated (blue) vertical beam profiles

The agreement is again generally good with an average RSS error of 6.6 %. The size of the hollow appears under-estimated in the ORBIT model; this may explain the more peaked distributions for 2.5×10^{13} ppp.

CORRELATED PAINTNG

Beam injected into the ISIS synchrotron is usually painted in an anti-correlated manner. However, the action of the vertical dipole can easily be reversed to achieve correlated painting with increasing amplitudes.

Experimental studies were repeated with correlated beam painting. Chopper scans are shown in Figure 5, good agreement in the measured and predicted values is observed.

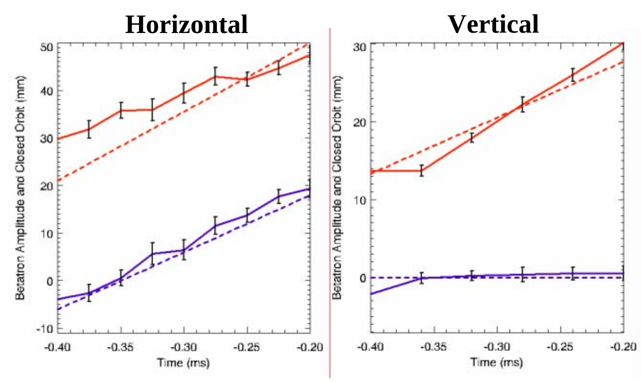

Figure 5: Chopper scan results for correlated painting

Studies of the beam profile over the injection period were also made; the results are shown in Figure 6. Good agreement is observed with an average RSS error of 6.8 %. The hollow structure of the low intensity profiles is not observed in the correlated case as the beam is painted from a small to large betatron amplitude. The high intensity beam distribution at -0.1 ms shows little difference to the anti-correlated case. The synchrotron has been operated using correlated painting with 2.5×10^{13} ppp at 50 Hz and injection loss was slightly reduced.

SUMMARY

The use of low intensity chopped beams has enabled accurate measurement of the relative betatron amplitude and the closed orbit during injection. These results are used to benchmark simulation studies using the ORBIT code.

Measured and simulated transverse beam profiles show good agreement. Initial experiments with correlated painting have also been performed with little change in the vertical beam profile observed. Further investigation of the relative merits of each painting configuration is the subject of future work.

Multi-channel beam profile monitors recently installed in the ISIS synchrotron, which allow the acquisition of profiles averaged over 2-3 turns will be used. This will reduce the effect of variation in the injected beam and enable closer comparison of measured and simulated profiles.

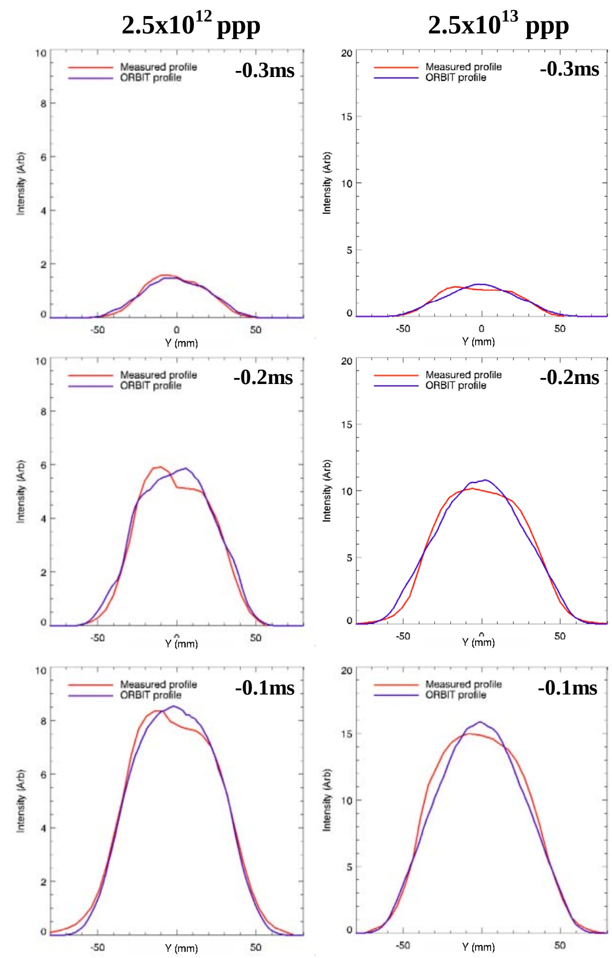

Figure 6: Measured (red) and simulated (blue) vertical beam profiles with correlated painting

ACKNOWLEDGEMENTS

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