INJECTION STUDIES 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, once the commissioning of a new dual harmonic RF system is complete, will accelerate about 3.5×10^{13} protons per pulse from 70 to 800 MeV, corresponding to mean beam powers of 0.2 MW. The multi-turn charge-exchange injection process strongly affects transverse beam distributions, space charge forces, beam loss and therefore operational intensity. The evolution of longitudinal distributions and subsequent trapping efficiency is also intimately linked with injection. Optimising injection is therefore a key consideration for present and future upgrades. Work is now under way looking at this process in more detail, and relates closely to other transverse space charge studies on the ring. This paper presents work including: space charge simulations of the present machine and comparison with observations; assessment of related loss mechanisms; and study of optimal painting schemes. Plans and preparations for more detailed experimental work are also summarised.

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 4 dipole magnets which remove un-stripped beam and collapse after injection to limit foil recirculation. A schematic of the injection elements is shown in Figure 1.

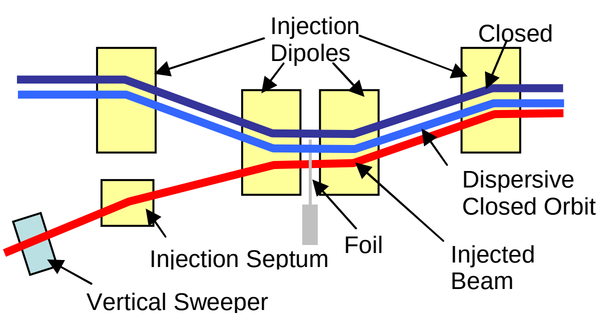

Figure 1: Schematic layout of ISIS injection system.

ISIS operates on a 50 Hz sinusoidal varying main dipole field. Injection begins 0.4 ms before field minimum, lasting 200µs (137 turns) in which 2.8×10^{13} protons per pulse (ppp) are accumulated. The beam is painted in an anti-correlated manner to reduce space charge forces. Horizontally painting uses the moving dispersive closed orbit generated by an energy mismatch between the constant injection energy and changing ring synchronous energy. Vertically by a programmable dipole upstream of the foil. Figure 2 shows the process in phase space.

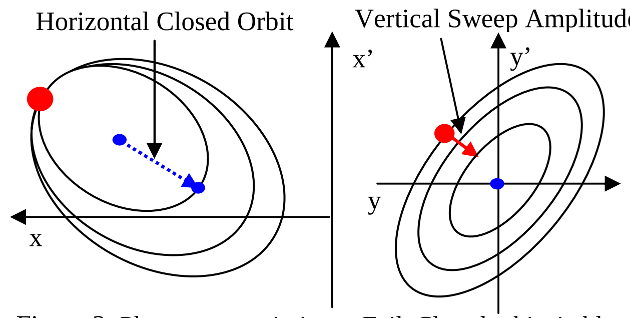

Figure 2: Phase space painting at Foil. Closed orbits in blue

INJECTION STUDIES USING ORBIT

The injection process has been studied using the multi-particle tracking code ORBIT [1]. Simulated transverse distributions under 2D space charge are fitted to measurements from the synchrotron at profile monitors, R5HPM1 in the horizontal and R6VPM1 in the vertical planes.

The simulation has been fitted to measured profiles at 0 ms in the acceleration cycle. At this point injection has ended and the beam has undergone a further 132 turns under minimal RF volts. The evolving profiles are also compared at time points -0.3 ms, half way through injection, and -0.15 ms, 33 turns after injection end. The measured and simulated distributions are shown in Figure 3, two left columns.

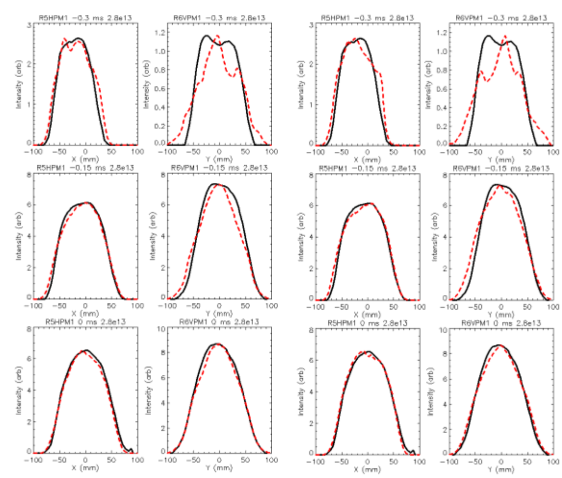

Figure 3: Measured (black) and Simulated (red) profiles at 3 machine time points. Left two columns, normal ISIS lattice. Right two columns, ISIS lattice with half integer driving terms.

Good agreement is reached at 0 ms. Comparisons at earlier times show good agreement in the horizontal. However, vertical simulation results at -0.3ms show structure disagreeing with measurements. This may be due to the profile monitor measurements which produce average profiles measured over 100's of pulses. The measurement is also subject to smearing as the detected ions are perturbed by the proton beam [2] although a nominal correction has been applied. New profile monitors currently in development should greatly improve measurement resolution [3].

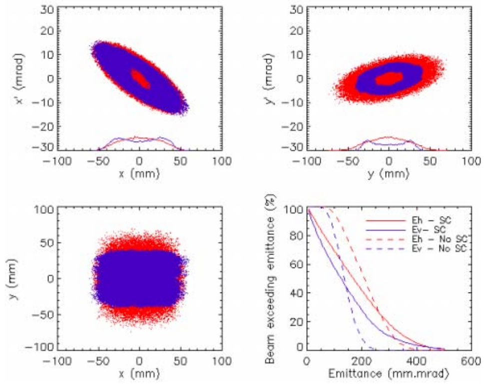

Figure 4: Phase space, Real space and Emittance occupancy of ISIS simulation at 0 ms with and without space charge.

Phase Space, Real Space and Emittance occupancy at 0 ms, turn 269, are shown in Figure 4. Blue plots show distributions with no space charge, red plots with space charge at 2.8×10^{13} ppp. The plots indicate ISIS is painted with hollow distributions. Injection amplitudes vary from 105-321 and 90-180 π mm mrad in the horizontal and vertical planes respectively. At high intensity space charge forces fill in the hollow centre and expand the halo, particularly in the vertical plane.

The most important driving terms on the ring are expected to be associated with the half-integer focusing errors, $2Q_x$=8 and $2Q_y$=7. Figure 3, right two columns, show the evolving simulated profiles in this case. They show little difference with respect to the unperturbed lattice. However, more detailed studies of emittance occupancy show an increased halo generation.

The ISIS collector system limits the ring acceptance to ~ 400 π mm mrad. Studies of the perturbed lattice shows 10.2±0.8 % and 3.7±0.2 % of the horizontal and vertical distributions exceed this limit. This is significantly larger than the ~ 1% injection losses measured on ISIS. Further study is required to understand this difference. The simulation predicts 14 foil hits per particle compared to the design estimate of 25 [4].

Convergence tests show that performing simulations using 10^5 macroparticles are reasonable. The perturbed and unperturbed cases running in the range 10^4 to 5×10^5, show ~ 1% emittance occupancy variations at the ISIS acceptance.

ALTERNATIVE INJECTION PAINTING STUDIES

The normal ISIS painting scheme is anti-correlated but this may not be the optimal system. Three additional painting methods have been studied. They have been labelled as '*Correlated to H*', (reversed vertical sweeper painting), '*Correlated to V*' (ramped injection dipoles) and '*Fast switch*' (ramped sweeper and dipoles). Painting ranges for each case are shown in Figure 5 and have been chosen to be the same as those resulting from the ISIS fit, thus allowing comparison. Fast Switch Painting is probably not feasible due to power supply and magnet limitations but is put in the study for reference.

The Dual Harmonic RF Upgrade [5] will increase ISIS accelerated intensity to ~ 3.75×10^{13} ppp. Comparison of painting methods at this intensity are also summarised.

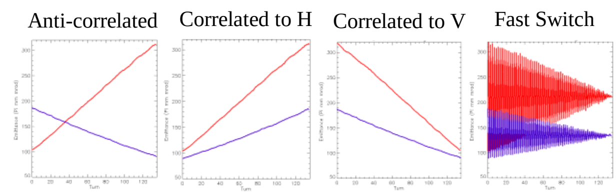

Figure 5. Centroid painting amplitudes over injection

Painting Results

Phase space and real space distributions at 0 ms are shown in Fig 6. Distinct differences for each painting case can be seen. 'Anti-Correlated' and 'Correlated to H' schemes have the least peaky distributions with corresponding small tune footprint, Fig 7. 'Correlated to V' has a more peaked central distribution driving a larger tune footprint. 'Fast Switch' lies between the two types.

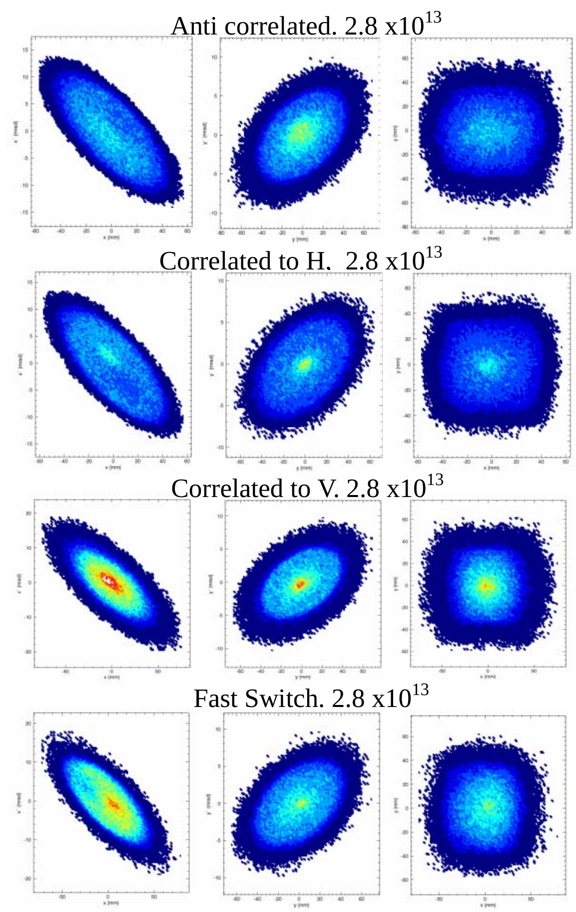

Figure 6: Phase space and real space distributions a 0 ms. Colour indicates particle density, with the same scale in all four cases.

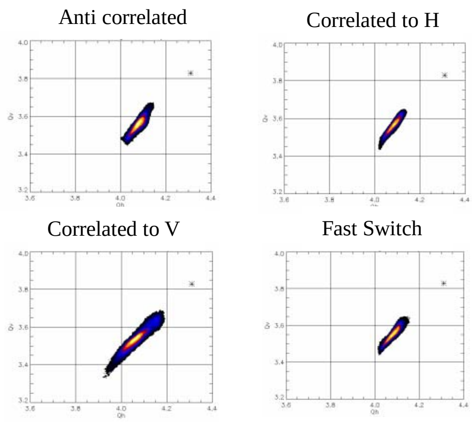

Figure 7: Single Particle Tune Diagrams at 2.8×10^{13} ppp.

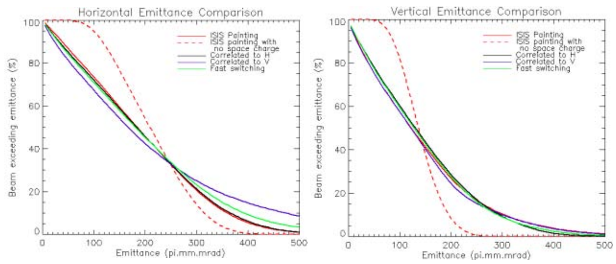

Figure 8: Emittance occupancy for each painting case.

Emittance occupancy at 0 ms, Figure 8, shows marked differences in beam distributions, particularly at the edges of the beam in the horizontal plane. Table 1 shows beam occupancy, beam loss, beyond the ISIS collector acceptance. The perturbed lattice increases loss in all cases, 'Anti-correlated' increasing ~ 50 % at 2.8×10^{13} ppp but remaining approximately constant, within error, at 3.75×10^{13} ppp. Overall 'Correlated to H' generates the least beam loss for all intensities and lattices, 'Correlated to V' the highest loss due to significant horizontal growth.

Table 1. Percentage ε_h , ε_v remaining > 400 π mm mrad

Intensity (10^{13})	2.8		2.8		3.75	
Lattice	Normal		½ int error		½ int error	
$\varepsilon_h \pm 0.8$, $\varepsilon_v \pm 0.2$	ε_h	ε_v	ε_h	ε_v	ε_h	ε_v
ISIS Anti-Corr	5.5	3.8	10.2	3.7	9.6	4.0
Corr to V, ε dec	14.7	3.6	16.7	4.5	16.9	5.3
Corr to H, ε inc	6.2	1.5	9.1	1.8	10.0	3.0
Fast Switch	9.3	2.4	11.8	2.6	11.8	3.5

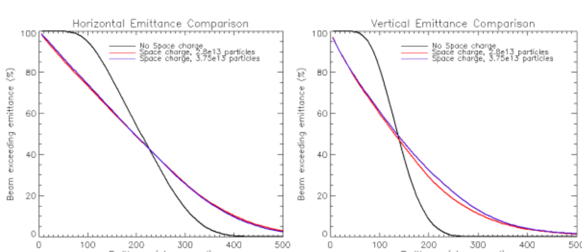

Figure 10. Emittance occupancy for 'Anti-correlated' painting as a function of simulated intensity.

Emittance occupancy at the current intensity, 2.8×10^{13} ppp and required DHRF intensity 3.75×10^{13} ppp for the nominal ISIS painting are shown in Figure 10. Small vertical variations are observed in the 150-350 π mm mrad range.

The number of foil hits for each painting method, lattice and simulated intensity are shown in Table 2. 'Anti-correlated' and 'Correlated to H' have ~14 at our current operating intensity. 'Correlated to V' is the worst scheme at ~24. During injection, this scheme increases the dipole bump to achieve the required painting amplitudes pushing the accumulated beam into the foil. Interestingly the foil hits for each painting case decrease with increasing intensity. This is probably due to the space charge filling in the hollow particle distributions and driving beam away from the foil.

Table 2. Foil hits per particle for each painting method.

	Normal			½ Int Error	
Intensity (10^{13})	0	0.4	2.8	2.8	3.75
ISIS Ant-Corr	15.8	15.5	14.2	13.4	12.6
Corr to V ,ε dec	27	26.9	23.8	22.9	22.5
Corr to H, ε inc	15.8	15.6	14.1	13.6	13.0
Fast Switch	19.3	19.0	17.6	16.8	16.5

SUMMARY AND FURTHER STUDIES

ORBIT simulations show a reasonable fit to measured profiles at 0 ms. Comparison at earlier time points show simulation and measurement diverging. Fitting to a range of measurements including low intensity painting amplitudes and utilising improved profile monitor diagnostics should improve agreement. Predictions of transverse beam loss require further study. Realistic lattice errors and foil scattering should also be included.

Painting distributions show least beam loss and foil hits for the 'Anti-correlated' and 'Correlated to H' case. This suggests horizontal painting distributions are the most critical to loss control on ISIS. The latter requires minor power supply changes to test on ISIS and should be pursued. 'Correlated to V' and 'Fast Switch' have higher losses and foil hits.

ACKNOWLEDGEMENTS

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REFERENCES

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