BEAM LOSS STUDIES OF THE ISIS SYNCHROTRON USING ORBIT

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Abstract

The ISIS synchrotron forms part of the accelerator chain for the spallation neutron source at RAL in the UK. The synchrotron is an 800 MeV, 50 Hz, RCS accelerating ~2.8x10^{13} protons per pulse (ppp). Beam loss is localised to 2 super periods of the ring using a system of collimators. The injection and acceleration processes, vacuum vessels and collimation systems have been modelled using the particle tracking code ORBIT [1]. This paper presents simulation results in comparison to measurements of longitudinal profiles and beam loss.

INTRODUCTION

High intensity operation of the ISIS synchrotron is ultimately limited by uncontrolled beam loss which activates the ring, limiting hands on maintenance. A dominant loss mechanism in the synchrotron is the non-adiabatic longitudinal trapping process which lasts up to 3 ms of the 10 ms ramp from 70-800 MeV. Detailed modelling of this process should provide a basis to further understand high intensity ring operation and improve machine performance.

In this paper the longitudinal trapping process is simulated using the particle tracking code ORBIT and compared to measurements for two modes of operation. The first mode (2RF) is a ring which has 6 single harmonic RF cavities running at h=2 and two further cavities running at h=4. The second mode (1RF) switches the h=4 cavities off. The 2RF mode is our normal operating setup and reflects a highly optimised ring. The 1RF mode represents a test case demonstrating high beam loss conditions. In both cases 2.8x10^{13} protons were injected into the synchrotron and accelerated. Measurements were taken from the beginning of injection to 3 ms for comparison with simulation: longitudinal line densities (beam profiles), acceleration efficiencies, and total temporal beam loss. Beam acceleration efficiencies in 1RF and 2RF modes were 74% and 93% respectively. Summed beam loss measurements have been converted to lost particles based on calibration measurements and normalised to match total acceleration efficiencies.

Previous studies using transverse beam profile measurements have shown profile evolution during injection is in reasonable agreement with simulation [2]. For this work it is assumed that transverse injection setup is very similar to standard configurations identified in these previous studies. A longitudinal tomography code [3] is also used to produce phase space plots for further comparison with simulation.

ORBIT SIMULATION

The particle tracking code ORBIT has been used in 1D to fit to longitudinal profile measurements. The code has been modified to include RF bucket energy offsets required to simulate frequency errors. Beam losses are derived using a momentum collimator set at $\Delta p/p=2\%$. Betatron tune ramping and acceleration for 3D runs are included by loading a new lattice on each turn with the appropriate parameters. Simulations in 1D use space charge with 128 bins and 6x10^{5} macroparticles. Simulations in 3D used the '3DFFT' space charge routine with 128x128x64 bins and ~1.3x10^{6} macroparticles. This particle count was based on consistent and convergent evolution of transverse emittances. The 3D model also included foil scattering, detailed realistic machine apertures and the collimator system.

1D SIMULATION RESULTS

Selected ORBIT parameters were varied to optimise agreement between measured and simulated pulse shapes. In both cases the RF volts were allowed to vary by 10%. Bucket offsets up to 0.3 MeV from 0 to 0.5 ms were required to improve the 1RF case. The phase between the h=2 and h=4 RF systems was varied by ±10° from the beginning of injection to 0.5 ms in the 2RF case. These variations are within measurement error of the operational values.

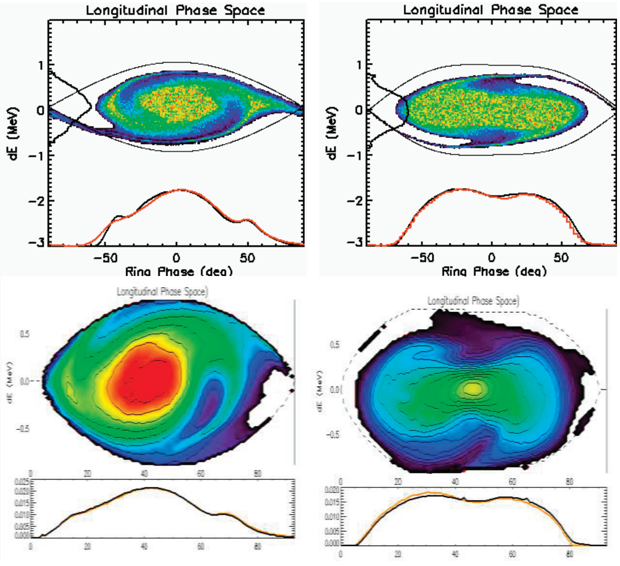

Figure 1: Longitudinal phase space at 0 ms. 1RF (left), 2RF (right) simulated (top), tomographic reconstruction (bottom). Black, simulated line density, orange measured.

Simulated phase space and line density projections at 0 ms during the acceleration cycle are shown in the upper plot of Figure 1. Simulated profiles are compared to measured profiles and show good agreement. Measured profiles have been scaled to match simulation peak height and re-phased. Phase space tomographic reconstructions based on profile data over 100 turns are shown for both 1RF and 2RF cases in figure 1, bottom. Key features of the complicated non-adiabatic trapping process are reproduced. ORBIT results at 1, 2 and 3 ms are shown in Figure 2. Total injection and acceleration efficiencies to 3 ms are 98.4% and 99.92% compared to measured values, 74% and 93% for the 1RF and 2RF cases respectively. It is expected that inclusion of transverse effects will increase the simulated loss magnitudes.

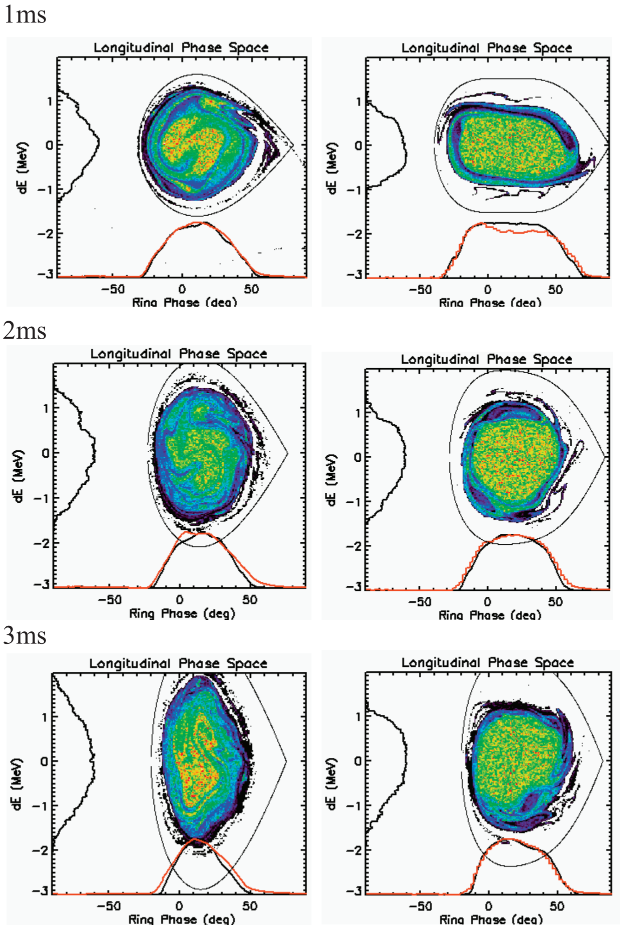

Figure 2: 1RF (left), 2RF (right) simulated phase spaces 1-3 ms. Black, simulated line density, orange measured.

It was clear during the fitting process that RF frequency error is a key parameter in obtaining good agreement, more detailed measurements would be developed for future studies. An algorithm to automate the fits is in development.

3D SIMULATION RESULTS

The longitudinal fitted parameters derived above were next used in a 3D model of the synchrotron. During ISIS operation the transverse tunes of the machine are ramped to minimise beam loss using trim quadrupoles. This has been included by loading a new lattice into the simulation with the required tunes on each turn. The simulation also included foil scattering, machine apertures and collimators which are important elements for accurately generating beam losses.

Longitudinal profiles from the 3D code were compared with the 1D results above. Examination shows that they are similar across the whole of injection and acceleration to 3 ms. Figure 3 shows an example at 1 ms for both the 1RF and 2RF cases.

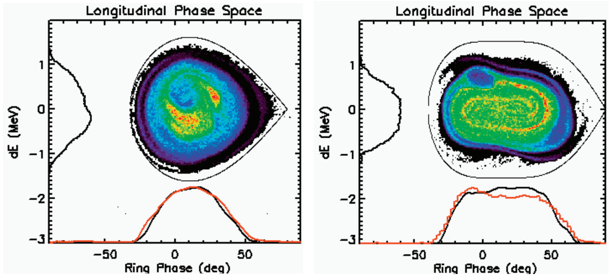

Figure 3: 1RF (left), 2RF (right) simulated phase spaces at 1 ms. Black, simulated line density, orange measured.

Simulated acceleration efficiencies were 63.6% and 97.3% for the 1RF and 2RF cases compared to measured 74% and 93%. This represents a significant decrease compared to the 1D result. Beam losses fall on the collectors almost equally between the transverse planes. This is observed on ISIS where temperatures on horizontal and vertical primary collimators are equal.

The 1RF result is low compared to measurement. Likely sources of error are the closed orbit position and envelope at the collimators. A second simulation with collimators pulled out from their original position of 75% horizontal and 80% vertical full aperture to 85% in both planes was run. This represents a change in collimator position of 10 mm and 3 mm in the horizontal and vertical planes and increases acceleration efficiencies to 79.3% and 99.5%, where almost all the loss saving comes from the horizontal plane. Hence it seems reasonable, at least for the 1RF case, to suggest some of the discrepancies are due to the uncertainties of beam centroid and envelope position. Efficiencies for the 2RF case are consistently lower and will be the subject of further study.

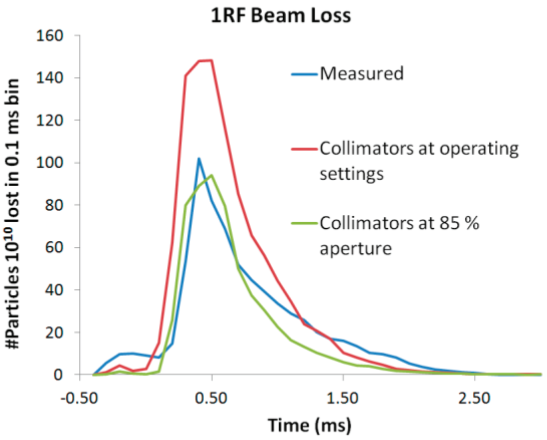

Figure 4: Comparison of measured and simulated beam loss for the 1RF case.

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Comparison of simulated and measured ring beam loss for the two collimator positions are show in Figure 4 and 5. Measured temporal loss distributions have good agreement with simulation results. Foil scattering losses during injection(-0.4 to -0.1 ms), peak trapping losses at ~0.5 ms which then decay to zero by 3 ms are reproduced. Absolute measured loss magnitudes have a large associated error , ±100%, due to beam loss monitors covering a finite solid angle of the accelerator. Normalising to acceleration efficiencies yields reasonable agreement and will be subject to further study.

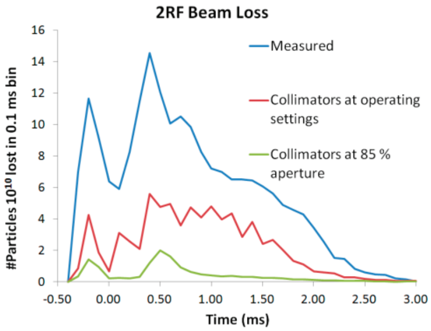

Figure 5: Comparison of measured and simulated beam loss for the 2RF case.

3D TRANSVERSE STUDIES

Beam losses predicted in the 3D simulations are much larger than those in 1D. Analysis of transverse emittance shows growth during acceleration, particularly in the 1RF case. Emittance at 99% occupancy is shown in Figure 6 for a ring with collimators set at 85% horizontal and vertical apertures. In the 1RF case vertical growth exceeds the collimator acceptance generating 14.1% loss. Losses are lower in the horizontal plane, 6.6%, and are complicated by the combined momentum-betatron collimation process. In the 2RF case the 99% emittance grows much less and does not exceed collimator acceptance resulting in ~0.25% loss in each plane. This is most probably due to the enhanced bunching factor provided by the additional h=4 cavities.

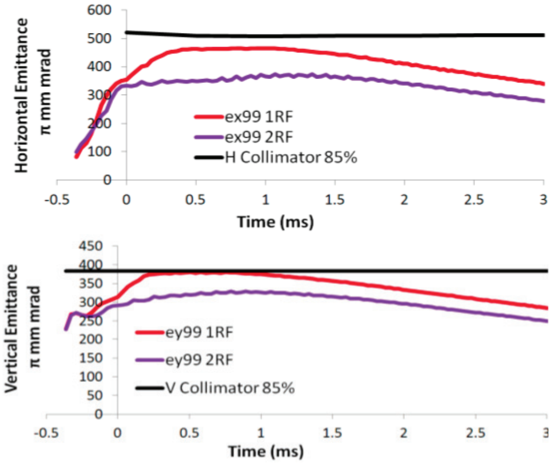

Figure 6: 99% Emittance evolution for 1RF and 2RF cases.

The increased transverse loss with lower bunching factor suggests loss mechanisms associated with transverse space charge. Incoherent tune distributions generated by ORBIT are shown in Figure 7, for the 1RF and 2RF cases. As expected the peak tune shifts are significantly smaller with the optimised bunching factors in the 2RF case. Also shown in the plots are zero intensity tunes, and the estimated tune shift for a KV distribution and peak shift for a waterbag distribution occupying the same 99% emittance as the simulated beam. In these simulations losses seem to be associated with beam redistributions from injection, and systematic space charge resonances, as no half integer driving terms were applied. The effects of these large tune shifts, and the associated 2 and 3D loss mechanisms, are the subject of much ongoing study at ISIS [4]. Work is now underway investigating evolution of transverse moments along the bunch with effects of relevant driving terms.

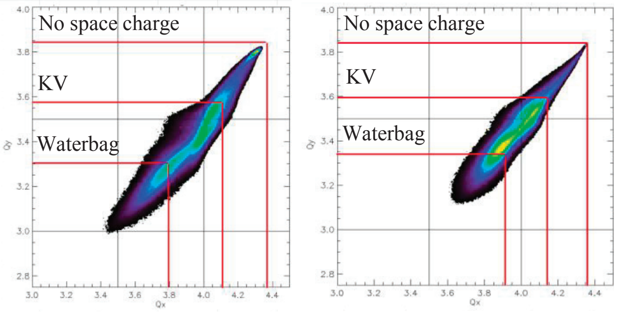

Figure 7: Tune distribution at 0 ms, 1RF (left), 2RF (right). Colour indicates particle density.

SUMMARY

Simulations in 1D have shown good agreement with measured line densities in the two operating modes. Transferring 1D results to a 3D model have yielded reasonably close acceleration efficiency and beam loss time distributions. Initial emittance and tune analyses give indications of some beam loss mechanisms for future studies.

ACKNOWLEDGEMENTS

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REFERENCES

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[2] B. Jones et al., 'Injection Optimisation on the ISIS Synchrotron', EPAC08.
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