SIMULATION AND MEASUREMENT OF HALF INTEGER RESONANCE IN COASTING BEAMS ON THE ISIS RING

C. M. Warsop, D. J. Adams, B Jones, B. G. Pine, H. V. Smith, R. E. Williamson,
Rutherford Appleton Laboratory, Oxfordshire, UK.

Abstract

ISIS is the spallation neutron source at the Rutherford Appleton Laboratory in the UK. Operation centres on an 800 MeV rapid cycling synchrotron (RCS), which provides 3×10^{13} protons per pulse (ppp) at 50 Hz, corresponding to a beam power of 0.2 MW. In common with many lower energy, high intensity proton rings, a key loss mechanism on ISIS is half integer resonance under space charge. This paper summarises experimental and simulation work studying half integer resonance in a "2D" coasting beam in the ISIS ring: understanding this is an essential prerequisite for explaining the more complicated case of RCS operation. For coasting beam experiments, the ring is reconfigured to storage ring mode with RF off and main magnets powered on DC current only. A 70 MeV beam is injected, painted appropriately, and manipulated so as to approach resonance. Understanding how the resonant condition develops is central to explaining observations, so realistic simulations of resonance, including injection, ramping of intensity and tunes are being developed. Results from the ORBIT code are presented and compared with experimental and theoretical results. Finally, future plans are summarised.

BACKGROUND

The ISIS Synchrotron

The ISIS synchrotron has a circumference of 163 m. It accelerates 3×10^{13} protons per pulse (ppp) from 70-800 MeV on the 10 ms rising edge of the sinusoidal main magnet field. At the repetition rate of 50 Hz this corresponds to a beam power of 0.2 MW. Charge-exchange injection takes place over 130 turns as the high intensity beam is accumulated, with painting in both transverse planes over the collimated acceptances of ~300 π mm mr. Nominal tunes are (Q_x,Q_y)=(4.31, 3.83), but these are varied using two families of 10 trim quadrupoles. A dual harmonic RF system captures and accelerates the un-bunched injected beam. Peak incoherent tune shifts exceed -0.4 at about 80 MeV, during the bunching process. Single turn extraction makes use of a fast vertical kicker at 800 MeV. Main loss mechanisms are associated with non-adiabatic trapping and transverse space charge. Loss associated with half integer resonance is relevant for present ISIS operations, and proposed upgrades [1].

Half Integer Loss Mechanisms

Coherent resonance theory [2] provides a valuable theoretical model explaining why incoherent limits can be exceeded, and predicting a resonance condition or coherent limit. However, it obviously does not provide a complete description of the loss mechanisms that limit intensity on a real machine. The behaviour of the beam as coherent resonance is approached, with enhanced envelope oscillations and associated emittance growth mechanisms, is of considerable interest. A better understanding of these processes may allow improved beam optimisation, a key motivation for these studies. Present work is focused on understanding 2D transverse models, but this will extend in the future to include longitudinal effects relevant for the ISIS RCS.

Solutions of the envelope equation for ISIS have been studied in [3], giving predictions of the coherent modes for the appropriate "large tune split" case. Subsequent studies have looked at formation of the parametric halo [4]. Complementing these studies is a programme of experimental work on ISIS, summarised in [5]. Here, the latest experimental results are presented, along with corresponding ORBIT [6] simulations.

Coherent Resonance

A basic aim of the work is the prediction and experimental observation of coherent resonance. Envelope frequencies (for the large tune split case with equal transverse emittances [2, 3]), are given by:

$$\begin{aligned}\omega_x^2 &= 4Q_{0x}^2 - 5Q_{0x}\Delta Q_{inc} \\ \omega_y^2 &= 4Q_{0y}^2 - 5Q_{0x}\Delta Q_{inc}\end{aligned} \quad \text{with } \Delta Q_{inc} = \frac{r_p N}{2\pi\beta^2\gamma^3\varepsilon}\frac{1}{B} \quad (1)$$

with: $\omega_{x,y}$ envelope frequencies, $Q_{0x,y}$ zero intensity tunes, ΔQ_{inc}, incoherent tune shift of RMS equivalent KV beam, r_p proton radius, N intensity, $\varepsilon=4\varepsilon_{rms}$, ε_{rms} RMS emittance, B bunching factor and β, γ relativistic parameters. With appropriate measurements of intensity, emittance, and tune, the appearance of resonance can be predicted. Once the coherent resonance is experimentally well understood, studies of the loss mechanisms and halo can follow.

EXPERIMENTS

Machine Configuration

Experimental work was planned to provide the simplest practical method for studying half integer loss. The complications of longitudinal motion are removed by reconfiguring the ISIS ring in storage ring mode (SRM). For this, RF systems are turned off and the main magnets are powered on DC to provide an un-bunched (B=1), coasting, or "2D" beam. Injection is reconfigured to give constant painting amplitudes in both planes, and to give the beam emittances required. The two families of trim quadrupoles allow values of Q to be selected, and azimuthal harmonics applied. Intensity toroids and beam loss monitors provide detailed information on circulating current and loss. Profile monitors allow calculation of ($\varepsilon_{rms,x}$, $\varepsilon_{rms,y}$). Position monitors provide measurement of Q values and beam spectra. Other loss mechanisms are avoided by careful machine setup: absence of instabilities is checked by monitoring spectra in all three planes [5].

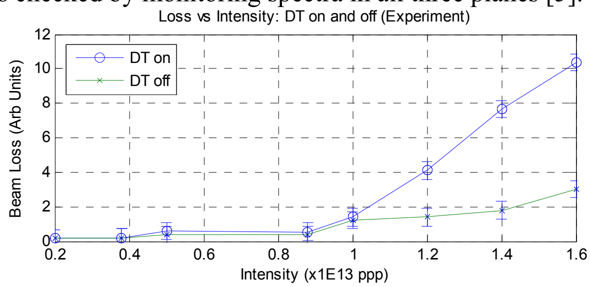

Figure 1: Measured loss vs intensity, driving term on, off.

Approach Resonance by Increasing Intensity

In this experiment ε, Q are fixed, and N varied until resonant loss is observed as predicted by equation (1). The constant painting amplitudes through injection allow intensity to be varied by changing the injected pulse length; the painted beam emittance will thus remain constant until resonance occurs. Intensity is increased and beam loss measured.

The peak loss during injection as a function of intensity is shown in Figure 1: error bars indicate pulse to pulse variations. At the higher intensities, total beam losses are ~20% or more. Parameters for the beam at 70 MeV, with B=1 were: $\varepsilon_{rms,x}=\varepsilon_{rms,y}=16\pm4\ \pi$ mm mr, $(Q_x, Q_y)=(4.31, 3.66)$. Tunes are chosen such that resonance is only approached in the vertical plane. For these values equation (1) predicts resonance at $0.9\pm0.2\times10^{13}$ ppp. Two sets of measurements were taken, one with harmonic excitation of trim quadrupoles applied (i.e. $2Q_y=7$) and one without. These are both shown in Figure 1 (driving term "DT" on/off). It can be seen that significant losses start to appear at about 0.9×10^{13} ppp, coincident with expected coherent resonance. It can also be seen that addition of the gradient driving term greatly enhances the loss. This strongly indicates the appearance of the expected resonance.

Other Tests of Resonance and Next Steps

Various other dependencies predicted by equation (1) have been explored experimentally, and have confirmed the expected behaviour. Experiments fixing ε, N and reducing Q by changing quadrupoles have produced loss as predicted, see [5]. Measurements, making ε larger by adjusting injection painting, have also demonstrated the expected behaviour, with resonance appearing at higher intensities for larger emittance beams. Collectively, these experiments indicate coherent resonance is being observed as predicted. However, experimental methods are being refined and more detailed and precise confirmation of equation (1) will be possible. Full exploitation of new profile monitors should provide improved emittance measurements, direct indications of growth (rather than indirectly via loss), and hopefully allow study of the predicted parametric halo.

SIMULATIONS

ORBIT Modelling of Experiments

A detailed ORBIT model of the ISIS ring has now been established, which includes: the AG lattice, 3D beam dynamics with space charge, injection painting, the foil, apertures and collimation. This was adapted to model the machine in SRM, including constant injection painting, suitable Q values, and harmonic driving terms. This has allowed (i) checks that the simulation and experimental behaviour agree (bench marking), and (ii) study of detailed simulation data (not available experimentally) to confirm half integer growth.

Nominal values for ISIS parameters were assumed for the ORBIT model, with adjustments made to *approximately* reproduce experiments. Future work will allow closer matching of the many parameters involved. However, the essential requirement is that they be close, exhibit the expected behaviour and agree with theory. The main parameters used were: $(Q_x, Q_y)=(4.30, 3.60)$, $\varepsilon_{rms,x}=\varepsilon_{rms,y}=15\pm2\ \pi$ mm mr (at onset of resonance), with representative driving terms ($2Q_y=7$) included as required. For these values, coherent resonance is predicted by (1) at $0.5\pm0.1\times10^{13}$ ppp. ORBIT simulations were run for 299 turns, with a total of $\sim10^6$ macro particles. The injection model includes accumulation and painting over the first 130 turns. Simulation runs were repeated for a range of injected intensities from $0.0\text{-}1.2\times10^{13}$ ppp.

Emittance vs Intensity

The 99% emittance from ORBIT on turn 299, for simulation runs at various intensities, with driving term on, is shown in Figure 2. It can be seen that the emittance increases substantially between 0.4 and 0.6×10^{13} ppp, as expected. Note the collimation limits in the model are at about 300 π mm mr, thus the emittance peaks near this value as particles are removed. This is consistent with the experimental observations of *loss* in Figure 1 (with allowance for different ε_{rms}).

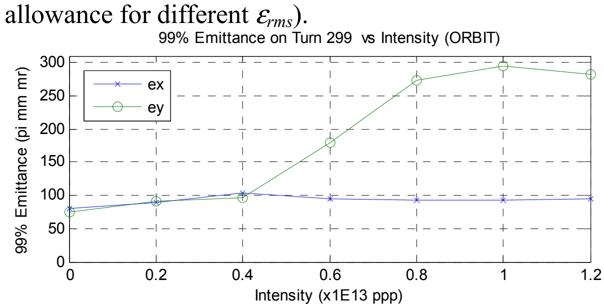

Figure 2: Particle emittance on turn 299 for ORBIT simulations at a range of intensities.

Emittance vs Turn

It is informative to investigate the evolution of the beam emittance with time or turn. The variations of ε_{rms} with turn for the 1×10^{13} ppp simulation are shown in Figure 3.

Results include simulations with the $2Q_y$=7 driving term on and off. It can be seen that no growth occurs in the non resonant, horizontal plane. In the vertical plane, growth is clear, and is most marked after turn ~68, where the accumulated intensity reaches about 0.5×10^{13} ppp, the predicted resonance. It is also clear that growth is greatly enhanced by the addition of a driving term. These factors all strongly suggest half integer resonance and are consistent with experiments.

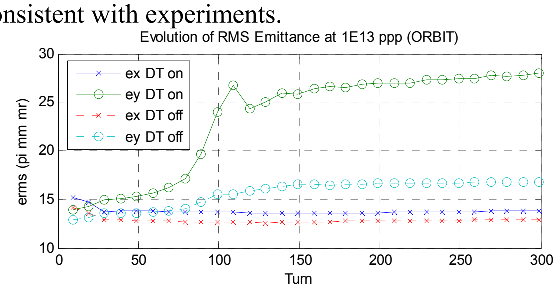

Figure 3: Evolution of $\varepsilon_{rms,x}$, $\varepsilon_{rms,y}$ over 299 turns, with driving term on and off, and intensity 1.0×10^{13} ppp.

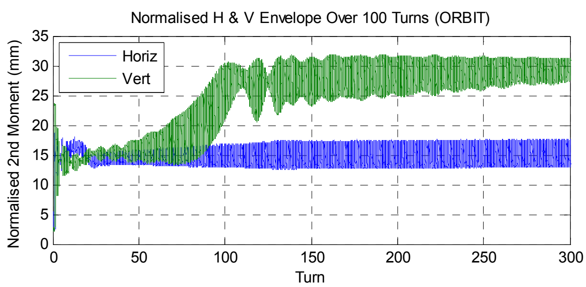

Figure 4: Evolution of horizontal and vertical envelopes over 300 turns, parameters as Figure 3.

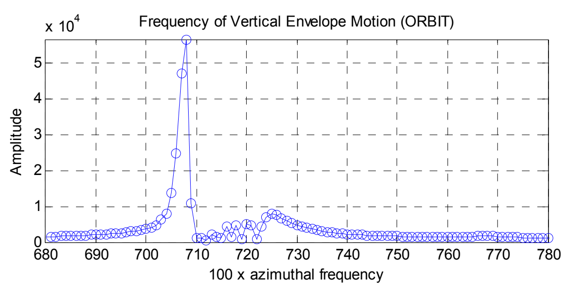

Figure 5: Frequency of vertical envelope over turns 0-100, parameters as Figure 3.

Results: Coherent Motion and Halo

To confirm that the emittance growth is associated with half integer, the evolution and frequency of second moments were analysed. These are shown in Figures 4 and 5. The blow up of coherent vertical envelope motion in the first 100 turns, corresponding to the emittance increase in Figure 3 is clear. The strong envelope components *near* the resonant frequency ($2Q_y$=7) are shown in Figure 5. The expected half integer parametric halo structure is also seen clearly: Figure 6 shows single particle phase space on turn 109.

Whilst the main simulation results can be explained by coherent resonance, other interesting features are also present. Variations appear in ε_{rms} and other beam parameters which are probably related to the time varying distributions and associated space charge during painting. This redistribution under space charge (with and without half integer effects) is of considerable interest, and will be the subject of future study.

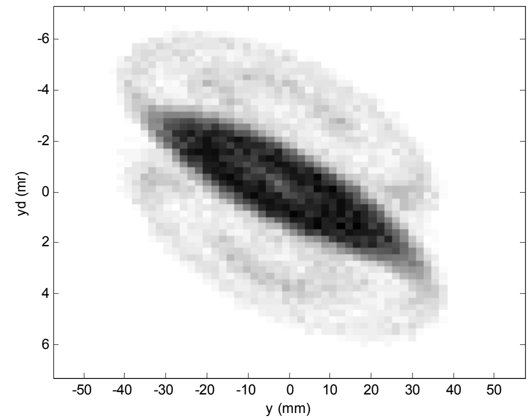

Figure 6: Density plot in single particle phase space (y,y') showing expected half integer structure (ORBIT).

CONCLUSIONS AND NEXT STEPS

Experiments observing half integer loss under space charge have given results in agreement with expectations from coherent resonance theory. Detailed ORBIT simulations of the same experiments have given results compatible with theory and observations.

Experimental methods are still being refined, and should provide more detailed confirmation of the coherent theory, as well as the opportunity to study associated loss mechanisms and halo. Experimental and simulation work to extend this to the 3D case is planned. Improved diagnostics allowing direct excitation and observation of coherent modes are also being considered.

ACKNOWLEDGMENTS

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REFERENCES

[1] B G Pine et al., Ring Transverse Beam Dynamics for ISIS Injection Upgrade, Proc. IPAC11, WEPS104, *and* C M Warsop et al., Status of Injection Upgrade Studies for the ISIS Ring, Proc. IPAC11, WEPS106.

[2] R Baartman, Betatron Resonances with Space Charge, AIP Conf. Proc. CP448, 1998.

[3] C M Warsop, Transverse Space Charge Studies for the ISIS Ring, Proc. EPAC06, Edinburgh, UK, p 312.

[4] C M Warsop et al., Space Charge Loss Mechanisms Associated with Half Integer Resonance on the ISIS Synchrotron, Proc. EPAC08, Genoa, Italy, p 373.

[5] C M Warsop et al., High Intensity Studies on the ISIS Synchrotron, Including Upgrades and Half Integer, Proc. HB10, Morschach, Switzerland, 2010.

[6] J Galambos, ORBIT - A Ring Injection Code with Space Charge, Proc. PAC99, p 3143.