STUDIES OF SPACE CHARGE LOSS MECHANISMS ASSOCIATED WITH HALF INTEGER RESONANCE ON THE ISIS RCS

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Abstract

ISIS is the spallation neutron source at the Rutherford Appleton Laboratory in the UK. Operation centres on a 50 Hz proton synchrotron, which accelerates ~3×10^{13} ppp (protons per pulse) from 70 to 800 MeV, corresponding to beam powers of 0.2 MW. Beam loss imposes limits on operational intensity, and a main contributing mechanism is the action of half integer resonance under high space charge. The same loss mechanism is also a potential problem in ISIS upgrade scenarios involving either higher energy injection into the existing ring, or the addition of a new 3 GeV, high intensity RCS (rapid cycling synchrotron). Progress on PIC (particle in cell) simulation studies investigating the effects of the driven coherent envelope motion, the associated parametric halo, along with implications of momentum spread, is reported. Where possible, comparisons are made with relevant theoretical models. Closely related benchmarking work, experimental studies and plans are also summarised.

INTRODUCTION

Underpinning upgrade studies for the ISIS machines is a programme of high intensity R&D work. This aims to develop simulations, confirm predictions via comparison with theory and experiment, and improve understanding of the important loss mechanisms. Associated with this is a development programme for diagnostics and experimental work.

In this paper we summarise progress on studies of an important loss mechanism: the half integer resonance. Continuing previous work [1], we investigate 2D behaviour via theory, simulation, and now experimentally by studying *coasting beams* with ISIS in storage ring mode (SRM). In this mode, ring RF and the AC component of the main magnet field are turned off, and unbunched beams circulate at 70 MeV. Some initial experimental results are presented, showing progress on commissioning new diagnostics and developing appropriate experimental techniques. Finally, we report briefly on initial work taking simulations from 2D to 3D.

The ISIS RCS has a mean radius of 26 m, and in normal operation accelerates about 3×10^{13} ppp from 70 to 800 MeV in 10 ms. Beam is painted over the transverse acceptances (~400 π mm mr) during the 150 turn charge-exchange injection process. Transverse space charge forces dominate at low energy when peak incoherent tune shifts are estimated at ~ -0.4. Nominal tunes are (Q_x, Q_y)=(4.31, 3.83), with adjustment possible via trim quadrupoles.

STUDY OF ENVELOPE MODES

Understanding the dependence of coherent envelope modes on beam emittances is important for a number of reasons: it gives a basis for studying space charge effects experimentally in SRM; it gives indications of possible loss mechanisms; and it is a check of theory and simulations. Painting is easily controlled on the ISIS ring, and this gives potential for detailed studies of envelope (and higher order) modes under space charge. In particular, by exciting envelope resonance on a small beam, there is the possibility of generating and measuring halo within the machine acceptance. Theoretical values are calculated below, which are then compared with simulations.

Theoretical Calculations

Envelope mode frequencies of KV beams in the smooth focusing approximation, for small linearised oscillations, have been calculated in [2, 3]. Here we use the notation and results from [2], (equations 3-8 to 3-10), and solve the envelope equations for the eigenfrequencies of a beam with non-equal emittances and tunes. The envelope frequencies, $\omega_{x,y}$, are given by:

$$\omega_{x,y}^2 = 2t_1 - t_2\omega_p^2 \pm \sqrt{4t_3^2 + t_3 t_4 \omega_p^2 + t_5 \omega_p^4}\ ,$$

where

$$t_1 = \left(Q_{x0}^2 + Q_{y0}^2\right);\ t_2 = \frac{3}{2} - \frac{ab}{(a+b)^2};\ t_3 = \left(Q_{x0}^2 - Q_{y0}^2\right);$$

$$t_4 = 6\frac{(a-b)}{(a+b)};\ t_5 = \frac{\left(9a^4 - 14a^2b^2 + 9b^4\right)}{4(a+b)^4};$$

$$\omega_p^2 = \frac{2\cdot N \cdot r_0 \cdot R}{\pi \cdot a \cdot b \cdot \beta^2\gamma^3}\,.$$

Here, Q_{x0} and Q_{y0} are zero intensity tunes, a and b are half widths of the KV beam with $a=\sqrt{(\varepsilon_x R/Q_{x0})}$, $\varepsilon_x= 4\varepsilon_{xrms}$, $b=\sqrt{(\varepsilon_y R/Q_{y0})}$, $\varepsilon_y= 4\varepsilon_{yrms}$, R the ring mean radius, N is the number of particles, r_0 the proton radius, β and γ relativistic parameters. Frequencies of the two envelope modes, for ISIS with N=2.5×10^{12} ppp at 70 MeV, with nominal tunes, and a range of RMS emittances (ε_{xrms}='Ex', ε_{yrms}='Ey') are shown as lines in Figures 1 and 2. The horizontal axis corresponds to different ε_{yrms}; the different curves correspond to varying ε_{xrms}. Note that in the range chosen, the beam crosses the vertical line ω_y=7, but avoids horizontal resonance. This treatment does not include momentum spread. Simulations (below) indicate higher order coherent modes also have significant effects [3], these will be the subject of future study.

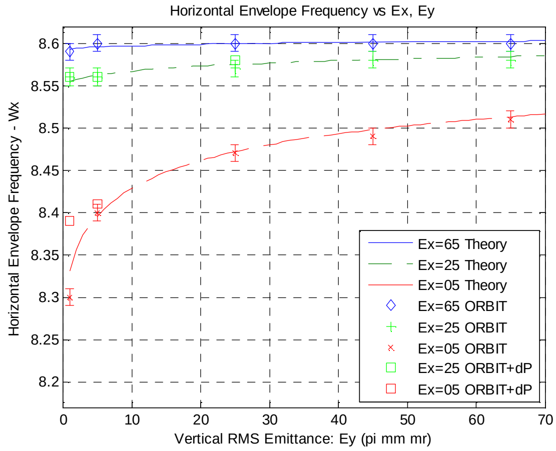

Figure 1: Horizontal Envelope Modes.

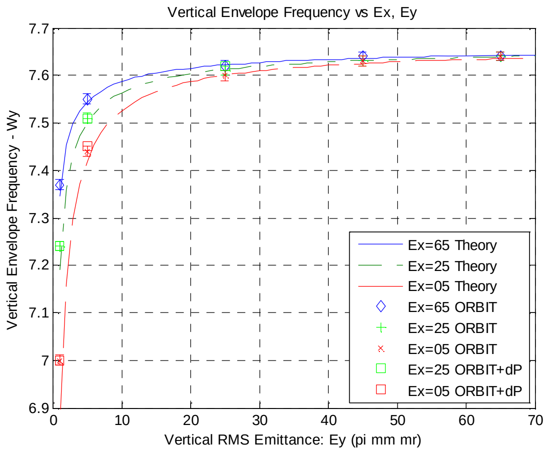

Figure 2: Vertical Envelope Modes.

Simulations without Momentum Spread

A set of 2D ORBIT [4] (PIC) simulations, corresponding to the theoretical calculations summarised in Figures 1 and 2, have been carried out for RMS equivalent beams in the ISIS AG lattice. A matched 4D waterbag (WB) distribution of 5×10^4 macro particles, with an intensity of 2.5×10^{12} ppp and negligible momentum spread, was tracked for 100 turns. A representative vertical driving term ($2Q_y$=7) was included. A set of results was obtained with ε_{xrms} and ε_{yrms} of the input distribution varying from 1 to 65 π mm mr. Results are summarised in Figures 1 and 2 (labelled “ORBIT”).

Simulations with Momentum Spread

The simulations were repeated for an input beam with a parabolic momentum distribution, dp/p=±0.004, uncorrelated to the transverse 4D WB distribution. Particles were “matched” such that their emittance had the same WB distribution as above, but centred on the appropriate dispersed orbit. Results are shown in Figures 1 and 2 (labelled “ORBIT+dP”).

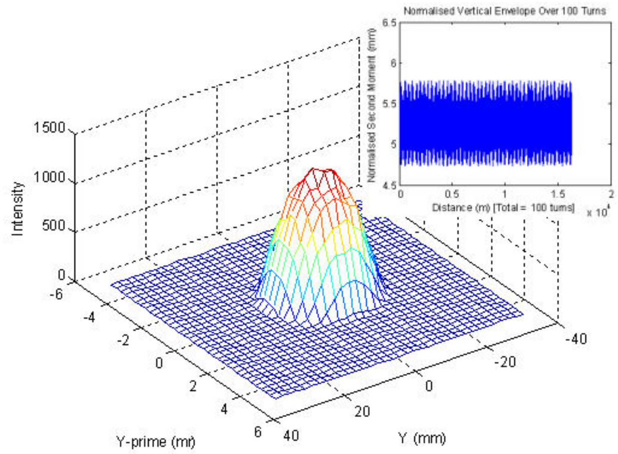

Figure 3: Vertical normalised (Y, Y') distribution after 15 turns, with envelope evolution over 100 turns (inset), above resonance (no halo). (ε_{xrms}, ε_{yrms})=(5, 5) π mm mr.

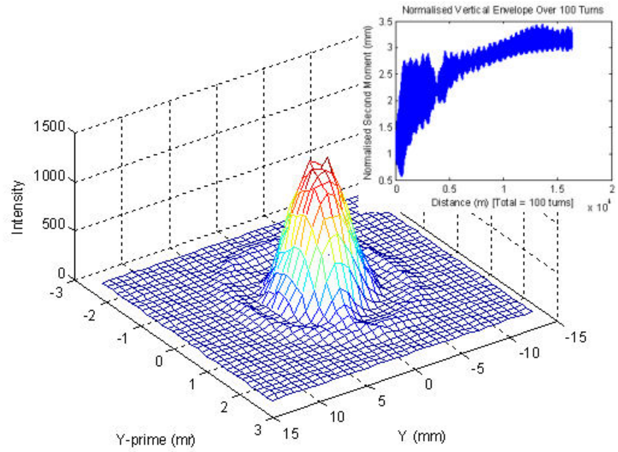

Figure 4: Vertical normalised (Y, Y') distribution after 15 turns, with envelope evolution over 100 turns (inset), at resonance (halo evident). (ε_{xrms}, ε_{yrms})=(5, 1) π mm mr.

Envelope Resonance with Small Emittance

Figures 1 and 2 show the theoretical predictions agree reasonably well with the simulations. However, once resonance is approached ($\omega_y\approx7$), beams in the simulation redistribute, and the comparisons are no longer valid. The simulations indicate that at nominal momentum spreads, behaviour is close to the single momentum case (square markers in the figures).

Figure 2 indicates that the vertical envelope should reach resonance with (ε_{xrms}, ε_{yrms})=(5, 1) π mm mr, where ω_y=7. Figures 3 and 4 show the beam phase space distributions and envelope evolutions, above and at resonance, respectively. Halo generated by parametric resonance with the oscillating envelope, and beam redistribution, is clear in Figure 4. These results include the nominal momentum spread described above, and suggest that generation of parametric halo with small, lower intensity beams should be an experimental possibility in SRM. However, measurement of the relatively low intensity halo could be challenging.

EXPERIMENTAL STUDIES

SRM experiments, investigating space charge, are being developed as part of a larger programme of machine study and diagnostic developments. New multi-channel, residual gas ionisation profile monitors are providing first results. Electron and strip-line monitors are also being installed. This is allowing more detailed study than has previously been possible.

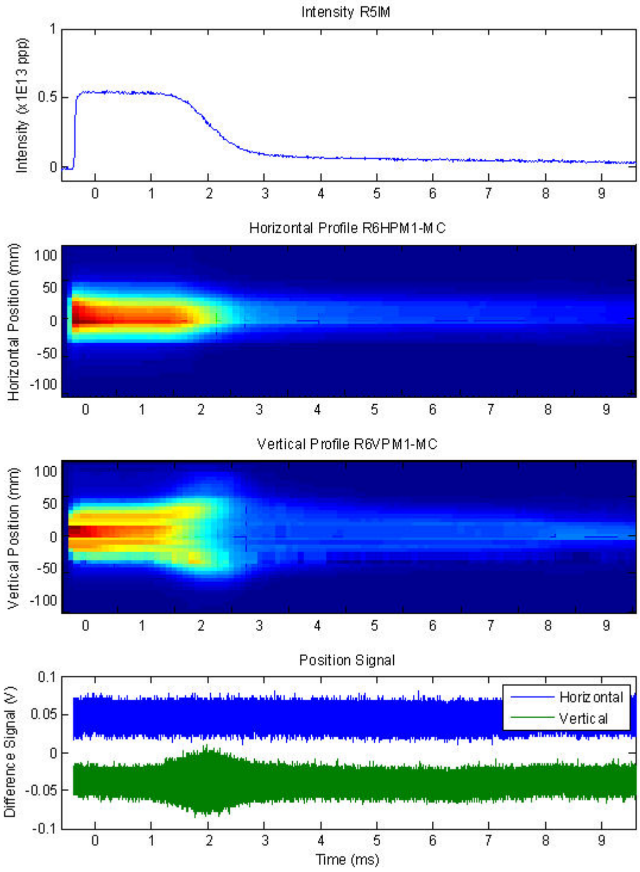

Figure 5: Experimental SRM results: Intensity, Horizontal and Vertical Profiles, Horizontal and Vertical Position Signals as a function of time.

Exploratory measurements in SRM have investigated coasting beams at intensities of 1-5×10^{12} ppp, with varying emittances. At ~1×10^{12} ppp, beams last for tens of ms, with little sign of instability. As beam intensity increases to ~3×10^{12} ppp, beam loss within 10 ms becomes evident. An example is shown in Figure 5: beam loss coincides with vertical dipole motion and growth. The frequency of the vertical dipole motion corresponds to the lowest frequency betatron sideband, suggesting a resistive wall instability. Depressing the tune away from the integer (Q_y~4) moves the sideband and stabilises the beam, again suggesting resistive wall instability. This is consistent with previous studies [5], and is of interest as it relates to instability in RCS mode.

The profiles in Figure 5 are uncorrected for space charge, but rough estimates (±~25%) indicate emittances of (ε_{xrms}, ε_{yrms})=(20, 20) π mm mr, for which envelope resonance is not expected. Future space charge studies will vary Q_y to push beam towards envelope resonance. The best techniques for probing space charge are still being developed, and more work identifying all the relevant loss mechanisms (e.g. instability) is required.

SIMULATION OF 3D DYNAMICS

ORBIT Simulations

ORBIT simulations of the full ISIS RCS cycle, in 3D, are now being used to study beam behaviour. The parallel implementation of the code is used with special treatment to allow fast ramping of the trim quadrupoles through the cycle. Expected loss patterns are reproduced, and there is evidence of transverse coherent envelope motion during the trapping process, when space charge peaks. Analysis is only preliminary, but it suggests a 3D manifestation of the half integer loss mechanism.

Set Simulations

The ISIS Set code [6] is now being expanded into a parallel, 3D implementation. This will draw on longitudinal code studies outlined in [7]. Careful benchmarking of non-linear motion is also underway, which will reduce uncertainty in halo and loss predictions.

SUMMARY AND PLANS

Theoretical and simulation models of 2D beams with non-equal tunes and emittances agree well, and provide a useful basis for experimental studies on ISIS. Experimental work is progressing, with new diagnostics giving more detailed information. Extension of codes and study to 3D motion is also giving valuable insight into loss on the operational machine.

ACKNOWLEDGEMENTS

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