

TRANSVERSE BEAM DYNAMICS IN THE ISIS SYNCHROTRON WITH HIGHER ENERGY INJECTION

B.G. Pine, C.M. Warsop, ISIS, STFC, Rutherford Appleton Laboratory, 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, which provides 3×10^{13} protons per pulse (ppp) at 50 Hz, corresponding to a beam power of ~ 0.2 MW. Studies are underway to increase the energy of the ISIS linac from 70 to 180 MeV. This would reduce transverse space charge in the synchrotron and enable a larger current to be accumulated, possibly up to 0.5 MW. As part of the study, transverse beam dynamics have been re-examined on ISIS, building up models from incoherent space charge tune shift through to 2D alternating gradient lattice simulations. These simulations, using the in-house space charge code Set, include harmonic perturbations to the focusing lattice and images from the unique ISIS vacuum vessel. A clearer picture of the dynamics is emerging where there may be important constraints on the highest intensities, including half integer resonance, image induced structure resonances and transverse instabilities.

INTRODUCTION

The ISIS synchrotron accelerates protons from 70 - 800 MeV at 50 Hz using a sinusoidal main magnet field. There are 10 super-periods in the machine, with specialised sections for charge exchange multi-turn H^- injection, and extraction. The circumference is 163 m. The design tunes are $Q_H = 4.31$, $Q_V = 3.83$, and there are two trim quadrupoles in each straight section to allow for manipulation of the horizontal and vertical tunes during the acceleration cycle. Potential future upgrades include adding a new 180 MeV linac, adding a new ring to accelerate the beam to 3.2 GeV and reach powers of ≥ 1 MW and eventually replacing the current synchrotron with an 800 MeV H^- linac [1]. Out of these options, building a new 180 MeV linac that would inject into the current synchrotron could be a very cost effective upgrade which would address important maintenance and reliability concerns with the current 70 MeV linac [2].

One of the main benefits of an upgrade in energy for the ISIS linac is the reduction in transverse space charge forces in the synchrotron. Space charge peaks during the non-adiabatic bunching process about 1 ms after the end of injection as ISIS runs at present, with an incoherent tune shift greater than -0.4. For the upgrade which will use a chopped injected beam, space charge will peak at the end of injection.

$$\Delta Q = -\frac{r_0 N}{2\pi\beta^2\gamma^3\epsilon B_f} \quad (1)$$

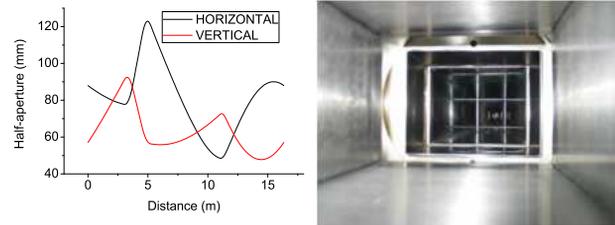


Figure 1: ISIS vacuum vessel design apertures over 1 super-period and photo inside vacuum chamber.

The incoherent space charge tune shift, Equation 1 [3], is proportional to beam intensity N , and inversely proportional to $\beta^2\gamma^3$ (the usual relativistic parameters), emittance ϵ , and bunching factor B_f . r_0 is the classical proton radius. Assuming the same painted emittance and bunching factor, the space charge tune shift will decrease by a factor of 2.6 for the 180 MeV injection upgrade, which will allow an increase to the total number of ppp from 3.0×10^{13} to 7.8×10^{13} or an increase in beam power from 190 kW to 499 kW.

While the incoherent tune shift is a useful tool for assessing space charge levels, it is a simplification of the actual dynamic processes involved. On ISIS the tunes are varied throughout injection and acceleration to avoid resonances and instabilities. The dominant vertical resistive-wall instability is presently avoided by dropping Q_V [4]. At substantially increased intensities, the growth rate is expected to be higher, but reduction in Q_V will be limited by the half integer ($2Q_V = 7$) resonance. This important 'bottleneck' may be avoided either with a damping system or by dropping Q_V below the half integer.

A set of simulation studies has been carried out looking at the effect of increasing intensity on the ISIS lattice. Several intensity limiting processes have been explored, including half integer resonance when the lattice is driven with representative quadrupole error terms, and an apparent third order structure resonances driven by image terms from the vacuum vessel which follows the profile of the beam envelope (Figure 1). An additional set of simulations has also been run exploring the behaviour of the beam when the vertical tune is set below the half integer, to avoid the vertical head-tail instability.

HALF INTEGER RESONANCE

Half integer resonance is a concern on ISIS and has been a subject of detailed study [5]. Studies of transverse dynamics for the injection upgrade have also included half integer resonance and are reported here. Simulations were

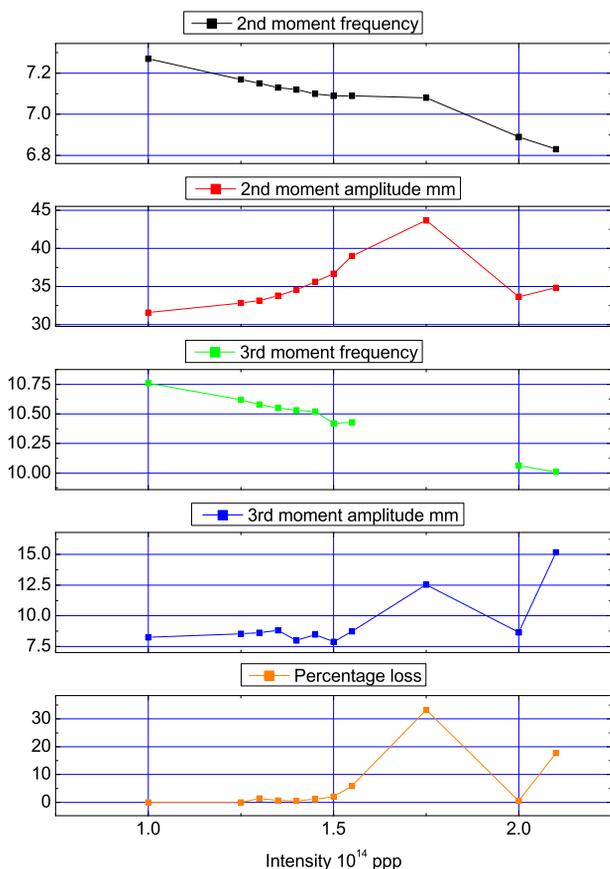


Figure 2: Intensity scan including half integer driving terms.

carried out using the in-house 2D space charge tracking code Set [6]. Set uses an FFT based particle-in-cell space charge solver and includes a matrix representation of the AG focusing lattice. The boundaries of the space charge calculation were set at the real apertures of the ISIS vacuum vessel which stay parallel to the beam envelope around the machine, and have an interesting effect on image fields and instabilities. For the half integer studies a harmonic driving term was applied to the trim quadrupoles in the simulated lattice providing errors at $2Q_V = 7$ at a magnitude equivalent to those estimated for the ISIS machine (stop-band width $\delta Q_{sb} \sim 0.02$). The tunes were set to ISIS design values. A 2D waterbag distribution of 50000 macro-particles was used in each case, and the simulations were run for 100 turns at a fixed energy of 180 MeV, representing a coasting beam. There were 128 space charge cells in each plane. To find the corresponding bunched beam intensity the intensity can be divided by the expected bunching factor of ~ 0.4 . The intensity was varied across the range of interest, $1.0 - 2.1 \times 10^{14}$ ppp. Bunches were matched to the lattice using RMS twiss parameters. Collimation at a representative 80% of the beampipe aperture was included in the simulations.

The results of this scan are shown in Figure 2 includ-

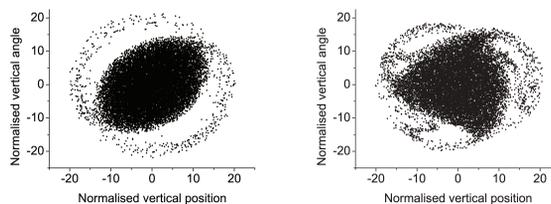


Figure 3: Half integer resonance for 1.5×10^{14} ppp and image induced third order resonance (without collimation) for 2×10^{14} ppp.

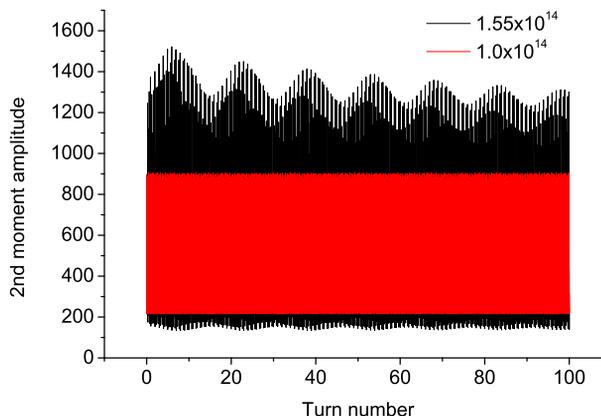


Figure 4: Comparing 2nd moment amplitudes for 1.0×10^{14} with 1.55×10^{14} ppp.

ing 2nd and 3rd moment frequencies and amplitudes and macro-particles lost during the 100 turns. As expected there is a dramatic spike in beam loss and 2nd moment amplitude as the beam passes through the $2Q_V = 7$ resonance. The left hand side of Figure 3 shows the vertical phase space after 100 turns, clearly displaying the two lobes of the half integer resonance.

Actually, beam loss starts substantially before the coherent mode reaches the half integer, and is significant (of the order of 5%) when the coasting beam intensity reaches 1.55×10^{14} ppp or bunched beam intensity of 6.2×10^{13} ppp. The beam envelope starts beating as the beam nears the half integer resonance and macro-particles at the edge of the distribution start to be lost, even though there is minimal RMS emittance growth. Figure 4 shows the 2nd moment amplitude of the bunch during the 100 turns comparing an intensity of 1.0×10^{14} with 1.55×10^{14} ppp, and clearly displaying the large envelope oscillation as the beam approaches resonance.

Half integer resonance will be a key concern for ISIS with upgraded injection. It is likely that intensities exceeding the above predictions would be possible by raising Q_V , but as described, vertical instabilities will probably impose limits. This is under study. Another option is dropping Q_V below the half integer, see below.

The 3rd moment frequency and amplitude are also displayed in Figure 2. The onset of the half integer resonance

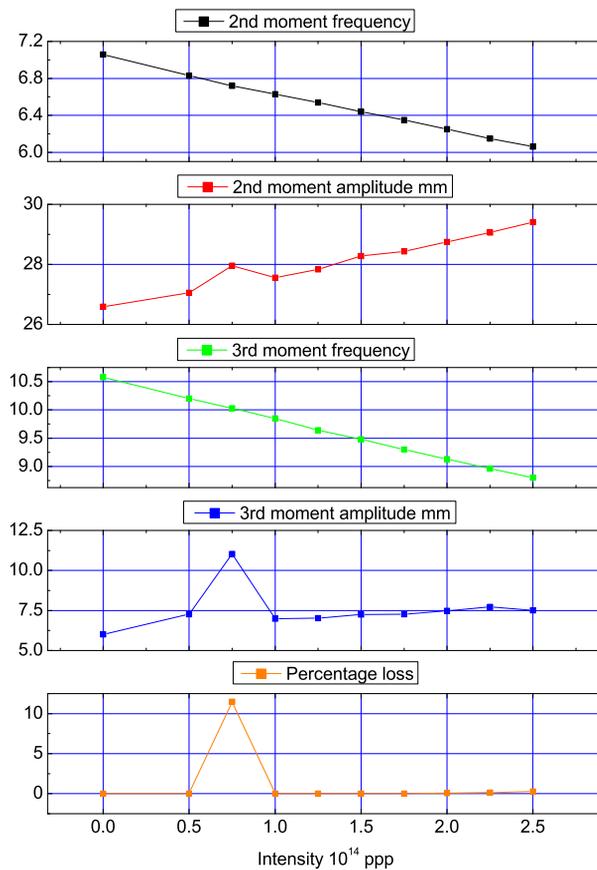


Figure 5: Intensity scan with Q_V below the half integer.

has a clear effect, as it becomes very difficult to measure the 3rd moment frequency, and there is a corresponding increase in the amplitude. As the intensity was raised above the threshold for the half integer resonance condition it can be seen that the 3rd moment approaches the $3Q_V = 10$ resonance line. This 3rd moment was not being driven and there were no sextupoles in the simulation, yet as the 3rd moment approaches 10 there was a dramatic spike in the 3rd moment amplitude and beam loss. The right-hand side of Figure 3 shows a plot of the vertical phase space at an intensity of 2×10^{14} ppp, without collimation to allow the interesting lobed structure to develop. It has been confirmed that the behaviour is being driven by image terms from the space charge solver, though is as yet unconfirmed experimentally. Due to the nature of the conformal vacuum vessel, image fields may excite some of the main resonance terms. At the nominal working point, this higher order resonance would not be an issue, as the half integer would impose the intensity limit.

VERTICAL TUNE < 3.5

In order to avoid the half integer resonance without running into the vertical head-tail instability one option is to reduce the vertical tune to below the half integer, and a number of simulations were performed to explore this scenario, Figure 5. The horizontal tune was set to the de-

sign value, whilst the vertical was set below 3.5. There were no half integer driving terms present in these simulations. There was no significant growth in the 2nd moment amplitude. However as the 3rd moment frequency passes through the $3Q_V = 10$ resonance line there is an increase in the 3rd moment amplitude and in the beam loss. This behaviour is equivalent to that seen in the previous simulation scan in Figure 2.

It must be emphasized that the image driven resonances seen in the simulations have not yet been investigated experimentally, so while they are an interesting concern it is not known to what degree they might limit the parameter space of a final upgrade solution. If such behaviour is shown to be a genuine feature of beam dynamics on ISIS then the option of lowering the tune would be challenging, as a third order structure resonance would be passed through during injection. Even if they are real, it is unknown how stable such a resonance would be under the influence of longitudinal dynamics and injection painting.

SUMMARY

Space charge scaling laws suggest that an upgrade of the ISIS injector from 70 to 180 MeV might enable the ISIS synchrotron to accelerate up to 0.5 MW of beam power. However, a bottle-neck between the half integer resonance and vertical instability may impose the transverse intensity limit on the machine. Detailed simulation studies suggest the solution of dropping Q_V below the half integer may be compromised by 3rd order image terms. Detailed study of working points, half integer resonance and image effects is essential for the upgrade.

REFERENCES

- [1] J.W.G. Thomason *et al.*, "Megawatt Upgrades for the ISIS Facility", Proc. HB08, Nashville, TN, USA, 2008.
- [2] C.M. Warsop *et al.*, "Status of Injection Upgrade Studies for the ISIS Synchrotron", Proc. IPAC11, WEPS106, San Sebastian, Spain, 2011.
- [3] R. Baartman, "Betatron Resonances with Space Charge", Workshop on Space Charge Physics in High Intensity Hadron Rings, Shelter Island, New York, USA, 1998.
- [4] C.M. Warsop *et al.*, "High Intensity Studies on the ISIS Synchrotron, Including Upgrades and Half Integer", Proc. HB10, Morschach, Switzerland, 2010.
- [5] C.M. Warsop *et al.*, "Simulation and Measurement of Half Integer Resonance in Coasting Beams on the ISIS Ring", Proc. IPAC11, MOPS018, San Sebastian, Spain, 2011.
- [6] B.G. Pine *et al.*, "Set Code Development and Space Charge Studies on ISIS", Proc. ICAP09, San Francisco, CA, USA, 2009.