SPACE CHARGE SIMULATIONS FOR ISIS

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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 accelerates ~3E13 protons per pulse (ppp) from 70 to 800 MeV, corresponding to beam powers of ~0.2 MW. Studies are under way for major upgrades in the Megawatt regime. Underpinning this programme of operations and upgrades is a study of the high intensity effects that impose limitations on beam power.

The behaviour of the beam in the 50 Hz rapid cycling synchrotron (RCS) is largely characterised by high space charge levels and the effects of fast ramping acceleration. High intensity effects are of particular importance as they drive beam loss, but are not fully understood with only limited analytical models available. This paper reviews several methods by which these effects are explored numerically on ISIS, and compares them where possible with experimental or analytical results. In particular we outline development of a new space charge code Set, which is designed to address key issues on ISIS and similar RCS machines.

INTRODUCTION

ISIS high intensity operation is restricted by beam loss, as irradiation of equipment limits access for essential maintenance. Understanding beam loss is therefore of vital importance, however due to the complex interactions between the beam particles and their environment such understanding is challenging both analytically and numerically.

The ISIS Synchrotron Group is actively studying high intensity effects of the beam in a number of different ways, both to improve performance of the accelerator and also to enable the design of upgrades which can achieve significantly higher beam intensities. Aspects of this work are reported here, including closely related profile monitor simulations, injection painting, beam dynamics, half integer studies and developments of codes.

PROFILE MONITOR

ISIS profile monitors are important for studies of injection painting, space charge, beam halo, betatron motion and instabilities, as well as suffering space charge effects of their own. The profile monitors on ISIS use ions, liberated from the residual gas by passage of the beam, to reconstruct transverse beam distributions. A (near) uniform electric field, perpendicular to the direction of the beam, accelerates ions to a suitable detector. The number of ions detected is assumed to be proportional to the local beam intensity. This process suffers from two major sources of error: 1) irregularity in the electric field used to drive the ions to the detector; 2) broadening effects produced by the space charge field of the beam, which at high intensities can dominate the measured profile width. Fortunately correction schemes for both of these phenomena have been found, and are discussed below.

Drift field effects

A model of an ISIS profile monitor (see Figure 1) was constructed in CST Studio Suite [1]. Figure 2 displays the potential produced by the electrodes in both transverse and longitudinal cross-sections. As can be seen the required linear field is not achieved perfectly – both transverse and longitudinal sections show deviation from the ideal behaviour.

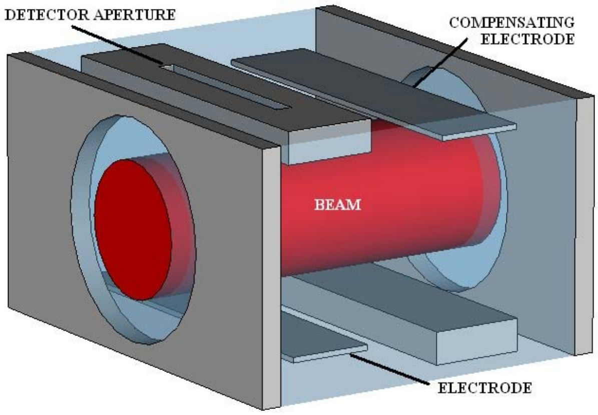

Figure 1: Residual Gas Profile Monitor.

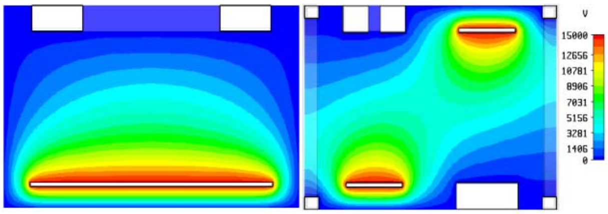

Figure 2: Electrostatic potentials: transverse - left, longitudinal - right.

In order to study these effects in more detail, potentials were calculated then extracted from the CST model, and used as the field source in a specially developed 2D particle tracker. Realistic beam distributions (parabolic, elliptic) were used as the source of particles. The results showed that a simple scaling correction was effective for reasonably well centred and behaved beam distributions [2]. 3D simulations [3] showed considerably more complex behaviour, as particles may oscillate along longitudinal field saddle points between the two electrodes in the monitor body. On investigation however this more complex behaviour could be accounted for by a modification of the scaling rule calculated for the 2D case. Figure 3 shows the result of a correction using the scaling rule on a simulated profile including what the ideal measurement would be, and the corresponding corrected profile.

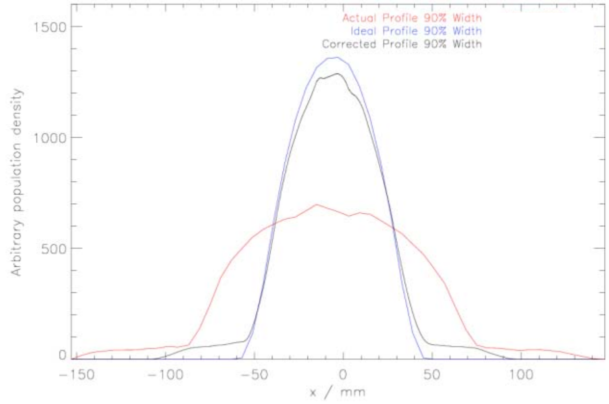

Figure 3: "Measured" - red, ideal - blue and corrected - black beam profiles, all from simulation.

Space charge broadening

Space charge broadening effects have been studied both by simulation [2, 3] and experiment [3, 4]. Simple models suggest that the measured profile width ought to be inversely proportional to the magnitude of the drift field. This was confirmed both experimentally and in simulations, and holds for all percentage widths of the beam, once modified for relativistic effects. An experimental measurement of the profile width relative to applied drift field voltage is displayed in Figure 4.

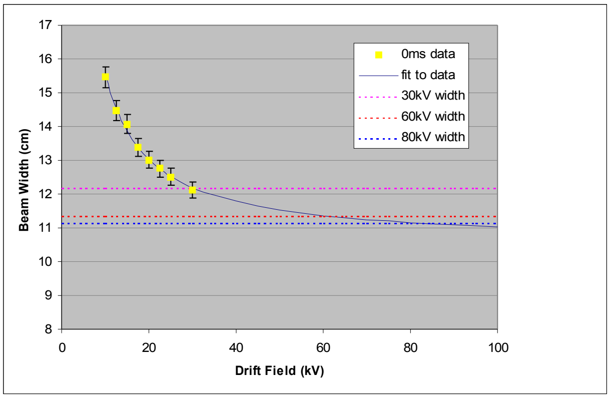

Figure 4: Measured profile width versus drift field voltage at 0 ms and a beam intensity of 2.12E13 ppp.

INJECTION

The ISIS multi-turn, charge exchange injection process accumulates ~3E13 ppp over 130 turns, or 200 μs, at a constant energy of 71.5 ± 0.5 MeV. The injection region is located in the middle of a straight section, to minimise interaction with the rest of the machine. The beam is effectively unbunched, as RF runs at low levels throughout injection. Injection begins -0.4 ms before field minimum of the main dipole magnets in the ring, i.e. on a falling magnet field (ISIS runs with a sinusoidal main magnet field). This naturally provides horizontal painting of the beam through the horizontal dispersion at the foil. Vertical painting is achieved using a programmable sweeper magnet in the injection line (see Figure 5). For standard operations vertical sweeping is anti-correlated relative to the horizontal, and is intended to produce a hollow beam distribution which will then be filled in under the action of the beam's space charge.

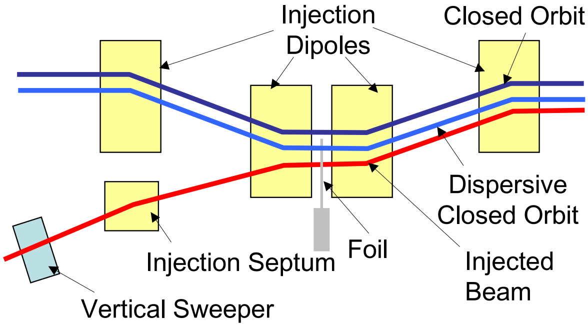

Figure 5: ISIS injection system.

The ISIS injection painting process has also been studied [5, 6] with the ORBIT simulation code [7]. Figure 6 shows betatron amplitudes during injection, measured using chopped beams, which show the anti-correlated painting dynamics. These are compared with simulated values.

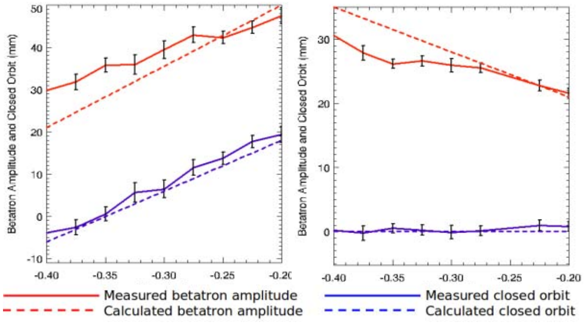

Figure 6: Anti-correlated painting on ISIS.

Further simulations include the action of space charge on the beam profile during injection. The results have been compared with experimental data taken with the profile monitors mentioned above, at both low (2.5E12 ppp) and high (2.5E13 ppp) proton intensities. The experimental data were corrected for drift field effects and the widening effect of space charge on the measured profile, and the results compared with profiles extracted from the simulation data (Figure 7). As can be seen there is a good agreement between the simulated and experimental results, which show the hollow painted beam being filled in under the influence of space charge.

These simulations were used to generate the beam phase space distributions shown in Figure 8. Transverse calculations include space charge; longitudinal dynamics reproduce expected horizontal movement, but without space charge.

Work is well advanced for longitudinal simulations of ISIS in ORBIT with space charge. Essential features of the beam loss versus time profile have been reproduced.

Models of the collimator system and the MICE [8] internal target have also reproduced observed loss patterns reasonably.

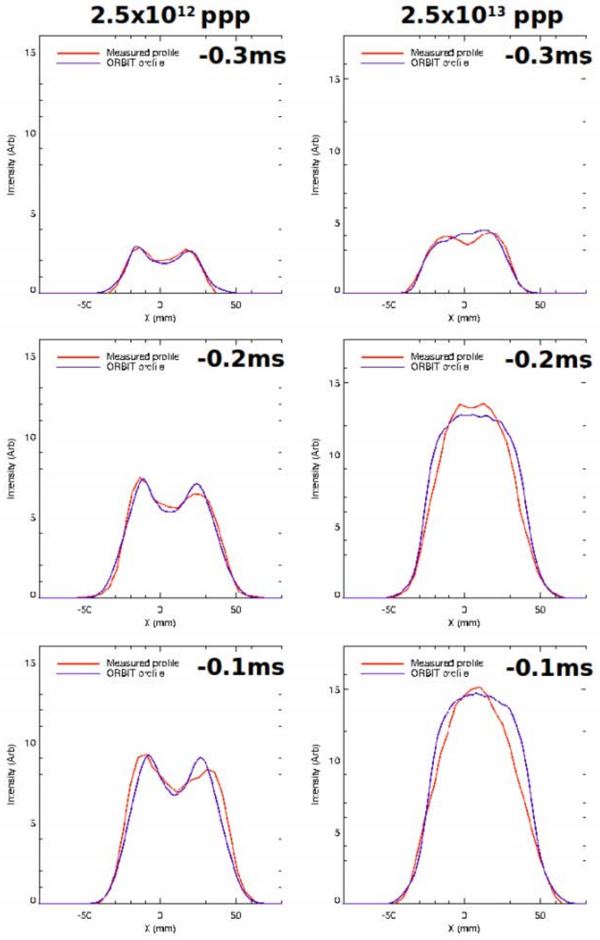

Figure 7: Anti-correlated painting – horizontal profiles.

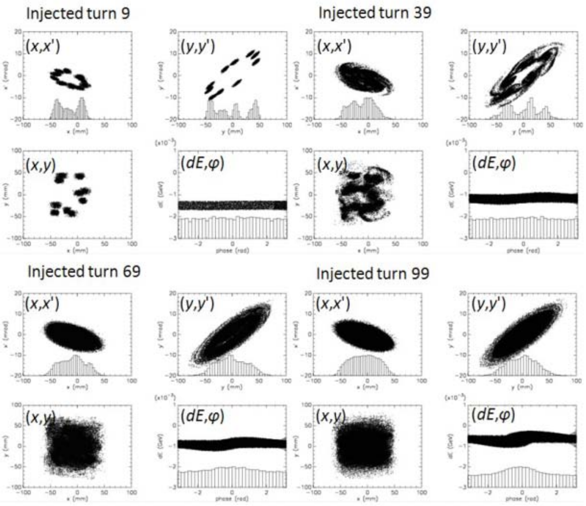

Figure 8: Simulations of injection: Normal anti-correlated case at 2.5×10^{13} ppp.

HALF INTEGER

Transverse space charge and half integer resonance have been identified as the main loss mechanisms on the ISIS RCS. During injection and trapping, bunch intensity reaches a maximum and incoherent tune depression due to space charge can reach ~0.4 in both planes. The beam is pushed towards the $2Qh = 8$ and $2Qv=7$ resonance lines. Initial work has focused on analytical studies and 2D simulations to confirm the predicted effects [9, 10].

2D ORBIT simulations were run with an RMS matched waterbag beam circulating in an alternating gradient model of the ISIS lattice. The driving terms (representing the main resonance lines) reproduced many expectations from studies of the envelope equation. In particular, stability was observed on the incoherent resonance. Emittance growth started to rise before the coherent resonance condition occurred however (Figure 9). This suggests that significant emittance growth, and hence the practical space charge limit, lie between the incoherent and coherent predictions.

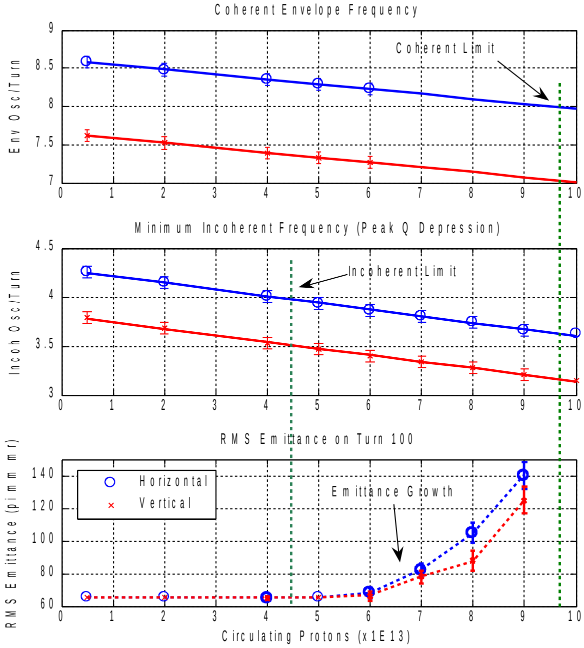

Figure 9: Intensity limits associated with half integer resonance and RMS emittance growth.

More detailed studies comparing halo structure as predicted by ORBIT and available theory have confirmed expected behaviour [11]. Simulations including the effects of momentum spread and longitudinal motion are in development.

Extensive experimental work is under way, running ISIS in storage ring mode (SRM) without RF or the AC component of the main magnets, enabling a beam to be stored for many turns as a coasting unbunched beam. This is ideal for studying 2D aspects of beam behaviour. SRM is becoming a rich experimental system for studying high intensity effects [12]. Figure 10 shows that beam intensity reduction and corresponding profile growth coincide with the start of an instability. Simulation and experimental studies are presently under way to understand in more detail the action of both instabilities and envelope resonance under high space charge. This work also clearly depends on a detailed knowledge of the profile monitors used to take measurements.

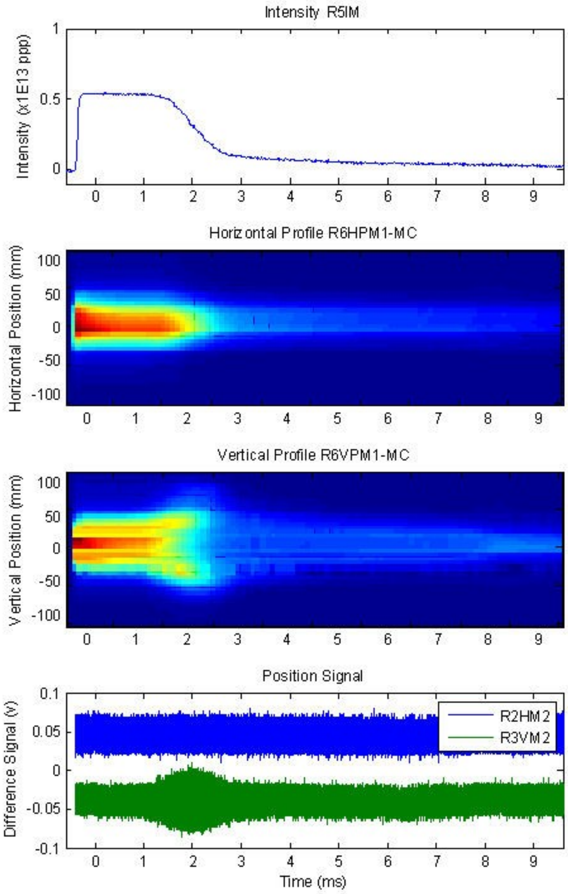

Figure 10: Beam intensity, horizontal and vertical profiles, horizontal and vertical position signals vs time.

SET

A new code Set is under development at ISIS. This code is intended to supplement the use of ORBIT for 2D and 3D beam tracking simulations, as a tool that can be readily modified and redeployed as required to meet a given purpose. In particular, the focus is on the challenges of the ISIS RCS, including image forces from the unique profiled vacuum vessel, halo predictions, 2D and 3D RCS space charge effects and overall to understand and predict beam loss. Set works using either MAD input data or its own matrix routines for generating lattices, and has an FFT based Poisson-solver for calculating the beam's space charge. Early simulation work [10, 11] focused on replicating ORBIT results for the half integer resonance. Example results for the ISIS lattice (2D, coasting beam) driven with a $2Qv = 7$ resonance are shown in Figures 11, 12 and 13. Figure 11 shows Set and ORBIT envelope frequencies as the intensity is swept from 1 – 14E13. Figure 12 shows the incoherent tune footprints after 100 turns, as the intensity is varied from 6E12 ppp to 13E13 ppp. Figure 13 shows beam phase and real space on the 100th turn for an intensity of 6E13.

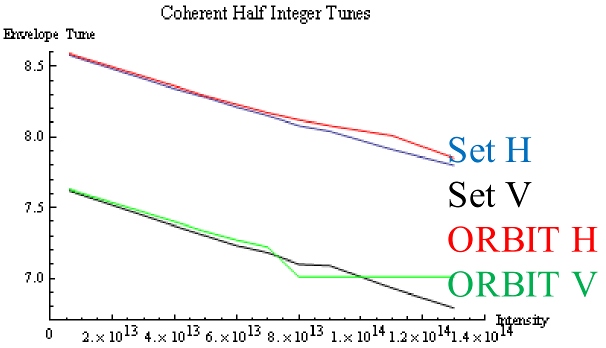

Figure 11: Envelope tunes intensity sweep.

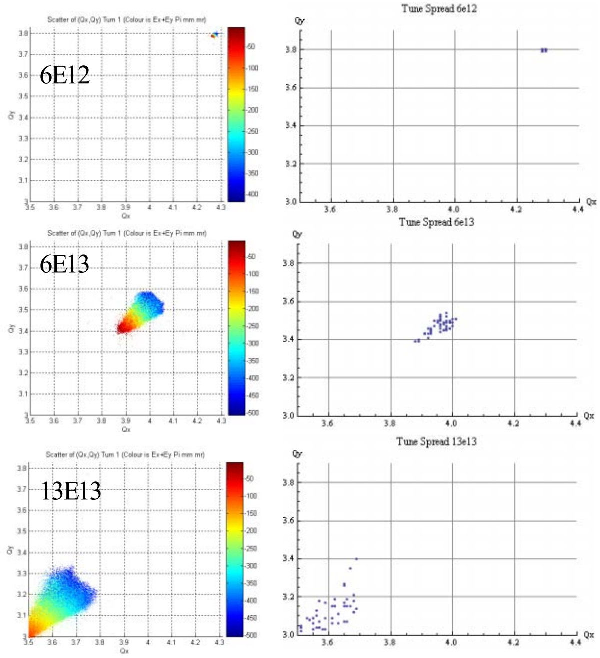

Figure 12: Incoherent tune comparison ORBIT - left, Set - right.

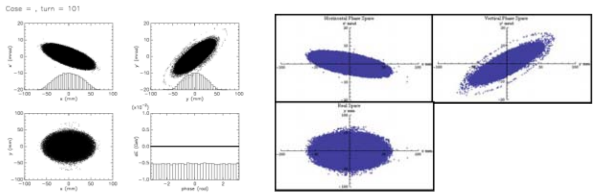

Figure 13: Phase space on 100th turn ORBIT - left and Set - right.

Set has been used to study tune shifts from image forces and closed orbits [13] and the results compared with Laslett theory (Figure 14). Direct space charge should have no influence on the coherent dipole tune, as the charge distribution of the beam moves with the centre of charge. However image forces will affect the coherent tune, as the centre of charge does move relative to the vacuum vessel. This is of particular interest on ISIS due to the vacuum vessel which follows the design beta function of the beam. At high intensities the machine is very sensitive to closed orbit changes, which may indicate beam loss driven by image forces. Present upgrade studies are investigating the benefits of increasing injection energy from 70 to 180 MeV. Set has been used to study the space charge limitations at this higher energy. The half integer simulations carried out for the nominal ISIS ring were reproduced, but for an injection energy of 180 MeV rather than 70 MeV. Simple scaling of the space charge force indicates peak intensities should increase by a factor of 3 over 70 - 180 MeV. As can be seen from Figure 15, the RMS emittance begins to rise at 3 times the intensity seen in the previous case.

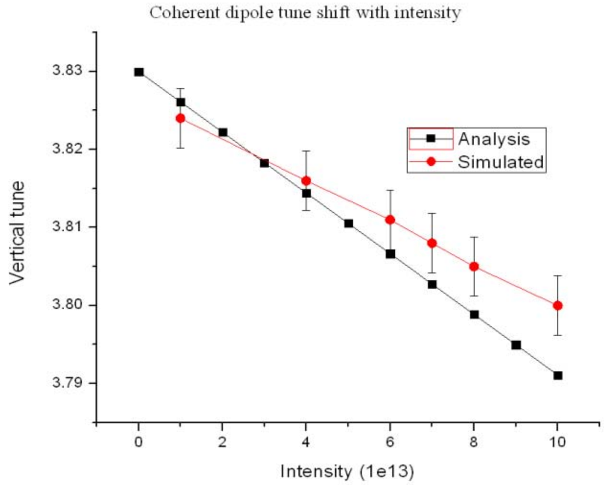

Figure 14: Simulated versus analytical tune shift.

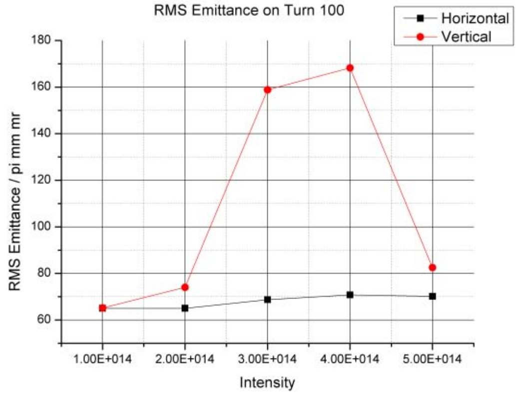

Figure 15: RMS emittance growth associated with half integer resonance for 180 MeV injection energy.

Image forces become more significant when the beam is executing a closed orbit, as image forces from the beam pipe only cancel when the beam is well centred. Figures 16 and 17 show the results of simulation runs including half integer driving terms from the trim quadrupoles (ISIS has special programmable quadrupoles distinct from the main lattice), and also an angular kick once per turn. Each set of simulations was run twice, to allow the resulting perturbed beam distribution to be matched into the lattice. Figure 16 shows the variation of closed orbit (RMS position) around the ring as a function of intensity, from 1 - 5E14 ppp. Figure 17 compares RMS emittance with and without a closed orbit at an intensity of 2E14 ppp. Image forces are clearly influencing the behaviour of the beam, much as we expect on ISIS. A more complete analysis, and eventually experimental work on the ISIS synchrotron, are to follow.

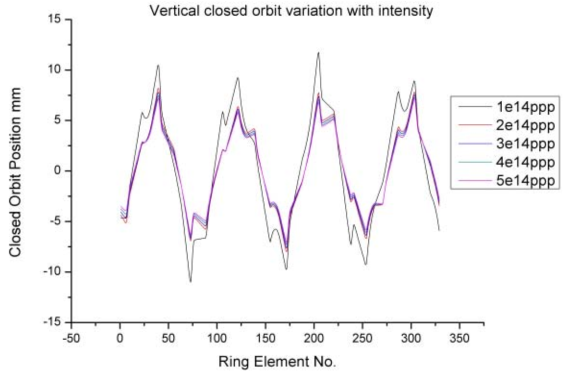

Figure 16: Matched closed orbit variation with intensity.

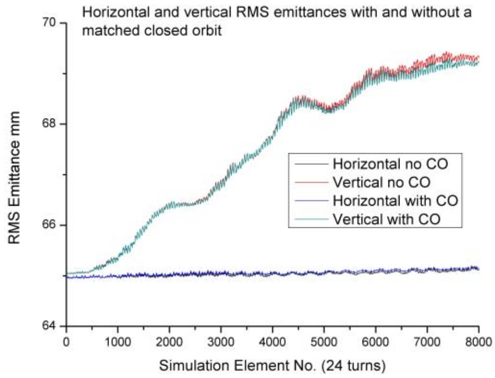

Figure 17: RMS emittance with and without matched closed orbit errors for 2E14 ppp intensity.

FUTURE WORK

ORBIT

Extensive work has been carried out developing a 3D model of ISIS in ORBIT that can run on a parallel system of computers, the SCARF cluster at Rutherford Appleton Laboratory [14]. This is largely complete, including injection and longitudinal motion with space charge, though fundamental RF only (simulations with the second harmonic RF are in development). A recent area of progress involved modifying ORBIT run scripts to allow for the ramping ISIS Q values, as shown in Figure 18. ISIS Q values are ramped to move the tunes away from dangerous resonances during injection and trapping. Previous simulations had used the fixed Q values (close to the initial values from Figure 18). Beforehand the lattice creation algorithms had to be run for each turn of the simulation for the new Q values. Beam was run around the first turn, beam distributions saved and then input into the next turn with a modified lattice. Results for the 99% emittance of the beam, comparing constant Q with ramping Q are shown in Figure 19. It appears that with the real (ramping) Q values, emittance in the horizontal plane is increased relative to simulations with a constant Q, whereas it is decreased in the vertical plane. These are preliminary results and it has not yet been ascertained what driving terms or growth mechanisms might be responsible for these phenomena.

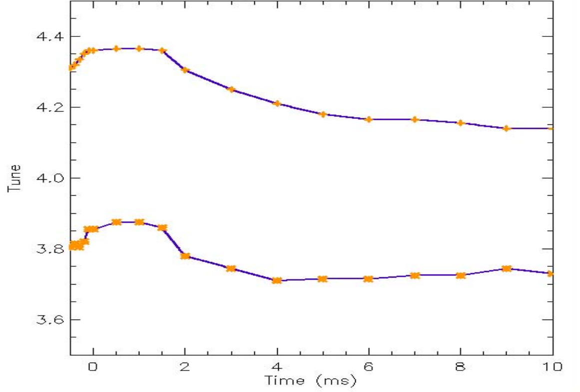

Figure 18: ISIS Q values during the cycle.

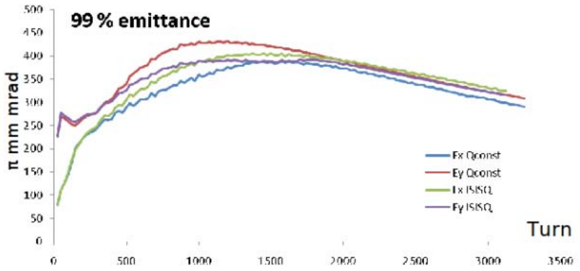

Figure 19: 99% emittance evolution comparing ramped Q with constant Q values.

Set

Work is also under way on a 1D longitudinal code which includes space charge and impedances. This will eventually be added to Set to make it fully 3D. Results are shown in Figure 20 for bunch length and phase convergence versus macroparticle number.

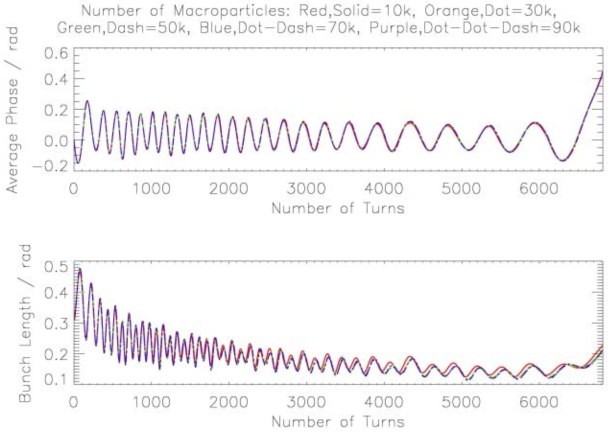

Figure 20: 1D convergence tests showing results for phase and bunch length.

A parallel version of 2D Set has been implemented, and successfully run on SCARF. Further work will add a realistic injection scheme, including the effect of foil scattering. The long term goal is to carry out a full simulation of the ISIS cycle and recreate the beam loss patterns seen on the real machine.

SUMMARY

Understanding space charge, and hence beam loss, is essential for the operation of a high intensity RCS, and even more important for the design of an upgrade.

Space charge simulations are being developed in a number of crucial areas on ISIS: to correct profile monitor measurements, to study injection processes, for the examination of half integer resonance effects, for longitudinal dynamics, and finally for 3D studies of loss patterns on ISIS. A new code Set is being developed to enable further study of key beam dynamics issues that are important for ISIS, such as image effects and any dominant loss mechanisms.

ACKNOWLEDGEMENTS

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