SPACE CHARGE AND HIGH INTENSITY STUDIES ON ISIS

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Abstract

ISIS is the spallation neutron source at the Rutherford Appleton Laboratory in the UK. Presently, it runs at beam powers of ~0.2 MW, with upgrades in place to supply increased powers for the new Second Target Station. Studies are also 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 the limitations on beam power. This paper summarises work looking at the key topics of injection painting, half integer resonance, and image effects under high space charge conditions, plus progress on overall machine modelling. A core aim of the work is to experimentally confirm simulations and theory; therefore progress on modelling the machine in both operational and specially configured modes is reported. Closely related diagnostics studies are also described.

INTRODUCTION

The addition of the Second Target Station to the ISIS Facility [1, 2] is a major upgrade that has required significant developments to the accelerator and infrastructure [3, 4]. Work is now under way to substantially increase the operational beam intensity in the ring to supply both the original and new target stations. On a longer time scale, detailed studies have started for ISIS upgrades in the megawatt regime, with favoured options requiring a new high power, 3 GeV rapid cycling synchrotron [5]. This paper summarises progress on a programme of ring high intensity R&D work that is required to underpin these projects. The aim is to understand the intensity limits of the present and upgraded machines, using the present ISIS ring wherever possible to verify experimentally relevant simulations and theory. This necessarily defines a broad range of work, covering diagnostics, experiments, simulation and theory, as outlined below.

The ISIS synchrotron accelerates ~3×10^{13} protons per pulse (ppp) from 70 to 800 MeV on the 10 ms rising edge of the 50 Hz, sinusoidal main magnet field. It has a mean radius of 26 m and nominal tunes of (Q_h, Q_v)=(4.31, 3.83). The high intensity beam accumulates over the 130 turn charge-exchange injection process, which takes place over ~400 to 200 µs before magnet field minimum. Beam is essentially unbunched during injection, and most loss occurs during the non-adiabatic "trapping" process in the first ~1 ms of acceleration. The dual harmonic RF system [6] minimises this loss, allowing higher intensity running. Space charge effects and optimal injection remain important issues for the highest intensities.

PROFILE MONITOR MODELLING

Background

Accurate and reliable measurements of transverse beam profiles are essential for studies of space charge. With this in mind, detailed modelling and experimental work has been undertaken to understand and quantify the errors in the ISIS residual gas ionisation monitors. This work links closely with ongoing developments of these devices [7].

The monitor operation is based on detection of ions generated by the beam as it interacts with the residual gas in the vacuum vessel. Ideally, a linear drift field is applied perpendicular to the direction of beam travel, and the ions swept to the edge of the aperture are measured with a suitable detector. The number of ions produced is assumed proportional to the beam intensity at a point, and thus the variation of detector signal with transverse position provides the beam profile. There are two main sources of error in the ISIS monitors: drift field non-linearities and beam space charge.

Drift Field Errors

Simulation of monitors has been based on a detailed CST Studio™ [8] model to determine the electrostatic potential, and then use of "in house" particle trackers to calculate ion trajectories and reconstruct beam profiles. Studies in 2D [9], looking at the effects of the drift field, indicated that a simple linear scaling correction could remove most errors for "normal, reasonably centred beams" (i.e. 2D parabolic or elliptical density distributions within 10 mm of the central axis). Extending calculations to 3D revealed more complicated effects resulting from longitudinal components of the drift field [10], with various complicated trajectories from different longitudinal sections of the beam ending at the detector. However, even including these effects, simple scaling corrections were found effective as long as distributions were again normal and reasonably centred.

Space Charge Errors

At high intensity, the space charge force of the beam also causes significant transverse deflections of ions, thus distorting measured profiles. This effect was also modelled in CST Studio™, by introducing various 2D charge distributions (e.g., parabolic, elliptical), and tracking ions to the detector [8, 9, 10]. Simple models suggest transverse trajectory deflection, and thus beam broadening, should be proportional to the reciprocal of the drift field. This was confirmed both experimentally [11] and in simulations. The relation actually holds for all percentage widths, with the constant of proportionality being linear with width for the normal distributions observed experimentally. This gives an effective scaling correction for space charge [10].

3D models including drift field errors and space charge confirm the efficacy of the correction. Figure 1 shows the input profile, the calculated "measured" profile based on ion trajectories, and the correction based on the above scaling laws. It is expected that the tails observed will be reduced by the finite angular acceptance of the detector, yielding beam widths that are accurate to within ±3 mm, the limitation imposed by the spacing of the detectors.

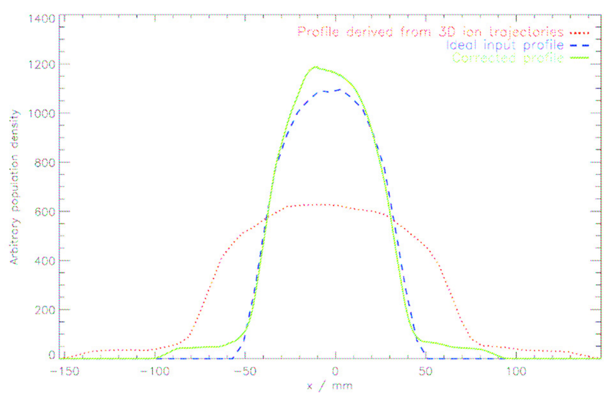

Figure 1: 3D profile simulation, profile derived from ion trajectories (red), input beam profile (blue) and corrected profile (green).

Summary and Future Work

This work has provided a detailed understanding of the monitor operation and limitations. The models allow simple corrections for normal beams and could provide a detailed analysis of more complicated distributions if required. The correction schemes have been successfully applied in comparisons between beam measurements and simulation, as outlined below. Although most aspects of the models have been checked experimentally, some final experimental confirmation of combined effects is planned. Understanding gained from these studies will also be incorporated in ongoing monitor developments, for example reducing drift field non-linearity [7].

INJECTION PAINTING

Background

The ability to reliably manipulate, model and understand injection painting is of great importance for present ISIS operations and upgrades, and for future megawatt upgrades. In addition, well founded models (where simulations agree with experiment), are of much value for space charge and related beam dynamics investigations. In this work, detailed comparisons are made between measured and simulated (ORBIT [12]) transverse profiles during injection, as a function of painting configuration [13, 14].

The ISIS multi-turn, charge-exchange injection process accumulates about 3×10^{13} ppp over 130 turns, at a constant energy of 70 MeV. The Al_2O_3 foil is placed at the centre of a horizontal, four magnet symmetric bump. Horizontal painting is achieved by movement of the closed orbit, resulting from the falling main magnet field. Vertically, a programmable "sweeper" magnet varies the injection point. The beam is effectively unbunched, with RF only coming on at low levels towards the end of injection. For standard operations, the vertical sweeper is programmed to give anti-correlated painting. However, reversing the sweeper current function in time provides a simple route for correlated painting trials.

Measurements and Comparisons with ORBIT

Detailed measurements of all key aspects of injection painting are possible on ISIS. Chopped beams allow for determination of the centroid painting as a function of time. Similarly sweeper currents, injection beam line profiles, etc., provide the other parameters required. These were used to set up a detailed ORBIT model [12, 14]. Measured and simulated transverse profiles were produced for three points during injection (0.3, 0.2 and 0.1 ms before field minimum), at low and high intensity (2.5×10^{12} and 2.5×10^{13} ppp respectively): the results in the horizontal plane for anti-correlated painting are shown in Figure 2. In these plots the measured profiles are shown in red, corrected as outlined above, and ORBIT predictions in blue, with intensities as labelled. Agreement is good, with essential features reproduced. In particular, it can be seen that hollow distributions survive at lower intensity, but are characteristically filled in and smeared as space charge increases. Similar measurements with time-reversed vertical sweeper current, produce the expected distributions for correlated painting, with good agreement between simulation and measurement [14].

Future Work

Further work incorporating refinements to measurements and more detailed beam modelling should improve on the agreement seen above. Following this, studies of different painting functions are planned, possibly with additional programming on the horizontal bump magnet. Of particular interest is understanding how to generate optimal distributions with space charge, whilst allowing for beam development during the painting process.

MACHINE MODELLING

Background

In order to understand and optimise the ISIS ring, and to test and benchmark codes, it is very useful to model all aspects of the machine beam dynamics. Whilst full 3D simulations of the whole cycle are the ultimate aim, partial simulations of either lower dimension or of key parts of the machine cycle are also very valuable, and essential initial steps.

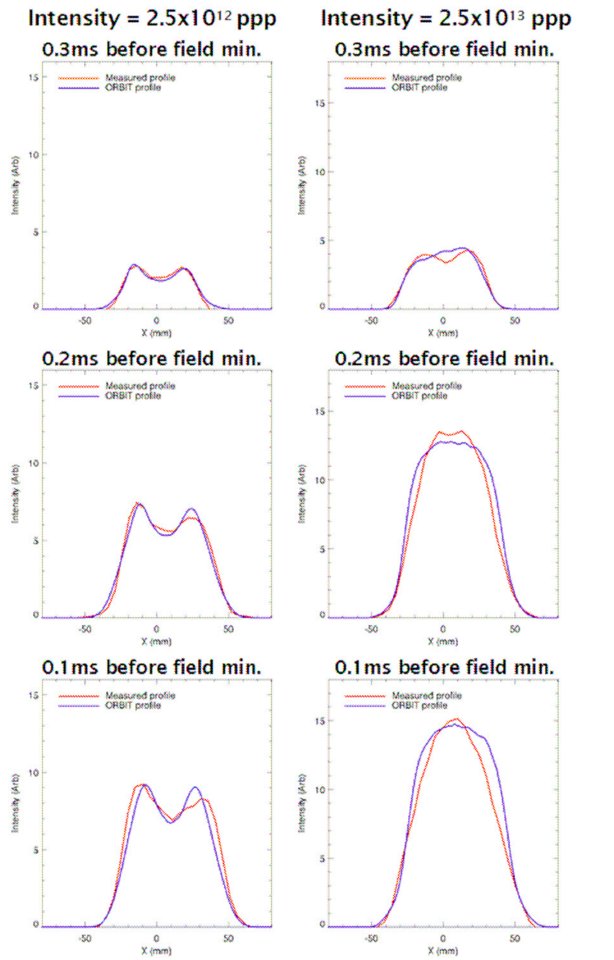

Figure 2: Comparison of experimental (red) and simulated (blue) horizontal profiles through injection.

Injection Process

The multi-turn injection process has been modelled with ORBIT, including vertical sweeping and dispersive movement of the horizontal orbit to provide the beam centroid painting [14]. Transverse calculations include space charge; longitudinal dynamics reproduce expected horizontal orbit movement, but without space charge (note the beam is essentially unbunched for most of injection). Figure 3 shows beam distributions (horizontal and vertical phase space, real space and longitudinal phase space respectively) on turns 9, 39, 69 and 99. These simulations are very similar to those used to generate the profiles in Figure 2.

1D Longitudinal Modelling

For a number of years 1D longitudinal motion has been successfully modelled with TRACK1D [15], and this modelling formed the basis of the present dual harmonic RF upgrade [6]. Work is now under way to implement ORBIT 1D longitudinal models, and compare with other codes and experiment. This will allow combined transverse and longitudinal (2.5 and 3D) simulations with space charge in the future. Studies using longitudinal tomography to reconstruct longitudinal phase space are

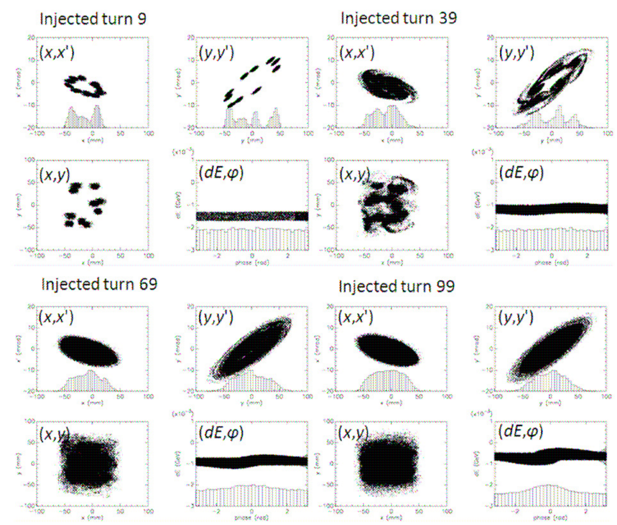

Figure 3: Simulations of injection: normal anti-correlated case at 2.5×10^{13} ppp.

also in progress, in collaboration with colleagues from CERN [16], with application to the fast cycling ramp of ISIS.

Full Cycle 2.5D Modelling and Future Work

Initial full cycle ORBIT runs with 2.5D have been completed, with space charge in the transverse plane (but not the longitudinal). Essential features of the loss versus time profile have been reproduced, but further work is required. It is expected that 3D ORBIT and Set (see below) models will be developed in due course. Models of the collimator system and the MICE internal target have also reproduced observed loss patterns convincingly.

HALF INTEGER LOSSES

Background

Transverse space charge, and in particular half integer resonance, is a main loss mechanism on the ISIS ring. During the trapping process, when the (~80 MeV) beam bunches and line density reaches a maximum, incoherent tune depressions peak at about 0.4, and beam is pushed toward $2Q_h$=8 and $2Q_v$=7 resonance lines. A full model requires a 3D simulation including synchrotron motion with the ISIS rapid ramping. For initial work, a simplified monochromatic 2D coasting beam has been studied.

Envelope Motion

As a first step, calculations using the envelope equation were used to predict the motion of the RMS equivalent beam [17]. These indicated that ISIS is in the large tune split regime, with horizontal and vertical envelope motion being essentially uncoupled. Associated coherent resonance theory then indicates an 8/5 coherent advantage over the classical incoherent space charge limit. Predictions were tested and confirmed with numerical solutions of the coupled envelope equations.

Simulations and Intensity Limit

ORBIT simulations in 2D, with an RMS matched waterbag beam circulating in a detailed model of the ISIS AG lattice, and including a representative $2Q_v$=7 [18] driving term, reproduced many expectations from the envelope equation. Most notable perhaps was stability on the incoherent resonance. However, before the coherent resonance condition was reached, RMS emittance ($\varepsilon_{\mathrm{RMS}}$) growth occurred, suggesting the onset of beam loss.

Including driving terms in both planes ($2Q_h$=8, $2Q_v$=7), thereby approximating the space charge limit as expected on ISIS, results in similar behaviour. Now emittance growth occurs in both planes. The results are shown in Figure 4, where coherent envelope frequencies, peak incoherent tune shifts and $\varepsilon_{\mathrm{RMS}}$ are plotted as a function of intensity. This indicates that significant $\varepsilon_{\mathrm{RMS}}$ growth, and hence the practical space charge limit, lies between the incoherent and coherent predictions.

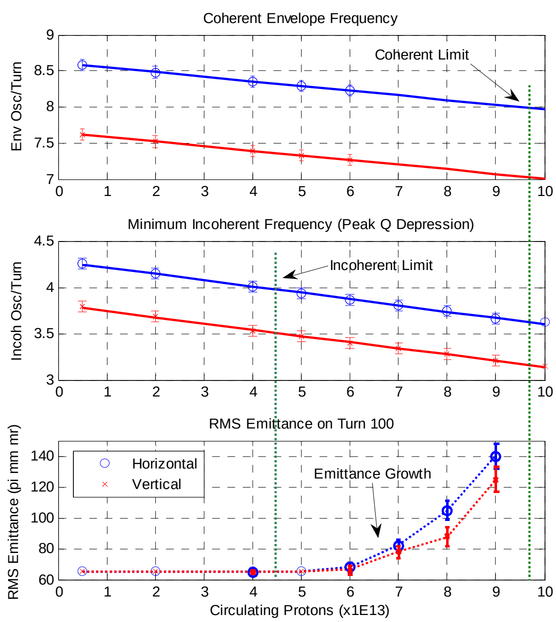

Figure 4: Intensity limits associated with half integer resonance and associated $\varepsilon_{\mathrm{RMS}}$ growth.

For machines that run at or near the space charge limit it is important to understand what causes the emittance growth, and what might be done to minimise it. Important factors include mismatch, redistribution of non-stationary distributions, presence of lattice driving terms and non-linear fields in the beam outer-core. It is also important to know whether code predictions are correct, and if they conform to any of the theoretical models available.

Halo Structure and Future Work

Halo structure generated in ORBIT simulations was studied using Poincaré mapping routines, where motion of test particles was locked to the envelope motion. This was compared with predictions for the 2:1 parametric resonance (driven by gradient errors) from a closely related analytical model: the main features were in good agreement [19].

More detailed studies comparing halo structure and halo generation (i.e. migration rates from the core) as predicted by ORBIT and available theory are planned. Simulations also need to expand to include initially momentum spread, and then longitudinal motion. Extensive experimental work is also starting. Trials are under way putting the ISIS ring into storage ring mode at 70 MeV so that coasting (“2D”) beams can be studied.

IMAGE EFFECTS AND SET CODE

Background

In order to understand and develop calculations for areas of particular importance for ISIS related work, a new code Set [20] is being developed. In order to understand key physics processes and be aware of limitations in simulation codes, this is seen as essential. One such area is the effect of images in the ISIS rectangular vacuum vessels and the role the associated image forces play in generating loss at high intensity.

Code Benchmarking and Initial Study

Detailed checks have verified the accuracy of Set space charge field solvers, for the relevant rectangular geometries, to within 0.1% of those calculated by CST Studio$^{\mathrm{TM}}$. Beam dynamics studies, looking at beam development near the half integer resonance at high intensity (see above), show good agreement with ORBIT for collective envelope frequencies, incoherent tune footprints, $\varepsilon_{\mathrm{RMS}}$ growth and evolution of beam distributions. The Set code also gives the expected coherent dipole (image) tune shifts with intensity: comparisons of Set with Laslett predictions are shown in Figure 5.

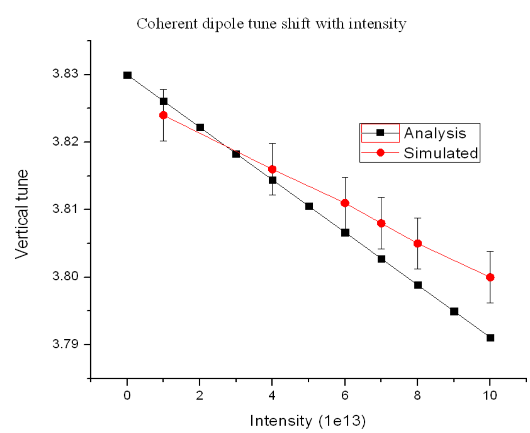

Figure 5: Coherent tune shifts, Set and Laslett predictions

Effects of Image Driving Terms and Next Steps

The effects of images on closed orbits at high intensity are now being studied with Set. Expected changes in closed orbits with intensity have been observed, as has evidence for additional non-linear driving terms. Plans for probing these effects experimentally on ISIS are presently being worked out. It is also envisaged that the Set code will be developed substantially to address key issues for ISIS upgrade studies, requiring detailed 3D modelling.

SUMMARY AND PLANS

Good progress has been made in the key areas necessary to underpin ISIS operations and upgrade studies, and address essential beam dynamics issues. This involves a broad programme of work including: experimental study and development of diagnostics, machine modelling and code benchmarking, code development and study of loss mechanisms. So far work has concentrated on space charge and related loss mechanisms, and injection. This work will now expand to cover other essential topics, including more detailed work on instabilities.

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