STUDIES OF LOSS MECHANISMS ASSOCIATED WITH THE HALF INTEGER LIMIT ON THE ISIS RING

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Abstract

ISIS is the spallation neutron source at the Rutherford Appleton Laboratory in the UK. The facility centres on an 800 MeV rapid cycling proton synchrotron, which provides 0.2 MW of beam power operating at high levels of transverse space charge (peak incoherent tune shift ~ 0.5), but with low loss. Half integer resonance is considered to be a main driver for loss that limits the intensity in high power, medium energy proton rings like ISIS. However, the detailed mechanisms causing loss as the half integer limit is approached are not well understood, particularly in the context of a real machine. In this paper we report progress on experiments on the ISIS synchrotron inducing half integer loss, comparing with detailed simulations, and attempts to relate these to simplified theoretical and simulation models. Studies here concentrate on 2D coasting beams, with a view to extending later to the more complicated 3D, bunched beam case of an operational machine.

INTRODUCTION

Motivation and Aims

Half integer resonance is considered to be a main intensity limitation in medium energy, high intensity proton machines. The existing incoherent and coherent resonance theories give valuable indications of intensity limits, but limited information on the beam behaviour as the half integer limit is approached and particles lost. The aim of this work is to understand more about the detailed mechanisms driving this loss and thus limiting intensity.

The starting point for the study is experimental observations, with the machine configuration optimised as far as possible to allow study of the essential processes. Detailed experimental studies of beam approaching half integer resonance are followed by comparison with (and benchmarking of) simulation codes. It is hoped these results can then be used to guide interpretation in terms of simplified and predictive beam models. This experimental emphasis forces the inclusion of important processes (e.g. approach of resonance) that are simplified in theoretical models, but are important in understanding real loss.

The underlying aim is to understand losses on an operational high intensity machine like ISIS, and requires a treatment of the full 3D dynamics including effects due to longitudinal motion. Presently, the simpler 2D transverse problem is studied with unbunched, coasting beams. In the longer term, experiments and studies will be extended to non-accelerated and accelerated bunched beams.

The ISIS Synchrotron

The ISIS synchrotron accelerates 3×10^{13} protons per pulse (ppp) from 70-800 MeV on the 10 ms ramp of the sinusoidal main magnet field. At the repetition rate of 50 Hz this provides an average beam power of 0.2 MW. Charge exchange injection takes place over 130 turns, with painting in both transverse planes as the high intensity beam is accumulated and contained in the collimated acceptances of ~300 π mm mr. The ring has a circumference of 163 m and a revolution time of 1.48 µs at injection. Nominal betatron tunes are (Q_x, Q_y)=(4.31, 3.83), but these are varied using two families of ten trim quadrupoles. The dual harmonic RF system captures and accelerates the initially unbunched beam, and allows enhanced bunching factors. Peak incoherent tune shifts of ΔQ~0.5 are reached at about 80 MeV, during bunching. Single turn extraction uses a fast vertical kicker at 800 MeV. Main loss mechanisms are associated with non-adiabatic trapping, transverse space charge and transverse instability. Understanding the action of half integer loss is central to minimising losses on the present machine, as well as guiding optimal designs for future upgrades.

EXPERIMENTAL OUTLINE

Machine and Beam Configuration

In order to study the essentials of transverse half integer resonance, these experiments make use of unbunched, coasting beams, with the ISIS ring in storage ring mode. The main magnet field is set at a DC level appropriate for the 70 MeV injected beam and RF systems are off. Betatron tunes are controlled with the trim quadrupoles. In these experiments lattice tunes are constant. A small emittance beam of ε_{rms} ~ 20 π mm mr in both planes is injected: painting amplitudes are constant through the pulse and of small amplitude. These beams ($\varepsilon_{100\%}$ ~ 100 π mm mr) fill a small fraction of the machine acceptance and thus allow the evolution of the beam profile to be observed. As beam accumulates, the increasing intensity depresses the coherent tune and pushes the beam over resonance [1]. Tunes are selected such that only one resonance is approached in the vertical plane: a harmonic driving term is applied to the $2Q_y$=7 line with the trim quadrupoles. Beam loss and transverse profiles are recorded as a function of key parameters such as tune, driving term strength and intensity. Transverse and longitudinal beam spectra are monitored to ensure coherent instabilities are avoided.

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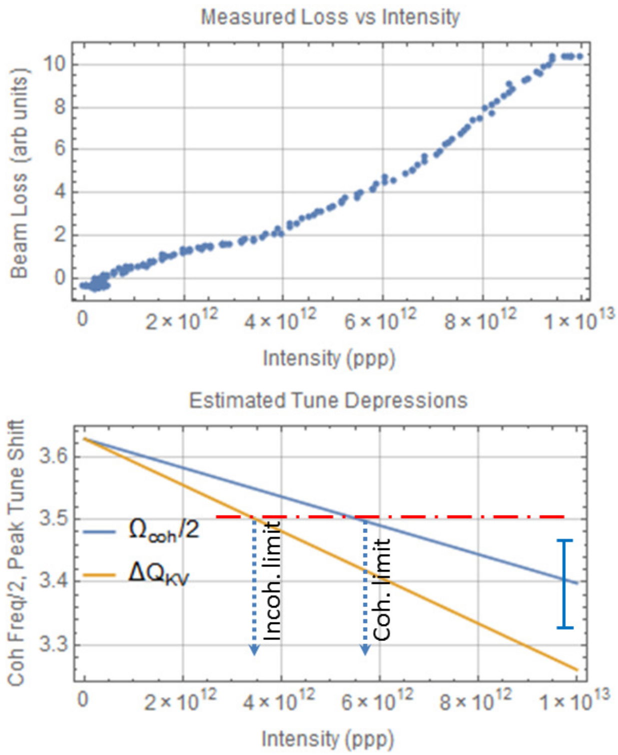

Figure 1: Observed beam loss vs intensity and corresponding estimated resonance conditions.

Review of Previous Experimental Results

These experiments continue work reported in [1]. Based on the same method, previous results indicated the appearance of large loss *near* intensities predicted by the coherent resonance theory, and which clearly correlated with quadrupole driving term strength. Measurement of transverse beam profiles showed development of half integer halo, “hips” or lobes that agreed well with detailed 3D ORBIT [2] simulations. Importantly, these lobes were shown to be controllable in the expected way by changing the phase of the applied driving term, effectively rotating the lobed structure in (y, y') space at the lattice location of the profile monitor. In this paper we build on this work, look in more detail at the time evolution of profiles and halo, and explore its dependence on driving term strength, tune and intensity. This work is still in progress, with continuing efforts to reduce measurement errors and develop models.

Experimental Developments

Measurements of transverse beam distributions make use of residual gas ionisation profile monitors. Previous studies [3] have demonstrated the corrections required for effects of drift field non-uniformities and beam space charge. More complete simulation models of the monitors are now being used to understand detailed behaviour with the complicated beam profiles generated in these experiments [4], and have confirmed the validity of measurements. Work is also under way verifying profile measurements by comparison with output from “harp” type profile monitors in the extraction line and comparing with profiles constructed from steering vs loss measurements. Developments in instrumentation and beam control are providing more accurate measurements of lattice parameters and errors [5]. A programme of diagnostics upgrades will also provide new capabilities, e.g. quadrupole kickers and detectors.

EXPERIMENTAL STUDIES OF HALO

Resonance and Evolution of Profiles

Recent experiments have used measurements of low intensity beams to establish with more certainty the initial painted emittance of the beam in the machine, before the action of space charge. This allows the calculation of intensity for coherent and incoherent resonance crossing, assuming no emittance growth. Results are shown in Figure 1 from an experiment where the initial $\varepsilon_{rmsx}=\varepsilon_{rmsy}=10\pm5$ π mm mr, $(Q_x, Q_y)=(4.38, 3.63)$, the $2Q_y=7$ driving term strength (stop band integral) $J_7=0.08$, and the beam ramps from $0\text{-}1\times10^{13}$ ppp over 130 turns of injection. The upper plot shows accumulated intensity vs beam loss (arbitrary units, peak is ~10% total loss). The lower plot shows the coherent envelope frequency halved (with estimated error) and the calculated peak incoherent tune shifts for a KV distribution. It is noted that loss builds up continually with intensity, with no obvious peaks that might be identified with particular resonance conditions. These are typical experimental results.

As reported previously [1], detailed ORBIT models of the experiment have been developed, which reproduce most experimental features. The model includes a detailed AG lattice, 3D beam dynamics, space charge, injection painting, the foil, apertures and collimation. It should be noted that not all machine parameters are known precisely during the experiment, so some judgement is required in specifying the beam. Results from the simulation of this experiment are summarised in Figure 2. This shows vertical phase space and profile evolution (at the location of the profile monitor) on turns ~30-130. It can be seen that the beam starts to blow up early during injection, presumably as the beam encounters the effects of the driving term with space charge, and continues to grow throughout the injected pulse. This is consistent with the observed continuous loss as the beam grows and repeatedly approaches resonance. It is noted that in previous studies [1] we observed a “brick wall” effect where very large losses occurred. The better estimates of emittance found here now suggest this effect occurs when beam grows enough to hit the collimator aperture, rather than indicating an initial resonance condition.

An example of the time evolution of corresponding measured profiles in the experiment is shown in Figure 3, and is a typical result (here $Q_y=3.67$). Note that corrections have been applied to the profiles, and whilst small distortions will be present, errors in the location of lobes are estimated to be within ~± 6 mm. These show the same essential features as the simulation, with the development of distinctive lobes and a peaked core,

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which is then gradually lost, leaving a smooth, single peaked distribution. This is discussed further below.

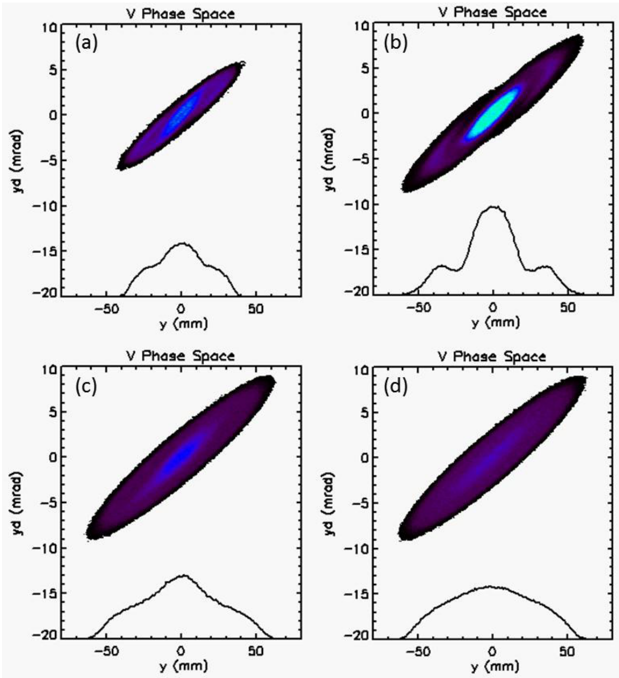

Figure 2: ORBIT results showing typical evolution of the beam in (y, y') space, over turns 30-130 (order a, b, c, d).

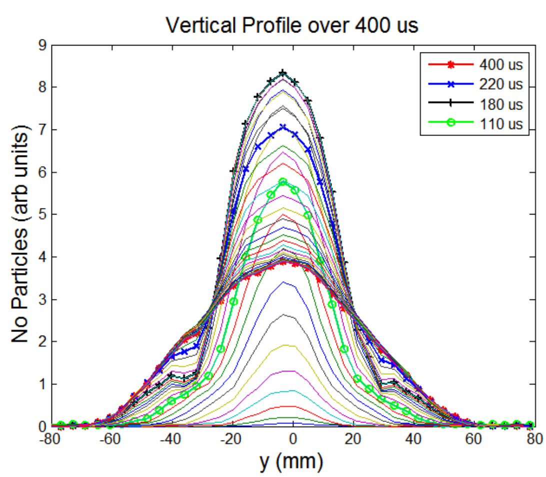

Figure 3: Measured vertical profiles at 10 μs intervals over 400 μs, including injection. Highlighted profiles show distinctive shapes developing through the pulse.

Effect of Quadrupole Driving Term Strength

The measurement above was repeated, but as a function of the strength of the $2Q_y$=7 driving term. Parameters were as above, with Q_y=3.63. The results are shown in the left column of Figure 4, driving term strengths (DT1, DT2, DT3) correspond to J_7= (0.06, 0.03, 0.02). The plots show the evolution over 400 μs (including injection) at 10 μs intervals, with the characteristic lobes highlighted. Representative vertical phase space and profiles from a corresponding set of ORBIT simulations are shown in the right column of Figure 4. It can be seen that the lobes move outward with increasing driving term strength in both experiment and simulation. Not all profile features agree, in spatial and time dependence, this being attributable to limited knowledge of beam parameters and imperfections in profile corrections (all under study). However, the essential features of increasing lobes and beam extent agree.

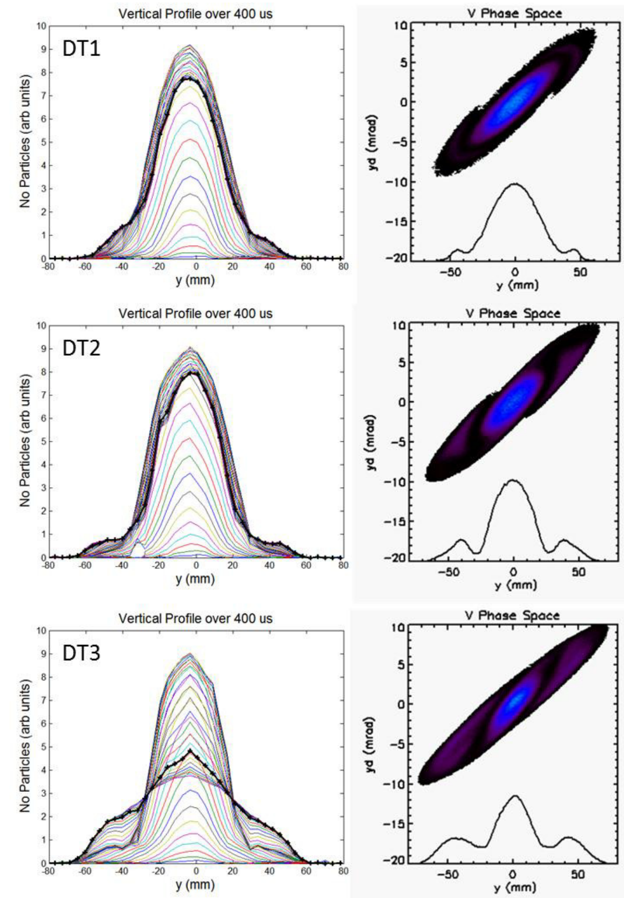

Figure 4: Variation of beam profiles with increasing driving term strength, top to bottom; left - measured profiles, right - ORBIT results (see text).

Effect of Lattice Tune

In these experiments the lattice tune is held constant throughout the beam pulse. A set of measurements was taken setting the lattice Q_y at different constant values, thereby changing the distance to the resonance condition. Driving term strength was constant at J_7=0.08, with other parameters as above. The left column in Figure 5 shows measurements for Q_y with (Q1, Q2, Q3)=(3.71, 3.67, 3.63), again over 400 μs, with characteristic features highlighted. The corresponding ORBIT simulation results are shown in the right column. Measurement and simulation again show the same behaviour, with lobes moving out as the lattice tune is nearer to the resonant value. As before there are differences in details between simulation and measurement, but essential features agree.

Measurements with Stabilised Halo

As described above, the beam distribution evolves in a complicated way with time, depending on the

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instantaneous injected intensity and the redistribution of previous injected turns. New experiments reducing the injector current (from ~22 to 11 mA), thus slowing down the intensity ramp and accumulation, have produced some interesting results. Careful selection of injection pulse lengths has produced lobes that have lasted for ~10 times longer than previous experiments. Figure 6, I1 shows the profile of a shorter pulse, totalling 1.15×10^{13} ppp. The lobe structure lasts for ~100 µs. Figure 6, I2 shows how a longer pulse with 1.4×10^{13} ppp produces a halo and core structure lasting for ~1 ms. This is not presently understood, but simulation studies are underway. It is thought that during the complex redistribution process, which frequently involves significant beam loss, stable or invariant distributions are formed. Understanding these observations could be most informative. The stable lobes also allow for experiments varying parameters during a single pulse, and initial trials are very promising.

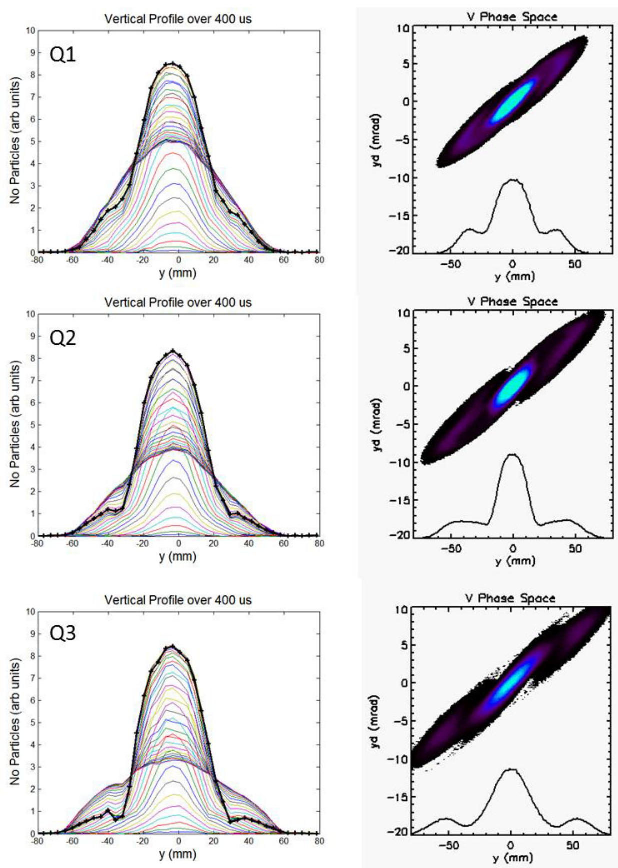

Figure 5: Variation of beam profiles with lattice tune: top to bottom Q_y=(3.71, 3.67, 3.63). Left measured profiles through injection, right ORBIT results.

BEAM MODELS AND BEHAVIOUR

Review of Beam Models and Behaviour

Comparison with expectations from key theory [6], and standard resonance theory below, suggests the behaviour observed (with lobes moving outward with increasing driving term strength, decreasing tune and increasing intensity) is reasonable. However, the motion here is more complicated than these simplified models.

Incoherent theory suggests loss nearer the lower intensity resonance condition in Figure 1 and incorrectly ignores any coherent response of the beam. Standard coherent theory, the higher limit in Figure 1, is not applicable once the beam redistributes and ε_{rms} changes.

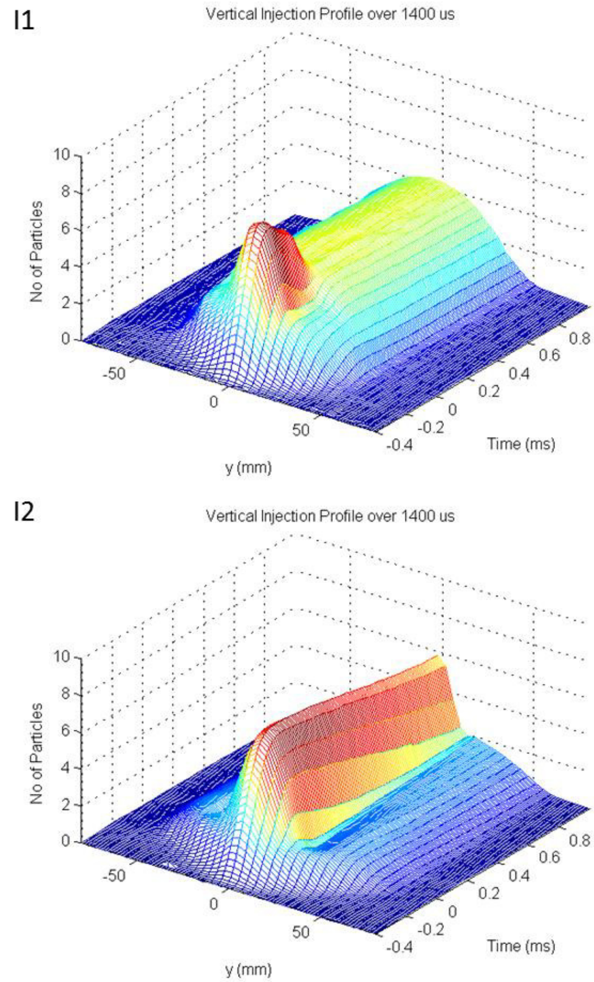

Figure 6: Time structure of beam profiles over 1 ms using slower intensity ramp rates, with total injected intensities of I1=1.15×10^{13} and I2=1.40×10^{13} ppp.

One of the more complete models is [6], which solves the driven resonance problem with space charge self consistently for a KV beam. However, for a realistic beam the stationary KV distribution must be replaced with a non-uniform real space density where motion will be non-linear in the beam core. Therefore this model cannot predict likely loss mechanisms. Effects of non-uniform charge densities in periodic quadrupole channels are studied in [7], which suggests near-regular, non-chaotic motion can only be expected at low space charge levels (and therefore perhaps at the *onset* of resonance).

In general the actual processes at work are dependent on the details of the particular machine. Mechanisms are potentially complicated, with multiple 1D or 2D resonances. However, in these experiments, it appears

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that just one resonance is excited in the vertical plane. Examination of beam motion in vertical (y,y') phase space from the ORBIT simulations (Figures 2, 4, 5), and corresponding experiments, suggests that over short time intervals trajectories trace out a two lobed half integer structure – very similar to that expected for a single particle quadrupole resonance with non-linear terms present. Below, we use this simplified model in a first attempt to *qualitatively* explain observations.

Simple Initial Model

The most basic 1D model of a half integer resonance with non-linearity comes from *single particle theory*, and is described by the Hamiltonian of the form:

$$H(J,\varphi) = \delta\, J + G_2 J\, \cos(2\varphi) + G_4\, J^2 \qquad (1)$$

where (J, φ) are action angle variables, δ the distance from resonance and G_2 and G_4 represent quadrupole error driving strength and an octupole term respectively. It is understood that this simple model is in many ways incorrect for the system being considered, not least because the potential outside the beam core is different (α log(r)). Also, unlike the single particle case, non-linear fields from space charge are a function of the time dependent beam distributions. However, it is possible that time averaged motion, over intervals in which beam distributions change little, may behave in key respects as expected from this Hamiltonian.

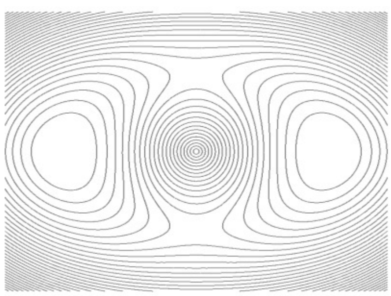

Figure 7: Example of resonant phase space structure from Equation (1) in normalised (Y, Y') space.

For these experiments, during early turns intensity is low and external non-linear terms small, and so G_4 can be neglected (1). The parameter δ is finite, beam is off resonance, and motion linear and stable. As intensity increases the tune depression will push particles toward resonance, reducing δ, and increasing non-linearity G_4, perhaps forming a characteristic two-lobed structure: e.g. Figure 7. Observed motion follows contours suggestive of Figure 7, until significant numbers of particles redistribute. We suggest that recent experimental results, Figure 6, I2, may correspond to a longer term invariant. Models based on (1), but with more realistic beam potentials are being studied.

Comparison with Simple 2D Simulations

In order to confirm that observations can be explained by the basic elements described, a simplified simulation was run with a 2D version of the ISIS code Set. This included a smooth focusing approximation to ISIS, PIC solvers for space charge, the vertical driving term (J_7=0.05), and tracking of a 4D waterbag distribution of 10^5 macro particles for 100 turns. Parameters paralleled experiments above: energy 70 MeV, intensity 4×10^{12} ppp, (Q_x, Q_y)=(4.31, 3.63), $\varepsilon_{rmsx,y}$=10 π mm mr. A waterbag beam was injected in a single turn, a simplification on actual multi-turn accumulation. The results are shown in Figure 8. The characteristic lobes are clear, as is the similarity to Figure 7 in phase space.

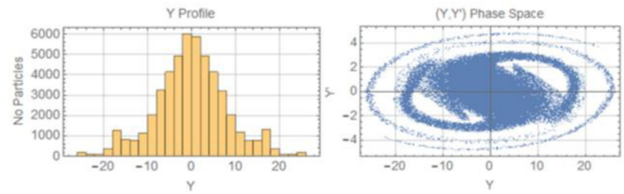

Figure 8: Set 2D simulations of the experiments.

SUMMARY AND FUTURE PLANS

Detailed experimental studies of beam as it approaches half integer resonance are providing more detailed observations of behaviour under the action of this key loss mechanism. General agreement with simulations is good, and work is under way to develop models that explain what is observed. Recent observations of “stable halo” are expected to provide more valuable information. Ongoing developments of machine measurements and diagnostics will improve knowledge of the beam and thus models. Work to develop simulations will continue, guided by experimental results. Studies looking at half integer effects in 3D bunched beam simulations will start soon.

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