HIGH INTENSITY LOSS MECHANISMS ON THE ISIS RAPID CYCLING SYNCHROTRON

C.M. Warsop, D.J. Adams, B. Jones, S.J. Payne, B.G. Pine, H.V. Smith, R.E. Williamson, RAL,UK.
V. Kornilov, GSI, Darmstadt, Germany.

Abstract

ISIS is the spallation neutron source at the Rutherford Appleton laboratory in the UK. Operation centres on a loss limited, 800 MeV, 50 Hz proton synchrotron which delivers 0.2 MW to two targets. Understanding loss mechanisms on the ISIS ring is important for optimal operation, machine developments and upgrades, as well as improving designs for future machines. The high space charge levels, combined with the low loss achieved for high power operation, makes the ring an ideal tool for studying the physics of beam loss, particularly in a fast ramping context. The ability to reconfigure the beam in storage ring mode, and ongoing developments of diagnostics and beam measurements, are allowing detailed studies of image effects, resonances, beam stability and activation. We summarise recent work and progress on these topics, comparing with theory and simulation where appropriate.

INTRODUCTION

The ISIS facility provides neutron and muon beams for condensed matter research. High power beams are supplied by a loss limited, 800 MeV, 50 Hz proton synchrotron. Understanding and minimising beam loss in the ring are key factors in ensuring improved machine performance, optimising future machine developments, and providing the best proposals for future upgrades.

Ongoing developments and proposed upgrades to the two ISIS neutron targets, with the accompanying requirements for low loss, reliable and consistent operations at higher powers, demand improved understanding and control of loss. Proposed upgrades to the existing ring, including the 0.5 MW design using a higher energy 180 MeV injector [1], require comprehensive beam models for their design. Similarly, upgrades and the next generation short pulse neutron sources in the 2 MW regime (and beyond) all require well benchmarked codes and theory to ensure optimal, realistic, low loss designs. A detailed, experimentally verified study of high intensity beam loss mechanisms is therefore essential to underpin these plans.

The ISIS ring is a valuable tool for studying high intensity beams. The challenging operating regime of low loss with high space charge; the fast acceleration ramp – combined with a number of key beam dynamics issues discussed below, provides important opportunities for new research. The ability to run the beam in experimental storage ring mode also opens up further areas for study.

First we review losses observed on ISIS operationally, then summarise relevant R&D topics.

HIGH INTENSITY BEAM LOSS ON ISIS

The ISIS RCS

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 ~350 π mm mr. The ring has a circumference of 163 m. Nominal betatron tunes are (Q_x, Q_y)=(4.31, 3.83), but these are varied using 2 families of 10 trim quadrupoles. The dual harmonic RF system captures and accelerates the initially unbunched beam, and allows enhanced bunching factors. The machine is harmonic number two, RF systems run at h=2 and h=4 with peak volts of 168 and 96 kV/turn respectively. Peak incoherent tune shifts of $\Delta Q \geq 0.5$ are reached at about 80 MeV during bunching. Single turn extraction at 800 MeV uses a fast vertical kicker. Main loss mechanisms are associated with non-adiabatic trapping, transverse space charge and transverse instability.

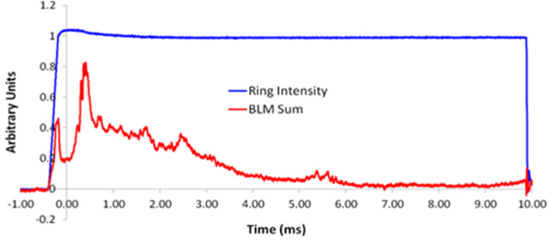

Figure 1: ISIS intensity and beam loss through the machine cycle (2.8×10^{13} ppp injected).

Summary of Losses

The average beam power delivered by the ring is typically 160-200 kW. To allow hands on maintenance, activation has to be limited; this determines tolerable loss levels and running intensity. Figure 1 shows the circulating current and beam loss signal through the 10.5 ms machine cycle. Overall losses are <5% and concentrated at lower energy, where activation is considerably reduced. During the injection and accumulation process (-0.5–0.0 ms) losses are about 2%. During the trapping process (0.0–2.5 ms) losses are <3%, and for the rest of acceleration (2.5–10.0 ms) losses reduce to 0.5% levels, finally reaching ~0.01% at extraction.

Most loss (> ~98%) and activation is localised in 3 of the 10 super-periods, which include the injection,

ISBN 978-3-95450-173-1

collimation and extraction systems. This control is achieved with a detailed, time dependent, empirical optimisation of machine parameters. Loss distributions are monitored using the 39, 3 m long, ionisation chambers distributed around the machine circumference. Beam transformers and loss monitors are linked to a fast machine protection system that trips the beam off if losses exceed defined limits. Activation levels around most of the ring are ~10-100 µSv/hour at 1 m.

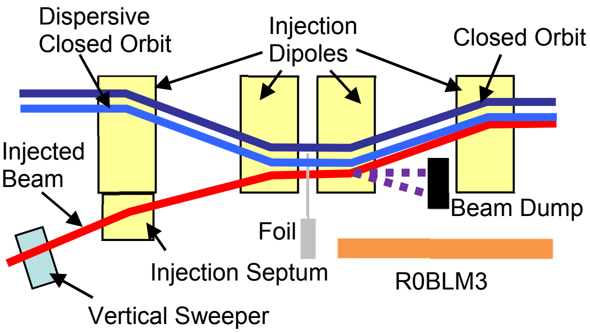

Figure 2: Schematic of the ISIS injection straight.

Injection

The H⁻ charge exchange injection process accumulates 3×10^{13} ppp over 130 turns. An Al_2O_3 foil, of area 120×40 mm and thickness 0.5 µm, strips the beam with estimated efficiency of ~98% (see next section): most stripping products are collected on a dedicated dump (Figure 2). The beam centroid is painted in both transverse planes. Horizontally, the injection point on the foil is constant, and dispersive closed orbit motion due to the falling main magnet field varies the betatron amplitude. Vertically, a steering magnet in the injection line sweeps the vertical position at the foil (thus requiring a larger foil). The average number of foil re-circulations per proton is estimated at 30. Upgrade designs [1] reduce re-circulations substantially to ~5, by using angular vertical painting and reducing vertical foil size.

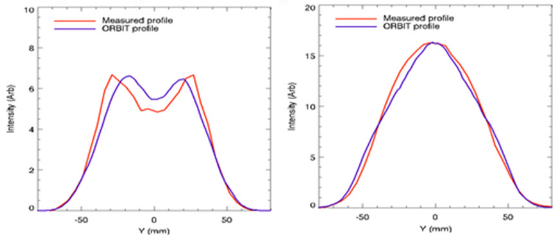

Figure 3: Simulated and measured vertical profiles after injection, left 2.5×10^{12} ppp, right 2.5×10^{13} ppp (red, measurement; blue, ORBIT result).

Space charge has a strong effect on the evolution of the transverse beam distributions, losses during injection and later in the cycle. Experience shows that, generally, larger amplitude, hollow painted beams give the best results. Comparisons of measured beam distributions with those from ORBIT [2] simulations have shown good agreement [3]. Results are shown in Figure 3, where the vertical beam profile after injection is shown at low and high intensity. The effect of space charge is to "fill in" the hollow painted distributions. These studies also showed that the machine is insensitive to correlated or anti-correlated painting between the two transverse planes. There is still much to be understood about the mechanisms redistributing the particles through injection, and this will be studied in more detail as simulation models develop.

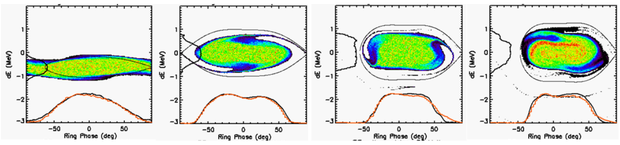

Figure 4: ORBIT simulation of the ISIS trapping process, showing (dE, ϕ) space at -0.2, 0.0, 0.2, 0.5 ms.

Longitudinal Trapping Process

The non-adiabatic, longitudinal trapping of the initially un-bunched injected beam is central to machine optimisation. In addition to the longitudinal capture, it has major effects transversely on space charge and stability via the bunching factor. Installation and optimisation of the dual harmonic RF system [4, 5] has reduced losses from ~10% to 3% levels. This allows much enhanced bunching factors, a larger longitudinal acceptance, and the ability to control bucket dynamics to optimise capture. An ORBIT simulation of typical operation with an injected intensity of 2.8×10^{13} ppp is shown in Figure 4: orange lines show experimental data [6].

The high beam currents cause significant beam loading in the RF cavities, and a feed forward beam compensation system corrects for this in the h=2 systems. It is expected similar systems for the h=4 systems will provide benefits in the future. Major developments of high power RF systems and digital control systems [5] are also expected to allow much finer optimisation in the future, when a more efficient beam dynamics solution may be possible.

Studies with an in-house 1D code have looked at the space charge and longitudinal stability on ISIS [7]. These show that the beam significantly exceeds the Keil-Schnell-Boussard (KSB) stability criterion through injection and acceleration, by factors of ~6. However, the machine runs successfully and with low loss. This is probably explained by stabilisation due to redistributions of the beam that are small compared with other effects, and simplifications implicit in the KSB criterion. This is an important topic as KSB is often used to guide machine designs, and is the subject of planned research on ISIS.

Transverse Space Charge

Transverse space charge peaks during the trapping process, as the beam bunches at low energy (~80 MeV). Peak incoherent tune shifts are ΔQ~-0.5, with some ORBIT simulations suggesting larger shifts, see Figure 5. Transverse beam sizes peak at this time, filling the available apertures (~350 π mm mr). A key feature of the ISIS lattice is the inclusion of trim quadrupoles that allow rapid variation of tune through the cycle, and this capability has been essential for successful operation. Examples of operational Q values (corresponding to high intensity coherent tunes) are shown in Figure 6. Early in the cycle tunes are generally high to avoid integer and half integer lines, but a ramp down will be noted in Q_y near 2 ms. This is required to avoid the vertical resistive-wall head-tail instability. Therefore beam is pushed over the half integer line and loss optimisation is a compromise between these two effects. The mechanisms causing loss associated with the half integer are the subject of research. In the rapid cycling, 3D context the process is complicated – no coherent quadrupole motion has been observed on the machine, but some initial ORBIT simulation results suggest it may be present. Further studies will exploit new diagnostics and simulations.

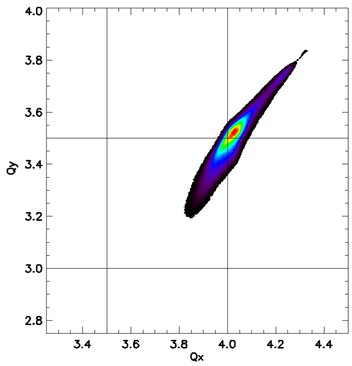

Figure 5: Incoherent tune spread from ORBIT simulations at 1 ms, intensity 2.5×10^{13} ppp.

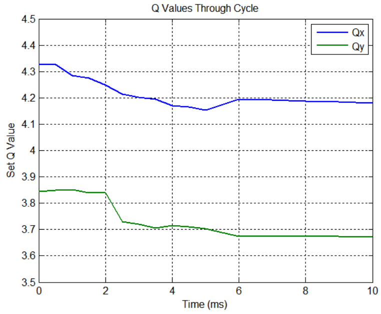

Figure 6: Programmed (Q_x, Q_y) through the ISIS cycle.

Most ISIS modelling studies have so far assumed a linear lattice, with the dominant non-linear behaviour arising from space charge. More recently, new measurements of loss whilst scanning (Q_x, Q_y) with low intensity beams [8], have revealed significant non-linear terms, Figure 7. Work is now under way to include these terms in machine simulations, and also investigate their origin with improved models and measurements of the machine lattice magnets.

The ISIS ring uses conformal, rectangular vacuum vessels that are profiled to the design beam envelopes. Whilst this has some benefits in reducing beam impedances and aiding efficient collimation, one key consequence is the generation of image driving terms and possibly enhanced losses: this is discussed in the next section.

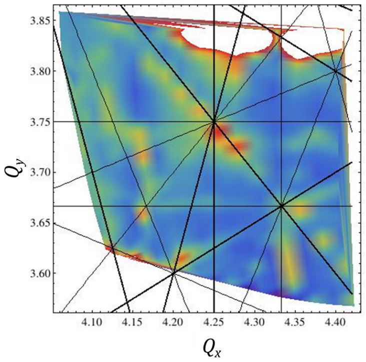

Figure 7: Measured ISIS tune map (low intensity).

Recent detailed studies of the ISIS working point for upgrade studies [1] have highlighted another consequence of these conformal vacuum vessels. As the machine tune is ramped (Figure 6) beam optics and envelopes change, and are no longer matched to the vessels, thus reducing the effective acceptance. ORBIT simulations show that whilst emittance growth reduces as Q values are moved up and away from half integer resonance lines, there can also be an increase in loss that correlates with the mismatched envelope. On the real machine there is a detailed *empirical*, time dependent optimisation of many parameters, including Q's, envelope harmonics and orbits, which takes these factors into account. Improvements to beam measurement and control are expected to shed more light on these effects, and potentially maximise use of aperture.

Head Tail Instability

A head-tail instability appears vertically, at about 2 ms into the ISIS cycle. Observations suggest it is driven by the resistive wall impedance: as Q_y approaches 4 growth rates increase rapidly. Before installation of the dual harmonic RF system, the instability was avoided by simply reducing Q_y. However, increasing intensities and longer, symmetric bunches have made the beam less stable, with the associated losses now limiting operational intensity. Experiments show an otherwise low loss, operational beam can be destabilised with a small change in bunch symmetry via a change in the phase between h=2 and h=4 RF harmonics. This is the subject of current research [9, 10]. A damper system is in development, with prototypes presently under trial.

Acceleration and Extraction

After about 4 ms, as energy ramps, transverse space charge reduces and beam emittances damp leaving “spare” acceptance and reducing losses. However, the limited acceptance of the extraction system (280 π mm mr) requires tight control of halo. The higher activation associated with the 800 MeV beam at extraction dictates loss levels of ~0.01%. A vertical closed orbit bump is used to aid fast extraction in the last 1 ms of the cycle. This moves the beam into lower quality regions of the lattice magnets and increases the effects of non-linearities. However, the careful control of lattice tunes (Figure 6), allows these to be avoided.

Recent upgrades to quadrupole switched-mode power supplies have improved beam control, but also introduced some interesting effects. Inadequate filtering has meant that switching frequencies have perturbed the beam as they sweep the horizontal betatron sidebands – these account for the peak in loss at 5.5 ms in Figure 1. This will be rectified with suitable modifications, but the potential for using the hardware as a tuneable, diagnostic dipole and quadrupole kicker is being explored.

HIGH INTENSITY R&D ON ISIS

In this section research and development work to understand and reduce beam loss is summarised.

Head-Tail Instability

This is a key topic for improving ISIS operations and also of significant interest for understanding more about the effect of space charge on beam stability [9, 10].

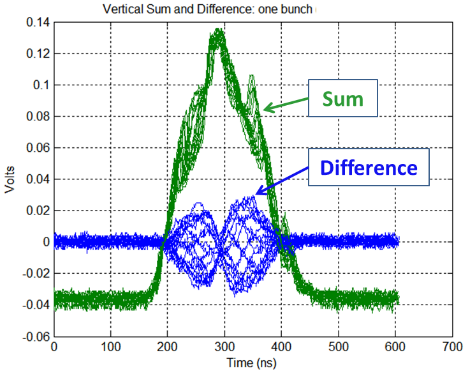

Figure 8: ISIS head-tail motion (single harmonic RF).

Some recent experiments and simulations [9, 10] of head-tail motion have concentrated on the simpler case, with just single harmonic RF operation and low intensities. Measured results have been compared with Sacherer theory and HEADTAIL [11] simulations. The mode structure observed experimentally, m=1, (Figure 8) does not agree with theoretical and simulation predictions, m=2. Growth rates suggested by theory are also much slower than those from measurements and simulations. Key next steps are investigating the driving impedance in more detail, developing more accurate simulations, and exploring limitations in the Sacherer theory, e.g. [12].

Image Force Studies and Space Charge

The conformal, rectangular ISIS vacuum vessels give rise to image fields that can form additional driving terms leading to loss at high intensity. In particular, it is thought that offset beams due to closed orbit errors at the dominant Q_x=4 harmonic could be causing significant loss on ISIS [13]. This is now under detailed study [14], with development of the Set code [15] for simulation studies and investigations of expected dominant driving terms from theoretical field calculations.

Half Integer Studies

Half integer losses are expected to have a significant effect on ISIS, but the underlying growth mechanisms are not well understood. Present studies are investigating the behaviour of coasting beams in storage ring mode, which allows investigation of the 2D, transverse resonance effect. Experiments pushing beams on to resonance show good agreement with simulations [16]. This work is allowing detailed benchmarking of codes and looking to develop models of beam loss, with the hope of controlling onset of this key resonance.

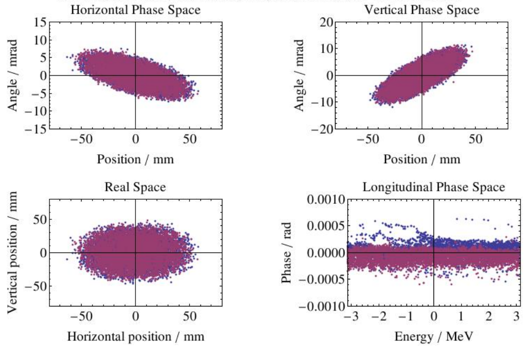

Figure 9: Set benchmarking with ORBIT.

ISIS Code Developments

An in-house code, Set 3Di, is being developed with a particular focus on ISIS work. It includes self-consistent space charge in transverse and longitudinal planes, treatment of AG and smooth focusing lattices, injection bumps, foil scattering and image forces. Detailed benchmarking against ORBIT models (Figure 9) and ISIS is underway. The code will be a powerful tool for studying many of the topics described above.

Modelling and Upgrade Work

Detailed ORBIT models of the ISIS ring have been developed that show good agreement with the operational machine [6]. Results of these are given above in Figures 3, 4 and 5. These well established models form the basis of upgrade designs [1].

Activation and Foils

New FLUKA [17] models of the ISIS collimator system [18] are giving new information on activation levels and the destination of lost particles and secondary products. Comparison of predicted activation with measurements is promising, and data are being used to understand where energy is deposited to help improve machine protection. Figure 10 shows energy deposition along the collimator straight in horizontal and vertical projection.

New comprehensive studies of the Al_2O_3 ISIS foil have been investigating its thickness, roughness, composition and structure. Details are given in [19]. A key finding is that foils are perhaps nearer 0.50 µm in thickness rather than the 0.25 µm expected. This implies stripping efficiencies should be nearer to 99.9%, but with increased

ISBN 978-3-95450-173-1

losses due to foil scattering. The implications for ISIS operations and loss levels are being evaluated.

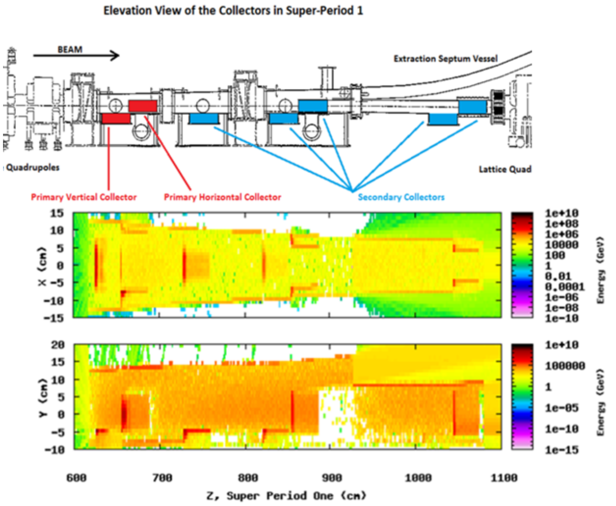

Figure 10: FLUKA simulations of ISIS collimators.

Measurements and Diagnostics

Accurate beam measurements underpin operations and R&D work. Updates of electronics for diagnostics, new magnet power supplies, and the installation of more powerful data acquisition hardware are all allowing better beam measurement systems to be developed. New systems to determine beam optics parameters, orbits, envelopes and optimise them are being commissioned [8].

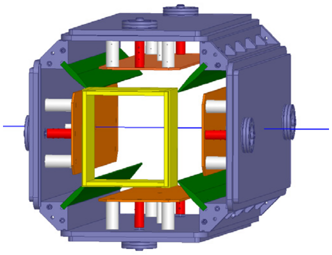

Figure 11: ISIS stripline monitor and kicker.

Research and development into new diagnostics is playing a key role, along with further studies to improve accuracy of ring profile monitors. Developments of loss monitoring, including the use of compact scintillators which can be placed within magnets, are providing enhanced protection. Damper systems and beam kickers are being developed and prototyped: Figure 11 shows a strip line kicker, due for installation next year.

SUMMARY AND PLANS

The ISIS RCS presently runs with low and well controlled loss, but to increase intensities and maintain reliability, work is underway to improve our understanding and control of the beam. To do this we are developing diagnostics, measurement systems, simulation models, and addressing key beam dynamics issues. Designs for major upgrades depend on experimentally verified codes and theory from this work.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of the ISIS Diagnostics, RF and Operations sections. Thanks also to members of ASTeC Intense Beams Group.

REFERENCES

[1] D.J. Adams et al., Ring Simulation and Beam Dynamics Studies for ISIS Upgrades 0.5 to 10 MW, THO3LR02, Proc. HB2014.
[2] J. Galambos et al., ORBIT – A Ring Injection Code with Space Charge, THP82, Proc. PAC99.
[3] B. Jones et al., Injection Optimisation on the ISIS Synchrotron, THPP096, Proc. EPAC08.
[4] C.R. Prior, Studies of dual harmonic acceleration in ISIS, Proc. ICANS-XII, RAL Report 94-025 (1994).
[5] A. Seville et al., Progress on the ISIS Synchrotron Low Power RF System Upgrade, WEPFI063, Proc. IPAC13.
[6] D.J. Adams et al., Beam Loss Studies of the ISIS Synchrotron using ORBIT, THPPP088, Proc. IPAC12.
[7] R.E. Williamson et al., High Intensity Longitudinal Dynamics Studies for an ISIS Injection Upgrade, THO1A04, Proc. HB2012.
[8] B. Jones, et al., Progress on Beam Measurement and Control Systems for the ISIS Synchrotron, THPME181, Proc. IPAC14.
[9] V. Kornilov et al., Instability Thresholds of the Head-Tail Modes in Bunches with Space Charge, WEO1LR02, Proc. HB2014.
[10] R.E. Williamson et al., Simulations of the Head-Tail Instability on the ISIS Synchrotron, MOPAB38, Proc. HB2014.
[11] G. Rumolo et al., Electron Cloud Simulations: Beam Instabilities and Wakefields, PRST-AB V5, 121002 (2002).
[12] G.H. Rees, Interpretation of the Higher Mode, Head-Tail Motion Observed on ISIS, Particle Accelerators, V39, p159, 1992.
[13] G.H. Rees et al., Image Effects on Crossing an Integer Resonance, Particle Accelerators, V48, p251, 1995.
[14] B.G. Pine et al., Image Fields in the Rectangular Vacuum Vessels of the ISIS Synchrotron, MOPAB39, Proc. HB2014.
[15] B.G. Pine et al., Space Charge Simulations for ISIS, TH3IODN02, Proc. ICAP 09.
[16] C.M. Warsop et al., Studies of Loss Mechanisms Associated with the Half Integer Limit on the ISIS Ring, MOPAB40, Proc. HB2014.
[17] A. Ferrari et al., “FLUKA: A Multi-Particle Transport Code”, CERN 2005-10 (2005), INFN/TC_05/11, SLAC-R-773.
[18] H.V. Smith et al., Activation Models of the ISIS Collectors, MOPRI115, Proc. IPAC14.
[19] H.V. Smith et al., An Overview of the Preparation and Characteristics of the ISIS Stripping Foil, MOPAB04, Proc. HB2014.