# STATUS OF INJECTION UPGRADE STUDIES FOR THE ISIS SYNCHROTRON

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*Abstract*

ISIS is the spallation neutron source at the Rutherford Appleton Laboratory in the UK. Operation centres on a high intensity proton accelerator, consisting of a 70 MeV linac and an 800 MeV rapid cycling synchrotron, which provides a beam power of 0.2 MW. Obsolescence issues are motivating plans to replace the ageing 70 MeV linac, and this paper summarises the status of studies looking at how a new, higher energy linac (~180 MeV) could be used to increase beam power in the existing synchrotron. Reduced space charge and optimised injection might allow beam powers in the 0.5 MW regime, thus providing a very cost effective upgrade. The key areas of study are: design of the injection straight; injection painting and dynamics; foil specifications; acceleration dynamics; transverse space charge; instabilities; RF beam loading; and activation. Results from work on many of these topics suggest that beam powers of ~0.5 MW may well be possible, but a number of areas still present significant challenges. Results and recent progress are summarised.

## INTRODUCTION

### *Present ISIS Operation*

ISIS operation centres on an 800 MeV rapid cycling synchrotron (RCS). It has a circumference of 163 m, and accelerates $3\times10^{13}$ protons per pulse (ppp) from 70 to 800 MeV on the 10 ms rising edge of the sinusoidal main magnet field. At the repetition rate of 50 Hz this equates to 0.2 MW. The high intensity beam is established via charge-exchange injection over ~130 turns while the main magnet field is falling. The 70 MeV $H^-$ injector provides ~25 mA of un-chopped beam that is 'adiabatically' trapped in two bunches by the ring dual harmonic RF (DHRF) system. The RF system consists of 10 ferrite-tuned cavities, with peak design voltages of 180 and 80 kV/turn for the $h$=2 and 4 harmonics respectively. The $h$=2 frequency sweep is 1.3-3.1 MHz. Beam is painted over the transverse acceptances, which are collimated at ~300 π mm mr. Nominal betatron tunes are ($Q_h$, $Q_v$) =(4.31, 3.83), with peak incoherent tune shifts exceeding ~0.4. Intensity is loss limited: the main mechanisms are longitudinal trapping and transverse space charge. Single turn extraction uses a fast vertical kicker and septum.

### *ISIS Megawatt and Injection Upgrades*

A range of ISIS upgrade routes is under study [1]. The favoured route increases beam power in two stages [2]. First, the beam energy from the existing RCS is increased by a factor of 4 using a new 3.2 GeV RCS, providing beam powers of ~1 MW. In the next stage, the 3.2 GeV ring is adapted for multi-turn charge-exchange injection from a new 800 MeV linac, increasing beam current and giving beam powers in the 2-5 MW regime.

Present studies, however, are concentrating on a lower power, lower cost upgrade option. Obsolescence issues are motivating plans to replace large sections of the existing 70 MeV linac. This investment could be combined with an upgrade to the injector (~180 MeV) and injection system into the present RCS. The reduced space charge and optimised, chopped injection would address two of the main loss mechanisms in the ring. Assuming a nominal choice of 180 MeV for injection energy, the space charge limit is raised to about $8\times10^{13}$ ppp, corresponding to 0.5 MW (neglecting other loss mechanisms). If practical, such a boost in power could also enhance the later upgrades mentioned above.

This study addresses the key issues in the ring; designs already exist for a suitable 180 MeV linac [3]. At these substantially increased beam powers numerous challenging issues arise, as outlined below. Important results have already been presented in [4, 5], with high intensity topics in [6]. This paper summarises progress.

## MAIN INJECTION UPGRADE TOPICS

### *Transverse Dynamics*

A key benefit of the upgrade is the reduction of transverse space charge as energy increases. The expected $\beta^2\gamma^3$ scaling suggests the $8\times10^{13}$ ppp, 0.5 MW intensities [6, 7]. These simple scaling predictions give useful guidance, but detailed simulations with the in-house code Set [7] confirm that these intensities are the upper limit, which depend on achieving optimal bunching factors, emittances and working points. The smaller energy ramp, 180-800 MeV, also reduces emittance damping, which may require an increase in the extraction system acceptance [6].

Instabilities are one of the major concerns for the proposed higher intensities. The most obvious problem is the resistive-wall head-tail instability already observed on ISIS [6], and is avoided by lowering $Q_v$. The growth rate can be expected to scale strongly with intensity, and lowering $Q_v$ further will tend to increase loss associated with the half integer resonance ($2Q_v$=7). Two solutions are under study: a damping system, and dropping the tune below the half integer ($Q_v$<3.5). For the latter, space charge studies including image terms have indicated a systematic resonance ($3Q_v$=10) could be an additional problem [7]. The next key stages of the study are R&D into these image effects and instabilities.

### *Longitudinal Dynamics*

Finding a set of longitudinal parameters that satisfy all the requirements for space charge, stability, and injection at the proposed $8\times10^{13}$ ppp is non-trivial. Initial studies using an idealised Hofmann-Pedersen distribution at injection suggested workable solutions should exist within the main design parameters of the existing DHRF system, with some developments for beam loading. Studies have now advanced to include modelling and optimisation of realistic distributions produced by longitudinal painting. The in-house code developed for this work includes tests to ensure stability and has been used to produce suitable, controlled distributions through acceleration. A number of painting schemes are being studied; presently the most successful exploits manipulation of an asymmetric DHRF bucket, whilst keeping injection energy constant and applying a constant offset to the ring synchronous energy. This results in well controlled distributions with low loss, good bunching factors (~0.4) and stable beams throughout the cycle. The requirements for practical transverse painting are also incorporated. This work is described in [8].

### *Injection Straight and Stripping Foil*

An essential prerequisite for the upgrade is the demonstration of a practical 180 MeV injection system into the existing ISIS ring, which satisfies the numerous constraints for painting and controlling loss. Detailed models of injection dipole magnets, power supplies, the injection straight, the foil and trajectories of stripped and un-stripped products have been established [5]. These have shown that solutions exist, compatible with designs described below. Full, optimised engineering models will be used to model the final designs as beam dynamics optimisations are completed. A 200 µg/cm$^2$ carbon foil is proposed, which is expected to give a stripping efficiency of 99.7%. Calculations indicate that foil temperatures and lifetimes will be acceptable (with the expected number of foil re-circulations). This work is detailed in [9, 5].

### *Injection Beam Dynamics*

Many constraints must be satisfied to define workable, high intensity injection. Key requirements include: practical foil parameters, low and controlled loss, and 3D painting of suitable beam distributions.

A solution has been found that is based in many ways on the existing ISIS injection scheme [5]. Four horizontal bump magnets are arranged symmetrically about the foil, but the beam now approaches from the outside of the ring. In the scheme presently under study, injection is timed with main magnet field minimum occurring half way through the 500 µs injected pulse, accumulating $8\times10^{13}$ ppp from the 43 mA H$^-$ beam. The beam is chopped, occupying about 220° of the ($h$=2) ring RF phase. At the injection point the beam is moved closer to the central orbit horizontally compared with existing injection to reduce bump dipole fields, and displaced vertically to reduce foil area and thus re-circulations.

The injected beam [3] has an un-normalised transverse emittance of 0.5 π mm mr at 1 sigma, and painting is anti-correlated in the transverse planes. Horizontal painting is controlled by independently ramping the four injection bump magnets, providing varying deflections from ~38 to 48 mr. In the vertical plane the injection point has constant displacement at the foil, with angular painting controlled by two steering magnets in the injection line. The horizontal bump arrangement is shown schematically in Figure 1. Two horizontal steering magnets are also required in the injection line to keep the beam horizontally aligned at the foil, compensating for the scaling bump magnets.

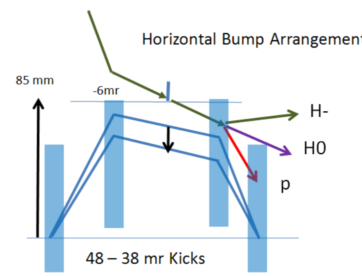


Figure 1: Schematic of 180 MeV injection straight.

A number of longitudinal painting schemes are under study, as discussed above. The manipulations of longitudinal parameters need to be compatible with transverse requirements for beam orbits, painting and reasonable bump magnet fields. The present best working design exploits manipulation of an asymmetric DHRF bucket to provide optimal distributions.

Simulations use the 3D, parallel implementation of ORBIT [10], including: detailed models of injection, the foil, apertures and collimation, as well as beam dynamics with space charge. Following careful optimisations, good solutions have been found with: transverse beam emittances stabilising within the acceptance at 300 π mm mr, suitable longitudinal beam distributions, and foil re-circulations averaging at ~5 (compared with 30 for the existing injection system). Note that not all loss mechanisms are included in the simulation. Beam distributions at the end of injection are shown in Figure 2.

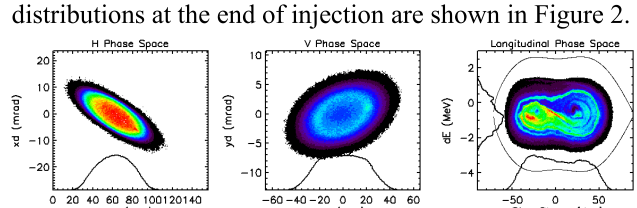


Figure 2: Beam distributions in ($x$,$x'$), ($y$,$y'$), ($\varphi$,$\Delta E$), at the end of injection.

The studies indicate that a range of reasonable solutions exist, with further scope for optimisation. One interesting alternative involves injection solely on the rising edge of the main magnet field.

### *Full Cycle Parameters and Simulations*

A full set of *working* beam dynamics parameters for the whole cycle have now been established. These are being studied via theory, 1, 2, and 3D codes (including Set and ORBIT). Of particular interest are the full cycle, 3D, parallel ORBIT simulations. As for the injection studies above, these include painting, apertures, collimation, and beam dynamics with space charge (but not instabilities). Simulation of the full ~$10^4$ turns has only recently been implemented and requires significant time on the RAL parallel cluster. Analysis of the results is still in progress. However, evolution of beam distributions and emittances all look reasonable, with low and controlled loss. Figure 3 shows examples of accelerated beam distributions.

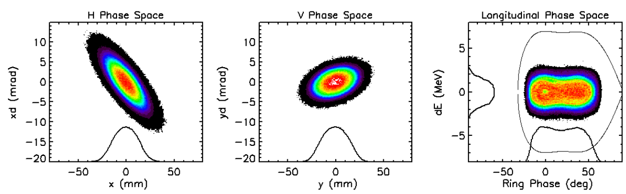


Figure 3: Beam distributions $(x,x')$, $(y,y')$, $(\varphi,\Delta E)$, 7.3 ms through the 10 ms acceleration process.

Some interesting features not seen in other simulations are presently being investigated, including horizontal emittance growth and 2% loss with representative quadrupole gradient errors. It is expected that further study will shed light on these effects.

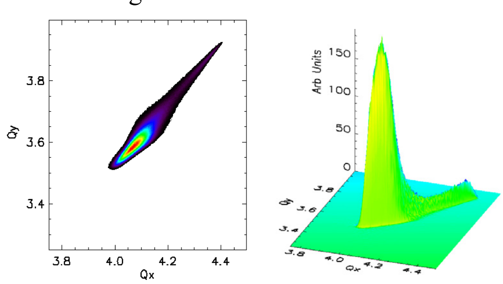


Figure 4: Incoherent tune footprint at $8\times10^{13}$ ppp.

The ORBIT simulations are of particular value as they are closely related to models of the existing machine, which agree well with experimental observations. One valuable cross check of theory, Set and ORBIT codes has been calculation (and agreement) of incoherent tune shifts. Incoherent tune shifts calculated by ORBIT at $8\times10^{13}$ ppp for present working values of the upgrade are shown in Figure 4. Further work is planned to allow simulation of instabilities.

### *RF Systems, Loss Control and Activation*

As indicated above, the main challenge for the RF systems is expected to be beam loading at the increased beam currents. A number of avenues are being explored to overcome this issue, including upgraded RF systems with higher specification valves.

It is expected that loss and associated activation will ultimately limit operational intensity. Detailed modelling and measurement studies are establishing scaling factors for activation at the higher proton energies. Calculations presently suggest activation should be manageable with the increased injection and trapping efficiency expected, assuming there are no additional losses (e.g. due to instabilities). Work to model and optimise loss control systems may help ease the constraints.

### *Diagnostics and Damping Systems*

The key diagnostics required for the upgrade (e.g. loss, intensity and profile measurements), are already under development. Investigations and countermeasures for instabilities are also being covered with new devices. An electron-cloud monitor was recently installed and commissioned [11], and a strip-line monitor that could form part of a damping system is to be installed shortly.

## SUMMARY AND CONCLUSIONS

Studies for a 180 MeV injection upgrade to the ISIS ring indicate that many key aspects of the proposal are workable. However, a number of key areas require significant R&D before intensities in the 0.5 MW regime can be comfortably predicted. These include transverse instabilities, effects of space charge, RF beam loading and loss control. If practical, this would offer an attractive, cost effective upgrade to the ISIS facility, that would also enhance future upgrades in the 1 MW regime.

## REFERENCES

[1] J W G Thomason *et al.*, Megawatt Upgrades for the ISIS Facility, Proc. EPAC08, Genoa, Italy, 2008.
[2] J W G Thomason *et al.*, Megawatt Upgrades for ISIS, Proc. HB08, Nashville, TN, USA, 2008.
[3] G H Rees, Linac, Beam Line and Ring Studies for ISIS Upgrades, ASTeC internal report GHR1, 2009.
[4] J W G Thomason *et al.*, Injection Upgrades for the ISIS RCS, Proc. IPAC10, Kyoto, Japan, 2010.
[5] B Jones *et al.*, Injection Upgrade on the ISIS Synchrotron, Proc. IPAC10, Kyoto, Japan, 2010.
[6] C M Warsop *et al.*, High Intensity Studies on the ISIS Synchrotron, Effects of Half Integer Resonance, Proc. HB10, Morschach, Switzerland, 2010.
[7] B G Pine *et al.*, Ring Transverse Beam Dynamics for the ISIS Injection Upgrade, Proc. IPAC11, WEPS104
[8] R E Williamson *et al.*, High Intensity Longitudinal Dynamics Studies for Higher Energy Injection into the ISIS Synchrotron, Proc. IPAC11, MOPS019.
[9] H V Smith *et al.*, Stripping Foil Simulations for ISIS Injection Upgrades, Proc. IPAC11, THPS057.
[10] J Galambos, ORBIT – A Ring Injection Code with Space Charge, Proc. PAC99, p. 3143.
[11] A Pertica *et al.*, A Micro-Plate Channel Based RFA Electron Cloud Monitor for ISIS, Proc. DIPAC11, Hamburg, Germany, 2011.