

A 180 MEV INJECTION UPGRADE DESIGN FOR THE ISIS SYNCHROTRON

J W G Thomason, D J Adams, B S Drumm, D J S Findlay, I S K Gardner, M C Hughes, S J S Jago, B Jones, R J Mathieson, J Pasternak, S J Payne, B G Pine, A Seville, H V Smith, C M Warsop, R E Williamson, D C Plostinar*, C R Prior*, G H Rees*
ISIS and ASTeC*, Rutherford Appleton Laboratory, STFC, Oxfordshire, OX11 0QX, UK

Abstract

ISIS is the spallation neutron source at the Rutherford Appleton Laboratory in the UK. Obsolescence and reliability issues are motivating plans to replace the present 70 MeV H^- linac. This paper presents an overview of a design to allow injection of beam into the present ISIS ring at 180 MeV, which would increase intensity as a result of reduced space charge and better optimised injection. The key topics addressed are design of the injection straight, injection painting and dynamics, foil specifications, acceleration dynamics, transverse space charge, instabilities and RF beam loading.

INTRODUCTION

Present ISIS Operation

ISIS has two neutron producing target stations (TS-1 and TS-2), driven at 40 Hz and 10 Hz respectively by a 50 Hz, 800 MeV proton beam from a rapid cycling synchrotron (RCS) [1]. The RCS accelerates $\sim 3 \times 10^{13}$ protons per pulse (ppp) on the 10 ms rising edge of the sinusoidal main magnet field, giving a total beam power of just under 0.2 MW. High intensity beam is established in the RCS via charge-exchange injection from a 70 MeV H^- injector over ~ 130 turns during the last $\sim 250 \mu s$ of the falling edge of the main magnet field. The injected beam is un-chopped, but the RCS dual harmonic RF (DHRF) system [2] 'adiabatically' traps it into two bunches during the early part of acceleration. Beam is painted over the transverse acceptances, which are collimated at $\sim 350 \pi$ mm mrad. Nominal betatron tunes are $(Q_h, Q_v) = (4.31, 3.83)$, with peak incoherent tune shifts exceeding ~ 0.5 . Intensity is loss limited, the main loss mechanisms being 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 to the multi-MW regime is under study [3], but present efforts are concentrating on a lower power, lower cost upgrade option. Reliability and sustainability issues are motivating plans to replace large sections of the existing 70 MeV H^- linac. This investment could be combined with an upgrade to the injector (to higher energy) and injection system into the present RCS, where the reduced space charge and optimised, chopped injection would address the two main loss mechanisms. The eventual choice of injection energy will be informed by parallel studies to determine possible upgrades to neutronics in TS-1, with

the overall aim being an optimal increase in neutron instrument capability and capacity at ISIS. However, for the time being, a nominal injection energy of 180 MeV has been assumed, where the space charge limit is raised to $\sim 8 \times 10^{13}$ ppp corresponding to more than 0.5 MW (neglecting other loss mechanisms). As at least one suitable 180 MeV H^- linac is already in operation [4], this study concentrates on the challenging issues that arise in the RCS at these substantially increased beam powers.

BEAM DYNAMICS OVERVIEW

The essentials of the injection dynamics designs have been described in [5], and are summarised here along with an outline of the key changes. Further details are provided in the subsequent sections.

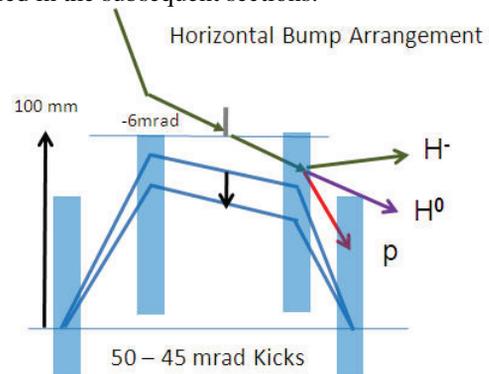


Figure 1: Schematic of injection straight.

Outline of Design

The proposed 180 MeV injection straight consists of a four magnet horizontal bump with a foil at the centre (Figure 1). For the upgrade, beam is injected from the outside radius of the machine with the foil centre now being displaced by ~ 100 mm from the central orbit. Vertical painting uses an angular variation at the foil with a fixed position to minimise foil size and thus proton traversals. Horizontal painting is varied with injection energy (using finite dispersion at the foil) and variation of the bump magnets. Provision is made for painting over most of the available aperture.

The 43 mA H^- beam from the linac is chopped at twice the revolution frequency, and injected over $500 \mu s$ to accumulate the nominal 8×10^{13} ppp beam. Options to inject before, after, or centred on main magnet field minimum are being considered. Pulse lengths and frequencies of the chopped beam are adjustable for optimal painting, as are injection energy and energy spread.

Key Developments

Main areas of work and progress are as follows:

- Detailed models of 180 MeV injection bump and dipole magnets have been established, including tracking of injected and stripped particles through 3D OPERA [6] models.
- Engineering designs of injection magnets have imposed limits on peak fields, which have in turn resulted in the need for significant dispersive horizontal painting using an injection energy ramp.
- A scheme for correcting envelope errors in the ring introduced by injection dipole magnets has been modelled.
- Constraints from injection and losses in 3D simulations have motivated further optimisations of longitudinal dynamics.
- Studies indicate that a change of Q_v to avoid the resistive-wall head-tail instability may not be practical.
- Damper systems are under development to combat instabilities.
- 3D ORBIT [7] simulations of the upgrade, for the whole acceleration cycle, suggest total losses <1%. Further work to understand and refine designs is in progress.
- The designs under development include as much flexibility as possible, allowing many configurations of the 3D painting scheme with the same hardware.

INJECTION STRAIGHT DESIGN

Designs for the 180 MeV injection septum and bump magnets are well advanced, with the latter being designed for deflections of 45 – 55 mr. OPERA models indicate acceptable field quality, and details of coils, cooling and power supply configuration are being finalised. Tracking studies through the straight with realistic field maps are confirming the viability of proposed painting schemes, indicating the destination of stripping products and optimal systems for their interception [8] (Figure 2). Latest studies of the 200 $\mu\text{g}/\text{cm}^2$ carbon foil indicate stripping efficiencies of 99.6% with practicable operating temperatures of ~1650 K.

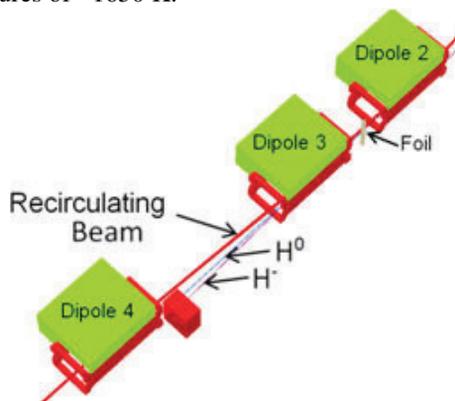


Figure 2: Particle tracking through the injection straight.

A full engineering design of the whole straight is being established and power supplies to provide the 26 kA required for the 0.22 T bump magnets, which include ramping capability for painting, are being specified.

LONGITUDINAL DYNAMICS

Workable longitudinal dynamics designs that satisfy difficult requirements on space charge, stability and beam loss have been identified for numerous injection configurations [9]. However, further constraints imposed by requirements for transverse painting, and work to reduce loss predicted in 3D ORBIT simulations, has driven more detailed and challenging optimisations. New working designs have been found using the in-house ISIS 1D code, and involve sweeping the energy of the injected chopped beam whilst manipulating the ring RF frequency to paint stable longitudinal distributions. Recent work has included careful damping of coherent motion after painting and manipulation of the DHRF bucket structure to minimise and contain halo. Figure 3 shows that stable beams are produced, with good bunching factors of ~0.5.

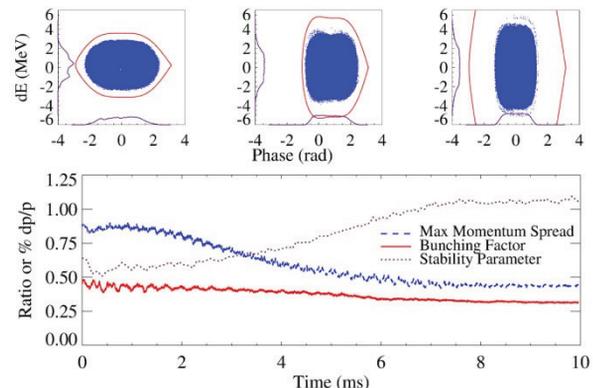


Figure 3: Longitudinal phase space at 0, 5 and 10 ms, and evolution of key parameters through the acceleration cycle for the present working design (based on injection before main magnet field minimum).

TRANSVERSE DYNAMICS

The key benefit of the increased injection energy is a reduction in space charge as characterised by the incoherent tune shift. Conservative estimates of scaling of peak shifts, and thus intensity, between the present 70 MeV operation and the upgraded 180 MeV scheme suggest a factor of ~2.6, *i.e.* intensities of ~ 8×10^{13} ppp. Simulations suggest that optimisation of beam dynamics may enhance bunching factors to ~0.5, resulting in scaling factors of up to 3.7. This may allow more flexibility and help to alleviate stability problems.

For present operations the working point is placed just below the $Q_v = 4$ line, which at high intensity can lead to loss due to excitation of the resistive-wall head-tail instability. Pushing Q_v down to avoid this results in half integer crossing as space charge forces increase. This may be a key intensity limitation for the upgrade.

The possibility of avoiding this instability by moving Q_v up or down by ~ 0.5 has been investigated. The consequences for the transverse dynamics of these alternative working points have been assessed using the ISIS code Set [10]. The 2D model includes the ISIS alternating gradient lattice, apertures, collimation limits, driving terms, and images. The studies showed that the variation of beta functions associated with Q_v variation significantly changes beam envelope with respect to the ISIS conformal vacuum vessels, thus effectively reducing beam aperture (Figure 4). These effects are still under study, but operating at such working points looks difficult. Studies around the present working point, however, indicate very low loss near the proposed 8×10^{13} ppp, with $Q_v \approx 3.9$, assuming the instability can be controlled in other ways (beam damper systems are being developed).

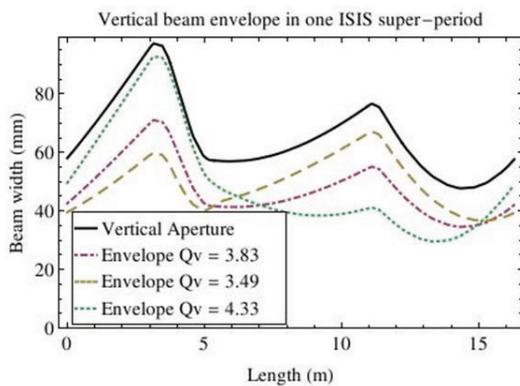


Figure 4: Variation of vertical envelope with Q_v .

3D DYNAMICS STUDIES

A detailed 3D ORBIT model, benchmarked on the present machine [11], is guiding designs. This includes details of the lattice, tune ramping, apertures, collimation, injection, foil interactions, acceleration and space charge. This model has helped to establish the viability of numerous 3D injection schemes giving essential data on foil traversals, emittance growth and beam loss through the complete acceleration cycle. This model generally predicts higher losses than 1 and 2D simulations and is driving a more detailed study and optimisation of the dynamics. Interestingly, simulations indicate that nearly constant, large amplitude transverse painting, with initially hollow distributions tend to provide the lowest losses over the whole cycle (as with present beam operations). Results also indicate that variation of tune near the existing working point produces envelope variations that affect collimation; this is being studied.

The best working designs, presently with injection on the falling edge of the main magnet field, with large, constant transverse painting amplitudes ($\epsilon_h = 72$, $\epsilon_v = 100 \pi$ mm mr), energy ramping (0.0 – 1.2 MeV) and carefully optimised ring RF, are suggesting losses of $< 1\%$ with beam contained within 300π mm mr. The loss is mostly at low energy and is well controlled, as shown in Figure 5. Understanding, minimising and verifying the

validity of these predictions is the subject of active R&D.

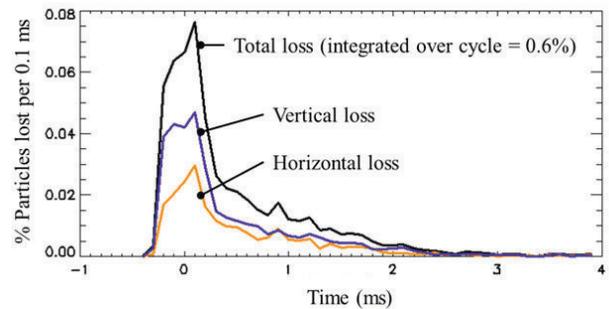


Figure 5: Temporal beam loss distribution from ORBIT.

OTHER KEY TOPICS

The resistive-wall head-tail instability is a concern for the upgrade so digital control electronics and power amplifiers for a new damper system are being assembled. A research programme to understand head-tail motion has been established, sharing experience on machines internationally. Provision is also being made for higher frequency damper systems should electron-cloud be a problem. Studies into longitudinal and transverse space charge effects are on-going [9, 10]. Planned upgrades to the ISIS RF system, based on TH558 valves [12] should address beam loading concerns. Simulations of beam collimators will ensure required loss control.

SUMMARY AND CONCLUSIONS

Workable designs have been found for most aspects of beam dynamics and hardware for a 180 MeV injection upgrade to the ISIS synchrotron. Studies suggest that intensities of ~ 0.5 MW should be possible, providing beam stability issues can be addressed and some finer details of space charge induced loss can be understood.

REFERENCES

- [1] D J S Findlay, "ISIS – Pulsed Neutron and Muon Source", PAC'07, p. 695.
- [2] A Seville *et al.*, "Progress on Dual Harmonic Acceleration on the ISIS Synchrotron", EPAC'08, p. 349.
- [3] J W G Thomason *et al.*, "Megawatt Upgrades for the ISIS Facility", ABDW HB'08, p. 434.
- [4] K Hasegawa *et al.*, "Operating Experience of the J-PARC Linac", LINAC'08, p. 55.
- [5] C M Warsop *et al.*, "Status of Injection Upgrade Studies for the ISIS Synchrotron", IPAC'11, p. 2760.
- [6] www.vectorfields.co.uk
- [7] J A Holmes *et al.*, "ORBIT: Beam Dynamics Calculations for High Intensity Rings", EPAC'02, p.1022.
- [8] B Jones *et al.*, "Progress on Designs for 180 MeV Injection into the ISIS Synchrotron", IPAC'13, MOPFI063.
- [9] R E Williamson *et al.*, "High Intensity Longitudinal Dynamics Studies for an ISIS Injection Upgrade", ABDW HB'12.
- [10] B G Pine *et al.*, "Space Charge Limits on the ISIS Synchrotron including effects of images", ABDW HB'12.
- [11] D J Adams *et al.*, "Beam Loss Studies on the ISIS Synchrotron Using ORBIT", IPAC'12, p. 3942.
- [12] www.thalesgroup.com