INJECTION AND STRIPPING FOIL STUDIES FOR A 180 MeV INJECTION UPGRADE AT ISIS

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Abstract

The Rutherford Appleton Laboratory (RAL) is home to ISIS, the world's most productive spallation neutron source. ISIS has two neutron producing target stations (TS-1 and TS-2), operated at 40 Hz and 10 Hz respectively with a 50 Hz, 800 MeV proton beam from a rapid cycling synchrotron (RCS), which is fed by a 70 MeV H$^-$ drift tube linac.

The multi-turn charge-exchange injection process used on ISIS has been the subject of a programme of detailed studies in recent years including benchmarked simulations and experiments. More recently, these studies have been expanded as plans for upgrading ISIS have focussed on replacement of the 70 MeV linac with a new, higher energy injector and a new synchrotron injection straight. Whilst much of these studies have been reported elsewhere, this paper presents a summary of the programme with some further details.

INTRODUCTION

The ISIS spallation neutron source now accelerates up to 3×10^{13} protons per pulse (ppp), cycling at 50 Hz corresponding to a total beam power of 0.2 MW which is split 40 pulses per second (pps) to TS-1 and 10 pps to TS-2. Fig. 1 is a schematic of the facility.

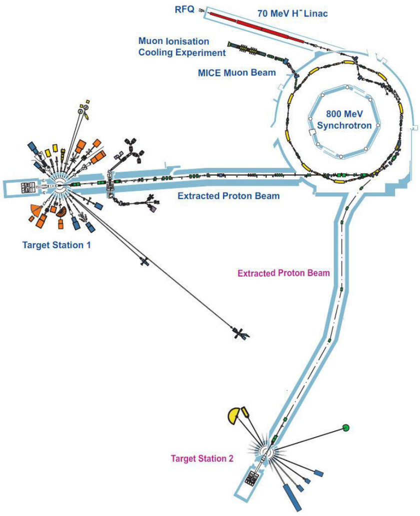

Figure 1: ISIS schematic layout.

With the successful operation of higher power spallation sources at J-PARC and SNS, a number of upgrade routes for ISIS are being studied. The favoured option is the addition of a 3.2 GeV RCS initially fed by bucket-to-bucket transfer from the existing 800 MeV RCS to provide ~1 MW. The later addition of a new 800 MeV linac would raise beam power further to the 2-5 MW range. Present studies, however, focus on replacement of the 70 MeV linac with a new ~180 MeV injector and new injection region of the RCS. The combined effects of reduced space charge and an optimized, chopped injection scheme could enable operation at 0.5 MW. This upgrade addresses reliability and obsolescence issues with the present linac and would provide a corresponding scaling in power for later upgrades.

70 MEV INJECTION

The 202 MHz, 70 MeV injector provides a 200 µs, 25 mA H$^-$ beam pulse. This beam is accumulated in the synchrotron over ~130 turns from 400 µs before the sinusoidal main magnetic field reaches its minimum. A 50 µg/cm^2 aluminium oxide foil is used to strip the H$^-$ to H$^+$ at injection with ~97 % efficiency. The 550 W waste beam of H^0 and H$^-$ is collected by a 40 mm long water-cooled graphite dump. Circulating beam is bumped towards the foil, located on the inside of the synchrotron, during injection by four serially powered injection dipoles. The dipoles bend the 70 MeV beam by 45 mrad creating a ~67 mm deflection at the foil. This bump is established and stabilised before injection begins and collapses over 100 µs after injection ends to limit foil recirculation to ~30 per proton.

Anti-correlated transverse painting is employed to reduce space charge forces within the beam. Horizontal painting makes use of the changing dispersive closed orbit during injection; as the main magnetic field falls the dispersive closed orbit moves away from the foil thus painting from a small to large emittance. Beam is painted vertically by moving the injection point; a single dipole magnet in the injection transfer line with a falling current is used to paint from a large to small emittance.

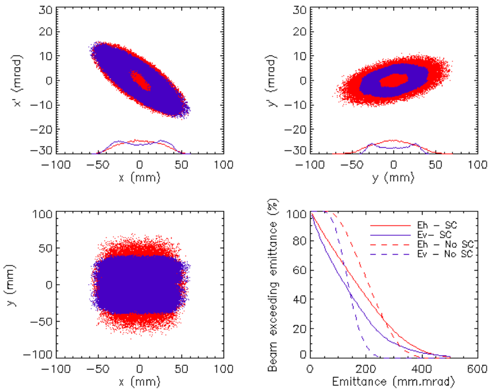

Figure 2: ORBIT simulations: Phase space, real space and emittance occupancy at 0 ms with (red) and without (blue) space charge.

ORBIT Simulations

Initial studies [1] of the ISIS injection process were performed using the multi-particle tracking code ORBIT [2]. Simulations included 2D space charge and realistic acceleration but excluded foil scattering and lattice errors. Injection painting was varied to match accumulated beam distributions to profile measurements and the model was used to assess the effect of space charge and to compare different painting schemes. Fig. 2 illustrates the effect of space charge on the painted distributions.

The model was later improved by benchmarking against more detailed measurements of the injection painting [3]. The ISIS injection beamline incorporates an electrostatic beam 'chopper' to produce beam pulses as short as 100 ns for diagnostic studies of the synchrotron. Turn-by-turn measurement of the transverse beam position allows estimation of a number of key parameters [4] including the betatron amplitude and closed orbit position. Several measurements over the injection period provide a direct measurement of the painting applied, Fig. 3.

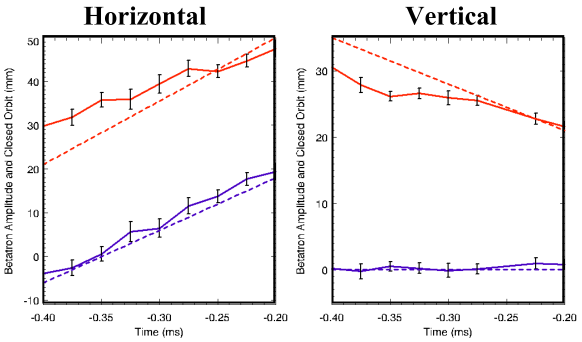

Figure 3: Measured (solid) and simulated (dashed) betatron amplitude (red) and closed orbit (blue) variation over injection.

The initial ORBIT model was developed to enable injection of a chopped beam and output of beam position monitor (BPM) data that could be analysed using the same software as the real BPM measurements. Injection parameters in the model were then varied to match the measured painting. Simulations of a full injection pulse could then be made using the matched painting scheme and resulting beam distributions compared to beam profile measurements using the ISIS Ionisation Profile Monitors (IPMs). Good agreement was found for both transverse planes with high and low intensity beams using correlated and anti-correlated painting [3].

Foil Simulation

An in-house code was developed to simulate the interaction of the injected beam with the stripping foil [5]. Nuclear inelastic and Coulomb scattering, electron loss and energy deposition in the foil were included allowing calculation of stripping efficiency, uncontrolled beam loss and foil heating. The simulation results were benchmarked against ISIS 70 MeV operation along with SNS and J-PARC designs [6, 7], Table 1. Comparisons of foil heating and beam scattering effects were also made and agreed well.

Table 1: Stripping Efficiency Benchmarking

Facility	Foil	Design	Simulation
ISIS (70 MeV)	50 μg/cm^2 Al_2O_3	96-98%	97.2%
SNS (1 GeV)	300 μg/cm^2 C	99.8%	99.5%
J-PARC (180 MeV)	210 μg/cm^2 C	99.7%	99.9%
J-PARC (400 MeV)	280 μg/cm^2 C	99.6%	99.6%

All the energy deposited in the foil is assumed to result in heating. The temperature of the foil during operation was calculated, Fig. 4. The equilibrium temperature of ~400 K is well below the melting point of 1800 K. This is consistent with operational experience on ISIS where foil failure is usually due to mechanical damage rather than evaporation. Good foils can last up to a year but may fail after a few hours due to damage suffered during mounting and insertion into the synchrotron.

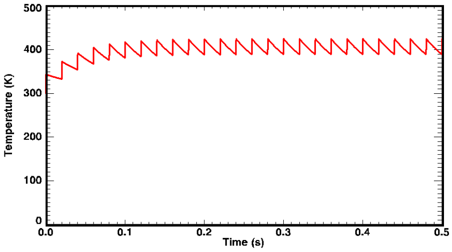

Figure 4: Temperature of the ISIS foil at 70 MeV.

Injection Straight Models and Tracking

Detailed engineering models of the ISIS injection region have been produced [8]: an OPERA [9] model of the injection magnets and a CAD model of the region including vacuum vessels and the beam dump.

A set of measurements was made of the ISIS operational hardware settings, beam profiles along the injection line, linac energy and momentum spread. A matching beam envelope was calculated using MAD [10] and the Twiss parameters for this envelope were used to generate a beam distribution which was tracked through the OPERA model. The injected beam narrowly clears the injection dipole coils and hits the foil at ~103 mm from the centre of the beam pipe. This is not the design value but agrees with the earlier simulations [3]. The beam

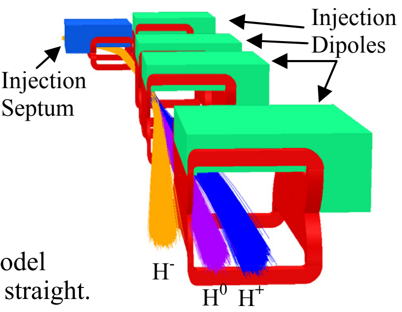

Figure 5: OPERA model of the ISIS injection straight.

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distribution at the foil position was processed with the foil interaction code described above. The resulting distributions of foil products were then tracked through the second half of the injection chicane, Fig. 5.

The full set of beam tracks was exported to a CAD model of the region and matched very well. Injected beam avoids vacuum vessels, unstripped and partially stripped beams are intercepted by the beam dump and the stripped beam misses the dump and circulates in the ring, Fig. 6.

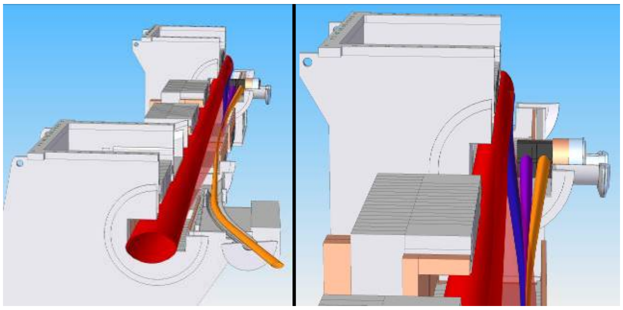

Figure 6: CAD model of the injection straight showing circulating beam (red) and injected H^- (orange), H^0 (purple) and H^+ (blue).

180 MEV INJECTION SCHEME

Recent studies have focussed on replacement of the ISIS linac with a new 180 MeV injector requiring a new injection region in the synchrotron. Injection at 180 MeV raises the space charge limit to approximately 8×10^{13} ppp, corresponding to 0.5 MW [11].

Many interdependent constraints must be satisfied to define a workable injection system including: suitable transport of the injected beam from the linac; practical injection straight geometry, magnets and power supplies with acceptable field uniformity and stability; suitable foil parameters; low and controlled loss and 3D painting of suitable beam distributions.

A workable solution has been found that meets these constraints [12]. Injection is from the outside of the synchrotron with a fixed injection point on the foil. Beam is injected on the falling edge of the main magnet field over 500 μs up to field minimum. The injection dipole strengths are independently varied to provide kicks over a range of 50-35 mrad in order to paint a horizontal centroid emittance over 75-105 π μm rad. Vertically the beam is offset 22 mm and painted in y′ between 3.55-1 mrad, giving a vertical centroid emittance of 107-80 π μm rad. Space charge forces during accumulation redistribute the beam to 300 π μm rad by the end of injection. The injected beam energy is varied linearly from 182-181 MeV and RF steering is used to achieve the required longitudinal beam distributions. Programmable dipoles will be needed in the injection transfer line to maintain a constant beam spot on the foil during painting.

This design is not yet fixed; other schemes are still being considered and may be preferred as magnetic, electrical and mechanical designs are developed.

3D ORBIT Simulations

3D ORBIT simulations, with 2.5D space charge, of the proposed injection scheme have been performed including realistic RF manipulation, collimators set to 85 % aperture, vacuum vessels, foil scattering and injection dipoles [13]. These simulations predict an average of 4.2 foil hits per particle including stripping. Beam loss over the first 1000 turns is 0.53 %, distributions at the end of injection are shown in Fig. 7.

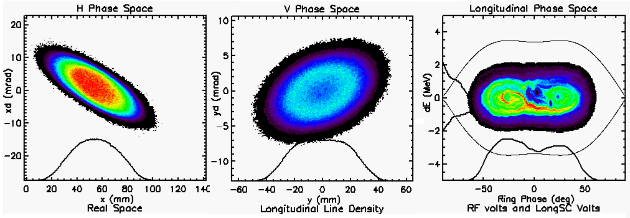

Figure 7: Transverse and longitudinal beam distributions at the end of injection, from 3D ORBIT simulations.

Foil Specification

At 70 MeV, ISIS operates with a stripping efficiency of 97-98 %. Activation due to beam loss is predicted to be five times higher when injecting at 180 MeV, so the loss levels need to be reduced correspondingly to ~0.25 %. Fig. 8 shows the stripping efficiency of carbon as a function of thickness for 180 MeV H^-. The minimum thickness necessary is 180 μg/cm^2. However, a thickness of 200 μg/cm^2 has been chosen as the baseline to allow for variation in manufacturing and some foil degradation during operation.

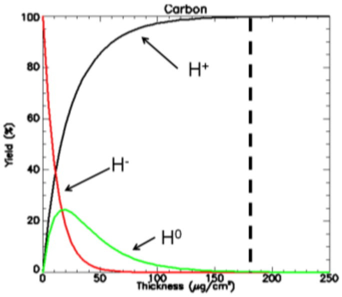

Figure 8: Stripping efficiency of carbon at 180 MeV.

This foil thickness leads to a negligible 2.25×10^{-3} π μm rad increase in the injected beam emittance. The proportion of beam calculated to undergo a nuclear inelastic scatter is 2.4×10^{-6} per passage, assuming 5 hits per particle this results in an acceptable loss level of 1.25 W along the ~5 m injection straight.

Data from the 3D ORBIT simulations of 180 MeV injection have been used in ANSYS [14] to study foil temperatures for realistic beam distributions. Foil hits over a 10×10 mm grid, equal to the ANSYS mesh size, were recorded in the ORBIT simulation and used to generate a realistic foil heat load in ANSYS. The foil size was scaled to encompass 10σ of the $\varepsilon_{rms} = 0.5$ π μm rad injected beam. Considering only the injected beam the peak operating temperature stabilised at 826 K, Fig. 9.

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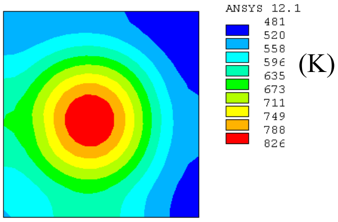

Figure 9: Foil temperature for injected beam only.

It is also important to consider the heating effect from circulating protons. Analysis of ORBIT foil hits including recirculated beam is shown in Fig. 10, the peak temperature reaches 1657 K after ~5 pulses. The temperature is, in this case, dominated by foil recirculation in the bottom left corner.

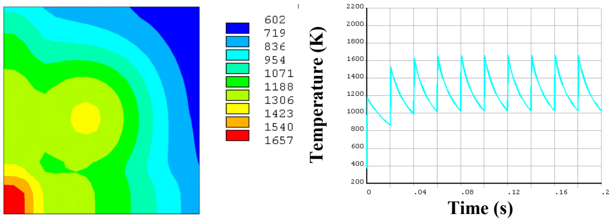

Figure 10: Foil temperature including recirculation (left) and the temperature evolution of the hottest area (right).

Operation with two foils has been studied including radiative effects between the foils [15]. The operating temperatures of two foils separated by 1 mm are approximately 250 K lower than the single foil case described above. However, as the single foil operating temperature is well below the carbon melting point the additional manufacturing and operational difficulties of a double foil system is expected to be impractical.

The effect of delta electron production was studied as in [16]. Assuming a threshold energy of 200 keV then 1.1×10^{-5} delta electrons, with an average energy of 0.27 MeV, are produced per incident proton. For 8×10^{13} ppp this corresponds to a 10 K reduction in peak foil temperature.

A further source of uncontrolled loss at injection is the Lorentz stripping of H^0 and H^- ions, many of which exit the foil in excited states, en-route to the beam dump. This problem is exacerbated by the Stark effect, where the electric field seen in the atom's rest-frame removes the degeneracy of the various H^0 eigenstates relative to orbital and magnetic quantum numbers [17]. The energy levels and lifetime of each Stark state vary with the field strength experienced, Fig. 11.

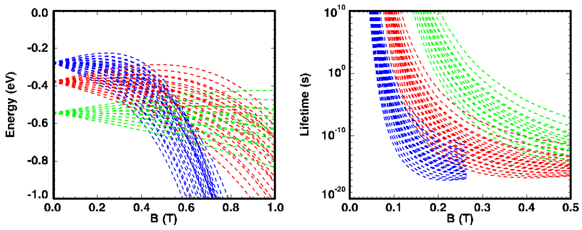

Figure 11: Stark state energy levels and lifetimes for n=5 (red), n=6 (green) and n=7 (blue).

The unstripped foil products must pass through the third injection dipole magnet before reaching the dump. At 70 MeV the peak field of this magnet is 0.11 T; this increases to 0.18 T for 180 MeV. Analysis of the Stark state stripping probabilities for these fields, weighted for the relative populations of each state, show that 96.9% of H^0 particles in excited states n = 2-9 will survive passage through the dipole at 70 MeV and only 70.8% survive at 180 MeV. The total uncontrolled beam loss increases from 12 to 16 W. Further particle tracking and activation studies are planned to assess the impact of this loss.

Particle Tracking

Beam dynamics vary significantly during injection therefore the particle tracking studies shown here focus on the most demanding time point, at the beginning of injection, when clearances are smallest. The geometric design trajectories are shown in Fig. 12. The injected beam has a horizontal width of ~1 mm at the foil. The maximum circulating beam width has been used to assess minimum clearances.

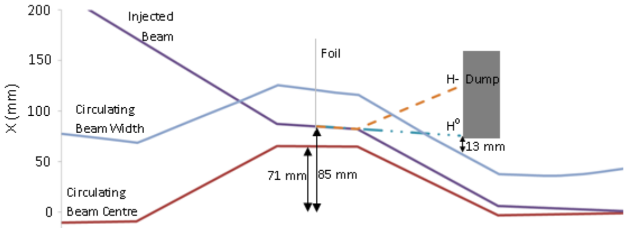

Figure 12: Geometric design trajectories for a 180 MeV injection system.

The magnetic profile along the central axis of the injection region for the injection dipole settings calculated in OPERA is shown in Fig. 13. The figure illustrates the extent of the magnet fringe fields; note that B_y is non-zero at the foil location.

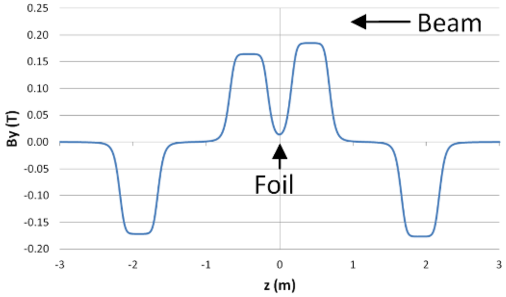

Figure 13: Longitudinal profile of the vertical magnetic field, B_y along $x=y=0$ axis through the injection region.

Representative beam distributions for the injected and recirculating particles were tracked through these fields, the results are shown in Fig. 14. Good agreement with the geometric design trajectories is seen, the tracked particle positions are within 1.5 mm of the design.

The present waste beam dump is a 40 mm long graphite block which accepts a 550 W beam of H^0 and H^-. Simulations using SRIM [18] show the projected range of 70 MeV protons in the dump is 20 mm, this increases to

106 mm for 180 MeV protons. The 180 MeV dump is required to accept 0.25% of the injected beam, a 350 W load. However, consideration must be given to foil degradation and failure scenarios where one or more full injection pulses may reach the dump. A simulation study of loss and activation in the region is planned which will enable a detailed design of a dump. Alternative materials with higher stopping power will be considered; activation may be an important factor in material choice.

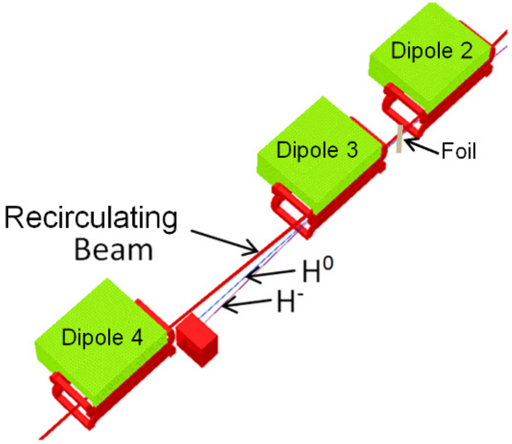

Figure 14: OPERA model of the 180 MeV injection region.

Electrons

It is also important to consider the path of the electrons stripped by the foil as they may oscillate in the fringe fields of the dipoles and cause unnecessary extra foil heating or component damage. We assume the electrons exit the foil with the same distribution and velocity as the incident H^- beam which corresponds to a kinetic energy of ~100 keV. The effects of electron-foil interactions are not considered here but are assumed negligible. The results are shown in Fig. 15. Due to the vertical offset of the injection point the electrons do not oscillate in the foil region. However, the electron beam does cross the foil plane and the stripping foil and holder should be designed to avoid this region.

At the nominal upgrade intensity of 8×10^{13} ppp the stripped electron beam has a power of 125 W. It may be necessary to include an electron capture device to remove this heat and reduce secondary electron showers.

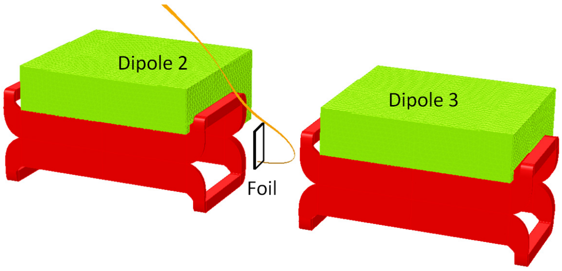

Figure 15: Electron trajectories in injection dipole fringe fields.

SUMMARY AND OUTLOOK

A programme of simulation and experiential studies of injection at ISIS has enabled the design of a new, higher energy injection region for future upgrades.

More detailed tracking studies of uncontrolled loss are needed to fully confirm the operability of the design and will also enable an accurate assessment of activation and inform further optimisation of the beam dynamics design and waste beam control.

Engineering design of the new dipole coils and a new septum is ongoing and may impose design changes due to space constraints. A detailed design of power supplies for these magnets is also needed. The strict requirements for stability and synchronisation are expected to make this a challenging project.

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