INJECTION UPGRADE ON THE ISIS SYNCHROTRON

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Abstract

The ISIS Facility at the Rutherford Appleton Laboratory in the UK produces intense neutron and muon beams for condensed matter research. The two neutron target stations are driven by a 70 MeV H^- linac feeding into a 50 Hz, 800 MeV proton synchrotron which accelerates up to 3.75×10^{13} protons per pulse, delivering a mean beam power of 0.24 MW.

Present upgrade studies are focussed on how a new, higher energy linac could increase beam power in the ISIS ring. Such an upgrade would replace one of the oldest sections of the ISIS machine, and with reduced space charge and optimised injection, may allow substantially increased intensity in the ring, perhaps towards the 0.5 MW regime [1]. A critical aspect of such an upgrade would be the new higher energy injection straight.

This paper summarises initial studies of 180 MeV H^- charge-exchange injection into ISIS including: specification of a new stripping foil with simulations of stripping efficiency, beam scattering and foil heating effects; and magnetic and particle tracking models of the injection straight.

EXISTING INJECTION STRAIGHT

ISIS operates with H^- charge-exchange injection through a 0.25 μm aluminium oxide foil at 70.4 MeV. The foil is mounted in the middle of four dipole bump magnets which also remove unstripped beam. The bump is collapsed after injection to limit foil recirculation. A schematic of the injection elements is shown in Fig. 1.

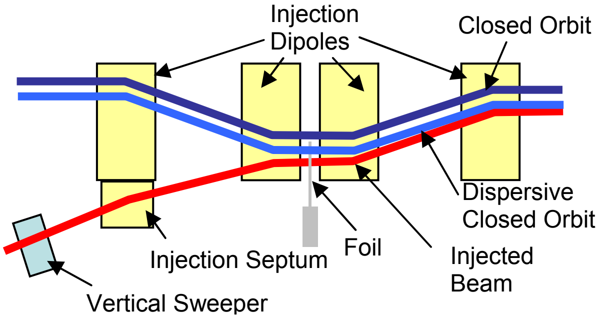

Figure 1: Schematic layout of ISIS injection system.

The beam is painted transversely to reduce space charge forces. Vertical painting is achieved with a programmable dipole upstream of the foil. Horizontal painting makes use of the moving dispersive closed orbit generated by an energy mismatch between the constant injection energy and the changing synchronous energy due to the falling main magnetic field in the ring.

Many factors influence the design of an injection region for higher energy. A fixed injection point could help reduce foil recirculation and thus reduce emittance growth. It would also be convenient to inject from the outside of the ring to minimise the impact of construction work on present operations. Consequently, several injection schemes using injection energy ramping, RF steering, variable injection magnets and fixed and varying main magnetic fields are all being considered.

However, for the following studies we assume simply that the existing scheme is maintained with injection dipole fields scaled appropriately for the increased beam energy. We assume the 180 MeV linac design in [2].

SIMULATION OF FOIL INTERACTION

A code has been developed to simulate the interaction of the injected beam with the stripping foil. Electron loss, nuclear inelastic and Coulomb scattering and energy deposition in the foil are included allowing calculation of stripping efficiency, uncontrolled beam loss and foil heating. Data and methods have been taken from [3-11].

Benchmarking

The simulation results have been benchmarked by comparison to the ISIS 70 MeV design and to design studies for SNS and J-PARC [12,13], Table 1.

Table 1: Stripping Efficiency Benchmarking Results

Facility	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%

Comparisons of foil heating and beam scattering effects have also been made and agreed well.

Stripping Efficiency

Assuming none of the injected beam misses the foil, loss in the injection straight is dominated by unstripped and partially stripped foil products which can be directed to beam dumps.

ISIS currently operates with ~2% loss at injection. Initial studies indicate that activation levels per lost particle will increase by a factor of five as the injection energy is raised from 70 to 180 MeV. It is desirable therefore to reduce the loss levels by an equivalent factor, to ~0.4%.

Aluminium oxide and graphite carbon have been studied as potential foil materials using available cross-section data. However, recent development of Hybrid Boron-Carbon (HBC) foils at KEK/J-PARC [14] may provide another suitable candidate.

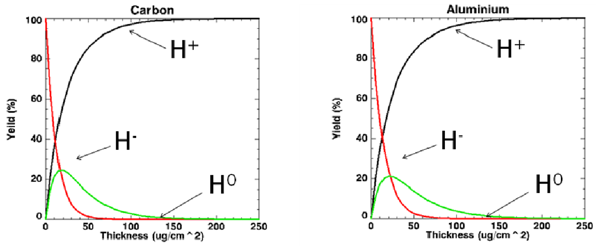

Figure 2: Stripping efficiencies of Al_2O_3 and C.

The results, Fig. 2 indicate that the minimum thickness needed to achieve a five-fold reduction in controlled loss levels would be 160 μg/cm^2 for carbon and 178 μg/cm^2 for Al_2O_3. The exact choice of foil thickness will be determined by the impact on scattering of recirculating beam and the operating temperature and foil lifetime.

Foil Heating

Controlling foil heating is a key factor in achieving an acceptable foil lifetime. The heating effects of Al_2O_3 and C have been studied for the existing 0.24 MW, 70 MeV beam and for 0.24 and 0.5 MW, 180 MeV beams, using emissivities of 0.2 for Al_2O_3 and 0.8 for C, Fig. 3.

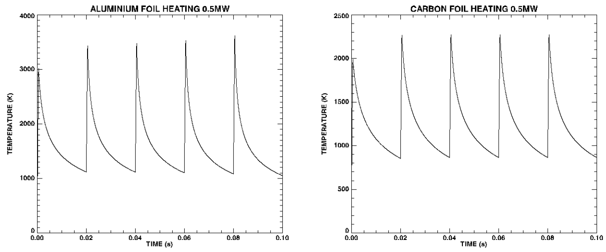

Figure 3: Foil temperature *vs* time for 0.5 MW, 180 MeV beams in Al_2O_3 (left) and carbon (right).

The melting point of Al_2O_3, 2345 K, is exceeded for a 0.5 MW beam. The carbon foil temperature however, does not reach its sublimation temperature of 3915 K.

Beam Loss due to Foil Interaction

Foil interaction may cause beam loss by moving beam outside of the machine acceptances; either transversely via large-angle nuclear scattering or multiple Coulomb scattering or longitudinally via energy deposition in the foil. The foil thickness and the number of foil recirculations determine the beam loss due to foil interactions. The number of foil traversals has yet to be determined; the following figures refer to a single traversal of a 200 μg/cm^2 carbon foil.

The estimated fraction of the beam undergoing inelastic nuclear scattering is 2.4×10^{-6} and the estimated emittance growth of the injected beam is 2.25×10^{-3} π.mm.mrad. On average, over a single traversal of the same foil, the energy lost is estimated to be 4.21×10^{-7} MeV.

A more careful analysis of the emittance and energy loss distributions with respect to the machine acceptances will be carried out as new injection schemes are studied.

A further source of uncontrolled loss at injection is the Lorentz stripping of H^0 and H^- ions, many of which leave the foil in excited states, downstream of the foil 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 [15]. The energy levels and lifetime of each Stark state vary with the field strength experienced, Fig. 4.

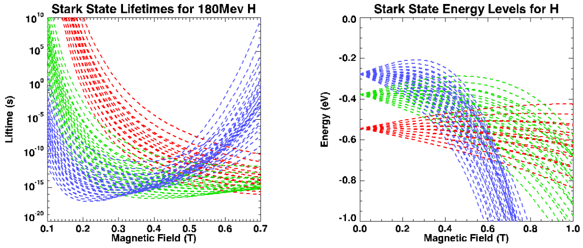

Figure 4: Stark state energy levels and lifetimes for n=5 (red), n=6 (green) and n=7 (blue).

The field-dependent lifetime of a state allows one to calculate the probability of an atom being stripped as a function of distance travelled in a field, Fig. 5.

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 would increase to 0.18 T for 180 MeV. Analysis of the Stark state stripping probabilities, weighted for the relative populations of each state, for these field strengths 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. Beam dump geometry in the upgraded straight may need to be adjusted to intercept this extra beam loss.

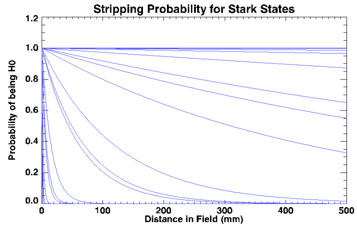

Figure 5: Stripping probabilities for states n=2-9 for 180 MeV H^0 travelling through a 0.18 T field.

FOIL SPECIFICATION FOR 180 MEV

These studies have enabled an initial specification of a foil for 180 MeV injection into ISIS, Table 2.

Table 2: Expected Foil Parameters for 180 MeV Injection

Material	Carbon
Thickness	200μg/cm^2
Efficiency	99.8%
Peak Temp for 0.24 MW	1340 K
Peak Temp for 0.5 MW	2275 K

INJECTION STRAIGHT MODELLING

Several models of the existing 70 MeV injection straight have been produced and will be used as a basis for any higher energy designs.

An OPERA [16] model which includes the four injection dipole magnets, the injection septum and a section of the injection beamline back to the last profile monitor before the ring has been developed.

A set of measurements were made of the ISIS operational hardware settings and beam dynamics, including TWISS parameters, linac energy and momentum spread. A matching beam distribution was generated and tracked through the OPERA model. The injected beam narrowly clears the injection dipoles and hits the foil at ~103 mm from the centre of the ring. This is not the design value but agrees very closely with earlier simulations [17] of ISIS injection using the ORBIT [18] code which are consistent with an operationally optimised beam position in the injection beamline.

The OPERA-tracked beam distribution at the foil position was processed with the foil interaction code described above. The resulting distributions of the foil products were then tracked through the second half of the injection chicane, Fig. 6.

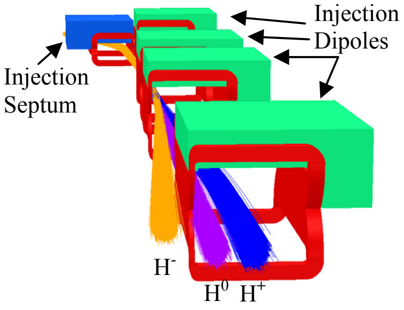

Figure 6: OPERA model of the ISIS injection straight.

The full set of beam tracks was imported into a CAD model of the region which includes vacuum vessels and beam dumps. The results are very good; unstripped and partially stripped beams are intercepted by the beam dump and the stripped beam avoids the dump and circulates in the ring, Fig. 7.

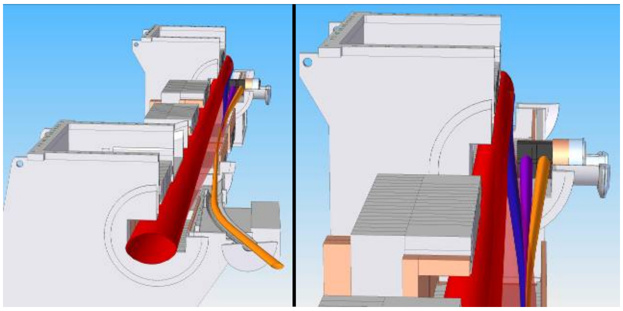

Figure 7: CAD model of the ISIS injection straight.

A further model of the injection region has been constructed using G4beamline, a single-particle tracking program based on the Geant4 simulation toolkit [19]. The model is able to import beam distributions from other codes and magnetic field maps from the OPERA model described above.

Use of the Geant4 physics models allows the generation and tracking of the effect of secondary particles produced by lost beam. This data will help with more accurate estimation of activation levels in the injection region. It is expected that this will be a useful tool in assessing the impact of modifications to the injection region.

FUTURE WORK

Full ring simulations of injection with a 180 MeV beam into ISIS will be done using ORBIT to determine optimal painting schemes. The foil interaction and particle tracking models described here will be used to optimise the design of a new injection straight to produce the required painting.

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