PROGRESS ON DESIGNS FOR 180 MEV INJECTION INTO THE ISIS SYNCHROTRON

B. Jones, D.J. Adams, B. Drumm, M.C. Hughes, A.J. McFarland, C.M. Warsop
ISIS, STFC, Rutherford Appleton Laboratory, UK

Abstract

The ISIS Facility at the Rutherford Appleton Laboratory in the UK produces intense neutron and muon beams for condensed matter research. A 70 MeV H^- linac and an 800 MeV proton synchrotron accelerate up to 3×10^{13} protons per pulse (ppp) at 50 Hz, delivering a mean beam power of ~0.2 MW.

A favoured first step to upgrade ISIS towards the megawatt regime is the addition of a new 180 MeV injector. Studies of this upgrade, which aims to increase mean beam power up to 0.5 MW are outlined in [1]. This paper reports on recent development of the designs including the injection septum, dipole power supplies and detailed tracking of partially stripped foil products.

INTRODUCTION

ISIS presently operates with ~130 turn H^- charge-exchange injection through a 50 μg/cm^2 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 Figure 1.

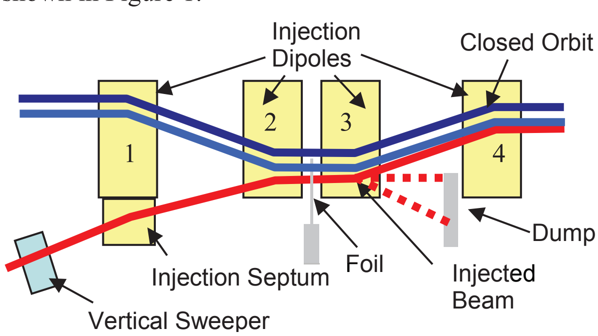

Figure 1: Schematic layout of the existing 70 MeV ISIS injection system.

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 falling main magnetic field. The injected beam is un-chopped, but is 'adiabatically' trapped by the dual harmonic RF system.

180 MEV INJECTION

Injection at 180 MeV raises the space charge limit to approximately 8×10^{13} ppp, corresponding to 0.5 MW [1]. Transverse and longitudinal painting schemes for this intensity have been developed for injection on the falling or rising edges of the sinusoidal main magnetic field or symmetrically about field minimum. Injection is from the outside of the synchrotron with a fixed injection point on the foil. The 43 mA H^- beam from the linac will be chopped at twice the revolution frequency, and injected over 500 μs. Initial injection system and beam dynamics designs [2] optimised for low foil recirculation and beam loss are now being revisited to take into account practical engineering constraints. The most promising working scheme at present uses constant painting amplitudes of $\varepsilon_h = 72$, $\varepsilon_v = 100\ \pi$ μmrad with position and angle of the injected beam at the foil held constant in both planes. Space charge forces redistribute the beam to 300 π μmrad by the end of injection. The injection dipole strengths are independently varied to provide kicks over a reduced range of 45 - 50 mrad to compensate for the variation of the main magnetic field and the ramping energy of the injected beam as it is painted longitudinally. Simulations with ORBIT [3] suggest this scheme will produce ~0.25% beam loss during injection.

ACCELERATOR ENGINEERING

New injection dipole magnets have been designed to provide a 45 - 55 mrad kick to the 180 MeV beams [2]. The new injection dipoles will be independently powered with differently varying waveforms to allow maximum optimisation of the injection bump. Preliminary designs for the power supply using high frequency H-bridge switching circuits, have been simulated using PLECS [4] circuit simulation software and an outline specification is being prepared for potential suppliers.

A new injection septum magnet is now being designed for 180 MeV operation. At 70 MeV the septum operates at 0.7 T, this increases to 1.1 T for 180 MeV necessitating a 40% increase in the magnet yoke volume to avoid saturation. The existing septum coil design is unsuitable for the operating currents required for 180 MeV operation and increasing the coil size is impractical.

A number of options to reduce the requirements on the septum have been studied. Firstly, beams were tracked in OPERA [5] to assess the required vertical aperture of the septum since the injected beam diameter is approximately half of its present value. A smaller aperture would decrease the current required to achieve the design flux density. A second option is to increase the magnet length, which would decrease the required flux density.

It has been calculated that to operate the septum with the same current density as 70 MeV operation requires a

30% reduction in vertical aperture and an extension of 80 mm in length. Particle tracking studies suggest this aperture reduction is achievable, detailed CAD modelling of the area is being carried out in order to fully define the limitations on the available space for the septum magnet.

One other potential solution is to build the septum as two separate magnets on one yoke. The first section could use thicker coils to provide the majority of the required flux. A second, thinner coil would be used where the septum meets Dipole 1 and thicker coils are impractical, Figure 4. An initial design of such a magnet has been modelled with good results, Figure 2. All parts of both coils run at a lower current density than for 70 MeV. The drawbacks of this design are that two power supplies are needed, and the magnet is 100 mm longer.

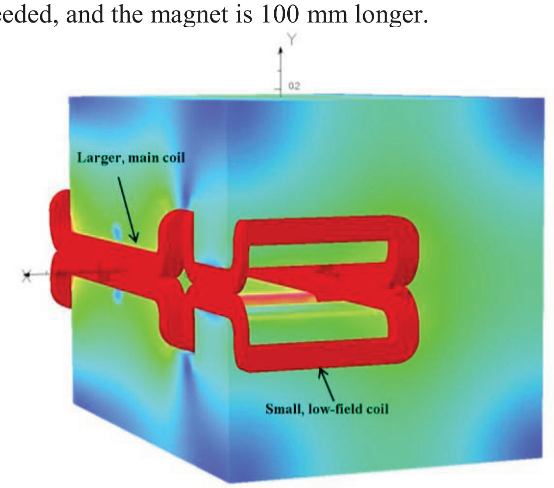

Figure 2. Initial design of a two-stage injection septum.

Initial mechanical engineering models, Figure 3, of the injection straight will be further developed to include all relevant infrastructure e.g. magnet cooling systems and vacuum vessels. This will validate the magnet designs, allow better specification of foil change and beam dump mechanisms and determine the maximum septum length. A decision on the septum design will be made as the CAD modelling and beam dynamics studies are finalised.

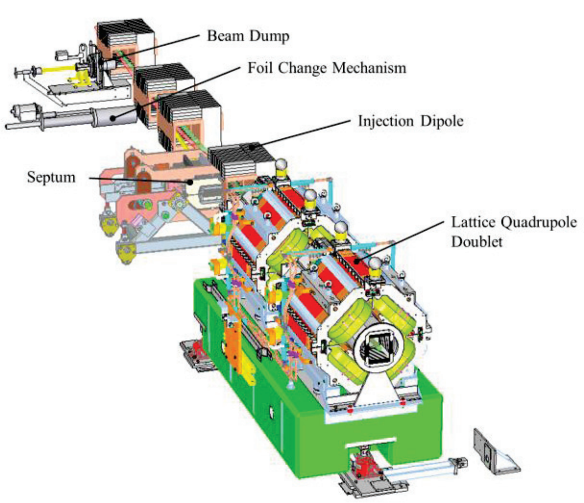

Figure 3: Initial CAD model of the lattice quadrupoles and new injection region.

PARTICLE TRACKING

A potential source of uncontrolled loss at injection is the Lorentz stripping of H^0 atoms in excited states as they pass through Dipole 3. The quantum states of the H^0 atoms exiting the foil are populated with a probability proportional to n^{-3} where n is the principal quantum number. The beam power associated with each state for 8×10^{13} ppp at 180 MeV is shown in Table 1.

Table 1: H^0 Quantum State Populations and Beam Powers

Principal Quantum Number, n	Proportion of Beam in State	Number of Particles in state	Power (W)
2	0.125	5.00E+10	72.0
3	0.037	1.48E+10	21.3
4	0.016	6.25E+09	9.0
5	0.008	3.20E+09	4.6
6	0.005	1.85E+09	2.7
7	0.003	1.17E+09	1.7
8	0.002	7.81E+08	1.1
9	0.001	5.49E+08	0.8

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 [6]. The energy levels and lifetime of each Stark state vary with the field strength experienced, Figure 4.

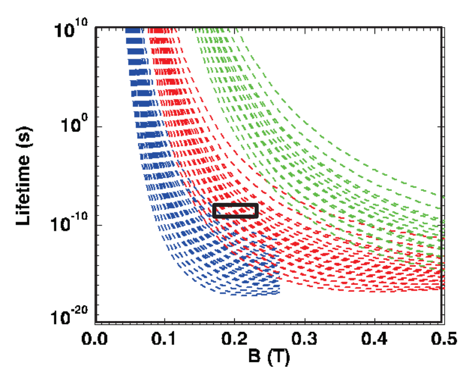

Figure 4: Stark state and lifetimes for n=5 (green), n=6 (red) and n=7 (blue). The region of interest is highlighted.

The ISIS injection dipoles have been designed to operate over 0.17 - 0.22 T and a 180 MeV beam will pass through the 0.5 m magnet in ~3 ns. We therefore assume that states n = 2 - 5 will survive as H^0 until reaching the dump, and that states $n \geq 7$ will strip almost immediately upon entering the magnet and will join the circulating beam. Assuming uniform population of the Stark states, approximately 50% of the particles in state n = 6 will strip inside Dipole 3 and may join the beam or may be lost. A particle tracking study has been carried out to assess how much beam is lost uncontrollably by this mechanism.

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A magnetic model of the injection region developed in OPERA was used to track particles. The model uses the following parameters:

Table 2: Parameters for OPERA Magnetic Model

Dipole Bend Angle	50 mrad
Dipole Field	0.195 T
Injection Position	X = 95 mm X'= 6 mrad Y = 0 mm Y'= 0 mrad
Injected Transverse Emittance	$\varepsilon_h = \varepsilon_v = 0.46$ mm mrad

The path of an H^0 beam distribution through Dipole 3 was sampled at 100 mm longitudinal intervals and the corresponding beam distributions used to track H* stripped to protons at that location, to the exit of the injection region.

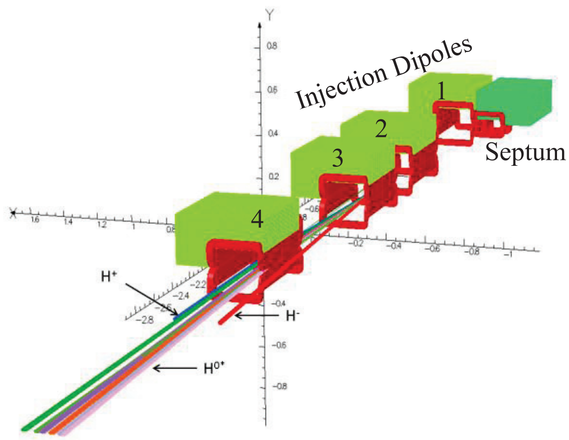

Figure 5: Trajectories for fully, partially, delayed and un-stripped particles.

Figure 5 shows the tracked beams; the blue, shorter track is beam stripped to H^+ at the foil; the red shorter track is unstripped H^- beam. The longer tracks show the path of H^0 particles which either pass through Dipole 3 or strip within it. The real and phase space distributions of the particles at the end of the injection region are shown in Figure 6.

The nominal on-momentum synchrotron acceptance is shown on the phase space plot of Figure 6. We conclude from this plot that i) particles stripping within the first 200 mm of Dipole 3 remain within the synchrotron acceptance and ii) particles stripping in the final 100 mm of the dipole are intercepted by the beam dump. However, particles stripping between 200 and 400 mm through the dipole are lost outside of the injection straight. It is estimated that this is only ~0.7 W of beam. These lost particles will be tracked in the ORBIT model to see where they deposit energy, but it is expected that the activation associated with such a low level of loss will not be a concern.

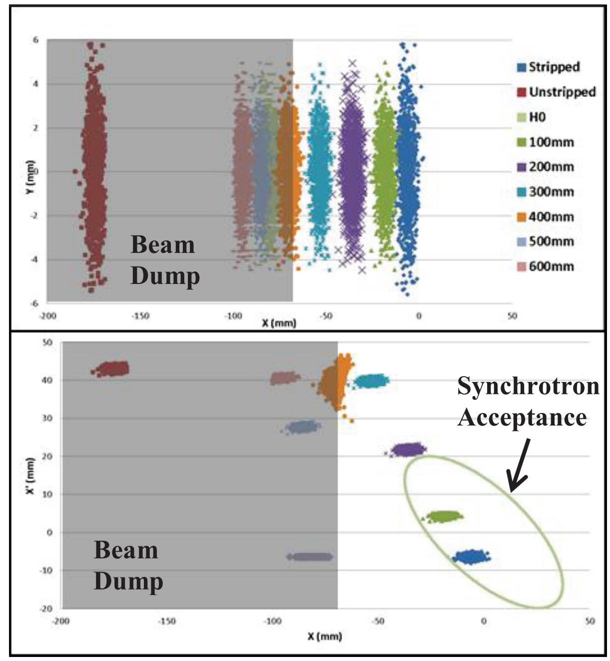

Figure 6: Real space (top) and horizontal phase space (bottom) distributions of fully, partially, delayed and un-stripped particles at the end of the injection region. The shaded area illustrates the beam dump.

SUMMARY AND PLANS

Flexible solutions for the injection region hardware are being designed and injection losses modelled in detail. Studies are continuing to determine the optimal beam dynamics for injection as our understanding of hardware limitations and loss mechanisms improves.

Tests of commercially available carbon stripping foils are planned on ISIS. These will include assessment of mechanical integrity compared to the presently used in-house Al_2O_3 foils. Trial operation with 70 MeV beam is also being considered.

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