A 180 MEV INJECTION SYSTEM FOR 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. It accelerates 3×10^{13} protons per pulse (ppp) at 50 Hz through a 70 MeV H^- linac and an 800 MeV proton synchrotron, delivering a mean beam power of ~0.2 MW.

A favoured first step to upgrade ISIS towards the megawatt regime is replacement of the linac with a new 180 MeV injector described in [1]. Studies of this upgrade, which aims to increase mean beam power up to 0.5 MW are outlined in [2]. This paper summarises an initial design for a new injection system including considerations for beam dynamics and related hardware.

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 Fig. 1.

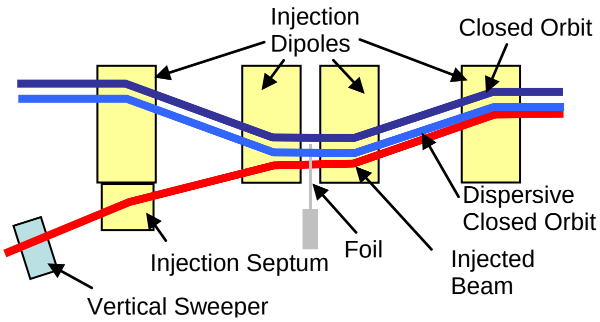

Figure 1: Schematic layout of the existing 70 MeV ISIS injection system.

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 changing synchronous energy due to the falling main magnetic field in the ring.

This paper builds upon previous studies [3] removing some simplifications and including realistic models of 180 MeV magnets. Transverse and longitudinal beam dynamics, foil recirculation and waste beam capture have all been considered. However, this is not yet a final design for the upgrade as other schemes are still being considered and may be preferred as magnetic, electrical and mechanical designs are developed.

180 MEV INJECTION SCHEME

Injection at 180 MeV raises the space charge limit for the ~300 π.μm.rad 99% transverse emittance beam to approximately 8×10^{13} ppp, corresponding to 0.5 MW [2]. Transverse and longitudinal painting schemes for such a beam 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. Of the proposed schemes, this paper studies the case which places the greatest demands on the injection dipoles. The magnets designed for this case should therefore easily accommodate the alternative schemes if necessary.

In this scheme, chopped beam is injected on the falling edge of the main magnet field over the 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 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. Programmable dipoles will be needed in the injection transfer line to maintain a constant beam spot on the foil during painting. The injected beam energy is varied linearly from 182 - 181 MeV and RF steering is used to achieve the required longitudinal beam distributions. 3D ORBIT simulations, Fig. 2, of the first 1000 turns predict an average of 4.2 foil hits per particle including stripping; beam loss over the first 1000 turns is 0.53%.

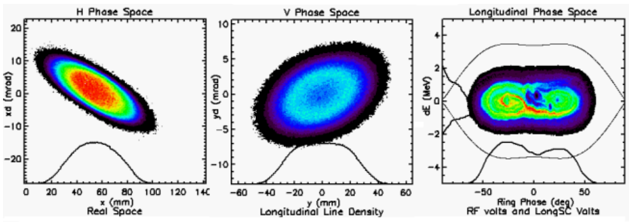

Figure 2: Transverse and longitudinal beam distributions at the end of injection, from 3D ORBIT simulations.

MAGNET DESIGN

New injection dipole magnets have been designed to provide a 50 mrad kick to the 180 MeV beams. The length of the magnets is restricted to that of the existing dipoles, 0.5 m, due to space constraints in the region. This has necessitated a 50% increase in the size of the magnet yokes to avoid saturation of the ferrite at 0.4 T. Effects on vacuum systems in the region will need consideration as the yokes are within the vacuum vessel.

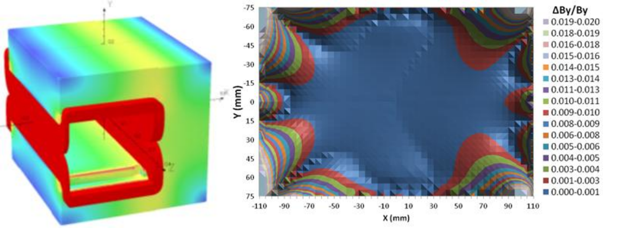

Figure 3: 180 MeV injection dipole model (left) and field homogeneity, ΔBy/By (right).

Fig. 3 shows the dipole design field and field homogeneity ΔBy/By. The good field region over $-90<x<100$ and $-45<y<45$ is better than 2.5×10^{-3}, this value matches that of the existing dipoles.

A 50 mrad kick requires a peak field of 0.203 T produced by a current of 25 kA. An initial design of a power supply system for these magnets has been produced [4]. The magnet and power supply development is a challenging project and it is expected that a prototype system will be constructed.

PARTICLE TRACKING

A magnetic model of the injection region has been created with OPERA-3D [5] and used for particle tracking studies to validate the magnetic and beam dynamics designs. A previous paper [3] showed the development of a model of the existing 70 MeV injection region with measured beam profiles tracked through the magnets. Resulting beam distributions showed agreement within 2 mm to profile measurements and benchmarked ORBIT simulations [6].

A model of a new injection region has now been created and used to track particles for the proposed injection scheme. Since the beam dynamics change during injection this study focuses on the start point 500 µs before field minimum, since this gives the smallest clearances at the beam dump. The geometric design trajectories are shown in Fig. 4. The injected beam has a horizontal width of ~1 mm. The maximum circulating beam width has been used to assess minimum clearances.

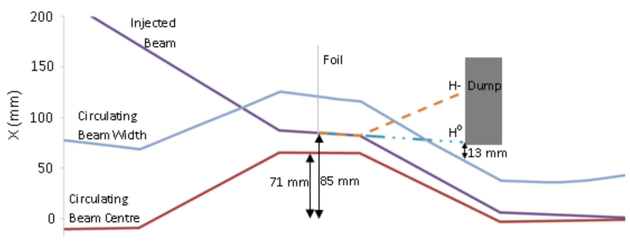

Figure 4: Geometric design trajectories for a 180 MeV injection system.

The magnetic profile along the central axis of the injection region for the injection dipole settings calculated in OPERA is shown in Fig. 5. The figure illustrates the extent of the magnet fringe fields; note that B_y is non-zero at the foil location. Representative beam distributions for the injected and recirculating particles were tracked through these fields, the results are shown in Fig. 6.

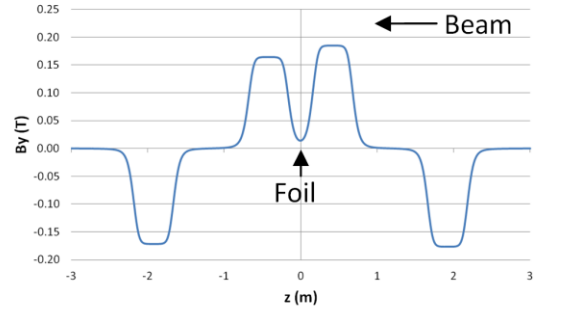

Figure 5: Longitudinal profile of the vertical magnetic field, B_y along x=y=0 axis through the injection region.

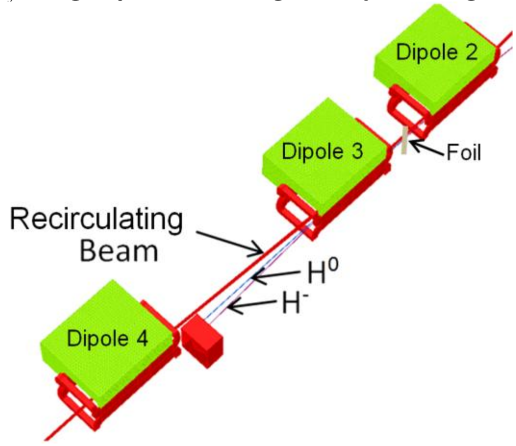

Figure 6: Beams tracked through a 180 MeV injection region.

Good agreement with the geometric design trajectories is seen in Table 1, the tracked particle positions are within 1.5 mm of the design.

Table 1: Horizontal displacements w.r.t synchrotron centre

	Design (mm)	OPERA (mm)	Difference (mm)
Circulating H^+ at foil	70.7	71.5	0.8
Injected H^+ at foil	85.0	84.1	−0.8
H^- at dump	124.2	122.7	−1.5
H^0at dump	75.9	76.7	0.8
H^+at dump	27.7	26.3	−1.4

The present dump is a 40 mm long graphite block which accepts a 550 W beam of H^0 and H^-. Simulations using SRIM [7] show the projected range of 70 MeV protons in the dump is 20 mm, this increases to 106 mm for 180 MeV protons. Under normal operation the dump is required to accept 0.3% 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.

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. In this initial study we assume the electrons exit the foil with the same distribution and velocity as the incident H^- beam, this corresponds to a kinetic energy of ~100 keV. The effects of electron-foil interactions are not considered here but are estimated to be small. The results are shown in Fig. 7.

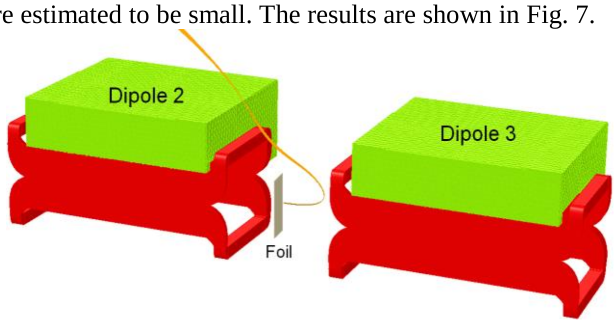

Figure 7: Electron trajectories in injection dipole fringe fields

Due to the vertical offset of the injection point the electrons do not oscillate in the foil region. The electron beam does cross the foil plane at x = 5, y = 90 mm, 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.

LATTICE PERTURBATION

The lattice focussing perturbation due to the insertion of the injection dipoles has been modelled. A circulating beam distribution with the design ISIS Twiss parameters was tracked through the OPERA model and compared to theoretical values, Table 2.

Table 2: Twiss parameters at the entrance face of dipole 1

	β_x (m)	α_x	β_y (m)	α_y
Calculated through Drift Space	2.91	−0.569	12.58	−1.096
Tracked through Drift Space	2.95	−0.621	12.60	−1.094
Tracked through Inj’n Bump	3.10	−0.610	12.09	−0.959
MAD Model	3.09	−0.597	12.07	−0.974

Linear lattice elements were added to a MAD model of the synchrotron to reproduce this perturbation and estimate the effect on the lattice focussing, Fig. 8.

A large horizontal beta beating is seen due to the perturbation from the dipoles. Further optimisation of the dipole fields may be necessary to reduce this. However it is possible to correct to within 5% using the 20 trim quadrupoles in the synchrotron lattice.

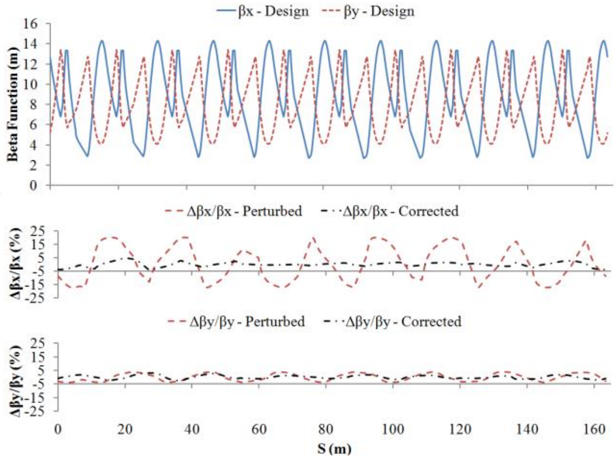

Figure 8: Betatron function for the ISIS synchrotron (top) and perturbation to this function with and without corrections for horizontal (middle) and vertical (bottom) planes.

FUTURE WORK

Further magnetic design work is required to optimise the coils for the new dipoles and to design the injection septum. The area in which the septum and dipole 1 meet is expected to have tight beam clearances and may force re-optimisation of the injection geometry.

The study also requires electrical engineering effort to design the power supplies for the new magnets. The tight synchronisation required between the individually powered dipoles as they vary during injection is expected to be challenging.

Detailed models of loss and activation in the region will inform further optimisation of beam dynamics design and specification of a beam dump and electron capture device.

The designs for 180 MeV injection into the ISIS synchrotron are challenging but studies so far indicate they are achievable.

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