INJECTION UPGRADES FOR THE ISIS SYNCHROTRON

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Abstract

ISIS is the world's most productive spallation neutron source, at the Rutherford Appleton Laboratory in the UK. Presently it runs at beam powers of 0.2 MW, with upgrades in place to supply increased powers for the new Second Target Station. Injection of beam into the present ISIS ring at higher energy than from the existing 70 MeV linac has significant potential to increase intensity as a result of reduced space charge and optimised injection. This paper outlines studies for this upgrade option, which include achieving a practical injection system at higher energy in the present ring, ensuring the modified longitudinal and transverse beam dynamics are possible with low loss at higher intensity and achieving low loss and loss control to allow for the increased activation at higher energy.

INTRODUCTION

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), driven at 40 Hz and 10 Hz respectively by a 50 Hz, 800 MeV proton beam from a rapid cycling synchrotron (RCS), which is fed by a 70 MeV H⁻ drift tube linac [1].

A detailed comparison of reasonable upgrade routes for ISIS that would increase beam power into the megawatt (MW) regime has been carried out [2]. The recommended upgrade route increases beam power to ~1 MW by taking the output of the existing ISIS facility and increasing beam energy by adding a ~3.2 GeV RCS. A later upgrade stage is then to accumulate and accelerate beam in the ~3.2 GeV RCS from a new 800 MeV linac for 2 – 5 MW beams.

However, a recent emphasis on reliability issues and affordability now requires that priority is given to the replacement of parts or all of the 70 MeV H⁻ injector. Replacement with a new, or partly new, linac of the same energy could address obsolescence issues with the present linac and ensure reliable operation for the foreseeable future. The more exciting, but more challenging, option is to install a higher energy linac (up to ~180 MeV, possibly based on a new design [3]) with a new optimised injection system into the present RCS. This upgrade might give a substantial increase in beam power, but only if a number of serious concerns can be addressed. It is interesting to note that if substantial increases in power from the present RCS are possible, then there may be a corresponding scaling in power when a ~3.2 GeV RCS is added. More detailed work on the MW regime options will start when present injection upgrade work is complete.

Extensive development and experimental testing of simulation codes is necessary both for the proposed upgrades to ISIS and for closely related experimental and simulation studies looking at loss mechanisms and associated high intensity limitations [4]. This work is under way using the SNS code ORBIT [5] and also the in-house code SET [6]. The latter is currently being expanded to cover 3D particle motion, exploiting the parallel computing facilities available at RAL.

INJECTION UPGRADE STUDIES

Presently the ISIS ring accelerates about 3×10^{13} protons per pulse (ppp) from 70 to 800 MeV on the 10 ms rising edge of the 50 Hz sinusoidal main magnet field. Charge-exchange injection of the un-chopped, 70 MeV, H⁻ beam takes place over ~300 µs before field minimum, which allows time for longitudinal capture and facilitates transverse painting. The main loss mechanisms are associated with non-adiabatic longitudinal capture, transverse space charge and the stripping foil.

The main potential benefits of a new higher energy linac and injection system are reduced transverse space charge and optimised injection using a chopper such as that under development as part of the Front End Test Stand (FETS) project at RAL [7]. However, there are numerous potentially serious issues that could negate these gains. Key areas, covered individually below, are practical designs for a higher energy injection straight, foil related losses, modified beam dynamics with effects of space charge, instabilities, control of beam loss and increased activation at higher energy, diagnostics and practical RF systems.

There are options for a range of injection energies and intensities for such an upgrade. It is the purpose of the study to identify realistic, optimal values. As a basis for calculations, 'study values' of 180 MeV injection energy, and 8×10^{13} ppp intensities for bunched beams (corresponding to 0.5 MW beam power) have been assumed, but ultimately may not be practicable.

Injection Straight and Stripping Foil

An essential first step has been to ensure that the existing 70 MeV injection straight of the ISIS RCS could be redesigned to operate at higher energy. Initial studies looking at power supplies and magnets for the required higher field levels suggest that injection at ~180 MeV is possible. More detailed work on AC performance and field quality of injection magnets will be an integral part of designs for a new injection straight specified by beam dynamics considerations.

In order to validate codes and calculations a detailed model of the existing 70 MeV injection system has been produced. This includes field maps from OPERA [8] simulations of the injection magnets, tracking of particle distributions derived from measured profiles and trajectories of stripped products (see figure 1). Agreement between beam profile measurements and predictions has been excellent [9]. This model will form the basis of new injection straight designs as dictated by beam dynamics, stripping foil and beam loss requirements.

Minimising and controlling unavoidable stripping foil related beam loss is of paramount importance. Detailed scattering and stripping models (with destinations of stripped electrons and foil heating included) are being developed to allow optimisation of foil parameters and prediction of loss distributions. A carbon foil of 200 μg/cm^2, with an expected efficiency of ~99.9%, looks promising for 180 MeV operation [9].
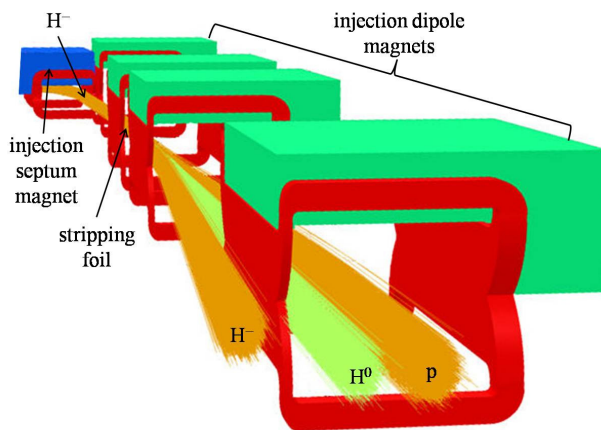

Figure 1: Model of the 70 MeV injection straight.

Longitudinal Beam Dynamics

The longitudinal dynamics for the 180 to 800 MeV acceleration process are critical in determining achievable peak intensities. Key issues are control of emittance (especially at extraction), longitudinal space charge and stability, bunching factor (for transverse limits) and provision of realistic RF systems. Studies have involved development and testing of a new longitudinal dynamics code, use of the existing ORBIT code and associated theoretical calculations. Study of the beam dynamics was split into the injection process (before field minimum) and acceleration (after field minimum).

For the initial assessment of acceleration a Hofmann-Pedersen distribution corresponding to expectations for 70% chopped beam at 0.5 MW ($\varphi = \pm110°$, $\Delta p/p = \pm0.6\%$, 8×10^{13} ppp in two bunches) was assumed at field minimum. Initial dual harmonic RF parameters for 'lossless' acceleration have been found that keep beam well below instability thresholds, with typical bunching factors of ~0.4 and reasonable distributions at extraction. Results of simulations are shown in figure 2. Peak RF voltages are 144 and 78 kV per turn for $h = 2$ and $h = 4$

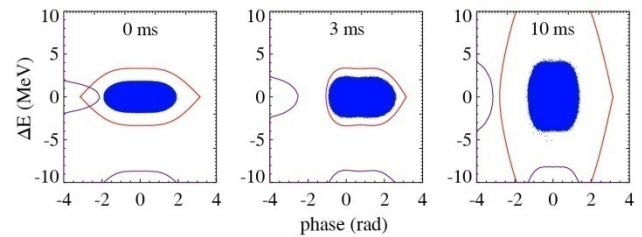respectively, with phase shifts between these sweeping from 0 to 80°. RMS emittances per bunch are 0.2 eVs.

Figure 2: Acceleration of test distribution at 0, 3 and 10 ms, with a bunch intensity of 4×10^{13} protons.

In addition to refinement of the above parameters, the next task is to optimise the more realistic beam distributions generated by the longitudinal injection painting process. It is not yet clear that these less ideal distributions will allow the near lossless acceleration required for substantially increased beam powers.

Transverse Beam Dynamics

Increasing injection energy from 70 to 180 MeV reduces space charge by a factor of ~3, but a corresponding scaling in beam intensity may not be realised. Key factors are transverse instability, reduced emittance damping at extraction, control of the bunching factor and emittance control of realistic painted distributions.

Present studies are using the 2D code SET [6] to study the transverse space charge limit. RMS matched water-bag beams of (ε_{rms-x}, ε_{rms-y}) = (42, 47) π mm mr are tracked for 100 turns, including effects of space charge at a range of intensities, with representative closed orbit and gradient errors and images. Collimation apertures are included at ISIS values. Initial simulations used the nominal tunes (Q_h, Q_v) = (4.31, 3.83). With gradient errors included, beam loss occurred at *coasting* beam intensities of 1.5×10^{14} ppp, associated with a coherent quadrupole (half-integer) mode (figure 3a). Without the gradient errors, loss did not appear until 2×10^{14} ppp, associated with what appears to be a coherent sextupole mode excited by image terms (figure 3b).

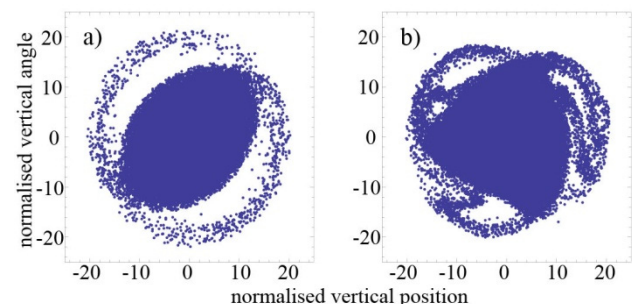Figure 3: Normalised vertical phase space showing effects of quadrupole and sextupole coherent modes.

During operations on the present ISIS machine, Qs are raised to avoid resonances. Studies raising Qs in the models showed a corresponding increase in the space

charge limit, higher than the values above. However, in the vertical plane, appearance of the resistive-wall head-tail instability on ISIS limits how far Q_v can be raised. In addition, higher intensities will require a lower Q_v than at present to stabilize the beam. Options under study are moving Q_v to below the half integer and introduction of a damping system.

Multiplying the *coasting beam* limits above by the expected bunching factors of 0.3 to 0.4 implies space charge limits below the *assumed* 8×10^{13} ppp. Hence transverse dynamics may impose the upper limit on intensity. Studies will now look in more detail at ISIS acceptances and bunching factors and will seek an optimal working point to maximise intensity.

Injection Dynamics and Beam Line

The design and optimisation of a new 180 MeV, chopped-beam injection scheme is constrained by numerous practical and beam dynamics requirements. Injection could be from either the inside or outside of the ISIS RCS, although an outer beam line would allow less disruption to ISIS operations during an injector upgrade. A suitable outer beam line has been designed [3], and at present injection options from the outside of the RCS are being studied. Schemes using injection energy ramping, RF steering, variable injection magnets and fixed and varying main magnets are all being considered. The main factors are minimising foil traversals and achieving 3D painting that produces the most stable distributions. Calculations from acceleration dynamics indicate tight constraints on painting. ORBIT results from a trial painting scheme at 8×10^{13} ppp, with fixed main magnet fields and anti-correlated transverse painting are shown in figure 4. Results suggest stable distributions with a low number of foil re-circulations, though the details are still under study.
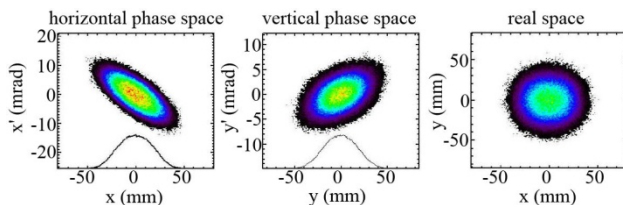

Figure 4: ORBIT trials showing painted distributions.

Activation and Collimation

Ultimately it is expected that beam loss and associated activation will limit intensity. Calculations and simulations using the MARS code [10] indicate that activation levels will increase by a factor of ~5 at ~180 MeV. This suggests that loss levels (or loss control) will have to improve by a corresponding factor.

Work is now under way modelling the existing ISIS collimator system with MARS, which will allow experimental verification of the code against ISIS at present operational energies. The code will then be used to produce the essential predictions of machine activation and loss control at higher injection energy.

Diagnostics and RF Systems

The tighter monitoring and control of beam loss required at higher intensity would make use of upgraded diagnostics, including higher resolution toroids and specialised local beam loss monitors based on scintillators. New, wide-band strip-line monitors, that could form part of a fast damping system to combat transverse instabilities, are presently being designed and installed on ISIS. The full system, with kickers, feedback control and driver amplifiers would be based on SNS designs. Diagnostics for monitoring electron clouds are also being developed and installed.

It is expected that for 180 to 800 MeV at ~8×10^{13} ppp the peak RF voltage requirements for the $h = 2$ and $h = 4$ systems will be similar to the design values of the present system. However, additional beam loading at much higher beam currents may need to be addressed by significant hardware upgrades.

SUMMARY

Studies are under way to assess the increases in beam intensity that may be possible by increasing injection energy and optimising injection into the present ISIS RCS. Studies of the injection straight, stripping foil and longitudinal dynamics have not yet indicated any major impediments to significant increases in intensity. However, studies are not complete, and it has yet to be shown that losses low enough for 0.5 MW levels will be possible, particularly taking into consideration transverse space charge and stability. In any case the studies required to establish the viability of the injection upgrade will provide valuable benchmarks for understanding the present machine and will establish the base line for alternative upgrade routes. Detailed design studies for MW regime upgrade options will build upon this work.

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