MEGAWATT UPGRADES FOR THE ISIS FACILITY

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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 due to start operation in 2008. This paper outlines favoured schemes for major upgrades to the facility in the megawatt regime, with options for 1, 2 and 5 MW. The ideas centre around new 3.2 GeV Rapid Cycling Synchrotron (RCS) designs that can be employed to increase the energy of the existing ISIS beam to provide powers of ~1 MW or, possibly as a second upgrade stage, accumulate and accelerate beam from a new 800 MeV linac for 2-5 MW beams. Summaries of ring designs are presented, along with studies and simulations to assess the key loss mechanisms that will impose intensity limitations. Important factors include injection, RF systems, instabilities, longitudinal and transverse space charge.

INTRODUCTION

The Rutherford Appleton Laboratory (RAL) is home to ISIS, the world's leading operational 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, which is fed by a 70 MeV H^- drift tube linac [1]. Recent accelerator upgrades should allow beam powers of up to 0.24 MW in the near future [2]. This 0.24 MW version of ISIS is the assumed starting point for any upgrade, and is shown in green in Figure 1.

FAVOURED UPGRADE ROUTES

A detailed comparison of reasonable upgrade routes for ISIS that will provide a major boost in beam power has been carried out in order to identify recommended optimal upgrades [3]. Designs are to be developed primarily for an optimised neutron facility, and will include the provision of an appropriate proton beam to the newly built ISIS TS-2 [4].

Upgrade 1: Add a new ~3 GeV Synchrotron

This upgrade increases beam power to ~1 MW (and gives a neutron yield of 3.2 compared with 0.24 MW ISIS) by taking the output of the existing facility and increasing beam energy by adding a ~3 GeV RCS. This new ring would require a new building, along with a new 1 MW target station. This could be built with minimal interruptions to ISIS operations, gives predictable increases in power at reasonable estimated costs and has well defined upgrade routes.

Synchrotron designs will include features required for fast injection directly from ISIS, plus the option for optimised multi-turn injection from a new 800 MeV linac, which would allow for upgrades to the 5 MW regime (see Upgrade 2 below). A key feature of the ring will be ~100 m set aside for RF acceleration systems, which are needed to achieve the required energy at 50 Hz (twice the frequency of the roughly comparable J-PARC ring [5]). A more detailed layout for this option, including a possible location and supplementary buildings is shown in blue in Figure 1.

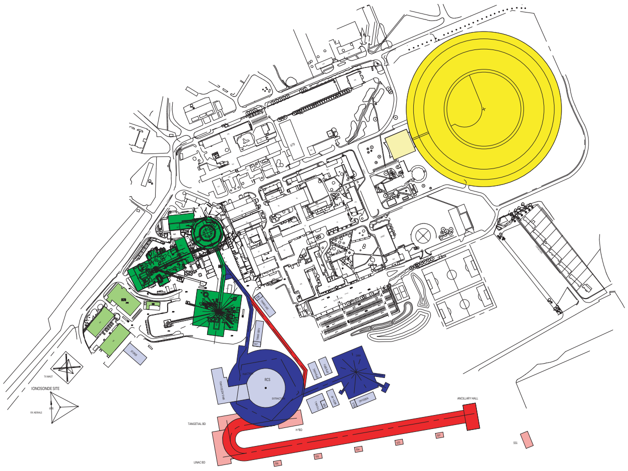

Figure 1: Schematic showing the RAL site with ISIS (green), the recently built Diamond light source (yellow), Upgrade 1 (blue) and Upgrade 2 (red).

Upgrade 2: A 800 MeV Linac Plus a 3 GeV Synchrotron

This upgrade uses a ~3 GeV, 50 Hz ring injecting directly from an 800 MeV linac, providing upgrade options to 5 MW (and a potential neutron yield of 16.0 compared with 0.24 MW ISIS). This option could either be a second upgrade from Upgrade 1, or a new green field option, although as a green field option it would need to be competitive with established designs such as that for the European Spallation Source [6]. As a second stage upgrade to ISIS, the machine given by Upgrade 1 could continue to operate whilst the new linac was constructed. Some interruption would be required while the new injection line and system for the ~3 GeV ring were constructed and commissioned. It should be noted that a significant collimation section or "achromat" would be required after the linac, to provide a suitably stable beam for injection. The overall accelerator configuration is similar to the J-PARC machine [5], but the synchrotron is slightly larger and runs at twice the repetition rate. This is a predictable upgrade option with reasonable estimated cost, based on well established design ideas, and is the recommended upgrade route to 2 – 5 MW.

A more detailed layout for this option as a second upgrade from Upgrade 1, including a possible location, and supplementary buildings is shown in red in Figure 1.

SYNCHROTRON DESIGNS

There are a number of possible candidates for the ~3 GeV, 50 Hz RCS, but studies are presently focused on a 3.2 GeV doublet-triplet design with five superperiods (5SP) outlined in [7] and a 3.2 GeV triplet design with four superperiods (4SP) outlined in [8]. The lattice for the 5SP design has been modified slightly to give the correct circumference for fast injection from the ISIS 800 MeV synchrotron, which has a mean radius (R_0) of 26.0 m. These rings, along with their beta and dispersion functions, are shown in Figure 2.

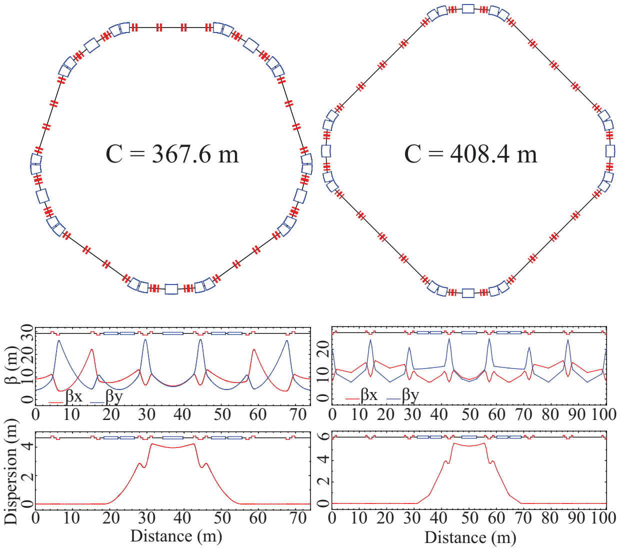

Figure 2: Schematic layouts for 5SP (left) and 4SP (right) RCS designs, with their respective beta and dispersion functions (below).

The 5SP ring has a mean radius (R) of 58.5 m (R/R_0 = 9/4) and RF cavities running at harmonic number h = 9, i.e. nine times the ring revolution frequency (6.1 – 7.1 MHz). This ring is optimised to give small dipole apertures and therefore to minimise the magnet power supply requirements, but has RF buckets which are smaller than those for the ISIS synchrotron. Meanwhile, the 4SP ring has a mean radius of 65.0 m (R/R_0 = 5/2) and RF cavities running at harmonic number h = 5, i.e. five times the ring revolution frequency (3.1 – 3.6 MHz). This ring gives RF buckets the same size as those for ISIS, making fast injection easier, but has larger apertures. Both of these ring designs (and appropriate variations) will be studied in detail in order to assess their suitability for the recommended upgrades. Initial work, however, has concentrated mostly on the 5SP design.

INITIAL RING STUDIES

Work is now underway to study the key issues for the ring designs, underpinned by extensive development of the relevant codes and benchmarking during machine physics studies on ISIS [9, 10, 11]. The main topics include space charge, injection, provision for RF, beam stability and loss control. As starting points, calculation and 1D simulation of the longitudinal dynamics of fast injection, calculation of transverse space charge intensity limits and 2D simulation of multi-turn injection have been chosen, along with the lattice modifications and corrections highlighted in the previous section. It should be noted, however, that all the results obtained so far, although encouraging, are only preliminary and extensive further work is required before the rings are fully characterised.

Longitudinal Dynamics of Fast Injection

Fast injection from ISIS into the 5SP and 4SP rings has been studied in 1D (without space charge at this stage) using ORBIT [12]. A schematic of fast injection is shown in Figure 3, alongside proton intensity distributions representative of the relative filling of the RF buckets in the ISIS/4SP and 5SP cases.

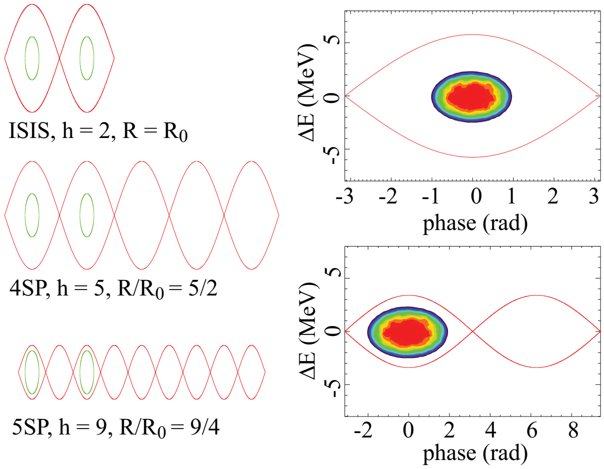

Figure 3: Schematic of fast bucket-to-bucket injection from ISIS into the 4SP and 5SP rings (left) with proton intensity distributions (right) representative of the relative filling of the RF buckets in the ISIS/4SP (top) and 5SP (bottom) cases.

First results for the more difficult 5SP case show that ISIS extracted beam pulses can be accelerated to 3.2 GeV, but that there is a potential problem with beam filamentation leading to halo and perhaps beam loss. Future work will optimise matching in order to minimise halo and will include space charge. Issues of longitudinal stability, minimisation of peak RF voltage and multi-turn injection requirements will all be addressed, along with the requirement to keep beam losses below about 0.01%.

Transverse Space Charge

Initial 2D space charge studies using the “Set” code developed at ISIS [10] have investigated intensity limits in the 5SP ring. Simulations assume an 800 MeV coasting beam with a waterbag distribution of RMS emittance (ε_{RMS}) = 27 π mm mrad and a rectangular cross-section vacuum vessel. 100,000 macro-particles are tracked over 100 turns with only space charge derived driving terms.

Nominal tunes for the 5SP ring are (Q_H, Q_V) = (7.21, 7.73). The incoherent tune footprints predicted by “Set” are shown in Figure 4 as a function of intensity. It can be seen that a number of major resonances are crossed by the incoherent tunes at higher intensity.

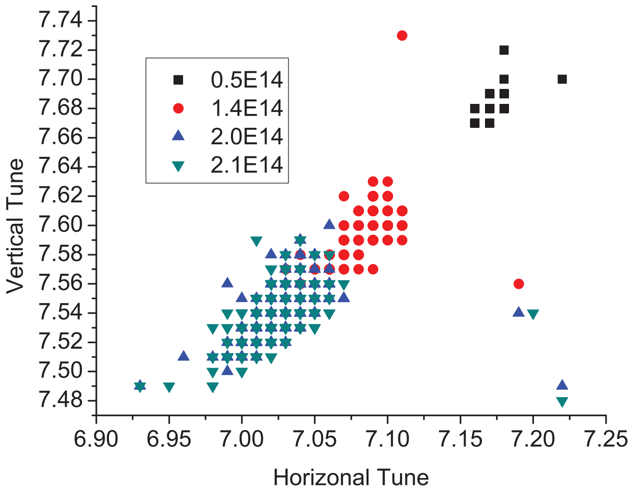

Figure 4: Tune spread variation with intensity (coasting beam equivalent) for the 5SP ring.

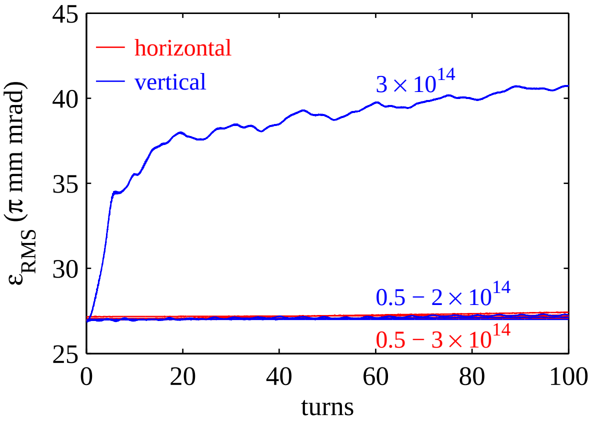

Figure 5: RMS emittance variation with intensity (coasting beam equivalent) for the 5SP ring.

The calculated ε_{RMS} results for coasting beam equivalent intensities between 0.5×10^{14} and 3.0×10^{14} protons per pulse (ppp) are shown in Figure 5. It is evident that there is little emittance growth at intensities below 2.0×10^{14} ppp, but that at 3.0×10^{14} ppp there is significant vertical emittance growth. Initial analysis suggests that this is due to systematic resonance $2Q_V = 15$ driven by space charge, but studies of the working point are still ongoing.

The next steps in this topic will be the assessment and inclusion of important driving terms and an investigation of working point and correction schemes. Further development of the “Set” code should allow its use in longitudinal and injection simulations.

Multi-turn Injection

Simulation studies of the multi-turn injection process with the ORBIT code have started with a simplified 2D model. Simple painting schemes with 3×10^{14} ppp and representative values for centroid painting give reasonable results. Work is now progressing towards simulations of 3D painting.

INITIAL LINAC STUDIES

A suitable linac for Upgrade 2 is being designed by the ASTeC Intense Beams Group at RAL [13]. This will have a 3 MeV, 324 MHz radio frequency quadrupole (RFQ), medium energy beam transport (MEBT) and chopper similar to those for the Front End Test Stand at RAL [14], and a 75 MeV, 324 MHz drift tube linac (DTL). There will then be a frequency jump to either 648 or 972 MHz, probably followed by a 190 MeV coupled-cavity linac (CCL) and an 800 MeV superconducting linac (SCL). Initial studies have produced beam envelopes for the DTL and a 972 MHz CCL, with the next stages being a re-evaluation of the MEBT optics and chopper, the optimisation of DTL inter-tank separations and matching, CCL cavity optimisation and an investigation of alternatives to the CCL (e.g. a spoke resonator structure).

FUTURE WORK

The main topics which need to be covered for megawatt upgrades for the ISIS facility have been identified and work on them has started, but there is a great deal still to be done in order to produce a robust physics design.

For the RCS, longitudinal studies of fast injection for the candidate rings must be completed and then extended for multi-turn injection, and 2D simulations of multi-turn injection expanded to 3D and to include acceleration. Correction schemes for transverse space charge need to be fully investigated along with potential sources of instability. A model of the injection region must be produced, as must a design and simulation of the collimation system, including beam loss and activation. When all the simulations have been compared, and a decision has been made on the optimal ring lattice and parameters, extensive modelling and calculations for individual elements of the design such as magnets, RF cavities and systems, main magnet power supply, injection and extraction systems and power supplies, collimators, diagnostics and vacuum systems will be required.

The linac design must be extended to include the SCL and its matching to the CCL and to compare CCL and SCL performance at 648 and 972 MHz. When this has been done the favoured design will be refined and error effects evaluated for the full linac. Consideration can then be given to appropriate RF systems, vacuum systems and cryogenics.

Obviously, in addition to the RCS ring and linac, there are many other elements to be included in the design study, such as transfer lines and a suitable "achromat". Other important factors will include choices of stripping foil (or a laser stripping system), RF cavity structure and, probably most importantly, neutron target, which may well be affected by lessons learnt during commissioning of the J-PARC [5] and SNS [15] spallation sources. However, it is anticipated that a robust physics design will be complete by the end of 2010, and that a full design including engineering, civil engineering and costing will be available to bid for funding in 2012.

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