# UPGRADES TO THE ISIS SPALLATION NEUTRON SOURCE

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## *Abstract*

With studies of a European Spallation Source (ESS) suspended and high-level discussions taking place over the future of neutrons in Europe, efforts are being made to ensure the sustained success of ISIS well into the foreseeable future. Recent developments include upgrading the injector by replacing the Cockcroft Walton with an RFQ, and installation of a new dual harmonic RF system that should eventually enable up to 50% more protons to be accelerated in the ring. A programme of ion source development also aims at improved reliability, enhanced beam current and longer life-time. This promise of more beam power has led to construction of a second target station providing users with additional experimental facilities starting in October 2008. In the longer term, ideas are forming either for a new high intensity proton driver or for a phased development of ISIS to the 5 MW level. As an alternative to generating neutrons, such a machine might also be part of a neutrino factory, a complex of accelerators generating neutrinos from muon decay. This paper describes these activities and identifies their relative importance on an international development scale.

## INTRODUCTION

At the heart of the ISIS facility at the Rutherford Appleton Laboratory (RAL) in the United Kingdom is a set of accelerators that together form an extremely robust, reliable and stable machine. The ISIS source celebrated its twentieth anniversary of neutron production in 2004, and with a proton beam output of 0.16 MW has held the accolade of the world's most powerful pulsed proton source for a number of years. Much high quality research has been carried out, with important developments over a range of topics relating to physical and biological sciences. Operational experience and technological progress have provided valuable guidance for studies towards future accelerator-based neutron sources. ISIS is increasingly seen as a benchmark not only for neutron production but also as a starting point for a high power proton accelerator. Many of the ideas behind its design have had a bearing on the US spallation neutron source (SNS), the Japanese high intensity accelerator facility (J-PARC), and spallation neutron facilities proposed for Europe, China and India.

However ISIS is now an elderly machine. Its purported successor - a new European Spallation source (ESS) [1] - was developed between 1990-2002, and discussions over its construction continue at a high level but no decision has yet been reached. Given the high demand for neutrons in Europe, it is important in the first instance to ensure that ISIS continues to run reliably at its present level. At the same time there is a need to look towards the future. A relatively modest upgrade seems feasible in the medium term, and regardless of whether ESS is or is not built, ways to increase the beam power to at least 1 MW and possibly as high as 5 MW are being explored.

## ISIS

The ISIS accelerating system (Figure 1) is based on a 70 MeV $H^-$ linac injecting via an $Al_2O_3$ stripping foil into an 800 MeV, 50 Hz proton synchrotron. Between 5 and 10% of the injected beam is lost during trapping and initial acceleration. Each pulse consists of two bunches of about 120 ns duration, directed onto a tantalum-clad tungsten target, where a variety of experiments are carried out for condensed matter research.

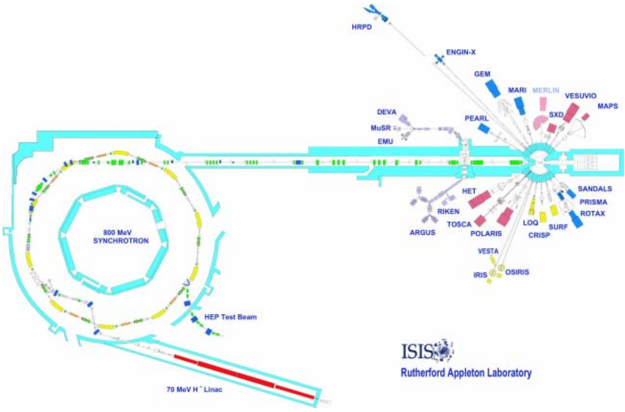

Figure 1: The ISIS Spallation Neutron Source

In its present configuration, the machine is limited by space charge to an intensity of $2.5 \times 10^{13}$ protons per pulse, but a programme of development aims to increase this by perhaps as much as 50% at relatively modest cost. The key to this was identified in an earlier study [2] and involves a combination of $h = 2$ and $h = 4$ RF cavities. By carefully balancing parameters, stable areas of longitudinal phase space can be increased, allowing more beam to be injected without change in either the peak bunch current or the transverse tune shift. It is important to keep beam loss as small as possible, which is achieved by modulating the peak voltages during the accelerating cycle and controlling the relative phases between the RF harmonics in a specific way The new cavities were installed in the summer of 2004. At the same time the opportunity was taken to upgrade the 70 MeV linac, parts of which dated back to ISIS's predecessor on the site, the old NIMROD accelerator. The ion source was updated and the ageing Cockcroft-Walton injector was replaced with a radio-frequency quadrupole (RFQ) constructed at the University of Frankfurt. The RFQ operates at 202.5 MHz and delivers $H^-$ micro-bunches at 665 keV. Some initial problems over alignment and the need to optimise the upgraded linear accelerating system have led to standard operation falling in the last two years to around the 140 kW level (180 $\mu$A). However machine runs in November 2006 have seen extremely promising performance. With only two of the four $h = 4$ cavities in operation and the $h = 2$ cavities still at the original production settings, over 200 $\mu$A of beam current have been accelerated, with 97% transmission, the highest ever achieved. These results suggest that with the full dual harmonic system operating under the theoretical, optimised settings, predicted loss of around 0.5% and beam powers up to 0.24 MW (300 $\mu$A) can become a reality.

In order to accommodate the increased power, a second target station (TS2) is being built. It will operate at 10 Hz, taking one pulse in five from the existing 50 Hz target (TS1). TS2 is designed for low beam power, 48 kW, receiving about 60 $\mu$A of the ISIS beam current. The cost of the project is in the region of £140 m[1], and construction involved the removal of part of a hill on the western edge of the laboratory. The building was finished in October 2006. In the centre, the monolithic core - a huge steel structure housing a tungsten target 6 cm wide by 30 cm long surrounded by 5.5 m of shielding - is taking shape. The beamline from ISIS is currently being installed and October 2007 should see the first beam on target. The experimental programme is due to start in 2008 and the enhanced cold neutron flux is expected to lead to breakthroughs on next generation materials for super-fast computers, data storage, sensors, pharmaceutical and medical applications, materials processing, catalysis, biotechnology and clean energy technology. An aerial view of the new facility with a schematic layout superimposed is shown in Figure 2.

## GENERIC ACCELERATOR R&D

Ideas for upgrading the facility to the megawatt level stem from work on the ESS and studies in the U.K. for proton drivers for a neutrino factory (NF).[2] High power proton machines for either purpose have to confront design goals well beyond anything ISIS has achieved, most importantly the need at high beam powers and intensities for an extremely low loss system. Elaborate collimation schemes need to be incorporated and special features included, such as fast beam choppers in the low energy stages of the linacs and achromatic arcs in the transfer lines from the linacs to the rings. Choppers are used to create gaps in the linac micro-bunch train so as to enable bunches to be trapped in stable regions of phase space in the accumulator/storage rings. A balance needs to be maintained between many parameters, with trade-offs between, for example, the ring injection period and the linac current. Charge exchange injection is the only practical way of reaching the desired intensities, and, in order to control stripping foil heating, the injection time need to be limited and this means a higher current from the linac.

Figure 2: Aerial view of ISIS showing the new extracted proton beamline and the building for Target Station 2.

### *Front-End Test Stand*

Bearing this in mind, among the most challenging R&D aspects are development of an $H^-$ ion source and the fast beam chopper. A long-standing aim at RAL has been the construction of a linac front-end test stand to demonstrate the feasibility of the low energy stages needed for a high power proton facility. This is now being realised. Because of synergies with other projects, parameters are not tied to any one proposal and funding is from a variety of bodies, including the U.K. research councils and the European Union Framework 6 CARE/HIPPI programme. The basic layout of the test-stand, shown in Figure 3, links an $H^-$ ion source, a low energy beam transport system (LEBT), a radio-frequency quadrupole linac (RFQ), a fast beam chopper and transport system (MEBT), and a comprehensive system of diagnostic equipment. Modifications to the ISIS Penning source aim for a current of 60–70 mA, a normalised rms emittance of 0.2 $\pi$ mm.mrad and a duty cycle of up to 10%. The work is already well on target. A combination of electromagnetic and thermodynamic modelling has provided insight into thermal properties and enabled discharge pulses of up to 1.8 ms to be achieved. Further experimentation has enabled the design current to be

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[1] U.K. £1≈ U.S.$2 at January 2007 rates.

[2] A neutrino factory uses a 4-5 MW proton driver to generate a secondary muon beam. The muons are accelerated rapidly and stored before they decay to give intense streams of neutrinos that are directed at distant detectors.

met. Now emittance measurements and studies are underway. Much remains to be done to realise a fully operational, long-lifetime source, but the present design is probably the best of its kind available today.

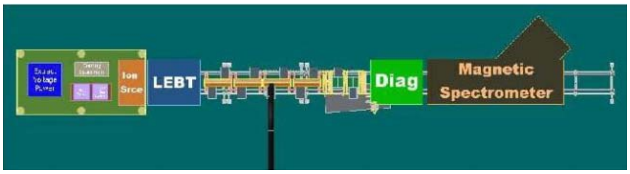

Figure 3: The Front-End Test Stand at RAL

From the ion source, the beam will be matched by a Low Energy Beam Transport system (LEBT), into an RFQ; then bunched and accelerated to 3 MeV. A magnetic LEBT with three solenoids has been identified as preferable to the operating ISIS electrostatic scheme. Design of the FETS RFQ has followed lengthy discussions over the choice of RF frequency. Taking into account global needs and the availability of hardware, a system based on 324 MHz has been chosen. This is the J-PARC frequency, and a 3 MW klystron, developed by Toshiba, has been ordered and recently delivered to RAL. Work is in progress to compare designs of high duty-cycle 324 MHz 4-rod and 4-vane RFQs. The 4-vane model promises a higher Q-value and a much lower RF requirement, and will therefore be the likely choice. A cold model has been manufactured in aluminium to test machineability, and a simple copper structure has been produced to study the brazing process. A bead-pull measuring system has been built to evaluate the field distribution and test readings against theoretical electrodynamic modelling. Parallel beam dynamics simulations, carried out on the RFQ cavity and cold model designs, suggest a transmission as high as 94%.

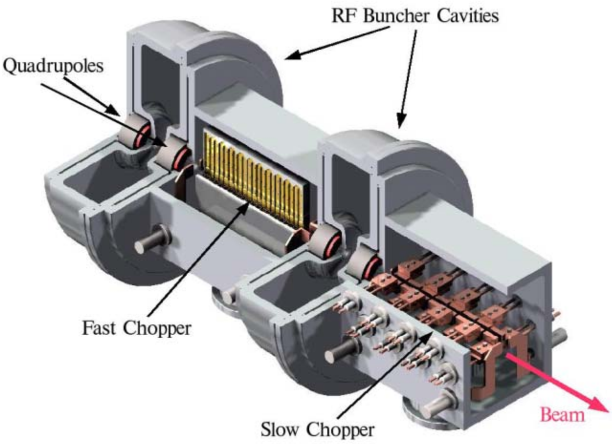

Figure 4: RAL Fast Beam Chopper

The fast beam chopper [3] which follows is one of the most crucial and important components of the structure for successful operation of a robust, low-loss machine. As FETS is seen as a generic accelerator R&D project, it has to show flexibility to meet a variety of needs. The chopper can be required to create gaps in the bunch train from the order of a few to a few hundred nanoseconds. For the ESS, for example, the chopper has to deflect about 72 microbunches from every 240 at the ring revolution frequency of 1.24 MHz. Many years of work have crystallised into a combined slow-fast structure. At 324 MHz, the gap between micro-bunches is of the order of 2.5 ns; and a deflecting electric field has to rise within this gap to kick the following bunches cleanly to a beam dump. A fast modular pulser has been developed that achieves $< 2$ ns rise time with a 15 ns flat top at $\pm 1.45$ kV, which is sufficient to deflect 3-4 microbunches. This creates a longer gap for a slow-rise, long duration field that deflects the rest. A module is shown in Figure 4. The slow pulse generator has reached an amplitude of $\pm 6.0$ kV with a duration of 0.2-100 $\mu$s; all specifications have been met apart from the required duty factor.

### *$H^-$ Linac*

The general aim of the EU CARE/HIPPI package [4], which partly funds work on FETS, is to explore accelerating structures for hadrons up to 200 MeV. The motivation is the likely construction of a new linac (Linac4) at CERN and proposals for an 180 MeV linac at RAL [5]. Both designs are similar and a schematic drawing of the U.K. layout is shown in Figure 5. FETS will be used for the front-end; then a drift-tube linac (DTL) will accelerate the beam to 90 MeV at 324 MHz. The DTL has 4 tanks, using one Toshiba klystron per tank. The remainder of the structure has a a triple frequency jump to 972 MHz leading into a side-coupled linac (SCL).

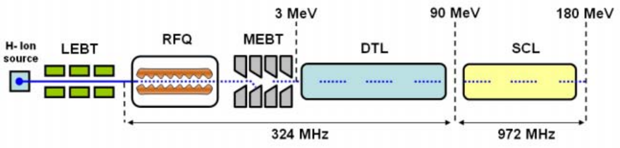

Figure 5: Structure of the 180 MeV $H^-$ linac

The linac stems partly from earlier ESS studies and partly from work on a neutrino factory. The RAL group has designed high intensity proton drivers at energies of 5, 8, 10, 15 and 30 GeV [6], all of which include booster synchrotrons fed from the same linac design. The argument for such a low energy relates to the need for very short proton bunches ($\sim$1 ns) and theory suggests that a small longitudinal emittance is best achieved by accumulating the beam at about 200 MeV. Studies of accelerating structures within HIPPI are therefore an important part of the U.K.'s NF programme as well as of interest for neutron sources.

## IDEAS FOR ISIS UPGRADES

By the end of 2007, ISIS should have new and upgraded equipment in place to raise the operating current to 250-

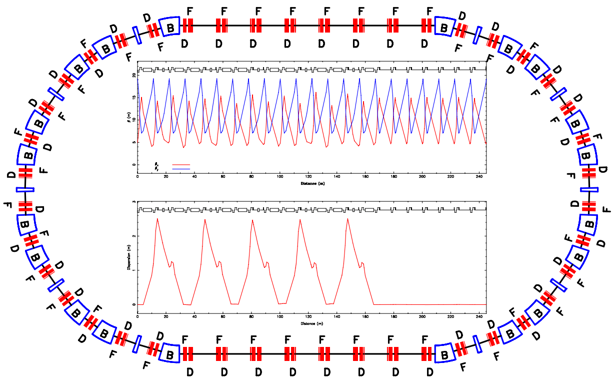

Figure 6: Details of the racetrack synchrotron

300 $\mu$A (200-240 kW of beam power). Beyond this, the only practical method of increasing the power of the facility is by raising the energy through the addition of a second ring. A synchrotron with a racetrack lattice structure has been devised with a mean radius of 78 m, three times the 26 m of the present ISIS synchrotron. ISIS's two bunches, each with an intensity of $1.9 \times 10^{13}$ protons, would go straight into this ring via bucket to bucket transfer at $h = 6$. Accelerating to 3 GeV would provide an approximate fourfold increase in energy and take the beam to the MW level of power.

Details of the ring, including optical parameters and magnetic specifications (see Figure 6), were given in [7]. Using a magnetic dipole field variation of the form

$$B(t) = B_0 - B_1 \cos 2\pi f t + B_2 \sin 4\pi f t, \quad B_2 = \frac{B_1}{4\sqrt{2}}$$

minimises the maximum value of $\dot{B}$ during the cycle and reduces the total RF voltage in the ring by about 30%. With this scheme, at $f = 50$ Hz repetition rate, it takes ∼570 kV to take the full ISIS pulse from 0.8 to 3 GeV in just under 12 ms. The final bunches are ∼72 ns in duration (compared with the current figure of ∼120 ns) with a momentum spread of $\pm 3 \times 10^{-3}$.

The advantages of this approach are that: space charge is reduced at 800 MeV; the present ring gives a well-defined beam and enables fast injection into matched RF buckets; and beam losses should be very low. It also provides many opportunities for further developments to higher beam power.

In this mode of operation, the machine would be used as a a spallation neutron source. However, the possibility exists of operating at $f = 16.7$ Hz and accelerating only one pulse in three from ISIS (the others being discarded) to 8 GeV over 30 ms. The aim would be experimental tests of bunch compression to ∼1 ns (rms) for the neutrino factory. Pion target tests could also be undertaken along with investigations of a prototype pion decay/muon capture channel.

Unfortunately, ISIS's existing target, TS1, is limited by its methane moderator to about 0.25 M, so adding a synchrotron would involve the additional expense of a new, third, target. A possible layout, including both a neutron and a muon target, is show in Figure 7. Note that construction would require removal of the rest of the hill that has already been excavated for TS2. The need for a new target for almost any acceptable power upgrade means an underlying cost of at least the £140 m of TS2, and the total would inevitably reach the order of a few hundred million U.K. pounds.

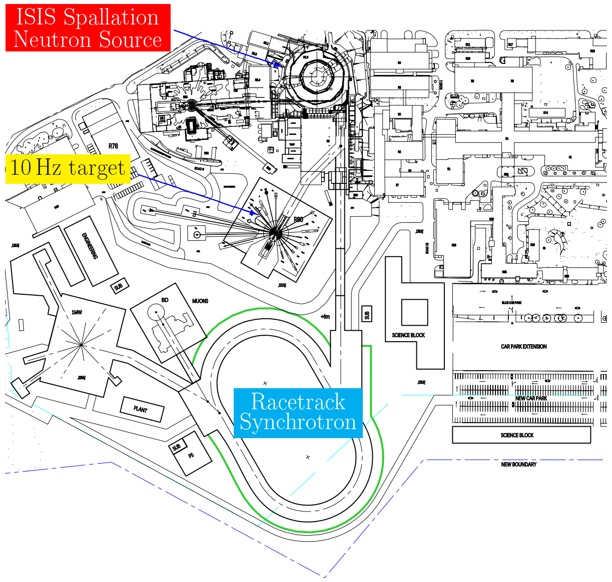

Figure 7: ISIS with the addition of a 3 GeV racetrack synchrotron

A more modest upgrade, though because of the additional target cost it hardly seems economically worthwhile, would be to replace the existing 70 MeV linac with the new 180 MeV design. At this energy, space charge levels at injection are halved, the number of particles in a bunch could be doubled to about $3.8 \times 10^{13}$, and initial studies suggest that the synchrotron could output ∼0.4 MW of beam power. The smaller energy sweep in the synchrotrons would also allow the machine to operate at the higher repetition rate of 65 Hz with the same peak $dB/dt$. This would give about $\frac{1}{2}$ MW beam power.

An alternative way of reaching $\frac{1}{2}$ MW would be to build an additional 800 MeV ring on top of the existing synchrotron in the ISIS tunnel. Injected from the same linac, two additional bunches of $\sim 1.9 \times 10^{13}$ could be accelerated, giving four on target at 50 Hz. Adding the new 180 MeV injector would increase the bunch intensity and take this nearer to 1 MW. However there would be practical difficulties in installing a second ring among the paraphernalia of the first.

For higher beam powers, options are to use the 180 MeV injector and add the 3 GeV synchrotron to ISIS. This would get nearer 2 MW. Nevertheless, only two of the six racetrack buckets would be filled. Building the second 800 MeV ring would double the number of bunches and fill four buckets for up to 4 MW. A higher energy of 4 GeV could also be conceived to reach a goal of 5 MW, but this target is heavily reliant on success at every step.

The upgrade route identified in [7] uses the racetrack synchrotron but, instead of ISIS, has a new 1.2 GeV booster. This would be detached from ISIS, which could continue in its present form until the new machine came on line. The booster comprises the 180 MeV linac injecting into two stacked rapid cycling synchrotrons (RCS) of mean radius 39 m, operating at 50 Hz and optimised for low loss charge-exchange injection. One ring would be filled immediately after the other, each with three bunches of $1.7 \times 10^{13}$ protons, and all six bunches would be fed into one of two stacked racetrack synchrotrons operating at 25 Hz. The racetracks would be extracted on alternate half-cycles, restoring the operating repetition rate of 50 Hz on target (Figure 8). The original idea was that this would provide an enhanced neutron source at 3 GeV, but could also be built for 6 GeV at which energy the bunches could be compressed to 1 ns and used as a 5 MW driver for a neutrino factory.

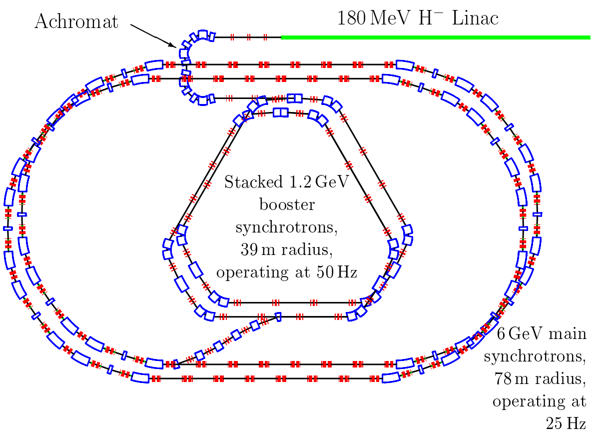

Figure 8: A stand-alone 4-5 MW proton driver

If the (possibly impractical) suggestion of combining neutrons with neutrinos is dropped, a simpler ring, designed specifically for neutrons, could be used. For example, half the beam from ISIS (after the present upgrade and TS2 is operating) could be accelerated in a "neutron optimised" ring (NO) of radius 52 m (twice ISIS's radius) at 25 Hz to 3.5 GeV. This would put $\frac{1}{2}$ MW on a new target (TS3) and 0.12 MW to TS1 and TS2. This could be doubled by adding an 800 MeV storage ring on top of the NO-ring to hold two bunches from ISIS for 20 ms pending arrival of the next two; then four bunches could be accelerated to 3.5 GeV. This would give four bunches on target at 25 Hz. The alternative, to make the storage ring into a second RCS, the two being extracted on alternate half cycles, would give the same beam power with two bunches per pulse at 50 Hz. Further increases could be achieved by using the 180 MeV injector to increase the number of protons per bunch and a second synchrotron in the ISIS tunnel to double the number of bunches, along the lines described above.

Other possibilities are effectively new machines separate from ISIS. For example, the ESS could finally be constructed as detailed in the baseline-design document. Alternatively older ideas based on an 800 MeV linac injecting into a 3.5 GeV RCS could be re-visited. An even older suggestion, driven by the neurtino community and undergoing a revival because of advances in technology, would involve a linac and a fixed-field alternating gradient accelerator (FFAG).

## SUMMARY

Many suggestions, with varying degrees of practicality, have been described above for upgrades to the ISIS spallation neutron source. However it should be made clear that there is no formal programme of development beyond the present dual harmonic installation and construction of TS2. The U.K.'s strategy is to support appropriate investment in the existing accelerators, targets and instruments, and to explore in an international context opportunities for a second-generation neutron source for Europe. The U.K. has the potential to build a megawatt-class spallation source through the upgrade of ISIS but has deferred planning of any specific option until the outcome of wider discussions of European plans is known.

## ACKNOWLEDGMENT

Grateful acknowledements are due to members of the ISIS upgrade team, especially C.M. Warsop, who identified a coordinated structure amongst a myriad of ideas.

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