ISIS UPGRADES — A STATUS REPORT

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Abstract

Since 2002 several accelerator upgrades have been made to the ISIS spallation neutron source at the Rutherford Appleton Laboratory in the UK, and upgrades are currently continuing in the form of the Second Target Station Project. The paper reviews the following programmes: a new extraction straight, replacement of the Cockcroft-Walton by an RFQ, installation of a second harmonic RF system, replacement and upgrading of ageing installed equipment, design and installation of improved diagnostics in conjunction with beam dynamics simulations, the Second Target Station Project, design and construction of a front end test stand, and the MICE programme. The paper also looks forward to possible future schemes at ISIS beyond the Second Target Station Project.

ISIS SPALLATION NEUTRON SOURCE

The ISIS spallation neutron source (originally simply called SNS) produced its first proton beam on 16 December 1984. At that time it was configured as a 665 kV Cockcroft-Walton preinjector, a 70 MeV H^- 4-tank drift tube linac, and a 26 m mean radius 800 MeV proton synchrotron with a cycling rate of 50 Hz driving a depleted uranium target*. The proton synchrotron was built in the hall originally constructed in the 1950s for the old 7 GeV proton synchrotron Nimrod, and the Cockcroft-Walton and linac were originally built as a new high energy injector for Nimrod. But Nimrod closed down in 1978, and the new 70 MeV injector was never used for Nimrod, but was converted from 1 Hz 75 mA proton operation to 50 Hz 20 mA H^- operation.

Although first beam from ISIS was produced in 1984, it was not until 1992 that the machine routinely reached its present beam powers. Since then annual output has increased by a factor ~20, not in terms of proton beam power on target, but in terms of science, at least as science measured in terms of volume of data produced and published due to enhancements made to the suite of neutron instruments.

It is often assumed that increased output from an accelerator is *ipso facto* a good thing, but it is not always clear that a good thing is necessarily the best thing. As regards accelerator facilities such as spallation neutron sources supported by a large user community, many things other than raw beam power determine the success or failure of facilities, such as reliability, quality of instrumentation, commitment to innovation, willingness to invest, provision of support facilities, quality and friendliness of support staff, cost effectiveness, and extent of engagement of the user community with the facility.

Usually the process of building and commissioning an upgrade to an accelerator system involves significant down-time, and of course the loss of opportunity during this down-time must be subtracted from the benefit eventually secured when the upgrade is complete.

The various upgrades which have already been made to ISIS and which may be made to ISIS in the future are as follows: new extraction straight for the synchrotron, replacement of the Cockcroft-Walton DC accelerator by an RFQ preinjector, installation of a second harmonic RF system on the synchrotron, replacement and upgrading of ageing installed equipment, design and installation of improved diagnostics, construction of a second target station, and the design of various upgrade schemes for increasing the proton beam power to ~1 MW and beyond. In addition, programmes associated with ISIS, design and construction of a front end test stand, ring R&D including the establishment of a significant beam dynamics simulation capability, and incorporation of the MICE project, are also described. Each of these is discussed in the sections below.

NEW STRAIGHT 1

Two of the issues† leading to the Straight 1 upgrade were the following: suspected leakage of ~200 MeV protons through collimators which were too thin, and inadequate aperture at the extraction septum. In 2002 new collimators were installed, and the septum magnet was replaced. The old collimators were not thick enough to completely stop protons with energies corresponding to times during the acceleration cycle when significant beam losses were sometimes observed, and so lower energy protons could have been emerging from the back of the collimators and causing the periodically observed damage to the RF screen within the ceramic vacuum vessel through the main dipole immediately beyond the collimator straight. Since the new thicker collimators were installed, the problem of beam damage to the RF screen seems to have been largely resolved, although mechanical modifications to the RF screen to allow for expansion due to beam heating were also made in 2004. A fuller account is given in [1].

* The target material was changed to tantalum in the early 1990s, and then to tungsten in 2001.

† Other reasons, more important operationally, were that the water cooling system for the extraction septum magnet and the busbar system feeding the magnet with ~10000 A were both failing, largely due to radiation damage through their close proximity to the collimators.

RFQ PREINJECTOR

There were a number of problems associated with the original 665 kV Cockcroft-Walton DC preinjector on ISIS including: periodical spates of electrical breakdown, X-ray radiation from electrons being accelerated down the column, and poor trapping of the beam by the first tank of the linac due to inadequate bunching. In 2004 an RFQ was substituted for the Cockcroft-Walton. The 4-rod 202.5 MHz RFQ was designed and built as a Frankfurt University - CCLRC collaboration, and was characterised and soak-tested on a dedicated off-line test stand before installation on ISIS. Since its installation the RFQ has run very well, and although its output is coupled straight into the input of the linac without any separate matching section, the fraction of beam which can be trapped and accelerated by the linac has increased significantly. Much fuller accounts are given in [2] and the references therein.

SECOND HARMONIC RF

In order to increase the amount of proton charge which can be trapped and accelerated by the synchrotron, a second harmonic component has been added to the synchrotron RF. The ten-superperiod synchrotron was built with six ferrite-loaded cavities for the $h=2$ RF sweeping from 1.3 to 3.1 MHz across the 10 ms acceleration cycle (in Straights 2, 3, 4, 7, 8 and 9), and this has enabled proton charges up to 4 μC to be successfully trapped and accelerated. In 2004 the installation of four ferrite-loaded second harmonic $h=4$ cavities was completed, in Straights 4, 5, 6 and 8, with the intention of enabling proton charges up to 6 μC to be successfully trapped and accelerated. Also in 2004 the neutron production target and its associated reflector were replaced to enable them to accommodate the increased beam power expected. The second harmonic (2RF) cavities are roughly half the length of the fundamental RF (1RF) cavities, and are swept between 2.6 and 6.2 MHz. Although the speed at which the new 2RF system can be commissioned with beam has inevitably been limited by the overriding need to maintain operations for the user programme, good progress is nevertheless being made. Exploration of the 2RF amplitude and phase parameter space has shown that the shapes of the beam bunches in the synchrotron may be manipulated very largely as expected, and even at non-optimum amplitudes and phases addition of the 2RF component has been shown to reduce beam losses during trapping and initial acceleration. Much fuller accounts are given in [3].

In addition to the work on the 2RF upgrade, collaborative[‡] work has also been carried out at ISIS on developing low output impedance (LOI) amplifiers to drive RF cavities. While not specifically necessary for the 2RF work currently being carried out at ISIS, LOI amplifiers could bring substantial control system and operational benefits by reducing the sensitivity of the RF systems to beam loading. Details are given in [4].

[‡] With Argonne National Laboratory, Illinois, USA and High Energy Accelerator Research Organization, KEK, Tsukuba, Japan.

UPGRADES TO INSTALLED EQUIPMENT

ISIS has been operating now for over twenty years, and was partly built from second-hand equipment. There is therefore a significant amount of equipment on ISIS that is 30–40 years old, and so an obsolescence mitigation programme has been mounted. Work carried out under the programme includes the following. The AC current for the main synchrotron magnets is currently generated by a 1 MVA motor-alternator set, and a single large multi-winding ~100-tonne choke[§] is used to couple current into the ten superperiods, but a new system involving three 300 kVA uninterruptible power supplies (UPSs) and ten separate chokes is being installed; the new system has not yet been completed, but the three UPSs have already been used successfully to power the synchrotron magnets at full current. A new set of drivers for the fast extraction kickers is being built, as with the increased beam current expected from the second harmonic RF upgrade greater kicks from the kicker magnets will be required; the present kickers can produce pulses up to 42 kV along a 7-ohm transmission to the kicker magnets, but the new kickers will run at up to 52 kV. The anode power supplies for the 202.5 MHz linac RF are being replaced and upgraded; the four 200 kW intermediate amplifiers already have new anode power supplies, and a prototype power supply system is running on one of the 2 MW final amplifiers. Partly because of issues connected with the second target station described below, and partly to bring it up to modern standards, the entire ISIS accelerator interlock system is being replaced and upgraded; the new system will comply with the IEC 61508 generic standard for functional safety. Descriptions of some of the obsolescence mitigation work are given in [5].

SECOND TARGET STATION

The neutron instruments on the present ISIS target station (TS-1) are over-subscribed, and because of this, and because of a wish to open up new opportunities for the application of neutron scattering techniques, a second target station (TS-2) optimised for the use of cold neutrons is being built (see Fig. 1). The beam for TS-2 is obtained by deflecting one pulse out of every five from the extracted proton beam line to TS-1, and so TS-2 will run at 10 Hz while the repetition rate of TS-1 will be reduced from 50 Hz to 40 Hz. Part of the reason for the second harmonic upgrade described above is of course to enable the synchrotron to produce sufficiently higher beam currents than at present so that the diversion of every fifth beam pulse from TS-1 to TS-2 does not finally lead to the beam power at TS-1 being less than it is at present. During 2007 the new proton beam line to TS-2 will be connected to the synchrotron, and neutron

[§] Actually a transformer, but in this context usually called a choke.

instruments should be available for users by the end of 2008. Some information on power supplies of the magnets in the new proton beam line are given in [6].

It should be noted that the opportunity to optimise the target, moderators and instruments altogether and entirely for cold neutrons has led to the expectation of world-leading performances in many cases, even through the proton beam power in the target is relatively modest. Much more extensive references are reachable through the link at [7].

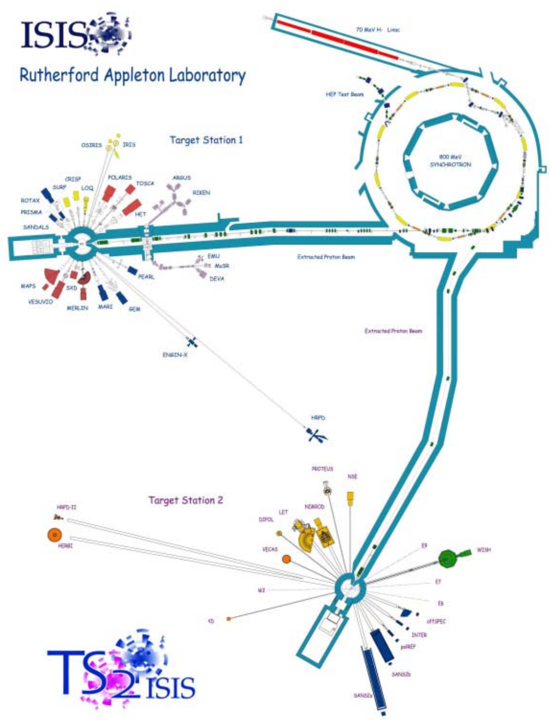

Figure 1: Layout of ISIS including TS-2.

FRONT END R&D

In order to contribute to the development of high power proton accelerators in general, to help prepare the way for ISIS upgrades through the design of a new 180 MeV injector linac (see below), and to contribute to UK R&D effort on neutrino factories, a front end test stand covering a variety of beam current and pulsed distribution régimes is being constructed at ISIS with the aim of demonstrating the production of high quality beams. The test stand is building on experience gained through the design, construction and operation of the test stand for the ISIS RFQ mentioned above. The new test stand is made up of five main elements, a 60 mA 2 ms 50 pps H^- ion source, a three-solenoid low energy beam transport (LEBT) to match the beam from the ion source into the RFQ, a four-vane 3 MeV 324 MHz RFQ, a beam chopper with <2 ns switching times, and a comprehensive set of diagnostics. The work is being carried out collaboratively[**], and also forms part of the R&D programme of the UK Neutrino Factory Collaboration. Good progress is being made on all fronts, and full descriptions are given in [8].

RING R&D

The mechanisms responsible for beam loss, and thereby potentially limiting the intensity of the ISIS proton synchrotron, are not fully understood. The ISIS synchrotron is one of the few machines world-wide where some of these important loss mechanisms can be studied experimentally, thereby facilitating benchmarking of computer codes and theoretical models, and contributing to future machine designs based on sound assumptions. In addition, improved understanding of these phenomena is fundamental to ISIS improvements and upgrades.

Experimental studies of beam dynamics and beam losses in the ISIS synchrotron are being facilitated by a number of developments [9]. A new fast residual gas beam profile monitor is being installed, which if not delivering information on a turn-by-turn basis is nevertheless fast enough to update every three turns. A new scintillator-based fine resolution beam loss monitor system is being developed and installed on the inside of the bend through the dipole immediately downstream of the collimator straight (Straight 1). Two retarding potential electron spectrometers are being installed in Straights 5 and 6 to make measurements of electron cloud densities with a view to increasing understanding of electron cloud effects on circulating proton beams.

Complementary theoretical studies are also being carried out. Transverse space charge studies are now under way, including calculations for coherent envelope modes and numerical solutions of the envelope equation to show the expected behaviour near half integer resonance. The predictions are being linked with more realistic beam models in space charge codes, and the calculations are being extended to images, coupling and non linear resonances. Since optimising injection is a key consideration for both present and future upgrades, charge-exchange injection studies are also under way, as the evolution of transverse and longitudinal distributions affects beam loss levels and therefore maximum operational intensities. Work being carried out includes space charge simulations of the present machine and comparison with observations, assessment of related loss mechanisms, and the study of optimal painting schemes [10].

MICE

The essential elements of a neutrino factory are the production of pions from a megawatt proton beam, capture and cooling of the decay muons, acceleration of the muons, and decay of the muons in a storage ring. The MICE (Muon Ionisation Cooling Experiment) programme is an exercise being carried out by an international

[**] With Imperial College, London, and the University of Warwick, with funding delivered by ASTeC (CCLRC), PPARC, and the EU.

collaboration to design, engineer, and build a section of cooling channel capable of giving the desired performance for a neutrino factory, and to place this apparatus in a muon beam and measure its performance in a variety of modes of operation and beam conditions. The muons are generated from a parasitic target intercepting a small fraction of the halo of the proton beam in Straight 7 of the ISIS synchrotron, and the MICE hardware is being built up in a large shielded hall adjacent to the ISIS linac hall. More details are provided in [11].

POSSIBLE FUTURE UPGRADES

At present ISIS is the world's leading pulsed spallation neutron source, but the new higher power machines at SNS at Oak Ridge in the USA and J-PARC at Tokai in Japan will eventually overtake ISIS, and so it is natural to look at schemes to increase beam powers at ISIS. Several schemes have been proposed over the last few years.

180 MeV injection

One obvious method for increasing the beam power from the ISIS synchrotron is to inject at an energy significantly higher than the present injection energy of 70 MeV. To prevent the neutron users from being subjected to an unacceptably long down-time, the present linac could not be upgraded. Instead a new linac would have to be built and tested alongside the present linac before being connected to the synchrotron (and of course a new linac would remove the current reliance on a linac half of which is fifty years old[††]). The new linac would be built in an existing hall adjoining the present linac hall, but construction work could not begin until ~2010 when the MICE[‡‡] experiment should be complete. Studies of a new 180 MeV linac are described in [12].

It may not be unreasonable to expect that roughly twice as much charge could be trapped and accelerated for 180 MeV injection than for 70 MeV injection, *i.e.* 12 μC instead of the 6 μC assumed to be finally possible with the 2RF upgrade described above, and some of the ring R&D outlined above is intended to enable a better assessment to be made of such an injection scheme. Of course more RF power would have to be delivered to the RF cavities, but at present only ~30% of the RF power applied to the RF cavities actually goes into accelerating the beam, so the extra RF drive power required is not great and may largely be within the scope of the existing RF hardware. The overall result could be a beam power of ~0.5 MW at 50 Hz. The target for TS-2 is limited to ~50 kW, and the existing target in TS-1 could not take ~450 kW without substantial and operationally inconvenient modifications. But it would always be possible to build a third target station (TS-3) and split the 450 kW between TS-1 and TS-3 — there would then be an opportunity for some fifty neutron instruments at ISIS.

[††] Tanks 2 and 3 of the present 70 MeV linac were originally built in the mid-1950s by Metropolitan Vickers for the PLA (Proton Linear Accelerator) at the then Rutherford High Energy Laboratory.

[‡‡] See MICE section above.

1 MW upgrade

Upgrades based on a 3 GeV synchrotron fed by bucket-to-bucket transfer from the present ISIS 800 MeV have been well described in the past [13, 14], and so will not be repeated in detail here. The principle is to increase beam power by accelerating the present beam current up to a higher energy — taking the 300 μA eventually expected from the present ISIS synchrotron from 800 MeV up to 3 GeV will result in a beam power of ~1 MW. It should be noted that the TS-2 upgrade has been engineered to incorporate a useful take-off point to feed a 3 GeV synchrotron, and there is ample room for a 3 GeV synchrotron on RAL land south of TS-2. It is intended to set up a project at ISIS to consider this 1 MW upgrade option further, and perhaps at the same time to widen the range of options being considered.

A solid water-cooled target is certainly practical at these beam powers, but, of course, for liquid metal (mercury) targets, operation at beam powers of 1 MW and above assumes that present concerns [15] over limited target lifetimes due to cavitation problems can be overcome.

Multi-megawatt upgrades

Schemes for an ISIS multi-megawatt upgrade based on the same 3 GeV synchrotron mentioned above have also been well described in the past [13, 14], and so again will not be repeated in detail here, although it should be mentioned that one of the aims would be to continue use of the new ISIS Second Target Station, which is, as described above, optimised for cold neutrons. Suffice it to say that the 3 GeV synchrotron could be fed by two booster synchrotrons fed in turn by the 180 MeV linac outlined above. But quite a different scheme might be possible, based on the SNS and ESS principle of a high energy linac and an accumulation/compressor ring. Such options will be considered within the ISIS project mentioned above.

CONCLUSION

As well as providing a large international community of users in the fields of physics, chemistry, materials science, geology, engineering and biology with a world-leading spallation neutron facility, ISIS is at the same time also carrying out a substantial programme of technical upgrades, and underpinning operations by carrying out significant R&D programmes. The overall aim is to enable to keep ISIS operating as a world-class facility for another twenty years, and also to contribute to the development of a European next-generation spallation neutron source.

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