ISIS — PULSED NEUTRON AND MUON SOURCE

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Abstract

The ISIS pulsed neutron and muon source is described. Up to now the accelerators have delivered a 145–160 kW proton beam at 50 pps to a tungsten neutron-producing target preceded by a graphite muon-producing intermediate target. However a second target station is now being constructed, and the beam power from the accelerators is being increased so that the first target station will not suffer in performance when the beam has to be divided between two target stations.

INTRODUCTION

In terms of science output ISIS [1] is still currently the world's leading spallation neutron facility, although PSI [2] is world's most powerful spallation neutron source. However, SNS [3] has recently become operational, and J-PARC [4] should soon become operational, and so ISIS is likely to be overtaken in terms of power over the next year or two. Hitherto at ISIS 180–200 µA of 800 MeV protons at 50 pps have been used to drive one neutron-producing tungsten target and one muon-producing intermediate graphite target. But at present a second target station (TS-2) is being constructed [5], also with a tungsten target (but without an intermediate target), and when TS-2 becomes operational it will run at 10 pps while the original target station (TS-1) will run at 40 pps. At the same time upgrades are being carried out to ensure that when TS-2 becomes fully operational the mean beam current to TS-1 will not be less than it has been previously. Currently each year on average ~750 experiments are carried out involving ~1500 visitors who make a total of ~4500 visits[*]. These numbers include roughly ~100 experiments and ~300 visits for muons. A schematic layout of ISIS is shown as Figure 1.

ACCELERATORS

The ISIS accelerator system consists of the following. The ion source is a caesiated surface Penning H^- ion source, and sits on a high voltage platform at –35 kV. The ion source uses ~20 ml/minute of hydrogen gas and slightly less than ~1 g of caesium per week, and delivers ~50 mA H^- current pulses ~200–250 µs long at 50 pps. A 90° bending magnet separates H^- ions from electrons, a cold box is used to help trap Cs vapour, and the whole assembly is pumped by two 1000 l/s vacuum pumps. Typical ion source lifetimes are ~4 weeks, and the time to change an ion source is ~3 hours.

A three-solenoid magnetic LEBT is used to match the beam from the ion source to the RFQ (an electrostatic LEBT is not used because deposition of Cs from the ion source would encourage high voltage breakdown). The LEBT incorporates an emittance scanner, a 1000 l/s vacuum pump, and a pneumatically operated beam stop. The bore of the LEBT is 60 mm, but in practice it has been found that the bore is slightly too small and is effectively collimating the beam from the ion source.

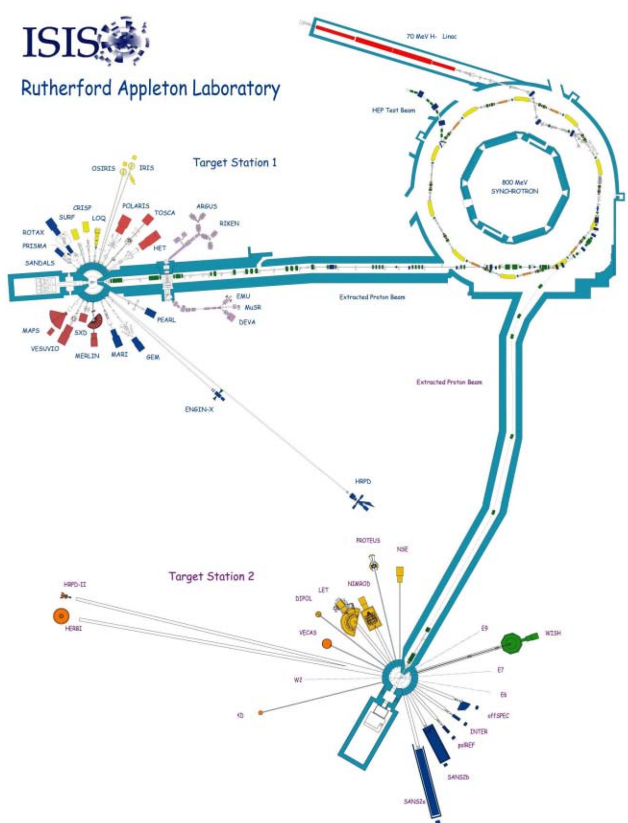

Figure 1: ISIS schematic layout.

A 4-rod 202.5 MHz RFQ accelerates tbe 35 keV H^- beam up to 665 keV. The RFQ was built at Frankfurt University as part of a collaboration between ISIS and Frankfurt University. The RFQ is driven by ~200 kW (peak) of RF from a Burle 4616 tetrode. The RFQ was installed on ISIS in 2004 to replace an ageing 665 kV Cockcroft-Walton DC preinjector. Before installation an off-line test stand [6] was built to characterise and soak-test the RFQ, and altogether some 2000 hours of running

[1] While the named author may have written this particular paper, all the work it summarises has been carried out by others, including D J Adams, G M Allen, M A Arnold, C J Barton, D L Bayley, R Brodie, T A Broome, J D Christie, M A Clarke-Gayther, M B Davies, P V Drumm, D C Faircloth, I S K Gardner, P E Gear, M G Glover, J A C Govans, N D Grafton, J W Gray, D J Haynes, S Hughes, H J Jones, A H Kershaw, M Krendler, C R Lambourne, A P Letchford, J P Loughrey, E J McCarron, A J McFarland, R P Mannix, T Noone, S J Payne, M Perkins, G J Perry, L J Randall, M J Ruddle, S J Ruddle, I Scaife, A Seville, A F Stevens, J W G Thomason, J A Vickers, S Warner, C M Warsop, and P N M Wright. The author takes full responsibility for any misrepresentation of the work of the aforementioned.

[*] On average, very roughly, each visitor visits ISIS three times a year.

were clocked up. An identical RFQ (which has been fully RF-conditioned) is held as a spare.

A 4-tank 202.5 MHz H^- Alvarez drift tube linac[†] accelerates the beam from 665 keV to 70 MeV. The beam current in the linac (and in the RFQ) is in the form of pulses typically 20–25 mA in amplitude and ~200–250 µs long. The drift tubes incorporate electromagnetic quadrupoles everywhere[‡], and the ability to make small changes to the focusing strengths has proved very useful in practice. Each tank is driven by ~2 MW (peak) of RF from one Thales TH116 triode fed by ~200 kW from a Burle 4616 tetrode. Tanks 1 and 4 were made in the 1970s and are essentially copies of Fermilab tanks. Tanks 2 and 3 were made in the 1950s and originally saw service as the second and third tanks of the PLA[§]. The RF is fed into each tank from a loop at the end of a ~30 cm diameter coaxial line through a cross-linked polystyrene vacuum window. A debuncher cavity driven by ~30 kW (peak) of RF is installed in the beam transport line between the linac and the synchrotron.

The ten-superperiod 163 m circumference rapidly cycling proton synchrotron (RCS) was built in the early 1980s in the hall originally occupied by the old 7 GeV proton synchrotron Nimrod. The ISIS synchrotron runs essentially in the h = 2 mode, although with the dual harmonic RF running [7] as described below an h = 4 component is added. Superperiods (SPs) 0 and 1 are used for charge exchange injection and extraction respectively, with SP1 also incorporating the collectors for beam collimation. SP1 is the most radioactive of the superperiods, and is surrounded locally by concrete shielding. The stripping foil in the synchrotron is 0.25 µm aluminium oxide, and on average foil lifetimes are many months. During the 10 ms acceleration cycle the synchrotron dipole magnets, fundamental frequency RF (1RF) and second harmonic RF (2RF) sweep over the ranges 0.18–0.70 tesla, 1.3–3.1 MHz and 2.6–6.2 MHz respectively. The main dipole magnets are each ~5 m long. Ceramic vacuum chambers[**] pass through each AC magnet and incorporate RF screens inside the chambers. With the 1RF only running some ~7% of the beam is lost at injection, and this lost beam, corresponding to a power of ~1 kW, is deposited on the collectors in SP1. However, with the dual harmonic RF (DHRF) running, the losses at injection have recently been shown to be roughly halved. The RF accelerating cavities are ferrite loaded, and the ~150 kW of RF for each cavity is provided by two Burle 4648 tetrodes driven by ~500 W solid state amplifiers. The bias current to vary the permeability of the ferrite varies between 200 and 2000 A across the 10 ms acceleration cycle. At the end of the 10 ms acceleration cycle the beam is extracted by six fast kicker magnets and a septum magnet as two proton pulses each ~100 ns long and with centres separated by ~320 ns.

Hitherto all the protons from the synchrotron have then been transported along a 155 m long extracted proton beam line (EPB-1) to TS-1, but a second proton beam line (EPB-2, 143 m long) is now being constructed into which one pair out of every fifth pair of proton pulses is deflected from EPB-1 by two new pulsed magnets [8] and a new septum magnet and transported to TS-2.

TARGETS

ISIS was originally built with a depleted uranium neutron-producing target, but in the early 1990s the target material was changed to tantalum, and then in 2001 to tantalum-coated tungsten. The target is essentially a series of plates cooled by heavy water, and a thermocouple on each plate is used to monitor the target temperatures. A beryllium reflector surrounds the primary target, and four moderators are placed close to the primary target. There are two water moderators at room temperature above the primary target, and two cryogenic moderators below, one liquid methane at 100°K, the other liquid hydrogen at 20°K. A photograph is shown in Figure 2.

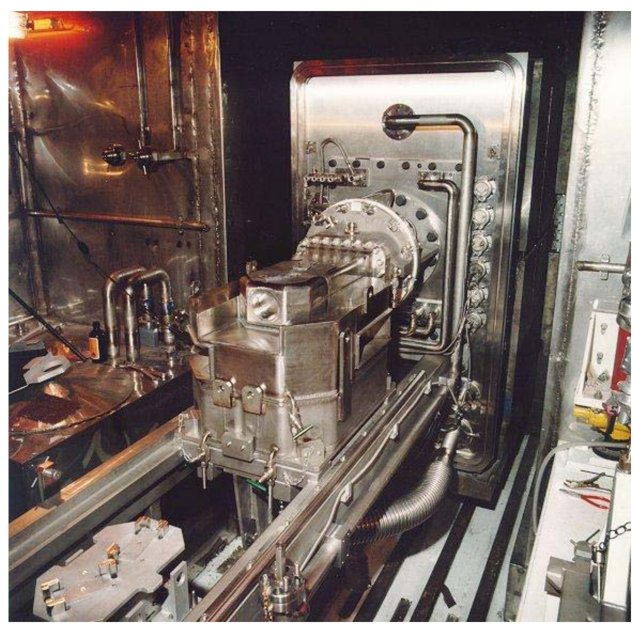

Figure 2: The tungsten target assembly in TS-1 — without the upper reflector and the two water moderators.

The intermediate target for muon production is a 1 cm thick graphite sheet oriented at 45° to the beam and located ~20 m upstream from the neutron-producing target (the proton beam produces pions in the graphite, and the pions decay to muons). In fact, three graphite sheets are mounted in a remotely movable ladder. The protons passing through the intermediate target are

[†] Four tanks: 665 keV – 10 MeV, 10 MeV – 30 MeV, 30 MeV – 50 MeV, and 50 MeV – 70MeV. The linac was originally built as a high energy injector for the 7 GeV proton synchrotron Nimrod, but before it could be used Nimrod was closed down.

[‡] Because of their small size the quadrupoles in Tank 1 are pulsed to reduce heat dissipation. The current pulses are ~1 ms long.

[§] The PLA (Proton Linear Accelerator) was manufactured by the Metropolitan Vickers Electrical Co. Ltd., and ran for ten years between 1959 and 1969.

[**] The ceramic vacuum chambers for the long dipoles were made as a series of relatively short straight "rectangular" ceramic pipes with angled ends then glass-jointed together vertically in a tall furnace.

scattered with an RMS multiple scattering angle of ~3 mrad, and a power of ~1 kW is dissipated. Although the graphite sheets are mounted in water-cooled frames, the graphite sheet in use is actually cooled mostly by thermal radiation. The muons are captured into two beam lines on either side of the graphite target. The forward-going scattered fluxes from the intermediate target are operationally inconvenient as they inevitably lead to undesirably high activation of beam line components downstream. A photograph of the intermediate target ladder is shown as Figure 3.

Figure 3: The intermediate target assembly — the ladder section is near the bottom of the assembly.

Muons (again from decay of pions) are also generated by a parasitic target intercepting a small fraction of the halo of the proton beam in SP7 of the synchrotron and used for the MICE[††] experiment [9] — an experiment intended to demonstrate that muons produced by pion decay from a high power proton accelerator can be cooled sufficiently to be successfully accelerated to GeV energies in neutrino factories.

SECOND TARGET STATION

The neutron instruments on the original ISIS target station (TS-1) have been over-subscribed for some time, 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[‡‡]. As described above, the beam for TS-2 is obtained by deflecting one pair of pulses out of every five pairs of pulses from the extracted proton beam line to TS-1, and so TS-2 will run at 10 pps while the repetition rate of TS-1 will be reduced from 50 pps to 40 pps. As also described above, the dual harmonic upgrade to the synchrotron RF is intended to produce an increase in beam current to compensate TS-1 for the loss of one out of every five pairs of pulses. At the time of writing (June 2007) the new proton beam line EPB-2 running to TS-2 is being connected to the synchrotron, and neutron instruments should be available for users by the end of 2008. 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 [5].

The primary target in TS-2 is a tantalum-coated tungsten cylinder 68 mm in diameter and 307 mm long. Unlike the TS-1 target the TS-2 target is not configured as a series of plates — it is a solid cylinder cooled through its surface (by heavy water). Such a design enables the moderators to be placed very close to the primary target, leading to significant gains in fluxes of moderated neutrons. A photograph of the apparatus for checking heat transfer from the TS-2 target is shown as Figure 4.

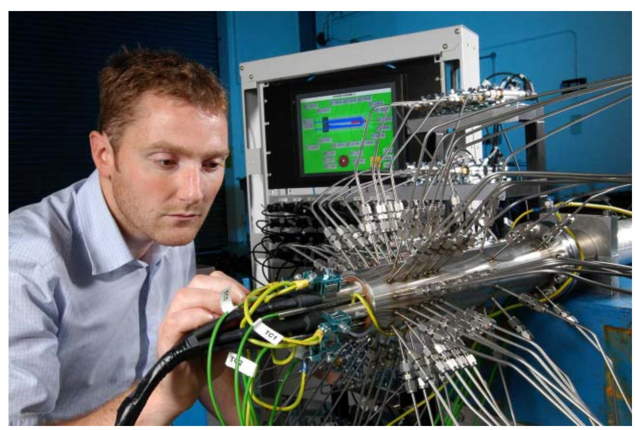

Figure 4: The solid cylindrical TS-2 primary target undergoing thermal tests.

OPERATIONS

The ISIS running pattern is roughly as follows. Typically each year there are five sequences each made up as follows: maintenance and/or shutdown period; ~1 week for machine physics and run-up; ~40-day user cycle (operating twenty-four hours a day, seven days a week); ~3-day machine physics period. Typically ISIS has run for 180 user-days a year; it is reckoned that 220 days is the maximum that could be tolerated without putting ISIS on to a fundamentally different basis.

Operationally, ISIS is run by a Crew made up of five teams of three people, and except during extended shutdowns when the evening and night shifts may be reduced from three to two people, the Crew is on shift 24

[††] Muon Ionisation Cooling Experiment, a world-wide collaboration.
[‡‡] The project was officially approved in April 2003.

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hours a day, 365 days a year. Each shift team is made up of a Duty Officer, an Assistant Duty Officer, and a Shift Technician. Outside normal office hours the Duty Officer is responsible for all operations on his shift, including user operations, and in addition he acts as the Radiation Protection Supervisor[§§]. There is a team of five health physicists, one of whom is on call outside normal office hours. In addition, there are ~30 people on call for the accelerator and target and ~15 for the neutron instruments and sample and environment issues who can be called in at any hour of the day or night to help resolve problems.

The control system for the ISIS accelerator and target hardware is based on a commercial product, Vsystem [10]. This system was chosen to ensure long-term continuity of support and development while minimising controls group staff numbers. The system has taken over from the original, interpreter-based system and currently allows access to over 10,000 control or monitoring parameters.

Over the past ten years the average availability of ISIS has been 89%, and the availabilities for each user cycle are distributed with a standard deviation of ±5%. The frequency distribution of the cycle availabilities is smooth, consistent with the view that accelerator and target downtimes are due essentially to random selection amongst a large number and wide variety of different causes. Very roughly, averaged over time, ~80% of the downtime is due to the accelerator systems, and ~20% to the target systems.

OBSOLESCENCE MITIGATION

After it has been operating for several years, the equipment in any large accelerator facility gradually becomes obsolete. Most of the equipment in ISIS has been running for ~25 years, and some of the equipment was already second-hand when ISIS was built. Accordingly ISIS is currently running an obsolescence mitigation programme running at an annual rate of ~5–10% of the current net book value.

Work carried out under the programme includes the following. The AC current for the main synchrotron magnets is generated at present 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 line to the kicker magnets, but the new kickers (see Figure 5) will run at up to 52 kV. The anode power supplies for the 202.5 MHz linac RF systems are being replaced and upgraded; the four 200 kW intermediate amplifiers already have new anode power supplies, and a prototype new anode power supply system has already run successfully on one of the 2 MW final amplifiers. Partly because of issues connected with the second target station, 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. See also [11, 12, 13, 14].

Figure 5: The new drivers for the fast kickers.

ACCELERATOR R&D

Primarily to underpin ISIS accelerator operations, an accelerator R&D programme is being carried out, and is briefly described below.

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, 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 chopped H^- beams. The test stand is building on experience gained through the design, construction and operation of the off-line 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 LEBT, a four-vane 3 MeV 324 MHz RFQ [15], a beam chopper with <2 ns switching times [16], and a comprehensive set of diagnostics. The work is being carried out collaboratively[‡‡‡], and is described much more fully in [17].

[§§] Supervising any work carried out in a radiologically designated area.
[***] In fact four UPSs are installed, but the fourth serves as a hot spare.
[†††] In fact twelve chokes are being bought — two to serve as spares.

[‡‡‡] With Imperial College, London, the University of Warwick, and the University of the Basque Country.

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Ring R&D

The mechanisms which are responsible for beam loss, and which thereby potentially limit the intensity of the ISIS proton synchrotron, are not fully understood. Since the ISIS synchrotron is one of the few machines world-wide where some of these important loss mechanisms can be studied experimentally, a series of theoretical and experimental work programmes has been launched. In particular, and summarised as contributions to this conference, studies on optimising injection [18] and of space charge loss mechanisms [19] are being carried out.

In addition, collaborative[§§§] work is being carried out at ISIS on developing low output impedance (LOI) amplifiers to drive RF cavities. While not specifically necessary for the RF systems currently in use 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 [20].

ISIS Upgrades

Over the past ten years or more much work has been carried out on new high power spallation neutron sources for Europe — *e.g.* the ESS [21]. However, at the same time, it has been only sensible also to look at upgrade options to existing European neutron sources. As regards ISIS, upgrades based on a 3 GeV synchrotron fed by bucket-to-bucket transfer from the present ISIS 800 MeV synchrotron have been well described in the past (*e.g.* refs. [22, 23]), but work continues, and a promising design for a new high performance 3 GeV synchrotron has come out of the International Scoping Study (ISS) Report presented at NuFact-06 [24]. In fact this design also accommodates multi-turn charge exchange injection, and so a subsequent upgrade stage where the 3 GeV synchrotron is fed by a 400–800 MeV linac is also possible. A solid water-cooled target is certainly practical at beam powers up to 1 MW, but, of course, for liquid metal (mercury) targets, operation at beam powers of 1 MW and above assumes that present concerns over limited target lifetimes due to cavitation problems can be overcome.

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