Science and Technology Facilities Council

# A Practical Guide to the ISIS Neutron and Muon Source

# Contents




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# Welcome

Late on the evening of 16 December 1984, a small group of people crammed into the ISIS control room to see history in the making – the generation of the first neutrons by the nascent particle accelerator.

Back then, ISIS was a prototype, one of the first spallation sources built to generate neutrons for research. The machine included just three experimental instruments, although there were always ambitious plans for more! In 1987 three muon instruments expanded the range of tools available to the global scientific community.

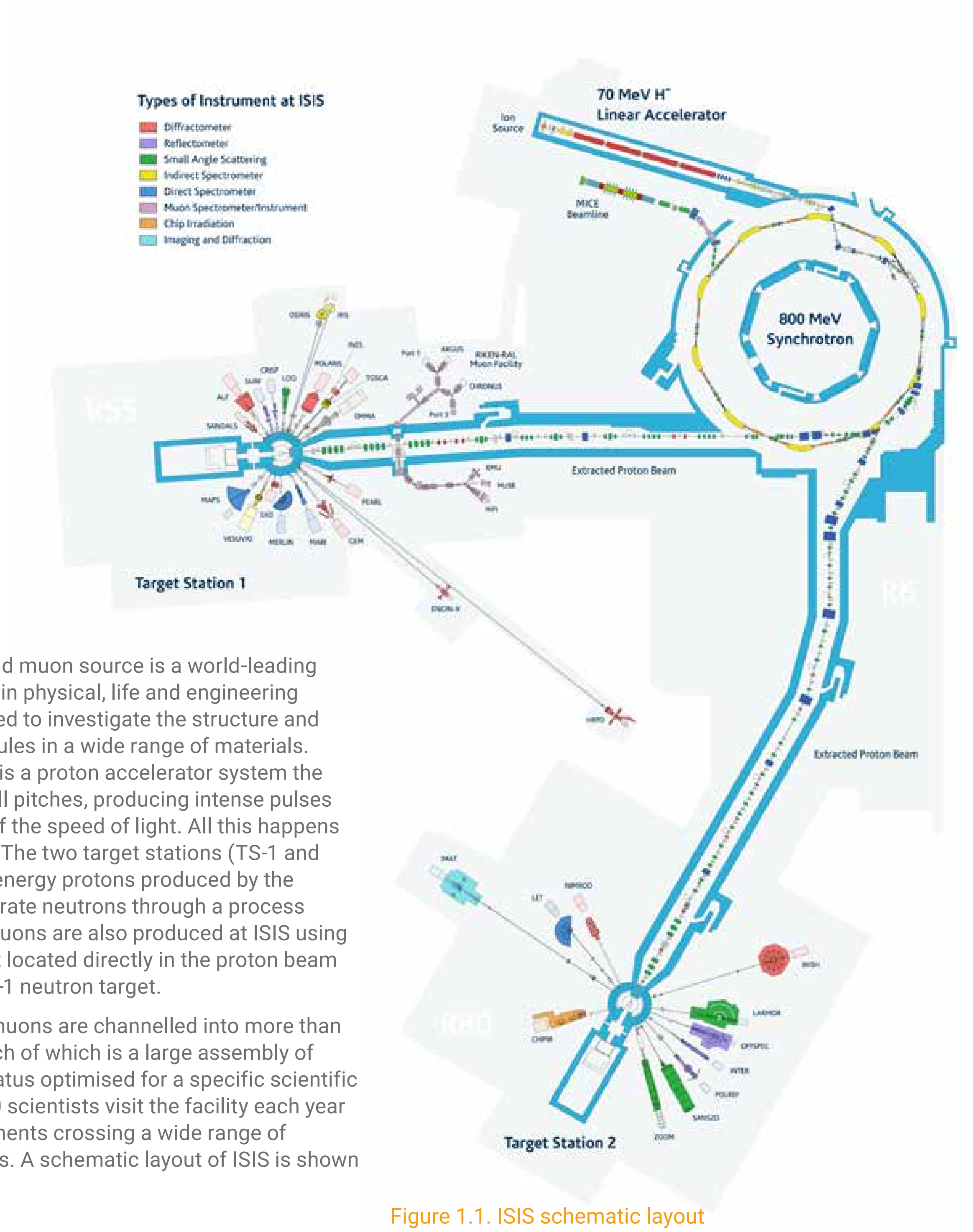
Since then we have built over 30 new instruments, not to mention a whole new target station! ISIS has grown in size and in strength to support a dynamic international user community of over 3,000 scientists, and over 15,000 papers have been published across a wide range of scientific disciplines. Spallation sources are widely established, a complementary tool to reactor based facilities and photon sources, forming a vital part of the global scientific infrastructure.

This was made possible by the engineers, scientists and technicians who design, build and operate the machine. Their innovation and dedication, rising to every challenge from incremental developments to major projects underpins all the science ISIS has enabled. This book is dedicated to them.

**John Thomason,** ***Accelerator Division Head***

# Introduction

**"...One of the most extraordinary machines ever built."**
**The Guardian**




The ISIS neutron and muon source is a world-leading centre for research in physical, life and engineering sciences, and is used to investigate the structure and dynamics of molecules in a wide range of materials. At the heart of ISIS is a proton accelerator system the size of eight football pitches, producing intense pulses of protons at 84% of the speed of light. All this happens 50 times a second. The two target stations (TS-1 and TS-2) use the high energy protons produced by the accelerator to generate neutrons through a process called spallation. Muons are also produced at ISIS using a thin carbon target located directly in the proton beam upstream of the TS-1 neutron target.

The neutrons and muons are channelled into more than 30 instruments, each of which is a large assembly of complicated apparatus optimised for a specific scientific purpose. Over 3000 scientists visit the facility each year to carry out experiments crossing a wide range of scientific disciplines. A schematic layout of ISIS is shown in Figure 1.1.

Figure 1.1. ISIS schematic layout



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# Why do we need ISIS?
# An overview of scientific applications

ISIS has a community of 3000 scientific users publishing over 600 papers a year. These cover a wide range of applications from new industrial materials to understanding cultural heritage, and from imitating nature to improving pharmaceuticals. This is just a sample of ISIS research that has led to benefits for society and the economy alongside blue skies research where the potential has yet to be realised.

## Advanced materials for the future

The development of new materials underpins technological advancement. Neutrons and muons provide valuable information on how the structure of atoms and molecules affects the properties of materials on a larger scale. This makes it possible to design materials from their building blocks for use in, for example, new types of batteries, cleaner energy sources and increased data storage.

## Biomimetics – inspired by nature!

Scientists have used a range of ISIS instruments to study how biological materials can have properties that are better than any we can manufacture on an industrial scale. This has included studying the webs of golden orb spiders, a frog that doesn't freeze at sub-zero temperatures and the whiteness of beetle scales and polar bear fur.

## Engineering materials without compromising safety

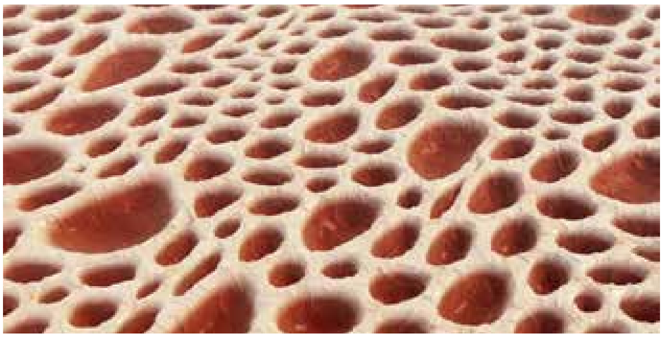
Any new materials designed to reduce environmental impact must meet, or exceed, stringent safety standards. In addition, materials used in engineering applications must be able to withstand extreme operating conditions such as high temperatures and pressures, or exposure to potentially corrosive environments. Scientists have used ISIS to understand how industrial materials can be made cheaper, greener and more efficient without compromising safety.

## Cleaner, greener transport

We are in a race against time to relinquish our dependence on fossil fuels. Scientists have used ISIS to study lighter engineering materials and greener industrial processes; improving efficiency and reducing waste heat. Hydrogen has potential as an alternative energy vector, especially in the automotive industry, but there are challenges to widespread usage. Neutrons and muons have been used extensively to look for solutions to this complex issue.

### Fixing broken bodies

An international team of scientists used the facility to discover a new material that can be 3D printed to create tissue-like vascular structures that could rebuild or repair damaged body tissue. The facility has also been used to study a non-surgical treatment for cleft palates, synthetic lung surfactants for premature babies and materials for longer lasting implants.



### Measuring Martian meteorites

A collaboration of scientists from organisations including the Natural History Museum came to IMAT to map the phases of Martian meteorites in 3D.

### Understanding seed storage with Kew Gardens

After an encounter at a conference, researchers from the Royal Botanic Gardens, Kew, visited the IRIS instrument to trial a technique that could help them determine how long they can store seeds for.

### Probing beneath the surface without leaving a scratch

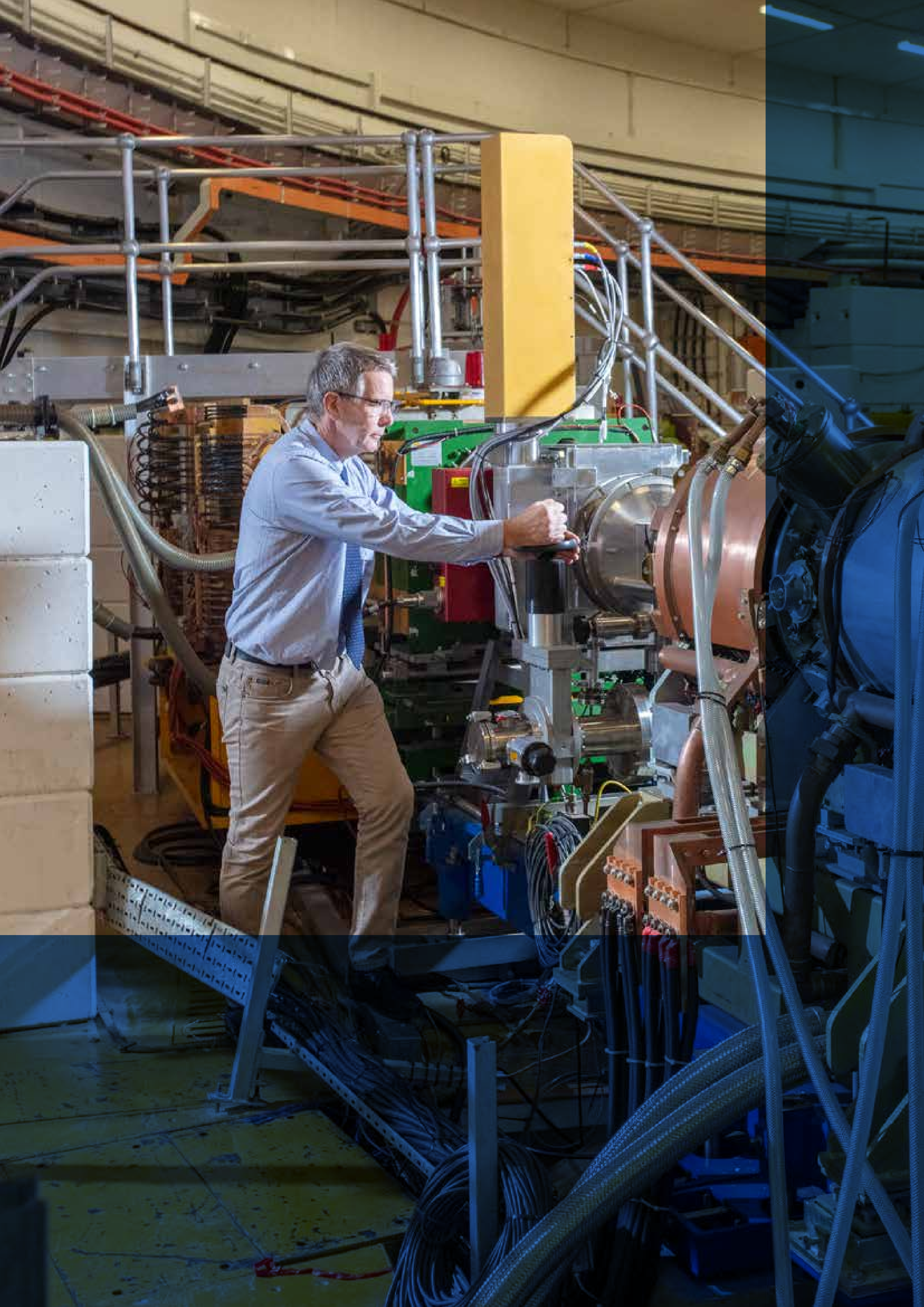
Scientists at ISIS have developed techniques that allow them to use neutrons and muons to probe the composition of ancient objects in three dimensions without damaging them, even looking deep beneath the surface. This helps us understand how they were made and used, and informs how we can protect important cultural artefacts.

### Could thermal neutrons be a threat to reliable supercomputing and self-driving cars?

In addition to the known effects of high-energy neutrons on electronic devices, which can be measured using ChipIr, scientists have been able to use another ISIS beamline to study the effect of thermal neutrons on commercial computing devices. They found that the failure rate due to thermal neutron damage in some environments is high enough to be a significant threat to systems in driverless cars, medical applications and supercomputing.

“Through the studies of atomic structure and dynamics made possible by Bertram N. Brockhouse and Clifford G. Shull with their development of neutron scattering techniques, valuable information is being obtained for use in e.g. the development of new materials.”

**Committee awarding the 1994 Nobel Prize for Physics for the development of neutron scattering**



# Production of neutrons and muons — in general

Neutrons don't live long in a free state in nature — the half-life of a free neutron is just 10 minutes. In practice, neutrons are found locked up inside atomic nuclei, but liberating the neutrons requires a great deal of effort. There are currently two ways to produce high numbers of neutrons — nuclear reactors and particle accelerators.

Muons are also produced at ISIS. They are unstable subatomic fundamental particles that live only for a short time – their mean lifetime (at rest) is only 2.2 μs. Muons are created in the atmosphere, where cosmic rays collide with atomic nuclei, generating pions. However, in order to obtain higher intensities, muons can also be produced by firing high energy protons from a particle accelerator into a target (at ISIS a graphite target). The protons from the accelerator interact with the protons in the target creating pions, which rapidly decay to produce muons.

Neutrons and muons provide highly complementary information about the nature of materials.

Table 1.1. Examples of large neutron sources.

| Source type | Examples | Power (MW) | Typical approximate neutron output ($s^{-1}$) |
|---|---|---|---|
| Proton accelerator | CSNS | 0.1 | $1\times10^{16}$ |
| | ESS (~2023) | 5 | $1\times10^{18}$ |
| | ISIS | 0.2 | $2\times10^{16}$ |
| | J-PARC | 1.0 | $1\times10^{17}$ |
| | Los Alamos | 0.1 | $1\times10^{16}$ |
| | PSI (not pulsed) | 1.3 | $1\times10^{17}$ |
| | SNS | 1.3 | $1\times10^{17}$ |
| Reactor | ILL, Grenoble | 58 | $1.5\times10^{15}$ flux ($cm^{-2}\ s^{-1}$) |
| | HFIR, ORNL | 85 | $2.5\times10^{15}$ flux ($cm^{-2}\ s^{-1}$) |

Most accelerator sources of neutrons are pulsed sources. Generally, for relatively low-output sources, a proton or deuterium particle beam hitting a target of low atomic number such as lithium or beryllium is the most efficient, but for high-output sources the most efficient route for the production of neutrons is proton-induced spallation. Nuclear reactors are highly reliable sources of neutrons (reactors are steady-state neutron sources, not pulsed sources), but reactors are incurring ever-increasing regulatory overheads.

There is, however, more to a successful neutron-scattering facility than simply high output. Other important factors include neutron pulse widths, flight path lengths, detectors for measuring the scattered neutrons, and the provision of technical support for accommodating samples of material being investigated. ISIS TS-2 may be currently running only at the modest power of 32 kW, but it produces world-leading science.

## 2.1 Neutrons from spallation

In proton-induced spallation, a beam of high-energy protons strikes a heavy metal target — tantalum, tungsten, mercury, lead, or even uranium. A high-energy proton hitting a heavy-metal nucleus can knock a few particles or clusters of particles out of the nucleus and can also split the rest of the nucleus into two excited fragments. The fragments then de-excite by emitting neutrons with energies of the order of 1 MeV, and the knocked-out particles can go on to induce further spallation reactions (see Fig. 2.1). The overall result at ISIS is some ~10-15 neutrons produced per incident proton.

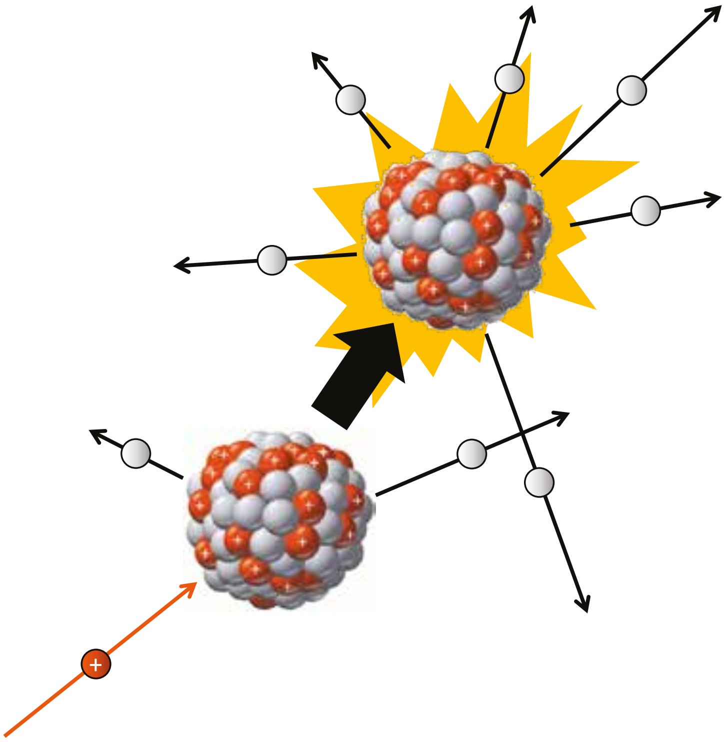


Fig. 2.1. Schematic representation of proton-induced spallation of a heavy nucleus giving rise to neutrons (shown in white).

**The ~200 μA of beam current delivered to the ISIS targets corresponds to $1.25\times10^{15}$ protons per second, and therefore some $2\times10^{16}$ neutrons per second are produced by ISIS.**

## 2.2 Moderators and reflectors — optimising the neutrons for the instruments

The neutrons emitted from spallation targets have energies of the order of 1 mega-electron-volt (MeV), whereas the instruments for looking at the structure of materials require neutrons with energies in the milli-electron-volt to electron-volt (meV – eV) region — some seven or eight orders of magnitude less. Not only that, the neutrons come out of the target in all directions, and need to be channelled into the instruments used by the scientists.

To achieve the necessary reductions in energy, i.e. to moderate the neutrons, the target is surrounded by moderator(s) made from low-atomic-number material in which neutron absorption is small. As the primary neutrons enter the moderator they rapidly lose energy by scattering repeatedly off the light nuclei (see Fig. 2.2). After a sufficient number of collisions, the neutrons achieve thermal equilibrium with the moderator material.The moderator(s) are surrounded by a reflector to try to return to the moderator neutrons that have started to scatter out of the moderators, and of course neutron absorption in the reflector must also be small to limit the number of neutrons lost. Reflectors are often made from either beryllium or heavy water — both are weak absorbers of neutrons.

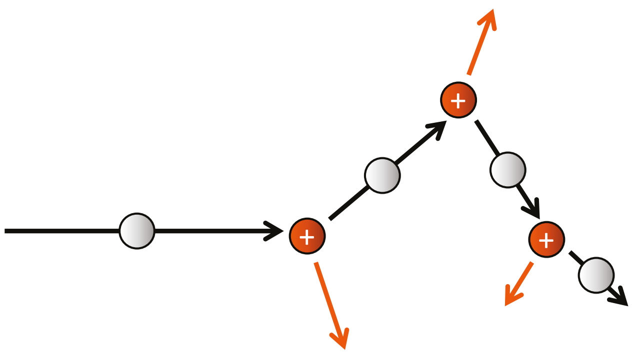


Fig. 2.2. Schematic representation of neutron moderation. Neutrons (white) undergo successive collisions with recoiling hydrogen atom nuclei (red), slowing them down. After some 14 collisions in hydrogen, neutrons with energies in the MeV region slow down to energies in the meV – eV region.

**The moderator material has a low atomic number so that the neutrons lose energy as quickly as possible, and absorption has to be small so that as few neutrons as possible are lost during the moderation process.**

These neutrons (now with energies in the meV – eV range) are used by the scientists in their instruments at ISIS, and the atoms and molecules in samples of materials placed inside these instruments scatter some of the neutrons into detectors surrounding the samples. The spatial distributions and energy distributions of the scattered neutrons can then be related to arrangements of atoms and molecules inside the samples (see Fig. 2.3).

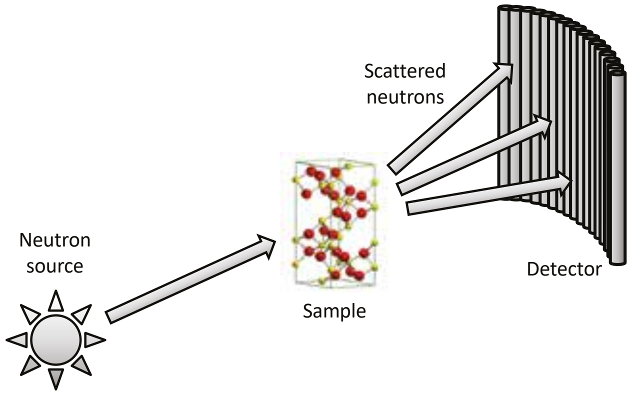



Fig. 2.3. Schematic representation of neutron scattering.

## 2.3 Muon production

Unlike neutrons, muons are not found inside atomic nuclei — instead they have to be produced on demand as tertiary particles. Protons (the primary particles) in the ISIS TS-1 proton beam generate pions (the secondary particles) in a ~1 cm thick graphite target, and after one or two tens of nanoseconds these pions decay into muons (the tertiary particles) some of which are captured by the ISIS muon facility (see Fig. 2.4). These muons can then be used to measure atomic structure by observing their patterns of decay after their capture within samples of material.

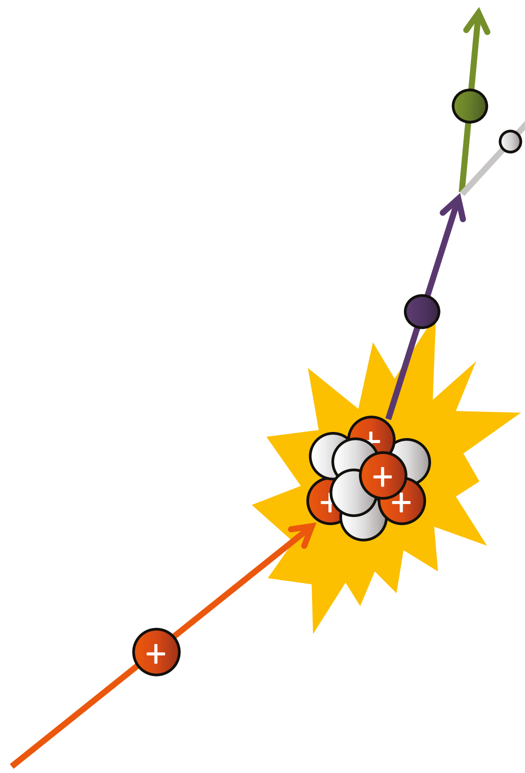


Fig. 2.4. Schematic representation of muon production. Protons (red) generate pions (blue) in a graphite target, which then decay to muons (green) and neutrinos (grey).

“From the original vision over 30 years ago, ISIS has become one of the UK’s major scientific achievements. As the world’s leading pulsed neutron and muon source, ISIS has changed the way the world views neutron scattering and has delivered major social and economic benefit for the UK and global economies.”

**Technopolis – ISIS Lifetime Impact Study 2014**

# Production of neutrons and muons – at ISIS

At ISIS protons are delivered to the neutron- and muon-producing targets in the two target stations as beams of 800 MeV protons. TS-1 and TS-2 receive 40 and 10 pulses per second (pps) respectively, and the mean proton currents delivered to the targets are ~180 and ~45 μA respectively. TS-1 therefore receives four times the number of pulses as TS-2, but for both targets the charge in each pulse of protons is ~4.5 μC or ~$2.8 \times 10^{13}$ protons.

Although the machine was designed for a maximum of 184 μA, it now runs routinely at up to 250 μA — a testament to the excellence of its designers.

The production of the 800 MeV proton beam is achieved in essentially four stages: ion source, RFQ, linac, and synchrotron as shown schematically in Fig. 3.1. Only in the synchrotron are beams of protons accelerated — elsewhere the particles accelerated are $H^-$ ions — protons with two orbiting electrons so that their overall electrical charge is negative. Charge-exchange injection, when the $H^-$ ions entering the synchrotron are converted to protons, is described in more detail below.

The RFQ, drift tube linac (DTL) and synchrotron are all accelerators using radiofrequency (RF) power. All RF-based accelerators produce bunched beams in which the bunch structures reflect the RF frequencies — RF-based accelerators do not produce truly continuous beams.

Throughout the entire $H^-$/proton acceleration process, the beam must be kept under good vacuum. Accordingly, many tens of vacuum pumps are used, and vacuum is maintained typically between $10^{-8}$ and $10^{-9}$ of atmospheric pressure.

**The ISIS vacuum pumps are either turbomolecular pumps with rotary backing pumps, or ion pumps. Turbomolecular pumps actually pump gas out to the atmosphere, whereas ion pumps 'hide' gas under the surfaces of their electrodes, and as a result have a finite pumping capacity.**

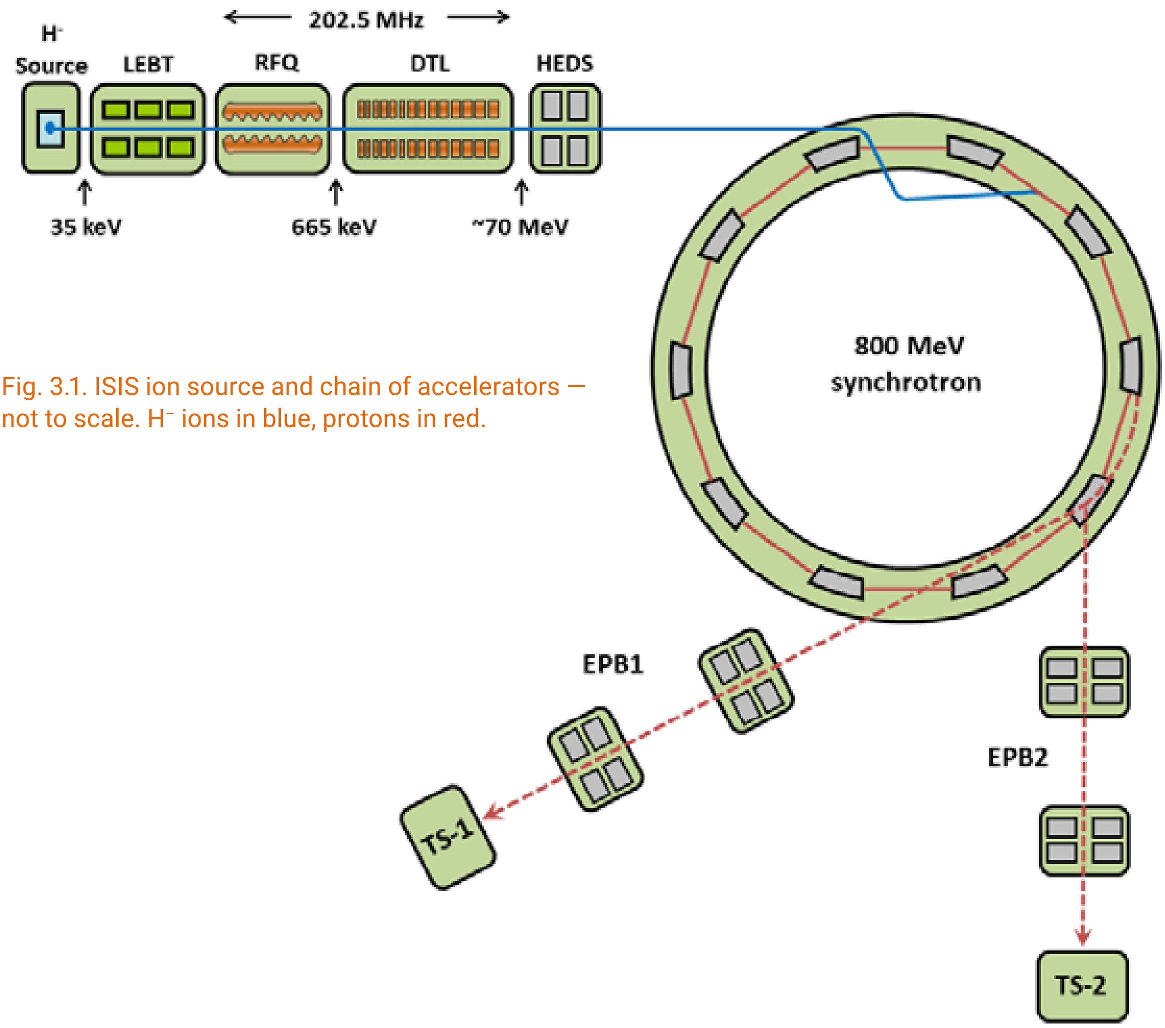



Fig. 3.1. ISIS ion source and chain of accelerators — not to scale. $H^-$ ions in blue, protons in red.

## 3.1 Ion source

The first stage of the ISIS machine is the ion source. This generates the negative hydrogen ($H^-$) ions that are accelerated through the RFQ and linac.

The ISIS ion source is a pulsed source of $H^-$ ions. Hydrogen gas can easily be ionised by arranging for an electric discharge to take place between an anode and a cathode inside a stream of hydrogen gas. Although a few $H^-$ ions and neutral hydrogen atoms ($H^0$ atoms) are produced in this way, most of the hydrogen ions that are produced are positively-charged ($H^+$ ions, i.e. protons), and their electric charge is balanced on average in the ionised gas by the same number of negatively-charged electrons. In order to increase the number of $H^-$ ions, it is necessary to make an effort to 'add' electrons to the protons in the ionised gas. This is achieved by 'encouraging' the cathode to emit as many electrons as possible, so that more electrons latch on to the protons to produce $H^-$ ions. Electron emission from a metal surface is stimulated by coating the metal with a material that emits electrons easily, and in the ISIS ion source this material is caesium — a volatile and chemically reactive Group-1 element.

A photograph of the ion source is shown in Fig. 3.2, and a cross-section through the 'heart' of the source is shown in Fig. 3.3.

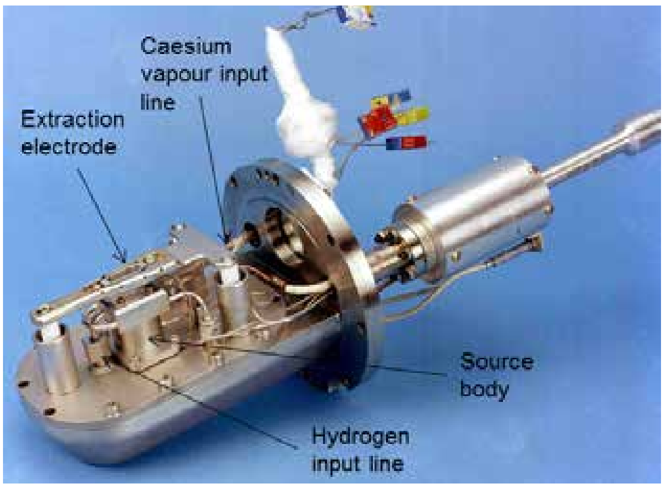



Fig. 3.2. The heart of the ISIS ion source assembly. The source body is shown in more detail in Fig. 3.3.

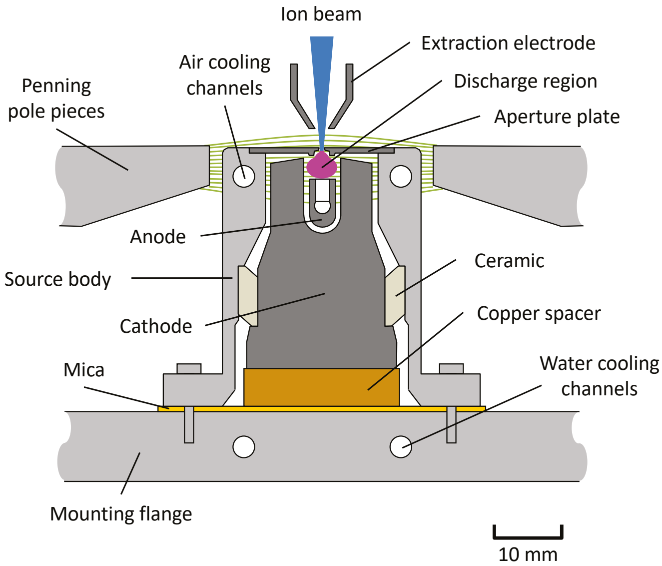



Fig. 3.3. A cross-section through the ISIS ion source. The discharge region is roughly the size of a peanut.

**When the ion source is operating, some 20 ml of hydrogen gas per minute is continuously delivered to the ion source from a hydrogen gas bottle.**

In operation, a stream of hydrogen gas with a little caesium vapour is delivered to the ion source. Since the ion source is vacuum-coupled to the rest of the accelerator system, it is necessary to remove the hydrogen gas and caesium vapour after they have fulfilled their purpose. If caesium vapour drifted into the rest of the accelerator system it could condense on high-voltage surfaces and promote undesirable electrical sparking. The ion source assembly is therefore continuously pumped by two large turbo-molecular vacuum pumps, and incorporates a refrigerator for cooling an internal surface onto which the caesium vapour is condensed.

When the ISIS ion source is running, $H^-$ ions and unwanted electrons are pulled out of the ionised hydrogen gas by a positively-charged extraction electrode. A 90° bending magnet is incorporated in the overall ion source assembly, and this is used to separate the electrons from the $H^-$ ions and remove them. The ion source assembly sits at a steady DC voltage of -35 kV. When the $H^-$ ions emerge from the earthed structure of the ion source assembly, they therefore have an energy of 35 keV and are ready to be presented to the RFQ via the Low Energy Beam Transport line (LEBT).

The LEBT consists essentially of three solenoid magnets that prevent the low-energy $H^-$ beam from increasing in size due to mutual repulsion of the $H^-$ ions ('like charges repel'). The magnet assemblies incorporate small steering magnets so that the $H^-$ beam can be aimed properly at the input aperture of the RFQ (see Section 3.2). The LEBT also incorporates a beam stop — basically a remotely movable sheet of metal that can be used to physically block the beam.

**The electron making a neutral hydrogen atom into a negatively-charged hydrogen ion is not strongly bound. Whereas it takes 13.6 eV of energy to remove the electron from a neutral hydrogen atom, it takes only 0.75 eV to remove the 'second' electron from a negatively-charged hydrogen ion**

## 3.2 RFQ

The ISIS RFQ (radio-frequency quadrupole) uses intense radio frequency electric fields to focus, bunch and accelerate the $H^-$ beam. It is located a metre or two downstream from the ion source and immediately upstream of the linac. The 665 keV RFQ is a replacement for the 665 kV Cockcroft-Walton DC voltage multiplier set used on ISIS up to 2004.

**Manufactured at Frankfurt University, the RFQ was extensively soak-tested off-line at RAL in R8 before installation on ISIS. The testing proved invaluable in that it provided an opportunity to eliminate teething troubles that would have caused severe embarrassment if the RFQ had been installed straight-away on ISIS.**

The essence of an RFQ is a transverse oscillating electric quadrupole field set up by four rods (hence 'quadrupole'). The net effect is to provide focusing forces to prevent the beam expanding due to the mutual repulsion of the $H^-$ ions. If each of the rods had a circular cross-section independent of length, the 35 keV $H^-$ beam could be kept going indefinitely. However, to obtain acceleration, 'wiggles' in the form of physical modulations of the cross-sections of the rods are gradually added to the electrodes producing the quadrupole field. This modulation both bunches and accelerates the beam because of the resultant longitudinal component of the electric field (see Figs. 3.4 and 3.5). The RFQ runs at the same RF frequency as the linac and is phased-locked to the linac RF systems. This ensures that the RFQ presents a bunched beam to the linac that matches exactly the expectations of the linac. In practice, the RFQ effectively decouples the ion source from the linac, thereby reducing the extent of variations in the beam in the linac, synchrotron, EPBs and on targets caused by changes in the ion source. The RFQ is powered by a 200 kW tetrode RF amplifier that is identical with the intermediate stage of the RF systems for the linac tanks.

**The Cockcroft-Walton DC voltage multiplier set was manufactured by Haefely in Switzerland and rated at 750 keV. A separate buncher cavity between the DC voltage multiplier and the linac was used to 'pre-bunch' the beam to match the expectations of the linac.**

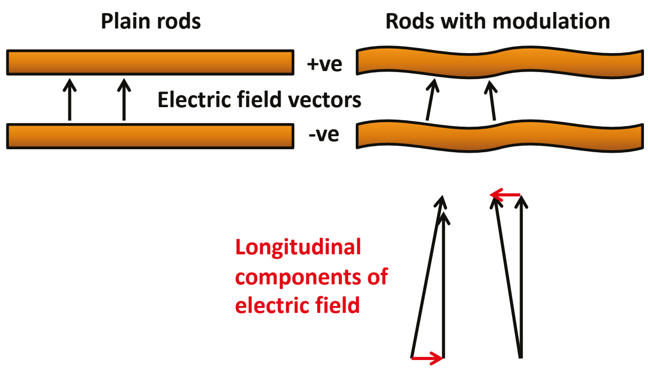
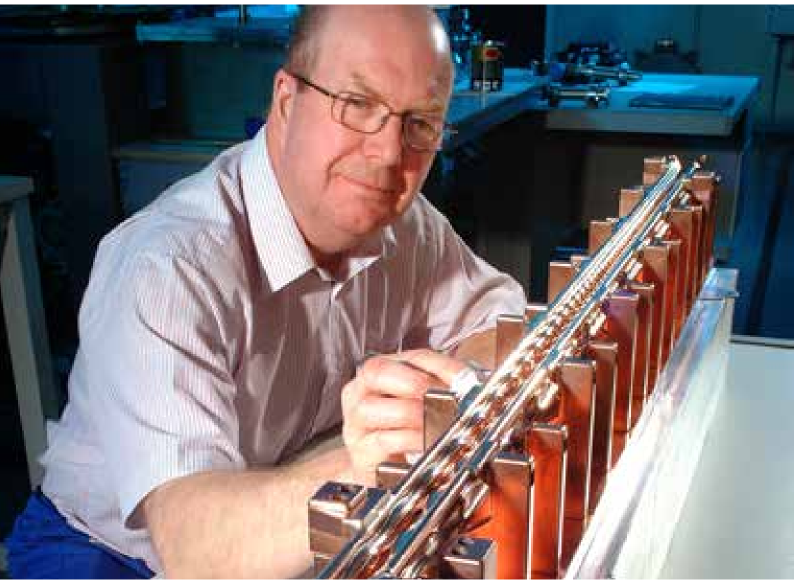



Fig. 3.4. Schematic illustration of electric fields between two RFQ rods. Left-hand side, focusing only; right-hand side, 'wiggles' create longitudinal component of electric field to accelerate and bunch particles.



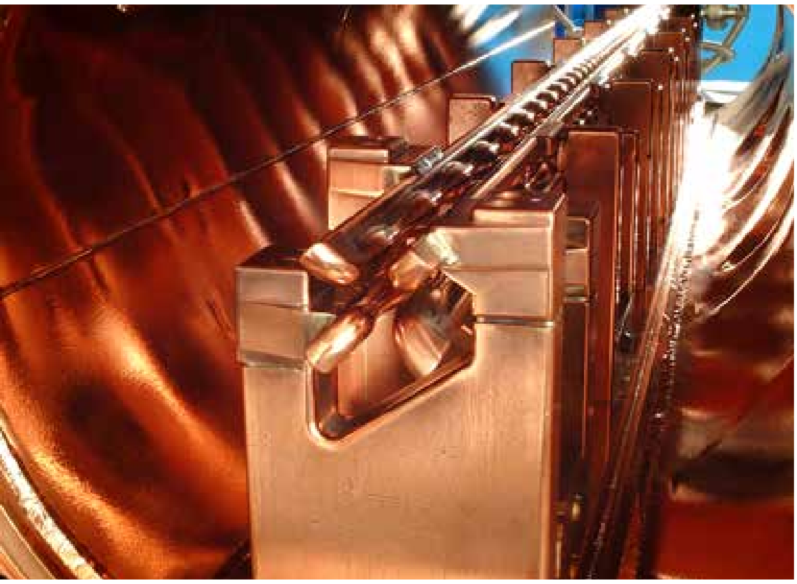


Fig. 3.5. The ISIS RFQ showing the four-rod assembly both outside and inside its copper-plated stainless-steel vessel. The four rods generate the quadrupole focusing field, and the modulations that gradually increase bothin depth and in wavelength produce the bunching and acceleration.

## 3.3 Linac

The linac consists of four accelerating tanks (as described in Table 3.1) in which high intensity radio-frequency (RF) fields accelerate the beam to 70 MeV. While it is possible to accelerate particles up to energies of the order of 10 MeV using DC voltages, energies significantly in excess of 10 MeV can only be reached by using RF accelerators in which the same voltages are effectively used again and again.

**The ISIS linac was originally envisaged as a new injector linac delivering 75 mA proton pulses at ~1 pps to the old Nimrod 7 GeV proton synchrotron. Tanks 2 and 3 of the ISIS linac were the second and third tanks of the Proton Linear Accelerator (PLA) built by Metropolitan Vickers which began running at RAL in the 1950s. Tanks 1 and 4 are essentially copies of linac tanks designed at Fermi National Accelerator Laboratory in the USA. (Originally, the PLA was going to be a 600 MeV linac, and was going to stretch most of the way down Fermi Avenue ('the runway')). The Alvarez type of linac was developed in the 1940s. See L W Alvarez, Phys. Rev. 70 (1946) 799.**

ISIS uses an Alvarez-type linac, in which $H^-$ ions are accelerated between the ends of successive hollow copper drift tubes laid out in a ~40–50 m long line. The ISIS 70 MeV linac is located in R5.1, and runs at an RF frequency of 202.5 MHz. The line of drift tubes is enclosed in four large copper cylinders or tanks. The whole structure is arranged to be highly resonant (Q's of ~50000) at the operating RF frequency, in order to develop the necessary high voltages between the drift tubes. The tank structures are sufficiently resonant that their dimensions must be very precisely determined by controlling the temperature of the tank cooling water to <<1°C, essentially eliminating the effects of thermal expansion and contraction.

As the tanks are resonant structures inside which the RF voltages and currents are oscillating, half the time the electric fields between the drift tubes are pointing the wrong way and so would decelerate rather than accelerate the beam. At these times it is arranged that the $H^-$ ions are hidden inside the copper drift tubes and so do not 'see' the backwards-pointing electric fields. Because the particles are accelerated during one half-cycle (2.47 ns) of the RF fields, the drift tubes and the gaps between the drift tubes have to become successively longer, as the $H^-$ ions are accelerated and travel greater distances during each half cycle. (Eventually, as energies increase, the drift tubes in a linac of the ISIS type become inefficiently long.)

As with all charged-particle accelerators, it is necessary to provide focusing forces to prevent the beam expanding. In a drift-tube linac the focusing elements are quadrupole magnets located inside the drift tubes. Photographs of Tank 3 are shown in Figs. 3.6 and 3.7.

**To limit power dissipation, the quadrupoles inside the short Tank 1 drift tubes are driven by pulsed power supplies.**

| Tank | Accelerates between | Length | Manu-factured | No. of drift tubes | Separate RF liner? |
|---|---|---|---|---|---|
| 1 | 0.665–10 MeV | 7.2 m | 1970s | 55 + 2×½ | No |
| 2 | 10–30 MeV | 12.0 m | 1950s | 40 + 2×½ | Yes |
| 3 | 30–50 MeV | 11.2 m | 1950s | 26 + 2×½ | Yes |
| 4 | 50–70 MeV | 12.1 m | 1970s | 23 + 2×½ | No |

Table 3.1. Outline parameters of the ISIS 70 MeV linac. Each tank has a half drift tube at each of its two ends. In Tanks 1 and 4, the inner surface of the vacuum vessel carries the RF wall currents that enable the tank to resonate. In Tanks 2 and 3, the wall currents are carried by a separate liner, and the only function of the vacuum vessel is to maintain the vacuum.

Fig. 3.6. Tank 3 with both the upper half of the steel vacuum vessel and the upper half of the copper RF liner removed.

Fig. 3.7. The interior of Tank 3 showing the long line of drift tubes; each drift tube is supported by two legs and incorporates a 3 cm diameter hole through which the $H^-$ beam passes. The upper half of the copper RF liner is in place in this photo.

A crystal-controlled oscillator provides high-stability low-power 202.5 MHz RF for the linac as a whole (and for the RFQ). Four chains of three RF amplifiers drive the linac tanks, one chain to each tank (see Fig. 3.8). Each chain of amplifiers consists of a 3 kW solid-state amplifier, a 200 kW tetrode intermediate-power driver stage, and a 2 MW triode high-power output stage. These powers are peak powers, i.e. the power when the RF is present. Since the RF is present for only ~2% of all time (the RF is produced in ~400 μs pulses 50 times a second), the mean powers are ~2% of the peak powers.

Each output stage is a coaxial triode running in grounded-grid configuration and delivering ~2 MW of power in ~400 μs pulses. RF power is taken to the linac along 12 inch diameter, 50 Ω coaxial lines. Various feedback circuits ensure that the phase and the amplitude of the RF in each tank is well controlled, and that the tanks remain resonant at the correct RF frequency.

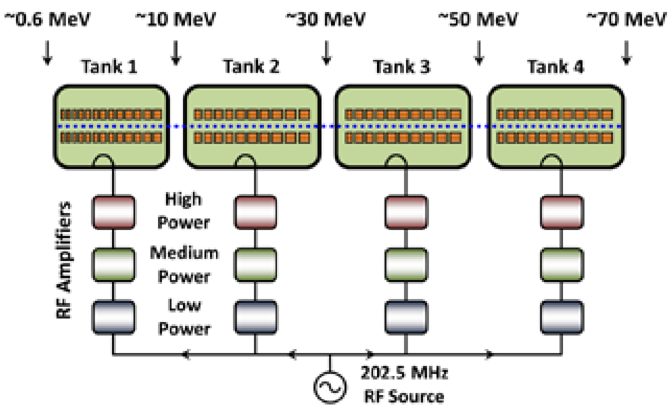



Fig. 3.8. Block diagram of linac and RF system. Feedback circuits necessary for successful operation are not shown in this diagram.

In the $H^-$ beam, the second electrons making up the $H^-$ ions are not particularly tightly bound, and if the vacuum inside the linac tanks is not good then significant numbers of $H^-$ ions can be stripped to leave $H^0$ atoms and $H^+$ ions (protons). These are then not focused correctly and plough into the drift tubes instead of passing through them. The numbers are not necessarily significant in terms of noticeable reductions in $H^-$ beam current, but they can induce significant radioactivity in the tanks. It is therefore important to maintain good vacuum levels inside the tanks. Beam loss monitors are installed down the length of the linac to provide warning signals when excessive beam losses occur. The output from the ISIS linac is a stream of $H^-$ ions lasting ~200 μs.

Beam from the linac is delivered to the ISIS synchrotron via the HEDS (high energy drift space), a ~50 m beam transport line. The HEDS incorporates two relatively sharp horizontal bends, many focusing and steering magnets, several sets of beam diagnostics, and a debuncher cavity fed by ~10 kW of RF. The primary function of the debuncher cavity is to reduce the energy spread of the beam from the linac before injection into the synchrotron.

**The stream of $H^-$ ions from the linac is injected into the synchrotron over ~150 turns. As the beam goes into the synchrotron the $H^-$ ions are stripped of their electrons to become protons, and the proton intensity in the synchrotron builds turn-by-turn. By injecting $H^-$ ions rather than protons it is possible to overcome electrostatic repulsive forces during the multi-turn process and as a result get to about 10 × higher proton intensity in the synchrotron.**

## 3.4 Synchrotron

The ISIS proton synchrotron is a machine with a circular orbit of radius 26 m (and a circumference of 163 m), designed to take the 70 MeV beam from the linac and accelerate it to 800 MeV. It is located in the same large room, R5.3 (the 'synchrotron room'), as the old Nimrod 7 GeV proton synchrotron that ran in the 1960s and 1970s. The ISIS synchrotron does most of the 'work' in generating the high-power proton beam that finally produces the neutrons and muons.

**The synchrotron room and the catacombs beneath the floor reflect the 8-fold symmetry of the old Nimrod synchrotron. The ISIS synchrotron has 10-fold symmetry.**

The synchrotron is another example of a machine where the same accelerating voltage is used over and over again. The ISIS 70 MeV linac is a 'once-through' machine in which identical voltages appear over and over again in a line some 40-50 m in length. In contrast, the ISIS synchrotron is a 'thousands-of-times-around' machine in which the accelerating voltage stays in the same place but the particles being accelerated pass through the voltage again and again.

The ISIS synchrotron is made up of ten sections or 'superperiods', numbered 0-9, in each of which the beam is bent through an angle of 36°. The essential elements of each superperiod are a dipole magnet and three quadrupole magnets. The dipoles (the first element in each superperiod) provide the 36° bend, and the quadrupoles provide focusing to prevent beam expansion. Collectively, these dipoles and quadrupoles are called 'the lattice magnets'. Superperiods also contain 'trim' magnets that are adjusted (essentially empirically) to make good the effects of the small imperfections that inevitably exist. The accelerating voltage is provided by ten RF cavities, each driven by its own tetrode-based high-power RF amplifier. Each wide-band high-power RF amplifier incorporates either one or two 250 kW tetrodes and is driven by a ~500 W wide-band solid-state RF amplifier. The solid-state amplifiers are driven by a sophisticated low-power RF system.

**To reduce the likelihood of beam expansion caused by mutual repulsion of the positively charged protons, it is important to ensure that around the circumference of the synchrotron the line-density of charge, i.e. the number of protons per metre of circumference, is as small as possible. It would be much worse to have the protons in two short bunches than two long smooth bunches. The addition of the second harmonic of the accelerating RF voltage spreads out the proton bunches, thereby increasing the maximum beam current than can be obtained from the synchrotron.**

Six cavities, the 'fundamental' or '1RF' cavities, are driven by two tetrodes and produce the overall 'strength' of the voltage (some ~100 kV per turn). The remaining four cavities, the 'second harmonic' or '2RF' cavities, are driven by single tetrodes and modify the 'shape' of the voltage to maximise the total number of protons that can be satisfactorily contained within the synchrotron. The synchrotron RF systems are complicated, and a profound understanding of these systems and the interactions of the RF with the beam are necessary to make the synchrotron work satisfactorily.

Every time the protons go round the synchrotron they pick up roughly 0.1 MeV of energy, and so it takes roughly 8000 turns of the synchrotron for the protons to be accelerated to 800 MeV. The main parameters of the ISIS synchrotron are shown in Table 3.2, and a schematic diagram of the synchrotron is shown in Fig. 3.9 — not every piece of apparatus is shown in this figure.

| During 10 ms acceleration cycle: | |
|---|---|
| Current through main magnets | 250–1050 A |
| Dipole magnetic field | 0.18–0.70 T |
| 1RF frequency | 1.3–3.1 MHz |
| 2RF frequency | 2.6–6.2 MHz |
| Proton momentum | 369–1463 MeV/c |
| Proton energy | 70–800 MeV |

Table 3.2. Main synchrotron parameters.

The synchrotron principle was first proposed by Oliphant during World War II. At that time Oliphant was professor at the University of Birmingham; latterly he became Governor of South Australia. See M L Oliphant et al., Proc. Phys. Soc. London 59 (1947) 666.

On ISIS the resonant frequencies of the accelerating cavities are swept over the ranges 1.3–3.1 and 2.6-6.2 MHz in synchronism with the frequency of the applied RF power. These large changes in resonant frequency are achieved by incorporating ferrite in the cavities and then varying the permittivity of the ferrite by applying bias currents that change appropriately over the 10 ms acceleration cycle time. Another reason why good synchronism is required.

Biased sine wave = $A + B\cos\omega t$, A ≅ 650 amps, B ≅ 400 amps. On ISIS the frequency of the sine wave applied to the synchrotron lattice magnets is a true 50 Hz, not a mains-locked 50 Hz.

The successful operation of a synchrotron depends critically on good synchronism. Because the protons have to be kept in the same orbit as they are being accelerated, the magnetic fields in the bending and focusing magnets have to increase with time to match. Also, the frequencies of the RF power applied to the accelerating cavities have to be swept to match the rate at which the protons are travelling around the synchrotron. In addition, the strength of the accelerating voltage has to match the rate at which the protons are being accelerated. A schematic block diagram — very much simplified — is shown in Fig. 3.10.

In practice, the magnets are fed by a biased 50 Hz sine wave AC current and everything is locked to this. Injection of particles occurs just before the magnetic field is at a minimum, and extraction occurs when the magnetic field is at maximum. To avoid excessive consumption of electrical power, the synchrotron magnets are resonated with capacitor banks. Basically, there are ten LC circuits that resonate at 50 Hz, in each superperiod the magnets being the L and a tenth of the capacitors in the capacitor bank being the C. The resonant nature of the lattice-magnet–capacitor-bank LC circuits means that voltages of the order of 10 kV are involved.

Beam loss monitors, four to each superperiod, are positioned all around the synchrotron to provide warning signals when excessive beam losses arise through poor synchronism.

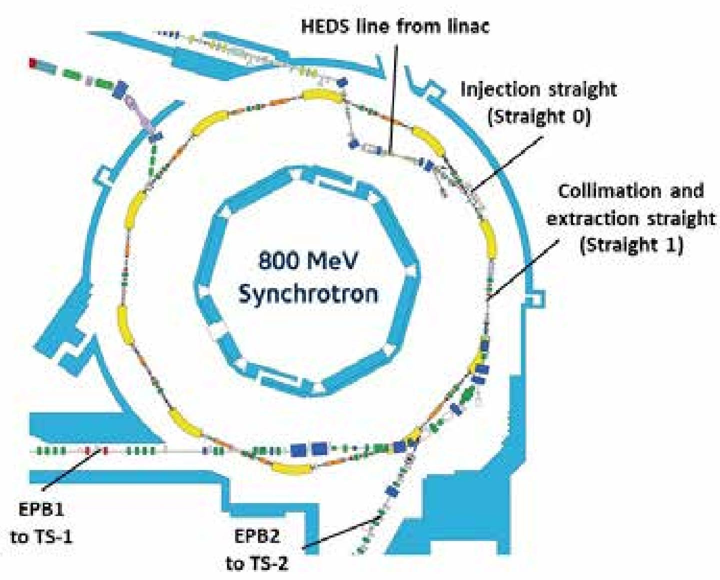



Fig. 3.9. Schematic diagram of the ISIS synchrotron. Yellow, dipoles; dark green, quadrupoles; red, trim magnets.

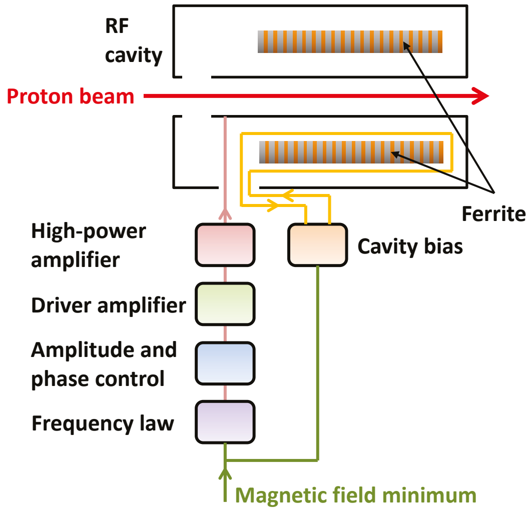



Fig. 3.10. Schematic diagram of the synchrotron RF system for one cavity. The frequency-law unit delivers low-power RF a frequency that changes over 10 ms to match the rate at which protons are circulating around the synchrotron ring; the frequency sweep starts when the magnetic field in the lattice magnets is at a minimum. The amplitude-and-phase-control unit is used to control the amplitude and phase of the high-power RF delivered to the accelerating cavity. Not shown, and of critical importance for operation in practice, are several feedback loops.

The 70 MeV $H^-$ ions from the linac enter the synchrotron in the 'injection straight', Straight 0, where they pass through a very thin stripping foil that removes the two electrons from each $H^-$ ion to convert it to a proton (see Fig. 3.11). The stripping process is not quite 100% efficient. The odd percent of $H^-$ ions are stripped to neutral H atoms, and these $H^0$ atoms are removed by stopping them in a graphite absorber. Until recently the stripping foil was 0.25 μm of aluminium oxide, but this has now been changed to a similarly thin carbon stripping foil. The stripping foil is very delicate, and great care has to be taken when it is installed.

The 200 μs pulse length from the linac is such that the stream of negative $H^-$ ions from the linac fills up more than 100 turns of the synchrotron with protons. This 'charge exchange' injection is the most efficient way of taking a long string of particles from a linac and wrapping the string many times around the circumference of a synchrotron. After injection is complete, a low-level accelerating voltage is applied, which gradually separates the uniform ring of charge into two bunches. Thereafter, stronger voltages can be applied by the RF cavities for acceleration.

Left to themselves, the two bunches of positive charge would soon expand due to mutual repulsion, and so the synchrotron superperiods contain quadrupoles to provide focusing forces to prevent this. The focusing quadrupoles cause off-axis protons in the beam to oscillate about the beam axis. To avoid build-up of destructive resonances it is essential that the number of these oscillations around the synchrotron orbit, 'the tune', is neither integral nor half-integral.

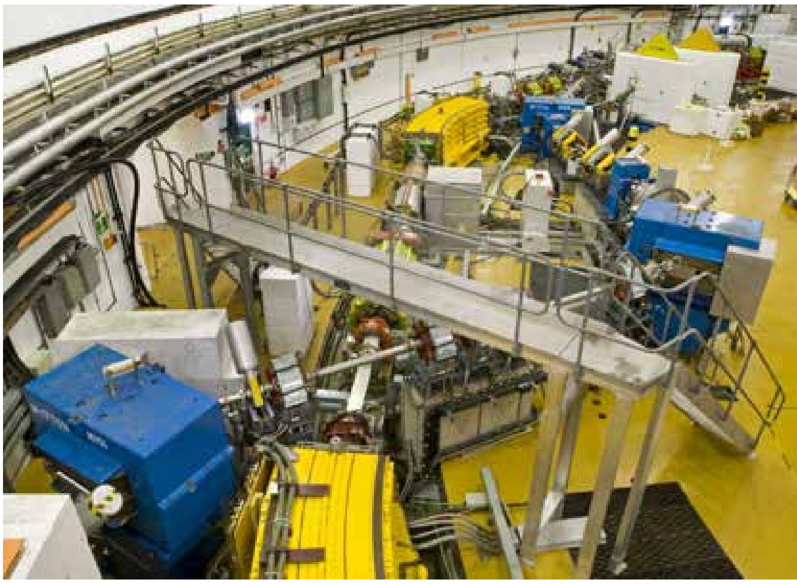


Fig. 3.11. HEDS line entering the synchrotron room. In this photograph, under the bridge, the HEDS line passes over the synchrotron orbit travelling from left to right.

Some ~5% of the beam that is injected into the synchrotron is lost at the beginning of the acceleration cycle. It is arranged that this 'bad beam' is scraped off on composite copper-and-graphite collectors in Straight 1. When the lost protons slow down and stop in the collectors they produce secondary particles, and so Straight 1 is the region of the machine where radiation dose rates are the highest. As can be seen in Fig. 3.12, concrete shielding is in place around Straight 1 to attenuate this radiation.

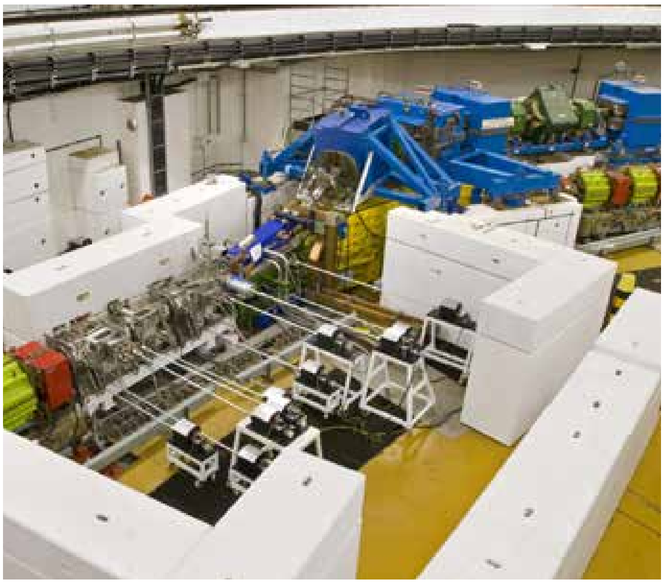


Fig. 3.12. Straight 1, enclosed by concrete shielding, where 'bad beam' is lost. The long horizontal rods are drive rods for the adjustable beam collectors incorporated in the beam line.

When the synchrotron has accelerated them to 800 MeV the protons are moving at 84% of the speed of light and taking 0.65 μs to travel once around the 163 m circumference. Since there are two bunches of protons orbiting the synchrotron, the centres of the bunches are 0.32 μs apart. After the width of the bunches is taken into account there is little more than 0.1 μs of space between the bunches. To extract the protons, a high-speed magnet must suddenly be switched on within 0.1 μs to kick the two proton bunches out of the synchrotron. ISIS has three such kicker magnets, each of which has its two poles energised separately. The kicker magnets deflect the bunches upwards, and a septum magnet then bends the bunches up into the extracted proton beam line (EPB).

**The kicker magnets for extracting the beam are not simple devices. They are single-turn ferrite assemblies to which a 5000 A pulse rising in 0.1 μs is applied by voltages of ~30-40 kV.**

**A septum magnet is specially designed so that the magnetic field inside the magnet is strong up to the boundary of the magnet, but falls essentially to zero immediately outside the magnet.**

## 3.5 EPB1 and EPB2

The two extracted proton beam lines (EPB1 and EPB2) deliver beam from the synchrotron to the corresponding target stations. Both EPB1 and EPB2 consist essentially of a long series of quadrupole magnets, interspersed now and then with bending and steering magnets. The quadrupole magnets keep the beam focused, and the bending and steering magnets bend and steer the beam in the correct directions.

The extraction kicker magnets and septum bend the beam up out of the synchrotron, and the beam is then transported over the top of superperiods 2 and 3. The beam is split between TS-1 and TS-2 by 'slow kickers'. These magnets are energised before every fifth pulse from the synchrotron and divert that beam pulse into EPB2 (see Fig. 3.13 and 3.14).

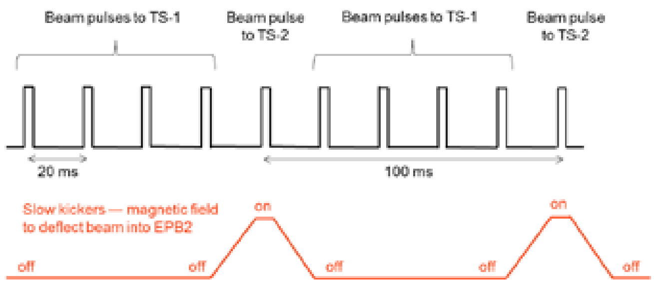



Fig. 3.13. Schematic representation of operation of slow kickers deflecting beam into EPB2. These kicker magnets are 'slow' because they have almost 20 ms to ramp up to full field and another 20 ms to ramp down, unlike the extraction kickers in the synchrotron that must switch on within 0.1 μs.

Both EPB1 and EPB2 lines are enclosed in thick steel and concrete shielding. The thickness of the shielding is such that complete loss of the beam at any point in the beam line can be accommodated. The function of the initial downwards bend in EPB2 and subsequent upwards bend nearer the TS-2 target is simply to minimise shielding costs; the nearer the floor the beam line is, the less steel and concrete is required to shield the beam line. Beam loss monitors are positioned along EPB1 and EPB2 to provide warning signals when excessive beam losses arise through bad steering or poor focusing.

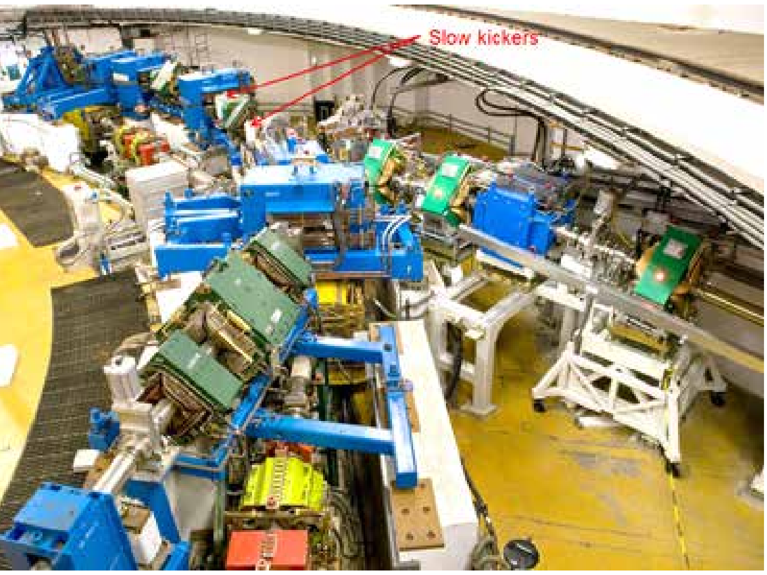



Fig. 3.14. Extracted proton beams EPB1 (on left-hand-side) and EPB2 (on right-hand side) leaving the synchrotron. One of the lattice quadrupoles (light green) and one of the trim quadrupoles (red) on the synchrotron orbit can be seen at the foot of the photograph.

## 3.6 Muon production

The ISIS Intermediate Target is incorporated in EPB1, positioned ~20 m upstream from the TS-1 neutron-producing target. This ~1 cm thick graphite target is placed directly in the beam to generate pions that then decay into muons — unstable particles with a mean life time of 2.2 μs.

Muons, produced by pions decaying at rest, are selected by the muon beam line that transports these muons to several instruments. Muons are sensitive local probes of atomic magnetism, and provide information to complement that obtained from neutron scattering.

The passage of the EPB1 800 MeV proton beam through this centimetre of graphite produces secondary particle fluxes that induce significant radioactivity downstream from the intermediate target. This is why radiation dose rates in 'the downstream EPB' are much higher than in the EPB upstream of the intermediate target, and why there is a steel shield around the intermediate target.

Fig. 3.15. ISIS Intermediate target

The muon target ladder, shown in Fig. 3.15, consists of three water cooled targets. Only one target is in the proton beam at any given time, but if one fails then a new one can be quickly inserted. Unlike at some other facilities the muon target is static (i.e. not rotating) and is edge cooled.

There are two muon beamlines feeding seven experimental areas. The EC muon beamline, named after the funder, the European Commission, is a surface muon beam. This beamline has a fixed muon energy and fixed muon charge. The RIKEN-RAL beamline, named after the funding from RIKEN, Japan and collaboration between RAL(ISIS) and RIKEN, is a decay muon channel which allows for the extraction of both negative and positive muons over a wide energy range. The muon being charged and having a spin means that the beams can be bent and focused by the use of magnetic and electric fields.

Unlike neutron scattering techniques, muons are implanted into the sample of interest and it is either the positrons, electron or muonic X-rays that are detected. The muons are a local probe and 'sense' the local environment.

## 3.7 Neutron-producing targets

The essential function of the two neutron-producing targets on ISIS is to convert the high-energy proton beam into as many neutrons as possible, whilst occupying as small a volume as possible. Maximising the number of neutrons per proton implies choosing a target material of high atomic number Z. Minimising the volume within which protons are converted to neutrons results in the highest neutron fluxes. Within each target, most of the power in the proton beam appears as heat, which has to be carried away by cooling water.

The choice of target material is determined by a number of considerations, such as thermal conductivity, melting point, machinability, chemical reactivity, induced radioactivity, availability and cost. Taking high atomic number to mean atomic numbers greater than any of the lanthanides ($57 < Z < 71$), possible candidates are tantalum, tungsten, mercury, lead, thorium and uranium (Z = 73, 74, 80, 82, 90 and 92 respectively). ISIS runs with tantalum- clad tungsten targets.

**Originally TS-1 ran with depleted uranium targets. Problems caused by radiation-induced swelling of the uranium target plates led to the use of tantalum targets in the 1990s, and since 2001 tantalum-clad tungsten targets have been used.**

**Ideally, the TS-1 and TS-2 targets would be made entirely of tungsten. However, at temperatures of a few hundred degrees Centigrade tungsten can react with water, whereas tantalum is much less reactive. Since it is impractical to cool the target with anything other than water, the tungsten is therefore clad with a thin layer of tantalum.**

The core of the TS-1 target is a rectangular block ~100 mm wide, ~100 mm high, and ~300 mm long, divided into twelve tantalum-clad tungsten plates water-cooled on both sides. The power in the incident beam is ~140 kW, and much of this is carried away by the cooling water (the remainder of the power is dissipated in the material around the target and the shielding). The core of the TS-2 target is a solid cylinder of tantalum-clad tungsten ~300 mm long and ~70 mm in diameter water-cooled at the front and on the curved surface of the cylinder.

The power in the incident beam is ~35 kW, and again much of this is carried away by the cooling water. The proton beam spots on the TS-1 and TS-2 targets are roughly Gaussian in shape with 1/e radii of 2.53 cm and 0.85 cm respectively. Schematic diagrams of the targets are shown in Figs. 3.16 and 3.18.

**The beam spots on the targets are approximately described by $dI / dS (r) = I_0 \exp(-r^2 / r_e^2) / (\pi r_e^2)$ where dI/dS is current per unit area, $I_0$ is the beam current, *r* is the radial distance from the beam axis, and $r_e$ is the 1/e radius. Although the TS-2 beam current is nominally one quarter of the TS-1 beam current, because the TS-2 beam spot is less than half the size of the TS-1 beam spot the mean heat loading on the beam axis at the front of the TS-2 target (watts per square centimetre) is greater than the corresponding heat loading on TS-1. And because TS-2 runs at one quarter of the pulse repetition rate of TS-1, the peak heat leading per pulse (joules per square centimetre) is almost a factor of 9 greater on TS-2 than on TS-1.**

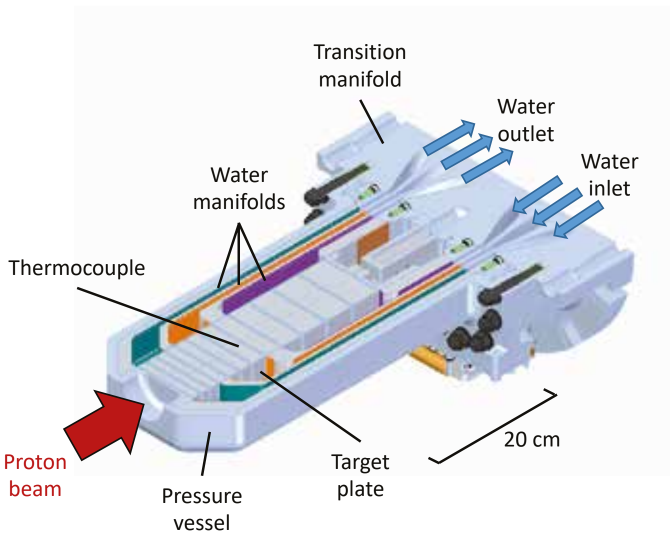
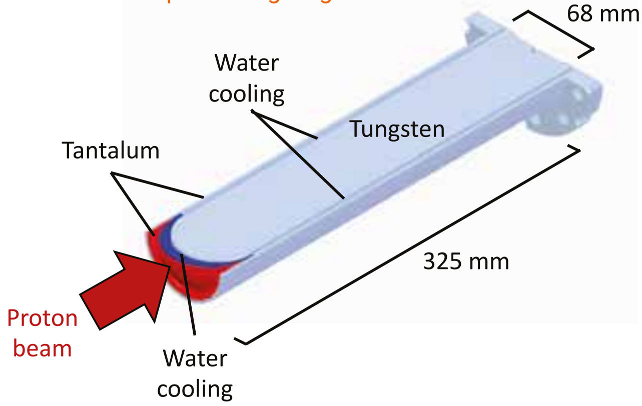



Fig. 3.16. Schematic diagram of TS-1 neutron-producing target.

Surrounding each neutron-producing target are moderators and a reflector, all of which have to be cooled. On TS-1 there are a total of four moderators — two water moderators at 300 K, a liquid methane moderator at 100 K, and a liquid hydrogen moderator at 20 K. TS-2 has two moderators, a liquid hydrogen moderator at 20 K and a solid methane moderator at 47 K. Surrounding each target, in principle wherever there is no moderator, is a beryllium reflector. On TS-1 the beryllium is in the form of rods encased in stainless steel; on TS-2 it is in the form of nickel-plated blocks. Photographs and diagrams for the TS-1 and TS-2 target systems are shown in Figs. 3.17 and 3.19.

The proton beams produce intense radioactivity within and around the targets, and so massive shielding is in place — several metres of steel followed by ~1 m of concrete (see Figs. 3.20 and Fig. 3.21) collectively referred to as ‘the monolith’. Expressed crudely but not unrepresentatively, the steel attenuates the high-energy neutrons, and the concrete absorbs them.

Fig. 3.18. Schematic diagram of TS-2 neutron-producing target.



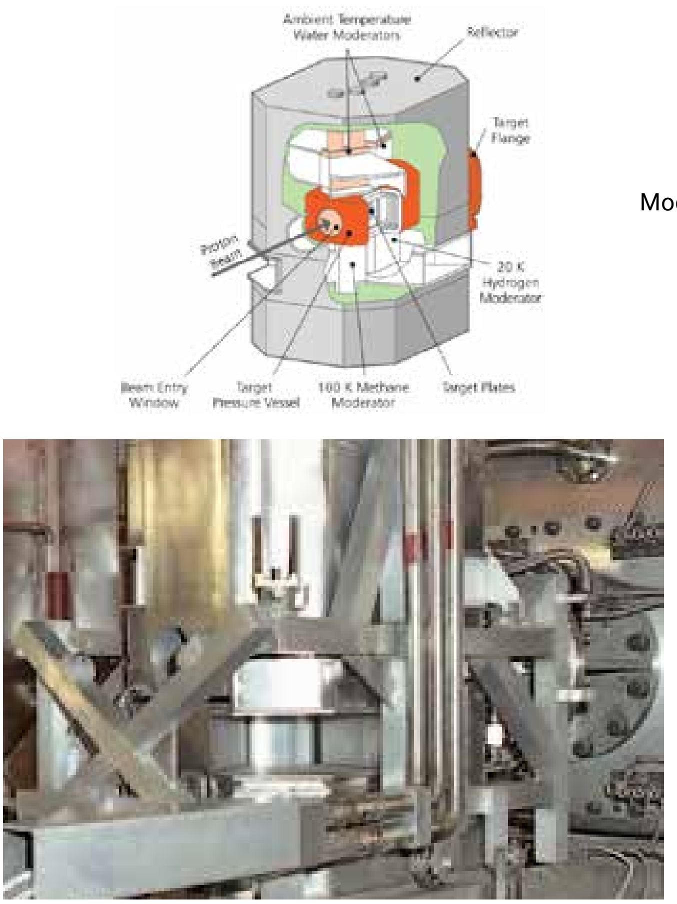




Fig. 3.17. TS-1 target, reflector and moderator assemblies.

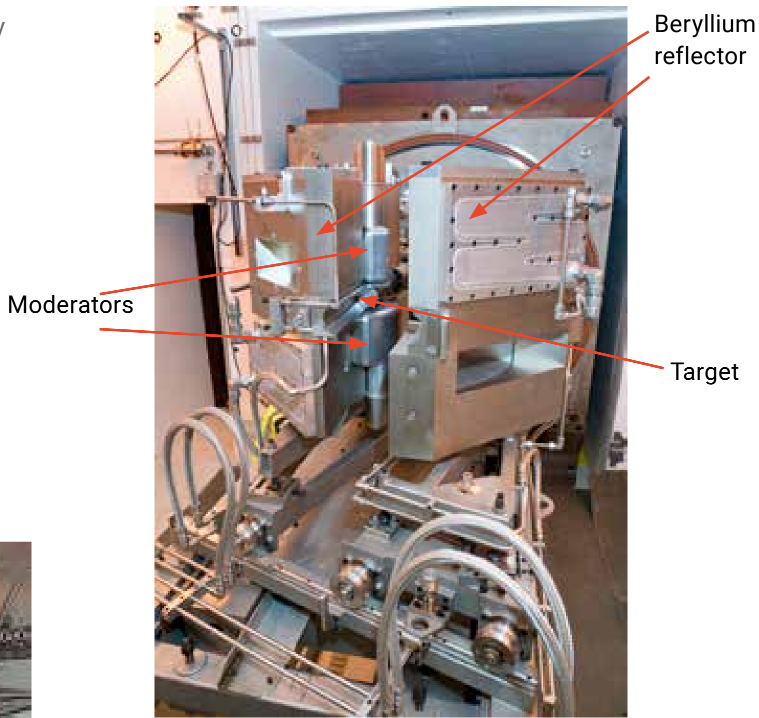



Fig. 3.19. TS-2 target, reflector and moderator assemblies.


Fig. 3.20. The steel core of the TS-2 monolith (during construction).

Fig. 3.21. The outer concrete layer of the TS-2 monolith (during construction)

"ISIS operations are providing an excellent capability to the user community, and are certainly world-class. ISIS has, since its creation, been able to create a culture of innovation that has had profound impact on, and will continue to change, the way neutron scattering is performed world-wide. Very few research institutions have demonstrated similar drives toward innovation and spread of the resulting technological development."

**International review 2013**

# Operating the machine

When the machine is operational for its users, the obvious overall requirement is to operate the ISIS machine continuously and reliably. At the same time, the amount of radioactivity in the structure of the machine must be minimised so that maintenance during off-times is not compromised. Minimisation of beam loss is critically important: the machine cannot be allowed to become so radioactive that it is not possible for people to work on it.

Continuous 24-hours-a-day operation requires six shift teams, with suitable provision made for handovers at the beginning and ends of shifts. Each shift team is made up of a Duty Officer (DO), an Assistant Duty Officer (ADO) and a Duty Technician (DT). It is impossible for the shift teams to possess expert knowledge of all the equipment incorporated in the machine, and so there are several tens of people who sign up to an 'on-call' roster and who can be called in at any time of the day or night to fix problems. Fig. 4.1 shows the ISIS Main Control Room (MCR) after its refurbishment in 2014.

Fig. 4.1. The ISIS Main Control Room (MCR) after its refurbishment in 2014.

## 4.1 Engineering

The successful operation of the ISIS machine depends critically on the machine being well engineered. All the physics sophistication in the world is to little avail if the engineering side is inadequate. Usually, when designs for accelerator-related hardware are being considered at ISIS, the main aim is to achieve a robust engineering design using the best materials for the job. During operations, much effort is made to minimise the beam losses that induce radioactivity. As described below, maintenance work in a radiation area can be greatly facilitated by suitable design of plant and equipment.

To make it easier to do maintenance-type work on the machine, the process of replacing components is designed to be as quick as possible. For example, to replace an ion pump in a high-radiation-dose-rate area, it should be unnecessary to remove all the many bolts required by Conflat vacuum seals in situ. Instead, in these circumstances the ion pump should have been incorporated in a demountable sub-assembly made up — again, for example — of an ion pump joined with a Conflat seal to T-piece on top with an eye-bolt on it.

The T-piece should have V-band quick-release vacuum seals on either side, and the whole sub-assembly should sit on a set of permanently mounted and accurately-aligned rails. Removal then becomes simply a matter of un-doing the quick-release seals, attaching (with a long pole, if necessary) the crane hook to the eye-bolt on top of the T-piece, and lifting the whole sub-assembly out. In this way people are exposed to the radiation for only a short time. A replacement sub-assembly, already leak-tested and pre-aligned on an identical set of rails in the workshop, can then craned in, and the quick-release vacuum seals re-made. An example is shown in Fig. 4.2.

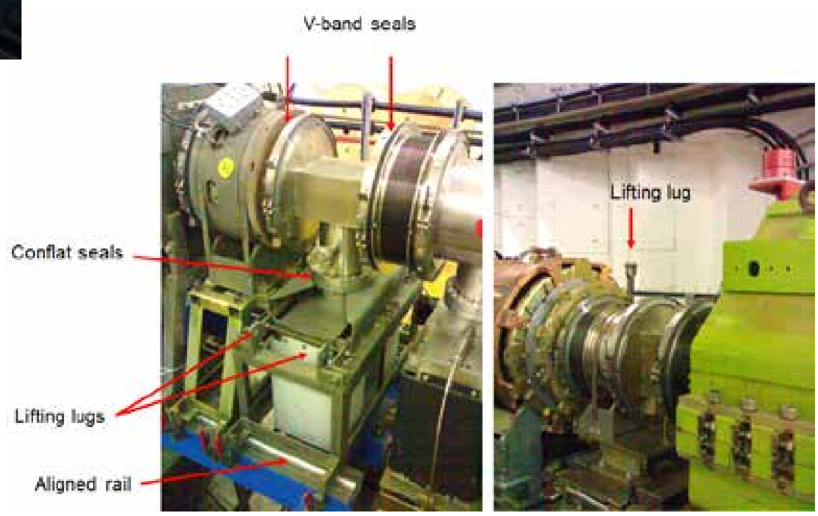



Fig. 4.2. Illustration of preparations for rapid replacement of a sub-assembly.

For doing a job of machine maintenance it is more important to minimise the dose from the job as a whole than to minimise the dose rate while the job is being carried out. It is better to accept dose rates that are twice as high if a job can be carried out in a quarter of the time.

Provision of suitable water-cooling arrangements is an important requirement for successful machine operation. There are a great many water pumps distributed around ISIS, most of them with duplicates standing by so that failing performance of a pump does not require downtime for the pump to be replaced. It is very important to maintain good water chemistry in the cooling-water circuits. Many circuits incorporate their own ion-exchange-resin columns to control pH and electrical conductivity, and since ISIS is located in a hard-water area even the 'raw water' in the cooling towers has to be treated.

**The major water plants around ISIS are: the cooling towers in R11 and their ancillary pumps in R10; the three refrigerators outside R5.1 supplying the linac; the refrigeration systems in R4 supplying 'chilled water'; the air-blast coolers above the east end of R55 for the synchrotron and EPB1 magnets; and the R80 cooling towers, which cool the EPB2 magnets and other equipment in TS-2.**

The provision of suitable ventilation throughout the ISIS machine areas is also important. Apart from the obvious purpose of removing heat, ventilation at ISIS mitigates the effects of radiation fields from lost beam. Radiation fields can ionise air, and ionised air (e.g. ozone) can be corrosive. Radiation fields can also activate the air, i.e. produce radionuclides in the air, but at ISIS the radionuclides produced in this way are all short-lived and represent little or no hazard. The synchrotron room is ventilated by the 1960s air conditioning system originally installed for Nimrod.

Air is re-circulated through the synchrotron room by two large air-conditioning fan sets in R4, a total of ~40 m³/s in a room with a volume of ~25,000 m³. Approximately 2 m³/s of this air is continuously discharged to atmosphere through the stack on the roof of R4.

The average transit time of air around the synchrotron air-conditioning loop is ~500 s, and the average residence time of air in the synchrotron room is ~10,000 s.

To match ambition to available resources, a significant amount of ex-Nimrod and second-hand equipment was incorporated in ISIS when ISIS was built. One example is that for ~20 years the AC component of the current driving the synchrotron lattice magnets was generated by a ~1 MW motor-alternator set consisting of a second-hand motor from a Sheffield colliery and a second-hand alternator from a Swedish tramway system. A ~100 ton choke taken from the decommissioned NINA electron synchrotron at the Daresbury Laboratory was used to match the alternator output into the lattice- magnets circuit. Another example is that most of EPB1 was made up of 1960s magnets and power supplies originally used on Nimrod.

## 4.2 Running the machines

The ISIS machine cannot be run continuously. Much of the maintenance work to support operations has to be carried out with the machine switched off; instrument scientists supervising the neutron and muon experimental programmes cannot work all the time, and people cannot be on call all the time. Over the years ISIS has run for typically ~180 days a year, with these 180 days being divided into four or five 'cycles', periods of several weeks when the machine is totally dedicated to neutron scattering on a 24-hours-a-day-7-days-a-week basis.

Traditionally, cycles begin on a Tuesday, and end on a Thursday or Friday. But, depending on how much of the machine has previously been powered down, it usually takes at least one week to set the machine up for running, and so 'run-up' time lasting one or two weeks is scheduled prior to each cycle. Further, several days of machine physics and accelerator R&D time is scheduled after each cycle. With these additions, the ISIS machine actually runs for ~250 days a year.

The machine physics and accelerator R&D time scheduled after each cycle is available for commissioning new hardware and software systems, and for experimental studies to explore high-intensity behaviour at the limits of the performance of the present machine. This work allows accelerator staff to maintain ISIS operations sustainably, establish better operating regimes, benchmark simulation codes and inform possible ISIS upgrades.

Fig 4.3 shows the reliability of the ISIS machine over the past ~20 years. Apart from 2008-2010, when there was some diversion of effort in order to commission TS-2, availability has been relatively uniform. However, maintaining this level of availability would not be possible without a vigorous programme to promote sustainability and mitigate obsolescence. Since the year 2000 (when plant and equipment on ISIS was at least 20 years old, and some 'second-hand' equipment was as old as 40 years) vulnerable plant and equipment has been systematically replaced, prioritising items which present the greatest risk to ISIS operations.

In order to run a high-intensity accelerator such as ISIS sustainably and allow hands- on maintenance of accelerator components, beam losses (and consequent induced radioactivity in the machine structure) must be as low as reasonably possible. On ISIS, beam losses are measured firstly by looking at ratios of signals from successive beam current transformers, in principle similar to conventional current transformers with the beam acting as a single-turn primary winding. Secondly, signals are taken from beam loss monitors — long argon-filled ionisation chambers running all down the linac, all around the synchrotron, and all along the proton beam transport lines. Both 'acute' and 'chronic' sensing regimes for beam trips are in use (the former for sudden severe beam losses, the latter for smaller beam losses that do not matter too much in the short term, but would matter in the longer term).

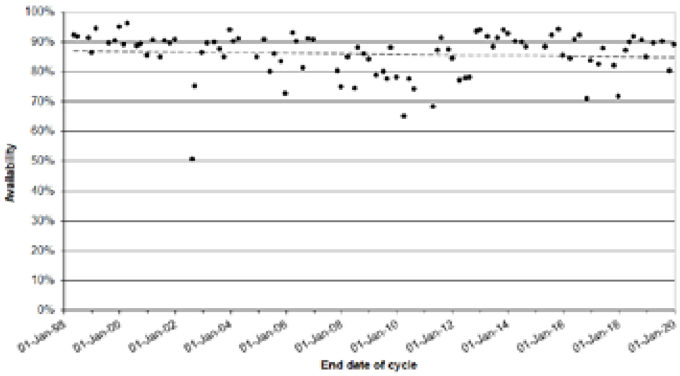



Fig. 4.3. Availability of the ISIS machine since 1998; the average is 86% with a standard deviation of 8%. Availability is defined simply as (number of beam pulses delivered to targets) ÷ (number of pulses scheduled to be delivered); ISIS counts every lost pulse as a lost pulse. Very roughly, ~75-80% of the down-time can be ascribed to the accelerators and their ancillary equipment, and ~20-25% to the target systems.

To complement the beam current transformers (which measure overall strengths of the beam) and the argon-gas-filled beam loss monitors, beam profile monitors and beam position monitors are also installed around the machine for optimisation of beam delivery. Most of the beam profile monitors are wire 'harps', sets of parallel wires spaced a few millimetres apart that can be inserted into the beam to deliver signals proportional to strengths of vertical and horizontal slices through the beam. Formally, these slices represent line integrals, and the sets of slices represent one-dimensional projections.

A few beam profile monitors are residual gas ionisation monitors, in which the beam ionises residual air in the beam line and the resultant ions are swept by a strong applied electric field into an array of channel electron multipliers (channeltrons) or microchannel plates (MCPs). These typically deliver ~10-20-point profiles.

Beam position monitors are essentially split capacitive pick-ups delivering two signals. The ratio of these signals is proportional to the 'centre-of-gravity' of the beam from the axis. Each of these beam position monitors delivers a single number for the extent to which the beam is off axis.

The information from the beam diagnostics can be input to computer programs in which the transmission of the beam from ion source to target as a function of settings such as magnet currents has been modelled. The computer can then be used to predict, for example, settings of magnets that should reduce beam losses and thereby improve beam delivery.

Since ISIS depends on several thousand items of equipment working together correctly and consistently, it is impracticable to control all this equipment by hand. Therefore, a computer-based system (with some 20,000 input/output channels) is used to monitor and control equipment all around ISIS. Key parameters and waveforms displayed on large video screens in the Main Control Room (MCR) provide the operations team with an overview of everything that is going on and drill-down menus enable a more detailed view of how individual items of equipment are functioning. Further, if the value of any parameter goes outside a previously specified range of acceptable values the operations team is warned and automatic responses are invoked — ranging from unobtrusive correction to immediate equipment shutdown. A large number of log files are automatically recorded and complete sets of machine parameters are stored so that after a shutdown these stored parameters may be loaded into the equipment to make it as easy as possible to get the machine up and running again. This computerised monitoring and control system is not the system upon which safe operation of ISIS depends — safety systems are hard-wired as described in Section 4.5 — but the monitoring and control system does indicate the status of the hard-wired interlocks.

## 4.3 Energy consumption

When running to both its target stations (TS-1 and TS-2) ISIS consumes ~12 MW of electrical power. Table 4.1 below provides an approximate breakdown by ISIS sub-system of power consumption when ISIS is running. (Power consumption falls to roughly one quarter when ISIS is not running, but of course a lot depends on just how much plant is truly shut down.) Ultimately, of course, almost all the ~12 MW ends up as low-grade waste heat.

The ISIS annual electricity bill is typically ~£9M.

| What | MW |
|---|---|
| Ancillary plant | 2.0 |
| MMPS | 2 |
| Synchrotron RF | 1.6 |
| TS-1 + TS-2 instruments | 1.1 |
| EPB1 | 1.0 |
| EPB2 | 1.0 |
| Linac | 0.8 |
| Inj. & extr. septums | 0.6 |
| EPB2 septum | 0.4 |
| Miscellaneous | 0.2 |
| Lighting | 0.2 |
| HEDS PSUs | 0.1 |
| Inj. dipole | 0.1 |
| | 11.9 |

Table 4.1. ISIS electrical power consumption.

Ensuring efficient energy consumption is central to the ISIS operations strategy. Energy savings have been achieved naturally by end-of-life equipment being replaced with more efficient units (ensuring that energy efficiency is part of the specification and thus enabling the utilisation of energy efficient technologies) and through an increased understanding of how energy is utilised whilst ISIS is either operational, shutdown or undergoing start-up.

## 4.4 Radioactivity arising from operations

When high-energy protons encounter material they can produce radioactivity either directly or indirectly — directly by proton-induced nuclear reactions, indirectly via the production of neutrons. Throughout this document, the need for beam losses to be kept as low as reasonably possible has been emphasised, which means minimising the number of particles from the $H^-$ and proton beams striking any parts of the internal structure of the machine.

When items of plant or equipment are removed from machine areas during maintenance and upgrade work, they are carefully monitored for any residual radioactivity and categorised either as spares (which can be repaired and safely stored for future re-installation) or as waste. Waste is further categorised depending on the type of material and level of radioactivity, before eventual recycling, treatment or disposal in strict accordance with a permit granted by the Environment Agency. Similarly, radioactive gases and liquids that result from operation are collected, assessed and safely discharged.

## 4.5 Safety

The most obvious hazards on ISIS are electrical and radiation hazards. Risks to personnel from electrical hazards are mitigated by conventional interlock systems. These physically prevent personnel access to high-voltage or high-current electrical conductors in apparatus unless the apparatus is powered down — and, in many cases, also earthed. Such interlock systems are often realised using mechanical key-exchange systems (such as 'Castell' keys). Risks from radiation are mitigated by the presence of massive shielding around machine areas, the efficacy of which is monitored by 'environmental' dosimeters placed around the ISIS facility. As a matter of routine, ISIS staff wear dosimeters that measure cumulative dose. For carrying out work in many machine areas staff also wear electronic personal dosimeters that continuously display accumulated radiation dose.

As regards machine safety, fast-acting, hard-wired interlocks ensure that anomalies in target operating conditions can immediately trip the beam. The trip circuits are wired directly to the ion source, to the linac RF systems, and to a physical beam stopper in the LEDS. In addition, a Beam Permit System (BPS) ensures that beam cannot be delivered to a particular machine area before the area is in a suitable state to receive beam.

The BPS obtains status inputs from the Personnel Protection System (PPS, see below) as well from the various items of equipment required to run beam to the area. The BPS also provides audible and visual warnings of the operational status of ISIS.

The Personnel Protection System (PPS) is designed to provide for the protection of personnel in machine areas subject to prompt radiation and other hazards such as high voltage. The system controls the locking and searching of defined accelerator areas or zones. It incorporates dual-guard-line, relay-based systems to provide (via the BPS), suitably interlocked signals to enable operation of potentially hazardous equipment (e.g. RF systems and the main magnet power supply (MMPS)) and the generation of radiation resulting from accelerated beams.

**The dual guard lines are two independent electrical circuits that run round the machine plant and equipment — for example, connecting in series all 'door open' switches on doors into machine areas. The guard lines are wired so that a break in a guard line or a short to earth disables machine operation.**

“When I can understand anything from how you are able to use bombardment by neutrons to see exactly where faults might have been in a weld on a piece of kit inside a formula one car, through to how you can use these techniques to assess the safety of an aeroplane, I can see the practical value of what you do.”

**Universities and Science Minister David Willetts at the opening of Target Station 2**


X-AXIS

# Neutron and muon techniques

## 5.1 Neutron techniques

Neutron scattering measurements made at ISIS are fundamentally of two types: elastic and inelastic. In elastic neutron scattering the neutrons scatter from atoms in the sample, but do not transfer energy to or from it.

By observing the patterns in space of the scattered neutrons, it is possible to establish where the atoms are positioned with exceptional precision. The neutron, possessing a dipole moment, is also sensitive to the magnetic properties of the sample, and can therefore resolve complex magnetic structures. Further information can be extracted by manipulating the alignment of the neutron's dipole moment to produce polarised beams of neutrons. The direct nature of the neutron interaction means that the theory that describes such events is well understood and neutron scattering provides absolute quantitative results.

If the neutron transfers energy to or from the sample, then as well as measuring the scattering pattern it is also possible to determine the energy of the scattered neutron. This is called inelastic neutron spectroscopy, and allows the determination of how the atoms are moving within the sample. The combination of knowing the position of atoms and how they are moving provides a complete description of materials, which can then be used to understand their behaviour.

The beauty of the neutron technique is that it can be applied to a wide range of length and energy scales in materials, which cover the underlying physical phenomena that drive their behaviour. Furthermore, because of the penetrating nature of the probe, it can be applied to an exceptionally broad range of conditions such as ultra-low temperatures and high pressures. On ISIS, neutron instruments fall essentially into six classes, as set out in Table 5.1.

Since the whole point of ISIS is to provide neutrons for experiments, there have to be 'holes' in the target monoliths. These allow the neutrons produced in the target-reflector-and-moderator assemblies to travel down neutron flight paths to the neutron instruments. There are eighteen flight paths on each target station, nine on each side. Each flight path has its own shutter, so that neutrons may be 'switched off' if required. The steel shutters are massive and heavy — each weighs ~20 tons. On TS-1 the shutters are moved mechanically via a gearbox. On TS-2 the shutters are moved hydraulically.

It makes very good operational sense for each neutron beam line to have its own independently operable shutter.

| Class of instrument | Instruments | Outline applications |
|---|---|---|
| Neutron diffraction | Gem, Engin-X, HRPD, Nimrod, Osiris, Pearl, Polaris, Rotax, Sandals, SXD, Wish , Ines, Nimrod, Sandals | Neutron diffraction experiments determine the atomic and/or magnetic structure of a material. This technique can be applied to study crystalline solids, gases, liquids or amorphous materials. Neutrons can also be applied to the study of large scale engineering materials. |
| Neutron spectroscopy | Iris, MAPS, MARI, Merlin, Tosca, Vesuvio, Let, Osiris | Neutron spectroscopy measures the atomic and magnetic motions of atoms and molecules. |
| Reflectometry | Crisp, Inter, Offspec, Polref, Surf | Neutron reflectometry is a technique for measuring the structure of thin films. It has applications from materials science through to soft matter and bioscience. |
| Small angle scattering | LoQ, Sans2d, Zoom, Larmor | Small angle neutron scattering is a neutron technique able to probe structures at length scales from around 1 nanometre to more than 100 nanometres. It has a wide range of applications from studies of polymers and biological molecules to nanoparticles to microemulsions and liposomes used for cosmetics and drug delivery. |
| Imaging | Imat | The penetrating power of neutrons allow real space images to be acquired |
| Chip Irradiation | ChipIr | High energy neutrons are used to test the performance of microelectronics when subject to conditions like those in the upper atmosphere. |
| Muon spectroscopy | Emu, MuSR, Hifi, Argus, Chronus | For condensed matter studies, positive muons are implanted into materials and the time-evolution of the muon polarisation is observed. Negative muons are also used for elemental analysis. |

Table 5.1. ISIS Instruments and their applications

Fig. 5.2. Double disk neutron chopper for the Zoom instrument

Fig. 5.1. One of the 18 beamline shutters being readied for installation into the TS-2 and then suspended from a crane during installation.

ISIS is a pulsed source providing a 'white' neutron energy spectrum, i.e. each pulse is made up of neutrons with a wide range of different energies. On ISIS, neutron energies are measured by the time-of-flight technique. Basically, a clock is started when the pulse of neutrons is produced, and the clock is stopped when a neutron is detected in a bank of counters. In an elastic scattering configuration when the energies of the incident and scattered neutron are the same, knowledge of the distance between the source and the counter and the time it took the neutron to travel from the source to the counter is sufficient to define the energy of the neutron. Distances involved are of the order of 10 m, and times of flight are roughly of the order of a few ms. 'Thermal' neutrons (neutrons in thermal equilibrium with room-temperature surroundings such as neutrons coming from the TS-1 water moderators) have an energy of 25 meV and travel with a speed of 2200 $ms^{-1}$. Neutrons coming from the cryogenic moderators on TS-1 and TS-2 have lower energies, and are travelling more slowly.

Several of the ISIS neutron beam lines incorporate beam choppers. Neutron choppers are rotating mechanical devices designed to block the neutron beam for some fraction of each revolution of the chopper. Their rates of rotation have to be synchronised to the neutron pulse production rate. Inevitably they are heavy and have to rotate quickly, therefore they have to be well-balanced dynamically. A typical use of a chopper is as a 'Fermi chopper', to select a particular narrow slice of energies from the wide range of energies coming from the moderator. With the incident energy thus defined, time-of-flight can be used to measure the energies of inelastically-scattered neutrons.

## 5.2 Muon techniques

Muons are electrically charged elementary particles, with similar properties to electrons but with 207 times the mass. They can't be broken down into smaller components, and can be negatively charged muons or positively charged anti-muons. At ISIS, the proton beam collides with a carbon target and generate pions, which decay into muons and neutrinos.

The muons are selectively channelled into beamlines where the samples lie. Muons are sensitive local probes of magnetism, and provide information to complement that obtained from other techniques.

In muon spectroscopy, spin-polarised muons are implanted into the sample, where they subsequently decay with a lifetime of just over 2 μs forming positrons. Inside the crystal lattice or molecules of the chosen material, the muon spins respond to the local magnetic field, and the positrons are emitted from the sample in the direction of the muon spin in that instant. It is this crucial asymmetric decay of the muons that allows their polarization to be measured or analysed inside the sample, and its evolution displayed as a function of time following implantation.

By monitoring the spin polarization of the muons, information on the sites they adopt in crystal lattices or in molecules can be gained, alongside knowledge on local structure and dynamics. The way the overall muon polarization equilibrates following implantation reveals how the magnetic and hyperfine fields are distributed from site to site and how they fluctuate in time.

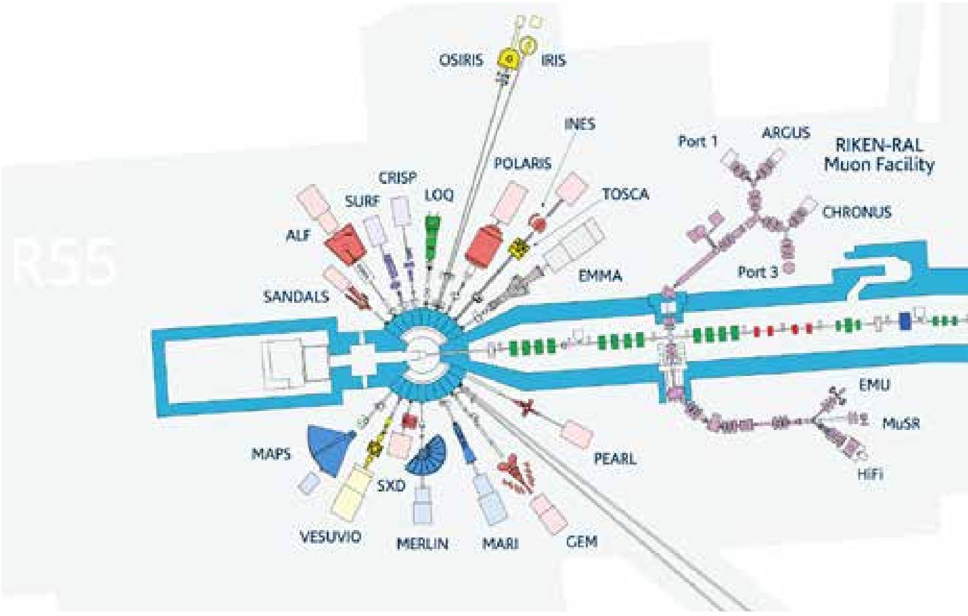



Fig. 5.3. Layout of instruments on Target Station 1. The two beam lines that continue past the foot of the diagram lead to Engin-X and HRPD.


Fig. 5.4. Layout of instruments on Target Station 2.

## 5.3 Sample environment

Measurements are made on samples in a wide range of different states; dilution refrigerators make use of helium properties to reach around 20 mK, high temperature furnaces can reach 2,000°C, high pressures up to 300 kbar can be achieved in pressure cells while superconducting magnets can create high magnetic fields, routinely to 10 T. The provision of these 'sample environments' is a very important function at ISIS.

Experiments are also supported in many general chemistry and other specialist labs. These labs are available for sample preparation but also material characterisation activities.

Measurement techniques available include X-ray analysis, physical and magnetic property determination (PPMS & SQUID), atomic force measurement, IR spectrometry, calorimetry and adsorption characterisation. These techniques are employed both to screen samples in advance of neutron scattering experiments and to provide additional data that enhances the completeness and quality of papers submitted for publication. Labs also offer specialist handling capability for flammable and toxic gases, soft condensed matter and biological capability.

Fig. 5.5. Shows DAE rack installation for the MARI beam line

Fig. 5.6. LET $^{3}He$ detector array

## 5.4 Detectors and data acquisition

Each neutron and muon instrument has a tailored detector system designed to detect, digitise and record where and when a neutron or muon event occurred. Detection takes place by way of sensing secondary charged particles produced by the neutron or muon interacting in a conversion medium – predominantly solid scintillator materials and pressurised gases.

The consequent electrical signals are conditioned prior to being transmitted to the instrument's data acquisition equipment, where they are digitised and sent as digital information to the instrument control computer. Figure 5.5 shows DAE Rack Installation for the Mari beamline.

At the control computer, detection events, time-of-flight data and information about the physical geometry of the instrument is stored alongside other experimental parameters as raw data for processing into useable experimental information.

Detector arrays can be very large, driven by the desire for increased detector coverage and spatial resolutions. The LET spectrometer (Figure 5.6) is the largest $^{3}He$ detector array at ISIS, with a 40 $m^2$ active area provided by 384, 4 m long $^{3}He$ tubes.

## 5.5 Mimicking cosmic rays

Accelerator-based neutron sources like ISIS have another important application – mimicking cosmic rays. The Earth is being continuously bombarded by high energy particles (mostly protons) which collide with the atmosphere to generate a steady 'rain' of high energy neutrons at the lower levels in which we live, work and fly aircraft.

These neutrons are effectively harmless for us, because we have evolved in them. However, over the last few decades, it has been realised that the modern electronic systems we use for flying, driving, going on the internet, delivering power, artificial intelligence and computing can be seriously disrupted by them. Disruptions occur when neutrons collide with the silicon that lies at the heart of all electronic devices.

As these devices become ubiquitous and more sophisticated, our society has become ever more reliant on them, so the issue has become increasingly important. The ChipIr instrument at ISIS mimics cosmic rays so that we can study and overcome the problems they create. This can only be done at accelerator-based neutron sources like ISIS because they can produce the very high-energy neutrons needed to mimic cosmic rays. Since coming online in 2018, ChipIr has been used by electronics companies from all over the world to study the effect of cosmic rays on their products, and learning how to overcome the issues caused. On this beamline, the neutrons directed towards the sample have energies that are typically one hundred million times higher than the other instruments.

Fig. 5.7. Motherboard in ChipIr

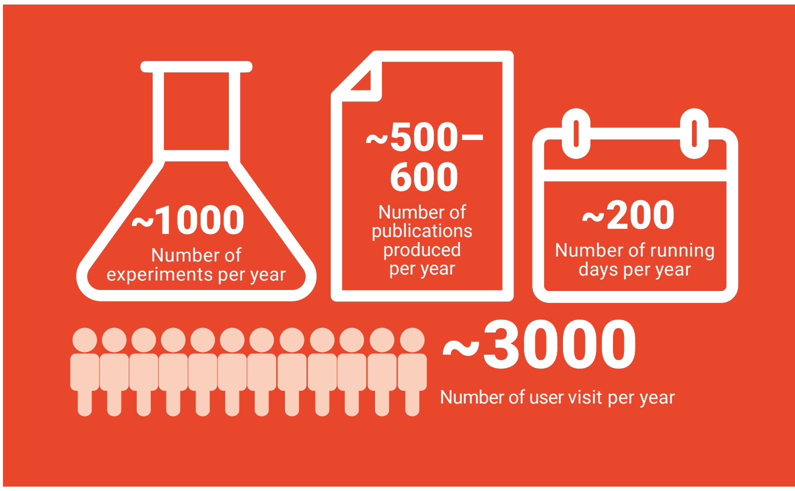



Fig. 5.8. Summary of ISIS annual science outputs

## Further reading


ISIS Website: www.isis.stfc.ac.uk

ISIS Annual Reviews: www.isis.stfc.ac.uk/Pages/Annual-Review-Archive.aspx

ISIS-II: www.isis.stfc.ac.uk/Pages/ISIS-II.aspx

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A.P. Letchford, et al., 'Testing, Installation, Commissioning and First Operation of the ISIS RFQ Pre-injector Upgrade', PAC'05 ROPC010 (2005)

N.D. West, 'Performance of the 70 MeV Injector to the ISIS Synchrotron', ICANS-XII (1993) A85 A92

P.J.S.B. Barratt, 'The ISIS Synchrotron RF System at High Intensity', ICANS-XII (1993) A109-A114

J.W.G. Thomason, 'Upgrades to ISIS for the New Second Target Station', EPAC'08 THXG03 (2008)

T.A. Broome, 'High Power Targets for Spallation Sources', EPAC'96 TUY04A (1996)

## 1970

The ISIS injector was built in the 1970s as a new 70 MeV injector for the 7 GeV proton synchrotron Nimrod, but before it could be used Nimrod was closed down. However the new injector for Nimrod was by no means all new – half of it came from the Proton Linear Accelerator (PLA) which ran for ten years between 1959 and 1969. The synchrotron was built specifically for ISIS in the early 1980s in the hall originally occupied by Nimrod.

**1978 – 1984**
Construction of ISIS reusing infrastructure from the Nimrod high energy physics experimental facility.

## 1980

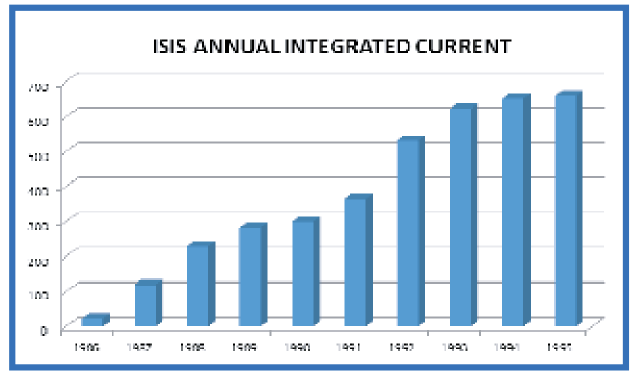
**1984**
At 19:16 on Sunday 16 December ISIS produced its first neutrons.

**1985**
Routine operations begin.

On 16 October at its official inauguration the neutron source was named ISIS by Prime Minister Margaret Thatcher.

**1985 – 1994**
Gradual ramping up of performance to produce annual integrated currents greater than 600 mA-hours

**1987**
First muons at ISIS were produced on 23 March 1987




## 1990

ISIS was originally called the Spallation Neutron Source (SNS), but was renamed as a reference to the ancient Egyptian goddess and the local name for the River Thames. The name was considered appropriate as Isis was a goddess who could restore life to the dead, and ISIS made use of equipment previously constructed for the Nimrod and NINA accelerators at the Rutherford and Daresbury Laboratories respectively.

## 2000

**2001**
Installation of new collector straight in synchrotron.

**2003**
Announcement of ISIS Second Target Station (TS-2).

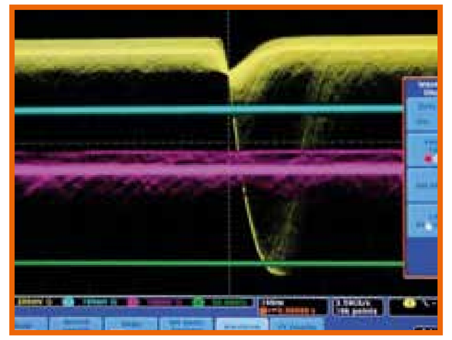
**2004**
Installation of ISIS RFQ and second harmonic RF system.

ISIS was recognised in the Guinness Book of Records as the most powerful pulsed neutron source in the world.

**2004 – 2007**
TS-2 construction.

**2007**
Installation of new magnets and muon collimator downstream of the intermediate target, and new switching magnets to direct beam to TS-2.

**2008**
On 3 August the first neutrons were produced at TS-2.



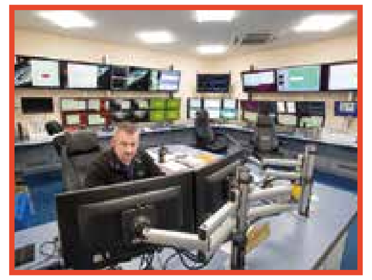
**2009**
Routine operations with initial suite of seven instruments begin on TS-2.

## 2010

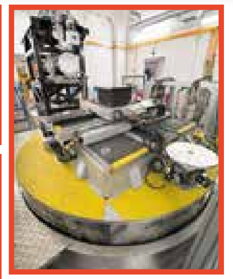
**2010**
Installation of new beam entry window for TS-1.

**2011**
On 14 March 2011, Science Minister David Willetts announced government funding for four new TS-2 'Phase II' instruments.

**2014**
Installation of new magnets around the intermediate target, and refurbished Main Control Room.



**2015 – 2017**
TS-2 Phase II instruments come online.



## 2020

Using the lessons learned from TS-2, there is an opportunity to redesign the TS-1 Target Reflector and Moderators (TRAM) to give improved performance for all TS-1 instruments. A feasibility study has concluded that upgrading and refurbishing both the TRAM and the associated services can give useful flux increases to all instruments. The project has moved to the implementation phase, aiming for installation starting in 2021.

**2021**
TS-1 target project and installation of new linac tank 4.

**2025**
Installation of new linac tank 1.

## 2030

**2030**
ISIS-II construction begins.

**2034**
ISIS' 50th Birthday!

> “ The concept of an ISIS-II short pulse facility is exciting and it has the potential to be very complementary to other sources.”
>
> **STFC Neutron Science and Facilities – Update to the 2017 Strategic Review**

## ISIS-II

The ISIS accelerators have been studied, improved and refined over many years, but at the start of 2016 a feasibility study was launched to explore ISIS-II, the next generation of the neutron and muon source for the UK.

The aim is to refocus facility upgrades in light of the advent of the European Spallation Source (ESS) in Sweden and new forecast scenarios for neutron and muon provision in Europe.

A working group was set up consisting of ISIS experts on accelerators, targets, neutronics, instrument science, detectors and engineering, to reflect the ambition of a full facility upgrade, not simply an accelerator upgrade.

This working group has produced a comprehensive roadmap for the feasibility and design studies and associated R&D to enable a fully informed decision on the optimal proton driver and target system architecture to build a megawatt-class short pulse neutron and muon facility on the Harwell campus with the best balance of technical capability and lifetime cost — ‘ISIS-II’. This could either be a stand-alone facility, or make use of existing ISIS infrastructure.

This challenging and ambitious project aims to gather enough detailed knowledge to enable a decision by 2027 and start construction by 2030 on a machine that will support the international research community for decades to come.