UPGRADES TO ISIS FOR THE NEW SECOND TARGET STATION

J W G Thomason*, ISIS, Rutherford Appleton Laboratory, STFC, Oxon., OX11 0QX, UK

Abstract

The new ISIS Second Target Station (TS-2) represents a major enhancement of the capabilities of the successful ISIS spallation neutron source, and correspondingly major enhancements have had to be made to the accelerator systems. As well as providing an outline of the new target station itself, this paper will describe the new dual harmonic RF system for the ISIS synchrotron which significantly increases the accelerated beam current to meet the needs of TS-2, and also the new proton beam transport line which diverts one out of every five pulses from the synchrotron to TS-2. In addition, the paper will summarise the substantial upgrades that have had to be made elsewhere on the ISIS accelerator system to underpin operation for at least another fifteen years, and will address possible future upgrades.

SECOND TARGET STATION

The Rutherford Appleton Laboratory (RAL) is home to ISIS, the world's most productive spallation neutron source. The ISIS neutron producing target (TS-1) is driven by a 50 Hz, 800 MeV, 200 µA proton beam from a rapid cycling synchrotron, which is fed by a 70 MeV H^- drift tube linac (DTL) which in turn accepts beam from an H^- 665 keV Radio Frequency Quadrupole (RFQ) pre-injector accelerator [1].

The ever increasing international demand for neutrons has motivated the building of a second target station (TS-2) at ISIS, which will operate at 10 Hz, and is optimised to provide cold neutrons. The primary target in TS-2 is a tantalum-coated solid tungsten cylinder 68 mm in diameter by 307 mm long. This design allows moderators to be placed very close to the primary target, leading to significant gains in fluxes of moderated neutrons. In the initial phase a suite of seven instruments for neutron scattering has been built, providing new opportunities in surface science, disordered materials, magnetic diffraction, small-angle neutron scattering and slow dynamics [2]. First experiments on the new instruments are scheduled to begin in October 2008.

The ISIS accelerator has been upgraded to achieve the increased beam intensity necessary to provide a 10 pps proton beam to TS-2 at the same time as maintaining the present intensity to TS-1, where the repetition rate is reduced from 50 pps to 40 pps. The schematic layout of the ISIS facility including TS-2 is shown in figure 1.

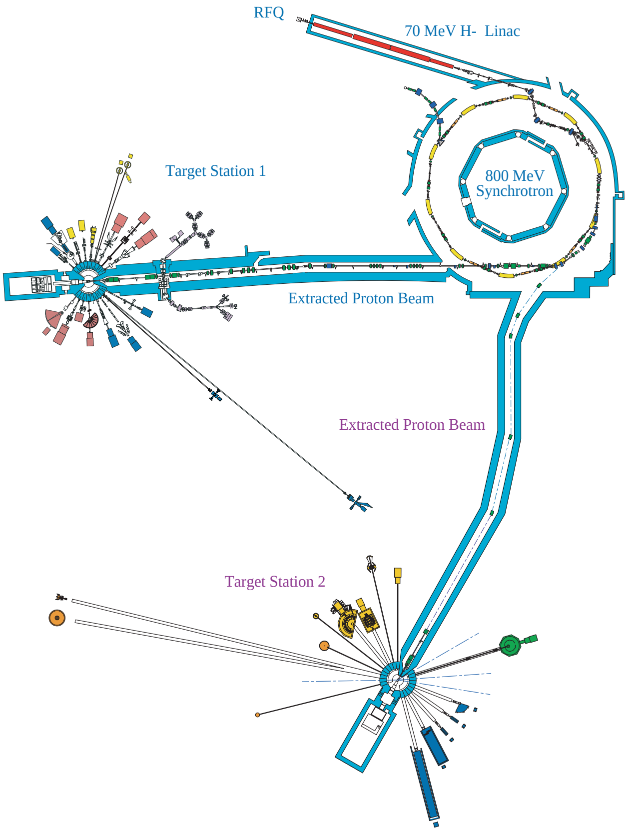

Figure 1: ISIS schematic layout.

INCREASED BEAM INTENSITY

Beam intensity in the ISIS synchrotron has been increased by the addition of two important elements: first an RFQ [3] (which replaces the old Cockcroft-Walton pre-injector) and second the installation in the synchrotron of four extra accelerating radio frequency (RF) cavities running at twice the frequencies of the six fundamental RF cavities [4].

The RFQ Accelerator

The ISIS RFQ was built at Frankfurt University as part of an ISIS/Frankfurt University collaboration, and was installed on ISIS in 2004. The 4-rod 202.5 MHz RFQ is driven by ~200 kW (peak) of RF from a Burle 4616 tetrode, and accelerates the 35 keV H^- beam produced by the ISIS ion source up to 665 keV. As the beam is accelerated through the RFQ it is also focused and bunched, giving a transmission efficiency of about 95% and an output beam which is almost entirely within the acceptance of the ISIS DTL. It is this increase in transmission efficiency (compared with about 60% for the

---

* The work summarised in this paper was carried out by a large project team, including: D J Adams, C W Appelbee, M A Arnold, C J Barton, D L Bayley, S L Birch, R Brodie, P V Drumm, J E Ellis, D C Faircloth, D J S Findlay, M D Fletcher, I S K Gardner, P E Gear, M G Glover, J A C Govans, J W Gray, S Hughes, S J S Jago, D M Jenkins, H J Jones, M Keelan, A H Kershaw, A J Kimber, M Krendler, C R Lambourne, A P Letchford, J P Loughrey, E J McCarron, A J McFarland, R P Mannix, W A Morris, S J Payne, M Perkins, C R Prior, E P Quinn, S J Ruddle, I Scaife, A Seville, A F Stevens, S P Stoneham, J A Vickers, S Warner, C M Warsop, S West, D M Wright and P N M Wright. The author takes full responsibility for any misrepresentation of their work.

old Cockcroft-Walton pre-injector) which provides the increase in the number of protons per pulse injected into the synchrotron required to meet the beam intensity demands of simultaneous TS-1 and TS-2 running.

The Dual Harmonic RF (DHRF) System

One of the main factors limiting maximum beam current is "trapping" loss in the synchrotron. With the six fundamental cavities alone, about 10% of the beam is lost during the first 2 ms of acceleration, when the initially unbunched beam injected at 70 MeV is captured in two bunches. These losses are associated with the fast non-adiabatic nature of the capture necessitated by the 50 Hz repetition rate, and the influence of repulsive space charge forces. The effect of these loss mechanisms can be reduced by modifying the accelerating RF waveform, allowing more accelerated beam at the same absolute loss levels.

The fundamental RF (1RF) cavities, running at twice the ring revolution frequency (1.3 – 3.1 MHz), provide up to 140 kV/turn for trapping and acceleration of the two bunches of protons. The additional four (2RF) cavities, running at four times the ring revolution frequency (2.6 – 6.2 MHz) and at voltages of up to 80 kV/turn should, with careful optimisation of relative phases and voltages, allow increased phase stable regions and enhanced bunching factors. Larger bunches, with more uniform longitudinal density distributions, allow capture of more beam and hence smaller beam loss.

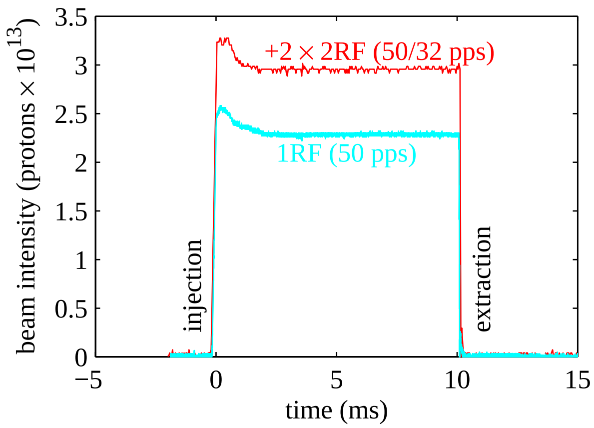

Figure 2: Comparison of DHRF beam intensities during 10 ms ISIS acceleration cycles.

As ISIS is a heavily loaded operating facility, experimental time with the DHRF system has been somewhat limited and a significant amount of this time has had to be devoted to overcoming hardware problems. For this reason effort has been concentrated on running with pairs of two out of the four 2RF cavities: this results in greater availability and reliability of the DHRF system during commissioning. However, even in this regime good improvements in beam intensity have been observed with absolute beam loss levels no higher than those normally seen with only 1RF cavities (see figure 2). The DHRF system has been run for all or part of each of the last five ISIS user cycles, although beam intensities at 50 pps have been limited to 2.65×10^{13} protons per pulse (212 μA) because of concerns about temperature monitoring on the TS-1 target (higher beam intensities have been achieved at the ISIS "base rate" of 50/32 pps). The latest results are presented in table 1.

Table 1: DHRF Results

Operating regime	**Trapped beam intensity (protons)**	**Total beam loss (protons)**	**Equivalent current to TS-1 (μA)**	
			50 pps	**40 pps**
1 RF (50 pps)	2.30×10^{13}	2.76×10^{12}	184	148
+2 × 2RF (50 pps)	2.65×10^{13}	1.60×10^{12}	212	170
+2 × 2RF (50/32 pps)	2.93×10^{13}	2.70×10^{12}	234	187

The ability to produce 187 μA to TS-1 at 40 pps (and hence 47 μA to TS-2 at 10 pps) means that even with only two out of four 2RF cavities running the DHRF system can provide enough beam intensity to run both target stations satisfactorily while experimentation continues to attain four 2RF cavity operation, and beam intensities approaching the theoretical maximum of 3.75×10^{13} protons per pulse [5].

TS-2 PROTON BEAM TRANSPORT LINE

The extracted proton beam line feeding TS-2 (EPB-2) extracts horizontally from the existing extracted proton beam line (EPB-1) and transports the beam over 143 m to the target, producing a circular beam with 18 mm half width and a centroid position stable to < 1 mm [6]. The schematic layout of EPB-2 is shown in figure 3 and magnet parameters are listed in table 2.

Extraction

One pair out of every fifth pair of proton bunches produced by the ISIS synchrotron is deflected from EPB-1 into EPB-2. The extraction system is in the horizontal plane and consists of two slow kicker magnets (K1 and K2), a septum, and a redesigned EPB-1 magnet (EHB4) which reduces the displacement required at the septum exit. The kickers operate at 10 Hz, have a rise time of 12 ms and maintain a maximum field for 600 μs to cover the extracted beam using an energy recovery pulsed power supply [7, 8]. K1 deflects the beam horizontally through the EPB-1 quadrupole magnets EQ6 and EQ7 and then K2 deflects the beam into the entrance of the septum. Figure 4 shows some of the extraction system magnets *in situ*.

Beam Line from Septum to Target

In the first section of the beam line (from the septum to HB2) the beam is dropped by 1.526 m and turned left

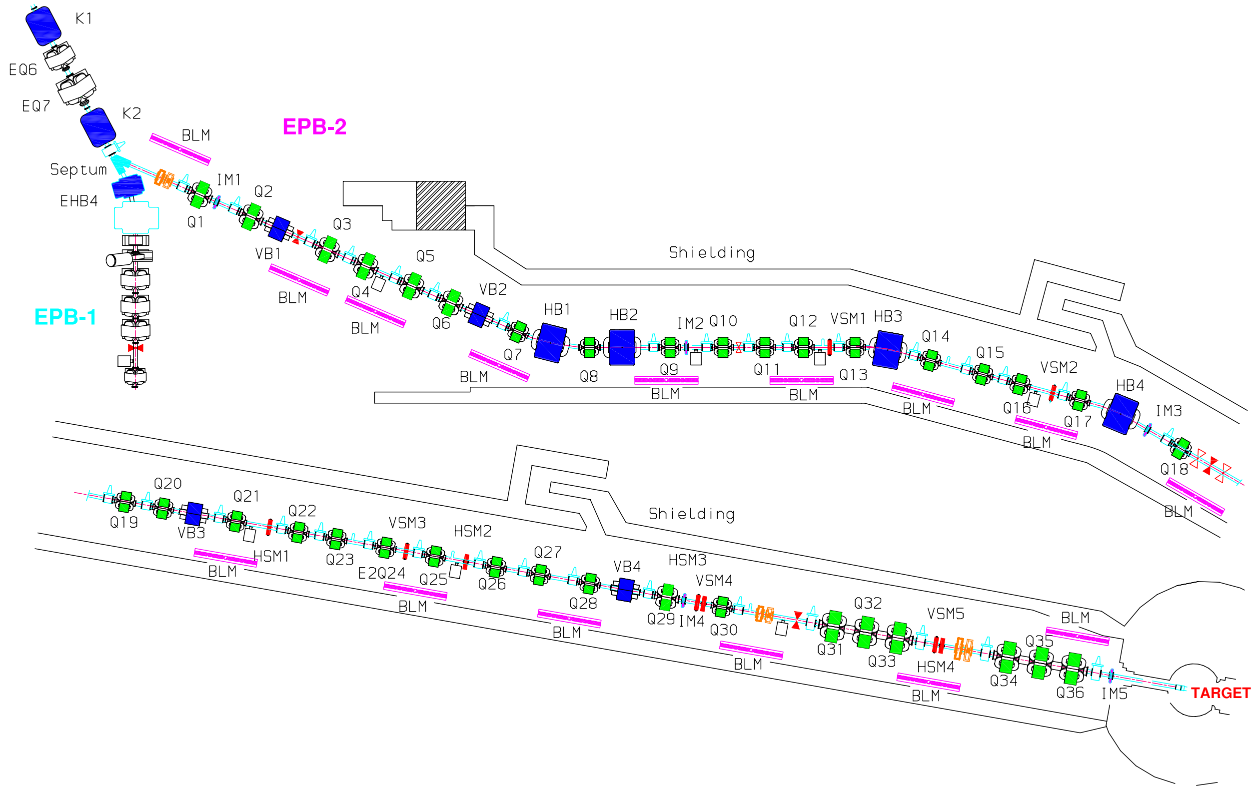

Figure 3: Schematic layout of EPB-2.

through 30°, allowing the beam line to pass through pre-existing buildings, and minimising shielding requirements and costs. The dispersion is closed at the exit face of HB2 to allow modularity in the remainder of the beam line. The second section (from HB2 to VB4) turns the beam right through 30° and increases to beam height by 0.87 m. Both bending sections are achromatic and have a 10 m FODO structure with 90° phase advance in each plane. The final section of the beam line (from VB4 to the target) uses a triplet structure to supply a beam waist at target in both planes. In order to accommodate the maximum beam size, Q(31 – 36), VSM(4, 5) and HSM(3, 4) are required to have a larger aperture than the other EPB-2 magnets.

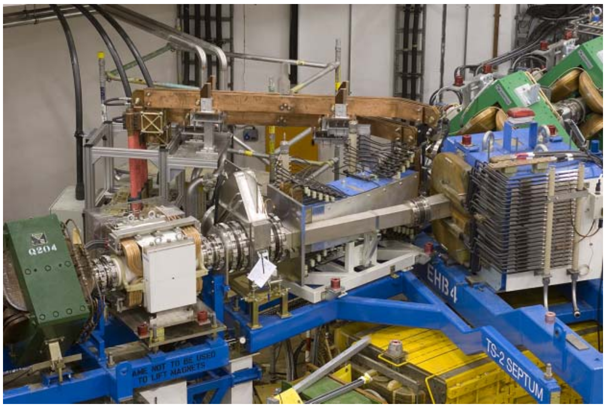

Figure 4: Magnets EQ7, K2, septum, EHB4, Q1 and Q2.

Magnet Design

Electromagnetic Finite Element Modelling techniques were used to design the magnets required to meet the specified beam line optics [9]. Knowledge of EPB-1 magnets and other designs worldwide, combined with basic analytical calculations, were used to provide an initial design for each magnet in table 2. These simple designs were then fine-tuned using 2D and 3D modelling to calculate ideal shims and chamfers. Choice of steel, configuration of conducting coils and handling of heat issues were all carefully considered before producing the final detailed designs.

Diagnostics and Beam Control

Machine protection is provided by 15 gas ionisation beam loss monitors (BLM) and five intensity (beam current) monitors (IM). Signal analysis from the BLMs trips the beam under high beam loss conditions, and the IMs allow beam intensities at extraction, during transmission and to target to be measured. Beam trajectories and widths are measured using 36 profile monitors and six position monitors distributed along the length of EPB-2.

Other Considerations

The realisation of EPB-2 has involved the concerted efforts of many groups throughout ISIS and from contract staff. As well as construction of the new TS-2 building, substantial civil engineering and building work has been

Table 2: EPB-2 magnets and their required parameters. K1 and K2 are slow extraction kicker magnets, VB(1 – 4) are vertical bending magnets, HB(1 – 4) and EHB4 are horizontal bending magnets, VSM(1 – 5) are vertical steering magnets, HSM(1 – 4) are horizontal steering magnets and Q(1 – 36) are quadrupole magnets.

Magnet type	Number	Frequency (Hz)	Maximum B or G (T / Tm^{-1})	Magnetic length (mm)	Deflection angle (°)	Half aperture (mm)	Field homogeneity (± %)
K1	1	10	0.15 T	500	0.69	100	0.25
K2	1	10	0.95 T	500	5.16	100	0.25
Septum	1	DC	1.05 T	1458	17.62	73	0.25
VB(1, 2)	2	DC	0.76 T	800	7.16	100	0.25
VB(3, 4)	2	DC	0.13 T	800	1.24	100	0.25
HB(1 – 4)	4	DC	1.05 T	1250	15.00	100	0.25
EHB4	1	DC	1.58 T	1038	18.44	78	0.25
VSM(1 – 3) HSM(1, 2)	5	DC	0.061 T	200	± 0.13	100	1
VSM(4, 5) HSM(3, 4)	4	DC	0.061 T	300	± 0.20	155	2.5
Q(1 – 6, 29)	7	DC	7.4 Tm^{-1}	500	-	100	0.5
Q(7 – 28, 30)	23	DC	3.8 Tm^{-1}	500	-	100	0.5
Q(31 – 36)	6	DC	8.2 Tm^{-1}	500	-	155	0.5

required to house the new beam line, including appropriate shielding and interlocks to ensure personnel and equipment safety. The beam line itself comprises custom-built vacuum chambers and an operationally optimised vacuum system. All the beam line components have been accurately aligned and rigorously tested and the EPB-2 power supplies and diagnostics have been integrated into the ISIS controls system.

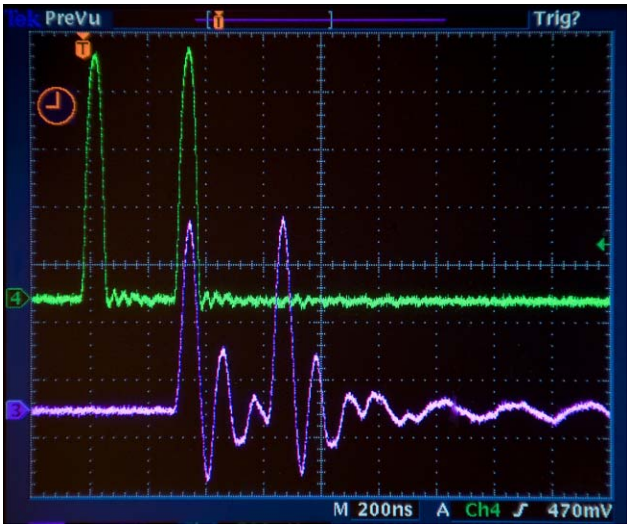

Figure 5: Oscilloscope traces of signal from IM5 (green) and induced current on the beam dump (magenta).

EPB-2 Beam Tests

EPB-2 underwent first beam commissioning tests on 14th December 2007. A temporary beam dump constructed from a block of graphite was installed at the neutron target position with a 50 Ω coaxial cable attached to monitor the current induced by the beam. To minimise activation of the beam dump the commissioning was to be limited to 1000 beam pulses at very low repetition rate, but in practice only about 50 pulses were required in order to demonstrate and measure satisfactory beam transport to TS-2. In fact with the EPB-2 magnets correctly set to their design currents beam to target was achieved at the first attempt. Figure 5 shows a pair of proton pulses from ISIS each ~100 ns long and with centres separated by ~320 ns, passing first through the last intensity monitor in EPB-2 and then hitting the beam dump.

Readings from the other intensity monitors showed that beam transport through EPB-2 is good, and beam envelope studies using the profile monitors indicated good agreement with theory. Trajectory studies showed some misalignment in both planes, probably due to a poor extraction trajectory. This should be corrected when further experimental work is carried out in July 2008 after the installation of the actual TS-2 target.

OTHER ACCELERATOR UPGRADES

In addition to the work already described (which has been specifically carried out to enable operation of TS-2) there have also been other substantial upgrades to the ISIS accelerators, intended to deal with the increased operational demands expected to be imposed by simultaneous TS-1 and TS-2 running and to underpin ISIS operations for at least another fifteen years.

The anode power supplies for the 202.5 MHz linac RF systems have been replaced and upgraded. New 40 kV, 45 kW switch-mode anode power supplies have been installed on each of the four high power RF amplifiers. This should improve stability and performance, providing longer lifetimes, reliability and efficiency.

A new system involving three 300 kVA uninterruptible power supplies and ten separate chokes is being installed to generate the AC current for the main synchrotron magnets [10]. This will replace the AC part of the present main magnet power supply, which consists of a 1 MVA motor-alternator set and a single large choke.

The fast extraction kickers, which kick the 800 MeV protons out of the ISIS synchrotron into EPB-1 via a septum magnet, have been fitted with a new set of drivers [11] (see figure 6). These operate at 48 kV (maximum of 60 kV) compared with the old 40 kV system, raising the beam vertically by 10 mm and resulting in reduced beam loss as the beam enters the septum.

Figure 6: The new drivers for the fast kickers.

Real time monitoring and logging of beam losses throughout ISIS (including EPB-2) is now done using new beam display and beam trip systems [12], which use a modern Field Programmable Gate Array (FPGA) design. This provides a faster beam trip reaction time and greater flexibility to meet future requirements.

Partly because of issues connected with TS-2, and partly to bring it up to modern standards, the entire ISIS accelerator interlock system has been replaced and upgraded. The new system complies with the IEC 61508 generic standard for functional safety. A new Central Timing Distributor (CTD) has also been installed on ISIS, which provides suitable pulse trains to allow ISIS running to either TS-1 alone or to TS-1 and TS-2 simultaneously at all required repetition rates.

POSSIBLE FUTURE UPGRADES

At present ISIS upgrade plans are based on a ~3 GeV rapid cycling synchrotron (RCS) fed by bucket-to-bucket transfer from the ISIS 800 MeV synchrotron [13]. Such an upgrade would increase the ISIS beam power to about 1 MW, giving a similar capability to SNS [14] and J-PARC [15] when they become fully operational. A promising five superperiod RCS design is currently being evaluated, with particular emphasis on high-intensity effects. This design also accommodates multi-turn charge exchange injection, and therefore facilitates a further upgrade path where the RCS is fed directly from an 800 MeV linac to produce beam powers in the region of 2 – 5 MW.

REFERENCES

[1] D J S Findlay, “ISIS – Pulsed Neutron and Muon Source”, PAC’07, p. 695.

[2] http://ts-2.isis.rl.ac.uk/

[3] A P Letchford *et al.*, “Testing, Installation, Commissioning and First Operation of the ISIS RFQ Pre-injector Upgrade”, PAC’05, p. 695.

[4] A Seville *et al.*, “Progress on Dual Harmonic Acceleration on the ISIS Synchrotron”, EPAC’08, MOPC121.

[5] M R Harold *et al.*, “A Possible Upgrade for ISIS”, PAC’97, p. 1021.

[6] D J Adams, “Proton Beam Line for the ISIS Second Target Station”, EPAC’04, p. 1443.

[7] P A Elkiaer *et al.*, “Slow Kicker Magnet System with Energy Recovery Pulsed Power Supply with Extended Flat Top”, PAC’07, p. 1395.

[8] S L Birch, “10 Hz Pulsed Power Converters for the ISIS Second Target Station”, EPAC’08, TUPD004.

[9] C M Thomas *et al.*, “Magnet Design for the ISIS Second Target Station Proton Beam Line”, PAC’05, p. 1652.

[10] S West *et al.,* “The Replacement of the ISIS White-Circuit Choke”, EPAC’08, THPP136.

[11] A J McFarland, “Design and Installation of the New Extraction Kicker Systems at ISIS”, EPAC’08, TUPD009.

[12] M R W North *et al.*, “Facility-Wide Real-Time Beam Loss Monitoring and Control Using FPGA Technology”, PAC’07, p. 4282.

[13] J W G Thomason *et al.*, “Megawatt Upgrades for the ISIS Facility”, EPAC’08, THPP083.

[14] http://neutrons.ornl.gov/

[15] http://j-parc.jp/