ICANS XIX,
19th meeting on Collaboration of Advanced Neutron Sources
March 8 – 12, 2010
Grindelwald, Switzerland

ACCELERATOR DEVELOPMENT FOR OPERATING TWO TARGET STATIONS AT ISIS

J.W.G. THOMASON*
STFC, ISIS, RAL, OX11 0QX, UK

ABSTRACT

The new ISIS Second Target Station (TS-2) represents a major enhancement of the capabilities of the ISIS spallation neutron source, and correspondingly major enhancements have had to be made to the accelerator systems. The paper will summarise the substantial upgrades that have had to be made on the ISIS accelerator system to deliver beam to TS-2, to provide the additional current required to run TS-2 while still maintaining sufficient beam to the First Target Station (TS-1) and to underpin facility operation for at least another fifteen years. The paper will also address the practicalities of moving safely and efficiently between the variety of operating modes presented by two target stations.

1. ISIS and the Second Target Station

The Rutherford Appleton Laboratory (RAL) is home to ISIS, the world's most productive spallation neutron source. The ever increasing international demand for neutrons has motivated the building of a second target station (TS-2) at ISIS, which is optimised to provide cold 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 [1].

The ISIS accelerator produces a 50 Hz, 800 MeV, 230 µA pulsed proton beam (where each pulse comprises a pair of ~100 ns long bunches separated by ~200 ns). Starting from a surface plasma H^- ion source, beam is fed into an H^- 665 keV Radio Frequency Quadrupole (RFQ) pre-injector accelerator, followed by a 70 MeV H^- drift tube linac (DTL) before multi-turn charge-exchange injection into a rapid cycling synchrotron (RCS) [2]. Three beam stops (ILBS1, IHBS1 and IHBS2) are located in the injector, and the RCS is housed in a hall which is split by shielding into an 'outer synchrotron' area and an 'inner synchrotron' area. Since September 2008, ISIS operation has demanded that four out of every five pulses from the RCS are delivered via an extracted proton beam line

* 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, R C Searle, 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.

(EPB-1) to the first target station (TS-1), where the overall repetition rate is now 40 pps: the remaining one out of every five pulses provides a 10 pps proton beam via a second extracted proton beam line (EPB-2) to TS-2. The ISIS accelerator has been upgraded to achieve the increased beam intensity required to maintain the proton intensity to TS-1 at its former (50 pps) level. Each target station is equipped with a dedicated target services area (TSA-1 and TSA-2). The schematic layout of the ISIS facility is shown in Fig. 1.

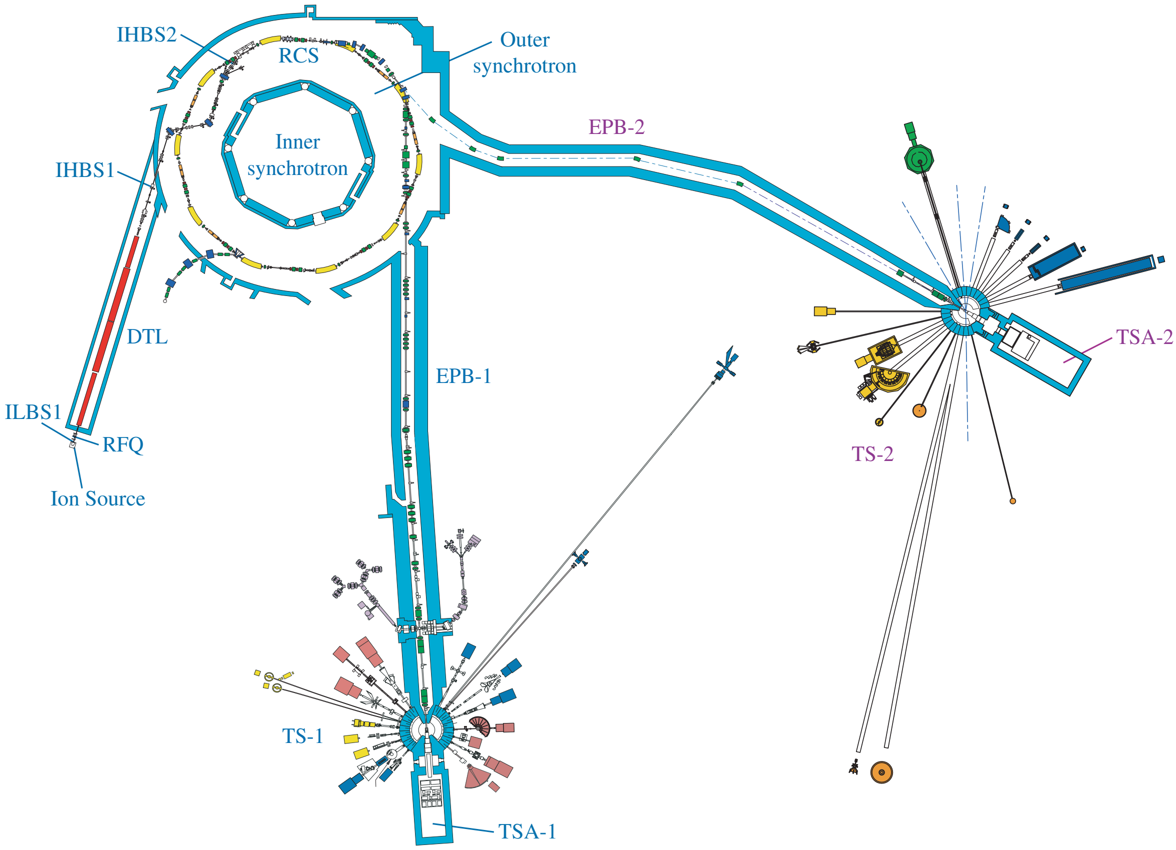

Fig. 1: ISIS schematic layout.

2. 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].

2.1. 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 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.

2.2. 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 160 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.

As ISIS is a heavily loaded operating facility, experimental time with the DHRF system has been 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. 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. The latest results are presented in Table I.

Table I: DHRF results.

Operating regime	**Trapped beam intensity (protons)**	**Total beam loss (protons)**	**Total 50 Hz current (μA)**	**Current to TS-1 (μA)**	**Current to TS-2 (μA)**
1 RF	2.30×10^{13}	2.76×10^{12}	184	184 (50 pps)	0
1RF + 2 × 2RF	2.88×10^{13}	2.65×10^{12}	230	184 (40 pps)	46 (10 pps)

The ability to produce 184 μA to TS-1 at 40 pps (and hence 46 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].

3. TS-2 Proton Beam Transport Line

EPB-2 extracts horizontally from 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 Fig. 2.

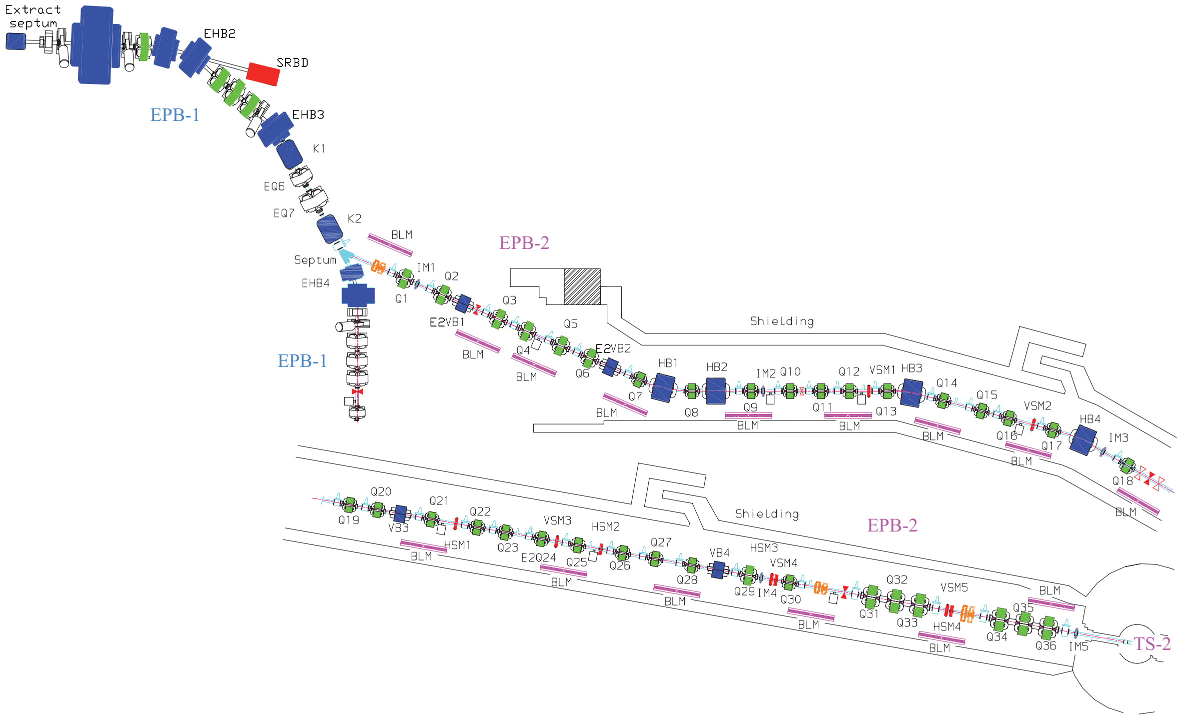

Fig. 2: Schematic layout of ISIS extraction and EPB-2.

3.1. 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.

3.2. 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 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 the 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.

3.3. 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 EPB-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.

3.4. 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.

3.5. 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 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.

4. 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 are being commissioned on 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 (plus one spare uninterruptible power supply and two spare chokes) has been 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. These can operate at higher voltage (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.

Real time monitoring and logging of beam losses throughout ISIS (including EPB-2) is now done using new beam display and beam trip systems [11], 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.

5. Operational Safety

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 upgraded system allows the flexibility to accelerate a proton beam to TS-1 and/or TS-2 at maximum repetition rates of 40 pps and 10 pps respectively with the ability to run at intermediate rates to either target station. Additionally there is provision to run a 50 pps beam to TS-1 only.

Fundamental to the ISIS risk control strategy are the Personnel Protection System (PPS) and the Beam Permit System (BPS). The PPS secures against access to ISIS areas that become hazardous to personnel under operational conditions (DTL, outer and inner synchrotron, EPB-1, EPB-2, TSA-1 and TSA-2, see Fig. 1). Best practice dictated the upgrading of the whole system to the IEC61508 [12] standard and this was followed for the BPS also.

The new Central Timing Distributor (CTD) provides the functionality to produce suitable pulse trains to allow ISIS running to two target stations. The CTD was excluded from the PPS/BPS as it contains a processor, which is difficult to certify under IEC61508. Therefore the PPS and BPS provide a 'beam permit' to the CTD to drive the 'Gated Machine Start' (GMS) signals which define those machine pulses carrying beam. ISIS 'base rate' running allows the machine to operate at 1/32 of normal repetition rate, with beam loss interlocks inhibited, to allow investigation of beam loss problems. This important feature is utilised when unaccountable beam loss occurs and is instrumental in setting up the machine. Additionally, beam operation at less than full repetition rate (assuming interlocks are complete) is software settable through the GMS timing signals.

Primary protection is via fail-to-safe delay boxes, which delay the ion source extraction and one of the DTL RF systems by 1 ms, ensuring no beam gets through the DTL unless all interlocks are made. A PPS failure will always prevent any beam transportation.

Secondary protection is by use of different modes of operation which prevent access to designated areas to ensure personnel safety. Generally, workers are separated from active beam areas by an extra inactive area (additional to the one they are in). Protection is given by isolating and earthing bending magnet elements and the use of physical beam stops in the injector, making beam transport to the contolled working area impossible. Busbars are broken and earthed, releasing Castell keys that are then used to make the beam interlocks again. A summary of ISIS operating modes is given Table II, with the locations of equipment used to disable the beam and controlled access areas shown in Figs. 1 and 2.

During operation, breach of any interlock, certain equipment failures and deselection of the mode switch will cause ILBS1 to be disabled, preventing beam transportation. Other preventative measures taken are automatic 'dumping' of the power supply which extracts H^{-} ions from the ion source, removal of the ion source accelerating potential and, depending on the violation, switching off of one of the DTL RF systems.

Table II: ISIS operational modes to two target stations

Operating mode	**Mode description**	**Repetition rate (pps)**	**Equipment used to disable beam**	**Controlled access available**
1	Ion source test	≤ 50	ILBS1, IHBS1	All areas
2	LEBT beam to ILBS1	≤ 50	ILBS1	DTL and all other areas
3	Linac beam to IHBS1	≤ 50	IHBS1	Inner synchrotron, EPB-1, EPB-2, TSA-1, TSA-2
4	Linac beam to IHBS2	≤ 50	IHBS2	TSA-1, TSA-2
4A	Beam to SRBD†	≤ 50	EHB2, EHB3	TSA-1, TSA-2
4B	Beam to TS-1	≤ 40‡	E2VB1, E2VB2	TSA-2
4C	Beam to TS-2	≤ 10	EHB4, EHB5	TSA-1
5	Beams to TS-1 & TS-2	≤ 40 & ≤ 10	None	None

In addition to the interlocks used to remove the beam permit to the CTD, each target system produces independent ‘fast interlocks’ which are specific and dedicated interlocks and directly turn off ion source extraction and the DTL RF systems to protect personnnel from hazards which may present themselves if critical target systems have failed.

A comprehensive search procedure is undertaken prior to machine operation where a press button search pattern is followed and confirmed by ISIS crew members. ‘Beam on’ conditions illuminate appropriate signage and change area lighting from white to blue.

In order to monitor and control the infrastructure of the ISIS safety systems and to maintain IEC61508 standards, a formal interlock change procedure has been put in place. This has been extended to cover non-IEC61508 interlock and safety systems and changes to shielding.

Finally, significant effort has been invested in updating ISIS safety documentation to reflect all the changes to equipment, interlocks and operating procedures necessary to accommodate running to two target stations.

6. References

1. http://www.isis.stfc.ac.uk/about-isis/target-station-2/
2. D. J. S. Findlay, *Proceedings of PAC’07*, (2007) p. 695.
3. A. P. Letchford *et al.*, *Proceedings of PAC’05*, (2005) p. 695.
4. A. Seville *et al.*, *Proceedings of EPAC’08*, (2008) p. 349.
5. M. R. Harold *et al.*, *Proceedings of PAC’97*, (1997) p. 1021.
6. D. J. Adams, *Proceedings of EPAC’04*, (2004) p. 1443.
7. P. A. Elkiaer *et al.*, *Proceedings of PAC’07*, (2007) p.1395.
8. S. L. Birch, *Proceedings of EPAC’08*, (2008) p. 1440.
9. C. M. Thomas *et al.*, *Proceedings of PAC’05*, (2005) p. 1652.
10. S. West *et al.*, *Proceedings of EPAC’08*, (2008) p. 3679.
11. M. R. W. North *et al.*, *Proceedings of PAC’07*, (2007) p.4282.
12. http://www.iec.ch/zone/fsafety/pdf_safe/hld.pdf

† Synchrotron Room Beam Dump.

‡ The 40 Hz can be switched to 50 Hz on disabling magnets E2VB1 and E2VB2 via a Castell key interlock so releasing a 50 Hz key switch. This will enable 50 Hz operation if prolonged operation in mode 4B (to TS-1 only) is expected. This is used directly in the CTD and is not part of the BPS.