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UPGRADES AND DEVELOPMENTS AT THE ISIS LINAC

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Abstract

The ISIS Spallation Neutron Source at the Rutherford Appleton Laboratory (RAL) in the UK has a 70 MeV H^- linac operating at 202.5 MHz. The linac consists of a 665 keV Radio Frequency Quadrupole (RFQ) and a 4-tank Drift Tube Linac (DTL). In order to ensure continued reliability, increase performance and lay the groundwork for possible facility upgrades in the future, a programme of R&D has been taking place in recent years. This paper will discuss three elements of that programme: the complete replacement of DTL Tank 4; the design of a Medium Energy beam Transport (MEBT) to go between the RFQ and DTL; and the Front End Test Stand (FETS), a demonstrator for the front end of a possible future high current, higher energy linac.

REPLACEMENT OF DTL TANK 4

Background

ISIS is the UK's venerable Spallation Neutron and Muon Source having produced first neutrons in December 1984 with routine operations beginning in June 1985. Originally simply called the 'Spallation Neutron Source' (SNS) it was officially inaugurated and named ISIS in October 1985 [1]. In order to minimise the cost, ISIS was largely constructed in buildings previously built for the Nimrod 7 GeV proton synchrotron (which operated between 1964 and 1978) [2] and also recycled some Nimrod accelerator components.

The 202.5 MHz, 70 MeV linac was originally designed as an upgrade for Nimrod operating at 1 pps but was repurposed for ISIS operating at 50 pps when Nimrod ceased operations. Tank 2 (10 – 30 MeV) and Tank 3 (30 – 50 MeV) had themselves already been recycled from the Proton Linear Accelerator (PLA) [3], which operated between 1959 and 1969. Tank 1 (0.665 – 10 MeV) and Tank 4 (50 – 70 MeV) were newly constructed in the late 1970s and were essentially copies of the Fermilab design.

The construction method of Tanks 2 and 3 (known as the 'old tanks')[1], with a thin-walled copper resonator inside a separate, split, steel vacuum vessel makes them eminently maintainable as evidenced by their continued operation at 50 times the original rep. rate despite being over 60 years old. Tanks 1 and 4 (known as the 'new tanks') were constructed with the then more modern method of sections of steel tube with an explosively bonded copper lining, bolted together and internally welded. Although cheaper to manufacture, this construction style does present some challenges should internal repairs to or maintenance of the tank become necessary.

Early in its life vacuum leaks due to cracks in the internal welds were detected in Tank 4. The solution was to fit copper patches with RF contacts and polymer o-rings, blind bolted to the inside of the tank which required craftsmen to work inside the tank with the drift tubes present. Although this was initially effective the vacuum pressure slowly deteriorated over time. This was addressed by the addition of more and higher capacity vacuum pumps and a variety of other ad hoc remedies. With knowledge that it would now be virtually impossible for anyone to work inside the tank due to beam loss induced activity (exacerbated by stripping of the H^- in the deteriorating vacuum) and somewhat different attitudes to staff duty of care, coupled with a growing fear of the consequences of a sudden, catastrophic failure of the tank, replacing Tank 4 eventually became the highest priority accelerator engineering project at ISIS.

As well as being operationally vital for ISIS, designing and building a new DTL tank also helps to develop essential skills which will be necessary for any future large scale facility upgrade.

Design of the New Tank

An early decision was that the new tank should be a direct plug-in replacement for the old tank with the same length and beam dynamics. Although dated by today's standards and not the design anyone would produce if designing it today, the primary objective was to secure reliable operation of the facility for future decades rather than specifically to improve its performance.

Due to the irreparable nature of the original tank being a major factor in requiring a replacement, one design goal was to build a tank which would not have this drawback. Early 3D RF modelling showed that it was possible to add shallow hatches along the tank with negligible impact on the calculated quality factor but which give relatively easy access to much of the inside.

As the tank is fitted with a bulk tuner[2], compensating for the small frequency shift produced by the hatches simply required a resizing of the bulk tuner. Figure 1 shows the tank during assembly with 3 of the hatches visible.

The new tank is made from 6, approx. 2 m long steel sections electroplated with copper. Unlike the welded original the sections are bolted together using Helicoflex seals [4, 5]. Each section has 2 hatches and for the section containing the RF feed the window housing is mounted on one of the hatches. Each hatch has a double seal formed by an RF contact and o-ring.

The drift tubes were internally redesigned with an improved cooling circuit and stem design. In some areas a lack of precise details about the original manufacturing methods also necessitated a redesign. Where vacuum brazing had been used in the original it was replaced by electron beam (EB) welding.

[1] 'Type 850' manufactured by the Metropolitan Vickers Electrical Co. Ltd in Manchester, UK.

[2] A T-shaped bar in the bottom of the tank to shift the frequency from 201.25 MHz used at Fermilab to 202.50 MHz used at ISIS.

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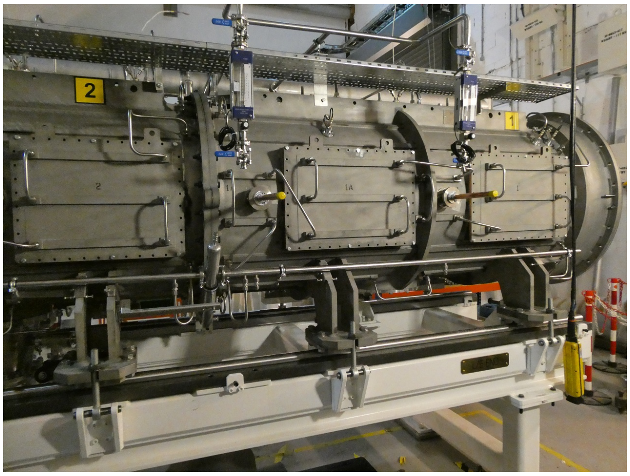

Figure 1: New Tank 4 showing maintenance hatches.

Quadrupole Magnets

A new electromagnetic quadrupole was designed to go in the drift tubes. The new magnet has the same magnetic length as the originals but with a new pole and yoke design, coil configuration and assembly arrangement. Considerable magnetic and thermal modelling and testing was performed before arriving at the final design. Cooling of the magnet is via contact with the drift tube body so the magnet plus beam tube are vacuum encapsulated in resin filled with glass beads to improve thermal conductivity. Figure 2 shows an example of a magnet sectioned to allow assessment of the encapsulation and a completed magnet assembly in the drift tube body prior to EB welding of the end caps and stem.

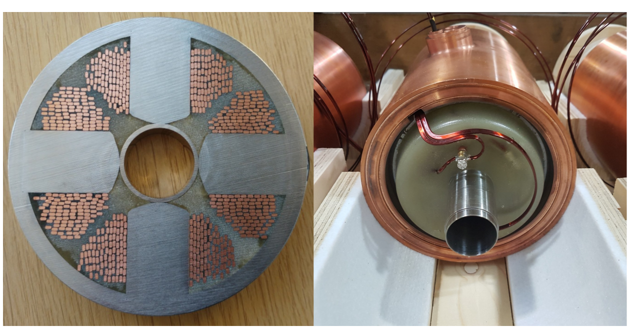

Figure 2: A section of a proto-type magnet (left); a magnet and beam tube assembly in a drift tube body (right).

Test Area

A large area previously occupied by the Cockcroft-Walton accelerator became redundant when an RFQ was installed in the ISIS Linac in 2004 [6]. This area was repurposed to make a Linac Test Area (LTA) in order to assemble the new tank and test it at full RF power. This required additional shielding so that the area could be occupied with the linac operating, installation of new water and electrical services and the construction of a complete duplicate of an ISIS Linac 2MW RF amplifier and associated systems.

Test Tank

Before embarking on construction of the full 12 m long tank it was decided to build a test tank to check the modelling results and evaluate manufacturing methods. The test tank was a single 2 m section but had most of the features of the full tank including flanges for a Helicoflex seal and was designed to be operated at full field level. No quadrupoles were fitted in the test tank. Several issues regarding copper plating quality and accuracy of EB welded parts were identified and resolved. The test tank also allowed the low level RF measurement techniques including bead-pull to be refined. Following installation in the LTA the test tank was characterised, conditioned to slightly above operational field level and soak tested at full power for a period of several weeks. The tank's performance was completely in line with calculations and no issues arose during soak testing.

New Drift Tube Shape

Successful progress with the test tank and good agreement between performance and modelling encouraged a bolder attitude to deviating from the original tank design. The 1970s tank had drift tubes with no face angle resulting in large gaps with poor transit time factor (TTF) and a peak surface electric field of little over one times the Kilpatrick factor (E_k). Quite early it was realised that the short quadrupoles and long drift tubes allowed for much more aggressive face angles so this feature was added to the design. Figure 3 shows the new drift tube shape. The ~15% improvement in TTF could give a reduction in RF power without beam of ~25% while still having surface field levels of no more than 1.6 E_k.

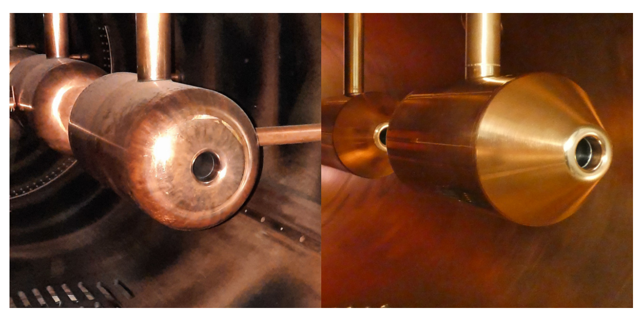

Figure 3: The old (left) and new (right) drift tube shapes. Note the vacuum patch just visible in the background of the left hand image.

A set of drift tubes with the new shape was manufactured for the test tank, installed and the RF characterisation and soak testing repeated.

The 12 m Tank

Tank 4 has an internal resonator length of 12.1 m and is 12.4 m long externally. It has 24 gaps formed by 23 full and 2 half drift tubes with one post coupler for every full drift tube. There is a quadrupole in every drift tube. RF power is fed via a plane vacuum window by a single

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12" air-side coaxial loop coupler at approximately the centre of the tank. There are 6 adjustable piston tuners, 5 manually adjustable for frequency and field shape adjustment plus one motorised tuner for dynamic tuning control.

The original tank was made from mild steel. Experience with the manufacture and electro-plating of the test tank led to a change to stainless steel. Calculations suggested that while this would lead to marginally worse short term beam loss induced activity, the increase in long term activity was not significant enough to override the manufacturing benefits.

Following manufacture of the 6 individual tank sections ISIS personnel travelled to the manufacturer to assemble, align and survey the complete tank. The penetrations for drift tube stems and post couplers were then machined in a single operation on a very large and accurate machine tool to avoid build-up of tolerances. The tank was then disassembled before being shipped to the platers and then sent to RAL for assembly in the LTA , installation of the drift tubes and realignment.

Because the test tank did not have quadrupoles some issues with the magnets were not seen at that stage. The primary problem was electrical shorts due to the way the quadrupole leads were routed and the machining and welding operations necessary after fitment in the drift tubes. These issues were identified early enough for small changes to design and procedures to be implemented on subsequent drift tubes.

Testing

The resonant frequency was correct with the tuners at the mid point of their travel as intended. The measured quality factor was 90% of the value calculated from 3D models indicating a required power of 1.3 MW compared to 1.6 MW for the old tank (without beam). The post couplers and tuners were set up using a method based on local tilt sensitivity measurements by beadpull [7]. The maximum gap voltage error was <2% which simulations indicated was acceptable.

Following tuning and stabilisation the tank was RF conditioned to 10% above nominal field level. The quadrupoles were powered during conditioning which was uneventful. The tank was then operated continuously at nominal power for two, six weeks periods, with maintenance and inspection carried out between them, to simulate linac operations. No significant problems with the tank arose during this soak testing.

Installation and Commissioning

Removal of the old tank from the end of the linac tunnel was a considerable challenge. It necessitated the removal of not only the shielding roof but some cabling and other services. To manoeuvre the tank over the shield wall and along the hall to the loading bay required very precise control of both of the building gantry cranes in tandem with very little room for error. Due to a height difference between the linac hall and the main road, connected by a steep slope, the tank had to be lifted from the slope to the transport vehicle by a large crane. The procedure was practised several times and refined using a lightweight mock-up of the tank. Figure 4 shows the tank after removal.

Figure 4: The old Tank 4 being delivered to RAL and being driven away over 40 years later.

Prior to removal of the old tank a careful survey of the electrical polarity of all quadrupoles was made as well as measurement of the magnetic polarity in the first and last quadrupole by Hall probe to ensure that the correct FDDF lattice would be established in the new tank.

The new tank was installed in sections with the drift tubes already in place. After alignment checks, connection of services, reinstatement of the shielding and recommissioning of the RF system the tank was reconditioned.

Beam commissioning was by a variation of the Δt method [8, 9] using RF pickups in the 70 MeV transport line to determine the RF field level and phase set points. Due to an equipment mis-calibration the field level was initially set too high resulting in large dp/p and a spate of RF window failures. After lowering the field level the x-ray emissions from the tank were dramatically reduced and window failures stopped. The dp/p was still high due to a now incorrect phase so the Δt procedure was repeated resulting in much better performance from the tank.

New Tank 4 has been operational since April 2022 and apart from the window failures mentioned above has performed reliably and consistently. The vacuum pressure is much improved resulting in lower beam loss from residual gas stripping.

MEBT UPGRADE

Background

When the RFQ pre-injector was installed on ISIS in 2004 [6] a decision was taken to leave the Cockcroft-Walton (CW) accelerator in place in case it was necessary to revert back to it due to problems with the

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RFQ. This placed a severe restriction on the length of the pre-injector so no MEBT was included and the RFQ was installed as close as possible to Tank 1 of the DTL. It was recognised that this would somewhat compromise the achievable beam current in the linac but it still achieved the goal of better transmission in Tank 1 and much improved reliability. The intention was always to install a MEBT once the CW accelerator was finally decommissioned but it took over a decade to finally start the project in earnest.

MEBT Design

Even with additional space available the MEBT has to be extremely compact: no more than 2 m long. In this space will be fitted 8 combined function quadrupole and steering magnets, four bunching cavities, a beam chopper and 4 beam position monitors (BPMs) [10]. Figure 5 shows a sectional view of the MEBT design. The MEBT components are installed on 3 'rafts' to ease installation. With the MEBT installed nearly 100% of the RFQ beam will be trapped and accelerated by Tank 1.

The combined function quadrupoles, which were originally designed for the FETS project (see below), have a magnetic length of 80 mm and maximum gradient of 20 T/m with a 43 mm bore.

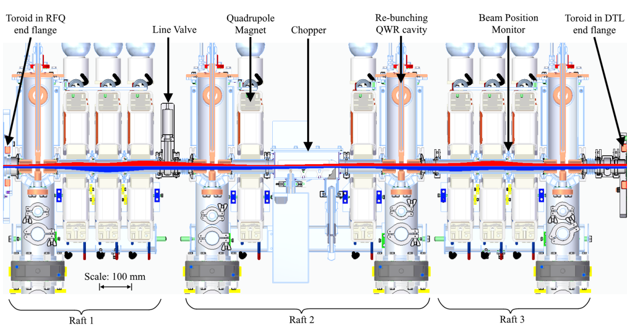

Figure 5: A sectional view of the ISIS MEBT design with simulated beam envelopes superimposed.

At the very low beam energy of 665 keV and relatively low frequency of 202.5 MHz a re-entrant pillbox type cavity for the bunchers is impractical. The MEBT will therefore use compact, two-gap quarter wave resonators (QWR). The QWRs are made from a copper plated stainless steel body with a copper drift tube and stem and have one fixed and one dynamic tuner. The peak gap voltage is ~30 kV requiring just a few kW of RF power.

ISIS does not currently have a beam chopper for routine operational use. One main source of synchrotron beam loss is during beam trapping after injection. In order to reduce this loss the MEBT will have a chopper operating at the synchrotron revolution frequency to inject beam only into the stationary bucket. The chopper consists of a single 160 mm long pair of parallel deflector plates operating at a potential difference of 15 kV. The rise time is of the order of 20 ns which corresponds to 4 bunches at the linac frequency. Modelling suggests that these partially chopped bunches will not lead to beam loss at high energy. The chopped beam is dumped onto a pair of water cooled tungsten wedges just downstream of the deflector.

Four extremely compact button type BPMs are placed between the quadrupoles on rafts 1 and 3. These are a development of a BPM first designed for FETS (see below). The BPMs will be used for beam position control and as RF pickups to allow setting up of the cavities by Δt measurements.

MEBT Test Stand

In order to commission and test the MEBT with beam before installation on the linac, a test stand is under construction using the spare ISIS RFQ. With the anticipated increase in transmission through DTL Tank 1, less current is required from the ion source for the same facility beam power. With this in mind a new un-caesiated RF driven ion source is being developed in parallel with the MEBT to replace the existing caesiated Penning type surface plasma source [11]. This should result in easier operation and longer, maintenance free lifetimes while delivering the same average current in a chopped beam to the synchrotron.

First beam was extracted from the ion source in August 2022. Beam commissioning of the MEBT test stand will begin in 2023 for possible installation in 2024.

THE FRONT END TEST STAND

Motivation

FETS [12] was originally conceived against a background of a possible UK bid to build the European Spallation Source (ESS) [13] and received early funding as part of a UK Neutrino Factory proposal [14]. Over its lifetime it has had many institutional and university collaborators [15] but is now primarily an ISIS internal project being completed in the context of ISIS sustainability and a possible future ISIS II facility [16, 17].

FETS Systems

FETS has been extensively described elsewhere [18]. It consists of an H- ion source, magnetic low energy beam transport (LEBT), 324 MHz 4-vane Radio Frequency Quadrupole accelerator (RFQ), medium energy beam transport (MEBT), diagnostics and full power beam dump. It is designed for a beam current of 60 mA with a duty factor up to 10% at 50 pps.

All of the components of FETS have been manufactured and tested (without beam) except for the fast beam chopper. For Phase 1 operation the beam dump has been installed directly downstream of the RFQ with just two quadrupoles for beam spot size control. There is a beam current transformer built into the output end flange of the RFQ and a single beam position monitor between the quadrupoles. Phase 1 is to allow initial beam setup of the RFQ and radiological surveys. For Phase 2 the full MEBT will be installed along with the laser wire diagnostic [19].

RFQ

The FETS RFQ is a 324 MHz, 4-vane structure of completely bolted construction with only one vacuum

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brazing operation on the end flanges. It is made from four, ~1 m long sections each of which is made from four quadrants: two minor vanes and two major vanes. Sealing between parts is achieved by beryllium copper RF contacts back by one 3D o-ring in each section [20, 21]. Inspection and alignment of the quadrants of each section was performed on a coordinate measuring machine in the RAL metrology department with external datums being referred to the internal vane profile to allow accurate alignment of the sections on the beamline. Dowels allow for dismantling sections and reassembly without requiring additional inspection. The repeatability of the dowelling was tested and found to work well. A vacuum pressure in the low 10^{-7} mbar was achieved on first assembly. The measured quality factor was above 90% of the calculated value.

Following installation of the completed RFQ, field flattening and tuning was performed with a four quadrant beadpull [22]. There are 62 adjustable tuners on the RFQ, four of which are motorised for dynamic frequency control and positioned to minimise field disturbances. After tuning the field un-flatness is <1% with <2% dipole content.

RF power for the RFQ comes from a Toshiba E3740A klystron and is supplied via two coaxial loop couplers [21]. The RFQ has been RF conditioned to above nominal field level at 5% duty factor. Conditioning took approx. two weeks. The required inter-vane voltage of 85 kV requires 545 kW as determined by measurement of the x-ray spectrum from the cavity [23]. As designed the cavity is relatively insensitive to thermal effects from operating at different duty factors.

First Beam

The first beam was accelerated by the RFQ in March 2022 at a rep. rate of 50/32 pps and a pulse length of 200 µs. Unfortunately very high noise levels on the beam current transformers made it impossible to determine the beam current. Beam loading suggested an accelerated current of 20 – 30 mA.

On the second attempt to accelerate beam a serious failure of the ion source extraction power supply meant that no beam could be injected into the RFQ. On the third attempt one of the LEBT solenoids was non-operational and the ion source emittance was larger than the design value resulting in beam loss in the LEBT and an inability to satisfactorily match the beam into the RFQ. Nevertheless a beam current of 28 mA was successfully accelerated at the same rep. rate of 50/32 pps and pulse length of 200 µs. The measured beam current at the RFQ exit is shown in Fig. 6.

SUMMARY

There is an active programme of linac R&D taking place at ISIS. These projects will enable continued reliable operation of the facility with increased performance over the coming years and prepare the way for development of the next generation of neutron source in the UK.

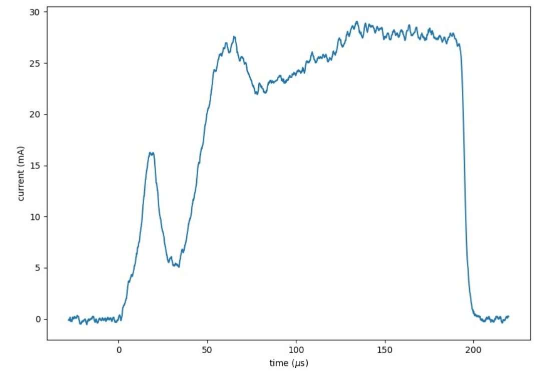

Figure 6: First measured beam current of 28 mA from the FETS RFQ.

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