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THE PRE-INJECTOR UPGRADE FOR THE ISIS H⁻ LINAC

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Abstract

A new maintenance-free, high current, high duty-factor H^- linac pre-injector is being commissioned for the ISIS pulsed spallation neutron and muon facility. As well as delivering a low emittance-growth, loss-free beam, the pre-injector incorporates a chopper to facilitate arbitrary bunch time-structures. A 50 Hz, 0.9 ms (4.5% duty factor) RF-driven H^- ion source operates extremely reliably and with a large available parameter space via a novel microwave ignition gun and a wideband solid-state RF amplifier. A 202.5 MHz medium energy beam transport (MEBT) incorporates eight quadrupole magnets with integrated xy steerers, four quarter-wave re-bunching cavities, four extremely compact beam position monitors and an electrostatic chopper in just two metres of footprint. Beam has been extracted from the ion source and MEBT commissioning is due Spring 2023. Thereafter, the entire pre-injector will be soak-tested offline for a year before installing on the user facility.

ISIS LINEAR ACCELERATOR HISTORY

An H^- linac is used at ISIS for charge-exchange injection into a rapid-cycling proton synchrotron. This delivers protons to two targets, which produce neutrons and muons for materials science studies. A pre-injector based around a solenoid low energy beam transport (LEBT) and 202.5 MHz radio-frequency quadrupole (RFQ) is used to form a high quality low energy bunched beam for subsequent acceleration by a drift-tube linac (DTL). In order to revert to the retired Cockroft-Walton multiplier stack in the event of a problem, old equipment was left installed in the area. The consequent lack of space meant that no matching components could fit between the RFQ and DTL. It was known that this would result in significant beam loss at two major locations in the linac. Therefore, having proven itself as extremely reliable over 15 years, space has been cleared such that the pre-injector may be moved back away from the DTL and a medium energy beam transport (MEBT) installed. The improvement in beam delivered by the MEBT is highlighted in Table 1. Because far less beam-loss is expected, the ion source no longer needs to generate as much beam current. This opens the door to modern long-life, high efficiency H^- technology. This paper describes the pre-injector installation status and the initial commissioning results of the ion source.

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Table 1: Improved beam transport afforded by the pre-injector upgrade.

Location	Existing	Upgrade
Ion source	55 mA	38 mA
LEBT	36 mA	36 mA
RFQ	35 mA	35 mA
DTL	25 mA	35 mA (chopped)

MEDIUM ENERGY BEAM TRANSPORT

The design of the MEBT has been described previously in detail [1]. It consists of eight quadrupole magnets, four re-bunching cavities, four beam position monitors and an electrostatic chopper.

Re-bunching Cavities

Four two-gap quarter-wave resonator (QWR) cavities operating at 202.5 MHz and -90° phase maintain the longitudinal structure of the beam bunched by the RFQ. Each QWR shown in Fig. 1 consists of a copper drift tube suspended inside a copper-plated stainless steel cylindrical cavity. Each QWR also incorporates four RF pickups, water cooling channels, fixed and dynamic slug tuners and a vacuum-pumping port. Features on the beam ports are used to align the drift tube bore to within 20 μm. Difficulties meeting the required welding and plating tolerances have necessitated prototypes being manufactured by several vendors. The QWRs are on the critical path for the project, but it is hoped that a satisfactory solution will be found to meet the MEBT beam delivery schedule of Summer 2023.

Figure 1: Quarter-wave resonator cavity prototype.

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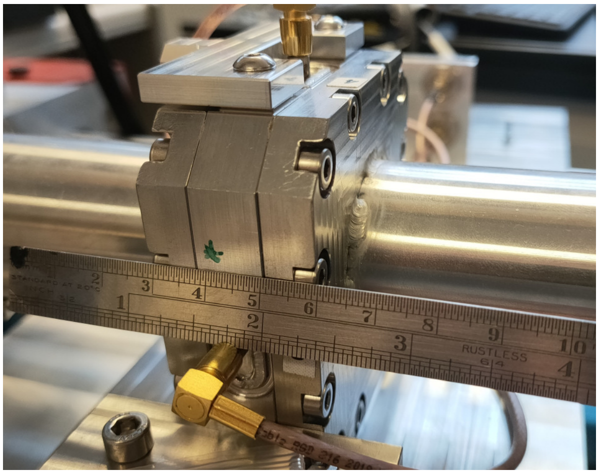

Figure 2: Button-type beam position monitor.

Beam Position Monitors

Four extremely compact button beam position monitors (BPMs) are installed in the MEBT in the 20 mm gap between quadrupoles. The BPM transverse dimensions are small enough for them to fit within the coils wound on the magnet yokes. As such, the BPMs are captive to the magnets and form part of the beam flight tube, as shown in Fig. 2. The 43 mm bore, 20 Tm^{-1} quadrupoles have additional windings for corrective xy steering, aided by the BPMs. As well as measuring the beam centroid position to within 0.1 mm, the button pickups will be used to ascertain time of flight in order to set up the QWR relative phases.

Chopper

A chopper is used to remove linac microbunches such that a clear region is formed in the synchrotron, enabling loss-less charge-exchange injection and clean high energy extraction. The beam is deflected by a total potential difference of 15 kV applied to 160-millimetre long parallel plates. The deflected bunches impact water cooled tungsten dump wedges, as shown in Fig. 3. The gap between the wedges (nominally 7.8 mm) will be adjusted iteratively until a good compromise is found between maximum chopped beam extinction and minimum un-chopped beam-loss. Electrically-isolated fibre-optic thermocouples monitor the temperatures of the deflector plates to ensure beam is lost only on the dumps.

RF ION SOURCE

The inclusion of a MEBT in the ISIS pre-injector will reduce linac beam-loss dramatically. This eases the output requirements from the ion source, meaning more modern and efficient technology may be used. Based on the highly successful SNS, Linac4 and CSNS ion sources using external RF coils [2–4], we have manufactured a high duty factor RF-driven H^- ion source for ISIS operations. Its design has been described previously in detail [5]. To summarise, a water-cooled solenoid RF-coil is wound around a ceramic plasma chamber, within which a pure hydrogen plasma is

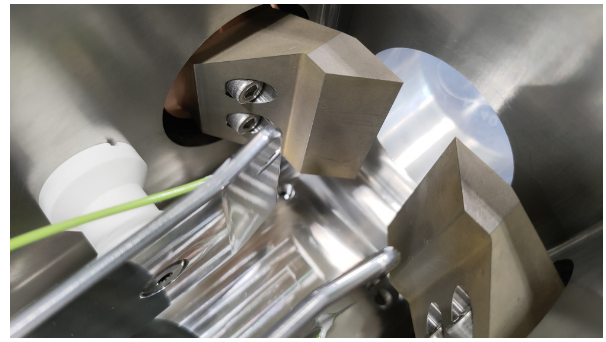

Figure 3: Chopper deflector plates and dump wedges.

ignited with a pulse length of 0.9 ms at 50 Hz repetition rate. A filter field generated by permanent magnets mounted external to the plasma chamber separates the plasma into 'driver' and 'production' regions, by energy-selecting the electrons. A pure volume process generates H^- ions: the output requirements are low enough that surface-enhanced processes via the addition of caesium are not foreseen.

Design Features

Figure 4 shows multiple novel features included in the RF ion source. The filter field is adjustable by rotating strategic pairs of permanent magnets. Several components are 3D printed using glass-reinforced nylon-12 in order to reduce costs and accelerate development time. The solid-state pulsed RF amplifier can output 100 kW across a bandwidth of 1.8 to 4.0 MHz, allowing a great deal of flexibility and physics studies into both the RF coupling efficiency and frequency-dependent H^- production yield. The plasma is switched on extremely reliably each pulse using an external ignition gun, which requires only 10 W of microwave power to deliver brief bursts of seed electrons into the plasma chamber. The ignition gun and plasma chamber have separate hydrogen feeds in order to optimise the plasma ignition and H^- production independently. A water-cooled tungsten puller electrode removes co-extracted electrons from the H^- beam using a dumping magnetic field. A re-entrant flange minimises the distance from extraction to the first LEBT solenoid magnet to just 200 mm. Four turbomolecular pumps ensure the vacuum pressure is below 10^{-4} mbar immediately after extraction to minimise H^- stripping losses. The ion source vacuum vessel is tilted 2° relative to the LEBT to correct the beam offset caused by the electron dumping field.

As well as generating the high current, low emittance, high duty-factor H^- ion beam required, every effort has been made to maximise lifetime, reliability and ease of use. There are no plasma-facing components which could erode or need replacing. Impurities are avoided by only having molybdenum or aluminium-nitride ceramic within the plasma's line of sight. The simple RF circuit has no active components to achieve a match to the plasma: instead utilising the flexibility afforded by the wide bandwidth amplifier. The amplifier itself has significant power overhead and may continue to run even with four modules inoperable.

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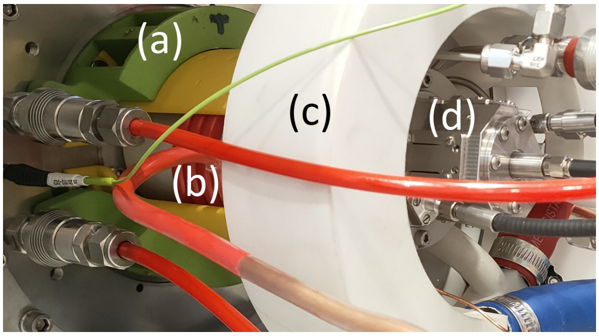

Figure 4: H⁻ ion source. Main components: filter magnets (a), RF-coil (b), cooling jacket (c), ignition gun (d).

RF Coupling Efficiency

The RF plasma is simple to operate, with no warm-up or power ramping required. It is important to get the best performance from the ion source as possible, though, as caesium will not be used to enhance the H⁻ yield. Therefore an experimental campaign was completed to ascertain the overall RF coupling efficiency,

$$\eta = \frac{P_{plasma}}{P_{generator}} = \frac{P_{generator} - P_{loss}}{P_{generator}}, \quad (1)$$

where $P_{generator} = P_{forward} - P_{reflected}$ is the measured RMS generator output power and P_{plasma} is the power absorbed by the plasma [6]. Figure 5 shows that η is almost independent of $P_{generator}$, which is useful as the beam production and transport may be tuned by adjusting $P_{generator}$, without significant detriment to the efficiency. The spike in efficiency at low power is when the plasma ignites with a combination of capacitive and inductive coupling.

Beam Commissioning

After a period of high voltage testing, the first 36 keV beam was extracted in August 2022 and measured on an AC current transformer, as shown in Fig. 6. The RF power was set to 40 kW at 50 Hz, whereas the extraction voltage was conditioned slowly, with the beam pulse length limited to 200 μs at 6.25 Hz. Initial studies have shown encouraging beam and electron currents which vary with RF power and

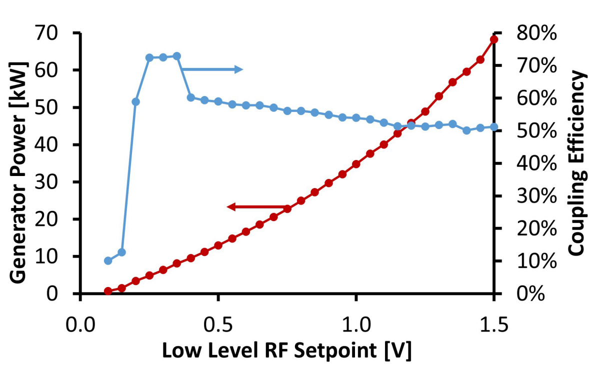

Figure 5: Generator power (red) and RF coupling efficiency (blue) as a function of input power at 3.23 MHz.

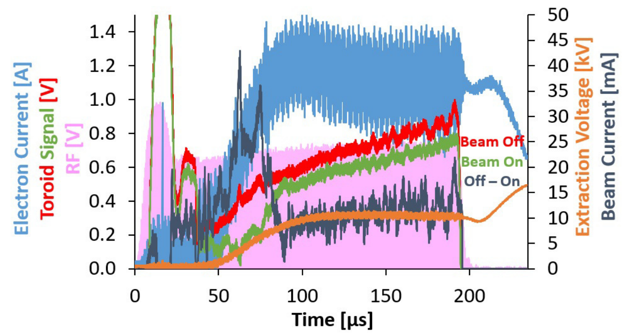

Figure 6: Initial beam commissioning. Axis label colouring denotes measurement type. Beam current is difference between toroid signals when extractor off and on.

extraction voltage, as expected. Unfortunately, significant RF noise was seen on all diagnostics, along with sparking between the electrodes, so enhanced screening is required.

PRE-INJECTOR TEST STAND

The pre-injector is installed on a test stand remote from the main ISIS accelerator. The RFQ emits up to 40 μSv/h of x-rays at 0.6 m, so the test stand is housed inside a lead shielding enclosure. A sophisticated personnel protection system ensures radiation and high voltage hazards are de-activated before access is granted inside. The accelerator equipment is installed on rails such that it can be transferred immediately to ISIS after testing, without further alignment. After commissioning and beam measurement campaigns, a period of extended soak-testing will begin to ensure all equipment operates reliably and with minimal failures. In particular, the RF-driven ion source promises an order of magnitude longer lifetime than the Penning source used presently, so long-term running for at least a year will demonstrate both the achievable lifetime and possible failure modes.

CONCLUSION AND OUTLOOK

The first H⁻ ion beam has been extracted successfully from the ion source. A detailed measurement campaign including emittance scans will be completed before focussing the beam through the LEBT. The RFQ and MEBT will be ready to accelerate beam by Summer 2023. Thereafter, the entire pre-injector will be soak-tested for one year in order to prove its viability and reliability for installation on ISIS. The pre-injector is a major upgrade for ISIS and will improve facility availability considerably.

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