ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPML059

RE-COMMISSIONING THE FRONT END TEST STAND NEGATIVE HYDROGEN ION SOURCE, BEAM TRANSPORT AND INTERLOCKS

S. R. Lawrie*, R. E. Abel, M. P. Dudman, D. C. Faircloth, A. P. Letchford, J. H. Macgregor, M. Perkins, T. M. Sarmento, R. C. Searle, M. O. Whitehead and T. W. Wood,
Science and Technology Facilities Council, ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Chilton, OX11 0QX, UK

Abstract

The front end test stand (FETS) is a demonstrator for a future high intensity, high duty factor negative hydrogen (H^-) ion injector. With the radio-frequency quadrupole (RFQ) nearing installation, the ion source has been re-commissioned in preparation for long-term operation. The 3 MeV beam exceeds the radio-activation energy of common engineering materials, so radiation shielding has been erected. A new interlocking scheme has been signed-off which integrates the existing ion source high voltage area with the new shielding access points, to ensure that the machine can operate safely during beam production. The existing vacuum arrangement has been extended to include the RFQ and medium energy beam transport (MEBT) line. A new programmable logic controller (PLC) has been built to operate the entire vacuum chain. The ion source high voltage equipment has been upgraded to minimise both spark rate and intensity. A collimating aperture and Faraday cup have been installed after the low energy beam transport (LEBT) section to ensure the beam is well aligned for injection into the RFQ. Re-commissioning the ion source has given a rugged shakedown of all these new systems before beam is required for the RFQ.

INTRODUCTION

The Front End Test Stand (FETS) project [1] has been under construction for a number of years to demonstrate the production and transport of a high intensity, high duty factor negative hydrogen (H^-) ion beam. Its primary goals are to: produce a 60 mA H^- beam at 50 Hz and 10% duty factor; deliver the world's first perfect fast chopper; operate a versatile laser emittance scanner; construct a novel bolted-together radio frequency quadrupole (RFQ); transport the H^- fully through a medium energy beam transport (MEBT) line and prepare it for loss-less injection into a linear accelerator. As the only hadron-based test stand under construction in the UK, FETS also helps educate a new generation of proton accelerator physicists and engineers. RFQ machining problems have delayed the achievement of key deliverables on the rest of FETS. Nevertheless, significant milestones accomplished in the last twelve months include: the commissioning of machine and personnel interlock systems; installation of a vacuum programmable logic controller; enhanced high voltage protection circuits; optimum ion source and LEBT settings found for good transmission into the RFQ. This paper details these and other developments.

RADIATION SHIELDING

The RFQ and MEBT will produce 60 mA, 2 ms pulses of H^- ions at 50 Hz repetition rate, giving a beam duty factor of up to 10%. The beam energy of 3 MeV exceeds the radio-activation threshold for materials such as copper and stainless steel, so minimising beam-loss is crucial. During the commissioning stages of the RFQ and MEBT, 18 kW of average beam power will be deposited on a dedicated water-cooled dump constructed from spun pure aluminium. Although this material will not become active, it will emit a significant flux of gamma rays during beam production. In addition, the strong electric fields of the RFQ and MEBT re-bunching cavities will generate bremsstrahlung x-rays from field-emitted electrons.

Therefore, a concrete blockhouse has been erected around the FETS beamline to reduce the external radiation dose to background levels. The blockhouse construction required a long shutdown of existing ion source and LEBT equipment and an overhaul of personnel interlock systems. Four access doors in and around the blockhouse necessitate a thorough search procedure and key exchange mechanism to prevent personnel access during beam operation. Figure 1 shows the main blockhouse entrance and some aspects of the personnel interlocking. Access into the blockhouse (a) is via two entrances locked by a trapped-key system (b). Two other internal doors must be closed. High-level lamps (c) indicate the operational state of FETS. When the interlock chain is made, the blockhouse internal lighting turns blue. If a user sees blue lights, they should press an emergency beam off button (d) and exit via a crash door. To mitigate the risk of personnel left inside, a search pattern is conducted and an array of buttons (e) depressed.

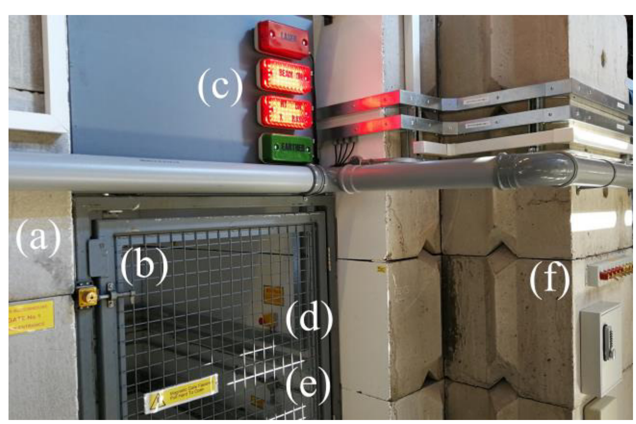

Figure 1: Radiation shielding blockhouse entrance. Labelled items described in text.

* scott.lawrie@stfc.ac.uk

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPML059

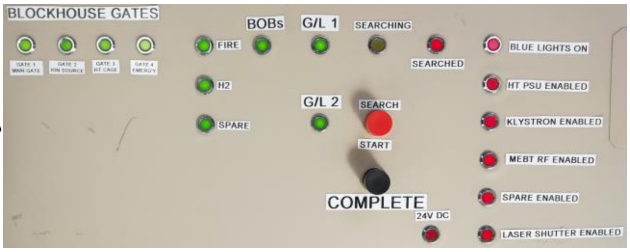

Figure 2: Personnel interlock chassis.

After the search is complete and access doors locked, keys are returned to a trapped-key exchange (f): only when all the red keys in Fig. 1 are returned will secondary keys be released to enable hazardous high voltage or RF power supplies. As well as the mechanical key exchange, a personnel interlock chassis, shown in Fig. 2, marshals dual-guard-line electrical signals to confirm doors are closed and the search has been completed. These multiple checks ensure a safe and robust system.

MACHINE PROTECTION

The FETS accelerator requires multiple different services such as water, vacuum and air handling. A machine interlock chassis tied to a programmable logic controller (PLC) interrupts beam production if any of the requisite services fail. For example, focussing magnets are energised only if rotameters measure good water flow and klixons indicate acceptable coil temperatures. Beam production is inhibited by removing timing to the ion source pulsed extraction power supply. In addition, a retractable Faraday cup (hereafter referred to as FDC1) in the LEBT is inserted automatically to prevent beam reaching the RFQ. Upon a beam trip, an audio buzzer informs the operators and the relevant lamp flashes, giving a quick visual indication which equipment is at fault.

VACUUM CONTROL

A vacuum PLC controls the operation of all pumps and valves in the accelerator. Upon commencement of a pumping operation, rotary pumps bring the vacuum below 10^{-1} mbar. Thereafter turbomolecular pumps are started in sequence with thirty-second delays to prevent mechanical resonances and large in-rush currents from the mains electrical supply. A pressure below 10^{-6} mbar triggers a 'vacuum good' signal to the machine interlock PLC, but the base pressure achieved throughout is better than 10^{-7} mbar. The accelerator is divided into three zones by in-line gate valves. This allows, for example, venting the LEBT to a nitrogen atmosphere for an ion source change, whilst maintaining good vacuum in the RFQ and MEBT. The line valves present a beam obstruction. Therefore, only when the vacuum PLC signals to the machine PLC that those valves are open, may the LEBT Faraday cup be withdrawn and beam sent to the RFQ. The vacuum PLC is operated with a password-protected touch-screen human-machine interface (HMI).

ION SOURCE COMMISSIONING

A shakedown of the shielding and PLCs was completed by re-commissioning the ion source and LEBT. In this manner, the RFQ can be installed and tested, safe in the knowledge that all personnel and machine protection systems operate correctly. This re-commissioning phase also allowed the testing of a new high voltage protection system and the confirmation of LEBT beam transmission.

High Voltage Protection

The ion source shown in Fig. 3 utilises two-stage acceleration. First the H^- beam is extracted (a) at around 18 keV using a vacuum-tube-based pulsed power supply unit (PSU) [2]. Then the beam is post-accelerated (b) to the 65 keV RFQ input energy using a direct current (DC) PSU. In the event of a high voltage breakdown, the extraction and DC PSUs would be shorted together, damaging the extraction drive circuitry severely. A new resistor-divider assembly (c) has been installed to shunt fault currents safely to ground. In addition, the post-acceleration electrode gap has been increased to reduce the spark rate. The new setup has resulted in no failures of the extraction PSU or other equipment during the re-commissioning period, so we are confident that the ion source can deliver beam reliably for the RFQ testing phase.

LEBT Transmission

Previous LEBT beam measurements, using transverse emittance scanners, showed inconsistencies within the three solenoid magnets and their embedded dipole steerers [3,4]. In addition, the accumulation of assembly tolerances resulted in H^- beam misalignment from the ion source. In this re-commissioning campaign, the limited space inside the shielding blockhouse precluded the use of emittance scanners, so an alternative method was employed to assess beam transmission. A collimating aperture was installed at the exact location of the RFQ; specifically, where the radial matcher transitions into the first modulation cell.

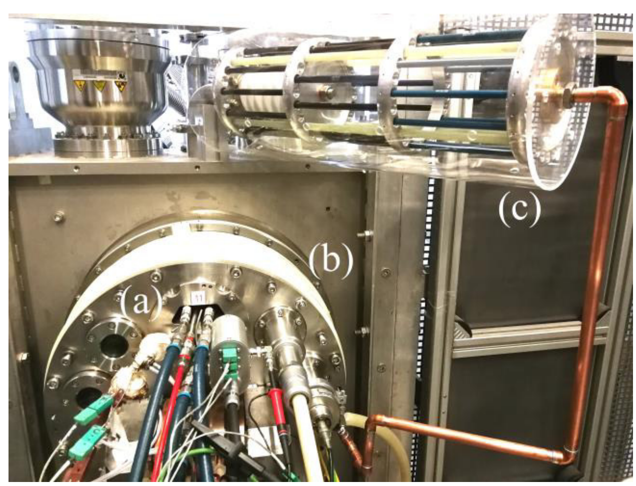

Figure 3: Ion source and high voltage protection circuit. Labelled items described in text.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPML059

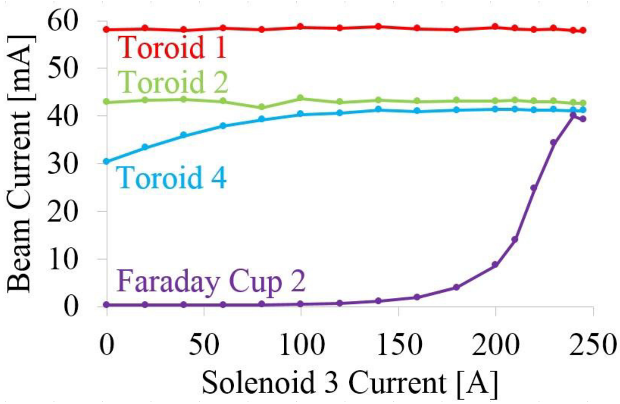

Figure 4: Measured beam current throughout the LEBT, as a function of solenoid 3 current. Solenoid 1 current fixed at 140 A. Faraday cup 1 and toroid 3 measurements were identical to toroid 2, so are omitted for clarity.

The RFQ acceptance requires a beam focussed strongly into that point, within an aperture radius of 3.646 mm. With a collimating hole of the same size and location, the expected beam transmission into the RFQ was measured. A current transformer toroid (hereafter referred to as T4) was located 48 mm upstream of the hole and a Faraday cup (FDC2) with suppression electrode was immediately downstream. There were also three other toroids (T1, 2 & 3) in the LEBT and the retractable FDC1 mentioned earlier. The ion source was operated at standard settings throughout: 700 µs long, 55 A discharge current pulses, 200 µs long, 18 kV extraction voltage pulses, 11.8 A sector dipole magnet current, 160 °C caesium oven temperature and 22 ml/min hydrogen flow rate. With solenoid 1 fixed at the nominal current of 140 A, solenoid 3 was adjusted as shown in Fig. 4. Above 100 A, the entire beam was transported from T2 to T4. However, the beam only became focussed sufficiently to pass through the collimating aperture and be measured on FDC2 when at 240 A. The discrepancies between currents measured on T2, T4 and FDC2 are due to residual gas ionisation stripping of the H^- beam. The larger difference between T1

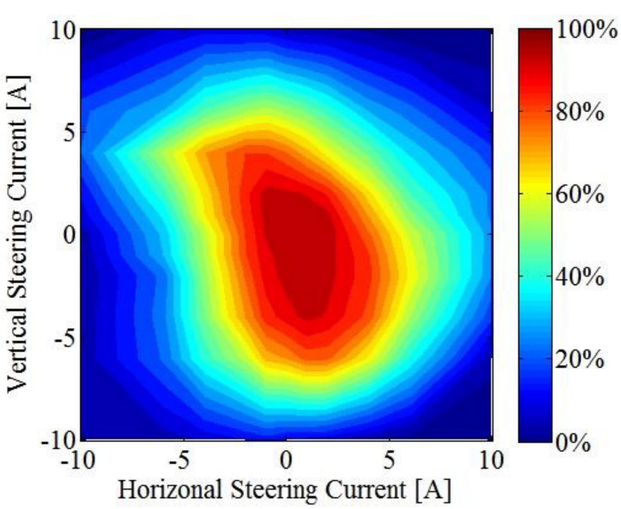

Figure 5: Proportion of the beam from T4 reaching FDC2 when sweeping the solenoid 1 integrated steering dipoles.

and T2 is due to artificial collimation between the ion source and LEBT. The beam current measured throughout is reduced by 20 mA compared to previous campaigns [5]. There is likely beam-loss because of the reduced focussing electric field in the larger post-acceleration gap, discussed above. Therefore, some iteration of the gap length will be performed to reach a compromise between higher beam currents and a low spark rate.

The ion source and LEBT alignment was estimated by sweeping the beam spot across the collimating hole using the steering dipoles embedded within solenoid 1. Previous campaigns [3,4] showed that it was somewhat difficult to tune the beam position empirically due to the interplay between the main solenoidal focussing field and the low level dipole fields. An improved alignment procedure resulted in an almost perfectly centred beam spot, as shown in Fig. 5. The range of steering available whilst maintaining excellent transmission indicates that the beam is somewhat smaller than the collimating aperture. This gives a wide tuning margin in both position and focussing strength from solenoid 3. This will be beneficial during the RFQ commissioning campaign.

MEBT RF CAVITIES

The MEBT is also nearing completion, with the focussing quadrupoles and re-bunching cavities installed. Two cavities have operated at full power and duty cycle, with the final cavity under test at present. These experiments confirm that the low-level RF control and temperature-stable water-cooling circuit function according to specification. These systems will also be needed for the RFQ, so it is prudent to prepare and commission them now.

CONCLUSIONS AND OUTLOOK

The FETS H^- ion source, vacuum control and machine- and personnel-interlocks systems have all been commissioned fully and signed off. At normal settings, such as 55 A discharge current, the ion source produces 60 mA of H^- beam current reliably at 65 kV and transports 40 mA into the RFQ acceptance, as measured by a collimating aperture and Faraday cup. The beam is centred well and the solenoids and steering magnets provide ample flexibility. The beam current will be increased by reducing the post-acceleration gap, whilst maintaining alignment. In addition, increasing the discharge current, extraction voltage and caesium oven temperature will yield higher beam currents, with the drawback of reduced source lifetime. A Penning ion source with plasma chamber dimensions scaled up by a factor of two (the '2X source') is under test at present [6] and has demonstrated recently extraction of H^- beam currents exceeding 100 mA at the 10% duty factor required for FETS. This ion source will be installed on FETS following further testing. In the meantime, the FETS blockhouse has been shown to shield adequately all x-rays generated by the ion source and re-bunching cavity high voltages. All equipment is operating nominally, ready for 2X source and RFQ installation.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPML059

REFERENCES

[1] A. Letchford *et al*, “Status of the RAL Front End Test Stand”, in *Proc. 6th Int. Particle Accelerator Conf. (IPAC’15)*, Richmond, VA, USA, May 2015, pp. 3959-3961, doi:10.18429/JACoW-IPAC2015-THPF105

[2] D. Faircloth *et al*, “A New Long Pulse High Voltage Extraction Power Supply for FETS”, in *Proc. 4th Int. Particle Accelerator Conf. (IPAC’13)*, Shanghai, China, May 2013, pp. 228-230.

[3] J. Back *et al.*, “Performance of the Low Energy Beam Transport at the RAL Front End Test Stand”, in *Proc. 5th Int. Particle Accelerator Conf. (IPAC’14)*, Dresden, Germany, June 2014, pp. 3406-3408, doi:10.18429/JACoW-IPAC2014-THPME073

[4] C. Gabor *et al.*, “Matching an H^- Beam into the FETS RFQ at RAL”, Rev. Sci. Instrum. 85, 02A745 (2014), doi: 10.1063/ 1.4862213

[5] D. C. Faircloth *et al.*, “Optimizing the Front End Test Stand High Performance H^- Ion Source at RAL”, Rev. Sci. Instrum. 83, 02A701 (2012), doi: 10.1063/1.3655526

[6] S. R. Lawrie *et al.*, “Recent H^- Diagnostics, Plasma Simulations and 2X Scaled Penning Ion Source Developments at the Rutherford Appleton Laboratory”, to be published in Rev. Sci. Instrum. 89 (2018).