The Front End Test Stand High Performance H^- Ion Source at RAL[a)]

D. C. Faircloth[1b)], S. Lawrie[1], A. P. Letchford[1], C. Gabor[1], P. Wise[1], M. Whitehead[1], T. Wood[1], M. Westall[1], D. Findlay[1], M. Perkins[1], P. J. Savage[2], D. A. Lee[2], J. K. Pozimski[1+2]

[1] STFC, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX14 0QX, United Kingdom
[2] Department of Physics, Imperial College, London SW7 2AZ, United Kingdom

(Presented XXXXX, received XXXXX, accepted XXXXX, published online XXXXX)

The aim of the Front End Test Stand (FETS) project is to demonstrate that chopped low energy beams of high quality can be produced. FETS consists of a 60 mA Penning Surface Plasma Ion Source, a 3 solenoid LEBT, a 3 MeV RFQ, a chopper and a comprehensive suite of diagnostics. This paper details the design and initial performance of the ion source and the laser profile measurement system. Beam current, profile and emittance measurements are shown for different operating conditions.

I. INTRODUCTION

A. FETS Overview

High power proton particle accelerators (HPPA) in the MW range have many applications including drivers for spallation neutron sources, neutrino factories, transmuters (for transmuting long-lived nuclear waste products) and energy amplifiers. In order to contribute to the development of HPPAs, to prepare the way for an ISIS upgrade and to contribute to the UK design effort on neutrino factories, a Front End Test Stand (FETS)[1] is being constructed at the Rutherford Appleton Laboratory (RAL) in the UK. The aim of the FETS is to demonstrate the production of a 60 mA, 2 ms, 50 pps chopped H^- beam at 3 MeV with sufficient beam quality. FETS consists of a high power ion source, a 3 solenoid magnetic Low Energy Beam Transport (LEBT), a 324 MHz, 3 MeV, 4-vane Radio Frequency Quadrupole (RFQ), a fast electrostatic chopper and a comprehensive suite of diagnostics.

At the time of writing the ion source and some of the diagnostics are operational. The LEBT is ready to be installed. Design of the chopper and RFQ are well progressed and the RF system for the RFQ has recently been commissioned to 1 MW.

B. Ion Source

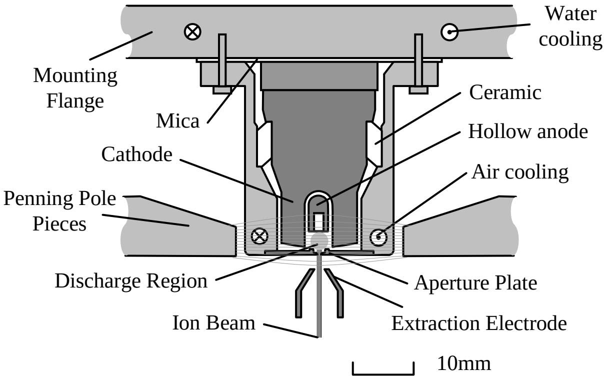

FIG 1: A cross section though the Penning source.

The source is of the Penning type[2], comprising a molybdenum anode and cathode between which a low pressure hydrogen discharge is produced (Figure 1). A transverse magnetic Penning field is applied across the discharge. The anode is hollow and has three equal sized holes. Cesium vapor is fed from an oven (160 - 190°C) via a heated transport line (300 °C) into one side of the discharge via two of the holes. Hydrogen gas is pulsed via a piezo electric valve into the discharge via the third hole in the anode. The source uses between 10 – 30 $\mathrm{mLmin^{-1}}$ of H_2 at 1 atmosphere. The anode and cathode are housed in a stainless steel source body. The body is air cooled and the mounting flange is water cooled.

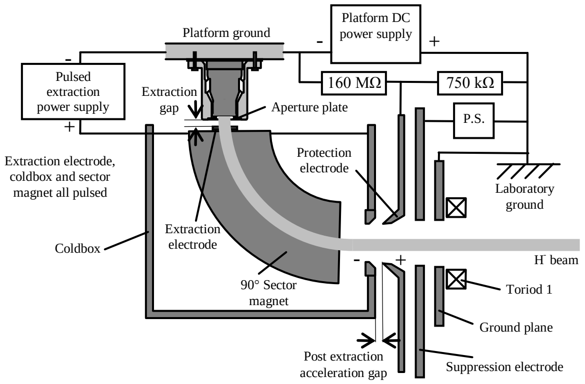

FIG 2: Schematic of the FETS ion source extraction and post acceleration system.

The beam is extracted through a 0.6 mm by 10 mm slit in the aperture plate (plasma electrode). There is a 2.3 mm gap between the extraction electrode and the aperture plate. The source is pulsed at 50 Hz. After extraction the beam is bent through a 90° sector magnet mounted in a refrigerated cold box (Figure 2). The sector magnet has two main purposes; to analyze out the electrons extracted with the H^- ions, and to allow the cold box (held at approximately 0 °C) to trap cesium vapor escaping from the source. The H^- beam emerges through a hole in the cold box and is further accelerated by a post extraction acceleration gap. A protection electrode is used as the low voltage side of the accelerating gap to limit the current to the power supplies in the event of flashover.

---

a) Contributed paper, published as part of the Proceedings of the 13th International Conference on Ion Sources, Gatlinburg, Tennessee, September, 2009.

b) dan.faircloth@stfc.ac.uk

II. SETUP

A. Design Improvements

The FETS source is a modified version of the operational ISIS source[3,4] that has reliably delivered beam for 25 years. Design improvements made on the Ion Source Development Rig (ISDR)[5] are implemented.

1. Duty Cycle / Cooling

The discharge pulse length is increased from 800 μs to 2 ms at 50 Hz. Previous modeling[6,7] and experimental work[8] has demonstrated the resultant extra heating can be mitigated by reducing the mica thickness and increasing the air cooling (both visible in Figure 1). The source operates best when the electrodes are kept between 400 - 600 °C. The pulsed discharge power supply is currently limiting the pulse length to 2 ms.

2. Extraction

It is planned that the extraction voltage will be increased from the operational ISIS source voltage of 17 kV to 25 kV. It has been shown[9] that increasing the extraction voltage increases the extracted beam current. The current, I_B is demonstrated to vary with extraction voltage according to the Child-Langmuir law[10]:

$$I_B \propto \frac{V^{\frac{3}{2}}}{d^2} \qquad (1)$$

Where V is the extraction voltage and d is the extraction gap. The extraction voltage is currently limited to 18.5 kV by the power supply; a new supply is currently being designed. Extraction from the source has been investigated previously[11,12] and this work is continuing with a detailed study into the plasma meniscus and electrode geometry[13]. It has been demonstrated[14] that beam currents of 78 mA can be achieved by increasing the width of the aperture slit from 0.6 mm to 0.8 mm.

3. Discharge Current

A 55 A discharge current is used on ISIS. Discharge current and hydrogen flow rate are the two main factors affecting plasma density in the source. Recent experimental work[13] has shown that there is an optimum discharge current for a specific extraction voltage and geometry. For the ISIS source the discharge current should be in excess of 65 A to produce a beam with minimum divergence. The FETS discharge power supply is capable of delivering up to 100 A.

4. Sector Magnet Poles

The sector magnet has a quadrupole component to focus the beam into a rounder profile after the slit extraction. This field component is best defined as a field gradient index, n.

$$n = -\frac{R_e}{B_e}\left(\frac{dB}{dR}\right) \qquad (2)$$

Where, R_e is the radius the centre of the beam follows as it goes through the sector magnet (80 mm) and B_e is the magnetic flux density at that radius. (at 17 keV B_e = 0.236 T)[15]. When n > 1 the beam is focused horizontally, when n < 1 the beam is defocused horizontally. For high current, low energy beams, space charge has a significant defocusing effect. Calculation of the exact beam trajectory is complex because the degree of space charge compensation is not accurately known. The ISIS operational source sector magnet has an n = 1.4. Recent simulations and studies[16] on the ISDR have shown the optimum index is actually n = 1.2. Previous studies[17] have found the best sector magnet design has a larger good field region[18] and proper field termination[11]. All these improvements have been implemented on the FETS source.

5. Permanent Magnet Penning Field

To allow the extraction voltage to be varied the sector magnet field must also be altered to match the beam energy. On the ISIS source the Penning field is produced by parasitic pole pieces on the top of the sector magnet poles. The source requires a Penning field of between 0.15 - 0.25 T, below this range the discharge becomes unstable, above it becomes noisy[15]. To allow different extraction voltages the Penning field is produced by a pair of $Nd_2Fe_{14}B$ permanent magnets. The magnets are mounted on the cold box to keep them below their Curie temperature (< 300 °C).

6. Post Acceleration

Previous studies[19] have shown that for minimum emittance growth the field in the post acceleration gap should be about 9 $kVmm^{-1}$. The post acceleration gap on the ISIS operational source is far too long (55 mm). The post acceleration gap on FETS is currently set to 6 mm. The post acceleration voltage is provided by the platform DC power supply (Figure 2). The actual post acceleration voltage is equal to the platform voltage minus the extraction voltage. On ISIS the platform voltage is 35 kV, giving a post acceleration voltage of 18 kV (0.33 $kVmm^{-1}$). For FETS the platform voltage will be increased to 65 kV, however design problems with the power supply currently limits operation to 40 kV giving a post acceleration voltage of 23 kV for a 17 kV extraction voltage (3.8 $kVmm^{-1}$). This will be increased in due course.

B. Present Setup

Figure 3 shows the experimental setup. The source is mounted on an isolating column attached to a differential pumping vessel equipped with three 800 Ls^{-1} turbo pumps. A laser profile measurement system is installed inside this vessel. A diagnostics vessel is connected to the differential pumping vessel via a short section of beam pipe. The diagnostics vessel can be moved along the beam line as it is constructed. After characterization of the source is complete the three solenoid LEBT will be connected directly to the first differential pumping vessel.

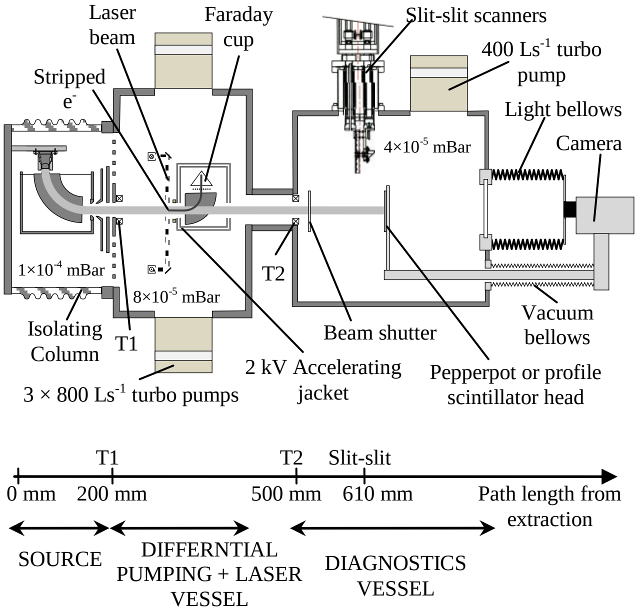

FIG 3: The overall experimental set up.

The ancillary equipment required to drive the ion source and to allow safe operation is described in previous papers[20,21,22].

C. Diagnostics

1. Laser Profile Measurement

The differential pumping vessel contains a laser wire beam profile measurement system[23], based on the photo–detachment of the outer electron of the H^- ions with a 671 nm wavelength laser. The detached electrons are accelerated by a 2 kV voltage applied to the accelerating jacket and bent through 90° by a dipole magnet. The electrons are detected in the faraday cup arrangement with a suppression electrode. The laser wire system allows the transverse beam density distribution to be determined at full beam power without affecting the beam. This is achieved by stepping the laser beam through the ion beam at a variety of different angles to collect many different projections and then combining these using either the Algebraic Reconstruction Technique[24] or the Maximum Entropy algorithm[25].

2. Diagnostics Vessel

The diagnostics vessel draws on equipment and techniques developed on the ISDR the following diagnostics are available:

- A pair of retractable slit-slit emittance scanners[26].
- A pepper pot emittance device[27] which can be moved along the axis of the beam whilst the beam is running and can be moved level with the slit-slit scanners.
- The head of the pepperpot can be replaced by a scintillator profile measurement head.
- A retarding potential energy analyzer[28].
- Beam current toroids.

III. INITIAL RESULTS

A comprehensive optimization process is in progress. Some of the key results obtained so far are shown.

A. Peak Current

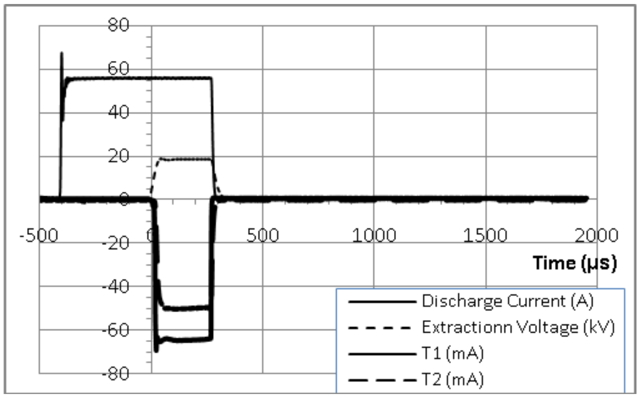

FIG 4: Waveshapes for an 18.5 kV extraction, 16 A sector magnet, 40 kV platform, 55 A discharge. 250 µs pulse length.

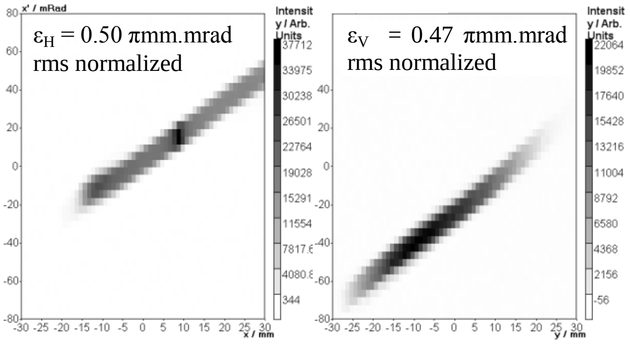

FIG 5: Emittance plots for the beam shown in Fig 4. (Note- the beam is not horizontally centered due to sector magnet alignment error.)

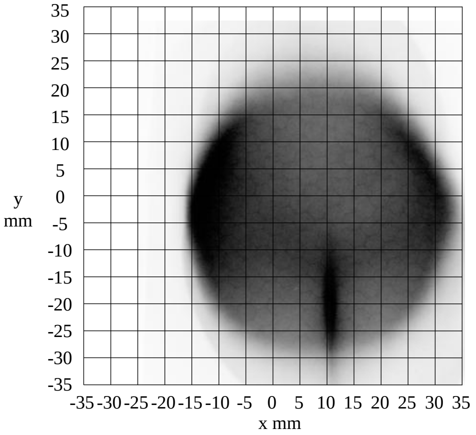

FIG 6: Scintillator profile image for the beam shown in Fig 4.

B. Longest Pulse Length

The extraction power supply is not capable of running at pulse lengths longer than 500 µs at 50 Hz. To test long pulse extraction the repetition rate of the extraction power supply is reduced to 3.125 Hz whilst keeping the pulsed discharge power supply running at 50 Hz. This allows 1.6 ms beam pulses to be extracted.

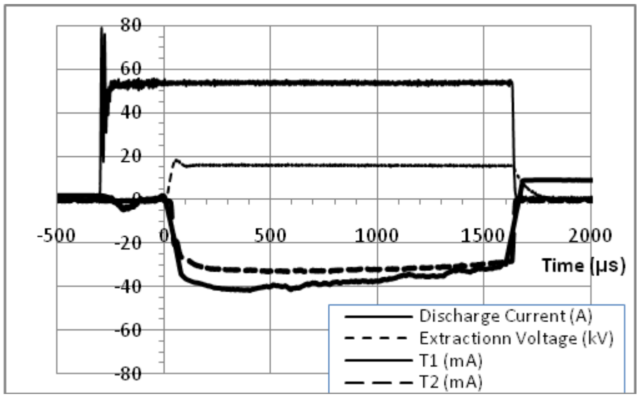

FIG 7: Waveshapes for a 15.7 kV extraction, 12.5 A sector magnet, 40 kV platform, 55A discharge, 1.6 ms beam. (Note that the droop and undershoot on the T1 trace is due to the use of non-optimized circuitry that had to be used temporarily as a makeshift.)

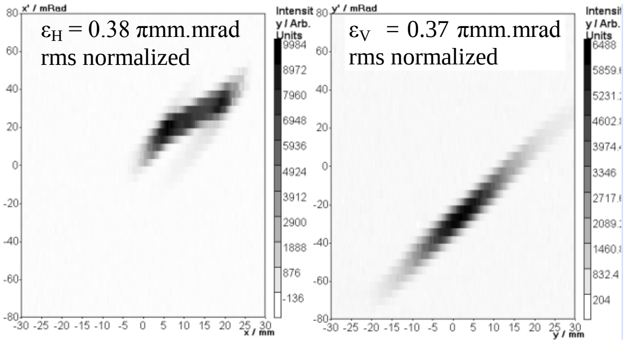

FIG 8: Emittance plots for beam shown in Fig 7.

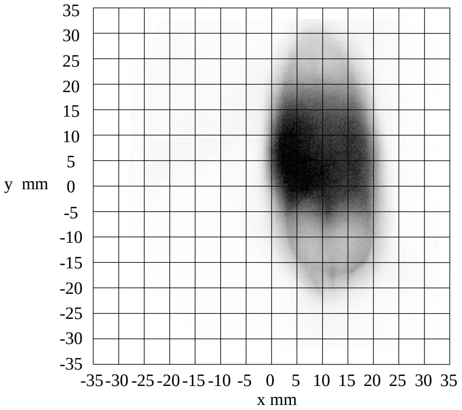

FIG 9: Scintillator profile image for beam shown in Fig 7.

C. Laser Profile Measurement

No profiles have yet been obtained from the laser wire system. The detached electron signal is swamped by a background signal. The cause of this background signal is under investigation. With the beam on, the background signal is in the order of 10 µA. The predicted detached electron signal is in the order of 1 nA for 600 mW laser power. Additional suppression electrodes have been installed and the detection electronics improved, in an attempt to reduce the background signal, however this has so far been unsuccessful. A higher power laser is the next step. An initial study of beam transport indicates that the suppression voltages on some of the electrodes can actually affect beam transport[29].

IV. DISCUSSION AND OUTLOOK

Modifications to the standard ISIS source have yielded significant improvements in source performance. Beam emittance has been reduced from 0.9 πmm-mrad[12] to less than half this value. Short pulse beam currents have exceeded the FETS requirement of 60 mA at the first toroid, however the beam is still too divergent and is collimated to 50 mA by the time it reaches the second toroid. The second toriod is currently positioned at the entrance of where the LEBT will be. Previous studies[30] show that a 60 mA beam with a divergence of 0.5 πmm-mrad can be transported by the LEBT. The long pulse tests show a significant reduction in beam current, accompanied by a reduction in beam emittance. Figure 7 shows a significant droop in beam current on the second toriod from 32 mA to 29 mA (almost 10%). Increased aperture width and extraction voltage are yet to be implemented. Work is underway to improve extraction[13], these additional modifications should further increase beam current and decrease emittance. When the limitations of the power supplies are overcome it should be possible to meet the beam requirements for FETS. There is however a possibility that beam current droop is still a problem, in which case a scaled source is required as demonstrated by previous researchers[31].

V. REFERENCES

[1] A. P. Letchford, D. C. Faircloth, M. A. Clarke-Gayther, D. C. Plostinar, Y. A. Cheng, S. Jolly, A. Kurup, P. J. Savage, J. K. Pozimski, J. J. Back, *"The RAL Front End Test Stand",* Proceedings of EPAC06, MOPCH112, (2006).

[2] V G Dudnikov, *"Surface Plasma Source of Penning Geometry"*, IV USSR National Conference on Particle Accelerators, (1974).

[3] R. Sidlow, P. J. S. Barratt, A. P. Letchford, M. Perkins, and C. W. Planner, *"Operational Experience of Penning H^- Ion Sources At ISIS",* Proceedings of EPAC 96, THP084L, (1996).

[4] J.W.G. Thomason, R. Sidlow, *"ISIS Ion Source Operational Experience",* Proceedings of EPAC 2000, THP4A07, (2000).

[5] J. W. G. Thomason, R. Sidlow, and M. O. Whitehead, *"Performance Of The H^- Ion Source Development Rig at RAL"*, Proceedings of EPAC02, THPRI012, (2002).

[6] D.C. Faircloth, J. W. G. Thomason, M. O. Whitehead, W. Lau and S. Yang. *"Thermal Modelling of the ISIS H^- Ion Source"*, Review of Scientific Instruments, Volume 75, Number 5, (2004).

[7] D.C. Faircloth and J.W.G. Thomason, *"Extending the Duty Cycle of the ISIS H^- Ion Source, Thermal Considerations"*, Proceedings of EPAC04, TUPLT139, (2004).

[8] D.C. Faircloth, M. O. Whitehead and T. Wood, *“Practical Experience in Extending the Ion Source and Injection System* H^- *Ion Source Duty Cycle”*, Review of Scientific Instruments Volume 77, Number 3, (2006).

[9] D. C. Faircloth, A. P. Letchford, C. Gabor, M. O. Whitehead, T. Wood, S. Jolly, J. Pozimski, P. Savage, and M. Woods, *“Understanding Extraction and Beam Transport in the ISIS* H^- *Penning Surface Plasma Ion Source”,* Review of Scientific Instruments Volume 77, Number 3, (2006).

[10] C. D. Child, *“Discharge From Hot CaO”,* Phys. Rev. **32**, 492 (1911).

[11] D. C. Faircloth, J. W. G. Thomason, and M. O. Whitehead, *“Electromagnetic modeling of the extraction region of the ISIS* H^- *ion source”*, Review of Scientific Instruments Volume 75, Number 5, (2004).

[12] J. W. G. Thomason, D. C. Faircloth, R. Sidlow, C. M. Thomas and M. O. Whitehead, *“The Effect of Extraction Geometry on the Measured ISIS* H^- *Ion Source Beam”,* Proceedings of EPAC04, TUPLT141, (2004).

[13] S.R. Lawrie, D.C. Faircloth, A.P. Letchford, C. Gabor, and J.K. Pozimski, *“Plasma Meniscus and Extraction Electrode Studies of the ISIS H Ion Source”,* THESE PROCEEDINGS.

[14] D.C. Faircloth, J.W.G. Thomason, R. Sidlow, A.P. Letchford, J. Pozimski, M.O. Whitehead, T. Wood, S. Jolly, P. Savage, M. Haigh, J. Morrison, I. Yew and G. Doucas, *“The Development of the ISIS* H^- *Surface Plasma Ion Source at RAL”*, Proceedings from the 18th Meeting of the International Collaboration on Advanced Neutron Sources, April 25-29, (2007).

[15] D.C. Faircloth, R. Sidlow, M.O. Whitehead and T. Wood, *“Separating the Penning and Analyzing Fields in the ISIS* H^- *Ion Source”,* Proceedings of PAC05, TPPE025, (2005).

[16] S. R. Lawrie, D. C. Faircloth, A. P. Letchford, M. Westall, M. O. Whitehead, T. Wood and J. Pozimski, *“Redesign of the Analysing Magnet in the ISIS* H^- *Penning Ion Source”,* Proceedings of the 1st International Symposium on Negative Ions, Beams and Sources, AIP Conference Proceedings 1097, (2009).

[17] D.C. Faircloth, M.O. Whitehead, T.W. Wood, A.P. Letchford, S.R. Lawrie and M.E. Westall, *“Multi-Beamlet Study Of Beam Transport In The ISIS* H^- *Ion Source Analysing Magnet”,* Proceedings of EPAC08, MOPPC143, (2008).

[18] S.R. Lawrie, D.C. Faircloth, A.P. Letchford, J.K. Pozimski, M. Westall, M.O. Whitehead and T. Wood, *“Modifications to the Analysing Magnet in the ISIS Penning Ion Source”,* Proceedings of EPAC08, MOPC150, (2008).

[19] D.C. Faircloth, M.O. Whitehead, T.W. Wood, C. Gabor and J.K.Pozimski, *“Study of the Post Extraction Acceleration Gap in the ISIS* H^- *Penning Ion Source”,* Proceedings of EPAC08, MOPC142, (2008).

[20] D.C. Faircloth, A.P. Letchford, P. Wise, S.R. Lawrie, C. Gabor, M. Perkins, M. Bates, M.O. Whitehead, T.W. Wood, M.E. Westall, P. Savage and J.K. Pozimski, *“Installation of the Front End Test Stand High Performance* H^- *Ion Source at RAL”,* Proceedings of EPAC08, MOPC144, (2008).

[21] D. C. Faircloth, S. Lawrie, A. P. Letchford, C. Gabor, P. Wise, M. Whitehead, T. Wood, M. Perkins, M. Bates, P. J. Savage, D. A. Lee and J. K. Pozimski, *“Commissioning the Front End Test Stand High Performance* H^- *Ion Source at RAL”* Proceedings of the 1st International Symposium on Negative Ions, Beams and Sources, AIP Conference Proceedings 1097, (2009).

[22] D. C. Faircloth, S. Lawrie, M. Whitehead, T. Wood, A. P. Letchford, C. Gabor, P. Wise, M. Perkins, M. Bates, M. E. Westall, J. K. Pozimski, P. J. Savage and D. Lee, *“Initial Results from the Front End Test Stand High Performance* H^- *Ion Source at RAL”,* Proceedings of PAC09, MO6RFP040, (2009).

[23] D. A. Lee, J. K. Pozimski, C. Gabor and P. Savage, *“A Laserwire Beam Profile Measuring Device for The RAL Front End Test Stand”,* Proceedings of DIPAC07, TUPB11, (2007).

[24] D. Raparia. J. Alessi, and A. Kponou., *“The Algebraic Reconstruction Technique (ART)”*, Proceedings of PAC97, 2P057, (1997).

[25] D.A. Lee, C. Gabor and J. K. Pozimski, *“Laser-based Ion Beam Diagnostics for the Front End Test Stand at RAL”,* Proceedings of EPAC08, TUPC058, (2008).

[26] S. R. Lawrie, D. C. Faircloth and A. P. Letchford, *”Improving the ISIS Emittance Scanner Software”*, Proceedings of EPAC08, TUPC057, (2008).

[27] S. Jolly, D. Lee, J. Pozimski, P. Savage, D. Faircloth and C. Gabor, *“Beam Diagnostics for the Front End Test Stand at RAL”*, Proceedings of DIPAC07, WEO2A01, (2007).

[28] D.C. Faircloth, J.W.G. Thomason, M Haigh, I. Ho-ching Yiu, J. Morrison and G. Doucas, “*Energy Distribution of* H^- *Ions from the ISIS Ion Source”*, Proceedings of EPAC06, TUPLS088, (2006).

[29] C. Gabor, D.C. Faircloth, D.A. Lee, S.R. Lawrie, A.P. Letchford and J.K. Pozimski, *“Diagnostic Experiments at a 3 MeV* H^- *Test Stand at Rutherford Laboratory (UK)”*, THESE PROCEEDINGS.

[30] S. Jolly, J. Pozimski, P. Savage, D. Faircloth, A. Letchford, J. Back, *“LEBT Simulations and Ion Source Beam Measurements for the Front End Test Stand (FETS)”*, Proceedings of EPAC06, TUPLS090 (2006).

[31] H. V. Smith and J. Sherman, “H^- *and* D^- *scaling laws for Penning Surface-Plasma Sources”,* Review of Scientific Instruments, Vol 65 (1), pp. 123-128 (1994).