The front end test stand high performance H^- ion source at Rutherford Appleton Laboratory[a)]

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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 three solenoid low energy beam transport, a 3 MeV radio frequency quadrupole, 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. © *2010 American Institute of Physics.* [doi:10.1063/1.3271169]

I. INTRODUCTION

A. FETS overview

High power proton particle accelerators (HPPAs) in the megawatt 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 upgrade to the ISIS accelerator and to contribute to the U.K. design effort on neutrino factories, a front end test stand[1] (FETS) is being constructed at the Rutherford Appleton Laboratory in the U.K. 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 three solenoid magnetic low energy beam transport (LEBT), a 324 MHz, 3 MeV, four-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

The source is of the Penning type,[2] comprising a molybdenum anode and cathode between which a low pressure hydrogen discharge is produced (Fig. 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 piezoelectric valve into the discharge via the third hole in the anode. The source uses between 10–30 mL min^{-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.

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 (Fig. 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 postextraction 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.

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[5] (ISDR) 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] have demonstrated the resultant extra heating can be mitigated by reducing the mica thickness and increasing the air cooling (both visible in Fig. 1). The source operates best

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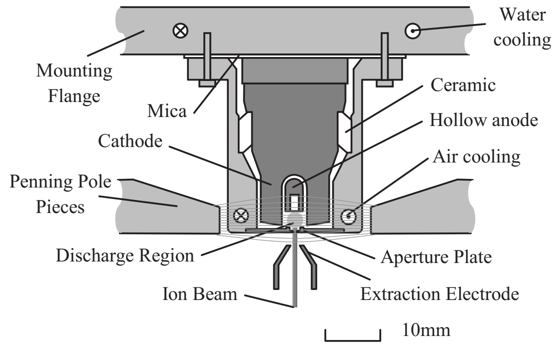

FIG. 1. A cross section through the Penning source.

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 17–25 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]

$$I_B \propto \frac{V^{3/2}}{d^2}, \tag{1}$$

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 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.

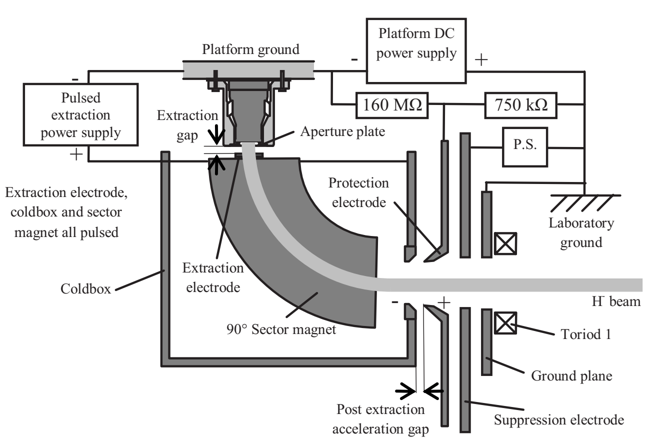

FIG. 2. Schematic of the FETS ion source extraction and postacceleration system.

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,

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

where R_e is the radius the center 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 that the optimum index is actually $n = 1.2$. Previous studies[17] have found that 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. Postacceleration

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

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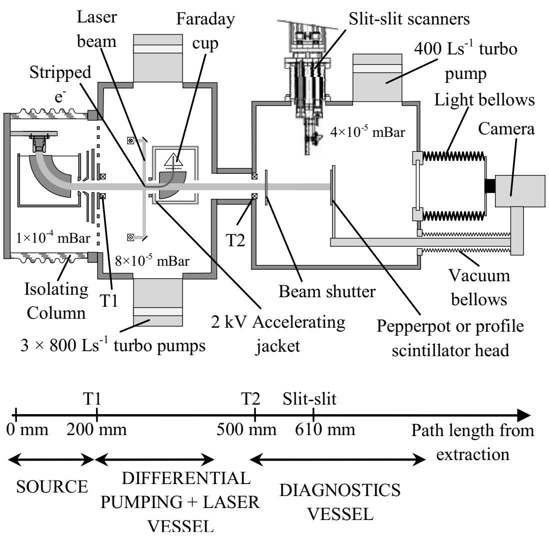

FIG. 3. The overall experimental setup.

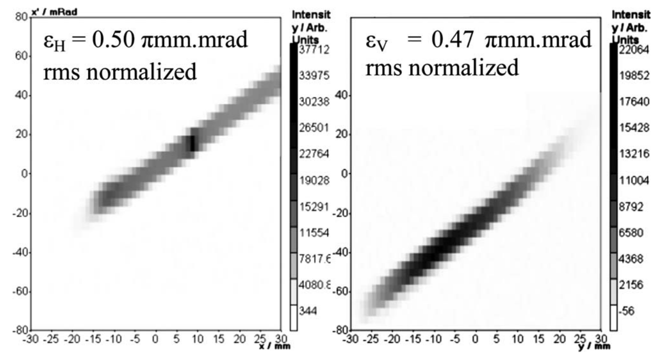

FIG. 5. Emittance plots for the beam shown in Fig. 4. (Note—the beam is not horizontally centered due to sector magnet alignment error.)

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

C. Diagnostics

1. Laser profile measurement

The differential pumping vessel contains a laser wire beam profile measurement system,[23] based on the photodetachment 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 while the beam is running and can be moved level with the slit-slit scanners
- the head of the pepper pot can be replaced by a scintillator profile measurement head,
- a retarding potential energy analyzer, and[28]
- beam current toroids.

III. INITIAL RESULTS

A comprehensive optimization process is in progress. Some of the key results obtained so far are shown (Figs. 4–6).

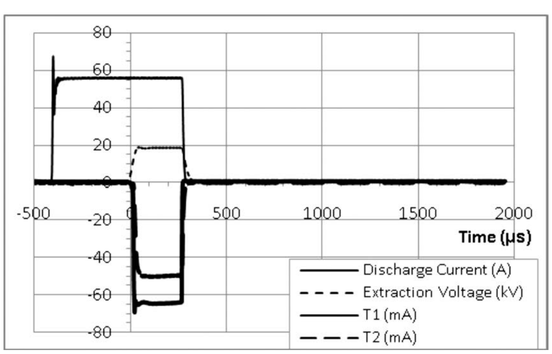

FIG. 4. Wave shapes for an 18.5 kV extraction, 16 A sector magnet, 40 kV platform, and 55 A discharge. 250 μs pulse length.

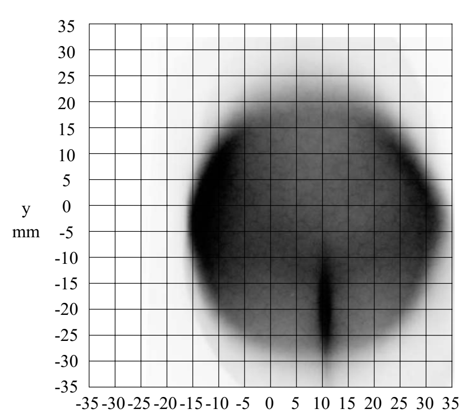

FIG. 6. Scintillator profile image for the beam shown in Fig. 4.

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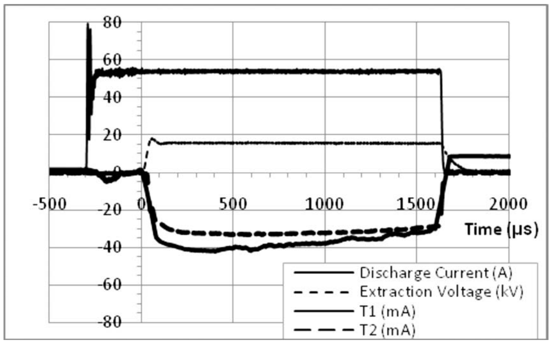

FIG. 7. Wave shapes for a 15.7 kV extraction, 12.5 A sector magnet, 40 kV platform, 55 A discharge and 1.6 ms beam. (Note that the droop and undershoot on the T1 trace is due to the use of nonoptimized circuitry that had to be used temporarily as a makeshift.)

A. Peak current

The peak currents obtained so far are shown in Fig. 4. A beam current of 50 mA has been measured in T2.

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 while keeping the pulsed discharge power supply running at 50 Hz. This allows 1.6 ms beam pulses to be extracted.

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 (Figs. 7–9).[29]

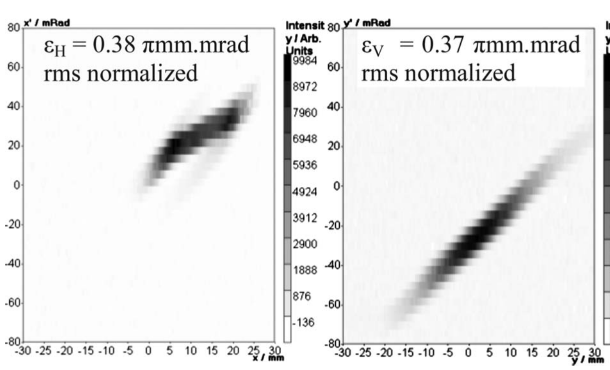

FIG. 8. Emittance plots for beam shown in Fig. 7.

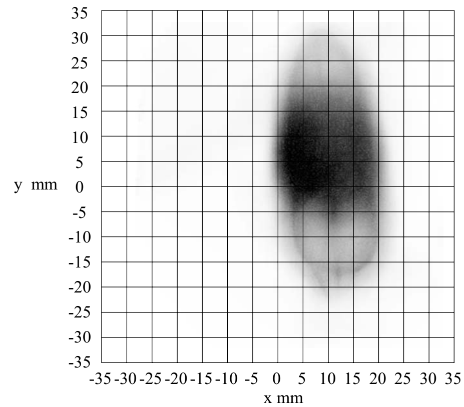

FIG. 9. Scintillator profile image for beam shown in Fig. 7.

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 π mm mrad (Ref. 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 toroid 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 π mm 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 toroid from 32 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]

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