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J. Macgregor , C. Cahill, M. Whitehead, T. Wood and N. Savard

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O. Tarvainen,[1,a)] R. Abel,[1] S. Lawrie,[1] D. Faircloth,[1] T. Sarmento,[1] J. Macgregor,[1] C. Cahill,[1] M. Whitehead,[1] T. Wood,[1] and N. Savard[2]

AFFILIATIONS

[1] STFC ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Harwell OX11 0QX, United Kingdom
[2] D-Pace, Inc., P.O. Box 201, Nelson, British Columbia V1L5P9, Canada

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[a)] **Electronic mail:** olli.tarvainen@stfc.ac.uk

ABSTRACT

The ISIS Penning ion source can routinely produce a 55 mA beam of negative hydrogen ions in 250 μs pulses at 50 Hz repetition rate. Extending the beam pulse length to 2 ms requires eliminating the 15%–30% droop of the current observed in long pulse operation and benefits from the suppression of discharge breakdown oscillations otherwise forcing to prolong the pulse length to 2.2 ms or longer. The droop can be compensated by ramping the discharge current during the pulse, whereas the discharge oscillations are suppressed by modifying the ancillary circuit of the pulsed arc power supply.

I. INTRODUCTION

The ISIS Penning ion source,[1] shown schematically in Fig. 1, is a cesiated pulsed DC discharge surface plasma source routinely delivering 55 mA beam of negative hydrogen ions (H^-) in 250 μs pulses for neutron and muon physics at 50 Hz pulse repetition rate. The H^- ions are produced on the cesiated cathode surfaces and are drawn into the discharge volume where they are believed to undergo resonant charge exchange[2–5] with slow neutral ground state hydrogen atoms, i.e., $H^-_{\rm fast} + H(1s)_{\rm slow} \rightarrow H(1s)_{\rm fast} + H^-_{\rm slow}$. These "second generation" slow H^- ions are then extracted from the discharge volume together with H^- ions produced by dissociative electron attachment to ro-vibrationally excited molecules,[6] i.e., $H_2(X^1\Sigma_g^+, \nu'') + e \rightarrow H_2^-(^2\Sigma_g^+) \rightarrow H^- + H$. The described surface production mechanism is considered to account for the majority of the extracted H^- beam.

Meeting the 60 mA, 2 ms, 50 Hz specification of the Front End Test Stand (FETS)[7] requires extending the ion source discharge pulse length to 2.2 ms, first allowing the discharge breakdown oscillations to subside and then extracting the 2 ms H^- beam pulse, together with eliminating the droop of the beam current observed in long pulse operation of the standard source (see Fig. 2). One approach for this was to increase the size of the discharge volume and extraction aperture as demonstrated by the 2X scaled source.[8] This paper investigates an alternative method of combating the droop when running a standard 1X source at extended pulse length. The origin of the beam current droop is described hereafter, whereas the model of the breakdown oscillations is presented elsewhere.[9] In short, the difference between the discharge breakdown voltage and the steady-state discharge voltage leads to an ignition transient, i.e., the discharge current fluctuating periodically with a diminishing amplitude for 100 μs (order of magnitude) before the cesium-hydrogen plasma reaches a quiescent equilibrium.

II. QUALITATIVE MODEL OF THE BEAM CURRENT DROOP

It is believed that the Penning source discharge is sustained by thermionic and secondary electrons emitted from the hot cesiated molybdenum cathode and accelerated across the cathode sheath potential to several tens of electron volts energy, thus ionizing the neutral gas in the discharge volume. The pulsed discharge power supply with its negative voltage terminal connected to the cathode is operated in current regulated mode; i.e., the discharge voltage V_D (cathode-anode potential difference) is a free parameter, adjusted by

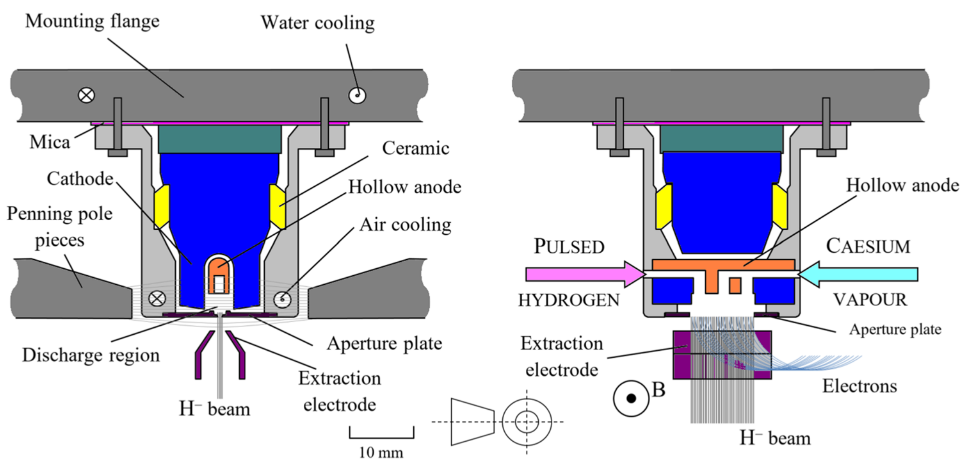

FIG. 1. A schematic drawing of the ISIS Penning ion source.

the power supply feedback system to maintain constant discharge current I_D. In a typical operation of the ion source, the discharge current is set to 40–60 A corresponding to a discharge voltage of 40–60 V. The steady-state discharge current is a sum of the electron current emitted from the cathode surfaces, I_e; the positive ion current drawn from the bulk plasma toward the cathode(s), I_+; and the electron (and negative ion) current into the anode and source body, I_-, i.e., $I_D = I_e + I_+ + I_-$. The latter two are referred hereafter as "ionization current," $I_i = I_+ + I_-$, originating from the ionization of the neutral gas in the discharge volume.

The contribution of the thermionic electron emission on the discharge current can be estimated based on transient thermal simulations[10] predicting the average temperature T_c and transient temperature rise ΔT_c of the cathode surfaces at various pulse lengths and duty factors. Linear extrapolation of the reported values yields an estimate of $T = 1550\,^\circ$C and $\Delta T = 200\,^\circ$C for the 2.2 ms, 50 Hz operation, with the standard thickness of the mica insulator between the cathode and source mounting flange providing electrical and thermal isolation between the two. Recent experiments[9] have revealed that the cesium (Cs) coverage of the cathode surfaces is above 0.5–0.7 monolayers, corresponding to the predicted minimum of the work function, most likely close to the 2.1 eV work function of Cs. Therefore, following Ref. 10, it can be estimated from the Richardson-Dushman equation $j_{e,thermal} \propto T^2 e^{-\phi/kT}$ that the thermionic electron emission current, $I_{e,thermal}$, is on the order 1–10 A increasing by a factor of 3–4 as the cathode surface is heated during the 2.2 ms discharge pulse. The electron impact ionization rate and the number of electron-ion pairs created per primary electron, accounting for the remaining fraction of the discharge current, depend on the H_2/Cs-ratio in the discharge volume. Typical hydrogen pressure, measured with a dedicated setup,[11] and Cs evaporation rate correspond to H_2/Cs-ratio of approximately 1:1, which implies that the discharge is sustained primarily by the ionization of Cs due to an order of magnitude difference in ionization cross sections of the two at relevant electron energies. Furthermore, as the ionization potential of Cs is approximately 4 eV, it can be estimated that each 40–60 eV electron, confined between the cathodes by the ~0.2 T magnetic field, can create up to 10 electron-ion pairs. Thus, 1 A of thermionic cathode emission current translates up to 10 A steady-state discharge current as both positive and negative charge carriers flow out of the discharge volume with the ambipolar plasma potential balancing their fluxes. It is assumed here that the rates of electronic excitation of Cs and ionization/excitation of the hydrogen molecules are negligible in comparison with the ionization rate of Cs; i.e., the given estimate must be treated as an upper limit.

Let us consider what happens during the 2.2 ms current regulated discharge pulse taking into account the thermal transient and the estimated increase in the thermionic electron current. In the beginning of the pulse, ~5 A electron current is required to sustain the ~55 A discharge current. During the pulse, the contribution of the thermionic electrons increases to 15–20 A, which implies that I_i is reduced to 35–40 A. In practice, this occurs due to a gradual decrease in the discharge voltage (see Fig. 2) and corresponding decrease in electron-ion pairs produced by each primary electron. The extracted H^- beam current is proportional to the plasma density (ionization rate) as shown in Ref. 11, which means that in 2.2 ms,

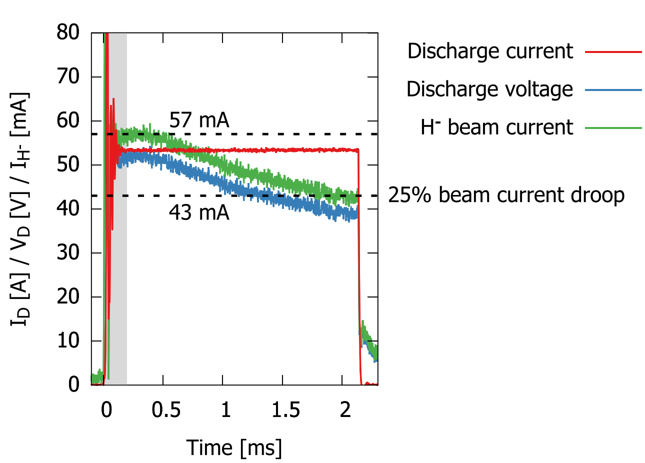

FIG. 2. An example of a 2.2 ms, 54 A discharge pulse of the 1X Penning source at FETS. The shaded area indicates the 200 μs discharge breakdown oscillation. The H^- beam current droops approximately 25% from 57 mA to 43 mA.

50 Hz operation with ~55 A discharge current, the expected droop of the beam current is 20%–30% matching the droop shown in Fig. 2. The model does not account for secondary electron emission, photoelectron current, or the contribution of negative ions, and should therefore be treated as a qualitative description despite the good agreement between the experiment and the above numerical example. Actual modeling of the discharge physics and surface effects would be required for quantitative analysis at various pulse repetition rates and duty cycles.

III. BEAM CURRENT DROOP COMPENSATION

Understanding the origin of the beam current droop allows compensating it by tailoring the temporal profile of the discharge current. This is demonstrated in Fig. 3, showing an example of a 1.7 ms discharge current pulse and the corresponding 1.2 ms H^- beam pulse of the 1X Penning source on the VESPA test stand[12] in two cases, with a constant discharge current setting of 53 A and the discharge current being ramped linearly from 48 A to 71 A to compensate the effects caused by the decreasing discharge voltage. The data were taken at 25 Hz repetition rate to control the surface temperatures using the available air cooling and standard thickness of the mica layer. The discharge voltage was observed to decrease by 10% during the 1.7 ms pulse even with the linear increase in the discharge current resulting to flat H^- beam pulse; i.e., the discharge is still in current regulated mode. This implies that a steeper slope or better cathode cooling might be required for longer pulses to maintain a constant discharge voltage. The discharge pulse length is limited by the pulsed arc power supply being able to deliver 100 mC charge per discharge pulse.

The effect of the linear discharge current ramp on the predicted ion source lifetime can be estimated with the measured IV-characteristics and the relative yields of energy-dependent sputtering of the molybdenum cathodes by Cs ions.[13] The sputtering yield depends strongly on the discharge voltage accelerating positive Cs ions (Cs^+ and Cs^{2+}), toward the cathode. It turns out that approximately 85% of the sputtering damage with 1.7 ms pulses can be expected to occur during the 400 μs discharge breakdown oscillations when the voltage and current fluctuate significantly, whereas the 1.3 ms flat part of the pulse accounts for the remaining 15%. The linear ramp of the discharge current has only a minor effect on the cumulative sputtering, bringing the above relative fractions to 80% and 20%. This is because the sputtering rate depends strongly on the incident ion energy (discharge voltage), which spikes in the beginning of the pulse. In the example shown in Fig. 3, the expected cumulative sputtering damage is in fact 10% smaller for the discharge pulse with a positive slope because the discharge current (plasma density) is lower during the breakdown oscillations.

IV. BREAKDOWN TRANSIENT SUPPRESSION

Suppression of the breakdown oscillations is beneficial for the long pulse operation for two reasons: it allows shortening the discharge pulse length, yet extracting a clean H^- beam pulse, and it presumably mitigates the cathode erosion due to sputtering. It has been hypothesized that the breakdown oscillations are due to Cs dynamics causing the surface work function and electron emission from the cathode surfaces to fluctuate periodically.[14] However, recent experiments[9] with the ISIS H^- Penning ion source have revealed that the breakdown oscillations are primarily driven by the discharge power supply and its auxiliary circuits, whereas Cs dynamics have a smaller effect on the transient. This is demonstrated in Fig. 4, showing two discharge current pulses, the first one with the nominal configuration of the FETS pulsed arc power supply (5 Ω, 1 μF) and the other one with an improved (1 Ω, 7 μF) RC "snubber" connected parallel to the discharge. The "snubber" resistance and capacitance were systematically varied in the ranges of 1–10 Ω and 1–7 μF to observe their effect on the breakdown oscillation and choose the optimum values. Further details are reported in Ref. 9. It is evident from the figure that the duration of the transient is reduced by an order of magnitude with the improved power supply circuit, which allows reducing the FETS discharge pulse length from 2.2 ms closer to

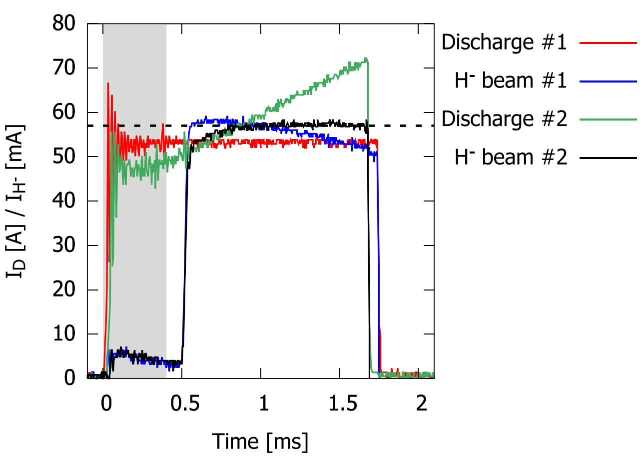

FIG. 3. The 1.7 ms discharge pulse and corresponding 1.2 ms, 25 Hz H^- beam pulse of the 1X Penning source at VESPA with constant (#1) and linear ramp (#2) discharge current. The achieved beam current of 57 mA is shown with a dashed line. The shaded area indicates the 400 μs discharge breakdown oscillation.

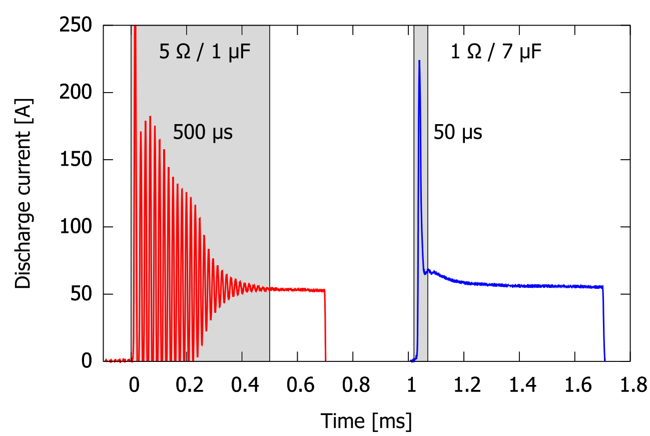

FIG. 4. The effect of the RC snubber connected parallel to the discharge on the breakdown oscillations. The latter discharge pulse is shifted by 1 ms for clarity. The shaded area indicates the discharge breakdown oscillation.

2 ms, thus helping with the temperature control of the electrodes. The effect of mitigating the breakdown oscillations on the cathode erosion is under investigation.

V. DISCUSSION

Although it was demonstrated that the beam current droop observed in long pulse operation of the 1X source can be compensated with the linear ramp of the discharge current, a number of further developments are needed to fulfill the FETS requirement with the 1X source. These include as follows: (i) increasing the capacity of the pulsed arc power supply to >200 mC to deliver the discharge current for the full 2 ms beam pulse; (ii) alternatively, one could double the area of the extraction slit, assuming that the current density scales with the aperture size, to reach 60 mA H^- beam with approximately half of the (ramped) discharge current. The effect of increasing the extraction aperture size from the nominal 0.6 mm × 10 mm to 1.2 mm × 10 mm on the beam current and quality is currently under investigation as it could have an adverse effect on the transport efficiency of the extracted beam. In both cases, it would probably be necessary to (iii) improve the cooling of the source by reducing the number of mica layers between the cathode and the source body to better control the cathode surface temperature at high duty factors. The droop can be eliminated by reducing the power density and ΔT_c of the cathode surface as proven with the 2X source.[8] Therefore, (iv) patterning the cathode surface, e.g., by introducing narrow grooves, and thereby increasing the surface area and reducing the power density and thermal shock effect could be a solution to mitigate the droop of the 1X source beam current, assuming that the pattern would not be eroded significantly as the source ages or would not lead to secondary discharges in the narrow gap between the cathode and anode outside the intended discharge region.

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