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Published version information

Citation: O Tarvainen et al. "Breakdown oscillations of the ISIS H⁻ Penning ion source hydrogen-caesium discharge." IEEE Transactions on Plasma Science, vol. 47, no. 11 (2019): 4971-4983.

DOI: [10.1109/TPS.2019.2940830](https://doi.org/10.1109/TPS.2019.2940830)

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Breakdown Oscillations of the ISIS H^- Penning Ion Source Hydrogen-Caesium Discharge

Olli Tarvainen, Robert Abel, Scott Lawrie, Dan Faircloth, John Macgregor, Tiago Sarmiento and Trevor Wood

Abstract—The ISIS Penning ion source is a pulsed DC discharge surface plasma source delivering a 55 mA beam of negative hydrogen ions (H^-) in 250 μs pulses to the ISIS accelerator for neutron and muon physics at 50 Hz pulse repetition rate [1]. The H^- ions are extracted from the hydrogen-caesium discharge sustained by a current regulated pulsed power supply delivering a current of 50–60 A. The discharge exhibits an ignition transient that requires the pulse length to be prolonged to 700 μs in order to extract a clean H^- beam pulse. The current and voltage fluctuations during the breakdown oscillation enhance the sputtering damage of the ion source cathodes, thus contributing to the lifetime limitation of the device. It has been hypothesized that the breakdown oscillations are due to caesium dynamics causing the surface work function and electron emission from the cathode surfaces to fluctuate periodically [2]. Experiments with the ISIS H^- Penning ion source, reported here, reveal that the breakdown oscillations are primarily driven by the discharge power supply and its auxiliary circuits whereas caesium dynamics have only a minor effect on the ignition transient. The conclusion is derived from careful characterization of the discharge current-voltage characteristics, optical emission measurements combined with a 0-dimensional model and comparison of different discharge geometries. Engineering solutions to mitigate the breakdown oscillations are presented and the potential effect of the applied modifications on the molybdenum cathode erosion by caesium sputtering is estimated.

Index Terms—Arc discharge plasmas, Ion sources

I. INTRODUCTION

PULSED sources of negative hydrogen (H^-) ions are used for producing the particle beams for large-scale circular accelerators and storage rings utilizing charge exchange injection [3]. Facilities employing pulsed H^- ion source operating or being constructed at the moment include the ISIS Neutron and Muon Facility [4], Spallation Neutron Source (SNS) [5], the Japanese Particle Accelerator Complex (J-PARC) [6], Los Alamos Neutron Science Center (LANSCE) [7], Brookhaven National Laboratory (BNL) [8], Fermi National Accelerator Laboratory (FNAL) [9], CERN (Linac4) [10] and the China Spallation Neutron Source (CSNS, Phase I) [11]. The given references include recent performance data of the ion sources at each facility.

The production of the H^- ions occurs in high-density plasmas and on the surfaces facing them through two primary mechanisms complementing each other; dissociative electron attachment (DEA) involving ro-vibrationally excited molecules and low energy electrons [12] (volume production)

and resonant tunneling of electrons from low work function caesiated metal surfaces to the affinity level of hydrogen atoms [13] (surface production), the latter results in significantly higher extracted beam current densities. Caesiated Surface Plasma Sources (SPSs) based on pulsed DC discharges were first developed in 1970 [13]. Since then alternative methods to sustain the hydrogen plasma, such as filament-driven [14] and inductively coupled RF [15] discharges, have been developed for SPS H^- ion sources. Pulsed DC discharges, however, still hold the record for the highest extracted H^- emission current density of $> 1 \text{ A/cm}^2$.

There are two variants of pulsed DC discharge SPSs applied for H^- ion production, the magnetron [13] (operating at FNAL and BNL) and Penning [16] sources (operating for example at ISIS and CSNS), that differ from each other by the discharge geometry. In this paper we will focus on the Penning source, where the discharge is sustained in a small volume between a window frame anode (at source body potential) and two opposing cathodes. A magnetic field is applied perpendicular to the cathode surfaces (see Fig. 1) to confine electrons and increase their path length during their oscillations between the cathode sheaths. Power is applied by creating a potential difference, which drives a discharge current of tens of Amperes. The H^- ions produced on the caesiated cathode surfaces are drawn into the discharge where they are believed to undergo resonant charge exchange [17], [18], [19], [20] with slow neutral ground state hydrogen atoms, i.e. $H_{\text{fast}}^- + H(1s)_{\text{slow}} \rightarrow H(1s)_{\text{fast}} + H_{\text{slow}}^-$. These "second generation" slow H^- ions are then extracted from the bulk discharge and form the extracted beam.

The high-density hydrogen-caesium plasma of the H^- Penning ion source is a rather peculiar example of a pulsed DC discharge but, nevertheless, has common characteristics with DC (glow) discharges applied for various purposes [21], [22]. These include high breakdown voltage required to initiate the ionization cascade, electron emission from the surfaces sustaining the discharge and the normal glow potential depending on the gas pressure, discharge geometry and the magnetic field strength. The discharge operates in a high current range where the voltage varies inversely with current (see Fig. 9 in Section V) and therefore the discharge is often colloquially referred to as an "arc". DC discharges can be unstable with respect to excitation of various types of oscillations and instabilities (see e.g. Refs. [23], [24], [25], [26], [27]). Oscillations can be excited for example due to so-called ionization plasma instability related to the decreasing impedance of the discharge [23], [28]. These oscillations are a fundamental property of the discharge but are affected by external electric circuits. In the ISIS H^- Penning ion

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Manuscript received XXX, 2019; revised XXX, 2019.

Fig. 1. Left and middle: Cross sections of the ISIS H^- Penning ion source. Right: The permanent magnet version of the ion source with the slit aperture plate, extraction electrode and half of the permanent magnets removed for visibility. The cathode is shown in green and anode in orange.

source the combination of the discharge current regulated operation and the difference between the breakdown voltage and the steady-state discharge voltage results to an ignition transient, which often drives such breakdown oscillations in high-current / low impedance mode of the plasma before the discharge reaches a quiescent equilibrium. The breakdown oscillations can be detrimental for the long-term operation of the ion source as the voltage fluctuations and prolonged pulse length to obtain flat H^- current pulses enhance the sputtering damage of the electrodes, which limits the lifetime of the ion source. The topic of this paper is the (physical) origin of the breakdown oscillations of the hydrogen-caesium discharge in the ISIS Penning ion source and their mitigation by (electrical) engineering choices.

II. THE ISIS H^- PENNING ION SOURCE

A Penning-type surface-plasma ion source [1] has provided H^- beam for the ISIS spallation neutron and muon facility at the Rutherford Appleton Laboratory (RAL) for nearly 35 years at $250\mu s$ 50 Hz beam duty cycle. Achieving this reliably requires a $>700\mu s$ discharge pulse, allowing the initial breakdown oscillations to settle and noise to subside before extracting the H^- beam at the trailing edge of the discharge pulse.

The design of the ISIS Penning SPS is shown in Fig. 1. The discharge occupies a 0.105 cm^3 volume surrounded by the hollow anode, opposing cathode surfaces and the aperture plate with 10 mm by 0.6 mm extraction slit. A $\sim 0.2\text{ T}$ magnetic field is applied perpendicular to the cathode surfaces. In the ISIS Penning source the magnetic field required to lengthen the electron trajectories between the cathodes and confine the plasma is produced by an electromagnet and shaped by the pole pieces extending close to the surface of the source body. The source used at the VESPA test stand (see the following section) for the development work described in subsequent sections utilizes a permanent magnet design shown also in Fig. 1 (right). Hydrogen gas pulses and caesium vapour from an external oven are fed into the discharge volume through holes in the anode. The source body (anode) is cooled by air that runs through the pipes embedded in the source body.

The cathode is primarily cooled by water running through the mounting flange, isolated from the source by a sheet of mica. Both the anode and cathode reach average temperatures of several hundreds of $^\circ\text{C}$, which helps to maintain optimal caesium coverage of the cathode surfaces required to sustain the discharge and produce the H^- ions. The surface temperature of the electrodes fluctuates several tens of $^\circ\text{C}$ during the discharge pulses [29]. The ions desorbed from the cathode are accelerated by the cathode sheath potential and have no direct line of sight to the extraction slit. They must hence undergo a resonant charge exchange with slow neutral hydrogen atoms to reach the outlet aperture. The jaw-shaped extraction electrode is used to create the electric field that extracts the beam in $250\mu s$ pulses created by pulsing the $\sim 17\text{ kV}$ voltage applied to the electrode. A scaled version of the ion source, designed to deliver 2 ms beam pulses without a significant droop in beam current, has been recently developed [30] and was used in this study for a particular experiment as described later. In this so-called 2X source the discharge chamber (linear) dimensions have been doubled from the 1X ISIS-design, thus increasing the distance between the cathode surfaces to 10 mm.

The discharge is initiated and sustained by a current regulated pulsed power supply with its negative voltage terminal connected to the cathode. The overall layout of the system [31] is shown in Fig. 2. The ISIS power supply consists of a single unit whereas the development power supplies used for this work are separated in two rack-mount units as indicated in the figure. The bulk DC power supply takes 240 V AC power from the mains supply and is full-wave bridge rectified to 340 V DC. Smoothing and filtering is provided by a $1500\mu\text{F}$ electrolytic capacitor bank. The power output stage and ion source electrodes are isolated from the mains by a transformer with a nominal 1:1 operation. The power rating of 800 V A shown in Fig. 2 corresponds to the development power supply used for the experiments described in Section VI. It allows pulsed currents up to 50 A with a $700\mu s$ width and a pulse repetition rate of 50 Hz, or an increased output current with a corresponding decrease in either pulse width or repetition rate. The auxiliary DC power supply provides low-voltage signals for the control board and instrumentation. The pulsed

Fig. 2. The block diagram of the pulsed discharge power supply. The development power supply used for the majority of the experiments consists of two rack-mount units as depicted in the figure whereas the standard ISIS power supply is a single rack unit.

power output stage uses Insulated Gate Bipolar Transistors (IGBT) of 1200 V, 400 A rating to output a current pulse with its amplitude and width limited only by the bulk DC power supply ratings and power dissipation into the IGBT heat sink. The variable pulse amplitude (discharge current) is achieved by operating the IGBTs in their linear region as transistor current sources. Achieving a discharge current of 20–100 A in this operation mode requires several parallel IGBTs. Splitting of the system into a bulk power supply unit and an output stage makes it possible to provide dedicated energy storage capacitors for each bank of IGBTs, which minimizes the stray inductance. The combined output current is measured using a Hall-Effect compensated closed-loop current monitor with a bandwidth of DC to 150 kHz.

The discharge current power supply is connected to the ion source cathode via a diode combiner and a parallel RC “snubber” shown in Fig. 3, which suppresses high-frequency noise and stabilizes the current feedback loop. The nominal values of the snubber resistor and capacitor of the operational power supplies of the ISIS Penning ion source are 1 Ω and 1 μF , respectively, whereas the power supply used for the development work described hereafter is by default equipped with 5 Ω and 1 μF snubber. These components were changed as part of the experiments attempting to mitigate the breakdown oscillations (see Section VI). The diode combiner box is used to connect the discharge with the pulsed power supply or a lower current DC power supply. Both power supplies can be operated in parallel, but generally the DC discharge is only applied during the ion source start-up to redistribute the caesium and heat the electrode surfaces to operating temperature. The DC power supply is set to zero in regular (pulsed) operation. An independent current monitor (Pearson Current Monitor Model 5046) was added in the diode combiner box to measure the current delivered to the discharge. Furthermore, the current flowing through the snubber resistor was monitored by measuring the corresponding voltage drop.

III. BREAKDOWN OSCILLATIONS OF THE H^- PENNING ION SOURCE DISCHARGE PULSE

An example of a 770 μs discharge current pulse of the ISIS H^- Penning ion source is shown in Fig. 4 together with the extracted 220 μs H^- beam pulse. In the given example the breakdown oscillations of the discharge current last for 100 μs

Fig. 3. The circuit diagram of the pulsed power supply RC-snubber and the diode combiner box. The snubber is integrated into the power supply chassis but shown here as a separate component for clarity. The output of the power supply is connected to the negatively biased cathode of the ion source.

with the rest of the pulse being flat. The duration of the oscillations depends on the discharge current, erosion history of the electrodes and density of caesium in the discharge. In long-term operation it is beneficial to minimize the caesium consumption to prolong the ion source lifetime, which is limited by sputtering of the molybdenum electrodes by caesium ions. Reducing the amount of caesium present in the discharge chamber superimposes high-frequency noise (on the order of MHz) on the breakdown oscillations and the beginning of the flat part of the discharge pulse (see Fig. 16 and related discussion in Section V). Thus, the H^- ions are extracted at the end of the discharge pulse to achieve a noiseless beam pulse regardless of the electrode damage and caesium density. The extraction system is biased using two high voltage power supplies: the ion source is biased to -36 kV relative to the ground and the first downstream electrode (extractor) is pulsed at 17 kV relative to the source potential. The H^- current detected before the extraction voltage pulse is due to ions leaking from the source and being accelerated by the -36 kV platform voltage.

The breakdown oscillation of the H^- Penning ion source discharge is first mentioned in the literature by Derevyankin et al. [2]. They associate the observation with the fluctuations of caesium coverage of the cathode surfaces with a period

Fig. 4. An example of the ISIS H^- Penning ion source discharge current, extraction voltage and H^- current pulses. The ion beam is extracted at the back of the discharge pulse to allow breakdown oscillations and possible high-frequency discharge noise (not shown) to dissipate.

of 5–50 μs corresponding to the transport time of caesium (velocity of 100–1000 m/s) between the opposite cathode surfaces at 5 mm distance. The caesium coverage of the surface presumably affects the discharge current through the variation of the surface work function and secondary electron emission coefficient [2]. Furthermore, the model states that an equilibrium corresponding to the observed breakdown oscillations is possible only if the caesium coverage of the molybdenum surfaces is suboptimal, i.e. below 0.6 monolayers corresponding to minimum work function [32]. Under such conditions increasing caesium concentration on the cathode surfaces leads to increased emission (discharge) current [2].

The model can be used for predicting the temporal behavior of the optical emission of caesium from the Penning discharge, which can be then compared to experiments. This was done with a 0-dimensional model based on the following assumptions: (i) caesium exists either on the surfaces or in the discharge volume i.e. caesium escaping the ion source through the extraction slit is compensated by the caesium evaporating from the oven. (ii) The release of caesium from the cathode surface is proportional to the caesium surface density and the residence time of caesium is determined by the incoming (sputtering) particle flux, not by thermal desorption as inferred from Refs. [33], [34] discussing sputtering and thermal residence time of caesium on transition metal surfaces. (iii) Neutral caesium leaving the cathode surface can be transported through the discharge volume across the cathode spacing d at its thermal speed v_{th} (core assumption in Ref. [2]) resulting to periodic fluctuations of the surface coverage, which is supported by the dominance of neutral caesium emission in the visible/near infrared optical emission spectrum (iv) The discharge in the low-impedance mode is sustained by electrons emitted from the cathode surfaces and accelerated by the sheath potential. (v) The electron emission current I_e from the cathode surfaces depends on the surface work function ϕ as $I_e \propto \exp^{-(\phi - \phi_{min})}$, where ϕ_{min} is the minimum work function taken from Ref. [32]. The given functional form reflects the nature of electron tunneling

through the potential barrier (see e.g. [35] for a comparison of theories) and satisfies the view of the electron emission being of thermionic origin [29] (vi) the fluctuations of caesium on the surfaces and in the discharge volume are damped by the distribution of caesium velocities and ionization, i.e. $n_{Cs} = f(d, v_{th}) \exp^{-\gamma t}$ where γ is the damping constant, and (vii) the light emission rate R of neutral caesium is proportional to the discharge (electron) current and caesium density in the discharge volume, i.e. $R \propto I_e n_{Cs}$, supported by the fact that caesium light emission of certain excited states, e.g. $6^2P_{3/2} \rightarrow 6^2S_{1/2}$, in ionizing plasmas probed in this paper is rather insensitive to variations of the electron (excitation) energy in the range of 10–100 eV, relevant in our case [36]. A semiempirical model [32] was used for the the work function of the molybdenum cathodes at different fractional monolayer coverages of caesium. The work function dependence on caesium coverage and the corresponding secondary electron emission coefficient are plotted in Fig. 5a. The predicted discharge current and caesium light emission (temporal) data are shown in Fig. 5b for caesium coverage below the optimum ranging from 0.2 to 0.6 monolayer and in Fig. 5c for caesium coverage above the optimum ranging from 0.6 to 1.0 monolayer. The damping coefficient and caesium velocity were chosen to match the number and frequency of the breakdown oscillations typical for the ISIS H^- Penning ion source. According to this simple model the phase between the discharge current and caesium light emission depends on which side of the work function minimum the ion source operates. Suboptimal caesium coverage suggested in Ref. [2] corresponds to the light emission and discharge current being in opposite phases. On the contrary, above the optimum coverage these two oscillate in the same phase. Although a periodic fluctuation of the caesium coverage, matching the observed breakdown oscillation frequency, was imposed here, the dependence of the caesium light emission phase on the cathode surface coverage would be qualitatively the same irrespective of the actual temporal variation of caesium coverage. It is worth noting that the hydrogen light emission would always be in phase with the discharge current independent of the caesium dynamics and cathode work function as hydrogen exists primarily in the gas phase, i.e. in the discharge volume. The first part of the experimental section of this paper is devoted to testing the hitherto uncontested hypothesis [2] of the breakdown oscillations being driven by the caesium dynamics.

IV. EXPERIMENTAL METHODS

The data presented hereafter were collected on two ion source test stands, FETS (Front End Test Stand) [37] and VESPA (Vessel for Extraction and Source Plasma Analyses) [38], at RAL. In both cases the basic diagnostics signals including the discharge current and voltage were recorded. The discharge current was measured either from the output of the pulsed power supply (see Fig. 2) or from the independent current monitor measuring the output current of the diode combiner box (see Fig. 3) as indicated later. The discharge voltage was measured with a x100 TekTronix oscilloscope

Fig. 5. (a) The work function dependence on caesium coverage of molybdenum [32] and the corresponding secondary electron emission coefficient (translating to emission current) used in the 0-dimensional model of the discharge current and caesium light emission. The modeled discharge current and caesium light emission at 852.1 nm with the caesium coverage fluctuating in the range of (b) 0.2–0.6 monolayers stabilizing to 0.4 monolayers, i.e. below the optimum, and (c) 0.6–1 monolayers stabilizing to 0.8 monolayers, i.e. above the optimum.

Fig. 6. Discharge current and voltage pulses of the H^- Penning ion source at (a) 30 A, (b) 50 A and (c) 70 A discharge current settings. Typical set value of the discharge current for the ISIS operations is 55 A. The data were taken at FETS and is averaged over 64 pulses for viewing purposes.

voltage probe connected between the cathode and grounded anode. The discharge light emission was recorded on VESPA with a photometric device developed to monitor the temporal behavior of different emission lines of hydrogen Balmer-series and caesium (Cs^0 and Cs^+) throughout the discharge pulse simultaneously. The light was collected by an optical fiber viewing the discharge through the extraction slit. The fiber is then split into four outputs each of them being connected to a Silicon PhotoMultiplier (SiPM, Hamamatsu S14420-1550MG) through an optical bandpass filter, e.g. Thorlabs FB660-10 (centered at 660 nm, FWHM of 10 nm) and FB850-10 (centered at 850 nm, FWHM of 10 nm) detecting the Balmer- α and $Cs^0 6^2P_{3/2} \rightarrow 6^2S_{1/2}$ emission of neutral caesium at 656.3 nm and 852.1 nm, respectively. The optical emission diagnostics device is not absolutely calibrated but can measure the temporal evolution of each selected emission line on pulse-to-pulse resolution although averaging the signals is often beneficial for improving the signal-to-noise ratio.

In the experiments the hydrogen flow, caesium oven temperature and the magnetic field of the ion source were set to

nominal values used regularly for ISIS operations (the source on VESPA uses permanent magnets to create the Penning field). Parametric sweeps of these settings were not carried out. The gas pressure and magnetic field strength have been demonstrated to affect the high-frequency noise of the discharge [39] whereas their effect on the breakdown oscillation characteristics is small in comparison to the discharge current setting. The effect of caesium on the breakdown oscillations and discharge noise was studied as explained in Section VII by controlling the air flow, which affects the electrode temperatures and their caesium coverage.

V. THE ORIGIN OF THE BREAKDOWN OSCILLATIONS

The experiments were started by determining whether the breakdown oscillations are primarily driven by caesium dynamics as postulated in Ref. [2] or the power supply circuit. Figure 6 shows the effect of the discharge current (setting) on the IV-characteristics and breakdown oscillations of the discharge pulse measured at FETS. The data is averaged over 64 discharge pulses to suppress the MHz-frequency noise. The

following observations can be made: (i) the breakdown voltage of 80–90 V at the start of the discharge pulse is independent of the discharge current setting, (ii) the duration and frequency of the breakdown oscillations depends on the discharge current setting, (iii) the steady-state discharge voltage of 35–70 V decreases with increasing discharge current, and (iv) the discharge voltage and current are not in phase.

The value of the discharge voltage required for the plasma breakdown can be explained by the fact that the ionization is driven by the electrons emitted from the cathode and the rate coefficient σv_e of electron impact ionization of caesium by monoenergetic electron beam reaches its maximum below 100 eV electron energy. Furthermore, the ionization rate coefficient of Cs is an order of magnitude higher than the corresponding rate coefficient of H₂ reaching its maximum at higher energy. Therefore, the ionization cascade in a caesium-hydrogen admixture is driven by the ionization of caesium, which suits the hypothesis of caesium dynamics dictating the breakdown oscillations. As a side note, this explains why the ISIS H⁻ Penning ion source cannot operate in high current pulsed mode without the addition of caesium. Figure 7 shows the ionization rate coefficient of the caesium-hydrogen mixture as a function of the primary electron energy (cathode potential) at various H₂-Cs mixing ratios. The cross sections (σ) for calculating the rate coefficients were taken from Refs. [40] (Cs) and [41] (H₂). The figure demonstrates that if the H₂-Cs mixing ratio of the two constituents is less than 10, the discharge breakdown voltage can be expected to be on the order of 50–100 V independent of the actual ratio, which matches the experimental evidence and estimated caesium and hydrogen densities in the Penning discharge. The partial pressures of hydrogen and caesium are estimated to be approximately the same (about 1 mbar) under nominal operation of the ion source, based on direct hydrogen pressure measurements and the vapour-pressure curve of caesium at ~ 160 °C, which is the nominal caesium oven temperature. The procedure of estimating the H₂-Cs mixing ratio in typical operating condition of the ISIS Penning ion source is described in detail in Ref. [42].

The duration of the discharge current and voltage oscillations as a function of the discharge current setting of 20–100 A is shown in Fig. 8. At high discharge currents only one voltage maximum was detected i.e. only the duration of the current oscillations is plotted in that case. At low discharge currents of ≤ 20 A the oscillations continue along the entire length of the 700 μ s discharge pulse whereas at high currents of ≥ 40 A their duration of approximately 100 μ s is independent of the current setting. This is an indication that the breakdown oscillations cannot be explained only by the caesium dynamics but are strongly affected by the snubber connected to the output of the power supply. The maximum current delivered by the snubber circuit in the given experiment is approximately 20 A (~ 100 V, 1 μ F capacitor discharging through 5 Ω resistor), which matches with the oscillations lasting through the pulse at lower than 20 A discharge current setting.

The duration of the breakdown oscillations can be connected to the load impedance of the power supply, which evolves

Fig. 7. The total electron impact ionization rate coefficient of Cs/H₂-mixtures (at constant total pressure) by monoenergetic electron beam corresponding to the primary electrons accelerated by the cathode sheath potential of the ISIS H⁻ Penning source. The dashed curve depicts the dependence of the rate coefficient maximum on the mixing ratio.

Fig. 8. The duration of the discharge current and voltage oscillations as a function of the discharge current setting. The data were taken at FETS.

during the transient as shown in Fig. 9a presenting an example measured with 40 A steady-state discharge current. The load impedance was calculated from the IV-characteristics of the power supply. The temporal variation of the impedance leads to the conclusion that the reactive component of the load decreases with time as the resistive component builds up with the plasma density. The steady-state plasma resistance depends inversely on the discharge current setting, as shown in Fig. 9b, reaching values below 1 Ω at discharge currents relevant for ISIS operations. The decrease of the resistance with increasing current results to lower cathode voltage being able to sustain the discharge indicating that the plasma conductivity increases with the discharge current.

The frequency of the discharge current oscillations and the phase between the discharge current and voltage as a function of the current setting are shown in Fig. 10 for the first 15 oscillations. The phase is determined for those oscillation periods for which the voltage oscillation is clearly detectable. The fact that the oscillation frequency depends on the discharge

Fig. 9. (a) An example of the temporal evolution of the load impedance at 40 A discharge set current setting and (b) the steady-state plasma resistance as a function of the discharge current exhibiting "negative resistance". The data were taken at FETS.

current setting varying between 25 and 65 kHz, and evolves with time is a strong indication that the temporal characteristics of the breakdown oscillations cannot be explained by the transport of caesium between the cathode surfaces. The caesium dynamics most likely affect the load impedance but do not alone explain the observed behavior. The decreasing trend of the phase between the discharge current and voltage imply that the reactive component of the load evolves with time and eventually vanishes when the current and voltage are in opposite phases ($\tan \phi = \frac{X_L - X_C}{R}$, where $\phi = \pi$ and thus $\tan \phi = 0$), which also marks the disappearance of the breakdown oscillations (-180° line in Fig. 10(b)) after which the steady-state DC discharge can be considered as an Ohmic load with "negative resistance" as described above.

The decrease of the reactive component can be explained by the snubber capacitance. When the pulsed discharge voltage/current is applied, the $1 \mu\text{F}$ capacitor is charged through the 5Ω resistor with $\tau = RC = 5 \mu\text{s}$ (see Fig. 3). When the plasma breakdown occurs the voltage across the anode-cathode gap drops below the voltage across the capacitor as the $\sim 1 \Omega$ plasma resistance allows driving the required discharge current with lower potential difference across the source electrodes. The current driven by the power supply then drops to a very low value because the discharging capacitor is

capable of supplying the required current only momentarily. The maximum current is defined by the (series) resistor of the snubber and the discharge. Since the snubber capacitor has a limited charge storage capacity, the current supplied by the capacitor drops, which causes the plasma resistance to increase. When the voltage across the capacitor becomes less than the discharge voltage required to sustain the requested discharge current the power supply starts driving the current, which leads to a drop of the plasma resistance. The described cycle repeats with a reduced amplitude until a steady-state is reached i.e. the non-linear (plasma) load connected parallel to the the snubber acts as a damping oscillator. The scenario explains a number of experimental observations. First, when the discharge current setting is less than the maximum current supplied by the discharging capacitor, the oscillations can continue throughout the plasma pulse (10 and 20 A current settings). Second, the decrease of the load impedance corresponds to the capacitor gradually reaching its steady-state charge defined by the voltage drop across the plasma (in steady-state the current through the "snubber" is zero). The number of the relaxation oscillations decreasing with the set current and the phase between the power supply current and discharge voltage approaching 180° in the steady-state is also consistent with this view casting in doubt the hypothesis of caesium oscillating between the cathode surfaces during the plasma breakdown and explaining the periodic fluctuations.

Optical emission photometry experiments conducted on the VESPA test stand with the same power supply used at FETS question the hypothesis even further. Figure 11 shows the discharge current, Balmer- α emission and $6^2\text{P}_{3/2} \rightarrow 6^2\text{S}_{1/2}$ neutral caesium emission. It is apparent from the figure that they all oscillate in phase, which does not match with the prediction of the 0-dimensional model and the original hypothesis of the caesium coverage being suboptimal. The hydrogen emission line is included to highlight that it oscillates in phase with the caesium emission i.e. the caesium light emission is proportional to the plasma density (a key assumption of the 0-dimensional model). The dip in the caesium emission after $550 \mu\text{s}$ is coincident with the rising edge of the extraction pulse. Similar dip was observed for all monitored emission lines of neutral and ionized caesium.

The hypothesis of caesium transport between the cathodes determining the breakdown oscillation frequency can be conclusively abandoned after comparing the standard ISIS 1X and the scaled 2X sources. As the distance between the cathode surfaces in the 2X source is doubled from the original design, it could be therefore expected that the oscillation period of the 2X source would be twice as long as the corresponding period of the 1X source due to increased caesium transit time between the cathode surfaces. However, this is clearly not the case as shown in Fig. 12 demonstrating that the oscillation frequencies in the two ion sources operating at the same discharge current setting are almost equal. The frequency averaged over consecutive oscillation periods is approximately 15% higher for the 1X source. The difference is most likely due to increased plasma volume in the 2X source (by a factor of 8), which affects the voltage required to sustain the discharge at certain current, thus affecting the plasma

Fig. 10. (a) The frequency of the discharge current oscillations and (b) the phase between the discharge current and voltage as a function of the discharge current setting. The data were taken at FETS.

Fig. 11. An example of the discharge current, Balmer- α emission and neutral caesium emission at 852.1 nm ($6^2\text{P}_{3/2} \rightarrow 6^2\text{S}_{1/2}$ transition) of the Penning ion source on VESPA.

Fig. 12. Comparison of the plasma breakdown oscillation frequencies of the 1X and 2X Penning ion sources as a function of the discharge current setting. The error bars correspond to the temporal variation of the oscillations along the discharge pulse. The data were taken on VESPA.

resistance and damping of the oscillations. Nevertheless, the observation confirms that the temporal characteristics of the breakdown oscillations are not explained by the transport of caesium between the cathode surfaces.

VI. MITIGATION OF THE BREAKDOWN OSCILLATIONS

The realization that the plasma breakdown oscillations are not caused by fundamental particle dynamics opens the door to apply engineering solutions to mitigate them. In the ISIS H^- Penning ion source this is the only viable choice since the minuscule discharge volume does not allow installing auxiliary electrodes, which is a proven technique for the purpose [43]. The experiments described in Section V indicated that the discharge characteristics can be affected by selecting the snubber components for a better response to the breakdown transient. An iterative process was adopted for measuring the discharge current with the independent current monitor (see Fig. 3) when 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 oscillations.

Figure 13 shows the current flowing through the Penning source plasma with various snubber component combinations starting from the nominal configuration used in the ISIS power supply. The given data were chosen as representative examples demonstrating the effect of the snubber component selection.

It was established that the duration of the breakdown oscillations could be minimized by reducing the snubber resistance and increasing its capacitance. The optimum, i.e. the best damping, was found with 1 Ω and 7 μF where the discharge ignites with a single voltage (and current) peak and then reaches the steady-state condition without any oscillations. This can be understood qualitatively by considering the snubber as an energy storage device that releases its charge when the plasma breakdown occurs and the pulsed power supply voltage drops below the breakdown voltage. Increasing the capacitance of the snubber increases the charge it can subsequently deliver whereas the resistor defines the maximum current. When both the charge and the maximum current are sufficiently high, the discharge can be sustained long enough by the snubber to

Fig. 13. Examples of the discharge current pulses with various snubber component combinations (a)–(f) and 50 A discharge current setting. The data were taken on VESPA.

overcome the action of the power supply feedback and, thus suppressing the breakdown oscillations.

Figure 14 showing the current flowing across the snubber resistor with $5\ \Omega / 1\ \mu\text{F}$ (a) and $1\ \Omega / 7\ \mu\text{F}$ (b) configurations (corresponding to plasma currents shown in Figs. 13a and 13f) confirms this qualitative description. In Fig. 14 positive values indicate charging of the snubber capacitor and negative values the snubber delivering current to sustain the discharge. With the nominal snubber configuration (Fig. 14a) the maximum current is limited to $\sim 30\ \text{A}$ whereas the modified snubber (Fig. 14b) delivers almost $100\ \text{A}$ current, which guarantees fast ignition of the discharge lacking any breakdown oscillations.

The suppression of the breakdown oscillations was confirmed further by measuring the optical emission of the Balmer- α and $6^2\text{P}_{3/2} \rightarrow 6^2\text{S}_{1/2}$ transitions of hydrogen and caesium together with the discharge and snubber currents with the modified snubber with $1\ \Omega$ and $7\ \mu\text{F}$ components. The result is shown in Fig. 15 where all curves have been normalized to their maxima. In the very beginning of the discharge when the snubber is charging only Cs-emission is detected, which is probably due to low power being delivered into the discharge and low dissociation degree of hydrogen at this point. When the discharge ignites, the light emission increases rapidly, followed by a current surge from the discharging snubber. A peak of caesium light emission is observed at the end of the

discharge pulse. This is due to slow discharging of the snubber through the decaying plasma observed also as a snubber current transient. The light emission oscillations visible in Fig. 11 have disappeared with the snubber modification, which is yet another sign of caesium dynamics not dictating the breakdown oscillation characteristics.

VII. DISCUSSION

The experimental work described in this paper has shown that the breakdown oscillations of the ISIS H^- Penning ion source discharge are not primarily driven by caesium dynamics as previously argued [2]. Furthermore, caesium light emission studies in conjunction with a 0-dimensional model of temporal fluctuations of the caesium coverage indicate that the ion source operates above the optimum caesium coverage (work function optimum). Although the caesium dynamics are not the causing the breakdown oscillations, it is emphasized that the amount of caesium on the surfaces affects the stability of the discharge pulse as well as the damping coefficient of the breakdown oscillations. This is demonstrated in Fig. 16 showing the discharge pulse at different cathode and anode (average) temperatures at constant caesium flux from the oven. Increasing the surface temperature induces non-periodic noise and prolongs the breakdown oscillations. This could be seen as an indication of entering the domain where the surface

Fig. 14. The current through the snubber resistor with (a) 5 Ω, 1 μF and (b) 1 Ω, 7 μF snubber resistor and capacitor. The plasma breakdown oscillations are suppressed in the latter case. Positive/negative current indicates charging/discharging of the snubber capacitor.

Fig. 15. An example of the discharge and snubber currents, Balmer-α emission and neutral caesium emission at 852.1 nm ($6^2P_{3/2} \rightarrow 6^2S_{1/2}$ transition) of the Penning ion source on VESPA with the development power supply equipped with a modified snubber with 1 Ω resistor and 7 μF capacitor.

work function depends on the caesium coverage, i.e. below one monolayer, where the discharge dynamics depend non-linearly on the temporally and spatially varying caesium coverage.

The caesium density in the discharge affects the sputtering rate of the molybdenum electrodes and the lifetime of the ion

source. Therefore, the caesium oven temperature is typically set to a value at which the discharge noise is barely suppressed and the clean H^- beam pulse is extracted at the back of the discharge pulse. The fact that the breakdown oscillations can be suppressed by equipping the snubber with appropriate components could allow shortening the discharge pulse which in turn could prolong the ion source lifetime. Furthermore, eliminating the discharge current and voltage fluctuations in the beginning of each pulse should have a beneficial effect in reducing the sputtering rate. This is demonstrated in Fig. 17 where the relative sputtering yields of the molybdenum electrodes are shown for the standard and modified snubbers. The temporal sputtering yield is plotted in Fig. 17a while Fig. 17b shows the cumulative release of molybdenum from the cathodes during a single discharge pulse. The relative yields were calculated using the energy-dependent sputtering yield reported in Ref. [45] together with the measured discharge current and voltage. It was assumed that the flux of the caesium ions (Cs^+) incident on the cathode surfaces is proportional to the discharge current. This assumption is supported by the optical emission data and comparison of ionization and excitation cross section of caesium by the primary electrons emitted from the cathodes [36], [40]. Furthermore, it was assumed that the energy of the ions accelerated across the plasma sheath is determined by the cathode potential i.e. the effect of the (unknown) plasma potential was not taken into account.

The two plots in Fig. 17 imply that the role of the breakdown oscillations on the cathode erosion and, thus, the lifetime of the ion source could be significant. This is because of the non-linear dependence of the sputtering yield on the energy of the caesium ions and the oscillations of the discharge voltage in the beginning of the discharge pulse. With the modified snubber these effects are presumably reduced. The cumulative sputtering plot highlights that 90 % of the damage can be expected to occur in the first $\sim 100 \mu\text{s}$ of the discharge pulse. With the modified snubber connected to the output of the development power supply the estimated cumulative yield measured across the discharge pulse is 56 % of the yield of the standard snubber and power supply. In reality the difference could be even more significant since the effect of Cs^{2+} ions detected during the breakdown oscillations through VUV-diagnostics [46] (emission lines at 181, 188, 193, 206 and 220 nm appearing during the breakdown oscillations) was not taken into account. The sputtering yield by the doubly charged ions is significantly higher and their production is enhanced during the voltage oscillations owing to the energy dependence of the ionization rate coefficient [40]. The effect of the discharge breakdown oscillations on the cathode erosion and ion source lifetime requires further studies comparing two ion sources after operation with the standard and modified power supplies over extended period of time, preferably >20 days matching the ISIS ion source maintenance interval.

Overall, the work presented in this paper underlines the fact that in the development of Penning ion sources the ancillary components of the ion source including the discharge power supply should be considered equally important to the physics and engineering of the actual ion source.

Fig. 16. The discharge current pulses recorded on VESPA with different cathode and anode (average) temperatures. The electrode temperatures were controlled by adjusting the air flow cooling the source body. All other operational parameters including the hydrogen gas feed rate and caesium oven temperature were kept constant during the sweep. The figure is modified from Ref. [44]

Fig. 17. The comparison of the (a) temporal and (b) cumulative cathode sputtering yields [45] of a single discharge pulse with the standard and modified snubbers estimated with experimental discharge current and voltage pulses.

ACKNOWLEDGMENT

This project has received funding from the European Unions Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 665593 awarded

to the Science and Technology Facilities Council.

Mark Whitehead is acknowledged for technical support.

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Trevor Wood Author's photograph and biography not available at the time of publication.