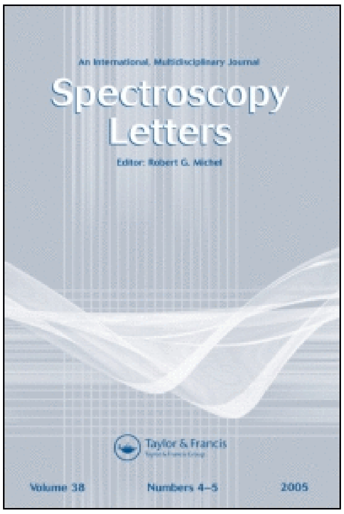


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# Two Self-Sustained Unstable Modes for Operation of a Hollow Cathode Discharge

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**ABSTRACT** Two self-sustained unstable modes for operation of a hollow cathode discharge (HCD) are observed under some *i-V* operating points of both positive and negative dynamic resistance. The instabilities manifest themselves either as oscillations or pulsations. Their frequency depends on the operating *i-V* point. The instabilities are found to correlate with the HCD space structure.

**KEYWORDS** hollow cathode discharge, mode for operation, negative glow macrostructure, *i-V* operating point



## INTRODUCTION

Glow discharges (GD) are known as a medium of numerous applications.[1] As a rule, the stability of the selected mode for operation is a necessity vs. cited applications. One of the GD modifications, for example, hollow cathode discharge (HCD), improves some of the properties of these applications.[2] An HCD is easier to stabilize because the plasma is localized in the cathode cavity, which can be more easily controlled through cooling or lowering the discharge current density. This is particularly important for commercial HCD lamps. Some instability due to both induced and spontaneous $\Delta i$-$\Delta V$ deviations was observed in the literature.[3–5]

Earlier, light- and galvanically induced instabilities of oscillating type were found to arise under an operating point on *i-V* branch of negative differential resistance or close enough to the inflection *i-V* point.[4] Under these operating points, the discharge is of lower degree of stability for disturbance. As a rule, the unstable mode for operation prevents the application of most GD. In particular, some diagnostic techniques of GD are limited by $\Delta i$-$\Delta V$ deviations of the order of $10^{-(4–5)}$ vs. the nominal *i-V* values.[3,5]

In this study, two self-sustained unstable modes for operation of an HCD are analyzed vs. the operating *i-V* point. Although these instabilities are discussed within the frames of an HCD, they may arise in other GD at certain combination of their operating parameters.

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## EXPERIMENT

The stability of an HCD DC operation is studied in the absence of any external perturbation. Figure 1a contains a schematic drawing of the standard experimental setup. Time-dependent change in the impedance

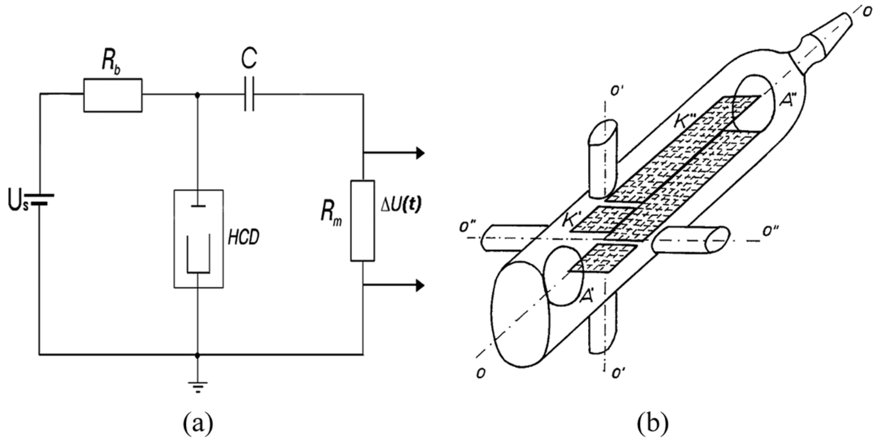


**FIGURE 1** **Experimental scheme: $U_s$ is power supply, $R_b$ is ballast resistor (11 kohm), $C$ (0.47 µF) is decoupling condenser, $R_m$ is measuring resistor (a). Discharge tube with two parallel Al nets–cathodes K′K′ and K″K″: A is anode (b).**

of the discharge was detected by measuring the voltage $\Delta U(t)$ across the 50 ohm resistor $R_m$. The $R_mC$ constant is low enough to resolve the shape structure of $\Delta U(t)$. The signal was sampled by the oscilloscopes LP142 (Le Croy, France) or C-108 (Elprod, Russia).

Two HCD modifications, that is, the trademarked lamp Ne/CaBa (Cathodeon Inc., England) a and homemade one (Fig. 1b), were used. They differ in the characteristic size of the cathode space and therefore in the optimal operating buffer gas pressure. In the trademarked lamp, the cathode–cylinder of radius of 1.5 mm limits the optimal buffer gas pressure to about 4 Torr.

The cathodes K′K′ and K″K″ (Fig. 1b) consist of two parallel Al nets. Two separate HCDs may develop independently within the nets K′K′ (20 × 20 × 20) mm mm and K″K″ (20 × 80 × 20) mm. In this modification, the plasma structure is observable along the axes OO, O′O′, and O″O″. The distance of 20 mm within the nets allows a stable mode for operation at about $2 \times 10^{-2}$ Torr of Ar in the HCD tube in Fig. 1b. The discharge was produced by applying a highly stable DC voltage and operated in a negative glow (NG) regime.

Earlier the modification K′K′HCD was studied within the frames of some coherent phenomena.[6] In the current experiment the K′K′HCD modification is used for measuring at low enough buffer pressure both the operation mode stability and monitoring of the plasma space structure.

## RESULTS AND DISCUSSION

The results obtained concern three aspects of an HCD self-sustained instability; that is, (1) the harmonic composition of the voltage across the resistance $R_m$; (2) the space localization in the NG; (3) the optical transfer to other plasma bulk.

1. Both regions of negative differential resistance $\partial U/\partial i < 0$ and great slope variety of some HCD *i-V* curves[4] draw the attention to *i-V* operating points of different $\partial U/\partial i$ values (Fig. 2a). Generally, self-sustained oscillating components were observed under some operating *i-V* points on *i-V* parts of both $\partial U/\partial i < 0$ and $\partial U/\partial I > 0$ (Fig. 3a) and under operating *i-V* point close enough to the critical low one.[4] At the beginning a self-sustained oscillating voltage component (~18 Hz, ~7 V) was detected under operating points of $\partial U/\partial i < 0$ in the Ne/CaBa HCD lamp (Fig. 3a). Both frequency and shape of oscillation change within the discharge current values of 1.5–1.9 mA. This alternative voltage was observed to modulate the spontaneous emission. Furthermore, the negative peaks of the oscillation were observed to extinguish the discharge and HCD passes into a twinkling mode for operation of the oscillation's frequency.

A lower level of the signal-to-noise ratio characterizes the spectral line intensity emitted under unstable mode for operation. In the same context, optical instabilities were observed in the spontaneous emission of an Ar/Cd HCD lamp (Narva, Germany). The current measurements revealed a multitude of nonlinear regions on the *i-V* curve (Fig. 2b). Only four to five narrow linear *i-V* bands provide a stable mode for operation in this HCD lamp. On the other hand, the value 5.5 mA is the

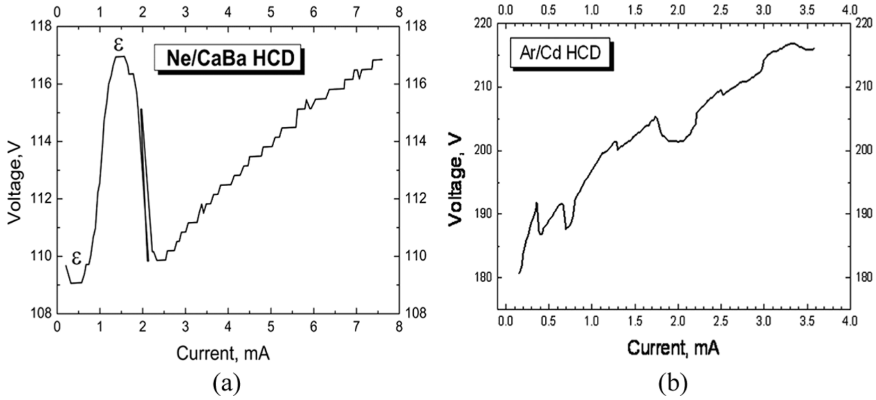


**FIGURE 2** ***i-V*** **curves: (a) Ne/CaBa HCD lamp: ε is inflection point; (b) Ar/Cd HCD lamp.**

maximum discharge current recommended. Self-sustained instability of pulsing type (Fig. 3b) and frequency (50 kHz) takes place for the Ne/CaBa HC lamp at $i \in (3.0 \div 6.8)$ mA where $\partial U/\partial I > 0$ (Fig. 2a). The correlation *instability–i-V–operating point* is the one unique that might be established in this optical geometry of the experiment.

2. The conventional cup-like HC geometry restricts a more detailed study and rationalization of the above instabilities. The discharge tube with the nets–cathode pairs K′K′ and K″K″ in Fig. 1b is used for monitoring the HCD space structure at a given *i-V* point so that any correlation with galvanic instability to be found. The basic measurements were performed by using the HCD between the cathode nets K′K′. One should note that Ne/CaBa HCD lamp and K′K′HCD tube differ in both buffer gas pressure and discharge current density. Hence, their comparison vs. the modes for operation is only qualitative. Figure 4a shows the *i-V* curve. Three *i-V* sections, that is, B, C, and D, may be marked correlating with three NG macrostructures, that is, B-, C-, and D- space modes (Fig. 4b). Every mode corresponds to an appointed plasma bulk in the cathode cavity. The B-mode takes place under voltage $U \in (253 \div 267)$ V. Plasma fills up fractionally the HC cavity in the B-mode. Besides, discontinuous transitions between $(255 \rightarrow 263 \rightarrow 267)$ V occur and self-sustained sine-like oscillation (~2 kHz) arises under either of these fixed $U$ values of $\partial U/\partial i > 0$. The C-mode covers the voltages succession $267 \rightarrow 305$ V where $\partial U/\partial i > 0$. Here plasma fills up the HC cavity around the axis OO (Figs. 1b and 4b) and no oscillation takes place up to 303 V. Oscillating instabilities are observed under *i-V* points (p) denoted as $a'$, $a''$, and $b$ in Fig. 4a. Self-induced periodic oscillations with frequency 1.8 kHz arise at points $a'$ and $a''$. An initial effect of period doubling (Fig. 3c) takes place at point $b$ as a manifestation of the nonlinearity around the inflection point. Further, a discontinuous transition occurs from C- to D-modes as a voltage jump down to point $c$. This jump forms negative differential resistance. Plasma structure enlarges along both axes, first along O′O′ and then along

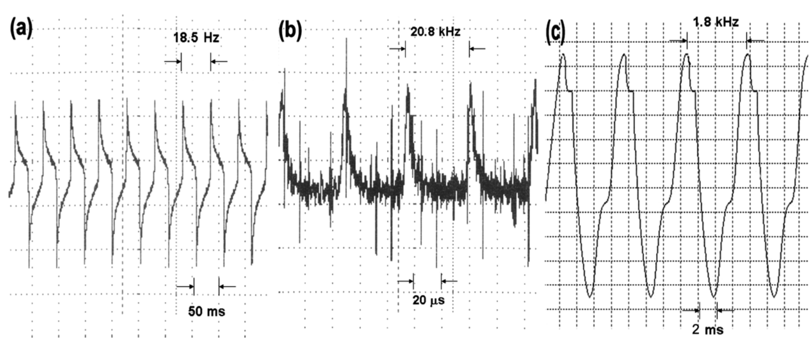


**FIGURE 3** **Self-sustained instabilities: (a) and (b) In an Ne/CaBa HCD lamp (Cathodeon Inc); (a) $\partial U/\partial i < 0$, $i = 1.5$ mA; (b) $\partial U/\partial i > 0$, $i = 3.15$ mA; (c) In K′K′HCD at point *b* in Fig. 4a.**

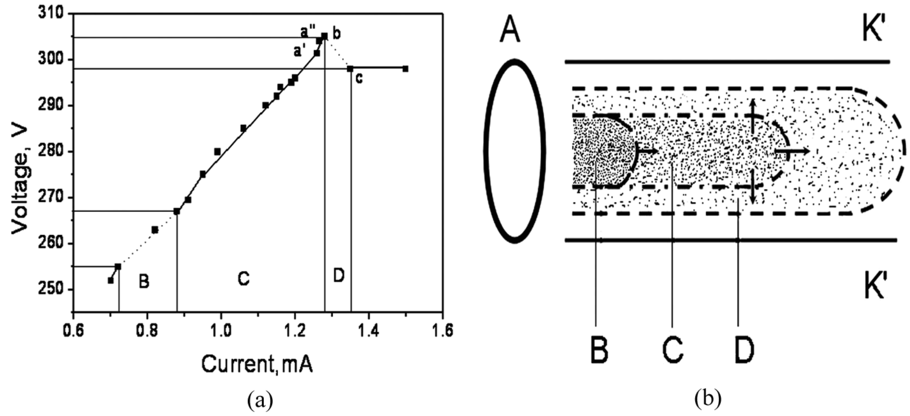


**FIGURE 4** **Low discharge current *i-V* section of K′K′HCD shown in Fig. 1b (broken lines denote transitional regions of discontinuous mode transitions). (a) Macro-structure of HCD plasma bulk under $p_{Ar} = 0.2$ Torr. B – initial NG under (253 ÷ 267) V; C – development of NG along the axis OO under (267 ÷ 305) V; D – enlargement of C – structure along axes OO and O′O′. The boundaries B-C-D are given by a dotted line (b).**



O″O″. Oscillating fluctuations of higher amplitude (±5 V) and frequency about 10–100 kHz arise in point *c* of the *i-V* curve. Earlier laser pulse–induced damped oscillations of low-frequency Ω were observed in time-resolved optogalvanic (OG) measurements.[3–5] Based on a simple model in Petrov et al.,[7] the same OG scheme was calculated to generate light-induced oscillations of upper frequency limit $\Omega^2 = \frac{1}{LC}\ \frac{R_b + R_i}{R_b - R_m} - \beta^2$, where $C$, $R_b$, and $R_m$ are marked in Fig. 1; $R_i = \frac{\partial U}{\partial i}$ is differential resistance; $L$ is equivalent inductance; and $\beta$ is damping in the discharge section. According to these calculations: (1) both *i-V* section of $R_i < 0$ and $|R_i| \approx 1\,\mathrm{K}\Omega$ is the necessary condition for oscillation of frequency $\Omega \approx$ kHz; (2) both $\Omega$ and $\beta$ rise at $R_i$ in the vicinity of $R_i \geq 0$; that is, $R_i \rightarrow R_i \geq 0$. The measured self-sustained oscillations (Figs. 3a, 3b) exhibit qualitatively the tendencies calculated for light-induced oscillation. The genesis of the observed instabilities under operating point $\partial U/\partial i > 0$ might be analyzed formally within the frames of an equivalent HCD circuit. Small deviation $\Delta u - \Delta t$ of the selected operation *i-V* point turns out to rise in amplitude under some specific values of discharge current and buffer density, Larmor's frequency, and frequency of collisions electron–atom.[8]

3. The combination of self-sustained oscillations and light-induced conductivity[3–5] is a precondition for OG transfer of instability. It might turn in a segmented GD including that used as a laser medium.[9] An OG transfer of instability was detected in the voltage across the K′K′HCD illuminated with the emission of K″K″HCD. Two detached powers supply the discharges inside the tube in Fig. 1b. The discharges are connected optically only. When the K″K″HCD operates under the *i-V* point of self-sustained oscillation, the voltage across K′K′HCD contains an alternative component of the same frequency. The transferring channel is based on all the spectral lines emitted, which means that any instability in a GD segment may be multiplied via all the rest.

## CONCLUSIONS

Two self-sustained unstable modes for operation of an HCD are observed in a trademarked spectral lamp. The low-frequency oscillations (of tens Hz) take place under *i-V* operating points of negative dynamic resistance. The discharge passes into a twinkling mode for operation of the same frequency. Pulsations of tens kHz frequency arise under *i-V* operating points of positive dynamic resistance. In order to prevent any unstable mode for operation, the corresponding *i-V* regions should be localized by previous measurement of the *i-V* curve.

Three NG macrostructures correlating with three *i-V* sections are observed in an HCD where the cathode consists of two parallel plates. Here every mode corresponds to an appointed plasma bulk in the cathode cavity. Self-sustained oscillating fluctuations take place under *i-V* operating points of both positive and negative dynamic resistance. An effect of period doubling arises near the inflection point.

Optogalvanic transfer of instability in a segmented GD is observed.

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