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Observation of a U-like shaped velocity evolution of plasma expansion during a high-power diode operation

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Abstract

The diode closure velocity has been investigated in pulsed high-power diodes operating with the mode of space-charge-limed bipolar flow. A combination of time-resolved electrical and optical diagnostics has been employed to study the basic phenomenon of the temporal and spatial evolutions of the diode plasmas. The results from the two diagnostics were compared. Since anode plasma rapidly expands, the diode closure speed v_d increases in the end of the current pulse. The diode closure speed v_d can be divided into three stages with a U-like whole shape. The obtained results can be used in various applications, for instance, the high-power microwave sources, electron-beam plasma heating, and material treating.

Keywords: Bipolar flow; Diode closure speed; High-power microwave devices; Optical diagnostics

1. INTRODUCTION

The study of plasma dynamics has renewed the interest in laser-produced plasma, microwave source, and material modification applications (Zhang *et al.*, 2008; Yarmolich *et al.*, 2008; Benford & Benford, 1997). Particularly in pulsed high power diodes, electron beams are generated using a cold cathode by the process generally termed as explosive electron emission (Mesyats, 1995; 2005). This explosive process causes the formation of a neutral cloud which is almost simultaneously ionized by electrons, leading to the formation of a plasma sheath in the vicinity of the cathode surface (Booske, 2008; Shiffler *et al.*, 2008). The plasma electron temperature and density can be estimated as several eV and about 10^{15} cm^{-3}, respectively (Liu *et al.*, 2008; Li *et al.*, 2008). The plasma expansion toward the anode reduces the diode impedance and ultimately leads to the diode shortening. Actually, the evolution of the expanding plasma is a rather complicated phenomenon which relates to plasma physics and has not been fully characterized (Shiffler *et al.*, 2008; Beilis, 2007; Vekselman *et al.*, 2008; Gleizer *et al.*, 2008). Cathode plasma expansion is responsible for the diode impedance instability and for the efficiency drop of high power microwave sources.

Generally, the most common and simple method to investigate the temporal behavior of plasma in planar diode is to compare the diode purveyance $P(t)$ with a one-dimensional model based on the classical Child-Langmuir law (Child, 1911; Langmuir, 1911). What worth noting is that the model should be modified according to real conditions (Saveliev *et al.*, 2003; Shiffler *et al.*, 2002; Watrous *et al.*, 2001; Saveliev *et al.*, 2001; Krasik *et al.*, 2001). For space-charge-limited bipolar flow, the ionic current is $\sqrt{m_e/m_i}$ times the electron current, where m_e is the electron mass and m_i is the ion mass. The charge neutralizations of the electrons by the ions allow increase of the current by 0.86 times independent of ion mass (Miller, 1982).

The main purpose of this paper is to obtain reliable data on the temporal behavior of the diode closure velocity in pulsed high-power diodes operating with the mode of space-charge-limited bipolar flow. In Section 2, we show details of the experimental setup and diagnostics. Other than current and voltage diagnostics, we utilize the digital image processing methods to analyze the light emission in the anode-cathode (A-K) gap region in Section 3. Conclusions that can be drawn from this work are summarized in Section 4.

2. EXPERIMENTAL SETUP AND DIAGNOSTICS

In this paper, we report on optical investigation of plasma produced by carbon-fiber aluminum (CFA) cathode in a

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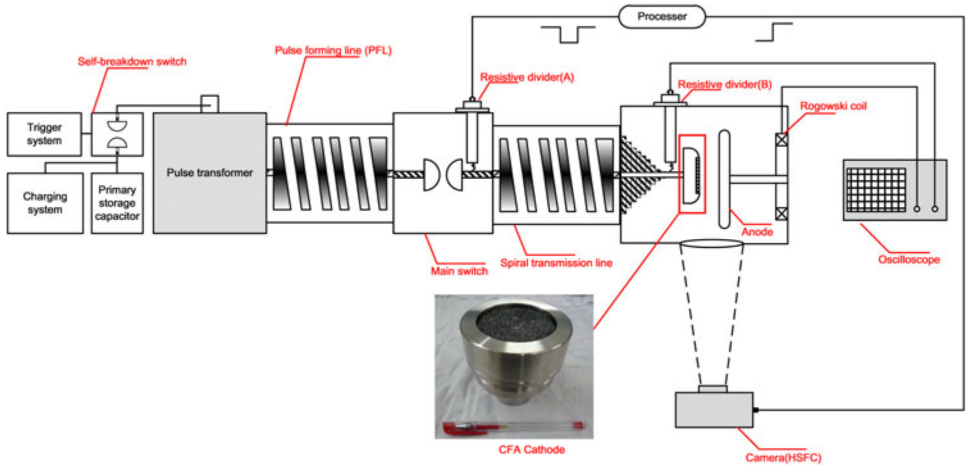

Fig. 1. (Color online) Schematic diagram of experimental setup.

high current diode. A vacuum liquid infiltration method for constructing CFA cathode has been described detail in Lie *et al.* (2004). Figure 1 presents a multi-needle CFA obtained by wire cutting and surface treatment. This cathode had 568 individual carbon fiber needles (1×1 mm^2) that are spaced by 3 mm and offset by about 2 mm with respect to the screening electrode surface. In order to decrease the edge effect, a ring-type screening electrode was used. The anode consists of 304 L stainless steel disk with 150 mm diameter.

The experimental bed was described in detail elsewhere (Yang *et al.*, 2013), and here it is briefly presented. The vacuum vessel operated with base pressures of $2\text{–}5 \times 10^{-5}$ Torr, utilizing a turbo-molecular pump backed by an oil roughing pump. The diode voltage and anode current were, respectively, measured using a resistive divider and Rogowski coil. The Rogowski coil was located at the anode holder; therefore, the current was the sum of electron current and ion current. Because the ratio of the electron mass to ion mass is very small, the value of the ion current is very low compared to the electron current. A high speed framing camera with four micro-channel plate image intensifier modules was used to observe the light emission from diode plasma. The spectral response of high speed framing camera is 280–1000 nm. In order to avoid the reflection light, the inner surface of the vacuum chamber was covered by low-reflectivity material. Figure 1 shows the schematic of the pulses and diagnostics.

3. RESULTS AND DISCUSSIONS

The typical waveforms of the diode voltage and current are shown in Figure 2. The average electric field in the A-K gap was nearly 160 kV/cm at the peak of voltage waveform. The current predicted for pure electron Child-Langmuir flow was 5 kA with the A-K gap of 1.5 cm and cathode diameter of 7.24 cm, however, the peak value of the current waveform is 10.6 kA which is 2.12 times the Child-Langmuir electron space-charge limited flow. In this paper, we hypothesize that the ions can be ejected from the anode surface under the impacting of electron, and then are accelerated toward the cathode, resulting in bipolar flow. The experiment result is slightly more than 1.86 for the reason of edge effects in finite area (Saveliev *et al.*, 2002) and ion current.

The exact property of the current flow (i.e., unipolar or bipolar flow) is of major importance in the explosive emission diodes because one of the most common methods for determining the diode closure velocity is to compare the dependence of the diode perveance with the effective distance of A-K gap. In order to determine the nature of current flow, the results of different sets of experiment (distinguished with number on the left of Table 1) are listed in Table 1 with the same condition as Figure 2 where U_d is the peak value of diode voltage, I_d is the peak value of diode current, P_{CL} $(= 2.33\pi(r_0/d_0)^2)$ is the diode perveance of the electron space-charge limited unipolar flow, where r_0 is the cathode radius, d_0 is the distance between A-K. $P(= I_d/(U_d)^{3/2})$ is the diode perveance of the experiment data. In Table 1, the

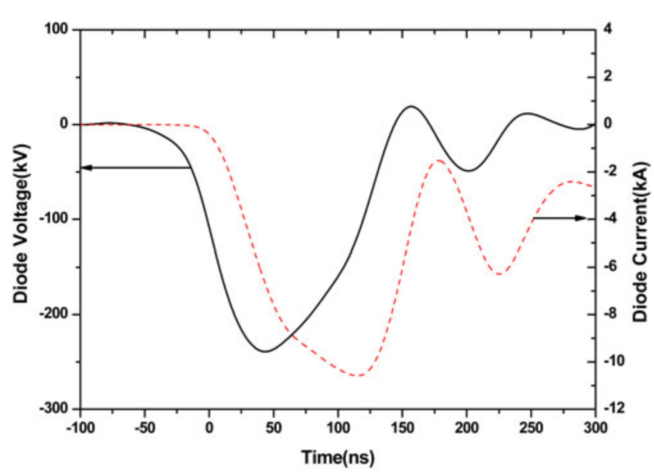

Fig. 2. (Color online) Experimental diode voltage and current pulse. The A-K gap is 1.5 cm. The cathode has a 7.24-cm diameter and is mounted in a corona bushing with a 9.2-cm outer diameter.

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Table 1. *The diode perveance of several times experiment*

Number	U_d(kV)	I_d(kA)	$P_{CL}(\mu A/V^{3/2})$	$P(\mu A/V^{3/2})$	$P/\ P_{CL}$
01	238	10.8	42.8	93	2.17
02	242	10.6	42.8	89.14	2.08
03	237	10.4	42.8	90.1	2.11
04	239	10.6	42.8	90.8	2.12
05	225	9.1	42.8	85.3	1.99
06	216	8.7	42.8	86.6	2.02

ratio of P/P_{CL} is approximately 1.9–2.2 which corresponds to the earlier results (Saveliev *et al.*, 2002).

Typical photographs of the diode plasmas corresponding to various stages of the diode current are presented in Figure 3b. The view was from the side with the cathode on the left and the anode on the right (Fig. 3a). The A-K gap was 1.5 cm. All of these were registered with constant frame duration of 25 ns. Frame positions within the pulse are indicated by black rectangles on the diode voltage and current waveforms (Fig. 3c). $t_d = 0$ corresponds to the start of the current pulse. Figure 3b shows that at the beginning of the current pulses (0–25 ns), the plasma formation on the surface of the CFA cathode. The plasma distribution of cathode surface is clearly not uniform in this period. There is slight or even no plasma in some regions of the cathode surface. In addition, the weak light from plasma appears in the vicinity of the anode surface. Furthermore, the intensities and areas of light emitting from both cathode and anode front surfaces gradually increase as time goes on. During the main part of the current pulse (25–125 ns), the plasma from the CFA cathode and anode are more stable without significant change in the effective size of diode. Finally, during the decrease in the current pulse (125–175 ns), the leading edge of anode plasma rapidly expands toward the region of A-K gap while there is no significant change in the contour profile of cathode plasma. According to the previous study, the bipolar flow was achieved only when an arrangement was made to ensure a fast generation of dense plasma on the anode (Saveliev *et al.*, 2003). During the whole pulse of current waveform (Fig. 3b), the light from the plasma in the vicinity of the anode surface can be seen, which further confirms the above hypothesis about the property of the current flow.

More accurate and quantitive information about the expansion velocity of diode plasmas was obtained by utilizing digital images methods (e.g., rasterization, image binaryzation, and outlinedistiling). The profiles of the plasma images of the diode area are showed in Figure 4. In Figure 4a, the longitudinal positions of the cathode and anode surface are Z_c = 92 pixel and Z_a = 192 pixel with the distance of A-K gap being 15 mm, thus the spatial resolution is 0.15 mm/pixel.

Based on the digital images methods, the average diode closure speed v_d in a certain period Δt can be simply calculated as $v_d = \Delta d/\Delta t$, where Δd is the change of distance of A-K gap. The effective distance of A-K gap and diode closure speed of various stages of the diode operation are shown in Table 2. The detail about the calculation method has been described elsewhere (Yang *et al.*, 2013). Analyzing the data from Table 2, the diode closure speed v_d can be divided into three stages. First, during the initial stage of current pulse (0–25 ns), v_d reaches 23.4 cm/μs for the reason of the unbalance between the plasma saturation electron

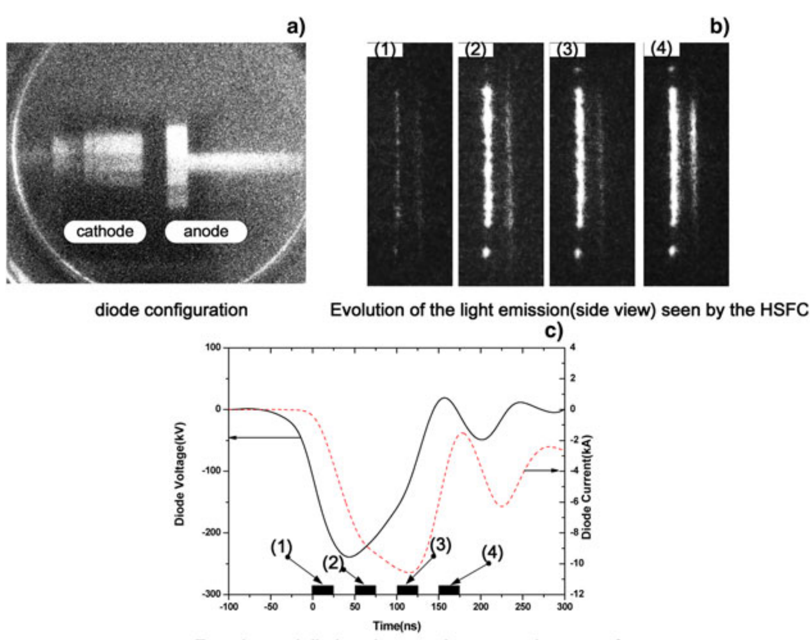

Fig. 3. (Color online) Typical side images from the diode. Numbered rectangles on the waveforms indicate positions of frames with corresponding numbers. The A-K gap was 15 mm.

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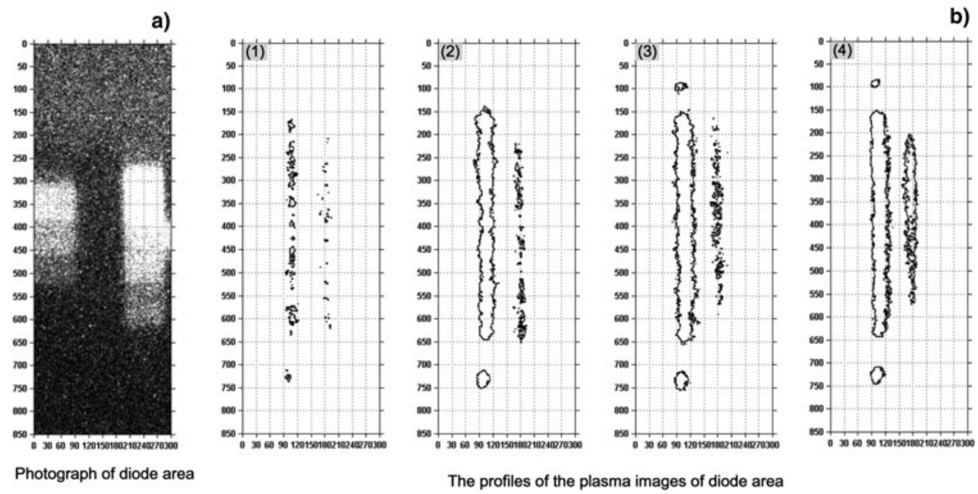

Fig. 4. the profiles of the plasma images of diode area.

Table 2. *The effective distance of A-K gap and diode closure speed of various stages of the diode operation. At* $t_0 = 0$ *the initial distance* $d_0 = 15$ *mm*

Number i	Time t_i(ns)	Distance of A-K gap d_i (mm)	Diode closure speed v_d(cm/μs)
0	0	15	0
1	25	9.15	23.4
2	75	5.55	7.2
3	125	4.95	1.2
4	175	2.85	4.2

current and the space-charge limited current (Yarmolich *et al.*, 2008; Vekselman *et al.*, 2008). During the main pulse (25–125 ns), the diode operates at the stable stage that v_d decrease from 7.2 cm/μs to 1.2 cm/μs; Finally, during the decrease in the current pulse (125–175 ns), the leading edge of anode plasma rapidly expands toward the region of A-K gap which cause the diode closure speed v_d to increase to 4.2 cm/μs (see Fig. 4b).

Additional insight can be gained by comparing the experimental measurements with that calculated by the one-dimensional model based on the Child-Langmuir law. If the diode operates in the mode of the space-charge-limed bipolar flow, the diode perveance P_{CL} is:

$$P_{CL} = \frac{P}{1.86} = \frac{I/U^{3/2}}{1.86} = 2.33\pi\left(\frac{r_{eff}}{d_{eff}}\right)^2 (\mu A/V^{2/3}), \qquad (1)$$

where I is the diode current, U is the diode voltage, r_{eff} is the effective emission radius of cathode, d_{eff} is the effective distance between A-K.

For the diode with explosive emission cathode in Eq. (1), it is necessary to consider the reduction of the A-K gap of the expanding plasma and the increase of the emission surface due to the expansion in the transverse direction, the correlation (1) could be rewritten as follows:

$$P_{CL} = \frac{P}{1.86} = \frac{I/U^{3/2}}{1.86} = 2.33\pi\left(\frac{r_0 + v_2 \cdot t}{d_0 - 2v_1 \cdot t}\right)^2 (\mu A/V^{2/3}), \qquad (2)$$

Where v_1 and v_2 are the speeds of cathode plasma expansion axial and crosswise to anode-cathode gap, respectively.

For the case of hemisphere emitting surface on the planar cathode, it was found that the experimental data are well described by the equation where the plasma spread speeds in the direction of anode and crosswise to A-K gap are equal (Pushkarev *et al.*, 2009).

When $v_1 = v_2 = v$, we will get that the diode closure speed v_d is:

$$K = \sqrt{\frac{I}{2.33 \cdot \pi \cdot U^{3/2} \cdot 1.86}}\; v_d = 2v = \frac{K \cdot d_0 - r_0}{t \cdot (K + 0.5)}. \qquad (3)$$

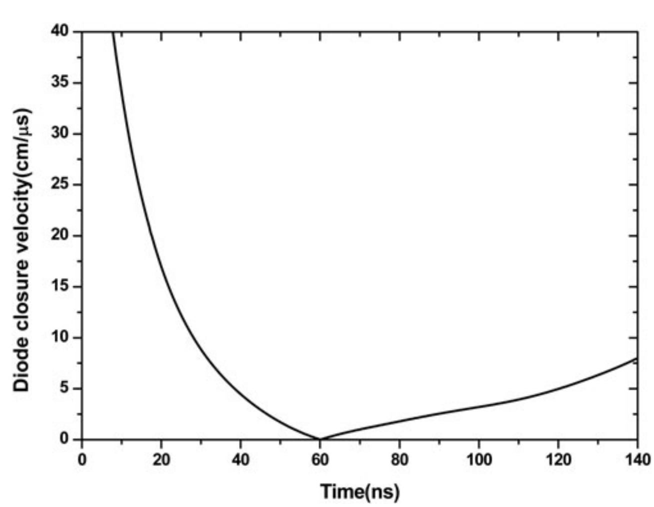

Fig. 5. The diode closure speed.

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The diode closure speed is shown in Figure 5. The pattern of the closure velocity presents U-like curve which is in accordance with the results from digital images methods.

4. CONCLUSIONS

A complete evolution process of expanding plasma within the diode is presented. The optical measurements of the light emission within the diode gap and the temporal dependence of plasma expansion velocity further confirm the theoretical prediction. Since anode plasma rapidly expands, the diode closure speed v_d increases during the decrease in the current pulse. Temporal dependence of plasma expansion velocity exhibits a U-like shape. For application in the high power diode, the phenomenon is very harmful. For instance, high power microwave devices driven by the high power diode require lower closure speed which is very crucial for output microwave pulse width (Korovin *et al.*, 2000; Benford & Benford, 1997). In addition, the bipolar flow could reduce tube efficiency by severely modifying the space charge flow (Shiffler *et al.*, 2002). The obtained conclusion can be used in different applications, for instance for the high-power microwave sources, electron-beam plasma heating, and laser-plasma interaction. In order to reduce the generation of anode plasma, new materials and material modification should be further investigated.

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