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Plasma characterization on carbon fiber cathode by spectroscopic diagnostics*

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This paper mainly investigates plasma characterization on carbon fiber cathodes with and without cesium iodide (CsI) coating powered by a $\sim$ 300 ns, $\sim$ 200 kV accelerating pulse. It was found that the CsI layers can not only improve the diode voltage, but also maintain a stable perveance. This indicates a slowly changed diode gap or a low cathode plasma expansion velocity. By spectroscopic diagnostics, in the vicinity of the cathode surface the average plasma density and temperature were found to be $\sim 3\times10^{14}$ cm^{-3} and $\sim$ 5 eV, respectively, for an electron current density of $\sim$ 40 A/cm^2. Furthermore, there exists a multicomponent plasma expansion toward the anode. The plasma expansion velocity, corresponding to the carbon and hydrogen ions, is estimated to be $\sim$ 1.5 cm/μs. Most notably, Cs spectroscopic line was obtained only at the distance $\leq$ 0.5 mm from the cathode surface. Carbon and hydrogen ions are obtained up to the distance of 2.5 mm from the cathode surface. Cs ions almost remain at the vicinity of the cathode surface. These results show that the addition of CsI enables a slow cathode plasma expansion toward the anode, providing a positive prospect for developing long-pulse electron beam sources.

Keywords: cold cathode, spectroscopic diagnostics, CsI coating, plasma expansion
PACC: 0660J, 2925B, 4180D, 5250D, 5270K

1. Introduction

There has been a continued interest in explosive emission cathodes that can be used in the generation of high-current electron beams driving high-power microwave (HPM) sources.[1−4] Electron emission occurs from plasma which is formed as a result of the explosion of microprotrusions on the cathode surface under the application of the accelerating pulse. It has been experimentally observed that both cathode and anode materials, coatings, contaminations, and vacuum environments all have direct effects on the explosive emission process.[5−8] Unfortunately, these cathodes typically suffer plasma motion which produces either sufficiently large changes in the dimensions of the diode or changes in the dimensions of the slow wave structure or microwave cavity.[9−13] In spite of recent research breakthroughs in this area, the long-lived, low work-function, uniformly emitting, low emittance, high current density cathodes are still one of the remaining challenges in the HPM arena.[14] However, an idealized electron beam source does not exist yet, this fact necessitates the research and development of different types of cathodes.

Recently, several explosive emission cathodes have emerged as providing high current density emission from cathodes with mechanically and thermally robust construction. These cathodes include carbon fiber cathodes, carbon velvet cathodes with or without CsI coating, and graphite cathodes.[15−21] Recent developments of CsI-coated carbon fiber cathodes have shown that those ideal goals for explosive emission cathodes may be technically feasible. CsI-coated carbon fiber cathodes are observed to operate stably for more than 10^6 pulses.[22] One of the most distinguished properties of CsI coating is significantly lower turn-on electric fields than that achieved with uncoated carbon fiber cathodes.[23] The nature behind these excellent properties of CsI-coated carbon fiber cathode has been investigated in recent work, and it has been suggested that CsI coating on graphite substrates can significantly reduce the work function of the system through a mechanism of induced dipoles.[7] Thus, the decrease in the work function is a major contributor to the improved emission when CsI coating is applied to carbon fiber. Nevertheless, the complete physics of the electron emission process for CsI-coated

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carbon fiber cathodes is far from fully characterized.

This paper investigates a high-current planar diode with cathodes made of carbon fibers, with and without CsI coating. Spectroscopic diagnostics were used to characterize the plasma of carbon fiber cathode. The effects of CsI coating on the diode operation are also presented. The rest of this paper is organized as follows. Section 2 gives a brief description of experimental configuration. Section 3 presents the experimental results. Discussions are given in Section 4.

2. Experimental setup

A planar cathode, 60 mm in diameter, made of carbon fibers, has been investigated in a high-voltage (HV) diode (Fig.1). This cathode was constructed by the squeeze casting technique, and by surface treatment in 10–15% sodium hydroxide solution, carbon fiber emitters distributed uniformly across the cathode surface. The axial length of carbon fibers standing the substrate was in the range of (3–5) mm, and there existed (2–3)$\times 10^4$ fibers per square millimeters, a high distribution density. The carbon fiber cathode was tested with and without CsI coating. The CsI coating was made by an application of saturated CsI water solution on the fiber surface followed by heating it to $\sim$ 80 °C during several hours. The carbon fiber cathode was placed on the cathode holder having a polished aluminum screening ring of 10 cm outer diameter. The edge of the carbon fiber cathode was screened by the cathode screening electrode. The surface of the carbon fiber cathode was offset by $\sim$ 1 mm with respect to the ring surface.

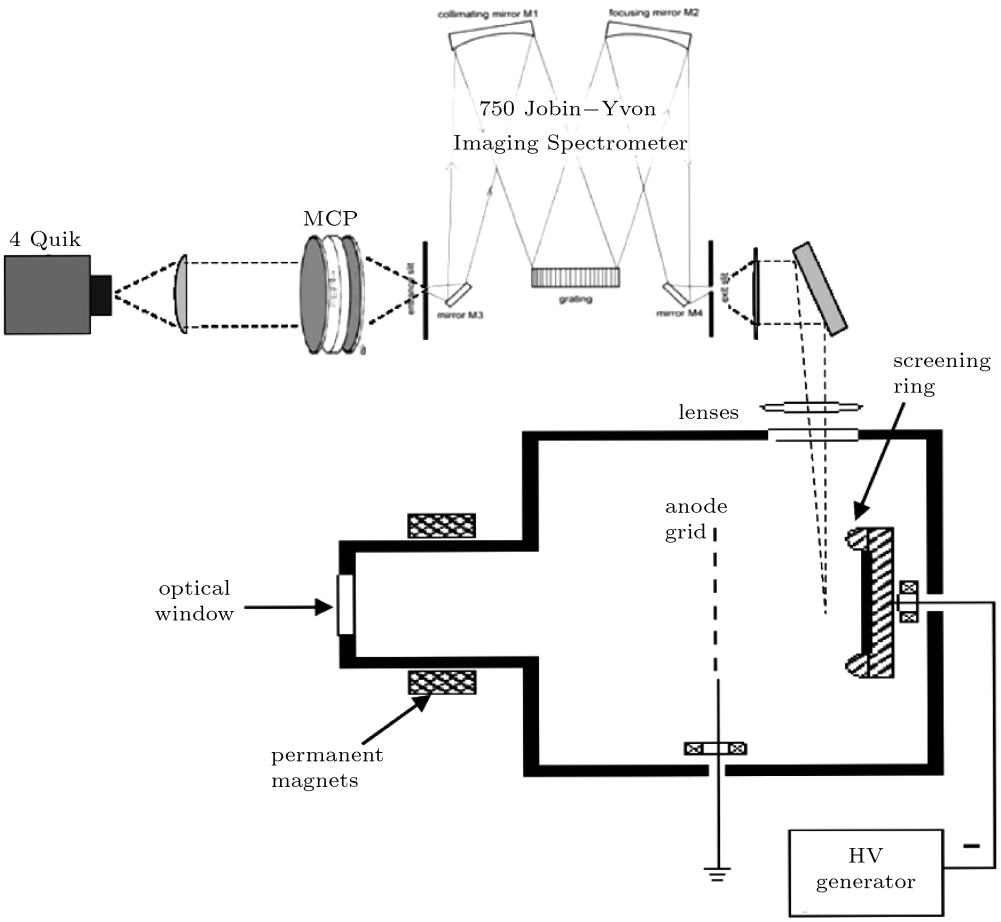


Fig.1. Experimental setup.

The diode was operated at 40–90 kV/cm electric fields. A 140 mm diameter stainless-steel grid with 70% transparency was used as an anode. The anode-cathode (AK) gap d_{ac} was varied within the range of 10–50 mm. The diode was placed inside a vacuum chamber of 50 cm diameter and 55 length. Diode vacuum of $\sim 1\times10^{-5}$ Torr (1 Torr=133 Pa) was achieved by two Edwards rotary pumps and two turbomolecular pumps. The diode was supplied by a high voltage generator with output voltage up to 300 kV, pulse duration of $\sim$ 300 ns, and impedance of 84 Ω. The experiment was run in a single pulse regime of the generator. The diode voltage φ_{ac} was measured by an active voltage divider, and cathode current I_c was registered by a self-integrated Rogowsky coil.

The spectroscopic diagnostics of the plasma light emitted by carbon fiber cathode were carried out by using a 750 mm Jobin–Yvon spectrometer (2400 grooves/mm grating and spectral resolution of $\sim$ 0.1 Å/pixel) (1 Å=0.1 nm). The light collection was made through a Plexiglas window (see Fig.1). A light transmitted through the window was focused on a 20 mm-height and 0.1 mm-width entrance slit of the spectrometer by an achromatic lens of 5 cm in diameter and 15 cm in focal length. A Jobin–Yvon spectrometer was used to study the spectral line profiles. The spectral line images at the output window of the spectrometers were recorded by the fast-framing camera 4Quik05A. In these experiments the frame duration was varied in the range of 50–400 ns. The duration of the frame was determined by the flux of light which was necessary to collect in order to obtain a reliable spectral line profile. The spectral dispersion and the instrumental full width at half maximum (FWHM) of the spectral lines in the range of 3000–6600 Å were calibrated by Oriel spectral lamps, and the relative spectral sensitivity of the Chromex-4Quick05A camera system was calibrated by using a tungsten light source.

3. Results and analysis

Figure 2 presents the comparison of the diode voltage, cathode current, and diode perveance for carbon fiber cathode with and without CsI coating. In Fig.2(a), one can see that the major difference in the voltage waveforms in two cases is in the voltage pulse duration. For the coated cathode, the voltage pulse duration was slightly increased relative to the case of the uncoated cathode. Moreover, the voltage waveform for the CsI-coated carbon fiber cathode had an obvious flat top of $\sim$ 200 ns. Namely, the diode voltage of the coated cathode remains unchanged for a longer time than that of the uncoated cathode, potentially indicating the lack of a fast diode closure. One common feature for two cases is that the voltages reached amplitudes exceeding 200 kV and shared almost the same rise front. Additionally, relative to the uncoated cathode, the coated cathode had a shorter time for diode voltage to reach its maximum value, this fact demonstrates a faster cathode turn-on or electric field establishment by CsI coating. Since CsI is a good x-ray emitter with a low first ionization potential, such a low turn-on electric field may not be too surprising.

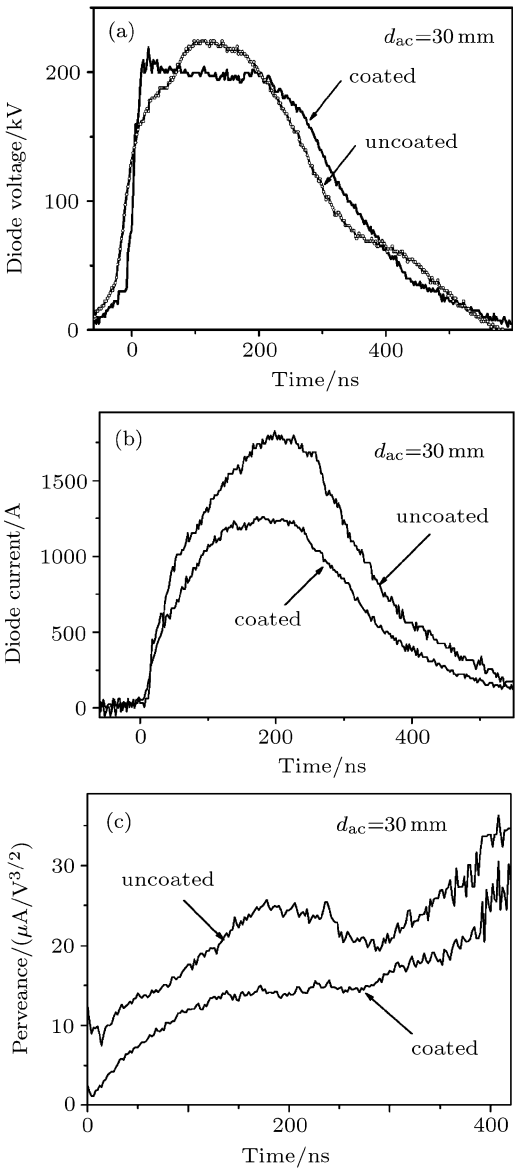


Fig.2. Comparison of the accelerating voltage φ_{ac}, cathode current I_c, and diode perveance P for carbon fiber cathodes with and without CsI coating. The A-K gap is d_{ac} = 30 mm.

One can see from Fig.2(b) that the difference in the diode currents for the coated and uncoated cathodes is in the range of maximum current. The maximum currents for the bare and CsI-coated carbon fiber cathodes reached 1.8 kA and 1.2 kA, respectively. It should be pointed out that the beam current from the CsIcoated cathode is lower in spite of the fact that the amplitude of diode voltage is almost the same as the case of the CsI-coated cathode. The total current is closely related to the emission area and the current density. The larger amplitude of the total current is possibly due to a larger emission area and/or to a higher current density. Since the CsI-coated cathode has a lower turn-on electric field than that of the uncoated cathode, the CsI-coated cathode should have a larger emission area. Thus, a high current density is responsible for a large total beam current. The beam current density, for space-charge limited emission, is determined by the well-known Child–Langmuir law $j_{\mathrm{e}} = \dfrac{4\varepsilon_0}{9}\sqrt{\dfrac{2e}{m_{\mathrm{e}}}}\dfrac{\varphi_{\mathrm{ac}}^{3/2}}{d_{\mathrm{ac}}^2}$. Thus, at the same diode voltage the change of the diode gap d_{ac}, as a result of cathode plasma expansion toward the anode, is an important factor affecting the current density. For the CsI-coated cathode, a low beam current likely indicates a slow cathode plasma expansion or even an almost unchanged diode gap.

Figure 2(c) shows the perveance evolutions $P(t)$ for the bare and CsI-coated cathodes at $d_{\mathrm{ac}} = 30$ mm. In each case, one can see a fast increase in the diode perveance at the delay time of $\tau_{\mathrm{d}} < 100$ ns with respect to the beginning of the accelerating pulse. The diode perveance quickly increased mainly due to an increase in the emission area S_{e} as the cathode is turning on. As the accelerating pulse proceeded, a "plateau" in the temporal dependency of diode perveance was observed in the case of the coated cathode. However, such a behavior is absent in the case of the uncoated cathode, and the diode perveance significantly exceeded that for the coated cathode, for which the high beam current is responsible. A quasistationary behavior of the diode perveance for the coated cathode strongly demonstrates a slow cathode expansion. After the stable stage of the CsI-coated cathode, the diode perveance continued to increase at $\tau_{\mathrm{d}} > 300$ ns, probably because of the appearance of the anode plasma. Once the anode plasma forms as a result of the bombardment of high-current electron beams, the space-charge limited current is developed into a bipolar flow. Thus, the plasma expansion is the combination of cathode and anode plasma movements, rather than pure cathode plasma expansion. Although the anode conditions (materials and transparency) and the initial A-K gap are identical for each case, the CsI-coated carbon fiber cathode can still exhibit the advantage of slow plasma expansion. Therefore, CsI coating can still enable the decrease in the plasma expansion velocity, this fact suggests a possibility of long-pulse electron beams.

The parameters of the plasma produced at the surface of the CsI-coated carbon fiber cathodes (plasma electron density n_{e} and temperature T_{e}, plasma ion temperature T_{i}, and plasma axial expansion velocity v_{p}) were obtained by nondisturbing spectroscopic measurements and by comparison of the experimental data with the results of collision-radiative modeling[24] The broadening of the H_α and H_β spectral lines was used to determine the values of n_{e} and T_{e} of the cathode plasma. These measurements were carried out by using the 750 mm Jobin–Yvon spectrometer at $d_{\mathrm{ac}} = 30$ mm. At larger distances from the cathode, the H_β spectral line intensity decreases, which makes spectral line analysis rather uncertain. The Gauss profile results from the convolution of the Doppler spectral line broadening and the instrumental broadening of the apparatus. The Lorentz profile results from the spectral line broadening which is caused by the Stark effect due to the electric microfields of charged particles in the plasma. Here we assume that the Doppler effect plays a major role in the H_α spectral line broadening and that the Stark effect is more pronounced in the H_β spectral line broadening. The temperature obtained from the H_α spectral line profile is used in the calculation of the H_β spectral line FWHM and its fitting to the Voigt profile. Furthermore, the density obtained from the H_β spectral line Stark broadening is inserted into the calculation of the H_α spectral line FWHM and the fitting of this spectral line profile to the Voigt profile. From this step the recursion continues, up to the step when the change in the FWHM of both the H_α and H_β spectral lines becomes smaller than the spectral resolution. The plasma ion temperature was determined as[25] $T_{\mathrm{i}} = 1.8 \times 10^8(\Delta\lambda_D/\lambda$ (eV), where λ_α is the wavelength of H_α and $\Delta\lambda_D$ is the Doppler broadening of the H_α spectral line. The plasma electron temperature was determined by a comparison between the measured $\mathrm{H}_\alpha/\mathrm{H}_\beta$ spectral line intensity ratio and the results of the collision-radiative modeling.

Hydrogen (H_α, H_β) and carbon (C I, 2478.56 Å; C II, 4267.3 Å; C III, 4255.4 Å) spectral lines were observed at $j_e \approx 40$ A/cm^2 (see Figs.3 and 4). In addition, the Cs II 4603.79 Å spectral line was observed in the vicinity of the cathode surface, in the case of CsI coated cathode (see Fig.3(c)). The Cs II was obtained only at the distance ≤ 0.5 mm from the cathode surface. Carbon and hydrogen ions were obtained up to the distance of 2.5 mm from the cathode surface. The H_α/H_β intensity ratio measured by the Chromex spectrometer in the vicinity of the cathode surface was found to be ~ 1.6 for $d_{ac} = 30$ mm. An analysis of the H_α and H_β spectral lines showed that in the vicinity of the surface $n_e \approx 4 \times 10^{14}$ cm^{-3}, $T_e \approx 5$ eV, and $T_i \approx 0.5$ eV for the CsI coated cathodes. The observation of the C and Cs ions in the vicinity of the carbon-fiber cathode is forceful evidence that the cathode material serves as a source for the plasma. This multicomponent plasma expands toward the anode with the velocity of the plasma lightest species, i.e., hydrogen. The plasma expansion velocity during the first 200 ns of the accelerating pulse duration was estimated as $v_p \approx 1.5$ cm/μs by using a time delay in the appearance of the H_β spectral line in the cathode vicinity and at a 5 mm distance from the cathode surface. Indeed, the above obtained expansion velocity corresponds to the carbon and hydrogen components of plasma within the diode gap. Surprisingly, Cs ions almost remain at the vicinity of the cathode surface.

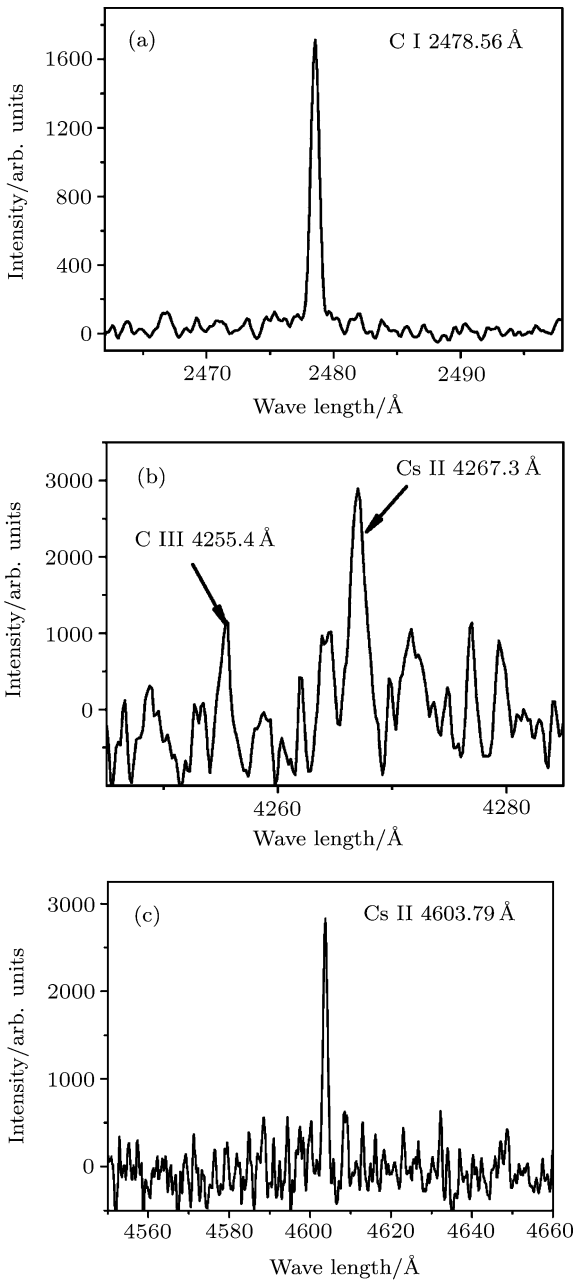


Fig.3. Carbon (C I, 2478.56 Å; C II, 4267.3 Å; C III, 4255.4 Å) and Cs II (4603.79 Å) spectral lines were observed at $j_e \approx 40$ A/cm^2.

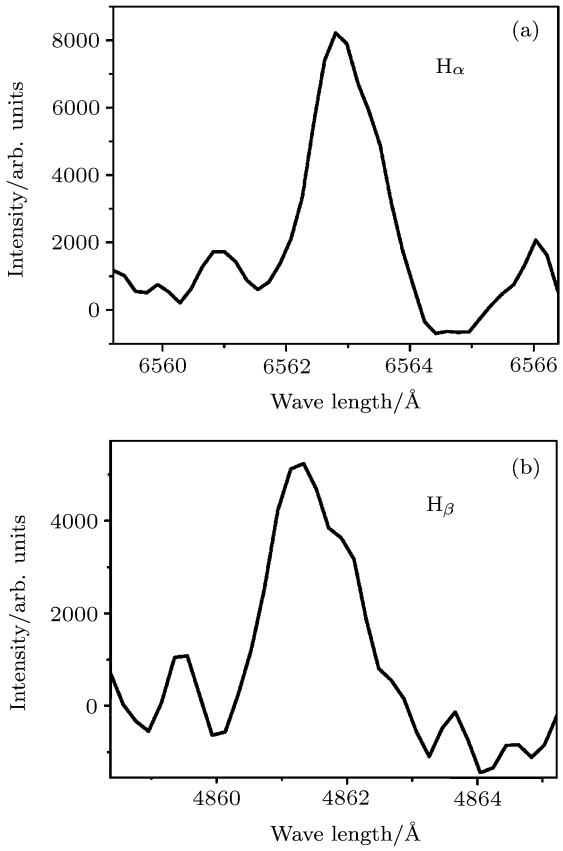


Fig.4. Hydrogen (H_α, H_β) spectral lines. The H_α/H_β population ratio and collisional radiative model determine the plasma electron temperature.

4. Discussion

The above results show that the CsI coating layers can not only improve the diode voltage, but also

maintain a stable perveance. This indicates a slowly changed diode gap or a low cathode plasma expansion velocity. Since the vacuum environments, the bulk materials of the anode, and the applied electric field are almost the same for each case, these improvements of diode characteristics mostly stem from the addition of CsI salt. By spectroscopic diagnostics, in the vicinity of the cathode surface the average plasma density and temperature were found to be $\sim 3\times10^{14}$ cm^{-3} and $\sim$ 5 eV, respectively, for an electron current density of ~ 40 A/cm^2. Further, there existed a multicomponent plasma expansion toward the anode. The plasma expansion velocity, corresponding to the carbon and hydrogen ions, was estimated to be $\sim$ 1.5 cm/μs. Most notably, Cs II was obtained only at the distance $\leq$ 0.5 mm from the cathode surface. Carbon and hydrogen ions were obtained up to the distance of 2.5 mm from the cathode surface. The Cs ions almost remain at the vicinity of the cathode surface.

What ions determine $v_{\rm p}$ is a key issue in understanding the above effect. Fortunately, the expansion velocity $v_{\rm p}$ had been suggested as[26] $v_{\rm p} = \dfrac{2}{\gamma-1}\sqrt{\dfrac{\gamma kT_{\rm i}}{m_{\rm i}}}f(n_{\rm e1}/n_{\rm e0})$. Here γ is the ion polytropic exponent, k is the Boltzmann constant, $T_{\rm i}$ is the ion temperature, and $m_{\rm i}$ is the ion mass. The $f(n_{\rm e1}/n_{\rm e0})$ is the function of the reduced concentration of cathode-flare peripheral layers. Obviously, the light elements in neutral gas are leading contributors to the plasma expansion. Thus, high concentrations of these light elements are deleterious to the generation of long-pulse electron beams. Most HPM source experiments have not had wall cleanliness sufficient to prevent the plasma within the diode or interaction region from forming by explosive emission. The surface layer of water and hydrocarbons is disassociated into hydrogen and other light elements. Therefore, the lightest, fastest atoms probably determine the plasma expansion velocity.

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