“POINT” X-RAY SOURCE ENGENDERED BY HOT SPOTS IN A HIGH-CURRENT DISCHARGE

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Abstract

The hot spots occurred in high-Z plasma of high current vacuum discharges are the bright sources of EUV and soft x-rays [1]. A thorough study of discharge dynamics and radiation performance of a vacuum spark was carried out [2-4]. The experimental model of industrial EUV/x-ray source was designed and tested [5], and its application for x-ray lithography and x-ray microscopy was examined. The experiments show that the hot spot is a high-density, high-temperature plasma configuration caused by “neck” formation in the discharge plasma and subsequent compression of the neck pinch, apparently because of the radiative losses from the compressing plasma [6]. Eventually, one or several high-density “micropinches” are formed in the neck, which emit a burst of soft x-rays generated by the highly ionized atoms mostly in the form of line radiation. The micropinch size displayed by the radiation near 1 keV is 40×150 µm^2; usually it decays into several spots of 3×10 µm^2 recorded in radiation above 4 keV. The x-ray output from a single micropinch is \( \sim 10^{15} \) W/cm^3 sr in a spectral band of 0.5-1.5 keV. The details of neck evolution are discussed and the limiting conditions of micropinch occurrence are outlined. The experimental data are compared with the computer simulation of high-Z plasma compression allowing for radiative losses [6].

I. INTRODUCTION

The hot spots formed in a vacuum spark were observed experimentally since the 60’s [1]. The plasma temperature of 1-2 keV and density of \( 10^{22} - 10^{23} \) cm^3 were measured [7]. The model of radiative compression of high-z pinch plasma was developed to depict the phenomenon [6]. The micropinches are the bright sources of soft x-rays. A vigorous study of plasma EUV/X-ray sources through the 80’s and 90’s (including the research [5]) was triggered, in particular, by a possibility to develop a promising means for integrated circuits production with the patterns of 50-70 nm using x-ray lithography. The objectives of this work were to: study the low-inductance vacuum spark with a variety of diagnostics, compare the experimental data with the theoretical model, and demonstrate its applicability for a number of applications. The recent experiments of the ALFT, Inc. (Canada) and the results of the Lebedev Physical Institute (LPI, Russia) are summarized here.

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II. EXPERIMENTAL SET-UP AND RESULTS

A. Vacuum spark

The discharge chamber schematic was described in [5]. Two devices based on a vacuum spark were tested: the ALFT x-ray source VSX-H1 (capacitance C = 2 and 3 µF, U = 10 – 15 kV, circuit inductance L = 32 nH, bank energy E = 0.1 and 0.3 kJ) and the LPI X-ray source (C = 4 and 5 µF, U = 15 kV, L = 40 nH, E = 500 J). Current-rise time to the peak value of 70 and 130 kA was 0.4 (0.5) and 0.7 µs. A steel or copper anode wire 1.2 mm in diameter was fixed in a massive anode holder protruding 3 – 6 mm out of it. The hot spots formed in the discharge plasma near the anode tip emitted the intensive bursts of x-rays, in particular, the radiation near 1 keV (line radiation of L-shell ions of iron or copper) commonly considered appropriate for proximity x-ray lithography.

B. Current I and dI/dt

Current derivative dI/dt was recorded with a magnetic probe (coil) placed in the coaxial part of the discharge chamber. To measure I(t) a low inductance circular shunt consisting of 300 resistors was installed in the back-current frame of the LPI discharge chamber. Time resolution of the dI/dt probe and the shunt was measured 5 ns and 10 ns, respectively, with an accuracy of 6%.

C. X-ray dosimetry

The following detectors were used to measure the radiant energy: a) calibrated x-ray film with a set of filters; b) radiochromic film; c) calibrated polymer resist; d) 9-channel thermoluminescent dosimeter (TLD) with a set of x-ray filters to measure the energy distribution in a spectral band between 0.5 keV and 10 keV [5]; e) Wilson cloud chamber [8] to record the x-rays in a spectral band between 1 keV and 10 keV (it was combined also with the x-ray spectrometer to measure the intensity and relative position of the x-ray lines in a single shot); f) calibrated scintillation dosimeter shielded by a 15-µm Be filter or a 100-µm Be filter to monitor the x-ray energy emitted in the spectral bands hν > 0.7 keV and hν > 3 keV, respectively; and g) calorimeter to measure the emitted energy in IR, visible, EUV, and x-ray spectral bands. A summary of the measurements is given in Table 1.
Table 1. Radiant energy (J) in different spectral bands.

<table>
<thead>
<tr>
<th>Method of measurement</th>
<th>Total spectrum</th>
<th>λ &gt; 200 nm</th>
<th>hv &gt; 0.5 keV</th>
<th>hv &gt; 3 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray film</td>
<td>--</td>
<td>--</td>
<td>2</td>
<td>10^3</td>
</tr>
<tr>
<td>Radiocromic film*</td>
<td>--</td>
<td>--</td>
<td>0.5-0.7</td>
<td>--</td>
</tr>
<tr>
<td>TLD</td>
<td>--</td>
<td>--</td>
<td>3-10</td>
<td>2×10^5</td>
</tr>
<tr>
<td>Cloud chamber</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>5×10^5</td>
</tr>
<tr>
<td>Scintillation dosimeter</td>
<td>--</td>
<td>--</td>
<td>5</td>
<td>10^2</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>60</td>
<td>10</td>
<td>4</td>
<td>5×10^4</td>
</tr>
</tbody>
</table>

*Measurements were performed with the ALFT discharge chamber (circuit parameters: C = 2 and 3 μF, L = 32 nH, E = 100 J and 300 J). All other data were obtained with the LPI discharge chamber (C = 5 μF, L = 40 nH, E = 500 J).

D. X-ray pinhole cameras

Two cameras were used: a) 70-μm pinhole covered with the 8-μm Be filter (hv > 0.5 keV), and b) camera with two pinholes: 10-μm pinhole with 20-μm Be filter (hv > 0.8 keV) and another 10-μm pinhole with 400-μm Be filter (hv > 4 keV). The spatial resolution of the second camera was measured as 5 μm. The x-ray images (micropinches) are shown in Fig. 1a, b; the image obtained with the first camera in a series of 80 shots is shown in Fig 1 c. In another series of experiments a 1-μm polyimide filter coated with 0.15-μm Bi layer (transparency window between 5 and 10 nm) was used (Fig. 1 d).

Figure 1. Pinhole images: a) 10-μm pinhole with 10-μm Be filter (left) and the same image with 400-μm Be filter; b) negative image of a micropinch with a 70-μm pinhole and 8-μm Be filter (ALFT); c) x-ray source image in a series of 80 shots (ALFT); and d) 10-μm pinhole with a 0.15-μm Bi filter (hv > 0.1 keV), five shots exposure.

The low temperature (50-100 eV) plasma (n_e~10^{21} cm^{-3}) produces the image in Fig.1d; the “neck” formed near the anode tip is visible completely (subsection F). The micropinches emitting radiation near 1 keV (Fig.1a, left) contain plasma of higher temperature (~ 100 – 300 eV) and higher density. They decay into several smaller spots (~ 10 μm) in radiation above 4 keV. The spectroscopically measured plasma parameters are: electron density n_e ~ 10^{23} cm^{-3} and temperature of 1.5 – 2 keV [7]. The micropinch changes its location from shot to shot within the anode neck. Superposition of micropinches results in the effective source size in a series of shots of 0.7 mm in diameter and 1.3 – 1.5 mm in length (Fig.1c, see also [5]). A contour of the anode surface emitting Kα radiation is visible in Fig.1c below the plasma source.

E. X-ray spectroscopy

Two Bragg spectrographs were used to record the X-ray spectra: a) LiF crystal, 27.35° Bragg angle, 300 mm radius, spectral band 1.4 – 2 A, and b) mica crystal, 34.2° Bragg angle, 500 mm radius, spectral band 10 – 13 A. The Wilson cloud chamber [8] detected the x-ray spectra in a single discharge (Fig. 2 a-d). The transmission grating spectrograph was also used to survey the spectrum between 0.1 keV and 1.2 keV [5].

Figure 2. X-ray spectra in a spectral band between 0.15 nm and 0.2 nm recorded with the Wilson cloud chamber coupled with the x-ray spectroscope (steel anode). No micropinch was recorded with the pinhole camera (top, left); micropinch image was recorded only in 1 keV radiation of the L-ions (bottom, left); micropinches were recorded both in radiation of L-ions and K-ions (Fig.1a) (right, top and bottom).

The micropinch is the result of dynamic plasma compression, so that the delay between the pulses emitted in the different spectral bands (lines) can provide evidence in favor of one or another theoretical model. The chosen lines and bands for time resolved spectroscopy were: 1) resonant line of He-like iron, 2) Kα, 3) Kα high-energy edge consisting of the characteristic lines of Fe XV – FeXX ions, 4) doublet 2p⁵ (S_1) – 2p³ 3s (P_1) and 2p⁵ (S_2) – 2p⁵ 4d (D_1) of neon-like iron, 5) spectral bands hv > 25 keV and hv > 100 keV. The PMT signals were recorded with a 6-channel oscilloscope (1-ns resolution). Because of the jitter of relative positions of the signals from shot to shot, the data of 100 shots were averaged in histograms, and statistically averaged mutual shifts were determined [4] (the leading edge of the He-like resonant line pulse was chosen as t = 0). The high-energy wing of Kα radiation (Fe XV – Fe XX) correlates to the neon-like ion emission at t =
- 1.5 ns; the thermal radiation [1] in a spectral band \( h > 25 \text{ keV} \) correlates to the He-like ion emission at \( t = 0 \); the nonthermal radiation [1] \( h > 100 \text{ keV} \) correlates to the beginning of \( K_\alpha \) radiation at \( t = -3 \text{ ns} \). The x-ray diode (0.1-ns resolution) was also used to measure the x-ray pulse in a spectral band near 1 keV (\( t_p = 3 - 5 \text{ ns} \)).

**F. Laser diagnostic**

The 5-frame laser shadowgraphy was developed to study dynamics of the discharge plasma [4] with 1.5-ns exposure time per frame and 20-ns delay between the frames. To measure electron density, magnetic field and current distribution in the pinch, laser interferometry was used together with the Faraday rotation method [2]. Three 2-ns-exposure images of the discharge plasma were recorded simultaneously: interferogram, faradaygram and shadowgram (Fig. 3), delayed with respect to the discharge beginning. The radial distributions of the measured parameters are shown in Fig. 4. The distributions of the linear electron density \( N_e(z) \) along the discharge axis are also given in Fig. 5.

**Figure 3.** Faradaygrams (top), shadowgrams, and interferograms (bottom) of a vacuum spark discharge at: a) 200 ns after the discharge start, b) 300 ns, and c) 400 ns. The anode is at the bottom of each frame. The arrows mark location of the developing necks near the anode tip and near the cathode. Frame size: 1.2×1.2 cm².

Initial diameter of plasma column is \( 1.5 \text{ cm} \). The anode neck forms near (1 mm) the anode tip (minimum initial radius); the micropinch X-ray images occur in the anode neck mostly. The cathode neck is formed, apparently, in the cross-section of minimum plasma density per unit length (Fig. 5). The maximum neck compression occurs near \( t=400 \text{ ns} \) (Fig.3c). The neck pinch is compressed to a radius of 100 \( \mu \text{m} \). Electron plasma density and temperature in the neck are \( n_e \sim 10^{21} \text{ cm}^{-3} \) and 50-100 eV respectively. The neck pinch is subjected to \( m=0 \) (sausage) and \( m=1 \) (snake) MHD instability. The first one causes the sub-neck formation (1-5) on the neck pinch (Fig. 6a), and the pinhole micropinch images are associated with these sub-necks. The snake instability causes the radial shift of the neck pinch (Fig.6b) deviating the micropinches from the axis and inclining them with respect to the z-axis (Fig.3a) resulting in hot spot jitter from shot to shot and source effective size increasing in a series of shots (Fig. 1c).

**III. DISCUSSION**

After discharge ignition the trigger plasma and the plasma cloud evaporated from the anode surface by the electron flux from the trigger plasma (accelerated in the applied electric field) fill the anode-cathode gap. The initial plasma column of 1.5-2 cm begins pinching by the magnetic field at a moment of 150-200 ns after the discharge start when the current achieves 30 kA. The plasma column shrinks as a whole with two regions shrinking much faster. One is near the anode tip, where the initial radius is minimum, and the other further to the cathode, apparently at the cross-section of minimum linear density (mass). Two necks are formed normally with micropinches occurring chiefly (>90%) in the anode neck. It should be noted, that the necks form because of the initial condition; they are not caused by MHD instability. The neck/micropinch evolution was described by the model [6]. The “zero-dimensional” approximation describes the pinch compression by \( d(N_i, \rho, dt)/dt = -I^2/c^2r \), where \( N_i \)
yields \( \frac{dr}{dt}/r = \frac{c}{2I}\sqrt{J(1 – Q_{\text{loss}}/Q_j)} \), where \( Q_j \) is the equation of energy balance has to be added [6], that plasma temperature. To determine the equilibrium radius, and one-dimensional modeling of the radiation absorption. Computer simulation of the pinch is formed with \((1+Z)N_iT = I^2/c^2\), where \( T \) is the plasma temperature. To determine the equilibrium radius, the equation of energy balance has to be added [6], that yields \((dr/dt)/r = (c^2/2I)\sqrt{(1 – Q_{\text{loss}}/Q_j)}\), where \( Q_j \) is the Joule heating per unit length and \( Q_{\text{loss}} \) is the energy losses from the pinching plasma including ionization loss, enthalpy loss due to plasma axial blowoff, and radiative loss \( Q_r \). The equilibrium radius corresponds to \( Q_r = Q_{\text{loss}} = Q_j \) for plasma consisting of the high-Z ions allowing for radiation absorption. Computer simulation of the equilibrium radius and one-dimensional modeling of the neck compression in iron plasma were performed in [6]. It was shown that the 1-mm-length neck shrinks to a radius of 100 \( \mu \)m; then the neck pinch evolves to a region of \( 10^{15} < N_i < 10^{19} \) cm\(^{-3} \) due to axial blowoff, where the equilibrium radius decreases to \( \approx 2 \) \( \mu \)m on the condition that plasma current exceeds 70 kA. Hence, the neck shrinks in two stages: 1) MHD compression to the equilibrium Bennett radius \(~ 100 \) \( \mu \)m and 2) formation of micropinch with a radius of several microns. The second compression occurs if: 1) discharge current exceeds 70 kA, and 2) linear ion density in the neck \( > 10^{16} \) cm\(^{-3} \). The experimental data and the calculated parameters [6] are compared in Table 2. Now one can fathom why the hot spots appear mostly in the anode neck. The anode neck forms in the region of high linear mass \( N_i > 10^{16} \) cm\(^{-1} \), so that it has relatively higher chance to shrink to the equilibrium radius at \( N_i > 10^{16} \) cm\(^{-1} \) and then evolve to the region where the micropinch can occur. The cathode neck forms in the region of minimum linear mass \( N_i < 10^{17} \) cm\(^{-1} \) and ends at \( N_i < 10^{15} \) cm\(^{-3} \) apparently missing a chance to produce the micropinch. Two experimental facts are inconsistent with the model: a) the current in the neck is much smaller then the discharge current [2] and b) polarization of the K-ion lines indicates a significant impact of the nonthermal electrons [10]. The effect of non-thermal electron generation, movement, and modified runaway can explain both inconsistencies [11].

### IV. SUMMARY

The micropinch x-ray source based on a vacuum spark was studied with a set of x-ray and laser diagnostics. Comparison of the experimental data with the computer simulation indicates that the radiative compression model of neck evolution is adequate to describe the experiment. The radiant energy emitted from the hot spots achieves \( 0.5 – 0.75 \) J/shot for 100-Joule machine and \( 5 \) J/shot for 500-Joule machine with \( 0.5 – 1 \) % conversion efficiency. Because of its small size (\( 0.7 \times 1.5 \) mm\(^2 \)) and high efficiency the source can find numerous applications, in particular for x-ray microlithography and microscopy [5].

### V. REFERENCES