The influence of the conditions of laser initiation on soft X-rays emission of vacuum spark

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Abstract. For exploring the influence of the conditions of laser initiation on soft x-ray emission of the laser-triggered vacuum spark we performed a series of experiments under different conditions of the laser beam focus on the cathode(anode) of the discharge system.

1. Introduction
The emission of soft x-ray radiation from vacuum spark discharge under the focusing of a laser pulse on the cathode is the subject of many publications [1-4] and recently the theoretical model of such a discharge was developed [5]. What caused our interest to the laser initiation of vacuum spark discharge under the focusing of the laser beam on the anode? Experiments have shown that the principal role for the dynamics of the development of the vacuum discharge plays the position of the focal point of the laser beam at the vertex of the cone-shaped electrode. A series of comparative experiments with different polarity electrode irradiated by laser and different positions of a focal point of laser radiation was conducted. Depending on the focus of the laser on the cathode or the anode of the discharge system, we say, respectively, about the cathode or the anode laser-initiated discharge.

2. Experimental setup
The scheme of the experimental setup is shown in figure 1[6].

Figure 1. Figure a - the arrangement of the elements of the discharge system in the vacuum chamber: 1) the area of the discharge; 2) anode (cathode); 3) cathode (anode); 4) optical lens; 5) two identical pin-diodes with K-edge filters; 6) capacity bank C=0.22 µF. Figure b-detailed area of spark discharge.
The experimental setup consists of a vacuum interaction chamber (pressure $P \approx 10^{-5}$ Torr), a high-voltage discharge system, initiating Nd: YAG laser ($\lambda=1.06 \, \mu\text{m}$, the pulse energy $E_{\text{laser}}=30\text{–}60 \, \text{mJ}$ and pulse duration $\tau\approx15 \, \text{ns}$) and the diagnostic system. In turn, the high-voltage discharge system consists of conical electrodes, low inductance capacitor bank (capacitance $C=0.22 \, \mu\text{F}$), high voltage DC ($U=10\text{–}15 \, \text{kV}$). The electrodes are made from iron. The gap between the electrodes $d_{AC}=5.3 \, \text{mm}$. The distance from the focus point of the laser beam to the top of the cone-shaped electrode $d=0.1\pm1.1 \, \text{mm}$ (see figure 1b). The size of the focusing spot of the laser radiation $D_f=100 \, \mu\text{m}$. Two identical pin-diodes with a matched pair of $K$-edge filters (Al $– 9 \, \mu\text{m}$ and Mg $– 17 \, \mu\text{m}$) were applied for the registration of soft X-ray radiation. They were placed inside the vacuum chamber at the distance of 20 cm from the discharge area.

3. Experimental results

The following are the results of a series of comparative experiments in order to determine the influence of laser focus settings for initiating of a vacuum spark x-ray emission. Figure 2 shows the oscillograms of signals from the soft x-ray pin-diodes for $d=0.1 \, \text{mm}$. In both cases the magnitude of the stored energy $E_c=18.1 \, \text{J}$ at voltage $U_c=12.8 \, \text{kV}$.

![Figure 2. Oscillograms of signals of x-ray pin-diodes at $d=0.1 \, \text{mm}$: a – cathode discharge; b – anode discharge. The magnitude of the stored energy $E_c=18.1 \, \text{J}$ at voltage $U_c=12.8 \, \text{kV}$.

Figure 3 shows the results of processing of a series of signals from pin-diodes for the condition $d=0.1 \, \text{mm}$.

![Figure 3. Integral emission of the soft X-ray of the vacuum spark plasma when $d=0.1 \, \text{mm}$: a – cathode discharge; b – anode discharge. The magnitude of the stored energy $E_c=18.1 \, \text{J}$ at voltage $U_c=12.8 \, \text{kV}$.

Here $N_{f,m}$ are values of integral over the duration of soft x-ray pulses are registered by the pin-diodes with Al ($m=1$) and Mg ($m=2$) $K$-edge filters. The magnitudes $N_{f,m} \, (m=1,2)$ are proportional to the number of quanta of soft x-ray. There are about 60 pulses in each experiment for a given polarity.
Figure 4 shows the oscillograms of signals from the x-ray pin-diodes for \( d \approx 1.0 \) mm.

![Oscillograms of signals from x-ray pin-diodes](image)

Figure 4. Oscillograms of signals of x-ray pin-diodes at \( d \approx 1.0 \) mm: \( a \) - cathode discharge; \( b \) - anode discharge. The magnitude of the stored energy \( E_c = 18.2 \) J at voltage \( U_c = 12.9 \) kV.

Figure 5 shows the results of processing of a series of signals from the x-ray pin-diodes for \( d \approx 1.0 \) mm.

![Integral emission of soft X-ray](image)

Figure 5. Integral emission of soft X-ray of the vacuum spark plasma when \( d \approx 1.0 \) mm: \( a \) - cathode discharge; \( b \) - anode discharge. The magnitude of the stored energy \( E_c = 18.2 \) J at voltage \( U_c = 12.9 \) kV.

Experiments showed that for the cathode discharge for any values \( d \) temporal and spectral characteristics of the soft x-ray emission are approximately preserved. These characteristics differ only in the amplitude of the signals, most likely due to the instability of the laser radiation (see figure 3a and figure 5a). With increasing the distant parameter \( d \) the delay duration of the anode discharge initiation increases about 3-10 times. From figure 3 it can be seen that when \( d \approx 0.1 \) mm the plasma anode discharge emits of soft x-ray significantly weaker than the plasma cathode discharge. When \( d \approx 1.0 \) mm the soft x-ray emission is comparable for both cases (figures 5a,b for 9 \( \mu \)m Al filter).

In Table 1 provides the estimates of the average values \( \langle N_{f_m} \rangle \) (\( m=1,2 \)) for the various experimental conditions of the vacuum spark initiation. Using the data from the right column Table 1 and the algorithm proposed in [Vovchenko E D, Melekhov A P 2016 The spectrum simulation of the soft x-ray for vacuum spark with laser initiation Journal of Physics: Conference Series (to be published)] we make simulation of the soft x-ray spectra for the cathode discharge and the anode discharge. Figure 6 shows the simulated spectra of the soft X-ray of the vacuum spark plasma for \( d \approx 1.0 \) mm. Spectra of vacuum spark was simulated for the electron temperature of the plasmas \( T_e < 1000 \) eV. In figure 6b we see the emergence of a strong, presumably, L-shell series of characteristic radiation of Cu and Zn ions in range \( \varepsilon_{x-ray} = 1200 \div 1800 \) eV. It can be seen that bremsstrahlung and K-series radiation are more intensive in the case of the cathode discharge in figure 6a. Given simulations spectra of soft x-ray are correct for the spectral range \( 500 \leq \varepsilon_{x-ray} \leq 2000 \) eV.
Table 1. Estimates of values $<N_f_m>$ (m=1,2).

| Conditions of the experiment | $<N_{f1}>$ (the average value for Al filter) | $<N_{f2}>$ (the average value for Mg filter) | $<N_{f1}>/<N_{f2}>$ (the ratio of the average values $N_{f1}$ and $N_{f2}$) |
|-----------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| d=0.1 mm, cathode discharge (Figure 3a) | 770 | 700 | 1.1 |
| d=0.1 mm, anode discharge (Figure 3b, for range of index pulses 20-42) | 150 | 90 | 1.67 |
| d=1.0 mm, cathode discharge (Figure 5a) | 2540 | 2390 | 1.07 |
| d=1.0 mm, anode discharge (Figure 5b) | 2520 | 1000 | 2.52 |

Figure 6. The simulated soft x-ray spectra of the vacuum spark plasma for $d$=1.0 mm: a - cathode discharge; b - anode discharge. The magnitude of the stored energy $E_c$=18.2 J at voltage $U_c$=12.9 kV. Also on the figures are shown the transmission spectra of Al and Mg film filters. The inset on figure 6b shows the full spectrum of anode discharge.

It is obvious that the significant role in the dynamics of the development of the discharge plays the presence of strong inhomogeneous external electric field. In the case of the anode discharge the electric field will slow the discharge initiating electrons. Almost all of electrons remain near the anode because the electron temperature of laser plasma is $T_e \leq 30$ eV.

The authors suggest that the defining role for the start of the development of the anode discharge play the stimulated field-emission of electrons from the cathode [8]. This electron emission is initiated by the radiation, ions, neutrals and neutral particles (droplets) from the laser plasma (anode).

4. Conclusions
In the case of the anode discharge the change of the position of the laser beam focus in relation to the edge of the electrode ($d$=0.1 mm up to $d$=1.0 mm) leads to the significant change of temporal and spectral characteristics of a vacuum spark. Currently some important details of the mechanism of formation of the anodic discharge are not well understood. For explaining the experimental results it is necessary now to develop an adequate model of discharge incorporating the distant parameter $d$.

References
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