DYNAMICS OF EUV-RADIATION FROM THE PARTIALLY CONTRACTED PLASMA DIODE

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The possibility of forming the directional plasma extreme ultraviolet (EUV) radiation under the partial contraction of the current channel by the dielectric insert in a high-current plasma diode is studied. The discharge characteristics and their impact on the dynamics of the radiation in the wavelength range of 12.2…15.8 nm are studied. The input efficiency of energy in the discharge is higher one in the case of partial contraction of the current channel by the dielectric insert which leads to an increase of the EUV-radiation intensity.

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INTRODUCTION

Nowadays, the powerful plasma radiation sources in the extreme ultraviolet range (EUV-radiation) are intensively developing for nanotechnology [1]. The input power in such devices achieves up to 500 kW for the output power of about 500 W! The low efficiency of system is explained, first of all, by the low conversion efficiency of the input energy into the radiation energy. The other reason is the impossibility (caused by the design features) to collect the all plasma radiation by the first collecting mirror. (Generally speaking, the limiting conversion efficiency is restricted by the value of 2.6% and the solid angle of the radiation collection is 3…4 steradian). To improve the efficiency of such system it is preferable to use the directional radiation source based on the high-current plasma diode [2]. In this case it is possible to achieve a higher output power for the same conversion efficiency and the optimal location of collecting mirror with equal area The principal moment of the directional radiation generation in plasma diode is a high density of the discharge current (up to 1.0 MA/cm^2) that is provided by minimization of the electrode working surface using the dielectric insulation. In the case of the plasma diode with rapidly rotating (for cooling) non-insulated disk electrodes it is difficult to receive such current densities because of the plasma expansion along the electrode surface. In this paper, the possibility to obtain the directional radiation for a system with non-insulated electrodes due to partial contraction of the current channel by short dielectric channel is studied. The channel is produced in the dielectric barrier that completely separates the discharge gap between two electrodes.

Because of the complexity of the system with rotating electrodes the experiments are carried out using the fixed electrodes.

1. SCHEME OF EXPERIMENT

The possibility to use the partial contraction of the current channel by the dielectric barrier for generating the directional EUV-radiation from the plasma of multiply charged tin ions is studied using a direct high current (up to 35 kA) pulsed low-pressure discharge ($P \sim 3\times10^{-6}$ Torr).

There are a dielectric insert ***D***, the tubular copper cathode with three igniters, the copper anode rod ***A*** and the coaxial current feeder in the discharge cell. The polarity of the electrodes change during the discharge, we refer to them as to the cathode and anode according to their polarity at the beginning of the discharge. Schematic illustration of the discharge cell is shown in Fig. 1. The discharge gap is completely blocked by a dielectric insert that has the shape of a glass cup with a hole in the center of ~ 2 mm in diameter. The cathode has a tubular configuration for extracting the radiation along the discharge. To localize the discharge between the electrodes, the length of the tubular cathode is 4 cm, and its outer and inner diameter are 1 cm and 0.8 cm, respectively. The cathode is fixed in the center of the cathode current-carrying flange 1. The diameter of the rod electrode is 0.5 cm. The lateral surface of the rod electrode is covered with ceramic insulator 2 and with protective ring 3. The protective ring with glass insert sets the current channel only through the central hole of the insertion. The cathode surface and the working anode end face is coated with pure tin layer of 0.05 cm in thickness. The distance between the cathode and the anode could vary within 3…10 cm by changing the length of the conductors 4. Conductors are located inside the glass insulators. The distance between the anode and the hole of the glass insert is varied in the range of 0.4÷0.6 cm. Discharge voltage is supplied to the electrodes by a coaxial feedthrough.

The discharge is excited between two electrodes coated with a tin layer after the pre-filling of the discharge gap by the primary plasma. The dense high-temperature plasma is produced by the pulsed evaporation of the electrode surfaces under the influence of the discharge. The powerful extreme ultraviolet radiation is observed in the inductive stage of the discharge as a series of short (100…200 ns) pulse peaks.

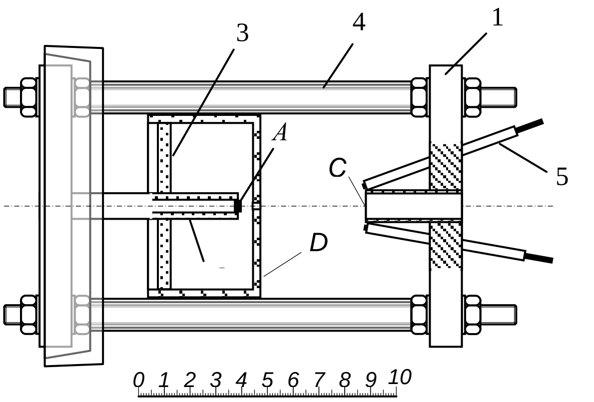

Fig. 1. Schematic of the discharge cell: A – a rod electrode (anode), C – a tubular electrode (cathode); D – a dielectric insert

2. EXPERIMENTAL RESULTS

In the experimental studies, the ability to generate directional EUV radiation in the plasma of multiply ionized tin atoms under the partial contraction of the current channel by the dielectric insert is demonstrated. The dynamics of the radiation (both integrated one and that in the wavelength range of 12.2…15.8 nm) as well as discharge characteristics are studied. Experiments reveal a number of features of the flow discharge at partial contraction of the current channel by the dielectric wall as compared with an identical uncontracted system. In the case of partial contraction of the current channel, processes change significantly in the high-voltage stage of the discharge. At a considerable distance to the holes, the dielectric surface is negatively charged and screen the electric field of the positive rod-shaped electrode. This reduces the penetration of the primary plasma to the rod electrodes. In this case, the applied discharge voltage can be either shifted to the rod electrode surface or delayed at the dielectric insert hole. But in both cases, the electron beam power is not enough for the intensive evaporation of the rod electrode surface material and the dense plasma formation. It is shown experimentally that the distance between the insertion hole and the rod electrode should not exceed 2…3 hole diameters. At large distances, the high-current inductive discharge is not excited. The stable discharge excitation is noted for the dielectric channel with a hole diameter of 0.2 cm, a channel length of 0.5 cm, and when the distance to the electrode end face is of 0.5 cm. Moreover, the high stability of the discharge from pulse to pulse is observed. The difference in the parameters under studying does not exceed a few percent.

Typical waveforms of the discharge current and voltage, the plasma radiation intensity in the wavelength range of 12.2…15.8 nm and photographs of the discharge gap are shown in Fig. 2. In the Fig. 2,f, there are shown the location of the rod electrode (anode *A*), the tubular electrode (cathode *C*), the glass insert (*D*) and the formation of dense plasma in the discharge gap.

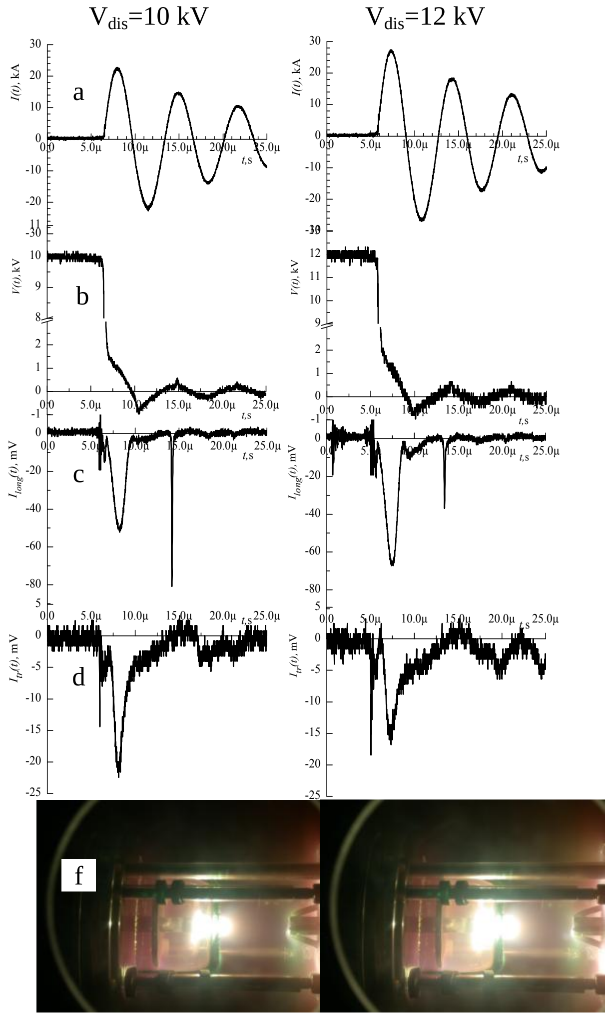

Fig. 2. Typical waveforms of the discharge current and voltage, plasma radiation intensity and photos of the discharge gap:
a – waveforms of the discharge current;
b – waveforms of the discharge voltage;
c – waveforms of the longitudinal radiation intensity in the range of 12.2…15.8 nm;
d – waveforms of the transversal radiation intensity in the range of 12.2…15.8 nm;
f – photos of the discharge gap

One can clearly see that in the first half-cycle of the discharge current oscillations a fairly wide (~ 4 μs) radiation pulse in the longitudinal direction (see Fig.2,c) is formed, while in the 3rd half-cycle there is a narrow (~ 0.4 μs) peak pulse. A wide pulse of recombination radiation is formed under conditions of prolonged (within the duration of the half-cycle of the discharge current oscillations) power input. The peak pulses appear during the short-term additional powerful energy input [3]. Comparing the amplitude of wide pulses in the first half-cycle for the longitudinal and transverse components of the radiation intensities (see Fig. 2,c,d) one can say that intensity in the longitudinal direction of radiation is 2…3 times higher than in the transverse one. It should be noted that the peak pulses are observed only in the longitudinal direction.

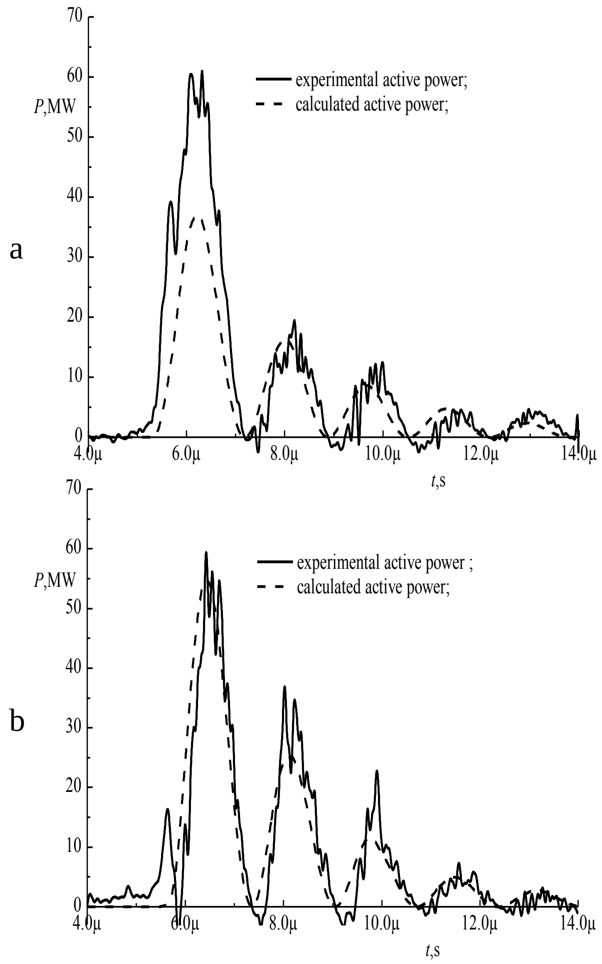

Fig. 3. Dynamics of active power input into the discharge: a) with dielectric insert (a); without dielectric insert (b)

To identify the processes which underlie the generation of high-power pulses of plasma radiation in the range of extreme ultraviolet, the studies of the dynamics of power input in the discharge are carried out. Fig. 3 shows the dynamics of the active power inputted into the discharge. These dependences are calculated for two cases: in the presence of the dielectric insert (a) and in the absence of the insert (b).

The solid line shows the experimental active power inputted into the discharge, the dashed line – the calculated active power. The appearance of negative values of the input power is explained by the methodology accuracy.

One can conclude from analyzing the Fig. 3 that in the first half-cycle more power is inputted in the case of the dielectric insert presence than without the insert, although the experimental values of active power were the same for the two cases. This is clearly seen on the Fig. 4 that shows the development of the energy input into the discharge. Fig. 4 shows the waveforms of the discharge current and the ratio of the energy input into the discharge to the energy stored in the capacitor for two cases: with and without the insert. The figure shows that 20% of energy more is inputted during the first half-cycle in the presence of the insert than in the absence of the insert.

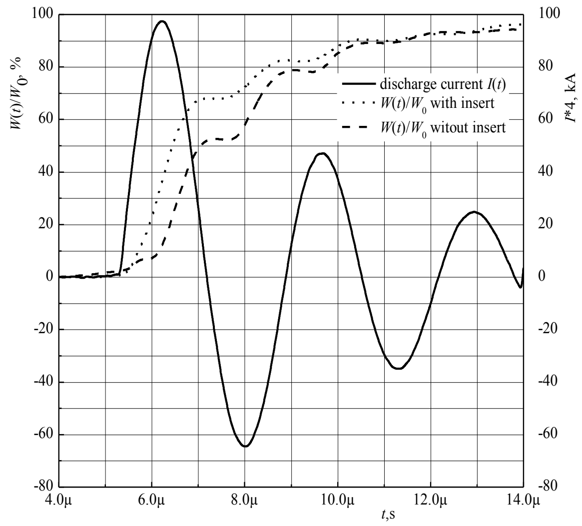

Fig. 4. Dynamics of energy input into the discharge

The dense plasma is formed due to the fact that the electron beam heats the working surface of the anode and the working material intensively evaporates with its subsequent ionization. This electron beam is generated in the electric double layer of the space charge that appears for a short time in current-carrying plasma in a high-current plasma diode.

Typically, the double layer occurs under such conditions that the current-carrying plasma can not transfer (due to the thermal motion) the entire current provided by the power supply [4]. The localization of the double layer is determined by the place where the current-carrying capacity of the plasma is minimal one [5]. Under the contraction of the current channel by the dielectric insert, the power supply current must exceed by 2...3 times the current that plasma can carry through the dielectric channel. The presence of the dielectric insert promotes the formation of an additional double layer in the dense plasma, and the double layer is formed near the insert hole. Due to the presence of additional double layer the additional power is inputted into the discharge.

The ratio of the longitudinal and transverse components of the radiation intensity (the sum for three half-cycles) of the discharge voltage under the presence of the dielectric insert is shown on Fig. 5. One can see on this figure that the longitudinal radiation intensity (the sum for three half-cycles) is by 3...5 times higher than the transverse one.

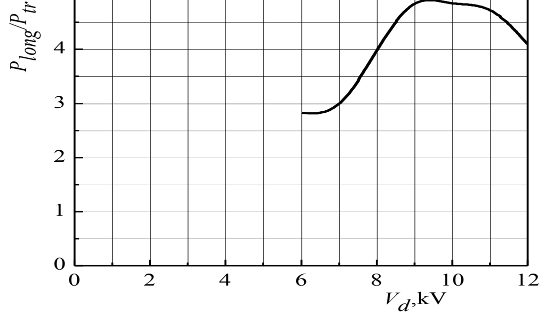

Fig. 5. Ratio of the total longitudinal and transverse component of the radiation intensity versus the discharge voltage

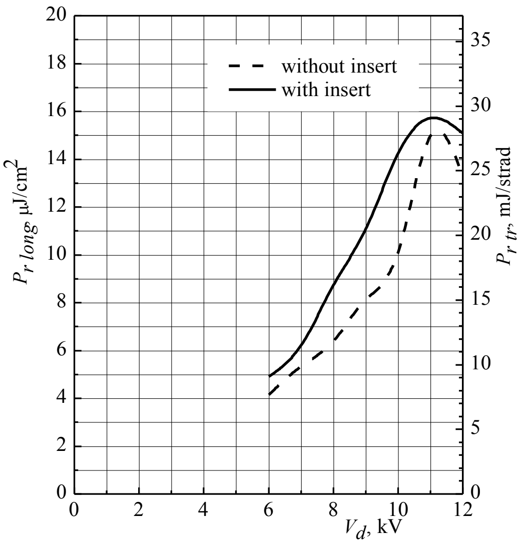

Fig. 6. The total longitudinal component of the radiation intensity versus the discharge voltage

Based on this, the dependence of the longitudinal component of the radiation intensity on the discharge voltage for the two cases is plotted (see Fig. 6). It is seen that in the presence of the dielectric insert the radiation intensity is higher than in its absence. This is explained by the higher efficiency of the energy input into the discharge.

CONCLUSIONS

Our experimental studies prove the possibility of using the partial contraction of the current channel by the dielectric insert in the high plasma diode for generating the directional EUV-radiation.

To ensure the efficiency and stable generation of directional radiation the optimal location and diameter of the insert hole are determined experimentally.

It is shown that the additional double layer is formed in the presence of the dielectric insert. And this additional double layer provides the higher efficiency of the energy input into the discharge leading to the increase of the radiation intensity.

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ДИНАМИКА ЭУФ-ИЗЛУЧЕНИЯ В ЧАСТИЧНО КОНТРАГИРОВАННОМ ПЛАЗМЕННОМ ДИОДЕ

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Исследована возможность формирования направленного ЭУФ-излучения плазмы при частичном контрагировании токового канала диэлектрической стенкой в сильноточном плазменном диоде. Исследованы разрядные характеристики и их влияние на динамику излучения в диапазоне длин волн 12,2…15,8 нм. Показано, что при частичном контрагировании токового канала диэлектрической стенкой наблюдается более высокая эффективность ввода энергии в разряд, приводящая к увеличению интенсивности ЭУФ-излучения.

ДИНАМІКА ЕУФ-ВИПРОМІНЮВАННЯ В ЧАСТКОВО КОНТРАГОВАННОМУ ПЛАЗМОВОМУ ДІОДІ

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Досліджено можливість формування спрямованого ЕУФ-випромінювання плазми при частковому контрагуванні струмового каналу діелектричною стінкою в потужнострумовому плазмовому діоді. Досліджені розрядні характеристики та їхній вплив на динаміку випромінювання в діапазоні довжин хвиль 12,2…15,8 нм. Показано, що при частковому контрагуванні струмового каналу діелектричною стінкою спостерігається більш висока ефективність введення енергії в розряд, що призводить до збільшення інтенсивності ЕУФ-випромінювання.