ANISOTROPY OF RADIATION FROM DENSE PLASMA OF MULTIPLY IONIZED ATOMS

Ya.O. Hrechko, N.A. Azarenkov, Ie.V. Babenko, D.L. Raybchikov,
N.N. Vusyk, A.F. Tseluyko
V.N. Karazin Kharkiv National University, Kharkov, Ukraine
E-mail: ievgeniia.borgun@mail.ru

It has been study the formation of anisotropic extreme ultraviolet radiation from the plasma of multiply ionized atoms. The mean free path of quantum in dense plasma has been estimated. The critical current for formatting anisotropic radiation in the tin ion plasma has been obtained. The dependences of the radiation directivity coefficient on the plasma parameters have been derived.

PACS: 52.20.-j, 52.50.Dg

The work associated with the development of plasma sources of extreme ultraviolet radiation on the basis of high-current discharges. The main challenges to the creation of the plasma source are a low conversion rate of external electrical energy into radiation energy and a strong destruction of the radiation focus system by the discharge products. In [1] it was shown that one of the possible solutions of these problems is the use of directional radiation generated in a pulsed high-current diode with a limited surface of the potential electrode. As shown in [2], for the efficient collection of radiation it is necessary to select the optimum location and configuration of the collecting mirror, taking into account the radiation direction. This work is devoted to the definition of functional dependencies of the radiation from the plasma parameters.

MATERIAL IS LOCATED AS FOLLOWS

An analysis of the experimental data, obtained earlier by the authors, can explain the mechanism of intense directional radiation peaks using the following phenomenological physical model. The model assumes that at any point of the radiating volume is generated by the primary photon, which is distributed in a random direction. On a mean free path λ in the interaction with the ion capture an electron the primary radiation photon induces secondary photon in the same direction (radiation-induced effect). Second quantum together with the primary again induces at the length of λ new photons in the same direction. Avalanche increased flow comes to the boundary of the radiating volume.

To simplify the calculations it was used a simple model of a homogeneous radiating volume in the form of a cylinder of length *L* and diameter *D*. Schematic representation of the physical model of the radiating volume is shown in Fig. 1.

One of the main elements in a phenomenological model of the formation of directional stimulated emission is the mean free path λ of the quantum in plasma. To assess its value, it can be used the approach proposed in [3]. In this paper is given an expression for the quantum mean free path in the dense plasma of multiply ionized atoms. The calculations have been performed for the case when the dense plasma forms a plasma pinch with a radius determined from the condition of equality the surface radiation losses and plasma ohmic heating

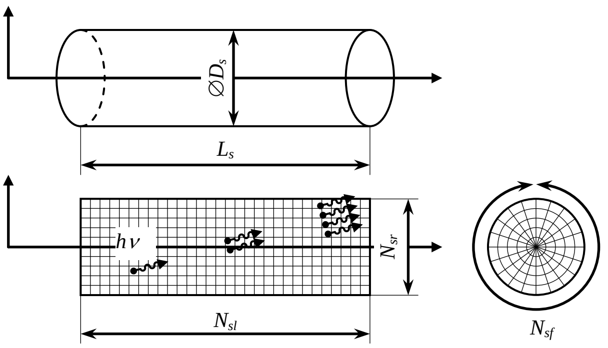

Fig. 1. Schematic representation of the phenomenological physical model. L_s and D_s – the length and diameter of a homogeneous radiating volume; N_{sl}, N_{sr} и N_{sf} – the number of partitions, respectively, the length, radius and azimuth angle into elementary cells

$$Q_3(r_{eq}) = Q_J(r_{eq}). \tag{1}$$

Equating the loss of the line emission of plasma column Q_{line} to Joule heating Q_J the authors have obtained the critical current for heavy ion plasma $Q_{line} = Q_J$

$$I_{cr} = 14 \cdot \frac{T_e^{3/4} Z_{ef}}{Z_n^2}, \text{ kÀ}. \tag{2}$$

It is shown that at the electron temperature T_e the average energy of photons leaving the plasma is about

$$E_\nu \cong (1...2) \cdot T_e. \tag{3}$$

An approximate expression for the mean free path of the quantum in plasma has been obtained

$$\lambda_\nu \cong 3 \cdot 10^{13} \frac{1}{n_e} \sqrt{\frac{Z_{ef}^3 T_e^3}{Z_n}}, \text{ cm}. \tag{4}$$

At the Fig. 2 it have been shown the results of calculation of the dependence of the reduced mean free path of quantum $\lambda_\nu \cdot 10^{-16} n_e$ of the electron temperature T_e for different effective charges of ions Z_{ef}.

Taking into account the criterion of the Bennett equilibrium (balance between a radial plasma pressure and the pressure of the magnetic field of the current) the mean free path can be rewritten as

$$\lambda_{\nu B} \cong 7{,}5 \cdot 10^{-3} \frac{d_{pc}^2}{I^2} \cdot \sqrt{\frac{Z_{ef}^3 T_e^5}{Z_n}}, \text{ cm}, \tag{5}$$

where it is considered that $n_e = Z_{ef} n_i$, and at $Z_{ef} >> 1,\ Z_{ef} + 1 \approx Z_{ef}$.

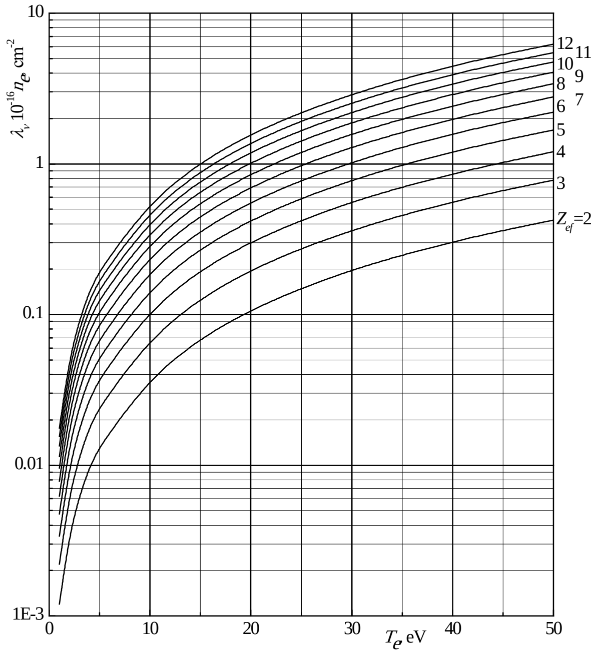

Fig. 2. Dependence of the reduced mean free path of quantum in a dense plasma $\lambda_\nu \cdot 10^{-16} n_e$ of the electron temperature T_e for different effective charges of ions Z_{ef}

Using cylindrical rod electrode with diameter d_a with isolated lateral surface (so that the current flows only through the end of the electrode) the expression for the mean free path of quantum can be written, expressing n_e through the discharge current I.

Assuming a uniform current density distribution over the cross section of the electrode the value I can be written as

$$I = \frac{1}{4} e n_e v_a \cdot \frac{\pi\, d_a^2}{4}, \tag{6}$$

where $v_a = \sqrt{\dfrac{8T_e}{\pi\, m_e}}$ – the average arithmetic velocity of plasma electrons. Then,

$$n_e = 16 \cdot \frac{1}{e} \cdot \sqrt{\frac{m_e}{8\pi \cdot 1{,}6 \cdot 10^{-12}}} \cdot \frac{1}{\sqrt{T_e}} \cdot \frac{I}{d_a^2}. \tag{7}$$

The multiplier $1.6 \cdot 10^{-12}$ in the denominator of the radicand emerged from the fact that T_e in eV is substituted in the same way as in (4). Substituting (7) into (4) we can write

$$I = 4{,}175 \cdot 10^{-3} T_e^2 \sqrt{\frac{Z_{ef}^3}{Z_n}} \cdot \left(\frac{d_a}{\lambda_{\nu A}}\right) \cdot d_a, \tag{8}$$

where Z_{ef} – an effective ion charge; Z_n – the ion atomic number; I – discharge current (kA); T_e – the plasma electron temperature (eV); d_a – an electrode diameter (cm); $\lambda_{\nu A}$ – the mean free path of quantum in plasma (cm) determined throw the electrode diameter

The expression 8 evaluates the minimum current when the directional radiation peak appearances for the electrode diameter d_a. From a physical model of directional stimulated radiation it can be seen that for formatting the significant radiation directivity must be $\lambda_\nu < d_a/2$. Therefore, as the threshold value it can be taken $d_a/\lambda_\nu \sim 2$.

Further calculation has been performed for tin, which Z_n = 50. The formation of radiation with a wavelength of 13.5 nm is observed for tin ion with ionization degree from 6 to 12. Therefore it has been taken the minimum value of the ionization degree $Z_{ef} = 6$. The energy of photons with a wavelength of 13.5 nm is E_ν = 92 eV, which corresponds to the value $T_e = E_\nu/3$, i.e. $T_e \approx 30$ eV, which agrees well with the literature [4, 5].

Under these assumptions for the electrode diameter of 0.5 cm the minimum current value at which there will be a directional radiation is I_{min} = 7.8 kA, that is in good agreement with the experimental data. According to the expression 8 the mean free path of quantum in plasma $\lambda_{\nu A}$ is defined as

$$\lambda_{\nu A} = 4{,}175 \cdot 10^{-3} \cdot \frac{d_a^2}{I} \cdot \sqrt{\frac{Z_{ef}^3 T_e^4}{Z_n}}. \tag{9}$$

Dependences of the mean free path of a quantum in plasma on the discharge current I in case the criterion.

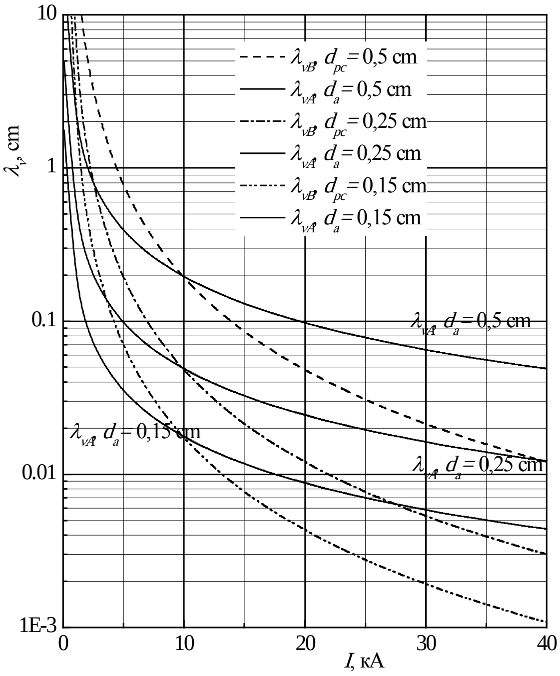

Fig. 3. The dependences of the mean free path of a quantum λ_ν (a) of the discharge current I:
$\lambda_{\nu B}$ – under the condition Bennett;
$\lambda_{\nu A}$ – for a uniform current distribution over the electrode cross section;
Z_n = 50, Z_{ef} = 6, $T_e \approx 30$ eV

Bennett $\lambda_{\nu B}(I)$ applied or a uniform current distribution over the entire electrode cross section $\lambda_{\nu A}(I)$ are shown in Fig. 3. The dependences corresponds to the case where the equilibrium diameter of plasma column equals to the electrode diameter, Z_n = 50; Z_{ef} = 6; $T_e \approx 30$ eV.

According to Fig. 3, at reducing electrode diameter d_a the mean free path of quantum in plasma decreases. In addition, calculated with the help of expression 5 and 9 the mean free paths of the quantum into plasma for the same parameters have the different functional dependences of the discharge current *I*. Under the Bennett criterion – it's inverse square law, and in the case of a uniform current distribution over the entire electrode cross section – an inverse relationship.

From a phenomenological model of the directional stimulated radiation, which is based on increased intensity of radiation on the mean free path of quantum into plasma λ_ν, it has been found that for the directional radiation it is necessary that the size of the emitting area *d* is significantly bigger than λ_ν.

$$d >> \lambda_\nu. \qquad (10)$$

Taking into account the condition 10, for the case of the directional radiation generation the expressions for the discharge current for the two cases can be written as follows:

$$I >> I_B = 8.66 \cdot 10^{-2} \cdot \sqrt{d_{pc}} \cdot \sqrt[4]{\frac{Z_{ef}^3 T_e^5}{Z_n}}, \qquad (11)$$

$$I >> I_A = 4.175 \cdot 10^{-3} \cdot d_a \cdot \sqrt{\frac{Z_{ef}^3 T_e^4}{Z_n}}. \qquad (12)$$

Fig. 4 shows the dependences of the critical current *I* for generating directional radiation in the plasma of multiply ionized tin atoms on the electron temperature T_e for ionization degrees $Z_{ef} = 6$ и 12 for the rod electrode diameter of 0.15 cm. The dependences $Z^Б_{ef}$ correspond to the critical currents derived from the expression 11 for the case of equality of the plasma gas-kinetic pressure and the magnetic field pressure of its own current (Bennett criterion). The lines Z_{ef} show the dependences of the critical current obtained from the expression 12, which corresponds to a uniform current distribution over the electrode cross section.

Using estimates of the mean free path for a uniform current distribution over the electrode cross section, based on the proposed phenomenological physical model, the dependences of the radiation directivity coefficient for 13.5 nm wavelength on the tin plasma parameters have been obtained. Under directivity coefficient α is supposed the ratio of the longitudinal component of the radiation intensity the transverse one with respect to discharge axis, so α = 1 is corresponded to the case of isotropic radiation registration.

The dependence of the directivity coefficient α on plasma density for different ratios of plasma pinch length and its diameter is shown in Fig. 5. According to Fig. 5 at the plasma density of about $3 \cdot 10^{16}$ cm^{-3} the radiation directivity drops sharply to 1. If the plasma density increases the longitudinal directivity will greatly amplify. The calculations assumed that the plasma pinch diameter is determined by the rod electrode diameter and for this dependence it was 0.25 cm.

Designing the plasma source it is important to know the effect of electrode diameter on the formation of anisotropic radiation. Therefore at the Fig. 6 it is shown the dependence of the directivity coefficient α on plasma density for different electrode diameters. Dependencies plotted for the case when the plasma pinch length is in two times more than its diameter $L_{pl}/d_a = 2$.

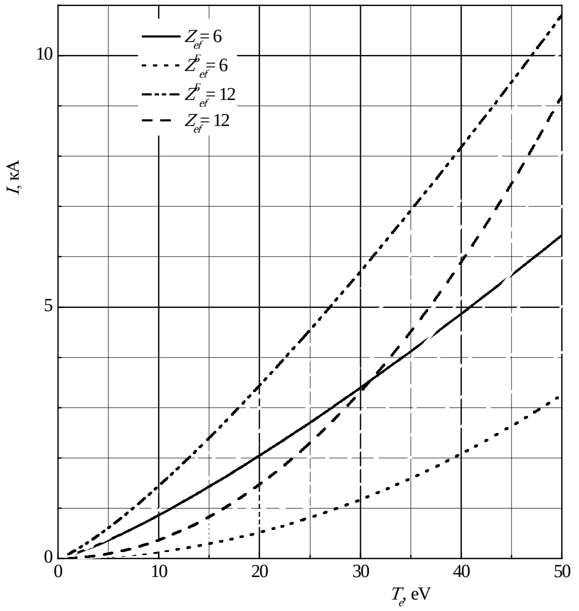

Fig. 4. The dependence of the critical currents of the generation of directional radiation I in the plasma of multiply ionized tin atoms on the electron temperature T_e and the ionization degrees Z_{ef} for rod electrode with diameter of 0.15 cm

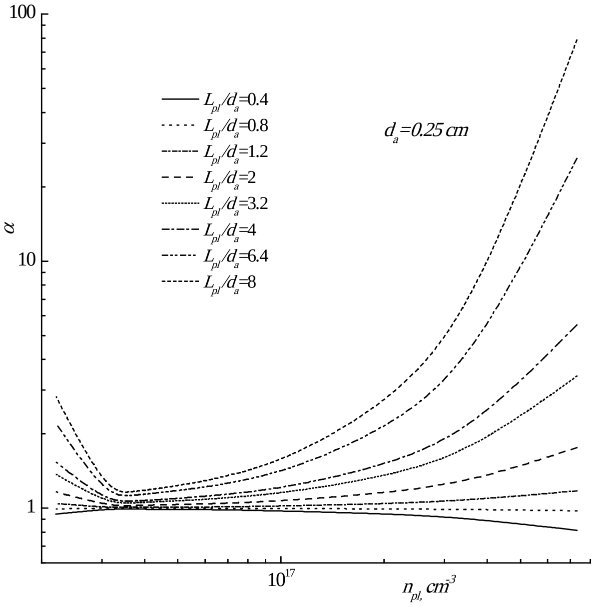

Fig. 5. The dependence of the radiation directivity on plasma density for different ratios of plasma pinch length and its diameter using electrode with diameter of 0.25 cm

According to Fig. 6, at the same values of the plasma density, using the electrode of larger diameter it can greatly amplify the radiation directivity. For example, at the plasma density of $7 \cdot 10^{17}$ cm^{-3} if the electrode diameter d_a is being increased in 10 times, the longitudinal directivity is amplified in 20 times.

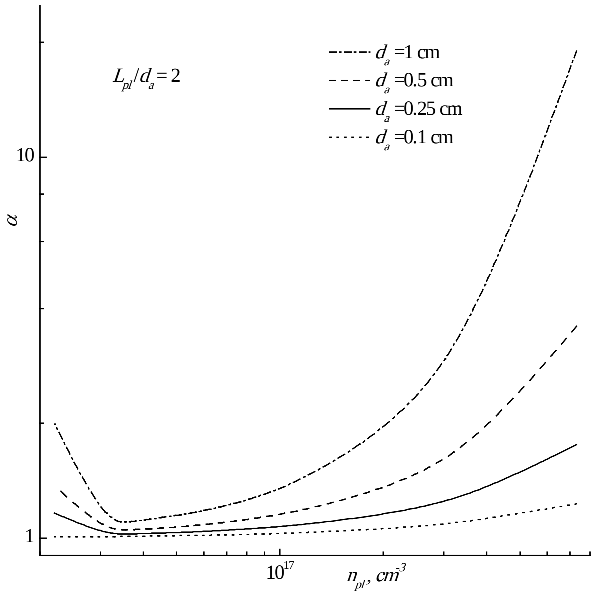

Fig. 6. The dependence of the radiation directivity on plasma density for different electrodes diameters at a ratio of plasma pinch length to its diameter $L_{pl}/d_a = 2$

CONCLUSIONS

Thus, the estimations of the mean free path of quantum with 13.5 nm wavelength in the dense plasma of multiply ionized tin atoms have been carried out. The evaluative formulas of critical discharge current which corresponds to the case of the directional radiation forming in plasma diodes with rod electrodes, which side surface is closed by insulator, and to implementation of equilibrium condition of plasma pinch have been given. The dependencies of the radiation directivity on the plasma density for different ratios of plasma pinch length to its diameter and the pinch diameter to the mean free path have been established. It has been shown that controlling the external discharge parameters such as the electrodes diameter, the power introduced into the discharge, the transverse magnetic field value, can be set the necessary radiation directivity.

REFERENCES

1. A.F. Tseluyko, V.T. Lazurik, D.L. Ryabchikov, Ie. Borgun, I.N. Sereda, D.V. Zinov`ev. Directivity of superradiation from plasma of high-current pulse plasma diode // *Problems of Atomic Science and Technology. Series “Plasma Electronics and the New Methods of Acceleration”*. 2010, №4, p. 66-69.
2. Ie.V. Borgun et al. Optimization of the collecting mirror location in extreme ultraviolet plasma source // *Problems of Atomic Science and Technology. Series “Plasma Physics” (21).* 2015, №1, p. 174-176.
3. E.V. Aglitskiy, A.V. Vihrov, A.V. Gulov, et al. *Spectroscopy of multiple charge ions in hot plasma*. Moscow: “Science”. 1991, 206 p.
4. M. Masnavi, M. Nakajima, E. Hotta, K. Horioka, G. Niimi, A. Sasaki. Estimation of optimum density and temperature for maximum efficiency of tin ions in Z discharge extreme ultraviolet sources // *Journal Of Applied Physics*. 2007, Issue 101, p. 033306(9).
5. A. Di Cicco, K. Hatada, E. Giangrisostomi, R. Gunnella, F. Bencivenga, E. Principi, C. Masciovecchio, A. Filipponi. Interplay of electron heating and saturable absorption in ultrafast extreme ultraviolet transmission of condensed matter // *Phys. Rev B.* 2014, Issue 90, p. 220303(R).

Article received 29.04.2015

АНИЗОТРОПИЯ ИЗЛУЧЕНИЯ В ПЛОТНОЙ ПЛАЗМЕ МНОГОКРАТНО ИОНИЗИРОВАННЫХ АТОМОВ

Я.О. Гречко, Н.А. Азаренков, Е.В. Бабенко, Д.Л. Рябчиков, Н.Н. Вусык, А.Ф. Целуйко

Изучается формирование анизотропного излучения в диапазоне экстремального вакуумного ультрафиолета из плазмы многократно ионизированных атомов олова. Приводятся оценки длины свободного пробега кванта в плотной плазме многозарядных ионов. Определен критический ток формирования анизотропного излучения в плазме ионов олова. Получены зависимости коэффициента направленности излучения от параметров плазмы.

АНІЗОТРОПІЯ ВИПРОМІНЮВАННЯ В ЩІЛЬНІЙ ПЛАЗМІ БАГАТОРАЗОВО ІОНІЗОВАНИХ АТОМІВ

Я.О. Гречко, М.О. Азарєнков, Є.В. Бабенко, Д.Л. Рябчіков, М.М. Вусик, О.Ф. Целуйко

Вивчається формування анізотропного випромінювання в діапазоні екстремального вакуумного ультрафіолету з плазми багаторазово іонізованих атомів олова. Наводяться оцінки довжини вільного пробігу кванта в щільній плазмі багатозарядних іонів. Визначено критичний струм формування анізотропного випромінювання в плазмі іонів олова. Отримано залежності коефіцієнта спрямованості випромінювання від параметрів плазми.