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Effect of Plasma Focus Sheath Radiation on Target Evaporation

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In the series of experiments, performed on PF-3 facility with different targets it was revealed that the diameter of the target, such as foam liner or polyethylene fiber [1], exceeds its initial diameter at the moment of the contact with the sheath. It shows that preliminary heating of the target by the sheath plasma radiation can transform the initially – condensed substance of the target into plasma state. Compression of dust targets in experiments with dust liners consisting of ensemble of fine-disperse grains [2] also says for the hypothesis of dust particles evaporation by the sheath plasma radiation.

In the present work we calculated plasma focus sheath radiative loses for neon, argon and hydrogen with 2% of xenon for electron temperature T_e= 3-15 eV, electron density $n_e = 10^{18}$ cm^{-3} and sheath thickness $d \sim 1$ cm. The excited levels population for these conditions are determined mainly by collisional impact electron exitation and deexitation processes and approaches the thermodynamical equilibrium (Boltzmann distribution). The quenching parameter β expressing the ratio of deexitation rate due to collisions with plasma electrons to spontaneous luminescence for the cross-section of excitation by electron impact in the Bethe-Born dipole approximation [3] for the parameters above and radiative transition wavelength $\lambda \sim 500$ Å equals $\beta \sim 1.4$. This means that ion distribution over atomic levels is close to Boltzmann's.

First we consider radiative losses in lines. Let us estimate the line broadening mechanism that predominates in the wings of the radiating ions' spectral lines. To do this requires estimation of Weisskopf radius $\rho_w=(C_4/v_e)$ for quadratic Stark effect in the broadening particle's (electron's) electric field. Here C_4 is the quadratic Stark effect constant, v_e - broadening particle's (electron's) velocity. The number of electrons in the sphere of Weisskopf radius $N_w=n_i\rho_w^3$. For electron density $n_e = 10^{18}$ cm^{-3}, T_e = 5 eV and typical value of $C_4 \sim 10^{-16}$ cm^4/s we find that $N_w \sim 10^{-6} \ll 1$. That corresponds to collisional mechanism of Stark broadening, which has Lorentz line shape with collisional width $\Gamma = 11.4 n_e C_4^{2/3} v_e^{1/3}$ [4], where v_e is electron thermal speed. Therefore we should consider this type of broadening for calculating radiative transfer problem in optically thick matter. The collisional contribution of ions is less than that of electrons, so we do not consider it.

Let us estimate the optical thickness of radiative plasma τ. For typical neon ion with a charge $Z_i = 2$ for $C_4 \sim 10^{-16}$ cm^4/s and radiative transition rate (deexcitation probability of an excited level in unit time) $\gamma \sim 10^{10}$s^{-1} we find that full line width $\Gamma_{tot} = \gamma + \Gamma \sim 10^{12}$s^{-1}. For spectral line with wavelength $\lambda \sim 500$ Å find that photon absorption cross-section $\sigma_{abs} \sim 2\pi\bar{\lambda}^2 \gamma / \Gamma_{tot} \sim$ $\sim 10^{-12}$cm^2. For absorbing ions density $n_i \sim 10^{17}$ cm^{-3} photon's mean free path $\ell_{qu} \sim 1/(n_i \cdot \sigma_{abs}) \sim 10^{-5}$cm. For sheath thickness $d = 1$cm we find that optical thickness $\tau = d/l_{\mathrm{qu}}$ $\sim 10^5 >> 1$. From this estimation one can see that processes of radiation reabsorption are predominating and in the case under consideration of thermal-equilibrium medium energy loss occurs in spectral line wings [3].

Radiative losses of plasma sheath in lines were calculated for each ion separately. The distribution of ions over ionization degrees was calculated by Saha formula for temperatures 3 and 5 eV. For temperatures 10 eV and 15 eV the calculation of average ionic charge was performed by tables [5].

Line intensities were calculated using [3]:

$$I_{\perp}(d) = B_{BB}(\omega_0)\Gamma\left[\pi\kappa_0 d\left(1 - \exp\left(-\frac{\hbar\omega_0}{T}\right)\right)\right]^{1/2}, \qquad (1)$$

where $B_{BB}(\omega)$ is the black-body intensity per unit solid angle, $\kappa_0 \approx \frac{\lambda_0^2}{2\pi}(\gamma/\Gamma_{tot})(g_1/g_0)n_i$ is the absorption coefficient in the centre of line. At that the conditions $\kappa_0 d >> 1$, $\hbar(\Delta\omega)_{eq} << \min(T, \hbar\omega_0)$ should be satisfied. Here (for $\Gamma >> \gamma$) $(\Delta\omega)_{eq} = \Gamma\sqrt{\kappa_0 d} >> \Gamma$ is the equivalent spectral line width.

The results for summary losses per unit area of plasma sheath for all spectral lines are presented in figure 1(left). Spectral line natural widths γ for neon, argon and xenon were determined from NIST database and by using formulas from [5]. We took account of 10 – 15 strongest lines for each ion, and use these parameters in Eq. (1).

The radiative losses due to nonrelativistic electron-ion bremsstrahlung was calculated as [5]:

$$I_{br} = 4.85 \times 10^{-24} n_e n_Z q^2 T^{\frac{1}{2}} \times g_{ff}(q,T) \text{ erg cm}^{-3}\text{ sec}^{-1}, \qquad (2)$$

where n_e, n_z electron density, z-charged ion density respectively, q is average ion charge, T – temperature in keV, g_{ff} - Gaunt factor. The continuum energy radiated in the process of radiative recombination to level n of a hydrogenic ion is given by [5]:

$$I_{rr}{}^{n} = 8.32\times10^{-23} n_e n_Z q x_n^{\frac{1}{2}} I_{q,n} \text{ erg cm}^{-3} \text{ sec}^{-1}, \tag{3}$$

where $x_n = I_{q,n}/T$, $I_{q,n}$ is the ionization potential. Summary losses per unit area of plasma sheath for bremsstrahlung and radiative recombination are shown in figure 1(right).

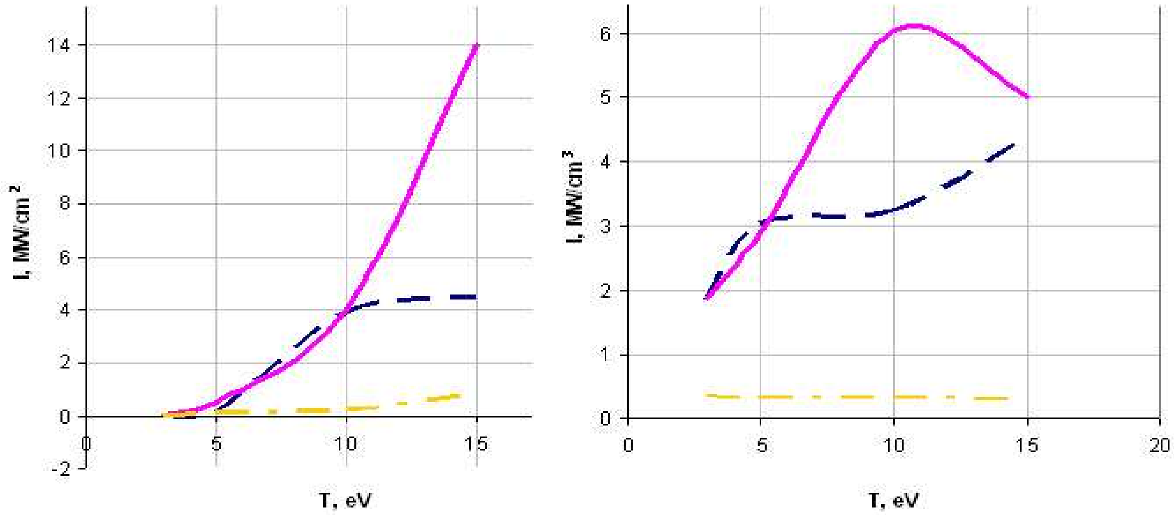

Fig1. Plasma sheath radiative loses as a function of temperature: in lines (left) and in spectral continuum (right); continuous magenta – Ar, dash blue – Ne, dot-dash yellow – H_2+Xe

For calculation of radiation intensity on the target located on the sheath's axes we approximated the PF-sheath with a cylinder of height L = 3 cm, thickness ΔR = 1 cm and inner radius R changing from $R_{\max}$ = 10 cm till $R_{\min}$ = 1.5 cm (see fig.2). $R_{\min}$ should be determined by target size which could vary from 0.1 mm in case of polyethylene fiber till 20 mm and more in case of liners and dust loads. This approximation conforms quite well to plasma sheath form observed in experiment. It should be mentioned that form of the sheath in flat (Filippov's) configuration depends strongly from the discharge regime.

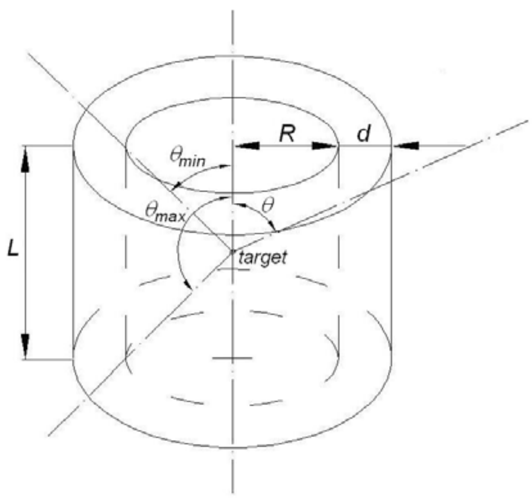

Fig.2. Radiation flux calculation scheme. Target is on the axes of the system. L – height of the sheath , d – its thickness, R – distance from the axes, r – direction to observer.

The total intensities from all the sheath that comes to the unit of the target's surface is obtained by integrating Eq. (1) and Eqs. (2, 3) divided by 4π over a solid angle bounded by $\theta_{\min}$ and $\theta_{\max}$ (see fig.2) with d replaced by $d/\sin\theta$, the path covered by the ray in the plasma.

The total energy W falling on a target is obtained by integrating the total intensities that comes to the target over the time of sheath moving towards the target from $R_{\max}$ to $R_{\min}$.

To estimate the possibility of target particles evaporation we need to compare the total energy falling on a target with the energy W_{ph} needed for phase changes and warming-up. For total evaporation of a particle the condition $W/W_{ph} > 1$ should be satisfied. The results of calculations for spherical particles of aluminium oxide (Al_2O_3) are shown of figure 3.

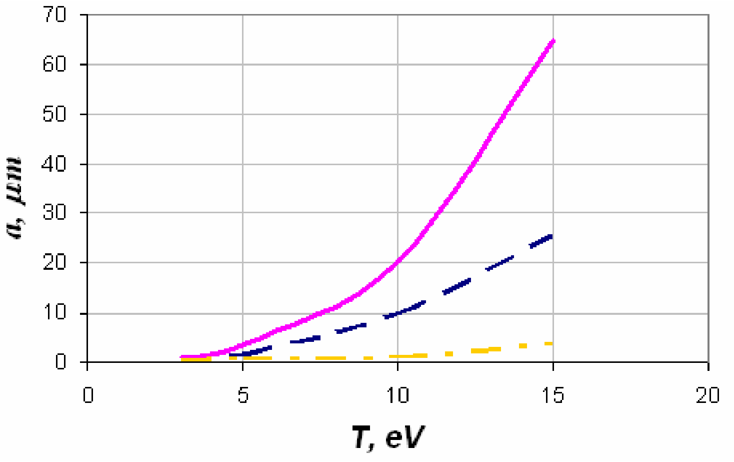

Fig. 3. Grains evaporation depending on sheath plasma temperature; continuous magenta – Ar, dash blue – Ne, dot-dash yellow – H_2+Xe

From this figure one can see that by the time of sheath reaching the target the great part of dust particles could be evaporated. For discharge in neon plasma temperature 10-15 eV is sufficient for evaporation of grains with 10-25 μm in diameter.

Thus we can see that by using intensively radiating gases we can expect the considerable change of the phase state of a condensed target even before its contact with the current sheath. Although the calculation of PF sheath radiation is much more accurate than that performed before in approximation of black body radiator it is still rough and gives only the order of magnitude. To make this calculation more precise we need experimental data on plasma sheath temperature and take account of thermophysical properties of targets. These will make a subject of our future research.

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