INFLUENCE OF THE MAGNETIC FIELD ON PARTICLE DYNAMICS IN CAPILLARY DISCHARGE OF THE SOFT X-RAY LASER

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In this paper the possibility of increase of quantity of flashes of soft x-ray laser radiation due to application of a small external magnetic field during development of the capillary discharge is considered.
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INTRODUCTION

In this paper the experimentally observed phenomenon [1-3] - Z-pinch evolution in the capillary discharge of the ultra-violet and soft x-ray laser is theoretically investigated. Experimental and computer researches [4] are also devoted to the capillary discharge. The cylindrical plasma system is considered as a thin tube - a capillary with length L and diameter D with the large voltage, applied to it. The experiments with the capillary discharge are carried out for generation of N_e-like line of argon (λ=46.9 nm). Consideration of this phenomenon from the point of view of the plasma particle dynamics is of interest in connection with the importance of the problem of the X-ray generation in economic compact systems, in particular, with the use of the capillary discharge and wide applications of the X-ray radiation.

In 1994 Rokka has offered to use the capillary discharge for the laser radiation generation on the Ne-like line of argon (λ=46.9 nm) [5]. In comparison with the installations, using management by the laser, for generation of X-ray laser radiation the installations, based on the capillary discharge, are inexpensive, compact, and have high factor of transformation of the electric energy in the energy of laser radiation.

One can increase the energy of laser radiation due to increase of the pulse duration. However, the soft X-ray laser, based on the capillary discharge, generates nanosecond pulses. The width and amount of pulses are limited by the plasma dynamics and by the time of maintenance of optimum plasma conditions. In this paper the possibility of increase of quantity of flashes of soft X-ray laser radiation due to application of a small external magnetic field during development of the capillary discharge is considered. The influence of a longitudinal magnetic field on pinch development is investigated in [6].

DYNAMICS OF THE COMPRESSED PLASMA COLUMN

Let us estimate velocity, which gets electron in an electric field without taking into account collisions:

$$v = c\sqrt{1-1/\left(1+e\phi_0/mc^2\right)^2} \;. \tag{1}$$

We find as follows:

$$t_1=\sqrt{\frac{4m_e L}{eE_o}} \tag{2}$$

time during which an electron passes the capillary, continuously being accelerated.

Characteristic time of electron collisions with a wall of the capillary equals

$$t_2=\frac{D}{2V_{the}} \tag{3}$$

I.e. $t_2>t_1$ electrons have time to pass all length of the capillary without collisions with a wall of the capillary.

In this paper the system of hydro-dynamical equations and a condition of adiabatic compression of a plasma column (see, for example, [7-9])

$$pn^{-\gamma}=Tn^{1-\gamma}=const \tag{4}$$

is used for the description of Z-pinch dynamics. Here p, n are the pressure and density, T is the temperature, γ is the adiabatic constant. We consider such value of the external magnetic field, that its action on electrons is essential, and on ions insignificantly. The equations, describing compression of a plasma column are submitted in [10]. We use the conservation law of the particle numbers [9]: $nr^2=n_0 r_0^2$. Then the velocity of compression of the plasma column is followed:

$$v_{contr}^2=\frac{1}{8}\rho_0\rho\alpha^2-\gamma \tag{5}$$

We use the normalization: $V_\rho=V_r/V_{sio}$, $N=n/n_o$, $\tau=\omega_{pio}t$, $\rho=r/r_{deo}$. Here $r_{deo}=\sqrt{T_{oe}/4\pi n_o e^2}$, $\omega_{pio}=\sqrt{4\pi n_o e^2/m_i}$, $V_{sio}=\sqrt{T_o/m_i}$.

Here the pressure resistance to compression of the plasma column is taken into account. Also the force, proportional to $\left[\vec{E}_z,\vec{H}_\theta\right]$ may determine a threshold and resistance to compression of the plasma column. H_θ is determined by a longitudinal electron current. E_z is determined by development of longitudinal instability, for example, Bunemann's one. Certainly, in this case the longitudinal electron velocity also restrains by instability development. Therefore fast increase of an external electric potential is necessary.

INFLUENCE OF THE EXTERNAL LONGITUDINAL MAGNETIC FIELD ON DYNAMICS OF THE PLASMA COLUMN

During some time after the pinch break the focusing force for electrons disappears and the plasma extends both in radial, and in longitudinal directions. Thus the big losses of energy occur. We show that the use of the small external magnetic field can reduce the energy losses and improve the plasma uniformity. Also thus the amount of laser pulses, which are developed during discharge, can be increase. Such magnetic field does not prevent to recreation of the breaken plasma column along the direction of the magnetic field. However it prevents to the column expansion up to its recreation and restoration of a longitudinal current. Thus, the time, necessary for the following pinch formation, is smaller. Also the energy expenses, necessary on compression of the following pinch, also are smaller.

In other words, the use of an external magnetic field is useful from the following reasons. For increase of an output of X-ray radiation its sources, based on the capillary discharge, when during the pulse of the external power supply several pinches are consistently developed, are investigated now in the world. Thus to reduce the dissipative losses on expansion and compression of the column and to reduce porosity between two pinches, it is useful to limit cross expansion of the broken off plasma column. We show below, that it is achieved by use of an external magnetic field.

On the one hand, at compression of the plasma column the force of the external longitudinal magnetic field should not essentially effect, that is the distance on which an electron displaced in the capillary under influence of compressing force should be not less then the capillary radius R, i.e. the inequality should be correct:

$$r_r = \frac{F_r}{m_e \omega_{ce}^2} = \frac{eH_\theta V_z}{m_e c \omega_{ce}^2} = \frac{2\pi \mathrm{m}_e rn}{H_{oz}^2} \alpha^2 c^2 \geq R \quad (6)$$

On the other hand, at expansion of the plasma column after its break the magnetic field should provide small-scale radial electron oscillations. It turns out, that the Larmour radius should be much less then the capillary radius:

$$R >> r_{ce} = \frac{m_e c V_{theo}}{eH_{oz}} \left(\frac{n}{n_o}\right)^{(\gamma-1)/2} \quad (7)$$

From here it follows, that the longitudinal magnetic field should correspond to the following condition:

$$\frac{m_e c V_{theo}}{eR} \left(\frac{n}{n_o}\right)^{\frac{(\gamma-1)}{2}} << H_{oz} \leq \alpha c \sqrt{\frac{2\pi \mathrm{m}_e rn}{R}} \quad (8)$$

EXPANSION OF THE BROKEN OFF PLASMA COLUMN

At absence of an external longitudinal magnetic field the radial expansion of the broken off plasma column occurs with ion-acoustic velocity

$$v_{ext} = \sqrt{\gamma}\,. \quad (9)$$

Let's show, that at expansion of the plasma column in the radial direction (after formation of break) at presence of the external longitudinal magnetic field the velocity of radial movement is much less than the velocity of the break reconstruction.

Namely, expansion of the broken off plasma column occurs due to radial movement of ions under action of polarizing force between electrons and ions (see Fig. 1). In absence of the external magnetic field such radial polarization arises because the electrons under action of force of own pressure try to extend in a cross direction.

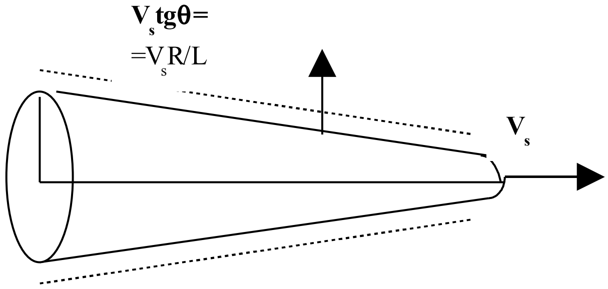

Fig. 1. Polarization of the electrons concerning ions of an extending plasma column

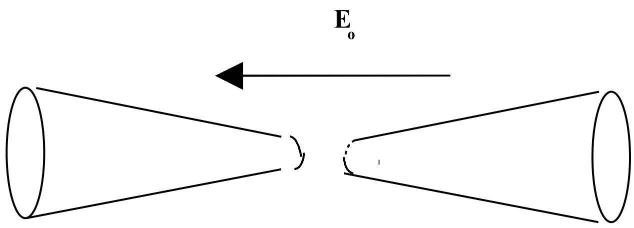

Fig. 2. Expansion and reconstruction the broken off plasma column

At presence of the magnetic field such relative polarization of the electrons and ions (see Fig. 2) results from electron movement along z axis along the magnetic field under action of their pressure. Thus relative polarization of the electrons and ions arises because the broken off plasma column represents two cones (see Fig. 2) which bases are located on the ends of the capillary. Thus a spatial configuration of these cones such, that due to polarizing force the cone heads move towards each, resulting to reconstruction of break during some time. Thus spatial scale of radial polarization much less $\frac{2R}{L}$ than spatial scale of longitudinal polarization.

RECONSTRUCTION OF PLASMA COLUMN BREAK

As a result of break of the plasma column at occurrence of the Z-pinch development, the longitudinal plasma current disappears hence, the focusing force disappears. After break as a result of disappearance of focusing force the plasma column begins to extend. Similarly the case of radial compression in linear approximation one can obtain the velocity of reconstruction of the plasma column break, which depends on the plasma temperature. The reconstruction is faster, when this temperature is more. This temperature is more, when the plasma column extends slowly. Hence the reconstruction occurs faster, when the plasma column extends slowly. Thus, using a magnetic field, it is possible to increase of the reconstruction velocity of the broken off plasma column and increase quantity of laser flashes during the discharge.

CONCLUSION

In this paper the possibility of increase of quantity of flashes of soft x-ray laser radiation due to application of a small external magnetic field during development of the capillary discharge is considered.

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ВЛИЯНИЕ МАГНИТНОГО ПОЛЯ НА ДИНАМИКУ ЧАСТИЦ В КАПИЛЛЯРНОМ РАЗРЯДЕ ЛАЗЕРА МЯГКОГО РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ

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Рассмотрена возможность увеличения количества лазерных вспышек мягкого рентгеновского излучения, которые успевают развиться в капиллярном разряде за время разряда, за счет применения магнитного поля.

ВПЛИВ МАГНІТНОГО ПОЛЯ НА ДИНАМІКУ ЧАСТИНОК У КАПІЛЯРНОМУ РОЗРЯДІ ЛАЗЕРА М'ЯКОГО РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ

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Розглянута можливість збільшення кількості лазерних спалахів м'якого рентгенівського випромінювання, що встигають розвитися в капілярному розряді за час розряду, за рахунок застосування магнітного поля.