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Role of initial vapor density in Z-pinch polyacetal capillary discharge

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Abstract An analysis of a Z-pinch in a capillary discharge is presented. It is supposed that the capillary is filled with a material ablated from the wall using a subnanosecond laser pulse of an energy of several tens of milijoules. The optimum initial atom density N_0 has been found.

Key words capillary discharge • electrical discharge • laser ablation • snow-plow model • Z-pinch

Introduction

Z-pinch in a capillary electrical discharge may create a long thin cylinder of non-stationary properly hot and ionized plasma, suitable for soft X-ray laser pumping [1]. Very efficient lasing at 46.9 nm (Ar^{8+}) has been achieved in a collapsing period of the discharge in argon filled capillaries. Overheated plasma is developed near the capillary axis for a short period and collissional excitation mechanism results in efficient laser pumping there.

We intend to use a capillary Z-pinch for the recombination pumping of hydrogen-like carbon ions. In this case a high concentration of the fully stripped carbon ions should be created inside a thin cylinder around the capillary axis during the plasma collapse. In the following period of a quick pinched plasma decay and cooling, a population inversion on the laser transition of the C^{5+} should be created due to collisional recombination [1]. If an evacuated capillary is used, no pinching regime is developed [3]. To get the capillary Z-pinch we intend to fill a polyacetal capillary with a material ablated from its wall. We intend to use a subnanosecond laser pulse with an energy of several tens of milijoules for this purpose.

Model of capillary Z-pinch

To find out optimum experimental parameters we use our simplified computer model of the capillary Z-pinch which is controlled by the discharge current circuit [2]. The principal scheme of our experiment is seen in Fig. 1. We can vary the capillary radius r_0, capacitance C, charging voltage U_0 and ablation laser pulse energy (which causes changes of initial vapor density N_0).

Plasma column dynamics is described by means of a simplified "snow-plow" model and the influence of external circuits is accounted by the Kirchhoff equations [2]. This

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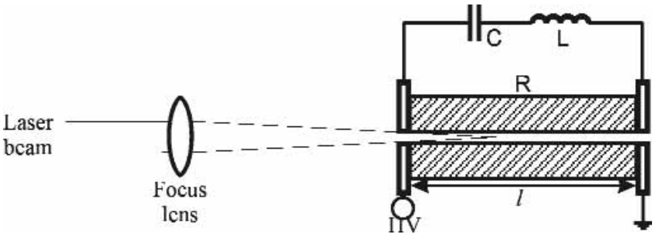

Fig. 1. Experimental arrangement.

system of equations, including a simple RLC circuit, may be written in the following form:

$$\frac{dx(\tau)}{d\tau} = \nu(\tau),$$

$$(1)\quad \frac{d}{d\tau}\left[\left(1-x^2(\tau)\right)\nu(\tau)\right] = \begin{cases} 0, & 0<\tau<\tau_s, \\ -\dfrac{I^2(\tau)}{x(\tau)} + \alpha x^{-7/3}(\tau), & \tau_s<\tau, \end{cases}$$

$$\frac{dU(\tau)}{d\tau} = -\beta I(\tau),$$

$$\frac{dI(\tau)}{d\tau} = U(\tau) - \gamma I(\tau),$$

where normalized time $\tau = \frac{t}{t_1}$ and normalized variables for the outer plasma sheet position $x = \frac{r}{r_0}$, sheet velocity $\nu = \frac{t_1 V}{r_0}$, capacitor voltage $U = \frac{U}{U_0}$ and current $I = \frac{I}{I_1}$ have been introduced. The characteristic time $t_1 = K r_0 \sqrt[4]{A N_0}\sqrt{\frac{L}{U_0}}$, where $K^2 = c\sqrt{\frac{\pi m_u}{2}}$ ($c = 2.9\times10^{10}$ cm s^{-1}, $m_u = 1.6\times10^{-24}$ g) and characteristic current $I_1 = \frac{U_0}{L_0}t_1$ are the principal dimensional characteristics. Separation time τ_s is defined by the equation $I^2(\tau_s) = \alpha$. Shapes of the solutions are determined by the three dimensionless parameters

$$(2)\quad \alpha = \sqrt{\frac{2\pi}{\rho_0}}\frac{p_0 c L}{U_0}, \quad \beta = \frac{t_1^2}{LC}, \quad \gamma = \frac{R t_1}{L}.$$

The value of parameter α determines namely the character of the plasma column compression. For low values of $\alpha \le 0.01$, higher compression is achieved, whereas for $\alpha \to 1$ the plasma column stays almost uncompressed. The square root of parameter β is the ratio of characteristic time of plasma compression and of the period of current oscillations. If $\beta \ll 1$ the pinching time is much shorter than the current pulse duration and a linear current increase approximation is relevant one. Parameter γ is the ratio of the characteristic pinch time and circuit decay time.

Table 1. Characteristic time t_1, characteristic current I_1 and dimensionless parameters α, β, γ, for $r_0 = 0.05$ cm, $U_0 = 45$ kV, C = 15 nF, L = 48 nH, R = 0.8 Ω (see [3]) and for two initial atom densities N_0.

N_0 [cm^{-3}]	t_1 [ns]	I_1 [kA]	α	β	γ	Fig.
5×10^{18}	18.2	17.2	0.042	0.458	0.33	2a
1×10^{19}	21.6	20.5	0.060	0.648	0.36	2b

Results

If the filling atom density N_0 (or initial pressure p_0 or mass density ρ_0) is changed, the characteristic time t_1 and all the dimensionless parameters are changed, see Table 1.

Fig. 2a and 2b demonstrate the pinch evolutions for the two mentioned initial densities $N_0 = 5\times10^{18}$ cm^{-3} and $N_0 = 10^{19}$ cm^{-3}, respectively. For lower initial atomic concentrations both the plasma separation and plasma pinch time are shorter. The dependence of the pinching time on the initial plasma concentration, resulting from repeated simulations, is seen in Fig. 3. If the initial atom density N_0 is very small, the pinch is very quick, but the number of ions driven to the core is relatively small. On the other hand, if the initial concentration N_0 is too high, the plasma column, connected to

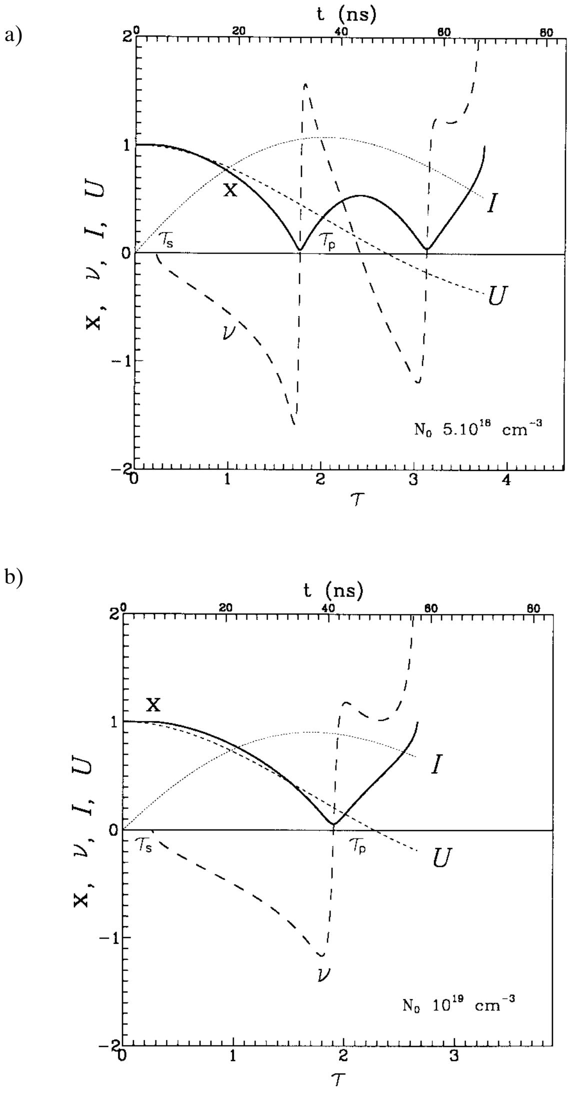

Fig. 2. Behavior of plasma Z-pinch in polyacetal capillary for ablated material density a) $N_0 = 5\times10^{18}$ cm^{-3} and b) $N_0 = 1\times10^{19}$ cm^{-3}; for other parameters see Table 1.

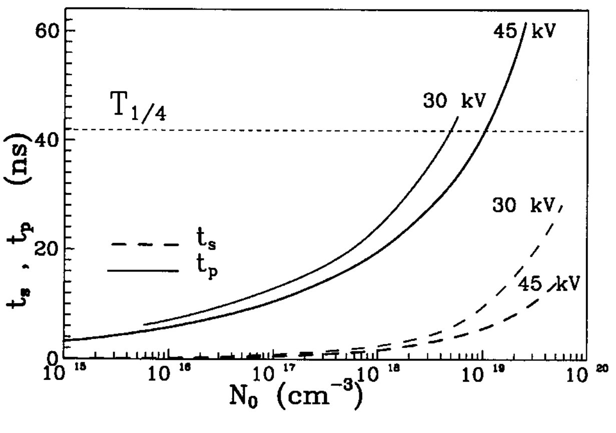

Fig. 3. Dependence of plasma separation time t_s and pinch time t_p on initial plasma density N_0 (r_0 = 0.05 cm, C = 15 nF, L = 48 nH, R = 0.8 Ω).

a given circuit, does not collapse at all. We have concluded that the optimum situation from the point of view of laser pumping occurs, if the pinching time t_p is approximately equal to a quarter of the ringing period of the resonant circuit $T_{1/4}$. According to this principle we can find an optimum initial concentration N_0 to any circuit and capillary radius. As the pinching time $t_p \cong 1.8\ t_1$ in the wide range of parameters, we judge the optimum initial concentration using condition t_1 = const. The dependence of the estimated optimum concentration N_0 on the capillary radius r_0 may be seen in Fig. 4a. Pinching and separation times t_p and t_s, calculated for the given radius r_0 and the estimated optimum initial concentrations N_0, are seen in Fig. 4b.

We conclude that the Z-pinch dynamics is very sensitive to the choice of capillary radius r_0 and initial filling density N_0. The optimum initial concentration is lower for the capillaries with larger radius, but the plasma column compression is more efficient with capillaries having larger radius. E.g. for the capillary radius r_0 = 0.025 cm and r_0 = 0.2 cm and the ratio of the radius r_p to the capillary radius r_0 is 0.266 and 0.0185, respectively. Beside this, the pinch decay is quicker for the capillaries with larger radii.

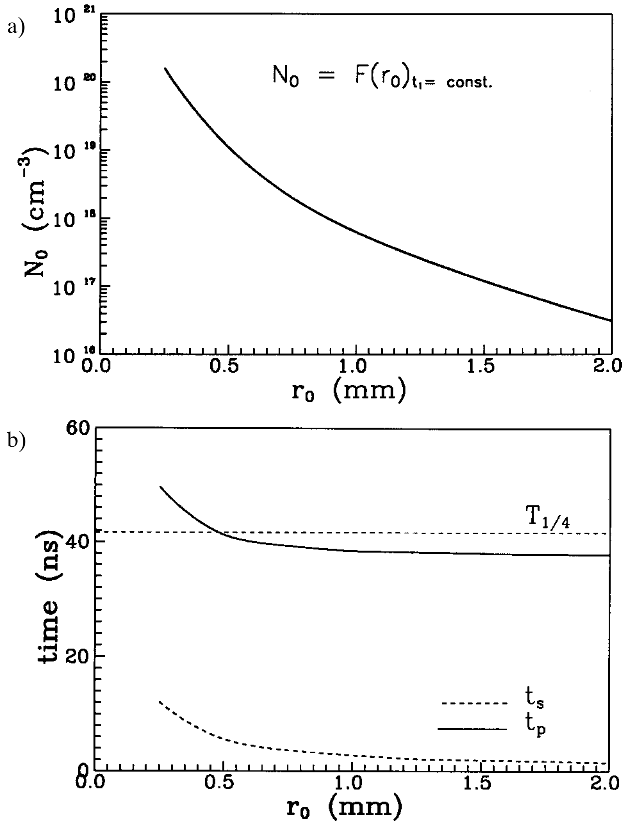

Fig. 4. Dependences of a) optimized initial plasma density N_0, b) plasma separation time t_s and pinch time t_p on capillary radius r_0, for characteristic time $t_1 = T_{1/4}$ = 42 ns.

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