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

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 (Ar8+) 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 collisional 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 C5+ 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].
system of equations, including a simple RLC circuit, may be written in the following form:

\[ \frac{dx(x)}{dt} = v(x), \]

\[ \frac{dU(x)}{dt} = -\beta I(x), \]

\[ \frac{dI(x)}{dt} = U - \gamma I(x), \]

where normalized time \( \tau = \frac{t}{t_1} \) and normalized variables have been introduced. The characteristic time

\[ t_1 = K r_0 \frac{4}{5} \sqrt{\frac{N_0}{U_0}} \frac{L}{U_0}, \]

are the principal dimensional characteristics. Separation time \( \tau_s \) is defined by the equation \( I^2(\tau_s) = \alpha \). Shapes of the solutions are determined by the three dimensionless parameters

\[ \alpha = \frac{2\pi R_0 e L I}{p_0 U_0}, \quad \beta = \frac{t_1^2}{L C}, \quad \gamma = \frac{R t_1}{L}. \]

The value of parameter \( \alpha \) determines namely the character of the plasma column compression. For low values of \( \alpha \leq 0.01 \), higher compression is achieved, whereas for \( \alpha \to 1 \) the plasma column stays almost uncompressed. The square root of parameter \( \beta \) 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 \( \gamma \) is the ratio of the characteristic pinch time and circuit decay time.

Results

If the filling atom density \( N_0 \) (or initial pressure \( p_0 \) or mass density \( \rho_0 \)) is changed, the characteristic time \( t_1 \) and all the dimensionless parameters are changed, see Table 1.

Table 1. Characteristic time \( t_1 \), characteristic current \( I_1 \) and dimensionless parameters \( \alpha, \beta, \gamma \) for \( r_0 = 0.05 \text{ cm}, U_0 = 45 \text{ kV}, C = 15 \text{ nF}, \)

\[ L = 48 \text{ mH}, R = 0.8 \text{ } \Omega \text{ (see [3])} \text{ and for two initial atom densities } N_0. \]

| \( N_0 \) [cm\(^{-3}\)] | \( t_1 \) [ns] | \( I_1 \) [kA] | \( \alpha \) | \( \beta \) | \( \gamma \) | Fig.
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<tbody>
<tr>
<td>( 5 \times 10^{18} )</td>
<td>18.2</td>
<td>17.2</td>
<td>0.042</td>
<td>0.458</td>
<td>0.33</td>
<td>2a</td>
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<tr>
<td>( 1 \times 10^{19} )</td>
<td>21.6</td>
<td>20.5</td>
<td>0.060</td>
<td>0.648</td>
<td>0.36</td>
<td>2b</td>
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Fig. 2a and 2b demonstrate the pinch evolutions for the two mentioned initial densities \( N_0 = 5 \times 10^{18} \text{ cm}^{-3} \) and \( N_0 = 10^{19} \text{ cm}^{-3} \), 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
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 cir-
cuit $T_{1/4}$. According to this principle we can find an opti-
mum initial concentration $N_0$ to any circuit and capillary
radius. As the pinching time $t_p \approx 1.8 t_1$ in the wide range of
parameters, we judge the optimum initial concentration
using condition $t_1 = \text{const}$. The dependence of the estima-
ted 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 opti-
mum 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 capillar-
ies with larger radius, but the plasma column compression
is more efficient with capillaries having larger radius. E.g.
for the capillary radius $r_0 = 0.025 \text{ cm}$ and $r_0 = 0.2 \text{ cm}$ 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.

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