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High-current capillary discharge with prepulse ablative plasma

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Generation of axisymmetric stable, long plasma channels with temperatures of 8 eV and electron densities ~10^{19} \text{cm}^{-3} by a high-current evaporating-wall capillary discharge with prepulse ablative plasma is reported. Results of spectroscopic measurements of the temperature and electron density of plasma produced in a polyethylene capillary are presented. The discharge provides a convenient source of dense highly ionized plasmas for laser-plasma interaction studies. © 2003 American Institute of Physics. [DOI: 10.1063/1.1530357]

INTRODUCTION

Propagation of high-intensity laser pulses over substantial distances is limited by the expansion of the laser spot size due to diffraction. Plasma channels are used to overcome this limitation by modifying the index of refraction so that the pulse is confined to a small spot size within the channel. The technique has been demonstrated experimentally using channels created by axicon-focused lasers and capillary discharges. Potential applications of channel-guided intense pulsed lasers include laser-driven accelerators and harmonic generators. Generation of dense long scale axisymmetrical plasmas is also important for studies of inertial confinement fusion driven by high-intensity lasers. Another area of interest is a soft x-ray source of dense highly ionized plasmas for laser-plasma interaction studies.

The obtained values were compared with those suggested by analytical and numerical models.

RESULTS

The plasma was produced by an evaporating-wall discharge in vacuum via a polyethylene (CH_2)_n capillary of 2 mm in diameter and 10 mm long. A schematic illustration of the experimental setup is shown in Fig. 1.

The discharge consisted of two stages. In the prepulse stage, a discharge was produced for a few microseconds using a delay line charged to 0.8 kV. The line consisted of three LC-cells (C = 5.5 \mu F, L = 0.4 \mu H). During this stage, the current density in the capillary scaled up to 50 kA/cm^2.

In the main stage, a capacitor of 0.6 \mu F charged to 30 kV was discharged via the capillary. The current consisted of damping oscillations (with the half period of about 1 \mu s), peak current density being on the order of 10^3 kA/cm^2. The net inductance of the discharge circuit, calculated from the oscillating rate, was found to be around 240 nH.

The discharge current (Fig. 2) was measured using a Rogowsky coil and a 300 MHz Tektronix oscilloscope. Applying a short high-voltage pulse to an auxiliary electrode situated inside the vacuum chamber triggered the prepulse stage of the discharge. Then, 2 to 3 \mu s later, the main stage was triggered by applying a similar pulse to the control electrode of an air spark gap, connected in series with the capillary. At this stage, the energy of the discharge was about 270 J. The peak current in the first half period was less than that in the second half period due to initial resistance of the air spark gap. The maximum discharge current was estimated to be about 32 kA.

We report here on the generation of dense (n_e \sim 10^{19} \text{cm}^{-3}) stable plasmas with temperatures of 7–8.5 eV using two step high-current capillary discharge. The initial low-power discharge (the pre-pulse) that ablates the capillary wall and generates low-temperature plasma is followed by a high-power discharge. The presence of the preplasma allows for the obtaining of an axisymmetric plasma column at the main stage of the discharge and provides spatial reproducibility from shot to shot. The temperature and electron density of the plasma were measured by spectroscopic methods.
IMACON-700 camera. The light of prepulse plasma was monitored in 200 ns frames separated by 800 ns. Obtained images indicated that about 2 µs after triggering the first stage, the capillary was filled with homogeneous plasma. The light of the main stage plasma was monitored in 20 ns frames separated by 80 ns. Streak photographs at the rate of 100 ns/mm were taken as well.

The temporal dependence of the plasma column diameter during both stages of the discharge is shown in Fig. 3(a). The dashed line describes the prepulse stage of the discharge, while the solid line describes the main stage. It is possible to see that in the first half period of the main stage current the plasma column diameter is substantially smaller than that of the capillary. This corresponds to the axial compression of the prepulse generated plasma, which occurs in the beginning of the main stage. The collected time-resolved images indicated that this compression was accompanied by the increasing of the discharge brightness. After a short period of ~1.2 µs, bright plasma emission filled the entire capillary diameter. The plasma column maintained axial symmetry during both stages of the discharge.

The spectra emitted by the plasma were investigated within the 200–800 nm region using the SpectraPro-275 Acton spectrograph equipped with a 1200 grooves/mm grating and a Princeton Instruments, Intensified Photodiode Array (IPDA) detector. The spectral resolution of our optical system was about 0.1 nm. The gate-on time of the IPDA detector was 200 ns. Actual sensitivity of the optical system was measured using the absolutely calibrated evaporating-wall capillary discharge.25

We observed the time evolution of intensities of the continuum and the spectral lines profiles emitted by the dis-
charge. Lines of carbon ions CII, CIII, CIV, and the Hα line of hydrogen were observed thereby.

The plasma temperature was estimated from the radiation intensity of the CIII 229.6 nm line. This line exhibits high-optical density and has the radiation intensity at its center corresponding to that of a blackbody at given plasma temperature.

The time evolution of the plasma temperature is shown in Fig. 3(b). It can be seen that the temperature is about 3 eV during the prepulse stage and rises up to 7–8.5 eV in the main stage. The radial profile of the temperature at 1.6 μs (relating to the beginning of the main stage) is shown in Fig. 4.

Electron density of the plasma was determined from the line broadening of the CII (2p22s3p2P) and CIII (2s2p1P–2p23D) emission lines. It was found to be about 2.5 × 1018 cm−3 during the prepulse stage and up to (1–2) × 1019 cm−3 during the main stage [Fig. 3(c)]. The electron density was estimated to within ±30%. It was found that the plasma parameters’ deviations due to the current oscillations are insignificant.

FIG. 4. Radial profile of the plasma temperature at 1.6 μs after the main stage has started.

DISCUSSION

Evaluations of the generated pressure have shown that under the conditions of our experiment the plasma pressure \( P_g \) is less than the magnetic pressure \( P_m \) only within the first half period of the discharge current. As more mass of the wall material gets involved in the discharge, \( P_g \) (estimated from the measured temperature and electron density) substantially exceeds \( P_m \). Detailed observation of the plasma channel evolution was conducted by means of frame and streak camera. The obtained plasma profile was relatively homogeneous, as can be seen from Fig. 4. No apparent evidences for magnetohydrodynamics (MHD) instabilities were observed.

After 20 pulses of the discharge current, the capillary diameter has increased by about 0.1 mm. Nevertheless, the temperature and electron density remained constant to within the experimental accuracy.

We performed MHD simulation of plasma dynamics in a capillary discharge taking into account wall material ablation due to the heat flux towards the wall, ohmic heating, and diffusion of the plasma across the magnetic field. In contrast to the usual MHD simulations of relatively long capillary discharges with shorter current pulses,24,27–29 we should take into account the flowing of the plasma out of the capillary ends and the axial component of plasma velocity. Moreover, because of the strong inequality \( \tau \gg l/υ_c \), we can neglect non-stationary effects and treat the discharge as quasistationary, which means in particular that the ablated mass in each moment is equal to the mass of the plasma flowing out of the capillary ends. Instead of simulation of a fully two-dimensional (2D) stationary MHD problem, considering the high-aspect ratio of the capillary, we introduced into 1D MHD equations the stream of the plasma out of the capillary, its energy, and the magnetic flux due to axial plasma velocity. To close the equations, we assumed given axial profile of plasma velocity \( v_z = 2c_e z/l \) and neglected relatively small dynamic plasma pressure \( ρv_z^2 \) in radial mechanical equilibrium of the discharge. Here, \( c_e \) is the local sound velocity, \( l \) is the capillary length, and \( z \) is the distance along the capillary axis measured from its middle. The adopted velocity profile means that axial plasma velocity at the capillary orifices is equal to the local sound velocity. We believe that this model is capable of giving satisfactory estimations of plasma parameters in the middle of the capillary. To obtain these parameters, we use a computer code that solves equations of our model by the relaxation method.

To take into account the turbulent boundary layer near the capillary walls caused by sheared axial plasma flow near the walls and strong amplification of heat and magnetic flux transport inside the boundary layer, we added the following turbulent terms to the thermal conductivity \( κ \) and to the specific plasma resistivity \( η \):

\[
κ = κ_p = Cc_v ϵ_s (r_c − r); \quad η = η_p + 4πCc_s ϵ_c^2 (r_c − r).
\]

Here, \( c_v \) is the specific heat of the plasma, \( c \) is the speed of light, \( r_c \) is the capillary radius, and \( C \) is a dimensionless coefficient, which is the same in both equations and which has been chosen to achieve correspondence to experimental data. In our case, \( C = 0.095 \). Finally, \( κ_p \) and \( η_p \) designate the coefficients determined by electron–electron and electron–ion collisions only.30 The process of ablated material ionization is described by the Saha equations assuming the relative composition 2:1 of hydrogen and carbon atoms. The plasma parameters \( κ_p \) and \( η_p \) are calculated accounting for electron collisions with both types of ions and their degree of ionization.

The mean-square value of the current during its main pulse is about 20 kA. Our simulation for the case of a 1 cm long and 2 mm diameter capillary and for this current value gives the results presented in Fig. 5. Simulated axial values of electron density (1.73 × 1019 cm−3) and plasma temperature (11.8 eV) are about 1.5 times more than the measured
values. This difference between the predicted and measured values can be a consequence of the fact that the measurements were performed for plasma situated in the vicinity of the capillary ends, whereas the model deals with the plasma parameters in the middle of the capillary. Due to the rapid expansion, the plasma parameters near the capillary ends should be lower than those in the middle, and may contribute to the experimentally observed values. It is very important that by choosing only one free parameter of the model we can achieve satisfactory simulations of two parameters—the temperature and the electron density. If the effects of the turbulent boundary layer were neglected, we would obtain from the model enormously high temperatures and low-plasma densities.

In conclusion, dense \( n_e \sim 10^{19} \text{ cm}^{-3} \) stable plasmas with temperatures of \( 7 \sim 8.5 \text{ eV} \) in a high-current evaporating-wall capillary discharge with prepulse ablative plasma have been generated. The presence of prepulse plasma allowed for the obtaining of the axisymmetric plasma column in the main stage of the discharge. This plasma column exhibited spatial reproducibility from shot to shot. The discharge provides a convenient source of dense highly ionized plasma for laser-plasma interaction studies.

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