Numerical Investigations of Initiation of Nanosecond Capillary Discharges

S. Eliseev[1], M. Timshina[2,5], A. Samokhvalov[3,5], Y. Zhao[4], V. Burtsev[2,5]

[1] *Physics Department, Saint Petersburg State University, St. Petersburg, 198504, Russia*

[2] *Ioffe Physical Technical Institute, Russian Academy of Science, St. Petersburg, 194021, Russia*

[3] *The Department of Physics and Engineering, ITMO University, St. Petersburg, 197101*

[4] *National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin, 150080, China*

[5] *"Burtsev Laboratory" limited company, St. Petersburg, 197022, Russia*

Nanosecond high-current gas discharges in extended capillaries have been actively investigated as a means of creating hot highly ionized plasma that is suitable for lazing in the extreme ultraviolet range [1-2]. Discharge-based relatively compact lasers have found application in various fields, such as lithography and surface modification and diagnostics [3-4]. Nowadays, efforts in development of such lasers are mainly focused on meeting the requirements of industrial applications.

A number of technological recommendations required for creating stable EUV lasers based on capillary discharges have been formulated over the years. One of the most crucial among them is that prior to the application of the main high-voltage pulse (with duration of a few tens of nanoseconds), the gas inside the capillary has to be uniformly preionized by a longer moderate-current pulse (20-40 A with duration under 100 μs) [1-2]. Although such necessity is more or less understood in general terms, the experimentally observed sensitivity of laser operation to prepulse parameters is yet to be interpreted in detail.

Several groups have reported existence of "optimal" preionization parameters in terms of preliminary current pulse amplitude and delay time before application of the main current pulse [5-9]. Increasing delay time or amplitude above the optimal typically led to a decrease in laser intensity [7], while decreasing below such could also lead to low shot-to-shot reproducibility and overall unstable laser operation [5]. An extreme example of the latter was reported in [10], where lasing was achieved in a non-preionized capillary discharge (similar configurations without preionization were considered in [11], a greatly decreased capillary lifetime was reported). We have performed a detailed numerical investigation of plasma dynamics during the preliminary and the main discharge stages with the goal to obtain a univocal interpretation for the available experimental data. Below a brief summary of the results obtained so far is given. Detailed discussion may be found in Refs. 12 and 13.

In order to obtain the full picture for the observed influence of preliminary ionization, it is necessary to understand the breakdown and plasma formation dynamics inside the capillary during the arrival of the high-voltage pulse. In case of a non-preionized or weakly preionized gas (no prepulse or relatively low prepulse amplitude) fast increase of potential at the powered electrode results in ionization wave, in which high electric field is localized in a small region (called "wavefront") that travels along the capillary with velocities in the range 1-10 cm/ns. An example of typical axial distributions of charged particle densities and electric field during ionization wave propagation (as obtained numerically using a fluid model of low-temperature plasma [14]) are presented in Figure 1. Due to high typical amplitudes and usually negative polarity of the applied voltage pulse in nanosecond capillary discharges, electrons are accelerated away from the wavefront, and "runaway effect" may take place. The "runaway" electrons may produce ionization far ahead of the front, potentially resulting in non-uniform and sporadic conducting regions that may short-circuit the capillary load before the main plasma channel can reach the grounded electrode. This, in turn, may result in an axially non-uniform compression dynamics of plasma as the main current pulse flows through the capillary, eventually disrupting laser generation. Also, for the case of longer capillaries the ionization wave propagation time may be comparable with the voltage pulse duration, and its considerable part could be reflected from the capillary load before the onset of conduction current.

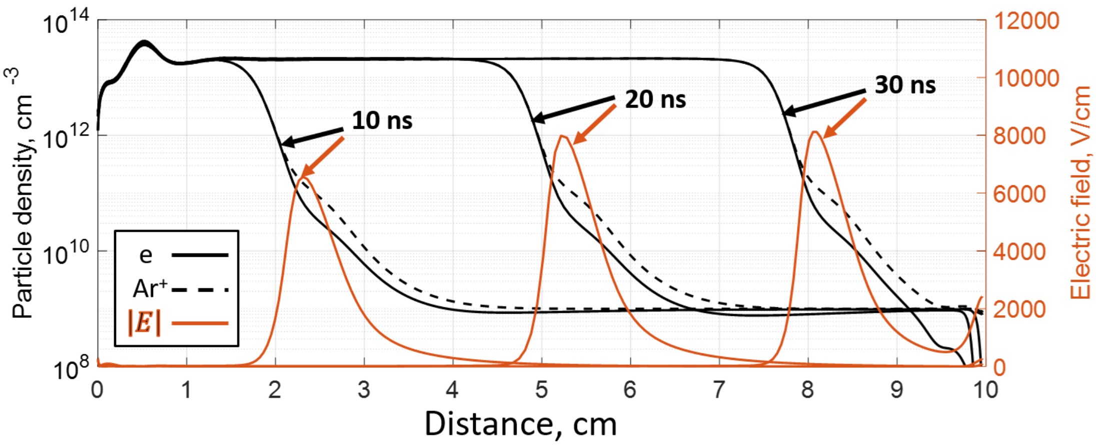

Figure 1. Longitudinal structure of an ionization wave obtained from fluid simulations of low-temperature plasma. Conditions: argon gas at 0.7 Torr, 6 kV voltage amplitude, alumina capillary with a 4 mm diameter and 10 cm length.

General trends in the dependence of ionization wave properties on experimental conditions are described in detail in [15]. Of particular importance here is that with the increase in plasma density in which the ionization wave propagates the wave velocity increases while the voltage drop in the front decreases. For this reason, increase in prepulse current amplitude results in a more uniform plasma channel at the start of the main current pulse, and less energy is reflected back from the capillary load, contributing to the increased stability and laser pulse intensity.

As prepulse current amplitude is increased further, other effects that can influence the laser intensity become important. As was demonstrated in [12], even at modest prepulse currents a redistribution of gas inside the capillary during the preionzation stage takes place, resulting in a concave radial gas density profile. This radial inhomogeneity influences the properties of the cylindrical compression shock wave during the main stage of a capillary discharge – greater radial inhomogeneity results in a less steep shock wave front. Considering that the laser pulse most likely takes place before the shock wave collapse, this results in a less concave electron density profile, increased rate of refraction losses and decreased laser intensity [13] (see, for example, the experimentally obtained structures of the laser pulse in the paper [2]).

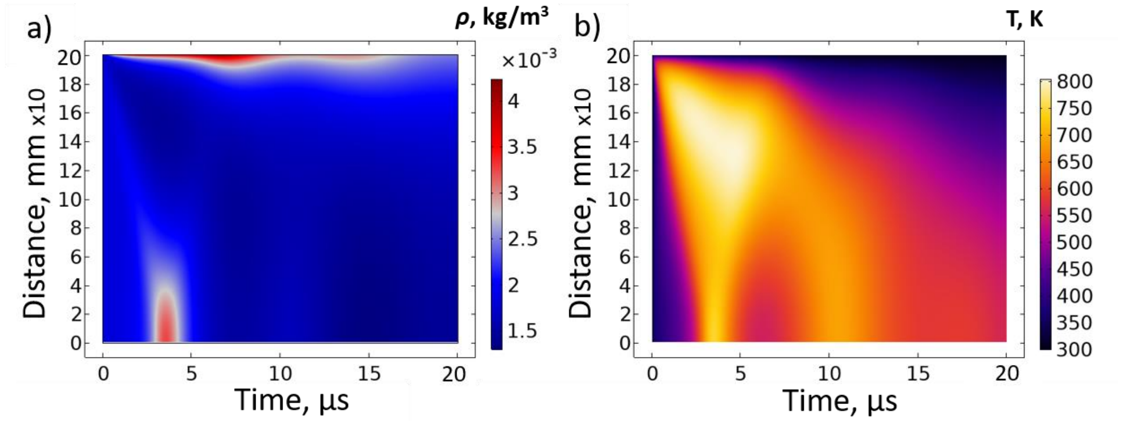

Figure 2. Calculated spatio-temporal distributions of (a) gas density and (b) gas temperature in a capillary during preionization stage. Conditions: argon at 0.7 torr, 2 mm capillary radius, current pulse with 20 A amplitude and 5 µs FWHM duration.

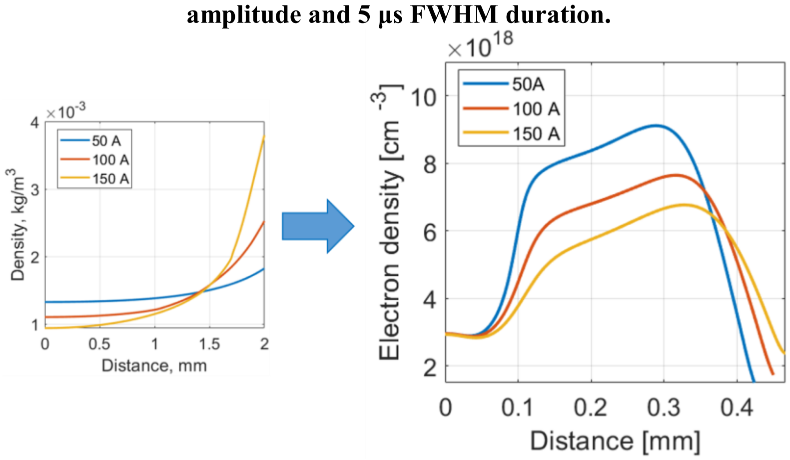

Figure 3. Simulation results for different prepulse current amplitudes: a) – plasma densities before the start of the main current pulse; b) – radial distributions of electron density before the on-axis shock wave collapse.

Another factor coming from preliminary ionization that may influence laser intensity and that has been considered in literature as the main responsible for the observed (quite different) trends is the thermal expansion of plasma through the anode aperture to the space outside of the capillary. This plasma may not be involved in the main discharge and can absorb some of the generated radiation, thus decreasing the laser intensity. However, since the plasma escape velocity increases as a squre root of temperature, this effect should start manifesting itself at longer delay times between the preliminary current pulse and the main one (see, e. g., Ref. 12).

The described above factors should all be taken into account while optimizing parameters of preliminary current pulse for EUV lasers based on nanosecond capillary discharges. From the physical point of view, however, of particular interest would be the proposed influence of initial radial inhomogeneity on the compression shock wave. The obtained results indicate that the preliminary ionization is the first controllable parameter that can be used to tailor compression dynamics to reduce refraction losses. The insight could promote search for other new ways to similarly influence the discharge to potentially increase the laser intensity and delve into shorter wave generation and amplification.

Acknowledgements

The work was supported by Russian Science Foundation (grant №20-72-00039).

References

[1] Rocca, J. J., et al, Physical Review Letters, 73(16), 2192, 1994.
[2] Tomassetti, G., et al., Optics communications 231.1-6 (2004): 403-411.
[3] Brewer, Courtney A., et al., Optics letters 33.5 (2008): 518-520.
[4] Ritucci, A., et al., Journal of Applied Physics 102.3 (2007): 034313.
[5] Niimi, G., et al., IEEE transactions on plasma science 30.2 (2002): 616-621.
[6] Sakamoto, N., et al., Plasma Devices and Operations 13.1 (2005): 67-73.
[7] Shuker, M., et al., Physics of plasmas 13.1 (2006): 013102.
[8] Tan, C. A., and Kwek., K. H., Physical Review A 75.4 (2007): 043808.
[9] Jiang, S., et al., Applied Physics B 109.1 (2012): 1-7.
[10] Szasz, J., Physical review letters 110.18 (2013): 183902.
[11] Burtsev, V. A., et al., Technical Physics 58.2 (2013): 192-199.
[12] Eliseev, S., et al., Journal of Physics D: Applied Physics 54.9 (2020): 095201.
[13] Eliseev, S., Samokhvalov, A., Zhao, Y., & Burtsev, V., "On the Mechanisms of Influence of Preliminary Ionization on the Plasma Dynamics of Nanosecond Capillary Discharges and the Properties of Discharge-based EUV Lasers", to be published.
[14] Timshina, M., et al., Journal of Applied Physics 125.14 (2019): 143302.
[15] Vasilyak, L. M., et al., Physics-Uspekhi 37.3 (1994): 247.