Investigations of Nanosecond Capillary Discharges as Water Window X-ray Sources

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Soft X-ray microscopy of biological objects is based on the use of X-ray radiation in the "water window" – the wavelength range from 2.3 to 4.4 nm. In this range, water is transparent to X-rays, while carbon (and organic compounds) absorbs it, which makes it possible to visualize the internal structure of cells *in vivo* [1,2]. The current level of development of the methods of X-ray microscopy and nanotomography has been mostly achieved with extremely expensive and bulky sources of synchrotron radiation. Achieving a comparable level of image quality and detalization but with simpler and more accessible soft X-ray sources could lead to a great progress in a number of fields in biology and medicine [3].

As potential water-window radiation sources nanosecond capillary gas discharges of specific configurations have been considered [3-6]. Great expectations have been placed on developments of gas-discharge sources of EUV radiation for lithography applications. However, shorter wavelengths require drastically different discharge conditions. And although X-rays in the "water window" and first magnified images have been obtained using capillary discharges in nitrogen [6-8], the current state of development of such sources is far from meeting the requirements set by nanotomography methods. In "Burtsev Laboratory" we perform research into nanosecond capillary discharges with the goal of creating a feasible prototype of a light source that would be suitable for visualization of the inner structure of living cells. Here we present some of the preliminary results of the systematic investigations of electrical and emissive properties of nanosecond capillary discharges and demonstrate the possibility of achieving line radiation within the "water window" range using a compact discharge setup.

Experimental studies were carried out using an experimental setup presented in Figure 1, which allows varying external conditions in a wide range, both in terms of the type and pressure of the carrier gas or gas mixtures used, as well as the internal configuration and geometry of the discharge chamber.

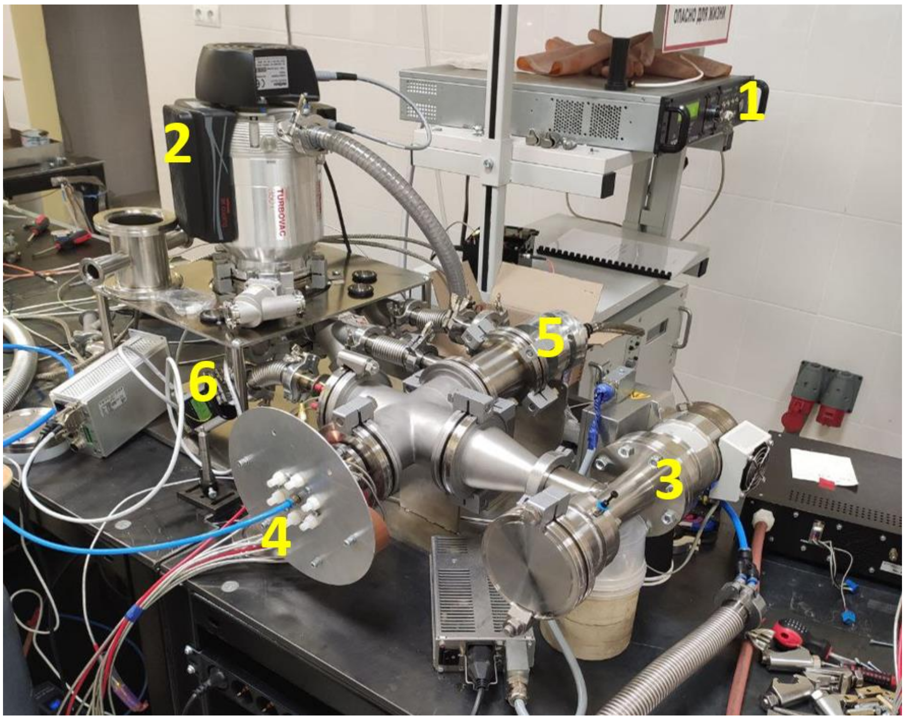

Figure 1. Experimental setup at "BurtsevLab": 1 – high-voltage power supply; 2,3 – pumping system; 4 – capillary load (cathode entry); 5 – EUV spectrometer (GIS-2); 6 – pressure sensor.

In the setup, the electrode system of compact geometry is enclosed in an alumina tube. Gas is fed through the opening in the cathode, goes through the capillary and is then pumped out by a vacuum system, creating a longitudinal gas density gradient. Power is supplied through a long cable line from a pulse generator based on ceramic capacitors charged with a high-voltage source and switched by a thyratron TPI1-10k/50. The voltage pulse at the entrance to the capillary load is recorded using a high-voltage divider. The measurement of the current pulse is carried out using a current sensor – a Rogowski coil – located in the connection node of the capillary and the return cable. The study of the temporal parameters of radiation is carried out using a fast photodiode (time resolution ~1 ns) and a set of X-ray filters (free-standing thin metal films). It is possible to vary the sharpening capacity (connected in parallel with the capillary load) to obtain the optimal combination of the current amplitude and its growth rate. Sample current, voltage and photodiode signals are presented in Figure 2a (see the caption of the figure for experimental conditions). Current pulses with 40 ns duration and amplitude as high as 20 kA could be obtained in a capillary of 1.5 mm diameter, which is among the highest reported for similar discharge configurations [4,5].

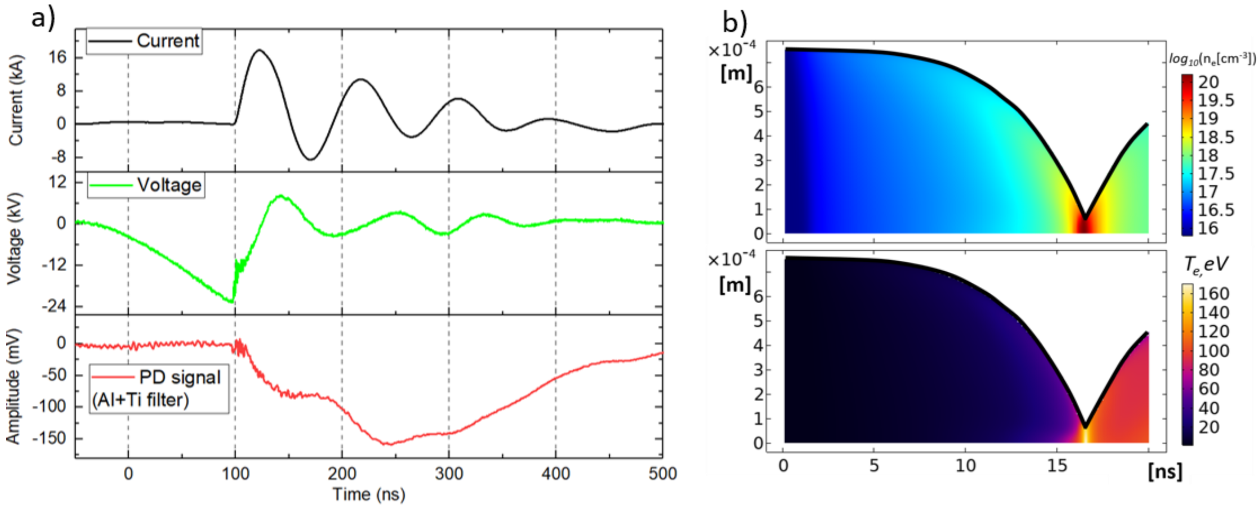

Figure 2. a) – current, voltage and photodiode signals recorded in a capillary discharge in argon at conditions: 1 Torr inlet pressure, 0.02 Torr exit pressure, 20 mm interelectrode distance, 1.5 mm capillary diameter; b) – MHD estimations of plasma dynamics (electron density and electron temperature) for conditions close to experimental: uniform pressure of 0.5 Torr, current pulse with 50 ns duration and 15 kA amplitude.

Systematic experimental studies are complimented with self-consistent numerical MHD simulations of discharge dynamics that are used to make estimates of plasma properties for given discharge conditions which help interpreting experimentally obtained trends. An example of such estimates is presented in Figure 2b.

Spectral characteristics of the radiation in the range from 2 to 50 nm are examined using an X-ray spectrometer of grazing incidence (GIS-2), installed through the differential pumping unit. Emission spectrum of the discharge in argon is presented in Figure 3a. A number of well-pronounced lines within the water window range were observed.

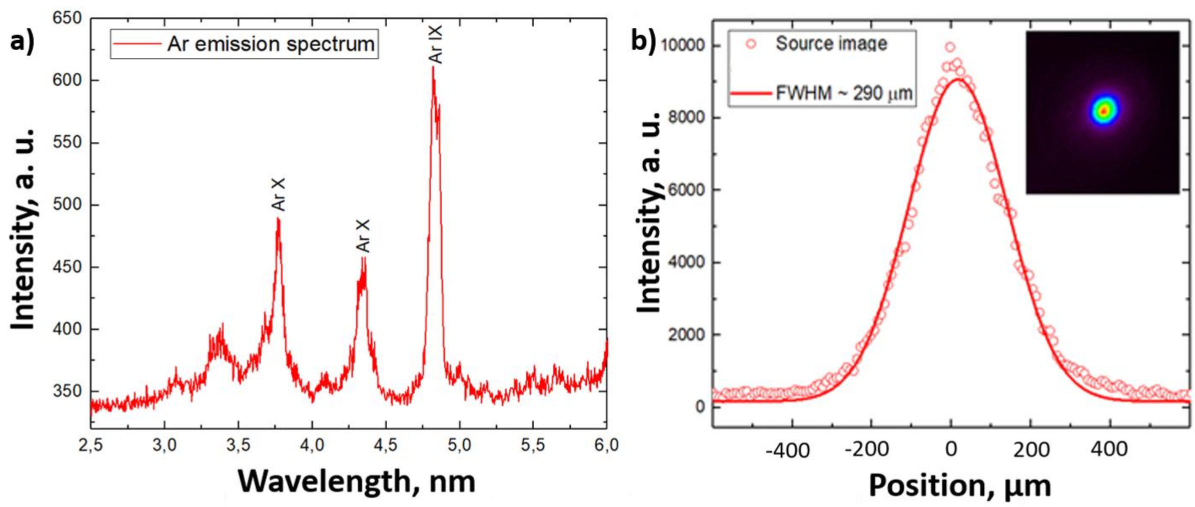

Figure 3. a) – spectra of a discharge in argon (2 Torr inlet pressure, 0.02 Torr exit pressure, alumina capillary with 1.5 mm diameter, 20 mm interelectrode distance; b) – snapshot image and intensity distribution of the source recorded through a combination of filters using a CCD camera.

Pinhole camera method was used for measurements of beam spatial distribution. A snapshot of the source taken through a combination of aluminum and titanium filters using the back-thinned CCD camera Greatyes GE 1024x1024 BI UV1 is presented in Figure 3b.

Thus, experimental results obtained for argon demonstrate good prospects of the developed discharge-based source for efficient generation within the water window range. Other gases and gas mixtures are currently being investigated as potential candidates for soft X-ray generation with the goal of establishing the final source parameters for manufacturing the optical system required for imaging.

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