Study of a discharge created by radiation from a terahertz free electron laser in a nonuniform gas flow

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This paper presents the results of a study of a discharge in a nonuniform flow noble gases (argon) created in a focused beam generated by a terahertz free electron laser (FEL) (frequency 2.3 THz). Data were obtained on the ranges of background gas pressures and gas injection rates at which the development of a discharge is possible. The dynamics of the discharge glow were studied in various wavelength ranges over a wide pressure range. It has been demonstrated that the plasma glows not only during FEL pulses, but also in the intervals between pulses of heating electromagnetic radiation.

Keywords: Terahertz radiation, gas discharge, ultraviolet radiation.

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The examination of gas discharges in quasi-optical beams of high-power electromagnetic radiation in the terahertz (THz) frequency range is relevant to a wide range of fundamental and applied research. Experimental studies of such discharges have become possible only recently due to the advent of unique and reliable sources of high-power radiation: gyrotrons and THz free electron lasers [1–3]. These studies are of interest primarily from an applied standpoint, since dense discharge plasma may serve as an intense source of optical, ultraviolet, and extreme ultraviolet radiation [4]. For more details, see review [5]. In the present study, we report the results of examination of a discharge arising in a focused beam generated by a THz free electron laser in a non-uniform flow of inert gas (argon).

The diagram of introduction of THz radiation of a free electron laser into the discharge chamber is shown in Fig. 1. Radiation of the Novosibirsk free-electron laser (FEL) (wavelength, 130 μm; pulse duration, 100 ps; pulse repetition rate, 5.6 MHz; maximum average power, 200 W) was introduced into discharge chamber *1* through diamond window *2* positioned at the Brewster angle in the focal waist of the mirror introducing radiation into the chamber. The optical system in the discharge chamber, which featured three parabolic (*3–5*) mirrors and a single planar one (*6*), then focused FEL radiation to a spot between mirrors *4* and *5* with a minimum transverse size (the width at half maximum of a Gaussian beam for radiation with a wavelength of 130 μm was close to 0.3 mm).

The discharge luminosity was examined within different wavelength ranges using an MS 5204i monochromator spectrograph (SOL Instruments). A grating with a density of 1800 lines per 1 mm (dispersion, 1 nm/mm; blaze wavelength, 280 nm) was used as a dispersion element. An HS 102H CCD camera (OOO Proscan) with a sensitivity range of 200–1100 nm was the detector. With a spectrograph entrance slit width of 40 μm, the instrument line width calibrated against a mercury lamp was 0.7 Å. Diagnostics of the discharge glow was carried out through an optical quartz glass port in the discharge chamber.

A discharge was ignited in a jet of inert gas introduced into the discharge chamber volume. Gas was injected transversely to the FEL beam between two focusing parabolic mirrors *4* and *5* (see the inset in Fig. 1) through an opening 300 μm in diameter in water-cooled copper tube *7*. A gas jet was introduced into the discharge volume under a high pressure (1–6 bar). The background gas pressure in the chamber could be adjusted within a wide range (0.05–1.5 bar) by varying the rate of discharge chamber evacuation by a forevacuum pump.

It was established in these experiments that a stable discharge in an argon jet injected into a buffer volume of the same argon may be maintained at buffer gas pressures of at least 0.15 bar and a maximum FEL power of 200 W. At lower powers, the buffer gas pressure threshold increases.

An example spectrum of a discharge in an argon jet is presented in Fig. 2, *a* within the 260–275 nm wavelength range. The background gas pressure in the discharge chamber volume is 0.35 bar, and the pressure in the line of gas injection into the chamber is 4 bar. The exposure time was 500 ms. Along with the Ar II lines, the Ar III and Ar IV lines (identified using the NIST database [6]) are found within this range. Therefore, this spectral section was chosen in order to monitor changes occurring in it under varying experimental conditions (adjustment of background gas pressure and distance from the gas target to the focal point of FEL radiation, addition of nitrogen, etc.). The main focus was on the intensity ratio of the Ar III line (269.4 nm)

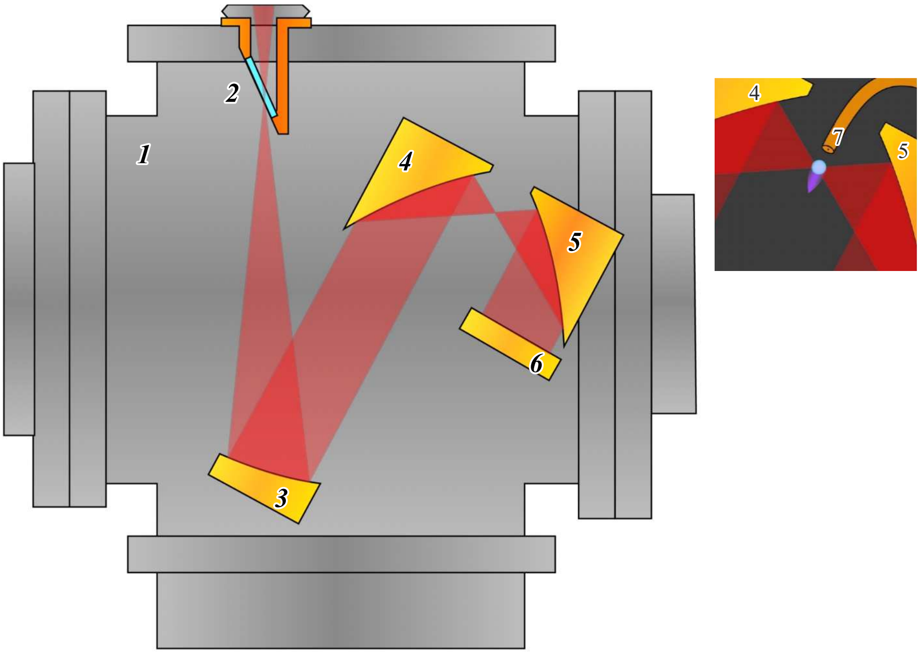

Figure 1. Discharge chamber (*1*) and diagram of FEL radiation input into it. *2* — Input window made of CVD diamond, *3* — 30° rotating mirror, *4* and *5* — 90° focusing mirrors, *6* — planar mirror, and *7* — gas injection tube.

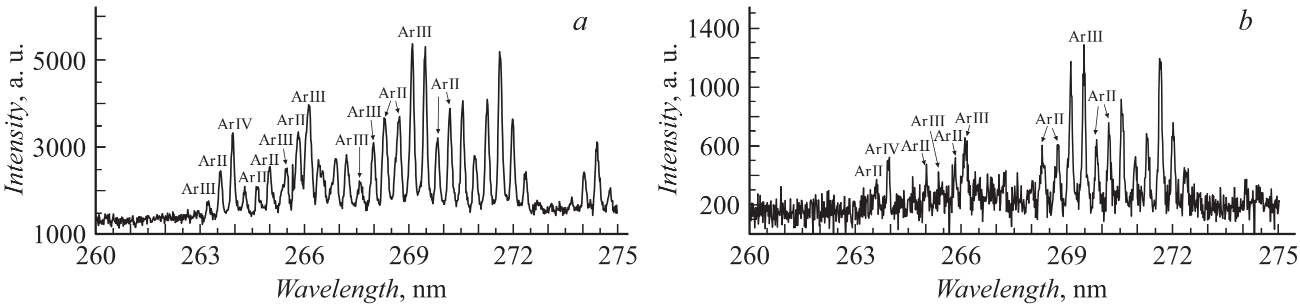

Figure 2. *a* — Spectrum of a discharge in an argon jet within the wavelength range of 260–275 nm (gas pressure in the discharge chamber, 0.35 bar; average FEL power, 200 W); *b* — spectrum of a discharge in an argon and nitrogen mixture within the 260–275 nm range (argon pressure in the injection line, 4 bar; background pressure of argon with added nitrogen, 0.3 bar; target–focus distance, 4 mm; average FEL radiation power, 200 W).

and the neighboring Ar II lines (269.7 and 270.17 nm). The examination of discharge luminosity at different distances from the gas target (shifted by a stepper motor) to the FEL radiation focus revealed that the highest ratio between the Ar III and Ar II lines could be maintained at a distance of 4 mm. The optimum background gas pressure (at an Ar III/Ar II ratio of 2.2) was 0.35 bar.

It should be noted that at sufficiently high background pressures, the discharge was largely shifted from the focus of electromagnetic radiation to the region in front of it (in the direction opposite to incident electromagnetic radiation); i.e., it was localized primarily in standing gas instead of the jet, since a high pressure is the optimum one for unassisted breakdown of gas in the THz frequency range (1.5 bar at 2.3 THz). The discharge was approximately 1 cm in diameter in this case. Reducing the background pressure by increasing the evacuation rate alongside with intensifying the gas injection into a jet, we managed to maintain a discharge precisely in the gas jet (at background gas pressures below 0.5 bar for maximum power). The discharge was then largely localized in the focal region of electromagnetic radiation. However, its diameter (several millimeters) was still significantly larger than the focal spot of heating radiation.

In order to make the breakdown conditions in the entire discharge chamber (except for the focal spot) less favorable and, consequently, scale down the discharge region while improving the energy input into the discharge, a small (less than 10%) amount of added nitrogen was introduced into the chamber. It should be noted that nitrogen was added

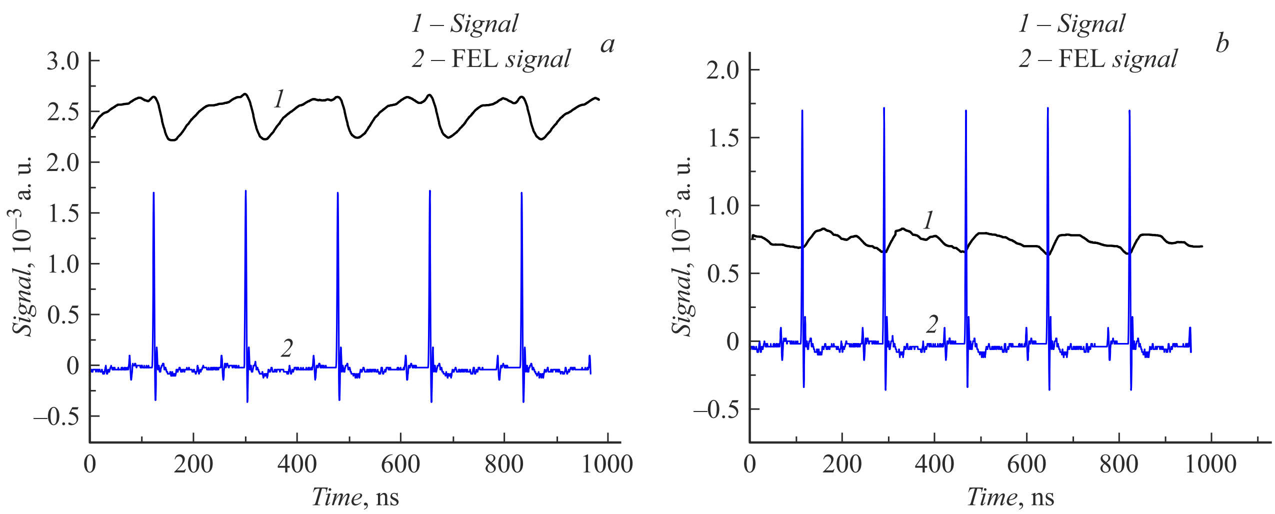

Figure 3. Time dependence of the photodiode signal (*1*) and the FEL radiation signal (*2*). *a* — Discharge in an argon jet; *b* — discharge in an argon jet with nitrogen added to the argon buffer volume.

directly into the discharge chamber through a separate injection line (i.e., not through the gas target together with argon).

Compared to the discharge in pure argon, the discharge with added nitrogen was more point-like and virtually did not move toward FEL radiation. Although the nitrogen addition was relatively small, an orange „plume" produced by the first positive nitrogen system in a hot gas jet was clearly visible. The second positive nitrogen system was more pronounced in the central („hotter") region of the discharge.

As in the case of the discharge in pure argon, the main focus was on the 260–275 nm range that contains a fairly large number of Ar II, Ar III, and Ar IV lines. When this part of the point discharge radiation spectrum was observed, the setup was fine-tuned to achieve the maximum possible ionization multiplicity of ions (in this case, argon ions).

Figure 2, *b* shows the 260–275 nm section of the discharge spectrum in an argon and nitrogen mixture recorded in the case when the intensity ratio of the Ar III line (269.4 nm) and the neighboring Ar II lines was at its maximum of 2.8 (the argon pressure in the injection line was 4 bar, the background pressure of argon with added nitrogen was 0.3 bar, the distance from the target to the focus was 4 mm, the average FEL radiation power was 200 W, and the exposure time was 500 ms). This section of the spectrum is convenient, among other things, in that it lacks intense molecular bands of the second positive system of nitrogen, which could overlap with the glow of atomic lines of argon. Thus, the addition of nitrogen made it possible to raise the Ar III/Ar II ratio from 2.2 to 2.8.

The temporal dynamics of the discharge in an argon jet injected into the buffer volume of gas in the discharge chamber was studied. The discharge glow was examined using a fast UPD-500-UP detector produced by Alphalas (170–1100 nm) with a rise time shorter than 0.5 ns. When the detector was connected to the oscilloscope, the load resistance was 50 Ω; therefore, the time constant in the measurement circuit was at the level of 5 ns. Since the interval between adjacent pulses at a FEL pulse repetition rate of 5.6 MHz is approximately 180 ns in length, it exceeds significantly both the time constant in the measurement circuit and the detector response time. It can be concluded that this setup allows one to trace in detail the dynamics of plasma glow between FEL pulses.

As before, it was demonstrated that plasma glows not only during FEL pulses, but also in the intervals between the pulses of heating electromagnetic radiation. It turned out that the discharge in the argon jet injected into a buffer volume of pure argon and the discharge in the argon jet injected into a volume of argon with added nitrogen have different temporal dynamics.

Figure 3, *a* shows the time dependences of the detector signal (upper beam *1*) and the FEL radiation signal (lower beam *2*). A strong „base" of discharge glow is clearly visible at all times (even between FEL pulses). It is also seen in spectra (see, e.g., Fig. 2). As before, we associate it with recombination radiation, primarily that of neutral argon atoms. With the arrival of FEL pulses, the electron temperature increases, which leads to „suppression" of recombination radiation, since its constant decreases with increasing temperature [7]. The discharge in the argon jet injected into a volume of argon with added nitrogen has the opposite dynamics: the discharge glow intensifies with the arrival of FEL pulses (Fig. 3, *b*). We currently associate such dynamics of glow with the fact that the glow of a point discharge observed in an argon jet with nitrogen added into the volume of the discharge chamber (and not into an argon jet, as was formerly the case) is dominated by line emission instead of recombination radiation, which naturally intensifies with the arrival of FEL pulses.

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Conflict of interest

The authors declare that they have no conflict of interest.

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