Powerful source of VUV-UV radiation based on nanosecond volumetric discharge

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\textbf{Abstract.} The radiation of a volumetric gas discharge in xenon, excited by a compact high-current (5 kA) high-voltage (about 300 kV) sub-nanosecond generator, was investigated using a fast pin-diode. It was shown that the radiation lies mainly in the range of the vacuum ultraviolet with a wavelength of less than 200 nm, and the radiation intensity does not depend on the pressure of the working gas in the investigated range of 0.1–3.0 atm.

1.  Introduction
An important direction of development of high-power laser complexes is the development of systems based on amplifying femtosecond pulses at a wavelength of 248 nm (the third harmonic of a Tr.Sa laser) in the active medium of KrF gas mixture [1]. These laser gas amplifiers operate at low gas pressures and, as a consequence, they have large volumes of gas active media. For the preionization of the KrF mixture, high-current electron beams with a wide aperture are used [2], which makes it possible to significantly increase the pressure of the gaseous medium (up to 3 atm) and, respectively, reduce the size of the laser.

A volumetric nanosecond UV pulse with a power of up to 5 GW was achieved in a gaseous environment of xenon (Xe) at a pressure of 3 atm [3]. Nanosecond electron-beam gas ionization in the working volume is very effective. But at the same time, the concomitant bremsstrahlung requires radiation protection of personnel, which complicates the design and worsens the operating parameters of powerful nanosecond VUV-UV generators and lasers.

In subsequent experiments, the preliminary ionization of the working medium in this system used a volumetric gas discharge formed by an auxiliary subnanosecond high-voltage discharge, which made it possible to improve the operating parameters of the generator while maintaining the output UV power [4].

Preliminary experiments showed that the main radiation of this discharge lies in the UV and VUV ranges. This discharge is also of own interest as a source of short-wave radiation for various applications. Therefore, the objective of this work is to study the ratio of the radiation intensity in these spectral ranges and its dependence on the pressure of the working gas.
2. Experimental details and discussion

The generator is a single coaxial design with low inductance (figure 1), consisting of a discharge chamber, a forming line in traveling wave mode, and a small-sized high-current subnanosecond high-voltage generator. The discharge chamber consists of a cylinder-hemispherical electrode, which forms an optimal distribution of the electric field in the discharge volume and a high-voltage ceramic insulator. The forming line is a design with variable geometry, while part of the line is connected to the output of the nanosecond spark gap of a high-voltage high-current generator. The small-sized subnanosecond (0.1–1 ns) high-current (5 kA) high-voltage (150–300 kV) pulsed generator, operating with a pulse repetition rate of 0.1–12.5 Hz (figure 1), is made according to the Tesla resonant generator circuit, where the capacity of the output nanosecond contour is divided and its equal components form a two-stage Marx generator.

The outer plate of the second stage of the Marx generator additionally performs the function of a matching line, which has a special coaxial design and provides a traveling wave mode. The design of the capacitors ($C_1$ and $C_2$) of the Marx generator, in contrast to [5], allows changing their capacitance to adjust the duration of the discharge pulse.

The capacitors were pulse-charged to (0.7–0.8) voltage amplitude at the first half-wave of Tesla generator operation, which significantly increases the dielectric strength of the insulating elements of the structure. These measures made it possible to reduce the size of the generator and, accordingly, reduce the energy losses in the skin layer and the parasitic inductances of the structure. The generator is discharged to the load from the bulk plasma arising in a gaseous medium with an adjustable cathode–anode distance in the range of 8–12 mm.

The dynamic resistance $R_i(t)$ of spark gaps ($T_2$, $T_3$) is significantly reduced by applying a gas H$_2$+Ar mixture at a pressure of 45 atm. The mode of high-current volume discharge in air at atmospheric pressure [4] was achieved by an experienced selection of $C_0$, $U_1$ values and adjustment of the discharge circuit capacitors ($C_1$ and $C_2$).

The discharge radiation was recorded by an open fast pin-diode FDUK-1UVSKM (Technoexan, Russia) in the energy range of 1–10$^4$ eV using a Tektronix TDS3032B oscilloscope with a time resolution of about 1 ns. The diode was placed on the axis of the discharge in a sealed tube, coupled with the discharge chamber, at a distance of 1.5 cm from the discharge gap. A typical signal of the diode is shown in figure 2.
Figure 2. Waveform of the VUV-UV pulse emitted by a volumetric discharge in Xe gas at a pressure of 3 atm.

Previously performed test experiments allowed to establish that in the volumetric discharge mode, plasma emission is observed only in the VUV-UV spectral range. A different picture was observed in the streamer discharge mode. In this case, the spectrum of less intense radiation of the streamer plasma is in the visible range. Such a significant difference in the energy and spectral characteristics of the volume and streamer modes of discharge is explained by the magnitude of the discharge volume. The streamer has a cross section of 1–3 mm, a large length and a small discharge volume. Consequently, the resistance of the streamer to the discharge current is significant; the discharge duration due to the discharge capacity of the generator reaches 300 ns, as a result, the discharge power drops sharply. Moreover, since the radiating volume of the streamer is small, the unexcited volume of gas effectively absorbs the VUV-UV radiation of the streamer and its spectrum is observed only in the visible spectral range. On the contrary, for the case of a volumetric mode of the discharge, with the same dimensions of the working gas volume, the plasma emitting volume exceeds a few orders of magnitude the emitting volume of the streamer. In this case, the dynamic resistance of a volumetric discharge becomes negligibly small, the discharge duration is less than 1 ns and its power is more than four orders of magnitude higher than the power of radiation of the discharge in the streamer mode.

Figure 3. The dependence of the intensity of VUV-UV pulses emitted by a volumetric gas discharge in Xe. Measurements are made with the open input window of the diode (1) or through the filter UFS-1 (2).

Measurements of the radiation of the plasma in the VUV and UV regions were carried out either with the detector window open or with the use of a UFS-1 optical filter that transmits radiation in the UV
spectral range (210–420 nm). In the former case, 10 MW radiation is recorded in the full spectral range of the sensitivity of the diode (VUV and UV); in the latter case, only radiation in the specified UV range was recorded. It can be seen from figure 3 that, firstly, the intensity of the radiation of a plasma in the VUV region is 7 times higher than the intensity of radiation in the UV range and, secondly, that the output of VUV and UV radiation from a bulk plasma in a gas discharge is practically independent of pressure in the range of values of 0.1–3.0 atm.

3. Conclusion

The experimental results show that, firstly, the main part of the radiation of this discharge lies in the VUV range. Secondly, the absence of dependence of the radiation intensity on the gas pressure allows us to assume that during a high-current volumetric discharge burning, a plasma pressure in the field of emission of radiation, which, in fact, determines the intensity and spectrum of radiation, at least an order of magnitude, exceeds the measured average pressure in the working volume, therefore, its change does not affect the intensity and spectrum of radiation. Thus, we can conclude that this discharge is an effective source of high-intensity VUV radiation.

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