

LASER APPLICATIONS AND OTHER TOPICS IN QUANTUM ELECTRONICS

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Repetitively pulsed UV radiation source based on a run-away electron preionised diffuse discharge in nitrogen

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Abstract. **An extended repetitively pulsed source of spontaneous UV radiation is fabricated, which may also be used for producing laser radiation. Voltage pulses with an incident wave amplitude of up to 30 kV, a half-amplitude duration of ~4 ns and a rise time of ~2.5 ns are applied to a gap with a nonuniform electric field. For an excitation region length of 35 cm and a nitrogen pressure of 30–760 Torr, a diffusive discharge up to a pulse repetition rate of 2 kHz is produced without using an additional system for gap preionisation. An investigation is made of the plasma of the run-away electron preionised diffuse discharge. Using a CCD camera it is found that the dense diffused plasma fills the gap in a time shorter than 1 ns. X-ray radiation is recorded from behind the foil anode throughout the pressure range under study; a supershort avalanche electron beam is recorded by the collector electrode at pressures below 100 Torr.**

Keywords: *extended UV radiation source, repetitively pulsed regime, run-away electron preionised diffuse discharge, radiation of second positive nitrogen system, runaway electrons, X-ray radiation.*

1. Introduction

At present, research and development of laser and spontaneous radiation sources of different spectral regions in which increased-pressure gases are used as a working medium are being continued [1–3]. To produce a volume discharge at an increased pressure, use is made of discharges formed due to preionisation by additional sources [4, 5]. In recent years it has been shown that high-efficiency lasers [6, 7] and UV and VUV radiation sources with a high pulsed power [8–12] can be made with the use of a run-away electron preionised diffuse discharge (REP DD). However, in lasers and spontaneous radiation sources excited by a REP DD use is usually made of a single-pulse regime. To obtain a REP DD at a high pulse-repetition rate f, it is necessary to lower the pump energy in a single pulse and shorten its duration. A repetitively pulsed REP DD regime without gas circulation through the gap was realised in Refs [13–16]. In Refs [13, 14] the diffusive nature of discharge with increasing interelectrode gap d was provided by lowering the amplitude of current through the discharge gap and the specific energy input. The authors of Refs [15, 16] reported the development of miniature lamps emitting radiation of the second positive nitrogen system and the lines of electrode material. The radiating discharge volume was equal to ~1 mm^3 and the pulse-repetition rate amounted to 1 kHz. The REP DD regime for f = 1 kHz was attained by decreasing the amplitude and duration of the voltage pulse as well as the size of the excited domain. However, investigations of repetitively pulsed spontaneous UV radiation sources for a specific REP DD excitation power above 1 MW cm^{-3}, $f \geqslant 1$ kHz and $d \geqslant$ 0.5 cm have never been carried out.

The aim of our work is to make and investigate an extended UV radiation source based on the excitation of increased-pressure nitrogen by a repetitively pulsed discharge.

2. Experiment equipment and measurement techniques

To produce a REP DD in our experiments, we used a four-channel FPG-60 generator [17], which was connected to gas-discharge gaps by one or four cables 4 m in length. The voltage amplitude of the incident wave in the transmitting line (a cable with a wave impedance of 75 Ω) could be varied between 0 and 30 kV. To investigate the discharge and radiation parameters in a broader range of experimental conditions, use was made of two discharge chambers with different cathode designs and different discharge gap dimensions. The cathodes had a small radius of curvature, which enhanced the electric field at macro- and micro-inhomogeneities. In the first discharge chamber (Fig. 1) with an excitation region of length ~35 cm, 50 or 100 steel sewing needles 0.7 mm in diameter served as cathodes; they were attached to one conductor and arranged respectively in one or two rows. The anode had rounded edges and was made of a part of a stainless steel cylinder of radius 7 cm. The interelectrode gap could be varied between 6 and 21 mm. Four identical voltage pulses were delivered from the FPG-60 generator to the cathode of the first discharge chamber via four cables. The delay between the pulses applied to the cathode via different channels was shorter than 1 ns. The chambers were filled with

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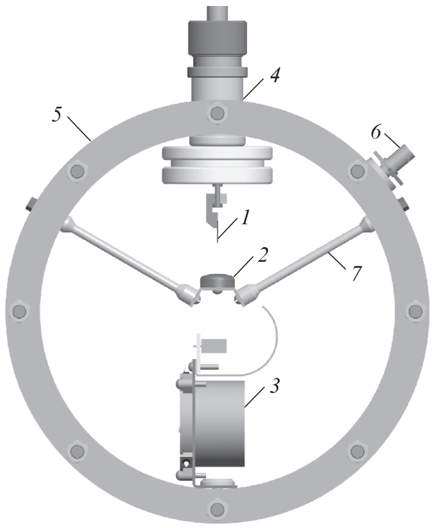

Figure 1. Structure of the first discharge chamber: (*1*) cathode of needles; (*2*) anode; (*3*) fan; (*4*) high voltage lead-in; (*5*) chamber body; (*6*) lead for measuring shunt current; (*7*) return current lead-out.

nitrogen with an impurity content of less than 0.01%. The gas under investigation could be pumped through the discharge gap by a fan with a velocity of up to 20 m s^{-1}. The discharge plasma radiation was recorded through the windows on the end flanges.

Voltage pulses were delivered to the second discharge chamber via one cable; the remaining three were connected to 75-Ω resistors. Accordingly, for the same voltage the power released in the discharge gap was 4 times lower than in the first discharge chamber. Two cathodes were used: a cylindrical tungsten cathode 0.3 mm in diameter and a tubular stainless steel one with a 6-mm diameter and a wall thickness of 0.2 mm. The anode was flat and was made of aluminium or copper foil. This permitted recording X-ray radiation and the supershort avalanche electron beam (SAEB) behind the anode. The interelectrode gap could be varied from 1 to 12 mm. In the second chamber there was no system for nitrogen circulation through the discharge gap, which initially gave rise to instability of discharge plasma position in the gap with increasing pulse repetition rate and voltage amplitude. On further increase in these parameters, we observed discharge contraction. However, for relatively low voltage pulse amplitudes and repetition rates, a diffusive discharge was formed in the gap, like in Refs [15, 16].

The temporal shape of radiation pulses was recorded with a fast-response Photek PD026 Solar Blind photodiode and a FEK-22 SPY photodiode located at respective distances of ~3.5 and 7.4 cm from the output window on the end flange of the first discharge chamber. The discharge emission spectra were recorded with EPP2000C-25 (StellarNet-Inc., an operating range of 195–850 nm) and HR4000 (Ocean Optics B.V., an operating range of 200–300 nm) spectrometers with known spectral responsivities. The integral discharge glow was recorded with a digital Sony A100 photographic camera. The discharge dynamics was recorded with an HSFC-PRO CCD camera. The discharge current was measured using a shunt made of chip resistors. The runaway electron beam behind the foil was recorded with a collector and the voltage pulses were measured with an ohmic (the first chamber) or capacitive (the second chamber) divider. A digital DPO70604 (6 GHz, 25 GS s^{-1}) or TDS3054B (0.5 GHz, 2.5 GS s^{-1}) oscilloscope was used for recording electrical signals. To record the X-ray discharge radiation, use was made of a scintillator and a photomultiplier. We also used a Kodak RAR 2497 photographic film, which was placed into a light- and soft-X-ray-tight envelope with a window covered with a 15-μm thick beryllium foil (its long-wavelength transmission edge corresponded to an X-ray photon energy of ~0.7 keV).

3. Experimental results and their discussion

The following results were obtained in the course of experiments. A diffuse discharge (REP DD) was produced in the spike–plane gap in the absence of an additional preionisation source in a broad range of nitrogen pressure (from 30 to 760 Torr), including for $f = 2$ kHz. Like in the case of lasers pumped by a transverse discharge [1, 5, 18], the gas had to be pumped through the gap for the formation of the diffusive discharge in a repetitively pulsed regime at increased pulse-repetition rates. We note that the nitrogen discharge contracted at a pressure above 100 Torr when two cylindrical electrodes were used. Figures 2 and 3 show photographs of the REP DD obtained in the first chamber. For $f = 2$ kHz and a nitrogen flow rate of ~20 m s^{-1}, a diffusive (Figs 2a and 3) or corona discharge (Fig. 2b) was produced on this facility, depending on the nitrogen pressure.

For long gaps (greater than 10 mm) and the highest generator voltage, the pressure in the discharge chamber had to be lowered (Fig. 2a). The discharge glow at a low pressure (below 50 Torr) was uniform and there were no bright spots on the electrodes. Increasing pressure under these conditions (Fig. 2b), as well as lowering the amplitude of voltage pulses and the pulse repetition rate, resulted in the formation of a corona discharge. The location of the glowing boundary of the corona discharge depended (other conditions being the same) on the generator voltage. There were no bright spots on the electrodes in the formation of the coronal discharge, either. To form the REP DD at a pressure of 760 Torr (Fig. 3), the interelectrode gap had to be decreased to 6 mm. Bright spots appeared on the cathode under these conditions. The oscilloscope traces of the voltage pulses and discharge current at a nitrogen pressure of 760 Torr shown in Fig. 4a are averages over 128 pulses.

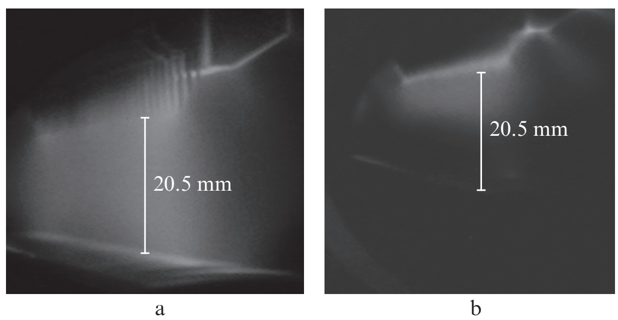

Figure 2. Photographs of the discharge glow for a pulse-repetition rate $f = 2$ kHz, an interelectrode gap $d = 20.5$ mm and a nitrogen pressure in the first chamber p = (a) 30 and (b) 80 Torr. The cathode of needles is at the top.

For a nitrogen REP DD for $f = 2$ kHz, we estimated the peak specific excitation power. The excitation power

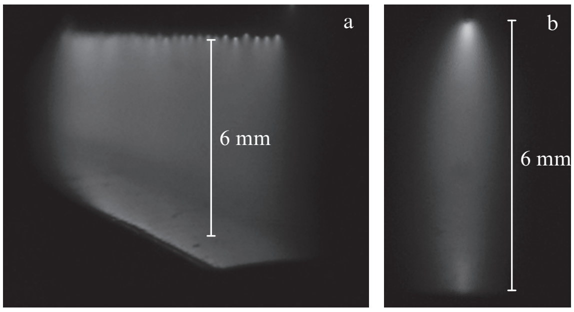

Figure 3. Photographs of the nitrogen discharge glow for $f = 2$ kHz, $d = 6$ mm and $p = 760$ Torr, which were obtained at an angle to the central axis of the discharge region (a) and from the end face of the first chamber (b). The cathode of needles is at the top.

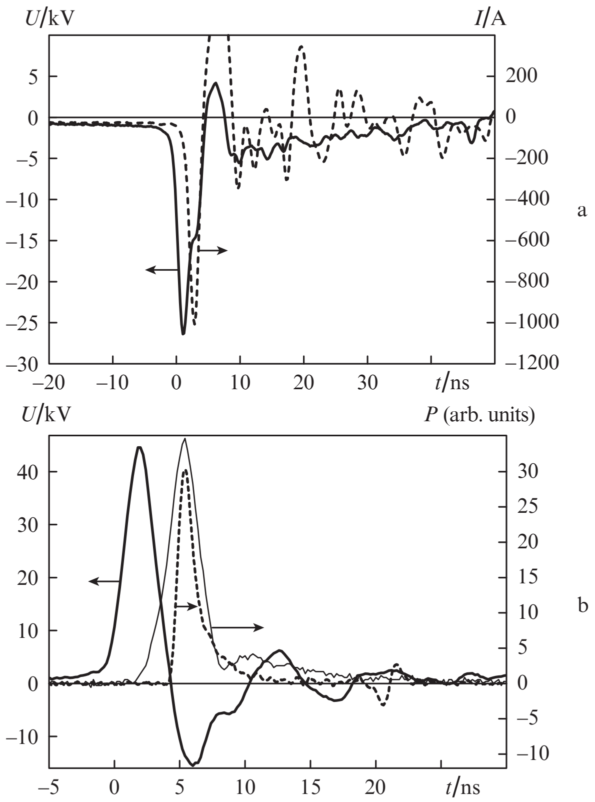

Figure 4. Oscilloscope traces of (a) the voltage and discharge current pulses in nitrogen for $f = 2$ kHz, $d = 6$ mm and $p = 760$ Torr and (b) the voltage pulses (the polarity was reversed in the drawing), as well as of spontaneous (thin curve) and laser (dashed curve) radiation in nitrogen for $f = 0.4$ kHz, $d = 6$ mm and $p = 300$ Torr in the first discharge chamber.

$$P = UI_{\rm con}, \tag{1}$$

where U is the voltage across the discharge gap measured by the voltage divider;

$$I_{\rm con} = I_{\rm osc} - C_0 \frac{\partial U}{\partial t} \tag{2}$$

is the conduction current calculated by subtracting the displacement current from the oscilloscope trace of current $I_{\rm osc}$; and C_0 is the capacitance of the 'cold' (neglecting the effect of plasma in the breakdown) discharge gap. The volume occupied by the discharge plasma after breakdown is calculated by the formula

$$V \approx \frac{dw}{2} L, \tag{3}$$

where w and L are the width of the plasma near the plane electrode and the electrode length, respectively. The specific excitation power $P_{\rm sp}$ was calculated by expressions (1)–(3):

$$P_{\rm sp} \approx P/V. \tag{4}$$

Its peak value was equal to ~10 MW cm^{-3} for a discharge plasma volume of ~6 cm^3.

Estimates of the power density of spontaneous emission to the total solid angle were also made on the assumption that the radiation spectrum remains invariable throughout the pulse. Formulas used for the calculation were borrowed from Ref. [19]. The calculation was performed by the formula

$$P_{\rm rad} = I(t)k, \tag{5}$$

where $I(t)$ is the photodiode current pulse;

$$k = \frac{W}{\int I(t)\,{\rm d}t} \tag{6}$$

is a proportionality coefficient;

$$W = \int_{\lambda_1}^{\lambda_2} \omega(\lambda)\,{\rm d}\lambda \tag{7}$$

is the total energy (J); λ_1, λ_2 are the bounds of the spectral interval recorded by the spectrometer;

$$\omega(\lambda) = \gamma A(\lambda) \tag{8}$$

is the spectral energy density (J m^{-1}); $A(\lambda)$ is the spectral energy density distribution (arb. units m^{-1});

$$\gamma = \frac{\int I(t)\,{\rm d}t}{\delta \int_{\lambda_3}^{\lambda_4} \chi(\lambda) A(\lambda)\,{\rm d}\lambda} \tag{9}$$

is an unknown dimensional proportionality coefficient (J); $\chi(\lambda)$ is the spectral responsivity of the photodiode (A W^{-1}); δ is the fraction of radiation recorded by the instrument; and λ_3, λ_4 are the bounds of the spectral sensitivity range of the photodetector. In the pursuance of power estimates we took into consideration that the source is extended. According to our estimates, the total power of radiation to an angle of 4π is equal to ~16 kW. This power increases by more than an order of magnitude on adding electronegative SF_6 gas to nitrogen. When use was made of the mixtures with SF_6, simultaneously the power of laser radiation was significantly higher. In particular, in Ref. [6] it was shown that the UV output nitrogen laser power increased 20-fold on addition of SF_6 to nitrogen. In the course of pumping, the average values of the E/p parameter in the nitrogen–SF_6 are higher than in nitrogen and are close to the optimal ones for a laser on the second positive nitrogen system [6, 7] (E is the electric field intensity and p is the nitrogen pressure).

The REP DD plasma emission spectrum was typical for a diffusive nitrogen discharge. The second positive nitrogen system and the $0 \to 0$ transition of the $C^3\pi_u \to B^3\pi_g$ band were highest in intensity (Fig. 5). Figure 6 shows the total radiation power density in the 300–400 nm range as a function of pressure and voltage for the first discharge chamber. These dependences were obtained in the measurement of the radiation power density through the end flange window (see Fig. 1). For the highest generator voltage (30 kV in the incident voltage wave), the optimal nitrogen pressure was equal to 270 Torr (Fig. 6a). Owing to the circulation of nitrogen through the discharge gap, the radiation power density in a pulse was hardly changed with increasing pulse repetition rate. A circulation velocity of 20 m s^{-1} was sufficient for retaining the radiation power density of single pulses with increasing frequency up to 2 kHz. The length of the radiating region in the absence of stimulated emission, like in Ref. [20], had no significant effect on the radiation power density. In particular, shortening the radiating region length from 35 to 4 cm resulted in less than a two-fold lowering of the radiation power density (Fig. 6b). In the execution of these measurements, a thin dielectric plate was placed in the interelectrode gap. In this case, the character of discharge did not change and the photodiode did not record the radiation from the domain behind the plate. The optimal pressure lowered with decreasing voltage, and the duration of radiation pulses shortened with increasing pressure. For a nitrogen pressure of 760 Torr, the half-amplitude duration of UV radiation pulses was equal to ~1 ns.

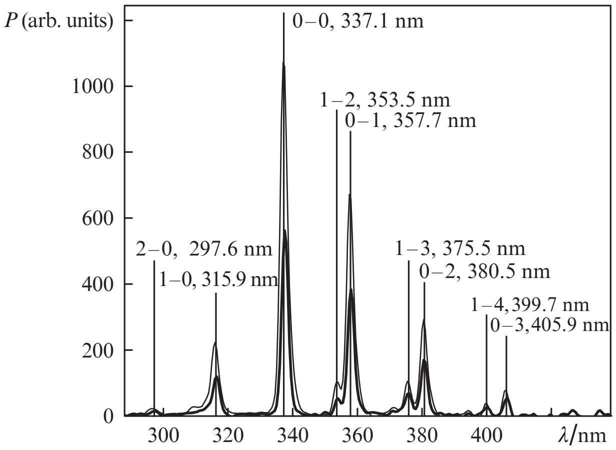

Figure 5. Spontaneous emission spectra of nitrogen for $f = 0.4$ kHz, $d = 6$ mm, $p = 300$ Torr (thin line) and 600 Torr (bold curve) in the first discharge chamber. Vertical lines indicate the edges of the principal bands of the 2^+ nitrogen system.

The use of a resonator made up of an aluminium-coated nontransmitting mirror and a quartz plate resulted in the attainment of an oscillation threshold at a wavelength of 337.1 nm. Figure 4b shows the oscilloscope traces of the voltage pulse as well as of spontaneous and laser radiation pulses for $f = 400$ Hz. The laser pulse lags behind the spontaneous radiation pulse by 3 ns and is twice as short in half-amplitude duration. The output laser power amounted to ~10 W in the repetitively pulsed regime.

With the use of a CCD camera, on the second facility it was shown that, without an additional preionisation source, the formation of a diffusive discharge in the gap occurred for a voltage exceeding 20 kV, within 1 ns (Fig. 7). A bright spot could appear on the cathode, also within 1 ns, whose position remained invariable during the course of a given pulse. New cathode spots might appear within several nanoseconds after the application of the voltage pulse to the gap (Fig. 7).

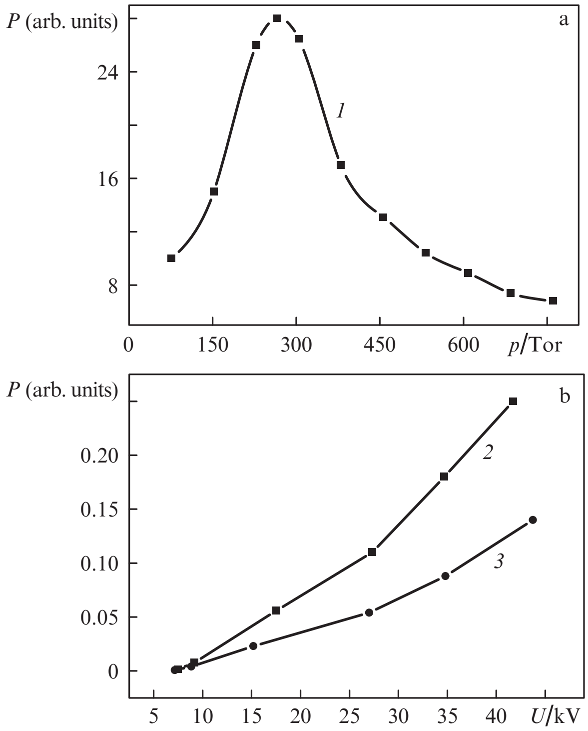

Figure 6. Dependences of the radiation power density on (a) the pressure and (b) the voltage across the discharge gap obtained on the first discharge chamber for (*1*) $f = 0.4$ kHz, $d = 6$ mm and (*2*, *3*) $f = 0.4$ kHz, $d = 10$ mm and $p = 76$ Torr. The length of discharge region is equal to (*2*) 35 and (*3*) 4 cm.

The investigations performed in this work bear out the possibility of producing diffusive discharges in a nonuniform electric field at an increased pressure without an additional preionisation source (see, for instance, Ref. [21] and references in Ref. [21]). A REP DD is formed due to the production of runaway electrons and X-ray radiation.

In the second discharge chamber, in which the excitation conditions were similar to those in the first one, behind the foil anode we recorded X-ray radiation – both with the help of a PM combined with a scintillator and from autographs on Kodak RAR photographic film. With the use of the photographic film, X-ray radiation was recorded at atmospheric nitrogen pressure. On lowering the pressure to 100 Torr and

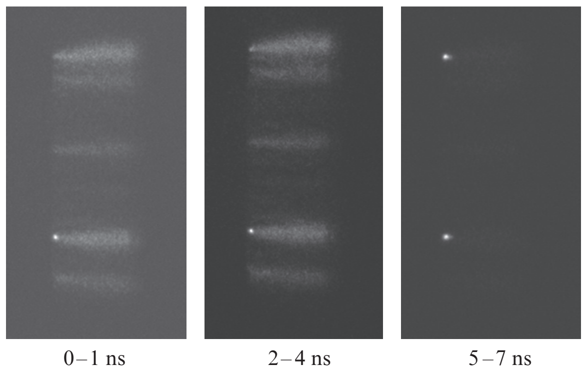

Figure 7. Photographs of the discharge glow at different instants after the onset of breakdown for $f = 0.4$ kHz, $p = 760$ Torr, $d = 2$ mm and $U = 22$ keV obtained on the second chamber with a tubular cathode.

below, we recorded a SAEB behind the foil anode. The results of detailed investigations into the SAEB and X-ray generation in the repetitively pulsed regime on the facilities of this kind are set out in Refs [13, 14, 22, 23].

The main process responsible for the excitation of the $C^3\pi_u$ level of nitrogen molecules is the direct impact of discharge electrons (not beam electrons), like in UV nitrogen lasers pumped by a transverse discharge. The main role of the runaway electron beam consists in the formation of a diffusive discharge at an increased nitrogen pressure. Owing to the runaway electrons, the diffusive discharge is produced at pressures exceeding 100 Torr, while the discharge contracts at an increased pressure when the transverse discharge is excited without an additional preionisation source. At a low pressure (below 100 Torr), the radiation efficiency of the second positive nitrogen system under transverse discharge excitation is higher than under REP DD excitation. The relatively low efficiencies of UV spontaneous and laser radiation under the REP DD excitation of nitrogen are due to the lower values of the parameter E/p in the gap in the course of pumping. The generation of a SAEB limits the maximal voltage across the gap prior to its breakdown [21]. SF_6 additions to nitrogen increase the E/p parameter values in the gap during pumping and improve the radiation efficiency of the second positive nitrogen system. In the REP DD excitation of nitrogen–SF_6 mixtures, the lasing efficiency of the UV nitrogen laser rises sharply and approaches the limiting efficiency of ~0.3 % [6, 7].

The excitation of the $C^3\pi_u$ molecular nitrogen level by a direct impact of discharge electrons is verified by the experiments on the excitation of nitrogen–SF_6 mixtures by an electron beam [24]. In the excitation by an electron beam, additions of SF_6 to a nitrogen–argon mixture result in a drastic decrease in the nitrogen laser efficiency. In pumping by an electron beam in the absence of an external electric field, an addition of SF_6 to nitrogen leads to additional energy loss of the beam electrons due to SF_6 molecules. In nitrogen–argon mixtures pumped by an electron beam, additions of SF_6 also lead to energy losses for the production of ArF^* molecules; under pumping by a REP DD, by contrast, adding SF_6 permits attaining optimal values of the E/p parameter across the gap and, accordingly, of the average energies of discharge electrons. Under pumping by a transverse discharge for non-optimal excitation pulse parameters, adding SF_6 also leads to an increase in nitrogen laser efficiency [25], but this increase usually does not exceed a factor of two. In the electron-beam excitation of nitrogen without the use of the magnetic field, the oscillation threshold on the 2^+ nitrogen system was not reached.

4. Conclusions

In this work, we have investigated the spontaneous emission and volume discharge in nitrogen at an increased pressure due to runaway electrons and X-ray radiation, including those at a pulse-repetition rate of up to 2 kHz. Data were obtained on the spontaneous radiation power at nitrogen pressures of 30–760 Torr and an excitation region length of up to 2 kHz. We have shown that varying nitrogen pressure under REP DD excitation makes it possible to control the duration of output pulses, which shorten to ~1 ns at a pressure of 760 Torr. This duration is shorter, by more than an order of magnitude, than the duration of the source of spontaneous radiation pumped by a transverse discharge with a pulse duration of 50–150 ns without an additional gap preionisation. Subsequently we plan to investigate the lasing and spontaneous emission with exciplex molecules in rare-gas mixtures with different halogenides (F_2, NF_3, HCl).

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