Diffuse discharges in SF$_6$ and mixtures of SF$_6$ with H$_2$, formed by nanosecond voltage pulses in non-uniform electric field

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Abstract: Results of experimental study of nanosecond diffuse discharge in SF$_6$ and gas mixtures of SF$_6$ with H$_2$, D$_2$ and C$_2$H$_6$ are presented. The aim of this work is to study parameters of discharge between two extended electrodes with a small radius of curvature in SF$_6$ and SF$_6$ with additives. It was shown that diffuse discharge can be formed in SF$_6$ at elevated pressure between blade electrodes with length of 30 cm. It was also confirmed that in a sharply non-uniform electric field a beam of runaway electrons is generated and that the gap breakdown occurs due to ionisation waves which begin on electrodes with small radius of curvature. Laser action in the infrared spectral region was obtained in SF$_6$–H$_2$ (D$_2$, C$_2$H$_6$) mixtures. The laser output up to 110 mJ was easily achieved which corresponds to ultimate intrinsic efficiency (with respect to deposited energy) of 10%.

1 Introduction

Electronegative SF$_6$ gas is widely used in electrical installations as gas insulation [1]. This is due to its high electrical strength, which significantly exceeds the electrical strength of nitrogen and air. Volume self-sustained discharge in SF$_6$ with small additions (≤10%) of different gases is used for various technological applications, in particular, in microelectronics for etching semiconductor materials [2, 3]. Besides, a volume discharge in mixtures with SF$_6$ is used for excitation of non-chain chemical lasers on HF (DF) molecules [4–8]. Therewith, volume discharge in SF$_6$ and its mixtures with H$_2$, D$_2$, and C$_2$H$_6$ in large gaps (≥10 cm) is easily formed without illumination only due to the creation of a large number of micro-roughness on the cathode surface [4, 5]. However, when the gap length is reduced to a value of the order of 1 cm maximal efficiency of HF (DF) laser similarly to other gas lasers pumped by a transverse volume discharge can be achieved only using preionisation, profiled electrodes and excitation pulses with certain parameters [6–8]. Moreover, volume discharge in SF$_6$ and its mixture in small gaps become unstable and after a relatively short time transforms into a constricted stage.

It has long been known that when a high-voltage pulse with a short rise time is applied to the gap with a sharply inhomogeneous electric field filled with helium or atmospheric air, a diffuse discharge is formed in the gap [9, 10] and X-rays caused by generation of runaway electrons are detected in the gap. It should be noted that relatively homogeneous energy deposition into gas between the electrodes is achieved both in volume and diffuse discharges. The difference lies in the fact that the diffuse discharge consists of a set of parallel diffuse jets, while plasma of a volume discharge in a discharge gap is more uniform.

Diffuse discharge in SF$_6$ in gaps between electrodes with small radius of curvature has been formed, as well [11]. In addition, in this work, autographs of a runaway electron beam were recorded on an X-ray photo-film. Generation of runaway electrons and X-ray radiation in SF$_6$ during breakdown of gaps with an inhomogeneous electric field using voltage pulses with an amplitude of tens of hundreds of kV and rise time shorter than 1 ns was studied in [12, 13].

Runaway electrons and X-ray radiation, which results from the deceleration of the electrons, provide preionisation of the gas mixture and formation of a diffuse discharge [11–13]. However, electrodes with small dimensions were used in [11–13].

Diffuse discharges formed in electrode systems with an inhomogeneous electric field (between blades, pins etc.) when high-voltage pulses with short rise time were applied was proposed to call runaway electron preionised diffuse discharge (REP DD) [14].

The aim of this work is to study parameters of REP DD in SF$_6$ and SF$_6$ with additives of other gases between two extended electrodes with a small radius of curvature. Similar systems were used earlier to obtain UV laser action on nitrogen and rare gas fluoride molecules [15].

2 Experimental facility and measurement technique

Two experimental facilities were used in experiments. Pure SF$_6$ and its mixtures with hydrogen were used in the main part of the experiments. Discharge in mixtures of SF$_6$ with deuterium, ethane and nitrogen was studied, as well. We investigated the formation of discharges between two extended electrodes by a RADAN-220 nanosecond pulse generator [16] (facility 1). Wave impedance of the pulse-forming line in RADAN-220 is 20 Ω. The line capacity is $C \approx 50 \mu F$. The amplitude of the voltage pulse on a high-resistance load was changed from 240 to 290 kV, which corresponds to maximal stored in the line energy $E \approx 2.1 J$. The duration of the voltage pulse at half-height in the forming line was ~ 2 ns, and the duration of the voltage pulse front edge in the transmitter line was ~ 0.5 ns. On connecting up the discharge chamber, the rise time of the voltage pulse lengthened to 1 ns, its half-amplitude duration also became longer. The duration of the discharge current pulse in SF$_6$ and its mixtures with H$_2$, D$_2$ and C$_2$H$_6$ due to large connection inductance was 10 ns.

The discharge chamber design is schematically shown in Fig. 1. In these experiments we employed a gap with a cathode–anode separation of 18 mm. Both electrodes from stainless steel with length of 30 cm were made in the form of blades with rounded
edges and an angle at the vertex of 5°; the radius of curvature of sharp edges was 0.05 mm. This provided an inhomogeneous distribution of the electric field in the gap and, correspondingly, its amplification at the electrode edges. The discharge gap design due to increasing the electric field at the electrode edges and on the front of the ionisation waves during discharge formation allows to produce electrons with energy of hundreds of eV – units of keV (fast electrons), while energy of part of electrons increased to tens – hundreds of keV (runaway electrons), which allows to form volume diffuse discharges in various gas mixtures at high pressure [17].

Besides, studies were carried out using second facility with the same nanosecond pulse generator. Transverse dimensions of the discharge region in facility 2 were reduced, and a flat anode made of thin Al foil can also be used. Due to reduced dimensions of the discharge region, it was possible to measure with better accuracy the breakdown characteristics of the discharge gap (the ionisation wave velocity). The discharge chamber of facility 2 with flat anode from Al foil and a collector was used for measurement of a beam of runaway electrons behind the anode. The facility design is shown in Fig. 2.

The internal diameter of the discharge chamber was 52 mm, which made it possible to connect the transmitting line of the RADAN generator to the electrodes with a low inductance and obtain voltage pulse rise time across the gap of 0.5 ns. Electrodes of various designs were used in facility 2. Three assemblies were used: both electrodes from razor blades (stainless steel), high-voltage electrode had a length of 19 mm, and grounded was as long as 38 mm; high-voltage electrode from razor blade 19 mm long and second flat electrode; tubular high-voltage electrode made of stainless steel foil of 100 μm thick with 6 mm in diameter and a second flat electrode made from 10 μm thick Al foil reinforced with a grid. The investigations were carried out with two voltage pulse polarities.

During experiments on facility 2 the following parameters were measured. Images of the discharge glow were taken with a Sony A100 reflex camera. The spectra of radiation were recorded with a StellarNet EPP2000-C25 spectrometer with calibrated spectral sensitivity in the wavelength range λ = 200–850 nm at a resolution of 0.75 nm or HR4000 spectrometer (Ocean Optics B.V.) with a resolution of 0.2 nm. The amplitude–time characteristics of visible and UV radiation were detected with a FEK-22SPU photodiode.

For measuring the ionisation wave velocity on facility 2, we used a DSA 72504D oscilloscope (25 GHz, 100 GS/s) and a PD025 high-speed photodetector (Photek) equipped with an LNS20 cathode, and the transient response rise time of the photodetector was about 80 ps. The relative timing jitter between light and voltage pulses was no longer than 10 ps. The optical radiation from different discharge regions was extracted through a side window (4) and was transmitted by a lens (3) to a photodiode located in a metal box (1). Upstream of the photodiode, there was a shield (2) with a 1 mm-width slit. On the slit plane, a magnified image of a part of the gap was formed, the magnification ratio was 2:1. When the plasma filled this region, the photodetector recorded the radiation from this region. The spatial resolution of the system for measuring the radiation from each region of the discharge gap was about 1 mm in the direction of the longitudinal gap axis. The radiation was measured in the regions near the cathode and anode. Signals from the capacitive voltage divider, shunt, collector and photodiode were transmitted to the oscilloscope.

The voltage across the gap and discharge current were measured with voltage divider and current shunt (facility 1). While in facility 2 the voltage was measured by a capacitive divider (6) (see Fig. 2) located at the end of the transmission line (5). The discharge current was measured by a shunt (8) composed of chip resistors.

3 Experimental results

3.1 Facility 1

Characteristics of the discharge and radiation, including the laser emission, were investigated with an electrode length of 30 cm using facility 1. Such studies were carried out for the first time. With negative polarity of the voltage pulse, the discharge was investigated in SF₆ and its mixtures with hydrogen, deuterium, ethane and nitrogen at pressures from 0.02 to 0.2 MPa. The most easily diffuse discharge was formed in pure SF₆ and SF₆ with small (<15%) additions of other gases at a pressure no more than 0.05 MPa. At high pressures, a diffuse discharge with spark channels was observed in the gap only in the part of pulses (no more than 10%), the radiation intensity of spark channels increased with increasing SF₆ pressure. Characteristic waveforms of the voltage across the gap, discharge current, spontaneous emission of diffuse plasma formed between blade electrodes in spectral range 300–650 nm and calculated input power into discharge in SF₆–H₂ mixture at a pressure of 0.04 MPa are shown in Fig. 3. The waveforms did not depend on the type of discharge (diffuse or

![Fig. 1](image1.png)

**Fig. 1** Structure of discharge chamber of facility 1: 1 – resonator mirrors, 2, 3 – electrodes; 4 – part of RADAN-220 generator, 5 – side window

![Fig. 2](image2.png)

**Fig. 2** Block diagram of facility 2: 1 – photodetector PD025 in metal box; 2 – screen with slit; 3 – lens; 4 – side window; 5 – transmission line of RADAN-220 generator; 6 – capacitive voltage divider; 7 – high voltage electrode; 8 – current shunt; 9 – ground electrode made of thin foil; 10 – collector; 11 – oscilloscope
The main energy was already deposited into the diffuse discharge in SF₆. The current of 0.03 MPa (0.88 V/(Pa × cm)) [1, 4]. Note that in the mixtures used in our experiments the SF₆ content was significantly higher than the content of other gases. It means that additives of H₂, D₂, C₂H₆ (15% and less) did not significantly affect the diffuse discharge formation and specific energy deposited into the diffuse discharge plasma.

The current pulse duration is 10 ns while peak electric power deposited into the discharge plasma is over 200 MW. The spontaneous emission duration in spectral range 300–650 nm is also about 10 ns and is close in form to the discharge current. Calculated from the current and voltage waveforms deposited energy was found to be 1 J. This energy deposition for measured active discharge volume of 20 cm³ corresponds to the specific input energy of Eₘ = 50 J/l, which falls within the range of the optimal input energy of non-chain discharge HF (DF) lasers [8].

Diffuse discharge in the system of blade electrodes, similarly to a volume discharge in non-chain chemical lasers with profiled electrodes [18, 19], can cease until the generator capacity is completely discharged. In this case, a repeated breakdown of the gap in the form of a spark is possible. The characteristic oscillograms of the current and glow pulses in the gap for this case are shown in Fig. 4.

The oscillatory discharge current and sharp increase of the visible radiation intensity observed at time instant about 300 ns in Fig. 4 are characteristic for the repeated spark breakdown. Duration of the second pulse of light in the discharge gap significantly increases in the case of secondary spark breakdown. The current amplitude of a spark oscillating discharge, which lagged behind the voltage pulse by 300 ns, was comparatively small (see Fig. 4). However, due to the high intensity of the spark emission in the visible spectral region, the amplitude of the second spontaneous emission pulse was relatively large. Delay time of the repeated breakdown similar to [7, 8, 18, 19] is reduced with increasing SF₆ or mixtures of SF₆ with other gases pressure.

Fig. 5 depicts images of the diffuse discharge glow obtained at different SF₆ pressures. It is seen that glow of the diffuse discharge in the gap is of low intensity. Numerous bright cathode and anode spots and spark leaders penetrating the gap, similarly to [20] are more visible. However, the length of spark leaders at a pressure of 0.04 MPa takes no more than 20% of the gap length. When the pressure was increased to 0.05 MPa, the discharge current decreased, and its homogeneity was improved (Fig. 5b). Therefore, the glow of the gap becomes less intense, the glow of the anode spots is also weakened, and the spark leaders disappear.

Weak discharge luminescence intensity was also observed in mixtures of SF₆ with small additions (<15%) of H₂, D₂ and C₂H₆. Nitrogen additions to SF₆ significantly increase the intensity of discharge emission in the UV and visible spectral regions. Similar discharge view was observed in typical non-chain chemical lasers with profiled electrodes with the use of preionisation, input energy being the same [21]. As in the case of discharge between the blade electrodes, bright cathode spots are visible, and the glow in the discharge gap is much weaker in intensity than the cathode spots.

Emission spectrum of a diffuse discharge in SF₆ between blade electrodes is shown in Fig. 6. Since the luminescence of the diffuse discharge is weak enough, it was necessary to do several pulses to fix the spectrum. The spectrum includes a large number of lines. Weak lines of the C-B transition of molecular nitrogen (337 and 357 nm) and a lot of lines of atomic fluorine in the region of 640–780 nm are visible in the spectrum. Fluorine atoms appear in the discharge plasma in the dissociation processes of SF₆. Atomic nitrogen line at 520.2 nm is the most intense in the diffuse discharge spectrum. The lines of molecular and atomic nitrogen are caused by the presence of a small (<0.1%) admixture of nitrogen in the SF₆ gas. With nitrogen content of 0.5% or more, the bands of the second positive nitrogen system dominated in the emission spectra. Similar line spectra were observed in [22] when investigating the glow of streamer heads and streamer channels in SF₆ gas in a pin-plane geometry. In this work, after the gap was closed by a channel and the discharge current increased, bands of continuous spectrum appeared in the discharge plasma emission.
regions of the spectrum at 250–310, 350–380 and 500–550 nm in fast and runaway electrons.

Within our experiments are also associated with the emission of SF$_6$ x upon collision with electrons [23, 24]. It can be assumed that the pressure of 0.04 MPa

Similar continuum bands in the spectrum were also observed in the tip-plane geometry during ignition of the discharge from the RADAN-220 generator [12], in the spectra of partial breakdowns in SF$_6$ gas [25] and in the spectrum of the negative corona discharge in SF$_6$ [26]. However, in [12] the intensity of second positive nitrogen system in the UV region in the diffuse discharge was significantly higher than in the diffuse discharge between the blade electrodes. This can be explained by high concentration of nitrogen impurity in [12] which is confirmed by noticeable increase of the radiation intensity of the second positive system with nitrogen additions.

Probability of spark breakdown in the gap increased significantly with SF$_6$ pressure. In a number of pulses along with spark breakdowns, numerous unfinished thread-like channels (spark leaders) are observed, which are attached to cathode and (or) anode spots and develop from them into the interelectrode space (see Fig. 7b).

Number of incomplete spark leaders, growing into the gap from cathode and anode spots on the blade electrodes, and their length increase with SF$_6$ pressure. As a rule, spark leaders growing from the anode were longer than those formed from the cathode. One can estimate the average speed of a spark leader development. For the gap of 1.8 cm and the pulse duration of 10 ns, this value can be estimated as 1.8 × 10$^5$ cm/s. We note that in a number of pulses at high pressures, the removal of particles of electrode material from the point of attachment of the spark to the cathode was observed. This led to the appearance of bright linear glow tracks with changed direction (see Fig. 8).

Small additions of other gases made it possible to obtain laser radiation on the transitions of various molecules and atoms using facility 1 [15, 27]. As was mentioned above, the additions did not significantly affect the diffuse discharge parameters. The maximal radiation energies were obtained in the mixtures of SF$_6$H$_2$ (D$_2$) = 8:1 composition at a pressure of 0.04 MPa as compared to SF$_6$C$_2$H$_6$ and SF$_6$H$_2$C$_2$H$_6$ active mixtures. Laser energy on HF molecules (wavelength range 2.8–3.2 μm) was as high as 110 mJ, while laser output on DF molecules (wavelength range 3.8–4.2 μm) reached 75 mJ. Maximal HF and DF laser efficiency with respect to deposited energy was as high as 10 and 7.5%, respectively, which corresponds its ultimate value [19, 21, 27]. Similarly to [8, 19, 21, 27], the integral radiation pulse of non-chain lasers with REP DD pumping had a single peak with power over 1 MW. Intense cascade transitions were observed in the generation spectrum. The cascade transitions prove the high uniformity of energy deposition into the active medium under REP DD pumping. It is known that cascade transitions do not occur in a non-uniform discharge when the integral radiation pulse exhibits the well pronounced spike-mode character [21]. Cascade transitions increase the efficiency of energy extraction from the active medium of non-chain chemical lasers, because a single excited molecule HF ($v = 3$) or DF ($v = 4$), where $v$ is the vibrational quantum number, may emit up to 3–4 photons.

### 3.2 Facility 2

Facility 2 allows to change design of discharge gap and to measure runaway electron beam parameters behind anode foil. It was also possible to record the time instant of appearance of radiation in different regions of the discharge gap at both polarities of the voltage pulse. On the basis of our measurements, the appearance of radiation, the ionisation wave velocities in SF$_6$ with the addition of 2.5% nitrogen were determined. Nitrogen was added to SF$_6$ for

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**Fig. 6** Spectra of diffuse discharge in SF$_6$, obtained for five pulses at a pressure of 0.04 MPa

(a), (b) In SF$_6$. (a) Its spectrum – at a pressure of 0.1 MPa (a) and 0.04 MPa (b, c)

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**Fig. 7** View of constricted discharge

(a), (b) In SF$_6$. (a) Its spectrum – at a pressure of 0.1 MPa (a) and 0.04 MPa (b, c)

In our experiments, weakly pronounced bands of the continuous spectrum were also observed in the wavelength regions around 270, 350–380 and 500–550 nm. Similar continuum bands in the UV regions at close wavelengths were observed in the SF$_6$ spectrum under excitation by electron beams with energy of 25–200 eV and were associated with the emission of excited fragments of SF$_6$ molecules after detachment of one or more fluorine atoms upon collision with electrons [23, 24]. It can be assumed that the regions of the spectrum at 250–310, 350–380 and 500–550 nm in our experiments are also associated with the emission of SF$_6$ fragments, $x = 1–5$, which are formed during dissociation of SF$_6$ by fast and runaway electrons.

Photographs of the constricted discharge in SF$_6$ and its spectrum are shown in Fig. 7. Bright spark discharge was evident in the gap at SF$_6$ pressure of 0.1 MPa. The spark breakdown at a pressure of 0.04 MPa occurred only at low amplitude of voltage pulse produced by the RADAN-220 generator. The glow of the spark channel is much more intense than that of the diffuse discharge. One pulse is enough to record the spectrum. In contrast to the diffuse discharge, intense continuum appears in the spectrum in the 220–700 nm region (Fig. 7c). UV bands of the second positive nitrogen system (337 and 357 nm) are also visible, which confirms the formation of a diffuse discharge in the first stage, and then its constriction.

Intensity of the numerous atomic fluorine lines is increased noticeably in comparison with the diffuse discharge. Characteristic continua in the spectrum of a constricted discharge were observed in the tip-plane geometry during ignition of the discharge from the RADAN-220 generator [12], in the spectra of partial breakdowns in SF$_6$ gas [25] and in the spectrum of the negative corona discharge in SF$_6$ [26]. However, in [12] the intensity of second positive nitrogen system in the UV region in the diffuse discharge was significantly higher than in the diffuse discharge between the blade electrodes. This can be explained by high concentration of nitrogen impurity in [12] which is confirmed by noticeable increase of the radiation intensity of the second positive system with nitrogen additions.

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increasing the radiation intensity of diffuse discharge plasma. In SF$_6$–N$_2$ mixtures, as was noted above, the second positive nitrogen system is efficiently excited and emits in the wavelength region 300–450 nm. This allows detecting the appearance of radiation in various parts of the gap during its breakdown by an ionisation wave which in conditions of our experiment consists of parallel moving streamers from an electrode with a small radius of curvature [17, 28].

Table 1 depicts velocities of the ionisation wavefront before and after the gap centre obtained from the delay of the luminescence appearance in various points of the gap. The velocity of the ionisation wavefront was higher for positive polarity of the high-voltage electrode did not significantly affect the diffuse discharge formation. Therewith diffuse discharge transforms into corona with all types of electrodes on installation 2. As was shown above, the discharge constriction was observed on the installation 1 when SF$_6$ pressure was increased up to 0.05 MPa (see Figs. 7 and 8). This is due to the large electrode length installation, and, respectively, increased inductance of the discharge circuit.

Investigations of laser radiation using installation 2 were not carried out due to the small active length. However, it clearly follows from the results obtained that the diffuse discharge formation using the cathodes with a small radius of curvature occurs due to generation of runaway electrons.

4 Discussion

From the results presented above it follows that it is easy to form a diffuse discharge in an inhomogeneous electric field in SF$_6$ and SF$_6$–N$_2$ mixtures with other gases. To do this, it is sufficient to use at least one electrode with a small radius of curvature. When a cathode with a small radius of curvature is used, a runaway electron beam is recorded behind the anode foil. Formation of a diffuse discharge occurs due to ionisation waves, which start from the regions of amplified electric field near electrodes and consist of separate diffuse jets (ionisation waves, streamers [17]). Diffuse jets develop in parallel and before meeting in the gap centre are cathode- and anode-directed streamers. The speed of the ionisation wavefront starting from the cathode (anode-directed streamers) under these conditions is less than for cathode-directed streamers. As the SF$_6$ pressure is increased the streamers stop in the gap after the pulse termination and a corona discharge is evident in the gap.

It is also possible to form a uniform diffuse discharge between extended electrodes with a small radius of curvature. This allows us to develop efficient gas lasers with REP DD excitation. In our experiment, a diffuse discharge was obtained with the electrode length of 30 cm, and efficient laser action was obtained on HF and DF molecules in mixtures with SF$_6$, as well.

The discharge constriction occurs by spark leaders, which start with bright cathode spots and penetrates into the gap with velocity of 2 cm/ns. The velocities of spark leaders are an order of magnitude or less than those of streamers. In the case of cathode-guided streamers, the speed of cathode-guided spark leaders is higher than that of anode-guided spark leaders. Note that a spark
the process of increasing electron energy is slowed down and ceases at large distances. Correspondingly, fast electrons do not appear. However, fast electrons effectively ionise gas near the head of streamers, thus ensuring fast propagation of streamers. This mechanism explains the efficient ionisation of the gas in front of the head of the streamer with both positive (cathode-directed streamer) and negative (anode-directed streamer) charges. In the case of the negatively charged electrode with small of radius of curvature, electrons with energies of tens of keV and above (runaway electrons) ensure the preliminary ionisation of the gas ahead of the front of the streamer, and some of these electrons are detected behind the foil anode (see Fig. 9a) and [10, 14, 17]. In the case of the positively charged electrode with small of radius of curvature, the preliminary ionisation of the gas is accomplished by soft X-rays (characteristic and bremsstrahlung) appearing at the deceleration of fast electrons. High efficiency of generation of the characteristic radiation during the deceleration of runaway electrons in light gases was demonstrated theoretically in [32]. Characteristic radiation was experimentally detected in the discharge in a non-uniform electric field in nitrogen and air [33], and in xenon at low pressures, as well as [34].

5 Conclusions

The use of electrodes with a small radius of curvature, for example, in the form of two blades, including long blade electrodes, makes it possible to form a diffuse discharge in SF$_6$ and SF$_6$ mixtures with other gases. This allows to develop non-chain infrared HF and DF lasers with ultimate efficiency. Formation of diffuse discharge occurs due to ionisation waves (streamers), which start from the regions with amplified electric field near the electrodes and consist of separate diffuse jets. Diffuse jets develop in parallel and constitute cathode- and anode-directed streamers before meeting in the gap centre.

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7 References

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The formation of diffuse discharge in an inhomogeneous electric field in SF$_6$ and SF$_6$ mixtures with other gases indicate that, in the process of the gap breakdown by the nanosecond negative and positive voltage pulses, the wave of ionisation (streamer) is formed and bridges the gap at a high velocity. The streamers appear near the electrode with small radius of curvature and the dynamics of its formation is very similar in different gases and gas mixtures. Therefore, the observed dynamics of the streamer formation during the breakdown under these conditions should be described by a single universal mechanism. This mechanism should explain high ionisation rates of a gas, which is confirmed by a high propagation velocity of the streamer. As it is known, when the breakdown occurs in the presence of high overvoltage, the electric field strength at the front of the streamer/ ionisation wave exceeds the critical value for the regime of continuous acceleration of electrons. We believe that the gas under these conditions is efficiently ionised by fast electrons with energies from hundreds of electron volts to several keV. The cross-sections for the ionisation of molecules and atoms are usually maximal at these electron energies [29]. The presence of fast electrons in discharges with a high overvoltage follows from the calculations performed in [30, 31] and Kunhardt and Byszewski [30] proposed to call them ‘trapped’ electrons. The electric field far from the head of the cathode-directed streamer and positive electrode with small of radius of curvature is weaker, consequently, the discharge HF (DF) laser with a solid-state pump generator’, Quantum Electron., 2015, 45, (11), pp. 989–992. Available at https://doi.org/10.1070/QE2015v045n11ABEH015889
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