ISSN 2347-3487

# LOW-INDUCTIVE EXTENDED Z-DISCHARGE AS A MANYRANGE SOURCE OF RADIATIONS

Vladimir Burtsev, Nikolay Kalinin, Sergey Vaganov
Ioffe Physical Technical Institute Russian Academy ofSciences, Politeknicheskya ul., 26, St. Petesburg 194021
Russia
burtsev321@gmail.com

## ABSTRACT

The present paper summarizes the results of studying of nanosecond low-inductive extended z-discharge as source of electromagnetic radiations and analyzes the works of other research groups that can throw upon additional light and hereunder promote to best understanding of physics of the phenomena and processes observed in authors' researches. The analysis is of main interest towards development of compact electrodischarge sources of coherent and low-coherent radiation including X-ray range.

## Keywords

High current extended z-discharge, pulsed electrodiscarge sources of EUV/SXR radiation, nanosecond high voltage discharge, a gas diode, a sliding discharge, runaway electrons.

## Academic Discipline And Sub-Disciplines

Provide examples of relevant academic disciplines for this journal: Physics; EUV/SXR Lasers and Sources

## SUBJECT CLASSIFICATION

E.g., Mathematics Subject Classification; Library of Congress Classification

## TYPE (METHOD/APPROACH)

Experimental Research; Analitical Review

Council for Innovative Research
Peer Review Research Publishing System
Journal: JOURNAL OF ADVANCES IN PHYSICS
Vol. 11, No. 2
www.cirjap.com, japeditor@gmail.com

# INTRODUCTION

For the first time the concept of creation and the result of search study of EUV-HXR electrodischarge lasers based on low-inductive extended z-discharges formed by running wave of the sliding discharge were presented at International Conference on x-ray lasers in Beijing, 2004 [1]. Further experiments were carried out using more powerful modified version named as "Extreme" installation and reported at X-ray conferences in Berlin, 2006 [2] and San Diego, 2007 [3]. A distinctive feature of these modifications is utilization of close geometry electrode system fed through long cable line from pulse generator based on double storaging-forming line with oil-paper dielectric. The double transit time of voltage wave in the transmission line was approximately equal duration of generated pulse ~ 100 ns in order to model stepped form of incident voltage wave.

The first model modification of the installation utilized single 75-Ω transmission cable RK-75-11-12 with coaxial high voltage socket connecting capillary load made from diameters 10x5 mm ceramic tube and coaxial return current conductor with 10,5 mm inner diameter. In unmatched mode, i.e. the mode of the double voltage realized at the stage of sliding discharge, the voltage across capillary load could reach 200 kV. In the second, higher power modification the transmission line consisted of eight cables connected to similar capillary load by means of eight high-voltage sockets and current collecting coaxial unit (Fig.1). The maximum current in this modification could reach 23 kA in unmatched mode, i.e. the mode of the double current realized at the stage of high-current discharge.

Now the third modification of experimental installation named "Extreme -M" in created at Ioffe Physical and Technical Institute that can operate at currents of 50-100 kA. The created installation has same circuit design as the previous ones: storaging-forming lines with oil-paper dielectric charged with voltage up to 100 kV, linear gas switches with electrical field disrortion, gas filled pulse shapers, a transmission long line, the low-inductive discharge load with close spacing of electrodes and a ceramic tube with diameters of 10x5 mm. The project includes possibilities to reduce the duration of the voltage rise time up to 1 nanosecond by means of a combination of various pulse shapers and to increase the discharge currents to 100 kA by adding modules of the storaging-forming double lines with oil-paper dielectric [4].

Due to the long pause in experimental researches caused by creation of the third modification of installation «Extreme-M» it is expedient to undertake the analytical survey of the researches carried out by other authors on near subjects. The survey generally covers the results that can throw upon additional light on considered phenomna and hereunder promote understanding physics of the processes observed in authors' researches and does not claim to be complete review of the involved researches. If readers become interested in these researches, they can find them in the references provided with their full output data.

When selection publications for analytical survey the keywords listed above were used.

# 1. LOW-INDUCTIVE EXTENDED Z-DISCHARGE AS MULTIRANGE SOURCE OF ELECTROMAGNETIC RADIATION

## 1.1. Traveling wave of sliding avalanche discharge

The results obtained with previous two modifications of installation are published in [4-8]. The present paper only briefly summarizes these results in order to give the chance to carry out the comparative analysis in the following sections. Traveling wave of sliding avalanche discharge serving as gas pre-ionization system in low-inductive tube with close spacing of electrodes was registered from the moment it started at the sharp edge of high voltage electrode till it reached graunded electrode. (Fig. 1). It was studied with different means.

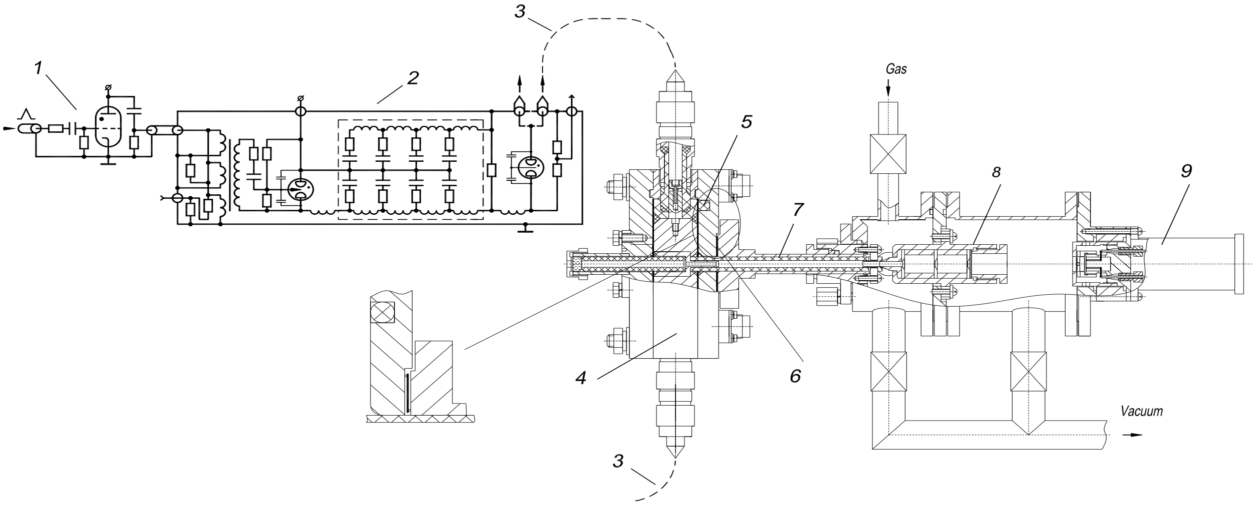
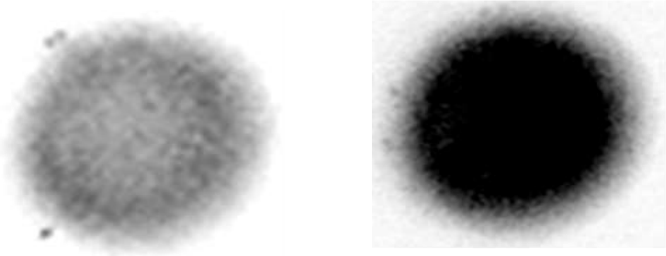


**Figure 1. Second modification of experimental installation «Extreme» for studying of capillary discharges**.

1- Thyratron generator, 2 – high voltage pulse generator, 3 – transmission line, 4 – current collecting device, 5 - Rogowski coil, 6 – current shunt, 7 - capillary load, 8 - differential gas pump unit and beam collimator, 9 - semiconductor diode.

They comprised total discharge current shunt, voltage divider on the input of discharge tube, photomultipliers and coaxial photoelectric cell with optical filters, high speed (K-008) CCD camera, semiconductor Si-diode with attached absorbing aluminum filters in order to register radiation of chosen range. The avalanche discharge was disclosed at detection limit of used instruments in the shape of faint annular plasma formation carrying longitudinal current about hundreds of amperes at finishing its front to output electrode that points to its avalanche nature (Fig. 2, the left picture).



**Figures 2. Butt end photos of plasma column luminescence**

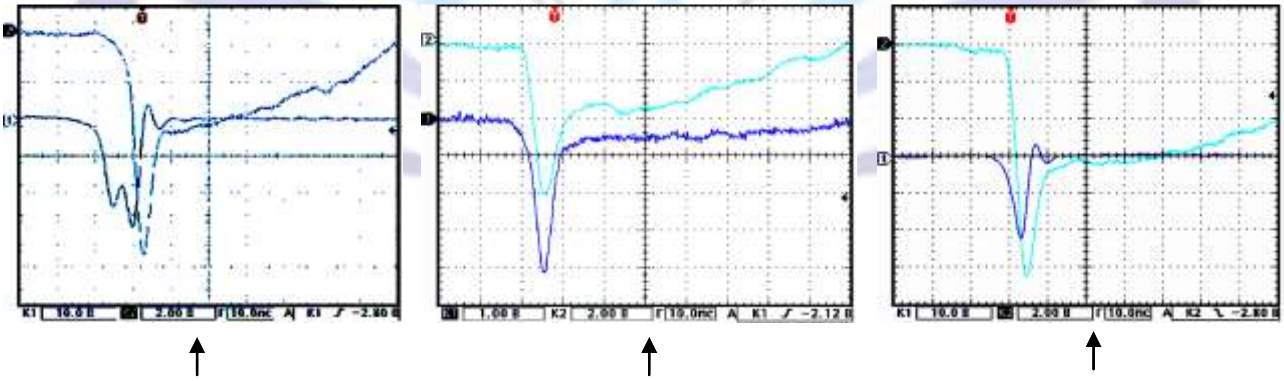
The stage of sliding discharge (left frame), the stage of high carrent longitudinal discharge (right frame).

Diameter of the hole in grounded electrode is of 3 mm. 2 ns- time of frame exposition. $p$ = 0.5 Torr, $U_0$ = 60 kV.

This is confirmed by results of theoretical consideration of avalanch discharge propagation due to the electrical drift of electrons in the longitudinal direction and traversal capacity current at the front edge of sliding discharge and also sustained by a good fit of the calculations to the experimental data of wave front motion depending on gas initial pressure [6]. Neither soft, nor hard X-ray could be revealed at the incomplete stage of the sliding discharge in argon within 0.001-1000 Torr pressure range. However the gegree of gas ionization was sufficient to form azimuthally symmetrical z-discharge at ceramic tube length up to 150 mm with inner diameter of 5 mm and wall thickness of 2,5 mm (Fig. 2, right frame).

## 1.2. EUV/SXR radiation of longitudinal high-current discharge

Spikes with duration FWHM ~ 5 ns of total discharge current and with a signal from Si-photodiode shielded by Al foils absorbing EUV/SXR radiation were observed starting from the moment of voltage drop across electrodes caused by development of high-current stage of discharges (Fig. 3).The signal from shielded photodiode stopped after spike while the current signal, from half maximum, still proceeded about 80-90 ns caused by the proceeding discharge of the transmission line. At this particular time weak and long-drawn in time EUV signal corresponding to the arrival of pinching plasma on the axis was observed at low pressure (~0.1 Torr) that was also observed on the second modification of installation capable to produce currents up to 22 kA. It should be mentioned that a noticeable prepulse of EUV/SXR radiation appears at pressures less than 0.1 Torr (upper oscillograms). This prepulse is associated with approaching of the front of sliding discharge to output electrode and switching over it a portion of electric eclectic line-of-force, forming a local longitudinal component of field. The prepulse was of no interest to create extended emitting discharge and was easily eliminated by slight increase in pressure (over 0.1 Torr).



(a) (b) (c)

**Figure 3. Signal traces from Si-diode (1) and total current from foil shunt (2)**

a)$U_0$= 60 kV, $p_0$ = 0.08 Torr, thickness of absorbing foil on photodiode 0.8 μm, b) $U_0$= 60 kV, $p_0$ = 0.2 Torr, thickness of absorbing foil on photodiode 0.8μm, c) $U_0$= 60 kV, $p_0$ = 0.2 Torr, open photodiode aperture.

The beginning of sliding avalanche discharged is shown by arrows.

The spikes in the signals of EUV/SXR radiation and in total current were discovered within the closed range of argon pressure 0.2…0.4 Torr (full investigation range was 0,001- 1000 Torr) and suggest their unpinched resonant origin. A suggestion was made that plasma medium is stepwise collisionally pumped by runaway electrons taking energy in longitudinal electric field and losing it in non-elastic collisions while opening deeper inner electron shells and forming multicharged ions plasma. Runaway mode occurs at the stage of high-voltage high-impedance discharge following overlapping of interelectrode gap by sliding discharge and the preceding stage of high-current discharge. Before this stage the configuration of electric fields is reconstructed predominantly so that transversal component of traveling wave is performed into longitudinal one that is still not shunted by high current discharge. At this moment longitudinal electric field intensity can reach its maximum values of 20 kV/cm that is enough to satisfy known local criterion of runaway electrons. It is important that it occurs along the entire length of the discharge tube and gives a hope to utilize stimulated gain of line emission from extended plasma column containing multicharged ions.

Application of 0.8 - 4 microns thick absorbing aluminum foil demonstrated in the signal spikes the presence of EUV/SXR radiation with the energies of quantum from ~ 25 eV to 1 keV that corresponds to wavelengths from ~ 50 to 1 nm. The value of discharge current in spike significantly exceeds the value in quasistationary part of the pulse and indicates preferred current carrying by runaway electrons gaining energy in maximum electric field (Fig. 3b). Direct experimental observation of runaway electrons was not performed because they could not detected beyond the muzzle of discharge tune due to the limitations of used measurement instrumentation. Unfortunably linear nature of emission was not also confirmed by spectral measurement during the spikes of radiation becouse the similar mesurements did not carry out.

## 1.3. Hard x-ray radiation of plasma column

A slightly divergent beam of hard X-ray radiation (HXR) with quantum energies 15-25 keV was discovered in the space beyond the muzzle in the range of initial pressure of 0.01 – 0.3 Torr using scintillation detector and exhaust beryllium foil. The pulse duration of HXR radiation corresponds to the duration of quasistationary discharge current with coinciding maxima. The signal from scintillation detector saturates with reduction of initial pressure indicating that bremstralung radiation from atoms and ions of plasma shifts to bremstralung radiation from wall and electrode elements.

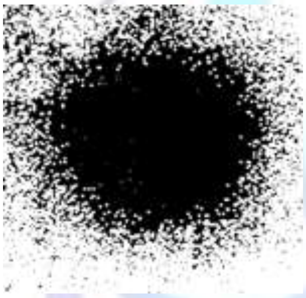


**Figure 4. An imprint of the XR beam obtained on the photo-film shielded by black paper. *p*= 0.01 Torr.**

Remarkably that during all this time, until the generation of HXR continued the voltage across the tube practically equals to zero ( see see on fiiting in left upper cornel of Fig5), in this casy rotational electrical fields should exits in the discharge tube space in order to accelerate the electrons. These fields can be registered only by noncontact measurement technique that offers great technical difficulty as well their interpretation. Identification of hot spots caused by development of plasma instabilities and taken with CCD camera equipped with light attenuation filters is difficult for the lack of experimental data. The beam of hard X-ray radiation (HXR) has divergence less than low $10^{-2}$ rad as it was determined by beam pattern obtained at 5 cm apart from the muzzle on X-ray film protected from visible light. The beam core diameter is approximately equal to the diameter of tube exhaust outlet equal to 5 mm (Fig. 4). Investigation of this interesting phenomenon should be continued.

## 1.4. Visible radiation of plasma column

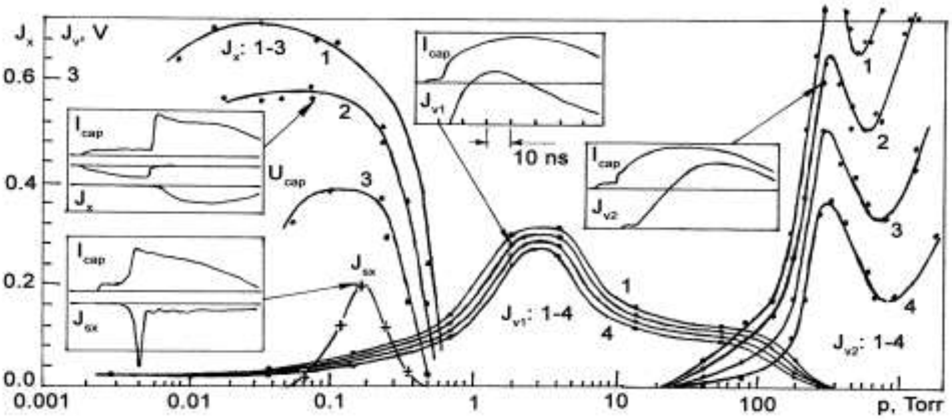


**Figure 5. The dependences of amplitudes of first and the second pulses of visible radiation $J_{v1}$, $J_{v2}$, and also amplitude of pulses of soft and hard X-ray radiation versus argon initial pressure at different voltages of incident wave $U_{ins}$ , kV: 1-70, 2- 60, 3- 50, 4- 40.**

Visible radiation of plasma column was investigated within the pressure range of 0.001-1000 Torr with the help of photomultipliers with optical filters. Broad maximum of radiation intensity was discovered with minimum at tens Torr.

After 100 Torr intensity of visible radiation again raises. It is connected with switching from diffuse discharge to streamer multichannel mode which is confirmed by images taken at the end of camber with CCD camera. The signal traces detected by photomultipliers exhibit steep leading edges with dominant component of UV radiation at low gas pressures and extended leading edges with dominant red component at high pressures. The observed radiation corresponds to quasistationary discharges of transmission line.

This view consolidates research results some of which were reproduces at second modification of installation. The amplitude dependence of EUV/SXR signal versus pressure $J_{sxm}(p)$ and dependence of radiation intensity together with the dependence of total current as a functions of time $I_{cap}$ are shown in the lower left corner (Fig 5). The current shape gives a good view of static delay of appearance of viable avalanches and the prepulse of avalanche discharge current with ~ 200 A amplitude followed with discharge current pulse with ~ 1 кA amplitude. If compared with signal traces on Fig. 3 it becomes clear why sliding discharge is hardly visible against current inrush up to 13 kA amplitude if the rest of transmission cables are connected. Since the third modification of the installation preserves preionization system based on sliding discharge it is possible to compare its efficiency and stability at discharge currents increased up to 50-100 kA.

Third modification of experimental installation will give an opportunity to continue investigation of nonpinch mechanisms suitable for creation of multirange sources of radiation. An additional point is that it can experimentally verify the interesting results obtained by numerical analyses of pinch mechanisms of plasma column creation with multicharged ions of intended multiplicity. These results will be published in special articles.

## 1.5. HXR radiaion at atmosphwric pressure

X-ray beam with quantum energy ~ 5 keV was registered with scintillation detector through_beryllium x-ray window at about atmospheric gas pressure. Unfortunately, these experiments are incomplete and postponed until the third modification of “Extreme-M” installation will be created in Ioffe Institute [7].

## 2. ELECTRODISCHARGE EUV SOURCES AND LASERS

Extended z-discharge is utilized in compact electrodischarge EUV/SXR lasers generally using two major pumping schemes: collisional excitation of multicharged ions pumping scheme (CEPS) and three-body collisional recombination pumping scheme (CRPS). The greatest advance in creation of compact electrodischarge lasers were achieved in Colorado State University, (USA) under the guidance of Prof. J.J. Rocca using CEPS. For example table-top and more compact desk-top lasers using 3d-3p transition of Ne-like Ar lines with wavelength 46.9 nm were buil [10, 11]. A number of research teams succeeded in reproducing his results in Italy [12], Japan [13], Czechia [14], Israel [15], Russia (Sarov) [16]. These lasers made possible to perform outstanding applied research and implement a series of demonstrative applications including EUV microscopy [17], interference lithography [18].

However attempts to build electric-discharge lasers with shorter wavelength was unsuccessful both for λ= 13.2 nm based on Ni-like Cd ions CEPS [19] and for $\lambda$ = 13.4 nm based on H-like N ions CRPS [20-22]. The problem is that the fundamental requirements in magnitude of specific pumping power $Q$ of active media that is necessary to attain intended magnification factor $k$ is rapidly increases with decreasing transition wavelength. In case of Doppler-broadened spectral line of quantum transition that is characteristic for electrical discharge pumping scheme, the dependence of excitation rate of upper laser level $q$ and specific pumping power $Q$ on wavelength is defined by power functions

$$q;\lambda^{-3}, \quad Q;\lambda^{-4}$$

The values of excitation rate $q$ of upper laser level and specific pumping power $Q$ for different wavelengths estimated in 1977 [23] are represented in Table 1.

| | | | | |
|---|---|---|---|---|
| $\lambda$, nm: | 0,1 | 1 | 10 | 100 |
| $q$, cm$^{-3}$.сек$^{-1}$: | $10^{32}$ | $10^{29}$ | $10^{26}$ | $10^{23}$ |
| $Q$, Wt.cm$^{-3}$: | $10^{17}$ | $10^{13}$ | $10^{9}$ | $10^{5}$ |

Until now, it seems impossible to find a method to solve the problems of pumping in electrodischarge scheme of generation with a wavelength of less than 1 nm. In the wavelength region > 1nm the situation is more realistic, but it should be noted that the estimates made took into account only the energy consumption due to quantum-mechanical considerations. In fact, there are many loss channels at every method of energy input into the medium and therefore it needs to energy input in medium considerably exceeding the specific energy of pumping,

i.e. $P > Qt_p$, where $t_p$ – pumping duration.

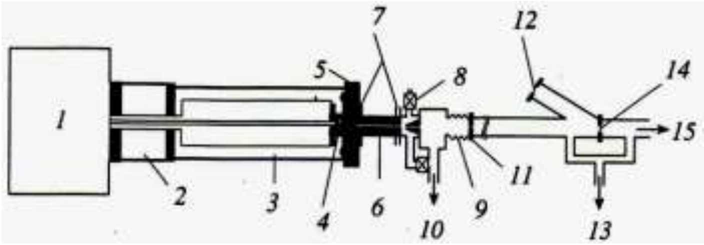


**Figure 6. Czech laser “Capex”** [14].

1) oil-filled Marx generator, (2) coupling section,filled with SF6, (3) fast water capacitor, (4) main spark gap, (5) insulator, (6) capillary, (7) Rogowski coil, (8) neele valve, (9) bellows, (10, 13) vacuum pump, (11) diaphragm,(12) diagnostic window, (14) filter, and (15) output to a detector

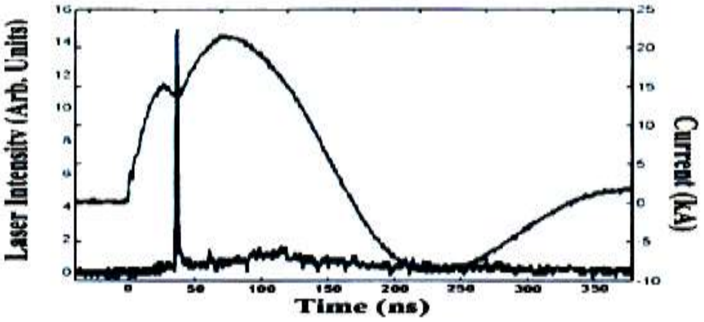


**Figure 7. Discharge current pulse (upper trace) and laser output pulse (lower trace) [11].**

One of the most important and fundamental channels of energy (power) losses on electrodischarge generating systems based on pinching discharges is the presence of a high magnetic energy remaining (stored) in the system after the pump is completed that is later inevitably dissipated in the discharge tube shortening its durability. 46.9 nm lasers on Ne-like Ar ions used a simple system of gas pre-ionization by an additional microsecond discharge. To facilitate the ignition of this discharge the inner diameter of the dielectric discharge tubes is chosen significantly smaller than the inner diameter of the coaxial return conductor (current lead). Figure 6 shows construction scheme of Czech laser “Capex”, used this ionization principle.

Using an inductive discharge load complicates pumping, but not disastrous for 46.9 nm lasers as Q<$10^{-9}$ Wt.cm$^3$. The sence of optimization of the inductance of the discharge load is crucial to its value being large enough for electric field to penetrate inside the capillary (extanal coaxial current conductor) and small enough to minimize the magnetic energy. A compact desk-top laser implemented in [11] is an example of such optimization. The dramatic increase in the EUV radiation occurs simultaneously with z-pinch discharge accompanied by a characteristic current drop (Fig.7).

Creation of electrical discharge 13.5 nm laser sources utilizing thy scheme of 46.9 nm lasers failed since shorter wavelength requires substantially higher values of specific pumping power and increases thermal load on the wall of tubes. The durability (life) of ceramic capillary discharge tubes did not exceed several shots and that is unacceptable for practical applications [19]. We foreseed results of [19] else in 2004 and started to develop the consept of low-inductive cappillary extended z-dscharges but not for acted in that time succefully EUV lasers but for future X-ray lasers.

Undestanding that the use of additional mks-discharges in close geometry of electrodes it is impossible we proposed to apply for these purposes a sliding discharhe, starting from sharp edge of high-voltage electrode and forming ionization wave. The main results of the researches obtained using the similar ionization scheme are summarized breifly in section 2 of the given article and detailed published in articles [4-7].

The analysis of these results raises the question, why in classical electric discharge EUV lasers, using additional mks-discharge preliminary gas ionization, the sharp burst of EUV in radiation is observed only at the time of discharge pinching around a maximum or before a current maximum and isn't observed at the voltage front. The fact of the matter is, gas preliminary ionization. The installation used in [1] and similar installations of other researchers utilized additional microsecond discharge preparing low impedance plasma column before the switching of high current discharge. There is no stage of high voltage nanosecond discharge under these conditions and hence there is no prerequisite for runaway electrons. As a result we obtain common Z-pinch accompanied by EUV burst with a characteristic current drop associated with the sharp increase of inductance of high current discharge.

In our case the sliding discharge carries the same longitudinal current of several hundred amperes, but with duration from a few nanoseconds to several tens of nanoseconds, depending on the gas pressure. Herein, plasma column originated by sliding discharge has no time to become low impedance but however azimuthally symmetrical that was shown experimentally.

Unique schematic features of "Extreme"-type installations significantly change the operation of electrodischarge radiation sources, opening functionality to create non-pinch systems including beams of runaway electrons. Compact electrodischarge sources of spontaneous emission radiation could find use in many applications that do not require high quality coherent radiation such as submicroscopy and interference lithography. Using spontaneous emission allows to move easily into the shortwave spectrum down to the "water window". Monochromatization of radiation sources can be implemented using reflecting mirrors with a multilayer coating [24].

With respect to perspectives of creation of electrodischsarge coherent short-wave sources using nonpinch mechanizm of pumping, namely mechanizm, based on collision excitation-ionization pumping by fast run away electrons, it may conclude after creation of third modification of installation «Extreme-M».

## 3. NANOSECOND SLIDING DISCHARGE AS A SOURCE OF ELECTROMAGNETIC RADIATION

The first group of works performed on similar topics, are the works of P.N. Dashuk and colleagues, focused on the creation of electrodischarge sources for various applications, including iodine lasers on photodissociation pumping. The approach developed by them was based on taking a sliding discharge for electrical breakdown of long discharge gap in electrically strength gas media and to form large emitting surfaces. They were the first [25] experimentally to detect X-rays emission during single-channel sliding discharge in air at atmospheric pressure in the form of two peaks (Figure 8).

In [25] they used voltage pulse generator with amplitude up to 170 kV, 3 ns pulse rise time, 350 ns pulse duration and 1 J energy capacity. The generator consisted of forming line and peaking spark gap responsible for the first pulse x-ray radiation with hardness up to 6-7 keV. We did not observed the similar phenomena because the installation we used has transmission line connected to a coaxial load to initiate a traveling wave of sliding avalanche discharge and there was almost no initial longitudinal component of the electric field.

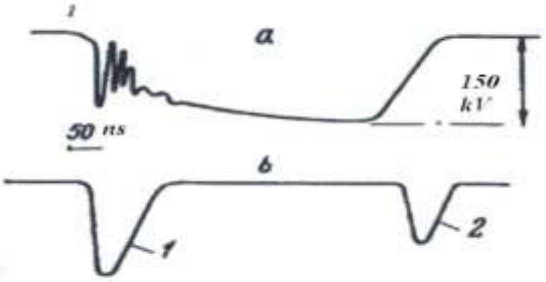


**Figure 8. Waveforms of voltage pulse applied at 20–cm discharge gap (a), X-ray radiation (b) [25].**

. The second peak appears after the short-circuiting of the discharge gap of a moving wave of sliding discharge and reconfiguration of the electric field with a predominant longitudinal component, that causes the appearance of high-energy electrons with energy ~ 7.5 keV and leads to and the corresponding bremsstrahlung. This is consistent with our work on the role of reconfiguration of the electric field in the formation of a high-voltage nanosecond discharge and the appearance of runaway electrons at conditions of confidently met runaway criterion (7-10)$10^4$ V/cm atm for the most gases [25].

The next paper [26] the same authors reports the results of the study of the surface X-ray source produced by a nanosecond sliding discharge in air and other gases. In this work, as well as in the previous publication, pulse voltage generator with amplitude up to 170 kV, with ~ 1 ns rise time and 1 J energy capacity was used. Studying the overlapping rate of plasma discharge gap in the pressure range of 0.01-1000 Torr demonstrated velocity maximum (3-7).$10^9$ cm at pressures close to atmospheric. This is inconsistent with our data [1-7], according to which the maximum velosity of propagation of the avalanche discharge is observed at pressures somewhat less than 10 Torr, when the same maximum rate of the electric drift of electrons along the surface of the dielectric tube reaches. Moreover, the drift rate falls with decreasing as well as with increasing of the optimal gas pressure that corresponds to our experimental and theoretical results obtained with proposed by us computational method [1]. Obviously, in the works of P.N. Dashuk and colleagues the overlapping rate was determined for the later moments of the sliding discharge evolution. In fact, there was observed [4-7] a second maximum at high pressures above 100 Torr that confirms this assumption (Fig 5).

The work [27] of the same authors is mostly devoted to the study of completed avalanche sliding discharge and its ability to generate X-rays. The voltage and currents waveforms becomes typical for gas discharges after sliding discharge overlaps the interelectrode gap. If this occurs the curves of X-rays intensity versus time тake of double-peak waveform correlated with the discharge current characteristic feature.

It is notable that in our studies of radiative characteristics of low-inductance discharge within the same wide pressure range 0.001-1000 Torr the nature of completed avalanche discharge was changed from defused to strimmer one in the range of 100 Torr. In this case the time dependence of the ultraviolet component also has a two-peak shape with a second peak moving to the first one when pressure approaches 100 Torr. This transitional pressure value is also appearing in [27] when one is discussing energy and radiative discharge characteristics in wide pressure range. The drop of X-ray emission and growth of minimum wavelength of the short-wave radiation can be attributed by decreasing of the portion of introduced energy per particle. Note that that the process of X-rays generation continues 10-18 ns after gap overlapping by the sliding discharge at low pressures and only 3 ns at high pressures. The matter is the value of decay constant of voltage drops at high-impedance discharge that is greater at low pressures. That is consistent with our assumption of the role of nonstationary stage of high voltage discharge that occurrs immediately after the gap overlapping by sliding discharge. That particular stage of discharge causes the generation of runaway electrons and X-rays but not itself sliding discharge, especially at the incomplete stage.

It should be noted that in the cited works [25-27] the authors use the term sliding discharges in a more broader sense, referring to incomplete and complete stage, nevertheless it would be more correct to refer the second stage to self- suistained high voltage discharge.

Paper [28] presents the results obtained in experimental studies to create an electron beam in plasma of sliding discharge in cylinder geometry. The same high voltage pulse generator was used with the discharge chamber, made of ceramic tube with an outer diameter of 60-100 mm, an inner diameter 5-40 mm and a length of 10-180 mm, 60-100 mm diameter coaxial return current conductor. Experimental conditions are similar to ours, except that we used a low – inductive ceramic tube with a diameter of 5x10 mm and a length of 50-150 mm, we also used heavy enough argon gas, capable under certain conditions to create multicharged ions plasma. In quoted paper was used a light helium gas and therefore EUV/SXR was not observed. The main goal of this work was to create a beam of accelerated electrons in the sliding discharge plasma, but not EUV.

The studies of nanosecond sliding discharge revealed forming of a beam of electrons accelerated to energies of tens of keV with total currents up to 4 kA that carry almost full discharge current within the tube. The effect of self-focusing of the electron beam into a diameter of about 1 mm was observed that is possible under on condition of neutralization of a spatial charge of the accelerated electrons. The existence of the optimal discharge length in terms of getting the highest current amplitude of the accelerated electrons was obsrerved.

At shorter gap lengths as the gas-filled diodes is developed in Institue of high current electronics IHCE (Tomsk) and Russian Federation Institute of experimental physics (Sarov) that will be discussed in the next paragraph. At larger lengths there should appear a mode of extended z-discharge with creation of multicharged ions plasma column and EUV radiation generation if one uses multishell atomic gases, as in our experiments. The energy of the accelerated electrons in this case is spent for ionization and excitation of similar gases over the entire length of the tube and can be taken as a basis for the creation of electrodischarge lasers that was done by us in our research works.

Paper [29] presents the results of utilization of SXR of the sliding discharge to generate photoelectrons at distances to 300 mm from the large emitting surface. The concentration of electrons in the gas volume spaced from the output plane of the emitter at a distance of 10-300 mm was registered by measuring of current flowing between two flat diagnostic electrodes. The carried studies allowed the authors to propose a methodology for calculating of the spectrum of X-ray radiation of nanosecond sliding discharge using the experimentally obtained dependence of photoelectron density on the distance from the source of emission by measuring the photocurrent at the collector electrode.

The carried-out calculations made possible to determine the dependence of the spectral density of the radiation flux versus the wavelength. The maximum density was observed at λ ~ 0.8 nm (Fig. 9). The results obtained agree rather good with the our results [4-7] obtained with absorbing foils.

## 4. HIGH VOLTAGE NANOSECOND DISCHARGE IN GAS FILLED DIODES AS SOURCE OF SUBNANOSECOND RUNAWAY ELECTRONS

The study, carried by Dashuk group, are in many ways similar to the work on low-inductance extended z-discharge, so their comparative analysis is useful for a better understanding of the physics and emission characteristics of sliding discharges, followed by high-voltage discharges [4-7]. While, the researches performed in the Tomsk, Yekaterinburg and Sarov were mainly focused on obtaining nanosecond and subnanosecond runaway electron beams in gas-filled and vacuum diodes with short overvoltage interelectrode gap. The nanosecond atmospheric pressure gas-filled diodes are most developed due to their simplicity and numerous applications, but their physics is quite complex and not fully understood, as confirmed by numerous publications, including the reviews [31, 32, 33] and discussions [34, 35]. Leaving aside the debate about the runaway criterion (it deserves separate consideration), the practical estimate of critical field can be given as [31]

$$E_{cr}/p = 3.38\ 10^{3} z/I,$$

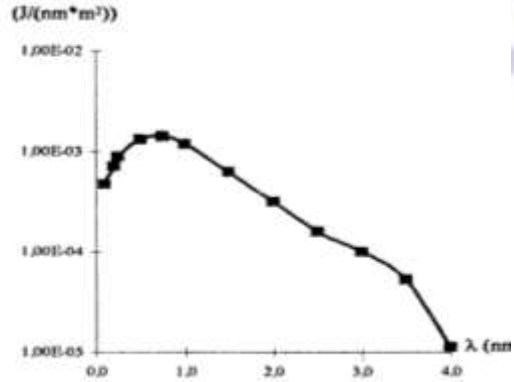


**Figure 9. SXR spectral flux density versus wavelength** [28].

where $I$- is average energy of inelastic electron loss (nitrogen, for example, z = 14, $I$ = 80 eV, $E_{cr}$/p = 590 V/cmTorr that is easily satisfied for most of nanosecond discharges). We will dwell upon the analysis of issues related to the physics of runaway electrons in relation to the phenomena discovered by us using the "Extreme" installations. It is known that in the low-temperature weakly ionized gas-discharge plasma electrons gain energy of directed motion from the electric field and spend it on the ionization and excitation of neutral particles. At high electric field strength to the gas initial pressure ratio the energy gained by electron on free path length can exceed the energy lost in inelastic collisions, so the electron will move with continuous acceleration. In the case of sufficiently short interelectrode gap the accelerated electrons move out beyond the anode region and can be utilized in various applications. In this case emission processes at the cathode affecting the continuous acceleration of electrons become important. We also detected (observe) X-rays radiation from extended z-discharges in beyond the anode region with average quantum energies of ~ 5 keV, which, obviously, were a consequence of the runaway electrons braking in argon at atmospheric pressure (see item 5 of the first section). Unfortunately, these experiments we have been postponed, and the main focus in the future has been given a low pressure discharge, as more promising for the creation of coherent radiation sources. It defined selection of further publications for analytical review of generation processes in z-discharges. The study of the formation of subnanosecond pulses of electron beam current in the gas filled diode at low pressures is discussed in [36]. The carried out experiments showed that when reducing the initial pressure there was an increase of the amplitude of the beam current beyond the outlet foil and a pulse half-amplitude duration starting from a certain pressure value, which depends on the type of gas (various gases were used, including argon). At a pressure of a few Torr suppression of generation of a subnanosecond avalanche beam occurs with transition to vacuum diode operating mode. Note that the diameter of the foil cathode was 6 mm and a cathode-anode gap was 14 mm. Comparing these results with our results obtained with gas pressure less than 1 Torr is possible to say that the tendency in increasing the beam current and duration is similar to the tendency of increasing the yield of scintillation detector with decreasing pressure but is strongly shifted toward lower pressures so that at pressures greater than 0.4 Torr, the signals from our EUV diode are absent and transition to vacuum diode mode in our case occurs at pressures less than 0.1 Torr. The photography of film phosphorescence under the action of elelectron beam is very similar to a trace of X-ray beam on the photofilm, protected by black paper (Figure 4).

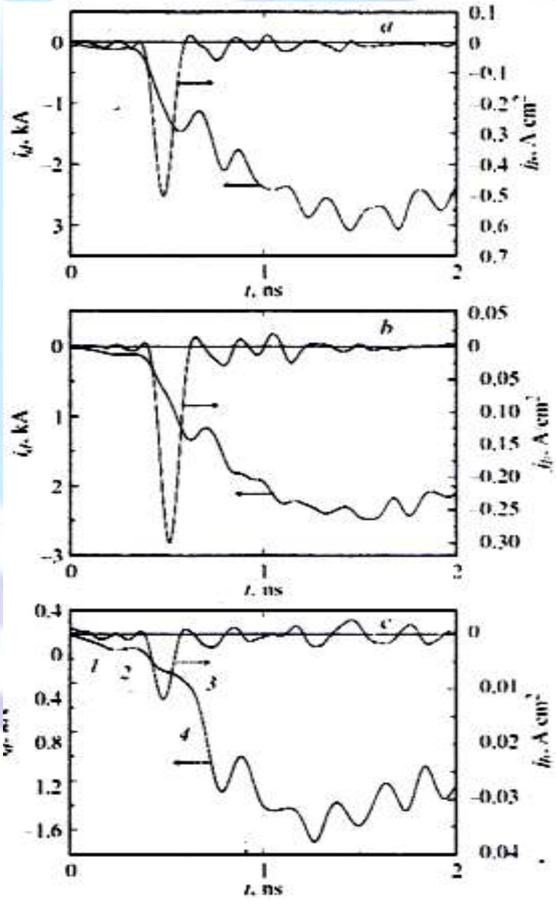


**Figure 10. Waveforms of discharge current and runaway electorn current.** 2100 (c) Torr. Interelectrode

In [37], the same authors reported the results of the study of the diffuse discharge generated in inhomogeneous electric field at increased nitrogen pressures using runaway electrons. In this work we are interested in recording of the front of full discharge current and sharp spikes of ejected currents of runaway electrons fasted to these spikes and making contribution into discharge currents transfer (Fig. 10). The effect practically disappears at pressures above three atmospheres and increases with decreasing of gas pressure. The previous paper reported the discovery of the maximum current density of the ejected beam at even lower pressures, more precisely, at ~ 30 Torr, after which the dependence curve goes down quite dramatically [36]. Unfortunately, in this paper lack data for the pressures in the intermediate-range of 0.1 - 30 Torr does not allow to clear the low value of pressure.

The spectra of X-ray radiation and runaway electrons in high-voltage nanosecond discharge at increased gas pressure were investigated in [38]. The spike on the current front created by runaway electrons with subsequent high-current discharge was called as volume discharge, initiated by an avalanche electron beam [39.]. This type of discharge was used by V. F. Tarasenko's group for the generation in UV, IR and visible regions of the spectrum [39, 40].The discovered electrodischarge pumping mechanism is similar to pumping of molecular media by volume discharge controlled or triggered by an electron beam or X-ray flux and is used in IR laser physics and engineering. However, unlike known methods, it is realized in the nanosecond range but not microsecond pumping time scale, and that is of great importance, though its nature remains the same - the penetrating radiation serves to provide volumetric and diffuse discharge while energy pumping is provided by the discharge itself. This is demonstrated by the ocilogramms shown in Figure 10. "Useful" pumping occurs after the voltage peak when the beam of runaway electrons starts to preionize gas medium and create multicharged ions.

The advantage of this (similar) approach to create a self-sustained volume discharge is that there is no need for an additional source of ionization. Also theare is the possibility to increase the working gas pressure that is very important. Technically, increasing the pump power there is the opportunity to enter EUV-SXR range if succeeded in getting stable and uniform plasma column of multicharged ions and avoiding self-absorption of radiation in a dense medium.

The situation is different in our case. A beam of runaway electrons is generated at the stage of high-impedance high-voltage nanosecond discharge that pumps extended plasma column by unpinched collision mechanism. Interaction of step-like accelerted runaway electrons with filling gas is so effective that they are not detected beyond the muzzele of the discharge tube. The runaway effect acted inside the tube is confirmed by the strong contribution of accelerated electrons into the total discharge current in the form of a sharp spike of recorded current amplitude as compared with the known Tomsk experimental data (~ 13 kA against 1kA) [39].

There is a question why change of operating conditions does not transform Tomsk-discharge into pure beam discharge. It isn't possible to answer this question yet, but one gets the impression that effect of runaway electron current spike "chipping away" by high-current discharge is intensified with increasing of gas pressure. We observed in our experiments the similar effects of suppression (disruption) of generation process with increasing of pressure (Figure 3 a, b). Note, that in contrast to our installation, Tomsk experiments used shorter discharge gaps (12 mm and 100 mm, respectively), so the "chipping away" occurred early and spikes had no time to grow endlessly.

## CONCLUSION

The carried-out analysis of experimental data obtained with "Extreme" installations together with results obtained on electrophysical installations of other types basically confirmed the previously made conclusions about the various mechanisms of generation of radiation, including those based on the effect of runaway electrons. So, the data resulted in this work on generation spontaneous EUV-SX radiation in low-inductive extended z-discharge at a transitive stage of high-voltage nanocecond discharge prepared by the completed avalanche sliding discharge and collisionally pumped by run away electrons do not contradict modern representations about a role high-voltage discharge in creation of effect continuous run away electrons and formation of plasma of manicharged ions. Perspectives in creation of short-wave lasers on plasma of manicharged ions with similar nonpinch pumping remain not clear. Following modification of the installation "Extreme-M can bring the contribution in the decision of this problem ". Authors hope also to clear up on this installation the mechanism of generation of week extending hard x-ray beam, observed on the previous modifications.

## ACKNOWLEDGMENTS

The authors thank В.И. Чернобровину и Е.П. Большакову for participation in the experimental work.

This work was supported by Russian Foundation for Basic Research, grants 12-08-01028 and 14-08-01166

## REFERENCES

1. V.A. Burtsev, E.P. Bolshakov, A.S. Ivanov et al. «Electrodischarge radiation source of capillary type». Proc. of 9-th International Conference on x-ray lasers ICXRL-2004 (24-28 May 2004, Beijing, China), pp.167-170.

2. V.A. Burtsev, E.P. Bolshakov, N.V. Kalinin, V.A. Kubasov, V.I. Chernobrovin. «Compact EUV laser on low-inductive capillary discharges». In Proc. of 10-th International Conference on X-ray lasers XRL 2006 (August 21-25, 2006, Berlin, Germany). Springer Proc. in Physics115, 2006, pp. 676-686.

3. Vladimir A. Burtsev, Evgeniy P. Bolshakov, Nikolay V. Kalinin, Vitaliy A. Kubasov, Vadim I. Chernobrovin. «EUV lasers on low-inductive capillary discharges». In Proc. of International Conference on Soft X-ray lasers and Applications VII. SPIE OP-320 (August 26-30, 2007, San-Diego, California, USA). Proc. of SPIE, vol. 6702, edited by Gregory J. Tallens, James Dunn, pp. 67020R1-8.

4. V.A. Burtsev, E.P. Bolshakov, A.S. Ivanov at all. Electrophysical problems in creation of compact effective sources of short-wave-length radiation on plasma of capillary discharges. In IEEE Transactions on Plasma Science. Special Issue on Pulsed Power Science and Technology, 2006, vol. 34, Issue 5, part 1, pp. 1929-1933.

5. V.A. Burtsev, P.N. Aruev, E.P. Bolshakov, V.V. Zabrodskii, N.V. Kalinin et al. Soft x-ray radiation of low-inductivecapillary discharge. Voprosi atomnoi nauki i techniki. Ser. Electrofisicheskay Apparatura. 2010, № 5(31), pp. 251-264 (in Russian).

6. V.A. Burtsev, E.P. Bolshakov,V.V. Zabrodskii, N.V. Kalinin. Electromagnetic radiation sources on base of low-indactive extended z- d0scharge. Technical Physics, 2003, v. 58, Is. 2, pp. 43-51.

7. V.A. Burtsev, N.V. Kalinin, S.A. Vaganov. Multi-range sources of electromagnetic radiation based on a low-inductive extended z- discharge. American Journal of Modern Physics. 2013, vol. 2(3), pp.117-123.

8. V.A. Burtsev, N.V. Kalinin.Matching of an extended high-current z- discharge to a pused power system. Technical Physics , 2013, v. 58, № 8, pp. 1106-1114.

9. Rocca J.J. Table-top soft x-ray lasers// Rev. Sci. Instrum. 1999, 70, p. 3799.

10.J. J. Rocca, V. N. Shlyaptsev, E. G. Tomasel, O.D. Cortazar, D. Hartshorn, J.L.A. Chilla. Demonstration of a discharge pumped tablle-top soft-x-ray laser. Phys. Rev. Lett. 1994, 73, 2192.

11. S. Heinbuch, M. Grisham, D. Martz, and J.J. Rocca. Demonstration of a desk-top size high repetition rate soft X-ray laser. Optics Express, May 2005, 13, № 11, p. 4050.

12.G. Tomassetti, A. Ritucci, A. Reale, L. Palladino, L. Reale, S.V. Kushlevsky, F. Flora, L. Mezi, A. Faenov, T. Pikuz, A. Gandieri. Toward a full optimization of a highly saturated soft-X-ray laser beam produced in extremely long capillary disharge ampligiers. Optics Communications, 231, pp. 403-411, 2004.

13.Yasushi Hayashi, Yifan Xiao, Nobuhiro Sakamooto, Hidekazu Miyahara, Gohta Niimi, Masato Watanabe, Akitoshi, Kazuhito Horioka and Eiki Hotta. Performance of Ne-like Ar Soft X-ray laser using capillary Z-pinch discharge. Jpn. J. Appl. Phys., 42, pp. 5285-5289, 2003.

14. Schmidt J., Kolacek K., Straus J., Prukner V., Frolov J., Bohacek V. Soft x-ray emission of a fast- capillary-discharge device. Plasma Devices and Operation, v. 13, № 2, p. 105-109.

14. К. Kolacek Ju. Schmidt ,V. Bohacek et. al. Properties of soft x-ray emission from a fast capillary discharge. 2003, v. 29, № 4, pp.318-324.

15. A.Ben-Kish, M.Shuker, R.A. Nemirovsky, A. Fisher, A. Ron, J.L. Schwob. Plasma dynamics in capillary discharge soft-x-ray lasers. Phys. Rev. Lett., v.87, № 1, Jully 2, 2001.

16. V.I. Afonin, O.N. Gilev, A.M. Gafarov. On the influence of preionization current directions on x-ray lasing in capillary discharge. In Proceedings of 10-th International Conference on X-ray lasers XRL 2006 (August 21-25, 2006, Berlin, Germany). Springer Proc. in Physics115, 2006, pp. 717-721.

17. C.A. Brewer, F. Brizuela, P. Wachulak, D.H. Martz, W. Chao, E.H. Anderson, D.T. Attwood, A.V. Vinogradov, I.A. Artyukov, A.G. Ponomarenko, V.V. Kondratenko, M.C. Marconi, J.J. Rocca, C.S. Menoni. ”Single shot extreme ultraviolet laser imaging of nanostructures with wavelength resolution”. Opt. Letters, 33, 518-520, 2008.

18. P.Zuppella, G. Tomassetti, F. Bussolotti et al. Recent progress in application of the Ne-like Ar soft X-ray laser at L’Aquila University. / // Proc. 28th ICPIG (July 15-20. 2007. Prague. Czech. Republic). Top. No.15. P. 1286 – 1288.

19. Gonzalez, M. Fratti, J.J. Rocca, V.N. Shlyaptsev, A.L. Osteheld. High power-density capillary discharge plasma columns for shorter wavelength discharge-pumped soft x-ray lasers. Phys. Rev. E 2002, v. 65, pp. 026404-9.

20. P. Vrba, M. Vrbova, N.A. Bobrova, P.V. Sasorov. Central European J. Phys., 2005, v. 3, p. 564.

21. E. Hotta, Y. Sakai, G. Niimi, Y. Hayashi, M. Watanabe, A. Okino, K. Horioka. Optimization of capillary discharge for SXR and EUV sources. In proc. of 28-th Intern. Conf. on Phenomena in Ionized gases ICPIG-08 (15-20 July, 2007, Prague, Czech Republic). 2007, pp. Ibid. pp. 69-72.

22. J. Jancarek, L. Pina, M. Vrbova, N. Tamas, R. Havlikova, G. Tomasseetti, A. Ritucci, P. Vrba. Czechosl. J. Phys. 2006, v. 56, Suppl. B, Part 2, B250.

23. A.V. Vinogradov, I.I. Sobelman. The problem of laser radiation sources in the far ultraviolet and x-ray regions. Soviet Physics JETP, 1973, v. 36, № 6, pp. 1115-1119.

24. I. Sovbelman, ФюЗю Shevelko, O. Yakushev et al.I A capillary discarge plasma source of intensive source of VUV radiation. Quantum Electronic, 2003, v. 33, № 1,pp. 3-6.

2. P. N. Dashuk, S. L. Kulakov. X-ray radiation of ns-sliding discharge in gas. Technical Physics Letters. 1979, v. 5, Is. .2, pp. 69-73( in Russian).

26. P. N. Dashuk, S. L. Kulakov. X-ray radiationof manychannel sliding discharge. Technical Physics Letters, 1981, v, 7, Is. 14, pp. 853-857. (in Russian).

27. Formation electron beam in plasma of slidind discharge. Technical Physics Letters, 1981,v.7, Is. 21, pp. 1315-1320 (in Russian).

28. P.N. Dashuk, S.L. Kulakov, Ju. Ribin. Ionization af gas by soft x-ray radiation of ns-sliding discharge. Technical Physics Letters , 1985, v. 11, )s.. 7, pp. 438-442.( in Russian).

29.P.N.Dashuk, S.L. Kulakov, E.K. Chistov. Reconstraction of the x-ray emission spvctrum of a nanosecond creeping discharge. Technical Physics Letters, 1998, v. 24, Is. 4,pp. 263-264.

30. V. O. Ponomarenko. G. N. Tolmachov. Spectra of x-ray emission from low-pressure gas discharge. . Technical Physics Letters, 2012,v . .38, Is. 16,pp. . Technical Physics Letters, 747-749.

31. G.A. Mecyaz, Yu.I. Bichkov, V.V. Lremnev. Pused nanocecond electrical discharge in gas. Physics-Uspechi Feb. 1972, v. 107, Is. 2, pp. c. 201-208.

32. .L. P. Babich , G.V. Boiko, V.A. Zukerman. High- voltage nanosecond disharge in dense gas at a high overvoltage with runway electrons. PhYsics-Uspehi, 1990, v. 33, Is. 7, pp. 521-540.

33. V.F. Тасасенко, С.И. Яковленко. The electron runaway mechanism in dense gases and production of high –power sub nanosecond electron beams .Physics-Uspehi, 2004, v. 47, Is. 9, pp. 887-905.

34.L. P. Babich, Analysis of a new electron-runaway mechanism and a record –high runaway –electron current achieved in dense-gas discharge. Physics-Uspehi, 2005, v. 48, Is. 10, pp.1065-1037.

35 V.F. Тасасенко, С.И. Яковленко. On the electron runaway effect and the generation of high-power subnanosecond beams in dense gases. Physics-Uspehi, 2006, v/49, Is. 7, pp. 767-770.

36. E. Kh. Baksht ,M.I. Lomaev , D.V. Ribko, V.F.Tarasenko. High-current density subnanosecond electron beams formed in gas fiiled diod at low pressures. Technical Physics Letter, 2006, v.32,Is. 11, pp.948-950.

37.V.F. Tarasenko, E. Kh. Baksht ,M.I. Lomaev et al. Transition of a diffuse discharge to a spark at nanosecond breakdown of high-pressurenitrogen and airin a minimum electric field. Technical Phsycs, 2033, v. 58, Is. 8, pp. 1115-1121.

38. S.B. Alekseev, E. Kh. Baksht, A.M. Boichenko et al. X-ray radiation and runaway electron beam spectra at a nanosecond discharge in atmospheric air.Technical Physics, 2012, v. 57, Is. 9, pp.1192-1198.

39. E. Kh. Baksht, A. G. Burachenko, V. F. Tarasenko. Lasing in nitrogen pumped by a runaway electron-preionized diffuse discharge. Quantum electronics, 2009, v.39, Is. 12, pp.. 1107-1111.

40. P.O. Vitkovskii,M.I. Lomaev, A.M. Panchenko et al. Lasing in the UV, IR and visible spectral ranges in a runaway –electron-preionized discharge. Qusantum Electrinics, 2013, v. 43, Is, 7, pp.605-609.

## Author' biography with Photo

**Vladimir A. Burtsev** was born in Maxatikha, Kalinin region, Russia, in 1934. He received the engineer degree in physical electronics from Leningrad Polytechnical Institute, Russia, in 1958, the Ph.D. degree in plasma physics from Efremov Scientific Research Institute of Electrophysical Apparatus, in 1970, and the Dr. Sc. degree from Kurchatov Institute of Atomic Energy, Russia, in 1982.

He became a Professor in plasma physics in 1987. Since 1958, he has been an Engineer, a Senior Scientist (1971—1974), a Head of division (1974-1991), and a Director of Scientific Center of high-power radiating systems (1991-1993), a Chief Scientist (1993-2010) in Efremov Institute. He currently is a Leader Scientist in the Ioffe Physical Technical Instutute of Russian Akademy of Sciences. His current scientific interests as formerly are plasma, lasers and high-current and high-voltage electron acceleratos physics.

Prof. Burtsev was a Laureate of the state prize of USSR in 1984. He is rewarded medals to Russia "300 years Saint Peterburg"in 2003 and honourable signs "I.V. Kurchatov" and "Veteran of the atomic science and industry."