# SPATIAL DISTRIBUTION OF CONTINUUM RADIATION FROM PLASMA OF PLANAR CAPACITIVE RF DISCHARGE IN ARGON AT 1 atm PRESSURE: PHOTOMETRIC STUDY

*V.Yu. Bazhenov[1], S.M. Gubarev[1], V.V. Tsiolko[1], R.Yu. Chaplinskiy[2]*

*[1]Institute of Physics NAS of Ukraine, Kiev, Ukraine;*
*[2] Institute for Nuclear Research NAS of Ukraine, Kiev, Ukraine*

*E-mail: gubarev@iop.kiev.ua*

The optical properties of a radio frequency capacitive discharge with isolated electrodes are investigated at atmospheric pressure in argon. The time-averaged spatial distributions of spectrally integrated continuum radiation intensity in a range of 490…580 nm across and along the discharge gap measured by means of digital camera are obtained. Peculiarities and variations of the continuum intensity profiles at gradual transition of RF discharge glow from low-current α to high-current γ mode are studied. Since bremsstrahlung radiation intensity at the electron-neutral atom interaction depends on electron density and temperature, an efficient tool for their diagnostics is given by analysis of the continuum intensity profiles.

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## INTRODUCTION

The capacitive RF atmospheric pressure glow discharges are widely used in many applications, including plasma sterilization [1-3], surface treatment of materials [4, 5], for creation of layers for liquid crystal alignment [6] and others. Advantages of such discharge type are low ignition voltage and ability to create dense uniform plasma in relatively large volume without the need of expensive vacuum equipment.

As it is known, RF discharge can operate in two different modes: low-current α and high-current γ modes. In α-mode electrons receive energy required for gas atoms ionization in quasi-neutral plasma by means of RF electric field, at that electron emission from surfaces of the discharge electrodes does not have essential effect on the discharge operation. Transition from α to γ mode occurs as a result of breakdown of space charge layers of the discharge in α mode, which leads to contraction of the discharge, and at subsequent cathode fall voltage growth, arcing may occur in the case of bare discharge electrodes. Use of dielectric barriers allows stabilization of planar RF discharge glow [7, 8]. In γ-mode electron avalanches appear in near-electrode layers, and the gas ionization by electron hits mainly occurs near the boundary between near-electrode layer and quasi-neutral plasma, at that electron emission from surfaces of the discharge electrodes essentially influences the discharge sustaining.

A set of experimental and theoretical works was targeted to the study of planar barrier RF discharges in argon at one atmospheric pressure [9-11]. However, the experimental studies of RF discharges at atmospheric pressure mostly appeared to be difficult due to poor reproducibility of the results obtained in different systems because of small discharge gap and high value of the electric disturbance.

Special attention is paid to study of the plasma source continuum radiation which can be used to evaluate the main parameters of the plasma including electron density $n_e$ and electron temperature $T_e$ through the simulation of the neutral bremsstrahlung radiation [12]. This method is very attractive due to its simplicity. Neutral bremsstrahlung is the main source of continuum radiation in the visible range from the plasma of non-thermal atmospheric pressure discharges with intensity $\varepsilon_{ea} \propto \frac{n_e n_a}{\lambda^2 T_e^{3/2}}$ where λ is radiation wavelength. However, preliminary researches have shown that, even in case of the discharge glow in γ mode as a whole, local areas in the discharge gap exist with spatial distribution of radiation intensity inherent to α mode. Thus, at determining correlation between the discharge glow modes and spatial distributions of $n_e$ and $T_e$ one should take this fact into consideration.

Following from the above considerations, the initial stage of our researches is targeted to determining behavior of spatial distributions of spectrally integrated continuum radiation intensity across and along the planar capacitive RF discharge gap upon variations of the discharge operation mode.

## 1. EXPERIMENTAL SETUP AND METHODS

A schematic of the experimental setup is shown in Fig. 1. The discharge is produced between the two parallel dielectric covered electrodes using RF electric fields with 13.56 MHz frequency. Each electrode has 1 by 5 cm area, with a gas gap spacing of 1 mm.

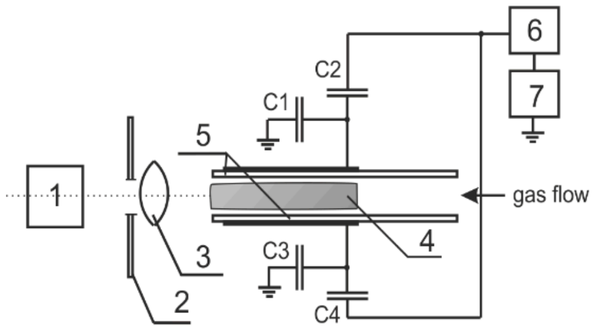


*Fig. 1. A scheme of the experimental setup.*
*1 – DSLR camera; 2 – aperture; 3 – lens;*
*4 – plasma in the discharge gap; 5 – dielectric barriers;*
*6 − impedance matching unit;*
*7 − RF generator (13.56 MHz)*

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For powering the discharge device, RF (13.56 MHz) generator 7 (MV-1.5, JSC "Selmi", Sumy) was used with impedance matching unit 6. Voltage RMS value after the matching unit could be varied in a range of 0÷1600 V. The power was supplied to the electrodes via capacitive dividers (C1-C2, C3-C4) for setting desired ratio of RF voltage values between the discharge electrodes. Argon at one atmosphere pressure was used as working gas in the experiments. Volume rate of argon feed was set in a range of 3 l/min by means of gas feed regulation system.

For study of the discharge emission spatial distributions, optical setup based on DSLR camera (Canon-EOS-350D) was used, which allowed simultaneous obtaining of the distributions across and along the discharge gap during each exposure (particular value in the experiments was 1/15 s =67 ms). The discharge gap imaging with 1:1 magnification was done by means of quartz achromatic lens with 150 mm focal length and 15 mm diameter. At that, the lens aperture was reduced in direction across the discharge gap by slit having 5 mm width. Such setup provided diffraction-limited resolution of about 50 µm FWHM in the image plane and about 1 cm depth-of-field required for correct observation of the emission from the whole discharge thickness.

Images taken by the camera in RAW mode were converted to 16-bit bitmap files with linear law of intensity conversion so that they could be immediately used for obtaining profiles of discharge intensity distribution. Spatial distributions of continuum radiation from the discharge gap were obtained by means of UFRaw and ImageJ software, and could be studied selectively for red, green and blue channels of color images. Although the discharge continuum radiation could be observed in each of mentioned color channels, the only green one was chosen for subsequent studies of spectrally integrated continuum emission intensity profiles in a range of ≈(490…580) nm determined by spectrum sensitivity of the DSLR sensor. It allowed the best characterization of bremsstrahlung emission from RF discharge plasma since shorter and longer wavelength ranges are contributed by emission lines and bands of argon atoms and excimers, as well as by molecular bands due to nitrogen admixture presence.

## 2. EXPERIMENTAL DATA AND DISCUSSION

Experimental V-I characteristic of the RF discharge (that is, discharge voltage $U_d$ dependence on the discharge current density $J_d$) is shown in Fig. 2. Practically linear part in a range of current density variation $J_d \approx 36…75\ mA/cm^2$ corresponds to low-current α-mode. Part with the negative differential resistance mainly corresponds to α-γ transition mode, and two utmost right points at the curve correspond to high-current γ-mode.

For the study of spatial distributions of continuum radiation intensity, transverse intensity profiles were obtained for three locations at the discharge image, as shown in Fig. 3.

Behavior of spatial distribution of the continuum emission intensity of argon in the low-current α, transition and high-current γ modes is shown in Fig. 4, which exhibits transverse distributions of spectrally integrated intensity of RF discharge radiation.

The researches have shown that at the discharge transition from α to γ mode, the shape of radiation intensity transverse profile changes. At low discharge current density, near both isolators of the electrodes in the discharge gap, wide regions with relatively low continuum radiation intensity exist, whereas at higher current density values the continuum radiation tends to fill practically entire space in the gas discharge gap.

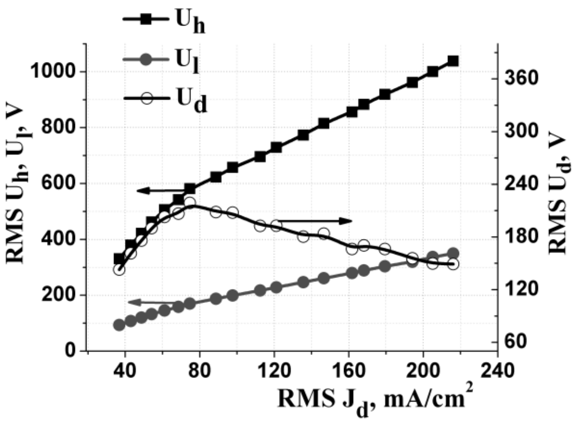


*Fig. 2. Experimental V-I characteristic of the RF discharge ($U_h$ at high voltage electrode; $U_l$ at low voltage electrode; $U_d$ is voltage fall at gas discharge gap; $J_d$ is discharge current density)*

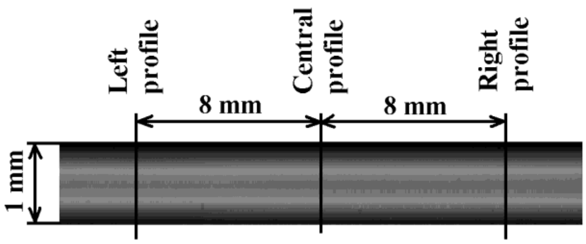


*Fig. 3. Sample image of the RF discharge demonstrating how the locations of transverse intensity profile measurements were chosen (shown with distorted aspect ratio)*

At the radiation intensity profiles (Fig. 4) one can conditionally define "α-peaks" and "γ-peaks", (that is, maxima of the radiation intensity in α- and γ-modes of the discharge glow). γ-peaks are located closer to the electrodes in vicinity of the boundary between near-electrode layer of ion space charge and quasi-neutral plasma of the bulk region.

Fig. 5 exhibits dependencies of the peak intensity values at its transverse profiles on high voltage RF electrode potential $U_h$. One can see that with the $U_h$ potential growth, and consequent current density and plasma density increase, the peak intensity values generally increase for both α- and γ-peaks. Decrease of α-peaks radiation intensity at $U_h$=700…800 V and practically simultaneous appearance and growth of γ-peaks is explained by the discharge transition from α to γ mode with respective redistribution of electric field in the gas gap. At that, in central part of the discharge gap electric field strength gradually decreases thus leading to decrease of bremsstrahlung radiation intensity in this region and α-peaks at its spatial distribution. Simultaneously, thickness of the near-electrode layer of ion space charge decreases, with respective electric field strength growth in the layer leading to appearance of electron avalanches, and γ-peaks of bremsstrahlung radiation intensity spatial distribution appear at the boundary between the near-electrode layer with quasi-neutral plasma.

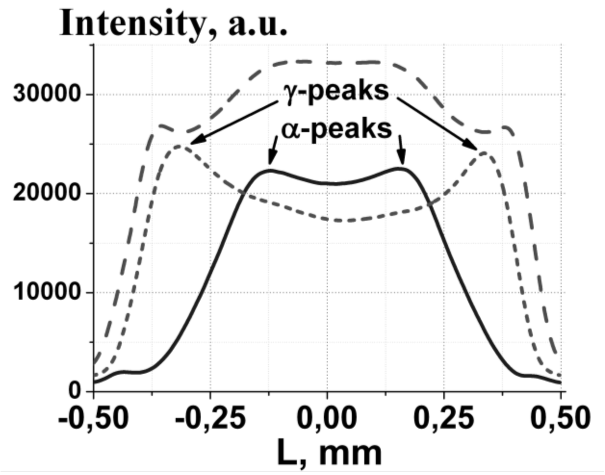


*Fig. 4. Transverse profiles of spectrally integrated radiation intensity at different RF discharge regimes (solid line – α-mode $U_h$=400 V; dash line – α-γ-mode $U_h$=900 V; short dash line – γ-mode $U_h$=1300 V)*

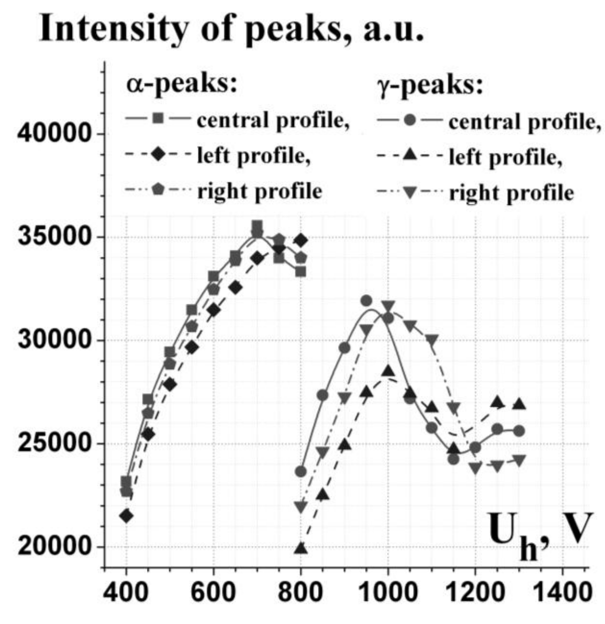


*Fig. 5. Intensity of the peaks at transverse profile of spectrally integrated RF discharge radiation intensity at different discharge regimes*

At further growth of applied voltage $U_h$>800 V, contribution of electrons knocked out of surfaces of the electrode dielectric plates to the process of plasma generation and discharge sustaining increases. Absence of α-peaks at $U_h$>800 V in Fig. 5 is due to the shape change of transverse radiation intensity profile. That is, at $U_h$>800 V during each RF cycle the discharge subsequently passes through α- and γ-modes, and at time averaging during the exposure α-peaks can overlap with γ-profile of the continuum intensity. The reason for γ-peaks intensity decrease in a range $U_h$=1000…1200 V could be due to increase of the spacing between RF electrodes caused by their thermal deformation during the experiment, which would result in the discharge transition to lower current operation in the deformation region with respective decrease of the radiation intensity. Thus, coexistence of different RF discharge modes at its different parts may be possible [13].

## CONCLUSIONS

Extensive photometric studies of spectrally integrated in wavelength range ≈(490…580) nm bremsstrahlung continuum radiation from the plasma of RF capacitive discharge in argon at one atmosphere pressure are performed for different discharge glow modes. Dependencies of the radiation spatial distributions across and along the discharge gap are obtained, and tendencies of their variations are determined at gradual transition of RF discharge glow from low-current α mode to high-current γ one. Comparative study of spatial distributions of the plasma continuum radiation at different discharge glow modes opens the prospects for further researches targeted to determination of electron density and temperature in weakly ionized plasma of RF discharges.

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## ПРОСТРАНСТВЕННОЕ РАСПРЕДЕЛЕНИЕ КОНТИНУУМА ИЗЛУЧЕНИЯ ИЗ ПЛАЗМЫ ПЛАНАРНОГО ЁМКОСТНОГО ВЧ-РАЗРЯДА В АРГОНЕ ПРИ ДАВЛЕНИИ 1 атм: ФОТОМЕТРИЧЕСКОЕ ИССЛЕДОВАНИЕ

***В.Ю. Баженов, С.Н. Губарев, В.В. Циолко, Р.Ю. Чаплинский***

Экспериментально исследованы оптические свойства ВЧ-ёмкостного разряда с изолированными электродами при атмосферном давлении в аргоне. Получены при помощи цифрового фотоаппарата усреднённые по времени пространственные распределения поперёк и вдоль разрядного промежутка спектрально интегральной в диапазоне 490…580 нм интенсивности континуума излучения. Изучены особенности изменения профилей интенсивности континуума при постепенном переходе ВЧ-разряда от слаботочного α- к сильноточному γ-режиму. Поскольку интенсивность тормозного электрон-нейтрального атома излучения зависит от плотности и температуры электронов, анализ распределений интенсивности континуума излучения является эффективным способом их диагностики.

## ПРОСТОРОВИЙ РОЗПОДІЛ КОНТИНУУМУ ВИПРОМІНЮВАННЯ З ПЛАЗМИ ПЛАНАРНОГО ЄМНІСНОГО ВЧ-РОЗРЯДУ В АРГОНІ ПРИ ТИСКУ 1 атм: ФОТОМЕТРІЧНЕ ДОСЛІДЖЕННЯ

***В.Ю. Баженов, С.М. Губарєв, В.В. Ціолко, Р.Ю. Чаплинський***

Експериментально досліджено оптичні властивості ВЧ-ємнісного розряду з ізольованими електродами при атмосферному тиску в аргоні. Отримано за допомогою цифрового фотоапарату усереднені за часом просторові розподіли поперек і уздовж розрядного проміжку спектрально інтегральної в діапазоні 490…580 нм інтенсивності континууму випромінювання. Досліджено особливості зміни профілів інтенсивності континууму при поступовому переході ВЧ-розряду від слабкострумового α- до сильнострумового γ-режиму. Оскільки інтенсивність гальмівного електрон-нейтрального атому випромінювання залежить від густини і температури електронів, аналіз розподілів інтенсивності континууму випромінювання є ефективним засобом їх діагностики.