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ON THE EVALUATION OF PLASMA PARAMETERS BY MEASUREMENT OF RF SIGNAL ABSORPTION IN LABORATORY CONDITIONS

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We have performed studies of radio wave interaction with atmospheric plasmas. In Helium a discharge was created by a system of resistive electrodes, wherein a surface current propagation is difficult. That is why discharge contraction does not occur at current densities up to 1–2 mA/cm^2. As our estimates show, electron density in such a discharge is about 10^{10} e/cc. RF probing studies at 2.45 GHz in 4 cm thick plasma layer (plasma chamber cross-section was 7×8 cm^2) have shown that no distinguishable absorption was present at the current density of 1 mA/cm^2. Thus, it is doubtful that significant electron densities of the order of 10^{11} cm^{-3} are achievable as claimed by the authors of method. Probably it is due to the difference in experiment geometries, because previous measurements were conducted in the layer of 5 mm height, while the signal wavelength is of the order of 12 cm. Also a near-electrode zone could influence the microwave power absorption the discharge cell in this case. The RF measurement test setup was also checked by fluorescent tube plasma with the known electron density and electron-neutral collision frequency. As it turned out, the RF absorption occurs in full agreement with theoretical estimations. Thus, when measuring the microwave absorption by atmospheric pressure plasmas, the skin layer depth has to be of the order of a plasma object thickness, and the signal wavelength — of the order of the object height. Otherwise, some alternative methods should be employed to determine plasma parameters in discharge. Refs 15. Figs 6.

Keywords: atmospheric pressure plasmas, microwave absorption, electron density.

Introduction. Plasmas with relatively high electron-neutral collision frequency in comparison with plasma frequency may have large skin layer depth even for rather low RF signal frequency. Such plasmas are often called "collisional", because in their electrodynamic model the collision frequency can't be neglected. If the size of collisional plasma object is comparable with the skin layer depth, then the RF wave propagates through it with some absorption. That's why the measurement of RF absorption can help to determine the electron density in such plasmas.

Collisional plasmas are found in electrical discharges with relatively high gas pressures, in forest fire flames, after hypervelocity impacts (including astrophysical events), in atmospheric re-entry events (spaceships, meteorites), etc. [1]. They were also suggested for building plasma antennas (p of the order of 5 Torr), where not only conduction (similar to a RF reflection from the plasma border) at the certain frequency band, but also an absorption of RF waves is utilized for switching on/off and beam-steering purposes [2]. Besides corona, ICP, microwave, arc and nonequilibrium arc discharges, such atmospheric pressure discharge plasmas as barrier discharges are created in laboratory conditions in pulsed mode only. While they were suggested for material processing, ozone generation and NO deactivation, bacterial decontamination and excitation of optical sources, their properties are not always determined completely.

1. Problems of atmospheric pressure plasma testing. American researchers invented the atmospheric pressure resistive barrier discharge in Helium (electron density was claimed to be of the order of 10^{11} e/cc) [3]. Due to high electron density the discharge plasma looked similar to a plasma behind shocks ahead of hypersonic vehicles [1]. In [4] authors say about the pulsed nature of discharge. The pulsed current was as high as 100 mA for the discharge chamber with diameter of about 10 cm. The average power was about 40 W. The

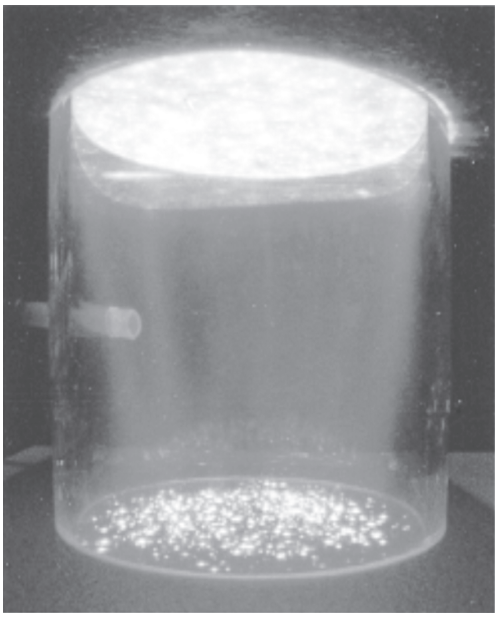

Fig. 1. Atmospheric pressure Helium discharge

picture of the discharge is shown in Fig. 1. The power supply had a voltage of about 30 kV with the average current of 10 mA. The current pulse length was about 1 microsecond. Our interest was attracted by the fact, that the authors [4] measured the electron density by a variety of methods. First of all, ionic density measurement presented the same values. They also noticed pronounced microwave absorption at 2.45 GHz in single-pulse discharge [5].

For the microwave measurements the electrode size 20×20 cm^2 and the inter-electrode distance 5 mm were used. According to the presented data [6], in the pulsed-periodic discharge the electron density was 10^{11} e/cc, while for the single pulse discharge it was found to be $5 \cdot 10^{11}$ e/cc. Signal absorption of about 50 % was registered.

For the Helium pulsed-periodic discharge generator some of plasma parameters have been presented, from which we estimated the electron density.

Current density is

$$j = 0.1/50 = 0.002 \text{ A/cm}^2.$$

From other papers [7–9] for current density 1 mA/cm^2 the E-field in the positive column is found, theoretically or experimentally, to have an order of 300–600 V/cm. Then reduced electric field is:

$$E/N = E/2.7 \cdot 10^{19} = 1 \div 2 \; Td.$$

From [10], electron drift velocity W is known to be $W = (0.45 \div 0.7) \cdot 10^6$ cm/sec. Then electron density is up to:

$$n = \frac{j}{eW} = 3 \cdot 10^{10} \text{ e/cc}.$$

So we get estimations an order less than that of other authors. Microwave absorption values measured in American test setup correspond to $5 \cdot 10^{11}$ e/cc electron density. These results are based on 1 eV electron temperature assumption. If it will be 2 times lower or higher, the collision frequency will differ twice. Our estimations of the electron density will

Fig. 2. Microwave absorption measurement test setup

give 1.5 times error for the twice variation of E/N values (in accordance with data for W of [10]).

However, the electron density results vary more. An electron density mentioned in [11] is 10^{11} e/cc in atmospheric pressure Helium discharge, but the current density is higher than 10 mA/cm^2. The calculation results in [8] are compared with experimental data for Helium atmospheric pressure discharge. It is shown there that the current density 4 mA/cm^2 matches electron density of the order of 10^{11} e/cc, and the current density of 0.8 mA/cm^2 matches electron density of the order $1.5 \cdot 10^{10}$ e/cc. As proved experimentally and shown in [12], the atmospheric discharge in Helium current density values is a transition type between Townsend discharge and "classical" glow, and it is not enough stable, because it has negative differential resistance, as an arc, and the glow did not develop yet. Golubovskii [13] has shown, that for the atmospheric pressure Townsend discharge current densities are as low as 0.1 mA/cm^2 or even less, and in glow discharge, which develops in 10 microseconds, the current density exceeds 5 mA/cm^2. In general, the above authors are in agreement and do not challenge our estimates.

Besides, the various results in Helium have been obtained by other researchers [14], who used dielectric barrier discharge and again with small inter-electrode distance (6 mm). At the current densities below 1 mA/cm^2 they claimed to obtain electron densities of about 10^{11} e/cc and higher by spectroscopic measurements. Their microwave data again agree with optical data. But as in the previous tests, they do not present discharge plasma photos (ion density by the authors of resistive barrier discharge in Helium was claimed to be optically confirmed between 10^{11} and 10^{12} e/cc, and they claimed that it verifies positively their microwave test results, though electron density may not be the same as that of ions). Also, in both cases the microwave propagation picture in the discharge cell is not considered. Golubovskii, for example, confirmed the possibility to obtain such electron densities at the specified current density range for the near-electrode zone, not the positive column [13]. So we continue to be where we stand in respect of the lower values of electron density differing from those specified by the authors of the method — not quite a standard situation, to say

the least. Also we have strong doubts that propagation of vertically polarized microwaves of decimeter band through 5–6 mm spaced electrodes could be similar to a free space propagation and think that the standard evaluation of a power decay rate seems more suitable in this case.

2. Our experiments. To realize the resistive barrier discharge we have used the porous, carefully wetted dielectric electrodes. The authors of [3–6] specified a "non-glazed ceramic" to be a good material for the electrodes.

Our choice was the minimum pore tiles of brown terracotta. Their size was $12 \times 6 \times \times 0.8$ cm^3. It is worth mentioning too, that the authors used a DC high voltage power supply (up to 30 kV) to obtain "more stable" plasmas. However, any such power supply creates a strong corona discharge. To decrease this negative factor we selected the AC power supply at 50 Hz (more information will be specified later). To create the plasma layer we have designed a vessel with two separated by 5 cm parallel walls of PMMA of 2 mm thickness. The cross-section of the layer was 8×10 cm^2, and the other two walls were made of thicker PMMA plates. The walls were glued. From the ends of the rectangular vessel 3-cm PMMA walls of 0.7 cm thickness were placed to decrease the discharge from electrodes through the air into the area where antenna is mounted, especially considering the Helium leakage at the contact between the electrodes and the vessel ends. See Fig. 3 for the illustration.

The discharge current is measured as a voltage across the 1.5 kOhm shunt by a scope, while the average voltage is measured by an AC milliammeter connected in series with 20 MOhm high voltage resistor. A ballast resistor R_b of 15 Ohm is used in series with low voltage winding in order to limit the breakdown current in the discharge chamber. Without a ballast, the contraction leads to a spark breakdown, otherwise the contracted discharge still looks like glow while becoming thin (about 2 mm) and moving inside the vessel. So a ballast resistor does not solve the problem of the discharge stabilization, as it is often done in discharge studies, but prevents the power supply equipment from malfunction. The

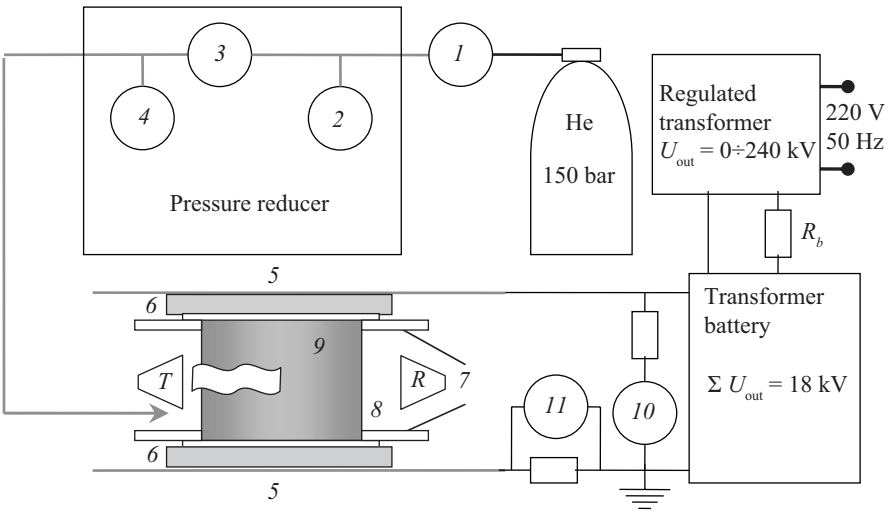

Fig. 3. Schematic of the discharge equipment:

1 — seal; *2, 3, 4* — pressure reducer; *5* — contact wires; *6* — ceramic electrodes; *7* — corona protection walls; *8* — the discharge vessel walls; *9* — plasma; *10* — ammeter; *11* — voltmeter; *T*, *R* — microwave antennas

grounding of the lower electrode does not influence the discharge current or the appearance of plasma, while the scope to measure the short discharge pulses can be easily connected to a HV circuit.

When the Helium supply flow is established to be 2.5 lpm (we used a reducer for Nitrogen) and some time passes to expel most of the air from the discharge vessel, after the power switch-on and the careful rising of the voltage up to the working voltage value (which is 18 kV RMS or 26 kV peak for our test setup), a dark Townsend discharge first builds up and then changes into a non-steady glow with very poor luminosity, which may be detected in a darkened room. The current pulses of a few milliamps are observed and crackling sound is heard in this case. This plasma presents no interest to us because of its low electron density and non-uniform spatial distribution, so after the "training" of electrodes and the vessel walls the voltage is increased close to the working voltage.

In the next mode (we shall call it an "intermediate mode") the current pulse amplitude may be as high as 25 mA. The current pulses are typically seen in series (see Fig. 4). This discharge has more pronounced but still weak pink luminance. Plasma looks to be distributed relatively uniformly over the discharge vessel, and its luminance may vary in accordance with local gas flow non-uniformities. In general, in this mode the more bright plasma is seen as being closer to the vessel walls.

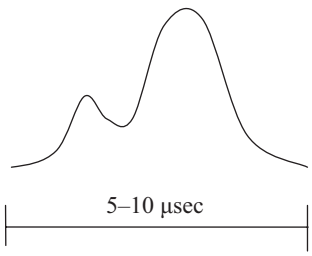

Fig. 4. The pulse sequence in the "intermediate" discharge mode

Golubovskii in [13] describes the similar current pulse train, where the weaker pulses follow after the stronger, and considers that to be a sign of the Townsend discharge. Our results may point at the non-simultaneous partial discharge over the vessel volume, while the low current prevents contraction. The same idea may be found in the papers [7–9, 11–12].

When the voltage is set to its maximum ("working voltage"), the plasma acquires luminance and is placed uniformly over the vessel volume (the simultaneity of the discharge over the volume was confirmed by the authors of the method through the set of photodiodes connected to the fast signal recorder). The form of current pulses gets changed. They are about 35 mA and their length reduces to 1–2 microseconds, which agrees with data of the authors. Some irregular pulses have twice as high amplitude, but their nature was not witnessed since we have not developed photo-registration means. The pulse repetition frequency may be raised up to 10 kHz in this mode, and the electrodes become hot, resulting in water vaporization and worsening of the discharge after a few minutes. The electron density calculation give 10^{10} e/cc, which is by an order below the values published by the authors of the method.

Our microwave tests of the plasma with signal power of 10 W at 2.45 GHz, supplied to the 74×45 mm^2 cross-section 135 mm length waveguide cut (TX antenna), have shown no visible attenuation. The corona signals were too high (10 % of the useful signal power) for the detector even with short loop input, so the band-pass filter should be placed before the detector. The following verification tests of the microwave setup with compact Π-shaped

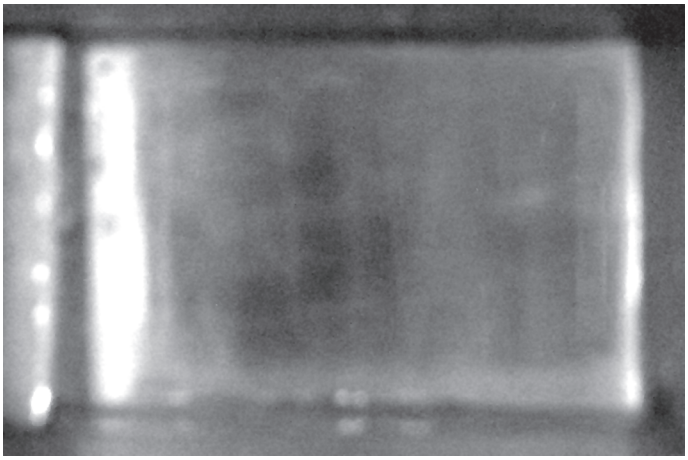

Fig. 5. Photo of the Helium atmospheric pressure discharge

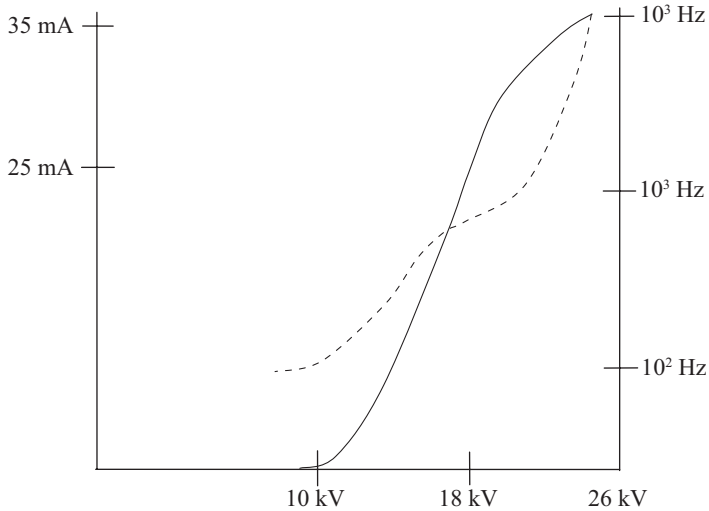

Fig. 6. Sketch of Volts-amps curve for the Helium discharge (solid) and PRF depending on voltage (dashed)

fluorescent tube OSRAM DULUX 11 W (electron density is of the order of 10^{12} e/cc — according to our estimates and data of [15], collision frequency is 10^{10} sec^{-1}) has proven its practical workability. The signal dampening after 1.2 cm diameter tube was about 50 %, which corresponds well to skin layer depth of the order of 1 cm. The rest of antenna aperture was covered with a radio absorbing material (carbonized rubber). In the absence of absorber the signal leakages are higher by 20 %. The tube was placed at the center of aperture orthogonal to the wide side. The interesting fact is that no pronounced shunting of transmitting antenna by the reactive currents in plasma was seen. When the plasma was placed closer to receiving antenna, the absorption was similar (60 %). The inter-antenna distance was about 12 cm, what is quite enough, taking into account the fact that the receiving antenna of 2 cm height is not a strong reflector in this band.

Conclusion. Our calculations and experiments with resistive barrier discharge plasmas are not quite in the agreement with those of the method's authors. But the similar

tests using a well-known fluorescent tube plasma produce results which correspond to theoretical estimations. So the microwave probing of plasmas by an incident wave, even near antenna, seems to be a reliable method, but only in case when the object allows the incident wave propagation (its cross-section dimensions are at least comparable with the signal wavelength), and its thickness is of the same order as the skin layer depth. For relatively lower electron density plasmas or inappropriate object dimensions (small inter-electrode distance) other RF methods may be tried, wherein some detectable losses could be seen at low signal frequency when probing plasma by capacitive coupling or somehow else.

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