# Development of methods for generation of collisional plasmas and study of the interaction of plasmas with electromagnetic fields at radio frequency

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## Introduction

Nowadays, high pressure gas discharge plasmas are widely used both in fundamental and applied research, including interaction of EM waves with plasmas [1-2], etc. For the experimental study of such phenomena a laboratory plasma source is required capable of generating plasmas in molecular gases (such as air) or atomic ones (helium) at pressures of hundreds of *Torr* and current densities ranging from decimal shares to tens of $mA/cm^2$. In this paper we describe different plasma generators and methods designed for experimental research in the following specific areas:

- Study of radio waves interaction with plasmas,
- Use of plasma formations as antennas,

While these issues have been under consideration for tens of years, modeling methods and devices for their realization are far from being perfected yet.

## 1 The study of radio waves interaction with plasmas

The collisional thermal plasmas occur during the hypersonic ($M > 4$) flight of the vehicle in the low atmospheric layer (below 30 km), sometimes causing difficulties for radio wave propagation. For the modeling of atmospheric pressure plasmas we implemented the method of Alexeff [3], who introduced a repetitive pulsed discharge in helium with porous electrodes. The corresponding method does not work in air, because even a nanosecond pulse at pressures over 50 Torr results in contraction of the discharge. The key parameter of plasmas is electron density, which was supposed to be of the order of 1011 e/cc [3]. The authors have studied the microwave propagation at 2.45 GHz through the discharge plasmas with inter-electrode distance of 5 mm [4]. The similar data were obtained by another team of researchers for classical barrier discharge in helium with 6 mm electrode spacing [5]. The electron density was of the order of 1011 e/cc, and their microwave measurements at 10 GHz confirmed that. In both cases the current density was of the order of 1 mA/cm2. Golubovskii numerically modeled the atmospheric pressure discharge in helium [6]. His electron density values in the near electrode zone for the same current density were identical to those published in [3-5]. But farther from the electrodes the electron density was calculated to be significantly lower and that might have a profound effect on radio wave propagation. So we designed the helium discharge chamber of rectangular shape with thin walls and electrode separation distance as high as 70 mm. Plasma layer thickness was 50 mm.

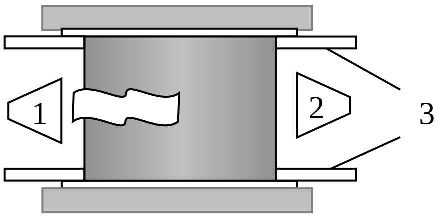

Figure 1: The schematic drawing of antenna location close to discharge chamber *where 1 is transmitting antenna, 2 is receiving antenna and 3 are corona shields*

Our measurements of the maximum current density were of the same order as the authors of [3-5] claim. The calculations via electron drift velocity give the electron density of the order of $3.3 \cdot 10^9$-$10^{10}$ *e/cc*. The RF signal of 2.45 GHz frequency of 10W power was used for the radio wave propagation experiment. A transmitting antenna was a length of waveguide placed closely to the chamber wall. A receiving antenna was a 1/8 wavelength dipole loaded with crystal detector. In helium discharge the received corona signal has 10% level in relation to the received microwave power, so we could not measure the useful signal decrement, which is twice as lower for $10^{10}$ *e/cc* at 2.45 GHz, but we could measure the signal decrement for the electron densities of $5 \cdot 10^{11}$ *e/cc*, measured in [4], and higher. However, the sufficient signal decrement was not observed. Then we verified our test setup with a compact fluorescent tube with current density of 250 *mA/cm*$^2$ (theoretical value for electron density is $2 \cdot 10^{12}$ *e/cc*). For the assumed $10^{12}$ *e/cc* and measured signal decrement of 50% the skin layer depth is found to be 7 *mm*, which agrees with the tube diameter of 1 *cm*; the similar electron density data are also published in [7]. So our test setup works satisfactory. We have not detected high electron density in the positive column in Helium, but, unfortunately, we also could not confirm our own estimations ($3.3 \cdot 10^9$...$10^{10}$ *e/cc*), because to do that we need a different receiver design.

## 2. The use of plasma formations as antennas

The usage of plasma columns as antennas has received much attention in recent years [8]. The plasma jets, which are formed by guiding the hot reaction products to a predetermined direction, can be also used for that purpose. Soshenko described the thermal “explosion” [9] of a reactive chemical mix in a chamber as the most efficient experimental method of testing atmospheric plasma jets. The hot gases expand and cool down adiabatically to ambient temperature, at which point free electrons disappear. Therefore, jet dimensions are limited. The generated plasma was driven out of the chamber via a conical nozzle, which had an exit hole of diameter about 3 *mm*. The length of the plasma jet was about 250 *mm*. The jet lifetime was about 1 *msec,* and the velocity of the jet head was about 500 *m/sec*. This velocity corresponds to a time of 0.5 *msec*, for the jet pass a distance of 250 *mm*, so we shall consider the jet to be in the steady-state mode. Let’s evaluate the parameters of this jet. The gas velocity at the nozzle exit depends on the gas temperatures at the both ends of the nozzle, because thermal energy of the reaction products is converted without loss into kinetic energy under adiabatic expansion. So, from the ideal gas EOS $p = \rho RT$ and Poisson adiabat $\frac{p}{\rho^\gamma} = const$ [10], we express the dependence of temperatures and pressures at the nozzle ends by using the following formula:

$$T_x / T_a = \left( p_x / p_a \right)^{1-1/\gamma},$$

where index *a* denotes the gas parameters at the nozzle exit, and *x* at the nozzle inlet. Let’s determine the dependence of gas velocity at the nozzle exit on the pressure. In [9], we can find a photo of the jet, which shows that the jet initial expansion angle was 45°, so the radial gas velocity is the same as the axial gas velocity. From the shock adiabatic data for air [10], we can find the relationship between the radial gas velocity at the air/jet boundary and the local air pressure. According to our measurements of the color temperature of similar reactions in open atmosphere, the reaction products can be as hot as 3500 *K*, which agrees with the literature [11]. Let’s assume the chamber pressure to be as high as $p_x$ = 1000 bar, and the reaction temperature under high pressures $T_x$ as high as 4000 *K.* By combining the known relationships, we get an $T_a$ of about 2300 *K*, and the plasma velocity at the nozzle about 2000 m/sec under a pressure about 65 bar. The reaction products of the chemical mix are, generally, solids [11]. According to [9], Soshenko used a propellant charge to ignite the mix and provide the gas generation. The $\gamma$ value for the decomposition products of propellants for this range of temperatures is 1.2-1.3 [10]. However, the known initial data is deficient, and the assumed initial values are not precise, that is why the results are only useful for evaluation purpose.

The length of the “barrel” section of a supersonic jet may now be calculated [12]. The “barrels” have a specific barrel-like shape and the gas pressure decreases from one end to the other end. Their structure is supported by a system of standing shock waves that surround the jet. A picture of first “barrel” is shown at the photo in [9] along with the picture of initial jet formation**,** because of the relatively long optical frame sampling time. The expansion angle of first “barrel” is less than 45° [12], so one can find the initial plasma expansion angle at the photo image, as we assumed before. Other “barrels” are not clearly visible. The first “barrel” length is evaluated by an empirical formula [12]:

$$L \approx d_a \sqrt{\frac{p_a}{p_0}\left(\gamma_a M_a^2 + 1\right)},$$

where the flow parameters at the nozzle exit are: $d_a$ is the jet diameter, $p_a$ is a gas pressure and $M_a$ is the Mach number, and $p_0$ is the atmospheric pressure. The velocity of sound in the plasma at the nozzle exit is about 850 *m/sec*, so *L* = 70 *mm*. Being an approximate result, it is not comparable with the conductive jet length of 250 *mm*. Even if one or two more “barrels” are used, they will be shorter than the first, because the jet pressure at their bases will be much lower, than that at the nozzle exit [12]. Intuitive considerations also make us doubt the value of the length-to-diameter ratio as high as 250:3 for the continuous plasma jet. Ahead of the “barrels”, a mixed flow of seeded hot gases and atmospheric air exists, and, according to Soshenko, the jet material there is still ionized. The origin of this has not been figured out yet. In some seeded flames the anomalously high electron production rate was detected, which probably was caused by non-equilibrium electron temperatures [13].

Our plasma source was built around a small plasmatron with a diaphragm. Unlike other authors, we elected not to use energetic materials in our tests. The reason for their decision to favor energetic materials was that in such case the convection losses do not influence plasma temperature much. However, we used a breakable diaphragm which was capable of sustaining chemical reaction in the closed volume under high pressure between components of non-explosive and non-pyrotechnic nature. Our choice was a mix of a non-ground alkali nitrate with coarse metallic powder fuel (basically 50-150 microns) and gas generating chemical additive. It is hardly iginited in open air and practically don’t burn. But while being heated from an arc generator in a closed vessel, it reacts rapidly. When certain pressure is reached the diaphragm breaks and reaction products flow out of nozzle forming plasma jet. Our tests with about 10 g of mix give 80 *cm* jet length for the nozzle diameter of 50 *mm* (See Fig. 2 for the test setup). The lower portion of the jet is presented in Fig. 3. The actual jet hydrodynamic parameters can't be figured out properly if using this picture. A faster photo registration means are necessary for that. Integral luminosity of the plasma corresponds to that of flames we generated by the small reference sources with temperatures in the range of 2000-2800 K (these were flames of chemical mixes containing metal fuels). During the tests we proposed and used the method for controlling the temperature in the jet and its decay dynamics by altering the properties of the source chemical mix. So, instead of "explosive" device of Soshenko, which does not control the plasma pressure inside the chamber, we use a device with a diaphragm, which helps to set the working pressure in the chamber and, thus, stabilize the plasma parameters.

Figure 2: Photo image of the test equipment

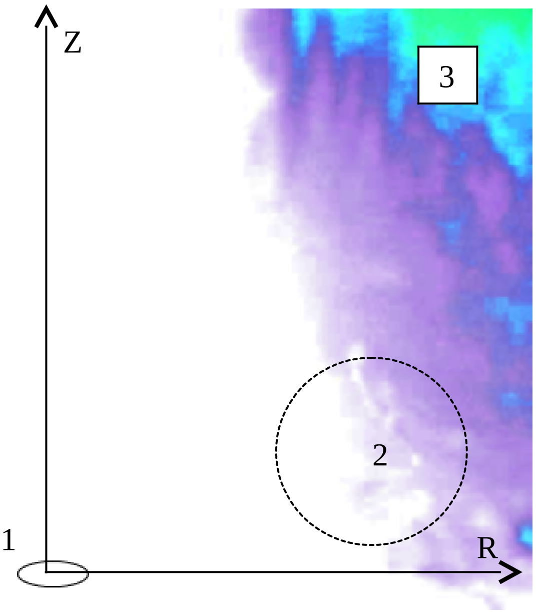

Figure 3: Photo of the plasma jet obtained in our experiments
*Integration time is 30 msec, colors are changed for the illustration purposes.*
*1 – nozzle exit hole, 2 – turbulent mixing zone, 3 – cooler gases zone,*
*Z – axis along which plasma jet propagates, R – radial coordinate.*

Plasma columns when used as antennas are typically excited by a capacitive coupling method [14]. For high excitation power that means a high voltage with considerably small dielectric thickness, which can hardly be implemented in the device based on plasma tubes. Actually, for the plasma jets this creates even more difficulties, considering especially the attempts to drive plasma antennas with megawatt level of power, as did some researchers who used a flux compression generator source for that [9]. However, the concept of transformer coupling to electron beams is world-wide known for years [15]. We suggest for that a low-inductance toroidal coil. Actually there were built multiple section coils wound by a copper foil around the core. The elements were connected in parallel and, by measuring the resonance frequency, the coils were found to have an inductance of the order of 100-300 nH. The preliminary testing with plasma tubes has shown that a toroidal coil can be used instead of capacitive coupling probe for the excitation of plasma columns as well as a capacitor probe with the difference that the generator output may have the lower impedance, that’s why the higher power supply to the plasma column is possible to realize this way. So the alternative device for plasma columns excitation is proposed, which is more suitable for high signal powers, than capacitive probe. It is necessary then to measure the device efficiency during the regular tests.

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