Resonance phenomena in microwave nonmagnetized plasma source

I.A.Kossyi
A.M.Prokhorov General Physics Institute of RAS, Moscow, Russia
Email: kossyi@fpl.gpi.ru

Abstract. Scheme of coaxial microwave gas-discharge plasma source based on a “plasma resonance” phenomenon is presented. Possibility of conditions realization at which energy of accelerated in the “resonance” electrons goes into ionization processes (in volume of chamber outside of “resonance” region) is discussed. Results of experimental investigation of a coaxial microwave plasmatron in which “resonance” mechanisms have been manifested are presented.

1. Introduction

In the present paper we report the results of the development and investigation of microwave gas-discharge plasma sources based on the phenomenon which is known as the "plasma resonance". This name comes from the fact that the plasma resonance involves nonlinear processes occurring in a spatially inhomogeneous nonmagnetized plasma in which the local value of the plasma density approaches the critical value

\[ n_{\text{crit}} = \frac{m(\omega_0^2 + v_{\text{eff}}^2)}{4\pi e^2} \]  

(\(\omega_0\) is the angular frequency of the incident microwave radiation, \(v_{\text{eff}}\) is effective electron–neutral collision frequency).

In a fairly narrow layer adjacent to the resonance surface, the microwave energy can be absorbed with high efficiency and converted into the energy of plasma electrons. The generation of fluxes of accelerated electrons in a plasma under the action of a pump electromagnetic field is a fundamental phenomenon which has been much investigated both experimentally and theoretically (see, e.g., [2–4]). Here, it is pertinent to note that these studies mostly concerned an inhomogeneous plasma in a highly rarified gas, in which the processes of interaction between electrons and gas molecules (atoms) can be ignored in describing fast electrons emission into the surrounding medium.

The problem of generation of fast electrons in the region of local resonance in inhomogeneous plasma was studied in a number of theoretical works published in the 1970s. In these works, the appearance of electrons with energies far above the thermal energy is associated with the presence of singularity of electromagnetic field, in which case the electric field substantially increases in the plasma resonance region.

Electrons interacting with this localized microwave field may gain energy through various mechanisms, such as collisions [5], the Cherenkov resonance acceleration mechanism [6], and the wave break at the nonlinear stage of plasma resonance developing in a strong pumping field [7,8].

In the 1980s, there appeared publications of experimental works devoted to investigation of the phenomenon of resonance acceleration and heating of electrons in inhomogeneous “overcritical” plasma by microwaves over a wide (from mm to dm) wavelength range (the review of these works can
Experiments were mostly carried out with high-power microwave beams interacting with a plasma produced immediately by these beams or with a plasma produced in other way. The electrons accelerated under conditions of resonance collisionless absorption of microwave beam energy were detected by using multigrid probes and electrostatic differential analyzers of electron energy distribution. In some experiments, when measuring the electron energy distribution function, provision was made for compensation of an adverse effect of the flow of electrons leaving the plasma. For this purpose, an electrode emitting slow electrons was introduced in the “overcritical” region to neutralize the positive plasma potential impeding the escape of electrons toward the walls.

The experiments demonstrated not only generation of beam of fast electrons but also abnormally strong heating of the bulk of electrons in the plasma resonance region. In case the emitter is absent and the plasma potential increases substantially, the acceleration and heating of electrons in the resonance layer is accompanied by acceleration of ions to energies close to the average energy of the beam of hot electrons. A detail description of the experiment and analysis of the results can be found, for example, in [9,10].

Theory and experiment in the 1970s and in the 1980s [2–10] allow us to formulate in the general form the conditions for resonance acceleration and heating of electrons in inhomogeneous plasma irradiated with microwaves (see section 3 of the present paper).

In the 1990s and to date, the development of a theory for plasma resonance and related experiment proceeds along the path very interesting and thorough analysis of so-called coaxial and “plane” microwave plasma sources which found wide applications, including in physical laboratories. A theory for the coaxial version was developed in [11–13]. The “plane” version (with a slit antenna) was analyzed in [14,15]. Conclusions following from recent theoretical studies agree with results obtained in the 1970s and in the 1980s.

Experiments carried out with the above microwave sources (see, e.g., [16–20]) demonstrated the presence of hot suprathermal electrons predicted theoretically.

In the present work, we attempted to realize the conditions such that the energy of electrons accelerated at the resonance is expended predominantly for ionization processes, resulting in the formation of a fresh plasma and glow surrounding the plasma-resonance region. A control parameter in this case is the gas pressure. It is essential that the pressure be low enough, lest the resonance be suppressed, and at the same time, it must be high enough to bring into action ionization processes in the gas surrounding the resonance region.

As an experimental device suited for realization of the resonance mechanism of the plasma production, we have chosen a coaxial microwave plasmatron close to the “Duo-Plasmaline” developed and investigated in [21]. As a “Mono-Plasmaline” this system with tailor made coaxial waveguide end has been realized and investigated at the General Physics Institute [22,23]. Gas-discharge sources described in [21–23] are operable over a wide range of the working gas pressures and are capable of producing a cylindrical plasma region where the plasma density exceeds the critical density.

Results of experimental investigation of a coaxial microwave plasmatron in which “resonance” mechanisms have been manifested are presented. A plasmachemical reactor based on a “resonance” plasmatron is described.

It is reasonable to note that resonance phenomenon has long been known and applied in a magnetized plasmas (electron-cyclotron (ECR) resonance at which cyclic frequency of microwave radiation equals to electron cyclotron frequency: \( \omega_0 = \omega_c \)). However field of ECR-discharges application is limited due to the necessity to impose of a strong magnetic field on a discharge volume. It adds complexity and price to a plasmatron construction.
2. “Resonance” coaxial microwave gas-discharge plasma source

2.1. Description of the Coaxial Microwave Plasmatron. Experimental Layout.

The coaxial microwave plasma source is shown schematically in figure 1. Radiation of a magnetron (1) is fed to a coaxial waveguide consisting of an outer cylindrical electrode (2) and an inner rod-electrode (5). The inner electrode is inserted into a quartz tube (3) which is welded up on the vacuum-chamber side. The outer electrode is shorter than the inner electrode; it tapers until it reaches the dimension of the quartz tube. Length of a quartz tube came out from the “truncated” external electrode is $L_{qt} \approx 10 – 15$ cm. Quartz tube diameter is $\theta_{qt} \approx 1.2 – 1.5$ cm. Diameter of coaxial waveguide external electrode (up to its conversion into a conical constriction) is $\theta_{ee} \approx 1.2 – 1.5$ cm.

The chamber is filled with a working gas. When the magnetron is switched on, a gas-discharge plasma (4) is produced near the surface of the quartz tube, on the length corresponding to the projection of the rod-electrode beyond the coaxial waveguide.

As a microwave source, we use a production magnetron like those commonly used in household appliances (in microwave ovens). The microwave wavelength is $\lambda_f \cong 12.5$ cm, and the mean power is $\overline{P} \leq 1$ kW. The magnetron generates a sequence of microwave pulses with a duration $\tau_f \cong 8$ ms and a time interval between pulses $\Delta \tau \cong 12$ ms.

![Figure 1](image)

Figure 1. Schematic of the coaxial microwave plasmatron: (1) magnetron, (2) outer electrode, (3) quartz tube, (4) near-the-tube overdense plasma, (5) inner rod-electrode, (6) wall of the reactor chamber, (7) volumetric “aureole”.

Figure 2 shows the experimental layout for studying the plasma produced by the coaxial microwave source. A plasmatron (1), which is similar to that exhibited in figure 1, is introduced into a cylindrical metal chamber of diameter about 350 mm (5). The preliminarily evacuated chamber is filled with the working gas (argon) at pressure $0.02 \leq \rho \leq 5$ Torr.

The chamber has two opposite quartz windows (8) for input and output of diagnostic radiation. Horn-lens antennas (2, 3) are used to transmit and receive the diagnostic beam of a microwave ($\lambda_d \cong 8$ mm) interferometer measuring the electron density in the plasma produced by the plasmatron.

Radial distribution of electron concentration is determined with help of single and double Langmuir probes (7). The single probe measured the floating potential.

Collimated photomultipliers (4) measured the radial profiles of the plasma radiation.

Spectral characteristics of microwave gas-discharge plasma have been determined with the help of AvaSpec 2048 FT (Avantis) spectrographs (6).
2.2. Experimental results

The most reliable technique in this experiment is microwave interferometry which does not perturb the plasma. The plasma density in the chamber was measured using a diagnostic microwave beam and the experimental arrangement shown in figure 2. The results of measurements of the average density are presented in figure 3. The diagnostic beam crosses the plasma at a distance of 2 cm from the end of the quartz tube of the microwave plasmatron.

![Figure 2](image)

**Figure 2.** Experimental layout: (1) plasmatron, (2, 3) horn-lens antenna of the microwave interferometer, (4) photomultiplier, (5) vacuum chamber of the reactor, (6) spectrograph, (7) Langmuir probe, (8) quartz windows, (9) overdens microwave gas-discharge plasma, (10) volumetric plasma (“aureole”).

![Figure 3](image)

**Figure 3.** Pressure dependence of the electron density averaged over the path length of the diagnostic beam in the plasma. The working gas is argon.

Figure 4 shows the dependence $n_e(p)$ and floating probe potential $\varphi_f(p)$ measured by probes at a distance of $r \approx 6.0$ cm from the axis. The radial profiles of the density measured by the probes are demonstrated in figure 5 (for $p = 0.1$ Torr).

In [4,9,10], where the plasma resonance in collisionless inhomogeneous plasma was studied, the use of special constructions of multielectrode probes and electrostatic differential analyzers placed near the walls of the vacuum chamber made it possible to construct the electron energy distribution function over a wide range of energies and not only to determine the bulk electron temperature but also to detect a group of suprathermal fast electrons in the tail of the distribution.
Figure 4. Electron density (1) and probe floating potential (2) as functions of the argon pressure in the chamber. $t = 5$ ms.

Figure 5. Radial profile of the electron density at $p = 0.05$ Torr, $\Delta Z = 0.3$ cm, $t = 5$ ms. The experimental dependence is approximated by the function

$$\frac{n_e}{10^{11}} = 0.35 + 4.06 \times \exp\left(-\frac{r}{3.68}\right)$$

(solid line).

In the present experiment, however, the electron mean path lengths are comparable with, or less than, sizes of the chamber, the use of energy analyzers similar to those employed in [4,9,10] is ruled out. The form of the $I-V$ characteristic of the single Langmuir probe used in the experiment described in the paper in the electron brunch is far from being ideal (this refers to both cylindrical and plane probes). In particular, as follows from the present experiments and also from experiments described in [16,18], the characteristic does not show a distinct saturation of the electron current. This makes the interpretation of this characteristic difficult, because the probe taking high electron currents from the plasma introduced strong perturbations into the plasma medium.
The probes in our experiments were usually in the regime of measurement of floating potential (the load resistance is high – at a level of hundreds of kΩ to 1 MΩ), in which case the perturbing effect of the probe is minimal. At the same time, the presence of a distinct saturation in the ion branch allows us to use this branch of the characteristic for estimating the ion density.

A characteristic thickness of the plasma shell can be inferred from the point-by-point measurements with collimated photomultipliers displaced in a direction orthogonal to the source axis.

3. Discussion

The experimental results allow us to conclude that our microwave gas-discharge source makes it possible to realize the situation that, at relatively low pressures of the working gas, the nonlinear processes occurring in the plasma-resonance region play a decisive role in the plasma formation. This view on the plasma formation mechanism is consistent, in particular, with very large values of the electron density and plasma potential in the chamber volume that fall outside the range predicted by conventional models of a microwave discharge (see, e.g., [24]):

\[ n_e \gtrsim 3 \times 10^{11} \text{ cm}^{-3} \gg n_{ic} \approx 6.4 \times 10^{10} \text{ and } \varphi_p \gtrsim 70 \text{ eV}. \]

These values can be consistently explained at the assumption that immediately near the plasmatron there is a resonance layer in which the microwave energy is efficiently converted into the electron energy. A narrow plasma layer adjacent the resonance layer (with the critical density) is a region where the energy of the electromagnetic wave is efficiently absorbed, resulting in the acceleration of the plasma electrons. The generation of fast electrons whose energy far exceeds the thermal energy was observed in a number of experiments [9,10,16–20]. Theory explains this as being due to the presence of singularity of an electric field in an inhomogeneous plasma, i.e. due to a considerable enhancement of the electric field in the plasma-resonance region. For electrons interacting with this localized microwave field, a change in their energy may be caused by different mechanisms: collisions, the Cherenkov resonance acceleration mechanism or the wave break in the nonlinear stage of the developing plasma resonance in a strong field of the pump wave. If the ion density has a linear profile, the electrons in the plasma-resonance region are accelerated primarily toward a lower plasma density.

A prerequisite to the definitely nonlinear interaction of an electromagnetic wave with the inhomogeneous plasma whose density is over the critical level is the presence of the electric field component directed parallel to the plasma density gradient.

The main characteristics of the plasma-resonance region can be calculated within the framework of available theories (see, e.g., [4]).

Thus, the width of this region is defined by the relation:

\[ \Delta R_{res} \approx R_p S. \]  

The strength of the enhanced electric field of the electromagnetic wave in this region is

\[ \vec{E}_{res} \approx \frac{\vec{E}_{0r}}{S}. \]

The characteristic energy of suprathermal electrons generated in a collisionless plasma in the resonance region can be estimated as

\[ \varepsilon_{eh} \approx e\vec{E}_{0r} R_p. \]

In equations (1–3), the variable \( S \) is greatest of three dimensionless quantities:

\[ S = \max \left\{ \left( \frac{V_{eff}}{\omega_0} \right)^2, \left( \frac{r_{De}}{R_p} \right)^{2/3}, \left( \frac{r_{osc}}{R_p} \right)^{1/2} \right\}. \]  

Here \( R_p \) is the characteristic dimension of the plasma inhomogeneity, \( \lambda \) is the microwave wavelength, \( r_{De} \) is the Debye radius, \( r_{osc} \) is the electron oscillation amplitude in the pump field, and \( \vec{E}_{0r} \) is the amplitude of the radial component of the vacuum electric field of the pump wave.
Turning to the experiment described in this paper, we note that almost all of the necessary conditions for the plasma resonance are satisfied at pressures $p << 1$ Torr. The electron density near the plasmatron is well over the critical level and at a certain distance $r_c$ from the source takes the value $n_{ec}$. Thus, there exists a resonance region in the spatially inhomogeneous plasma, and the density gradient of this plasma is orthogonal to the plasmatron axis, i.e., it is in the radial direction. The electromagnetic wave emitted from the plasmatron also possesses the electric field component $E_{or}$ in the radial direction.

It should be pointed out that existence of a considerable radial component of microwave electric field $E_{or}$ in the vicinity of dielectric tube in investigated device (as well as in “Duo-Plasmaline” system [21]) arises from constructive features of microwave energy outlet from coaxial waveguide. Standard configurations where plasma is produced within a dielectric tube (inner surface wave configuration) does not provide means for considerable $E_{or}$ component appearance and can not satisfy the conditions for resonance acceleration (heating) of plasma electron component.

Processes of electron acceleration developing in a resonance region are adequately described by equations (1 – 4) in a broad area of microwave power including our experimental value as well as values characteristic for [2–6,9,10].

Argon pressures used in our experiment satisfy the inequality $\nu_{eff} \ll \omega_0$ which is the necessary condition for resonance interactions. (Using the approximate relationship for argon [24] $\nu_{eff} \approx 7 \times 10^9 p$, where $p$ expressed in Torr is the pressure which might be expected to bring about strong effects at the resonance, we find $p << 2$ Torr.)

Under our experimental conditions, the parameter $S$ which characterizes the intensity of nonlinear processes at the resonance is defined by the ratio $\frac{\nu_{eff}}{\omega_0}$ and at $p = 0.1$ Torr amounts to $S \approx 5 \times 10^{-2}$.

In the experiment we have $R_p \approx (1 – 2)$ cm, so that the width of the discharge region (see equation (1)) is $\Delta R_{res} \approx (0.05 – 0.1)$ cm.

The radial component of the vacuum microwave electric field does not exceed $E_{or} \approx 100$ V/cm, and from equation (2) it follows that the electric field is enhanced at the resonance to $E_{res} \approx 2 \times 10^3$ V/cm.

The characteristic energy of the suprathermal electrons generated at the resonance is estimated by equation (3) as $\varepsilon_{eh} \approx 80$ eV.

At $p = 1.0$ Torr we have $S \approx 0.5$. This means $\Delta R_{res} \approx 1$ cm and $E_{res} \approx 200$ V/cm. The electron mean free path at this pressure $l_e \approx \frac{1}{n_m \sigma} \approx 3 \times 10^{-2}$ cm ($\sigma$ is the electron elastic scattering cross-section) is much smaller than the dimension of the resonance region, and the enhanced field $E_{res}$ differs only slightly from the vacuum field. Under these conditions, the average energy (or temperature) acquired by the electrons at the resonance can be estimated in the conventional models [24] by the formula

$$T_{e, \text{res}} \approx \frac{E_{res}^2 \varepsilon_{eh}^2}{3 m_e n_e (\omega_0^2 + \nu_{eff}^2)}.$$

7
where $\eta_e$ is the fraction of the electron energy lost at collisions with neutrals. For typical values of a reduced electric field $\frac{E_{\text{res}}}{n_m}$ in our experiment, we have $\eta_e \approx 0.1 - 1$ [24]. Using these values of $\eta_e$ we find that the average energy acquired by the electrons at the resonance would be on the order of $T_{\text{er}} \approx (0.1 - 1) \text{eV}$ – much smaller than the calculated electron energy for the case of low argon pressures ($\varepsilon_{\text{ch}} \approx 80 \text{ eV for } p = 0.1 \text{Torr}$).

The suprathermal electrons that are generated at the resonance and then are accelerated in the direction along the plasma density gradient can lose their energy at collisions with neutrals, thereby producing the ionization in the chamber volume.

Presumably, another source of the volume ionization is the flux of UV photons originated on the surface of the quartz tube bombarded by electrons that are reflected from the potential barrier formed by quasi-steady fields of separated charges in the plasma. According to [25], the most likely mechanism of photoionization under conditions of our experiments is the stepwise photoionization.

Thus, it is quite possible that, under conditions realized in our experiment, the electrons, oscillating in the pump field in a collisionless plasma within a narrow resonance region, gain energies on the order of 100 eV and then expend it efficiently for ionizing the gas in the chamber volume outside the resonance region.

As demonstrated in the experiments (see, e.g., [4,9,10]), the energy distribution function (EDF) for electrons that passed through the resonance region contains a group (or groups) of high-energy electrons (beams) whose energy is determined by expression (3). In this case, the EDF is characterized by a high temperature of the bulk electrons. (The high temperature is a result of high effective collision frequencies which are due to developing plasma instabilities at the resonance and are substantially higher than the electron-ion and electron-neutral collisions frequency).

Depending on the specific form of the EDF, the plasma potential can be determined by the temperature of the bulk (Maxwellian) of the EDF [24]:

\[
\phi_p \approx \frac{kT_{\text{er}}}{e} \ln\left(\frac{M_i}{m_e}\right)
\]

or the energy of the suprathermal electron beam:

\[
\phi_p \approx \frac{\varepsilon_{\text{ch}}}{e}
\]

(according to which part of EDF makes the main contribution in an electron flux on a chamber walls).

One more demonstrative result is the time evolution of the electron density $n_e$ and the probe floating potential $\phi_f$ early in the discharge pulse. Characteristic of the time behavior of $n_e$ and $\phi_f$ is the presence of a delay of $\Delta t \approx (1 - 2) \text{ ms}$ relative to the beginning of the microwave pulse (and relative to the appearance of radiation, to judge from the multiplier signal). After this delay time, the plasma density and the plasma potential rapidly grow. The analysis of photomultiplier signals and high-speed photographs of the discharge leads us to the conclusion that a plasma shell around the quartz tube of the plasmatron forms in a time shorter than $\Delta t \approx (1 - 2) \text{ ms}$. The observed delays may be associated with the time required for the electron density in the formed plasma shell to reach and exceed the critical level, after which time there appears a plasma-resonance region with singularity in the electric field of the electromagnetic wave.

For an electromagnetic wave travelling in the radial direction from the maximum-density side toward lower densities, the depth of penetration into plasma is on the order of

\[
\delta \approx \frac{c}{\omega_p}
\]

that under our experimental conditions amounts to several centimeters and is comparable with a
characteristic radial sizes of the plasma layer. This means that the nonlinear processes of interaction of the electromagnetic wave with the plasma can develop on the inner slope of the electron-density profile toward the quartz tube as well as on the outer slope toward the chamber wall.

4. Conclusion
The results of our investigations lead to the conclusion that, under conditions realized in the experiments, the parameters of the plasma created in the volume of the reactor chamber by the microwave plasmatron are governed by nonlinear processes occurring in the plasma-resonance region. The high electron density $n_e$ and the high plasma potential $\phi_p$, which bear witness to the definitely nonlinear interaction of the electromagnetic wave with the plasma created by this wave, are observed in the range of the working gas (argon) pressures $0.03 \leq p \leq 0.5$ Torr. In most of this interval, the plasma density at a distance of several centimeters from the plasmatron is substantially (three to five times) higher than the critical density for incident microwaves.

This "resonance" microwave source of plasma can find application in various fields, including plasma chemistry (in particular, for chlorine and fluorine containing gases utilization), gas-discharge sources of visible light and ultraviolet radiation, etc. There is a further application for which excitation of plasma along the dielectric by means of surface electromagnetic wave under the “plasma resonance” conditions is of immediate interest. The case in point is problem of supersonic aircraft flow past regime control. Discharge supported by surface electromagnetic wave has been considered as a possible way of this problem handling in number publications (see for example [26]). Overdense plasma production under the resonance conditions offers a possibility to enhance the action on a supersonic flow structure due to the high efficiency of energy input in a near-the-surface plasma layer.

Acknowledgements
This work was supported in part by Samsung Electronics Co., LTD, the Netherlands Organization for Scientific Research (project NWO 047.016.019), grant of Russian Foundation for Fundamental Research No 07-02-00011-a and by grant of Russian Federation President NSH-5382.2006.2. Authors are grateful to Prof. Batanov G.M. and Dr. Silakov V.P. for fruitful discussions.

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