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# MICROWAVE RESONANT CAVITY METHOD FOR THE INVESTIGATION OF THE CORONA DISCHARGE

TIBOR ŠIPÖCZ*, PETER LUKÁČ*, ŠTEFAN VEIS*, Bratislava

A specially adjusted and modified microwave cavity method has been applied for determining the electron density in the ionizing zone of the direct current and impulsive corona discharge at atmospheric pressure in air and in argon. The discharge was sustained between the inner and outer cylinders of an open coaxial cavity which had been developed purposely for the investigation of the corona. Electromagnetic waves of $TM_{011}$ mode, and 3 cm resp. 10 cm wavelength bands were used for measurements. This modified method made it possible to register electron densities in the corona about 4 orders lower in comparison with the waveguide method. From the shift observed in the resonance frequency of the cavity it can be concluded that the mean electron density in the corona discharge is less than $10^8$ cm$^{-3}$.

## МЕТОД МИКРОВОЛНОВОГО РЕЗОНАТОРА В ИССЛЕДОВАНИИ КОРОННОГО РАЗРЯДА

Специально приспособленный и модифицированный метод микроволнового резонатора был использован для определения концентрации электронов в зоне ионизации постоянного и переменного тока коронного разряда при атмосферном давлении в воздухе и аргоне. Разряд поддерживался между внутренним и внешним цилиндрами в открытой коаксиальной полости, которая была сконструирована специально для исследования коронного разряда. Для измерений были использованы электромагнитные волны $TM_{011}$ моды колебаний с длиной волны в диапазоне 3 см и 10 см соответственно. Этот метод позволил регистрировать концентрации электронов в коронном разряде примерно на четыре порядка ниже по сравнению с методом, использующим волновод. Из наблюдаемого сдвига резонансной частоты резонатора сделано заключение, что средняя концентрация электронов в коронном разряде меньше, чем $10^8$ см$^{-3}$.

## I. INTRODUCTION

The corona discharge is characterized by a few peculiarities which make its diagnostics, by the methods ordinarily used in the investigation of the other types of discharge, very difficult. It is well known that the corona discharge arises in gases at

* Katedra experimentálnej fyziky Prírodovedeckej fakulty Univerzity Komenského, Mlynská dolina, 816 31 BRATISLAVA, Czechoslovakia.

higher pressure (approximately equal to atmospheric pressure) by the action of a strongly non-uniform electric field of a high intensity. The typical conditions for the corona to originate are: a small radius of curvature of the electrode and a great potential difference between the electrodes.

The space between the electrodes consists of two main parts:

a) the ionizing zone — a narrow region in the vicinity of the coronating electrode where all ionizing processes take place;

b) the outer region — the conduction of the electric current in this region is caused by means of the flow of the ions having the same polarity as the coronating electrode.

The processes taking place in the outer region are relatively well known and theoretically described [1], [8], [9]. As regards the ionizing zone the situation is quite different. The processes here are more complicated and, at present, there exists no adequate theoretical model describing them. There is a lack of experimental data that would enable us to solve the formulated problem.

The most widely used experimental methods for the study of the corona are: Measurements of the *VC* characteristics and the oscillographic record of the progress of the discharge current in an unstable regime. The data obtained by these methods are insufficient for a better understanding of the processes within the ionizing zone. There exist no reliable data concerning the density and temperature of the electrons and their dependence on the coordinates.

One of the most suitable methods that make it possible to measure these quantities is the microwave method. This method is very sensitive, it does not affect the measured quantities, and is applicable in a wide range of plasma parameters [2]. In 1959, in paper [3], the application of the waveguide method for the measurements of the electron density in the corona had been described. The discharge was realized in a part of the coaxial waveguide. Unfortunately this arrangement did not prove to be sensitive enough. The waveguide method could not register electron densities below $10^{12}$ cm$^{-3}$. We have used a modified resonant cavity method which enables us to measure electron densities of far lower values. The application of this method to the study of the corona discharge is the subject matter of the present work.

## II. EXPERIMENTAL ARRANGEMENTS

It is well known that plasma represents a medium with a complex dielectric constant, the real part of which is determined by the electron density and effective collision frequency

$$\varepsilon_p = 1 - [ne^2/\varepsilon_0 m(\omega^2 + v^2)], \tag{1}$$

$n$ — electron density; $\varepsilon_0$ — dielectric constant in the vacuum; $e$ — charge, $m$ — mass of the electron; $\omega$ — angular frequency of the probing signal; $v$ — effective collision frequency of electrons.

When a low density plasma is inserted into a resonant cavity, its resonance frequency is changed to a small extent. The relation between the resonance frequency shift and electron density (first-order perturbation theory [2]) is given by

$$\frac{\Delta f}{f} = \frac{1}{2}\frac{\bar{n}}{n_c}\frac{\omega^2}{v^2+\omega^2}\frac{V_p}{V_r}C_V, \tag{2}$$

$f$ — resonance frequency of the empty cavity; $\Delta f$ — resonance frequency shift due to the inserting of plasma; $\bar{n}$ — average value of the electron density; $n_c$ — critical electron density; $V_r$, $V_p$ — corresponding volumes of the cavity and plasma; $C_V$ — geometry factor defined by

$$C_V = V_r \int n|E^2|\,\mathrm{d}V / \bar{n} V_p \int |E^2|\,\mathrm{d}V, \tag{3}$$

**E** — electric field vector within the cavity (without the plasma).

The minimum measurable frequency shift is inversely proportional to the quality of the cavity. Therefore the lowest measurable value of the electron density is given

$$n_{min} = 2 g_\omega n_c V_r (V_p C_V Q)^{-1} (1 + v^2 \omega^{-2}), \tag{4}$$

$Q$ — quality; $g_\omega$ — numerical factor depending on the method of measurement of the frequency shift, its value being within the interval 0.1—0.3.

Using a high quality resonant cavity makes it possible to measure a very low electron density.

At first a simple experiment was carried out. We used a cylindrical $TM_{010}$ microwave cavity and in the centre of an end plate an isolated coronating point was placed. The corona current was very low (three orders of magnitude lower than that corresponding to the corona between coaxial cylinders) and no shift was registered in the resonant frequency of the cavity.

Therefore we had to find such experimental arrangement, where it would be possible to increase the corona current and volume of plasma in the cavity. Coaxial cylinders proved to be the most adequate arrangement for this purpose. Another advantage of this arrangement was that the discharge tube for the corona served at the same time as a coaxial cavity for the microwaves. The plasma arose directly within the resonant cavity itself, and there was no necessity of making any corrections on account of the glass tube and end holes of the cavity [5].

In order to realize a corona discharge in a closed cavity it would be necessary to insulate its end plates from the inner electrode. An open coaxial cavity was found to be more suitable.

Open microwave resonant cavities are coming more and more into use for measurements in plasma physics [4] because they possess several advantages as compared with the closed ones:

1. the spectrum of the resonance frequencies is less dense — the possibility of degeneration and of the crossing of resonance frequencies for various modes is diminished,

2. the introduction of the plasma into cavity is made easier,

3. the matching with the plasma is simplified, etc.

The calculation of the dependence of the electric field on the radius has shown that the intensity of the electric field attains its maximum value in the immediate vicinity of the inner electrode (where electron density is the highest) for modes of the $TM_{0nq}$ type [6]. The geometry factor of these modes is the highest and therefore they are the most suitable for our purpose,

The quality of the open resonant cavity is approximately proportional to the cube of the length of the cavity, and is only a weak function of its radius [7]. We therefore selected as long a discharge tube as it was possible.

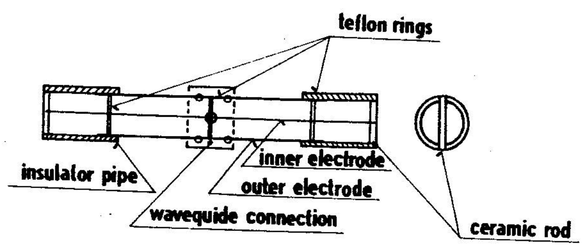


Fig. 1. Resonant cavity for the 3 cm microwave band which served also as a discharge tube for the corona.

For measurements we used a microwave apparatus operating in 3 cm and 10 cm microwave band. As a coaxial resonant cavity brass tubes of a 28 mm diameter for 3 cm and 80 mm for 10 cm band were used, which served, at the same time as discharge tubes. The length of the tubes was 400 mm and 700 mm, respectively. In the axis of the tubes a wire was fixed. During our experiments we have used inner electrodes (wires) of various materials (Mo, W, constantan) of different radii (0.015; 0.025; 0.004; 0.05; 0.1 mm). In Fig. 1 is shown the drawing of the discharge tube for the 3 cm band.

The resonant cavities were connected to the standard waveguide of the rectangular cross section of the 3 cm and 10 cm band by circular orifices of 7 and 18 mm, respectively. The relative position of the waveguide and resonant cavity ensured excitation of a TM mode resonance. The resonance frequency and its shifts were measured by the usual microwave equipment [5]. A simple scheme of the measuring circuit for 3 cm band is illustrated in Fig. 2. Similar was the system for the 10 cm band.



As it was mentioned, the cylinders of the open coaxial cavity simultaneously served as discharge tube electrodes for the corona discharge. The inner conductor was supplied with a positive or negative d.c. voltage (from a TESLA power source), or with a 50 Hz pulsation voltage (of sinus shaped pulses from a BAUR source). The high voltage circuit enabled us to measure the *VC* characteristic of the discharge.

To determine the electron density we have measured the resonance frequency of the cavity when the high voltage was switched on and switched off. In the case of the pulsating corona we measured the resonance frequency at different times changing the phase shift between the high voltage pulse and the signal corresponding to the resonance curve of the cavity [5].

## III. RESULTS AND DISCUSSION

We produced a corona discharge in air at atmospheric pressure in an open discharge tube. The measured *VC* characteristics showed a typical quadratic course. The maximum corona current which was obtained (related to the unit of the axial length of the tube had an approximate value of 50 μA/cm if a d.c. voltage was applied to the discharge tube used for measurements at the 3 cm wavelength and the value of 30 μA/cm if the pulsating voltage was applied to the tube used for measurements at the 10 cm band. A further increase of voltage leads to a breakdown.

The discharge tube, as a resonant cavity, was characterized by its resonance frequency. Fig. 3 shows the measured resonance frequency of the cavity for the 3 cm band as a function of radius of the inner electrode.

In order to measure the relation between the discharge current and the resonance frequency of the cavity we performed a large number of measurements within the entire scale of parameters permitted by our experimental equipment. The measured detuning of the cavity was in all cases very small and cannot generally be attributed to the action of the electrons of the corona discharge. In fact during our experiments a few side effects appeared which also caused a resonance frequency shift and rendered our measurements very difficult.

The inner electrode was deviated by electrostatic forces towards the outer electrode. As a result of the change of the geometry of the coaxial resonant cavity its resonance frequency was increased. The electrostatic force, together with the fluctuations of the corona current (mainly in the negative corona), produced an oscillation of the wire, and made it impossible to take any measurements. These effects could only partially be removed by placing teflone rings into the tube, (see Fig. 1) and by increasing the mechanical tension of the wire.

Table 1 shows the measured resonance frequency of the cavity for the 3 cm band at different inner electrode radii. The aggregate error of this value was estimated from measurements and is caused mainly by the inner electrode deviation from the axis. The frequency shift due to the inserting of the corona discharge into cavity was very low and varied within a wide range around the value which is shown in the last column. The microwave equipment allowed us to measure as low a resonance frequency shift as 0.2 MHz.

Using the same equipment we performed also a few experiments with the corona discharge in argon at atmospheric pressure. The effects of the corona on the resonance frequency of the cavity were similar to those in the experiment in air.

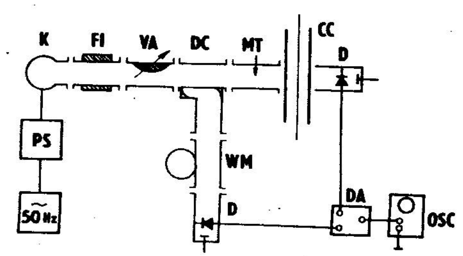


Fig. 2. Microwave circuit for the 3 cm wavelength: K — klystron, FI — ferrite isolator, VA — variable attenuator, DC — directional coupler, MT — matching transformer, CC — coaxial cavity, WM — wavemeter, D — diode, DA — differential amplifier, OSC — oscillograph, PS — phase shifter.

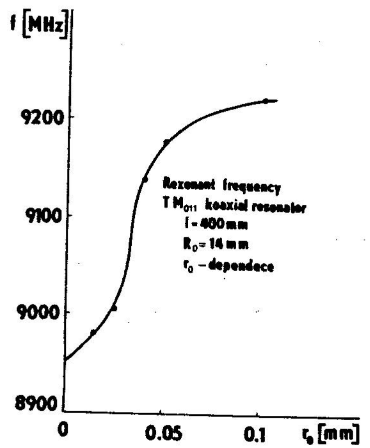


Fig. 3. Measured dependence on the inner electrode radius of the open coaxial cavity for the 3 cm band without discharge. $R_0$, $r_0$ — radius of the outer and inner electrode, $l$ — length of the resonant cavity, resonance on the $TM_{011}$ mode.

Table 1

Resonance frequency of the open coaxial cavity and its shift due to corona discharge

| electrode radius $r_0$ [mm] | resonance frequency $f$ [MHz] | frequency shift $\Delta f$ [MHz] |
|---|---|---|
| 0.015 | 8976.9 ± 3.0 | 0.64 |
| 0.025 | 9057.6 ± 2.6 | 0.60 |
| 0.040 | 9137.4 ± 2.5 | 0.60 |
| 0.050 | 9184.0 ± 2.3 | 0.43 |
| 0.100 | 9223.0 ± 2.0 | 0.20 |



## IV. CONCLUSIONS

The use of the modified microwave cavity method and a specially adjusted open coaxial resonant cavity enabled us to shift the lower limit of the measurability of electron density down to $10^8$ cm$^{-3}$ i.e. four orders of magnitude lower than afforded by the published waveguide method. Inspite of this marked improvement it was impossible to measure the density of electrons in the corona discharge. This proves, that the mean electron density in the corona discharge in air and in argon at atmospheric pressure is not higher than $10^8$ cm$^{-3}$.

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