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The Dual Mode Microwave Afterglow Apparatus for Measuring the Electron Temperature Dependence of the Electron-Ion Recombination

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Three dual mode microwave apparatus (one using S-band and two using X-band) have been developed to determine ambipolar diffusion and electron-ion recombination rates under conditions such that $T_{gas} = 300K$ and T_e is varied from 300 K to 6300 K, in the afterglow period of the dc glow discharge. The TM_{010} cylindrical cavity (in S-band) and TM_{011} open cylindrical cavity (X-band) are used to determine the electron density during the afterglow period and a non-resonant waveguide mode is used to apply a constant microwave heating field to the electrons. To test the properties of the apparatus the neon afterglow plasma has been investigated. At T_e = 300 K a value of $\alpha(Ne_2^+) = (1.7\pm0.2)$ x $10^{-7} cm^3/s$ is obtained which is in good agreement with values of other investigators. Also similar variations of α as $T_e^{-0.4}$ (S-band) and as $T_e^{-0.42}$ (X-band) obeyed over the range $300 \leq T_e \leq 6300K$ are in good agreement with some other previous measurements. The simplicity of the X-band microwave apparatus also allows the measurements of the gas temperature dependency and the study of electron attachment and may be used simultaneously with optical or mass spectrometry investigations.

1 Introduction

The electron-ion recombination is one of the dominant charged particles loss processes in a plasma. The capture of a free electron by a positive molecular ion is an electron-ion recombination process called dissociative recombination. This process was first described by Bates [1, 2]. Its efficiency is characterized by the recombination coefficient which depends on the particular experimental conditions (for example, electron and gas temperature, gas mixtures). Since 1949 when Biondi and Brown [3] used the microwave cavity technique for measuring the electron densities during the decay period of a microwave plasma (i.e. stationary afterglow technique) to determine the recombination coefficients, a number of other methods were developed. A few reviews were published (e.g. Biondi [4], Oskam [5], Bardsley and Biondi [6], Delpech et al. [7], Eletskij and Smirnov [8], Mitchell [9], Ivanov [10], Biondi [11], Florescu and Mitchell [12]) in which these new methods were described and the results obtained were summarized and discussed.

Because the values of the recombination coefficients are dependent on the plasma parameters such as electron temperature and gas temperature, their study has led to the research of electron temperature/energy dependence of the dissociative recombination coefficients. If a plasma (or afterglow plasma) is subjected to a microwave electric field the electron energy (or ”electron temperature”) of the plasma increases. This effect can be utilized as a diagnostic tool to obtain information about electron removal processes in gaseous discharge afterglows. The first experiments were conducted by Goldstein et al. [13] by applying pulsed microwave heating power during the decay period of a d.c. glow discharge located in a microwave X-band waveguide. A very successful method

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of continuously heating afterglow plasmas was developed by Biondi et al. (e.g. [11], [14]). Later Vinogradov et al. [15] have developed an alternative method of heating the electron gas of a non-self-sustained discharge in the stage of plasma decay with a longitudinal pulsed electric field. They were able to reach an electron energy of up to 1-2 eV.

Significant developments having been made in experimental techniques using storage rings (Larsson [16], Adams et al. [17], Florescu and Mitchell [12]) concerning the studies of electron energy dependence of cross sections of the recombination process. Also flowing afterglow as a new technique used to obtain recombination rate data and product information are discussed and recent data are reviewed (e.g. Mitchell [9], Adams et al. [17], Georghegan et al. [18], Smith and Španěl [19]).

In spite of development of this new technique the stationary afterglow was the first technique used to study dissociative recombination [11]. More recently, there has been a resurgence of interest in the former technique with the development of the Advanced Integrated Stationary Afterglow (AISA) apparatus at Prague (Plašil et al. [20]) and another apparatus at Brno (Meško et al. [21]).

We have developed a new method, based on Biondi's approach with a d.c. glow discharge afterglow plasma using one microwave source in the S-band microwave range (around 3 GHz) and another one operating in the X-band microwave range (around 9 GHz) which enables the simultaneous measurement of the electron and gas temperature dependence of the recombination coefficients (Mikuš and Lukáč [22]). These techniques will be described in more detail in this paper and then applied to the study of a neon gas discharge afterglow - neon was also the subject of recent theoretical investigation (Ngassam and Orel [23]). It will be seen that the apparatus with the X-band microwave source offers an improved, flexible measuring technique.

2 Theoretical background

2.1 The electron density decay

The dissociative recombination of a molecular positive ion with electron can be described by the following scheme

$$AB^+ + e \Leftrightarrow (AB)^* \rightarrow A^* + B + kinetic\ energy. \tag{1}$$

The superscripts + and * refer to ionized and excited states, respectively.

This process is characterized by the recombination coefficient α_{tot} which can be determined, for example, by the stationary afterglow method. On the assumption that the afterglow period is governed only by the electron-ion recombination process with ambipolar diffusion and that the electrons quickly achieve a stationary energy distribution, then the electron density time variation can be described by the simplified continuity equation (e.g. McDaniel [24], Chen [25])

$$\frac{\partial n_e(\vec{r},t)}{\partial t} = D_a \bigtriangledown^2 n_e(\vec{r},t) - \alpha_{tot} n_e^2\,(\vec{r},t), \tag{2}$$

where D_a is the ambipolar diffusion coefficient given by the relation

$$D_a = D_+ \left(1 + \frac{T_e}{T_g}\right), \tag{3}$$

where D_+ is the positive ion diffusion coefficient, T_e and T_g are the electron and ion(gas) temperatures, respectively. Using the Einstein relation, D_+ can be expressed as

$$D_+ = \frac{\mu}{e}\, k\, T_g, \tag{4}$$

where e is the electron charge, k is the Boltzmann constant and μ is the mobility of positive ions which does not depend on electron temperature. Therefore the ambipolar diffusion coefficient can be very simply used to check the values of the electron temperatures calculated from the microwave power heating.

The ambipolar diffusion coefficient is determined from the decay time constant τ_D of electron density in the late afterglow period (when ambipolar diffusion prevails) using the relation

$$D_a = \frac{\Lambda^2}{\tau_D}, \tag{5}$$

where Λ is the characteristic diffusion length of the plasma container and for a finite cylindrical tube of radius R and height L is given by (e.g. Mc Daniel and Mason [26])

$$\frac{1}{\Lambda^2} = \left(\frac{2.4}{R}\right)^2 + \left(\frac{\pi}{L}\right)^2. \tag{6}$$

The diffusion is reduced by choosing a higher gas pressure so that the recombination process becomes dominant. Assuming that $n_e(\vec{r},t) \approx n_+(\vec{r},t)$, then the Eq. (2) can be approximated by

$$\frac{\partial n_e(\vec{r},t)}{\partial t} = -\alpha_{tot}\, n_e^2(\vec{r},t). \tag{7}$$

The recombination coefficient α_{tot} can be determined from the solution of Eq. (7)

$$\frac{1}{n_e(\vec{r},t)} = \frac{1}{n_e(\vec{r},t_0)} + \alpha_{tot}(t - t_o), \tag{8}$$

where t_0 is the initial time.

2.2 Microwave heating of electrons

We consider a three component ionized gas consisting of electrons, singly charged positive ions and neutral atoms. All components are assumed to have a uniform Maxwellian energy distribution characterized by temperatures T_e, T_+ and T_g, respectively. Because the ions are in good thermal contact with the neutral atoms, their temperatures can also be regarded as equal ($T_+ = T_g$).

When the high frequency microwave electric field, given by $\vec{E} = \vec{E}_0\ cos\ \omega t$ (where ω is the angular frequency of electric field of the maximal value $\vec{E}_0$) is applied to this ionized gas (plasma) then the average electron kinetic energy ('temperature' T_e) increases due to microwave heating. Using the electron velocity distribution function f_0 developed by Margenau [27] the electron 'temperature' T_e can be expressed as [14]

$$T_e = T_g + \frac{e^2\ E_0^2}{3\ m_e\ k\ \delta\ (\omega^2 + \nu_{en}^2)}, \tag{9}$$

where m_e is the mass of an electron, k is the Boltzmann constant, $\delta = 2m_e/m_a$ and m_a is the mass of a neutral atom, ν_{en} is the frequency of elastic collisions between electrons and neutral atoms (approx. 5 x 10^8 s^{-1} for neon at the pressure approximately 2.7 kPa, e.g. Chen [28]), which can be neglected in comparison with the microwave angular frequency (approx. 5 x 10^{10} s^{-1}). The time average value of the electric field $< E^2 >$ is equal to $E_0^2/2$.

Because this average value of the microwave electric field is proportional to the microwave power P propagating through the plasma we can express the electron temperature in a very simple form

$$T_e = T_g + K\ P, \tag{10}$$

where the value of K depends on the gas, microwave angular frequency and geometrical dimensions.

2.3 The electron temperature dependence of the dissociative recombination coefficient

A discussion and relevant calculation of the various recombination processes is available in literature (see e.g. Smirnov [29], Flannery [30]). In decaying of an inert gas plasma at medium pressures the most probable recombination process is the dissociative one which is responsible for the large recombination coefficient observed.

Bardsley [31] has discussed the dissociative recombination process in detail. The calculation to estimate the value of this recombination coefficient requires detailed knowledge of the wave function of the molecular and atomic states indicated in reaction (1), from which the potential energy curves and auto ionization probabilities as a function of the internuclear separation of the atoms must be calculated (Ivanov [10]). The theoretical calculations of the recombination coefficient as a function of the electron temperature is in general expressed as

$$\alpha(T_e) = \alpha(300K)\left(\frac{T_e}{300K}\right)^{-\zeta}, \tag{11}$$

where $\alpha(300K)$ is the dissociative recombination coefficient at room temperature and ζ can vary from the value 0.1 to 1.5.

3 Experimental apparatus

3.1 Dual-mode microwave apparatus in S-band

Our first microwave apparatus is similar to that one developed by Biondi with coworkers (see e.g. Frommhold et al. [14]) working in S-band. We have used a microwave cavity technique to measure electron density decay in the afterglow period of the pulsed d.c. discharge. Electron energy has been increased by heating with continuous traveling microwaves with a special waveguide structure. This dual-mode microwave apparatus is shown in Fig. 1.

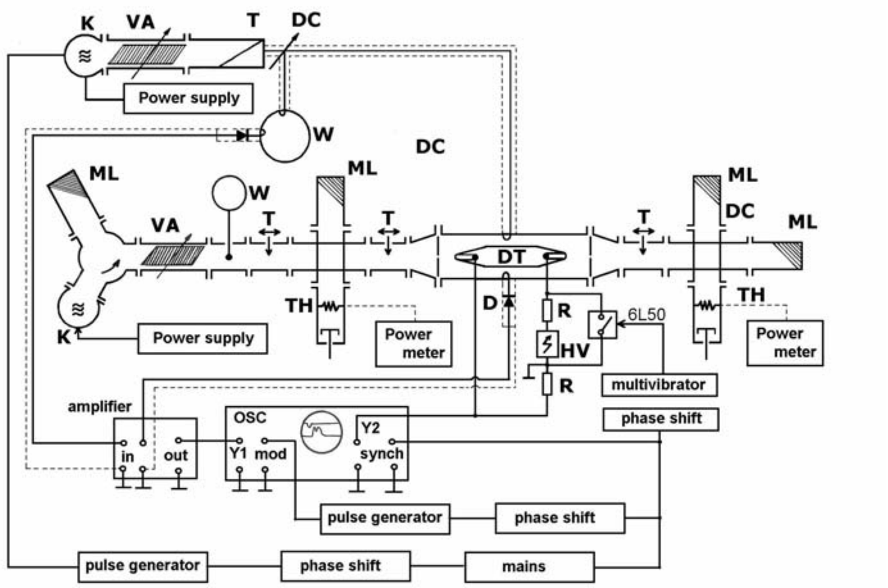

Fig. 1 Diagram of dual mode S-band microwave afterglow apparatus employing microwave heating of electrons where the following notations is used: K - klystron, VA - variable attenuator, WC - waveguide to coaxial transition, T - sliding screw tuner, DC - directional coupler, DT - discharge tube, W - wattmeter, ML - matched load, TH - thermistor head, R - resistor, HV - high voltage source, FC - ferrite circulator.

To accommodate the discharge tube within the microwave cavity requires the tube ends to have a "swan neck" - the special shape of the discharge tube is shown in Fig. 2 and its cross-section is shown in Fig. 3. As will be seen, the need for holes in the cavity walls to allow the mounting of the discharge tube has disadvantages.

The glass or quartz discharge tube is cylindrical with an inner diameter of 28 mm. The length of the untapered part is 80 mm and the length of each taper joining the tube to the the vacuum system is 40 mm. The molybdenum (or nickel) electrodes are at the end of the discharge tube and must be positioned outside of the microwave cavity. After a special purification process the discharge tube was filled with neon to the desired gas pressure. The d.c. glow discharge was initiated by a number high voltage pulses until a fairly stable and repeatable afterglow was obtained. The pulse repetition was 50 Hz.

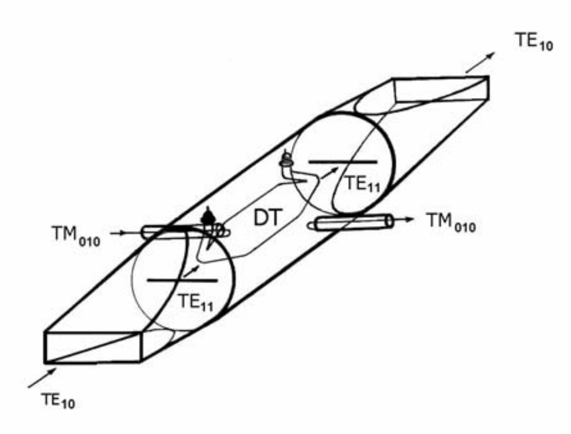

Fig. 2 Cutaway drawing of a cylindrical cavity waveguide section with discharge tube (DT).

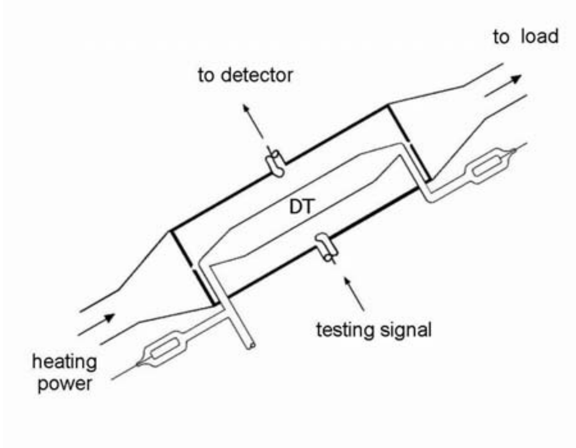

Fig. 3 Cross section of a cylindrical cavity waveguide section with discharge tube (DT).

The cylindrical microwave cavity (with a height of 300 mm and inner diameter of 73 mm) operated in two modes. The high Q quality mode TM_{010} which was excited by very low energy probing signal (less than 20 μW) was used to determine the electron density decay from the detuning of the cavity with time as the plasma decays - the resonant frequency changes. The resonant frequency of the cavity only with the discharge tube was around 2750 MHz.

The "microwave averaged electron" density of the afterglow $< n_e(t) >$ at time t given by

$$< n_e(t) >= \frac{\int_{cavity} n_e\,(\vec{r}, t)\;\; E^2\,(\vec{r})\;\; dV}{\int_{cavity} E^2(\vec{r})\; dV} = \frac{\Delta\; f(t)}{C} \tag{12}$$

is determined from the measured cavity frequency shifts $\Delta f(t)$. The quantity C represents a group of physical constants and measurable quantities. $E^2(\vec{r})$ is the non-perturbed electric field distribution function in the cavity and $n_e(\vec{r}, t)$ is the space distribution of electron density.

The electrons are heated above the ambient gas temperature by means of the steady microwave heating field which is continuously propagated in a"second" non-resonant circular waveguide mode TE_{11}. Propagation of this mode through the cavity is permitted by resonant coupling rectangular irises (54.2 mm x 1 mm, dimensions determined experimentally) which enclose the measuring section of the cavity. It has been determined experimentally that at a frequency around 3000 MHz the heating traveling wave is transmitted essentially without reflection by the irises or the glass tube.

The microwave heating power supplied by the 20SR53 klystron (TESLA, Czech Republic) operating continuously (CW) at a frequency around 3000 MHz is reduced by around 20 percent after transition through the cavity. The value of the transmitted power is adjusted by a variable calibrated attenuator and measured by bolometer heads which are attached to the main waveguide line in front and behind the cavity structure by the directional couplers.

The transition from the rectangular waveguide operated in mode TE_{10} to the circular waveguide operated in mode TE_{11} is achieved with tapered waveguide sections, which produced negligible reflection. The traveling wave heating power not absorbed by the plasma is absorbed in a matched load at the end of waveguide line.

The electron temperature is calculated from the measured traveling wave power. For the TE_{11} mode an electric field intensity (and thus temperature of plasma electrons) is derived by well known relationships from the transmitted power (see e.g. Vrba [32]). The following relation exists between the electric field intensity E in the center of the waveguide and the maximum transmitted power P for the TE_{11} mode:

$$P = 0.188\; a^2\; \sqrt{\frac{\epsilon}{\mu}} \sqrt{1 - \left(\frac{\lambda}{\lambda_{crit}}\right)^2}\; E^2, \tag{13}$$

where a is the cylindrical waveguide diameter , λ is the free space wavelength of the heating microwaves, λ_{crit} is the critical wavelength which is equal to $1.706a$; ϵ is the dielectric permittivity and μ is the magnetic permeability of air.

For our waveguide parameters and for the wavelength used we have established a relation between the electron temperature in the neon gas and the transmitted microwave power P by means of Eq. (10):

$$T_e = T_g + 26\ P, \tag{14}$$

where T_e is in degree of K and microwave power P is expressed in mW.

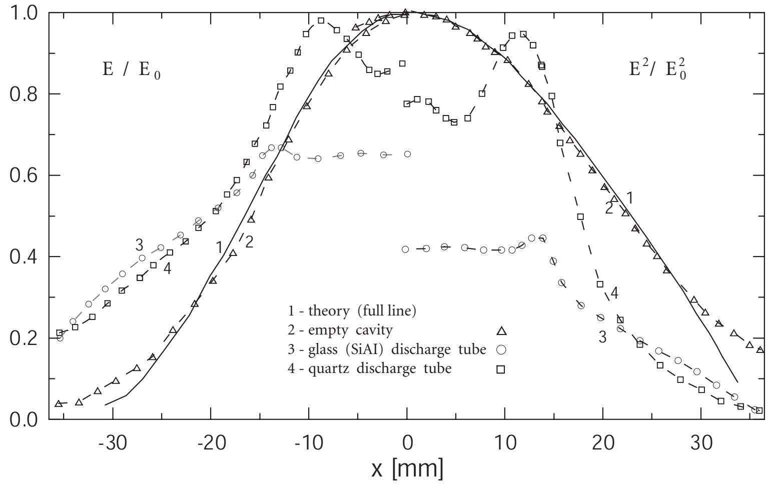

Fig. 4 Absolute (on the left side) and squared (on the right side) values of electric field distribution in radial direction of the cylindrical TM_{010} cavity with and without glass or quartz discharge tube.

3.2 Dual-mode microwave apparatus in X band - variation a)

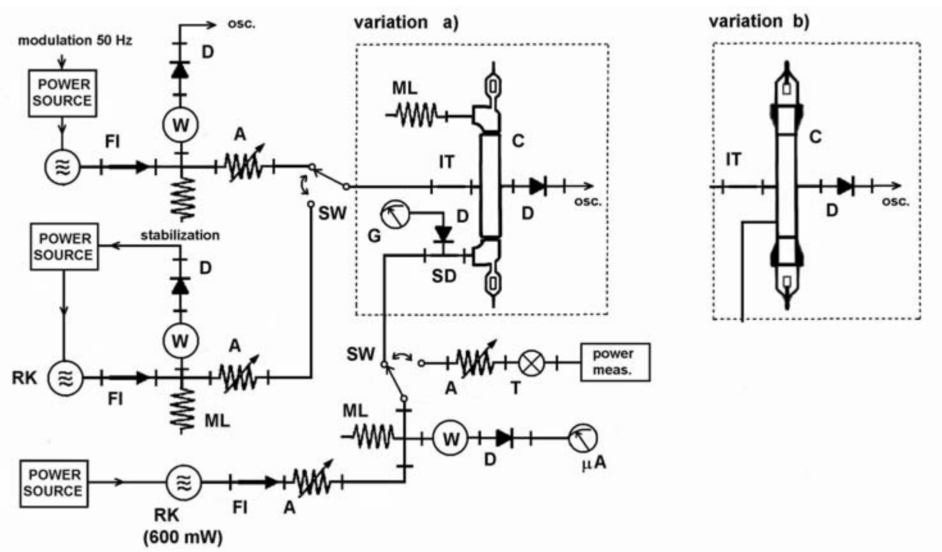

Fig. 5 Diagram of dual mode X-band microwave afterglow apparatus variation a), and variation b): FI - ferrite isolator, D - diode, A - attenuator, RK - reflex klystron , ML - matched load, W - wavemeter, T - thermistor, C - cavity, IT - impedance transformer, SD - standing wave detector slotted line

The main reasons to develop a new apparatus were to simplify the shape of the gas discharge tube, to keep the large characteristic diffusion length of the tube, to minimize the electric field perturbation of the cavity and to allow measurements at higher gas temperatures [22]. Therefore the variant a) was the intermediate step to fulfill these aims. An outline of the modified microwave apparatus working in $X - band$ is shown in Fig. 5.

The most important part of the apparatus is the dual-mode microwave cavity. We have used an open cylindrical microwave cavity excited in the TM_{011} mode [15], which was used to measure the electron density in discharge tube as a function of time t. It is shown in Fig 6.

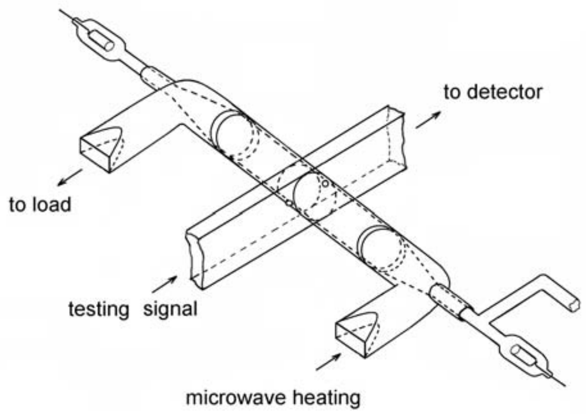

Fig. 6 Cutaway view schematic of the open cylindrical TM_{011} cavity waveguide section for variation a).

The diameter of the cavity was 26 mm and its length 200 mm. The discharge tube was very simple - a cylindrical quartz tube with an inner diameter of 22 mm and a length of 300 mm - located in the minimum (nearly zero) electric field intensity of the cavity to eliminate its effect on the measured electron density value. The resonant frequency of the open cavity was around 8600 MHz, as determined with a very low power probing signal (less than $20\mu W$) by a dynamic or stationary method. The discharge tube was conically ended with end bulbs containing electrodes.

The open microwave cavity is also used as a circular waveguide oscillating in a non-resonant TE_{11} mode. At both ends of cavity there are non-contact microwave bends incorporating a transition from a circular to rectangular waveguide to allow connection to standard waveguide equipment at X-band, to apply continuous traveling microwave heating to the electrons at a non-resonant frequency. The heating microwave power was less than 900 mW. We have measured practically no loss of microwave power through gaps between the open cavity and the waveguide bends. Separate measurements of the standing wave ratio have shown that there were no wave reflections in cavity/waveguide pieces.

The relation between the microwave heating power and the electron temperature for the neon gas pressure higher than 1kPa is independent on the gas pressure and is given by

$$T_e = 300K + 7.75\ P, \tag{15}$$

where T_e is in degree of K and microwave power P is expressed in mW. This relation is not valid in the case of diffusion cooling of electrons (at pressures less than 100 Pa).

3.3 Dual-mode microwave apparatus in X-band - variation b)

To further simplify the shape of the discharge tube, allow the use of an r.f. discharge in place of the original d.c. discharge and to heat up the discharge tube we have developed variation b) of the dual mode microwave apparatus in $X - band$ which is schematically shown in Fig. 5 part b). The details of the dual-mode microwave open cylindrical cavity are shown in Fig.7.

The probing microwave open cylindrical cavity oscillating in a mode TM_{011} is made from molybdenum plate of 0.4 mm thickness to enable it to be heated up to 650 K. The diameter of the cavity was 25.5 mm and its length was 200 mm.

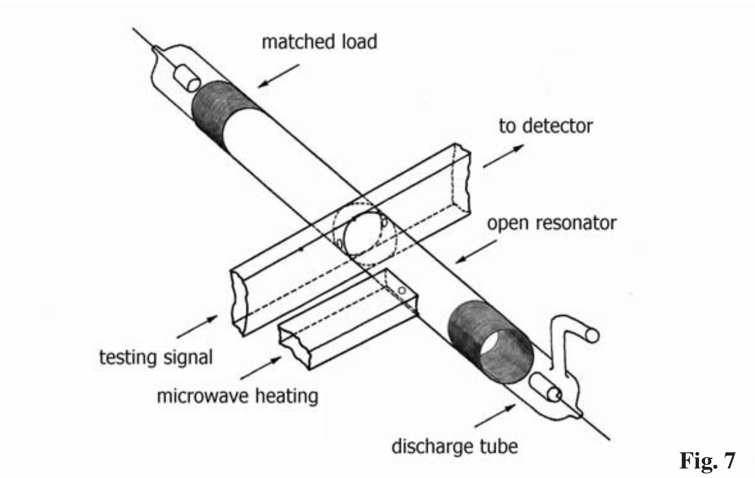

Fig. 7 Cutaway view schematic of the open cylindrical TM_{011} cavity - waveguide section variation b).

The quality factor of the cavity is 1000 at the highest gas temperature and it remains practically the same at laboratory temperature. The maximum resonant frequency shift due to heating of the cavity was 10 MHz. The quartz discharge tube used, with inner diameter of 21.5 mm, had no influence on the resonance frequency of the cavity.

The microwave heating power was introduced by a waveguide launcher positioned off center of the discharge tube. From this point the waves are traveling in both directions inside the cavity and the transmitted power is absorbed in adjustable loads at both ends of the cavity to prevent any standing waves occurring in the cavity or radiation into free space. Carbon powder mixed with Portland cement, as recommended by Montgomery [33] was used as the absorbing material for the loads which were in the shape of cylinders and were mounted on the cavity. Their shape did not change with the temperature.

The calculated electron temperature as a function of incident microwave power was calculated as in the previous case. The calibration of electron temperature was made by measuring the ambipolar diffusion coefficients in the late afterglow period at higher neon gas pressure. This led to the following relation

$$T_e = T_g + 6.8\ P, \tag{16}$$

where T_e is given in Kelvin degree and microwave power P in mW.

4 Experimental results

4.1 Electron density measurements

To determine the recombination coefficients according to relation (8) we have to know the exact absolute value of electron density decay in the afterglow period. These "average" values can be measured from the microwave cavity frequency shifts $\Delta f(t)$ by using relation (12). As can be seen, we have to know the space distribution of the electron density and the electric field intensity in the cavity. The theoretical electric field intensity distribution in a closed, unperturbed (without the holes and a glass tube) cylindrical TM_{010} microwave cavity is proportional to the zero-order Bessel function in the radial direction. In our previous paper (Pipišková, and Lukáč [34]) we have shown that a glass tube affects the electric field configuration and the electric field intensity in a cylindrical TM_{010} microwave cavity which in turn modifies the absolute electron density value determination.

We have carried out the same measurement in the first experimental dual mode set up, for the S-band microwave range. The results of the measurements are shown in Fig 4. with the quartz and SiAl glass discharge tube, respectively. After the evaluation of measurements we have found the following relation

$$< n_e > \ = 452\,\Delta f \qquad [\,cm^{-3},\ Hz] \tag{17}$$

between cavity detuning Δf (in Hz) and "average" electron density in cm^{-3}, if the homogeneous radial electron density distribution is assumed.

4.2 Electron temperature measurements

In order to verify the values of the electron temperature calculated according to relation (14) from the microwave heating power, we have undertaken the measurement of the ambipolar diffusion coefficients (see relations (3), (4)) in the late period of a neon afterglow plasma at $\approx$ 140 Pa and 2.6 kPa. Typical curves of the decline of electron density with time for the neon afterglow under diffusion conditions at various microwave power are presented in Fig. 8 and Fig. 9.

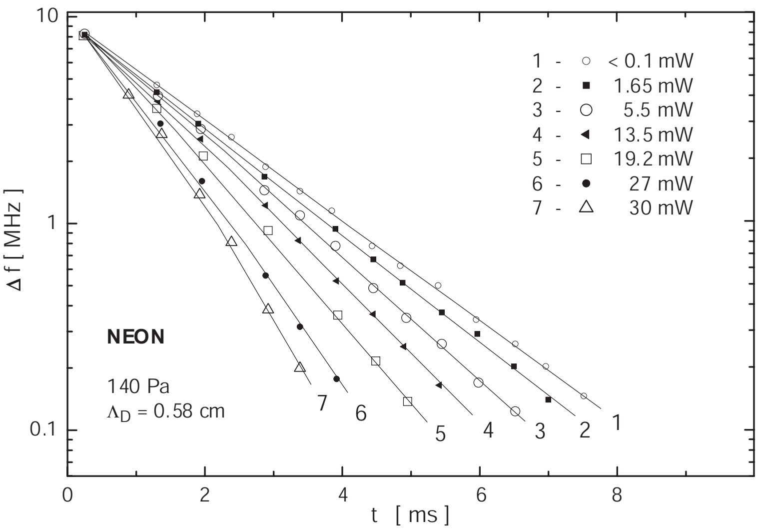

Fig. 8 Measured electron density decays in the afterglow at $T_g = 300K$ for various microwave heating powers to determine electron temperature.

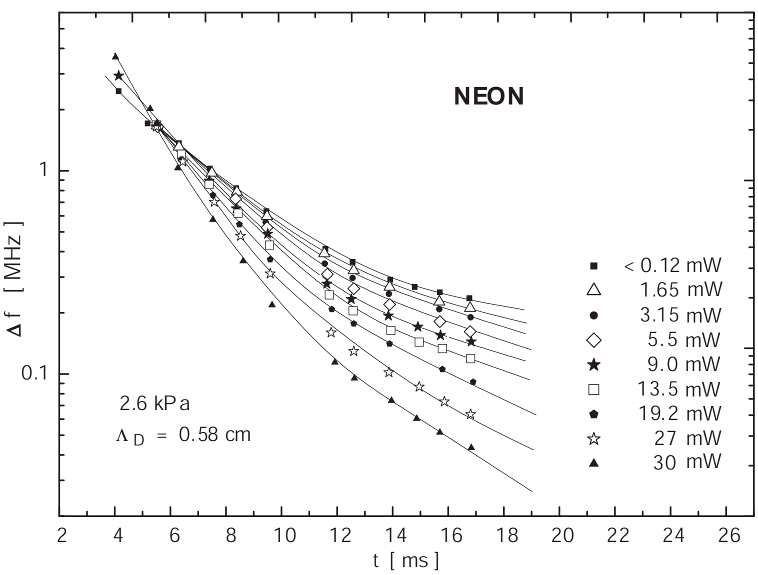

Fig. 9 Measured electron density decay during the afterglow at T_g = 300 K and for various microwave heating powers to determine electron temperature

At the pressure of 140 Pa (Fig. 8) the recombination term is neglected and the afterglow plasma is controlled by ambipolar diffusion. No diffusion cooling was observed because the fundamental diffusion length is relatively large Λ_D = 0.58 cm. Therefore the decay of electron density is exponential with a time constant given by $\tau_D = \Lambda_D^2/D_a$.

The calculated mobility is 4.1 $\mathrm{cm^2V^{-1}s^{-1}}$ which is equal to that for Ne+ ions in neon gas. Using relations (3), (4) we have experimentally determined the electron temperature at three different gas pressures (140 Pa, 400 Pa and 2.6 kPa). At a pressure of 2.6 kPa it was not possible to neglect the recombination term.

Therefore we have determined the ambipolar diffusion coefficient from the linear part of the exponential electron density decay at the late afterglow period. The theoretical curve and experimental data of the electron temperature as a function of microwave heating power are shown in Fig. 10. Very good agreement can be seen.

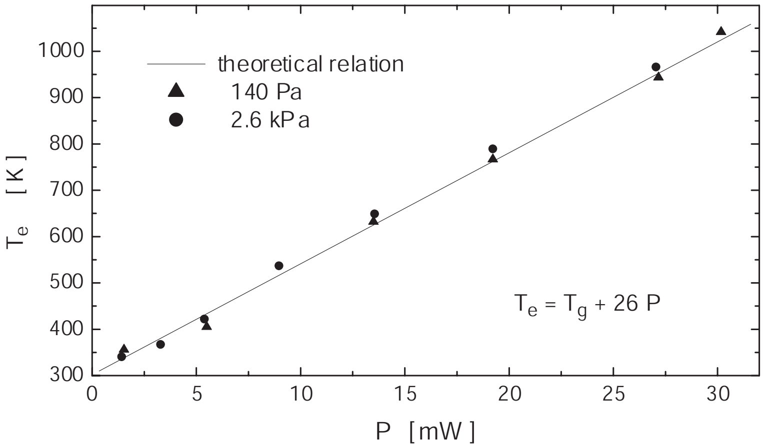

Fig. 10 The calibrated dependencies of electron temperature as a function of incident microwave power.

4.3 Sample gas filling and purification

The standard vacuum system has been used to fill the gas discharge tube with research grade pure neon. The glass discharge tube could be baked out at about 450^{o}C before filling. To avoid contamination of neon gas with the traces of active gases we have evaporated the barium getter on the inner walls of the sphere (like a cold trap) containing the neon gas and connected to the discharge tube and associated vacuum system. The neon was finally purified by means of the cataphoretic separation method (Riesz and Dieke [35]).

4.4 Measurement of $\alpha(T_e)$ with microwave S-band apparatus

Typical results for the measurement of the reciprocal electron density as a function of time in a recombination controlled afterglow period of dc discharge are shown in Fig. 11. as for several microwave heating powers or corresponding electron temperatures. The gas temperature was taken the laboratory temperature and the neon gas pressure was 2.66 kPa. As expected, the experimental time dependent reciprocal electron density curves are less linear for higher electron temperatures because of the increasing importance of ambipolar diffusion.

The values of the recombination coefficients are determined from the slope of the linear part of the decay curves. The measured values of the recombination coefficient for neon $\alpha(Ne_2^+)$ as a function of electron temperature are shown in Fig. 12. which are plotted in a log-log scale. The value of α at room temperature is (1.55 $\pm$ 0.15) x $10^{-7}\mathrm{cm^3s^{-1}}$ which is slightly lower than values of other authors, but in very good agreement with theoretically calculated value published recently by Ngassam and Orel [23]. This difference can be caused by the shape and excitation of the d.c. glow pulsed discharge when the radial electron density distribution is not homogeneous as we have supposed during evaluation of the "average electron density".

The value of the exponent ξ is given by the slope of the straight line in Fig. 12.

This line represents a variation of α in the form of a simple power law so that the electron temperature dependence is given by the relation

$$\alpha_{Ne_2^+}(T_e) = (1.55 \pm 0,15) \text{ x } 10^{-7} \ T_e^{-0.40\pm0.02} \qquad [\, \mathrm{cm^3\ s^{-1}, K}\,]. \tag{18}$$

This dependence is slightly different to that given by Frommhold et al. [14].

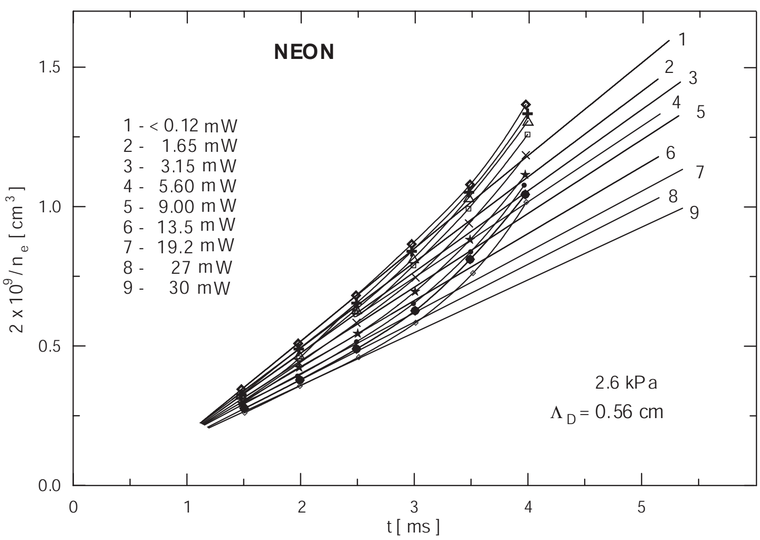

Fig. 11 The reciprocals of "average microwave electron density" as a function of afterglow time for different microwave power by S-band dual mode microwave apparatus.

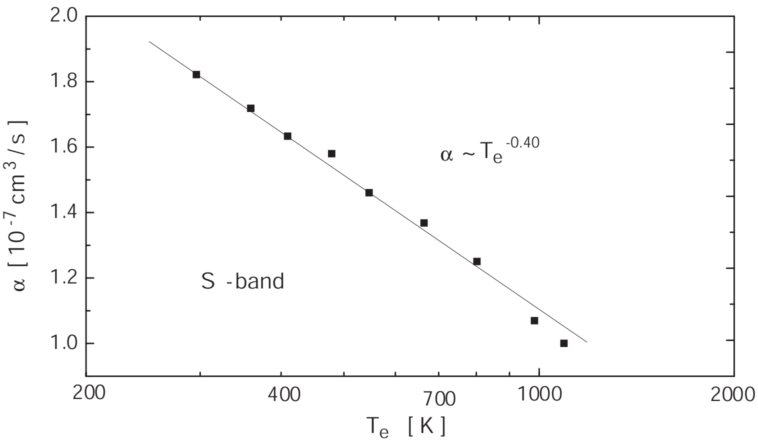

Fig. 12 Measured variation of the recombination coefficient $\alpha(Ne_2^+)$ as a function of electron temperature by S-band dual mode microwave apparatus.

4.5 Measurements of $\alpha(T_e)$ with microwave X-band apparatus - variation a)

To determine the absolute value of electron density we have calibrated the open microwave TM_{011} cavity by means of different dielectric cylinders according to Lukáč [36] and Gregory [37]. Then for average microwave electron density we have obtained the relation

$$< n_e >= 213\,\Delta f \qquad [\mathrm{cm}^{-3}\,\mathrm{s}^{-1}]. \tag{19}$$

Experimental data of reciprocal electron density at several electron temperatures are shown in Fig. 13. (at the neon pressure 4.53 kPa). It can be seen that the reciprocal electron density at first increases linearly with time and then, as a result of the increasing importance of ambipolar diffusion, increases more rapidly. We have made correlations for this effect at higher electron temperature. The values of $\alpha(Ne_2^+)$ are shown as a function of electron temperature in Fig. 14, which is plotted in log-log scale.

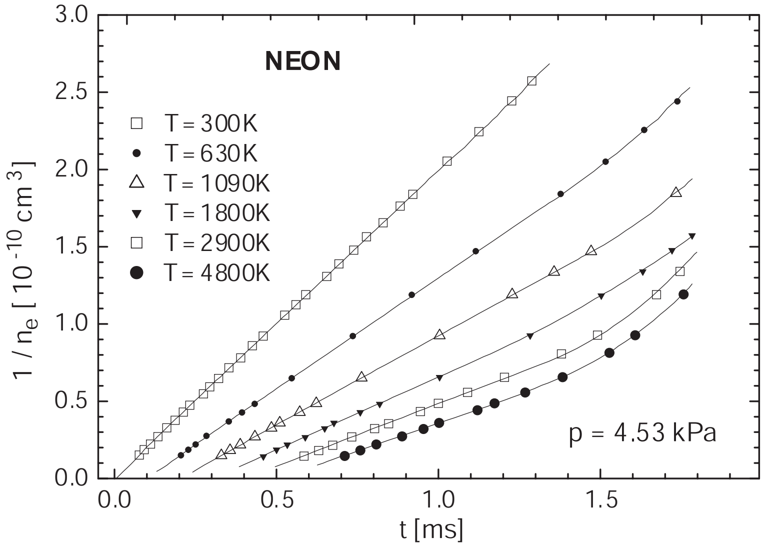

Fig. 13 The reciprocal of "average microwave electron density" ($1/n_e$) as a function of afterglow time (t) for different electron temperature while $T_{gas} = 300K$ by the X-band dual mode microwave apparatus - variation a). The time zero point has been displaced 0.1 ms for various curves for clarity.

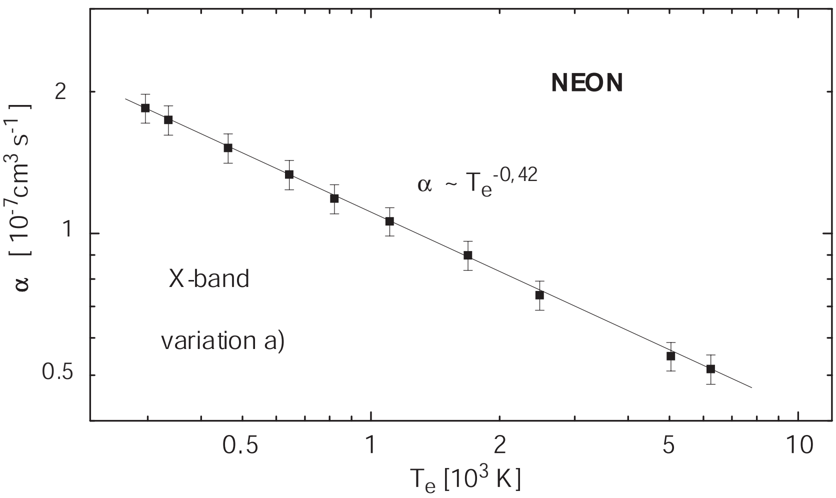

Fig. 14 Measured variation of the recombination coefficient $\alpha(Ne_2^+)$ as a function of electron temperature by X-band dual mode microwave apparatus - variation a).

4.6 Measurements of $\alpha(T_e)$with microwave X-band apparatus - variation b)

As in the previous case we have used the open microwave TM_{011} cavity to measure the "average electron density", calibrated in the same way. The neon gas pressure was 3.64 kPa. Experimental data of the reciprocals of the microwave electron density are shown in Fig. 15. Evaluated data of the recombination coefficient as a function of electron temperature are shown in Fig. 16 in log-log scale. This dependence is practically the same as in Fig. 14. Therefore we can express both measured values by the following relation (with an estimation of errors)

$$\alpha_{Ne_2^+}(T_e) \;=\; (1.8 \pm 0.1)\;\; \text{x}\;\; T_e^{-0.42 \pm 0.02} \qquad [\text{cm}^3\ \text{s}^{-1},\ \ \text{K}] \qquad (20)$$

for the electron temperature interval 300 K up to 6300 K.

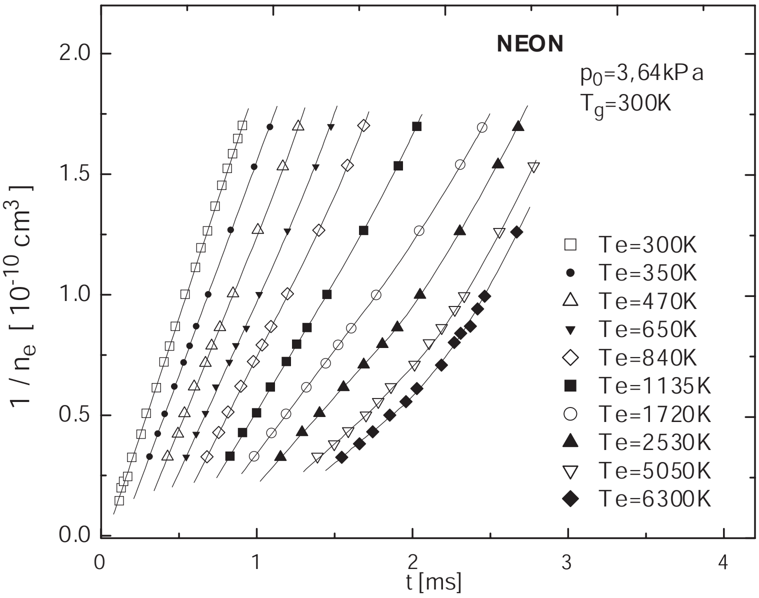

Fig. 15 The reciprocal of"average microwave electron density" $(1/ < n_e >)$ as a function of afterglow time (t) for different electron temperature while T$_{gas}$ = 300 K by the X-band dual mode microwave apparatus- variation b). The time zero point has been displaced 0.1 ms for various curves for clarity.

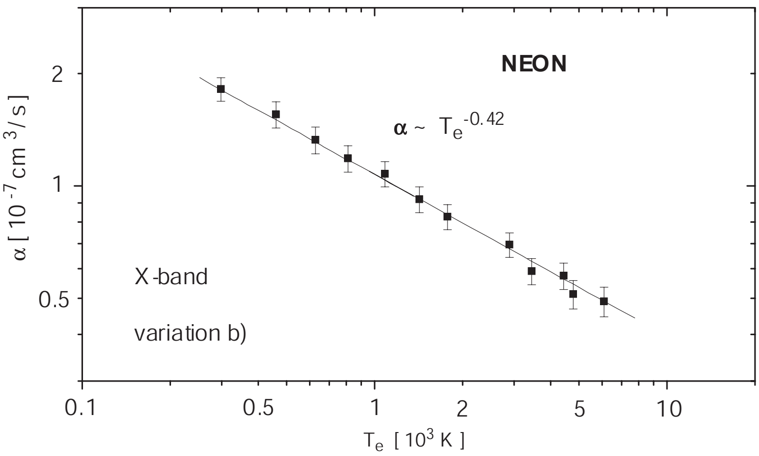

Fig. 16 Measured variation of the recombination coefficient $\alpha(Ne_2^+)$ as a function of electron temperature by X-band dual mode microwave apparatus - variation b).

5 Conclusions

Our present results are compared with previous studies of the electron and/or gas temperature dependencies of the recombination coefficients by different methods in the Table 1. As can be seen, our experimental data agree well with more authors. We have shown that the electron heating by means of a constant microwave field using a non-resonant TE_{11} circular waveguide mode seems to be the best. The special type of discharge tube (see Fig.2) does not appear a particularly convenient way to excite the d.c. or r.f. glow discharge and investigate its afterglow plasma. The non-homogeneous and non-symmetric space electron density distribution may cause an error in determining the average microwave electron density. The electric field distribution in a TM_{010} S-band cavity due to inserted quartz or another glass discharge tube has to be measured and evaluated because it can lead to error up to 50% in determining the absolute value of electron density.

Table 1 Comparison with other results.

α [cm^3/s]	T_g [K]	T_e [K]	ξ_g	ξ_e	**Measurement method**	**Heating method**	**Reference**
?	300	?	-	0.9	Light quenching	Microwave cavity	Farrhat [38]
?	300	?	-	0.5-0.66	Light quenching	Microwave cavity	Taylor [39]
2 x 10^{-7}	300	300-600	-	0.25	Microwave cavity	Microwave cavity	Hess [40]
2 x 10^{-7}	300	900-2400	-	0.4	Microwave cavity	Microwave cavity	Hess [40]
?	300	?	-	1.4	Light intensity	Microwave	Nygaard [41]
1.7 x 10^{-7}	300	300-11000		0.43	Microwave cavity	Traveling microwave	Frommhold [14]
1.8 x 10^{-7}	300-500	= T_g	0.42	0.42	Microwave cavity	Oven heating	Kasner [42]
1.8 x 10^{-7}	300	300-4600	-	0.49	Microwave cavity	Traveling microwave	Philbrick [43]
1.4 x 10^{-7}	450-900	= Tg	0.5	0.5	Double probe	Shock wave	Cunningham [44]
1.4 x 10^{-7}	900-3500	= Tg	1.5	1.5	Double probe	Shock wave	Cunningham [44]
?	300	10000-25000	-	0.36	Relaxation disch. current	Glow discharge	Vinogradov [15]
1.8 x 10^{-7}	300	300-1500	-	0.36	Microwave cavity	Microwave cavity	Lukáč [45]
?	300	?	-	0.4; 1.4	Light intensity	Microwave	Tálský [46]
1.8 x 10^{-7}	300	300-6000	-	0.42	Microwave cavity	Traveling microwave	Mikuš [22]
3 x 10^{-7}	300-2000	300-2000	0	?	Microwave antenna	Capacitor bank	Chen [47]
1.5 x 10^{-7}	300-10000	300-10000	0.5-1.5	0.5	Theoretical calculation	"Calculation"	Ngassam [23]
1.55 x 10^{-7}	300	300-1100	-	0.4	Microwave cavity	Microwave S-band	our result
1.8 x 10^{-7}	300	300-6300	-	0.42	Microwave cavity	Microwave X-band	our result

On the basis of the experimental results obtained for our developed experimental X-band microwave apparatus (especially variation b)) we can conclude that it has several advantages:

1. The discharge tube is very simple - a straight tube which can be used for both d.c. and r.f. glow discharges;

2. The construction and the shape of the open TM_{011} resonator is also very simple and it has a reasonably high quality factor (of around 1000): the effect of the glass discharge tube on its parameters is negligible and moreover, this type of the cavity can be also made by plating thin metal (e.g. gold, copper) film on the outer surface of the glass/quartz discharge tube as we provisionally tested in our laboratory;

3. By using a quartz discharge tube it can be heated in the oven together with the cavity to enable measurements of the gas temperature dependence of electron loss processes in afterglow plasmas.

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