Inductive RF discharge in water vapor in toroidal geometry

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Abstract. This paper presents the results of comparative experiments on the excitation of inductively coupled plasma in water vapor in cylindrical and toroidal discharge chambers having the same outer diameter. The plasma temperature in the cylindrical and toroidal chambers was determined using the Boltzmann plot method. With equal discharge power and pressure, the temperature in the toroidal chamber was found to be higher than that in the cylindrical chamber. This is attributed to the lower heat transfer and the absence of a near-axial layer in the toroidal chamber as compared with cylindrical geometry.

1. Introduction

Inductive RF discharge is used in many applications: coating, etching, and emission analysis of the composition of substances, purification and decontamination.

For effective use of inductive discharges in emission spectral analysis, it is necessary to provide the highest energy density with a minimum plasma volume in order to reach maximum temperature at minimum power consumption.

The temperature of inductively coupled plasma is determined by the electric power released in it and the heat loss, which is in turn determined by the heat transfer across the plasma surface and convection. The heat flux through the plasma surface is proportional to the surface area, so that to reduce the heat loss, it is necessary reduce the surface area.

Conventional inductive RF discharge devices are cylindrical tubes, on whose outer surface a spiral inductor is wound. Due to the skin effect, energy is released in the outer layer of the plasma near the tube wall, as indicated by the radial temperature distribution in the plasma volume [1]. The inner near-axial plasma layer is the least heated and of no interest to the excitation of spectra. In this regard, it has been proposed to optimize the inductive RF discharge by using discharge tubes of toroidal geometry.

In the case of a cylindrical chamber of diameter $D$, the plasma surface area is given by $S_c = \pi D(l + D/2)$, where $l$ is the thickness of the plasma loop, which is slightly larger than the inductor width (about 10 mm). For a toroidal chamber, the surface area of the plasma loop is $S_K = \pi^2 Dd$, where $D$ is the outer diameter (diameter of the axis) and $d$ is the inner diameter (of the cross section) of the torus. For $d < (D+2l)/2\pi$, the toroidal geometry is more effective.

The toroidal geometry showed it’s advantages in “tokamak”–type inductive closed-loop free-ferrite lamp [2]. The luminous efficacy of such type of lamps reaches 90 lumen per Watt. Some characteristics of inductive discharge with axial coil type were measured as plasma resistance, currents and electric field in plasma turn in the frequency range from 0.16 to 1 MHz. But there isn’t any...
bibliographic data regarding using of coreless axial inductive discharge in spectroscopy under higher frequencies.

2. Experiment
The discharge was excited in a quartz tube 1 by a single-turn copper inductor 2 (figure 1). The inductor was supplied with a 50 MHz current from an RF source. The load power was 300 W. A vacuum pump was placed on one side of the quartz tube, and a vessel containing tap water and fitted with a metering valve on the other side. The vacuum system was similar to that shown in [3]. Before turning on the RF source, air was pumped out of the system to a pressure of ~ 0.1 mbar. After that, water vapor was fed to the system by means of the metering valve.

We used two types of quartz tubes: cylindrical (figure 1a) and toroidal (figure 1b). The dimensions of the cylindrical tube were \( D = 40 \text{ mm} \) and \( l \approx 20 \text{ mm} \), and for the toroidal tube, \( D = 40 \text{ mm} \) and \( d = 8 \text{ mm} \). Thus, \( S_C = 5 \text{ cm}^2 \) and \( S_R = 3.2 \text{ cm}^2 \). One end of the cylindrical tube was made flat to detect radiation from the thin plasma layer.

![Figure 1](image_url)

Figure 1. Experimental setup of cylindrical geometry (a) and toroidal geometry (b); 1 is the plasma discharge tube, 2 is the inductor, and 3 is the spectrometer lightguide.

The pressure in the discharge tube was monitored by a Testo 552 vacuum gauge and was from 0.1 to 1 mbar. The lower value was limited by the productivity of the vacuum pump and the upper one was limited by the maximal power of RF source. The stable inductive discharge under 300 W RF power exists up to 1 mbar of pressure.

The plasma radiation spectrum was recorded by a Kolibri-2 spectrometer (VMK Optoelektronika) with a spectral range from 180 to 1100 nm through a fiber-optic lightguide 3 having inner diameter 1 mm. In the case of the cylindrical discharge tube, the fiber was placed parallel to axis of the tube at different distances from the axis. Side light was limited using an additional light-proof tube into which optical fiber was inserted. In the case of toroidal geometry, the optical fiber was directed perpendicular to the plane of the axis of the quartz discharge tube.

3. Results and analysis
Figure 2 shows the emission spectra of the inductive discharge in cylindrical geometry with registration near the wall (figure 2a) and in toroidal geometry (figure 2b).

Comparison of the two spectra in figure 2 shows that the relative intensity of the \( \text{H}_\beta \) (486.1 nm) hydrogen line is higher in toroidal geometry than in cylindrical geometry. In addition, in toroidal geometry, the \( \text{H}_\gamma \) (434.1 nm) hydrogen line becomes visible, whereas, in cylindrical geometry, it is practically invisible. This indicates the greater importance of the plasma temperature for toroidal geometry.

The temperature was estimated by the Boltzmann plot method using the relation
where $E$ is the energy of the upper (excited) level, $I$ and $\lambda$ are the intensity and wavelength of the corresponding spectral line, $A$ and $g$ are the transition probability (in $10^8$/s) and the statistical weight of the excited level respectively, $k$ is Boltzmann’s constant, and $C$ is a constant. The temperature can be determined knowing the slope of the graph plotted in the coordinates $\ln \left( \frac{I_\lambda}{Ag} \right)$ and $E$ and using the relation $T = \frac{1}{k \cdot \tan \phi}$, where $\tan \phi$ is the slope of the graph. The method is described in detail in [4].

**Figure 2.** Inductive discharge spectra: near the wall in cylindrical geometry (a) and in toroidal geometry (b).

Figure 3 shows a graph of determining the temperature from the first three lines of the Balmer series (Hα, Hβ, Hγ). The points in the graph were least-squares fitted to straight lines, after which the slope of each line was calculated and used to determine the plasma temperature. The graph shows three cases: a cylindrical tube with the optical fiber near the wall, a cylindrical tube with the optical fiber on the axis, and a toroidal tube.

**Figure 3.** Boltzmann’s plot computed from (1) for the first three lines of the hydrogen Balmer series under pressures: a) – 1 mbar, b) – 0.3 mbar. The dashed line corresponds to data ○, the dotted line – to data □, and the solid line – to data ◊.

For the cylindrical tube under pressure 1 mbar, the near-wall temperature was 3300 K, and the temperature on the axis was 2700 K. For the toroidal tube under the same pressure, the temperature was 4100 K. For 0.3 mbar of pressure the near-wall temperature in cylindrical tube was 3900 K while...
for the toroidal tube it was found to be equal 4200 K. It can be seen that the plasma temperature is higher in toroidal geometry than in cylindrical geometry. Also, it should be noted that for the lower pressure the mean temperature is higher.

From the figure 3, it can be concluded that the plasma is not in thermodynamic equilibrium (experimental points are not exactly at the approximation lines). In [5] it is experimentally shown that the pressure of the water plasma up to 3 mbar is not sufficient for elementary collisions to be in equilibrium. But the conclusion about the relativity of the temperatures still can be done.

Since, in toroidal geometry, the entire heat flux passes through the surface of the glass tube, this geometry is effective only for plasma-forming gases with thermal conductivity higher than the thermal conductivity of quartz glass, which at a temperature from 500 to 1000 K is about 2 Wm⁻¹K⁻¹. This condition is satisfied for water plasma and is not satisfied for, e.g., argon, whose thermal conductivity is an order of magnitude lower [6]. Therefore, to select the optimal geometry, one should take into account the type of the gas used.

4. Conclusions
The experimental investigation of the continuous inductive discharge in toroidal geometry with water vapour was carried out for the first time. The comparison with the classical cylindrical geometry showed that a toroidal discharge tube has advantages over a cylindrical one for the purpose of reaching the maximum plasma temperature for a given power.

The results can be used to develop and optimize inductive coupled plasma devices for specific applications.

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