Model of a small surface wave discharge at atmospheric pressure

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Abstract. Self-consistent model of a small microwave plasma source based on a surface wave sustained discharge at 2.45 GHz is presented in this study. The model includes dispersion relation of azimuthally symmetric surface waves, sustaining the discharge in a high permittivity ceramic tube (\(\varepsilon_{ld} = 9.3\)) and the radial distribution of the field components at curtain values of the electron density are obtained. The electron Boltzmann equation under the local approximation is solved together with the heavy particle balance equations. A detailed collisional-radiative model for argon discharge at atmospheric pressure is implemented in the model. The changes in the EEDF shape and the mean electron energy with the value of the electron density are investigated. Results show that the EEDF is close to Maxwellian at our experimental conditions for the plasma density above \(2.10^{20}\) (m\(^{-3}\)).

1. Introduction

The surface wave (sw) discharges at atmospheric pressure are object of intensive investigations due to their applications for environmental and industrial purposes as detoxification of hazardous gases, hydrogen production, plasma chemistry, cutting and surface modification of metals. Modelling of these discharges is difficult because a large number of reactions between charged particles and neutrals and complexity of the processes even in argon gas [1-3]. Theoretical results for the electron energy distribution function (EEDF) for specific gas discharge conditions [2, 4] show that it can deviate from Maxwellian at low plasma densities in the surface wave discharge at atmospheric pressure. These changes in the shape of EEDF require specification of the range of plasma parameters where the double probe diagnostics and collisional-radiative models which assume Maxwellian distribution function can be applied.

This study presents a model of plasma column sustained by sw in a small radius ceramic capillary of portable microwave plasma source [5]. Discharge is self ignited at power levels below 10 W and it works at atmospheric pressure both in continuous and pulse regimes. The model includes dispersion relation of azimuthally symmetric surface waves, sustaining the discharge in a high permittivity ceramic tube (\(\varepsilon_{ld} = 9.3\)). The electron Boltzmann equation under the local approximation is solved together with the heavy particle balance equations. The optical and double probe measurements of the plasma parameters show that our source produces dense plasmas [6] and detailed collisional-radiative model for argon discharge at atmospheric pressure is implemented in this self-consistent model. The changes in the EEDF shape and the mean electron energy at different values of the electron density are investigated. The electron temperature and populations of \(1s2-1s5\) and \(2p1-2p10\) and higher levels of excited argon atoms are determined at our experimental conditions.
2. Description of the plasma source and its model.
The sw exciter is open coaxial line and the dielectric of this line is an alumina ceramic tube with inner
diameter of $d = 1$ mm and outer of 2 mm and length of 11 mm. The electric field has two components
$E_r$ and $E_z$ at the end of the exciter which cause the breakdown of the gas and propagation of the surface
waves. Microwave signal at frequency $f = 2.45$ GHz from generator MPG-4M (0-120 W) through a
double directional coupler Narda-3022 and triple stub Maury 1878C is fed to the source.

The discharge is self-ignited at microwave power levels below 10 W and it works in continuous
and pulse regimes in argon and argon-helium gas mixture. The length of the plasma column is
controlled by the applied microwave power and the source could operate as a plasma jet. Forward and
reflected power from the plasma source is measured by power meter HP 437B. Electron temperature
($T_e \sim 1.6$ eV) and density ($n_e \sim 4 \times 10^{20} \text{ m}^{-3}$) are estimated by optical diagnostics and asymmetric double
probe characteristics. Optical emission spectroscopy observation of argon discharge are realized by
HR Ocean Optics Spectrometer. The light from the plasma column is collected by lens system
(through the same small hole) coupled to optical fibre, which is connected to the spectrometer.
Spectrometer UV-VIS is used for determination of the neutral gas temperature ($T_g \sim 1500$ K) from OH-
band present in the spectra.

A flow chart of the theoretical model is shown on figure 2. The iterative self-consistent model
includes solver for the dispersion equation (DE) for the sw, Boltzmann equation for the electrons,
module with collisional-radiative model for the heavy particles and electron particle balance equation.
The dispersion equation of sw is solved for the case of thin cylinder approximation in cylindrical
coordinates, with waves propagating in axial direction along the plasma column. The components of
the azimuthally symmetric mode ($TM_{00}$) are $E_r$, $E_z$, $H_r$ with a maximum of the field amplitude at the
plasma-dielectric interface. The plasma column is assumed homogeneous in radial direction and
dielectric constant is calculated with averaged value of the electron concentration $n_e$ and effective
value of the electron-neutral collision frequency $\nu_{en}$. Applying the boundary conditions across the tree
structure domains (plasma-dielectric-air) the dispersion relation is solved numerically via an iterative
procedure. The values for the wave damping rate $\alpha$ and the phase constant $\beta$ are obtained for initial

**Figure 1.** Small surface wave discharge

**Figure 2.** Flow-chart of the model
value of the electron concentration and electron-neutral collision frequency. With the complex wave vector the distribution of the electromagnetic field in radial direction is obtained and also the value of effective electric field at the local position is calculated as $E_0 = \sqrt{E_x^2 + E_y^2}$. The electron Boltzmann equation (BE) under the local approximation is numerically solved for the EEDF using two-term expansion for the stationary regime of the discharge. Initial parameters for this solver are the obtained value for the effective field from the DE module, neutral gas pressure, electron concentration, mean electron energy, gas temperature and initial values of the concentrations of heavy particles.

The following heavy particles are included in the model: Ar s-levels (1s2-1s5), the Ar 2p-levels (2p1 -2p10), blocks for Ar(2s3d) and higher levels, atomic Ar+ and molecular Ar2+ ions and exited molecules Ar2*. The kinetic processes considered in the BE are elastic collisions and inelastic collisions (excitation, de-excitation, ionization, step-wise ionization, dissociative recombination for Ar2+ and tree body recombination etc.) and Penning ionization for the excited molecules.

3. Results

The Boltzmann equation is solved via iterative finite difference method and EEDF and the value of the mean electron energy are obtained. The shape of EEDF is close to Maxwellian for values of the electron density above $2 \times 10^{20}$ (m$^{-3}$) (figure 3a). The tail of EEDF at electron densities lower than $2 \times 10^{20}$ (m$^{-3}$) significantly deviates and it is below the black line of Maxwellian distribution especially in the energy range above 11 eV which is in agreement with results in [2]. The mean electron energy (effective electron temperature) calculated from EEDF decreases with increase of the plasma density (Figure 3b) but it is higher than the electron temperature obtained in sw discharges in a quartz tube with same inner diameter. The radial distribution of electron temperature at $n_e = 4 \times 10^{20}$ m$^{-3}$ (EEDF is Maxwellian) is presented in figure 4 and it has weak increase in the direction to the tube wall.

![Figure 3. Results for EEDF: (a) shape and (b) mean electron energy at different values of $n_e$.](image)

With obtained EEDF and mean electron energy (electron temperature), electron density and gas temperature we calculate the population of excited levels of argon atoms by collisional-radiative model. Model for argon discharge at atmospheric pressure takes into account the species at s-levels Ar(1s2-1s5), at 2p-levels Ar(2p1 -2p10) and blocks for Ar(2s3d) and higher levels, atomic Ar+ and molecular Ar2+ ions, exited molecules Ar2* are also implemented in the model. The main kinetic reactions are included in the model: electron-impact excitation from ground state, from 1s levels, the electron-impact de-excitation from 1s, electron-impact population transfer, atom-collisional population transfer, electron-impact ionization and Penning ionization of excited particles, electron collisional recombination for atomic and molecular ions, 3-body collisional association reactions, electron-impact and atom-collisional dissociation reactions.
Figure 4. Radial distribution of the electron temperature in the plasma column.

Figure 5. Population densities of: a) 1s b) 2p from CMR at at \( n_e = 4 \times 10^{19} \text{ m}^{-3} \)

Results for the absolute population of 1s and 2p levels at our experimental conditions \( (T_E, T_e, n_e) \) obtained with this model are presented in figure 4. Populations of 1s and 2p levels of the Ar atoms strongly depend on the plasma density and the mean energy of electrons and their population distribution is far away from equilibrium.

4. Conclusion
The model of surface wave discharge at atmospheric pressure in argon gas in a high permittivity ceramic tube \( (\varepsilon_r = 9.3) \) is developed. The Boltzmann equation for electrons is solved together with the collisional-radiative model for argon plasma at atmospheric pressure. Result for EEDF shows that it is close to Maxwellian distribution if the plasma density in the capillary is above \( 2 \times 10^{20} \text{ m}^{-3} \). The mean electron energy and \( T_e \) decreases with increase of the plasma density and radial position.
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