Optimization of Electrothermal Microwave Plasma Thruster for Nanosatellites

IEPC-2019-647

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September15-20, 2019

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Abstract: The electrothermal microwave plasma thruster is based on a microwave coaxial plasma source with surface wave discharge, allowing very effective heating of the neutral gas in the dielectric chamber at low energy consumption. The flow of the hot gas through the chamber nozzle generates thrust, which allows adjustment and maintenance of the nanosatellite's orbit. For this purpose, the plasma thruster is simulated and its dimensions and parameters are optimized. Theoretical studies here are mainly related to determining the dispersion characteristics of surface waves in a dielectric tube and especially in a standing wave mode. The propagation of microwave signal at frequency of 2.45 GHz from the feed line to the exciter of surface waves and in the region of the plasma column is investigated. The structure is presented as coaxial line and load – dielectric chamber filled with plasma with fixed parameters (including the gas temperature) and screening metal enclosure with orifice (nozzle). The metal enclosure causes reflection of the EM wave from the chamber end and as a result – a standing wave in the discharge is established. This structure requires the system to be considered as two separate regions: coaxial line with TEM wave propagation and plasma column in dielectric tube with metal enclosure with TM wave. In the EM field simulations the chamber length and metal enclosure radius are varied, because they affect the dispersion relation of surface waves and respectively the resonant chamber length. Minimum values of voltage standing wave ration (VSWR) and maximum values of axial electric field are obtained at several different fixed values of plasma density.

I. Introduction

MOST of the established satellite thruster technologies have difficulties meeting the limitations coming with the nanosatellites, such as the CubeSat standard. CubeSats require systems to control orientation and orbit altitude but many of them are launched with no propulsion system on board thus limiting their operational lifetime. The size and weight requirements of CubeSats limit the parameters of the associated propulsion systems adding complex design challenges[1]. The electrothermal thrusters are suitable for such systems, because they efficiently transfer the electric energy[2] into heat of the propellant, with thrust produced by a neutral propellant expanding through a nozzle. The microwave electrothermal thrusters have high potential for micro-satellites propulsion systems[3,4] because of their low power consumption in the range of 1-10 W, small dimensions, and their long-period stable operation.

In Radiophysics and electronics department an electrothermal microwave plasma thruster is developed, which meets the power limitations of CubeSat and it works at low power levels 2-10 W. The thruster uses microwave surface wave discharge in a dielectric tube. The microwave energy is absorbed along the length of the plasma column, resulting in heating of the neutral gas in the entire chamber. The electrodes of the discharge are not in direct contact with the plasma column contributing to longer operational life. The thruster could operate in both pulsed and continuous wave regimes, which allows very precise control of the satellite's orientation and orbit. The precise

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matching of such system ensures self-ignition of the discharge and up to 97% absorption of the microwave power[5,6]. The aim of this study is to develop a full-wave model of compact electrothermal microwave plasma thruster using COMSOL Multiphysics and to obtain the optimal dimensions for good matching of all elements of the system. Results for the standing wave ratio (SWR) of the plasma exciter dependence on the plasma density, column length, and metallic enclosure radius are obtained in two-dimensional axisymmetric model. They show that additional matching of the system is required. Three-dimensional model is developed as a next step using COMSOL Multiphysics where the matching stub and feeding line lengths are determined.

II. Design of Electrothermal Microwave Plasma Thruster

Schematic of the plasma thruster is shown in Fig. 1. The propellant gas (argon) is fed to the dielectric chamber through the core capillary of the coaxial transmission line. Microwave power from the generator is transmitted through the same line to the coaxial surface wave exciter. The length of the transmission line is $\leq \lambda_g/4$ and thus ensuring strong electric field with E_r (radial) and E_z (axial) components at the entrance of the chamber. The strong field causes breakdown in the gas and plasma fills the chamber. The plasma column starts to behave as a waveguide for microwave surface waves, which propagate at the plasma-dielectric interface. The metal enclosure of the chamber reflects the surface waves and standing wave appears. At appropriate length of the dielectric chamber, the plasma column behaves as a plasma resonance structure. The absorbed power in this resonant chamber causes increase of plasma density. The microwave power is expected to be absorbed into the plasma with high efficiency as a result of strong interaction of the waves with the electrons in the resonant plasma cavity. Collisions between charged and neutral particles transfer the microwave energy into kinetic energy of the neutral particles, or in other words – heats up the gas. The hot gas expands and escapes the resonant cavity through simple orifice and thus creates thrust.

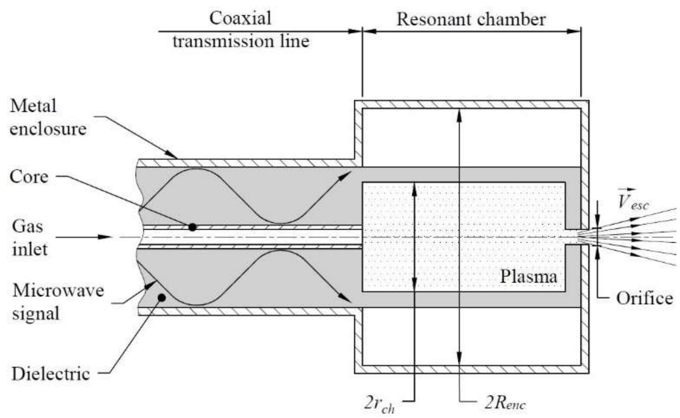


Figure 1. Schematic of electrothermal microwave plasma thruster.

The proposed thruster is capable of extending the CubeSat capabilities with orbit maintenance, attitude control, and planned deorbiting in order to avoid turning the decommissioned satellite into space junk. The relatively simple design of the thruster and low power consumption make it very suitable for nanosatellites[7].

The surface wave discharges have many industrial applications in the last couple of decades. The Department of Radiophysics and Electronics at Faculty of Physics of Sofia University has substantial experience in experimental and theoretical investigations in the field of surface wave discharges at low and atmospheric pressures. Small surface wave discharge at atmospheric pressure, described in Ref. 6, is used as the basis of the proposed thruster. The referenced plasma source operated at 2.45 GHz frequency at atmospheric pressure and power level below 10 W with very high efficiency of power absorption.

All considerations about the thruster's size and power consumption are made to fit the 1U size of the CubeSat standard. The 1U is a cube with 10 cm long edge and mass up to 1.33 kg. The maximum power consumption of the thruster is taken to be 2 W. The theoretical studies here are mainly related to determining the optimal geometrical parameters of the thruster and achieve minimum voltage standing wave ratio (VSWR). In the ideal case VSWR = 1, which would mean that all generated power is absorbed without any reflection (and in this case – without loss). The proposed thruster is mainly consisted of three components: (a) – generator of MW power, (b) – coaxial feed line, and (c) – resonant chamber filled with plasma. The plasma column with varying electron concentration is characterized by variable impedance, which makes the matching with the coaxial line difficult and is in fact the main challenge in this study. Before considering the matching conditions, we need to discuss the assumptions for determination of the plasma parameters.

A. Plasma Parameters

For the purpose of the analysis, the plasma is taken with fixed parameters, depending on the electron concentration and electron temperature. The investigated discharge is considered at pressure p = 8 Torr, electron temperature T_e = 1.5 eV, neutral gas temperature T_{gas} = 300 K, microwave generator frequency f = 2.45 GHz, and power P_0 = 2 W. The collision rate is then[8]

$$\nu_{en} = 1.84 \times 10^{-8} T_e^{3/2} N_0 \quad , \tag{1}$$

where N_0 is the number of the neutral gas particles calculated using the ideal gas law. The real part of the plasma conductivity is calculated[8] using

$$\sigma_{pl(r)} = \frac{\varepsilon_0 \nu_{en} \omega_{pl}^2}{\omega_0^2 + \nu_{en}^2} \quad , \tag{2}$$

where ε_0 is the permittivity of free space, ω_0 is the angular frequency of the exciting wave, and ω_{pl} is the plasma frequency. The plasma frequency is calculated[8] using expression

$$\omega_{pl} = \sqrt{\frac{e^2 n_e}{\varepsilon_o m_e}} \quad . \tag{3}$$

The real part of the plasma permittivity is given by[8]

$$\varepsilon_{pl(r)} = 1 - \frac{\omega_{pl}^2}{\omega_0^2 + \nu_{en}^2} \quad . \tag{4}$$

For the estimation of the average electron density of the plasma column and the corresponding surface wavelength in it are used both the dispersion law for configuration plasma-dielectric-vacuum-metal enclosure[9], which includes direct and stepwise ionization processes in the theoretical model, and microwave discharge experimental data[10]. From the dispersion law shown in Fig. 2, one can derive the relation between the electron density n_e and the surface wave wavelength in the plasma column. For the purpose of the analysis, four different electron concentrations (for which the gas heating is significant) are investigated: 0.5, 1, 1.5, and 2×10^{19} m^{-3}.

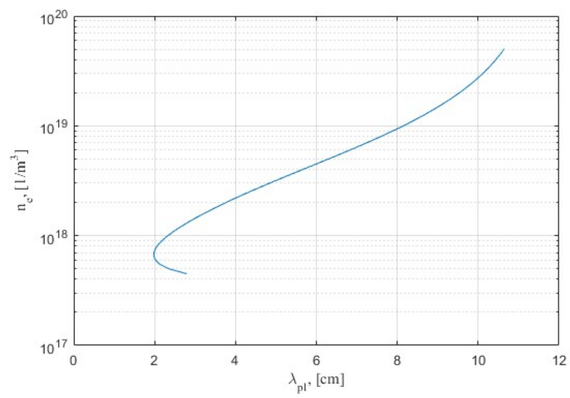


Figure 2. Electron density n_e versus wavelength in the plasma λ_{pl}.

B. Resonant Chamber Design

The metal enclosure radius influences the electron concentration[9] in the plasma column by redistribution of the EM field of surface wave in radial direction. The length of the chamber is related to the reflection of the wave back into the plasma column and thus increases the efficiency of absorption of the microwave power by the plasma. Schematic of the simulation is shown in Fig. 3. The microwave power is fed to the resonant chamber through the coaxial transmission line as a TEM wave. Excited surface waves propagate along the plasma-dielectric interface as traveling waves. When they reach the end of the plasma chamber, they are reflected by the metal enclosure. Ideally, the plasma chamber has to behave as a quarter-wave resonator in a standing wave mode. In order to investigate the relation between the VSWR and the geometrical parameters of the thruster, series of simulations have been run using COMSOL Multiphysics with varying the length of the plasma chamber, metal enclosure radius, and with the chosen plasma parameters. The VSWR is calculated for all combinations. The results for each electron density are shown in Fig. 4.

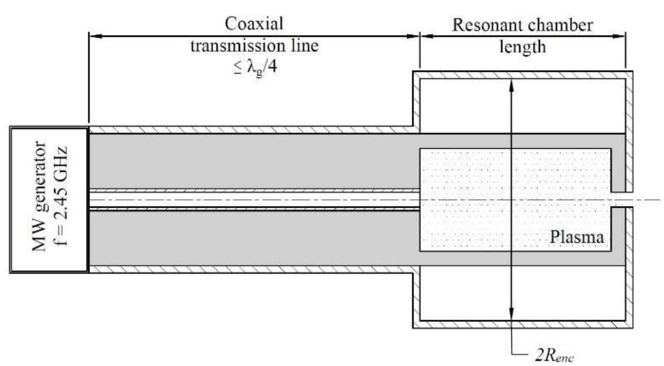
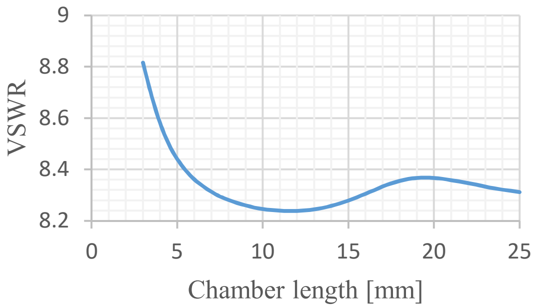
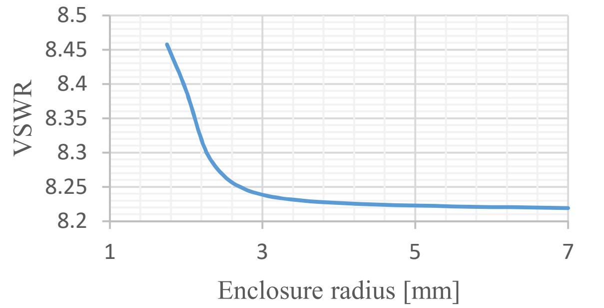


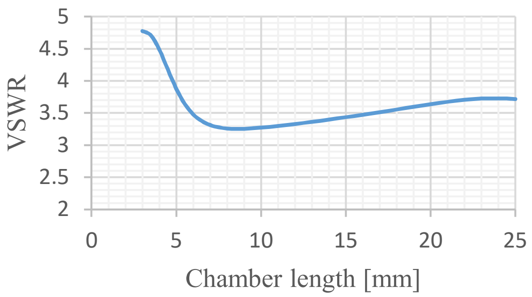
Figure 3. Simulation schematic with varying length of resonant chamber and radius of metal enclosure.



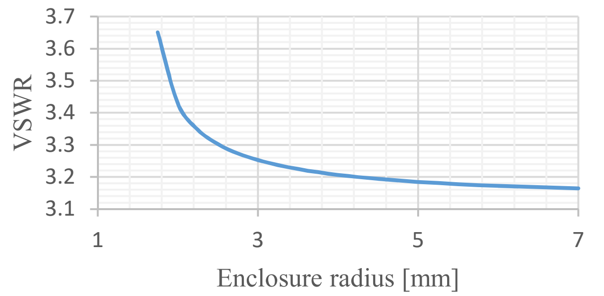
a) VSWR versus chamber length at $n_e = 0.5\times10^{19}\ m^{-3}$.



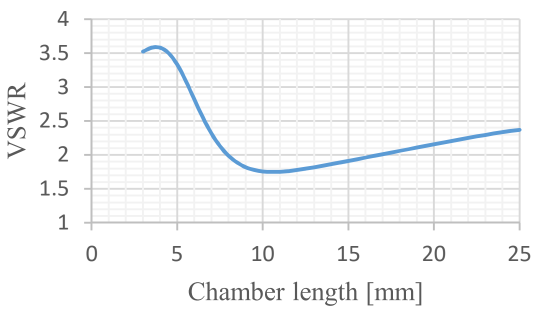
b) VSWR versus enclosure radius with chamber length fixed at 12 mm and $n_e = 0.5\times10^{19}\ m^{-3}$.



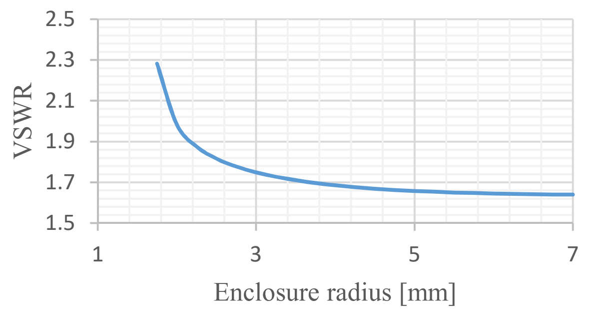
c) VSWR versus chamber length at $n_e = 1\times10^{19}\ m^{-3}$.



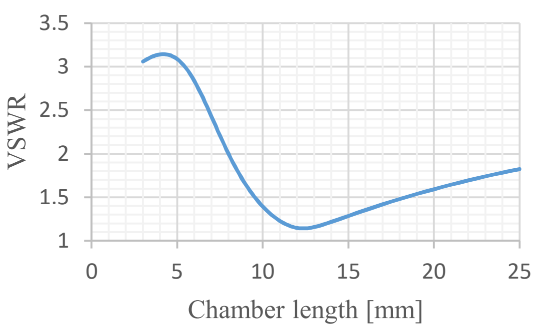
d) VSWR versus enclosure radius with chamber length fixed at 8.5 mm and $n_e = 1\times10^{19}\ m^{-3}$.



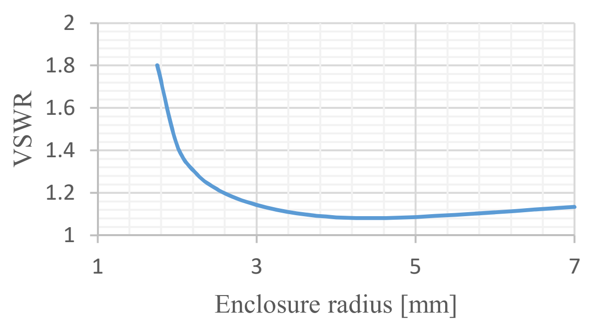
e) VSWR versus chamber length at $n_e = 1.5\times10^{19}\ m^{-3}$.



f) VSWR versus enclosure radius with chamber length fixed at 10.5 mm and $n_e = 1.5\times10^{19}\ m^{-3}$.



g) VSWR versus chamber length at $n_e = 2\times10^{19}\ m^{-3}$.



h) VSWR versus enclosure radius with chamber length fixed at 12.5 mm and $n_e = 2\times10^{19}\ m^{-3}$.

Figure 4. Calculated VSWR at different electron concentrations and variable chamber length and enclosure radius.

As it can be seen the VSWR is high in almost all cases, which means that the matching between the plasma load and the generator needs to be improved.

C. Matching of Plasma Load

The plasma load is with variable impedance, which makes the impedance matching with the microwave generator somewhat challenging. The plasma impedance changes with input power levels and geometrical dimensions of the resonant chamber. One possible way of matching the plasma load with the microwave generator is to add additional piece of matching transmission line. The matching line is placed at distance $\lambda_g/4$ from the resonant chamber. Equivalent circuit[11] of the system is shown in Fig. 5. The input impedance Z_{in} can be calculated[11] using the equation

$$Z_{in} = Z_0\left(\frac{j}{\cot(kd)} + \frac{Z_0 + jZ_{pl}\tan(kl)}{Z_{pl} + jZ_0\tan(kl)}\right)^{-1} , \quad (5)$$

where $Z_0 \approx 50\ \Omega$ is the characteristic impedance of the coaxial lines and Z_{pl} is the plasma load. By varying the length d of the open line, the imaginary part of Z_{in} could be minimized close to zero. This could be achieved if d is $\lambda_g/4 < d < \lambda_g/2$, where $\lambda_g = \lambda_0/\sqrt{\varepsilon_r}$ is the wavelength of the signal inside the coaxial transmission lines and ε_r is the relative permittivity of the dielectric inside the coaxial line. Series of simulations are conducted using the COMSOL Multiphysics software where the length d of the matching line is varied. The results are shown in Fig. 6.

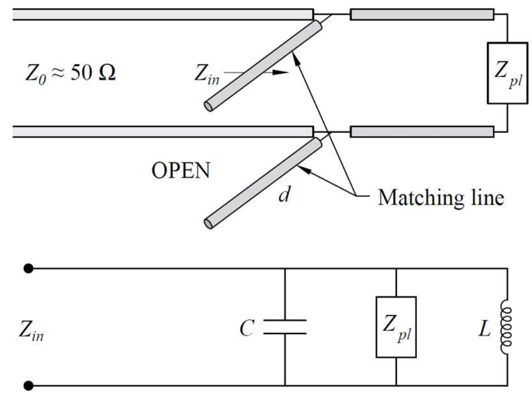
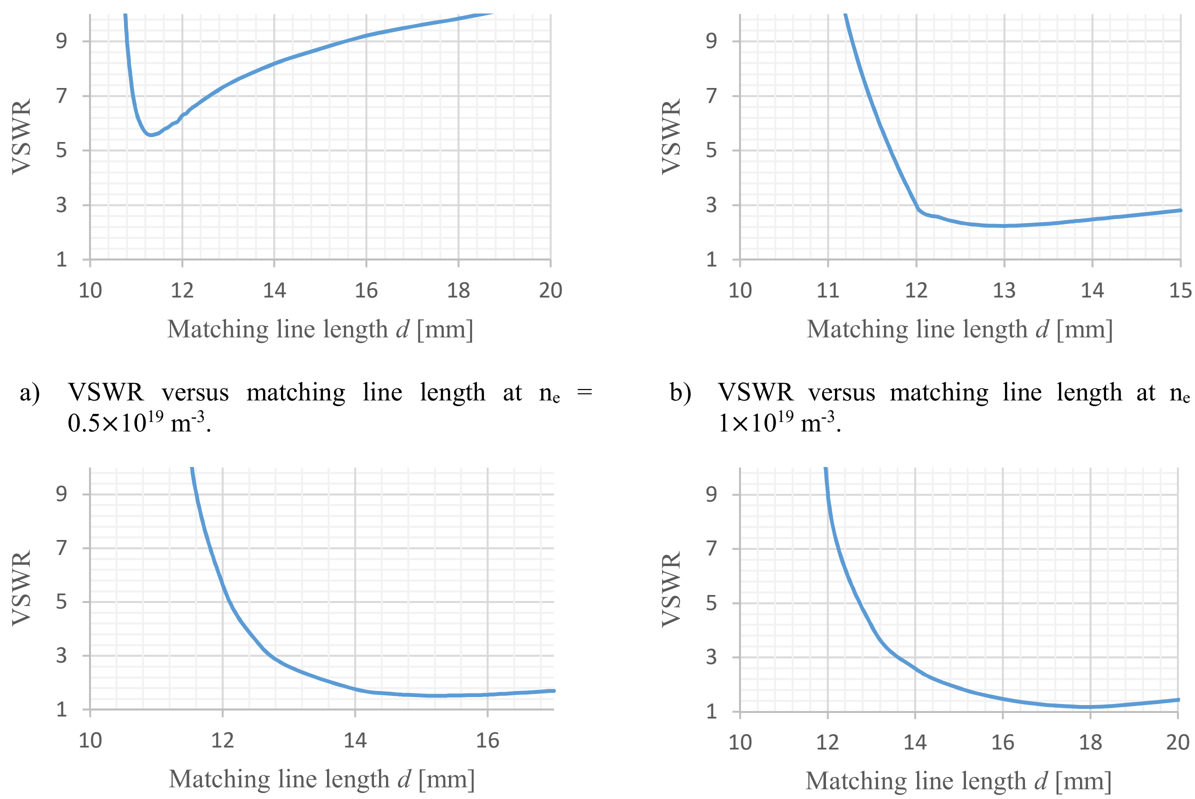


Figure 5. Equivalent circuit of microwave circuit.



a) VSWR versus matching line length at $n_e = 0.5\times10^{19}$ m^{-3}.

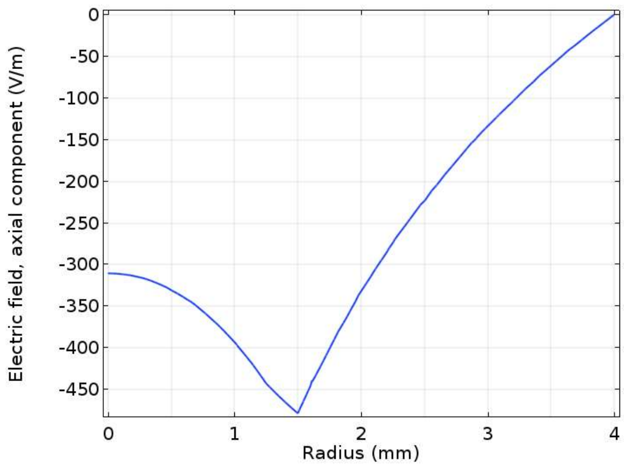
b) VSWR versus matching line length at $n_e = 1\times10^{19}$ m^{-3}.

c) VSWR versus matching line length at $n_e = 1.5\times10^{19}$ m^{-3}.

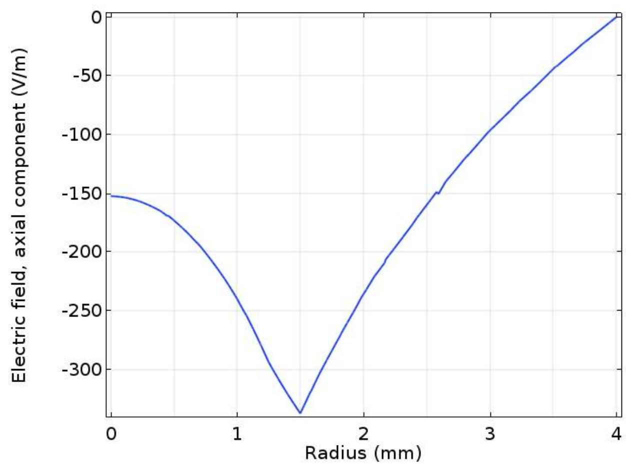
d) VSWR versus matching line length at $n_e = 2\times10^{19}$ m^{-3}.

Figure 6. VSWR at different electron concentration and variable matching line length.

Obtained results show that at higher densities good matching (VSWR <1.5) is achieved at specific length of the stub, while at lower densities a $\lambda_g/4$ impedance transformer must be included in the thruster construction. Axial field distribution for 1.5 and 2×10^{19} m^{-3} electron densities are shown in Fig. 7.



a) Axial component of the electric field distribution along the radius of the thruster at $n_e = 1.5\times10^{19}$ m^{-3}.



b) Axial component of the electric field distribution along the radius of the thruster at $n_e = 2\times10^{19}$ m^{-3}.

Figure 7. Axial electric field distribution along the radius of the thruster at different electron densities.

III. Conclusion

Full-wave model of the electrothermal microwave plasma thruster is developed and effects of plasma density, resonant chamber length and metal enclosure radius on the matching of the system are investigated. Optimal dimensions of all elements of the thruster are obtained for four values of plasma density with respect of the minimal VSWR. Inclusion of an open transmission line as a matching device in the thruster construction improves the performance and lowers the VSWR. Additional $\lambda_g/4$ impedance transformers must be included at lower plasma densities and is subject of future research.

Acknowledgments

The current research is financially supported by the Bulgarian Science Fund, Ministry of Education, under contract № КП-06-ОПР 01/1.

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