Electromagnetic Field Distributions and Energy Transfer in Waveguide-Based Axial-Type Microwave Plasma Source

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INTRODUCTION

We analyze electrodynamic properties of a waveguide-based axial-type microwave plasma source (MPS) for hydrogen production by methane decomposition presented in Fig. 1.
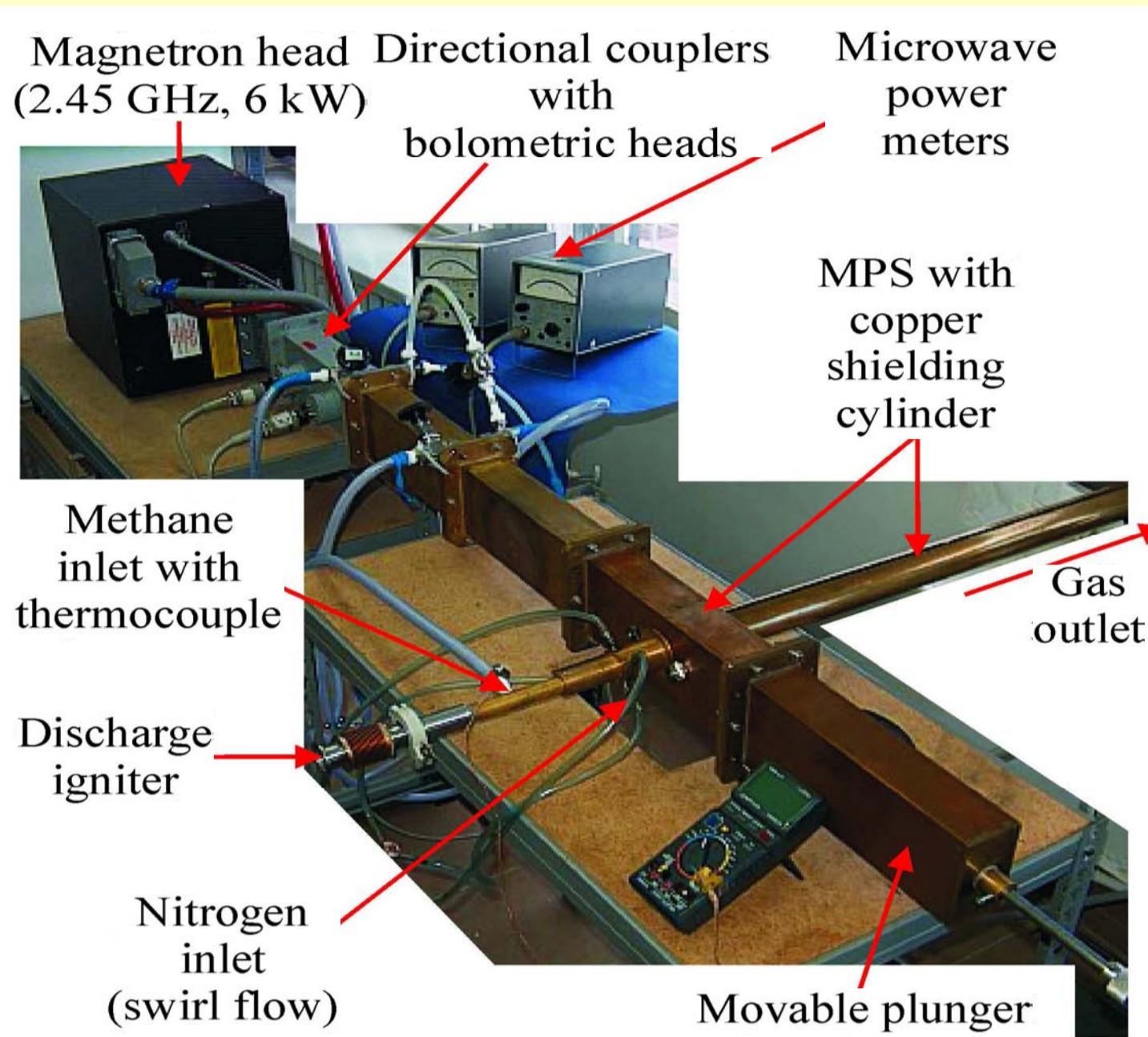

Fig. 1. Photo of waveguide-based axial-type microwave plasma source

Microwave power is supplied to the MPS via a standard rectangular waveguide with a reduced-height section in the discharge region. A movable short on the other side of the MPS is a means of tuning, which allows for impedance matching and efficient transfer of the microwave power to the plasma. The discharge takes place in a quartz tube, which penetrates through the wider waveguide walls. The processed gas is delivered to the discharge region through a metallic tube. The discharge is stabilized by an additional swirled gas flow.

The presented MPS allows for operation at incident microwave power levels up to 6 kW with the gas flow rate 50 – 200 l/min.
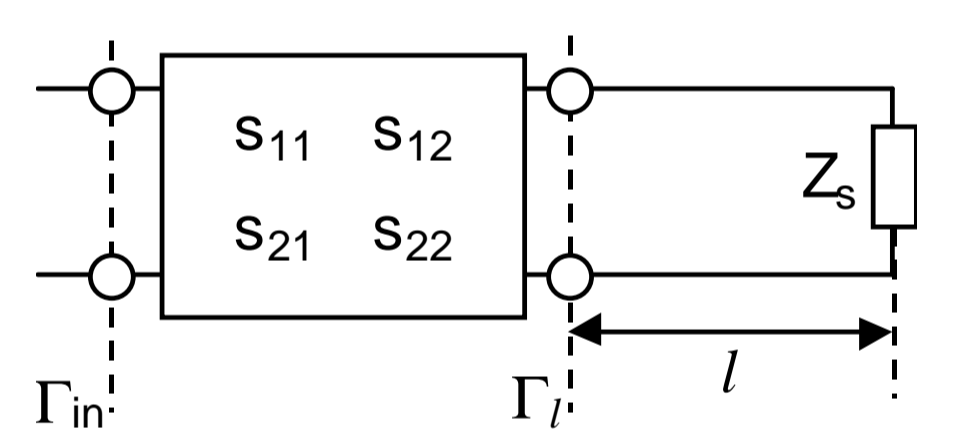
TWO-PORT NETWORK METHOD

Figure 5. MPS represented as a two-port network terminated with a short-circuited transmission line of length l

The reflection coefficient in the input plane of the two-port, Γ_{in} can be calculated from [5]:

$$\Gamma_{in} = s_{11} + \frac{s_{12}s_{21}\Gamma_l}{1 - s_{22}\Gamma_l}$$

where s_{11}, s_{12}, s_{21}, s_{22} are the elements of the scattering matrix. Γ_l is the reflection coefficient from the short circuit in the output plane of the two-port and it can be found from

$$\Gamma_l = \frac{z_l - 1}{z_l + 1}$$

Normalized impedance of the short circuit transformed through the length l is

$$z_l = j \tan(2\pi l/\lambda_g)$$

METHOD OF CALCULATIONS

Tuning characteristics

One of essential characteristics of any MPS is power transfer from the feeding line to the plasma. It can be expressed as ratio P_R/P_I, where P_I, P_R are the power of the incident and reflected waves, respectively. The ratio is equal to the square of the module of the wave reflection coefficient. Tuning characteristics of the MPS is a dependence of P_R/P_I on the position of the movable short normalized to the wavelength. It is easy to obtain experimentally and give an important information about the plasma source.

Tuning characteristics depend on MPS's geometry and dimensions as well as plasma parameters. They can be obtained using equivalent circuit theory and method presented in [3,4] if characteristic MPS dimensions are much smaller than the waveguide wavelength λ_g. This is not the case for our MPS, for which characteristic dimensions are in the range 0.2 .. 0.5 of the wavelength, so the analysis of the power transfer has to be done in terms of electromagnetic field distributions.

The tuning characteristics can be obtained with COMSOL directly, by building such a geometry of the MPS in which the movable short is represented by a segment of a rectangular waveguide of regulated length l, short-circuited at the end.

Changing the length of this segment and determining the wave reflection coefficient for each length allows one to obtain the needed dependence:

$$P_R/P_I = |\Gamma|^2 = f(l/\lambda_g).$$

For determining the electromagnetic field distributions in the MPS we use 3D geometry as presented in Fig. 2. The plasma region (REV1) is filled with homogenous plasma of the complex relative electric permittivity ε_p given by the Lorentz formula

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega(\omega - j\nu)}$$

where ν is the electron collision frequency for momentum transfer, ω is the angular frequency of the wave, $\omega_p = [ne^2/(\varepsilon_0 m_e)]^{1/2}$ is the plasma frequency, n is the electron density, e is the elementary charge, m_e – the electron mass.

All calculations we perform for the field frequency $f = 2.45$ GHz and a standard waveguide WR430 as the main part of the feeding line. The lengths of the tapered waveguides and the reduced-height section are $\lambda_g/2 = 74$ mm. According to our experimental results, we take that the cylindrical region occupied by plasma has the length 6 cm and the radius 1 cm and is displaced 0.5 cm up from the gas inlet tube end.
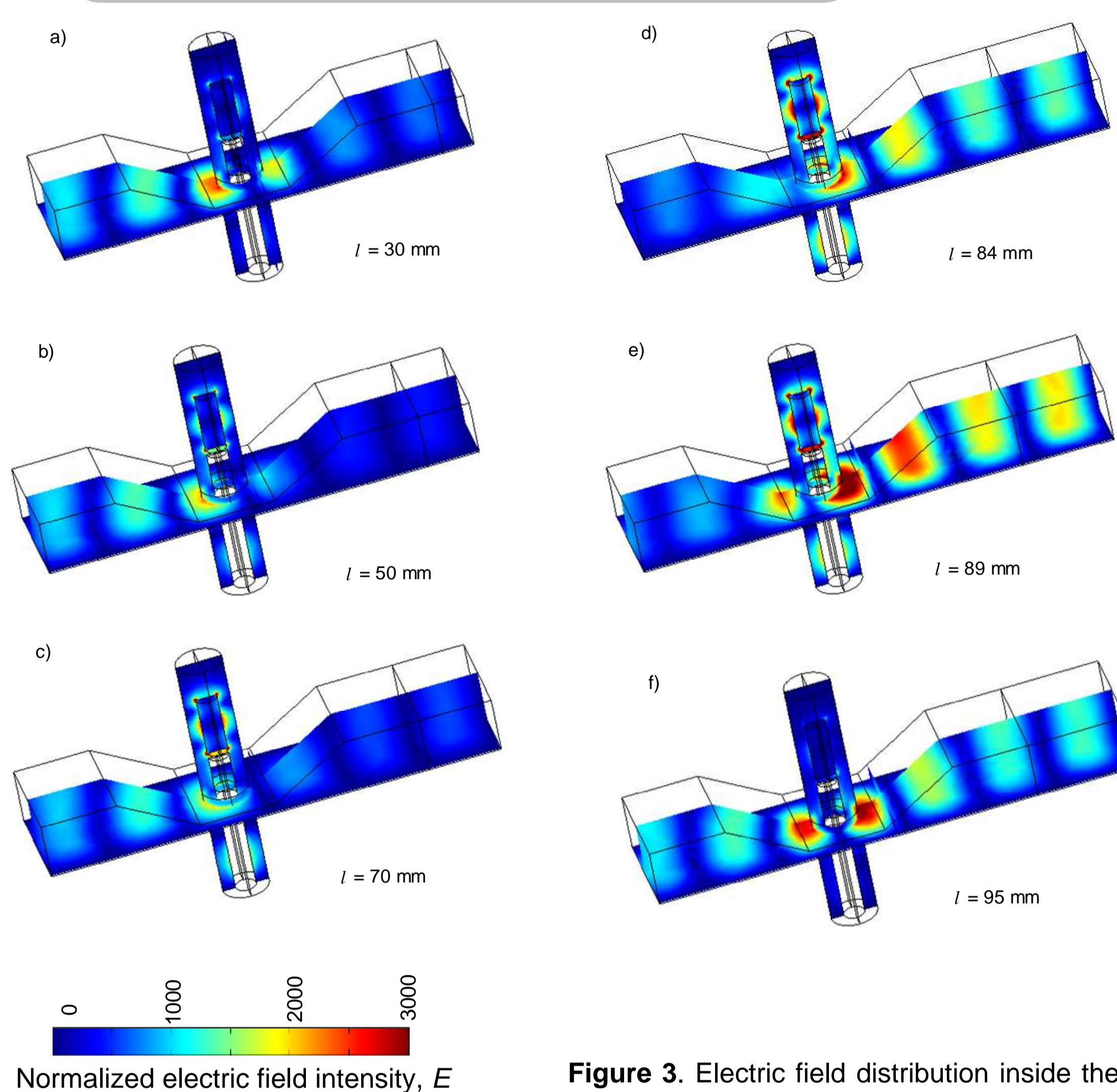
NUMERICAL RESULTS – DIRECT METHOD

Figure 3. Electric field distribution inside the MPS for different positions of the movable short; plasma parameters are $s = 0.1$, $n = 10$, $h = 10$ mm, $P_{in} = 1$W.
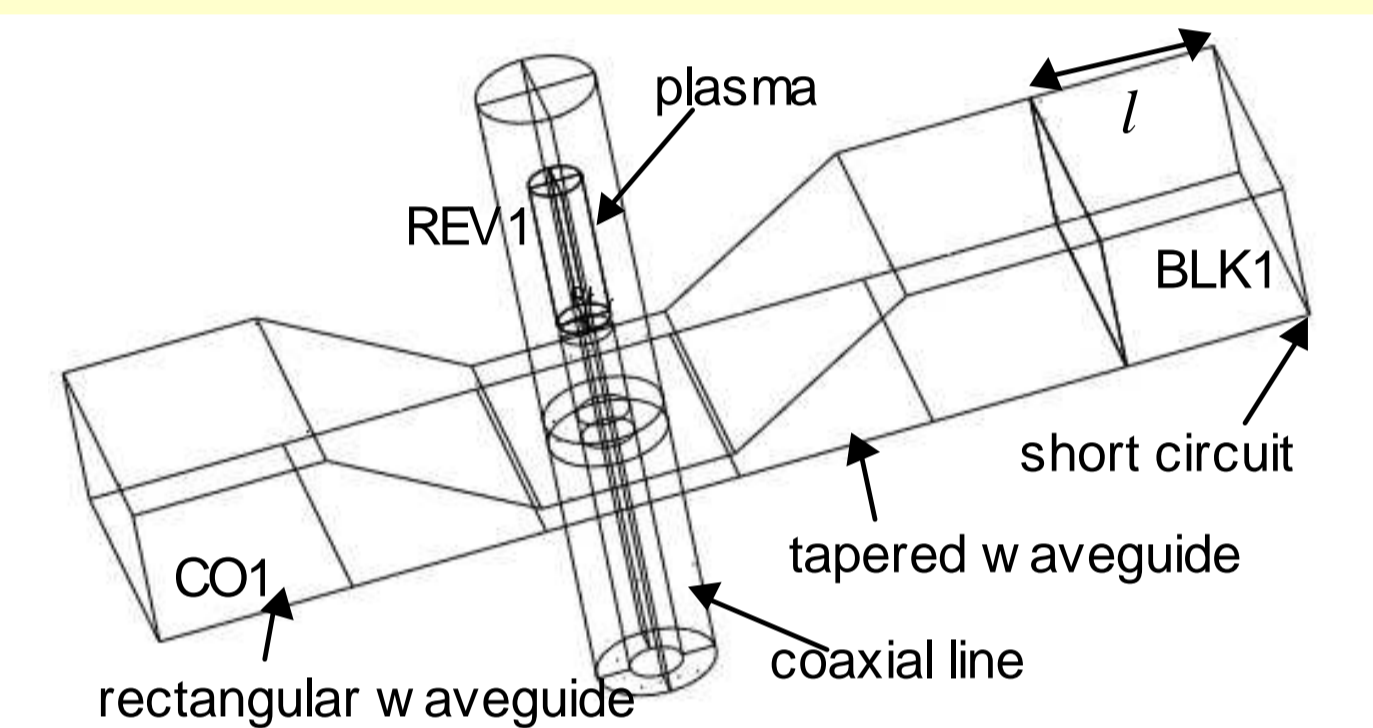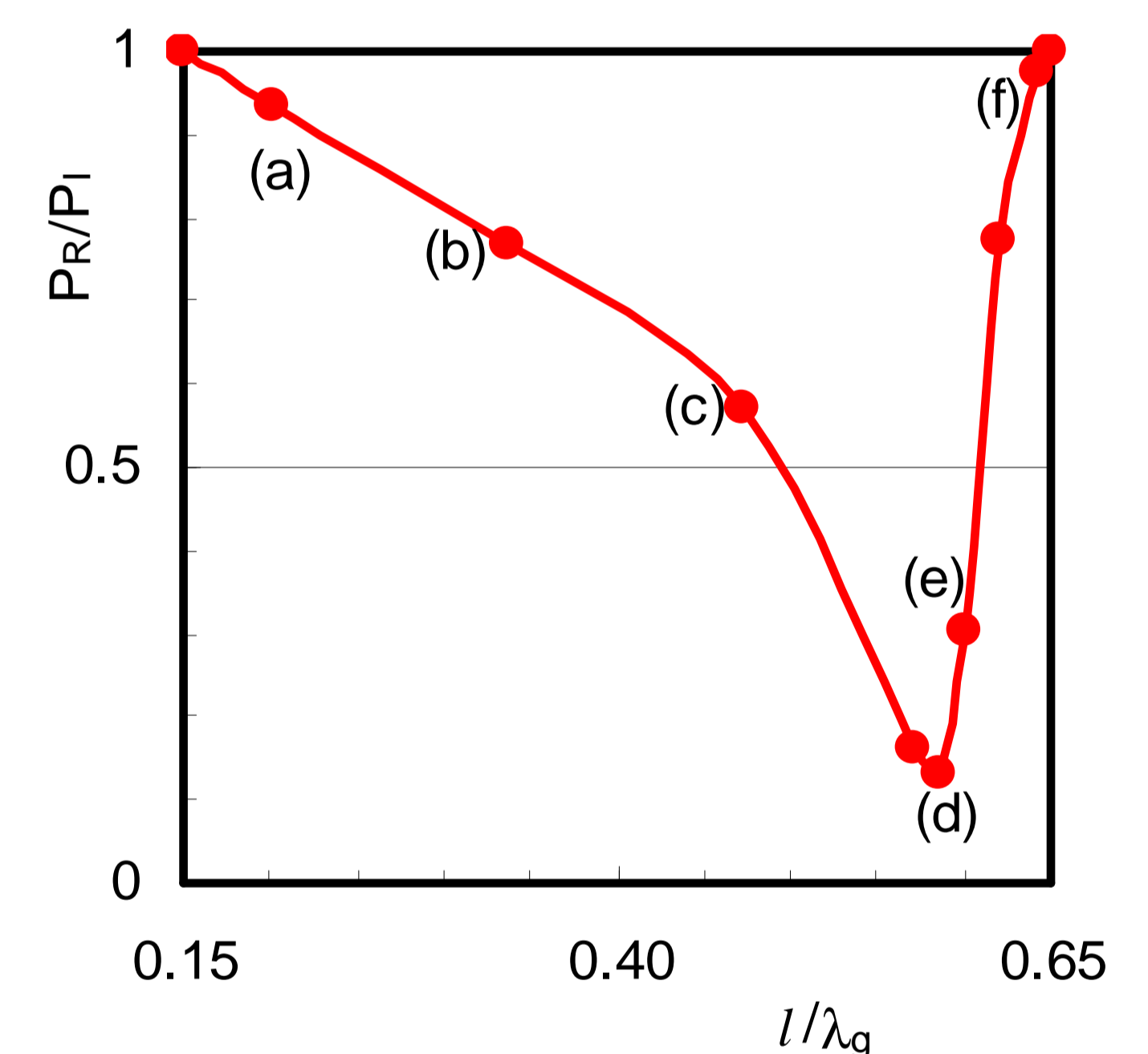

Figure 2. Geometry of the MPS used for simulations.

Figure 4. Tuning characteristics of the MPS. The letters in brackets correspond to the respective figures of Fig. 3.
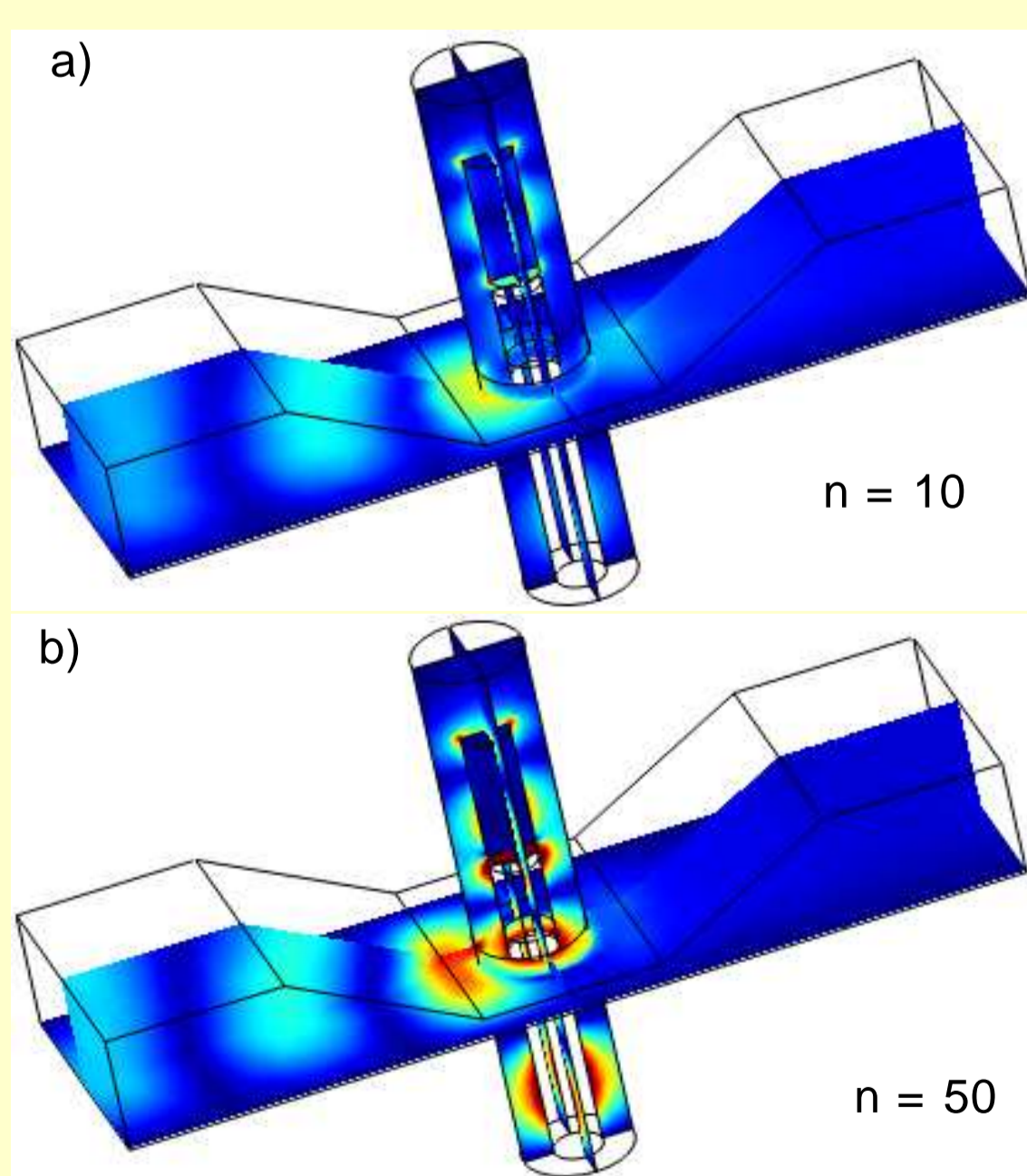
NUMERICAL RESULTS - TWO-PORT NETWORK METHOD

Figure 6. Electric field distribution inside the MPS terminated with a matched load (a) for $n = 10$ and (b) for $n = 50$. All the other conditions and the color scale is the same as in Fig. 3.

Figure 7. Influence of normalized electron density n on tuning characteristics of the MPS.

Figure 8. Influence of the height of the reduced-height section h on tuning characteristics of the MPS.

It can be seen that the shape of the characteristics strongly depends on the electron density. The minimum values of P_R/P_I below 0.1 can be obtained for every presented values of n except for $n = 200$. This means that for these smaller values of n it is possible to find such a position of the movable short that coupling between the electromagnetic field and the plasma is good and almost 90% of incident power is absorbed in the plasma.

For electron density $n = 200$, only about 20% of incident power is absorbed in plasma in the best case. The reason is that with increasing electron density also the plasma conductivity increases and the plasma behaves like a good conductor and strong skin efect can be expected. From the other side it might be an unexpected result since in real discharges the plasma exists because the microwave power is absorbed in the plasma, hence one could expect that more power is absorbed in plasma with greater electron density.
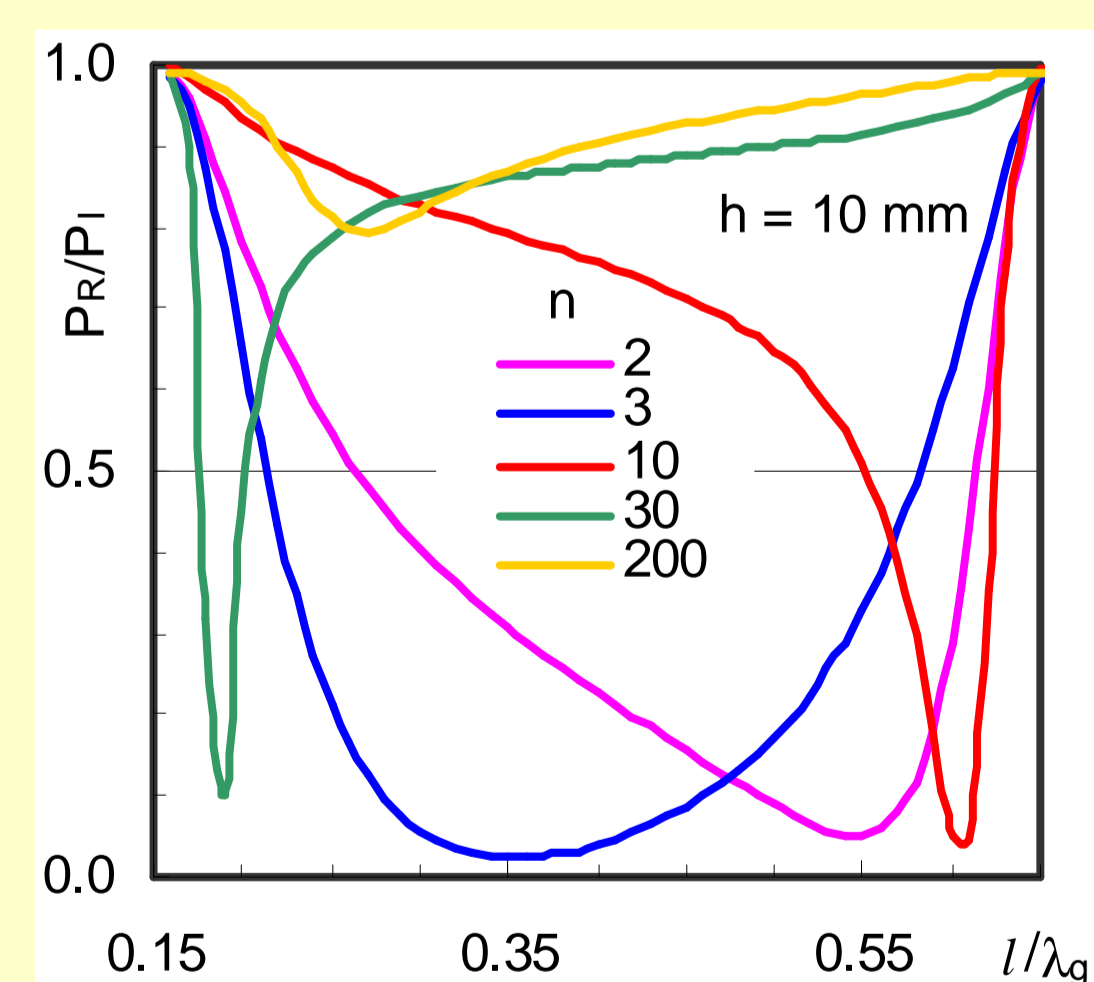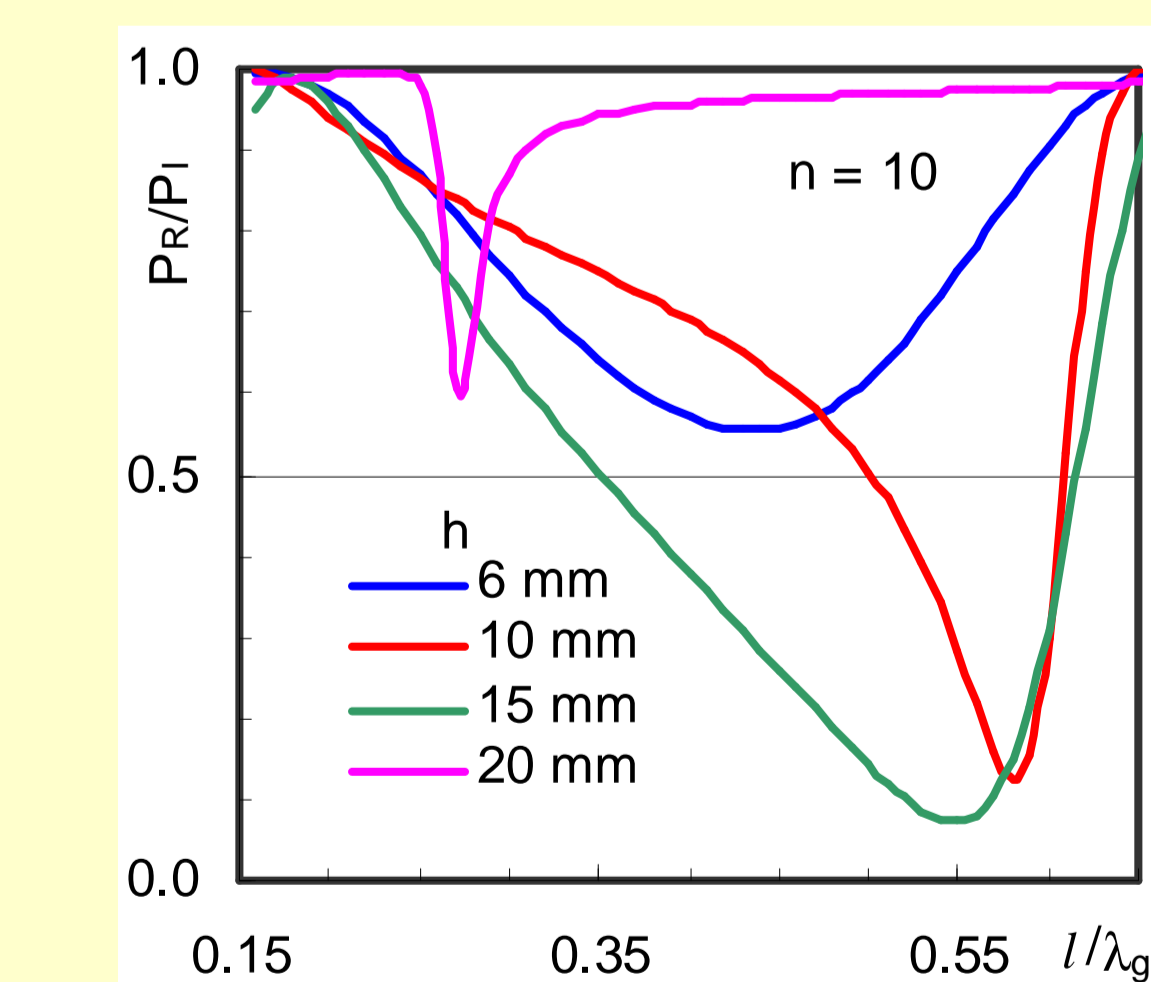
To explain this behavior let us note that our model is not a self-consistent one and does not take into account any discharge processes. We have imposed that the plasma is homogenous in the whole region it occupies, while in real discharges plasma is non-homogenous and absorption of microwave power occurs merely in regions with lower electron density. This question is to be examined by us in detail in the future

CONCLUSION

We have examined changes of the electric field distributions in waveguide-based axial-type microwave plasma source during tuning procedure of the MPS. The distributions strongly depend on position of the movable short so does the wave reflection coefficient of the incident wave.

We have proposed a method of determining tuning characteristics of the MPS consisting in treating the MPS as a two-port network, calculating its scattering matrix coefficients and calculating the reflection coefficient from analytical expressions.

The results show that the tuning characteristics depend on plasma parameters such as the electron density and on MPS dimensions such as the height of the reduced-height waveguide section. It is possible to find such position of the movable short for which the reflected wave power is less than 10% of incident wave power.

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Acknowledgements