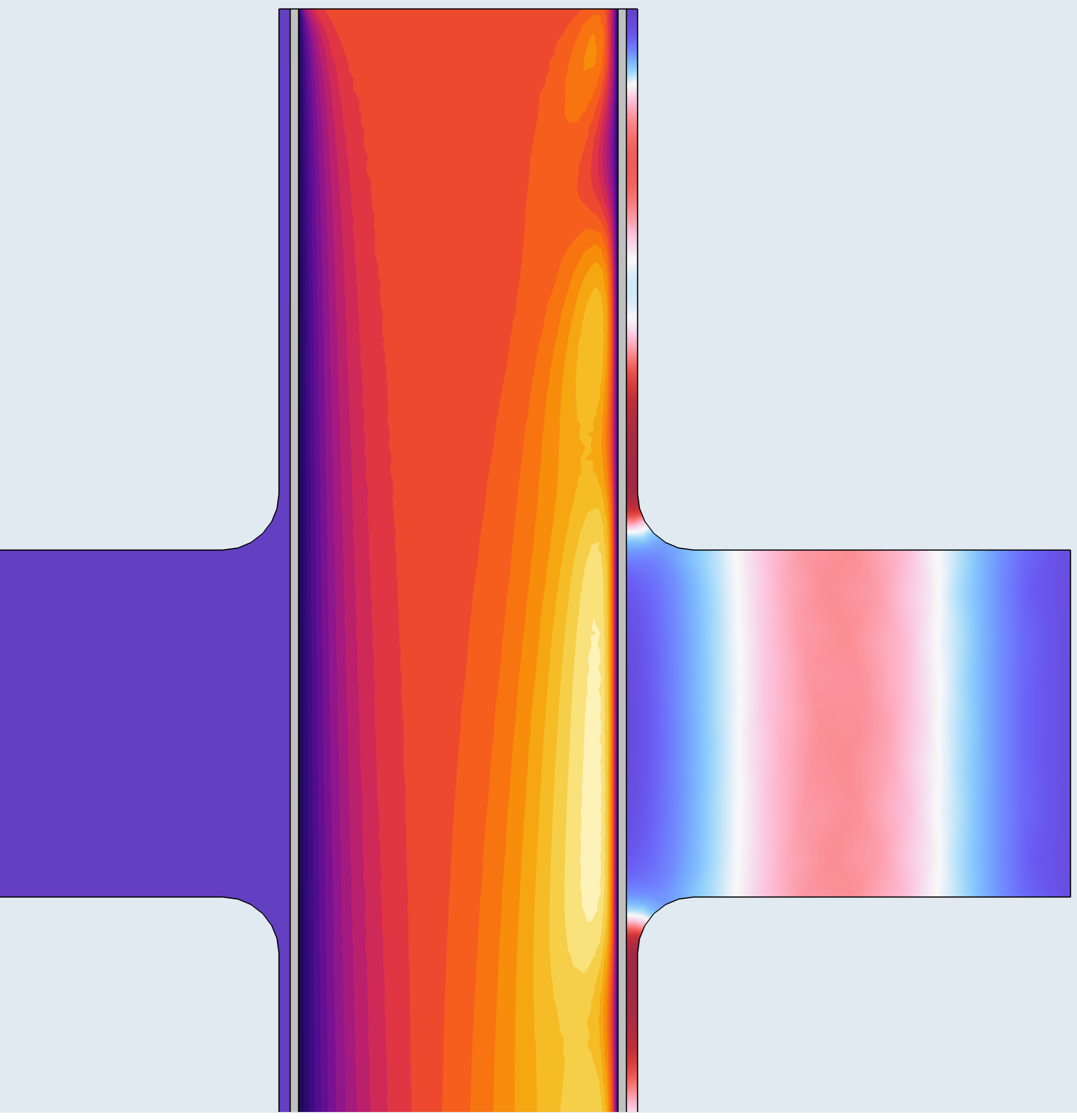

Atmospheric Plasma Modeling

Atmospheric plasmas, also called Thermal plasmas, are much more challenging to be simulated than at low pressure since high gas temperature and skin effect are expected from thermodynamic and electromagnetic coupling.

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Introduction

Microwave plasmas (0.3-300GHz) are used in industry for various applications such as in microelectronics or decomposition of greenhouse gases [1]. Contrary to the use of DC plasmas, microwave plasmas do not need electrodes that may pollute or disturb the discharge at high pressure. Furthermore, contrary to the evanescent mode occurring in the RF plasmas at lower frequency (13.56MHz, 27.12MHz), the microwave frequency (915MHz, 2450MHz) can be propagative [2]. High pressure microwave plasmas are still studied in laboratories since they are experimentally characterized by specific phenomena of contraction or filamentation under given conditions that may affect the stability of the discharge and thus be a limitation for an industrial application [1]. In that context, the modeling of a microwave plasma with COMSOL Multiphysics® is a necessary step to optimize the development of a plasma reactor for a given application.

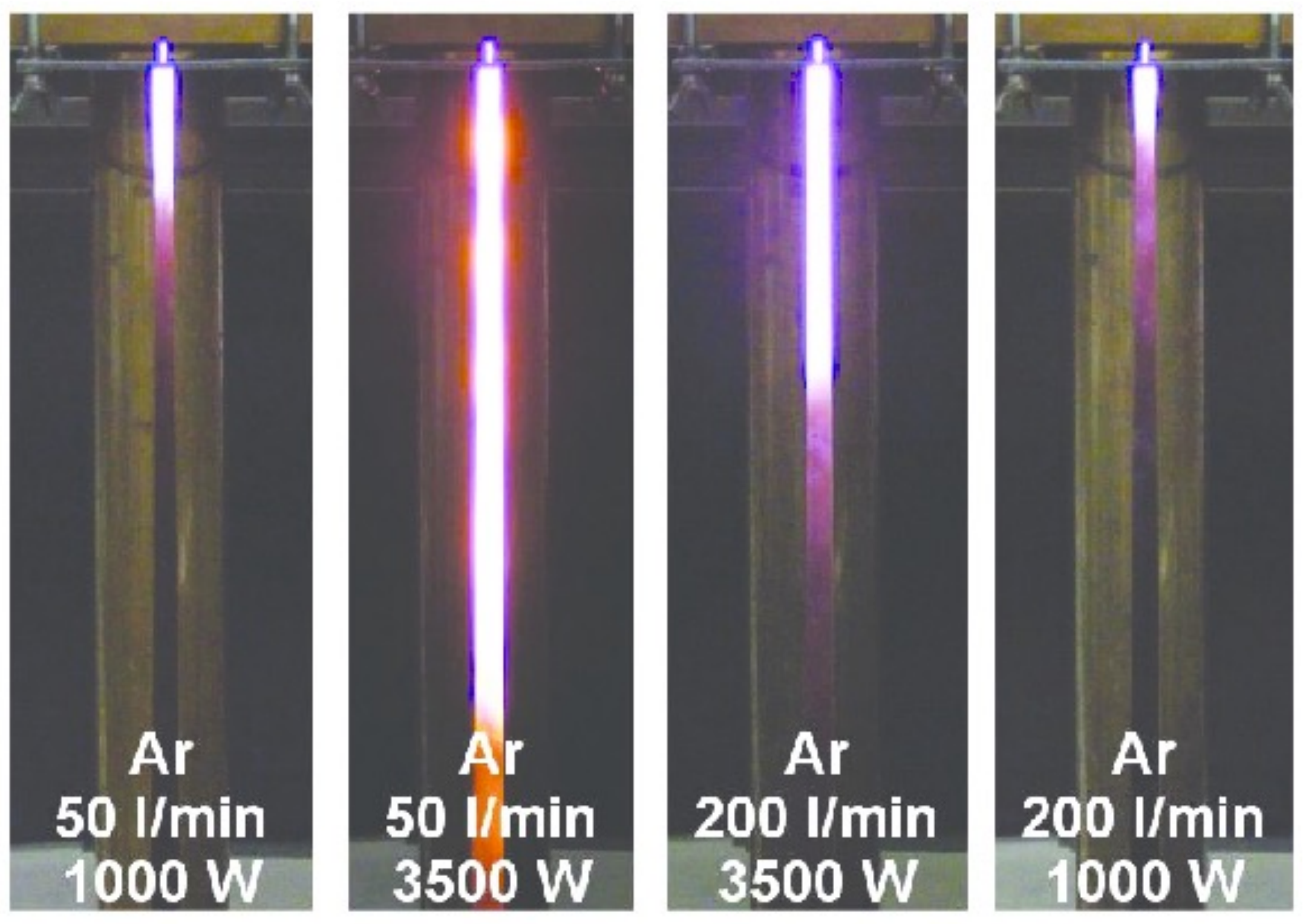

FIGURE 1. Cylindrical microwave plasma source operated with Argon at atmospheric pressure [3].

Methodology

A fully coupled thermal plasma is simulated with the wave propagation (RF Module), the plasma (Plasma Module), the heat transfers (Heat Transfer Module) and the flow regime (CFD Module).

The Helmholtz equation governs the wave propagation ($\omega = 2\pi f$):

$$\left(\nabla^2 + \mu_0\mu_r\sigma\frac{\partial}{\partial t} + \frac{\varepsilon_r\mu_r}{c^2}\frac{\partial^2}{\partial t^2}\right)\begin{Bmatrix}\boldsymbol{E}\\ \boldsymbol{B}\end{Bmatrix} \quad \begin{Bmatrix}\boldsymbol{E}\\ \boldsymbol{B}\end{Bmatrix} = \begin{Bmatrix}\boldsymbol{E}(x,y)\\ \boldsymbol{B}(x,y)\end{Bmatrix} e^{-i\omega t} e^{ikz}$$

The Heat equation governs the increase in gas temperature:

$$\left(\rho(T)C_p(T)\frac{\partial}{\partial t} - k(T)\nabla^2\right)T = \underbrace{\frac{n_e e^2}{m_e}\frac{\nu_m}{{\nu_m}^2 + \omega^2}\frac{{E_0}^2}{2}}_{\text{wave-heating}}$$

k(*T*) is the thermal conductivity in W/m/K

Results

In a standard rectangular waveguide, the transverse electric (TE10) mode is the dominant mode with:

$$k^2 = {k_{10}}^2 = \frac{\omega^2}{c^2} - \frac{\pi^2}{a^2}$$

k is the wavenumber in rad/m

At high pressure, the plasma is dispersive with:

$$k^2 = \frac{\omega^2}{c^2}\underbrace{\left[1 - \frac{\omega_p^2}{\omega^2 + \nu_m^2} - i\frac{\nu_m}{\omega}\left(\frac{\omega_p^2}{\omega^2 + \nu_m^2}\right)\right]}_{\varepsilon_r(\omega)}$$

When the plasma reacts as a conductor, a skin depth appears, and a waveguide-to-coaxial coupling generates a TEM mode.

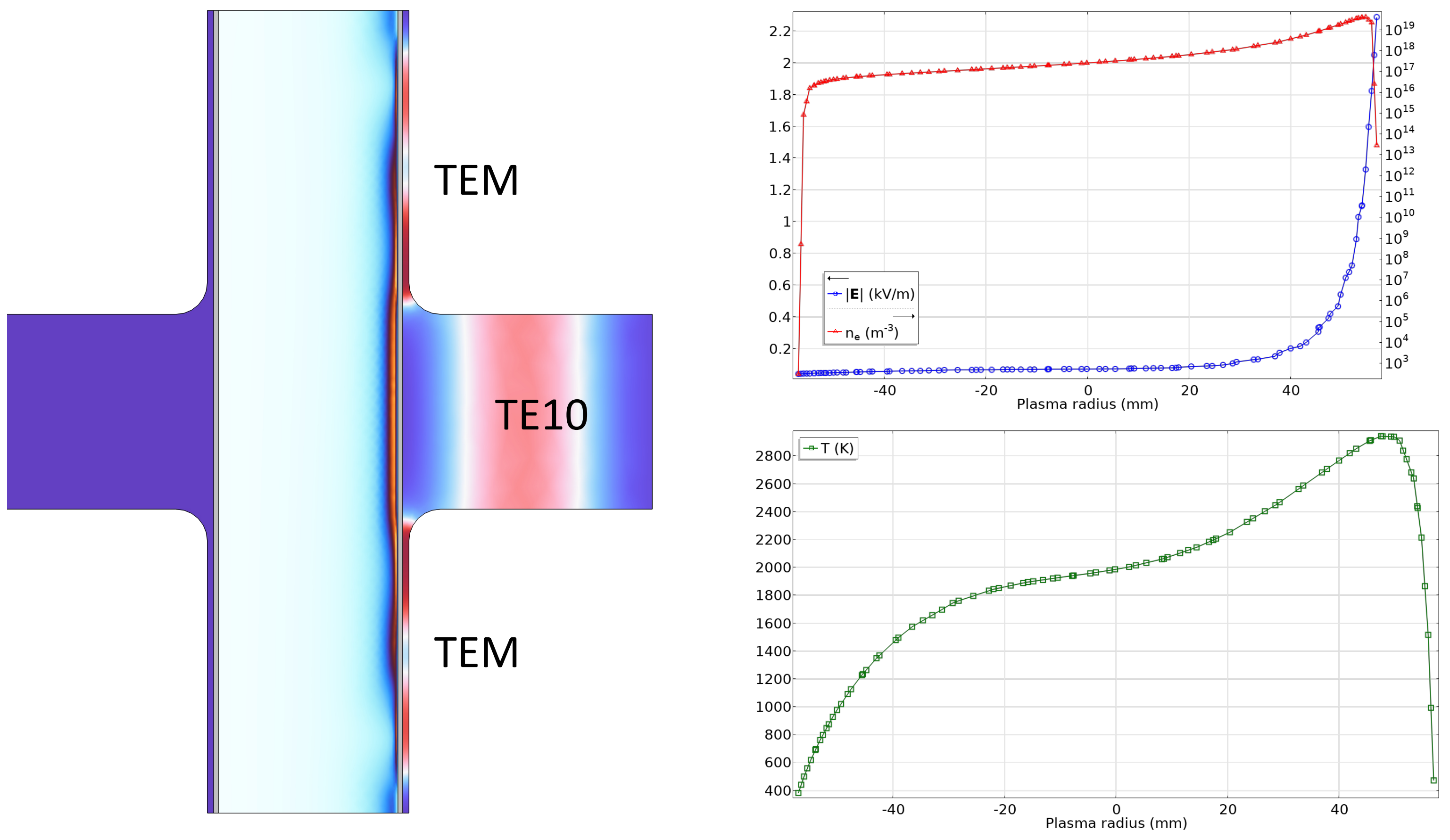

FIGURE 2. Left: Waveguide-to-coaxial coupling. Right: Profiles of the plasma density and electric field (up), and gas temperature (down).

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3. B. Hrycak, M. Jasinski and J. Mizeraczyk, Tuning characteristics of cylindrical microwave plasma source operated with argon, nitrogen and methane at atmospheric pressure, PRZEGLĄD ELEKTROTECHNICZNY (Electrical Review), ISSN 0033-2097, R. 88 NR 6/2012.

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