Determination of electron density in microwave plasma torch by microwave interferometry

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Introduction

The microwave plasma torch is a well known design of plasma source recently experiencing a renaissance in many applications, that are most often based on the presence of an admixture in the working gas. Simple molecular gases (O_2, N_2, H_2 etc.) or organic molecules (hydrocarbons and alcohols) are most often used as admixtures. Among these, graphene nanosheets synthesis by decomposition of ethanol was recently studied in detail [1, 2]. However the nature of this synthesis, formation of nanoparticles and their agglomerates together with intensive C_2 emission spectra in the H_β region causes difficulties for determination of electron density from Stark broadening of H_β emission profile.

In this work, we discuss the numerically enhanced microwave interferometry for electron density measurement of the plasma torch sustained in argon with various admixtures. The free electron density in plasma (abbrev. as plasma density) and experimentally observed phase shifts are linked [3] via the complex relative plasma permittivity $\varepsilon_{\mathrm{pl}}$ (1).

$$\varepsilon_{\mathrm{pl}} = 1 - \frac{n_{\mathrm{e}} e^2}{\varepsilon_0 m_{\mathrm{e}}} \frac{\omega - \mathrm{i}\nu_{\mathrm{m}}}{\omega(\omega^2 + \nu_{\mathrm{m}}^2)} \tag{1}$$

where n_{e} is the plasma electron density, e is the elementary charge, ε_0 is the permittivity of vacuum, m_{e} is the mass of the electron, ω is the angular frequency of microwaves and ν_{m} is the collision frequency for electron-neutral momentum transfer.

Due to small dimensions of the plasma, the interferometry needs to be calibrated by the numerical model. Second important reason for its development is the likely case, where the plasma density is in fact “overcritical” for the interferometer frequency, and the assumed transmission process turns into a scattering problem. Finally, the numerical model also evaluates the sensitivity of measured phase to common experimental problems (plasma filament offset or the mutual misalignment of the waveguides).

Experimental set-up

The 2.45 GHz atmospheric pressure plasma torch enclosed in quasi-cylindrical reactor chamber (150 mm i.d., 400 mm height) is sustained in argon atmosphere with varying admixtures of molecular gas (O_2, N_2, H_2 and ethanol). The investigated parameters are the discharge power (up to approx. 170 W) and the flow rate of the admixture (mostly varied between 0 sccm and 20 sccm). The gas inlet is realized through the central nozzle of the torch electrode.

For the diagnostics, the Mach-Zehnder configuration of 34.5 GHz interferometer (with its probing arm extending inside the reactor chamber) is used, as depicted in Fig. 1. Signals from the probing and reference arm are eventually combined via the magic tee section and measured by two detectors. This interferometer setup is noteworthy for the absence of the discharge tube walls (between interferometer waveguides and plasma) combined with close proximity to the discharge.

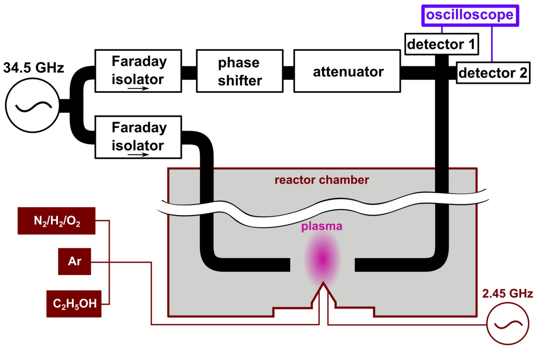

Figure 1: *The side view diagram of the experiment.*

Numerical model

In the first order approximation, the interaction between electromagnetic (EM) wave and plasma can be described analytically. The conditions are that the wave propagation can be reduced to one dimension (i.e. the plasma domain should be a homogeneous planar slab, with perpendicularly incident EM wave). For most filamentary discharges, however, the plasma column (filament) diameter is small compared to the beam width, which leads to scattering and therefore a numerical model must be used instead. In our experiment, the probing microwave beam exiting the waveguide has width of 7 mm, while the inhomogeneous plasma filament is rarely over 2 mm in diameter.

The finite element method (FEM) software COMSOL Multiphysics offers a wide selection of physics modules, but the high frequency wave–matter interaction is most naturally described by the RF module (based on direct computation of Maxwell equations), where each geometric domain is defined by a set of material constants (permittivity, permeability, conductivity). This way, the whole reactor chamber may be defined and modeled.

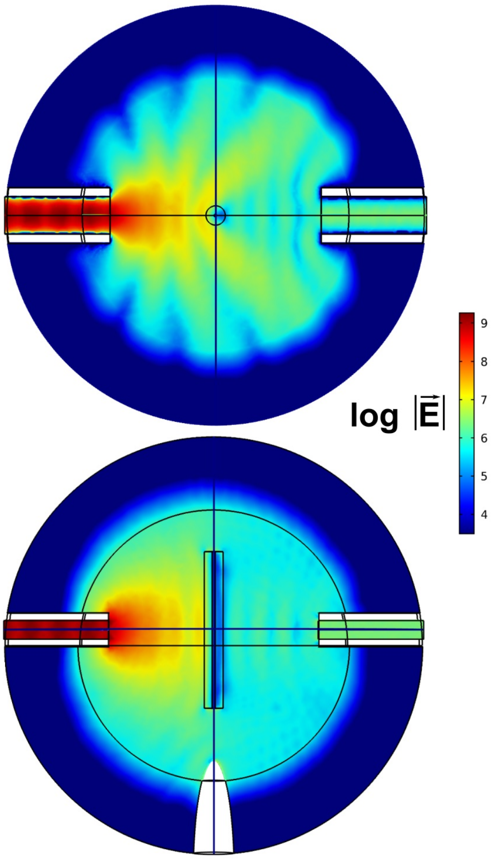

Figure 2: *The top- and side- view of the model with color coded EM field.*

The downside of this approach is the large volume of the reactor, as, generally speaking, any relevant computation requires a mesh grid with several mesh elements per wavelength. At 34.5 GHz (wavelength under 1 cm), this full 3D model is inevitably extremely memory and CPU hungry. Fortunately our recent work (modeling and experimental) has confirmed [4], that in this probing arm geometry – two waveguides facing each other – the measured phase is affected only by objects that are placed directly between these waveguides. This means, that only this critical volume (surrounded by the non-reflective perfectly matched layers) needs to be modeled (see Fig. 2), thus substantially improving the performance.

Results and discussion

The computed fit of phase shift relation to plasma density for different collision frequencies and plasma filament diameters is plotted in Fig. 3. Using the high collision frequency scenario, the plasma density obtained from measurement reaches 2×10^{20} for pure argon and slightly decreases with the increasing amount of admixture. These values are in general agreement with other reports [5]. An instrumental error of the phase measurement is estimated around 0.5 deg.

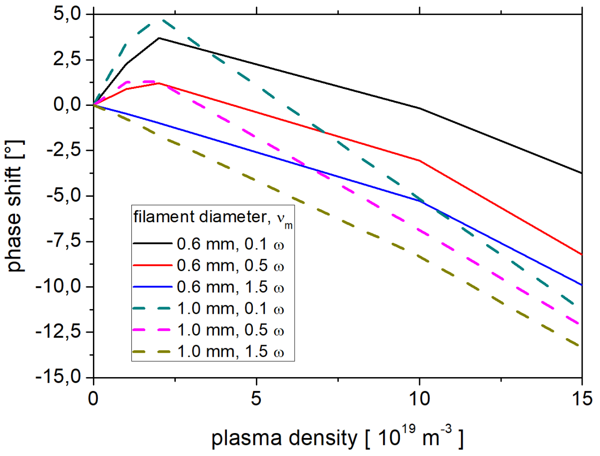

Figure 3: *The phase shift as a function of plasma filament parameters.*

It should be noted, that the experimental data are affected by gradual heating of waveguide walls, which then expand, leading to increased propagation constant inside the waveguide and finally, a phantom phase shift. Despite being subtle, this effect may add up over a long section of the (thermally conducting) waveguide. This forces us to carry out the interferometry just before and just after any change in discharge settings. Such approach can be obviously problematic when this change of the discharge settings needs some time to take effect (e.g. flow rate).

Moreover, the model can be also used to evaluate most of the experimental imperfections. As a typical example the manual operation of the interferometer may cause a small misalignment of the these two facing waveguides, which could potentially introduce a significant error (should the phase be sensitive to this offset). Furthermore, even if the interferometer parts are totally fixed, the filament itself often bends to one side. All these deviations (and more) are included in the numerical study.

Fortunately, the results in Fig. 4 show, that these common alignment errors are not critical and the phase significantly depends only on the plasma filament diameter and permittivity.

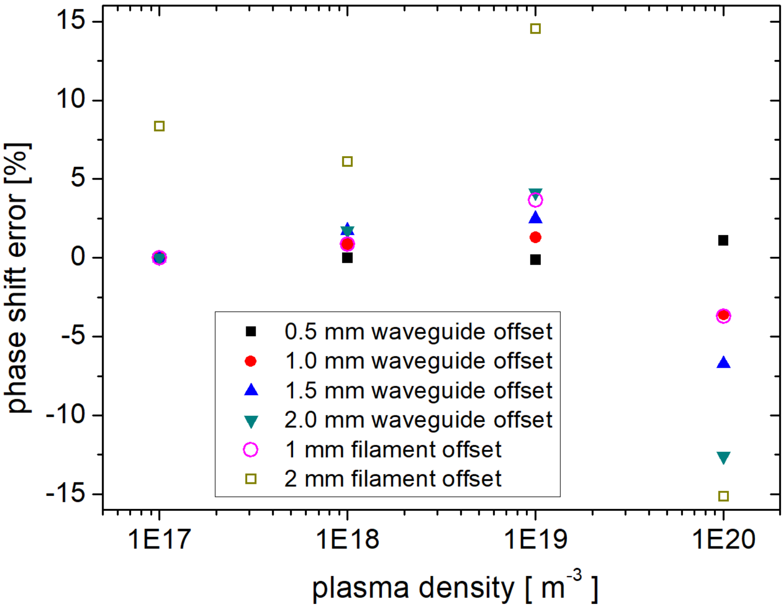

Figure 4: *The plasma induced phase shift as a function of waveguide and plasma filament lateral offset*

Conclusions

The diagnostics of microwave torch plasma via the numerically enhanced microwave interferometry was succesfully carried out. The obtained results (order of magnitude 10^{20}) are in agreement with plasma densities common to the atmospheric torch discharge. The experimental data also identify two main challenges for our further work - the mechanical precision improvement (better anchoring of the waveguides) and the elimination of heating effects from the measurement (more effective and precise approach).

Acknowledgement

This work was supported by The Czech Science Foundation (GA CR) under grant 18-08520S and by Ministry of Education, Youth and Sports of Czech Republic by the project LO1411 (NPU I).

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