Modelling of microwave-driven micro-plasmas in HCPCF

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The paper presents simulations of micro-driven argon micro-plasmas filling Hollow-Core Photonic Crystal Fibers (HCPCFs). The one-dimensional (radial) stationary model solves the fluid transport equations for electrons and positive ions, the electron mean energy transport equations, Poisson's and Maxwell's equations for the fields and the gas energy balance equation, coupled to the electron Boltzmann equation for the calculation of the relevant electron parameters. Results are obtained and discussed for various pressures (1 mbar – 3 bar) and internal waveguide radii (25 – 200 μm).

During the past few years, research on the development of compact, low-cost and high efficiency ultraviolet (UV) sources has been thriving. The most common UV sources widely used in industry are the excimers lasers based on the electrical discharge of a gas mixture. However, the latter are known for their intrinsic drawbacks making them unsuitable to the emerging industrial of miniaturization and ease of maintenance. As an alternative solution, we propose transposing conventional UV gas sources to the world of optical fibres. The scheme relies on Hollow-Core Photonic Crystal Fibre (HCPCF) [1] and capitalises on its light-guiding in air to insert and confine a gas mixture into the hollow-core.

In particular, we are developing and studying an UV source based on microwave-driven micro-plasmas filling a HCPCF (see Figure 1) [2]. The source exhibits an unprecedented compactness, flexibility, low-cost and high conversion efficiency, as demonstrated by: (i) an ionisation degree 10 times higher than that obtained with conventional dc excitation and less sensitive to charge accumulation; (ii) a free fibre-end for an easy optical access; (iii) a multi-feature action, both as a frequency filter through a tailorable transmission window (selection of narrow and stable emission lines from the excited gas mixture filling the hollow-core) and a spatial modal filter via a phase-matching of the guided micro-plasma and optical mode.

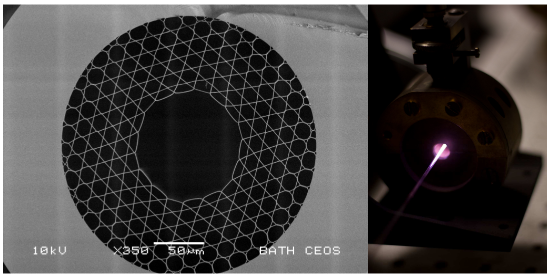

Fig. 1: Example of the cross-section of the HCPCF used during experiments (left) and image of the Ar micro-plasma created (right).

The micro-plasma ($n_e \sim 10^{16}$ cm^{-3} electron density, estimated by electromagnetic calculations) is produced by a surface-wave (SW) discharge (running at 2.45 GHz frequency) in argon, at p ~ 0.1 bar gas pressure and $T_g \sim$ 1000-1400 K gas temperatures (measured by optical emission spectroscopy diagnostics). Our first approach to simulate this system replaces the cladding structure (air-holes region) by a capillary cylindrical quartz tube (r_1 = 25-200 μm radii). Simulations use an one-dimensional (radial) stationary fluid-type code solving, in a self-consistent way, the continuity and the momentum transfer equations for electrons and positive ions, the electron mean energy transport equations, Poisson's equation for the space-charge electrostatic field, Maxwell's equations for the SWelectromagnetic field and the gas energy balance equation [3,4]. The description of the wave-plasma energy coupling uses the SW attenuation constant (obtained either as an eigenvalue to

Maxwell's equations or from the electron power balance equation) to check for the physical coherence of model results [3]. The model is solved coupled to the kinetic electron Boltzmann equation (homogeneous and stationary, written in its classical two-term approximation), considering inelastic collision processes with ~ 40 excited states of argon, as well as electron-electron collisions. The resulting electron energy distribution function is used to calculate the electron transport parameters and rate coefficients required by the fluid code, with a spatial dependence introduced by the local mean energy approximation [3,4].

Figure 2 shows the profiles, as a function of the normalized radius r/r_1, of the plasma electron and ion densities and of the electron mean energy and the plasma potential. One observes the formation of a thin space-charge Debye sheath (extending over 4% only of the discharge radius), associated with a potential drop that roughly corresponds to five times the electron mean energy (~20 V). This sharp variation of the potential leads to an electrostatic space-charge field about 10^3 times higher than the microwave electric field. Notice, however, that these results are extremely dependent on the discharge radius and the gas pressure.

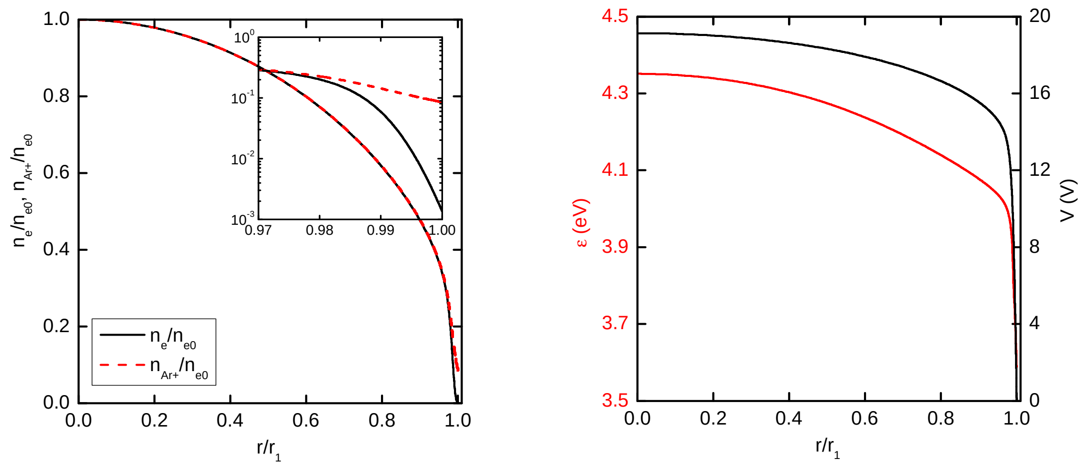

Fig. 2: Radial profiles, as a function of the normalized radius r/r_1, of the following quantities: left, the charged particle densities (electrons, solid curve; ions, dashed curve). The inset is just a zoom of this figure over the space-charge sheath region; right, the electron mean energy (red curve) and the plasma potential (black). Typical results obtained for r_1 = 50 µm, $n_e = 1.2\mathrm{x}10^{16}$ cm^{-3}, p = 0.1 bar and T_g = 1000 K.

The paper will show also the populations of the main excited states with argon, calculated by coupling a collisional-radiative model to the discharge code. This upgrade will allow obtaining predictions about the radiation emitted by the plasma before to be propagated through the HCPCF.

Acknowledgements

Work partially supported by the French ANR program and the French DGA under contract ASTRID-2011-UVfactor. Work partially supported by the Portuguese FCT under the contract of Associated Laboratory IPFN/IST.

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