Generation of plasmas in 100 μm core diameter capillaries using a microwave excitation based on a surfatron

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Argon microplasmas have been generated at low pressure (1 mbar – 3 bar range) in quartz capillaries down to 100 μm core diameter using a microwave excitation based on a surfatron. The latter enables the propagation of an azimutally homogeneous (m=0 mode) surface wave along the external dielectric surface of the capillary and the generation of a few centimeters long plasma inside the hollow core of the capillary. Electromagnetic simulations coupled to wave propagation simulations enabled to optimize the surfatron structure and to find optimal conditions for the ignition of such microplasmas. Optical emission spectroscopy measurements put into evidence high degree of ionization.

The development of compact, cheap and flexible sources emitting in the ultraviolet (UV) range is yet a considerable challenge to satisfy needs like waste water decontamination, skin illness treatment or wavelength conversion through nonlinear optical processes in the deep UV. In order to satisfy these needs we proposed an original solution to create a microplasma directly in a gas-filled capillary based on a microwave excitation system using a surfatron. The undeniable advantages of this solution are the lack of electrodes to initiate the microplasma and the ionization rate which is higher than that obtained with a DC excitation set-up. Moreover, it must be underlined that no access is required to the capillary ends.
We were the first to achieve experimental demonstration of stable and robust microwave microplasmas built up and sustained in gas-filled capillaries with 100 μm core diameter [1-2]. In the present work, we present new steps in the simulation and in the characterisation of the system, in order to understand the physics involved in the generation of such microplasmas.

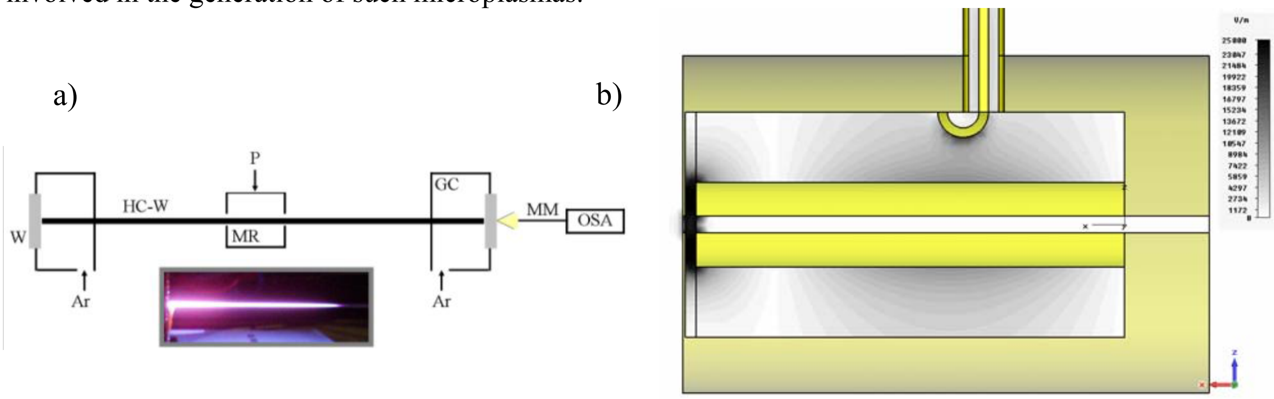

Fig. 1: a) Experimental set-up: W: glass window, Ar: gas supply, HC-W: capillary (L = 60 cm), P: microwave power, MR: microwave excitation device, GC: gas chamber, MM: multimode fiber, OSA: optical spectrum analyser. Inset: image of a microplasma column sustained in the Φ = 100 μm Ar-filled capillary. b) Zoom of the surfatron device, with electric fields calculated by solving Maxwell equations.

The microwave excitation device used in the experiment is a surfatron operating at 2.45 GHz with a 200W generator. This microwave resonator enables to obtain a very efficient microwave energy coupling to the gas (close to 90%). It is a re-entrant cavity consisting of a resonant coaxial structure whose inner metallic part ends at one side before the end of the cavity, creating then a gap which induces very high azimutally homogeneous electric fields (see Fig. 1b). The latter enable the propagation of an azimutally homogeneous (m=0 mode) surface wave along the external dielectric surface of the capillary inserted in the center of the microwave resonator (see Fig.1a) and the generation of a few centimeters long plasma inside the hollow core of the capillary filled with a gas (using only a few tens of Watt). Electromagnetic simulations coupled to wave propagation simulations enabled to optimize the surfatron structure and dimensions and to find optimal conditions for the ignition of such microplasmas.

Considering a radially homogeneous plasma, phase curves (evolution of the wave attenuation α and the wave number β as a function of electron density n_e, for a given frequency, 2.45 GHz here) have been calculated (see Fig.2). The power absorbed by the plasma per length unit dP/dx, is equal on the one hand to the power lost by the wave, $2\alpha(x)\times P_{inc}$, and on the other hand to the power required to maintain electrons in the discharge, $\theta\times n_e(x)\times S$, where S is the plasma section. It can be shown that $d(n_e)/dx=-2\alpha(x)n_e / (1 - (n_e/\alpha(x)) \times d\alpha(x)/dn_e)$. Beginning at the end of the plasma column, and assuming that the corresponding n_e value on the phase curve corresponds to $\alpha=\beta$, we can use the $d(n_e)/dx$ law with the simulated $\alpha(n_e)$ phase curve (and its derived $d\alpha(x)/dn_e$ curve) and then simulate a theoretical evolution of the electron density as a function of the plasma length x. Considering the experimental plasma length obtained for a given experimental power, we can then estimate a theoretical $n_e(x)$ plasma density profile. For our Φ=100 µm plasma diameter case, we obtained maximum electron density values at the gap of the order of a few 10^{15} cm^{-3}.

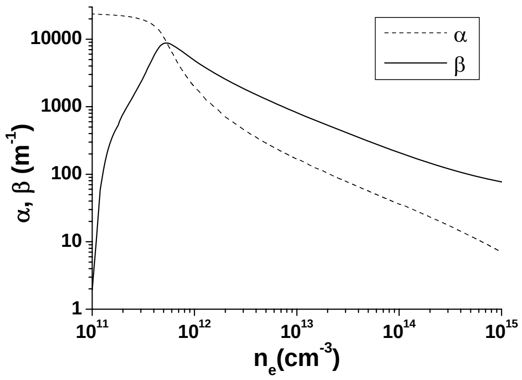

Fig. 2: Phase curve calculated for a Φ=100 µm capillary at 2.45 GHz for an homogeneous plasma density n_e with a $\nu = 5\times10^9$ s^{-1} electron-neutral collision frequency.

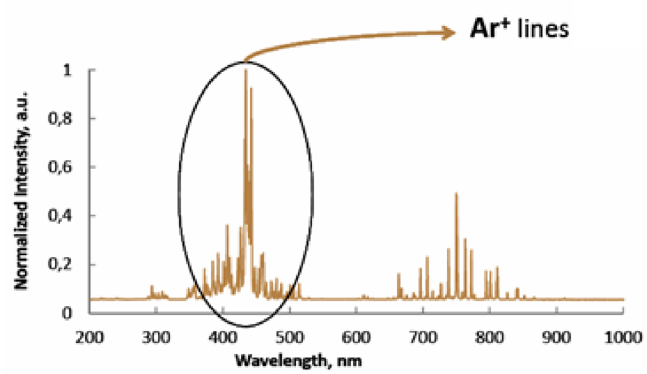

Fig. 3: Measured glow-discharge spectrum emitted by the microplasma column created in an Φ=100 µm Ar-filled capillary.

Moreover, optical spectroscopy measurements performed in the plasma axis direction through the glass window in the gas chamber (see Fig.1a) enabled to put into evidence the high degree of ionization reached in the plasma, as it can be seen on Fig.3, with very strong Ar+ emission lines (λ=457.8, 476.5, 488 nm …).
An additional measurement based on the spectroscopic study of the OH rotational band (present as impurities) coupled to a spectroscopic simulation software allowed us to estimate the plasma temperature nearly to 1400 K, which has been confirmed by a thermal simulation.

Our original way based on the use of a surfatron device for the ignition of stable and efficient microwave microplasmas down to 100 µm core diameter Ar-filled capillaries enabled to create an UV light source directly inside the capillary. It must be noted that other UV lines may be generated by changing the gas. Moreover, we plan to perform electron density measurements in the plasma, in order to compare the coherence of the experimental plasma length observed for a given input microwave power, and the one obtained from the combination of our propagation code and the axial power dissipation law.

[1] B. Debord, R. Jamier, F. Gérôme, C. Boisse-Laporte, P. Leprince, O. Leroy, J.-M. Blondy, F. Benabid, *International Workshop on Microplasmas (IWM6)*, Paris - France (2011).
[2] B. Debord, R. Jamier, F. Gérôme, C. Boisse-Laporte, P. Leprince, O. Leroy, J.-M. Blondy, F. Benabid, *CLEO*, Baltimore – Maryland – USA (2011).