Modulation-Induced Filament Tearing in Microwave Atmospheric Plasma Jet

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***Abstract*— A typical 1-D surface wave discharge reacts to varying power by changing its length. If the temporal change of incident power is high, the discharge column may not react sufficiently fast. The effect is demonstrated by high resolution images of plasma plume tearing-off during rapid power decrease in amplitude modulated microwave argon jet.**

***Index Terms*— Atmospheric-pressure plasmas, plasma diagnostics.**

LOW temperature plasmas of atmospheric pressure discharges are widely used in various technological applications, such as plasma surface modification, activation, sterilization, plasma-enhanced chemical vapor deposition of thin films, or plasma assisted destruction of toxic compounds. Discharges operated using pulsed or modulated power are of considerable interest for both fundamental and applied research. They can have simultaneously higher active particle density and lower gas temperature than the continuous wave (CW) plasma at the same mean power. These practical advantages of modulated microwave jet were used, e.g., in our recent work [1].

The atmospheric pressure plasmas in heavy noble gases often exhibit substantial radial contraction of the plasma channel. This effect may negatively influence the homogeneity in some applications. This problem can be overcome by adding molecular admixture, which promotes diffusive, non-contracted character of the plasma. Recently [2], [3], it was found that filamentary nature, typical for the argon jet, can be easily affected by small variations in experimental conditions, namely power and gas flow. In this way, the plasma inhomogeneity can be partly compensated by an optimization of temporal delocalization of the filament(s). In this paper, we report on transient phenomena in power modulated microwave jet.

The nonthermal microwave plasma jet excited in SAIREM Surfatron 80 is operated in argon at atmospheric pressure. The microwave generator SAIREM GMP 20 KED (2.45 GHz, 0–2 kW) is amplitude modulated (AM) by function generator. Rectangular AM envelope (150 W in minimum, 350 W in maximum, duty cycle 1:1, 250 W mean power) with frequency 265 Hz is used in this paper. The argon plasma is excited in a fused silica capillary with inner diameter of 1.5 and 4 mm outer diameter by high electric field in the surfatron [4] launching gap. The capillary ends 25 mm from the launching gap and the plasma column extends $\sim$1 cm outside the capillary end into the surrounding atmosphere. The argon flow of 1.45 slm is maintained by the mass flow controller. The surfatron body is cooled by water and the discharge tube by a compressed air flowing around it.

The tip of the active discharge is imaged by digital single lens reflex camera Nikon D3100 with objective Nikon 55–300 mm f/4.5-5.6G AF-S DX VR set to maximal zoom from 1.2 m distance. The gain is set to ISO 3200 in order to achieve good signal at shortest exposure times.

In CW operation, the plasma exhibits typical argon filamentary structure. Depending on incident power and gas flow, the filaments are either straight and colinear with capillary axis or they are helically twisting around its inner diameter [2], [3].

After switching on the AM, this filamentary structure visually disappeared as the discharge appeared filling the whole capillary cross section. Therefore, a short exposure imaging was carried out to prove if the filaments really disappear and the plasma becomes diffusive. Fig. 1(a) and (c) shows that at certain instants the discharge is still filamentary. The filaments tend to wind around the inner wall of the capillary, which is typical for locked modes described in [2] and [3]. Vice versa, Fig. 1(b) and (d) suggests that the plasma can be really diffusive, at least when imaged with 250 μs exposure time.

In Fig. 1(b), one can observe that part of the plasma column is tearing-off. It is visually similar to plasma bullet [5]. However, detailed electric measurements would be needed for the confirmation. This happens during the falling edge of modulation envelope, when the incident power rapidly decreases. The surface wave discharge reacts to lowering power by shortening its length. However, it seems that the tip of the plasma column is not able to retract quickly enough and the tearing-off takes place. This separated plasma plume then lives for a certain time and even after, its residual ionization helps in a propagation of the plasma during the rising part of AM envelope. The twisting of the filaments continues in the separated plasma plume as it exhibits strongly helical appearance.

Fig. 1(c) demonstrates strongly localized inhomogeneities—in the filament tips, the argon is radiating, whereas in-between them, the nitrogen from the surrounding air is excited. To decide, if it is inhomogeneity in gas composition or an inhomogeneity in electron energy distribution function, more research is needed.

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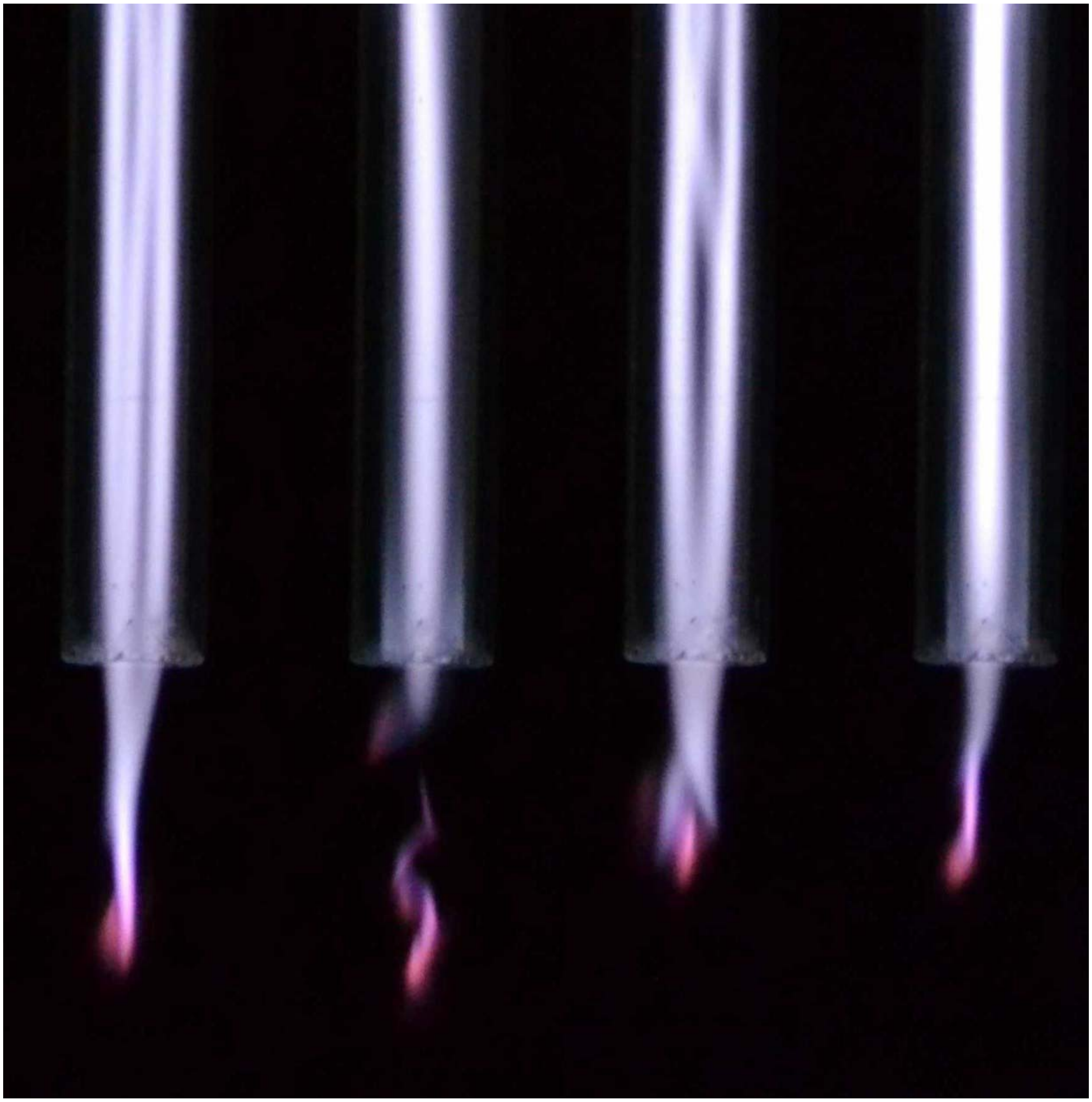

(a) (b) (c) (d)

Fig. 1. Side view of the tip of the microwave plasma jet in argon with AM input power (265-Hz AM frequency, rectangular envelope-150 W in minimum, 350 W in maximum, and duty cycle 1:1). Exposure time 250 μs, ISO 3200. Sequence of the images was taken in different phases of the modulation envelope [(a) = 1 ms, (b) = 2 ms, (c) = 3 ms, and (d) = 4 ms]. At the falling edge of envelope (second image from the left), the plasma plume end separates from the bulk plasma.

In conclusion, the photographs demonstrate plasma column tearing-off caused by the rapid decrease of the incident power during the AM. This phenomenon has been typically described as taking place in submicrosecond timescales. However, we observe it for modulation frequency of 265 Hz.

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