Spatially resolved and phase synchronized optical diagnostics of power modulated plasma jet

L. Potočňáková[1], J. Voráč[1], P. Synek[1, 2], J. Hnilica[1] and V. Kudrle[1]

[1] *Masaryk University, Faculty of Science, Department of Physical Electronics, Kotlářská 2, CZ-611 3 Brno, Czech Republic*

[2] *The Central European Institute of Technology (CEITEC), Masaryk University, Kamenice 5, CZ-62500, Brno, Czech Republic*

In this work, phase synchronized ICCD imaging of power modulated microwave plasma jet operating at atmospheric pressure was performed. The overall plasma effluent appearance and flow dynamics were found to be strongly influenced by the modulation frequency, mostly through the formation of a vortex at the boundary of expanding hot plasma channel and cold surrounding atmosphere.

1. Introduction

Atmospheric pressure plasma jets are well known and suitable for many applications [1]. They are often operated in pulsed or modulated regime, which can provide further advantages over continuous wave regime. Particularly, it is the ability to achieve higher active particle density at the same mean excitation power or significantly lower thermal loading of the substrate for the same treatment rate. These effects can be attributed to a non-linear relation between the supplied power, electron temperature and gas temperature. In our previous studies [2, 3], we demonstrated the application potential of microwave plasma jet with power modulated by sinusoidal wave.

The pulsed and modulated discharges are of great interest also for the fundamental plasma physics research, as they represent a suitable experimental tool for the study of the plasma kinetics [4, 5]. In this work we used optical examination of modulated discharge to study the non-stationary gas flow phenomena and the distribution of excited species in the discharge and its vicinity.

2. Experimental setup

As a plasma source, the atmospheric pressure microwave plasma jet - surfatron [6] - was used. The plasma was excited inside the fused silica discharge tube (2 mm inner diameter, 4 mm outer one) in argon with 2600 ppm(v) of water vapour by the surface wave propagating along the interface between the plasma and the dielectric tube wall. As for other discharges with surface wave, also the surfatron plasma exhibits typical elongated plasma form with slow decrease of the plasma density towards the discharge tube end. The discharge tube was open into outer atmosphere, where the plasma effluent mixed with air and where a possible material treatment would take place. This plasma plume was the main focus of our attention in this research.

Power to the surfatron was supplied by microwave (2.45 GHz) generator in amplitude modulated (AM) mode, for which sinusoidal envelope (modulation frequencies 90 Hz and 1710 Hz, 150 W in minimum and 300 W in maximum) was used. The discharge was observed by ICCD camera, either directly (covering UV-VIS-NIR range) or through suitable bandpass filters. For phase synchronized measurements, the camera was triggered by the function generator used for modulation of the power generator.

3. Results

In Fig. 1, the time averaged (200 single shots of 10 μs each) image of the discharge at (a) 90 Hz and (c) 1710 Hz can be seen. The trigger delay was set to observe the discharge in the rising part of the sinusoidal modulation period. Comparing the images for the two frequencies, several features can be discussed. While the plasma effluent at lower AM frequency has rather regular shape of a plume, a transient vortex [7] is formed for higher frequency. The temporal instability, i.e. fluctuation of the discharge is visualized in Fig. 1 (b) and (d) through the relative standard deviation. The lower part of the discharge part (close to the tube exit, where the gas flow is laminar) is quite stable for both frequencies. For 90 Hz, the deviations are mostly present only around the very end of the discharge, but for 1710 Hz they appear to be significant in the whole area from the vortex structure to the plasma jet tip.

The absence/presence of the vortex and its development can be recognized also in Fig. 2.

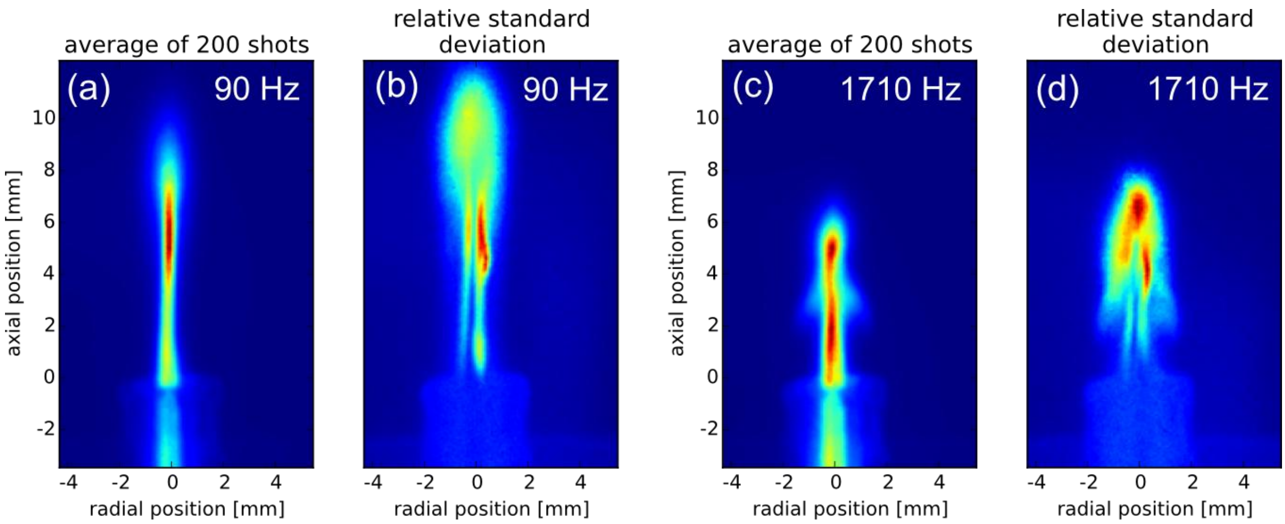

Fig. 1: The time averaged images of the discharge during the rising slope of sinusoidal AM modulation at (a) 90 Hz and (c) 1710 Hz and corresponding relative standard deviations ((b) and (d)).

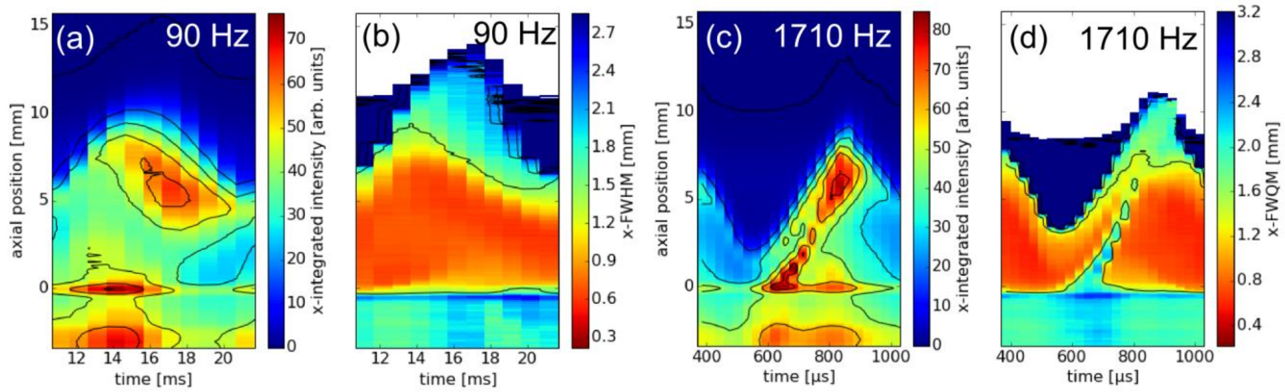

Fig 2. (a) and (c) - axially resolved time evolution of laterally integrated intensity of the discharge for one period of sinusoidal modulation at 90 Hz and 1710 Hz and (b) and (d) - corresponding full width of the discharge at quarter maximum of its intensity.

In Fig. 2 (a) and (c), there is an axially resolved time evolution of laterally integrated intensity of the discharge. For both frequencies, the length of the discharge follows the sinusoidal modulation, but even though the power setting was the same for both AM frequencies, the discharge was longer for 90 Hz, especially in the power minimum. The emission is not axially homogeneous as local emission maximum can be observed in the effluent. It is best visible during the decreasing power (i.e. decreasing length of the discharge) at 90 Hz while for 1710 Hz it happens when the discharge elongates. In Fig. 2 (b) and (d), the width of the discharge is shown. For 90 Hz, no unexpected evolution can be found – the discharge is the widest at the end, where it is more turbulent. For 1710 Hz, the movement of the vortex is clearly recognizable in the Fig. 2 (d) as the narrow strip of locally widened discharge channel. It starts shortly after the minimum elongation of the discharge and can be traced up to the turbulent tip of the discharge.

Using various bandpass spectral filters, it was found out that the vortex is emitting the strongest at wavelengths around 307 nm corresponding to the OH radical. Although there was a water vapour intentionally added into argon, this result suggests that the vortex is probably formed due to interaction of the discharge with the surrounding air atmosphere. As it was not observed for 90 Hz, the vortex presumably originates in faster gas heating during the steeper rising slope of the AM envelope at 1710 Hz. The friction between the rapidly accelerating hot plasma and cold environment would then result in the annular vortex encircling the plasma channel.

The increased rate of air mixed into the argon discharge in the presence of the vortex might be one of the reasons, why the stronger quenching and shortening of the discharge was observed for higher AM frequency. On the other hand, such effect might be advantageous for higher efficiency of the surface plasma treatment by pulsed or modulated discharges. Thanks to the vortex, more airborne reactive species such as OH or NO_x radicals, crucial for various kinds of treatment, can be produced. In case of plasma deposition, where some precursor is deliberately admixed into the discharge, the existence of vortex causes more turbulent behaviour, better mixing and better homogeneity, which might be strongly beneficial, too.

4. Conclusion

Atmospheric pressure microwave plasma jet with sinusoidal power modulation at two modulation frequencies was studied by means of the phase synchronized ICCD camera imaging. The discharge was found to have a different shape and length for different modulation frequencies and in different modulation phases. The main distinction between the AM frequencies was the formation of transient vortex for higher frequency. The vortex probably originates in the friction between rapidly expanding hot plasma channel during the rising modulation slope and the cold surrounding environment. The presence of the vortex negatively influences the plasma itself but might be very useful for applications, where mixing of plasma with air or precursors is needed.

5. Acknowledgement

This work was supported by the project CZ.1.05/2.1.00/03.0086 funded by European Regional Development Fund, project LO1411 (NPU I) funded by Czech Ministry of Education, Youth and Sports and the project TE02000011 funded by Technological Agency of Czech Republic.

6. References

[1] M. Laroussi, T. Akan, *Plasma Processes and Polymers* **4** (2007) 9

[2] L. Potočňáková, J. Hnilica, V. Kudrle, *International Journal of Adhesion and Adhesives* **45** (2013)

[3] J. Hnilica, L. Potočňáková, M. Stupavská, V. Kudrle, *Applied Surface Science* **288** (2014)

[4] St. Behle, A Brockhaus, J Engemann, *Plasma Sources Science and Technology* **9** (2000) 1

[5] N. Britun, T. Godfroid, S. Konstantinidis, R. Snyders *Applied Physics Letters* **94** (2011) 14

[6] M. Moisan, C. Beaudry, P. Leprince, *Physical Letters A* **50** (1974)

[7] S. Zhang, A. Sobota, E.M. van Veldhuizen, P.J. Bruggeman, *J. Phys. D:Appl. Phys.* **48** (2015)