Spatial distribution of emission spectra of microwave torch plasma in atmospheric nitrogen

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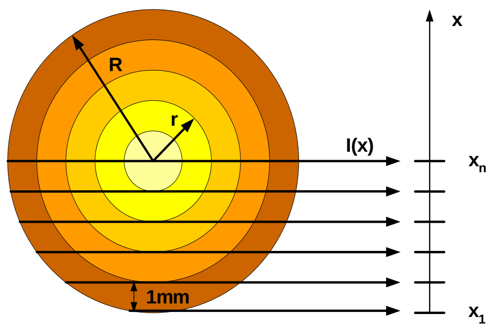
Abstract
We present spatial distribution of emission spectra of microwave (MW) plasma generated by Litmas Red MW torch (2.45 GHz, 3 kW) in nitrogen. We employ optical emission spectroscopy (OES) as a main diagnostic tool. We measured spectra from various distances from the plasma axis and analyzed horizontal profiles of plasma emission after Abel inversion. We mostly observed NO, N_2^+ and CN spectra. From the measured and the Abel-inverted horizontal profiles we found out that the emissivity decreased with increasing distance from the plasma axis. Emissivity also decreased with increasing height, but the shape of the profiles was kept.

Introduction
Atmospheric pressure MW plasmas present considerable interest for a wide range of applications, such as air pollution control, surface treatment, or carbon nanotube growth [1].
MW torch generates plasma close to Local Thermodynamic Equilibrium (LTE) conditions. In our previous works [2] we investigated the basic characteristics of atmospheric pressure MW nitrogen plasma torch. Here we present spatial distribution of generated MW plasma emission. After adapting the optical bench for vertical and horizontal movement, we record spectra from various positions from the plasma axis and we analyze Abel-inverted horizontal profiles to get the information on the spatial plasma distribution.

Abel inversion
Microwave torch plasma is a cylindrically symmetric light source of certain thickness. This is why, when recording the emission spectra, we get the spectrum integrated along the whole plasma diameter (line-integrated spectrum) and not a spectrum from one specific point. This leads to incorrect measurements of the light intensity, which seems to be stronger than it really is. Abel inversion (Fig.1) allows us to transform the measured line-integrated light intensity I(x) into the radial emissivity e(r).



$$I(x) = 2\int_r^R \frac{re(r)}{\sqrt{r^2 - x^2}}dr \qquad e(r) = \frac{1}{\pi}\int_r^R \frac{dI/dx}{\sqrt{x^2 - r^2}}dx$$

Figure 1. Abel inversion.

Experimental setup
Litmas Red MW plasma torch powered by a 5 kW magnetron, supplied from special power generator, (Fig. 2) was used to generate atmospheric pressure nitrogen plasma with properties close to LTE. The magnetron has a maximum power output of 3 kW. The torch is able to generate plasmas in the temperature range of 1000-5000 K.

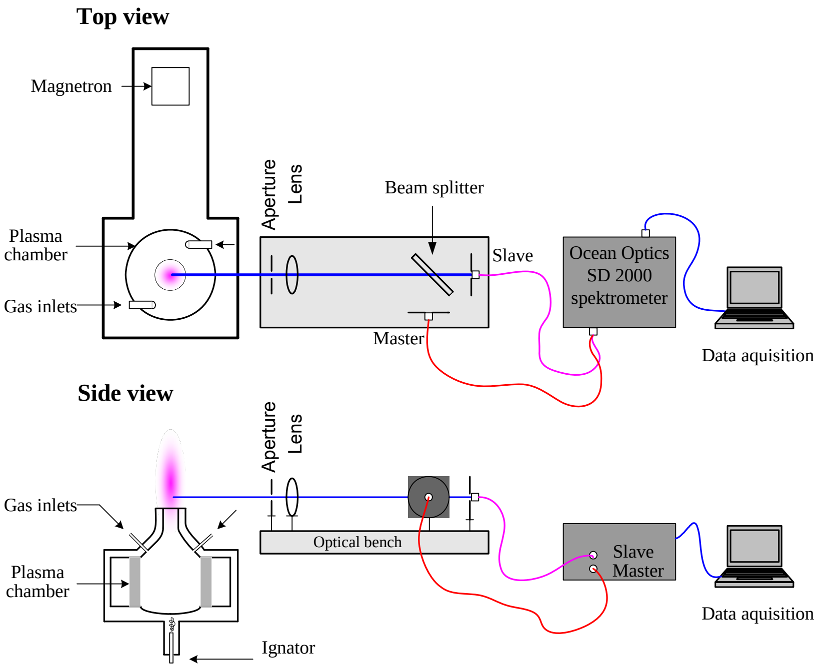


Figure 2. Experimental setup.

Microwaves generated by magnetron are focused to the cylindrical plasma chamber made of a hardened teflon or Al_2O_3. The MW discharge is ignited by pneumatic insertion of a metal ignator into the plasma chamber. The brush-shaped ignator (synchronized with microwaves from the magnetron through the electronic unit) causes a local enhancement of the electric field resulting in a discharge ignition. The whole system is externally cooled with water and air. Contrary to the typical MW torch systems [3], in our case the gas is inserted downstream and tangentially through the two holes of the nozzle into the cylindrical plasma chamber. This is causing the swirl flow in the cylinder and generated swirling plasma is consequently blown out upstream through the central orifice of the nozzle. Blown out plasma is then analyzed by optical emission spectroscopy. Emitted light is guided through the optical bench containing an aperture, a fused silica lens and a beam-splitter positioned at 45° to divide the light beam to enter the two optical fibres of the Ocean Optics SD2000 spectrometer – Master which covers the spectral range of 200-500 nm and Slave 500-1100 nm. The optical bench is movable horizontally as well as vertically. Experimental setup and the basic torch characteristics are described in more detail in [2].

Measured spectra

We identified emission of N_2 molecules, N_2^+ ions and NO and CN radicals in the emission spectra (Fig. 3).

Strong emissivity of N_2^+ (B-X) compared to N_2 (C-B) transition was confusing at the first sight, because ionization process of N_2 requires more energy than excitation of N_2 to its C state. That is why we expected N_2 (C) state to be more populated than N_2^+ (B) state, but in this case the N_2 (C-B) emissivity would be stronger than that of N_2^+ (B-X). In addition, the N_2^+ (B) is not supposed to be formed by electron excitation, because generated plasma most probably does not contain electrons with such high energies as needed for this process (~19 eV). Possible explanation was found in Boudam et al. [4]. This paper considers these reactions as the most probable way of the formation of N_2^+ (B) state:

$$N_2\,(X,\,\nu>15) + N_2\,(X,\,\nu>15) \rightarrow N_2(a') + N_2\,(X,\,\nu)$$

where $N_2(X)$ is a ground electronic state of N_2 molecule and ν is its vibrational quantum number, $N_2(a')$ is metastable state of N_2 molecule. Then

$$N_2(a') + N_2(a') \rightarrow e + N_2^+(X) + N_2$$

which is called chemi-ionization process. Finally

$N_2^+(X) + N_2 (X, \nu>11) \rightarrow N_2^+ (B) + N_2 (X)$.

We assume that in our case this way of generation of N_2^+ (B) can be involved, which would explain the paradoxical ratio of the emissivity of N_2^+ (B-X) and N_2 (C-B) transitions.

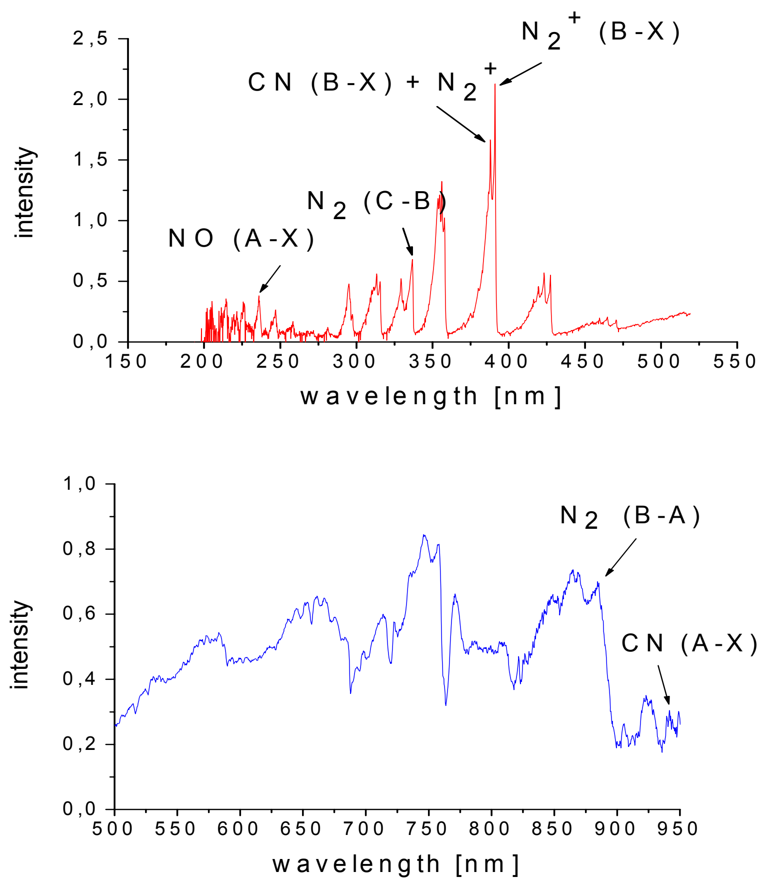


Figure 3. Measured spectra in UV and VIS region.

Spatial distribution of emission spectra of microwave nitrogen plasma

Horizontal profiles in various heights were needed for the spatial distribution. The experiments were carried out at 15 l/min flow rate and 1.46 kW magnetron power. The plasma temperature at these parameters, determined as the rotational temperature by comparing experimental and simulated (LIFBASE) CN spectra, was 4000±500K [2]. We measured the emission intensities in various positions from the plasma axis. The spacing between 2 points was 1 mm. We applied Abel inversion to these horizontal profiles. Abel-inverted horizontal profiles are presented in fig. 4-5. Units for the measured intensity I(x) and Abel-inverted emissivity e(r) are: $\mu W.mm^{-2}.nm^{-1}.sr^{-1}$ and $\mu W.mm^{-3}.nm^{-1}.sr^{-1}$, respectively. We express the intensity in absolute units because the optical system was calibrated with optical standards: W and D lamps.

Thanks to the cylindricaly symmetric shape of the plasma (which is a condition for Abel inversion) we show just one half of the profiles (Fig. 4). In the case of NOγ emission, the profile was not symmetric (Fig. 5) so both halves are shown. We expected the strongest emission of NO to be at the edge of the plasma, where heated nitrogen gets to the contact with surrounding air and reacts with O_2, which leads to the formation of NO. It was shown that the maximal emissivity is in the certain distance from the plasma axis and not at the plasma edge. The explanation is that the plasma was not ideally symmetric, but it could be spiral-twisted. This would also explain why the maximum of emissivity was not at the same distance from the plasma axis in various heights (h).

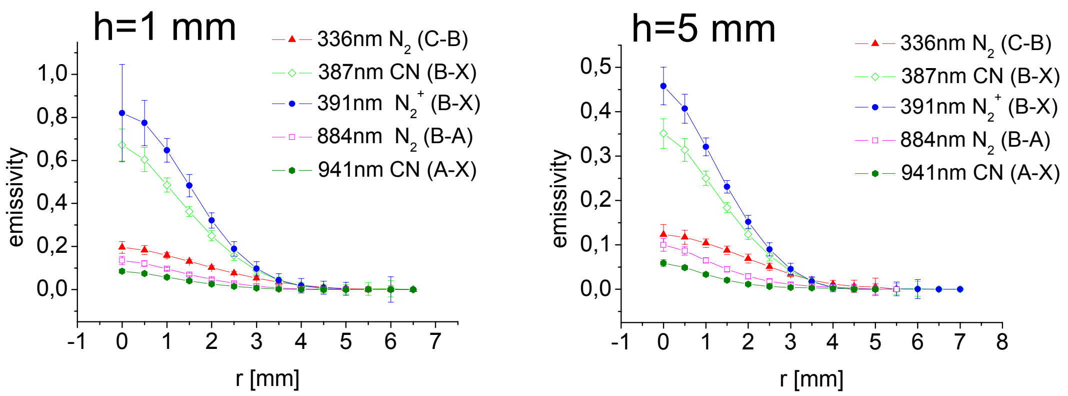


Figure 4. Abel-inverted horizontal profiles in h=1 mm and h=5 mm.

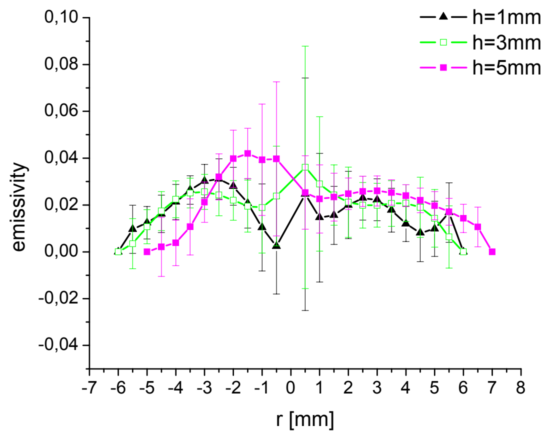


Figure 5. Abel-inverted horizontal profiles of NOγ.

Summary and perspectives

We investigated spatial distribution of emission spectra of microwave N_2 plasma at atmospheric pressure. OES was used as a main diagnostic method. We recorded the spectra in various distances from the plasma axis and in various heights and analyzed Abel-inverted horizontal profiles.

Emission of N_2, N_2^+ NO, and CN radicals was identified. Confusing strong emissivity of N_2^+ (B-X) relatively to N_2 (C-B) transition was explained by other way of formation of N_2^+ (B) state than electron excitation. Measured and Abel-inverted horizontal profiles showed that emissivity decreases with increasing distance from the plasma axis (except for the NOγ transition). In this case the maximum emissivity at certain distance from the plasma axis (not at its edge) was explained by the asymmetric plasma shape. Emissivity also decreases with an increasing height. In the future we plan further investigations of emission spectra distribution and behaviour of the involved species.

Acknowledgments

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