Laser schlieren deflectometry for temperature analysis of filamentary non-thermal atmospheric pressure plasma

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The heat convection generated by micro filaments of a self-organized non-thermal atmospheric pressure plasma jet in Ar is characterized by employing laser schlieren deflectometry (LSD). It is demonstrated as a proof of principle, that the spatial and temporal changes of the refractive index n in the optical beam path related to the neutral gas temperature of the plasma jet can be monitored and evaluated simultaneously. The refraction of a laser beam in a high gradient field of $n(r)$ with cylindrical symmetry is given for a general real refraction index profile. However, the usually applied Abel approach represents an ill-posed problem and in particular for this plasma configuration. A simple analytical model is proposed in order to minimize the statistical error. Based on that, the temperature profile, specifically the absolute temperature in the filament core, the FWHM, and the frequencies of the collective filament dynamics are obtained for non-stationary conditions. For a gas temperature of 700 K inside the filament, the presented model predicts maximum deflection angles of the laser beam of 0.3 mrad which is in accordance to the experimental results obtained with LSD. Furthermore, the experimentally obtained FWHM of the temperature profile produced by the filament at the end of capillary is (1.5 ± 0.2) mm, which is about 10 times wider than the visual radius of the filament. The obtained maximum temperature in the effluent is (450 ± 30) K and is in consistence with results of other techniques. The study demonstrates that LSD represents a useful low-cost method for monitoring the spatiotemporal behaviour of microdischarges and allows to uncover their dynamic characteristics, e.g., the temperature profile even for challenging diagnostic conditions such as moving thin discharge filaments. The method is not restricted to the miniaturized and self-organized plasma studied here. Instead, it can be readily applied to other configurations that produce measurable gradients of refractive index by local gas heating and opens new diagnostics prospects particularly for microplasmas. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4761924>]

I. INTRODUCTION

Atmospheric pressure plasma discharges are widely used for different technological applications like surface modification, PECVD of thin films, decontamination, or plasma medicine.^{1–4} For the process optimization and control, the discharge properties should be determined precisely. Especially, temperature conditions play an important role for the kinetic reactions inside the plasma and for the general energy balance of the system.⁵ However, these can be difficult to discover due to the filamentary character of most non-thermal atmospheric plasmas. The contracted filaments often exhibit sub-millimeter dimensions and the estimation of radial temperature profiles is a subject of advanced approaches like fluid modeling,^{6,7} or highly resolved spectroscopy, or interferometry.^{8,9} Other experimental methods consider an interaction between the plasma and a calorimetric probe,¹⁰ but they lose information on the locally resolved temperature profile by generating average values. Visualization methods like near-infrared thermography, schlieren monitoring, or rainbow

schlieren deflectometry can solve the spatial characterization, too.^{11–17} However, the information on temperature is mostly only qualitative or ambiguous due to artificial effects. Considering the chaotic regimes of atmospheric plasmas and the complexity of highly resolving methods for temperature measurements, some aspects of local heat processes remain hidden in the micro dimension of time and space.

Up to now, only experiments with arc plasmas or plasmas of larger dimension than sub-millimeter scale of filaments have been found in the literature.^{18,19} A special case is the estimation of a plasma density profile for fusion plasma devices and measuring the laser deflection by phase objects.^{20,21} Previously mentioned methods treat light refraction effects and schlieren measurements mostly qualitatively, although they do report about using Abel's transformation for the diagnostics. However, in these cases, the problem to separate the effects of gas temperature and density of charge particles in the plasma remains unsolved. Also, an enhanced spatial resolution would be desired. Moreover, numerical problems arise from the Abel transformation.

Refraction of the laser beam is an effect of a gradient field inside and outside the microfilament.²² The refraction analysis allows to discuss the temperature profile generated with a filament at a spatial resolution given by the cross section of the

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laser beam (several microns) and a time resolution given by the response time of the photodiode (several ns). The angular deflection is given analytically as an integral transformation of a general refractive index profile with cylindrical symmetry. The question on the refractive index could be answered with a concept that is based on the Abel transformation.²³ However, the accuracy of the solution is obstructed with numerical derivation during data processing. An alternative concept omits the numerical problem of the derivation with an inverse solution for the middle point of the profile.²⁴ But here also, the numerical approach for the integration is required, yet with weakened numerical intricacy. In contrast to this, we suppose an analytical profile of the refractive index, which allows to derive an analytical solution for the deflection angle. The estimation of the profile parameters proceeds by a fitting procedure or by a simple evaluation of the form feature of the measuring signal. Therefore the presented concept can improve the accuracy of the filament investigation in comparison to classic Abel's tomography. In addition, the motion of filaments is detected as well. Therefore, characteristic frequencies of the discharge dynamics can be obtained by a fast Fourier transform (FFT) of the laser spot motion simultaneously, too.

The exemplary proof of refraction analysis is demonstrated on a non-thermal atmospheric pressure plasma jet operating in a self-organized regime.²⁵ The discharge regime of the plasma source is suitable for the task because of a symmetric patterning and regular steady dynamics of the filaments. Plasma parameters and conditions of this jet have been already characterized in a recently published study,⁷ which presents a comparative base for the results of laser schlieren deflectometry (LSD) analysis.

II. THEORY OF BEAM REFRACTION

Let us consider the laser beam refraction in a radially symmetric optical milieu. In this study the refractive index profile of the milieu is only caused by temperature gradients. The fundamentals for the beam trajectory are Fermat's principle of the smallest optical distance or Snell's law.²⁶ Based on this, the general form $\varphi(r)$ of the trajectory can be derived as a function in polar coordinates

$$\varphi = \int \frac{dr}{r \sqrt{\left(\frac{r}{\rho} f\right)^2 - 1}}, \quad (1)$$

where $f = f(r)$ is the profile function. The refractive index is given with $n = n_0 f$, where n_0 is the refractive index of the surrounding. ρ denotes a lateral beam position (Fig. 1). The resulting angular deflection δ of the beam trajectory can be written as follows:

$$\delta = \pi - 2 \int_{r_0}^{\infty} \frac{dr}{r \sqrt{\left(\frac{r}{\rho} f\right)^2 - 1}}, \quad (2)$$

where r_0 is the minimal distance of the laser trajectory from zero.²⁷ The integral transformation in the Eq. (2) represents a dependence $\delta = \delta(\rho)$ and enables formally to reconstruct the

FIG. 1. Scheme of laser beam deflection within the gradient field of the refractive index n caused by an axially symmetric plasma filament. The notation of trajectory parameters used in the equations is shown in the diagram. The trajectory is plotted schematically.

profile f from a measurement of δ inversely by Abel transformation

$$f(x) = \frac{n(x)}{n_0} = \exp \left[\frac{1}{\pi} \int_x^{\infty} \left(\frac{d\delta}{d\rho} - \frac{\delta}{\rho} \right) \sqrt{1 - \left(\frac{x}{\rho} \right)^2} d\rho \right], \quad (3)$$

where $x = f \times r$ (for a large number of experimental conditions in gas $x \cong r$ is a good approximation). The concept of data processing based on Eq. (3) represents an ill-posed problem due to numerical derivatives in the integral. The problem becomes relevant, if the analysis of miniaturized plasma is considered. The accuracy and noise propagation regarding to this problem are published in review.²⁸ The bigger numerical problems can be partially reduced if the reconstruction is restricted to the central value of the profile. For this situation, Eq. (3) gives a simple singular solution at $x = 0$

$$f(0) = \frac{n_1}{n_0} = \exp \left[-\frac{1}{\pi} \int_0^{\infty} \frac{\delta}{\rho} d\rho \right] \cong 1 - \frac{1}{\pi} \int_0^{\infty} \frac{\delta}{\rho} d\rho. \quad (4)$$

Note that despite the elegance of Eq. (4), the value $f(0) = 0.99986$ is reached for usual conditions assumed in the plasma. Therefore, the high magnitude accuracy of 10^{-5} is needed for the estimation of $f(0)$ and for the concept of the Abel's inversion, too.

In this paper, an alternative analytical concept is presented, which does not require advanced numerical techniques. A simple hyperbola-like profile is proposed for the refractive index

$$n = \begin{cases} n_1 & \text{for } r \leq \frac{k}{\Delta n} \\ n_0 - \frac{k}{r} & \text{for } r > \frac{k}{\Delta n}, \end{cases} \quad (5)$$

where n is the refractive index in a surrounding gas, n_0 denotes the refractive index in the central circle – core of the

FIG. 2. Proposed refractive index profile and related temperature profile describing an axial symmetric plasma filament (a). Corresponding deflection angle of a laser beam depending on the impact parameter (b). The absolute value of the deflection rises sharply to a maximum with ρ approaching zero and falls to zero (no deflection) for the exact center of the filament.

filament, $\Delta n = n_0 - n_1$, $r_1 = k/\Delta n$ is the radius of the “filament core” (let us denote the inner circle area of constant refractive index n_1 as a core of the filament), and $D = 2R = FWHM = 4r_1$ is the full width in half maximum of the refractive index profile. The visualization of the assumed refractive index profile is shown in Fig. 2(a) (the same profile is used in the contour diagram Fig. 1).

With the hyperbolic profile, the Eq. (2) can be integrated directly. The integration leads to the analytically simple result for the angular deflection

$$\delta = \begin{cases} \pi - 2 \frac{\arccos(a)}{\sqrt{1-a^2}} & ab \leq 1 \\ \pi + \frac{2}{\sqrt{1-a^2}} [\arcsin(a) - \arctg(c_1)] - 2\arctg(c_2) & ab > 1, \end{cases} \quad (6)$$

where

$$c_1 = \frac{a^2 b + 1}{\sqrt{1-a^2} \sqrt{a^2 b^2 - 1}}, \quad c_2 = \sqrt{a^2 b^2 - 1},$$

$$a = \frac{k}{n_0 \rho}, \quad b = \frac{n_1}{\Delta n}.$$

The parameter $ab = kn_1/(n_0 \Delta n \rho)$ defines classes of beam trajectories. If the value is below 1, the laser beam goes outside of the circle r_1 which is characterized with refractive index n_1 . If the value ab is bigger than 1, the beam crosses the border of the hyperbolic profile and goes through the central circle where the refractive index n_1 is constant. The value of n in the filament core falls near to 1 for a very high neutral gas temperature and remains above 1, for ionization degrees lower than 10^{-3} which is typically the case for non-thermal atmospheric pressure plasmas. The maximal deflection angle is reached, if the beam touches the border of the core. In this case it is targeting the point with the highest gradients of the refractive index in a tangential direction. This amplitude of the deflection pulse $\delta(\rho)$ is reached with the following critical lateral

beam position ρ_1

$$\rho_1 = \frac{kn_1}{\Delta n n_0} = r_1 \frac{n_1}{n_0} \cong r_1. \quad (7)$$

The above approximation is permitted for most situations with gases under normal pressure ($b > 4000 \gg 1$). If the impact parameter ρ decreases the beam crosses the filament core and the deflection angle is decreased because the core does not contribute to the refraction and the incident angle decreases, too. The dependence of the deflection angle on the impact parameter is shown in Fig. 2(b).

The signal can be obtained experimentally, if the filament crosses the laser beam with a defined velocity or if a stationary filament is scanned transversally by a moving laser beam. The evaluation of the measured data can follow the routine fitting procedure or lead to the localization of deflection maximum in the $\delta(\rho)$ directly. Both routines, first of all, determine the width of the filament core on x axis. Therefore, the FWHM of the profile can be obtained as twice the width of the filament core ($FWHM = 4r_1$). The maximal deflection angle is then resulting from Eq. (6) and is given by

$$\delta_1 = \delta(\rho_1) = \pi - 2 \frac{\arccos(\frac{1}{b})}{\sqrt{1-(\frac{1}{b})^2}} \cong \frac{2}{b} = 2 \frac{\Delta n}{n_1}. \quad (8)$$

Here, the approximation is also possible because of a large value b . If the gas temperature is the sole reason for the deflection of the beam, Landolt's law can be considered^{29,30}

$$n_1 = 1 + \frac{T_0 p_1}{T_1 p_0} (n_0 - 1) \cong 1 + \frac{T_0}{T_1} (n_0 - 1), \quad (9)$$

where $p_{1,2}$ and $T_{1,2}$ denote pressure and temperature conditions of gas, respectively, and $n_{1,2}$ are corresponding values of refractive index in the gas. Then Eq. (7) can be expressed as an effect of temperature and pressure of the gas

$$\delta_1 = 2 \frac{n_0 - 1}{n_1} \left(1 - \frac{T_0 p_1}{T_1 p_0} \right) \cong 2 (n_0 - 1) \left(1 - \frac{T_0}{T_1} \right), \quad (10)$$

where T_0 is the far field gas temperature (laboratory temperature), T_1 is the maximal temperature of the filament located in the filament core, and p_0 and p_1 are the corresponding pressures. Equation (10) can be simplified with an assumption $p_1/p_0 \cong 1$ for shock-free subsonic gas conditions and $n_1 \cong 1$ as factor. The inverse relation estimates the temperature T_1 while the deflection amplitude δ_1 is measured

$$T_1 = T_0 \frac{1}{1 - \frac{1}{2(n_0-1)} \delta_1}. \quad (11)$$

III. EXPERIMENTAL SET-UP

As a primary application and experimental implement, LSD has been substantiated on a non-thermal atmospheric pressure plasma jet operating at radiofrequency (RF, 27.12 MHz). The plasma source is specifically designed for local deposition of thin functional coatings by PE-CVD and shown schematically in Fig. 3. The plasma is generated at the

FIG. 3. Schematic drawing of the non-thermal atmospheric pressure plasma jet. The gas flows through the quartz capillary with ring electrodes in between the filamentary plasma is ignited. Indicated are the locations where the diagnostics are applied: effluent (LSD) and active discharge zone (OES).

inner wall of a quartz capillary between two outer capacitively coupled ring electrodes. The inner capillary diameter is 4 mm. The RF power is supplied by a DTG2710 generator (Dressler) with typical values in the interval between 5 and 20 W for one jet. Here, the RF power was fixed at 7 W in all experiments. The discharge is fed with Argon (5.0) which can be dosed with a mass flow controller (MKS Instruments, Inc.) in the range from 0.1 to 3 slm. A flow rate of 0.1 slm was chosen for this work. The gas flow drives the plasma downstream of the nozzle, forming a characteristic effluent, the plume. The laser of the LSD arrangement is led perpendicular through the effluent region, directly below the nozzle, at vertical distances between 0 and 7 mm from the nozzle.

Depending on the operation parameter flow rate vs. power, different regimes of the plasma jet can be established. The systematic overview of distinguished regimes has been published in Ref. 25. The filamentary structure of the plasma jet represents a common attribute of this kind of discharges. The locked mode (LM) of the jet has been chosen as a representative regime in this study. Characteristic for the LM is an equidistant location of all filaments around the inner wall of the capillary and a steady azimuthal rotation of the filaments around the axis of the capillary. In this study the LM of 3 filaments has been used (LM3). Their rotating frequency can be precisely tuned with gas flow and RF power. Maximum values around 80/3 Hz are detected. Observed characteristics of the LM are interpreted as a self-organized phenomenon which enables to demonstrate all the principle features of LSD illustratively. Moreover, the plasma parameters (e.g., neutral gas temperature, electron concentration) of the LM have been investigated in detail in a recent study.⁷

The capability of the proposed method LSD is verified by applying optical emission spectroscopy (OES) as a comparative diagnostic. In particular, the rotating frequency of the discharges is monitored and serves as a reference for LSD. OES was performed by applying a photo-diode array spectrometer TransSpec 2000 which operates in the spectral region from

FIG. 4. Experimental set-up of LSD used for diagnostic of the plasma jet. The cross-section of the jet displays three rotating plasma filaments (LM3). The laser beam passes the plasma effluent perpendicularly to the jet axis. The movement of the laser spot behind the jet is detected either with a fast camera or with a photodiode. The coordinates and intensity profile of the spot are evaluated by means of a PC or by an oscilloscope using real-time FFT mode.

200 to 1100 nm at a specified dispersion of 3.2 nm/diode. Emission spectra were collected from a focused volume with diameter of ~ 1 mm at the capillary wall located between the electrodes (Fig. 3) at sampling frequencies of maximum 700 Hz. However, the data are not processed simultaneously and the information about LM frequency is obtained ex post. The evaluation procedure has been already established for previous investigations on the jet.²

The LSD set-up consists of a He-Ne laser, a photodiode, and an oscilloscope (Tektronix TDS 714L, Fig. 4). The laser is classified as 3A (maximum 5 mW) and operates in the TEM₀₀ mode at a wavelength of 632.82 nm continuously. Deflection of the laser beam is measured with a photodiode in a distance of 13.5 m from the jet. The signal from the photodiode is evaluated with the oscilloscope as a FFT simultaneously. All data have been processed by FFT applying the Hanning window method.³¹ Alternatively, the motion of laser spot is monitored with a high speed camera and the beam deflection can be evaluated by post-processing of data obtained from a movie on a projection screen in two dimensions. The minimal sample frequency of 200 Hz is recommended.

IV. RESULTS

A. Low frequency dynamics of the discharge

Characteristic frequencies of the plasma jet in the LM3 have been measured by means of the two methods described in Sec. III. The OES signal has been collected in parallel to the low frequency analysis with the LSD. The subsequently processed FFT of the OES signal has been compared with the LSD fundamental frequencies for 117 different rotation speeds in LM3. The results shown in Fig. 5 demonstrate a positive correlation between the optical emission of the filaments and their effect on the laser beam deflection. Frequencies obtained by means of both methods are related to one transition of all filaments through the optical path per revolution, therefore the fundamental frequency of one filament is given by division by the number of filaments (e.g., 3 for LM3). Moreover, the fundamental frequency measured with

FIG. 5. Typical spectrum of the measured LSD signal with the fundamental frequency f_1 corresponding to the LM3, where 3 filaments rotate with frequency of 70/3 Hz (a). Correlation diagram for the optical emission signal and the fundamental frequency of the LSD signal (b).

LSD is equivalent to the fundamental frequency of the visual motion of filaments obtained with OES. The regression analysis shows a high relative predictive power with regard to the equivalence between the methods ($R^2 = 0.9988$). The accuracy of the frequency obtained after OES reaches 0.4%. The frequency error made with LSD is two times higher than the one derived from the OES data, because of the data reduction during the real-time data processing and possibly due to measuring in the effluent, too (different axial position relative to the OES measurements and increased jitter of the filaments as compared to the active discharge region). The close coupling of the LSD signal on the visual dynamics of discharge opens new diagnostic aspects of the atmospheric pressure micro plasma. Particularly, effects causing the change of refractive index in the plasma channel can be investigated in time scales limited only by the speed of a camera or a diode. Due to sufficient intensity of the laser beam, no accumulations are required, either.

B. Gas temperature in the discharge

The gas temperature of the plasma jet has been measured with LSD in the effluent. The laser spot has been projected on the screen 13.5 m away from the plasma jet and monitored with a high speed camera. Fig. 6(a) shows a photograph of the laser spot. The angular divergence of the laser beam is 1.6 Mrad. However, the radial intensity distribution makes it possible to find the centre of the spot precisely. This has been used for the video tracking of the laser spot, while the microplasma filament crosses the laser beam trajectory. The spot movement has been evaluated from the video by retrieving the spot centre with a VIDEO SPOT TRACKER software (CISMM, UNC Chapel Hill). The obtained positions of the spot centre are shown in Fig. 6(b). The statistical distribution of the angular deflection is limited by the maximal deflection angle $\delta_1 = 0.15 - 0.19$ Mrad which determines the maximum of the temperature profiles according to Eq. (11). The surrounding temperature and refractive index are given with $T_0 = 295$ K and $n_0 = 1.00025$, respectively. The resulting maximal temperature of the neutral gas in the effluent is $T_1 = (450 \pm 30)$ K. A reference experiment in the same configuration but without plasma generates negligibly small fluctuations of the deflection angle compared to the experiment with

FIG. 6. Photograph of the laser spot on the screen (a). The result of the video spot tracking (b). The square points show the various positions of the laser beam centre on the screen during the measurement. The maximal deflection δ_1 and error interval are marked.

the plasma ignited. The frequency analysis of the tracked spot motion enables to obtain the characteristic frequencies with the same results as above (Sec. IV A), too.

C. Temperature dynamics in the discharge

The time dependence of the deflection angle caused by defined dynamics in the plasma (LM3) can be simulated using the analytic properties of the temperature profile generated by one filament. The one filament rotating frequency of 70/3 Hz is assumed for the regime of a steady rotation of three filaments in the jet according to the results in IV.A. Transitions of the filaments through the beam are considered both in the front and in the back of the capillary. The LSD signal is calculated for different characteristic widths of the temperature refractive index profiles (FWHM). In Fig. 7 the LSD signals for two values of a profile width and the corresponding FFT analysis are shown. In the case of a sufficiently small (FWHM = 0.1 mm) profile width of the filament temperature, the pulse shape of the separated profiles generates a broad spectrum of frequencies. The fundamental frequency is related to the rotation of the filaments in the capillary. All higher harmonic frequencies characterize the pulse form of the filaments with a maximum of the amplitude which corresponds to the smallest characteristic delay in the time dependency of deflection angle. The maximum amplitude occurs at about 800 Hz for LM3 with a fundamental frequency of 70 Hz and FWHM of 0.1 mm. If the width of temperature profiles is broadened, the pulses overlap and the collective interactions of filaments due to temperature broadening become relevant. In this case, the maximum of higher harmonic frequencies is shifted to the lower value and the amplitude is reduced, as well. An extreme situation occurs if the profile occupies the whole 1/3 of the capillary space (FWHM = $2\pi R/3$, where $R = 2$ mm is the inner diameter of the capillary). Then the fundamental frequency represents a single dominant peak and the higher harmonic frequencies are not present in the spectrum. The ratio of the amplitudes a_2/a_1 of the second harmonic and the fundamental frequency is a marker for the proportionality of the FWHM in the jet. The decreasing dependency a_2/a_1 with increasing FWHM has been calculated and selected values are given in Table I.

FIG. 7. Effect of the filament thickness on the resulting frequency spectrum. LSD signal produced with a thin profile of refractive index (small FWHM) (a) generates a large frequency spectrum (b). Broader FWHM of the profile (c) causes the dominant amplitude of the fundamental frequency in a FFT spectrum (d). The proportion of the fundamental frequency and higher harmonic frequencies is a significant marker for the thickness of the profile.

The results on the a_2/a_1 ratio have been used for the evaluation of experimental data. For the consistency of all results here, the experimental parameters of the plasma are kept constant as described in Secs. IV A and IV B. The frequency spectra of the LSD signal have been collected at different axial positions below the capillary in order to characterize the spatial changes of temperature profiles in the plasma effluent. The spectral range is focused on the fundamental and second harmonic frequency and their amplitudes are measured. The results are shown in Fig. 8. The a_2/a_1 ratio has been calculated and fitted with a piecewise linear function. The amplitude of the second harmonic frequency decreases linearly with increasing nozzle distance and reaches the noise level at position 2.4 mm. The fundamental frequency remains a sole characteristic of the periodic behavior in the effluent from 2.4 to 7.0 mm. In this interval, the temperature dynamics seems to be a harmonic wave. The measurement of the amplitude ratio leads to the determination of the temperature profile width (Fig. 8(b)). The FWHM of the temperature profile starts with 1.6 mm at the end of the capillary and increases non-linearly in the direction of the gas flow. The maximal value of FWHM is attained at 2.4 mm where the second harmonic frequency disappears. Note that the emission of the plasma effluent in the OES spectra is observed only up to the point 1.4 mm.

TABLE I. The widths of the refractive index profiles and the corresponding ratios of FFT amplitudes for second harmonic frequency a_2 and fundamental frequency a_1 .

a_2/a_1	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
FWHM [mm]	4.2	2.6	1.9	1.5	1.2	0.97	0.78	0.63	0.50	0.39	0.30

The results demonstrate the plausibility of the FWHM estimation. Indeed, one can expect the relevance of a heat dissipation and damping of the flow velocity in the plasma effluent. The sensitivity of the method on the temperature gradients shows in an exemplary manner that the heat dynamics is correlated with the plasma temporally, but exceeds its visual boundaries significantly.

FIG. 8. Measurement of amplitudes for the fundamental and second harmonic frequency as a function of the axial position of the LSD measurement in the effluent. The amplitude ratio has been calculated and the linear fit of the result is plotted, too (a). The effect of the axial position on the profile width. Two typical regions are indicated regarding the results of the frequency analysis and calculation of profile width (b).

V. DISCUSSION

The presented method LSD along with the evaluation procedure opens new aspects for the diagnostics of microplasmas. The analytic concept of the data evaluation makes it possible to evaluate the profiles of microfilaments. The technique circumnavigates the complications that are attached to the Abel transformation, e.g., its ill-posed character. However, by assuming an analytic shape the statistic error of numerical operations is replaced with a systematic error of the model and the resulting values achieve a higher confidential level. In contrast to the mathematically suitable construction of the profile (Eq. (5)) regarding to the exact integration of the beam trajectory, the postulated model does not represent a direct solution of the fundamental equations of heat transition in a homogeneous fluid. Despite this, the model can be fitted on a large class of physically relevant profiles characterized by a central maximum. Two non-correlated free fitting parameters represent an advantage for any relevant approximations using the described model. In contrast to the one-formula profiles like Lorenz or Gauss profile, the variation of one fitting parameter of the hyperbolic profile does not change the profile completely. The parameter k is related to the gradient and the parameter n_1 determines the height of the profile independently. Hence, the hyperbolic model could be an optimal compromise for the description of a real refractive index profile on the one side and for the calculation of filament properties from a LSD signal on the other side. Therefore, the model can be combined with the Fourier law of heat transport³² in order to estimate the radial heat flux density q at radial position r_1 as

$$q = \frac{\lambda}{r_1^2} \frac{T_1}{T_0} (T_1 - T_0), \quad (12)$$

where λ is thermal conductivity of gas ($0.016 \text{ W m}^{-1} \text{ K}^{-1}$ for argon³³), $r_1 = \text{FWHM}/4$ is the radius of the filament core, T_1 and T_0 are the maximal gas temperature and the far field gas temperature, respectively. Equation (12) enables to calculate the quantity q for the results presented here. The obtained value of q is 24 MW m^{-3} in the effluent at the axial position $z = 0$. The magnitude of the value is not unusual in the physics of microplasmas because of the total visible volume of the filaments of about 2 mm^3 at a supplied power of 7 W . The volume of the space between the electrodes in the capillary is about 100 times larger than the volume of the plasma itself. Therefore the estimation of the quantity q plays an essential role in the diagnostics of non-linear dissipation processes in similar plasma sources.

The theory of the LSD relates the change of refractive index to a change in the neutral gas temperature with the help of Landolt's law. The experiment was set up in a way that both quantities are closely coupled without disturbing effects. The mixing of different gases (argon and air) in the experiment led to errors of about 4% only. The charged plasma species can contribute to a reduction of the refractive index, too. However, the electron density reached the magnitude of 10^{14} cm^{-3} in this experiment.⁷ Therefore the calculated effect on the refractive index was also negligible. The resulting maximal temperature $T_1 = (450 \pm 30) \text{ K}$ in the effluent could be discussed in context with previous results on the temperature conditions in the

plasma jet.³⁴ The temperature T_1 should be higher than the surface temperature at the end of the capillary ($T_C = (370 \pm 6) \text{ K}$), which was obtained by an infrared camera. Furthermore T_1 should be smaller than the rotational temperature of OH ($T_r = (520 \pm 50) \text{ K}$), which was evaluated by means of optical emission spectroscopy. The temperature of 450 K obtained with the LSD is therefore fully consistent with the results of others diagnostic techniques.

VI. CONCLUSION

The application of the LSD with an analytical model makes it possible to investigate local thermal properties of a filamentary atmospheric pressure plasma and its low frequency dynamics simultaneously. For the particular class of microplasmas investigated here, the demonstrated frequency analysis of the plasma is an appropriate tool for identifying and characterizing self-organized processes and the formation of regular structures if they occur within the studied regimes of the chosen plasma source. The filamentary plasma at atmospheric pressures exists often in irregular chaotic regimes and the frequency analysis can produce characteristic noise spectra without diagnostics frequencies. In this situation the LSD signal can be also evaluated statistically in order to estimate the gas temperature. In the case of quasi stationary filamentary regimes, the LSD can be performed similar as for the case of the self-organized dynamic regimes so that the laser beam scans the stationary filaments transversally with a defined raster velocity.

The analytic model of LSD enables to reconstruct radial cross-sections of the temperature in the discharge space alternatively to the Abel techniques, whose application is nearly impossible for non-thermal filamentary plasma at atmospheric pressure due to numerical problems. Therefore, the aim of this work was to demonstrate the capability of the analytic approach of LSD for the evaluation of these parameters on small-scaled plasmas, such as the filamentary discharges with filament diameters of 0.3 mm . The LSD analysis of the effluent of the miniaturized non-thermal atmospheric pressure plasma jet results in a gas temperature of about 450 K which is fully consistent with previous analyses with other techniques. Moreover, the deflection can be measured as displacement of the laser spot on a projection screen, which enables to monitor the variations in both radial and axial dimensions of temperature profiles. The LSD technique has the ability to characterize the self-organized regime in this plasma source with a simultaneous frequency spectrum. The characteristic width of the temperature profile can be obtained from an evaluation of FFT amplitudes. The accuracy of the method can be significantly increased using deflection measuring systems which are usually used in cantilever-based systems.³⁵ The results enclose hot gas dynamics, which exceed the visibly appearing boundaries of the plasma and are still determined by the self-organization of the plasma. Moreover, the combination of the frequency analysis and temperature analysis open the possibility for temporally resolved temperature tomography of microplasmas in future studies. However, critical discussion is necessary for routine applications. Particularly, it should be verified for the particular

plasma if diffraction, absorption, and scattering effects have to be considered. For the present study, these difficulties can be disregarded because of the low ionization degree and non-thermal conditions.

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