Simultaneous Thomson and Raman scattering on an atmospheric-pressure plasma jet

Simultaneous Thomson and Raman Scattering on an Atmospheric-Pressure Plasma Jet

A. F. H. van Gessel, E. A. D. Carbone, P. J. Bruggeman, *Member, IEEE*, and J. J. A. M. van der Mullen

***Abstract*—In this paper, laser scattering is applied to a cold atmospheric-pressure microwave plasma argon jet in direct contact with air. Spatially resolved measurements clearly show the air entrainment in the plasma jet. Consequently, the contributions from Thomson scattering and Raman scattering (N_2 and O_2) overlap. With a specially designed fitting method, we are able to obtain n_e and T_e, in spite of the significant Raman contribution.**

***Index Terms*—Atmospheric-pressure plasmas, plasma density, plasma diagnostics, plasma temperature, Raman scattering, Thomson scattering.**

COLD atmospheric-pressure plasmas, for example, plasmas that are used in medical applications [1], are in direct contact with air. Consequently, there is entrainment of species like nitrogen and oxygen into the plasma. Due to the low gas temperature and electron density, these molecules are not strongly dissociated. This complicates Thomson scattering measurements, because a Raman scattering signal from the molecules is superimposed on the Thomson signal.

We investigate a microwave surfatron launcher (2.46 GHz), which produces a plasma in a ceramic tube with an inner diameter of 0.8 mm, ending in air. Through the tube, an argon flow of 1.0 slm is applied. The setup is similar to that in [2], with the difference that the surfatron launcher is cooled with a flow of 20 slm of air around the tube. The total microwave input power is approximately 40 W. Note that we are measuring outside the tube in the effluent and that most of the power is dissipated inside the launcher. The laser that is focused in the plasma is a Nd:YAG laser (Edgewave IS6II-E) operating at 532 nm. It has a pulse energy of 4 mW and a repetition rate of 4 kHz. The scattered light is collected by a *triple grating spectrometer* (TGS) and imaged on an iCCD. For details on the setup, we refer to [3].

Three types of laser scattering can be observed: Rayleigh scattering, Thomson scattering, and Raman scattering. Rayleigh scattering, elastic scattering on heavy particles, is much stronger than Raman scattering and Thomson scattering. The spectrum is peaked at the laser wavelength. The Rayleigh signal is filtered out optically with the TGS which acts as a notch filter [3]. Thomson scattering is elastic scattering on free electrons [4]. With a Maxwellian electron velocity distribution, the spectrum is Gaussian shaped due to Doppler broadening. The width gives the electron temperature T_e, and the intensity is proportional to the electron density n_e. Raman scattering is inelastic scattering on molecules [5]. The spectrum has peaks at wavelengths depending on the rotational states of N_2 and O_2.

In Fig. 1, two images of measurements with the iCCD and the TGS (the images have been corrected for imaging errors of the TGS) are shown. The first image is made close to the tube end. Due to the small size of the plasma, only a part of the image is covered by plasma, and most of the image shows Raman scattering of the surrounding air at room temperature. Inside the plasma (at position 0), however, there is a clear Thomson signal, without the Raman signal. This indicates that, close to the tube, there is only very little air entrainment into the plasma jet. Because the densities of N_2 and O_2 are known in the surrounding air, the Raman signal can be used to absolutely calibrate the intensity, which is needed to obtain absolute electron densities. The Thomson signal is fitted with a Gaussian profile, from which we obtain $n_e = 4.6 \cdot 10^{20}$ m^{-3} and $T_e = 1.5$ eV in the center of the plasma.

The second image shows a similar measurement, taken further downstream. A Thomson signal is visible in the center of the image, but also the Raman signal clearly penetrates to the center of the plasma. The Raman and Thomson signals overlap, and to separate them, we use a specially designed fitting method. By calculating the theoretical spectra of Thomson scattering and N_2 and O_2 Raman scattering [4], [5] and fitting these to the measured data, we are able to subtract the Raman signal. The remaining Gaussian Thomson signal yields the results $n_e = 1.8 \cdot 10^{20}$ m^{-3} and $T_e = 1.7$ eV in the plasma center.

The spatial resolution is limited by the optics of the TGS and is approximately 60 μm. The diameter of the argon jet is approximately 0.8 mm, although air penetrates the plasma until the very center. The diameter of the plasma is smaller, about 0.4 mm. The detection limit for n_e is approximately 10^{19} m^{-3} in conditions where there is a few percent of air present, which opens perspectives for a wide range of plasma sources.

Manuscript received December 6, 2010; revised May 12, 2011; accepted May 22, 2011. Date of publication July 29, 2011; date of current version November 9, 2011.

The authors are with the Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands (e-mail: a.f.h.v.gessel@tue.nl; e.a.d.carbone@tue.nl; p.j.bruggeman@tue.nl; j.j.a.m.v.d.mullen@tue.nl).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2011.2158562

REFERENCES

[1] M. G. Kong, G. M. W. Kroesen, G. Morfill, T. Nosenko, T. Shimizu, J. van Dijk, and J. L. Zimmermann, "Plasma medicine: An introductory review," *New J. Phys.*, vol. 11, p. 115 012, Nov. 2009.

[2] J. M. Palomares, E. I. Iordanova, A. Gamero, A. Sola, and J. J. A. M. van der Mullen, "Atmospheric microwave-induced plasmas in Ar/H_2 mixtures studied with a combination of passive and active spectroscopic methods," *J. Phys. D, Appl. Phys.*, vol. 43, no. 39, p. 395 202, Oct. 2010.

[3] M. J. van de Sande and J. J. A. M. van der Mullen, "Thomson scattering on a low-pressure, inductively-coupled gas discharge lamp," *J. Phys. D, Appl. Phys.*, vol. 35, no. 12, pp. 1381–1391, Jun. 2002.

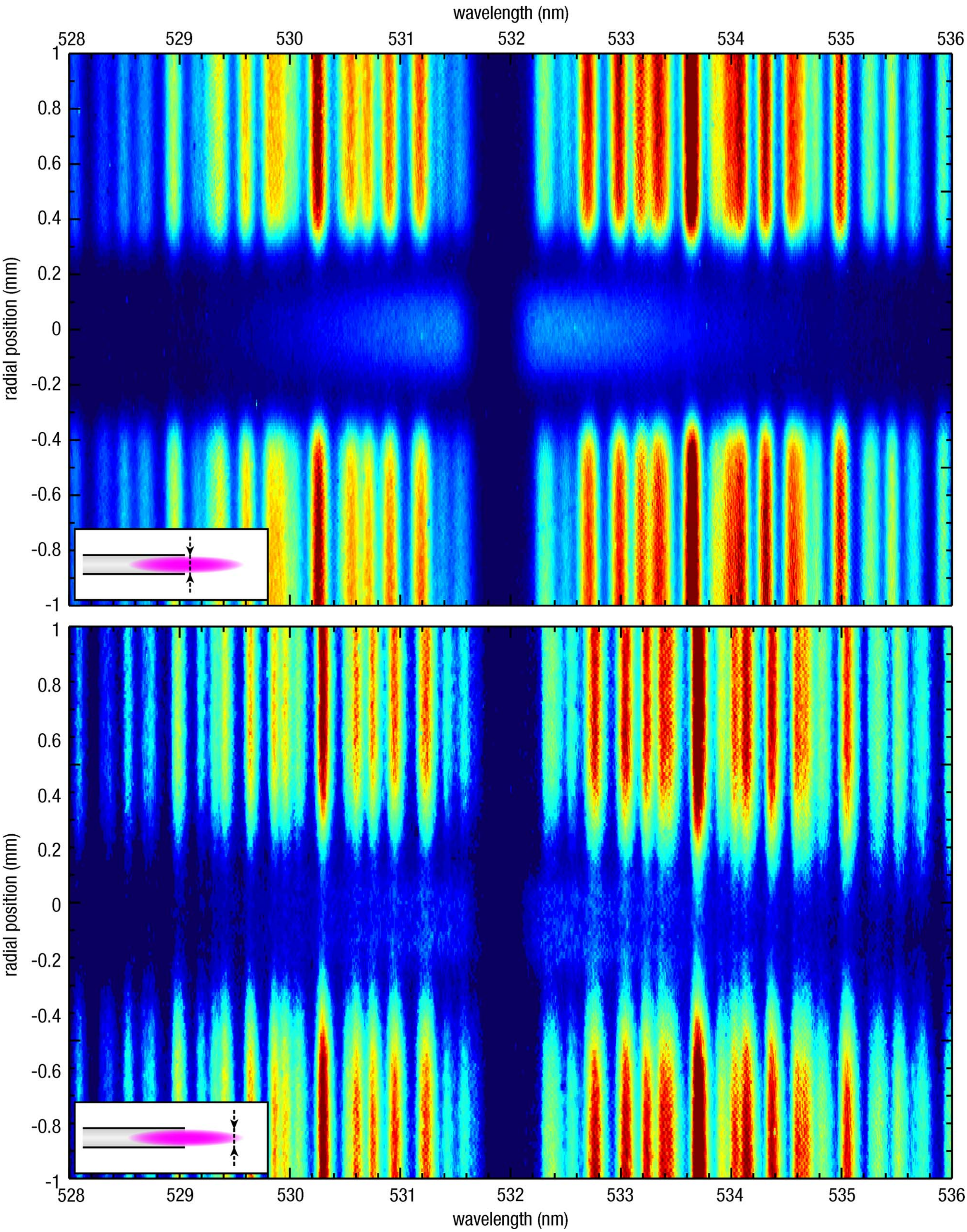

Fig. 1. iCCD images of the scattered laser light on an atmospheric-pressure plasma jet, at axial positions of (*top*) 1.0 mm from the tube end and (*bottom*) 4.75 mm from the tube end. Horizontally, the wavelength is shown, and vertically, the radial position along the laser beam is shown. The part at the laser wavelength (532 nm) is removed by the TGS.

[4] N. de Vries, J. M. Palomares, W. J. van Harskamp, E. I. Iordanova, G. M. W. Kroesen, and J. J. A. M. van der Mullen, "Thomson scattering measurements on a low pressure surface wave sustained plasma in argon," *J. Phys. D, Appl. Phys.*, vol. 41, no. 10, p. 105 209, May 2008.

[5] C. M. Penney, R. L. S. Peters, and M. Lapp, "Absolute rotational Raman cross sections for N_2, O_2, and CO_2," *J. Opt. Soc. Amer.*, vol. 64, no. 5, pp. 712–716, 1974.