

STANDING STRIATIONS DUE TO LASER INDUCED DEPOPULATION OF METASTABLE ATOMS

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Low pressure non-isothermal plasmas exhibit a variety of instabilities [1]. If the positive column plasma of a discharge is locally perturbed, stationary relaxation phenomena may arise which represent simple spatial patterns [2]. As no time dependencies appear these standing striations represent excellent objects for the study of the physical mechanism leading to the instability. In particular the different elementary processes involved can be examined in detail.

However, systematic investigations suffered from the complex influences due to the perturbation applied. The experimental approach presented here overcame these problems by a novel experimental technique employing a cw laser using the fact that the plasma perturbed contains atoms in metastable states which are essential for the discharge mechanism. The laser was used in order to perturb the plasma by the irradiation of light at a well defined position of a discharge. If the wavelength was tuned to a transition outgoing from a long-lived (metastable) state, the subsequent decay of the excited atoms may end on a resonant state, which is strongly coupled to the ground state. Thus, this kind of perturbation leads to an effective depopulation of metastable atoms, which are not disposable for ionization processes in the region of irradiation.

For our experiments a cylindrical ($r=1.0$ cm) dc neon glow discharge ($p_0=115$ Pa) was locally irradiated with light of the wavelength $\lambda=633.4$ nm corresponding to the transition $1s_5 \rightarrow 2p_8$ (Paschen notation). The $2p_8$ states radiatively decays to the $1s_4$ state with a branching ratio of $\beta=0.62$ [3]. The irradiated part of the discharge was chosen to have an axial extent of about 4 mm covering the entire cross section of the discharge tube. The one-dimensional axial relaxation was investigated both with respect to the excited state atoms [laser induced fluorescence (LIF)] and the electrons (Langmuir probes). Spatially resolved results were obtained by moving the perturbation with respect to the diagnosing laser beam and the probe.

For LIF measurements a small part of the perturbing laser beam was focused into the center of the discharge. The frequency stability of the laser radiation was controlled by a Fabry-Perot interferometer. Fluorescence light was observed perpendicularly both to the laser and the discharge tube. In order to discriminate continuous background radiation the diagnostic beam was chopped with an acousto-optic modulator and the fluorescence signal was detected with a lock-in amplifier. With this technique even the region of irradiation could

be investigated despite the fact that both perturbing and diagnostic laser beam have the same wavelength leading to an overwhelming continuous fluorescence in the region of laser perturbation. The electron energy distribution function was derived from the current-voltage characteristics of a Langmuir probe (tungsten wire, $r= 50 \mu\text{m}$, $l=2.5 \text{ mm}$) taken with a source measure unit using the Druyvesteyn method.

The laser power was chosen in order to avoid any influence due to power fluctuations on the structure observed (saturation). Stationary axial profiles of the metastable densities, electron densities, mean electron energies and potentials, respectively, are shown in Fig. 1. The metastable densities were measured for different discharge currents (0.5 mA ... 8 mA).

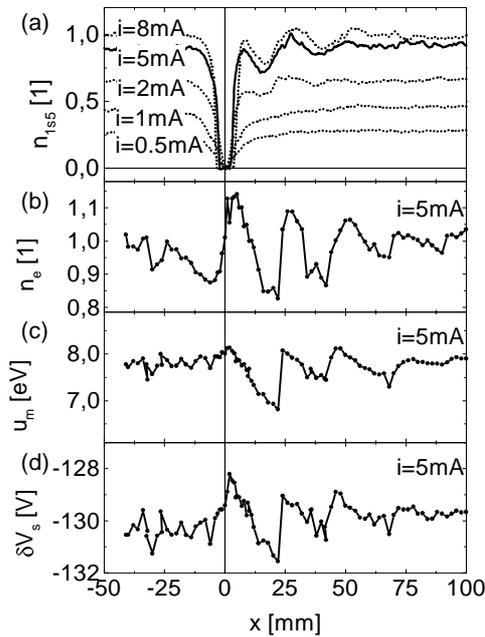


Fig. 1: Axial profiles due to laser induced perturbation at $x=0\text{mm}$. Cathode side is for $x<0$, anode for $x>0$, respectively. (a) shows the metastable density for different discharge currents. (b-d) refer to probe measurements at $i=5 \text{ mA}$. (b) shows the relative axial electron density profile, (c) the electron mean energy and (d) the deviation from the plasma potential, respectively.

Fig. 1(a) clearly indicates that the metastable density vanishes in the region of irradiation. Then, the density rises to the value of the positive column within a few centimeters. The metastable density in the column grows with discharge current but can be found to saturate for larger currents. Towards the cathode a diffusion-like profile (exponential growth) can be observed for all currents. Towards the anode ($x>0$) the exponential profile became modulated if the current is increased. For a current with a modulated spatial density profile ($i=5\text{mA}$) current-voltage characteristics of a Langmuir probe were taken. Figs. 1(b)-(d) show electronic properties derived from these measurements. The relative electron densities [Fig. 1(b)] were found to decay towards the perturbation coming from the cathode to nearly 90% of the equilibrium column value. Within the perturbation region the density grows rapidly to values of about 115% with a subsequent damped oscillatory relaxation towards the anode. It should be noted that the first maximum of the electron density relaxation is considerably shifted with respect to the

maximum of the metastables. In the course of space this phase shift between the electrons and the metastables vanishes corresponding to the vanishing amplitude of the oscillation. The mean energy u_m [Fig. 1(c)] of the electrons was found to be nearly unaffected on the cathode side ($x<0$) until the perturbation was reached. Then u_m decreases linearly to 80% of the initial value and suddenly increases again leading to a damped sawtooth like modulation. From Fig.

1(d) it can be seen that the perturbation leads to an increase of the deviation from the potential which is sawtooth like damped towards the anode corresponding to the behaviour of the mean energy.

The observed behaviour can be understood easily for the region towards the cathode. The decrease of metastables leads to a reduced electron production as stepwise ionization is suppressed. In order to maintain the continuity of the discharge current the axial field is increased yielding an enhanced mean energy. Towards the anode kinetic effects have to be considered as for the first minimum of the electron density [Fig. 1(b), $x=25$ mm] the mean

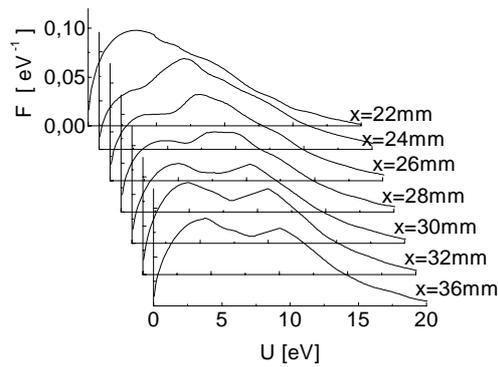


Fig. 2: Electron energy distribution function $F(U)$ for different axial positions towards the anode.

energy became minimum [Fig. 1(c), $x=25$ mm], too. Despite these facts the continuity equation for the electrons is still fulfilled due to the occurrence of high energy electrons which can be seen from Fig. 2. Here the electron energy distribution function is shown for different positions along the phase of the oscillation. It can be seen that the strong increase of the potential [Fig. 1(d)] corresponds to an acceleration of a high energy part in the electron energy distribution. The high energy part is redistributed to the bulk of the distribution in the course of space.

A variation of the discharge current shows that the structure of the spatial relaxation profile changes at $i_c=1.5$ mA [see Fig. 1 (a)]. It was found that the amplitude of the oscillation increases above i_c and becomes saturated for currents of about 5mA. The wavelength of the

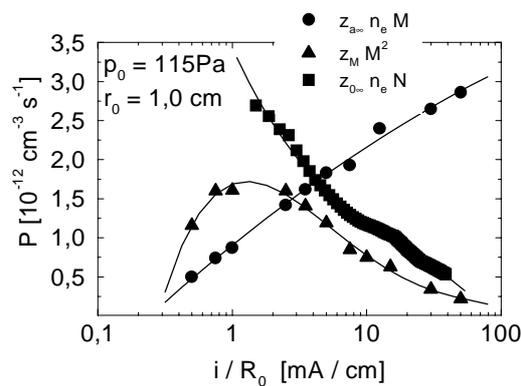


Fig. 3: Ionization production terms for direct, step-wise ionization and pair collisions, respectively, as a function of the discharge current in the discharge investigated.

oscillation slightly increases, too, but was also found to become saturated for higher currents. The spatial damping of the oscillation decreases from i_c to an asymptotic finite value. The threshold behaviour could be associated to elementary processes as can be seen from Fig. 3. Here the electron production due to the relevant ionization processes is displayed. The production terms were derived with rate coefficients from [4] and particle densities from our experiments. It can be seen that direct ionization is most efficient for small currents, i.e. large fields, whereas step-wise ionization becomes the governing process for higher currents. Pair collisions contribute most

in a transition region.

It can be concluded from our work that standing striations due to laser induced depopulation of metastable atoms strongly exhibit a kinetic character. The mechanism of accelerated electrons in a modulated field which trigger an enhanced light emission leading to the striations observable seems to be similar to the physics of ionization waves [1,5]. The interaction of different elementary processes lead to different ionization regimes within one cycle of the oscillation.

The discharge current acts as a control parameter for the structure of the striations. A change in structure is related to a change in the governing elementary processes.

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References

- [1] P.S. Landa, N.A. Miskinova, and Yu.V. Ponomarev: *Sov. Phys. Usp.* **23**, 813 (1980).
- [2] V.I. Kolobov, and V.A. Godyak: *IEEE Trans. Plasma Sci.* **23**, 503 (1995).
- [3] A. Ben-Amar, R. Shuker, and G. Erez: *Appl. Phys. Lett.* **54**, 3688 (1983).
- [4] A. Rutscher, and S. Pfau: *Beitr. Plasmaphys.* **7**, 187 (1967) (*in German*).
- [5] F. Sigeneger, Yu.B. Golubovski, I.A. Porokhova, and R. Winkler: *Plasma Chem. Plasma Process.* **18**, 153 (1998).