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Elementary processes in the dynamics of two simultaneously excited fireballs in plasma

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This work is dedicated to Tilmann Märk, a great scientist and academic teacher and a wonderful friend on the occasion of his 70th birthday.

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A B S T R A C T

Two simultaneously excited fireballs in front of two positively biased electrodes immersed in plasma were investigated by emission spectroscopy under different experimental conditions (gas and pressure, plasma density). Experimental results were obtained regarding the spectral composition of the light emitted by the fireballs, the influence of the appearance of the second fireball on the spectrum of the light emitted by the first fireball, the electron temperature and density, as well as on the elementary processes involved in the appearance and dynamics of the fireballs.

1. Introduction

Fireballs are intensely luminous complex almost spherical space charge structures in plasma consisting of a positive inner core (an ion-rich plasma), confined by an electrical double layer which sustains a potential jump, i.e. an electric field [1–3]. The potential drop across the double layer is almost equal to the ionisation potential of the gas atoms. A common way to obtain fireballs is to apply a positive potential to an electrode of certain size immersed in plasma with sufficient neutral background gas pressure. In this case, the fireball appears at a critical value of the applied voltage. At higher values of the voltage, two situations were observed: In the first case, the fireball passes into a dynamic state, consisting of periodic disruptions and re-aggregations of the double layer, giving rise to strong oscillations of the current collected by the electrode [4–6]. In the second case, a more complex structure develops in front of the electrode, consisting of several concentric luminous shells (like an onion), known as concentric multiple double layer [7–9], or as a network of intense luminous plasma spots, located near each other, almost equally distributed on the electrode surface, known as non-concentric multiple double layer [10–12].

Previous emission spectroscopy investigations of fireballs [13,14] showed that electron-neutral impact excitations and ionisations play the most important role in the phenomenology of the appearance and dynamics of fireballs in plasma. Thus, the existence of fireballs is ensured, on one side, by the equilibrium existing between the generation and accumulation of charged particles (electrons and ions) through ionisation and excitation, and, on the other side, by losses of charged particles through recombination and diffusion. If this equilibrium cannot be maintained, the fireball passes into its dynamic state.

Here we report on the spectral analysis of two fireballs excited in front of two positively biased electrodes in plasma. Spectra of the light of one of the fireballs were recorded and analysed under different experimental conditions (gas pressure, plasma density, mixture of gases in different ratios, voltages on the electrodes). The influence of the second fireball on the spectra of the light from the first fireball was also analysed. From the spectral data we

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estimated the electron temperature, density and the dependence of these quantities on the helium addition.

The obtained results could be very useful in the understanding of the phenomenology involved in the appearance and dynamics of non-concentric multiple double layers. Here, the interaction between the individual fireballs composing the multiple structure, particularly the elementary processes involved in the correlation between their individual dynamics, is not fully understood.

2. Experimental results

The experiments were performed in the target chamber of the University of Innsbruck double plasma (DP) machine with the usual separating grid between the two chamber-halves removed in order to obtain a larger homogeneous plasma volume. A discharge is created between a hot filament that acts as cathode and the walls of the chamber acting as anode. On the inner walls of the vacuum vessels small permanent magnets (with $B = 1$ T on the surface) with alternate polarity are fixed, which support the plasma confinement. Because of its small dimension, the filament collects only a negligible part of the ions, most of them diffusing to the centre of the chamber. The positive space charge developed in the centre of the chamber will attract many electrons into this region, so that a diffusion plasma with a high degree of ionisation will be created in this way.

The experimental arrangement is shown in Fig. 1. Two tantalum disc electrodes (E1 and E2 in Fig. 1) were introduced into the diffusion plasma region and were positively biased with respect to the unperturbed plasma potential. The light emitted from the region in front of the electrode E1 can be detected through a quartz window and is focused by a lens onto the slit of an UV-vis spectrometer. The spectrometer-lens system was always adjusted to detect the light coming from the centre of the fireball in front of the electrode E1 (FB1), with a spatial resolution of approximate 1 mm. When no fireball exists in front of electrode E1, the system was adjusted to detect the light coming from the axis of the electrode E1, 1 cm in front of it. A cylindrical Langmuir probe is also introduced between the two electrodes for the electrical diagnosis of the plasma. Spectra of this light were recorded under the following conditions: without fireballs, with fireball in front of the first electrode (E1), with fireball in front of the second electrode (E2) and with two simultaneous existing fireballs in front of both electrodes, respectively.

For the first measurements we used argon as working gas, with a pressure $p = 10^{-3}$ mbar, a discharge voltage of $V_{dis} = 60$ V and a discharge current of $I_{dis} = 95$ mA. The Langmuir probe measurements indicate the next plasma parameters: plasma potential $V_{pl} \cong 1$ V, plasma density $n_{pl} \cong 10^9$–10^{10} cm^{-3} and two populations of electrons, with the temperatures $T_{e1} \cong 0.2$ eV and $T_{e2} \cong 1.2$ eV. Two typical spectra of the light from the centre of the fireball in front of electrode E1 under these experimental conditions are shown in Fig. 2. The figure is divided in two parts corresponding to two wavelength intervals (250–700 nm and 700–950 nm, respectively) because of the strongly different amplitudes of the spectral lines (approximate one order of magnitude). We observe that, without excitation of a fireball on E1, the residual spectrum is not influenced by a fireball on E2. On the contrary, a fireball on E1, as well as the simultaneous excitation of both fireballs has a strong influence on the spectral composition of the light emitted from the region in front of E1.

A second set of measurements was performed in order to study the influence of the gas pressure on the spectrum of the light emitted from the region in front of E1. As we have seen above, a fireball on E2 has influence on the spectrum only if there is a fireball in front on E1. Therefore we have performed this set of experiments only in two situations: with a fireball in front of E1 and with both fireballs in front of the two electrodes, respectively. Fig. 3 shows the spectra of the light emitted from the centre of the fireball in front of E1 for the two situations described above and for different values of argon pressure, discharge voltage and current being $V_{dis} = 60$ V and $I_{dis} = 95$ mA, respectively. As expected, the amplitudes of the spectral lines corresponding to the excited species increase with increasing gas pressure. Concerning the amplitudes of the spectral lines from ionised argon (ArII), the dependence on the gas pressure is complex. While in the case of range 450–500 nm (marked by circles in Fig. 3a and c) the amplitudes decrease with increasing gas pressure (some spectral lines even disappear), in the case of the ranges 400–450 nm and 525–575 nm the amplitudes increase with the increase of the gas pressure.

The aim of the third set of measurements was to study the influence of the addition of helium on the spectra of the light emitted from the centre of the fireball in front of E1. Fig. 4 shows the comparative spectra obtained only with argon and with a gas mixture helium:argon 1:1, respectively, in the presence of fireballs on both electrodes and under the following experimental conditions: gas pressure $p = 5 \times 10^{-3}$ mbar, discharge voltage and current $V_{dis} = 60$ V and $I_{dis} = 80$ mA, respectively. It can be observed that the presence of helium influences some populations of argon, both neutrals and ions. In most cases the argon lines decrease with the addition of helium in the discharge. There are two exceptions, namely the lines Ar* 706.7218 nm and Ar* 727.2936 nm, the intensity of which increases when helium is added to the discharge. A possible explanation for this increase could be the contribution to these lines by two transitions of helium, namely He* 706.5190 nm and He* 728.1349 nm, respectively. The limited resolution of the spectrometer prevented a clear distinction between the argon and helium lines.

Finally, in the last series of experiments we have analysed the influence of the bias applied to the electrode E1 on the spectra of the light emitted from the centre of the fireball in its front. Fig. 5 shows these spectra recorded for different values of the bias of E1 with respect to ground, keeping constant the bias of E2 with respect to ground $V_2 = 125$ V, under the following experimental conditions: He:Ar 1:1 mixture, gas pressure $p = 5 \times 10^{-3}$ mbar, discharge voltage and current $V_{dis} = 60$ V and $I_{dis} = 80$ mA, respectively. As we observe, the intensity of the spectral lines, i.e. the density of the neutrals and ions in front of E1 is proportional to the bias of E1. Regarding the influence of the bias of E2 on the spectra, the experiments prove that there are just small changes, more important when the bias of E1 is small.

3. Electron temperature and density

Under local thermodynamic equilibrium (LTE) conditions the electron temperature T_e can be assumed as equal to the excitation temperature T_{exc} and can be determined from the intensity ratio of two or more spectral lines belonging to the same ionisation stage as following [15]:

$$I_{ki} = N_0 \frac{1}{4\pi} \frac{hc}{Z(T)} \frac{A_{ki}}{\lambda} g_k e^{-E_k/k_B T_{exc}} \quad (1)$$

where N_0 is the total number density of atoms (particles), λ is the transition wavelength, A_{ki} is the Einstein's coefficient of the $k \to i$ transition, g_k is the statistical weight of the upper level, E_k is the energy of the upper level, $Z(T)$ is the partition function, h is the Planck's constant, k_B is the Boltzmann's constant and c is the speed of light. Thus, the electron temperature can simply be calculated by using Eq. (1), from the intensity ratio (I_1/I_2) of two spectral lines