Dynamics of Fireballs

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(Received: 30 August 2008 / Accepted: 13 December 2008)

New forms of anode double layers, called "fireballs", have been observed in a thin unmagnetized discharge plasma. A fireball can appear on a small additional electrode biased positively with respect to the unperturbed plasma potential above the ionization potential of the background gas. They are created by excitation and ionization processes in front of the electrode. A double layer separates the fireball from the ambient plasma. One novel form of fireball is a long cylindrical firerod. Such types were previously only seen in magnetized plasmas. Also a pear-shaped fireball has been observed in a dipole magnetic field. In this case a permanent magnet is fixed behind the electrode. By pulsing the electrode voltage the dynamics of fireballs have been investigated. Axial and radial growth and decay have been studied. Ballistic ions and ion acoustic waves are generated by dynamic fireballs. High frequency oscillations near the electron plasma frequency are observed inside fireballs. These may not be produced by beam-plasma interactions since the fireball can be smaller than a plasma wavelength. Sheath-plasma instabilities may produce such high frequency oscillations.

Keywords: Fireball, electron impact excitation, electron impact ionization, ballistic ion modes, ion acoustic waves, high frequency instabilities

1. Introduction and setup

When a positively biased electrode is immersed into a low-pressure dc discharge (of a few 10^{-3} mbar) frequently a localized glow around the electrode is visible which is due to the acceleration of electrons to energies sufficient for electron-neutral excitations (on the order of 10-20 eV). This can occur in the sheath around the electrode, but the luminous boundary often expands to much larger distances from the electrode than the Debye length. In this case a double layer has formed in the plasma and the fireball becomes a highly nonlinear structure, involving the physics of ionization, double layers, beams and associated instabilities. Although much work has been done [1-7] there are many open questions as regards the time-space evolution, stability and properties in magnetic fields. Some of these will be addressed in this contribution.

Recently also thorough investigations of fireballs in argon plasma by means of optical emission spectroscopy were carried out and many Ar^{I} and Ar^{II} lines were identified in the spectrum across the fireball [8]. Outside the intensity of the spectra dropped sharply.

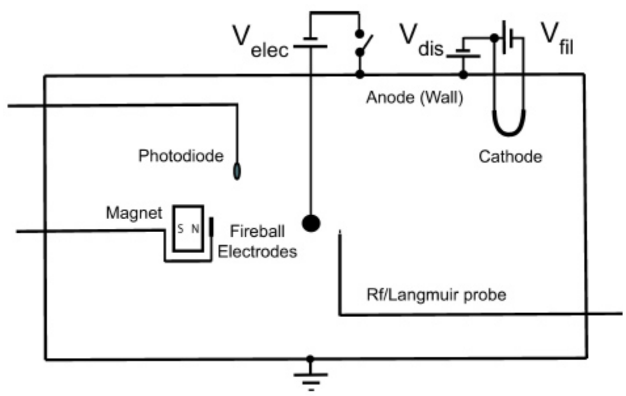

Fig. 1. Schematic of the experimental setup, the Innsbruck DP-machine, where the separating grid was removed in order to create a greater volume of homogeneous plasma. The plasma confinement is strongly improved by a cage of strong permanents magnets on the inner chamber walls.

Fireballs are studied in a simple dc discharge device [3,5-7]. A filamentary cathode, biased negatively with respect to the grounded chamber wall, produces plasma densities of 10^8-10^9 cm^{-3} in Ar, Ne and H_2 at pressures of 1…5×10^{-3} mbar. Either a spherical brass electrode or a stainless steel disk electrode of 1 cm diameter each is inserted into the unmagnetized plasma of the Innsbruck DP-machine. The separating grid of the DP-machine was removed (see Fig. 1). The electrode is biased positively with a dc or pulsed voltage of the order of 100 V. The visi-

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ble structure of the fireballs is recorded with a digital camera. A movable, coax-fed Langmuir probe is used to study density, waves and beams. A movable photodiode provides space and time resolved light measurements. A strong permanent SmCo magnet (0,2 T, 2,5 cm diameter) is used to produce fireballs in a dipole magnetic field.

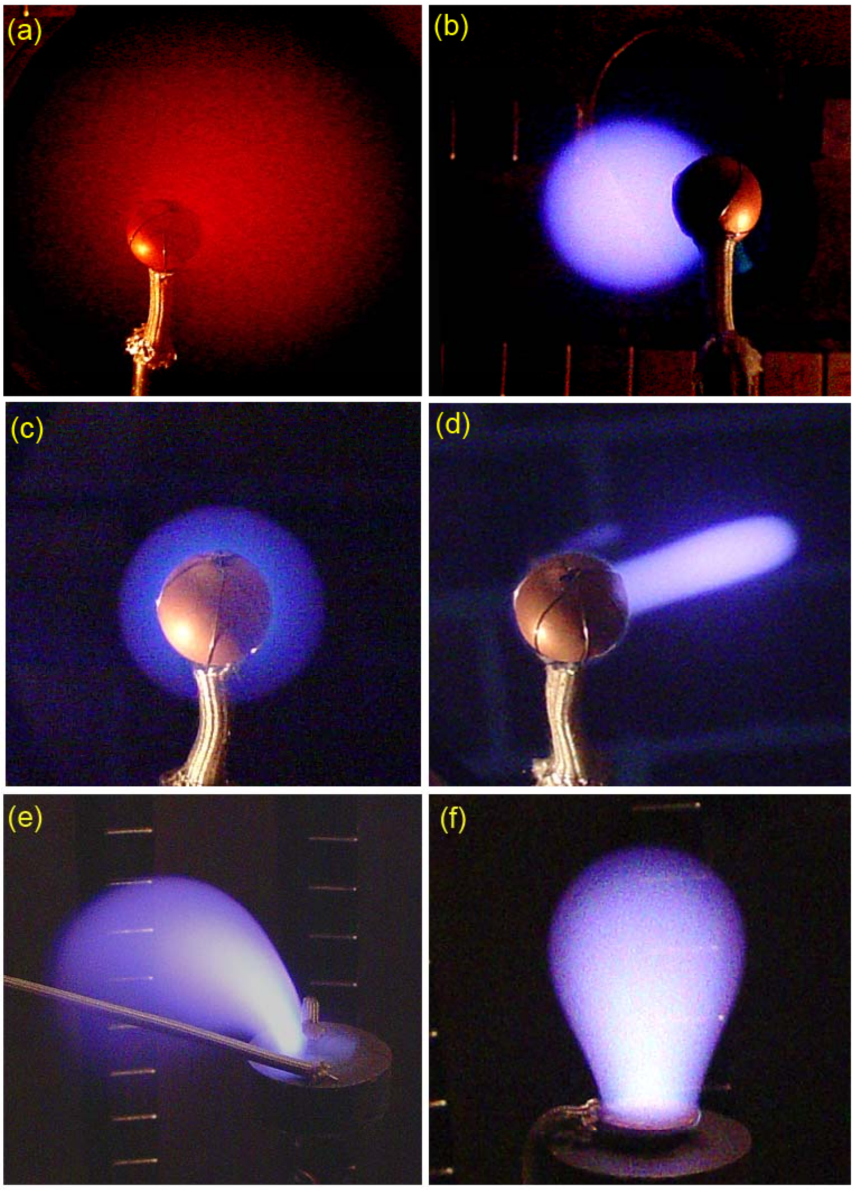

Fig. 2. Images of different fireball formations: (a) Unstable fireball in neon, which appears diffuse due to fluctuations. (b) Stable spherical fireball on argon whose sharp boundary indicates the presence of a double layer. (c) Luminous sheath at voltages below the threshold for fireball formation. (d) Firerod in an unmagnetized argon plasma. (e) Fireball in hydrogen on a disk electrode in a dipole magnetic field. The magnetic field is produced by a strong permanent magnet (SmCo) inserted off-axis behind the disk. (f) In this case the magnet is fixed on the axis of the disk.

2. Experimental results and discussion

Figure 2 shows some of the different shapes of fireballs observed. A fireball in neon with diffuse boundary is shown in Fig. 2a. Figure 2b shows a stable fireball in argon with a sharp boundary. Many previous experiments have shown the existence of a double layer at this boundary [3,5-8]. The spherical shape forms self-consistently irrespective of the shape of the electrode. The radius decreases with increasing electron density (cathode temperature, electrode voltage) and gas pressure. The size and location are sensitive to probe perturbations, which upset the balance between plasma production and losses in the fireball. So it is not easy to introduce a probe into a fireball, but if the probe is sufficiently small and enough care is taken it can be done.

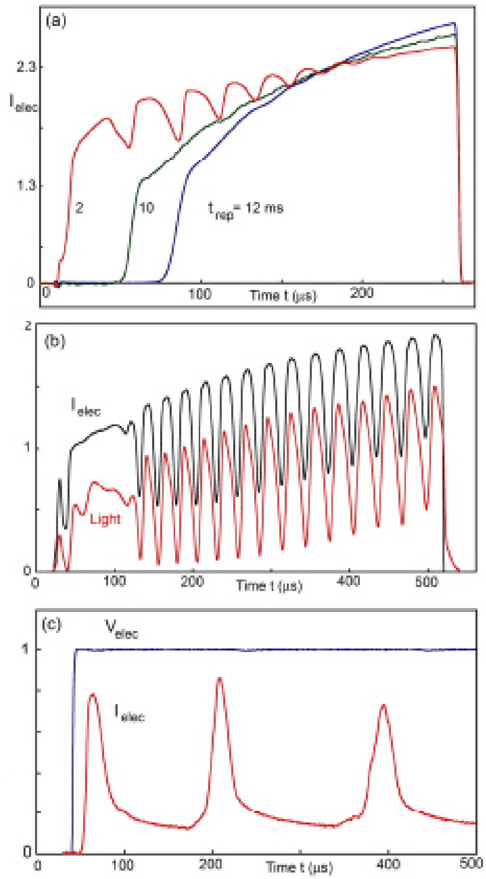

Fig. 3. (a) Electrode currents in an unmagnetized Ar plasma for different pulse repetition times. No background discharge is provided (V_{dis} = 0). The fireball onset and stability depends on the background density which decreases with increasing repetition time.
(V_{elec} = 58 V, $I_{elec,max}$ = 0.2 A, pulse width 250 µs, p = 3.8×10^{-3} mbar Ar)

(b) Electrode current and light emission in a magnetized argon plasma. Note the delayed onset of a strong instability which partly disrupts the current and light emission. Its frequency decreases from 41.7 to 32.3 kHz. After current switch-off the light decreases with a decay time of τ = 6 µs.
(V_{dis} = 20 V, V_{elec} = 55 V, t_{rep} = 1 ms, p = 5×10^{-3} mbar)

(c) Electrode voltage and current in a Ne plasma). The fireball is highly unstable with short current pulses and long repetition times which are determined by the plasma dynamics in the chamber rather than in the fireball.
(V_{elec} = 80 V, V_{dis} = 30 V, t_{rep} = 1 ms, $I_{dis,max}$ = 180 mA, p = 9×10^{-3} mbar)

Figure 2c shows a luminous sheath at voltages below the threshold for fireball creation. It is concentric with the spherical electrode and reveals a radial electric field. Figure 2d shows an argon firerod [2,3], which is frequently seen in magnetized plasmas. However, in the present case there is *no* magnetic field and the rod can form in different directions. Surface conditions of the electrode do not determine its direction since the rod is invariant upon rotation of the sphere. The influence of surface effects was recently also investigated to a certain extent [8].

Finally, Fig. 2e and f show fireballs in hydrogen on the disk electrode in the dipole field of a strong SmCo magnet. When the magnet is inserted off-axis behind the positively biased disk a localized fireball forms on part of the surface, usually off-axis, while other regions show a luminous sheath. The fireball follows the diverging field lines. An axially symmetric fireball is formed with the disc electrode centered in the middle of the magnet. We obtain a pear-shaped fireball which is less sensitive to probe perturbations than the unmagnetized fireballs. Since the electrons are magnetized they can only be energized along the magnetic field near the spherical boundary.

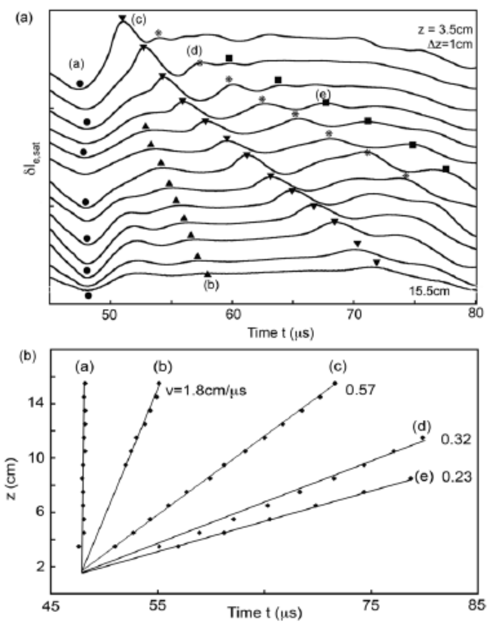

Fig. 4. (a) AC component of electron saturation current versus time at different axial positions measured from the surface of the electrode outside the fireball.
(b) z–t diagram of perturbations in $\delta I_{e,sat}$. The first perturbation (a) is instantaneously present at all locations, hence is thought to be a global plasma potential change occurring on the electron time scale. The following perturbations (b-d) travel at supersonic speed and are interpreted as ballistic signals of streaming ions [9]. The last perturbation (e) travels at the ion acoustic speed for kT_e = 2 eV.
(V_{elec} = 65 V,. V_{dis} = 0, I_{elec} = 70 mA, 3.6 mbar, argon)

The formation of fireballs depends on many parameters (electrode voltage V_{elec} and current I_{elec}, discharge current I_{dis} and voltage V_{dis}, neutral gas type and pressure p, pulse length t_{pulse} and repetition rate t_{rep}) and therefore produces a variety of effects. In particular the stability of fireballs can vary considerably. Some examples of stable and highly unstable electrode currents I_{elec} are shown in Fig. 3.

After the disruption of a fireball, several ion ballistic and ion acoustic phenomena can be observed. Figure 4a shows the temporal evolution of the probe signal taken at increasing distances from the electrodes and Fig. 4b the corresponding time-of-flight diagram for the propagating density perturbations in argon. In both figures the various propagating phenomena are indicated by (a) - (e): (a) is a change of the plasma potential occurring on the electronic time scale; (b) - (d) are ballistic ion modes corresponding to different acceleration voltages; (e) is an ion acoustic wave travelling away from the fireball after its disruption.

In spite of the excitation and ionization processes which are important here, there are certain similarities of the results with an early work on highly supersonic ion pulses propagating away from the cold plate of a Q-machine when a high voltage pulse is applied to it [9].

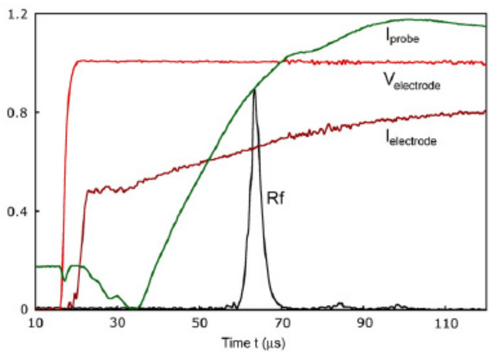

Fig. 5. Turn-on of a stable fireball with electrode voltage and current, Langmuir probe current and 136 MHz rf signal. A sharp line is produced since the density increases at turn-on and the frequency scales with plasma frequency. (V_{elec} = 63 V, $I_{elec,max}$ = 116 mA, V_{dis} = 26 V, t_{pulse} = 0.5 ms, t_{rep} = 1.1 ms, $p = 4\times10^{-3}$ mbar Ar).

Double layers are well known to produce ion and electron beams both of which can create instabilities. Therefore also the double layer at the boundary of a fireball creates an electron beam inside itself, which can potentially excite electron plasma waves. We have observed high-frequency oscillations inside a fireball, as shown in Figs. 5 - 7. The signals were taken by a small Langmuir probe used as rf probe after the same probe has first registered the rise of the electron saturation current inside the fireball. The rf signal was fed into a tunable small bandwidth amplifier tuned to the desired rf.

The rf signals appear as well-localized peaks on the time axis (Fig. 5 and 6). Our interpretation is therefore that the frequency equals the plasma frequency and thus reflects the plasma density present in the fireball at this moment during the temporal evolution of the fireball. Consequently Fig. 6b shows a drop of the frequency during the decay of a fireball when its density and thus also the local plasma frequency drop.

3. Conclusion

When a positive voltage step (≅ 100 V) is applied to an electrode in a weakly ionized plasma the collected current shows a dramatic rise after a short delay. Light emission is produced by inelastic electron-neutral collisions requiring electron energies of more than 15 eV. Ionization also occurs at this energy level. If an electron-ion pair is created in the sheath the electron is rapidly collected while the ion takes more time to be accelerated away from the electrode. This leaves an excess positive space charge layer in the originally electron-rich sheath. A double layer is created which moves away from the electrode as the ions are accelerated. The increasing surface area of the double layer allows for larger electron currents to be collected from the background plasma and a fireball is created.

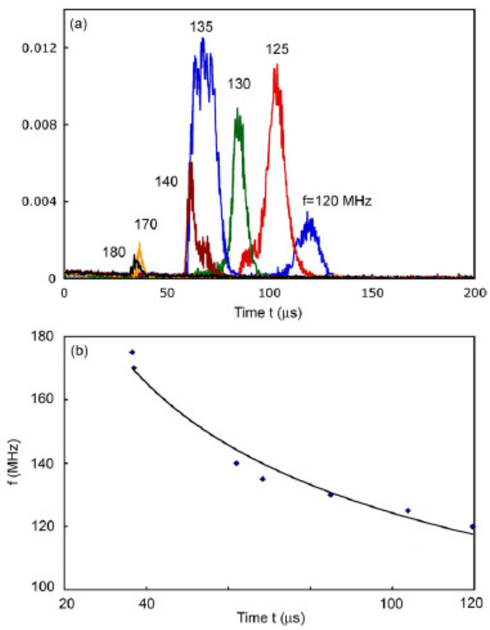

Fig. 6. (a) Rf emission lines versus time at different frequencies; (b) Frequency versus time showing a decay due to a density drop in time.

The delicate space charge balance frequently leads to very unstable situations. When a fireball disrupts various density perturbations propagate into the surrounding plasma. Double layers as such produce ion and electron beams both of which can create instabilities. The electron beam inside a fireball can potentially excite electron plasma waves. Consequently we have also observed high-frequency oscillations inside a fireball.

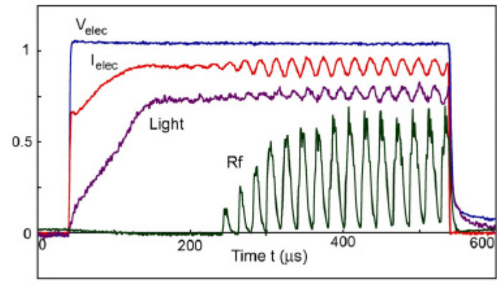

Fig. 7. 100 MHz rf emission lines from a pulsed fireball which becomes weakly unstable in time.
(V_{elec} = 58 V, $I_{elec,max}$ = 150 mA, V_{dis} = 0, t_{pulse} = 0.5 ms, t_{rep} = 1.1 ms, $p = 3.7\times10^{-3}$ mbar Ar).

Acknowledgement

This work was supported by the University of Innsbruck, by project L302-N02 of the Austrian Science Fund and the Excellentia Programme for graduated women of the University of Innsbruck.

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