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Plasma Fireballs

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Abstract: Fireballs are localized discharge phenomena on positively biased small additional electrodes in thin plasmas with a sufficiently high background gas pressure. They appear as sharply bounded spherical or cylindrical space charge structures with a higher luminosity, density and plasma potential than the ambient plasma. Originating from a normal electron-rich sheath in front of the additional anode, a fireball can appear as soon as the electrons, accelerated in this sheath, surpass the ionization energy of the background gas. Eventually the sheath detaches from the electrode and a double layer (DL) is formed at the boundary of the fireball. The DL's height must be higher than the ionisation energy of the background gas. The appearance of fireballs is accompanied by hysteretic current jumps in the electrode's current-voltage characteristic. They can become unstable to relaxation oscillations. Growth and collapse of fireballs produce large density and potential variations near the electrode and the background plasma. Unstable fireballs emit bursts of fast ions and ion acoustic waves. High frequency emissions near the electron plasma frequency was also observed. New shapes of fireballs were observed in dipole magnetic fields.

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 [1,2,3,4,5,6] 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.

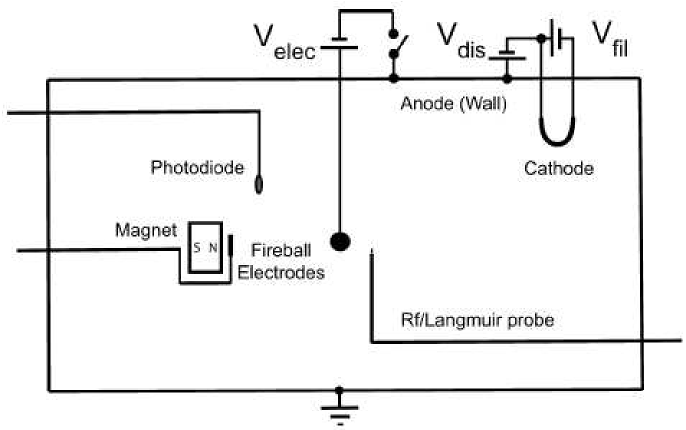

Fig. 1: Schematic of the experimental setup, the Innsbruck DP-machine, where the separating grid was removed in order to create a greater volume of homogeneous plasma. The plasma confinement is strongly improved by a cage of strong permanents magnets on the inner chamber walls.

Fireballs are studied in a simple dc discharge device [3,5,6]. 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. A spherical brass electrode of 1 cm diameter is inserted into the unmagnetized plasma of the Innsbruck DP-machine with the separating grid removed (see Fig. 1). The electrode is biased positively with a dc or pulsed voltage of the order of 100 V. The visible 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 magnet (0,2 T, 2,5 cm diameter) is used to produce fireballs in a dipole magnetic field.

Fig. 2 shows some of the different shapes of fireballs observed. A fireball in neon with diffuse boundary is shown in Fig. 2a. Fig. 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]. 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. Fig. 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. Fig. 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. Finally, Fig. 2e and f show fireballs in hydrogen in the dipole field of a strong SmCo magnet. When the entire magnet is biased positively 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 a 1 cm diameter disc electrode centred in the middle of the magnet. It forms a pear-shaped fireball. It 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.

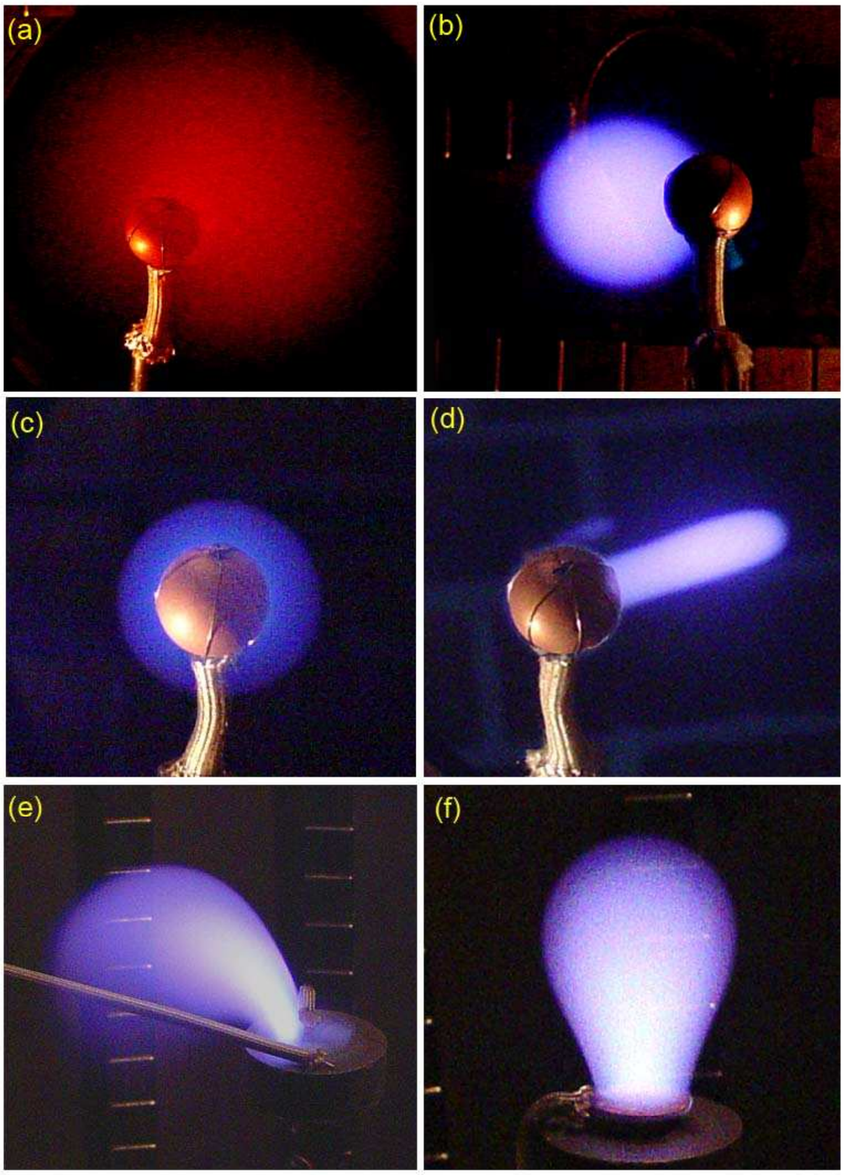

Fig. 2. Images of different fireball formations: (a) Unstable fireball in neon, which appears diffuse due to fluctuations. (b) Stable spherical fireball on argon whose sharp boundary indicates the presence of a double layer. (c) Luminous sheath at voltages below the threshold for fireball formation. (d) Firerod in an unmagnetized argon plasma. (e) Fireball in hydrogen in a dipole magnetic field off-axis and (f) on axis.

The time evolution of fireballs has been studied with a pulsed electrode voltage. The rise time for current and light is a few microseconds. The light decay is much slower than the current decay since the energetic electrons are no longer collected by the electrode but must thermalize in the plasma. Pulsing the fireball also produces transient responses in the electron saturation current of probes. Axial and radial time-of-flight measurements have shown ballistic ions and ion acoustic waves emitted from the fireball. The latter may be due to ion-beam plasma instabilities. Using a high-frequency receiver (10-500 MHz) the excitation of plasma waves inside a fireball has been detected. These indicate the presence of electron beams produced at the double layer. When plasma production and losses get out of balance the fireball can undergo relaxation oscillations, which have earlier been analyzed within the framework of chaos [5]. These produce similar transient effects as pulsing the electrode voltage. Thus, unstable fireballs produce bursts of particles and waves, little of which have been studied in magnetic fields.

Acknowledgements

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