Pulsed, unstable and magnetized fireballs

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Abstract: Fireballs are nonlinear space charge structures with higher plasma density, potential and luminosity in front of positively biased electrodes in weakly ionized plasmas. They are bounded by a double layer whose potential step is of the order of the ionization potential of the background gas. A fireball is an integral part of the entire discharge plasma. We have investigated fireballs created by highly transparent grids which allow electron transmission through the electrodes and optimize the ionization efficiency.

1. Introduction

The study of discharge phenomena near positively biased electrodes in plasmas has a long history [1]. Much attention has been focused on so-called fireballs. Previous investigations were devoted to their stability [2], the current-voltage characteristics of the electrode [3,4], single and multiple double layers [5], chaotic behaviour [6] and fireballs in uniform magnetic fields [7]. In spite of these extensive efforts many open topics still remain. We have proven that large fireballs act as anodes thereby determining the bulk plasma density. Vice versa, the plasma source can limit the strength of the fireballs. Fireballs can also appear in afterglow plasmas, by temperature or space-charge limited emission (hot cathodes) and by sputtering producing intense fireball pulses (70 A, 450 V). The physics of unstable fireballs is addressed and novel fireball properties in mirror and cusp magnetic fields are presented.

2. Experimental set-up and results

The experiments were performed in the Innsbruck dc discharge device [8] (cylindrical vacuum chamber with a diameter of 45 cm and 90 m length) with surface magnets for primary electron confinement (see Fig. 1a). Unmagnetized plasma (density $n_e = 10^8$–10^9 cm^{-3}, electron temperature $kT_e \cong 2$ eV) was produced in Ar, He and Ne at pressures of 1–5·10^{-3} mbar. Two types of cathodes were used, either standard incandescent tungsten wires (two filaments, each 0,5 mm diameter, 5 cm long) or a barium oxide-coated nickel wire (5 cm long) possessing very different emission properties. Fig. 1b shows the current-voltage characteristics of the cathodes. The W cathode has a temperature-limited emission at about 1800 C° producing co-

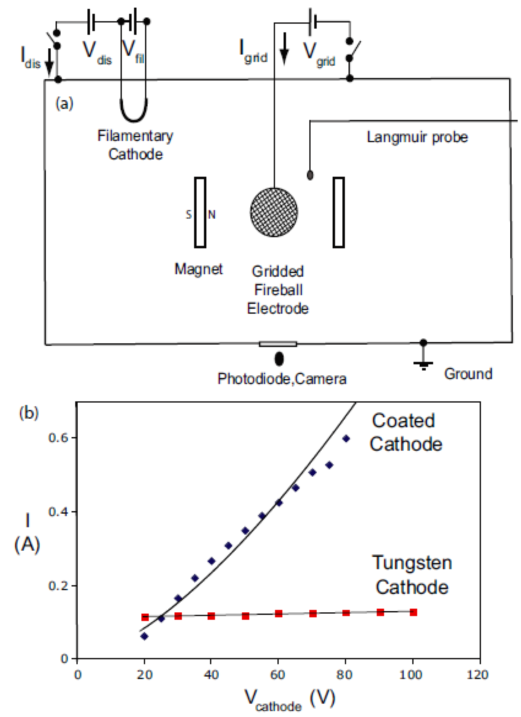
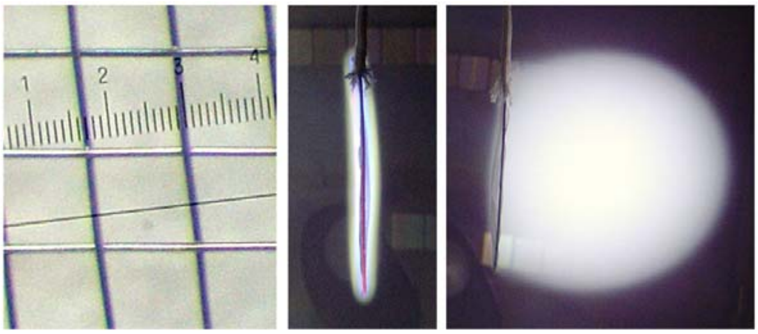


Fig. 1: (a) Experimental setup. (b) Current-voltage characteristics $I_{dis}(V_{dis})$ of a coated cathode, showing space-charge-limited emission (line $I \sim V^{3/2}$), and a W cathode with temperature-limited emission.

pious light which can interfere with the observation of fireballs. The coated cathode has a space charge-limited emission at only 800 C where the current increases with voltage. It produces little heat and light and can emit up to $I > 30$ A in pulsed mode. In steady state the coating and filament would be destroyed. In the present experiments mostly the coated cathode has been used.

In the present experiments a transparent grid of 5 cm diameter was used as an electrode, a highly transparent stainless steel mesh (0,25 mm line spacing, 0,02mm wire thickness, this spacing being of the same order of magnitude as the Debye length). Fig. 2a shows the grid, whereas Fig. 2b,c show the two most frequent forms of space charge structures in front of the grid: a luminous sheath on both sides of the grid (b), and (c) a fireball on just one side. A self-pulsating fireball was found to assume state (b) during the pulse pauses. Fireballs were investigated both with and without magnetic fields. Non-uniform field configurations of dipoles, mirrors and cusps were generated with two strong SmCo permanent magnets (6,5 cm diameter, 16 cm axial spacing). The conducting magnets are grounded while the grid can be moved radially through the midplane as well as inclined with respect to the field.

A large fireball can draw currents comparable to or larger than the discharge current. During the evolution of a fireball [8] electrons are accelerated in the sheath of the positively biased electrode, excite and ionize neutrals, which leads to an expansion of the sheath into a double layer of potential just above the ionization potential. A stable double layer is formed when the



(a) **(b)** **(c)**

Fig. 2: (a) Expanded view of the electrode grid. (b) Luminous sheath on both sides of a positively biased grid. (c) Fireball forming only on one side of the electrode (V_{grid} = 50 V, I_{grid} = 0,1 A, $p \approx 10^{-3}$ mbar Ar).

pressures nmv^2 of the accelerated electrons and ions balance, which implies an electron-to-ion current density ratio $j_e/j_i = (m_i/m_e)^{1/2}$, where $m_{e,i}$ are the electron and ion masses, respectively [9]. Pressure balance can also explain the spherical or elliptical shape of fireballs since its lack would not lead to a stationary configuration.

As observed by many investigators, fireballs can be highly unstable. One form of instability is a repetition of fireball pulses [4,10]. The detailed mechanism of the instability has not yet been fully explained but the general understanding is that a steady state is only achieved when ionization in the fireball exactly replaces the ions ejected. For a high-current fireball Fig. 3 shows growth and collapse, leading to the conclusion that plasma depletion in front of the electrode leads to electron drifts exceeding the thermal velocity which triggers the current disruption. The pulse width is determined by the sound speed and fireball dimension. Fig. 3 show simultaneous measurements of the light emission, grid current and density. The ratio of grid current to the ion saturation current, which is proportional to the electron drift velocity ($v_{d,e} \sim I_{grid}/n$), is also shown. The density is obtained from the ion saturation current of a small Langmuir probe (0.25mm diameter, 5mm length) located at 1 cm in front of the grid centre inside the fireball. For a peak probe current $I_{i,sat} \cong 50$ µA, probe area $A = 3{,}9\ \mathrm{mm}^2$ and sound speed $(kT_e/m_i)^{-1/2} \cong 2\cdot10^5\ \mathrm{cm\,s^{-1}}$ one finds a peak density $n \cong 4\cdot10^{10}\ \mathrm{cm^{-3}}$.

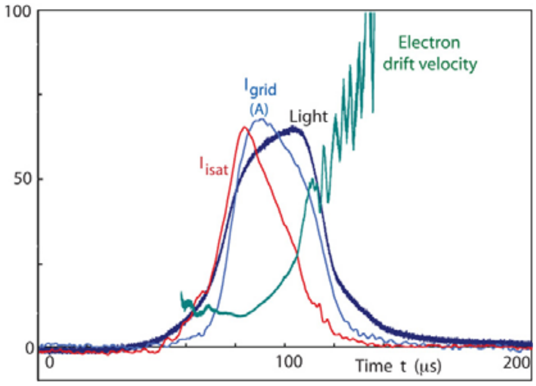


Fig. 3: Unstable high-current fireball. The time dependence of the fireball current shows a half width of $\Delta t \cong 20$ µs with $I_{grid,max} \cong 70$ A at a constant $V_{grid} = 450$ V). The light emission (arbitrary units) indicates electron energization by a double layer. The ion saturation ($I_{i,sat} \cong 50\ \mu$A at $V_{probe} = -80$ V) to a Langmuir probe 1 cm in front of the grid shows a strong increase during the fireball, indicating heating and ionization. The ratio of collected electron current (I_{grid}) to ion saturation current ($I_{i,sat} \sim$ density) is proportional to the electron drift velocity. The current collapses when the drift velocity exceeds the electron thermal velocity.

During the growth of the fireball, plasma density, grid current and light rise approximately together (Fig. 3). First, the density begins to collapse, then the current and light decrease. This sequence of events establishes clearly the cause-effect relation. At the peak density and current the electron drift velocity is $v_{d,e} = I_{grid,max}/(ne2\pi r^2) \cong 2{,}8\cdot10^8\ \mathrm{cm\,s^{-1}}$ comparable to the electron thermal velocity $v_{t,e} = 2{,}3\cdot10^8\ \mathrm{cm\,s^{-1}}$ at $kT_e \cong 15$ eV. Note that the fireball electrons have been energized at the double layer. As the density decreases the drift speed has to exceed the thermal speed which is impossible due to the Buneman instability. Under

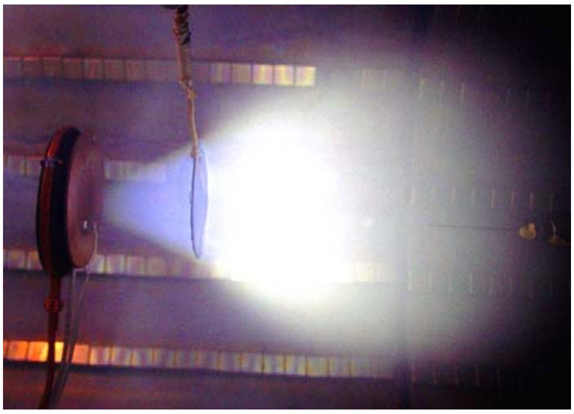


Fig. 4: Pear-shaped fireball in a diverging magnetic field from a strong permanent magnet. Energetic electrons pass through the grid and reflect from the magnet due to mirror reflection and a potential drop. Current collection is from the right side only (V_{grid} = 60 V, $I_{grid} \cong$ 0,7 A, V_{dis} = 50 V, $I_{dis} \cong$ 0,35 A,

such conditions the current is either limited by anomalous resistivity or by the formation of a potential well, a “virtual cathode”.

Fig. 4 shows a pear-shaped fireball in a diverging magnetic field from a strong permanent magnet on the right-hand side of the grid and the light between grid and magnet. There is a floating electrode in front of the magnet, no electron source at the magnet and the magnetized electrons move along field lines as seen from the light boundary. Thus, the luminous blue region on the left-hand side is not a current-carrying fireball but is produced by electrons transmitted through the grid and reflected near the magnet. There is a distinct change in colour at the grid. From beam injection experiments we know that 100 eV electrons produce blue light while 15–20 eV electrons produce gray-yellow-white light. Thus the transmitted electrons are much more energetic than those in the fireball. They originate from the cathode and are accelerated by both the discharge and grid voltage which allows them to traverse the grid. The light gap in front of the magnet indicates a significant potential drop which decelerates 100 eV electrons. The mirror effect also reflects electrons outside the loss cone.

Acknowledgments

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