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Fireballs

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FIREBALLS

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Outline

- Fireballs and double layers (DL)
- Various fireballs – multiple fireballs
- Low frequency instabilities around a fireball
- High frequency instabilities inside a fireball
- Newest investigations on pulsating fireballs
- Conclusion

R.L. Stenzel, C. Ionita, R. Schrittwieser, "Dynamics of fireballs", *Plasma Sources Science and Technology* 17 (2008), 035006 (11pp).

R.L. Stenzel, C. Ionita, R. Schrittwieser, "Plasma Fireballs", *IEEE Transactions on Plasma Science* 36 (2008), 1000-1001.

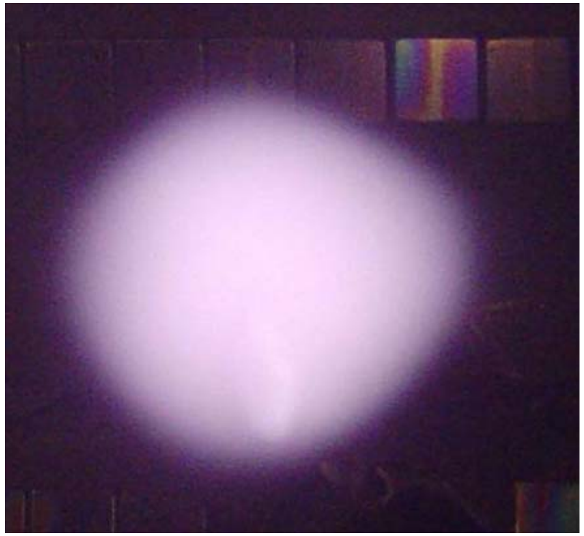
C. Ionita, R.W. Schrittwieser, R. Stenzel, "Dynamics of fireballs", *Journal of Plasma and Fusion Research Series* 8 (2009), 750-754.

R.L. Stenzel, J.M. Urrutia, C. Ionita, R. Schrittwieser, "Positively biased probes in magnetized plasmas", *Contributions to Plasma Physics*, in print.

Ball of fires or fireballs

A positively biased electrode in a thin background plasma (with sufficiently high neutral pressure) can create a "fireball":





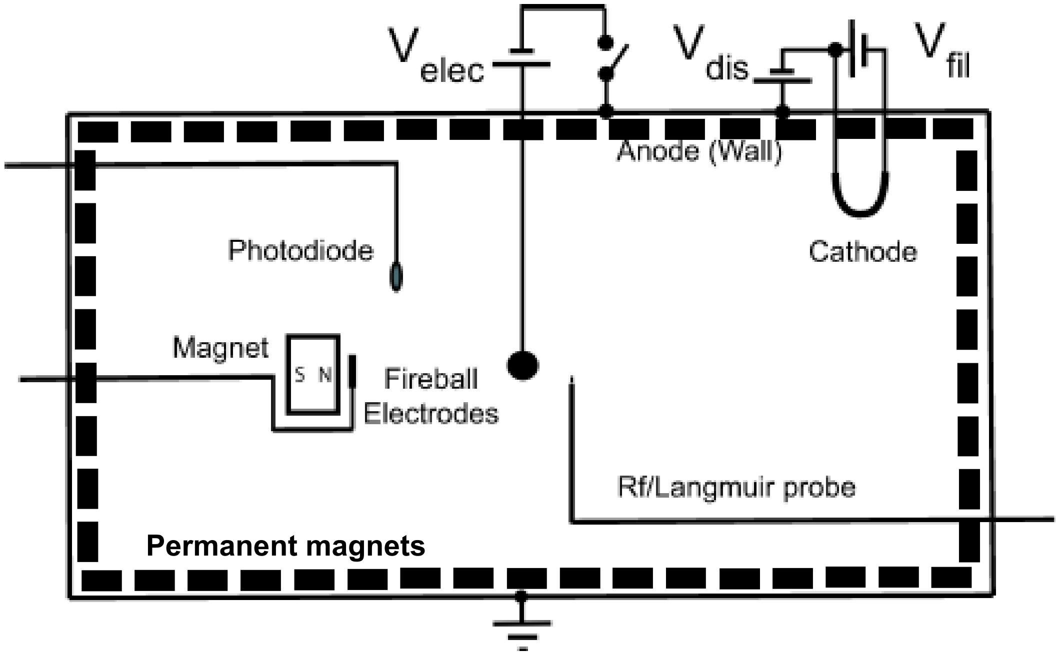
Photos from the Innsbruck DP-machine with $n_{pl} \cong 10^{15}$-10^{16} m^{-3} and $p \cong 0{,}5$ Pa

Left and centre photo: a positively biased electrode of 10 mm diameter:

- **Left photo: electrode glows due to the strong electron current.**
- **Centre photo: electrode is water-cooled.**
- **Right photo: Fine grid of 5 cm diameter is positively biased and fireballs are excited on both sides.**

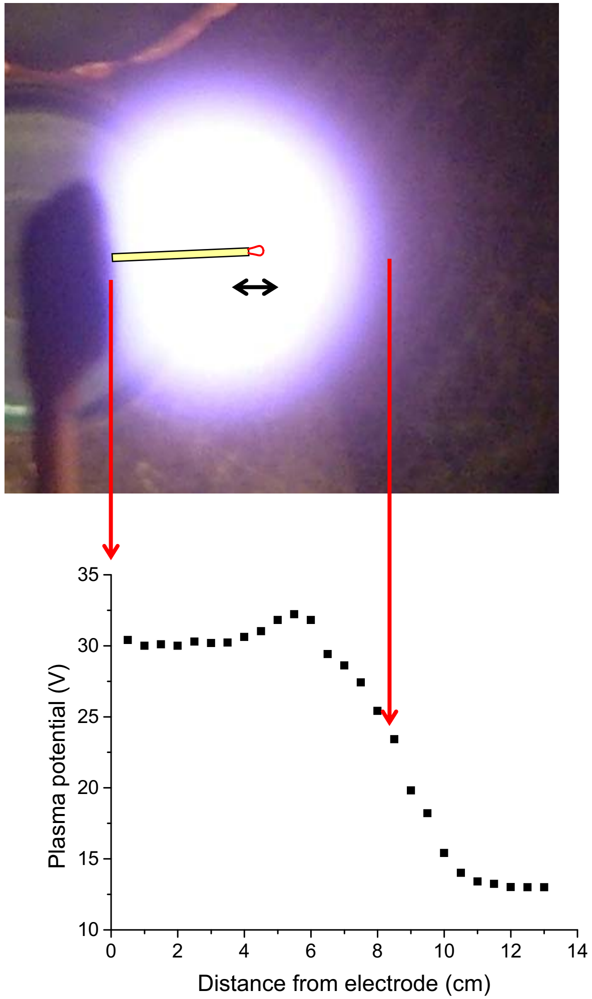
Single fireball with "anode double layer"

Electronic circuit and potential profile:



Schematic of the University of Innsbruck DP-machine:

Separating grid is removed to create a greater volume of homogeneous plasma.



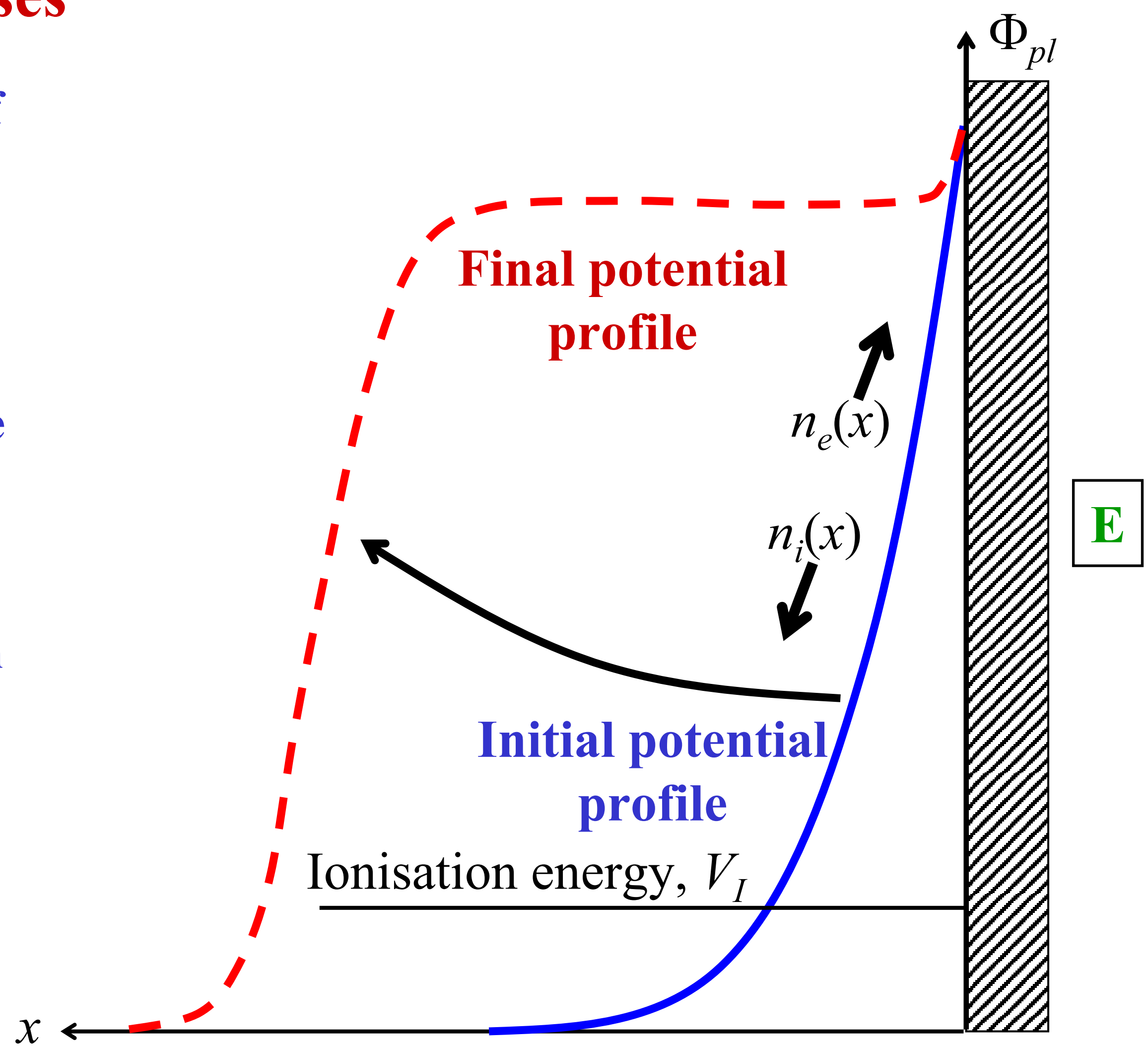
Axial profile of the plasma potential in front of a flat electrode E.

Formation of an anode double layer I

The sheath for high biases

The later observed expansion of the potential profile in front of the electrode E to form a fire-ball is a much more complex process.

For a theoretical approach have to integrate at any point within the sheath the density of electrons, taking into account their impact excitation and ionisation reactions, and of the ions created thereby. This has to be inserted into Poisson's equation yielding a complicated integro-differential equation.



Multiple fireballs (concentric)

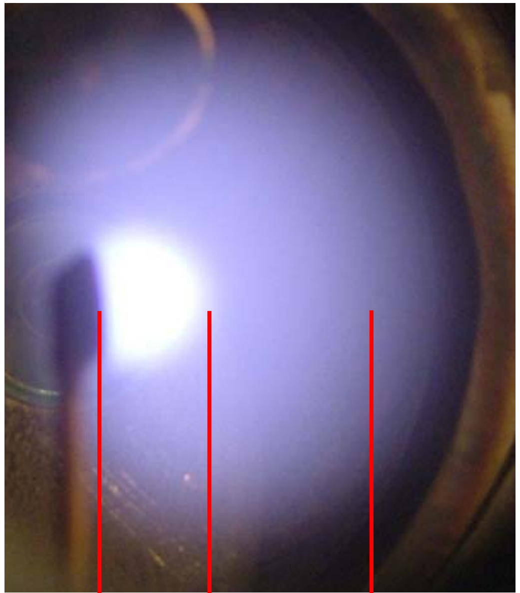
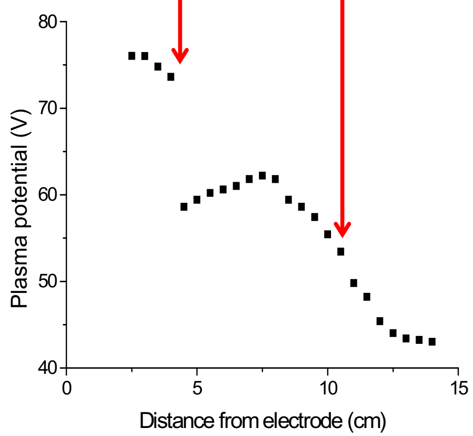
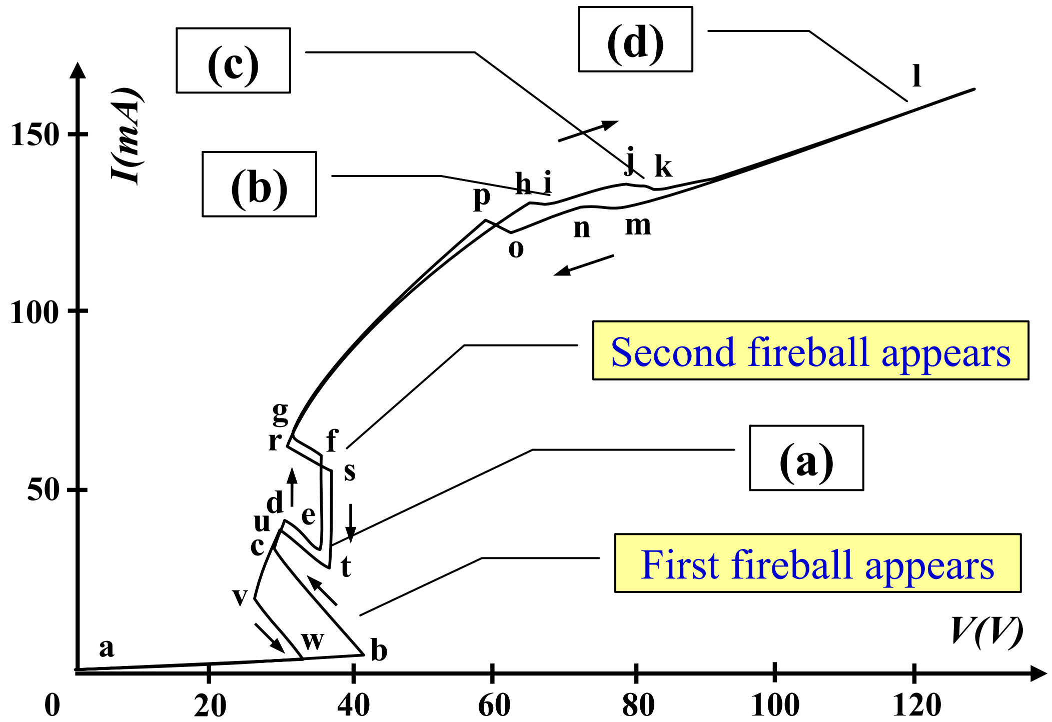


Photo-graphy of a con-centric MFB; electrode diam. 8 mm



Axial profile of the plasma potential in front of E.

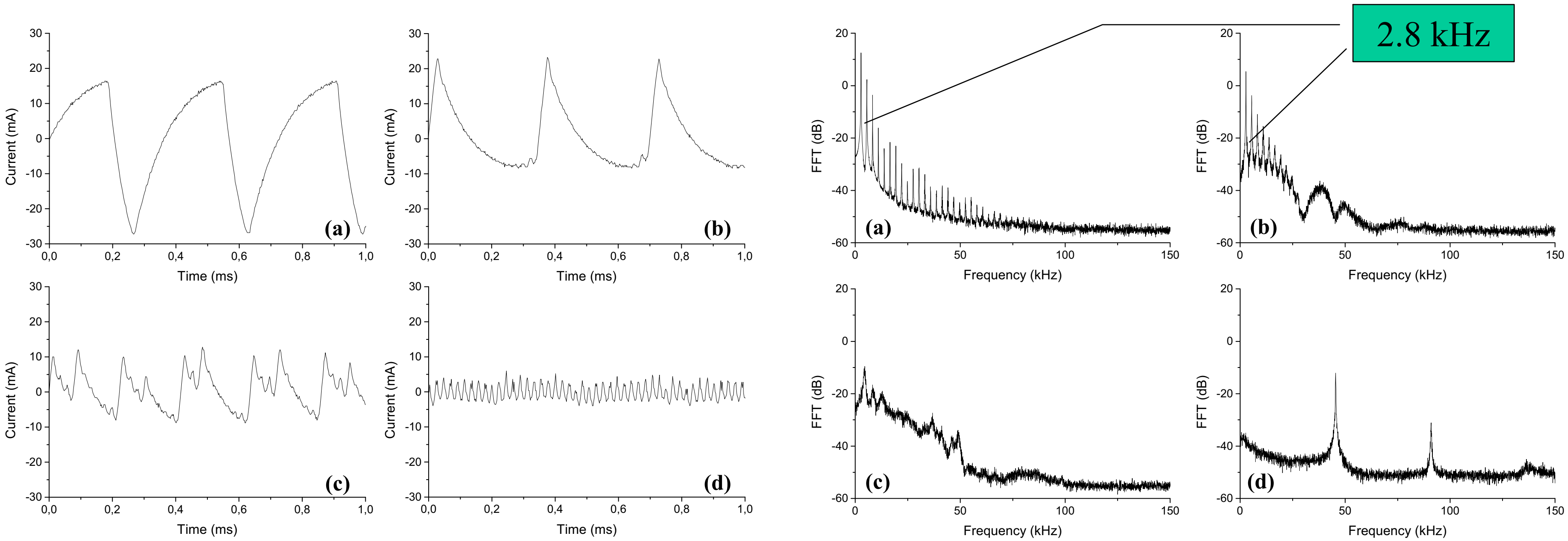
A concentric double fireball with its current-voltage characteristic:



Static current-voltage characteristic in the case of a con-centric double fireball. At each of the hysteretic current jumps (a – d) another type of oscillations appears.

Oscillations associated with the double fireball

Time series and FFTs:

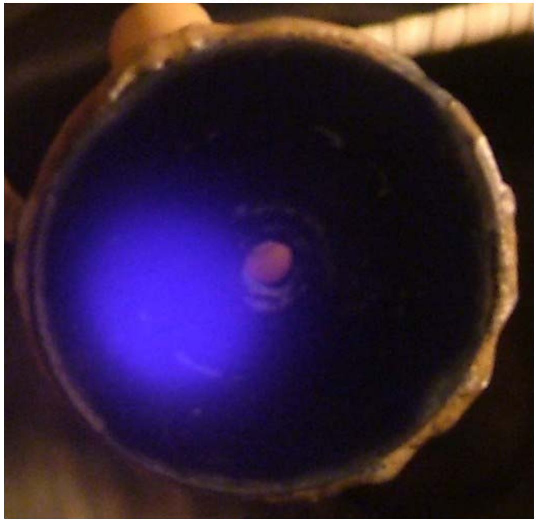


Time series and FFTs of the current collected by the electrode E :

after the current jump d → e (a), after the current jump h → i (b), after the current jump j → k (c), and at high voltage on A (point l) (d).

D.G. Dimitriu, M. Aflori, L.M. Ivan, C. Ionita, R.W. Schrittwieser, "Common physical mechanism for concentric and non-concentric multiple double layers in plasma", *Plasma Physics and Controlled Fusion* 49 (2007), 237-248

Multiple fireballs (non-concentric)



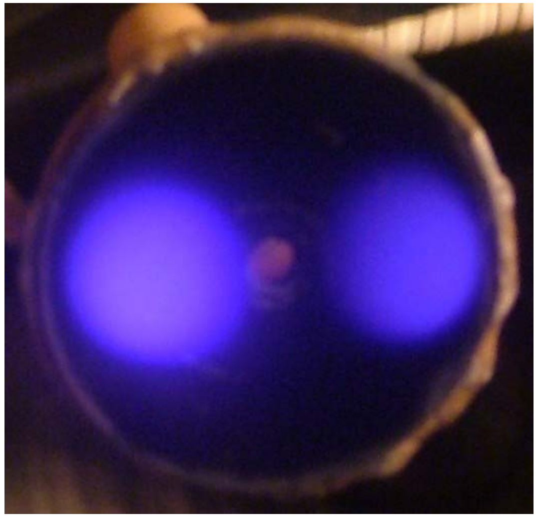
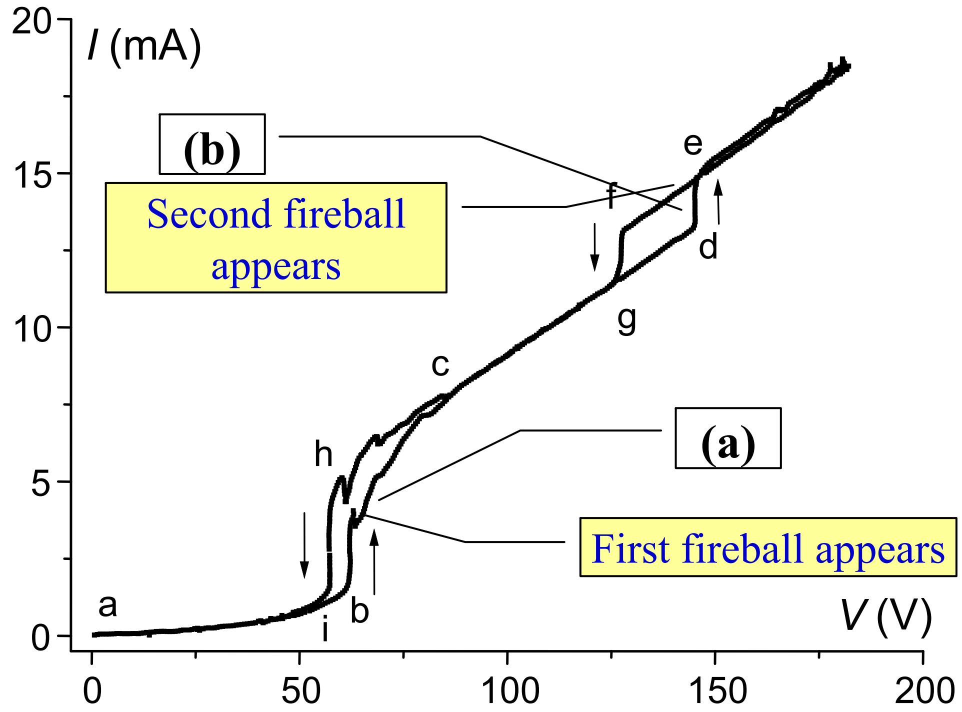


Photo-graphy of a non-concen-tric MFB; elec-trode diam. 30 mm

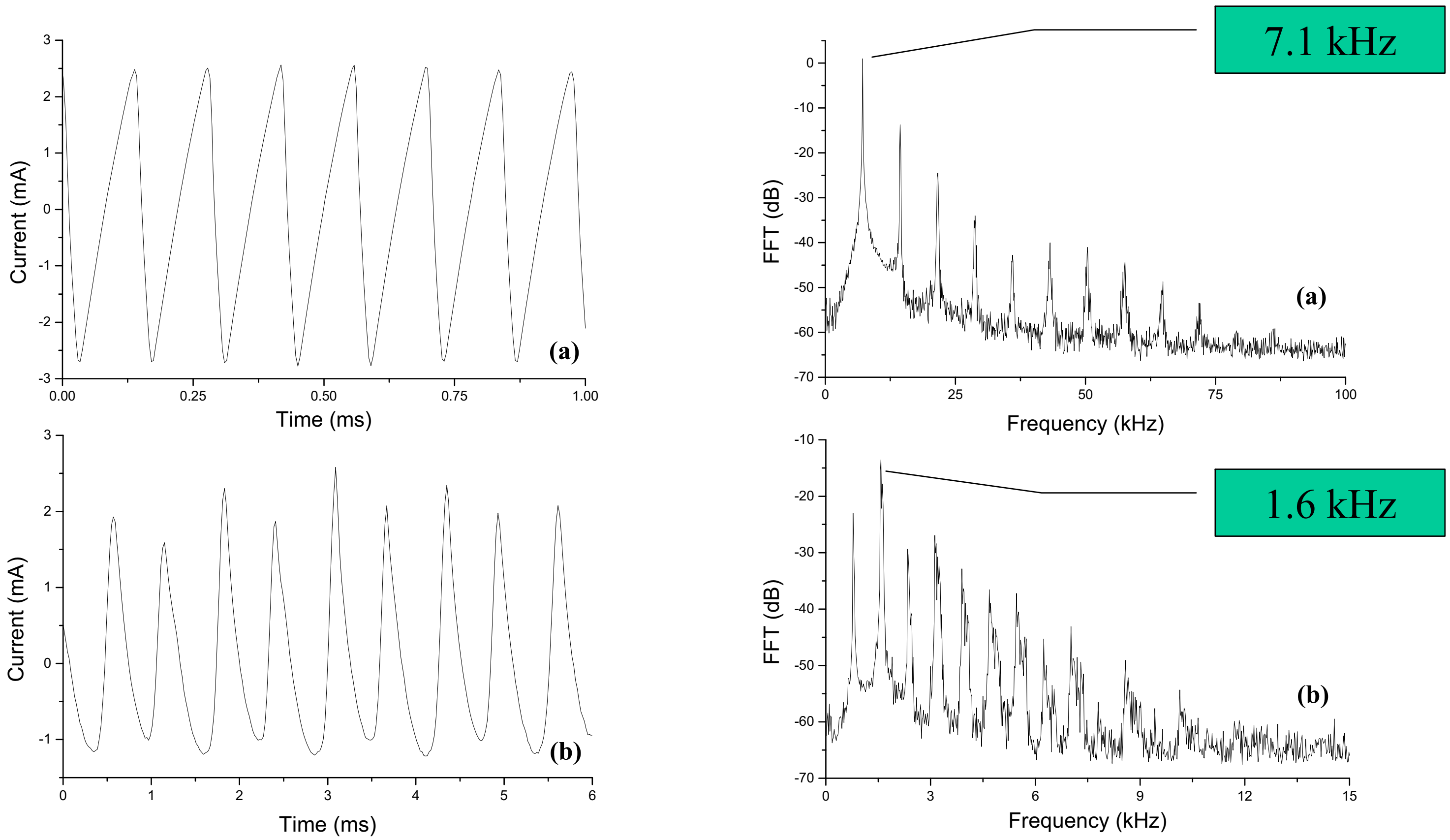
A non-concentric double fireball with its current-voltage characteristic:



Static current-voltage characteristic in the case of a non-concentric double fireball. Also in this case different oscillatory patterns appear at each current jump.

Oscillations associated with the double fireball

Time series and FFTs:



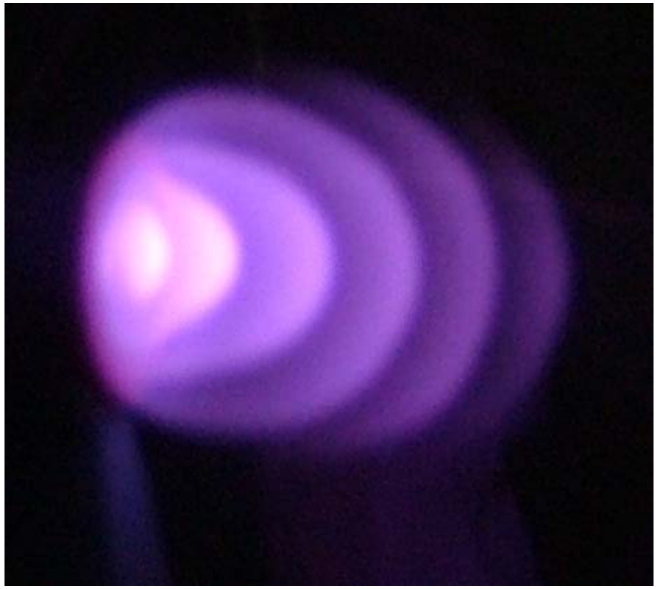
Time series and FFTs of the current collected by E :

after the current jump b → c (a) and after the current jump d → e (b).

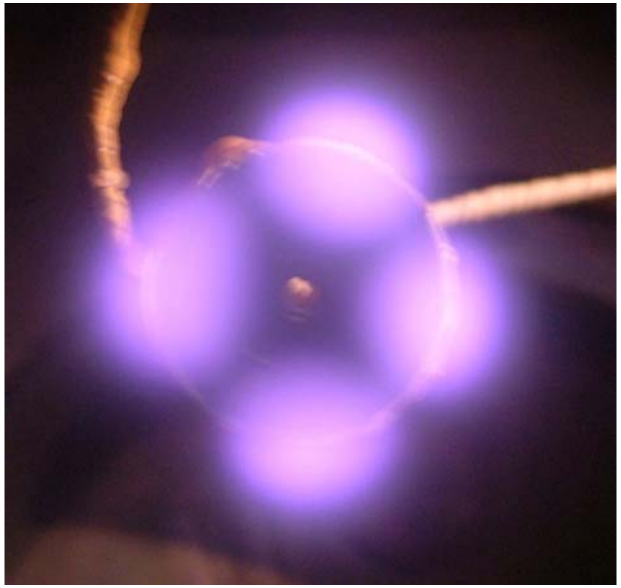
Further variants of multiple fireballs

These can be created by higher biases and/or different forms of the electrode:

A double fireball in a dynamic state

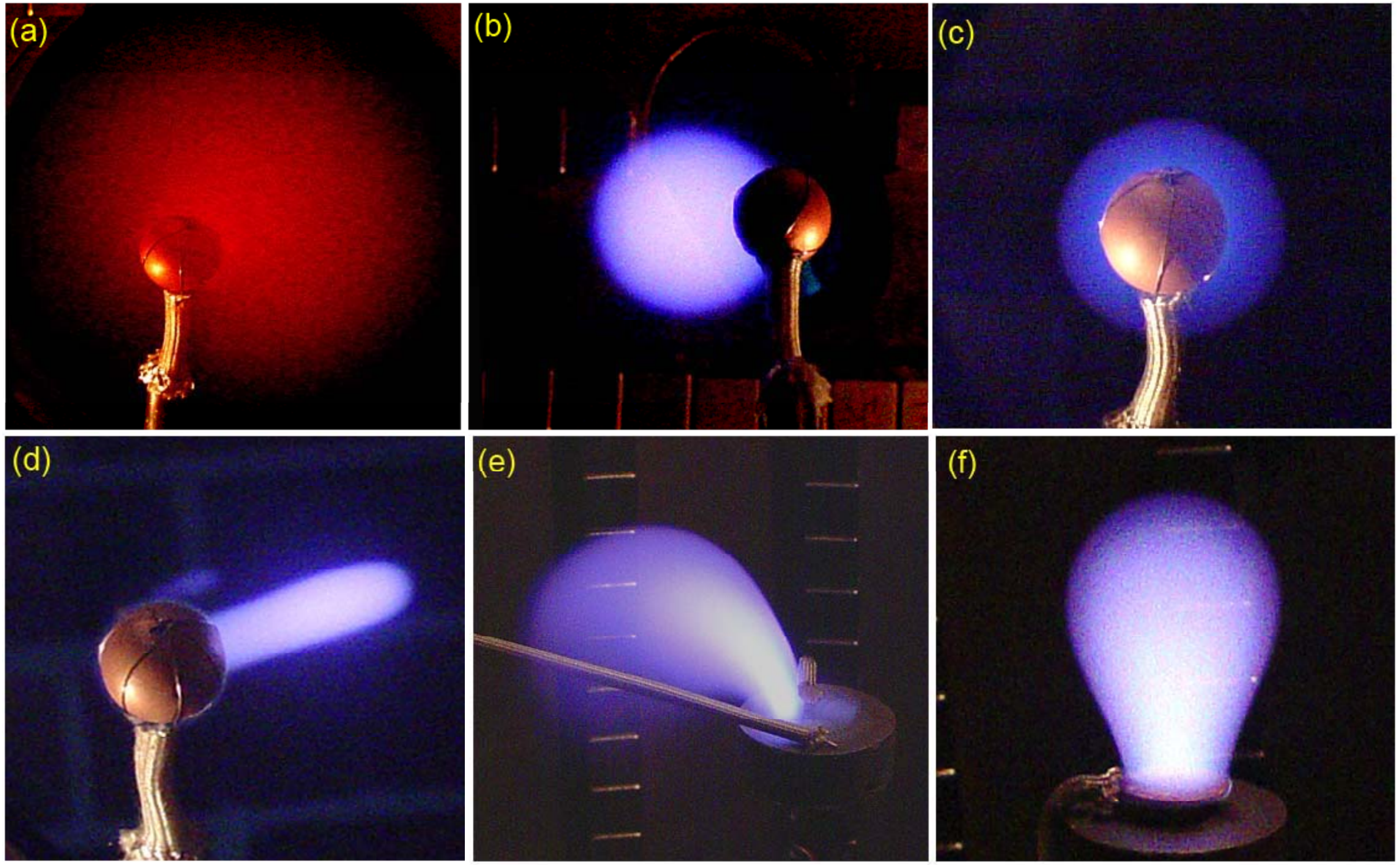


A multiple concentric or onion-shaped fireball



Four plasma spots (non-concentric MDLs) on a large ring electrode

Fireballs in different gases and geometries



(a) Fireball in Ne with diffuse boundary due to fluctuations.

(b) Stable fireball in Ar with sharp boundary formed by a DL. Radius decreases with increasing electron density and gas pressure. Size and location sensitive to probe perturbations.

(c) Luminous sheath at voltages below threshold for fireball creation; concentric with spherical electrode.

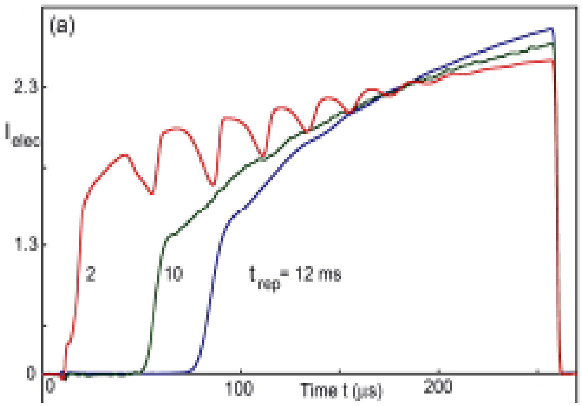
(d) Ar firerod frequently seen in magnetized plasmas. However, here is *no* magnetic field. Surface conditions of the electrode do not determine its direction since rod is *invariant* upon rotation of the sphere.

(e) Fireball in hydrogen on a strong SmCo magnet. When the entire magnet is biased positively a localized fireball forms usually off-axis; fireball follows diverging field lines.

(f) Axially symmetric fireball with a 1 cm diameter disc electrode centred in the middle of the magnet. This pear-shaped fireball is less sensitive to probe perturbations. Since the electrons are magnetized they can only be energized along the magnetic field near the spherical boundary.

Low frequency oscillations and waves I

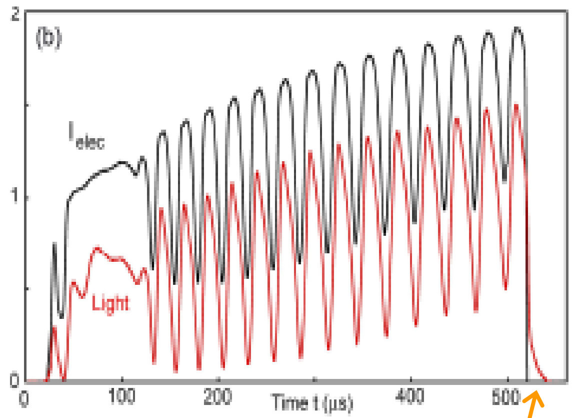
Typical waveforms of electrode current, light and voltage for fireballs in pulsed mode:



(a) Electrode currents for an un-magnetised fireball for different pulse repetition times t_{rep}. No back-ground discharge (V_{dis} = 0 V) in this case.

Fireball onset and stability depends on background density which de-creases with increasing repetition time.

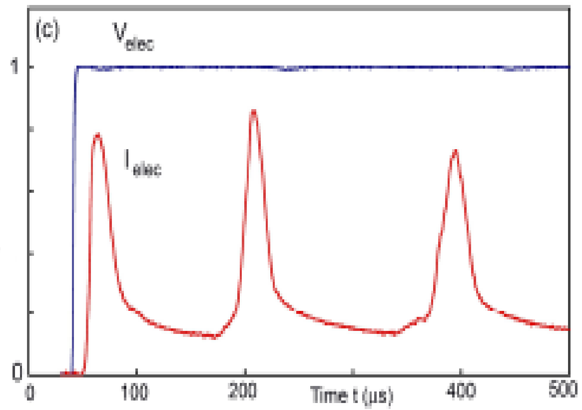
(V_{elec} = 58 V, $I_{elec,max}$ = 0,2 A, pulse width 250 µs, p = 3,8·10^{-3} mbar Ar)



(b) Electrode current and light emission for a magnetized fireball.

Note the delayed onset of a strong instability which partly disrupts the current and light emission. Its fre-quency 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 Ar)



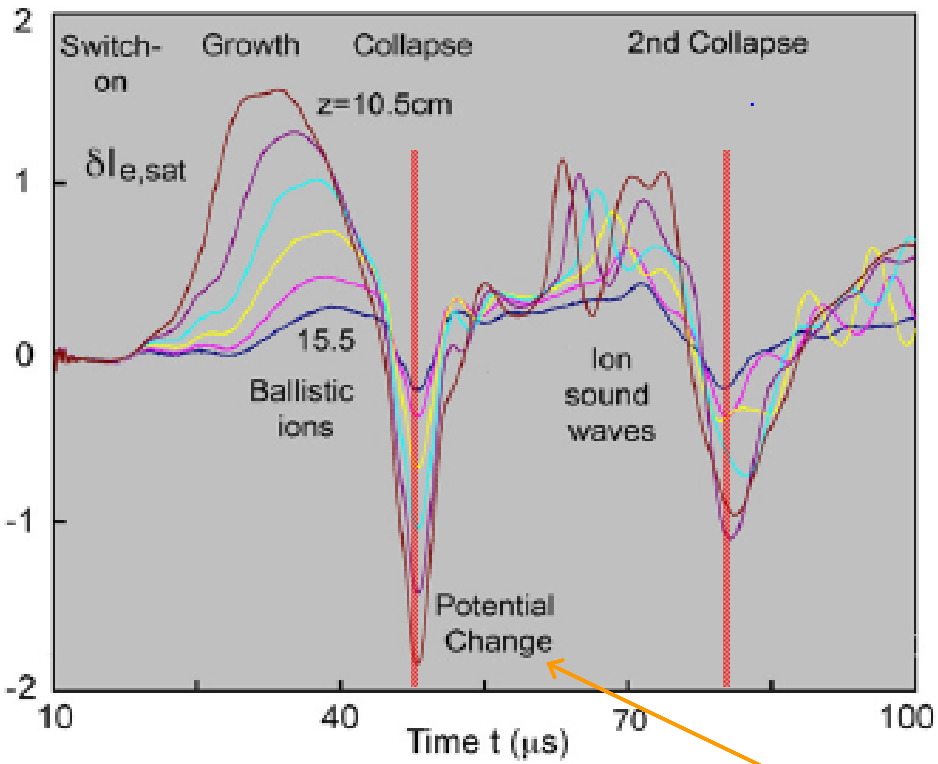
(c) Electrode voltage and current in a Ne plasma).

The fireball is highly unstable with short current pulses and long repetition times which are deter-mined 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)

Low frequency oscillations and waves II

Perturbation of electron saturation current $I_{e,sat}$ of a probe versus time at different axial positions z from the electrode:



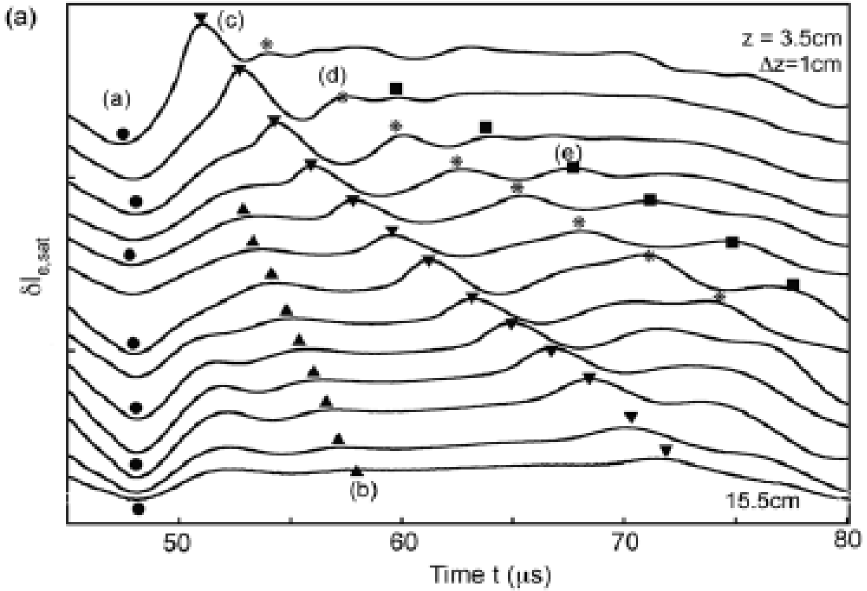
Electrode voltage V_E = 65 V switched on at t = 10 μs for 500 μs, t_{rep} = 4 ms.

Fireball is unstable and has its first disruption at t = 48 μs, a second disruption at t = 82 μs (shown by red vertical bars)

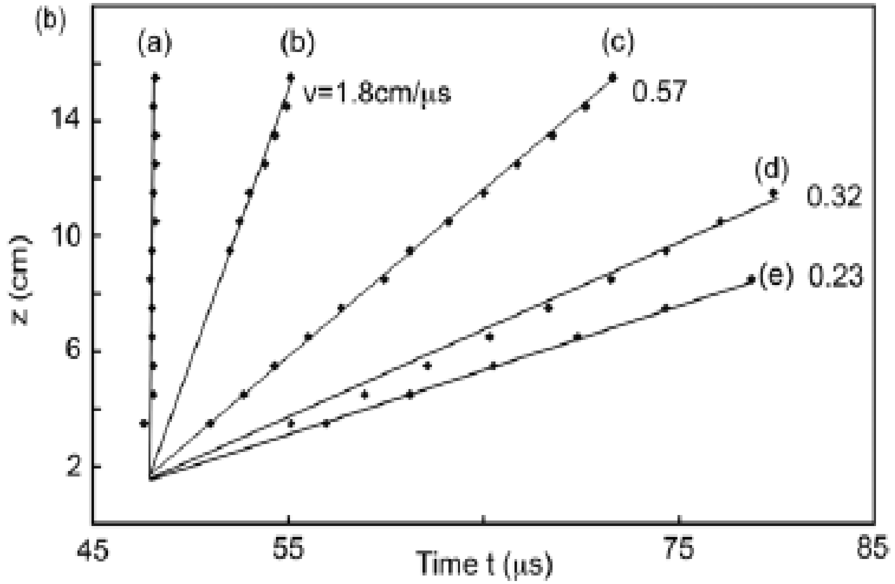
Propagating perturbations are ion bursts and ion acoustic waves; space-independent perturbations are interpreted as plasma potential changes;
(Ar, $p = 2{,}7\cdot10^{-3}$ mbar, V_{dis} = 0 V, I_{elec} = 70 mA)

Low frequency oscillations and waves III

Time-of-flight diagram for the propagating low-frequency density perturbations following the first disruption in Ar



(a) AC component of probe electron saturation current, $\delta I_{e,sat}$, versus time at different axial positions.



(b) z–t diagram of perturbations in $\delta I_{e,sat}$.

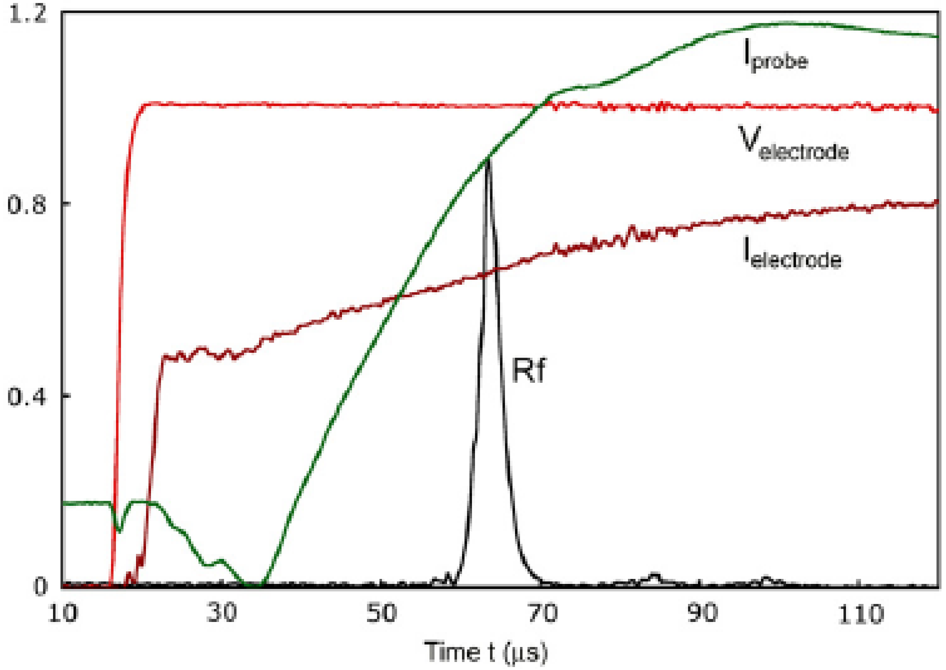
The first perturbation (a) is almost instantaneously present at all locations, hence it is thought to be a global plasma potential change, occurring on an electron time scale.

The following perturbations (b–d) travel at supersonic speed and are interpreted as ballistic signals of streaming ions, expulsed at different heights of the DL.

The last perturbation (e) travels at the ion acoustic speed for $kT_e = 2$ eV.

High-frequency oscillations and waves I

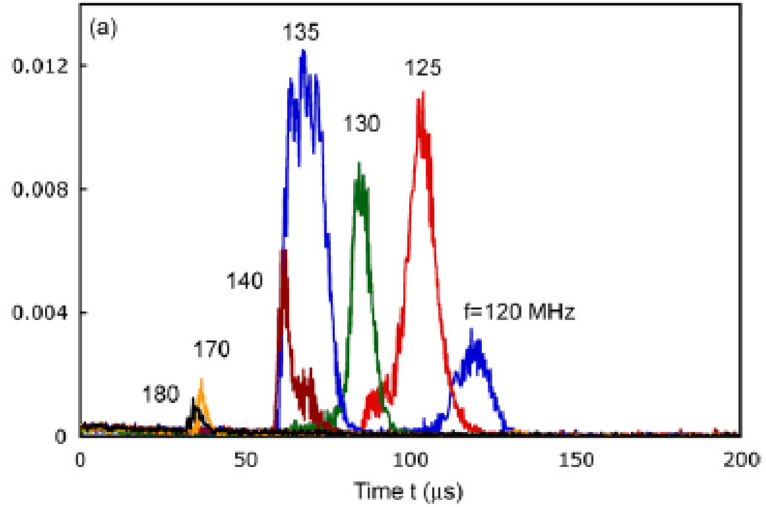
High-frequency oscillations inside a fireball

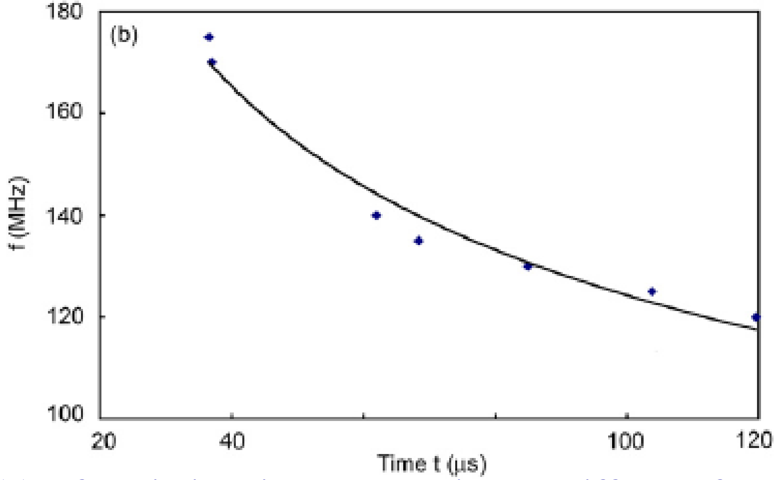


Onset of a stable fireball with electrode voltage and current, electron probe current and 136 MHz rf signal
(i.e. the receiving amplifier for the probe signal was tuned to 136 MHz)**.**

A sharp line is produced since the density increases during onset, and the frequency scales with the plasma frequency. Thus the signal with 136 MHz is only produced at a certain well-defined time.

(V_{elec} = 63V, $I_{elec,max}$ = 116 mA, V_{dis} = 26V, t_{pulse} = 0,5 ms, t_{rep} = 1,1 ms, $p = 4{\cdot}10^{-3}$ mbar Ar).



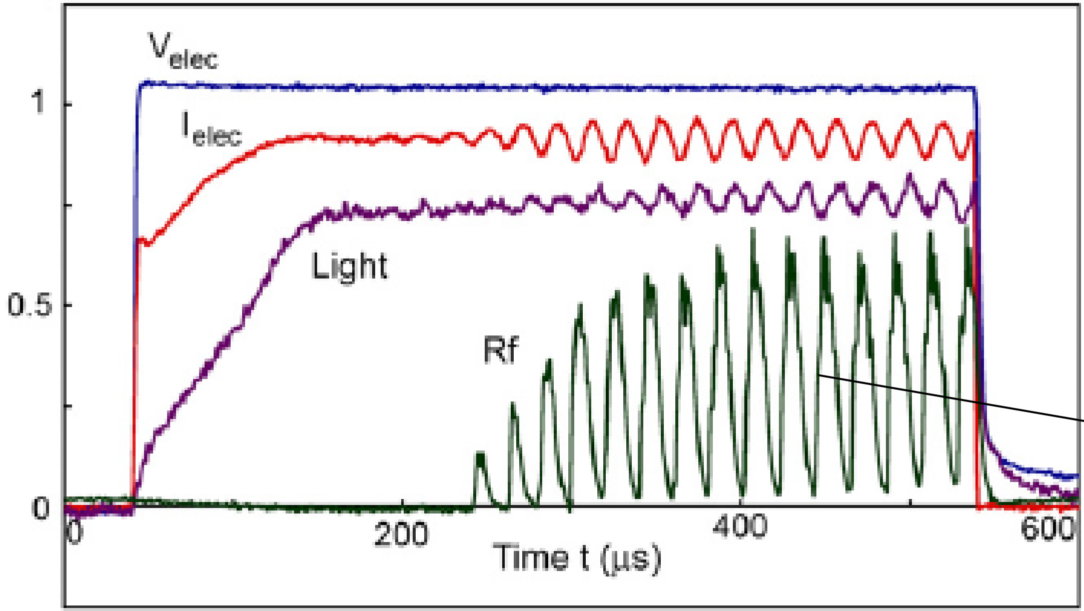


(a) Rf emission lines versus time at different frequencies and thus different densities during the decay of the fireball.

(b) Frequency versus time showing a decay due to a density drop in time when the fireball decays.

High-frequency oscillations and waves II

High-frequency oscillations inside an unstable fireball



100 MHz rf emission lines from a pulsed fireball which becomes weakly unstable in time.

(V_{elec} = 58V, $I_{elec,max}$ = 150 mA, V_{dis} = 0, t_{pulse} = 0,5 ms, t_{rep} = 1,1 ms, $p = 3{,}7{\cdot}10^{-3}$ mbar, Ar).

This is not the 100MHz signal itself but just the envelope during the low frequency oscillation of the unstable fireball!

Are the rf emissions due to electron beam–plasma instabilities? Probably not: Small size of the fireball and its spherical geometry complicate any comparison with theories for one-dimensional beam-plasma systems. If the electron beam had a velocity determined by a 15 V double layer ($v_b \cong 2{,}3{\cdot}10^8$ cm/s), the wavelength of a 100 MHz emission would be $\lambda = v_b/f_p \cong 2$ cm which exceeds the radius of the fireball. The growth rate would have to be comparable to the frequency.

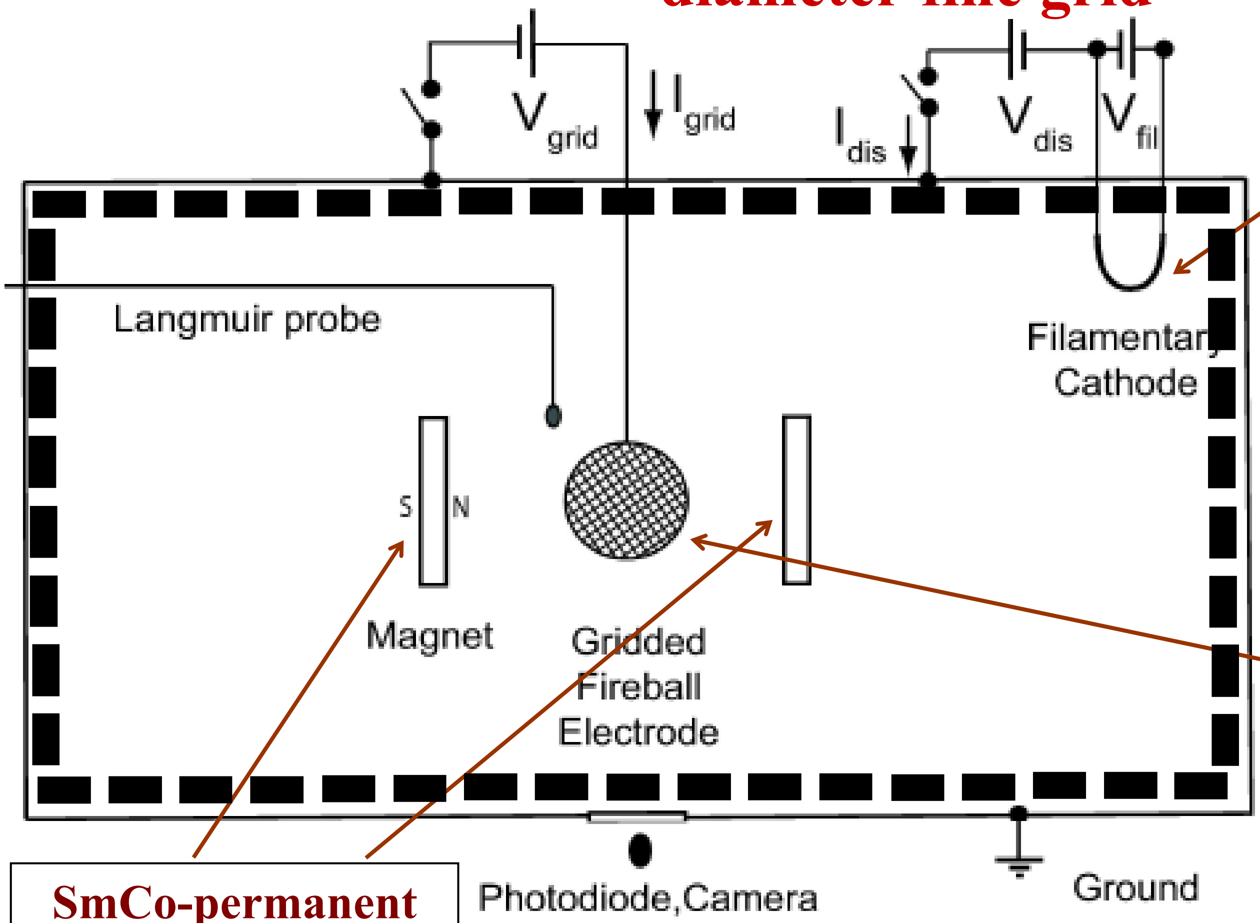
Another possible explanation is the sheath–plasma resonance [1]: The mechanism is the *finite electron transit time through a sheath* which creates a negative differential resistance and can lead to oscillations of a resonant system such as the sheath–plasma resonance [2]. The high-frequency oscillation is often modulated by low-frequency instabilities as shown above.

[1] R.L. Stenzel, *Phys. Fluids* B 1 (1989), 2273–82.

[2] M. Sanduloviciu and E. Lozneanu, *Plasma Phys. Control. Fusion* 28 (1986), 585–95.

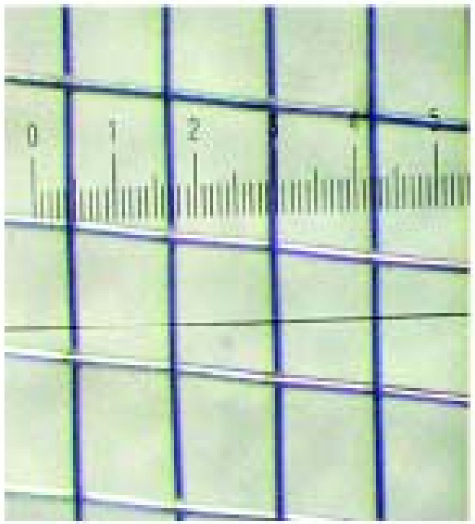
Fireballs excited by grids I

Experimental set-up in Innsbruck DP-machine with a 5 cm diameter fine grid



BaO-coated filaments

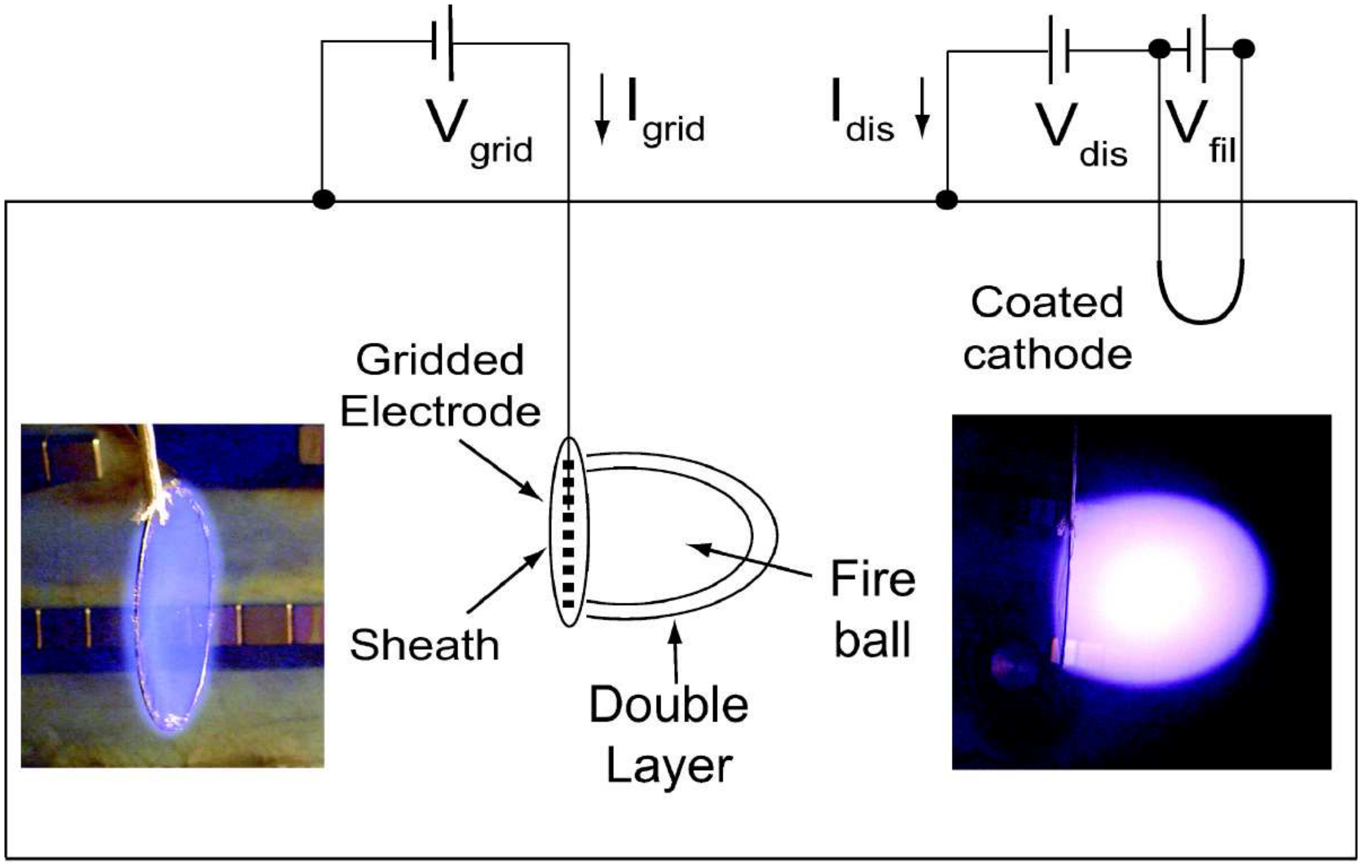
Grid
(0,25 mm spacing, 0,02 mm wire thickness, > 60% optical transparency



SmCo-permanent magnets
6,5 cm diameter,
16 cm axial spacing

Fireballs excited by grids II

Various luminous phenomena around the grid

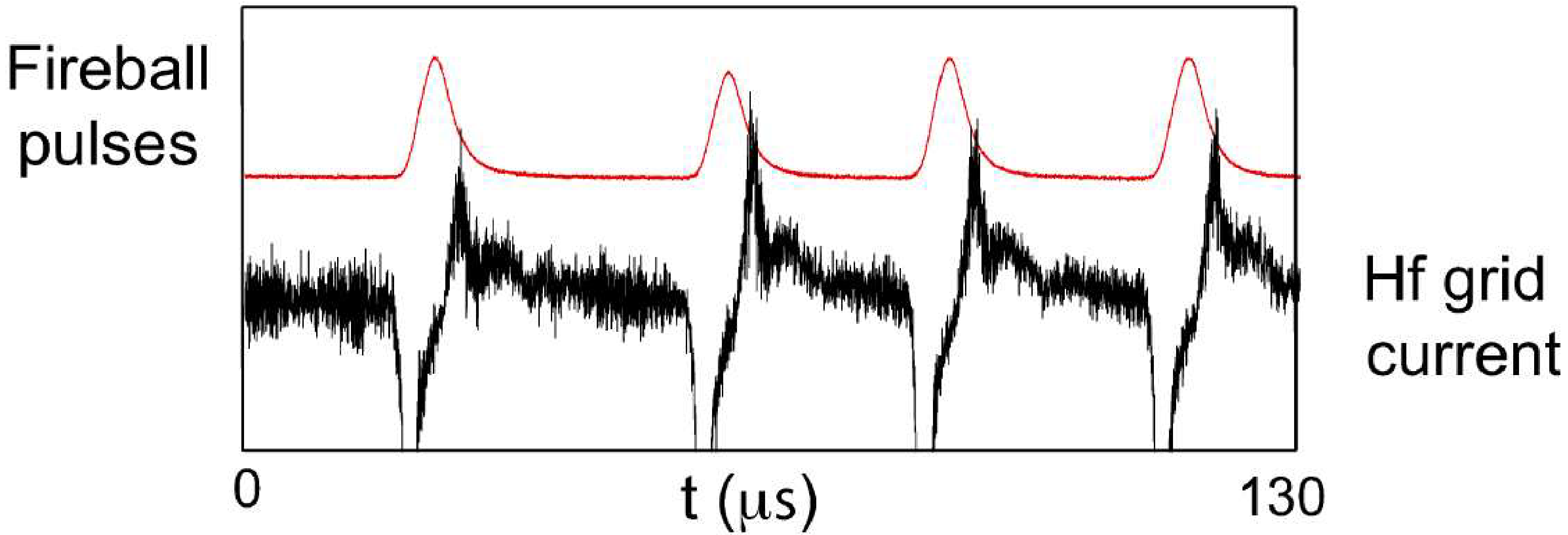


Plasma density 10^8 - 10^9 cm^{-3}, electron temperature $kT_e \simeq 2$ eV, Ar, He and Ne at pressures $p = 1 - 5{\cdot}10^{-1}$ Pa

At first only a luminous sheath appears on the grid (left photo), which evolves into a fireball (right photo) for higher biases.

High frequency signals on the grid current

The fireball is unstable and therefore pulsating



Luminosity of the fireball and hf-signals to be observed on the grid current. Note that the HF appears mainly <u>in between</u> the fireball pulses.

Repetition rate of pulsating fireball

Fireball repetition rate and intensity depend mainly on grid voltage

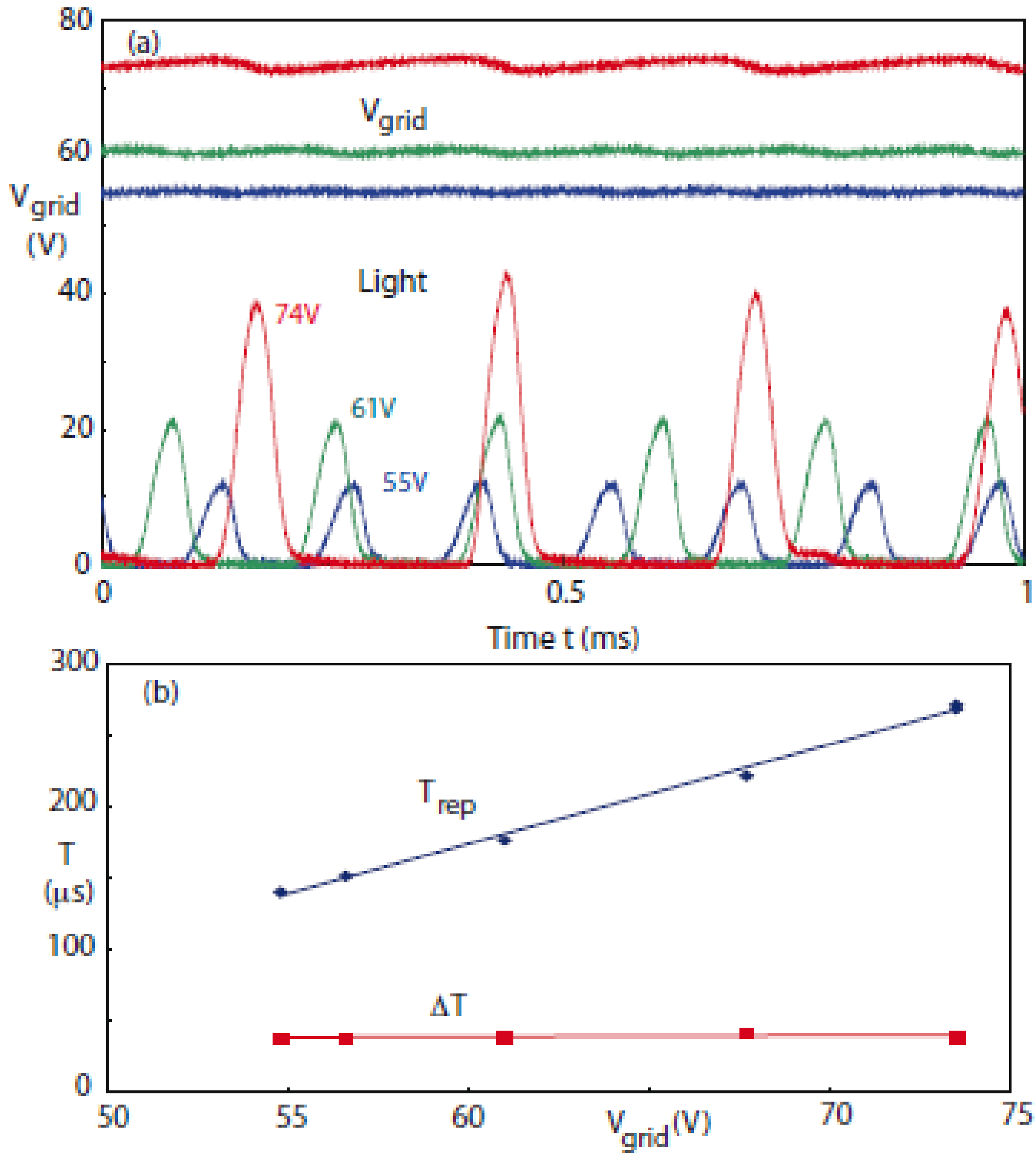
(a) Pulsating fireballs at three different grid voltages.

Note that also the grid voltage varies a little due to the current pulsations.

(b) Dependence of pulse repetition time T_{rep} and half width ΔT on grid voltage V_{grid}.

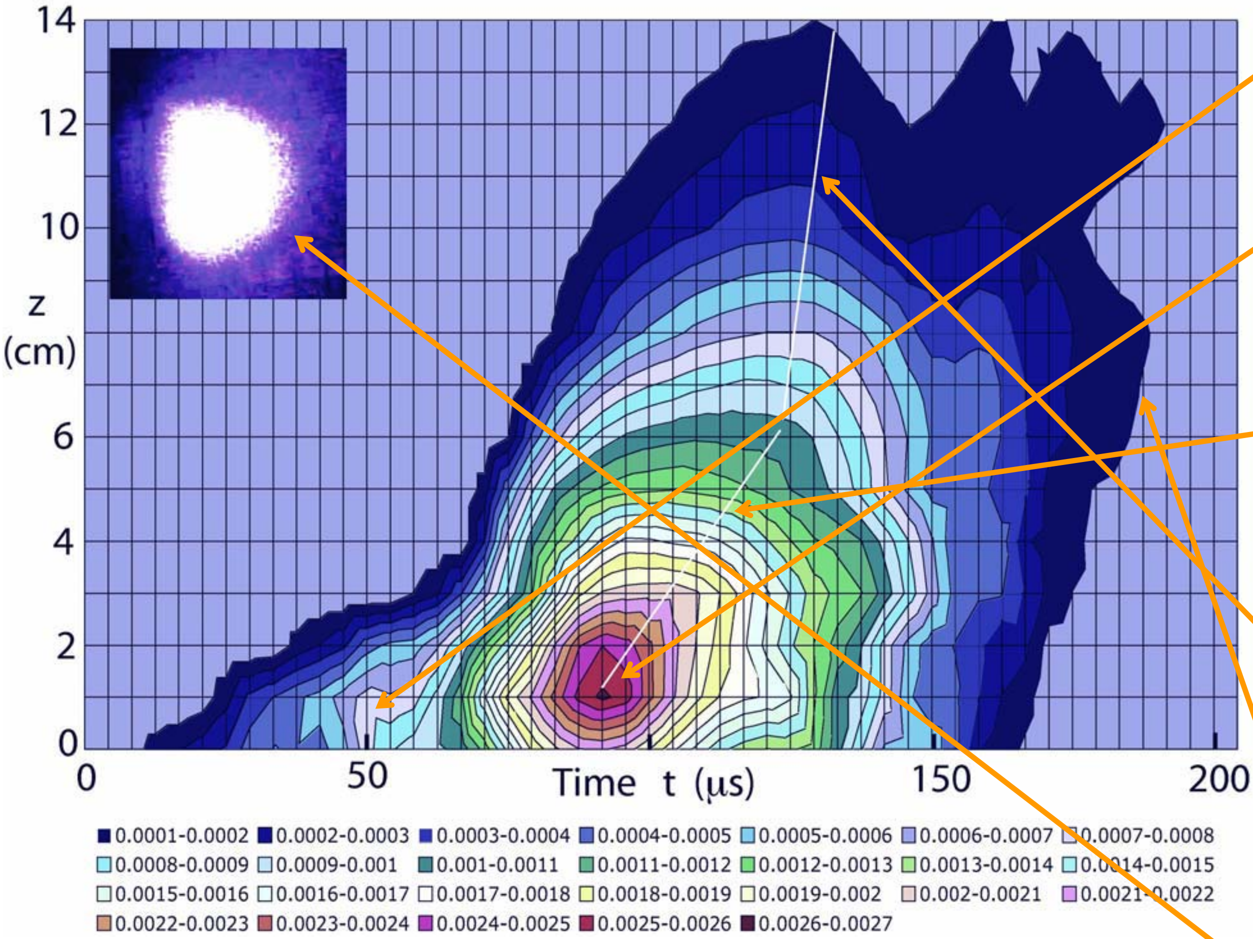
Note that only T_{rep} increases, whereas ΔT remains constant.

BaO-coated cathode,
$V_{dis} = 50$ V,
$I_{dis,max} = 30$ mA,
$p = 1\cdot10^{-3}$mbar Ar



Temporal evolution of the fireball density

The typical lifetime of a fireball is given by the ion transit time



Contour plot of space-time dependence of density for an unstable fireball, $n \propto I_{i,sat}(z,t)$.

First the density in a luminous sheath grows (z < 2 cm, t < 60 μs).

Then rapid ionization occurs in the fireball, peaking at z = 1 cm, $t \simeq$ 90 μs. The ions expand axially.

Inside the fireball (z < 6 cm) the contour crest moves at the sound speed $c_s \simeq 2{\cdot}10^5$ cm/s (white line).

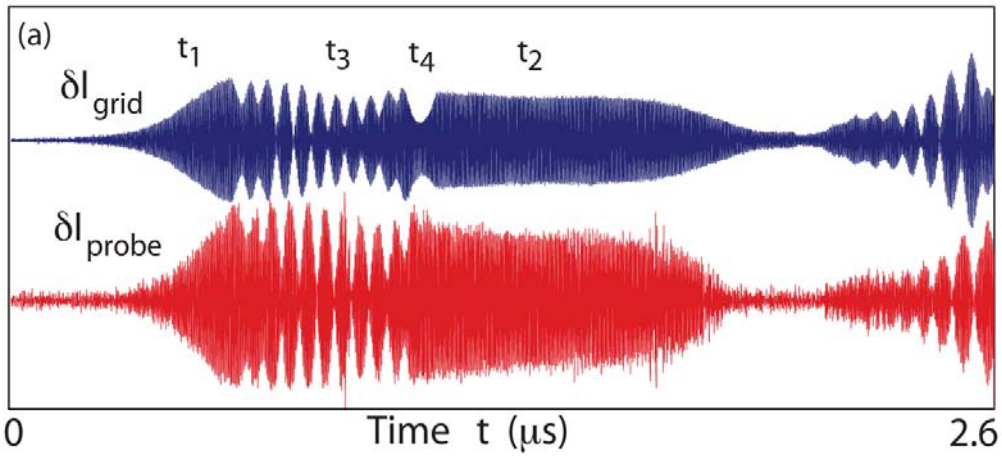
Outside the fireball the ions move at a larger speed corresponding to the double layer potential.

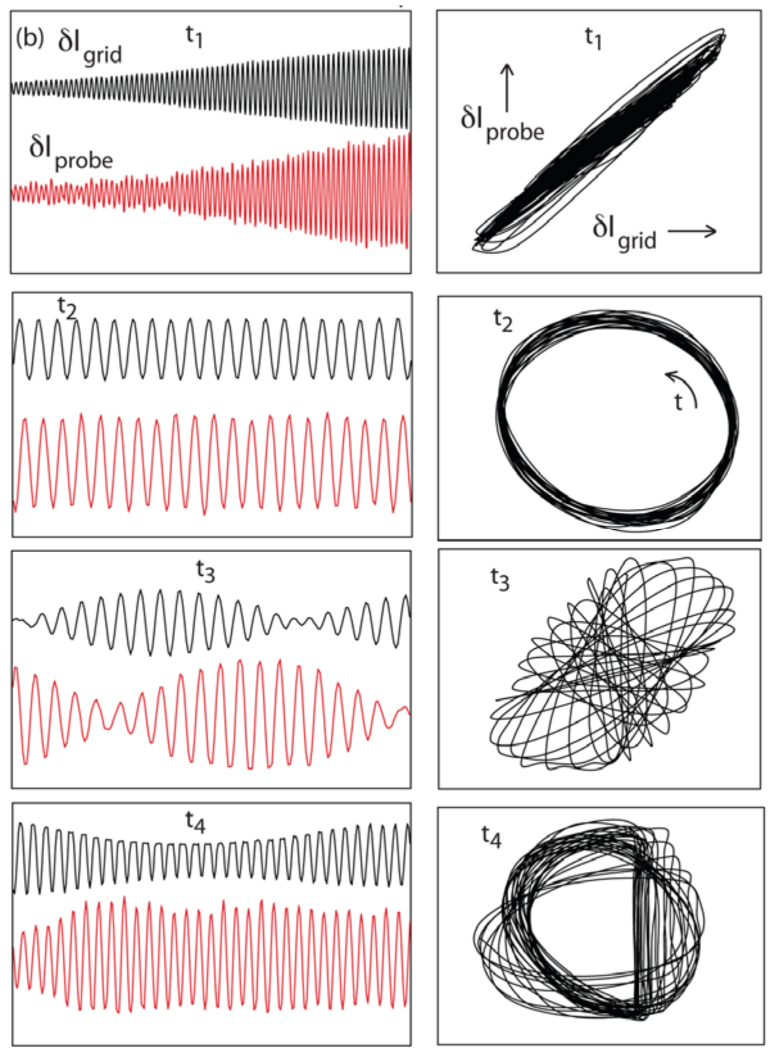
Ion production does not balance the ion outflow, leading to density loss and current collapse.

Insert shows fireball image from a single frame of a movie of randomly occurring sputtering fireballs.

HF oscillations between pulsating fireballs I

Typical waveforms and hodograms of the HF





(a) Waveforms of bursty sheath-plasma oscillations detected in the grid current I_{grid} and on a probe adjacent to the grid, I_{probe}.

(b) Comparison of waveforms and hodograms showing phase relations.

t_1: From growth to steady-state, phase shifts by 9°.

t_2: Phase shift is 90°.

t_3: Wave beats arise in both signals with delay causing the hodogram to rotate.

t_4: Nonlinear clipping of I_{grid} creates distorted hodograms.

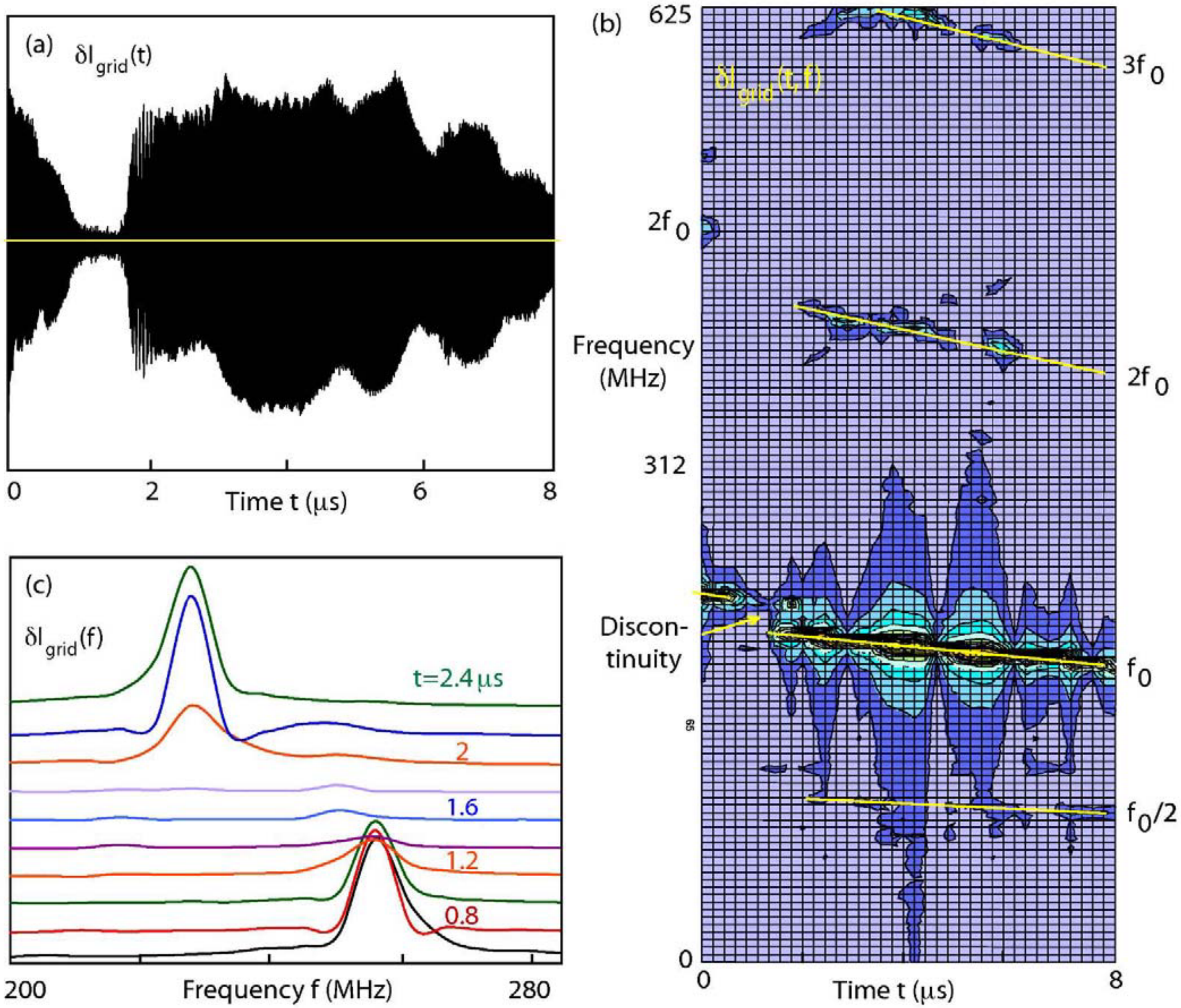
HF oscillations between pulsating fireballs II

Temporal evolution of frequency, and amplitude drop-out

(a) Waveform of I_{grid} with amplitude drop-out.

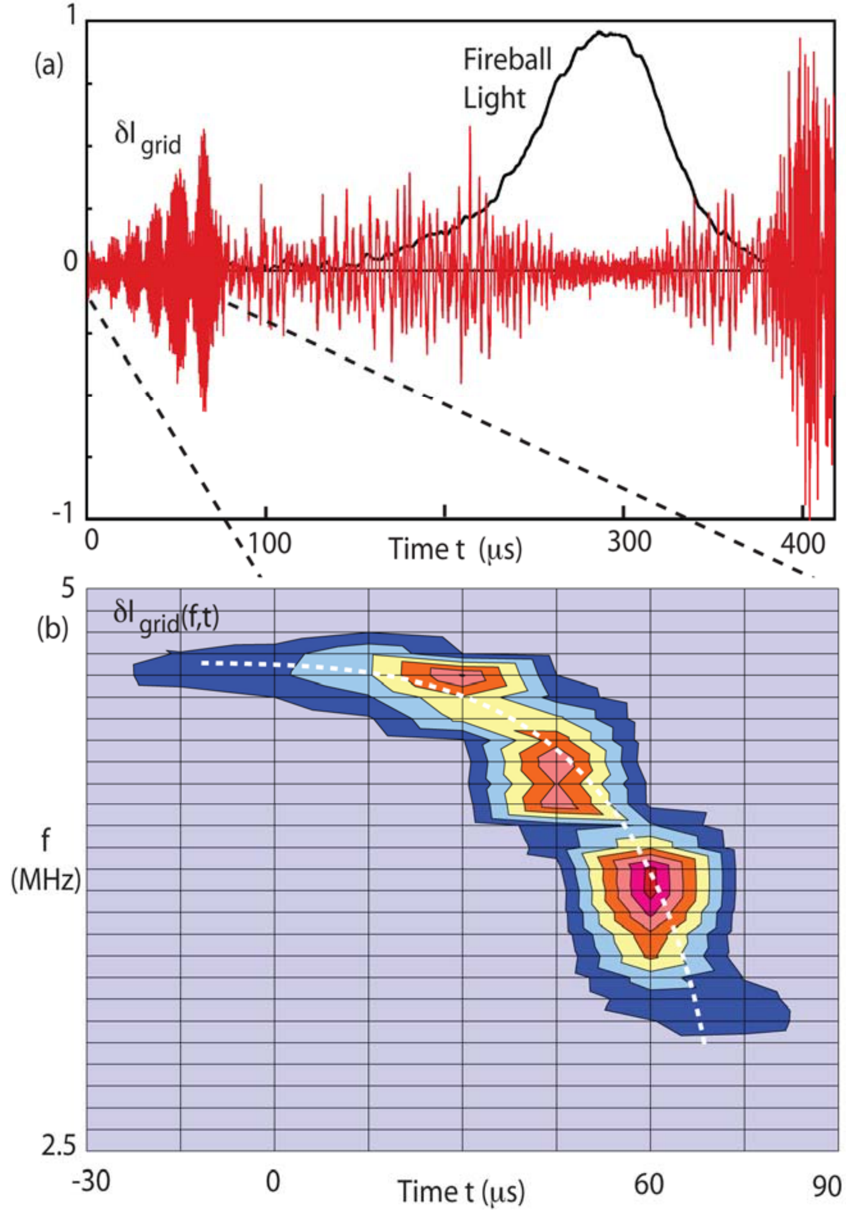
(b) Spectrum of I_{grid} obtained by FFT for 40 successive time intervals. Frequency decay, harmonics and frequency jumps are observed.

(c) An abrupt frequency decrease is observed at the amplitude drop-out for many bursty wave-forms.



HF oscillations between pulsating fireballs III

Temporal evolution of frequency and relation to the formation and decay of the fireball

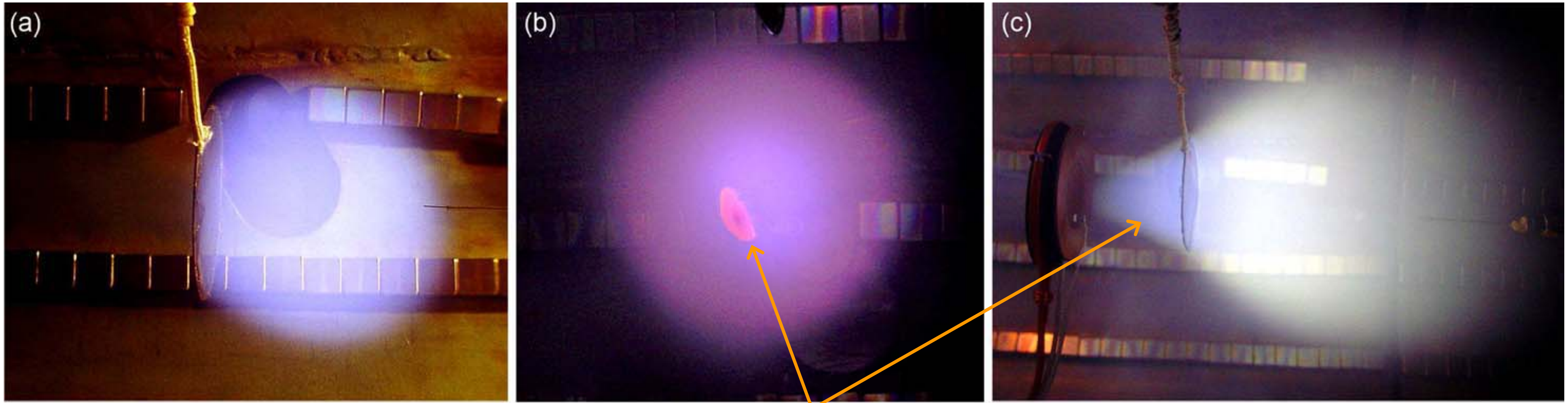


(a) HF oscillations δI_{grid}, and fireball light on a long time scale. The HF oscillations die out at the beginning of the fireball, indicated by the light signal, and restart at the end, since during the fireball the sheath voltage drop is too small to satisfy the instability criterion $\omega\tau_{transit} > 2\pi$.

(b) Spectrum shows again a precipitous frequency drop prior to amplitude loss, interpreted as sheath expansion due to ionization that leads to fireball formation.

Fireballs in magnetic fields I

Influence of magnetic fields on the shape of fireballs.



Images of stable Argon fireballs for different electrodes and magnetic fields:

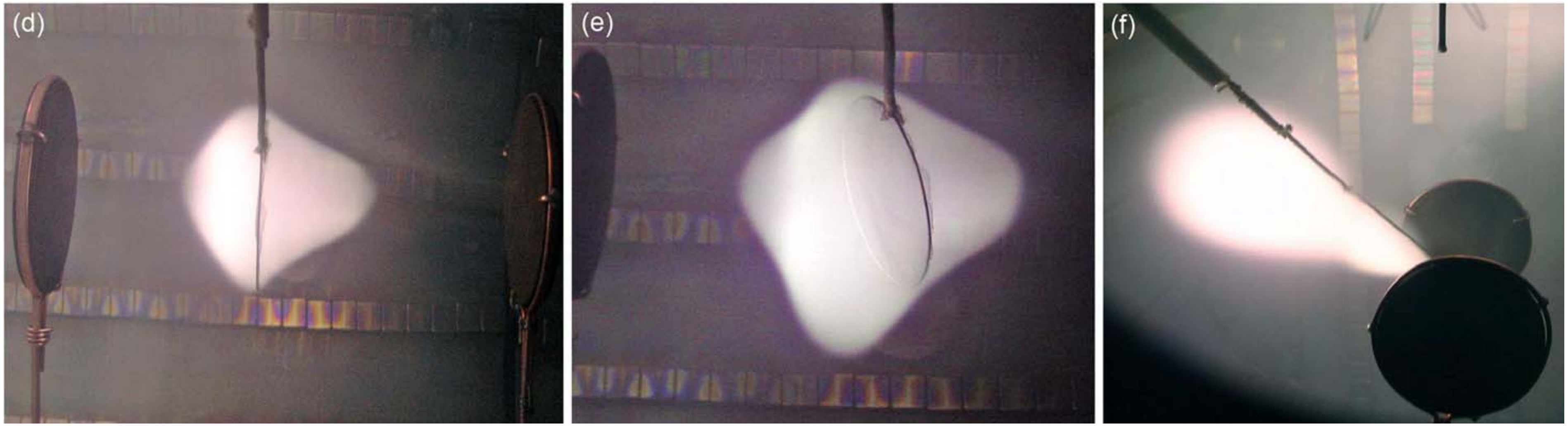
(a) Unmagnetized fireball on one side of a 5 cm diam grid.

(b) Spherical fireball nearly concentric with a small glowing grid (1×2 cm).

(c) Pear-shaped fireball of the 5 cm grid in the diverging field of a single magnet. Note that the grid is transparent to energetic electrons which are reflected by the magnet.

Fireballs in magnetic fields II

Influence of magnetic fields on the shape of fireballs.



Images of stable Argon fireballs for different electrodes and magnetic fields:

(d) **Fireball of the 5 cm diam grid located near the null point of a cusp magnetic field. Electrons for the fireballs on each side are collected radially and reflected axially.**

(e) **Asymmetric fireball created by tilting the grid near the cusp null point.**

(f) **Fireball created by the 5 cm diam. grid rotated by 90° with respect to the cusp axis. A long radial fireball is formed. Its ionization is sufficient to almost sustain the discharge without cathode ($I_{grid} \approx 1$ A, $I_{cathode} \approx 1$ mA – usually the background discharge current is ≈ 100 mA).**

Conclusion

- **Fireballs can form in front of a positively biased electrode in a plasma with sufficiently high neutral background pressure if the difference between the plasma potential and the electrode bias exceeds the ionisation potential of the gas.**
- **In this case a confined volume of different plasma, surrounded by a double layer, is created in front of the electrode. This evolution is caused by excitation and ionisation collisions of the accelerated electrons in the sheath with atoms of the background gas.**
- **The fireballs are frequently unstable both in the low-frequency (ion) range and the high-frequency (electron range):**
  - **the former give rise to various ion wave phenomena propagating away from the fireball.**
  - **the latter give rise to high frequency oscillations inside the fireball.**
  - **Also in between the pauses of a pulsating fireball strong hf oscillations are observed which are due to sheath-plasma interaction.**

Thank you very much for your attention!

♥ And HAPPY BIRTHDAY, PADMA!!! ♥

12th of August 1975, Eindhoven, ICPIG

12th of August 1988, Kreuth, IPELS

19th of July 2007, Prague, ICPIG