Microwave Diagnostic of the Pulsed Plasma Generation in the Hollow-Cathode Glow Discharge

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The radius and speed of the cylindric ionization front that expands during the application of a high-voltage pulse upon a double-plate hollow-cathode, is measured by reflection of 8 mm-microwaves.

By comparing the number of transported electrons and their ionizing action, ionization by single electron collisions is shown to be impossible.

In the "normal regime" below a certain voltage threshold, a pulse height variation has only an influence on the final plasma radius but not on the local speed of the cut-off surface during recombination.

1. Introduction

In the course of a program to search for plasma-satellites in different plasma sources the pulsed hollow-cathode glow discharge showed plasma oscillations with unexpected intensity (1 – 2 kV/cm) and frequency (30 – 100 GHz) [1], [2]. These plasmons appear simultaneously with the generation of the pulsed plasma (as defined by the onset of the pulsed plasma light emission and the cut-off of 35 GHz-microwaves) and are damped out on a 100 ns time scale (presumably due to heating of the electrons or wavelength shortening).

In contrast to expectation the intensity of the plasma-satellites increases and their spectral quality improves when the applied pulse voltage is reduced.

A lower voltage threshold is reached when the stationary glow discharge plasma suddenly does not react any more on the applied pulse. Also the disconnection of one of the two cathodes from its pulse generator leads to a total inefficacy of the pulse, even at highest voltage.

This strange behaviour suggests that the two applied high-voltage pulses are *only in cooperation* able to start a threshold dependent plasma generation.

Its step-function-like nature must be different from the slowly continuing ionization at higher voltages, when the current develops a spiky behaviour [3]. Only in this spiking regime the action of electron beams can be observed on the helium ion line at 469 nm, whereas below the spiking threshold there is practically no ion line emission.

The presented investigations were intended to clarify the extremely efficient and fast plasma generation at low voltages, that seems to leave the dense initial plasmon gas (of the order of 100 plasmons $\hbar\omega_p$ per plasma electron) as a byproduct. The resulting efficiency of 10 – 15% is rather high for a density increase from 10^{11} to $10^{13}\,cm^{-3}$ within a 20 ns time scale, and indeed ionization by single electron collisions will be proved to be impossible by comparison of the number of transported electrons and their ionizing action.

By microwave reflection the location and radial speed of the cut-off surface is determined, for the ionization as well as for the recombination phases.

A "normal" voltage regime is found, being below that threshold, when the plasma radius reaches a fixed limit of 75% of the cathode radius. It is characterized by the fact that this speed during recombination is independent of the pulse voltage.

2. Experimental set-up

Two types of hollow-cathodes have been used. For the microwave reflection measurements the one with large a cathode diameter of 40 mm and common anode was best suited (described in [3], Fig. 1), whereas the cut-off measurements were performed with a smaller design, characterized by separated anodes (described in [1]).

Both cathodes were pulsed separately (400 ns pulse length), each by a 50 Ω – square-pulse generator of its own [2], [3]. The connecting 50 Ω –

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cables were terminated at *both* ends in order to minimize cable reflections.

The charging voltage U_0 was kept below the threshold of 7.5 kV, above which a series of current spikes appeared [3]. The actual applied pulse voltage (without plasma load) is smaller by a factor of ~4, due to an internal voltage division in the generator.

For microwave generation, tunable high power clystrons were used at 35 GHz (though their cathodes needed refreshing by overheating their power was estimated to be of the order of 0.1 W). The clystron and the power supplies were put into a shielded measuring cabin, because the electromagnetic interference by the hollow-cathode pulsing caused the microwave oscillation to stop otherwise. Back-reaction via the waveguide was minimized by an isolator.

When investigating the microwave reflection by the plasma the measuring diode was decoupled from the direct clystron input by a magic *T*. The through-passing wave-guide was closed at one side by a movable short-circuit, while the other ended as an antenna that was glued into a hole of a 32 mm vacuum blind flange. Its front (sealed by a quartz window) had a distance of 34 mm from the hollow-cathode center.

Microwave polarization was vertical (*i.e.* perpendicular to the cathode surfaces).

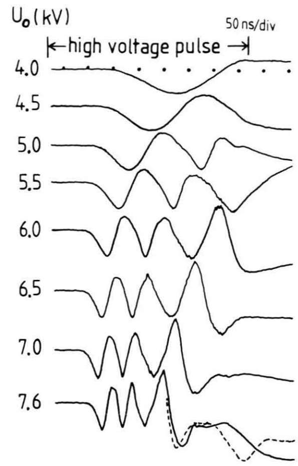


Fig. 1. Microwave signal versus time (50 ns/div) in a wave guide resonator with the plasma as one of the mirrors (coupled via an antenna) and an adjustable short-circuit piston as the other. Clystron (OKA; 35 GHz) and measuring diode were decoupled from each other by a magic *T*. The short-circuit was adjusted to obtain maximum stationary signal at the diode. Above a charging voltage $U_0 = 7.5$ kV the discharge current becomes modulated by a train of short spikes. The broken line at $U_0 = 7.6$ kV corresponds to this case. The length of the high-voltage pulse (400 ns) is indicated at the top.

3. Results

a) *Microwave reflection measurements*

The best results during the ionization phase (Fig. 1), were obtained when the stationary diode signal was maximized by moving the short-circuit.

On the other hand, for the recombination phase (Fig. 4) a position with zero initial diode voltage was chosen.

The temporal sinusoidal modulation of the diode-signal in Fig. 1 is due to the moving ionization front that expands between the cathode plates in radial outward direction. It acts like a movable microwave resonator-mirror, thereby tuning the through-passing wave guide of the magic *T* (that is closed at the other end by the fixed short-circuit plate) between minimum and maximum resonance. According to the reduction of the standing wave by one *half*-wavelength after the other, each *full* cycle 2π of the signal modulation corresponds to an increase of the plasma radius by $\lambda/2 = 4.3$ mm (vacuum wavelength, because tuning takes place outside the wave guide).

Raising the charging voltage U_0, the number of cycles and thus the final radius R_f at the end of the 400 ns pulse increases. At $U_0 = 6.5$ kV the expansion reaches an upper limit of $R_f = 15$ mm (3.4 cycles), though the cathode radius of 20 mm should allow further ionization (Figure 2). Still higher voltages increase only the extreme speed (in the 10^5 m/s range) of the ionization front in a linear way (Fig. 2), but the sharp stop at $R_f = 15$ mm becomes even more pronounced.

Extrapolating the voltage towards zero radius and zero speed, an *ignition threshold* of $U_0 = 3$ kV is obtained (corresponding to an actual pulse voltage of initially *0.7 kV* at the cathodes).

In Fig. 3 the traces of the pulse voltage and the diode signal are displayed simultaneously, showing the sudden stop of ionization at the end of the pulse. At $U_0 = 4$ kV the pulse voltage has an approximately flat top, whereas at $U_0 = 6.5$ kV a reduction by 0.24 kV below the idling pulse voltage of 1.56 kV (in the middle of the pulse) indicates a plasma current of 10 A (as given by the parallel cable/termination resistance of 25 Ω). Thus the total dissipated *electrical power is 26 kW* (for both cathodes), at a time when the plasma radius has reached 6.4 mm (1.5 cycles).

The recombination phase of the pulsed plasma is displayed in Fig. 4b, where the peaks of the ionization phase (Fig. 4a) appear in reversed order (the difference to Fig. 1 is due to the zeroing of the stationary diode signal by adjusting the short-circuit piston).

The lines connecting points of equal phase, *i.e.* equal position, are parallel in Figure 4b. That means, the speed of the reflecting cut-off surface during recombination is only dependent on its actual position, but not on the final radius R_f (as given by U_0). One could be tempted to explain this by a plasma density independent of the height of the applied voltage; then, however, a strange recombination process taking place only at the cylindrical plasma edge would have to be supposed. Because generally recombination occurs as the inverse process that is responsible for ionization, this would be consistent with the model of a *thin* radially expanding ionization front.

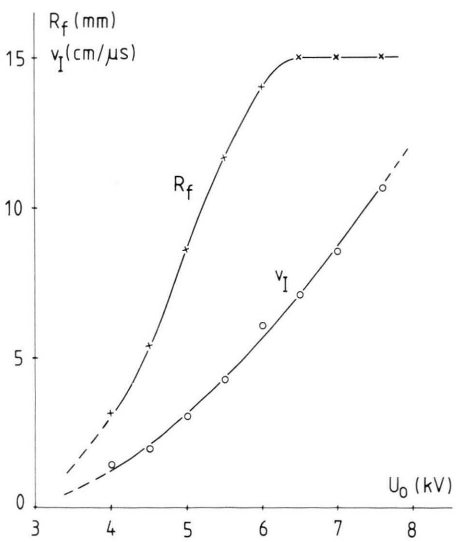
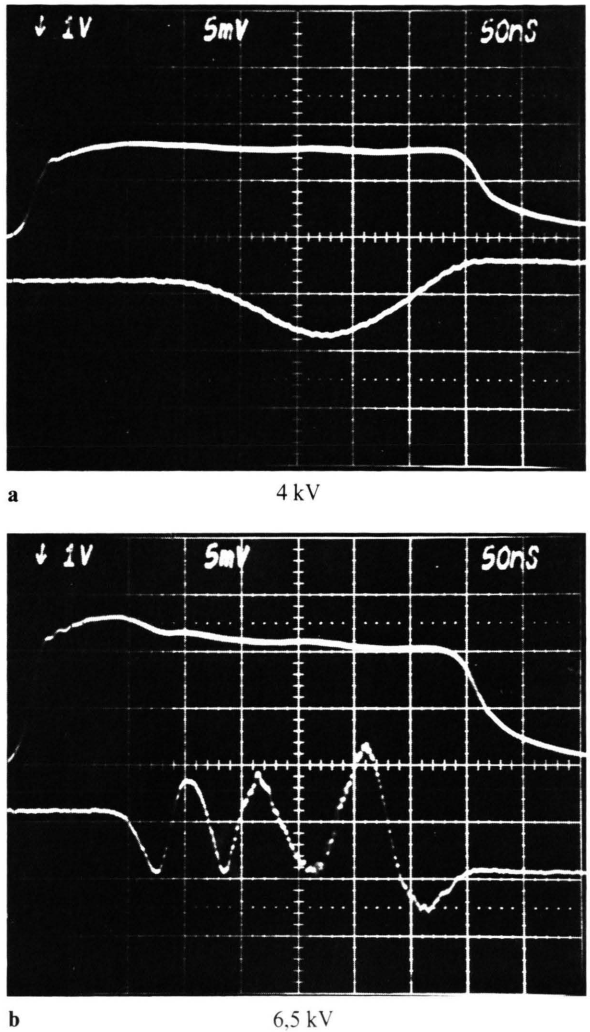


Fig. 2. Final plasma radius R_f, as present at the end of the high-voltage pulse (crosses), and speed of the reflecting ionization front v_I (circles) versus U_0. The values were derived from Fig. 1 (the speed corresponds to the interval $\frac{1}{2}\pi - \frac{3}{2}\pi$ of the sine curve).



a 4 kV

b 6,5 kV

Fig. 3. Original oscilloscope traces from Fig. 1 with the corresponding high-voltage pulse (600 V/div). (2 beam 400 MHz oscilloscope Tektronix 7844, 50 ns/div). (a) U_0 = 4 kV, (b) U_0 = 6.5 kV.

b) Microwave transmission measurements

The double-anode design (as given in [1]) with its outer glass vacuum chamber enabled microwave transmission without guidance effect (as it was the case with the metal discharge chamber of Chapt. 3a, where the increased sensitivity was advantageous). Therefore the onset of microwave cut-off can be associated with a plasma diameter of the order of one wavelength (8.6 mm).

Figure 5 shows the threshold to achieve total cut-off at U_0 = 3.5 kV (pulse voltage 0.85 kV). The time

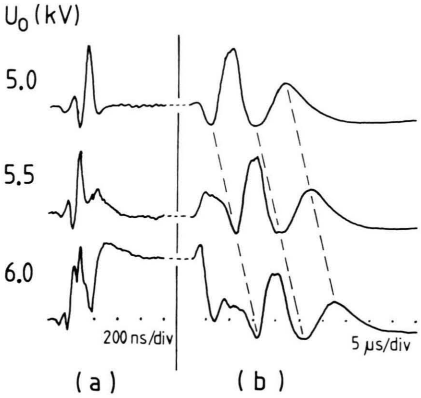


Fig. 4. Arrangement as in Fig. 1, only the short-circuit was adjusted until the stationary diode signal became zero. (a) Ionization phase (200 ns/div), (b) recombination phase (5 µs/div).

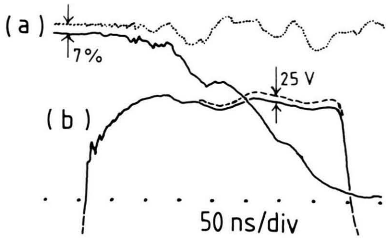


Fig. 5. Microwave cut-off at 35 GHz (full line) versus time (50 ns/div). The dotted line was taken without plasma but with operating pulser. Both polarizations showed cut-off. (b) Top part of the high-voltage pulse (120 V/div). The broken line was taken without plasma. During the last 150 ns it is lowered by 25 V due to a plasma current of 1 A.

between the 90% and 10% points is 230 ns, but only during the last 150 ns an appreciable plasma current (1 A for each cathode) is flowing. Thus the total dissipated electrical energy amounts to 0.26 mJ, sufficient to ionize $6.4 \cdot 10^{13}$ He-atoms out of the ground state.

It is interesting to note that already the *stationary* plasma (maintained by 10 mA) lowers the transmission by 7%, though its plasma frequency should be much less than 35 GHz. This attenuation was found to be maximum when varying the pressure around 3.2 mbar (twice the necessary minimum operating pressure to prevent the glow discharge from being "blown out" by the pulses).

4. Analysis of the ionization energy balance

If ionization out of the He-ground-state is assumed (metastables reach only typical densities of $10^{11}\,cm^{-3}$ in comparable discharges [4], [5], and need not be considered here), an efficiency of 10–15% of the electrical input can be derived:

a) In Chapt. 3a, at $U_0 = 6.5$ kV an electrical input power of 26 kW was found at a time when the plasma had already expanded to a radius of $R = 0.64$ cm (actual front speed $v_I = 7 \cdot 10^6$ cm/s). With the height of $d = 1.5$ cm for the plasma cylinder the volume increase results as $2\pi R\, d v_I = 4.2 \cdot 10^7\,cm^3/s$.

From [6] (where a plasma frequency of 40 GHz was found at $U_0 = 7$ kV) the density can be taken as $2 \cdot 10^{13}\,cm^{-3}$, so that $8.4 \cdot 10^{20}$ ionizations take place per second. The power, as required for ionization, thus amounts to 3.3 kW (with $E_I = 24.6$ eV), being 13% of the electrical input.

The integrated balance over the total plasma generation time of 300 ns (ending with the full volume of $10\,cm^3$) yields a similar result: the average currents of 10 A for each cathode (cf. Chapt. 3a) transport a total of $3.8 \cdot 10^{13}$ electrons in 300 ns. *Each of these electrons*, which were accelerated by the cathode fall of 1.32 kV, *must be responsible for 5 ionizations* in order to guarantee the final plasma electron number of $2 \cdot 10^{14}$. Spending 5 times the ionization energy their kinetic would be reduced by 10%.

b) The cut-off measurements near the ignition threshold with the hollow-cathode of Chapt. 3b corroborate these results: the final plasma volume of $0.6\,cm^3$ ($d = 1$ cm) contains $0.9 \cdot 10^{13}$ electrons (using the cut-off density of $1.5 \cdot 10^{13}\,cm^{-3}$ at 35 GHz). According to Chapt. 3b only $6.4 \cdot 10^{13}$ ionizations are possible energetically, so that the efficiency would have to be 14%.

5. Mean free path for ionizing electron collisions

The cross section for ionizing electron collisions at 1 keV is $10^{-17}\,cm^2$ for helium, giving a mean free path of 4 cm at a neutral density of $2.6 \cdot 10^{16}\,cm^{-3}$ (1 mbar). At the above velocity of $1.9 \cdot 10^9$ cm/s each 2 ns an ionization occurs. As each electron, that has been accelerated by the cathode fall towards the opposite cathode, must generate five ionizations on an average (cf. Chapt. 4a), a *total path of 22 cm* (during a time of 11 ns) results for it.

But for high energy electrons (1 keV) the elastic collision frequency with the neutrals is 1.8 GHz at 1 mbar, so that the mean free path of 1 cm allows only few reflections at the opposite cathode falls (which act like mirrors of a resonator), before scattering destroys the confinement.

And also the time constant of 11 ns would round off the sharp edge (< 5 ns) at the end of the last sine curves in Figure 1 *. That means definitely that ionization by single electron collisions is impossible.

Of course one could introduce collective electron effects to get the required total ionization path of, say, $1-2$ cm (given by the cathode interdistance d and the scattering collisions). But then one would have to explain the start phase, when the plasma density is too low for collective effects, and the final cooperative saturation process on a *macroscopic scale*, that leaves a *constant* plasma density along the z-direction [1], [6].

* The 20 ns time scale of Chapt. 1 refers to the current rise time as displayed in Fig. 3b (70 ns after high voltage application).

It should be stressed that not only is the density constant along the negative glow, but also continues into the dark spaces. That poses a special problem: in the start phase the low-density ion space charge ($< 10^{11}$ cm^{-3}) must extend at least several mm in thickness to build up the cathode potential of 2 kV. In this acceleration region a plasma of a density substantially different from the one in the negative glow should be expected.

6. Conclusion

Only further measurements, *e.g.* CO_2-laser interferometry of the dark spaces, or spatially resolved photography of the ionization front (using a pulsed channel plate), can perhaps clarify the exotic plasma state of the stationary hollow-cathode glow discharge, which shows an unusual sensitivity to transient electric fields.

Acknowledgements

The experiments were carried out in 1980 in the Institut für Experimentalphysik V, Ruhr-Universität, Bochum.

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