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Breakdown, scaling and volt–ampere characteristics of low current micro-discharges

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Abstract
We give preliminary results on the breakdown and low current limit of volt–ampere characteristics of simple parallel plate non-equilibrium dc discharges at standard (centimetre size) and micro-discharge conditions. Experiments with micro-discharges are reported attempting to establish the maintenance of E/N, *pd* and j/p^2 scalings at small dimensions down to 20 μm. It was found that it may not be possible to obtain properly the left-hand side of the Paschen curve. The possible causes are numerous but we believe that it is possible that long path prevention techniques do not work at high pressures. Nevertheless, the standard scaling laws seem to be maintained down to these dimensions which are consistent with simulations that predict violation of scaling below 10 μm. Volt–ampere characteristics are also presented and compared with those of the standard size discharges.

1. General introduction

Micro-discharges are the new front of research in the field of non-equilibrium plasmas [1] holding promise for both realizing non-equilibrium conditions at atmospheric pressures and also giving a possibility of specialized applications in fields of nanotechnologies [2] and light sources [3]. It is regularly assumed that these discharges operate in the abnormal or normal glow regimes. However, for hollow cathode micro-discharges it was found that under standard experimental conditions the hollow cathode effect is not significant [4]. Such results raise the issue of the scaling of discharge properties as a function of pressure (p) and characteristic dimension (d).

Numerous papers have studied breakdown at elevated pressures and distances between electrodes considerably smaller than 1 cm. For example, breakdown mainly at the right-hand side of the Paschen curve has been studied at pressures above the atmospheric by Terashima *et al* [5], while RF breakdown in micro-structured electrode arrays was studied by Gericke *et al* [6].

Recently we analysed the scaling of low pressure discharges close to the minimum and to the left of the minimum of the Paschen curve [7–10]. It was shown first that the standard Townsend's theory should be extended to include secondary electron yields by photons, metastables and gas phase ionization due to fast neutrals [7], that *pd* scaling holds unless new physical phenomena enter the kinetics [8] and that the Paschen curve itself is not sufficient to give a proper model of the secondary electron yields: one needs to model the volt–ampere characteristics also [9]. Finally, we have shown that the constricted discharge, i.e. the conducting channel (created by the instantaneous increase in the local charge density and the resulting cathode fall), reduces the operating voltage if the ionization rate depends strongly on the local E/N. It also extends in the radial direction and feeds by diffusion of charged particles the neighbouring channels allowing them to operate in the non-self-sustained Townsend regime [10].

In this paper we show the preliminary results of the experiments and some simulations attempting to test the *pd* scaling in parallel plate dc micro-discharges. A part of the goal is to verify the possibility of applying micro-discharges operating in Townsend's regime to produce optimal light sources. Light sources could not employ Townsend's regime under standard dimensions because the current is limited and

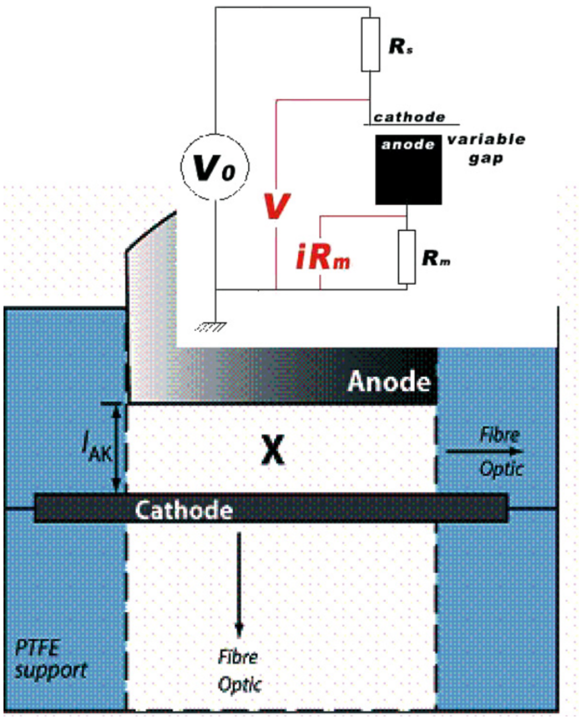

Figure 1. Experimental set-up for micro-discharge measurements. (This figure is in colour only in the electronic version)

thereby the density of radiation is small. On the other hand, Townsend's regime allows operation under conditions that favour UV production [11]. Micro-discharges operating in a Townsend regime hold promise [11] of providing sufficient overall photon production thanks to j/p^2 scaling (j = discharge current/discharge area), while taking advantage of the regime and the possibility of adjusting operating parameters in order to optimize photon production by operating at a very high E/N in the entire gap.

2. Experiment and procedure

2.1. Experimental apparatus and procedure

For centimetre dimensions [8, 12–14] we determine the small changes in voltage by running a very weak Townsend discharge (to avoid breakdown time delays) and by pulsing the current which leads to a change in the operating voltage. The breakdown voltage is obtained by extrapolating the measured voltages to zero current.

Two systems were built: one for the intermediate gaps (of the order of 0.5 mm) and one for the small gaps. The intermediate gap system uses Teflon foils of thicknesses 0.5 and 0.1 mm to obtain gaps over the radius of 3 mm. Thin sheets of stainless steel were used as electrodes. This system did not allow changes in the gap without the opening of the system. Even though it was possible to make a 0.1 mm gap one could not guarantee reasonably parallel electrodes and determination of the gap so we only present data for 0.5 mm.

The system that was built for small gaps (figure 1) allowed variable gaps without having to open the vacuum system and disassemble the electrode system. One of the electrodes was a cylinder that was movable continuously. The zero position was established by checking the contact between the two electrodes and then the movable electrode was pulled away. To improve pumping a 0.1 mm gap was left between the movable electrode and the dielectric walls (extending all the way to the other electrode).

All measurements presented here were performed in pure Ar.

2.2. Simulation procedure

A particle in the cell (PIC) code was used with an updated set of facilities to model secondary electron production [15, 16]. Growth of ionization followed until the discharge became self-sustained and that voltage was declared as the breakdown voltage. In addition, it was possible to follow volt–ampere characteristics by changing the current flowing through the system. In the model it was also possible to add electron emission due to an increased field at the cathode and due to tunnelling.

3. Breakdown voltages and volt–ampere characteristics

3.1. Gas breakdown: measurements and comparisons

In principle, a Paschen curve (here we assume that it is the dependence of the breakdown voltage on the value of *pd*) should be valid at all gaps unless some new physics enters the critical stage of secondary electron production. The possible candidates for the 'new physics' that are expected to change the kinetics and cause the violation of the *pd* scaling are field emission, phase transitions in the gas at high pressures, tunnelling effects, and a few more. Applicability of the same physical set of data and phenomenology in higher current discharges is further complicated by possible nonlinearities of the system.

We have measured Paschen curves for dc micro-discharges at gaps of 20, 40 and 100 μm. In the system designed to cover the smallest gaps it was not possible to achieve stable operation in the Townsend regime (though the whole set of measurements was aimed at establishing which regimes were covered in the measurements). Thus, we could not extrapolate measurements to the zero current as is done for standard size low pressure discharges.

The measured Paschen curve is shown in figure 2. Having in mind uncertainties in the determination of the breakdown voltage, the scatter of the results is within the experimental uncertainties that are expected. When the voltage is gradually increased until breakdown occurs, it is possible that it may exceed the breakdown voltage and overvoltage could be considerable. Thus, we should take into account only the lowest observed breakdown voltages for a given *pd* and with that in mind we could conclude that to the right of the Paschen minimum and at the minimum good agreement and *pd* scaling for different gaps have been observed.

At *pd* below 0.4 Torr cm a sharp rise is expected based on our simulations and standard size discharge phenomenology. Our simulations included all possible mechanisms known

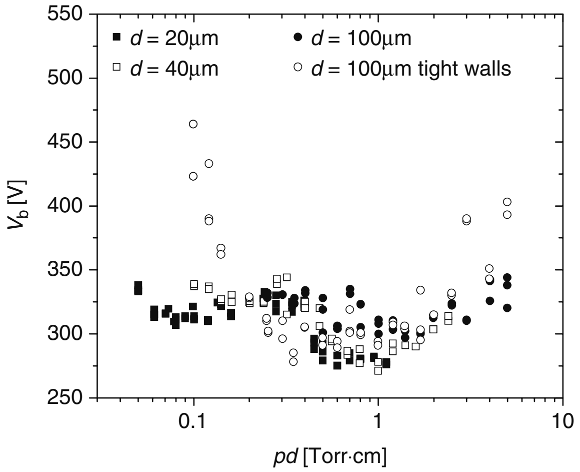

Figure 2. Paschen curves for breakdown with a small gap between the electrodes and walls (20 μm gap, 40 μm and 100 μm). Measurements with a gap of 100 μm and with closely fitting electrodes inside the glass tube are shown as open circles.

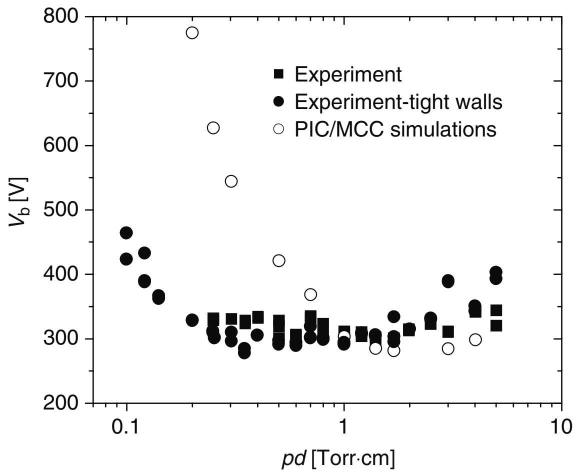

Figure 3. Experimental and theoretical Paschen curves for 100 μm. Solid circles—experiment with tight walls, solid squares—standard experiment, open circles—calculations with fixed γ [7].

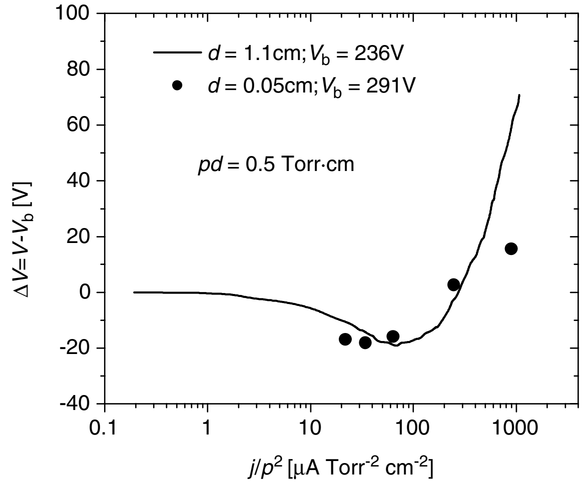

Figure 4. Volt–ampere characteristic for a micro-discharge in Ar at 0.5 Torr cm obtained at gaps 1 cm (line) and 0.5 mm (symbols).

to us: secondary electron emission induced by cathode bombardment, field emission and quantum tunnelling, and only the first mechanism made a significant contribution to our conditions. On the other hand our experiments do not confirm the existence of the sharp rise. Some authors attribute the flat left-hand side of the Paschen curve to the field emission but the simulations have shown that such an explanation is valid only below 5 μm [15, 16]. Our simulations show the expected rise in the breakdown voltage that is even greater than that in the experiment regardless of the included field emission (see figure 3) when a fixed set of secondary electron yields is used [7]. We have even tried to fit the experimental data by adjusting the secondary electron emission yield, and in that case, even when we allowed the secondary emission yield to go up to an unrealistic value of 10, the rise to the left of the minimum is faster than in the experiment. For experimental reasons it was not possible to cover all gaps and pressures as desired. Similar flat characteristics on the left-hand side have even been observed for centimetre size gaps [17], but under these conditions the only plausible explanation is the long path breakdown due to rounded electrodes. In our case, long path breakdown is a possible explanation for two reasons: the characteristics stay flat and the voltage equal to the minimum, while the field emission controlled characteristics are expected to drop towards the lower *pd* (as E increases) [15, 16]. If the long path explanation is correct then the penetration of the discharge into the gap between the electrode and the insulator allows the discharge length to vary as required and the breakdown voltage stays close to the minimum value. However, all options are still open for explanation and further studies may be required to resolve this issue.

We have also built a system with closely fitting walls (sacrificing the pumping speed) and repeated the measurements albeit only at 100 μm. As a result (see figures 2 and 3) we could extend the measurements along the left-hand side of the Paschen curve replicating an increasing dependence. It, however, occurs at a somewhat lower *pd* than for the centimetre size discharges (see figure 3 points for fixed secondary yields) leaving the issue of long path breakdown versus other explanations still open.

Even after our best efforts (assuming exceedingly high γ) we could not fit the measured Paschen curves for the micro-discharges, not even the curve with the closely fitting walls. At the gap of 100 μm field emission required exceedingly high voltages while γ required values in excess of 10 at the lowest *pd*.

An important issue in analysing the secondary electron production and in developing models is that it is not sufficient to model just the Paschen curve [7], but one needs to model the V–I characteristics also [7, 9].

3.2. Volt–ampere characteristics

In figure 4 we show the V–I characteristics for a moderate size reactor with a gap of 0.5 mm. The results are shown in comparison with older centimetre size reactor results [8, 14] in order to test the validity of j/p^2 scaling at smaller gaps. In principle, day-to-day and run-to-run changes in the breakdown

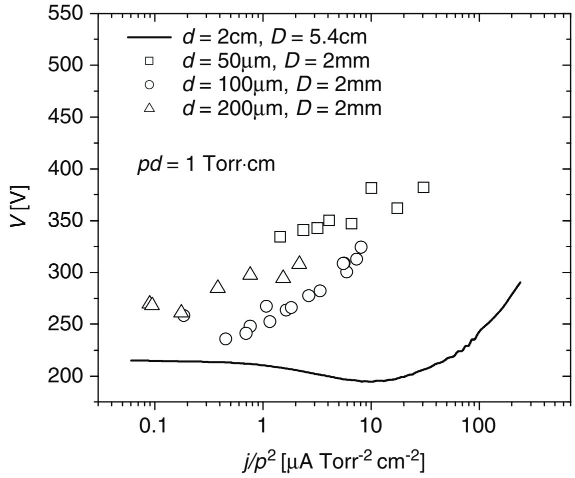

Figure 5. Volt–ampere characteristics for $pd = 1$ Torr cm. Open symbols assume that the entire radius is covered by the discharge.

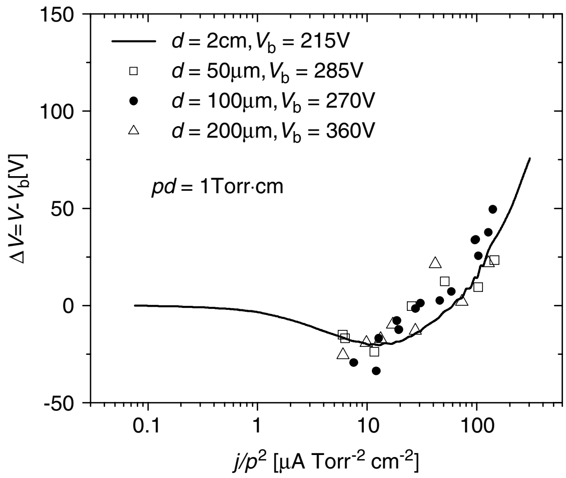

Figure 7. Volt–ampere characteristics for $pd = 1$ Torr cm where the discharge voltage has been scaled to the estimated breakdown voltage.

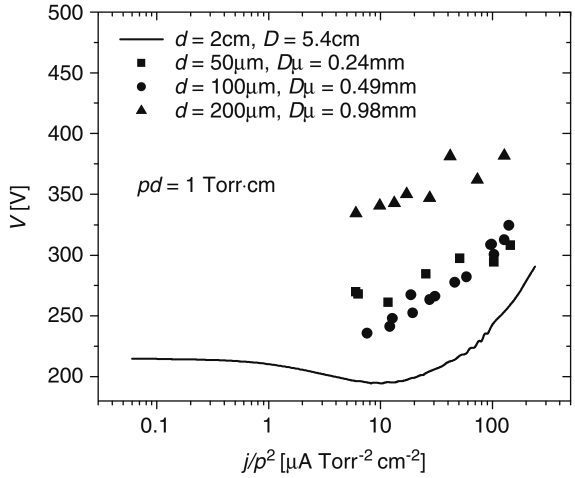

Figure 6. Volt–ampere characteristics for $pd = 1$ Torr cm. Solid symbols use pD normalization to scale D from the low pressures.

voltage (V_b) could be as large as even several tens of volts. On the other hand, the small changes required to determine the negative differential resistance [13] are much smaller; so the best way to present the results is to use the voltage relative to the breakdown voltage ($\Delta V = V - V_b$). However, to achieve that we need stable measurements in Townsend's regime and when we cannot succeed we need to present the actual voltages as done in figures 5 and 6. In the analysis we assumed that the entire radius is uniformly covered by the current in the determination of the current density.

In figure 5 we show the results for 1 Torr cm. The results, normalized by the same procedure as in figure 4 (i.e. by assuming that the discharge develops across the entire radius), are shown as open symbols (plotted against the standard data for centimetre size measurements [8]).

Until recently proper determination of the area of the discharge has not been employed to determine the current density except for centimetre sized discharges [18]. Usually the actual area of the electrode was employed. Having in mind that at high pressures the discharge tends to operate in a constricted mode, we have assumed that the width of the discharge is much narrower than the width of the electrode (2 mm). Thus, it is important to apply a realistic diameter of the discharge in order to obtain correct current densities (j = current/effective discharge area) and to produce an appropriate j/p^2 scaling. Taking into account that, at fixed pd, pressure (p) × discharge diameter (D) scaling holds (e.g. [19]), we were able to estimate the expected diameter of the micro-discharge (D_μ) from the standard size discharges. We start from the size of the constricted channel for a centimetre size discharge that was determined by the ICCD camera. We apply pD_μ scaling to the effective diameter of the conducting channel for each of the micro-discharges where we could not make the measurement with the camera. This allowed us to rescale the V–I characteristics with a proper j/p^2 parameter (figure 6). After using the scaled diameter we get a fairly good agreement between different gaps although the breakdown voltage itself may not be the same (figure 6).

If one were to scale all the curves by subtracting the estimated breakdown voltage for each set of measurements, one would get an excellent agreement between the different sets of data as can be seen in figure 7. As we could not extend the measurements to exceedingly small currents in the Townsend regime we had to determine the breakdown voltage by fitting one point in the glow regime to be of the same value for all three sets. Variation of the obtained breakdown voltages in this case does not exceed the expected variations in discharges of this type. Figure 7 shows good agreement between the newly measured and the older [8] data for centimetre gaps. The results also indicate that we have mostly the discharge in the normal and abnormal glow and not really in the Townsend regime that was our goal.

4. Conclusions

In this paper we have tested the pd and j/p^2 scaling from a few centimetres to 20 μm. It works well for volt–ampere characteristics and for Paschen curves, with the exception of the left branch of the Paschen curve. This is consistent with the theory [15, 16] which predicts the violation of scaling when field emission becomes significant only at gaps smaller than 10 μm. However, explanation of the flat left-hand side branches of the Paschen curve is still open and in order to achieve the j/p^2 scaling we had to impose rescaling of the radial dimension of the discharge.

While there were attempts to perform similar measurements for micro-discharges before [20] this is the first such experiment that covers at the same time both pd and j/p^2 scaling from the standard centimetre size discharges [12–14]. In addition to allowing one to set up models for micro-discharges based on the relevant physical phenomena, validation of scaling allows one to employ standard swarm data in standard fluid and kinetic theories according to the usual procedures and also subject to the same limitations due to applicability of the hydrodynamic expansion and the resulting spatial (and temporal) locality [21–23]. It is thus interesting to seek conditions where some of the kinetic phenomena may affect the discharges more strongly than in the standard conditions that could lead to violation of scaling.

In any case the understanding of scaling may be of crucial importance for developing models of micro-discharges and applications such as those that involve light sources [1, 24–27]

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