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Similarity law for rf breakdown

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Abstract – This paper demonstrates that the similarity law for the rf gas breakdown has the form $U_{rf} = \psi(p \cdot L, L/R, f \cdot L)$(where U_{rf} is the rf breakdown voltage, p is the gas pressure, L and R are the length and diameter of the discharge tube, respectively, f is the frequency of the rf electric field). It means that two rf breakdown curves registered for narrow inter-electrode gaps or in geometrically similar tubes and depicted in the $U_{rf}(p \cdot L)$ graph will coincide only when the condition $f \cdot L = \text{const}$ is met. This similarity law follows from the rf gas breakdown equation and it is well supported by the results of measurements.

Introduction. – Recently a considerable number of papers were devoted to gas breakdown in rf electric field (see [1–18]). It is associated with a broad application of rf discharge in plasma technology processes as well as with an opportunity to determine the electron drift velocity in a strong rf electric field (see [13,16] and the references cited therein).

As is known [10,11,13,15–18], an rf breakdown curve contains a region of multi-valued dependence of the breakdown rf voltage U_{rf} on the gas pressure p in the range of low gas pressure values. The presence of this region is associated with an enhanced flow of electrons out of the inter-electrode gap due to the drift motion in the rf field when the amplitude A of the electron displacement in the rf field is close to one-half of the inter-electrode distance L. The rf breakdown curve usually consists of the diffusion-drift, Paschen and multipactor branches [13]. A detailed description of the processes occurring in each of these branches is given elsewhere [13]. The authors of earlier papers [1–4,8] observed the rf breakdown curves with a "jump" which was the transition from the diffusion-drift branch to the Paschen one. Then Levitskii [10] was the first to demonstrate that the rf breakdown curve possessed actually not a "jump" but a multi-valued region.

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Despite the availability of detailed experimental data on rf breakdown in discharge vessels of various geometry in a number of gases as well as of the results of rf discharge simulation, the similarity law for rf discharge breakdown which can be applied to all branches of the rf breakdown curve in a broad range of inter-electrode gap, gas pressure and rf electric field values is still missing.

The authors of paper [5] suggested the following similarity law for the rf gas breakdown:

$$U_{rf} = \psi\,(p \cdot L,\ f/p)\,. \tag{1}$$

This law furnishes a good agreement for the diffusion-drift branches of rf breakdown curves [5–7]. However, for the sections of Paschen branches registered by the authors of [7] for various frequencies, the application of the similarity law (1) demonstrates considerable divergence of rf breakdown voltages. Again, the parameter f/p is not suitable for the description of multipactor branches, for which the rf breakdown voltage does not depend on gas pressure, but is a function of the inter-electrode gap L and the frequency f. Consequently, the similarity law (1) is not universal for all three branches of the rf breakdown curve.

Francis [19] analyzed the possible similarity parameters for elementary processes in plasma. He showed that for the alternate current discharges along with conventional

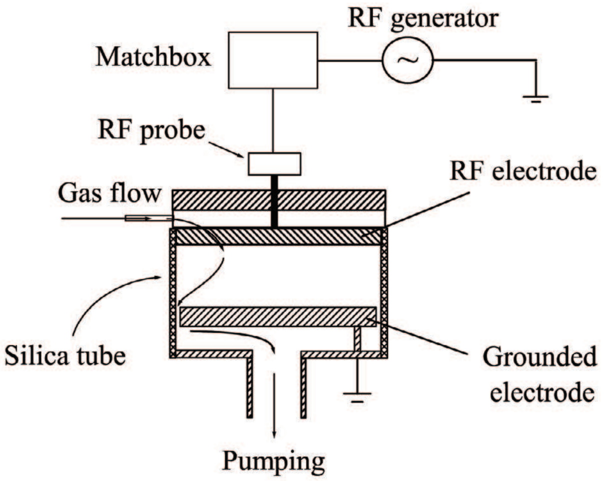

Fig. 1: Schematic of our experimental set-up.

similarity parameters E/p, pL, pR, the following similarity parameters $f\cdot L$, $f\cdot R$, f/p are also important. It is expedient to clarify what is the role the similarity parameter $f\cdot L$ plays in the rf gas breakdown.

The present paper considers the gas breakdown equation in rf electric field. The rf breakdown voltage U_{rf} is shown to depend not only on the product of the gas pressure and the inter-electrode distance $p\cdot L$ and the ratio of the inter-electrode gap to the discharge vessel radius L/R, but also on the product of the rf electric field frequency and the gap $f\cdot L$. Two rf breakdown curves depicted in the graph $U_{rf}(pL)$ will coincide only when the product $f\cdot L=\text{const}$ for them. The similarity law we found for rf breakdown $U_{rf}=\psi(p\cdot L, L/R, f\cdot L)$ is supported by the results of experiments.

Experimental setup. – The rf discharge was ignited in the pressure range $p\approx 0.05$–20 Torr with rf frequencies $f=2\,\text{MHz}$, $f=13.56\,\text{MHz}$ and $f=27.12\,\text{MHz}$. The distance between the parallel-plate electrodes (143 mm in diameter) was varied over the range $L=3$–25 mm. The rf voltage, with an amplitude $U_{rf}<1300\,\text{V}$, was fed to the upper electrode, the other one was grounded. The electrodes were located inside a fused silica tube with an inner diameter of 145 mm (see fig. 1). The gas was supplied through small orifices in the powered electrode and then pumped out via the gap (1 mm) between the second electrode and the wall of the fused silica tube. This distance was necessary both to allow adequate gas flow and to allow for thermal expansion of the electrode, whilst preventing discharge breakdown in this region.

The gas pressure was monitored with 10 and 1000 Torr capacitive manometers (MKS Instruments). The gas flow was set with a mass flow controller to 5 sccm, and the pressure regulated by throttling the outlet to the pump. The rf voltage was measured with an rf current-voltage probe (Advanced Energy Z'SCAN).

We used the technique proposed by Levitskii [10] to measure the breakdown curves of the rf discharge. Near to, and to the high-pressure side of, the breakdown curve minimum the gas pressure was fixed before slowly increasing the rf voltage until gas breakdown occurs. To the low-pressure side of the minimum the curve may be multi-valued, *i.e.* the curve turns back towards high pressure and breakdown occurs at two different values of the rf voltage. Therefore in this range we first decreased the gas pressure, then fixed the rf voltage value and only then increased the gas pressure slowly until discharge ignition occurred. At the moment of discharge breakdown the rf voltage shows a sharp decrease, and a glow appears between the electrodes serving as our criterion for the onset of gas breakdown. The uncertainty in the measured breakdown voltages did not exceed 1–2 V over the whole U_{rf} range under study.

The phenomenological model of rf breakdown. – Let us take the equation for gas breakdown in rf electric field in a cylindrical vessel with a gap L between flat electrodes of radius R [12,13]:

$$\frac{\nu_i}{D_e}=\left(\frac{2.405}{R}\right)^2+\frac{D_L}{D_e}\frac{\pi^2}{(L-2A)^2}=\left(\frac{2.405}{R}\right)^2+\frac{D_L}{D_e}\frac{\pi^2}{\left(L-2\frac{V_{dr}}{\omega}\right)^2},\qquad(2)$$

where ν_i the ionization rate of gas molecules via electron impact, D_L and D_e are electron diffusion coefficients along and across electric field, $A=V_{dr}/\omega$ is the electron displacement amplitude in the rf electric field, V_{dr} is the electron drift velocity, $\omega=2\cdot\pi\cdot f$ is the cyclic frequency of the rf field. This equation was obtained through the consideration of the electron balance equation taking into account gas molecule ionization via electrons, diffusion anisotropy along and across the electric field direction as well as the electron drift in the rf field. It was also assumed that the electron concentration vanishes on the electrodes and walls of the discharge chamber. In the case of isotropic electron diffusion ($D_L=D_e$) this equation was first obtained by Kihara [9].

We will write the ionization rate in the form $\nu_i=\alpha\cdot V_{dr}$, where

$$\alpha=A_0\cdot p\cdot\exp\left(-\frac{B_0}{E_{eff}/p}\right),\qquad(3)$$

$$V_{dr}=\mu_e E_{rf}=\mu_{e0}E_{rf}/p\,,\qquad(4)$$

A_0 and B_0 are the constants depending on the gas species, μ_{e0} is electron mobility at the gas pressure of $p=1\,\text{Torr}$, E_{rf} is the rf electric field amplitude, E_{eff} is the intensity of the effective field, then for the reduced effective electric field E_{eff}/p we have

$$\frac{E_{eff}}{p}=\frac{E_{rf}}{p\cdot\sqrt{2}}\cdot\frac{\nu_{en}}{(\nu_{en}^2+\omega^2)^{1/2}}=\frac{U_{rf}}{\sqrt{2}\cdot(pL)}\cdot\frac{\nu_{en0}\cdot(pL)}{\left[\nu_{en0}^2\cdot(pL)^2+(2\pi)^2\cdot(fL)^2\right]^{1/2}},\qquad(5)$$

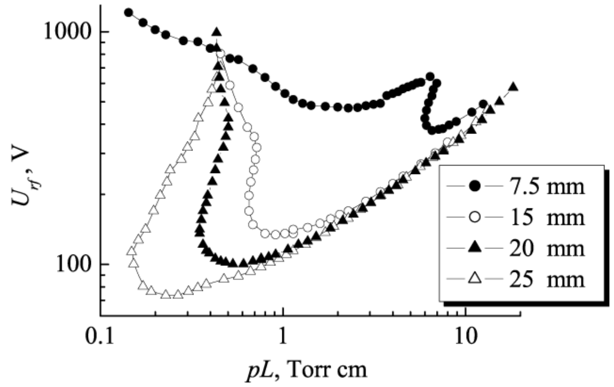

Fig. 2: Rf breakdown voltage U_{rf} against pL product in nitrogen for various inter-electrode gap values, $f = 13.56$ MHz.

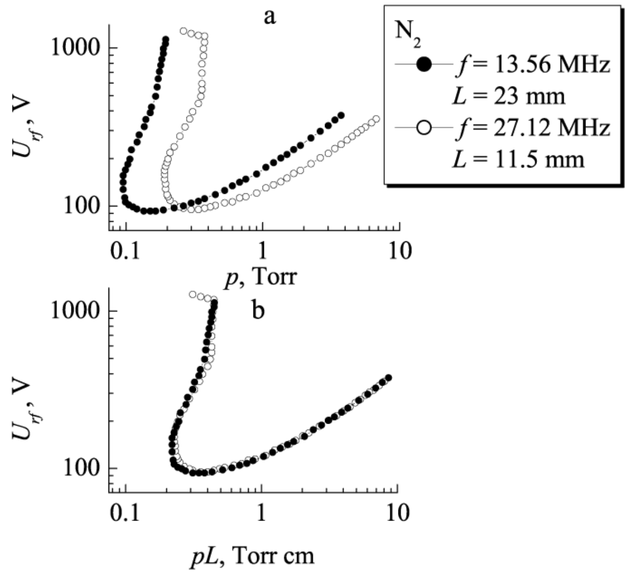

Fig. 3: Rf breakdown voltage U_{rf} against nitrogen pressure (a) and pL (b) product for $f = 13.56$ MHz, $L = 23$ mm and $f = 27.12$ MHz, $L = 11.5$ mm.

ν_{en0} is the electron-neutral collision rate at $p = 1$ Torr. Let $D_L = D_{L0}/p$, $D_e = D_{e0}/p$, D_{L0} and D_{e0} be the electron diffusion coefficients along and across the electric field at the pressure $p = 1$ Torr, respectively. Let us take into account that $E_{rf} = U_{rf}/L$, then eq. (2) may be put in the form

$$\frac{A_0\mu_{e0}}{D_{e0}} \cdot \frac{U_{rf}}{(pL)} \cdot \exp\left[-\frac{B_0}{E_{eff}/p}\right] \cdot (pL)^2 = \left[2.405 \cdot \left(\frac{L}{R}\right)\right]^2 + \frac{D_{L0}}{D_{e0}} \cdot \frac{\pi^2}{\{1-(\mu_{e0} \cdot U_{rf})/[\pi \cdot (pL) \cdot (fL)]\}^2}. \quad (6)$$

We will not solve the equation derived because another of our papers [15] contains the numerical solution of this rf breakdown equation for three different types of discharge chamber design. In the present paper it is sufficient to have eqs. (5), (6) just in the derived form.

Experimental results and discussion. – The main aim of our paper is to find a similarity law for rf gas breakdown. For a dc gas breakdown (in a constant electric field) the similarity law has the form $U_{dc} = \psi(pL)$ and it is called the Paschen law [20,21]. However, as was shown in paper [22], the Paschen law is valid only for narrow gaps when the inter-electrode distance is small compared with the discharge tube radius, $L \ll R$, as well as for geometrically similar tubes. For cylindrical discharge tubes with arbitrary L and R values the similarity law for dc gas breakdown should be written in the form [22]

$$U_{dc} = \psi\left[pL,\ \frac{L}{R}\right]. \quad (7)$$

The dc breakdown curves registered in two discharge tubes coincide when the L/R ratios for these tubes are the same and the curves are plotted as $U_{dc}(pL)$.

We registered rf breakdown curves in nitrogen, hydrogen, argon and NF_3 for various inter-electrode gap values. Figure 2 depicts rf breakdown curves plotted as $U_{rf}(pL)$. The figure demonstrates that rf breakdown curves registered in nitrogen for various inter-electrode gap values coincide only at large pL values, whereas increasing inter-electrode gap shifts rf breakdown curves to lower gas pressure and rf voltage values. To our regret we had no opportunity to perform experiments with the electrodes of different radii R and to register a set of rf breakdown curves for geometrically similar discharge tubes (for $R/L = \text{const}$). However it follows from papers [4,11] that the ratio of gap width to tube radius affects the gas breakdown when $L/R > 0.4$–0.5. At the largest gap value we studied $L = 25$ mm we have $L/R = 0.34$, therefore the contribution of the L/R parameter into the rf breakdown curve pattern hardly plays an important role.

However eqs. (5), (6) show that the rf breakdown voltage U_{rf} depends not only on pL and L/R but also on the product of the rf electric field frequency and gap width $f \cdot L$. The book by Francis [19] reports that we can use $f \cdot L$, $f \cdot R$, f/p quantities as similarity parameters for alternating current discharges. Therefore, we may assume that two rf breakdown curves registered for the frequencies f_1 and f_2 with the inter-electrode gap values of L_1 and L_2 will coincide when they are plotted in the scale $U_{dc}(pL)$ under fulfilment of the condition $f_1 \cdot L_1 = f_2 \cdot L_2$. Figure 3 demonstrates that two such breakdown curves, registered in nitrogen for $f = 13.56$ MHz, $L = 23$ mm and $f = 27.12$ MHz, $L = 11.5$ mm possess a similar shape and are shifted with respect to each other along the pressure scale when they are plotted as $U_{dc}(p)$, and almost coincide in the $U_{dc}(pL)$ graph. The same coincidence can be observed for breakdown curves in hydrogen (fig. 4) and in NF_3 (fig. 5) at the same frequency and gap values. Therefore we may conclude that the similarity law for rf gas breakdown has the following form:

$$U_{rf} = \psi\left(p \cdot L,\ \frac{L}{R}, f \cdot L\right). \quad (8)$$

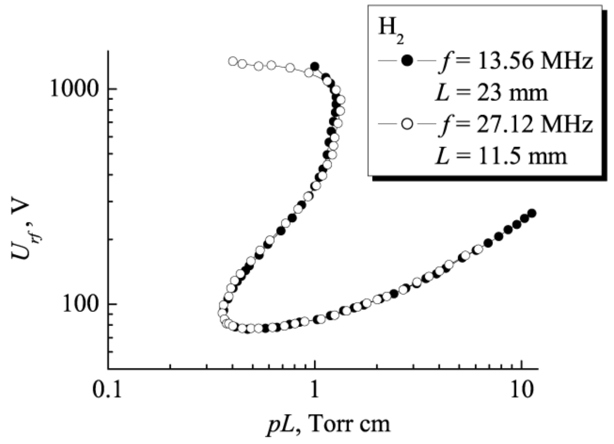

Fig. 4: Rf breakdown voltage U_{rf} against pL product for hydrogen with $f = 13.56\,\mathrm{MHz}$, $L = 23\,\mathrm{mm}$ and $f = 27.12\,\mathrm{MHz}$, $L = 11.5\,\mathrm{mm}$.

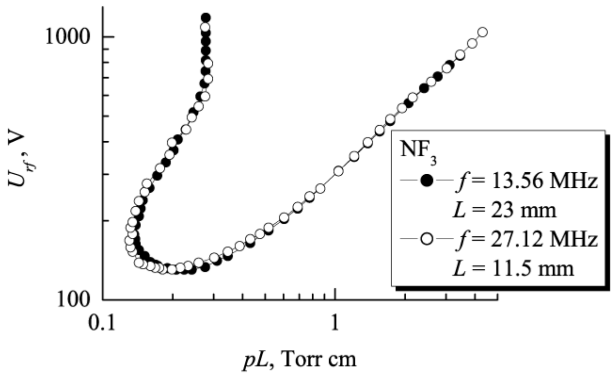

Fig. 5: Rf breakdown voltage U_{rf} against pL product for NF_3 with $f = 13.56\,\mathrm{MHz}$, $L = 23\,\mathrm{mm}$ and $f = 27.12\,\mathrm{MHz}$, $L = 11.5\,\mathrm{mm}$.

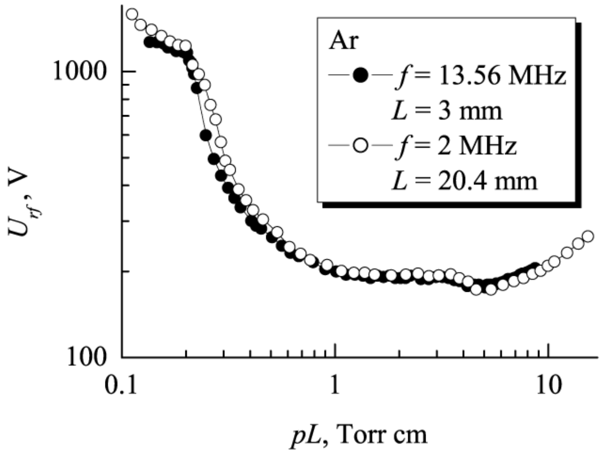

Fig. 6: Rf breakdown voltage U_{rf} against pL product for argon with $f = 13.56\,\mathrm{MHz}$, $L = 3\,\mathrm{mm}$ and $f = 2\,\mathrm{MHz}$, $L = 20.4\,\mathrm{mm}$.

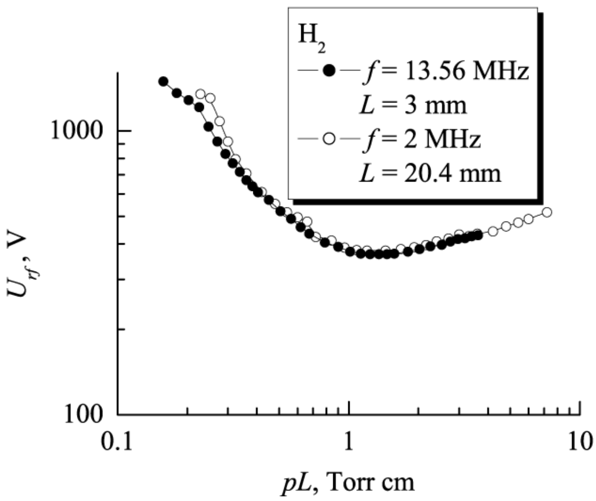

Fig. 7: Rf breakdown voltage U_{rf} against pL product for hydrogen with $f = 13.56\,\mathrm{MHz}$, $L = 3\,\mathrm{mm}$ and $f = 2\,\mathrm{MHz}$, $L = 20.4\,\mathrm{mm}$.

The difference between the rf breakdown curves shown in fig. 2 is associated with the fact that the curves were registered for different gap values L and a fixed frequency f, *i.e.* for different values of the product $f \cdot L$.

In figs. 3–5 we observe a good coincidence of diffusion-drift branches of rf breakdown curves registered when $f \cdot L = \mathrm{const}$. But rf breakdown curves may also possess Paschen and multipactor branches. The Paschen branch is well observed for narrow gaps ($L < 10\,\mathrm{mm}$) or low frequency of the rf electric field. In fig. 6 we see the rf breakdown curves in argon for $f = 2\,\mathrm{MHz}$, $L = 20.4\,\mathrm{mm}$ and $f = 13.56\,\mathrm{MHz}$, $L = 3\,\mathrm{mm}$. It is clear that in this case we observe the coincidence not only of diffusion-drift (for $pL > 3.5\,\mathrm{Torr\,cm}$), but also of Paschen branches of registered rf breakdown curves at lower pL value. Rf breakdown curves in hydrogen presented in fig. 7 possess only Paschen branches within the pressure range we studied. They also demonstrate good coincidence under the condition $f \cdot L = \mathrm{const}$.

It is difficult to make any judgment on the behaviour of multipactor branches from our results, because the rf generators we possess allowed us to measure only a transient region between the Paschen and multipactor branches. However, the authors of papers [23–27] also use the $f \cdot L$ parameter when describing the characteristics of the multipactor discharge thus favouring the applicability of the similarity law we suggest also to this branch of the rf breakdown curve.

Conclusions. – Thus using the equation for rf gas breakdown we have shown that two rf breakdown curves registered with different inter-electrode gap values L and different rf electric field frequencies f and plotted as the $U_{rf}(pL)$ graph coincide only when the product of the frequency and gap value for them satisfies the relation $fL = \mathrm{const}$. In the general form the similarity law for the rf gas breakdown is expressed as $U_{rf} = \psi(p \cdot L, L/R, f \cdot L)$ and it is well supported by experimental results. We observe not only the coincidence of diffusion-drift branches of rf breakdown curves for the description of which our equation of rf breakdown is derived, but also the coincidence of Paschen branches.

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