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Can the "Maximum Power Principle" Be Applied to Pulsed Dielectric Barrier Discharge?

Danil Dobrynin, Dmitri Vainchtein, Matteo Gherardi, Vittorio Colombo, and Alexander Fridman

***Abstract*— In this paper, we report a qualitative model of operation and energy release in pulsed dielectric barrier discharges (DBDs). We demonstrate that pulsed DBDs operate according to the "maximum power principle" and explain the relevant physical processes. Compared to experimental data, the proposed model allows an accurate estimation of the discharge pulse energy as a function of dielectric properties, electrode size, and pulse parameters (shape and voltage amplitude).**

***Index Terms*— Dielectric barrier discharge, energy analysis, nanosecond-pulsed plasma.**

I. Introduction

PRINCIPLES of the maximum (or minimum) power have been used for a theoretical description of major low-temperature plasma discharges, including arc discharges, glow discharges, as well as gliding arcs and gliding barrier discharges [1]–[5]. Although these principles can be viewed in the framework of the so-called "fourth principle of energetics in open-system thermodynamics" [6]–[9], in plasma, they were explained based on the underlying physical laws [10]–[12]. In this paper, we describe power release in microsecond- and nanosecond-pulsed dielectric barrier discharges (DBDs). We demonstrate that pulsed DBDs operate according to the "maximum power principle" and explain the relevant underlying physical processes.

DBD in various configurations and gases have been extensively studied [13]–[18] since its introduction by Siemens [19]. Equivalent electrical circuits and electrical models of DBDs have been developed [20]–[25] in relation to their applications in ozone generation (see [13]–[15], [26]). Typically, power measurements and calculations are based on measurements of a time-integrated current (charge or Q–V characteristics [27]–[30]), allowing to obtain the integral power characterization of the discharge [13], [23], [31], [32].

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However, the application of this method is significantly limited for short-pulsed discharges, compared to longer pulses or continuous wave DBDs (see [23], [32]). This is primarily due to the importance of the development stages of pulsed DBDs, especially due to the differences in physics of these discharges on short-time scales for various gases, electrode configurations, and other operating conditions [28]–[30], [33]–[41]. In this paper, we propose a simplified model of a microsecond/nanosecond-pulsed DBD based on a simple equivalent circuit and show that such a simplified approach adequately follows the obtained experimental data.

II. Evolution of DBD Plasma: Concept of Electrode Glow—"Pancake"

The development of a flat DBD can be described as a three-stage process [see Fig. 1].

1) During the first few hundreds of picoseconds, the discharge starts with the development of avalanches traveling from the negative (in this case—grounded) electrode toward the high-voltage positive electrode (anode) covered with a dielectric.
2) As the avalanches reach the anode, electron concentration and local electric field are sufficient for the initiation of streamers. At this point, at about 1 ns, the presence of a dielectric surface facilitates the development of a surface discharge (surface-directed streamers), which shows up in experiments as a bright glow area near the positive dielectric-covered electrode. This electrode glow—"pancake"—appears prior to the main volumetric discharge due to effects of the surface. The appearance of the electrode glow ("pancake") and the propagation of a surface wave along the anode were reported in our previous publication (see a photograph in [42]). It should be mentioned that the physics of the anode surface wave is similar to that of the surface discharge induced due to charge accumulation on the dielectric after cathode-directed streamers reach the instantaneous dielectric-covered cathode (see [43]).
   In the equivalent-circuit language, the "pancake" can be described as an additional capacitor, which accumulates a portion of full discharge energy.
3) At the third stage, the main volumetric discharge starts to develop with the evolution of traditional cathode-directed streamers. This stage corresponds to the most energetic phase of the DBD.

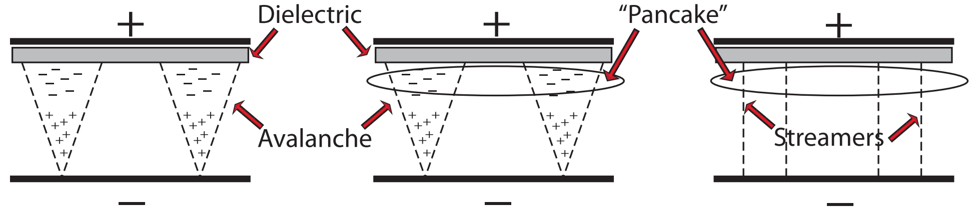

Fig. 1. Three stages of DBD development. Left: avalanches propagate from cathode (bottom) to anode (top). Center: the "pancake" appears near anode. Right: streamers develop and start propagating toward cathode.

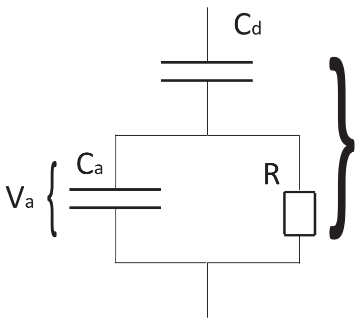

Fig. 2. Equivalent electric circuit during the main phase of discharge. C_d corresponds to a dielectric, C_a corresponds to an air gap, and R is a time-varying resistance of plasma in the gap.)

In the following section, we estimate the energy release in the "pancake" and compare it with the total energy release in the system during the discharge.

III. Energy Release During the Volumetric Discharge

We start with estimating the energy released in a full DBD discharge. For that purpose, we consider a simplified equivalent electrical circuit shown in Fig. 2. Here, the dielectric is represented by a capacitor with the capacity C_d, and the air (plasma) gap is represented by a parallel capacitor (capacity C_a). When the plasma appears in the air gap, its resistance becomes finite, and we denote it by R.

In the first approximation, we can assume that the capacitances C_a and C_d are constant. Characteristic ratio $C_a/C_d \sim 1/\varepsilon$, where $\varepsilon \approx 4$ is the conductance of a dielectric. On the other hand, the resistance R changes depending on the temperature in the plasma gap, which, in turn, depends on the current.

An equivalent circuit shown in Fig. 2 corresponds to the system of equations, which is a combination of Ohm's law and the conservation of charge

$$\begin{aligned} V(t) &= q_d/C_d + q_a/C_a \\ q_a/C_a &= J_R R \\ \frac{dq_d}{dt} &= \frac{dq_a}{dt} + J_R \end{aligned} \tag{1}$$

where J_R is the current through plasma, and q_a and q_d are the charges on the two capacitors.

For a generic profile of an impulse $V(t)$, (1) is a system of time-dependent ODEs. System (1) can be readily solved for a sinusoidal profile of the voltage $V(t) = V_0 \exp(-i\omega t)$. Here, $1/\omega$ is a characteristic voltage rise time. In this case, the impedance of the air gap (parallel C_a and R) is

$$R_a^Z = \left[\frac{R}{1+(C_a\omega R)^2}\right] + \left[\frac{C_a\omega R^2}{1+(C_a\omega R)^2}\right] i.$$

The full impedance is

$$R_{\text{tot}}^Z = \left[\frac{R}{1+(C_a\omega R)^2}\right] + \left[\frac{1}{C_d\omega} + \frac{C_a\omega R^2}{1+(C_a\omega R)^2}\right] i.$$

Thus, for the voltage on the gap, we obtain

$$\frac{\left|R_{\text{tot}}^Z\right|}{\left|R_a^Z\right|} V_a = V_0.$$

For the square of the ratio of the impedances, we have

$$\frac{\left|R_{\text{tot}}^Z\right|^2}{\left|R_a^Z\right|^2} = \left(\left[\frac{1}{C_d\omega R} + \frac{C_a\omega R}{1+(C_a\omega R)^2}\right]^2 + \left[\frac{1}{1+(C_a\omega R)^2}\right]^2\right)[1+(C_a\omega R)^2]. \tag{2}$$

Opening the parenthesis and simplifying, we arrive at

$$\frac{\left|R_{\text{tot}}^Z\right|^2}{\left|R_a^Z\right|^2} = \frac{1}{C_d\omega R} + \left(1 + \frac{C_a}{C_d}\right)^2. \tag{3}$$

The evolution of the system is guided by the time dependence of the effective resistance of plasma, $R(t)$. As $R(t)$ cannot be measured directly, it is reasonable to replace it as an independent variable as the power released at the gap

$$P = \frac{1}{2}\, V_a(t)^2/R(t). \tag{4}$$

This generic equation might be corrected in special cases, for example, when discharges develop in the mode with runaway electrons that carry away some of the energy from the gap, [44], [45]. We now introduce nondimensional variables

$$\beta = \frac{V_a^2}{V_0^2}, \quad p = \frac{2P}{C_a\omega V_0^2}, \quad k = \frac{C_a}{C_d} = \text{const.} \tag{5}$$

Expressing $R = R(p, \beta)$ and substituting

$$C_a\omega R = \beta/p; \quad C_d\omega R = \beta/pk$$

into (2), we obtain

$$k^2\ p^2 + \beta^2(1+k)^2 - \beta = 0. \tag{6}$$

Characteristic plots of (6) for three typical values of the parameter k are shown in Fig. 3. In the following section, we investigate the main aspects of these plots.

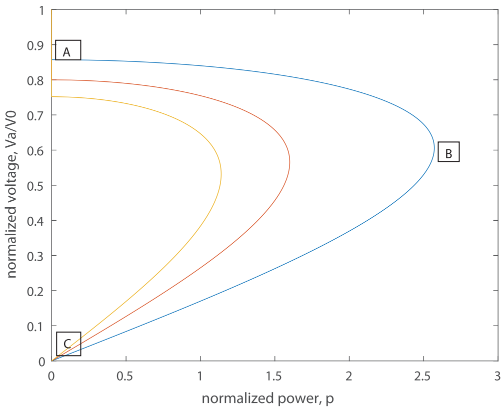

Fig. 3. Normalized voltage, V_a/V_0, on the gap as a function of the normalized power released on the gap, $p = 2P/(C_a\omega V_0^2)$, for $k = 1/3$ (left curve), 1/4 (middle curve), and 1/6 (right curve).

IV. DBD Plasma Development—"Maximum Power Principle"

The discharge process starts at point (A) in Fig. 3, as at the beginning, plasma is cold, and thus, $R \to \infty$ and $p = 0$. The evolution of the system can be viewed as a transition from (A) to (B), where the power p reaches the maximum. The curve continues toward to origin [point (C)], where $R = 0$ (essentially a short circuit).

The points on the curve from (A) to (B) to (C) are parameterized by decreasing value of $R(t)$. As the discharge starts developing, plasma heats up, and $R(t)$ drops. As a result, P increases, and V_a correspondingly drops. All along the curve, the plasma is in the nonthermal regime, and thus, the conductivity is defined by the ionization level, I. The higher the value of I is, the smaller is R. The value of I changes due to the power P released in plasma: the larger is P, the larger is I and, correspondingly, if P drops, so does I.

There is a major difference between the top and bottom branches. On the top branch, a small drop in R; in other words, a shift to the right along the curve causes P to increase. An increase in P causes I to increase, which, in turn, decreases R further. Thus, we have a self-sustained motion along the top branch. The situation is reversed on the lower branch. Now, a small drop in R shifts the system to the left along the curve, causing P to decrease. The decrease in P causes I to decrease, which increase R back. Thus, the system cannot propagate along the lower branch. The system comes to point (B) and is stuck there until streamers essentially bring the plasma resistance to zero, upon which the systems jump straight to the origin. In other words, while the system can occupy the points on the top branch (and indeed passes through all of them), the bottom branch is unphysical.

The time evolution of the voltage V and the power P along the top branch occurs with a varying rate. While in the beginning both variables change with somewhat of a fast rate, the rate of change of P vanishes at point (B)

$$at(B), \quad \frac{dP}{dV} = \frac{dP}{dt} = 0. \tag{7}$$

Therefore, in terms of the power release, the system spends most of the time there, just like a pendulum spends most of the time near the turning points. The function $p = p(\beta)$ has a maximum at

$$\beta = \frac{1}{2(k+1)^2}, \quad p = \frac{1}{2k(k+1)}.$$

The original dimensional quantities at point (B) are

$$\frac{V_a^2}{V_0^2} = \frac{1}{2(k+1)^2}, \quad P = \frac{C_d\omega V_0^2}{4(k+1)}. \tag{8}$$

The resistance $R(t)$ is

$$R_B = V_a^2/2P = (k+1)/C_d\omega. \tag{9}$$

At that moment, the resistance R effectively matches the impedance of the dielectric capacitor (when the value of k is small).

We can make the following conclusions so far.

1) The system evolution is governed by the decrease in the plasma resistance until it reaches approximately the impedance of the dielectric barrier, at which state the discharge power reaches the maximum and the evolution drastically slows down.
2) The maximum power release of the discharge is proportional to the capacitance of the dielectric and the square of the applied voltage and only weakly depends on the properties of the air gap.

V. Pulsed Energy and the Average Power as a Function of Dielectric Parameters

To compute the total energy release prior to the full discharge, the power P must be integrated over the time τ, which is the duration of the build-up. However, as we discussed above, the change in power P slows down near the point (B). Thus, we can assume that the system spends almost all the time there. The total energy released in a pulse can be estimated as

$$E_t \sim \frac{C_d V_0^2}{4(k+1)}(\omega\tau). \tag{10}$$

Recall that, in a typical discharge, ω is defined by the time of the growth of the voltage, while τ is the total duration of the impulse. Therefore, over a long time, the average power can be expressed as

$$P_{av} = E_t f \sim \frac{C_d V_0^2}{4(k+1)}(\omega\tau) f \tag{11}$$

where f is a pulse frequency.

Thus, analyzing (11), we can make the following major conclusions.

1) The system spends most of the time in the state with the maximum power; thus, the average power of the discharge is essentially equal to the maximum power.
2) The maximum power release of the discharge is proportional to the square of the applied voltage.
3) The energy release in the pulse, as well as the average power, mostly depends on the properties of the dielectric. Increase in the area or in the dielectric permittivity of dielectric, or decrease in its width, results in larger average power.

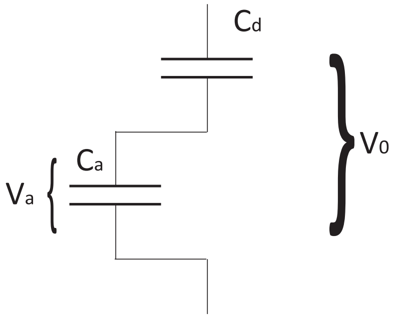

Fig. 4. Equivalent electric circuit during the build-up phase.

4) The total energy is larger for steeper growing voltage profiles. In this perspective, with other parameters fixed, nanosecond pulses release more power than the microsecond pulses.

VI. Energy Stored in the Near-Electrode Glow

We now turn to the build-up of the charge during the initial stage of charging of the capacitors. On the first stage, there is no current, $R \to \infty$, and the effective contour is shown in Fig. 4.

Substituting $R \to \infty$ into (1), we obtain

$$V_d + V_a = V_0, \quad V_d C_d = V_a C_a. \tag{12}$$

The energy contained by the plasma capacitor is thus

$$E_a = \frac{1}{2}\frac{C_a V_0^2}{(1+k)^2}. \tag{13}$$

Note that, unlike the total energy release [see (10)], the energy contained in the plasma capacitor prior to the discharge is independent of ω and τ. Comparing (13) with (10), we get

$$\frac{E_a}{E_t} \sim \frac{2C_a}{C_d(1+k)(\omega\tau)}. \tag{14}$$

It is the energy E_a that we can observe in the form of a "pancake."

Based on (13), at this point, we can make the following conclusion.

For a given power generator, the ratio of the energy release in the "pancake" and the energy release in a pulse is defined by the ratio of the capacitances of the air (plasma) gap and the dielectric.

VII. Experimental Validation

A general schematic of the experimental setup is shown in Fig. 5. We used the FID Tech Company power supply that generates pulses with the amplitude up to 15.5 kV, 10-ns duration, and 1-ns rise time. The pulse was delivered to electrodes by a 100-ft-long RG393/U high-voltage cable. For the power measurement, a current shunt was mounted on the ground shielding of the high-voltage cable [10]. The pulse voltage waveform and the instantaneous energy are shown in Fig. 6.

We used a copper cylinder (2.4 cm in diameter) covered with a 1-mm-thick quartz as DBD electrodes. The ground electrode was either plane metal or liquid holder containing either distilled water or 40% ethanol–water mixture.

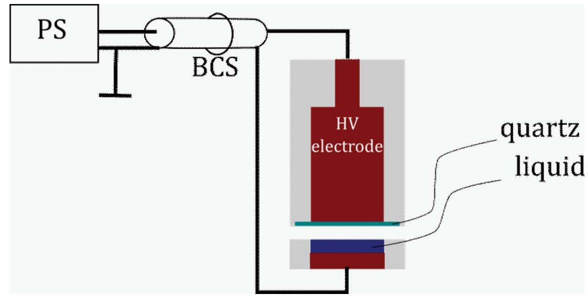

Fig. 5. Experimental setup.

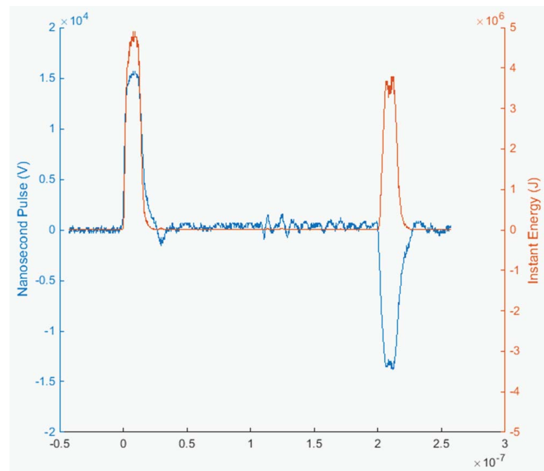

Fig. 6. Nanosecond pulse and discharge energy (applied voltage 15.5 kV).

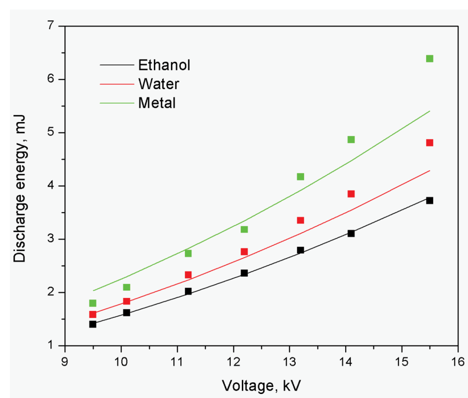

Fig. 7. Discharge energy as a function of voltage for different dielectric barriers. Symbols are the experimental data, and lines are theoretical model (10).

Experimental results of DBD pulse energy measurements were compared with calculated values for different ground electrodes (plane metal, water, or water/ethanol mixture) (see Fig. 7). The energy in the discharge was calculated using the values presented in Table I (note that the high-voltage electrode was covered with a 1-mm-thick quartz in this case). In the experiment, the energy was measured for the whole pulse, but the discharge ignites twice on the rising and falling edges of the pulse. Therefore, pulse characteristics were $\tau = 5$ ns and $1/\omega = 1$ ns, and the final energy value was doubled. A good agreement between theoretical results (10) and experimental data confirms the predicted dependence of pulse energy release on various systems parameters, such as including voltage, dielectric permittivity constant, and dielectric thickness.

TABLE I

VALUES OF EXPERIMENTAL SYSTEM PARAMETERS USED FOR CALCULATIONS

d_{air}	ε_{air}	d_{quartz}	d_{liquid}	ε_{water}	$\varepsilon_{(ethanol/water)}$
$1mm$	1	$1mm$	$2.3mm$	81	50
$C_{(quartz/metal)/}$	$C_{(quartz/water)}$	$C_{(quartz/ethanol)}$	$k_{(quartz/metal)}$	$k_{(quartz/water)}$	$k_{(quartz/ethanol)}$
$2.5pF$	$2.1pF$	$1.8pF$	0.125	0.153	0.171

VIII. CONCLUSION

In this paper, we described the power release in microsecond- and nanosecond-pulsed DBDs. We demonstrated that pulsed DBDs operate following the "maximum power principle" and explained the relevant underlying physical processes. Specifically, we presented the following.

1) The system evolution is governed by the decrease in the resistance of plasma until the resistance reaches approximately the impedance of the dielectric barrier, at which state the discharge power reaches the maximum and the evolution drastically slows down. The system spends most of the time in the state with the maximum power; thus, the average power of the discharge is essentially equal to the maximum power.
2) The maximum power release of the discharge is proportional to the capacitance of the dielectric and the square of the applied voltage and only weakly depends on the properties of the air gap.
3) The energy release in the pulse, as well as the average power, mostly depends on the properties of the dielectric (area, thickness, and permittivity). The increase in the area or in the dielectric permittivity of dielectric, or the decrease in its width, results in larger average power.
4) The total energy is larger for steeper growing voltage profiles. In this perspective, with other parameters fixed, nanosecond pulses release more power than the microsecond pulses. A good agreement between theoretical results (10) and experimental data confirms the predicted dependence of pulse energy release on systems parameters, including voltage, dielectric permittivity constant, and dielectric thickness.

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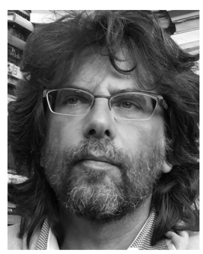

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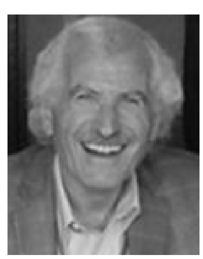

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