# Study of radio frequency breakdown in a device with movable electrodes

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Criteria for gas breakdown in a DC electric field have been explored since the very beginning of plasma science, and are nowadays well described in many textbooks. The situation is different for breakdown in capacitively coupled radio frequency (RF) field, which has been described with a systematic approach only in relatively recent times. The basic physics underlying the RF breakdown process has been described by Kihara [1], who derived the following breakdown criterion, based on a 1D balance between electric field acceleration and electron diffusion:

$$\exp\frac{B_0 p}{2E_b} = A_1 pL\left(1 - \frac{E_b/B_0 p}{C_2 L/\lambda}\right) \tag{1}$$

Here $p$ is the pressure, $E_b$ is the effective RF voltage at breakdown ($E_b = E_{RF}/\sqrt{2}$), $L$ is the distance between the electrodes, $\lambda$ is the wavelength of electromagnetic waves in vacuum corresponding to the chosen frequency ($\lambda = c/f$), and $A_1$, $B_0$ and $C_1$ are gas-dependent constants. Writing $E_b = V_b/L$, the breakdown voltage $V_b$ can be recognized to depend on $pL$ and $L/\lambda$ (or, alternatively, $fL$).

In the '90s, Lisovskiy and Yegorenkov have performed a very detailed set of studies of RF capacitive breakdown between plane electrodes [2, 3]. They demonstrated the presence of an inflection point in the curve of $V_b(pL)$, corresponding to the transition from a low-pressure regime where surface phenomena at the electrode surface are important (diffusion-drift branch), to a higher pressure one where volume phenomena dominate (emission-free branch). They also showed the existence of a pressure range, on the left side of the curve, where the curve is multi-valued, and determined the limitations of Kihara's model, deriving improved values of the parameters $A_1$, $B_0$ and $C_1$, which anyway did not allow expression (1) to fully describe the experimental data.

Subsequently, they argued that in the case of a long tube, the breakdown voltage should obey a similarity law which includes the aspect ratio $L/R$, where $R$ is the electrode radius, that is [4]

$$V_b = f(pL, fL, L/R). \tag{2}$$

According to their observations, this dependence reduces to the two-parameter one, $V_b = g(pL, fL)$, originally suggested by Llewellin-Jones and Morgan [5], only for $L/R < 0.4$–$0.5$.

In this contribution we have studied experimentally the three-parameters dependence (2) for the case of large $L/R$. The experiments have been performed in a quartz tube with 5.0 cm inner diameter, connected to a rotary pump and a globe valve allowing gas flow. The system is

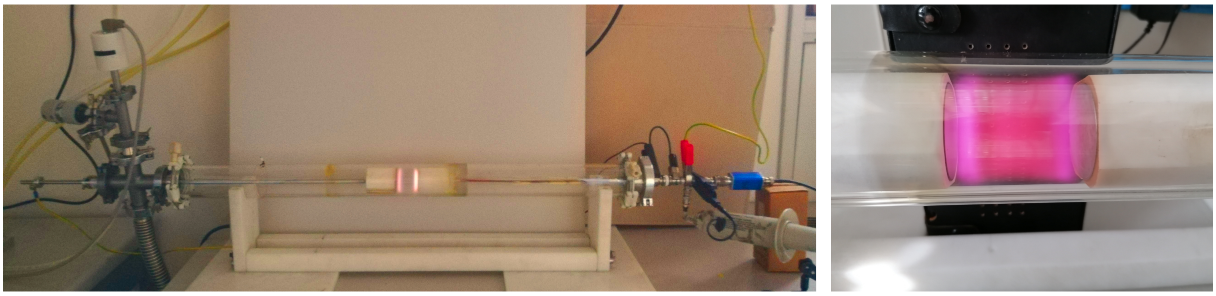

Figure 1: The experimental apparatus used for this study, and an example of plasma ignited between the electrodes after breakdown.

able to be filled with multiple gases, but this work focuses on discharges in helium; a pressure gauge allow to measure the pressure inside the system, which is kept in the order of $1-10\,\mathrm{mBar}$. The tube has two circular aluminium plain electrodes with a diameter of $4.0\,\mathrm{cm}$: one is fixed, and it is connected to a wide band RF amplifier, whereas the second one is movable, allowing to change the value of $L$, and grounded. The electrodes are embedded in dielectric Teflon support structures, allowing them to stay in position inside the tube; such structures are shaped so as to allow the gas pressure to equalize on both sides of them. The RF voltage provided by the amplifier is raised by means of a simple resonant circuit, composed of an inductor wound on iron powder toroid, and of the capacitance of the device itself. For the present work four inductors were available, giving resonance frequencies of 2.7 MHz, 3.9 MHz, 5.7 MHz and 7.3 MHz. The applied voltage is measured by means of a Tektronix P6015a probe. The amplifier is driven by a Red-Pitaya board, which also measures the applied voltage: the card slowly increases the applied voltage at a rate of about 4 V/s, until it detects a drop in the resonance amplification, which is taken as the sign of plasma breakdown. Note that in all the following the reported voltage are measured peak-to-peak.

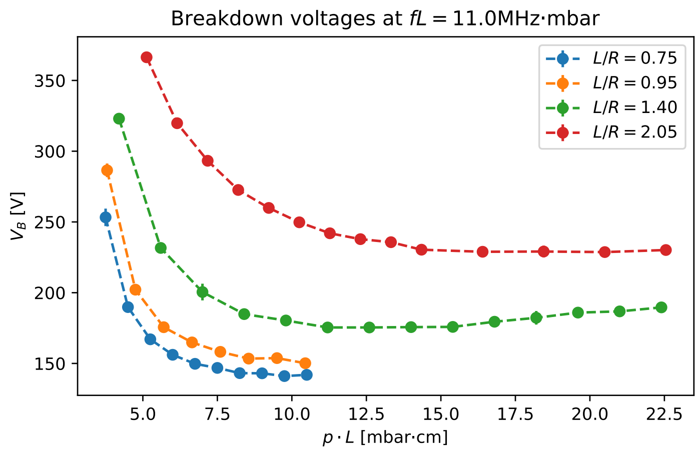


Figure 2: Breakdown voltage as a function of $pL$, for different values of $L/R$, at $fL = 11$ MHz cm.

The first set of measurements performed aimed at building the classical curves of breakdown voltage as function of $pL$, ensuring to keep the other two scaling parameters ($fL$ and $L/R$) constant. Keeping the electrode distance constant, the helium pressure was varied and the breakdown potential is measured. Then the inductor, and thus $f$, was changed, and $L$ was changed accordingly, so as to keep $fL$ constant, and the measurements were repeated. This gave a second curve at the same $fL$, for a different value of $L/R$. The same was repeated for the other two inductors. Specifically, the four values of $L$ were 1.5 cm, 1.9 cm, 2.8 cm and 4.1 cm. The results are shown in fig.2. It is to be remarked that no attempt was made to reconstruct the multi-valued behavior at the left extremum of the curves, due to the high voltages required to explore such branch. It can be seen that the curves display a broad minimum, and that this minimum rises and moves to the right as $L/R$ is increased. This is understandable, since as the ratio $L/R$ increases, the boundary surface increases leading to higher losses and worse confinement, and therefore requiring a more important electron production of the plasma to self-sustain the discharge. Furthermore, from this graph one can get a hint of what was stated in the introduction, that when $L/R$ tends towards the value 0.5 the dependence of the breakdown voltage on this parameter becomes unimportant.

Following this, the breakdown phenomenon was studied as function of the $fL$ parameter, that is the second parameter in (2). This was obtained by keeping the electrode distance $L$ constant, and using the four frequencies allowed by the setup. The procedure was repeated for different $L$ values, each time changing the pressure $p$ so as to keep $pL$ constant. The results are shown in fig. 3, for different $L/R$ values ranging between 1 and 2.5. The small number

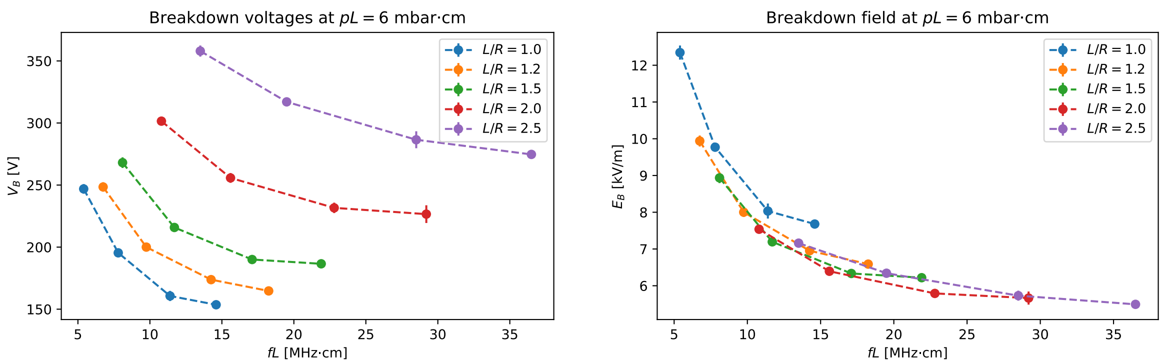


Figure 3: Breakdown voltage as function of $fL$, for different values of $L/R$, at $pL = 6$ mbar cm (left). Breakdown electric field as a function of $fL$, for the same conditions (right).

of available inductors did not allow to fully reconstruct the breakdown curves, but the data show the tendency of the breakdown voltage to decrease with frequency. It was not possible to determine if the curves tend to an almost constant value, or if a minimum can be found and a regrowth at higher frequencies takes place, like for example was observed by Walsh *et al.* for RF breakdown at atmospheric pressure [6]. The existence of a minimum in the breakdown curve as a function of frequency at atmospheric pressure was also predicted through a modeling effort by Nguyen *et al.* [7]. The observation and characterization of this minimum at different pressures will be the object of future investigations. It is anyway apparent that using a large enough frequency is crucial to achieve a low breakdown voltage. An interesting result was obtained replotting the same data in terms of the breakdown electric field $E_b$. This is also shown in fig. 3: the different curves appear to almost collapse onto a single one, suggesting the possible existence of a relation of the kind $E_b = f(pL, fL)$, independent of the $L/R$ value. It is worth mentioning here that the $fL$ values between 10 and 30 MHz cm at which the leveling of the curves is seen for the present data correspond to $L/\lambda$ in the range between $3 \times 10^{-4}$ and $10^{-3}$.

Finally, the dependence on the aspect ratio $L/R$ was investigated keeping fixed both $pL$ and $fL$. This was achieved by taking data with the four different frequencies, adjusting both the electrode distance $L$ so as to keep $fL$ fixed, and the pressure so as to keep $pL$ fixed. The outcome is shown in fig. 4. It can be clearly seen how, as one could expect, the breakdown voltage rises with $L/R$. Furthermore, the curves obtained at the same $pL$ value and different $fL$ appear to almost superpose. This suggests that in terms of the scaling parameters the dependence on the breakdown voltage on $fL$ is not very pronounced. This is the consequence of the curves shown in fig. 3 reaching an almost constant value at high enough $fL$. It implies that a dependence of the kind $V_b = h(pL, L/R)$, similar to the one obtained in DC [8] can be considered in this frequency region.

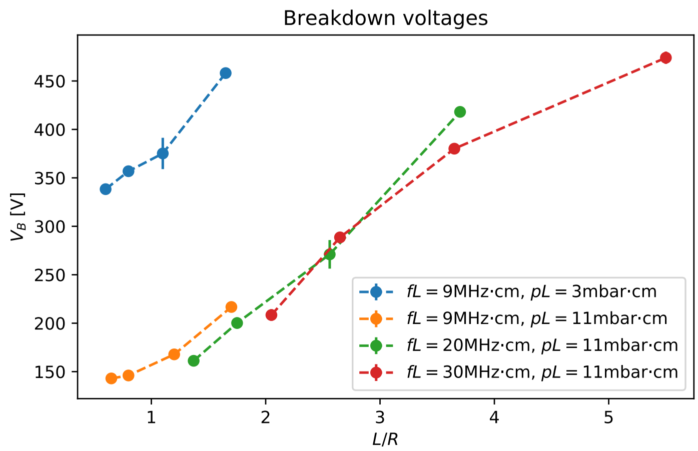


Figure 4: Breakdown voltage as function of $L/R$, for different values of $pL$ and $fL$.

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