Initiation of breakdown in bubbles immersed in liquids: pre-existed charges and proximity of bubbles

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We computationally investigated the role of randomly distributed initial seeds of electrons inside bubbles of various size. We show that avalanche-to-streamer transition and streamer formation in weakly uniform electric fields are determined by the applied electric field and the parameter *pd* (bubble size times bubble pressure), as well as by the location and amount of initial free charges inside the bubble. Streamers are not formed in bubbles with rather small size, unless pre-existed or injected charges are large enough to initiate breakdown. We discuss initiation of streamers in strings of three bubbles. We show that orientation of the strings along or perpendicular to the electric field vector, proximity of the bubbles and bubbles size are crucial for streamers formation and re-initiation in the neighbouring bubbles.

1. Introduction and description of the model

The presence of gas bubbles immersed in liquids provides a medium requiring a lower electric field strength for breakdown. Recent experiments [1] have shown, for example, that bubbling the transformer oil ($\varepsilon/\varepsilon_0$ = 2) with air or sulfur hexafluoride leads to the decrease of breakdown voltage by 34% and 19%, respectively. Korobeinikov *et al* [2,3] investigated the breakdown initiation in water ($\varepsilon/\varepsilon_0$ = 80) using artificially produced long-lived microbubbles 40–100 *μ*m in size. In all cases, the discharge was initiated in a bubble, with the pre-breakdown time in the presence of a bubble being much shorter than in its absence. It was also shown that the discharge can travel along strings of bubbles and eventually bridge the gap between the electrodes. To lend an insight to how streamers are initiated in an isolated bubble and strings of bubbles filled with air and immersed in liquids with different permittivity, we computationally investigated the role of randomly distributed initial seeds of electrons inside bubbles of various size. The algorithm used in the model is discussed in detail in Ref. [4] and so will be briefly reviewed here. The model, *nonPDPSIM*, is a multi-fluid hydrodynamics simulation in which transport equations for all charged and neutral species and Poisson's equation are integrated as a function of time. Updates of the charged particle densities and electric potential are followed by an implicit update of the electron temperature by solving the electron energy conservation equation. The electron transport coefficients and rate coefficients for bulk electrons as a function of T_e are obtained by solving Boltzmann's equation for the electron energy distribution. The photoionization is computed by producing Green's functions.

The gas mixture used for all cases is atmospheric pressure humid air $N_2/O_2/H_2O$ = 79.5/19.5/1 at 300 K. There are 24 species included in the model with 256 reactions between them. To initiate a streamer, a small spot of seed-charges (electrons and N_2^+) was placed near the bottom, right or top boundary of the bubble. The seed plasma had a diameter of 50 μm and peak density of 10^8 cm^{-3}. The model geometry is shown in Fig. 1. The positive streamer is sustained in a single bubble or a string of bubbles immersed in a dielectric liquid with $\varepsilon/\varepsilon_0$ = 2, 16 or 80. The gap between top and bottom electrodes is 0.8 cm. The applied voltage creates almost uniform electric field E_0 (75 to 120 kV/cm) at the location of the bubble.

The numerical grid uses an unstructured mesh

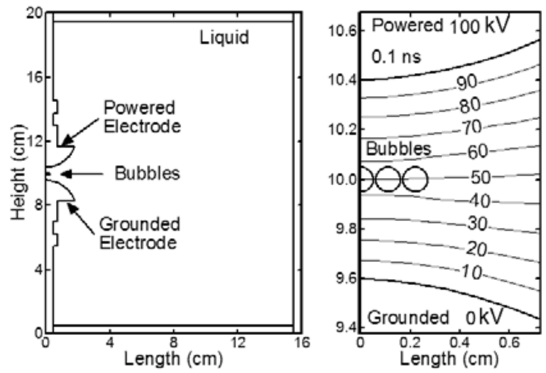

Figure 1. (Left) Geometry of the computational domain. The bubbles are located between top and bottom electrodes in the region of a weakly uniform electric field. (Right) Blow-up of the string of three 500 μm bubbles. Lines show the initial distribution of the potential (kV). The geometry is symmetric across the left line.

with triangular elements with different refinement regions in order to resolve the interior of the bubble as well as larger surrounding region near the bubble. The bubble radii we investigated are in the range of 100 –500 μm. For the cases discussed here, the mesh consisted of approximately 8000 -11000 nodes, of which about 7000-10000 are in the plasma region. The geometry is symmetric across the left line.

2. Single Bubble

One of the most important phenomenon governing the evolution of streamers inside bubbles is the bubble polarization in an external electric field. The electric field $\vec{E}$ within the air bubble with radius r_0 embedded in a dielectric of constant relative permittivity $\varepsilon_r = \varepsilon/\varepsilon_0$ and placed in the uniform external electric field $\vec{E}_0$ that is aligned with the polar axis, is parallel and uniform [5]:

$$\vec{E} = \frac{3\,\varepsilon_r}{1+2\,\varepsilon_r}\vec{E}_0 \qquad (1)$$

According to expression (1), the electric field in a bubble cavity is enhanced by a factor of 1.2 and 1.33 for dielectric liquid with permittivity $\varepsilon/\varepsilon_0$ = 2 and 4, respectively. For liquids with $\varepsilon/\varepsilon_0$ >16 the field is enhanced by a factor of 1.5. Due to exponential dependence of ionization coefficient on the electric field, this effect has a direct implication for the

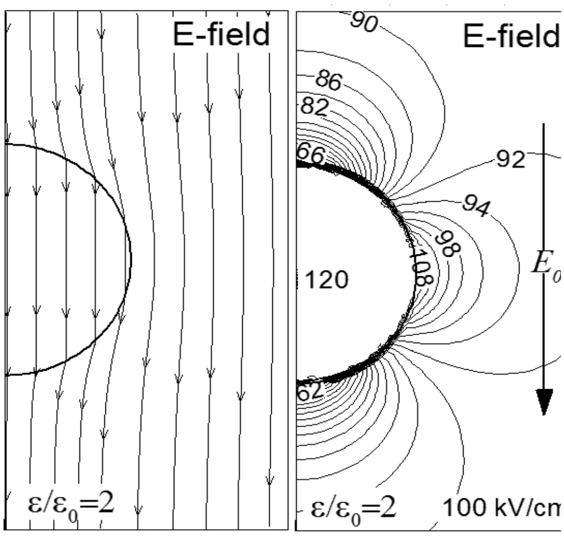

Figure 2. Initial distribution of the electric field (streamlines) and electric field (contours) around a 300 µm bubble. The electric field is enhanced near the equator of the bubble and depleted near the poles. The streamlines show the direction of the electric field but not field magnitude. Conditions: the external medium is a dielectric liquid ($\varepsilon/\varepsilon 0$ = 2), the applied external field E_0=110 kV/cm.

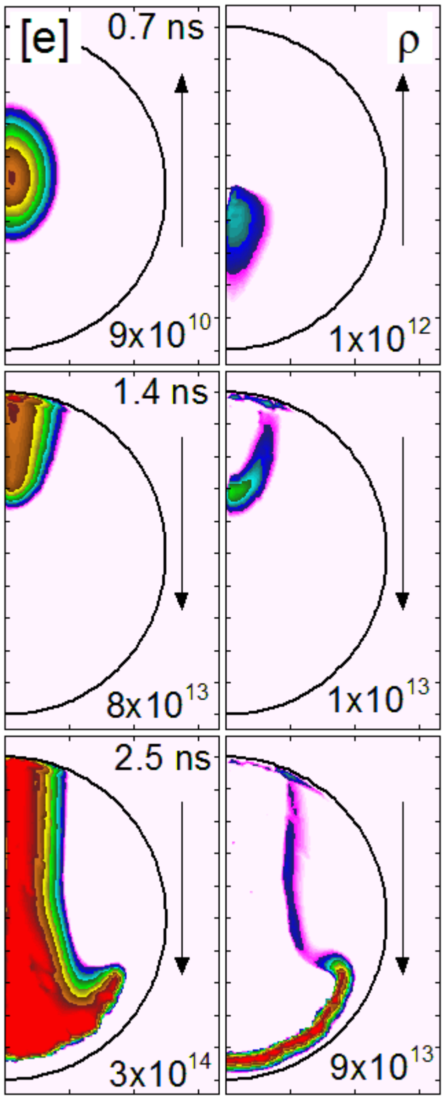

Figure 3. Avalanche-to-streamer transition inside a 500 µm bubble. Three frames shows evolution of the electron density (3 decade log plot) and space charge (2 decade log plot). The initial cloud of electrons is located at the bottom of the bubble. The cloud travels to the top of the bubble. The avalanche-to-streamer transition is manifested by the appearance of the space charge at t= 1.4 ns. Once the transition occurs, the positive streamer propagates downward to the bottom of the bubble. Conditions: E_0=110 kV/cm, liquid $\varepsilon/\varepsilon_0$ = 2.

streamer development inside bubbles immersed in liquids with various $\varepsilon_r = \varepsilon/\varepsilon_0$. Next we note that the induced field outside the buble is that of a dipole oriented along the direction of the applied electric field E_0 [5]. The electric field at the poles of the bubble is decreased by a factor of $1+2(1-\varepsilon_r)/(1+2\varepsilon_r)$ compared to the unperturbed external electric field. At the equator the electric field at the surface of the bubble is

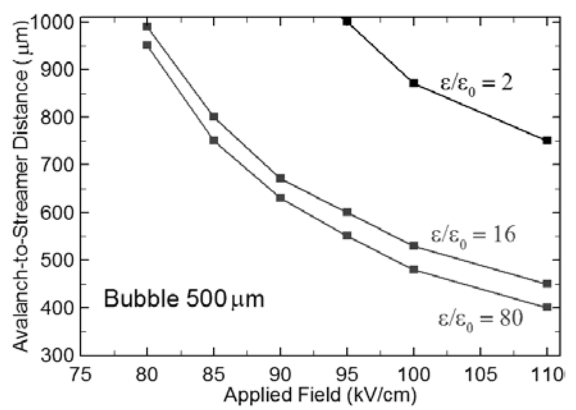

Figure 4. Avalanche-to-streamer distances vs applied external field for a 500 µm bubble. Conditions: liquids with $\varepsilon/\varepsilon_0$ = 2, 16 and 80, initial charge Q = 1 x 10^{-17} C.

enhanced by a factor of $1-(1-\varepsilon_r)/(1+2\varepsilon_r)$ compared to the applied field. As an example, the initial distribution of the electric field streamlines and electric field contours around a 300 μm bubble are shown in figure 2. The disparity between the field depletion and enhancement increases with the increase of dielectric permittivity of the liquid.

The development of the streamer inside a bubble critically depends on the availability of the initial statistical electrons. The essential amount of initial charge usually pre-exists in bubbles immersed in liquids even with low conductivity. If the charge is high enough for the avalanche-to-streamer transition to occur, the streamer rapidly develops. If the charge is small, the streamer development critically depends on the location of these charges. As an example (figure 3), we investigated an avalanche-to-streamer transition initiated inside a 500 μm bubble with the initial cloud of seed electrons located at the bottom of the bubble. The total amount of charge was 1 x 10^{-17} C. During the first 1.4 ns the cloud travels to the top of the bubble. The avalanche-to-streamer transition is manifested by the appearance of the space charge high enough to sustain the streamer. Once the transition occurs, the positive streamer propagates downward to the bottom of the bubble.

The avalanche-to-streamer distances for a 500 µm bubble for different values of applied external field are shown in figure 4. For low applied fields the avalanche travels 800-900 µm for the transition to occur. For high fields, the corresponding paths are of the order of 400 µm ($\varepsilon/\varepsilon_0$=80) and 700 µm ($\varepsilon/\varepsilon_0$=2). For the applied fields below 95 kV/cm , the paths for the avalanche-to-streamer transition exceed 1000 µm as shown in figure 4. As such, there is no avalanche-to-streamer transition for bubbles with radii smaller than 500 µm (and the same initial charge). By increasing the initial charge (placed at the bottom of the bubble to allow for the maximal possible path of the avalanche) the avalanche-to-streamer can be initiated in bubbles with smaller radii.

3. Vertical and horizontal strings of bubbles

Streamer evolution in the string of three vertical bubbles with separation D=100 µm between the bubbles is shown in figure 5. After the avalanche-to-streamer transition occurs in the top bubble, the high electric field in the streamer head protrudes through the liquid layer towards the middle bubble. The discharge in the middle bubble, in its turn, re-initiates the discharge in the bottom bubble. As such, the streamer can travel from bubble to bubble avoiding the liquid phase (provided the bubbles are in close proximity as shown in figure 5). Note, that in the absence of the top bubble, streamers in the middle and the bottom bubbles are not initiated. The streamer cannot be re-initiated if the liquid layer between the bubbles is thick enough to mitigate the electric field. This is the case then the layer is of the order of or exceed the typical distance

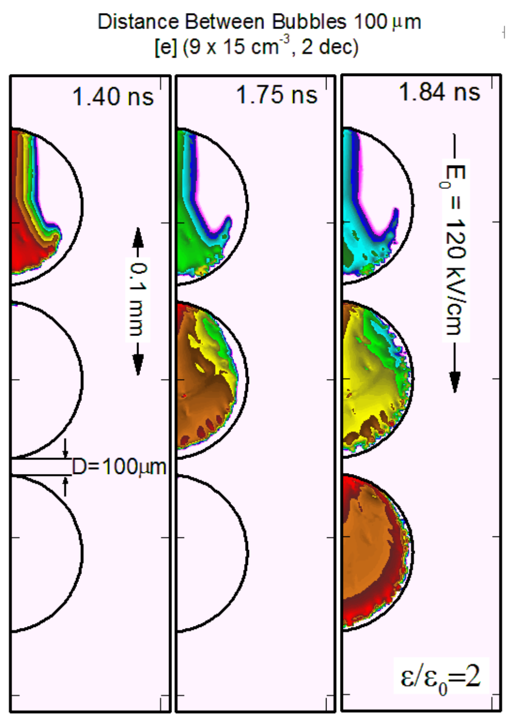

Figure 5. Streamer evolution in the string of three vertical bubbles separated by 100 µm liquid layer. The streamer travels from bubble to bubble avoiding the liquid phase. For 300 µm liquid layer separation the streamer in the middle bubble dies out. Conditions: liquid with $\varepsilon/\varepsilon_0$ = 2, E_0=120 kV/cm.

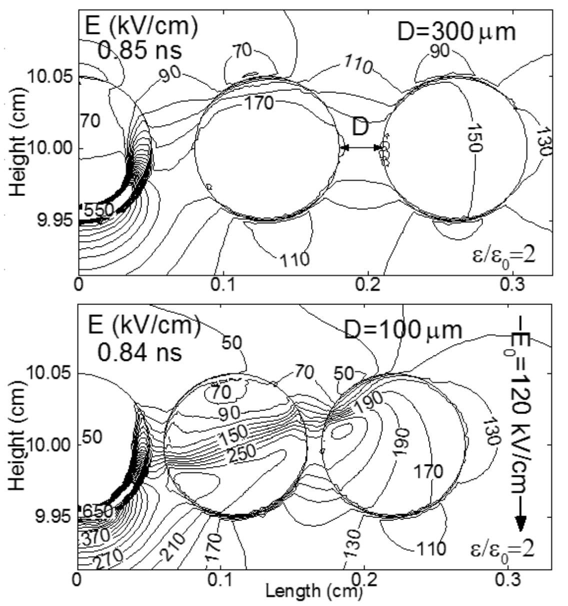

Figure 6. Electric field contours for the horizontal string of bubbles at t= 0.85 ns. The distance between the bubble surfaces is 300 and 100μm. For large separation, there is no streamer development in the middle and the right bubbles. For smaller separation, the tilted electric field vectors result from the superposition of the applied field and the field from the space charge of the streamer. Conditions: liquid with $\varepsilon/\varepsilon_0 = 2$, E_0=120 kV/cm.

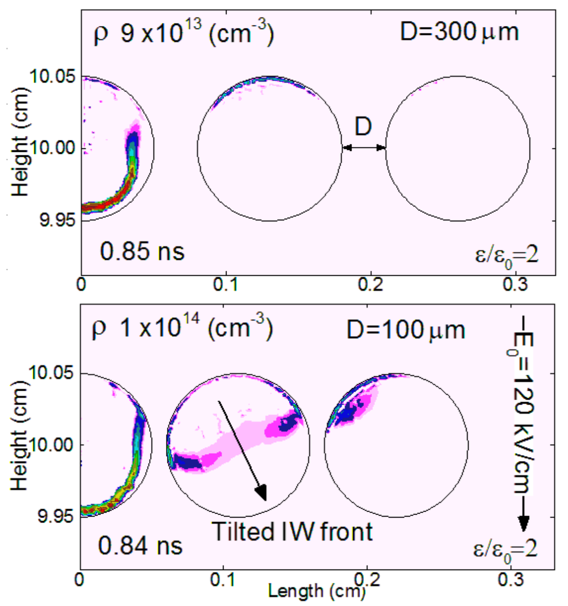

Figure 7. Tilted streamer front shown for the space charge density for the strings with two separations (300 and 100 μm). There is no streamer development in the middle bubble in the first case. For the smaller separation the tilted and planar front of the streamer in the middle bubble is clearly seen. Conditions: liquid with $\varepsilon/\varepsilon_0 = 2$, E_0=120 kV/cm.

over which the electric field in the streamer head decreases essentially. For example, for 300 μm liquid layer separation the streamer in the middle bubble dies out.

The evolution of the streamer hopping from bubble to bubble critically depends on the string orientation. The effect is partially attributed to the superposition of the applied field and the field produced by the space charge of the developing streamer. For example, electric field contours for the horizontal string of bubbles are shown in figure 6 for the distance between the bubble surfaces 300 and 100 μm. For large separation, there is no streamer development in the middle and the right bubbles. For smaller separation, after the streamer develops in the first bubble, the tilted electric field vectors result from the superposition of the applied field and the field from the space charge of the streamer. As a result, the tilted streamer front appears in the middle and, partially, in the right bubble as shown in figure 6. The effect of the tilted streamer front is additionally shown in figure 7 where the space charge density is plotted for the strings with two separations (300 and 100 μm). There is no streamer development in the middle bubble in the first case. For the smaller separation the tilted and planar front of the streamer in the middle bubble is clearly seen.

4. Acknowledgement

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5. References

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