Breakdown in bubbles in liquids

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Plasma breakdown and instabilities in the multiphase plasma-gas bubble-liquid system

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**Investigate**
- Bubble shape and size
- Deformation
- Discharge behavior (glow, filament, streamer prop)
- Realistic shapes in electric fields

Image courtesy of PCRF

Pillai, N. PhD Dissertation.
Objective 1: Expand bubble-liquid modeling approach to inform the experimental setup. Experiment adapted by the high-resolution simulations.

Objective 2: Benchmark and validate experiment and simulation for different gas flow situations. The simulations are adapted to the experiment accordingly.

Objective 3: Couple multiphase 3D interface resolved code (PHASTA) and 2D plasma-focused code (nonPDPSIM).

Objective 4: Characterize the properties of the plasma and investigate the streamer breakdown dependent on voltage and bubble properties.
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Experimental geometry (A) is modeled in 2D (E). Single bubble profile (C) modeled as 2D mesh (D). 2D model simulated in nonPDPSIM (F).
Experiment Setup

- Ar bubbles: 1 mL/min (~10 s⁻¹)
- Trigger system controlled by bubble position
- Delay generator corrects timing between elements
- ICCD delayed to collect light at chosen time after pulse
- Images collected by Andor iStar (f)

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**front view**

**cross section**

- a) Collimated LED
- b) Photodetector
- c) Oscilloscope (trigger generator)
- d) Digital delay generator
- e) ns pulser
- f) Backlight
- g) Imaging/spectrometer
Experiment Setup

- Bubble boundary images taken with backlight
- Images fitted to ellipse in MATLAB
- Position and size determined statistically
- Error bars are determined by pixel size

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<tbody>
<tr>
<td>0.0 ± 9.6</td>
<td>0.0 ± 3.0</td>
<td>1741.7 ± 3.0</td>
<td>1270.1 ± 2.6</td>
<td>1.7368 ± 0.0060</td>
<td>0.6840 ± 0.0012</td>
<td>-2.2 ± 0.5</td>
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Nanosecond Pulser
- 4 ns risetime
- 30 ns pulse width
- 20 MHz oscillations dampen over 500 ns
- 75Ω Impedance

Current
- Filtered to detect discharge current easier
- HPF set to 100 MHz
Global imaging of discharge by using long gate-widths over 1 & 2 “periods”
- At low ICCD amplifications discharge appears volumetric (propagation directly through bubble)
- Increased camera sensitivity show some evidence of curved emission suggesting some surface streamer propagation
  - Optical lensing simulation needed for more detail

Pillai, N. PhD Dissertation.
Imaging Results

S-curve pattern

Gate: 20 ns   MCP: 200
Gate: 5 ns   MCP: 100
Gate: 10 ns   MCP: 200

Initial breakdown
electric potential
[kV]

ns pulser waveform

0 100 200 300 400
time [ns]
Imaging Results

Early Recombination

- 100 ns after single discharge
- Emission produces across the interface
- Assuming $n_e \sim 10^{14}$ cm$^{-3}$ & recombination coefficient $\beta \sim 10^{-7}$ cm$^3$/s
- $\tau^3 = (\beta n_e)^{-1} \sim 100$ ns

Imaging Results

Recombination electric potential vs. time

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<th>Gate</th>
<th>MCP</th>
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<td>2 ns</td>
<td>150</td>
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ns pulser waveform

Electric potential [kV] vs. time [ns]

Gate: 2 ns  MCP: 150

Gate: 2 ns  MCP: 150

Gate: 2 ns  MCP: 100

min max

Sponsel
Bubble/electrode collisions were simulated in PHASTA
- Liquid film layer separating bubble and electrode exists
- ~400 μm thick
- Initial volumetric propagation through gas followed by surface propagation across liquid/gas interface
Salt discharge required closer gap distance and thinner pin/bubble film layer. Images for large gate (20 ns exposure) and short gate (2 ns exposure) were captured showing more volumetric behavior.

Maxwellian relaxation time
- \( r^4 = \varepsilon_r \varepsilon_0 / \sigma \approx 4.5 \text{ ns} \approx \text{voltage rise-time} \)
- Emission side oscillates with positive pulse
- Sustained emission for first couple periods

Bubbles in increased conductivity

$\sigma = 1590 \ \mu\text{S/cm}$

Pulse width for conductive solution: 14 ns

Potential rise

Peak-to-falling potential

Negative potential

Peak-to-rising potential

All images captured with 2 ns gate.
Simulations for bubbles in conductive solutions underway.
Triggering pulser/ICCD timing off bubble position allows for capturing time resolved images.
Images of deformed bubbles match simulations with evidence of clear surface propagation.
Diffuse emission in unperturbed bubbles are more difficult to interpret.
Some pattern suggest surface streamers due to serpentine pattern, however, other images show diffuse glow throughout bubble.
3-D geometry of bubbles and lensing make direct comparison to 2-D simulations difficult.
Thank You
Questions and Comments

References