

# Plasma Formation in Deformed Gas Bubbles



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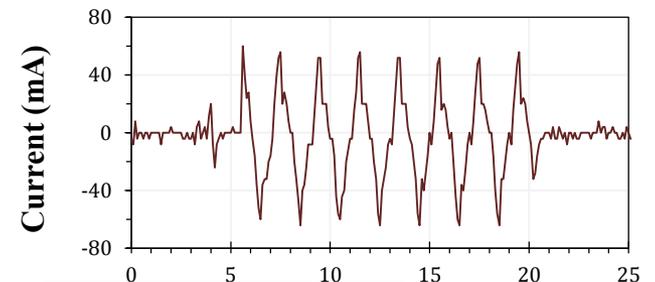
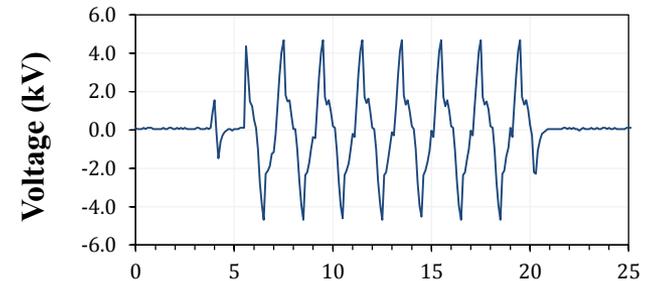
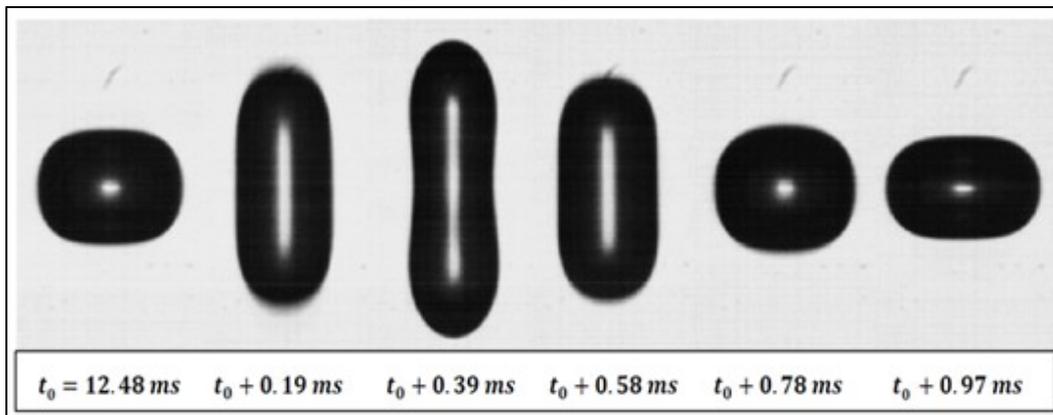
# Overview

- The electric field in a gas bubble can be **actively enhanced by distorting the bubble's shape**. This may lead to a practical means of producing plasma in isolated bubbles for a variety of environmental applications
- An experimental device has been developed to trap single bubbles, excite them into violent nonlinear distortions and characterize them with a high speed camera.
- Evaluation of bubble images to date indicates moderate enhancement of the field (2.3) for observed bubbles with the potential to be as high as 10-50 with further deformation.
- Early experiments of streamer formation in liquids indicate that bubbles have a strong influence on the ignition and propagation of liquid streamers, with violent energy transfer occurring between the two.

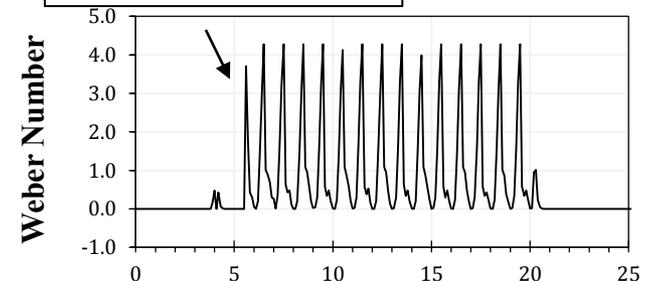
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# Exciting the Spherical Harmonic Modes

- Excitation of specific modes can be used to produce high curvature distortion of the bubble shape
- The  $L=2$  mode can be excited with an uniform A.C. field
- In this example, a 0.2 mm bubble is driven close to the natural  $L=2$  mode (1 kHz) at  $14 \text{ kVcm}^{-1}$



$p_E$  oscillates at  $f_{press} = 2f_{volt}$



Time (ms)

# Electrostatic Modeling of the Electric Field Inside the Distorted Bubble

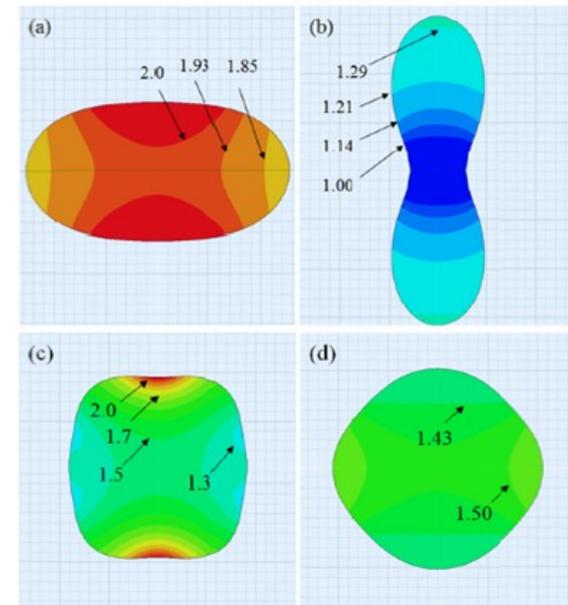
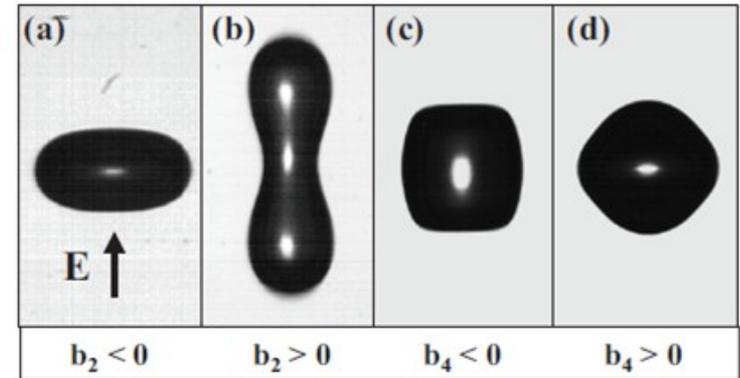
- Use electrostatic solver to estimate the field inside deformed bubbles

- Conditions

- uniform D.C. field
- $\epsilon_r = 80$ ,  $\kappa = 20 \mu\text{S m}^{-1}$
- define  $G_0 = 1.5$  (case of a sphere)
- symmetry  $\rightarrow$  quarter model
- solutions with energy error  $< 0.005\%$

- Observations

- field enhanced for negative  $b_l(t)$
- field depressed for positive  $b_l(t)$
- Max enhancement = 2.3

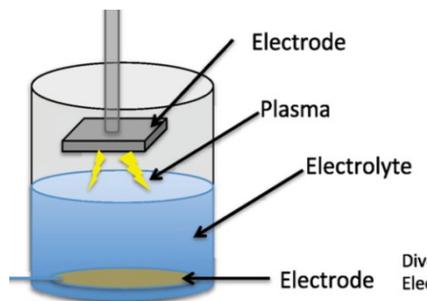


# Atmospheric Discharges in/near water...

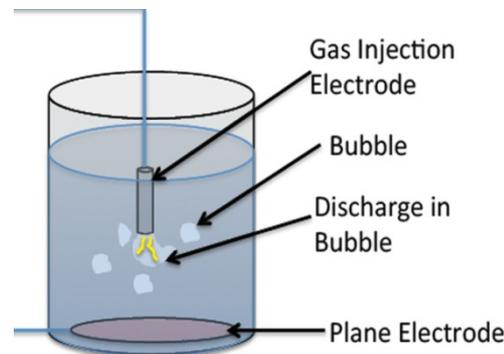
- ...produce strong reactivity in liquids through the production of radicals ( $\text{OH}^\bullet$ ,  $\text{HO}_2^\bullet$ ,  $\text{O}_3^*$ ,  $\text{H}_2\text{O}_2$ ) and UV radiation for applications in water purification, waste processing, and materials synthesis



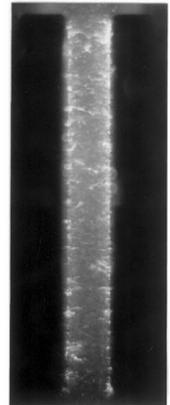
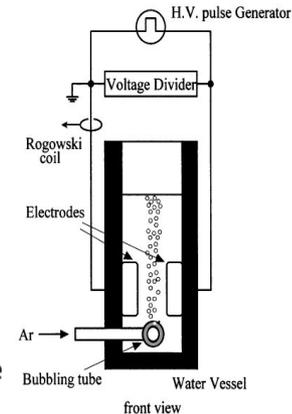
- ...but suffer from a number of limitations



*Indirect discharges* produce plasma in a secondary gas phase with high reduced field, but have low processing throughputs



*Bubble discharges* offer a promising way to inject radicals deeper into the processing volume, but remain limited due to the difficulty in transporting high fields across the dielectric fluid.



# Shape Distortion Can be Achieved with Intense Electric Fields

- “Leaky” fluid dielectrics, like water, are susceptible to electric stress determined by the Maxwell stress tensor,

$$T_{ij} = \epsilon E_i E_j - \frac{1}{2} \epsilon (\mathbf{E} \cdot \mathbf{E}) \delta_{ij}$$

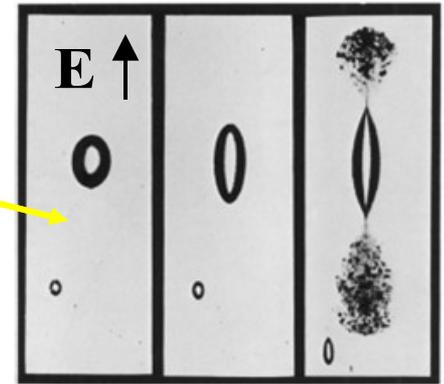
$$p_n = [\mathbf{T} \cdot \mathbf{n}] \cdot \mathbf{n} \quad (\text{normal stress})$$

- For a gas bubble<sup>33</sup>

- electric stress:  $p_E \sim \frac{1}{2} \epsilon |\mathbf{E}|^2$
- surface tension stress:  $p_\gamma \sim \frac{\gamma}{2R_0}$
- Weber number:  $W_e = \frac{p_E}{p_\gamma} = \frac{\epsilon |\mathbf{E}|^2 R_0}{\gamma}$

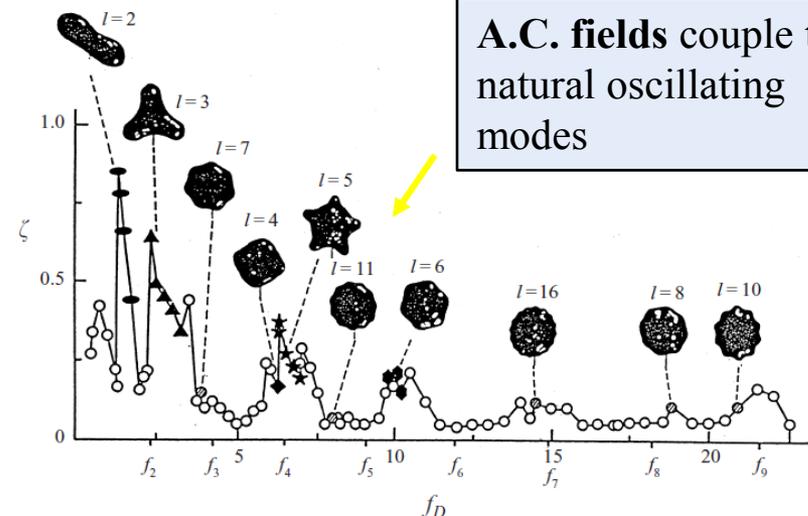
Ex.  $R_0 = 0.5 \text{ mm}$   
 $E_0 = 5 \text{ kV/cm, in water} \longrightarrow W_e \sim 1$

D.C. fields stretch and destabilize bubble shape



Garton, Krasucki, *Proc. Royal Soc. Lon.* 1964.

A.C. fields couple to natural oscillating modes

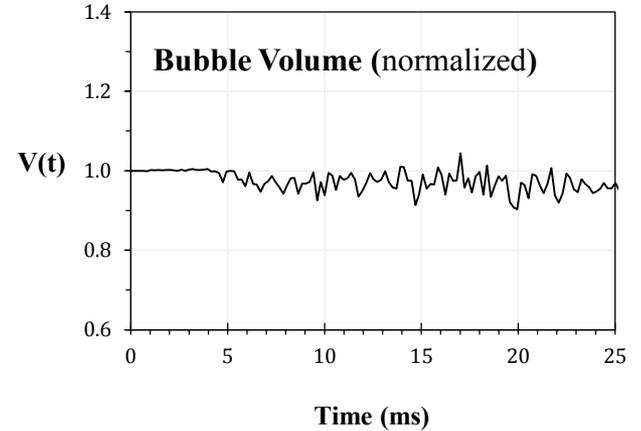
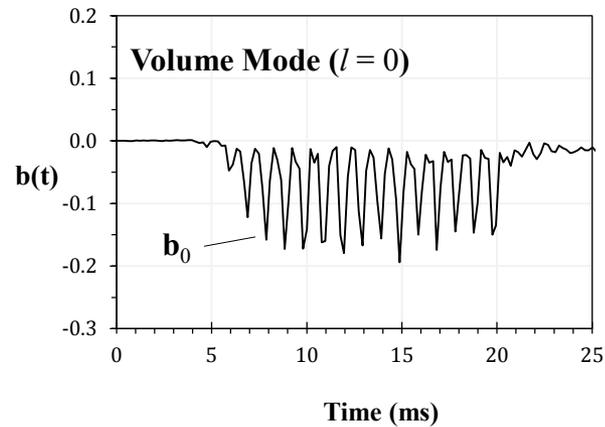
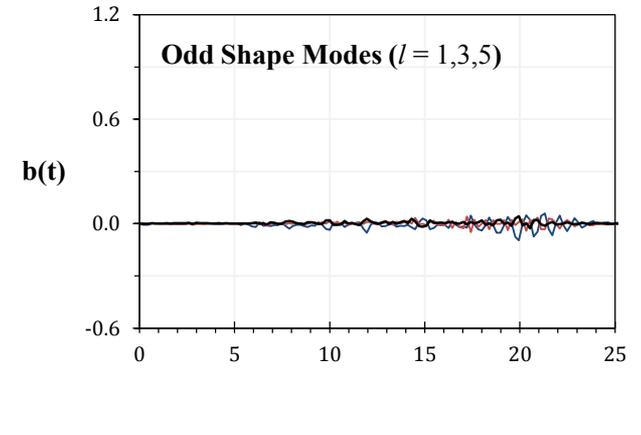
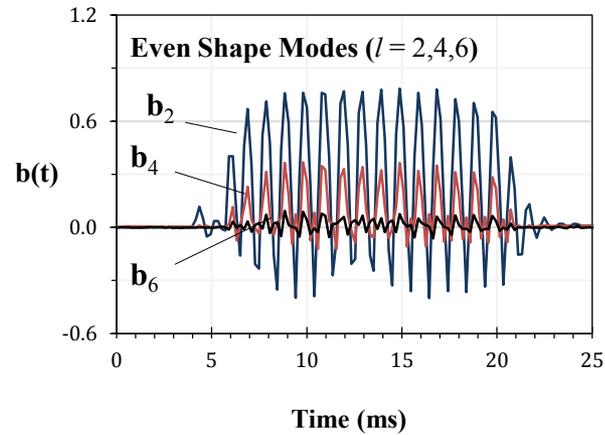
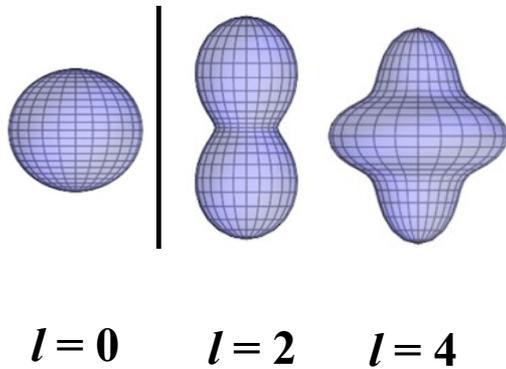


Azuma H, *Jour. Fluid Mech.* 1999

# Mode Decomposition

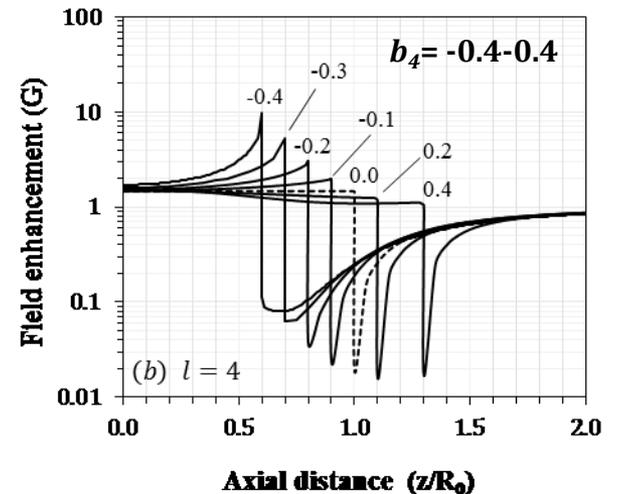
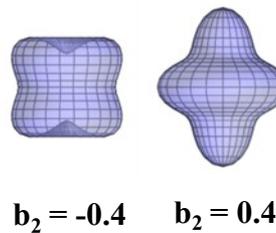
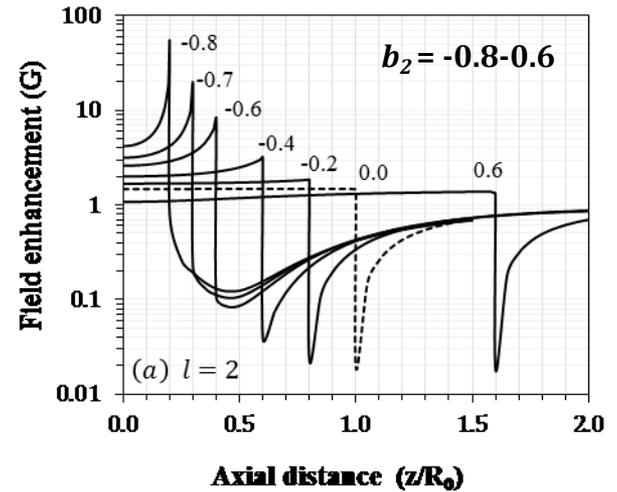
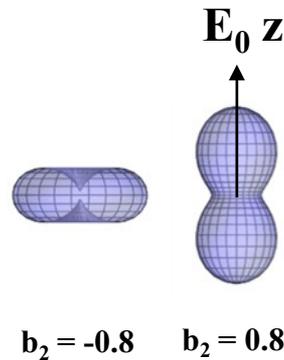
Excited Bubble can be decomposed into Legendre polynomials

$$R(\mu, t) = R_0 \left( 1 + \sum_{l=0}^{\infty} b_l(t) P_l(\mu) \right)$$



# Extrapolating to More Extreme Deformation

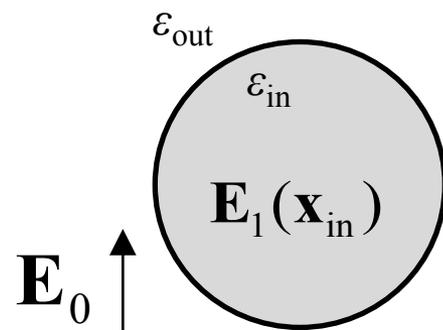
- Estimate field enhancement for extreme deformation
- Conditions
  - isolate pure modes,  $l = 2, 4$
  - measure axial field along axis of symmetry
- Observations
  - field enhanced for negative  $b_l$
  - field depressed for positive  $b_l$
  - dramatic increase in field enhancement as shape contracts



**E could be enhanced by a factor of 10-50 in the bubble!!**

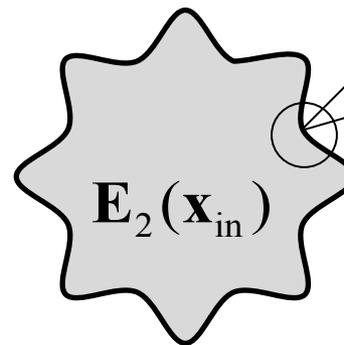
# Plasma Ignition in Gas Bubbles can be Aided by Enhancing the Electric Field in The Bubble

- Field distortion can be achieved by distorting the dielectric boundary between the bubble gas and fluid.
- Field enhancement is dramatically increased near high curvature boundaries
- The enhancement for a gas sphere in water is  $3/2$

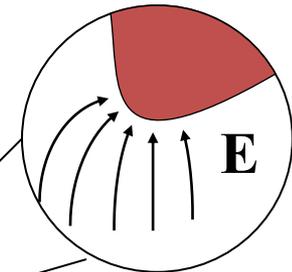


Shape 1

shape  
distortion



Azuma H, *Jour. Fluid Mech.* 1999

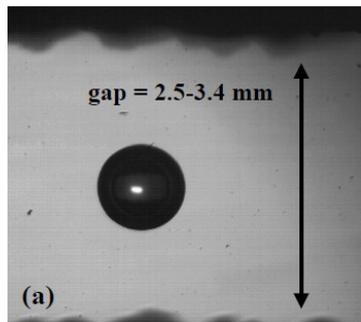
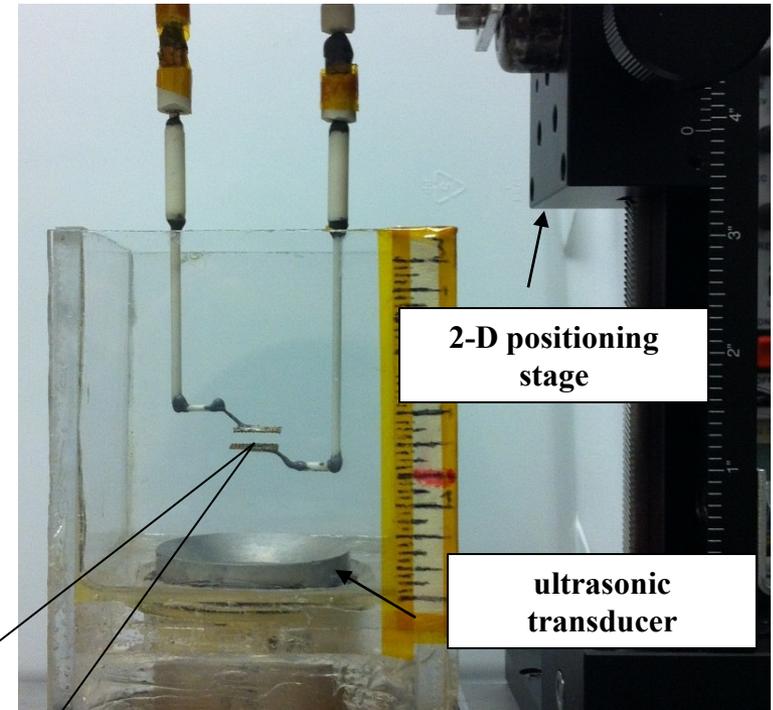


Large curvature at the  
boundary can  
dramatically enhance the  
local field

Shape 2

# Experimental Approach

- **Purpose:**
  - study isolated bubble under repeatable conditions
  - measure shape distortion from an applied electric field
  - Ignite plasma in isolated bubbles
- **Approach**
  - Acoustic wave excited by ultrasonic transducer
  - Bubble trapped in the node of a 26.4 kHz sound field
  - Electrodes placed around bubble and used to drive shape distortions with electric field

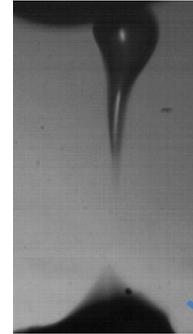


wire mesh electrodes



telescoping lens + high speed camera

# Bubble Breakup at High Field Strengths



Field enhancement should be intense in highly contracted areas

$E = 7.3 \text{ kV cm}^{-1}$   
 $W_e = 2.6$

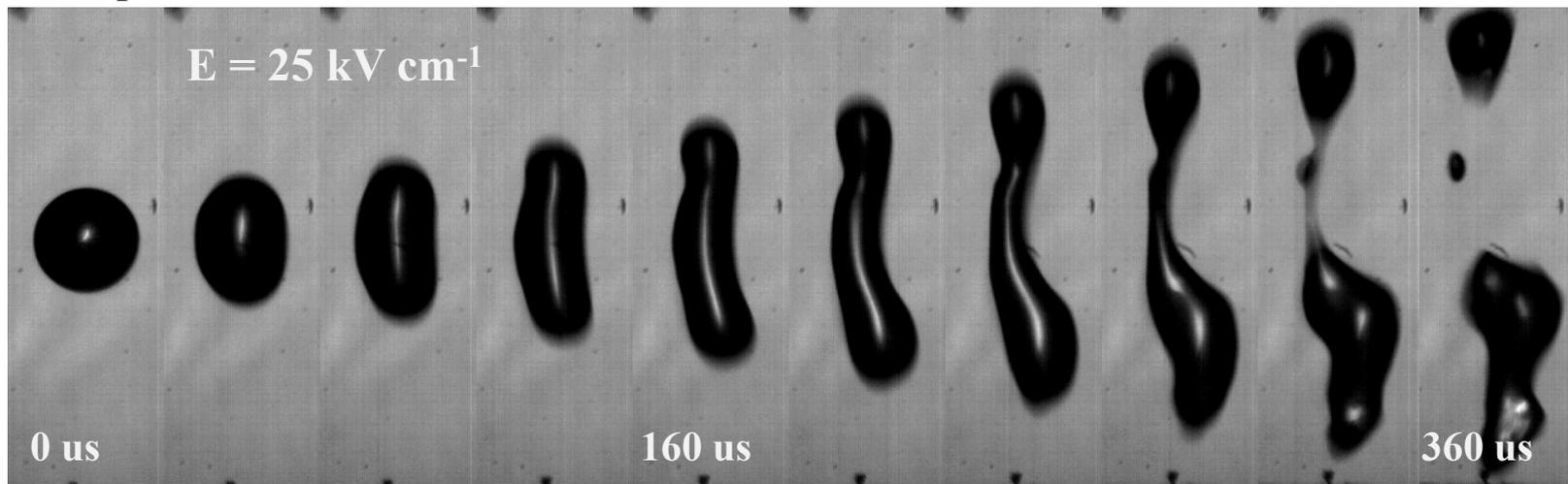
$E = 14.6 \text{ kV cm}^{-1}$   
 $W_e = 9.7$

$E = 21.2 \text{ kV cm}^{-1}$   
 $W_e = 22$

$E = 25 \text{ kV cm}^{-1}$   
 $W_e = 28$

40  $\mu\text{s}$  per frame

3.0 mm

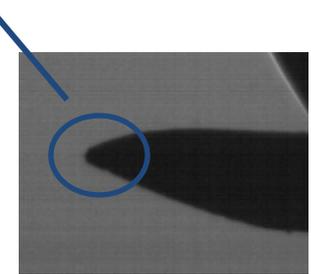


# Liquid Streamer-Bubble Interactions

- Liquid streamers can be ignited by intense fields ( $\sim 1\text{MV/cm}$ ) at sharp electrode tips
- streamer-bubble interactions are characterized by violent, anisotropic energy transfer

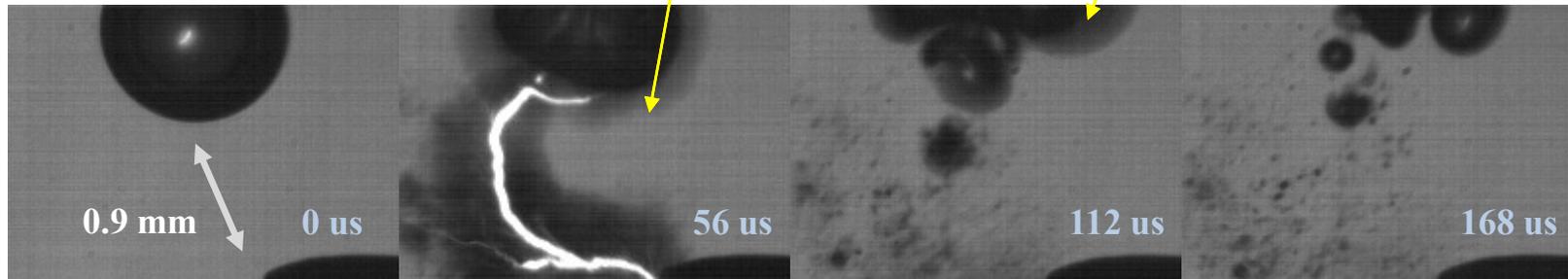
$$R_{\text{tip}} \sim 100 \text{ } \mu\text{m}$$

$$E_{\text{tip}} \sim V/R_c$$
$$E_{\text{tip}} \sim 1.2 \text{ MV cm}^{-1}$$



streamer bends to make contact with bubble

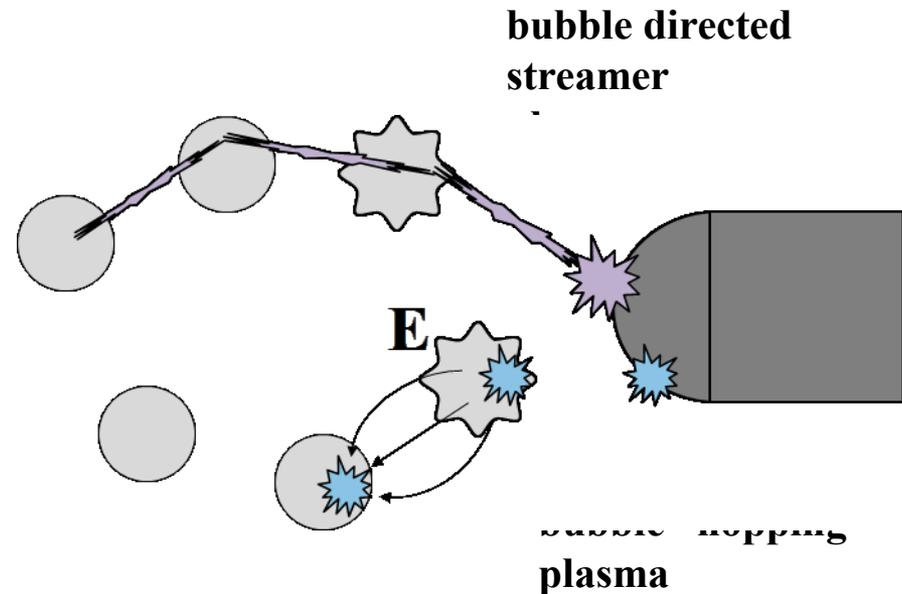
bubble is immediately destabilized



$$V = 12 \text{ kV}, \tau_{\text{pulse}} = 1 \text{ } \mu\text{s}, \tau_{\text{rise}} = 100 \text{ ns}$$

# Towards plasma in isolated bubbles...

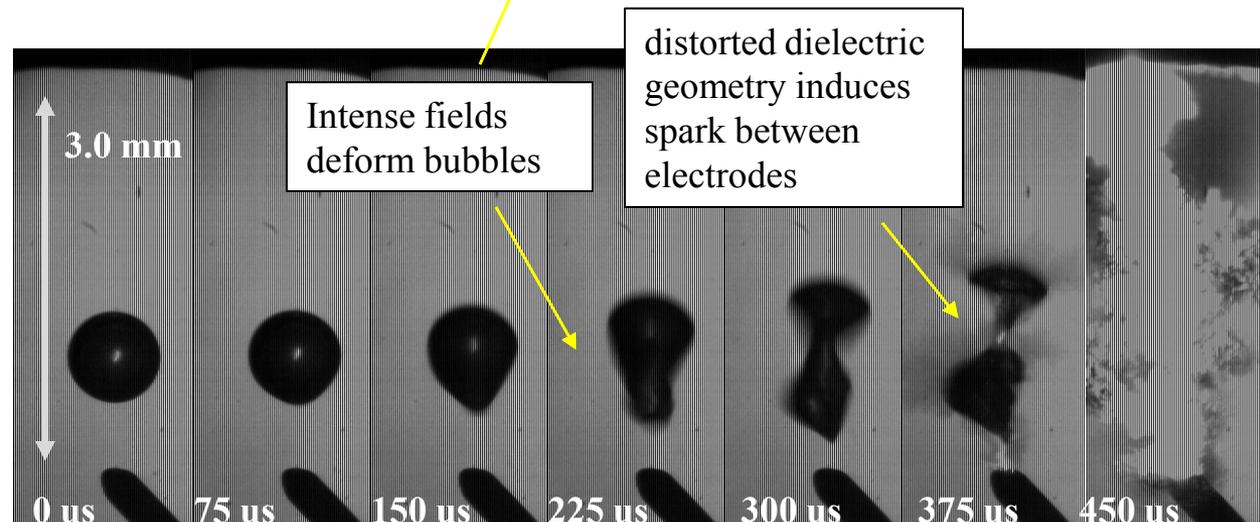
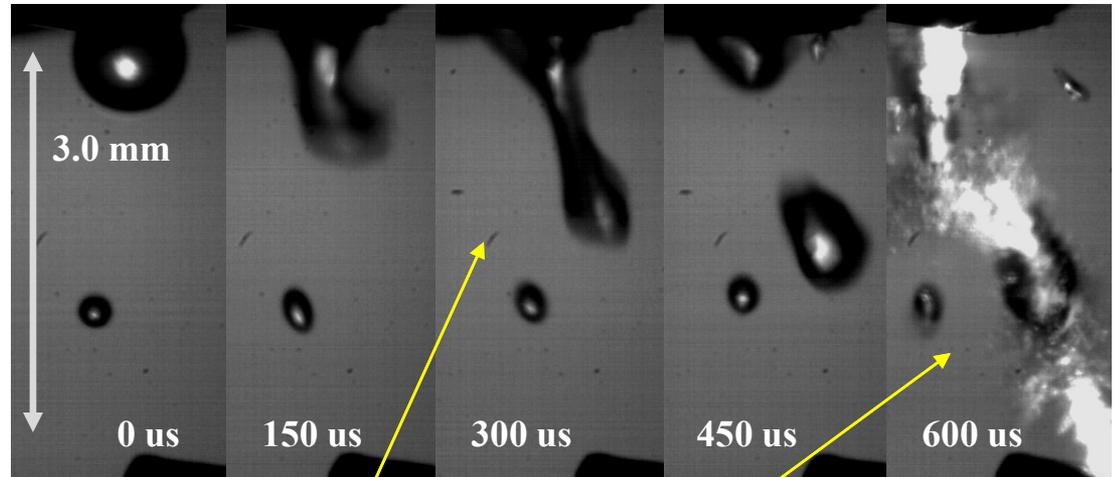
- **Goal:** enhance plasma production in liquids by igniting plasma in isolated bubbles
- Isolated bubbles offer...
  - high E/N medium
  - increased penetration of radicals
  - minimized erosion effects
- plasma ignited via one of two mechanisms
  - Bubble directed liquid streamer
  - Plasma “hopping” between isolated bubbles



**In both cases, field enhancement resulting from shape distortion aids in plasma ignition**

# Influence of Bubble Shape on Streamer Ignition & Propagation

- Distorted bubble shapes can be used to extend liquid streamers (and radical production) far into processing volume
- Operating conditions
  - Point to plane geometry
  - voltage: 11.2 kV
  - pulse length: 1 ms

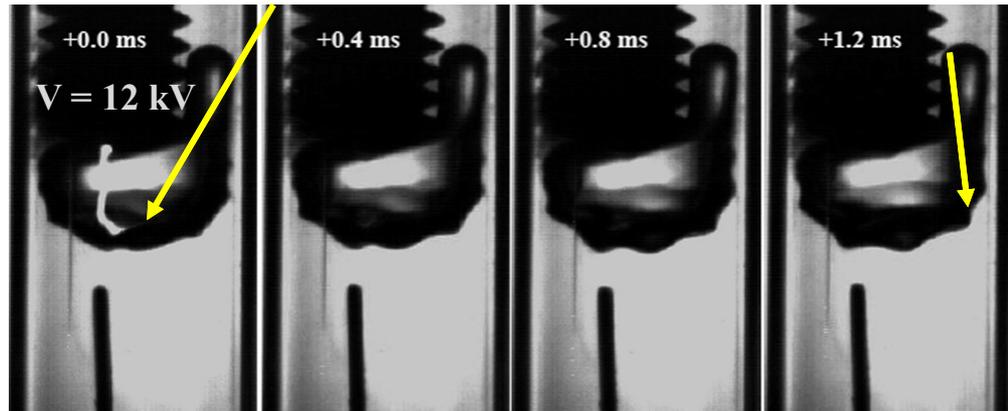


# Plasma Formation in Gas Bubbles

Intense field pressure at streamer head ( $100\text{s kV cm}^{-1}$ ) excites local distortions

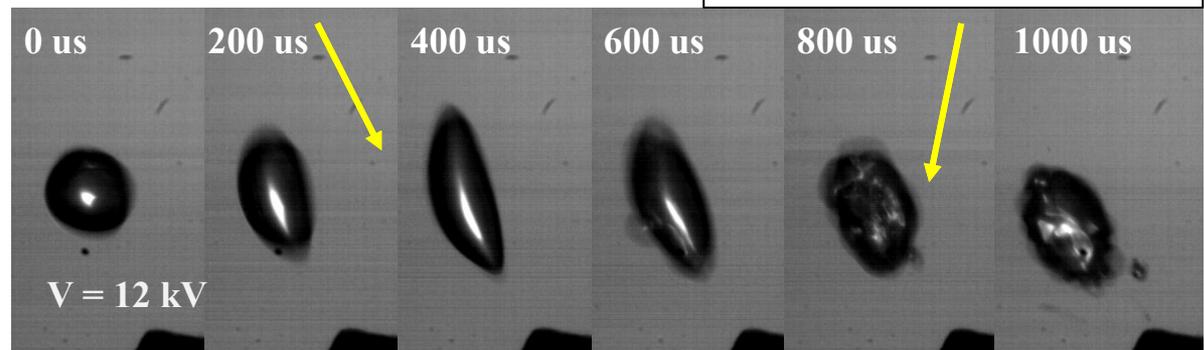
streamer excites high  $k$  oscillations on bubble surface (capillary waves)

Capillary oscillations are characteristic of streamers excited in bubbles attached to an electrode

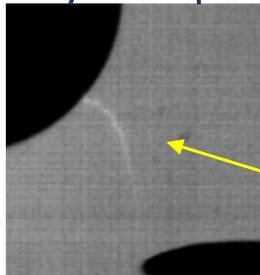
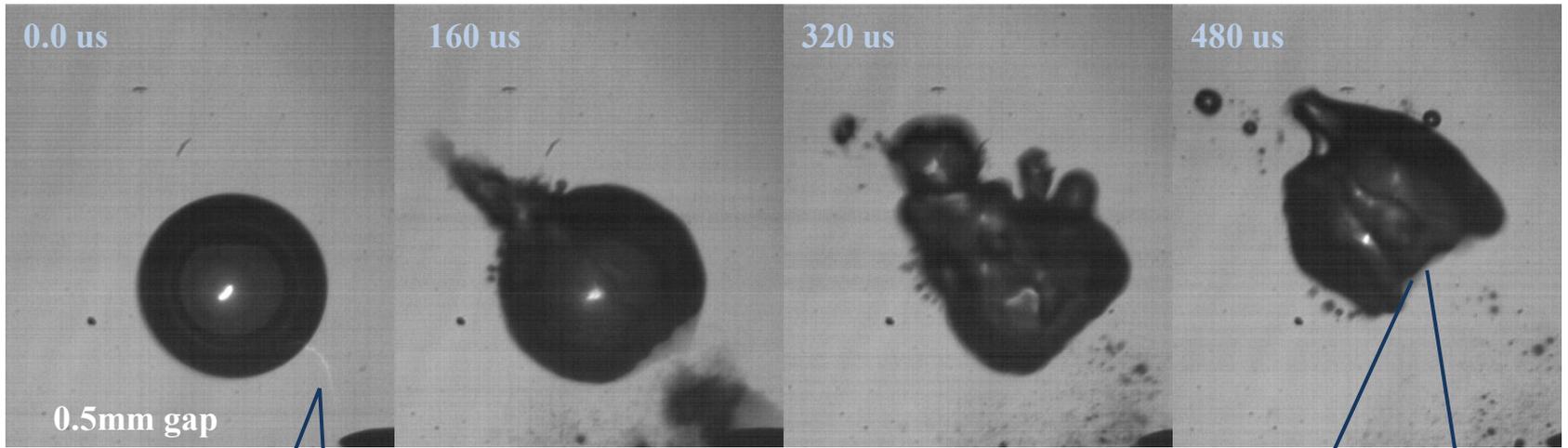


bubble stretches in response to field

high  $k$  ( $< 10 \mu\text{m}$ ) oscillations spontaneously excited



Observation of similar behavior in pulsed detached bubbles indicates the successful ignition of plasma in isolated bubbles



streamer bridges  
gas bubble and  
H.V. electrode

streamer leaves “abscess”  
track along the bubble’s  
body

