NC STATE UNIVERSITY

Department of NUCLEAR ENGINEERING

Breakdown in bubbles in liquids

Nicholas Sponsel[1], Naveen Pillai[1],Sophia Gershman[2]
Igor Bolotnov[1], Katharina Stapelmann[1]
[1]Deptartment of Nuclear Engineering, North Carolina State University, Raleigh, NC
[2]Princeton Plasma Physics Laboratory, Princeton, NJ

NSF
PPPL
Princeton Collaborative Research Facility
NEUP Nuclear Energy University Program
U.S. Department of Energy

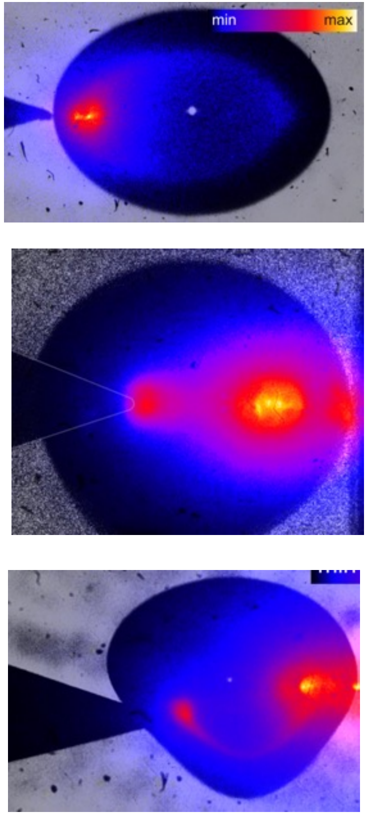
Motivation

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

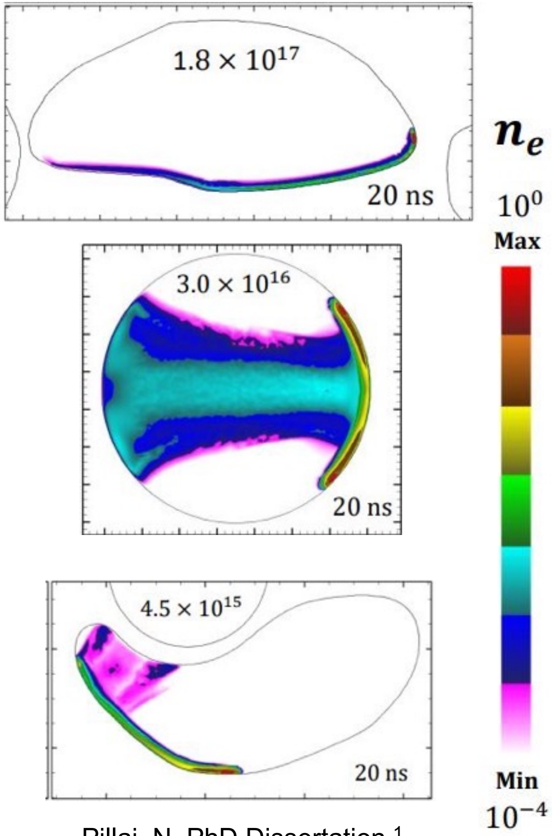
NSF Grant No. PHY 2107901

<u>Investigate</u>

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



Imaging courtesy of PCRF

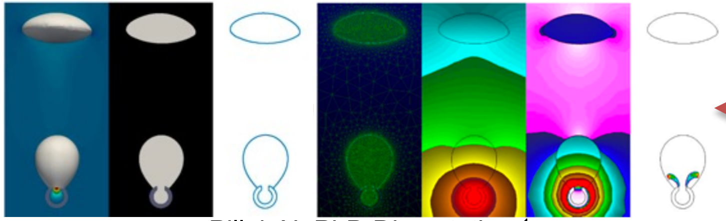


Pillai, N. PhD Dissertation.[1]

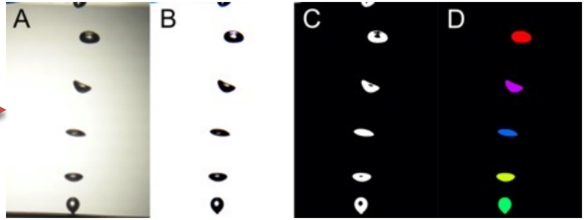
NSF
PPPL
Princeton Collaborative Research Facility
NEUP Nuclear Energy University Program
U.S. Department of Energy

Motivation

Department of NUCLEAR ENGINEERING



Pillai, N. PhD Dissertation.[1]



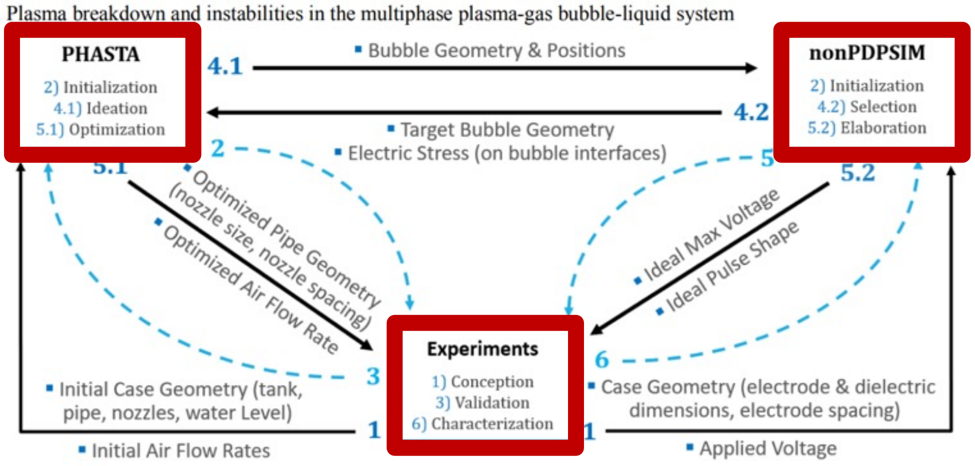
Pillai, N, et al. *Journal of Fluids Engineering* 144.2 (2022)[2].

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).

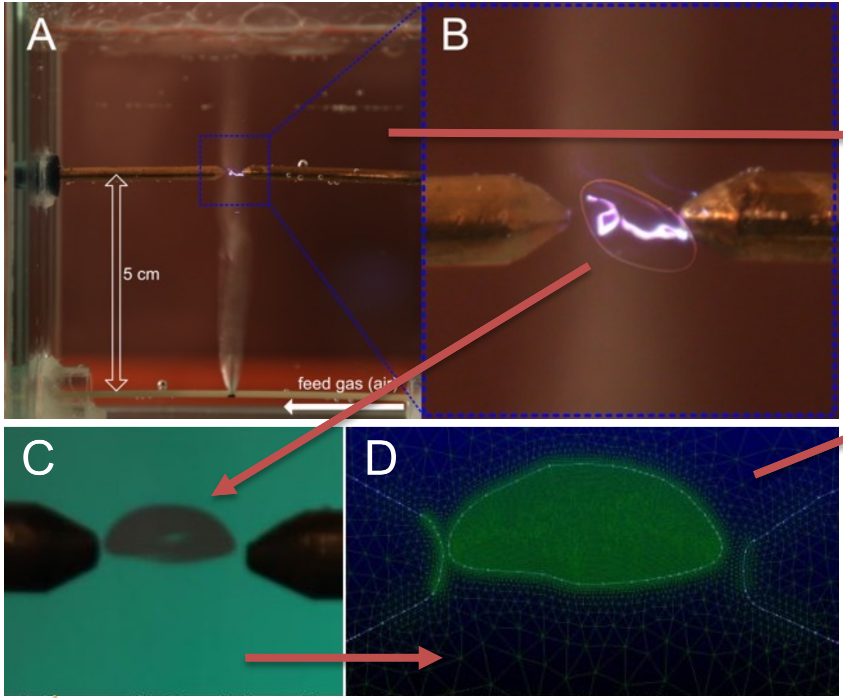
Objective 4: Characterize the properties of the plasma and investigate the streamer breakdown dependent on voltage and bubble properties.

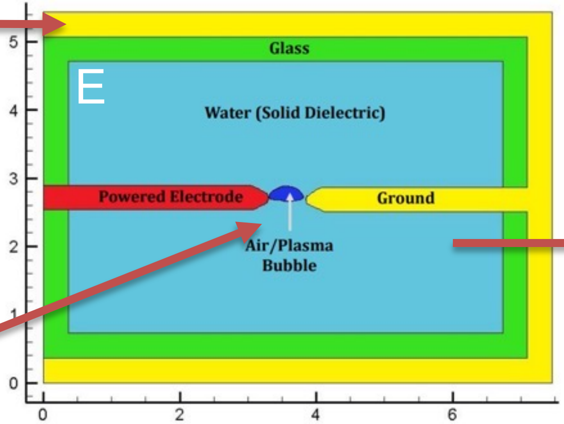


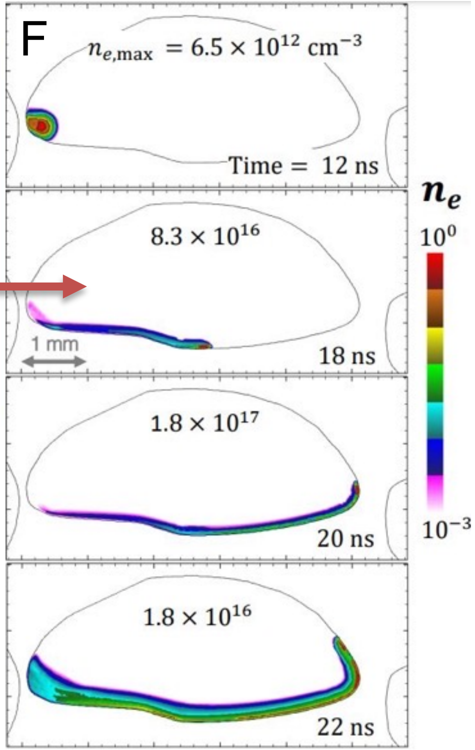
Motivation

Department of
NUCLEAR ENGINEERING

Objective 4: Characterize the properties of the plasma and investigate the streamer breakdown dependent on voltage and bubble properties.







Experimental geometry (A) is modeled in 2D (E). Single bubble profile (C) modeled as 2D mesh (D). 2D model simulated in nonPDPSIM (F).

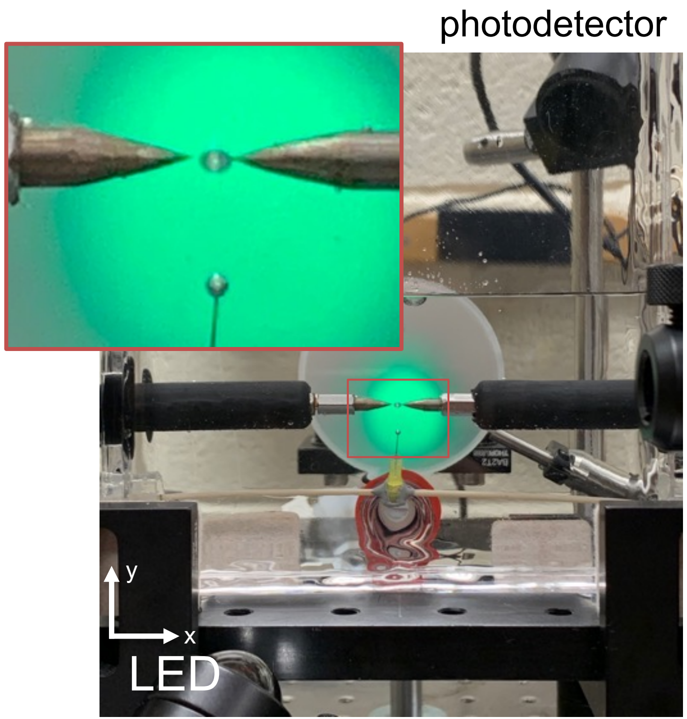
NSF
PPPL
Princeton Collaborative Research Facility
NEUP Nuclear Energy University Program
U.S. Department of Energy

Pillai, N. PhD Dissertation.[1]

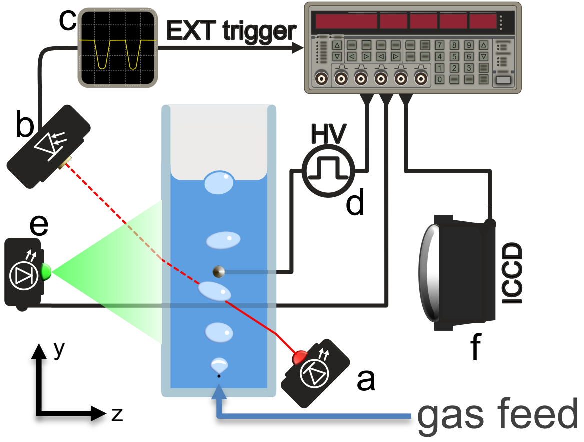
Experiment Setup

- 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)

front view

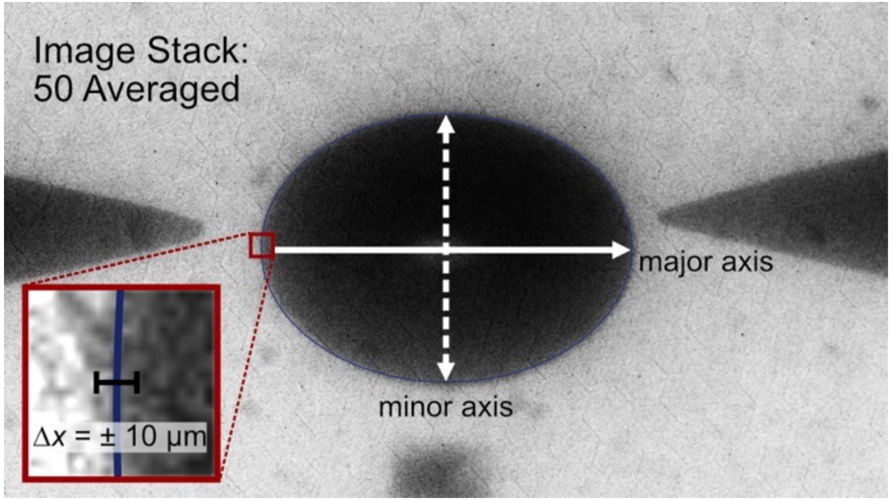


cross section



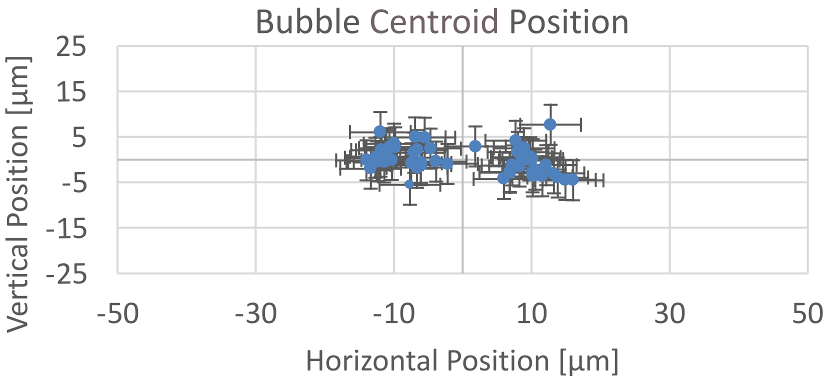
a) Collimated LED
b) Photodetector
c) Oscilloscope (trigger generator)
d) Digital delay generator
e) ns pulser
f) Backlight
g) Imaging/spectrometer

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



Centroid x-position [μm]	Centroid y-position [μm]	Major axis Diameter [μm]	Minor axis Diameter [μm]	Pixel-counted Area [mm^2]	Eccentricity [unitless]	Angle [°]
0.0 ± 9.6	0.0 ± 3.0	1741.7 ± 3.0	1270.1 ± 2.6	1.7368 ± 0.0060	0.6840 ± 0.0012	−2.2 ± 0.5

NSF
PPPL
Princeton Collaborative Research Facility
NEUP Nuclear Energy University Program
U.S. Department of Energy

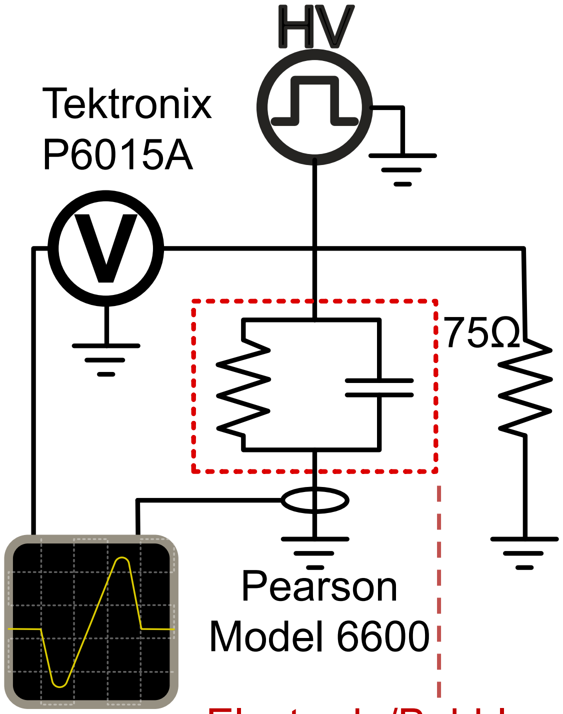
Experiment Setup

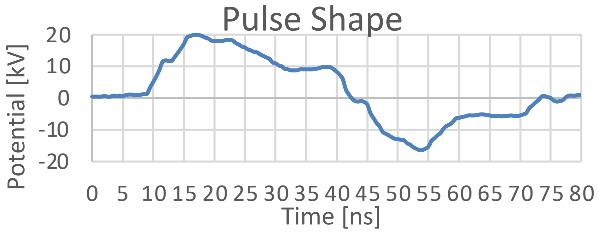
Department of NUCLEAR ENGINEERING

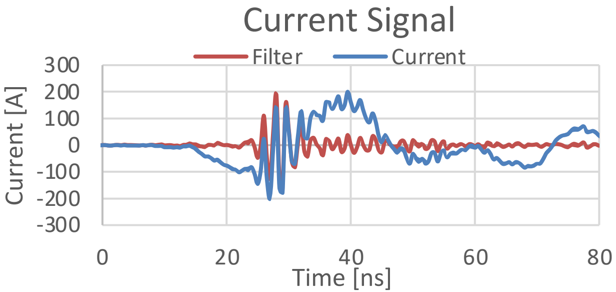
Nanosecond Pulser
- 4 ns risetime
- 30 ns pulse width
- 20 MHz oscillations dampen over 500 ns
- 75Ω Impedance

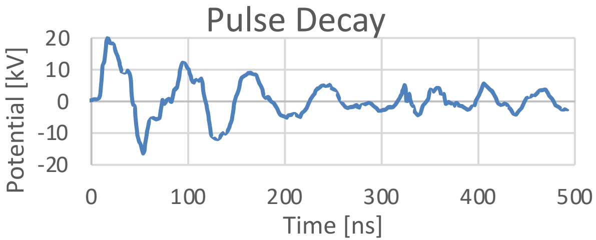
Current
- Filtered to detect discharge current easier
- HPF set to 100 MHz

Megaimpulse NPG-18/100k



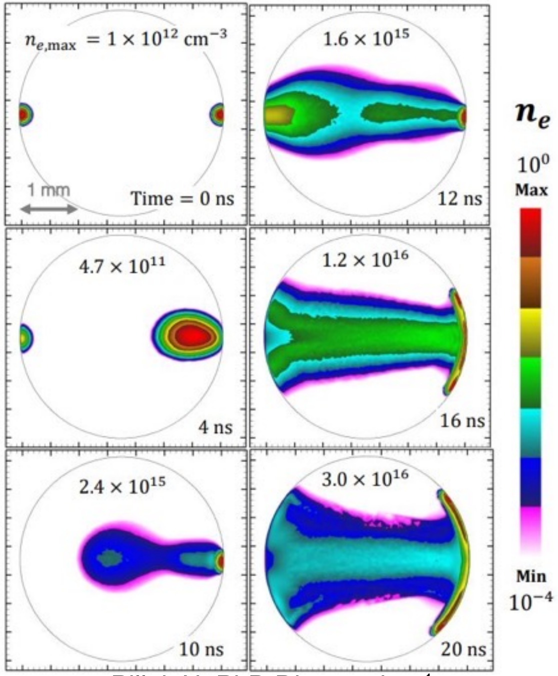






NSF
PPPL
Princeton Collaborative Research Facility
NEUP Nuclear Energy University Program
U.S. Department of Energy

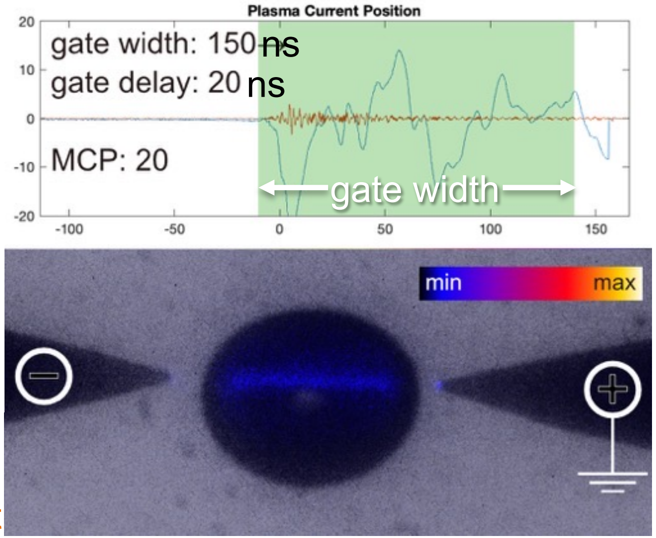
Imaging Results

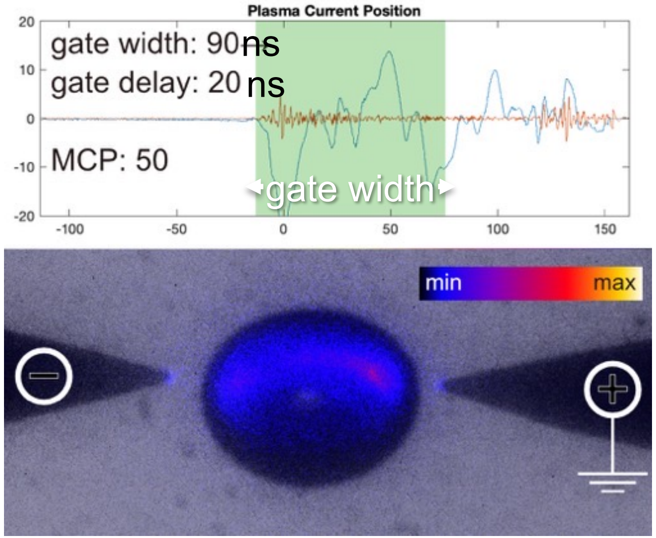


Pillai, N. PhD Dissertation.[1]

Global imaging of discharge by using long gate-widths over 1 & 2 “periods”

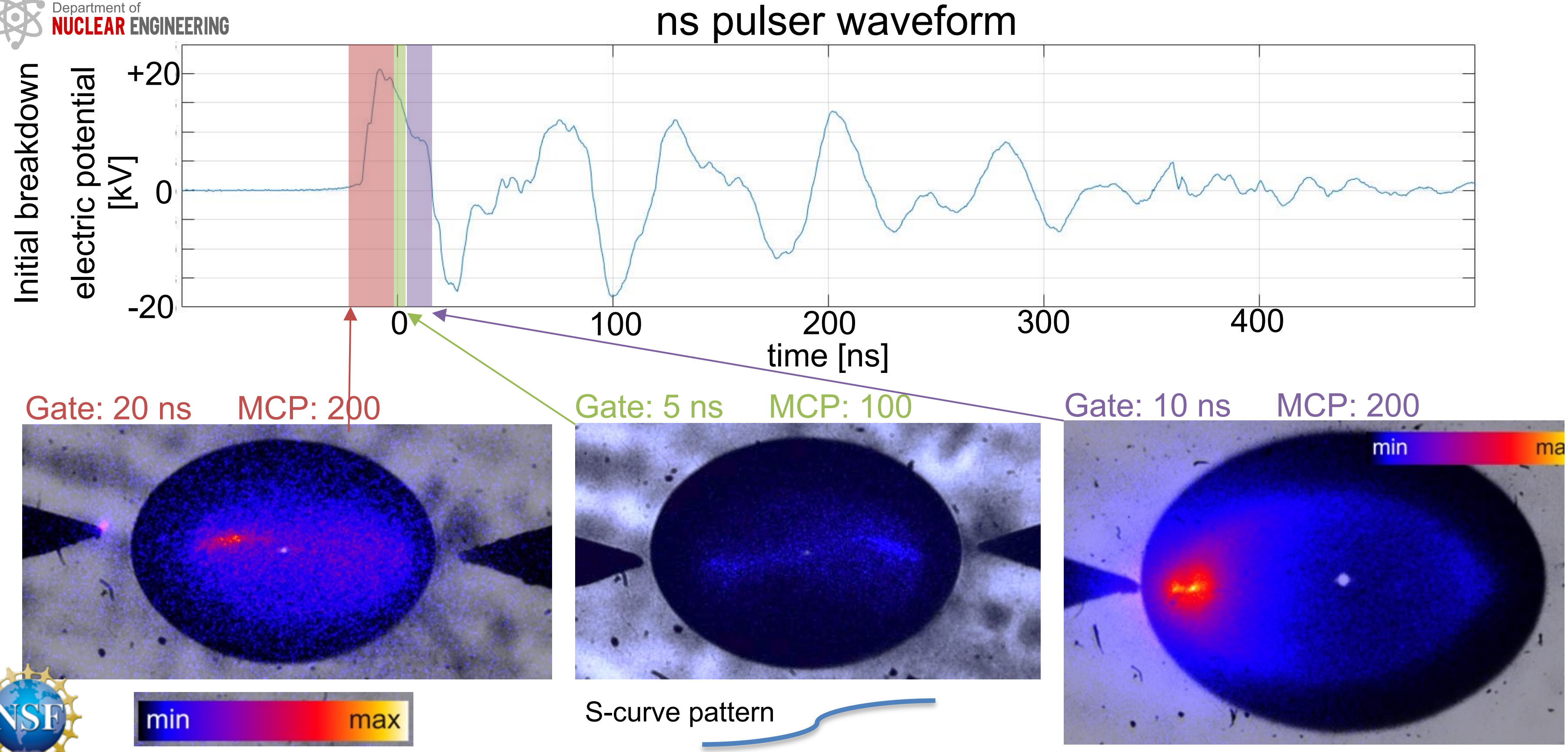
- At low ICCD amplifications discharge appears volumetric (propagation directly through bubble
- Increased camera sensitivity show some evidence of curved emission suggesting some surface streamer propagation
  - Optical lensing simulation needed for more detail





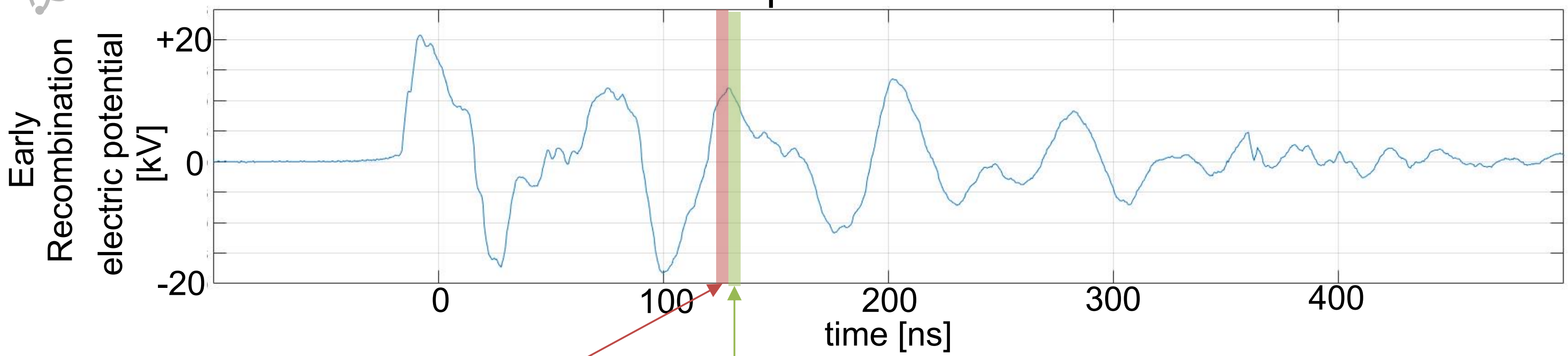
— Potential [kV]
— Filtered Current

Imaging Results

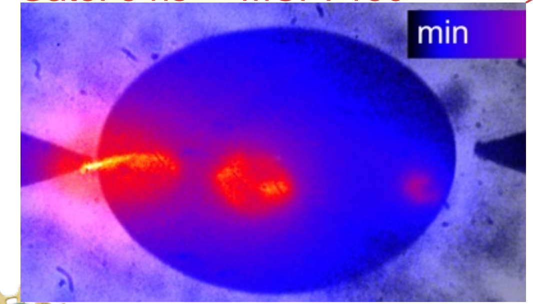


Imaging Results

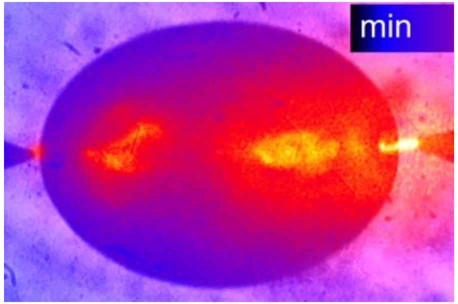
Department of NUCLEAR ENGINEERING



Gate: 5 ns MCP: 150



Gate: 5 ns MCP: 150

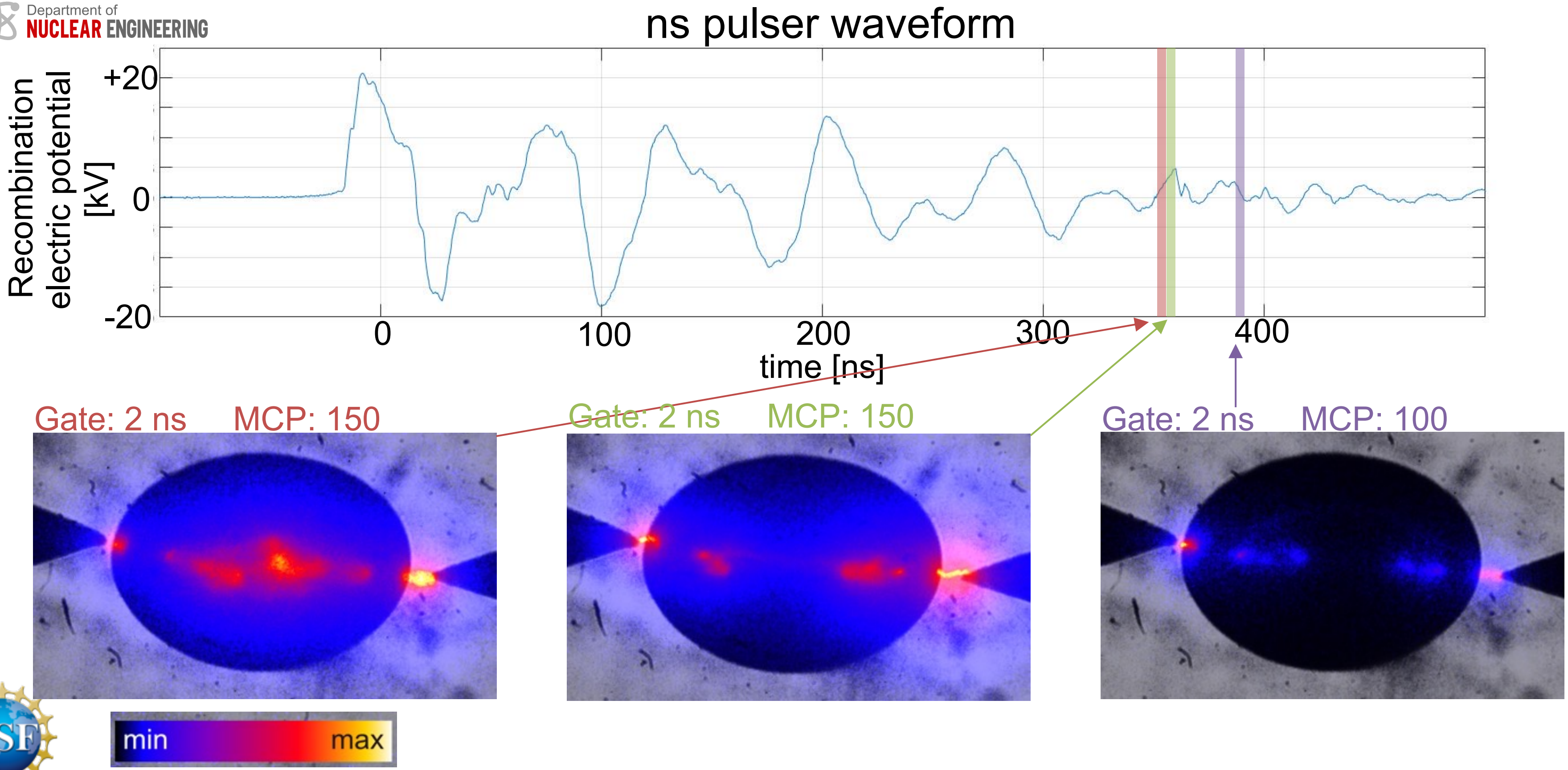


- 100 ns after single discharge
- Emission produces across the interface
- Assuming $n_e \sim 10^{14}$ cm^{-3} & recombination coefficient $\beta \sim 10^{-7}$ cm^3/s
- $\tau^3 = (\beta\ n_e)^{-1} \sim 100$ ns

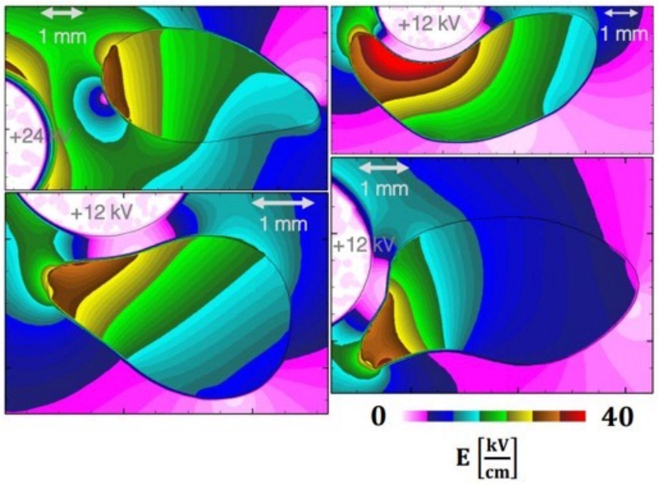
[3] Gershman et al (2010) DOI: 10.1140/epjd/e2010-10258-0

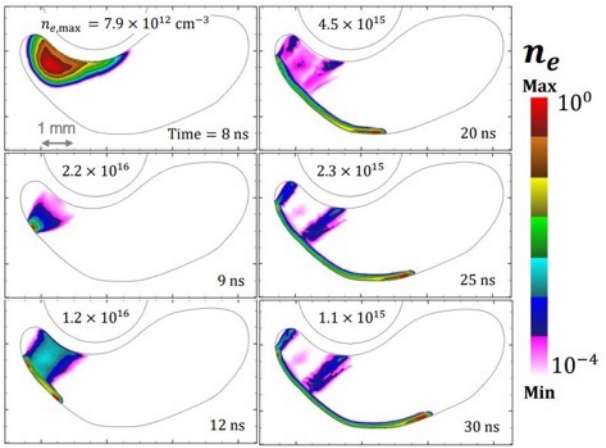
Imaging Results

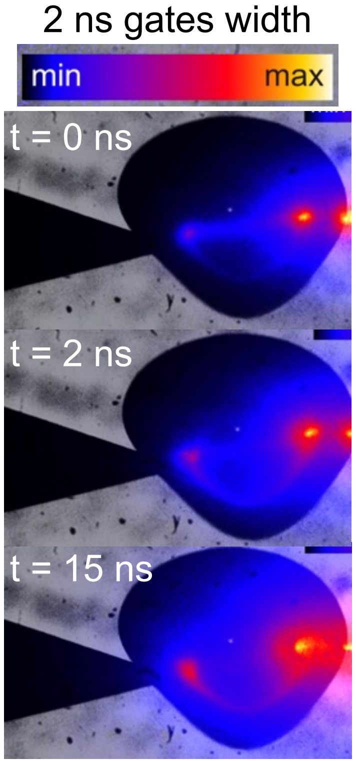
Department of
NUCLEAR ENGINEERING

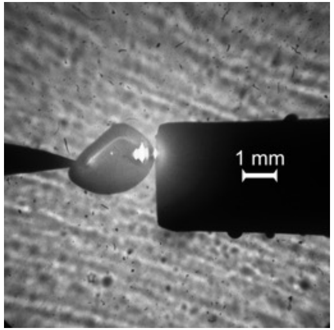


Deformed/Collisional Bubbles









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

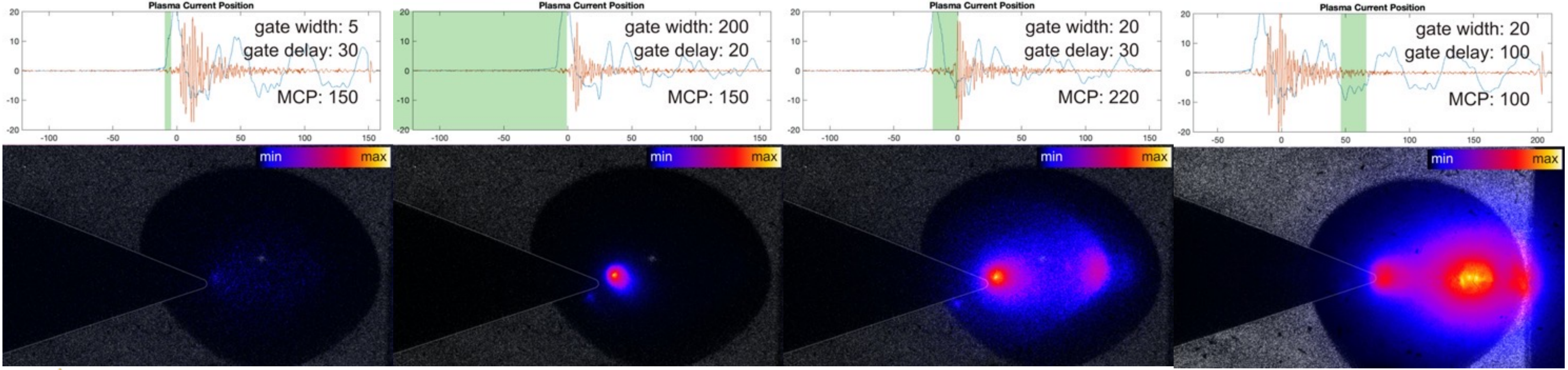
Bubbles in conductive solution

σ = 1590 μS/cm

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

- $\tau^{4} = \varepsilon_r \varepsilon_0/\sigma \approx 4.5$ ns ≈ voltage rise-time
- Emission side oscillates with positive pulse
- Sustained emission for first couple periods



[4] Yang, Yong, Young I. Cho, and Alexander Fridman. CRC press, 2017.

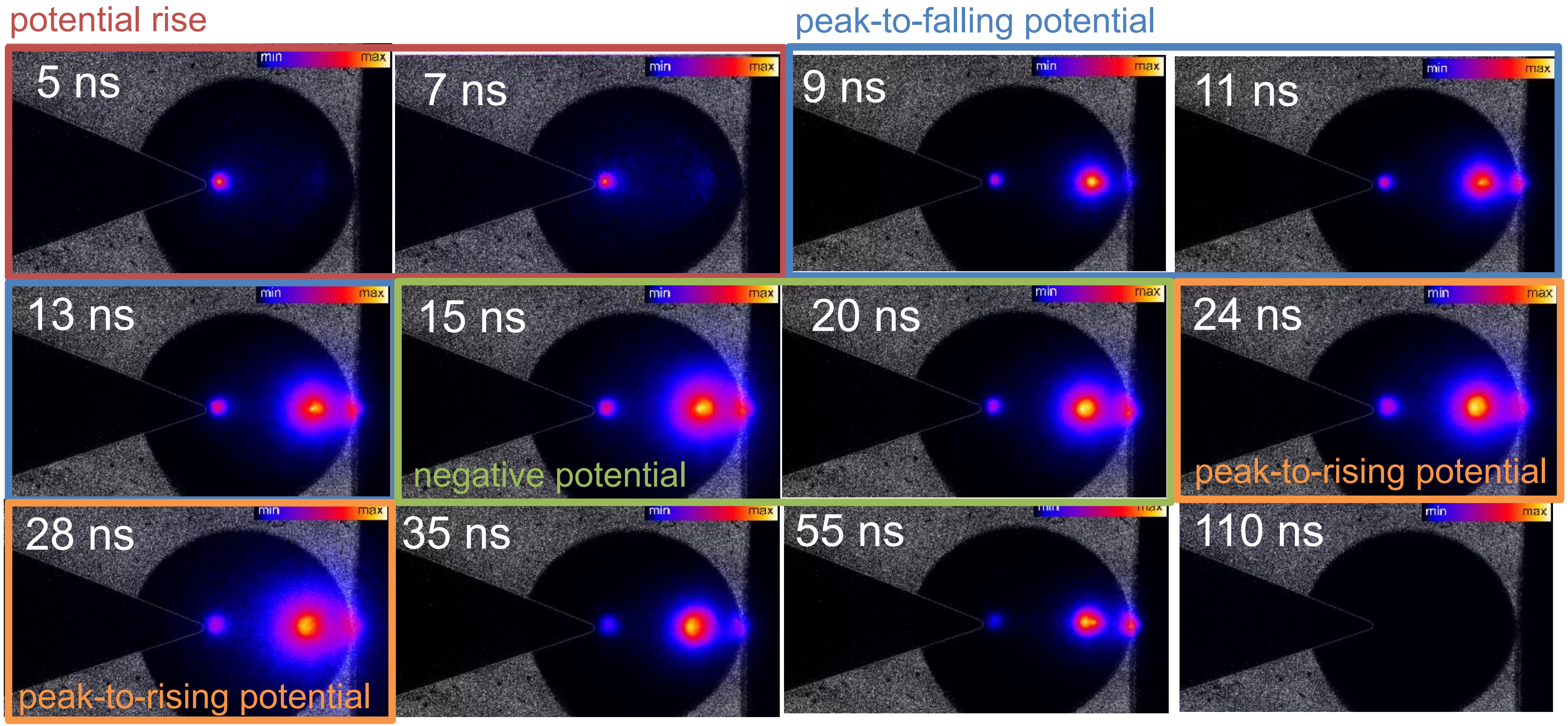
Bubbles in increased conductivity

Department of NUCLEAR ENGINEERING

σ = 1590 μS/cm

Pulse width for conductive solution: 14 ns

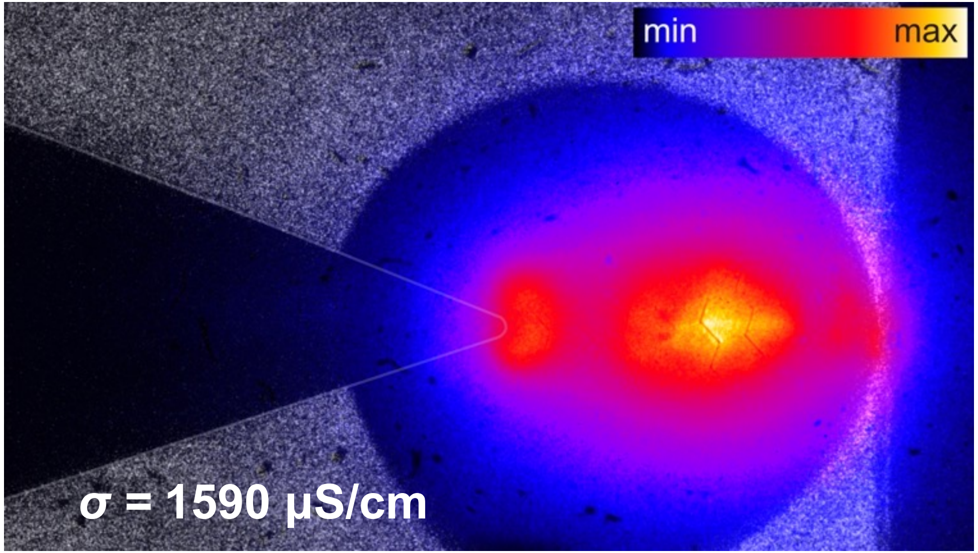
All images captured with 2 ns gate



Conclusion

Department of NUCLEAR ENGINEERING

- 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



Princeton Collaborative Research Facility
NEUP Nuclear Energy University Program
U.S. Department of Energy

Thank You

Questions and Comments

References

[1] Pillai, Naveen. "Direct Numerical Simulation of Interface-Resolved Bubbly Flows Facilitating Plasma Formation." (2021).

[2] Pillai, Naveen, et al. "Direct Numerical Simulation of Bubble Formation Through a Submerged “Flute” With Experimental Validation." *Journal of Fluids Engineering* 144.2 (2022).

[3] Gershman, S., and A. Belkind. "Time-resolved processes in a pulsed electrical discharge in argon bubbles in water." *The European Physical Journal D* 60.3 (2010): 661-672.

[4] Yang, Yong, Young I. Cho, and Alexander Fridman. *Plasma discharge in liquid: water treatment and applications*. CRC press, 2017.

Princeton Collaborative Research Facility

U.S. Department of Energy