Probing Interfacial Induced Flows and Instabilities Induced by Plasma Action at the Gas-liquid Interface

Janis Lai
University of Michigan
janislai@umich.edu

John E. Foster
University of Michigan
jefoster@umich.edu

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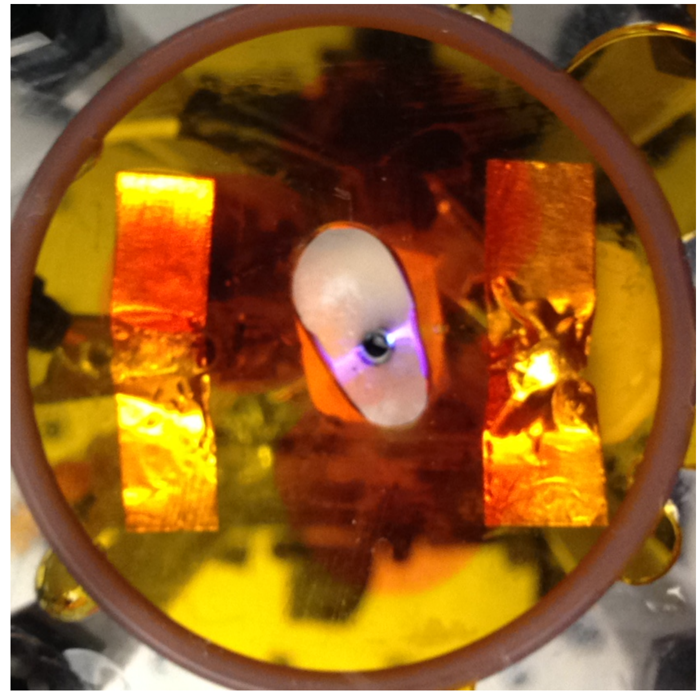
Motivation: Plasma-liquid interactions

- Radicals and RONS produced by plasma is transported into the bulk liquid
- The transport has important implications in applications such as plasma medicine and plasma-based water purification
- Nature of radical transport via liquid-gas interface is thus important in understanding plasma-driven reactivity.
- Swirl patterns observed in previous studies can be crucial in the transport process
- Instabilities at the gas-liquid interface can be the source of the swirl currents observed



Streamers reaching liquid-gas boundary, oxidizing yellow methyl orange into an orange color, showing species transport into the bulk liquid.

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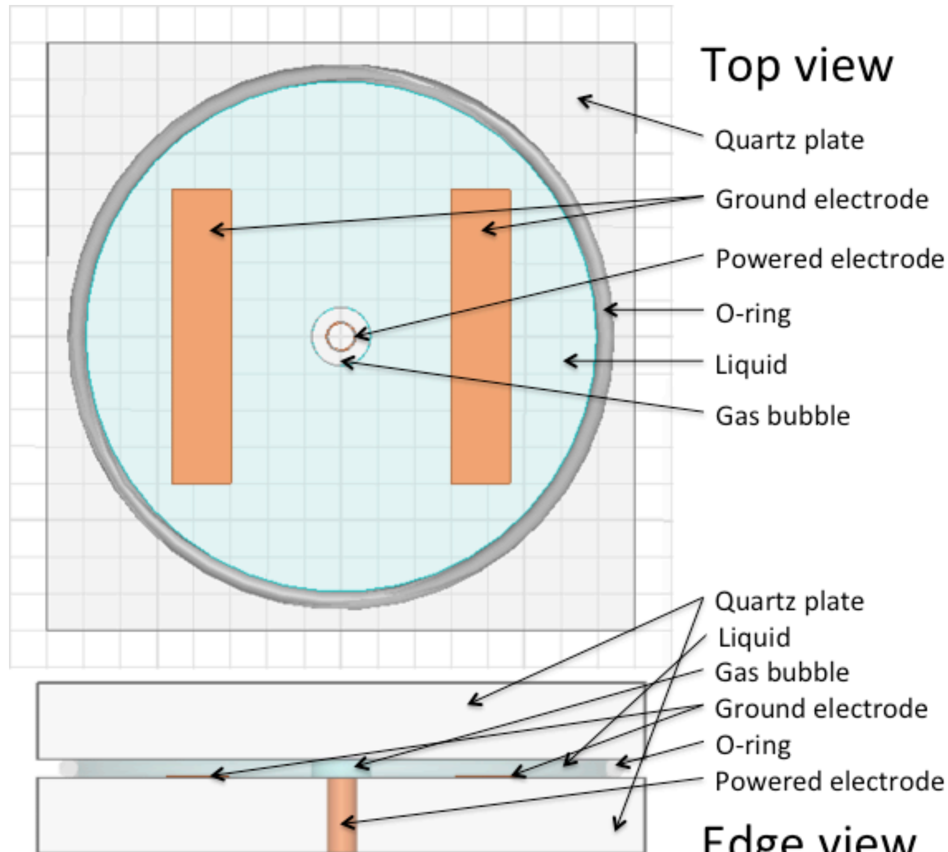
Experimental set-up

- 2D Hele-shaw-like cell enclosed a bubble in liquid between two quartz plates
- ns-pulser is used to initiate plasma breakdown
- Bubble's gas-liquid interface is available for active interrogation such as imaging and spectroscopy measurements



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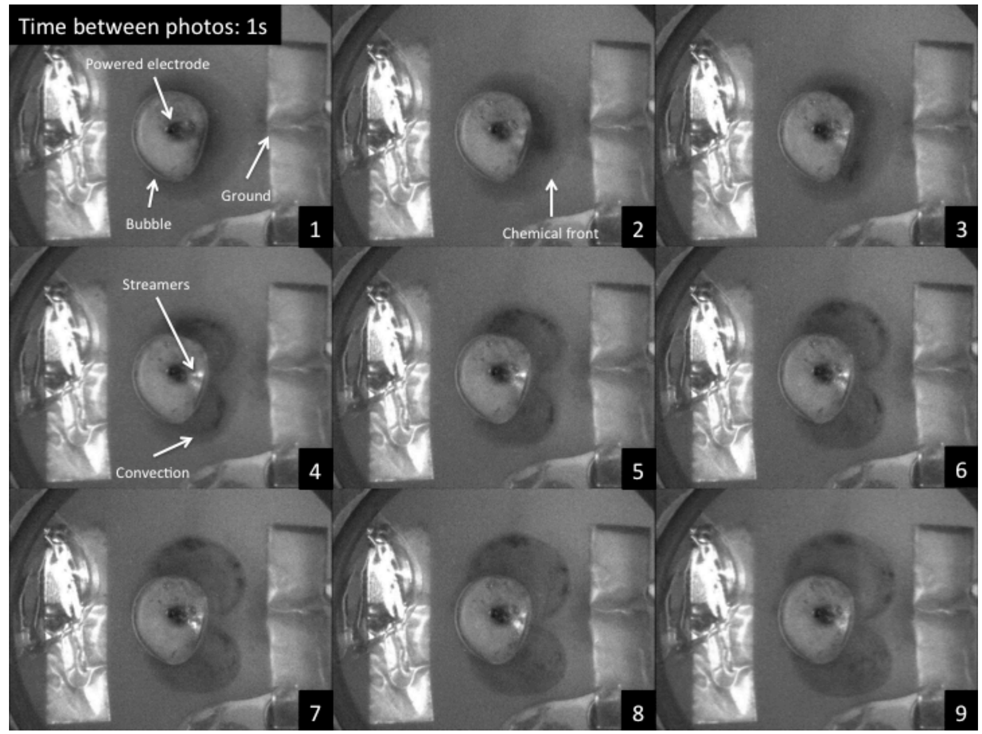
Previous work

- Using chemical probes (methyl orange), the oxidation fronts were imaged (right)
- Swirl flow patterns were observed in the streamer mode
- Speculated that swirl patterns might be caused by body forces where streamers interact at the bubble boundary
- Circulation facilitates active species transport in bulk liquid



Time-lapsed image of swirl patter observed in methyl orange solution. Streamers caused two distinct lobes of swirl currents.

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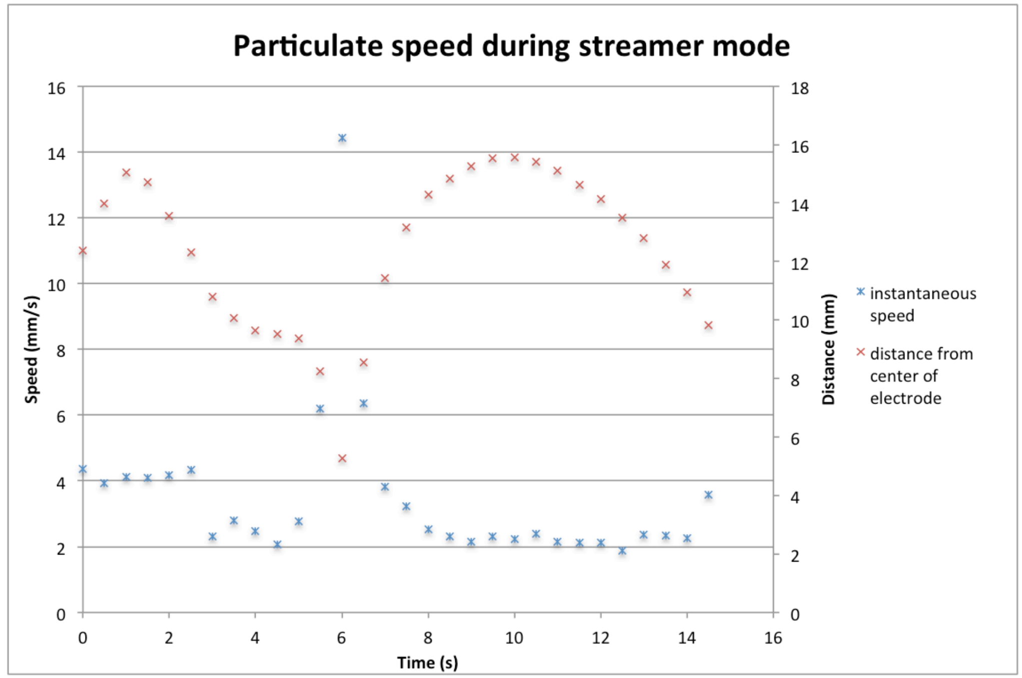
<u>Previous work</u>

- Precipitate particles were tracked in video data taken.
- Particulates flow velocity considerably sped up at the interface (suggesting circumferentially acting force present).
- Evidence of swirls transporting active species through the bulk liquid.
- Further question: what is the cause of the swirl currents?



Particle speed and its corresponding distance from center of electrode at various time.

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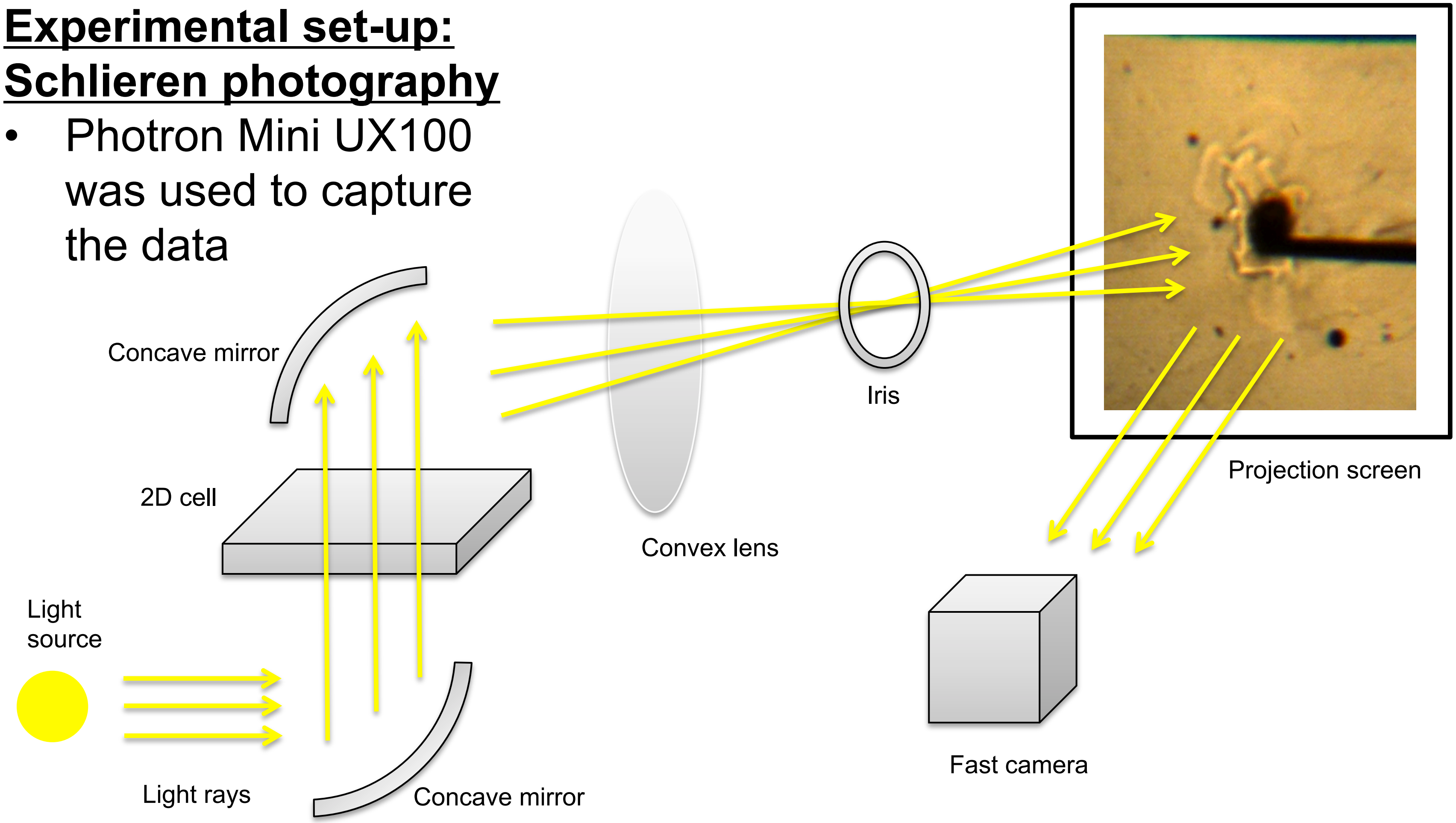
Experimental set-up: Schlieren photography

- Photron Mini UX100 was used to capture the data



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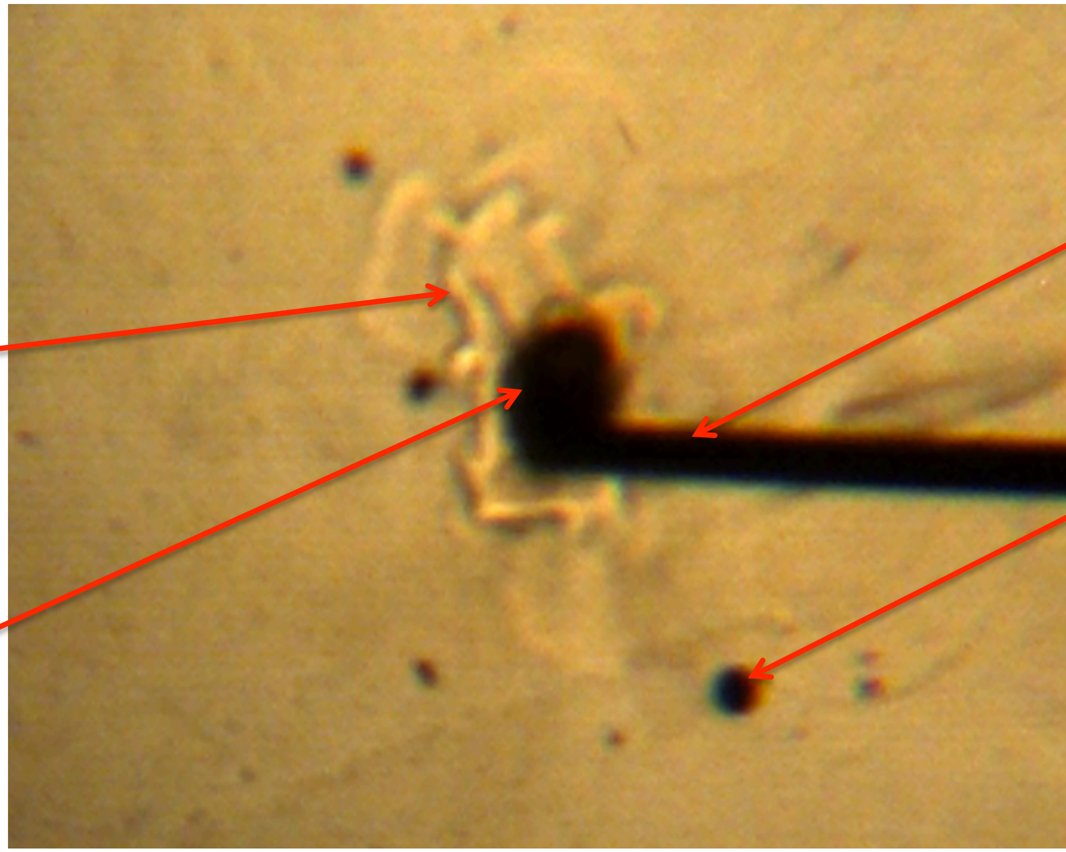
Results: Schlieren photography

Density gradient observed

Air bubble



Center electrode/ Gas inlet

Air bubble

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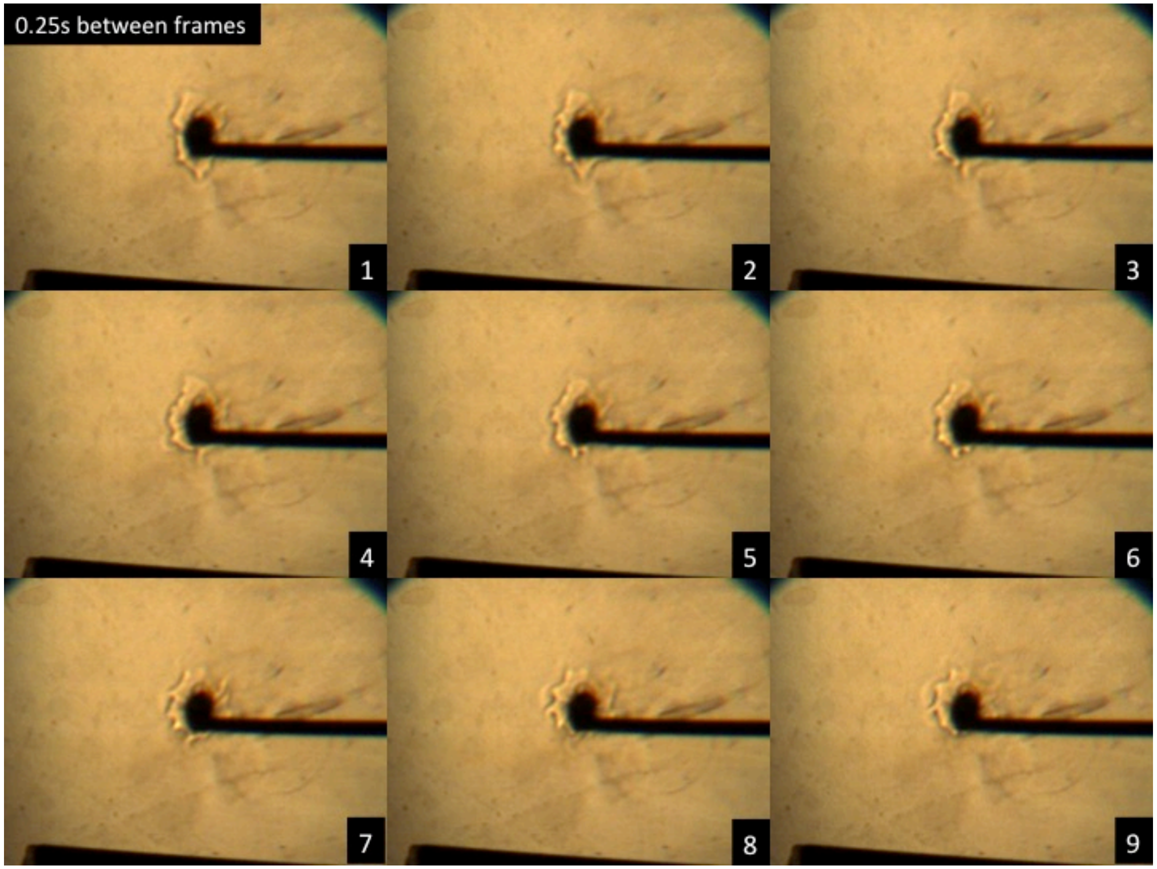
Results: Schlieren

- Gradient front is active and exhibit instability-like structure
- Area near bubble is lighter thus indicates positive density gradient region
- Dark line indicates negative density gradient region
- Gradient front remains similar distances from bubble in time
- Density gradient suggests the possibility of presence of Rayleigh-Taylor instability



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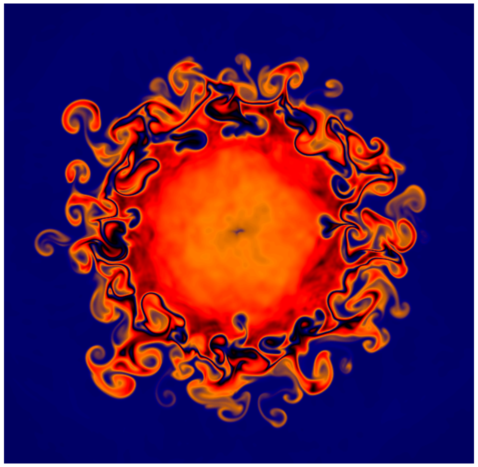
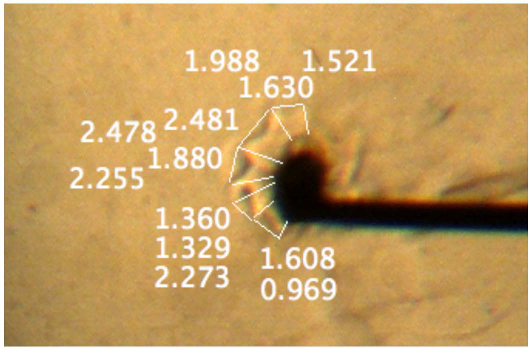
Results: Rayleigh-Taylor instability

- Instability of an interface between fluids of different densities, where the lighter fluid pushes onto the heavier fluid
- Growth rate is usually calculated as $\gamma = (Agk)^{1/2}$, where $A = (\rho_h-\rho_l) / (\rho_h+\rho_l)$ is the Atwood number, k is the wave number and g is acceleration imparted on the heavy fluid [1]
- While k is readily measured between visible nodes (right), the density of fluid needs to be experimentally obtained using calibrated concentration of fluorescent probes, or calibrated absorption of methylene blue; and acceleration can be estimated using PIV data if split imaging can be used to overlay PIV data on top of Schlieren imagery



Self-gravitating fluid Rayleigh-Taylor instability
http://christopheremoore.net/hydrodynamics-cl/



[1] Bychkov et al., 1991. Sov. Phys. JETP 73(4)

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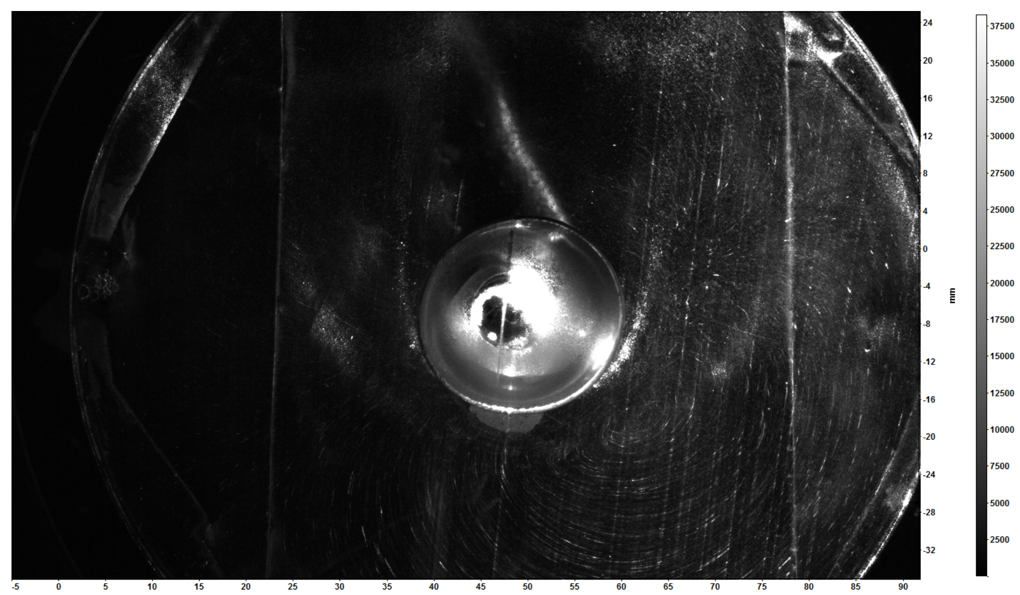
Experimental set up: Time-resolved Particle Image Velocimetry (PIV)

- PIV system from LaVision Inc. was used to measure fluid flow field (collaboration with Prof. Manera and Dr. Petrov)
- A pulsed sheet laser is used in conjunction with a timing unit to shine light on microbeads mixed in with tap water used in the test cell
- Microbeads are particles of the same density of water that reflects laser light
- Images of reflected laser light allows for the tracking of movement of said microbeads by analyzing the images taken at a time fixed interval by a fast camera



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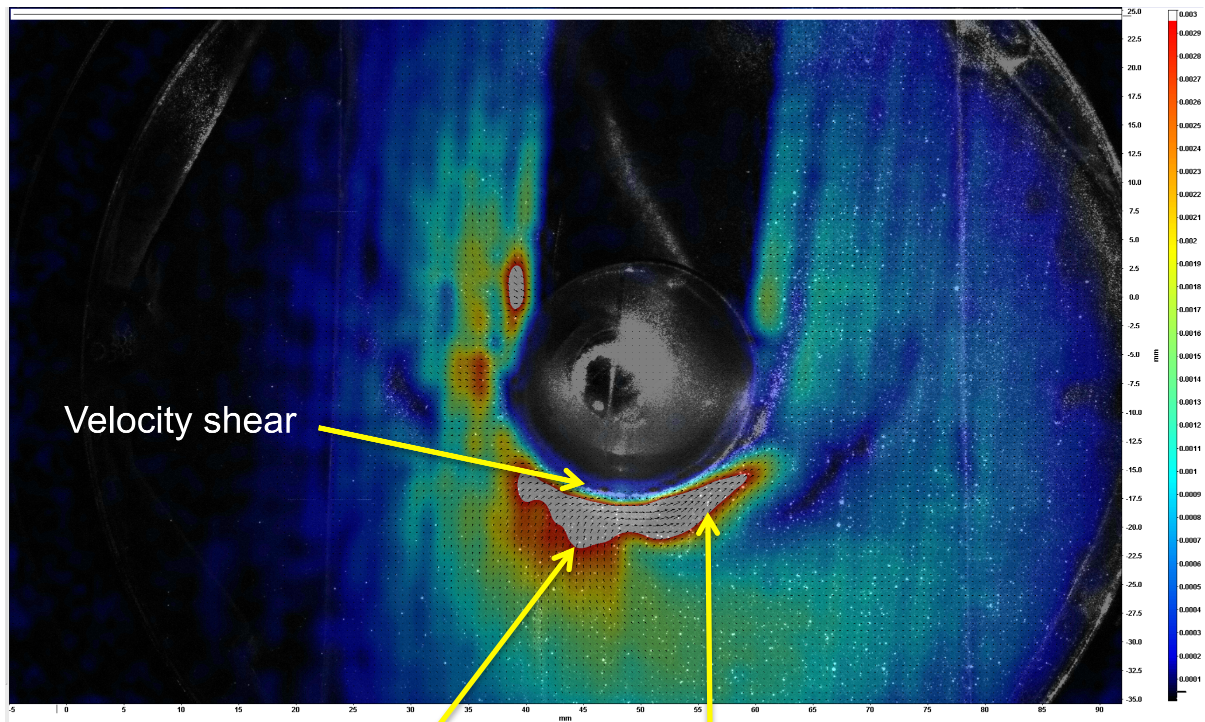
Results: PIV

- Sharp velocity shear occurs between bubble boundary and high speed region in bulk liquid
- This extreme shear is indicative of presence of Kelvin-Helmholtz instability
- In bulk liquid, particles are pulled into the interface, accelerated along the interface and ejected back into the bulk liquid
- This fluid movement derives active species transport into bulk liquid



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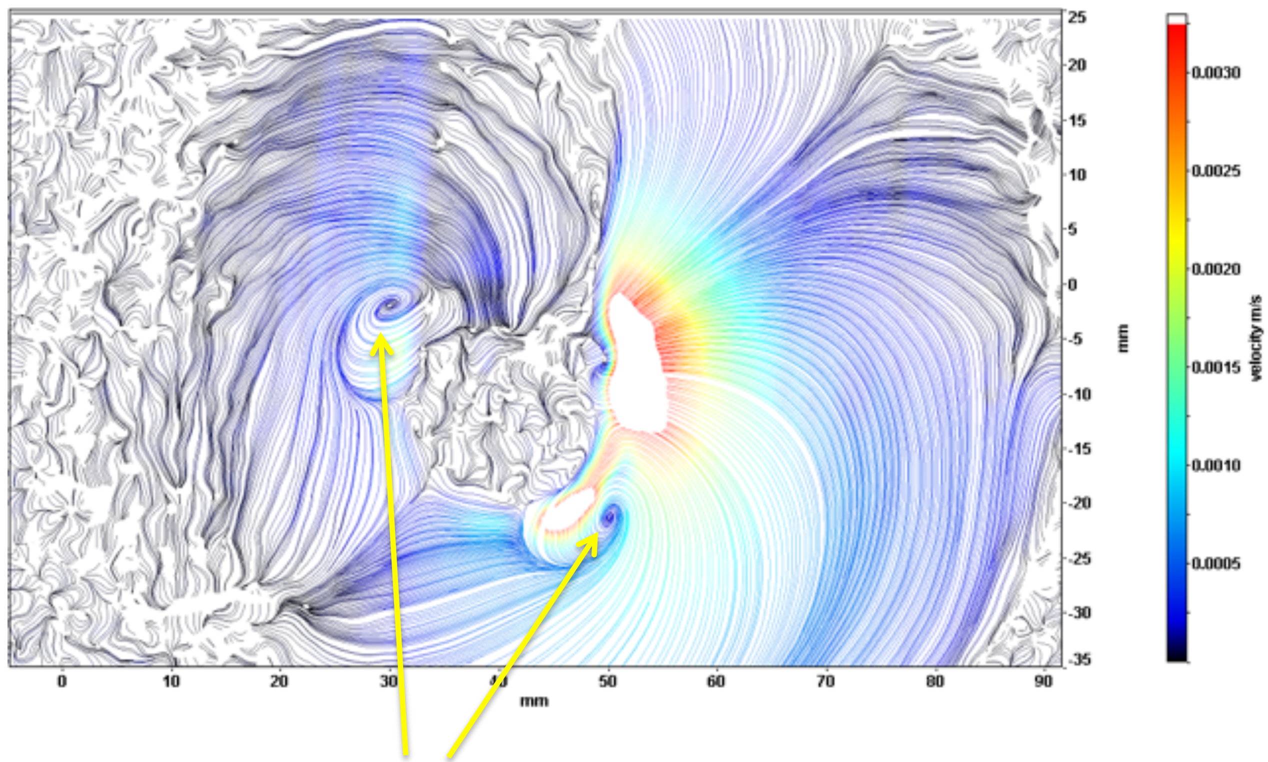
Results: PIV

- Coherent vortex-like structures are evident near the interface
- Such vortices are often presence in Kelvin-Helmholtz instability
- Flow field appear to be presence in area far away from interface
- Range of velocity here was between 0.5 to 3 mm/s, though it is important to note that the white area has speeds exceed that of 3mm/s



Center of swirls

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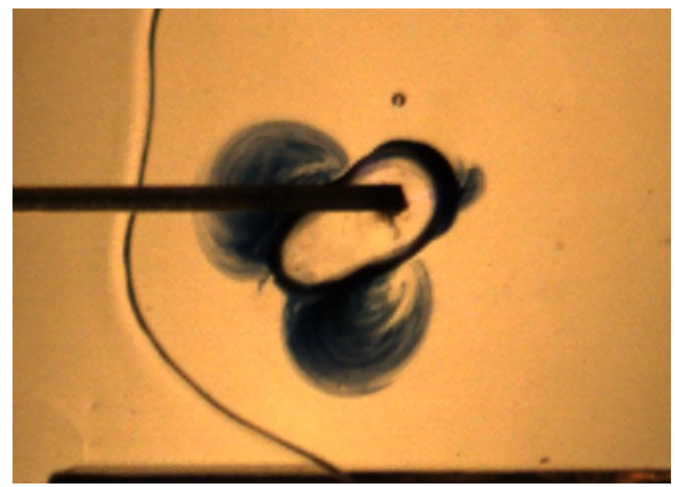
Results: Kelvin-Helmholtz Instability

- Instability of an interface experiencing velocity shear
- Growth rate is again calculated as $\gamma = (Agk)^{1/2}$, where $A = (\rho_h - \rho_l) / (\rho_h + \rho_l)$ is the Atwood number, k is the wave number and g is acceleration derived from velocity shear [1]
- While k is readily measured between visible nodes (right bottom), the density of fluid needs to be experimentally obtained using calibrated concentration of fluorescent probes, or calibrated absorption of methylene blue; and acceleration can be estimated using PIV obtained

Kelvin-Helmholtz waves over Monument, Colorado
Photo credit: Terry Robinson
https://charliesweatherforecasts.blogspot.com



[1]http://wwwf.imperial.ac.uk/~ajm8/Hydrostab/kelvin.pdf

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Future work

- Schlieren photography
  - Improves the resolution of images by directing images into camera
  - Improves the sharpness of images by employing a dual lens system
  - Improves the contrast of images by replacing iris with knife's edge
  - Images initial phase of plasma formation to understand Rayleigh-Taylor instability growth rate
- PIV
  - Employs fluorescent microbeads to look at fluid flow
  - Improves the light transmission efficiency by replacing the plexiglass set up with quartz parts
  - Removes shadow of bubble by replacing the sheet laser with a collimated bottom lit laser
  - Images initial phase of plasma formation to understand Kelvin-Helmholtz instability growth rate

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