Electrostatic self-assembly of concentric foam shells for cryogenic laser targets

19th HAPL Workshop
Madison, WI
October, 2008

Z Bei & TB Jones
Dept. of Electrical & Computer Engrg.

DR Harding
Laboratory for Laser Energetics

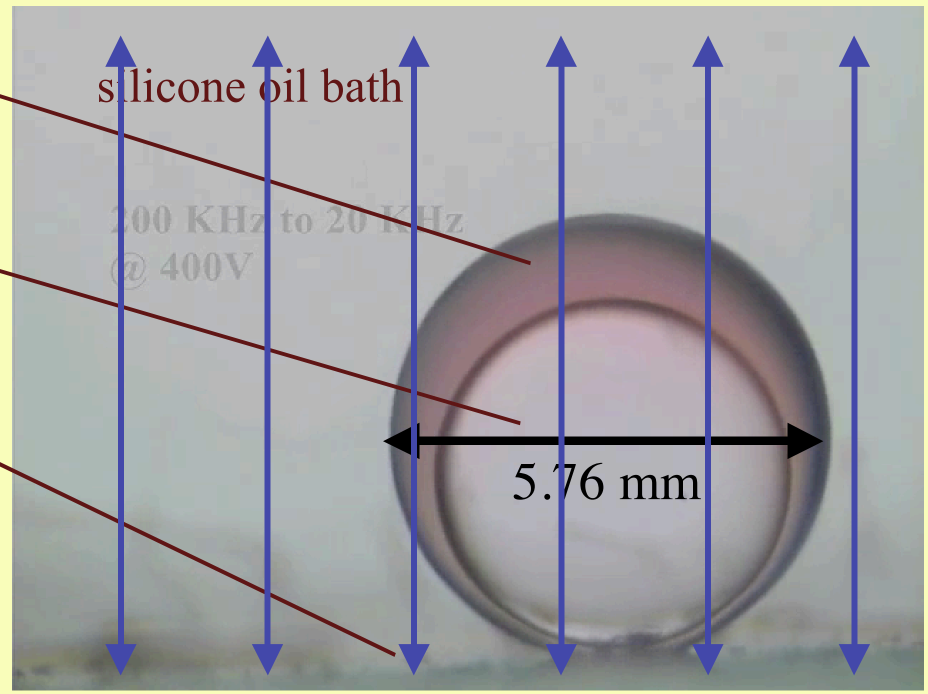
University of Rochester

Typical parameters for droplet centering

Outer shell: 55 µl DMA w/Span 80 w/red dye (N,N-dimethylacetamide)

Inner droplet: 45 µl silicone oil

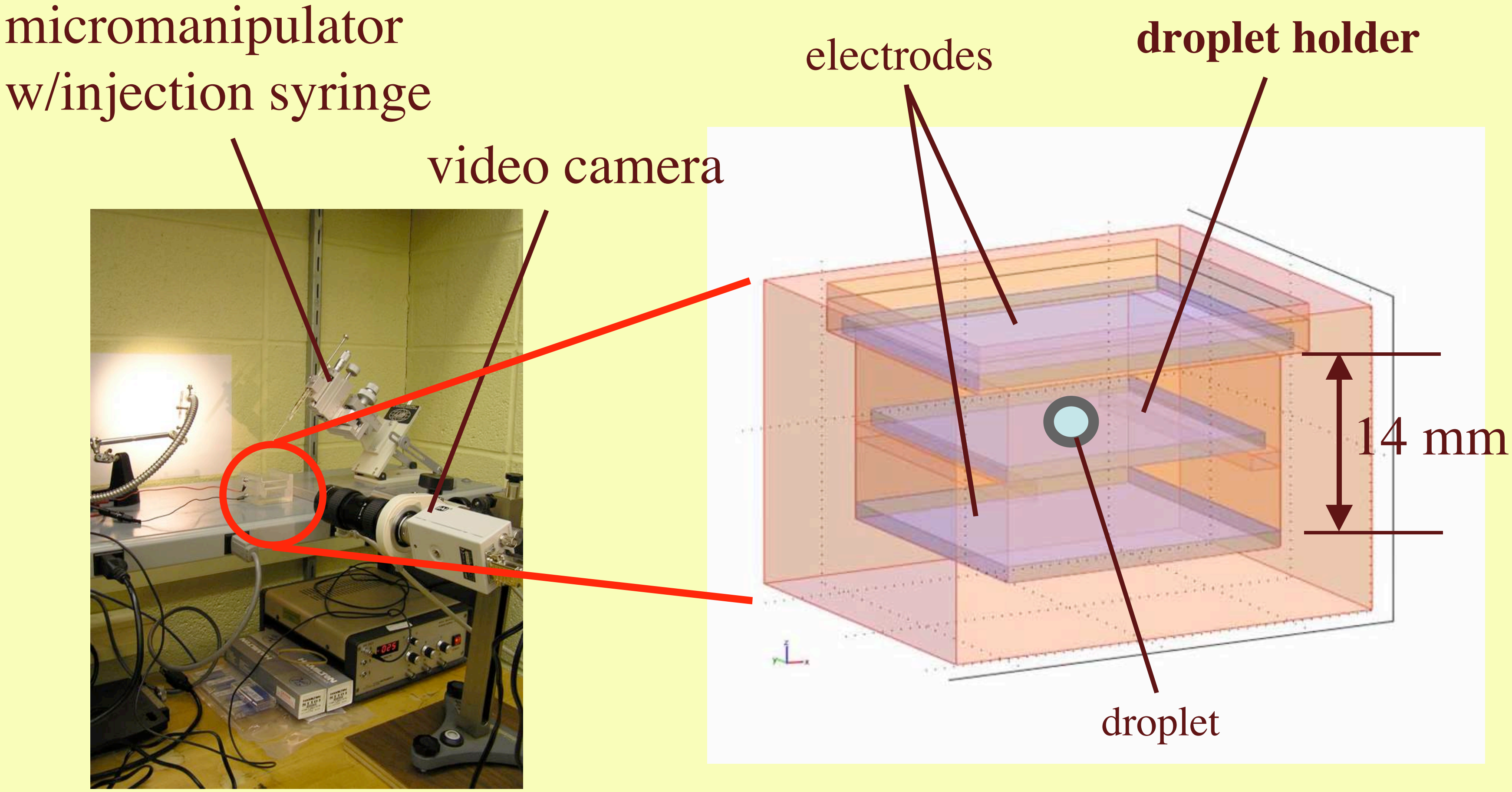
Holder: ITO glass w/droplet resting on ITO side, coated with Teflon-AF



$E \approx 3 \cdot 10^4\ V_{rms}/m$

DMA & silicone oil are density matched to within ~0.2%.

Experimental apparatus with holder

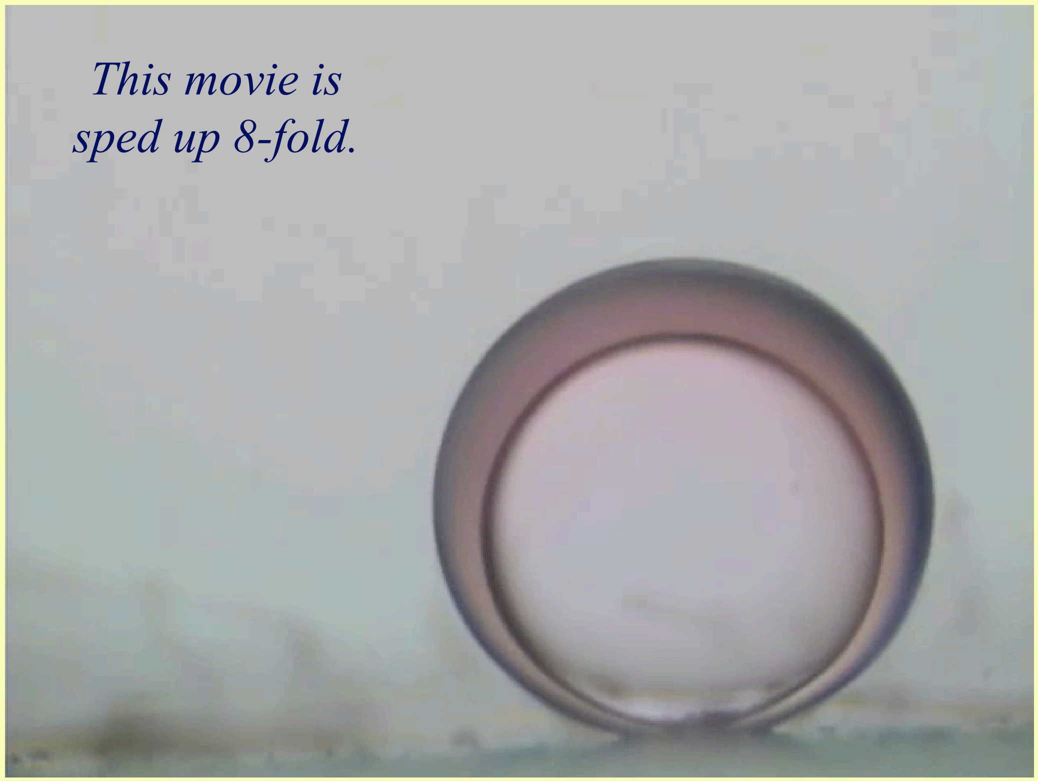


Original “aquarium”

Centering phenomenology

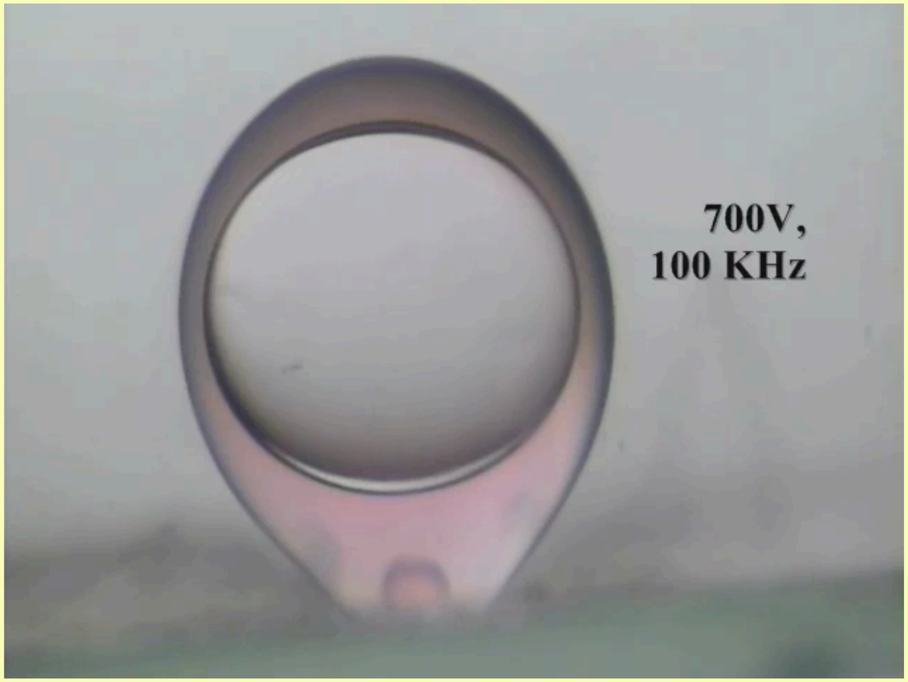
Outer shell: 55 µl DMA droplet w/Span 80	Inner droplet: 45 µl silicone oil/TECE
$\kappa = 37.8$ & $\sigma_2 \approx 10^{-3}$ S/m	$\kappa_1 = \kappa_3 = 2.5$ & $\sigma_1 \approx \sigma_3 \approx 2 \bullet 10^{-6}$ S/m

$E \sim 2 \bullet 10^4\ V_{rms}/m$ @ $f \sim 20$ kHz ➔ 200 kHz



E-field centering depends on frequency.

E-field induced droplet distortion

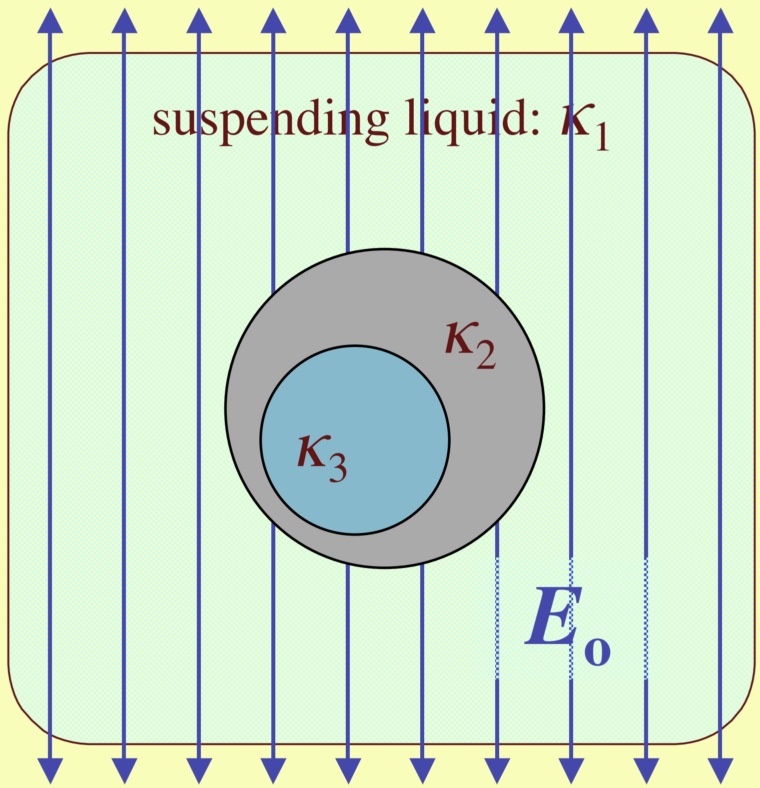


Droplets elongate in the electric field …..

but centering time is reduced -- might we exploit this effect to accelerate centering?

For this experiment, centering time reduced from 80 s to ~45 s.

Why does electrostatic self-assembly work?



<u>Energy argument</u>

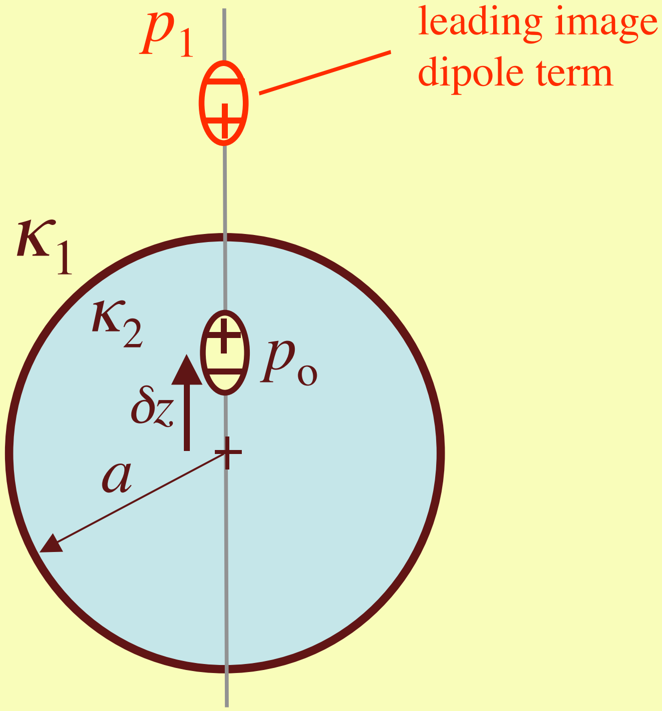
When inner droplet is centered, it is in equilibrium.

This equilibrium will be either a MIN or a MAX of the electrostatic energy.

Therefore, equilibrium will be either **stable** or **unstable**.

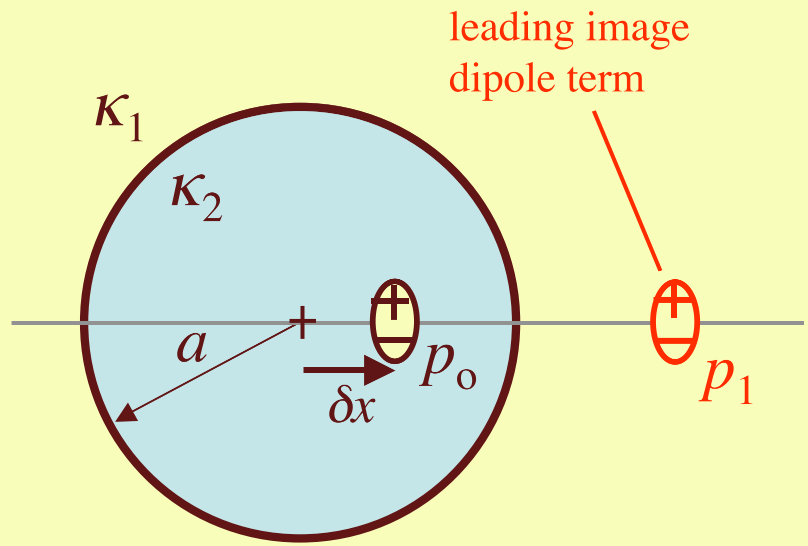
Image dipole interpretation of centering:

Assume $\kappa_2 > \kappa_1$



z-displacement

$p_o p_1 < 0 \;\therefore$ *STABLE*



x-displacement

$p_o p_1 > 0 \;\therefore$ *STABLE*

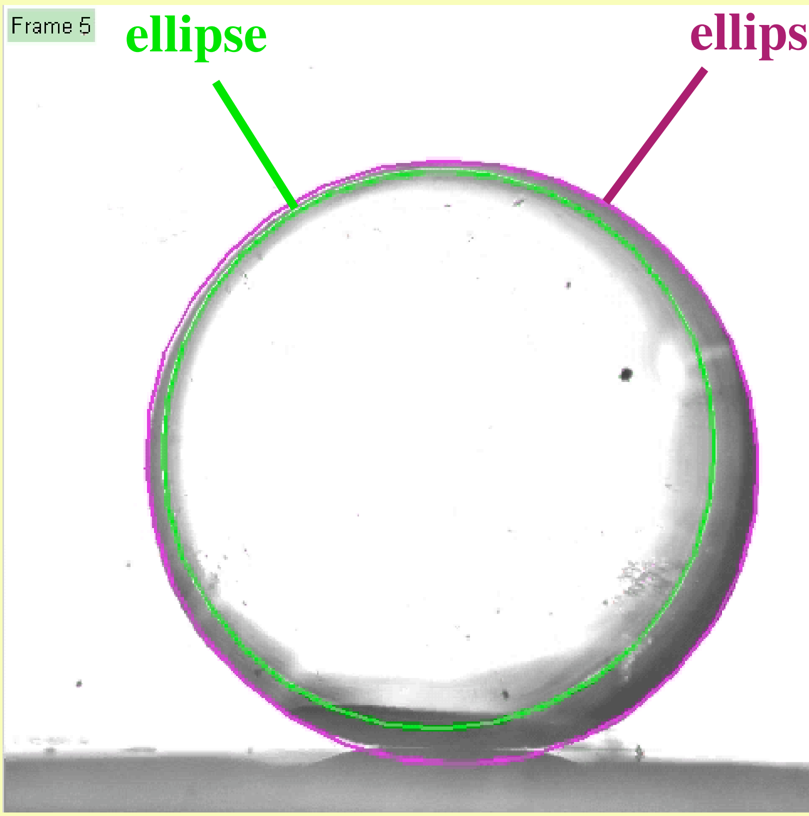
$\kappa_2 > \kappa_1$ **guarantees stability;** κ_3 **has no influence!**

Image analysis based on ellipsoid fit:

center-to-center misalignment

inner fitted ellipse

outer fitted ellipse



9 _m/pixel; 1.5 fps

δz = vertical

δx = equatorial

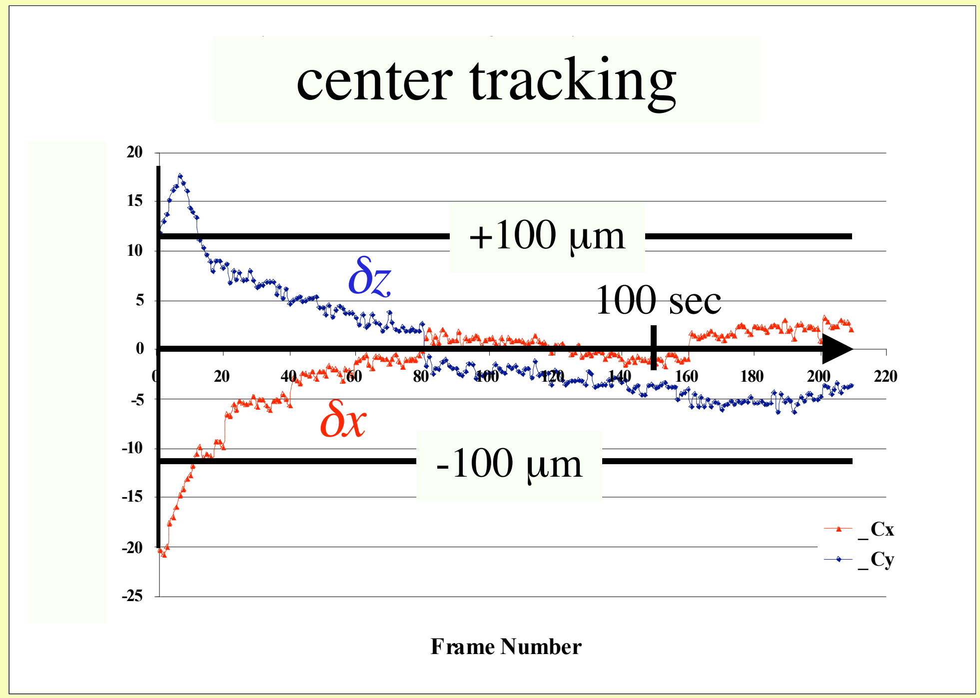
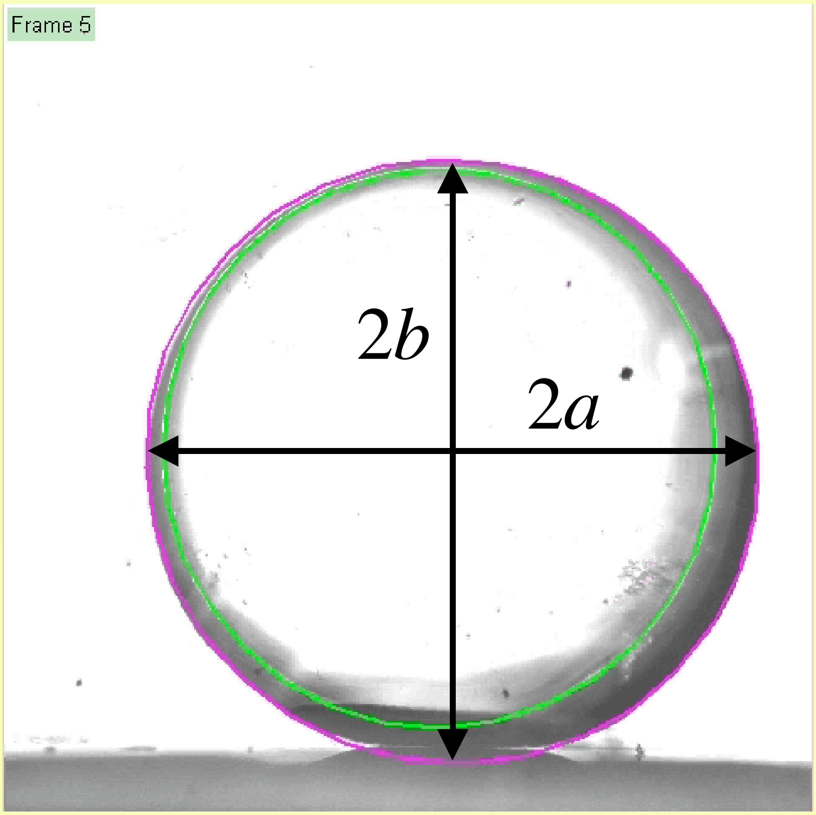
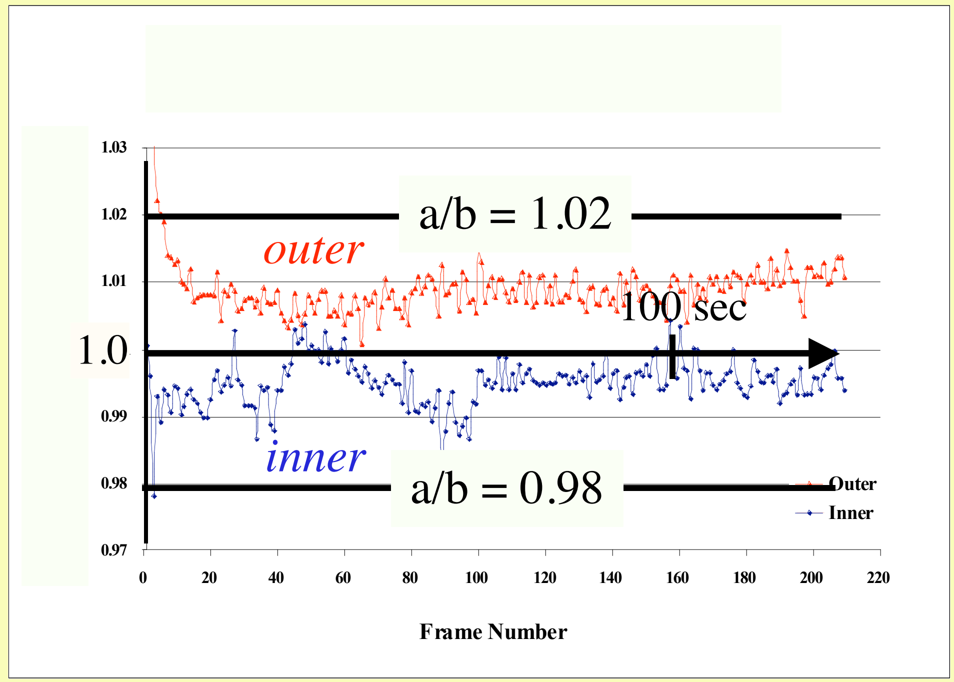


Image analysis based on ellipsoid fit:

ellipsoidal distortion in terms of a/b

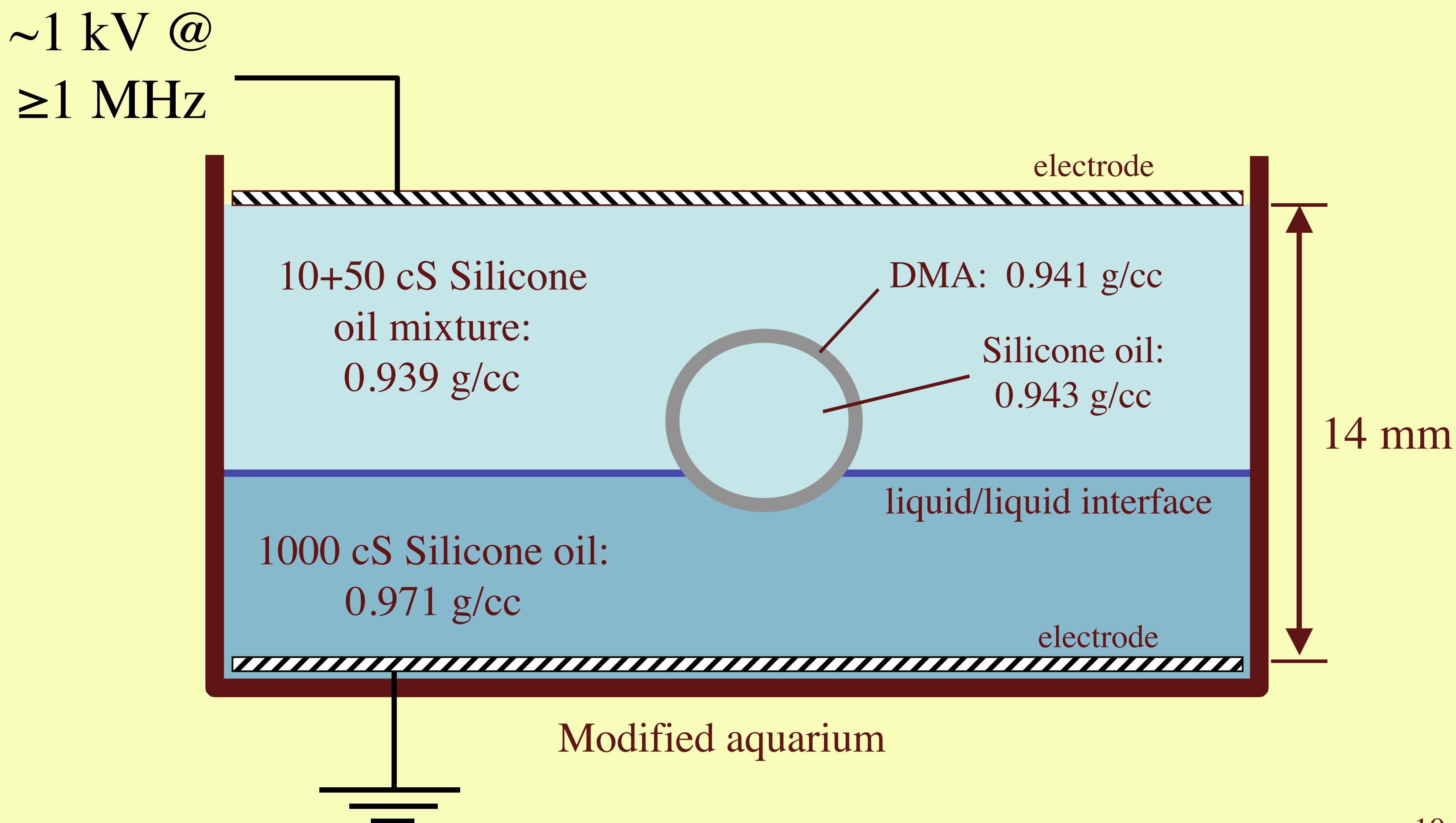




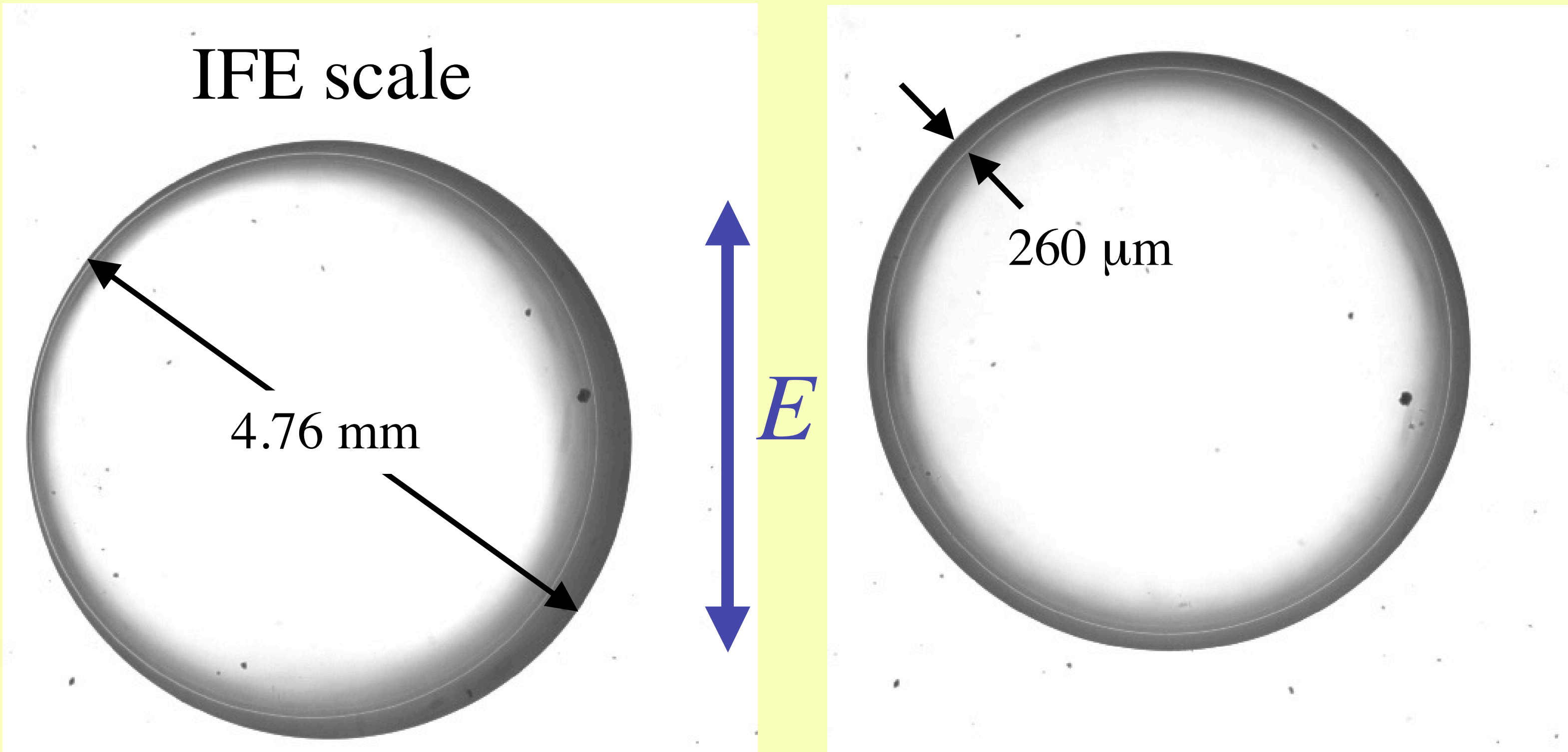
9 m/pixel; 1.5 fps

Glass holder plate causes both vertical mis-alignment (~45 μm) & oblate vertical distortion of outer shell (a/b ~ 1.01).

A better idea: density gradient suspension: the silicone oil parfait



Results with gradient suspension



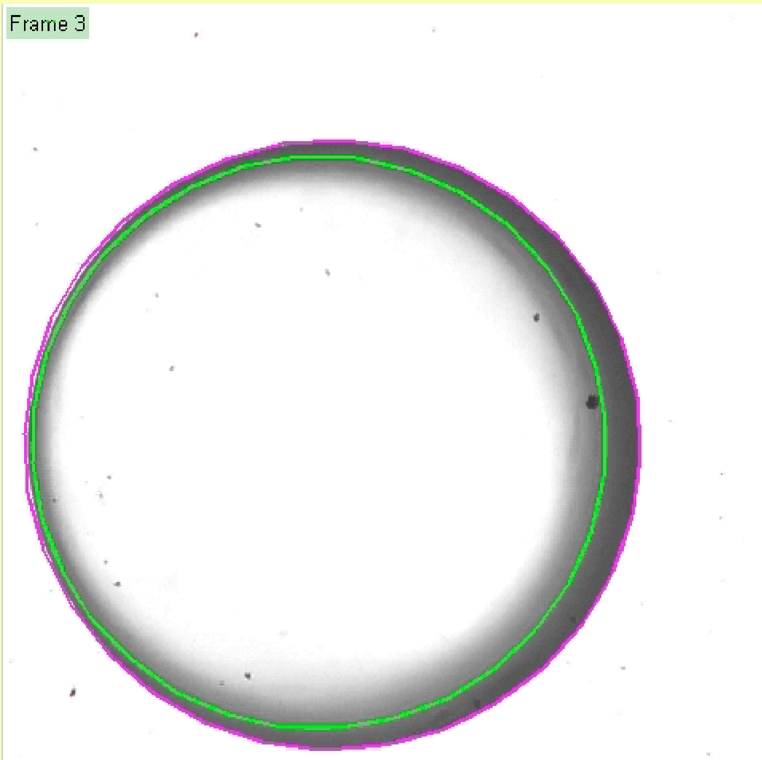
$t \approx 0$ s $t \approx 60$ s

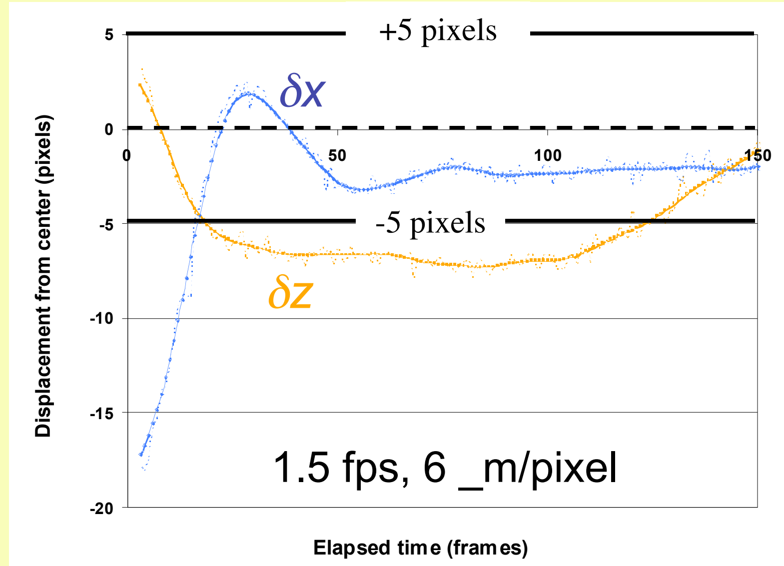
DMA + Mordant blue dye: 0.1 g/liter

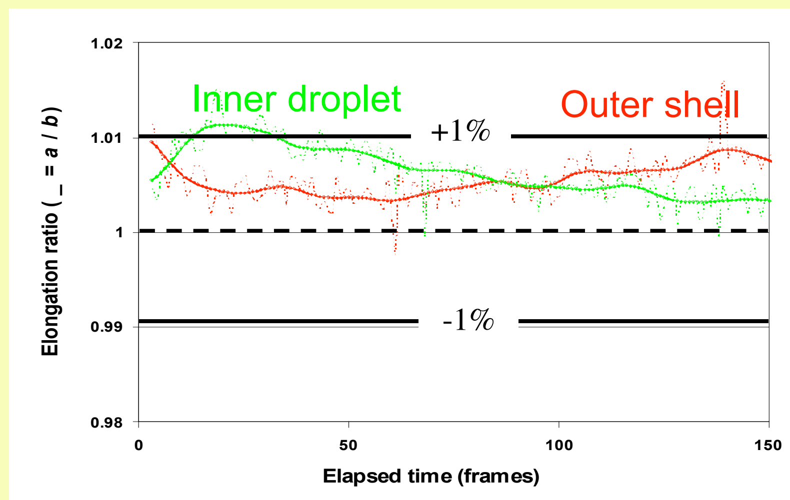
elect. conductivity: $\sigma \approx 2.5 \cdot 10^{-3}$ S/m

$E \approx 3.6 \cdot 10^{4}$ V_{rms}/m @ 3.8 MHz

DMA + Mordant blue dye shell







Δcentroid: <20 μm

elongation: <1%

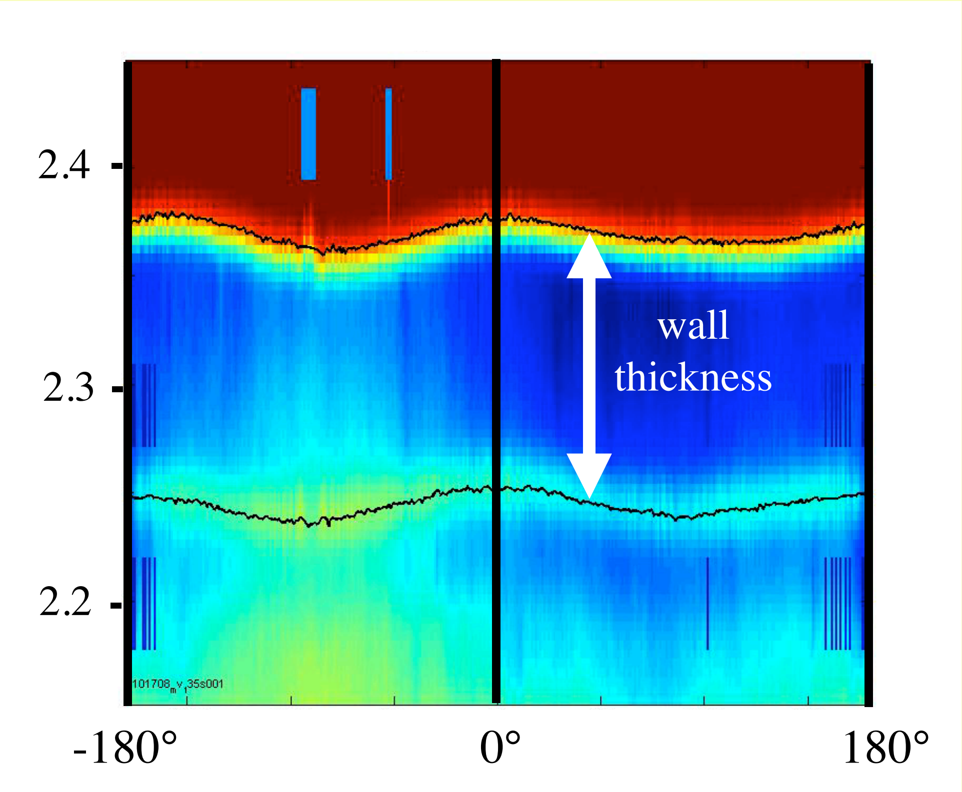
How good is this shell?

oil/DMA/oil droplet:
 diameter = 4.76 mm
 wall = 260 μm

outer surface:
 ~4.7 μm rms

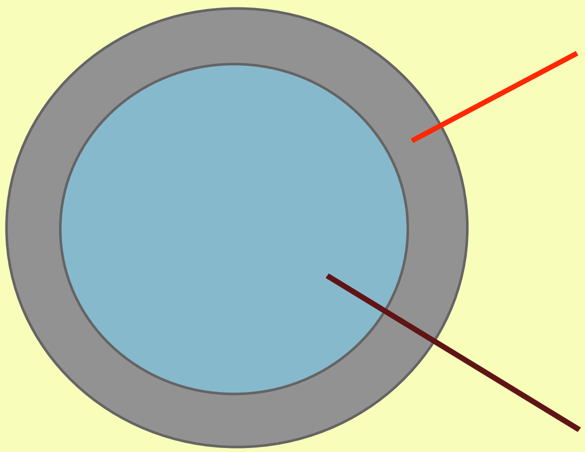
inner surface:
 ~4.5 μm rms

“unwrapped” power spectral density



Dominant mode: m = 2

Requirements for foam shell formation



Outer shell will contain the monomer in solution (e.g., resorcinol/formaldahyde), which is likely to be electrically conductive

Inner droplet: inert liquid mandrel

Shielding due to higher shell conductivity increases frequency requirement of E:
~1 kV @ ≥1 MHz (*fortunately at very low current*)

Electrical properties of expt'l liquids

constituent	conductivity ¶“	dielectric const. κ
Suspension liquid: Silicone oil	$<10^{-6}$ S/m	~2.5
Outer shell:		
DMA (N,N-dimethylacetamide)	**~2•10^{-4} S/m**	**37.8**
DMA+Mordant blue dye (0.1 g/l)	**~2.5•10^{-3} S/m**	**37.8**
Resorcinol/formaldehyde	**~2.53•10^{-2} S/m**	**???**
Inner droplet: Silicone oil	$<10^{-6}$ S/m	~2.5

Estimates for critical frequency for IFE shell:

$$f_{\text{shielding}} = \frac{1}{2\pi}\,\frac{2\sigma_2\, d}{\varepsilon_3\, R} = \begin{cases} \sim 200 \text{ kHz (DMA)} \\ \sim 3.8 \text{ MHz (DMA+dye)} \\ \sim 40 \text{ MHz for R/F} \end{cases}$$

Challenge for the chemists:

Identify polymer foam chemistries that minimize or avoid ionic salts.

- Use radical initiators?
- Avoid surfactants if possible.
- Photo-initiated polymerization would be ideal.
- Keep monomer solution conductivity $\leq 10^{-3}$ S/m:

ion salt molarity of ~1 mM yields $\sigma \sim 10^{-3}$ S/m.

Important questions

- How close must densities be matched? <0.2%?
- How rapidly is concentricity approached? ~60 seconds
- Is particle elongation a problem? $a/b < 1.01$
- Does use of density gradient suspension avoid need for surfactant? Apparently yes!
- What geometry to use for centering droplets?
- Will Joule heating-induced convection obstruct centering in early phase of polymerization?
- Are there polymer foam-forming solutions with electrical conductivity in the range of $\sim 10^{-3}$ S/m?

Thanks to many contributors

<u>University of Rochester</u>

W Bittle, J Fooks, D Jacobs-Perkins, W Wang, M Wittman

<u>UCLA</u>

R Garrell, A Tucker-Schwartz

<u>General Atomics</u>

J Hund, J Kilkinney, A Nikroo, RR Paguio