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Introduction to Optofluidics

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Optical Radiation Pressure Effects on Fluid Interfaces and Isotropic Fluids

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Introduction to Optofluidics
Optical Radiation Pressure Effects on Fluid Interfaces and Isotropic Fluids

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Outline

I. Breakthrough experiments

II. Description of the linear regime in deformation

III. Experimental confrontation; possible side effects

IV. Nonlinear behaviors: a route towards "opto-hydrodynamics"

V. Jets and large aspect ratio liquid columns

VI. Finite size effects and optical "Taylor" cones

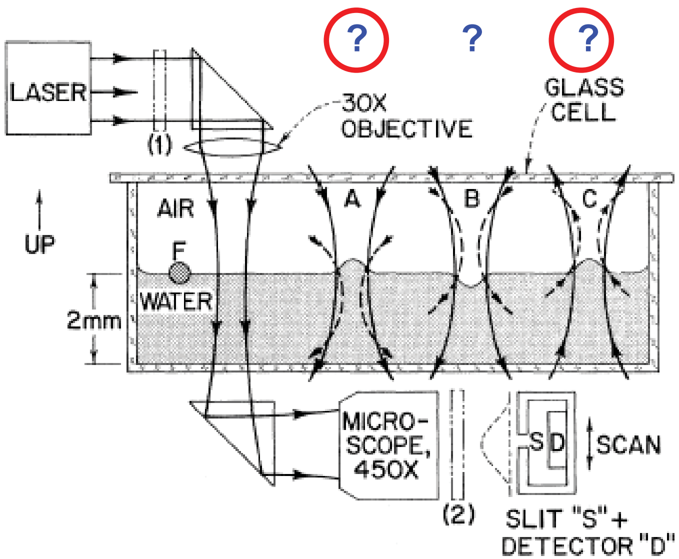
VII. Concluding remarks

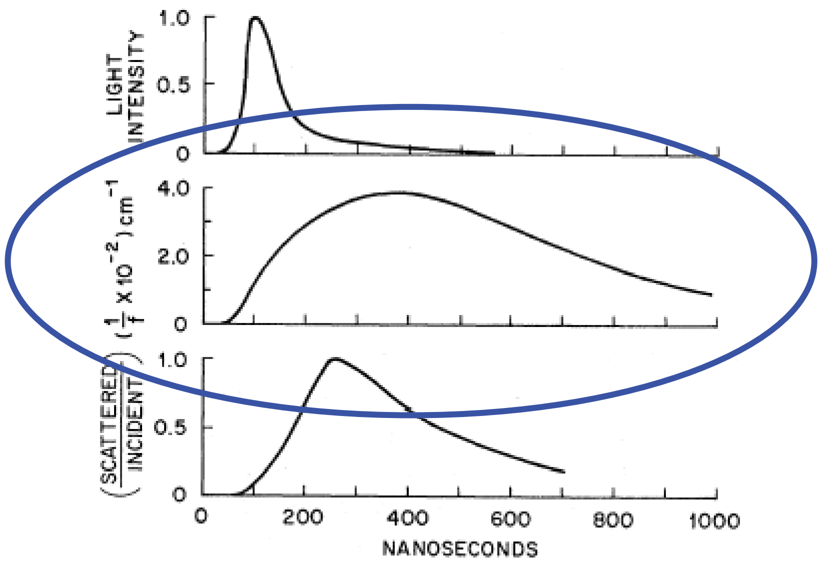
The Very First Experiment

VOLUME 30, NUMBER 4 PHYSICAL REVIEW LETTERS 22 JANUARY 1973

Radiation Pressure on a Free Liquid Surface

A. Ashkin and J. M. Dziedzic
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 10 November 1972)





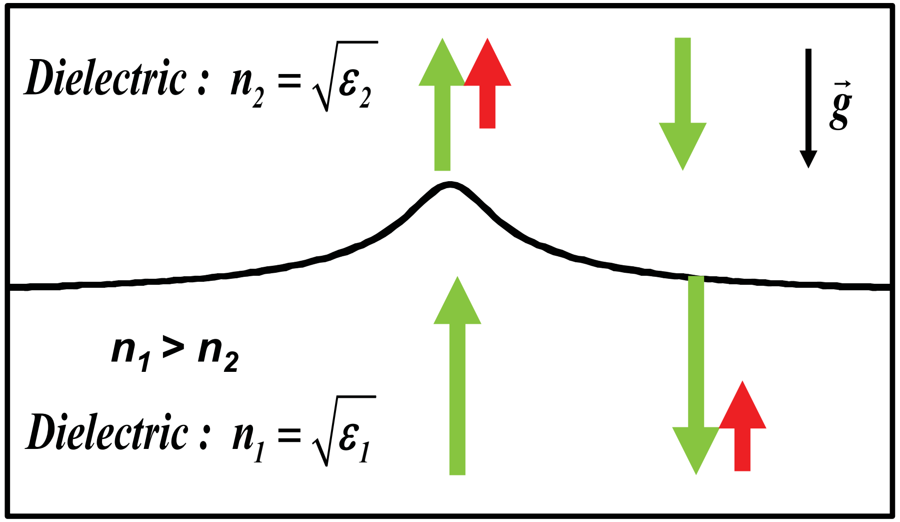
frequency doubled Nd^{3+}:YAG (λ=0.53 µm), Peak power 1-4 kW

Pulse duration 60 ns, waist ω_0 = 2.1 µm

Water free surface (σ = 72mN/m) → a few µm

$$\omega_0 = 3 - 30\,\mu m, P \leq 2W \Rightarrow \Pi = 1 - 10\,Pa$$

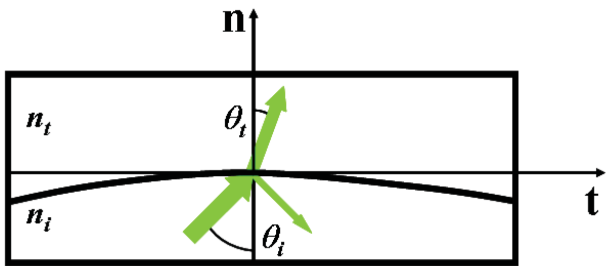
Ashkin and Dziedzic observation at Liquid Interfaces



Deformation towards the optically less dense fluid

$\longrightarrow$ **Compatible with the Minkowsky expression of the photon momentum** $\vec{p} = n\dfrac{h\nu}{c}\hat{z}$

Qualitative explanation



(i) an incident photon gives to the interface the momentum

$$\left(n_i h\nu/c\right)\left[\sin\theta_i \mathbf{t} + \cos\theta_i \mathbf{n}\right]$$

(ii) a reflected photon picks to the interface the momentum

$$\left(n_i h\nu/c\right)\left[\sin\theta_i \mathbf{t} - \cos\theta_i \mathbf{n}\right]$$

(iii) a transmitted photon picks to the interface the momentum

$$\left(n_t h\nu/c\right)\left[\sin\theta_t \mathbf{t} + \cos\theta_t \mathbf{n}\right]$$

Elementary variation of momentum on the interface portion of area S during the time dt: $d\mathbf{Q} = d\mathbf{Q}_{\parallel} + d\mathbf{Q}_{\perp}$

$$d\mathbf{Q} = d\mathbf{Q}_{\parallel} + d\mathbf{Q}_{\perp} = \left[n_i \sin\theta_i - \left(R(\theta_i,\theta_t)n_i \sin\theta_i + T(\theta_i,\theta_t)n_t \sin\theta_t\right)\right]\frac{Nh\nu}{c}Sdt\mathbf{t}$$
$$+\left[n_i \cos\theta_i - \left(-R(\theta_i,\theta_t)n_i \cos\theta_i + T(\theta_i,\theta_t)n_t \cos\theta_t\right)\right]\frac{Nh\nu}{c}Sdt\mathbf{n}$$

Reflection and transmission Fresnel coefficients in electromagnetic energy: $R(\theta_i,\theta_t), T(\theta_i,\theta_t) = 1 - R(\theta_i,\theta_t)$

N: photon number per unit area and unit time

$$n_i \sin\theta_i = n_t \sin\theta_t \longrightarrow d\mathbf{Q}_{\parallel} = \mathbf{0} \longrightarrow d\mathbf{Q} = d\mathbf{Q}_{\perp} = n_i \cos\theta_i \left[1 + R(\theta_i,\theta_t) - \frac{\tan\theta_i}{\tan\theta_t}T(\theta_i,\theta_t)\right]\frac{Nh\nu}{c}Sdt\mathbf{n}$$

laser intensity $I = \left(N_0 \cos(\theta_i)\right)h\nu$ for an incident wave tilted by an angle θ_i at the interface

$$\mathbf{\Pi}_{Rad} = d\mathbf{Q}/Sdt = n_i \cos^2\theta_i \left[1 + R(\theta_i,\theta_t) - \frac{\tan\theta_i}{\tan\theta_t}T(\theta_i,\theta_t)\right]\frac{I}{c}\mathbf{n}$$

- normal to the interface
- directed toward the dielectric medium of lowest index of refraction

Stationary interface deformation, the EM view (I)

Electromagnetic force density in fluid j:

$$\boldsymbol{f}^{M}_{em,j} = -\frac{1}{2}\varepsilon_0 \boldsymbol{E}_j^{\,2}\,\nabla\varepsilon_j + \frac{1}{2}\varepsilon_0 \nabla\left[\boldsymbol{E}_j^{\,2}\,\rho_j \frac{\partial\varepsilon_j}{\partial\rho_j}\right] + \cancel{\frac{\varepsilon_j - 1}{c^2}\frac{\partial}{\partial t}\left(\boldsymbol{E}_j \times \boldsymbol{H}_j\right)},\ j = 1,2$$

interface | Interface+bulk | Abraham

Bulk: NS Equation

$$\rho_j\left(\cancel{\frac{\partial \boldsymbol{u}_j}{\partial t} + \boldsymbol{u}_j.\nabla\,\boldsymbol{u}_j}\right) = -\nabla p_j + \cancel{\eta_j \nabla^2 \boldsymbol{u}_j} + \rho_i\,\boldsymbol{g} + \left(\boldsymbol{f}^{M}_{em,j}\right)_{Bulk},\ j = 1,2$$

$\longrightarrow$ $-\nabla q_j = 0$ **With pseudo-pressure** $q_j = p_j + \rho_i g z - \frac{1}{2}\varepsilon_0 \boldsymbol{E}_j^{\,2}\,\rho_j \frac{\partial\varepsilon_j}{\partial\rho_j}$

Interface

EM Stress Tensor $\nabla\,\boldsymbol{T}^{M}_{em,j} = \boldsymbol{f}^{M}_{em,j}$

$$\boldsymbol{T}^{M}_{em,j} = \frac{1}{2}\varepsilon_0\left(\rho_j \frac{\partial\varepsilon_j}{\partial\rho_j}\right)_T E_j^{\,2}\,\boldsymbol{I} - \frac{1}{2}\varepsilon_0\varepsilon_j E_j^{\,2}\,\boldsymbol{I} + \varepsilon_0\varepsilon_j\,\boldsymbol{E}^t_j\,\boldsymbol{E}_j$$

Hydrodynamic Stress Tensor $\boldsymbol{T}^{hyd}_j = -p_j\,\boldsymbol{I} + \cancel{\eta_j\left(\nabla\,\boldsymbol{u}_j + {}^t\nabla\,\boldsymbol{u}_j\right)}$

Stationary interface deformation, the EM view (II)

Normal surface stress jump $\quad \left[T_2^{hyd} - T_1^{hyd}\right].n_{1\to 2} + \left[T_{em,2}^{M} - T_{em,1}^{M}\right].n_{1\to 2} = \sigma\kappa\, n_{1\to 2}$

$$\left(q_1 - q_2\right)\boldsymbol{n} + \left(\rho_2 - \rho_1\right)gz\,\boldsymbol{n} - \frac{1}{2}\varepsilon_0\left(E_2^{\,2}\rho_2\frac{\partial\varepsilon_2}{\partial\rho_2} - E_1^{\,2}\rho_1\frac{\partial\varepsilon_1}{\partial\rho_1}\right)\boldsymbol{n} + \left[\boldsymbol{T}_{em,2}^{M} - \boldsymbol{T}_{em,1}^{M}\right].\boldsymbol{n} = \sigma\kappa\,\boldsymbol{n}$$

$$\left(q_1 - q_2\right)\boldsymbol{n} + \left(\rho_2 - \rho_1\right)gz\,\boldsymbol{n} - \frac{1}{2}\varepsilon_0\left(\varepsilon_2 E_2^{\,2} - \varepsilon_1 E_1^{\,2}\right)\boldsymbol{n} + \varepsilon_0\left(\varepsilon_2\,\boldsymbol{E}_2^t\boldsymbol{E}_2\,\boldsymbol{n} - \varepsilon_1\,\boldsymbol{E}_1^t\boldsymbol{E}_1\,\boldsymbol{n}\right) = \sigma\kappa\,\boldsymbol{n}$$

$\longrightarrow$ Interface and bulk electrostrictive contributions cancel

Since $\quad \nabla q_j = 0 \quad \longrightarrow \quad q_j = Cte \qquad \left(q_j = p_j + \rho_i gz - \frac{1}{2}\varepsilon_0\,\boldsymbol{E}_j^{\,2}\,\rho_j\frac{\partial\varepsilon_j}{\partial\rho_j}\right)$

Flat interface $\quad \left.\begin{array}{l} q_j\left(r=\infty, z=0\right) = p_j\left(r=\infty, z=0\right) \\ and\ p_2\left(r=\infty, z=0\right) = p_1\left(r=\infty, z=0\right)\end{array}\right\} \longrightarrow \quad q_2 - q_1 = 0$

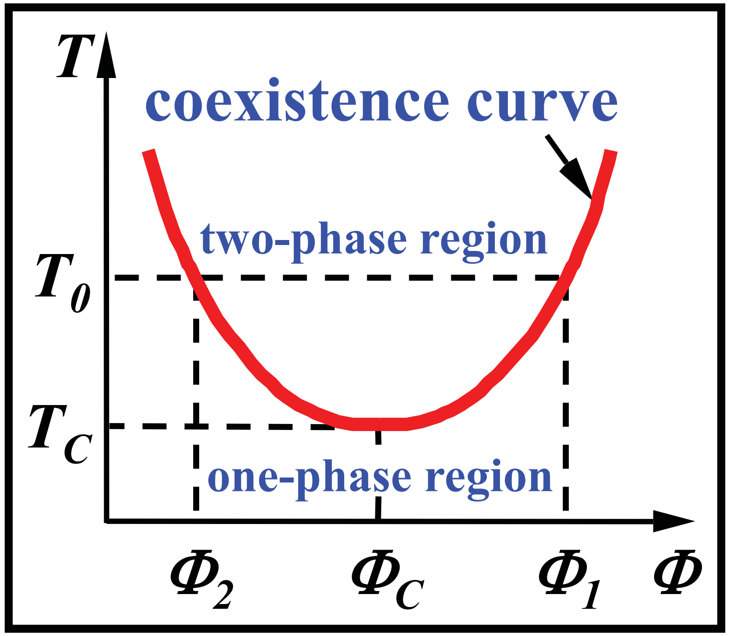
$$\left(\rho_2 - \rho_1\right)gz - \frac{1}{2}\varepsilon_0\left(\varepsilon_2 E_2^{\,2} - \varepsilon_1 E_1^{\,2}\right) + \varepsilon_0\left(\varepsilon_2\,\boldsymbol{E}_2^t\boldsymbol{E}_2\,\boldsymbol{n} - \varepsilon_1\,\boldsymbol{E}_1^t\boldsymbol{E}_1\,\boldsymbol{n}\right).\boldsymbol{n} = \sigma\kappa$$

buoyancy **radiation pressure** **Laplace Pressure**

$$\longrightarrow \quad \left(\rho_2 - \rho_1\right)gz - \frac{1}{2}\varepsilon_0\left(\varepsilon_1 - \varepsilon_2\right)\left[E_t^{\,2} + \frac{\varepsilon_1}{\varepsilon_2}E_{n,1}^{\,2}\right] = \sigma\kappa \qquad \left(\begin{array}{l} D_{n,1} = D_{n,2} \\ E_{t,1} = E_{t,2}\end{array}\right)$$

Near-critical liquid interface

Trapping Force ~ pN → surface force ~ 10 Pa !



Correlation Length of density fluctuations $\xi^+ = \xi_0^+ \left(\frac{T - T_C}{T_C}\right)^{-\nu}$

Interfacial Tension $\sigma = \sigma_0 \left(\frac{T - T_C}{T_C}\right)^{2\nu}$

Density contrast $\Delta\rho = (\rho_1 - \rho_2) = (\Delta\rho)_0 \left(\frac{T - T_C}{T_C}\right)^{\beta}$

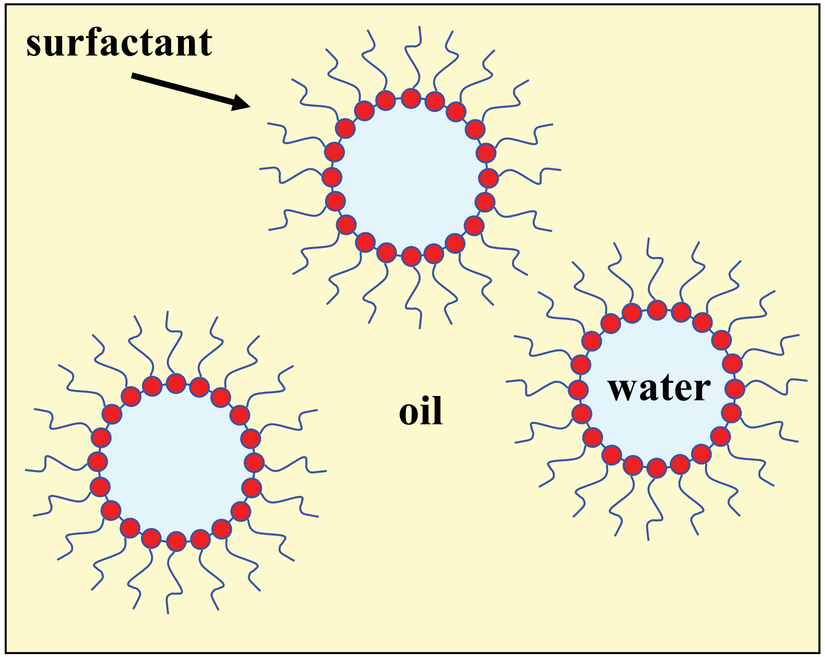
Refractive Index contrast $\Delta n = (n_1 - n_2) = (\Delta n)_0 \left(\frac{T - T_C}{T_C}\right)^{\beta}$

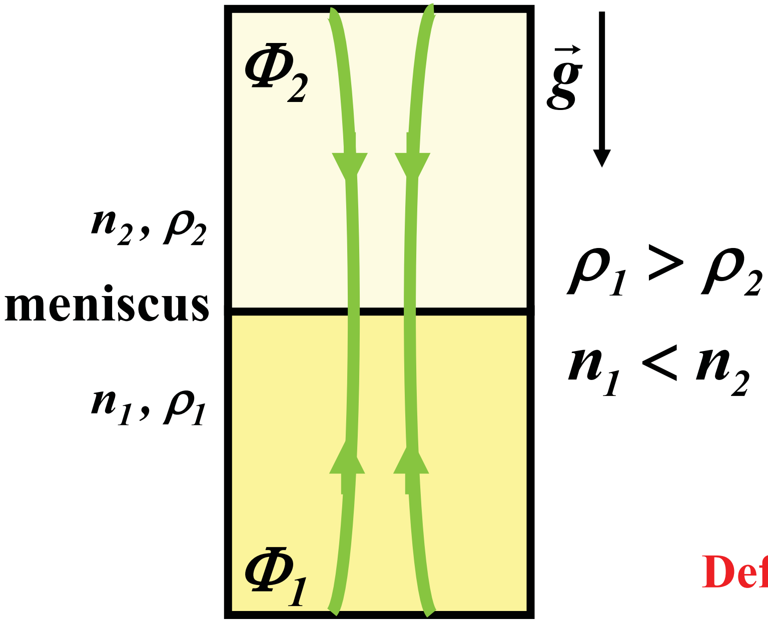
Ising Class (d=3, n=1): β=0.325, ν=0.63

Universal Ratio $R^+ = \left(\frac{\sigma_0 \xi_0^+}{k_B T_C}\right) = 0.39$

$\sigma_0 \xi_0^+ = Cte$ → Use of Surpramolecular systems

Near-critical micellar phases of microemulsion





Composition

- **SDS: 4% in weight**
- **Butanol: 17 %**
- **Toluene: 70 %**
- **water: 9%**

$$r_{micelle} \sim \xi_0^+ = 40\ \text{Å}$$

$$T_C \simeq 32\ °C$$

$\in$ Ising Class (d=3, n=1)

Typical values at $T\text{-}T_C \approx 1$ K :

$$\sigma \approx 10^{-7} N/m \quad \left(\sigma_{water/air} = 72\times 10^{-3}\ N/m\right)$$

$$\Delta\rho \approx 50 kg.m^{-3} \qquad \Delta n \approx 0.006$$

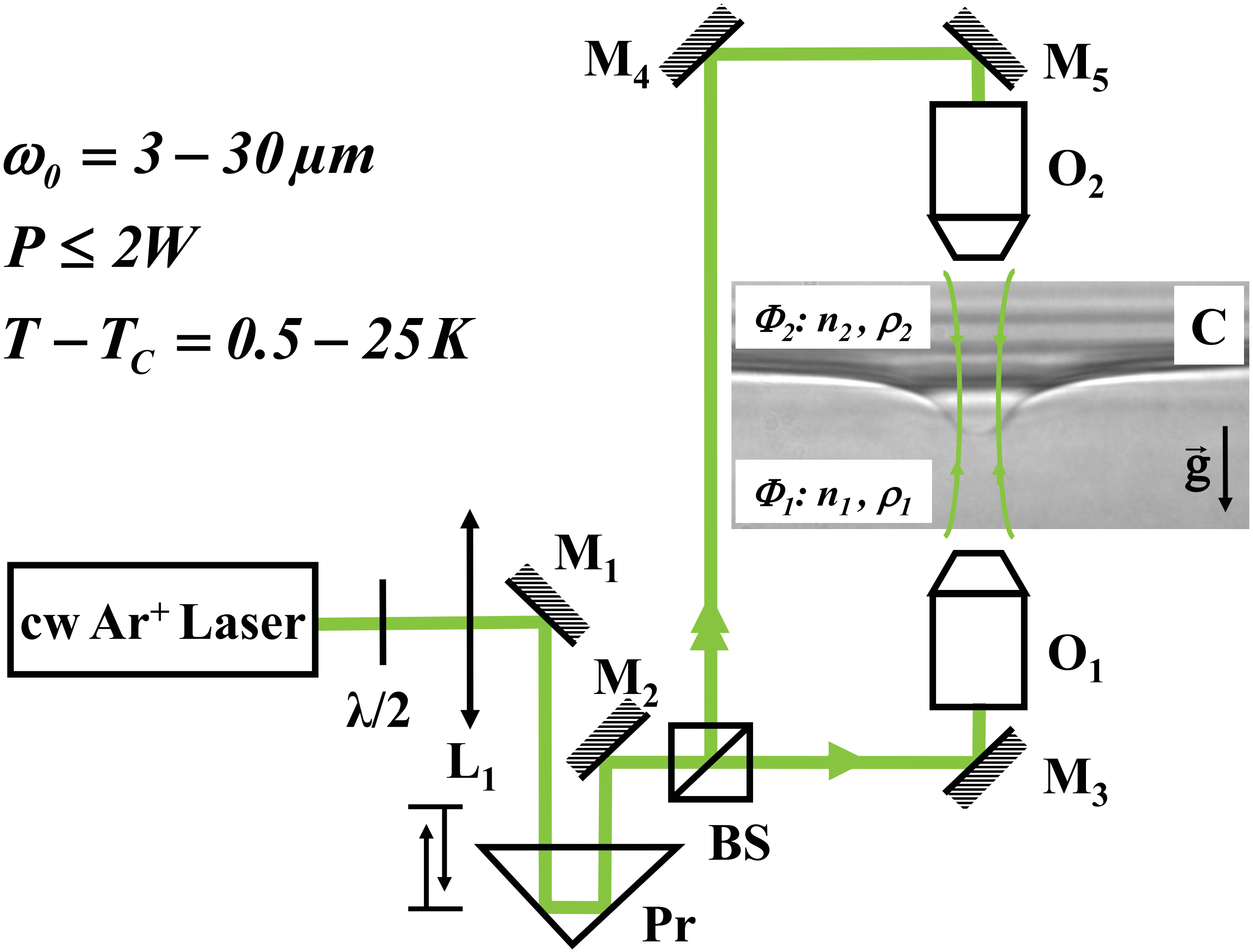
Deformations: nm $\longrightarrow$ 10-100 µm

Experimental set-up

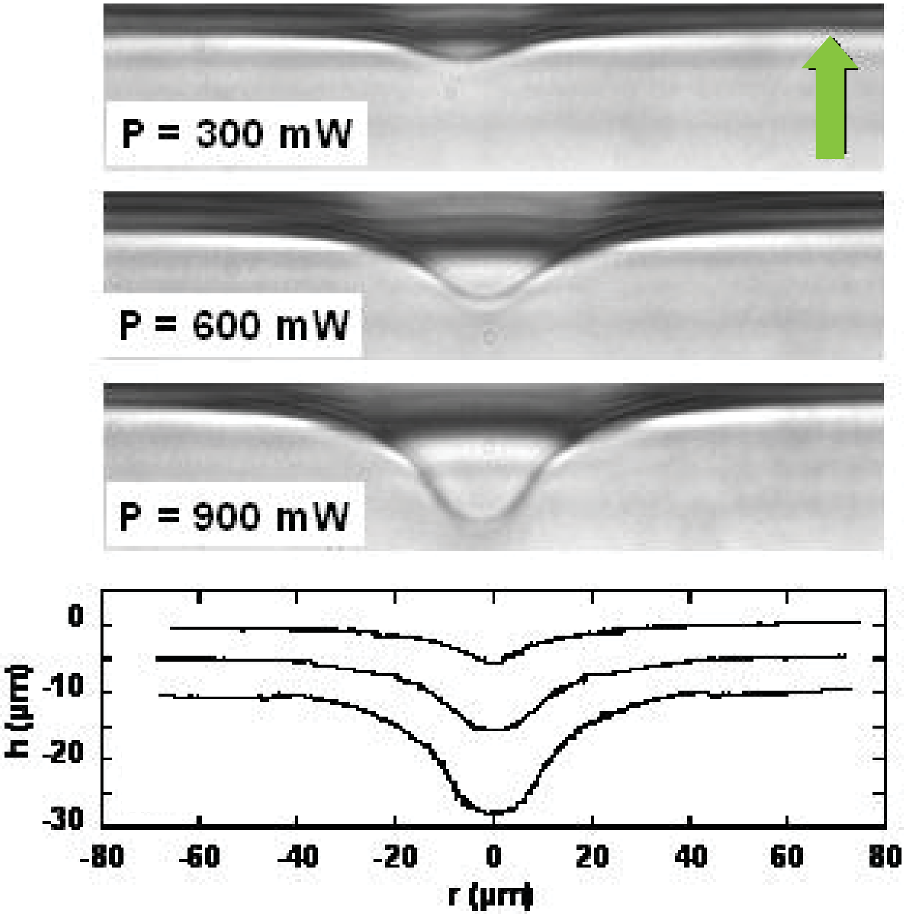
$\omega_0 = 3 - 30\,\mu m$

$P \leq 2W$

$T - T_C = 0.5 - 25\,K$

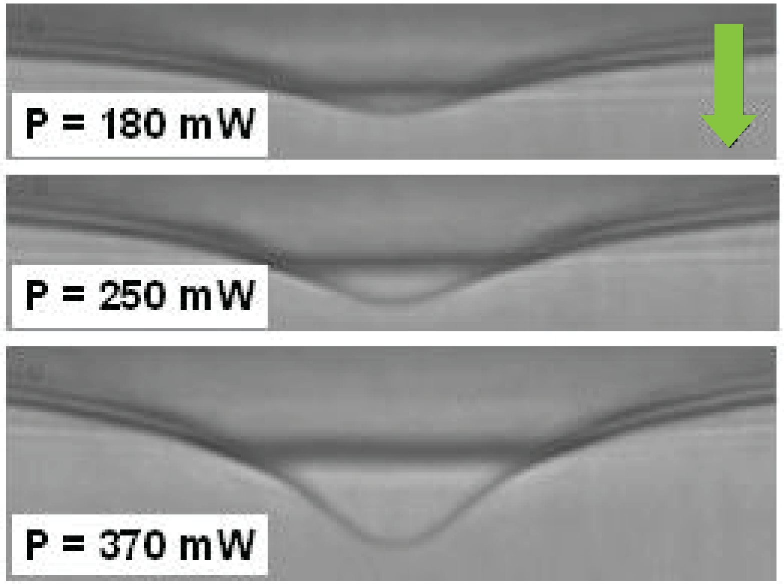


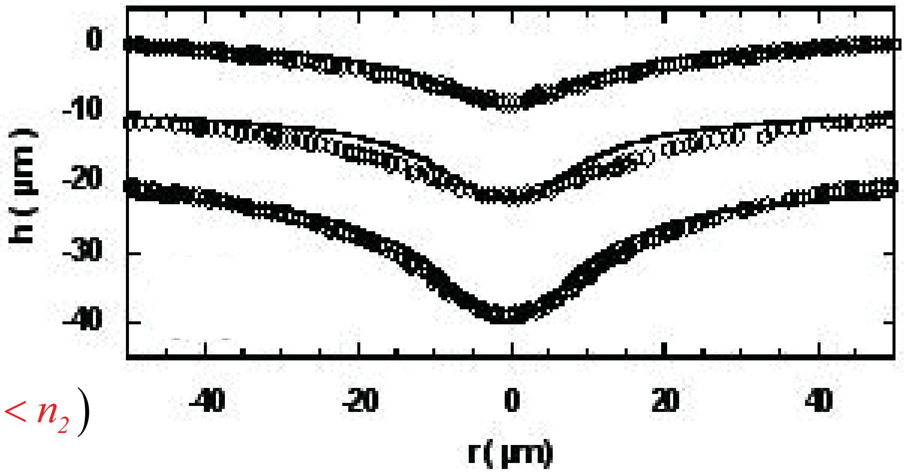
Up/down symmetry in linear deformations



n_2

n_1





$(n_1 < n_2)$

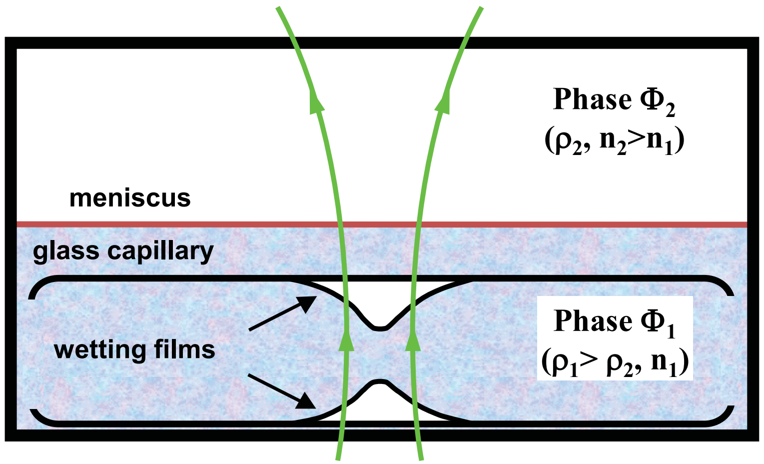
ω_0 = 7.5 µm, T-T_C=8K

$\longrightarrow$ Interface Pulling

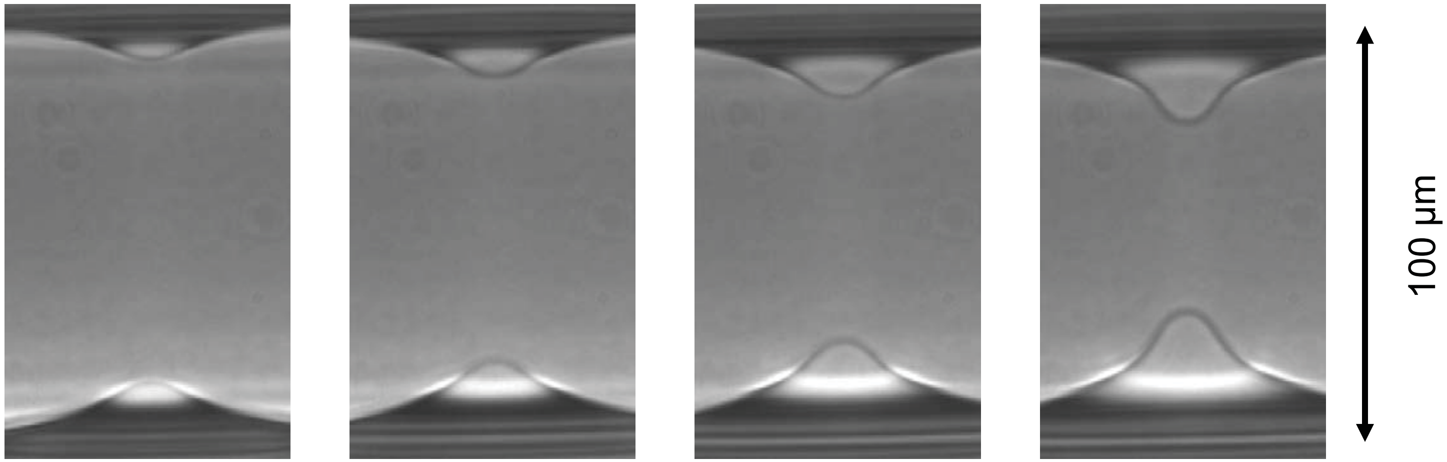
ω_0 = 7.5 µm, T-T_C=3K

$\longrightarrow$ Interface Pushing

Up/down symmetry in linear deformations (II)



$T-T_C = 15$ K
$\omega_0 = 5.3$ µm



P: 900 1100 1400 1600 mW

Height of Linear Deformations (|h'(r)|<<1)

Balance equation at normal incidence in stationary conditions:

$$\Delta\rho g h(r) - \sigma\kappa(r) = \frac{2n_1}{c}\left(\frac{n_1 - n_2}{n_1 + n_2}\right)\frac{2P}{\pi\omega_0{}^2}\exp\left(-\frac{2r^2}{\omega_0{}^2}\right)$$

buoyancy **Laplace Pressure** **radiation pressure**

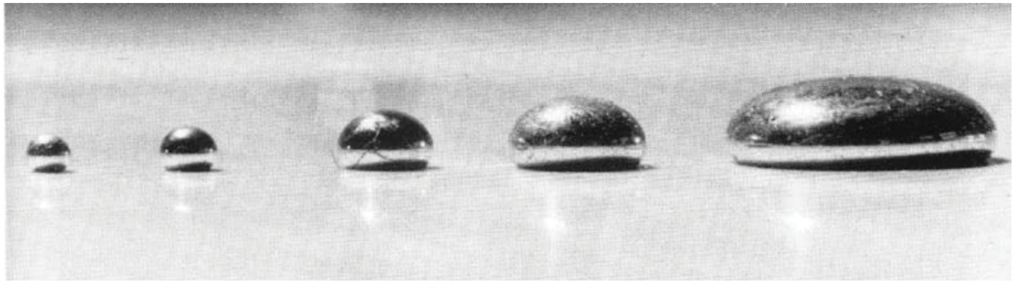
Curvature: $|\partial h/\partial r| << 1 \longrightarrow \kappa = \frac{1}{r}\frac{d}{dr}\left(\frac{r\,h'(r)}{\sqrt{1+h'(r)^2}}\right) \simeq \Delta_\perp h(r)$

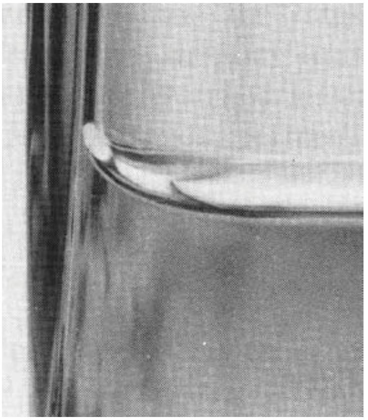
Hankel transform (cylindrical symmetry): $h(r) = \int_0^\infty \tilde{h}(k) J_0(kr) k dk$

General expression of the interface deformation:

$$h(r) = \frac{2n_1}{c}\left(\frac{n_1 - n_2}{n_1 + n_2}\right)\frac{P}{2\pi}\int_0^\infty \frac{e^{-\frac{k^2 w_0^2}{8}}}{\Delta\rho g + \sigma k^2} J_0(kr) k dk$$

Optical Bond Number





$$Bo = \frac{buoyancy}{Laplace} = \frac{\Delta\rho g R}{\sigma / R} = \left(\frac{R}{l_c}\right)^2$$

$Bo = 1 \longrightarrow$ **Definition of the capillary length** $l_c = \sqrt{\frac{\sigma}{\Delta\rho g}}$

Definition of an optical Bond number Bo as

If $|\partial h/\partial r| << 1 \longrightarrow \boldsymbol{\kappa(r) \approx \Delta_\perp h(r) \propto h/\omega_0{}^2}$

$$\frac{buoyancy}{Laplace} = \frac{\Delta\rho g h}{\sigma h/\omega_0{}^2} = \left(\frac{\omega_0}{l_c}\right)^2 = Bo = \left(\frac{\mathit{Excitation\ length}\ \mathrm{scale}}{\mathrm{Screening}\ \mathit{length}\ \mathrm{scale}}\right)^2$$

$\longrightarrow$ **Laser deformation ~ virtual particle of size ω_0**

"Non-local" deformations

Bo <<1: gravity neglected

$$\cancel{\Delta\rho g h(r)} - \sigma\kappa(r) = \frac{2n_1}{c}\left(\frac{n_1-n_2}{n_1+n_2}\right)\frac{2P}{\pi\omega_0^{\ 2}}\exp\left(-\frac{2r^2}{\omega_0^{\ 2}}\right)$$

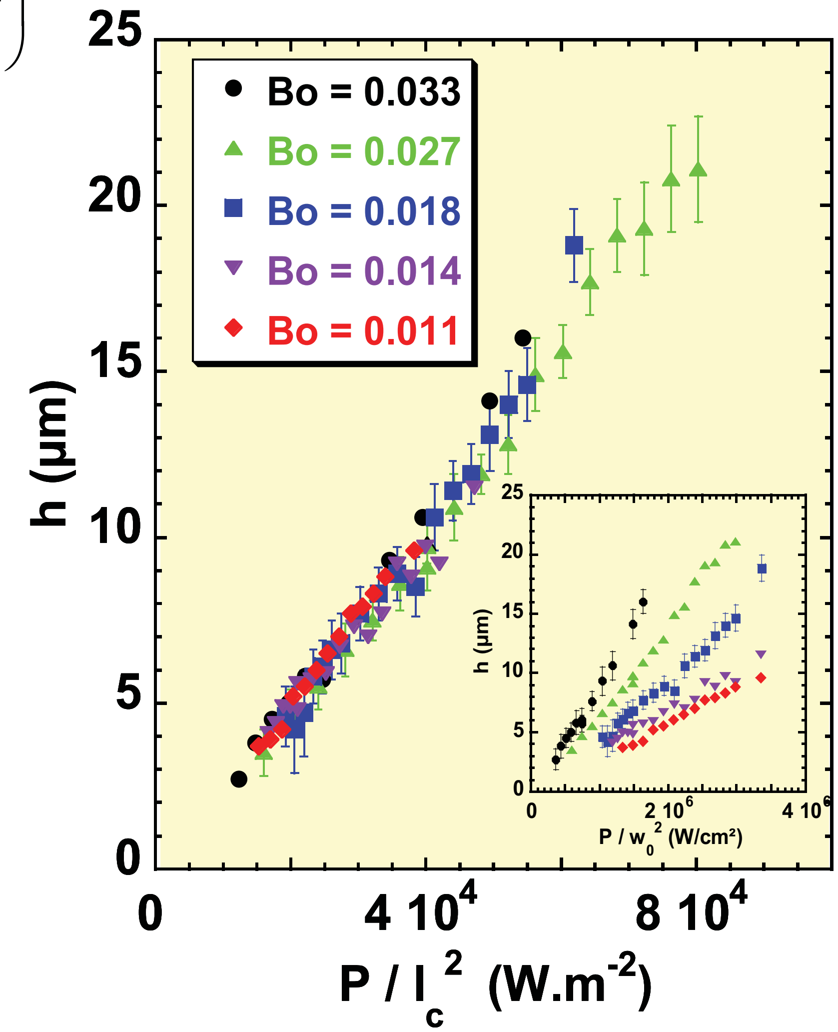
$$\Delta_\perp h \propto I(r) \quad \longrightarrow \quad h(k) \propto I(k)/k^2$$

$$h(r{=}0) = \frac{1}{4\pi c g}\left(\frac{n_1-n_2}{\Delta\rho}\right)\frac{P}{l_C^2}\,ln\left(\gamma\,\frac{\omega_{cl}^2}{\omega_0^2}\right)$$

with $\qquad \omega_{cl} = \frac{2\sqrt{2}}{\gamma}\,l_C$

$$\longrightarrow \; h(r{=}0,\,Bo \ll 1) \propto \frac{P}{l_C^2} \qquad \textbf{Non-local}$$

$\omega_0 = 7.5\ \mu m$
$T\text{-}T_C = 8$ to 25 K



"Local" deformations

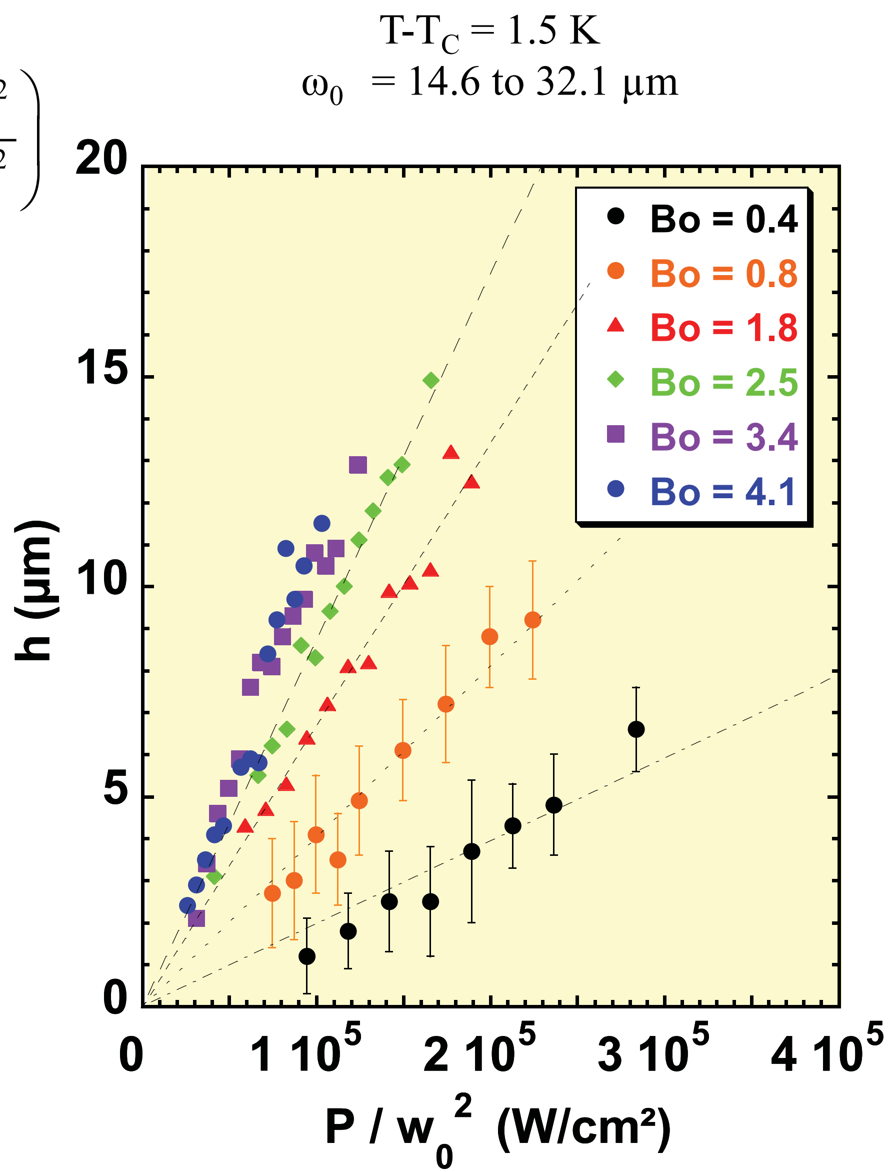
Bo >>1: surface tension neglected

$$\Delta\rho g h(r) - \cancel{\sigma\kappa(r)} = \frac{2n_1}{c}\left(\frac{n_1-n_2}{n_1+n_2}\right)\frac{2P}{\pi\omega_0^2}\exp\left(-\frac{2r^2}{\omega_0^2}\right)$$

$$h \propto I(r) \quad \longrightarrow \quad h(k) \propto I(k)$$

$$h(r) = \frac{2\,n_1}{c}\left(\frac{n_1-n_2}{n_1+n_2}\right)\frac{I(r)}{\Delta\rho g}$$

$$\longrightarrow \; h(r=0, Bo \gg 1) \propto \frac{P}{\omega_0^2}$$ **Local**

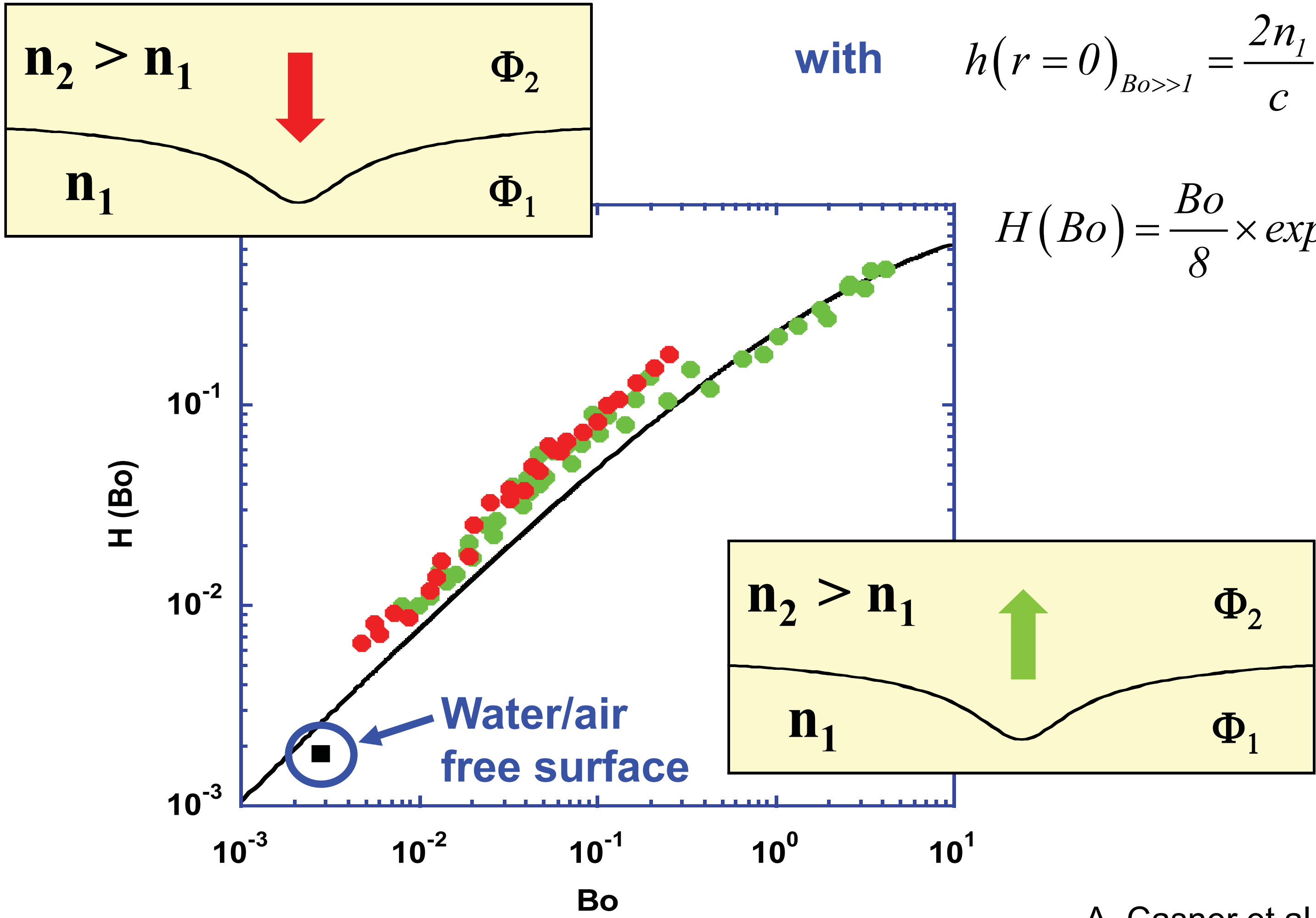


Universal scaling relation

$$h(r=0) = \frac{2n_1}{c}\left(\frac{n_1-n_2}{n_1+n_2}\right)\frac{1}{\Delta\rho g}\frac{P}{2\pi}\int_0^\infty \frac{e^{-\frac{k^2 w_0^2}{8}}}{1+\left(l_c k\right)^2}kdk = h\left(r=0\right)_{Bo>>1}\times H\left(Bo\right)$$

with $$h\left(r=0\right)_{Bo>>1} = \frac{2n_1}{c}\left(\frac{n_1-n_2}{n_1+n_2}\right)\frac{I\left(r=0\right)}{\Delta\rho g}$$

$$H\left(Bo\right) = \frac{Bo}{8}\times exp\left(\frac{Bo}{8}\right)\times E_1\left(\frac{Bo}{8}\right)$$



A. Casner et al, PRL. 87, 054503 (2001)

Linear dynamics

Normal surface stress jump

$$\left[\boldsymbol{T}_2^{hyd} - \boldsymbol{T}_1^{hyd}\right].\boldsymbol{n}_{1\to 2} + \left[\boldsymbol{T}_{em,2}^{M} - \boldsymbol{T}_{em,1}^{M}\right].\boldsymbol{n}_{1\to 2} = \sigma\kappa\,\boldsymbol{n}_{1\to 2}$$

but now with

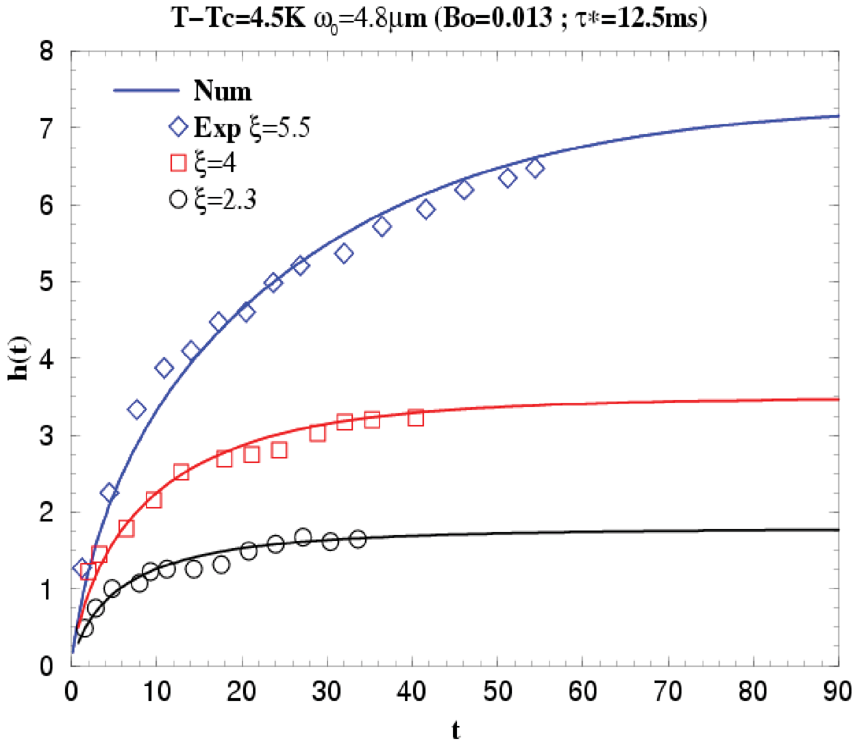
$$\boldsymbol{T}_j^{hyd} = -p_j\,\boldsymbol{I} + \eta_j\left(\nabla\,\boldsymbol{u}_j + \nabla^t\,\boldsymbol{u}_j\right)$$

Scalings for: $\left|\partial h/\partial r\right| << 1$

$$Viscous\ stress \sim RP:\ \eta\frac{u}{\omega_0} \sim \Pi \longrightarrow u \sim \frac{\Pi\omega_0}{\eta} \qquad \tau \sim h/u$$

$$Bo \ll 1 \qquad h \sim \Pi\omega_0^{\,2}/\sigma \qquad \tau \sim \eta\omega_0/\sigma$$

$$Bo \gg 1 \qquad h \sim \Pi/(\Delta\rho g) \qquad \tau \sim \eta/(\Delta\rho g\omega_0)$$



Linear model leads:

$$\tau\left(\omega_0^{-1}\right) \simeq \frac{4\langle\eta\rangle\omega_0}{\sigma}(1+Bo)^{-1}$$

$$\begin{cases} Bo \ll 1 \to \tau \sim \eta\omega_0/\sigma \\ Bo \gg 1 \to \tau \sim \eta/(\Delta\rho g\omega_0) \end{cases}$$

$$\left(Bo = \frac{\Delta\rho g\omega_0^{\,2}}{\sigma}\right)$$

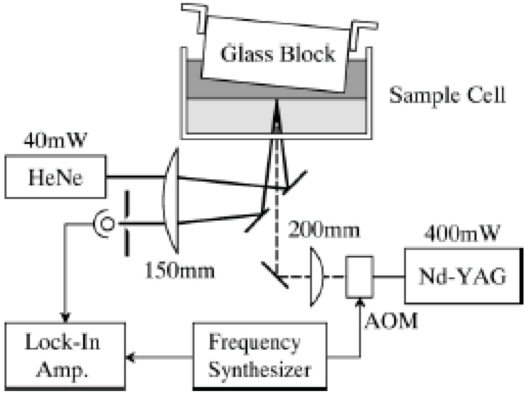
R. Wunenburger et al, PRE. 73, 036315 (2006)

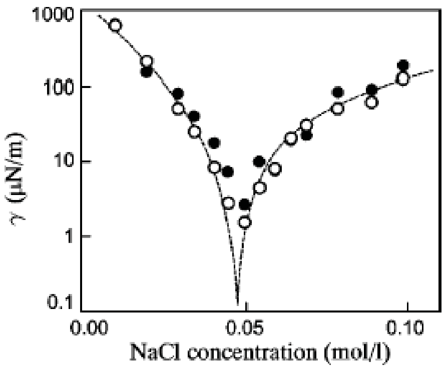
Contactless measurement of surface tension and shear viscosity

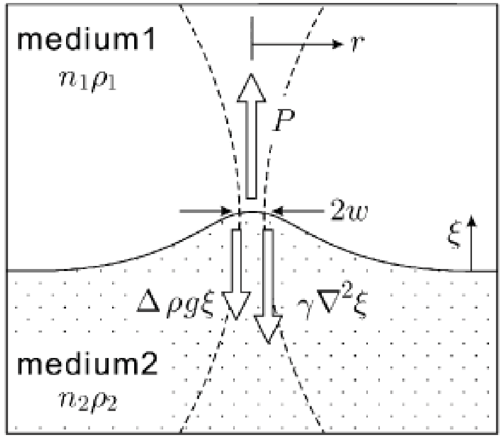
PHYSICAL REVIEW E **66**, 031604 (2002)

Measurement of ultralow interfacial tension with a laser interface manipulation technique

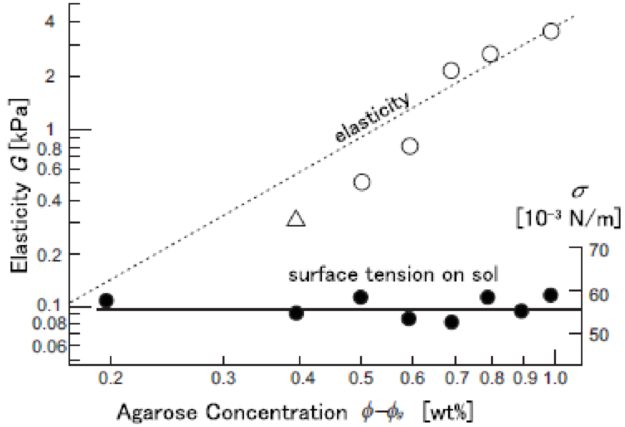
Shujiro Mitani and Keiji Sakai
Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

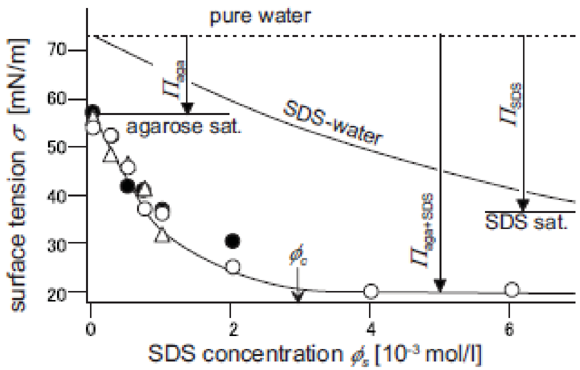






→ Ar⁺ laser: a few tens of nm





PHYSICAL REVIEW E **78**, 041405 (2008)

Surface tension and elasticity of gel studied with laser-induced surface-deformation spectroscopy

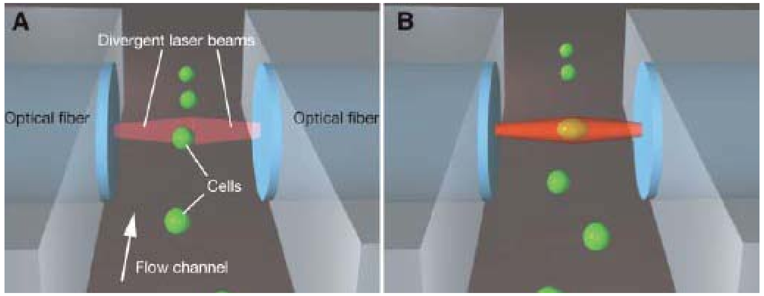
Y. Yoshitake*
Tokyo Denki University, Hatoyama, Hiki-gun, Saitama 350-0394, Japan

Optical Stretcher and developments

Biophysical Journal Volume 88 May 2005 3689–3698 3689

Optical Deformability as an Inherent Cell Marker for Testing Malignant Transformation and Metastatic Competence

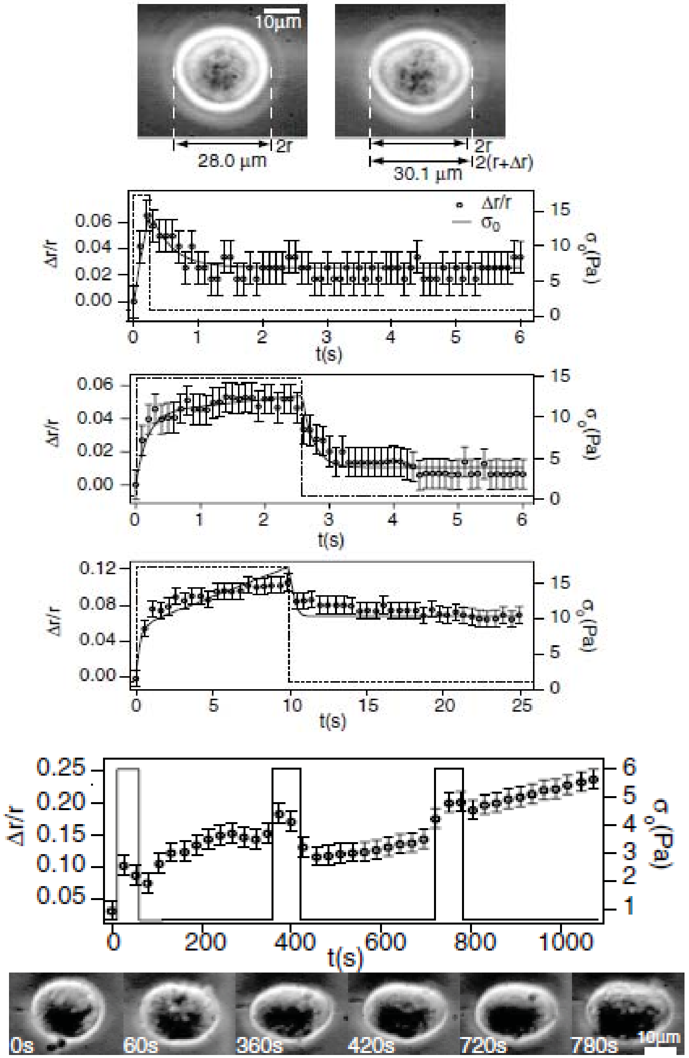
Jochen Guck,*† Stefan Schinkinger,*† Bryan Lincoln,*† Falk Wottawah,*† Susanne Ebert,* Maren Romeyke,* Dominik Lenz,‡ Harold M. Erickson,§¶ Revathi Ananthakrishnan,*† Daniel Mitchell,¶ Josef Käs,*† Sydney Ulvick,¶ and Curt Bilby¶



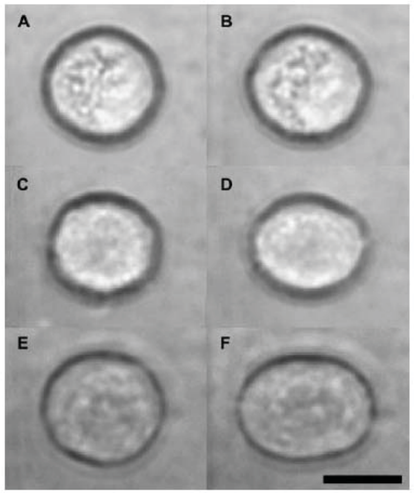
PRL 94, 098103 (2005) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2005

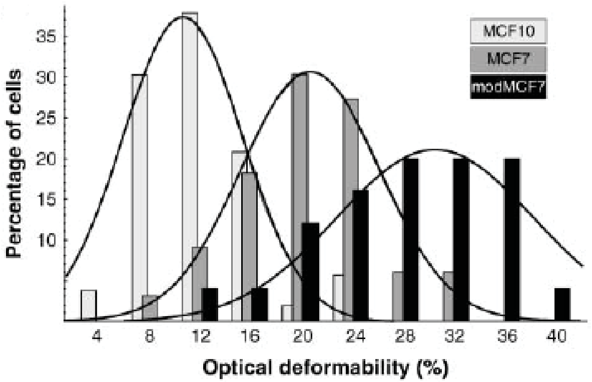
Optical Rheology of Biological Cells

Falk Wottawah,[1,2] Stefan Schinkinger,[1,2] Bryan Lincoln,[1,2] Revathi Ananthakrishnan,[1,2] Maren Romeyke,[1] Jochen Guck,[1] and Josef Käs[1]



600 mW



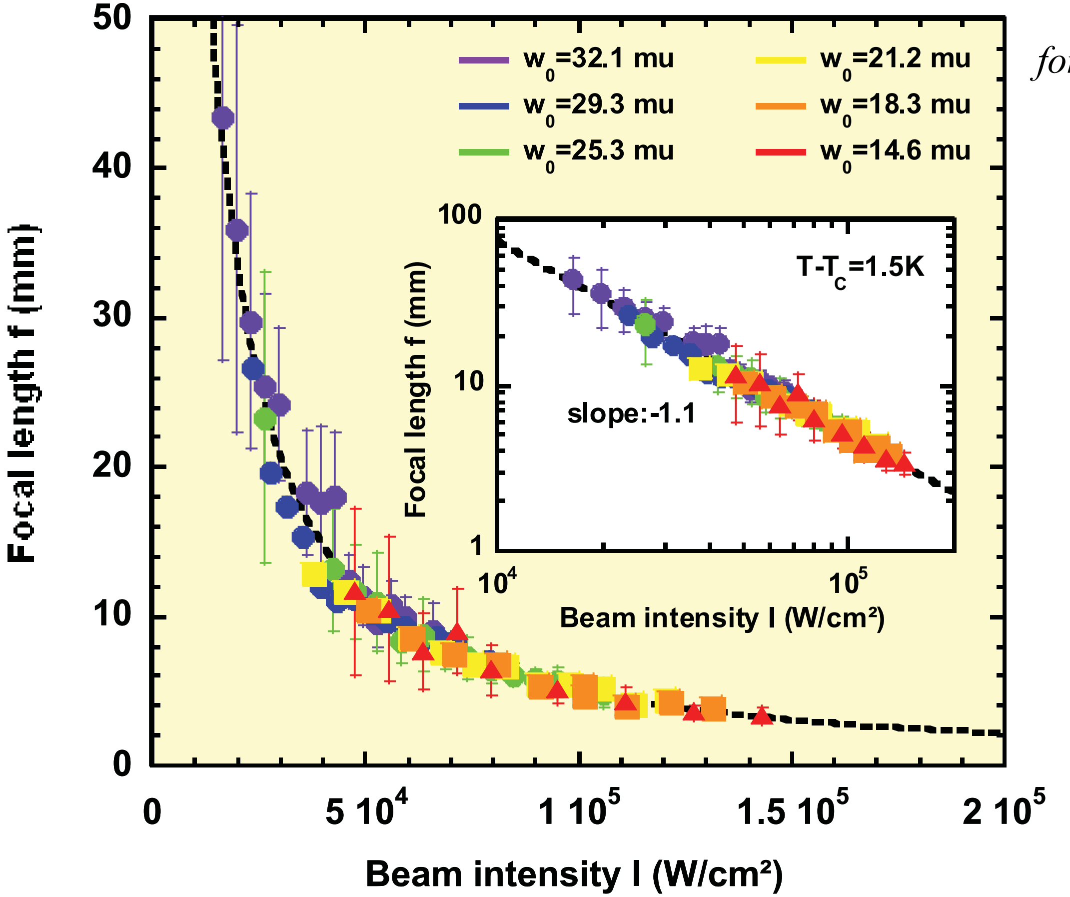


Optical deformability of normal, cancerous, and metastatic breast epithelial cells

Optical application: adaptive lensing

Focus distance: $$\frac{1}{f}=\frac{n_2-n_1}{2n_2}\left(\Delta_{\perp}h\right)_{r=0}$$

$$\longrightarrow \quad \frac{1}{f}=\frac{\left(n_2-n_1\right)}{2n_2}\frac{h\left(r=0\right)}{l_C{}^2}\propto I\left(r=0\right)\left(\frac{T}{T_C}-1\right)^{-2(\nu-\beta)}$$



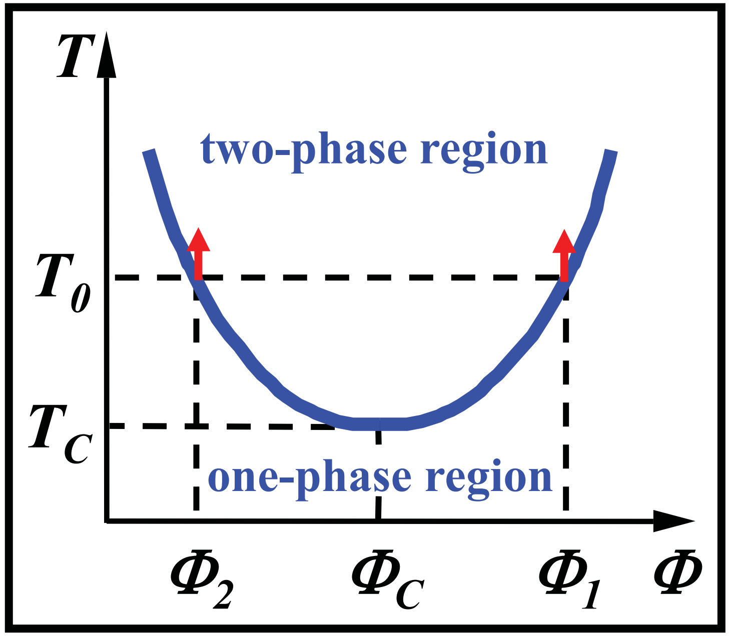
$for\ \ Bo/8 \ll 1$

A. Casner et al, Optics Lett. 26 (1418) 2001

Pure thermal effects ?

Laser overheating: $\alpha_a = 3\times 10^{-4}\,cm^{-1}$ $\quad \Lambda_T = 1.28\times 10^{-3}\,W.cm^{-1}.K^{-1}$

$$\Delta_r T_E(r) + \frac{\alpha_a}{\Lambda_T} I(r) = 0 \longrightarrow T_E(r) = \frac{\alpha_a P}{4\pi\Lambda_T}\left[E_1\left(\frac{\omega_{bc}^2}{\omega_0^2}\right) - E_1\left(\frac{2r^2}{\omega_0^2}\right) - ln\left(\frac{2r^2}{\omega_{bc}^2}\right)\right]$$



$$T_E(r=0) = \frac{\alpha_a P}{4\pi\Lambda_T} ln\left(\Gamma\frac{\omega_{bc}^2}{\omega_0^2}\right)$$

$$T_E(r=0) \approx 0.1\times P_W \ (K)$$

Negligible except for:

$$T - T_C \leq 1K$$

and/or

$$P \geq 2W$$

Thermal Nonlinearity

$$n \approx n^L + \left(\frac{\partial n}{\partial T}\right) T_E(r) \quad \textbf{with} \quad \left(\frac{\partial n}{\partial T}\right) = -5\times 10^{-4}\,K^{-1}$$

Negligible

Optical nonlinearities of micellar phases ?

Electrostrictive variation of the micelle concentration

$$\Phi_E(r) = \frac{\chi_T \Phi_0^{\,2}}{\sqrt{\varepsilon^L}c}\left(\frac{\partial \varepsilon^L}{\partial \Phi}\right) I(r) \qquad \textbf{with} \qquad \chi_T = \frac{v_m}{\Phi_0 k_B T}\left(\frac{T - T_C}{T_C}\right)^{-\gamma}$$

$$\varepsilon \approx \varepsilon^L + \left(\frac{\partial \varepsilon^L}{\partial \Phi}\right)\Phi_E(r) \equiv \varepsilon^L + \varepsilon^{NL} I(r)$$

$$\longrightarrow \quad n = \sqrt{\varepsilon} = n^L + \frac{\varepsilon^{NL}}{2n^L} I(r) \qquad \textbf{with} \qquad n^{NL} = \frac{v_m \Phi_0}{2k_B T \varepsilon^L c}\left(\frac{\partial \varepsilon^L}{\partial \Phi}\right)^2 \left(\frac{T - T_C}{T_C}\right)^{-\gamma}$$

S. Buil et al, Phys. Rev. E 63, 041504 (2001)

$$h(r << \omega)_{Bo<<1} \approx -\frac{P}{4\pi\sigma c}(n_2 - n_1)^L \left[1 + \frac{2P}{\pi\omega_0^{\,2}} \frac{(n_2 - n_1)^{NL}}{(n_2 - n_1)^L} exp\left(-2\frac{r^2}{\omega_0^{\,2}}\right)\right]\left[ln\left(\frac{8}{\Gamma Bo}\right) - 2\frac{r^2}{\omega_0^{\,2}}\right]$$

$$\frac{(n_2 - n_1)^{NL}}{(n_2 - n_1)^L} = \frac{v_m}{2k_B T \varepsilon^L c}\left(\frac{\partial \varepsilon^L}{\partial \Phi}\right)^2 \frac{(\Phi_2 - \Phi_1)}{(n_2 - n_1)^L}\left(\frac{T - T_C}{T_C}\right)^{-\gamma} \approx \frac{v_m}{4k_B T \varepsilon^L n^L c}\left(\frac{\partial \varepsilon^L}{\partial \Phi}\right)\left(\frac{T - T_C}{T_C}\right)^{-\gamma} < 0$$

NA: $T - T_C = 8K \qquad P = 1W \qquad \omega_0 = 3.5\mu m \qquad \longrightarrow \qquad \dfrac{2P}{\pi\omega^2}\dfrac{(n_2 - n_1)^{NL}}{(n_2 - n_1)^L} = -8\%$

Droplet disruption by the optical radiation pressure

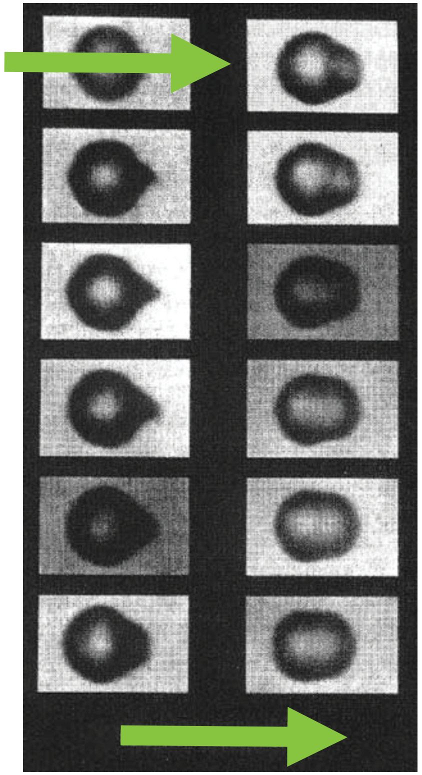
916 OPTICS LETTERS / Vol. 13, No. 10 / October 1988

Shape distortion of a single water droplet by laser-induced electrostriction

Jian-Zhi Zhang and Richard K. Chang

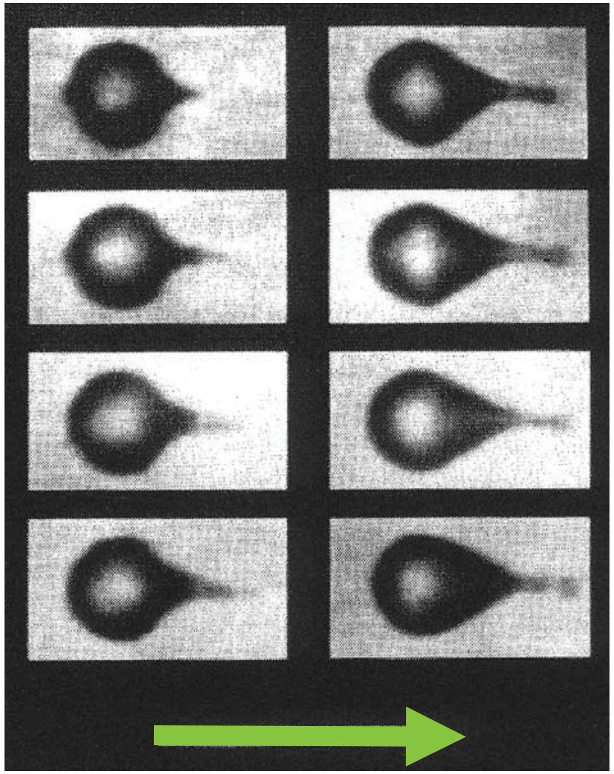
Section of Applied Physics and Center for Laser Diagnostics, Yale University, New Haven, Connecticut 06520

Deformation



100mJ, 400ns; 0-22μs

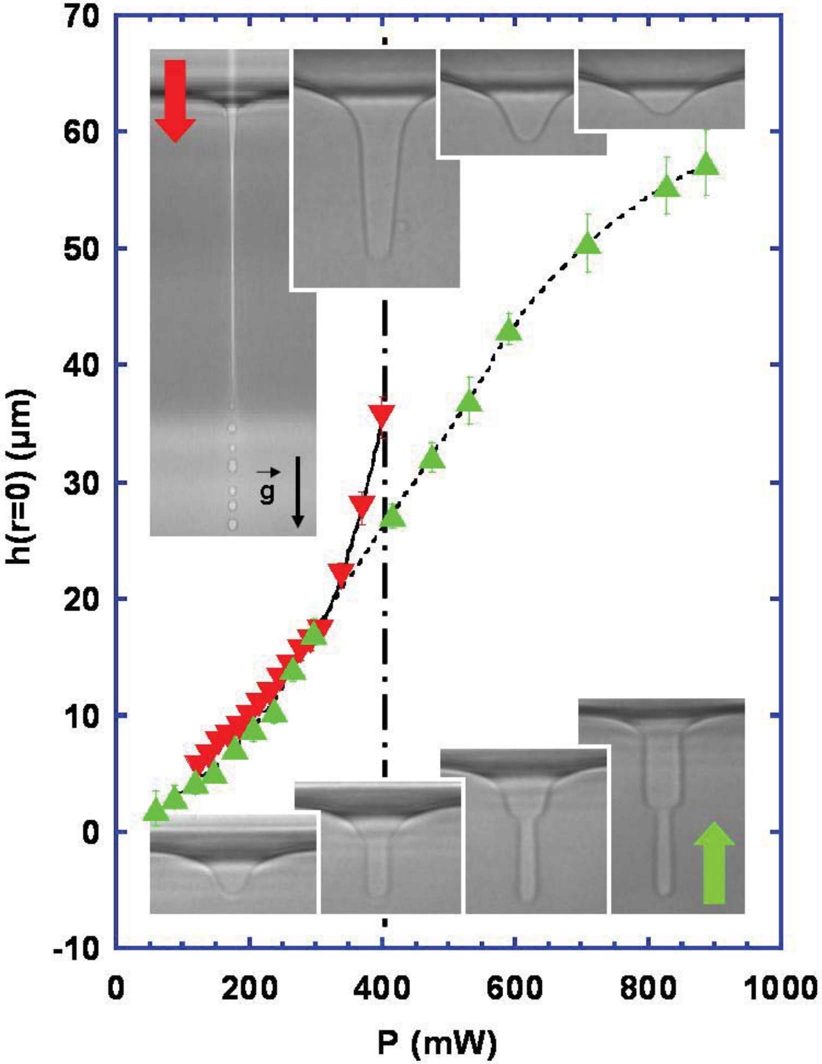
Jetting



200mJ, 400ns; 1-15μs

Up / Down symmetry breaking in shape

P= P↑=400   310   370 mW

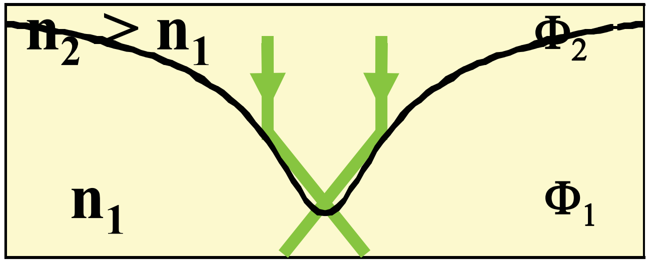


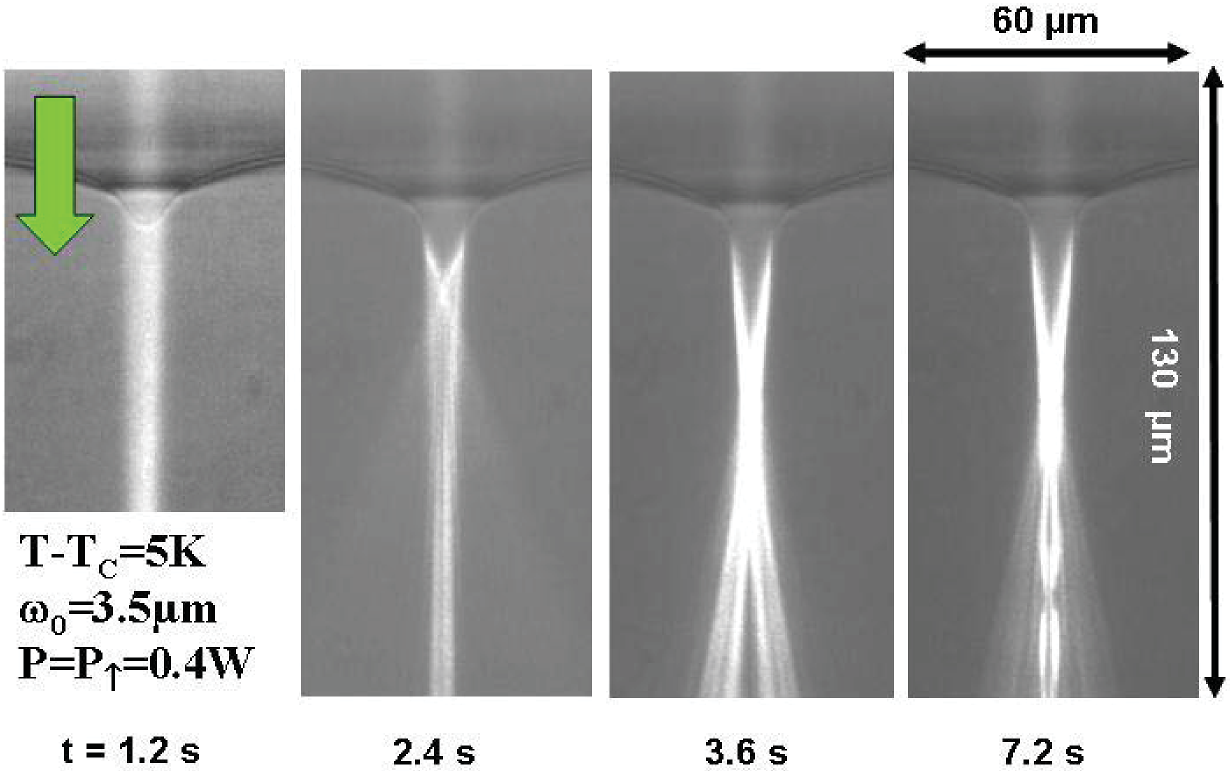
P= 270   410   590   830 mW

$T-T_C$ = 3 K
ω_0 = 5.3 µm

A. Casner et al., PRL90, 144503(2003)

Origin of the jetting





Opto-hydrodynamic instability

When light propagates from Φ_2 to Φ_1 total reflection can be achieved

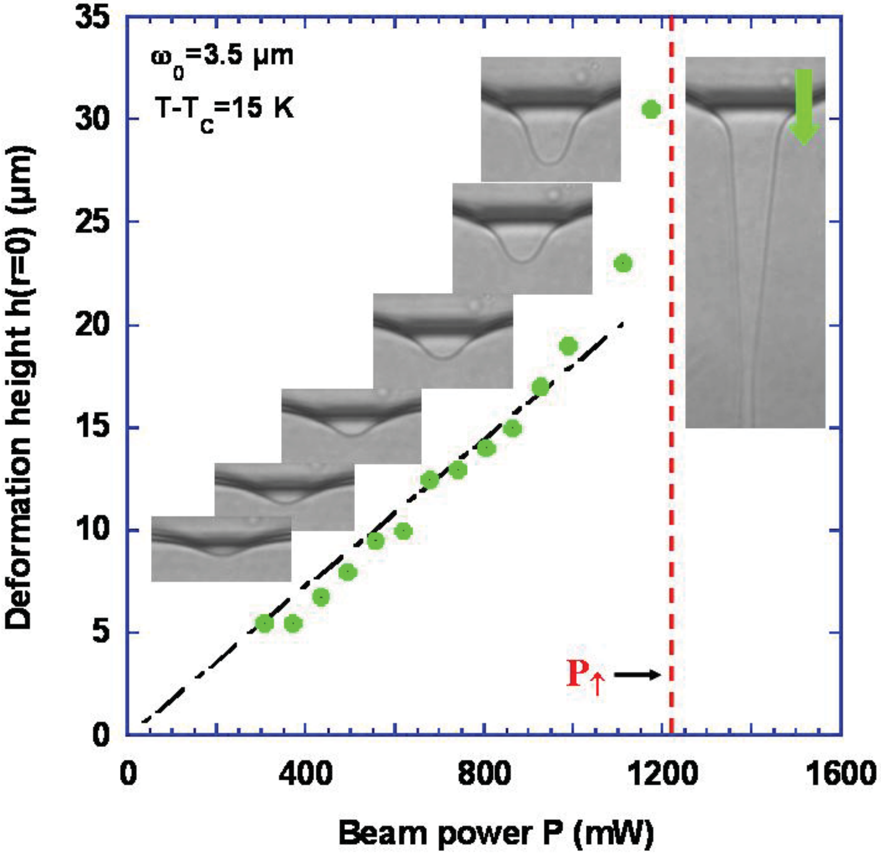
Condition of total reflection:

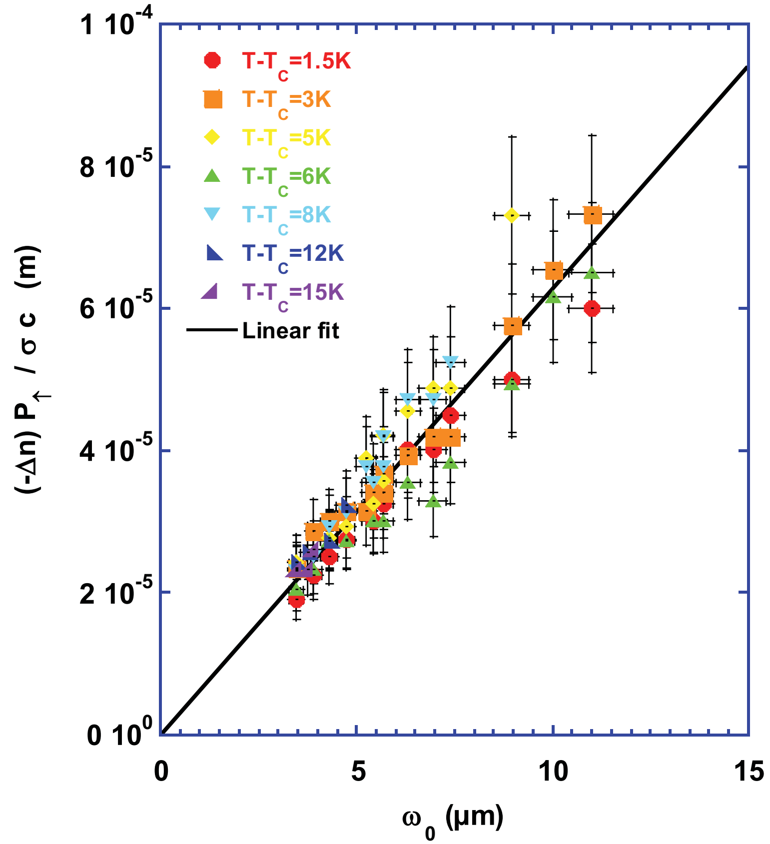
$$\sin\theta_t(r)=\frac{h'(r)}{\sqrt{1+h'(r)^2}}>\frac{n_1}{n_2}\quad \textbf{with}\quad -\frac{\sigma}{r}\frac{\partial}{\partial r}\left(\frac{rh'(r)}{\sqrt{1+h'(r)^2}}\right)=n_1\cos^2\theta_i\left[1+R(\theta_i,\theta_t)-\frac{\tan\theta_i}{\tan\theta_t}T(\theta_i,\theta_t)\right]\frac{I}{c}$$

Scaling:

$$-\frac{\sigma}{r}\frac{\partial}{\partial r}\left(\frac{rh'(r)}{\sqrt{1+h'(r)^2}}\right)\approx\frac{2n_2}{c}\left(\frac{n_1-n_2}{n_1+n_2}\right)\frac{2P}{\pi\omega_0^2}\exp\left(-\frac{2r^2}{\omega_0^2}\right)\longrightarrow\frac{n_2}{c}\left(\frac{n_2-n_1}{n_2+n_1}\right)\frac{P}{\pi\sigma}\frac{1}{r}\left[1-\exp\left(-\frac{2r^2}{\omega_0^2}\right)\right]>\frac{n_1}{n_2}$$

$$P>P_{\uparrow}\sim\frac{\sigma c\omega_0}{\Delta n}$$





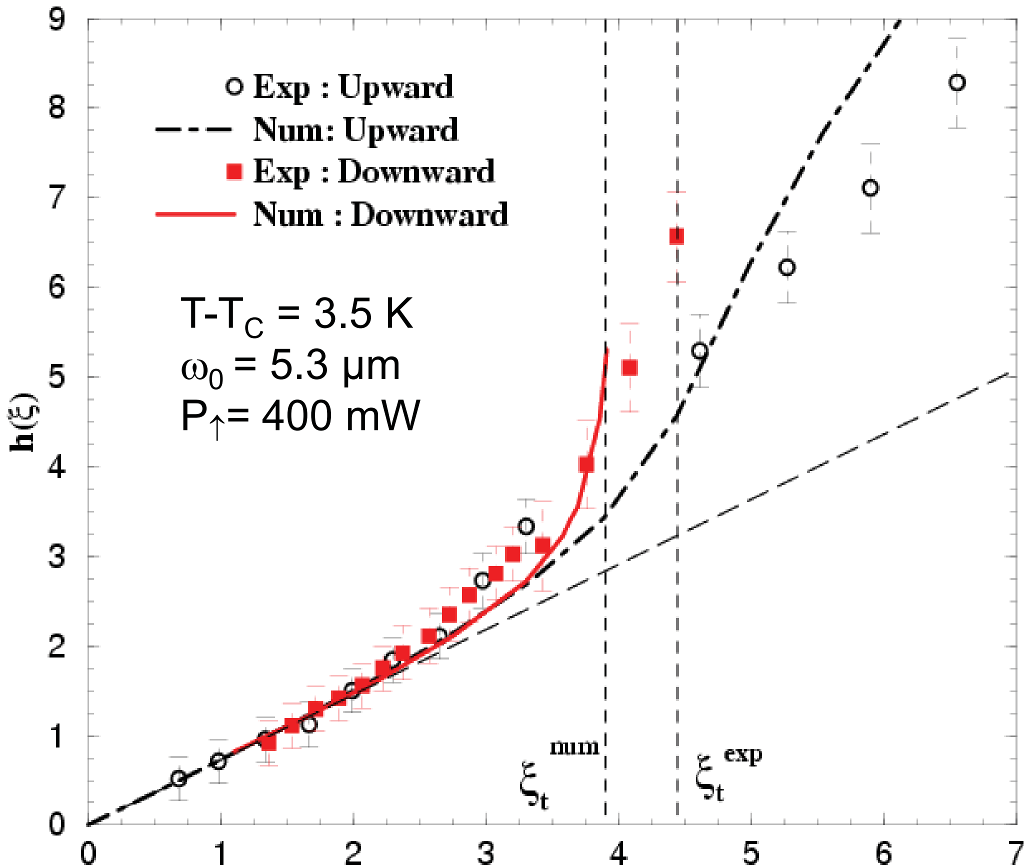
Height of large amplitude deformations

$$\Delta\rho g h(r) - \frac{\sigma}{r}\frac{\partial}{\partial r}\left(\frac{r h'(r)}{\sqrt{1+h'(r)^2}}\right) = n_1 \cos^2\theta_i \left[1 + R(\theta_i,\theta_t) - \frac{\tan\theta_i}{\tan\theta_t} T(\theta_i,\theta_t)\right]\frac{I}{c}$$

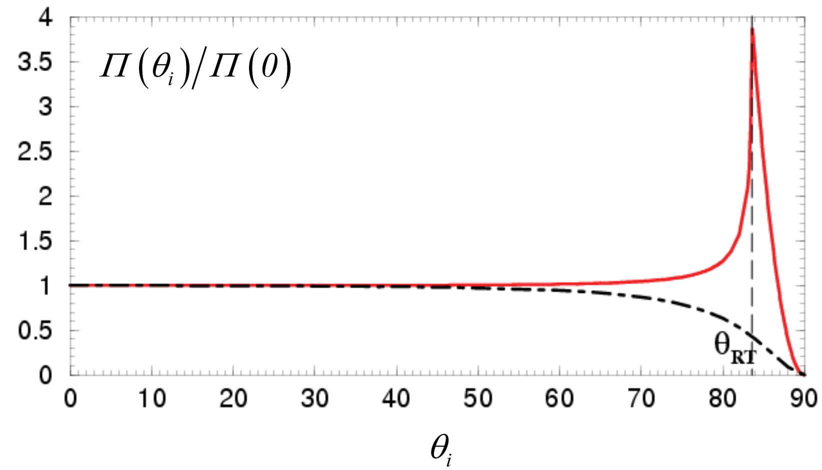
Numerics (direct/BIEM)

$$\cos\theta_i = \frac{1}{\sqrt{1+h'(r)^2}}$$

$$\cos\theta_t = \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \frac{h'(r)^2}{1+h'(r)^2}}$$



$$\xi \equiv \frac{Radiation\ Pressure}{Laplace\ Pressure} = \frac{4P}{\pi c \omega_0 \sigma}\frac{n_i(n_2-n_1)}{(n_2+n_1)}$$

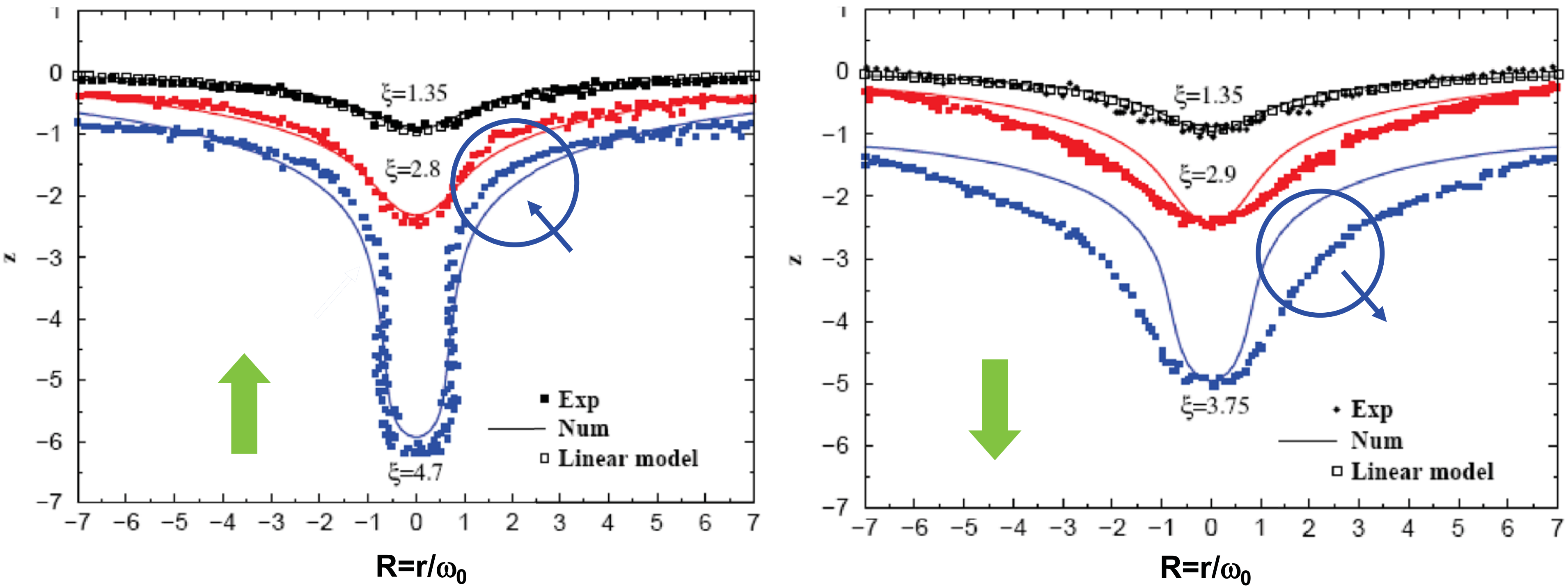


H. Chraibi et al, Eur. J Mech. B/Fluids 27, 419 (2008)

Large deformations close to the critical point

$T\text{-}T_C = 3.5$ K, $\omega_0 = 5.3$ µm

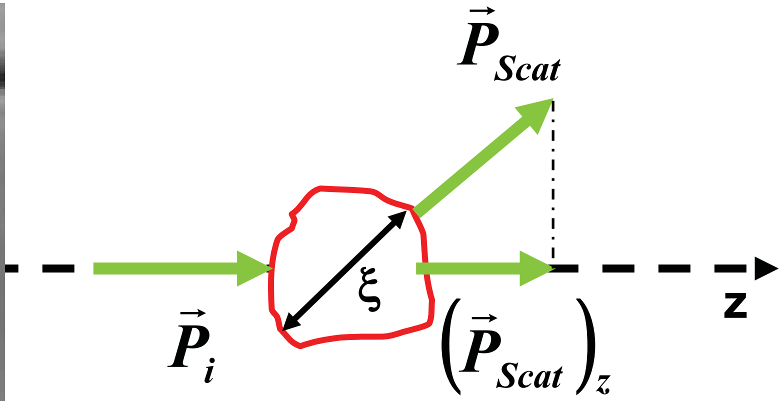
Bo=0.015



→ **Asymmetry in the propagation direction: Flow?**

H. Chraibi et al, Eur. J Mech. B/Fluids 27, 419 (2008)

Liquid flow within the jet: scattering forces on near-critical density fluctuations ?



Scattering Force in the Rayleigh Regime ($\xi << \lambda_0/n$)

$$\vec{F}_v = \frac{nI}{c} \oint_{\Omega} \left(\hat{k}_0 - \hat{k}_{Scat}\right) \sigma\left(\hat{k}_{Scat}\right) d\Omega$$

$$\vec{F}_v = \frac{\pi^3}{\lambda_0^{\ 4}} \frac{nI}{c} \left(\phi \frac{\partial \varepsilon}{\partial \phi}\right)^2 k_B T \chi_T f(\alpha)$$

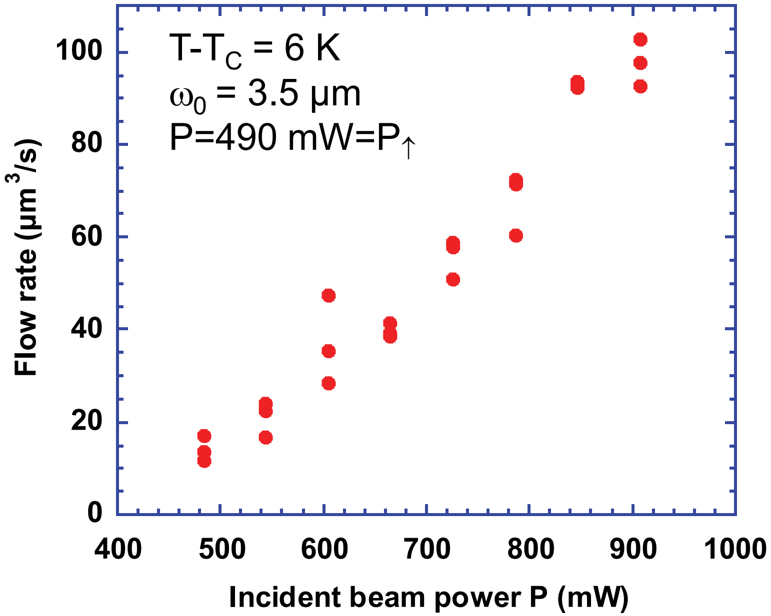
with $\alpha = 2\left(2\pi n \xi / \lambda_0\right)^2$

Osmotic Compressibility $\chi_T = \chi_T^{\ 0} \left(\frac{T - T_C}{T_C}\right)^{-\gamma}$

and $\gamma = 1.24$

Poiseuille Flow: $Q = \frac{\pi}{128\eta} \left|\vec{F}_v\right| d^4$

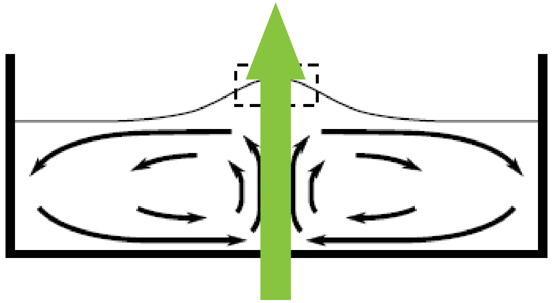
N. A.: $Q \approx 40\text{-}640\ \mu m^3/s$



R. Schroll et al. Phys. Rev. Lett. 98, 133601 (2007)

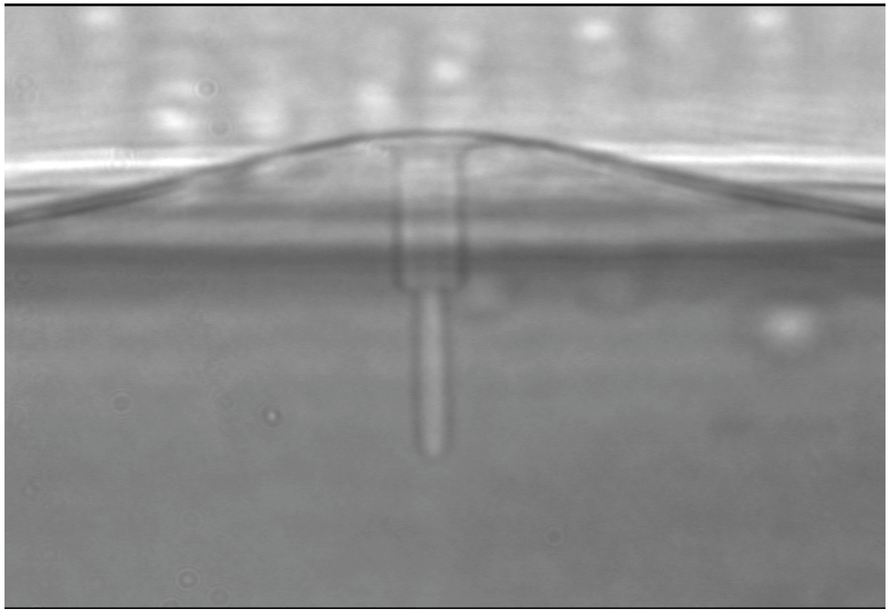
Radiation pressure vs scattering forces

Fluid flow induced interface deformation ?



$\Phi_2, n_2 > n1$

Φ_1, n_1



T-T$_C$=3.5K, ω_0=4.8µm, P=1180mW, /2

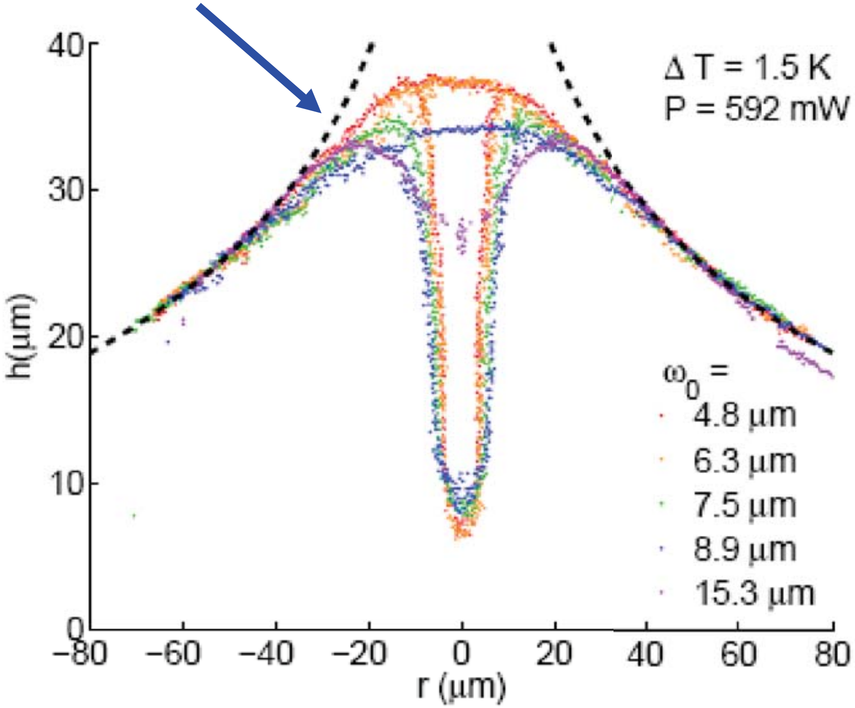
Deformation from scattering forces: 1L Model

Stokes equation: $F_v \propto \mu \nabla^2 u$ **(scaling)**

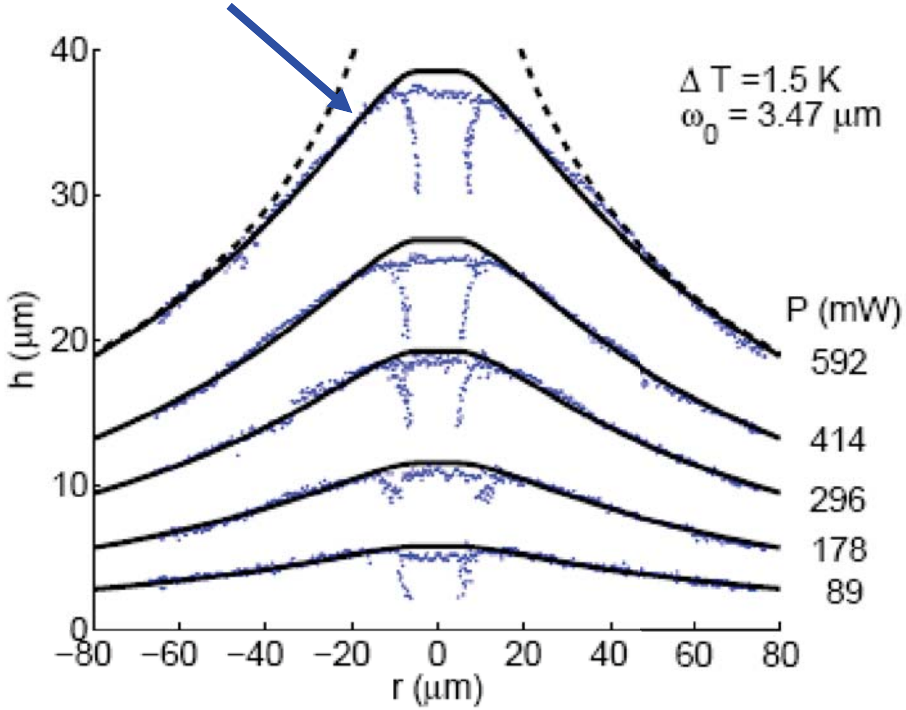
$$\chi_T \left(P/\omega_0^{\ 2}\right) \propto \mu u/\omega_0^{\ 2} \longrightarrow u_0 \propto \chi_T P/\mu$$

No waist dependence at first order ?

Pure buoyancy solution: $-\sigma_{ZZ}/\Delta\rho g$



buoyancy + Laplace pressure

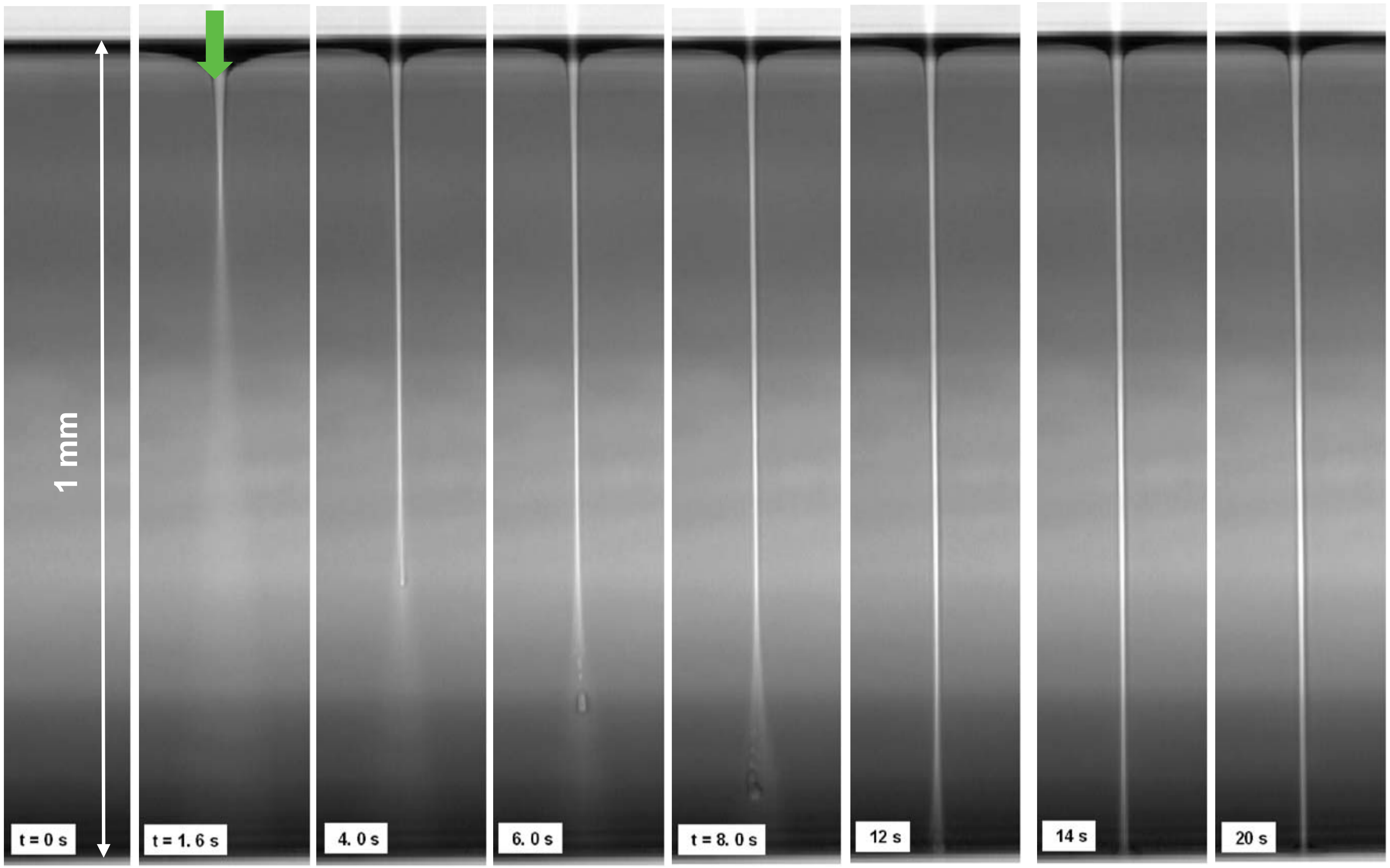


Light induces collective flow in suspension: openings in Optical Nano-Chromatography ?

R. Schroll et al , PRL 98, 133601 (2007)

Laser-sustained liquid column and …

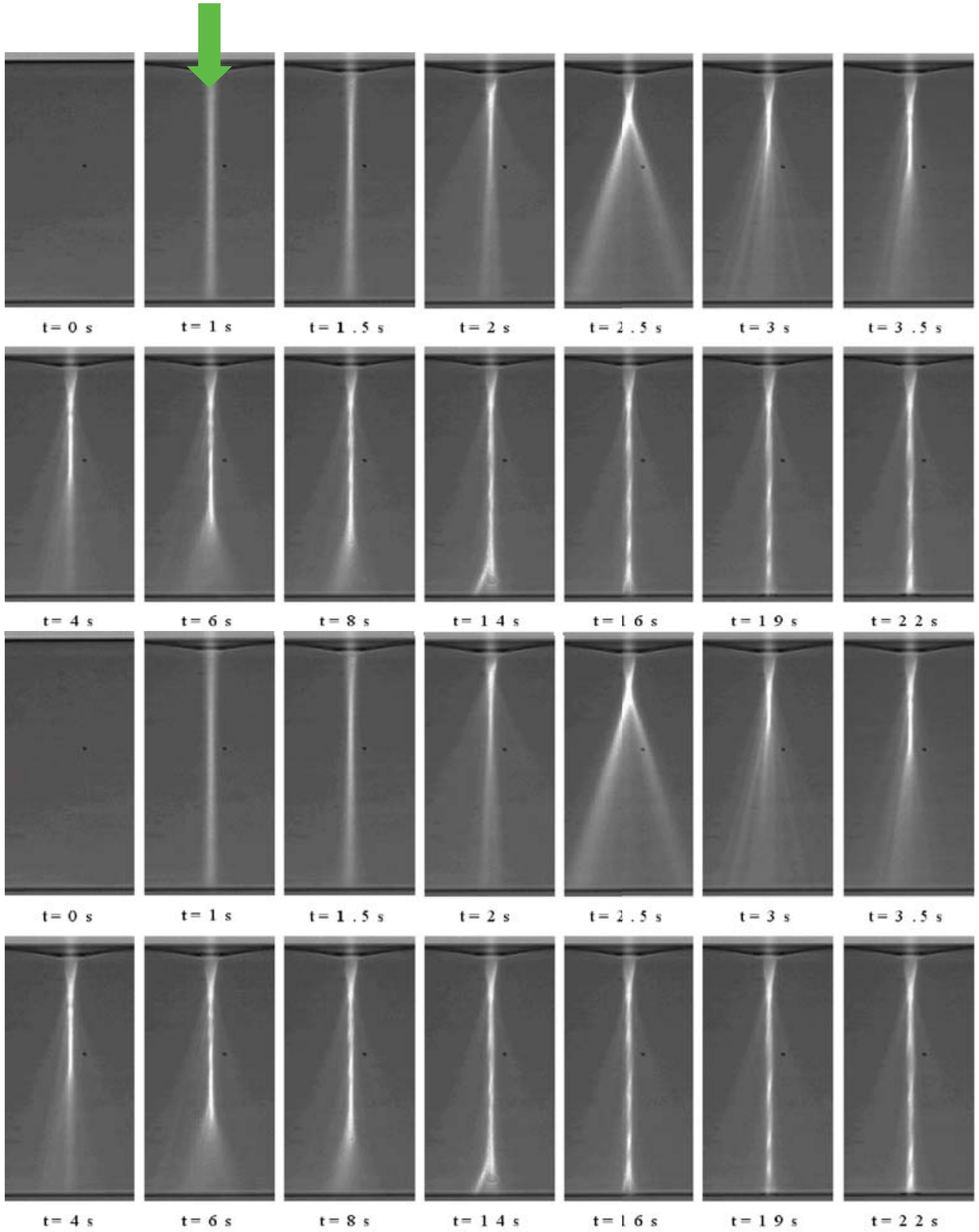
Liquid bridges unstable (μ-g) for aspect ratio: $\Lambda = L/2R \geq \pi$



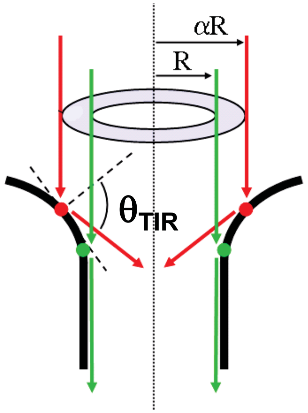
$T - T_C = 4$ K, $\omega_0 = 3.47$ μm, $P = 0.47$ W $> P_\uparrow$

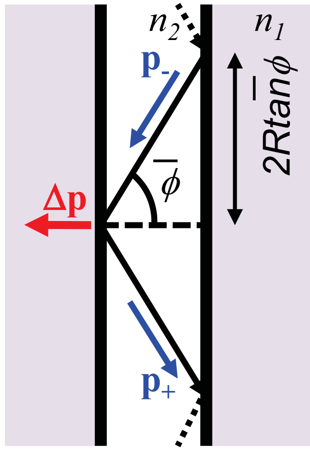
$\Lambda \approx 70$!

…Formation of a stable self-adapted optical fibre



Liquid column stability: a ray optics approach





$$\Delta p = \left\|\mathbf{p}^{+} - \mathbf{p}^{-}\right\| = 2n_2\left(\frac{h\nu}{c}\right)\cos\bar{\phi}$$

$$\bar{\phi} = \frac{1}{2}\left(\theta_{TIR} + \frac{\pi}{2}\right)$$

$$P_A = 2\pi\int_R^{\alpha R} I(r)\,r\,dr = P\exp\left(-\frac{2R^2}{\omega_0^{\,2}}\right)\times\left[1 - \exp\left(-\frac{2(\alpha^2-1)R^2}{\omega_0^{\,2}}\right)\right]$$

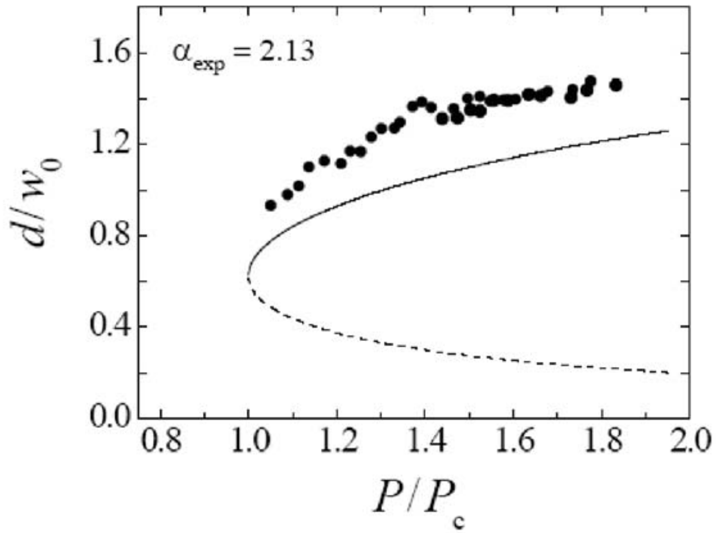
$$\Pi_{Rad} = \frac{P_A/h\nu}{4\pi R^2\tan\bar{\phi}}\Delta p = \frac{n_2}{2c}\frac{\cos\bar{\phi}}{\tan\bar{\phi}}\frac{P_A}{\pi R^2} \approx \frac{n_2-n_1}{4\pi c}\frac{P_A}{R^2}$$

$$\left(\frac{\cos\bar{\phi}}{\tan\bar{\phi}} \underset{n_2\approx n_1}{\approx} \frac{n_2-n_1}{2n_2}\right)$$

$$\Pi_{Rad} = \Pi_{Laplace} = \frac{\sigma}{R}$$

$$\longrightarrow\; P\frac{n_2-n_1}{4cR^2}e^{-\frac{2R^2}{\omega_0^{\,2}}}\left(1-e^{-\frac{2(\alpha^2-1)R^2}{\omega_0^{\,2}}}\right) = \frac{\sigma}{R}$$

E. Brasselet et al, Eur. Phys. J. E 26, 405 (2008)

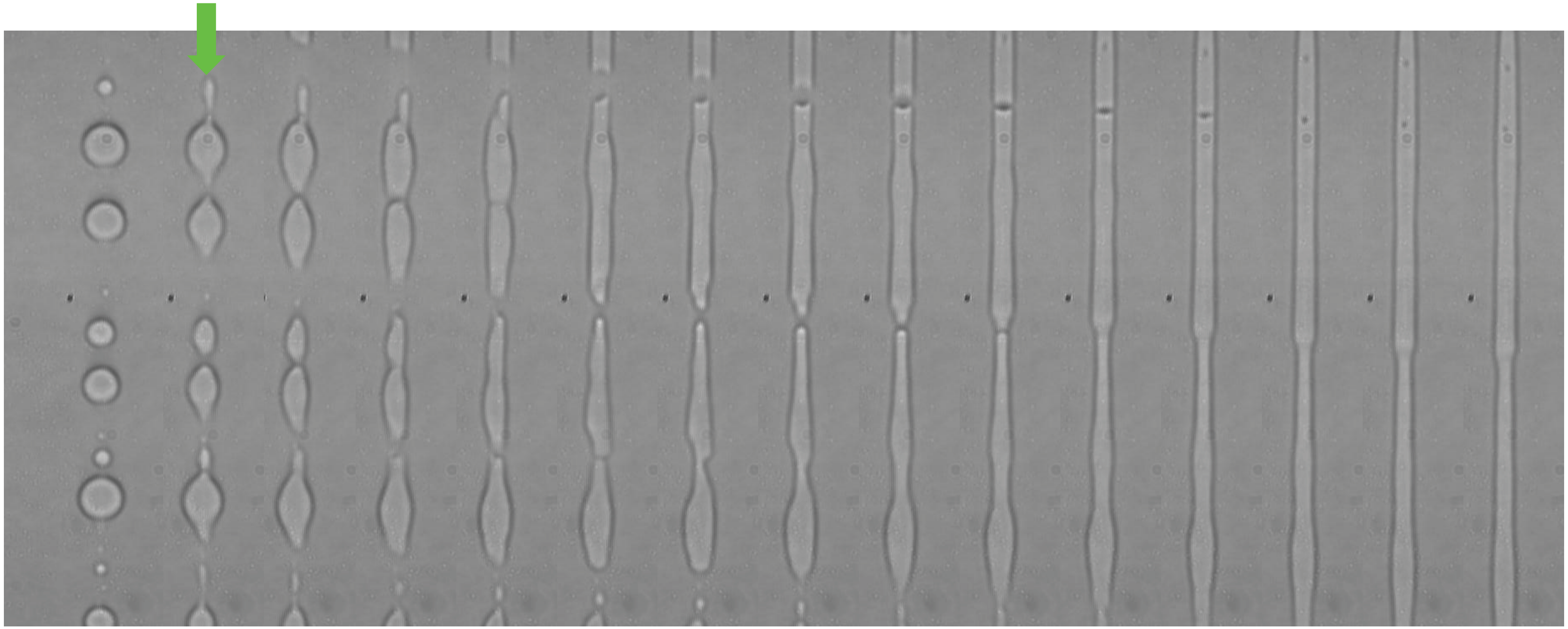


E. Brasselet et al, PRL 101, 014501 (2008)
E. Brasselet et al, PRA 78, 013835 (2008)

Full quantitative electromagnetic model $\longrightarrow$

Rebuilding the liquid jet

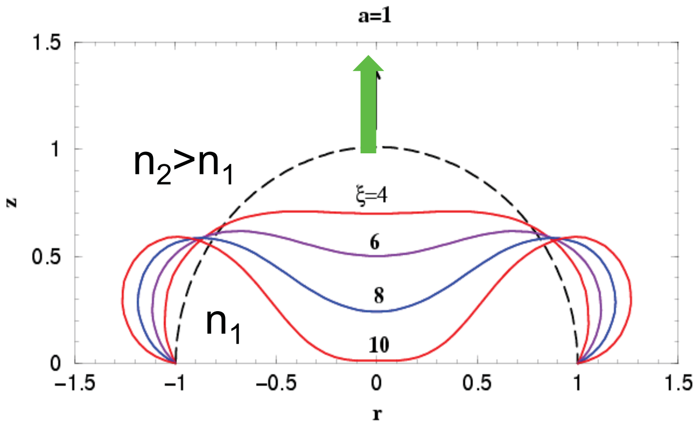
Transition from droplet to annular flow driven by radiation pressure



$T\text{-}T_C = 5$ K, $\omega_0 = 3.5$ µm, $P=630$ mW$>P_{\uparrow}$

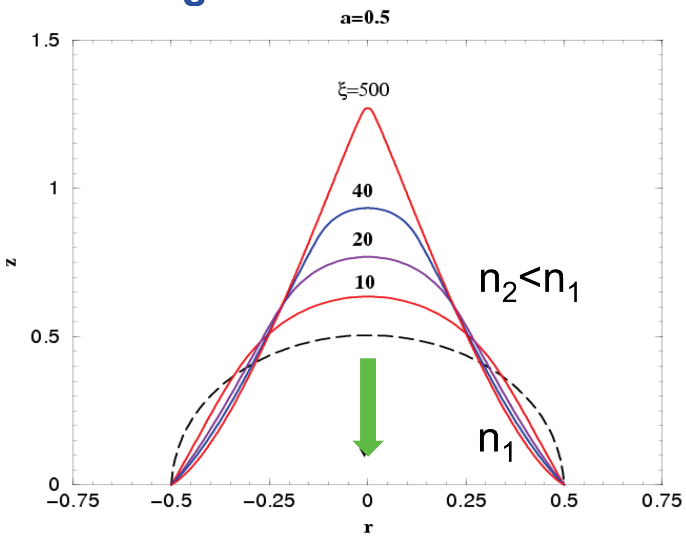
Finite size effects on deformations

Squeezing

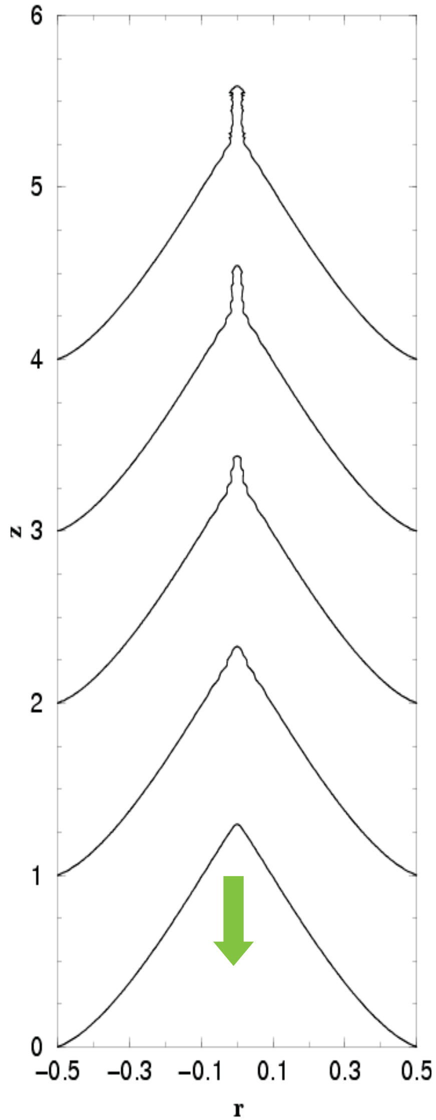


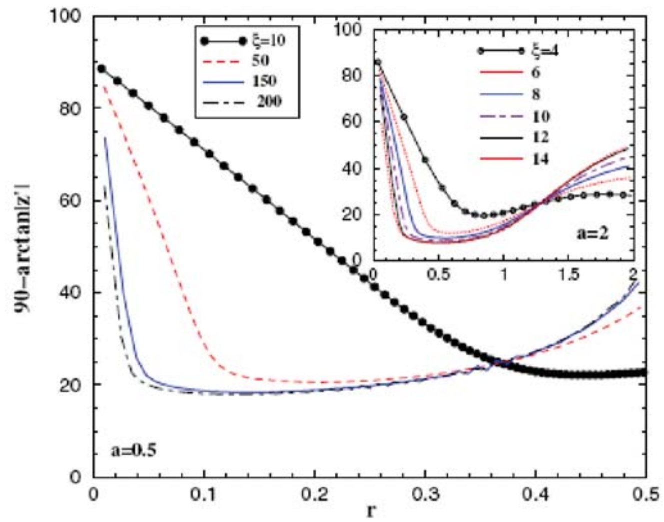
$$a = R/\omega_0, r \equiv r/\omega_0, \xi \equiv \frac{\Pi_{Rad}(0)}{\Pi_{Laplace}(\omega_0)}$$

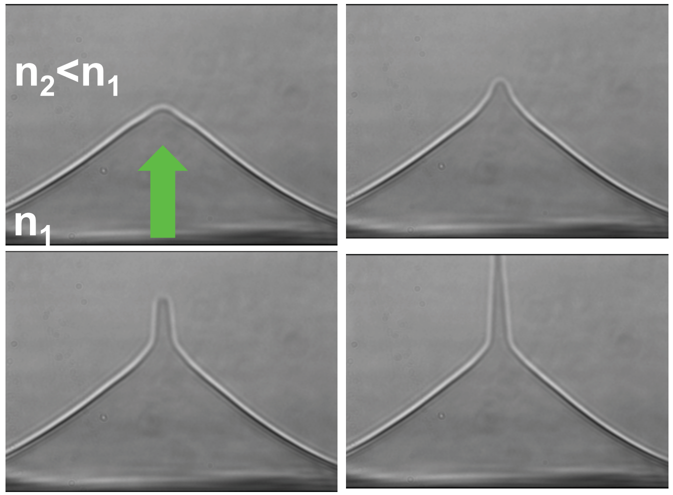
Stretching



$a=R/\omega_0=0.5$; $\xi=700$







P=590 mW, ω_0=4.2 μm, T-T_C=5K

H. Chraibi et al, Phys. Rev. E 77, 066706 (2008)

Concluding Remarks

Interface Deformation: the linear case

→ Universal description versus Bo
→ Up/down Symmetry
→ Electrostriction and secondary effects
→ New interface deformation process: bulk scattering forces
→ Finite size effects

"Opto-hydrodynamic" Instability of a Fluid Interface

→ Beam-centered Liquid Micro-Jet; Taylor cones
→ Stable High Aspect Ratio Liquid Bridge
→ Flow driven by scattering forces on density fluctuations

Further Insights

→ Total Laser Micro-fluidics
  → Two-phase flow and control over droplet formation
→ Adaptative Optics
  → Soft lensing, reconfigurable and self-adapted liquid waveguides