An Experimental Investigation of the Effects of Surfactants on Spilling Breakers

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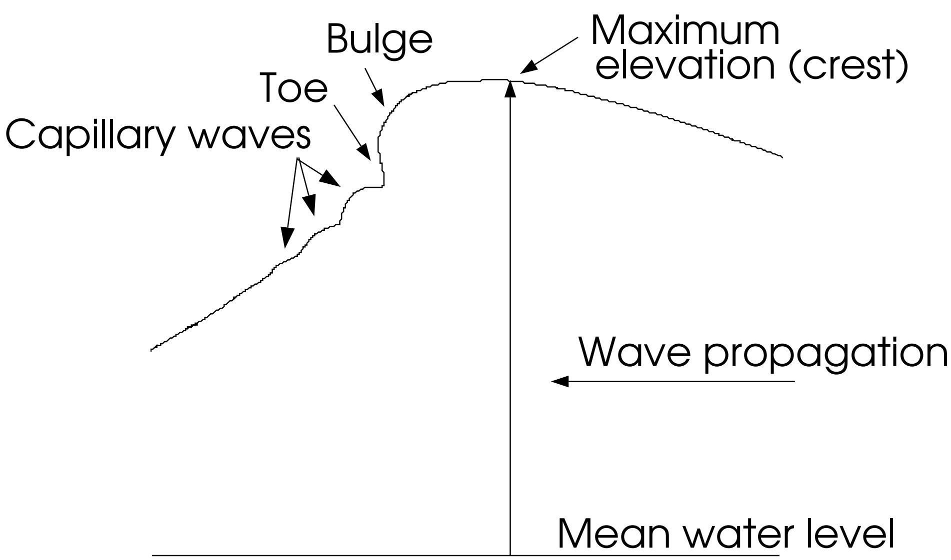
Supported by the National Science Foundation

Weak or short-wavelength breakers in clean water

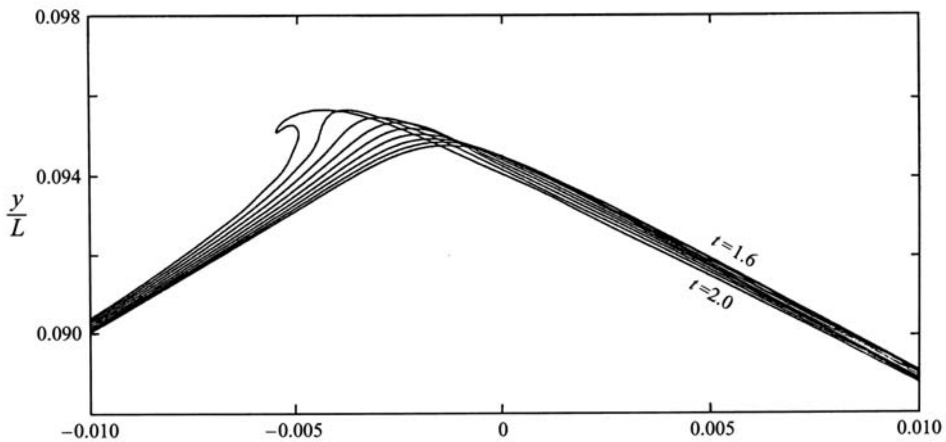


- As wave steepens, bulge, toe and capillary waves form
- Shape of crest region is independent of wave frequency. Lengths scale with $L_c = \sqrt{(\sigma/(\rho g))}$
- Transition occurs when flow separates under the toe. Toe then moves downslope
- Little or no overturning of the free surface

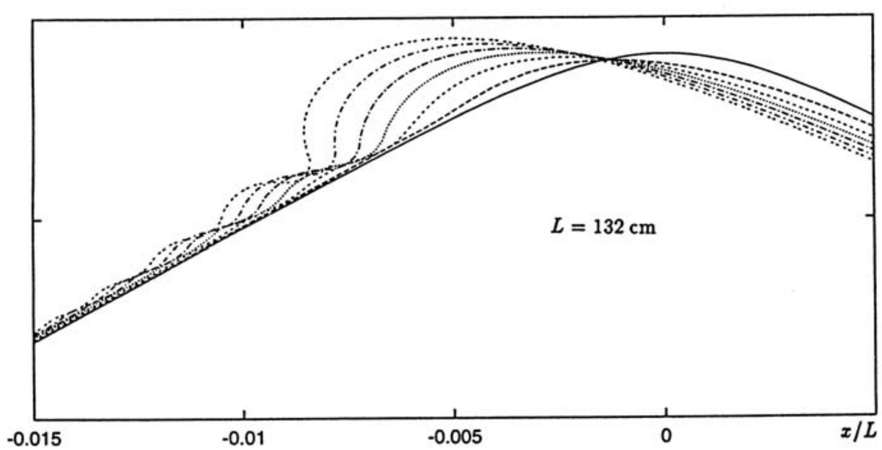
Previous work (Clean water)

- Longuet-Higgins(1992, 1996, 1994 (with Cleaver), 1994 (with Cleaver and Fox), 1997 (with Dommermuth))
- Yao, Wang and Tulin (1994), Tulin (1996)
- Mui and Dommermuth (1995)
- Ciniceros and Hou (2001)
- Okuda (1982)
- Ebuchi, Kawamura and Toba (1987)
- Duncan, Qiao, Behres and Kimmel (1994)
- Duncan, Qiao, Philomin and Wenz (1999)
- Qiao and Duncan (2001)

Clean Water Calculations



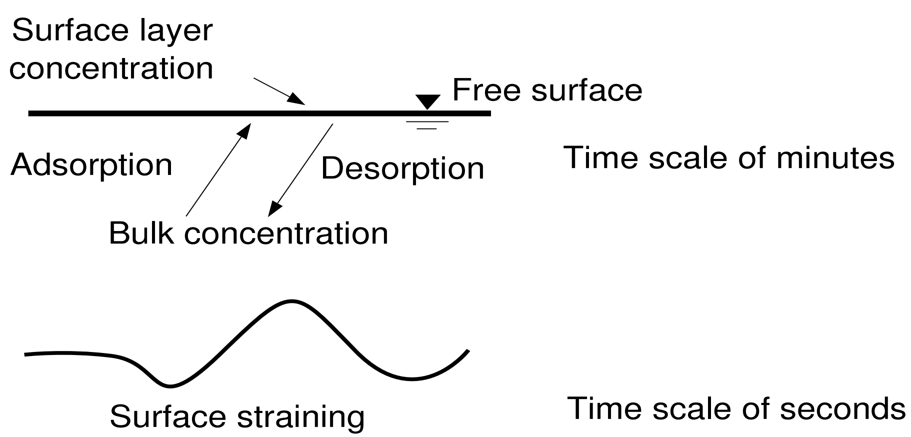
Without surface tension. Longuet-Higgins and Dommermuth (1997)



With surface tension. Longuet-Higgins (1997)

Similar findings with wave groups when waves are short, Tulin (1996)

Surfactants

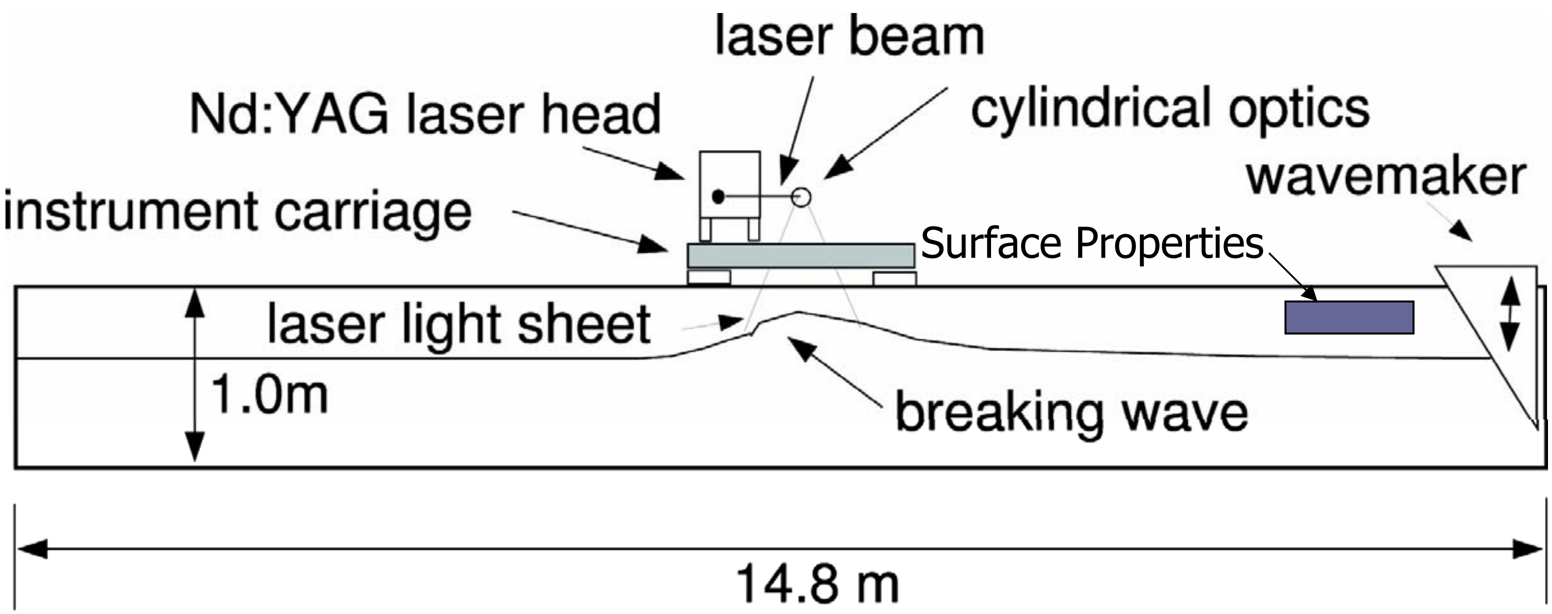


- Surfactant mono-layers lower surface tension and create surface viscosity and surface elasticity.
- Since surface tension is dominant in weak and/or short wavelength spilling breakers, surfactants are likely to have a dramatic effect.

Plan of Research

- Performed breaking wave experiments with several surfactants (Triton X-100 (TX), Sodium Dodecyl Sulfate (SDS), Hemicyanine, Rhodamine B).
- Used Froude-scaled mechanically generated breakers.
- Measured Crest profile histories of breaking waves.
- Performed *in situ* measurments of surface dynamic properties.
- Correlated wave measurements with surface dynamic property measurements.

Experimental setup



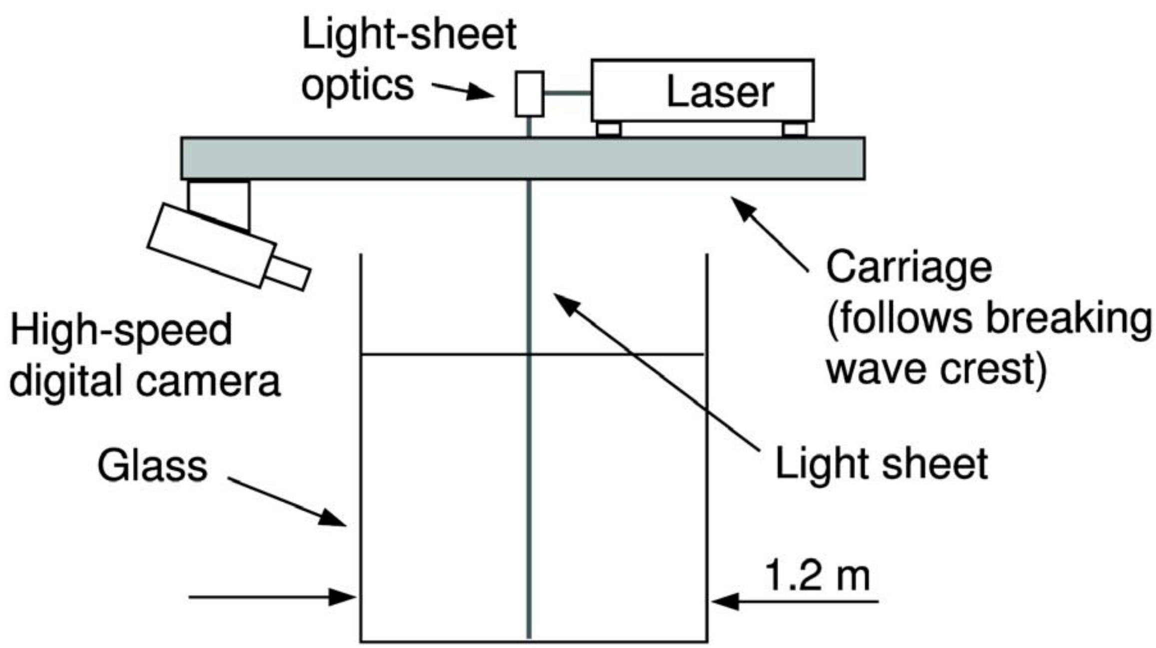
<u>Side View</u>

- Wave maker and carriage controlled by same computer.
- Weak breakers generated with dispersive focusing.
- Skimming-filtration system used extensively.

Water treatment

- Experiments with each surfactant performed in a single tank of water
  - Start with tank of filtered tap water
  - Add chlorine (10 ppm)
  - Skim, filter, bubble for two or three days
  - Lower chlorine level by adding hydrogen-peroxide
  - Add rhodamine 6G for visualization
- Perform clean-water experiments
- Add surfactant, perform experiments on next day.
- Repeat
- There are other surfactants in the tank too!

Wave measurement

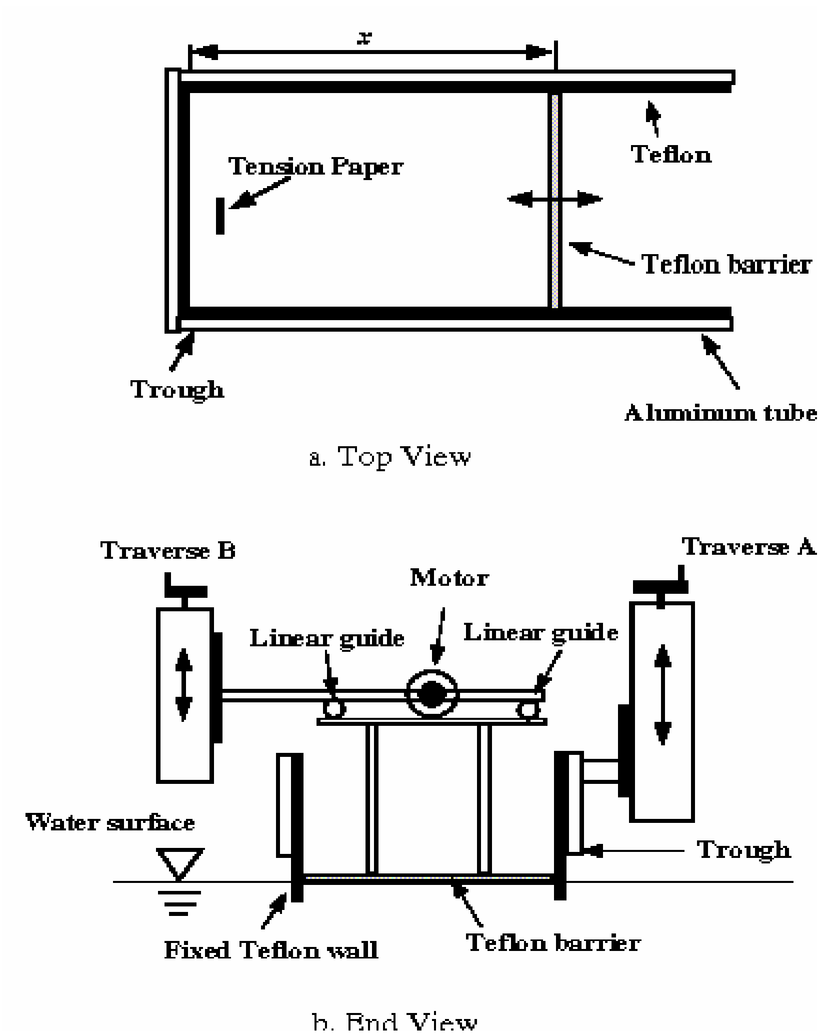


The water is mixed with fluorescent dye
(Rhodamine 6G, <1ppm)

End View

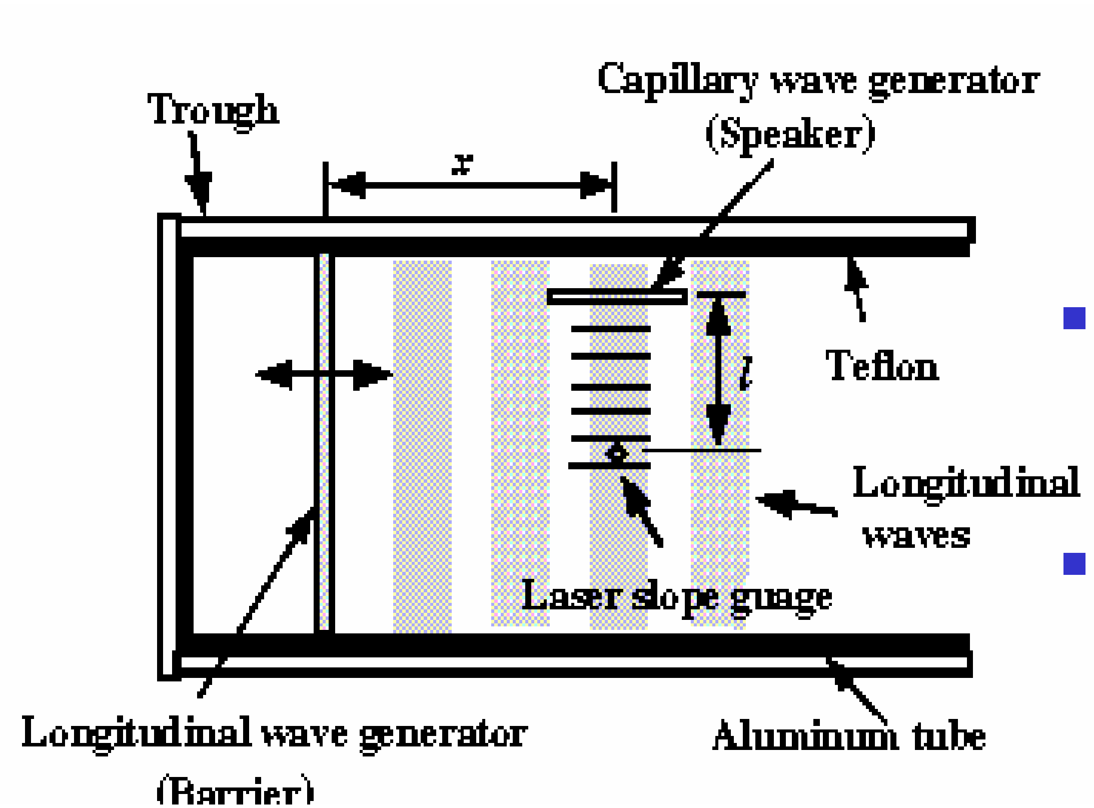
- The carriage follows the wave crest
- The camera and laser head are mounted on the carriage
- The light sheet is oriented along the center-plane of the tank
- The camera looks down at an angle of about 5 degrees from horizontal

Surface properties measurement
Surface pressure isotherm



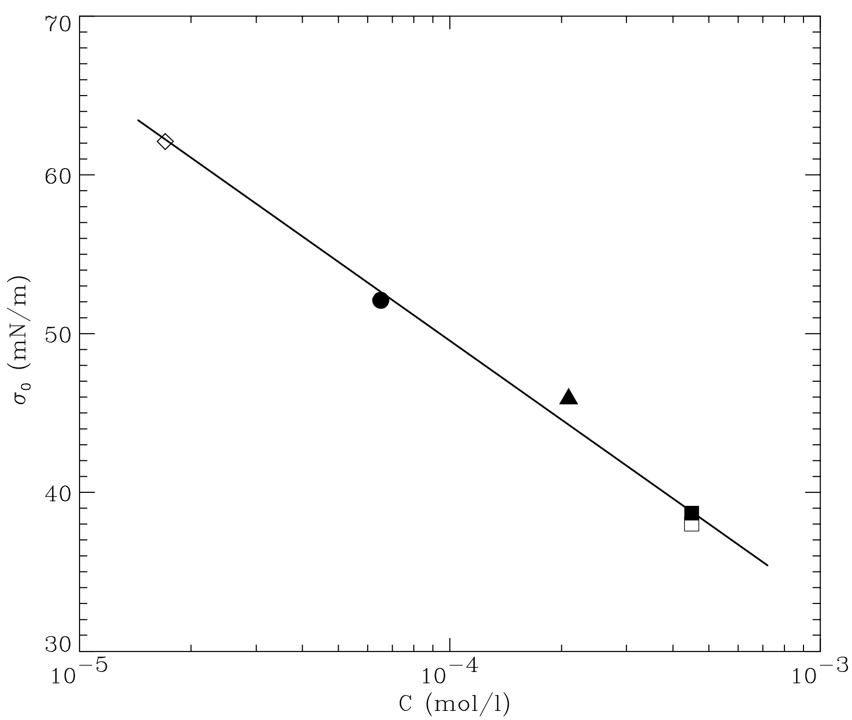
- Langmuir trough.
- Lowered onto water.
- Movable Teflon barrier.
- Wilhelmy plate used to measure surface tension.
- Compress surface while measuring surface tension.
- Obtain surface pressure isotherm ($\pi = \sigma_c - \sigma$ versus A/A_o)

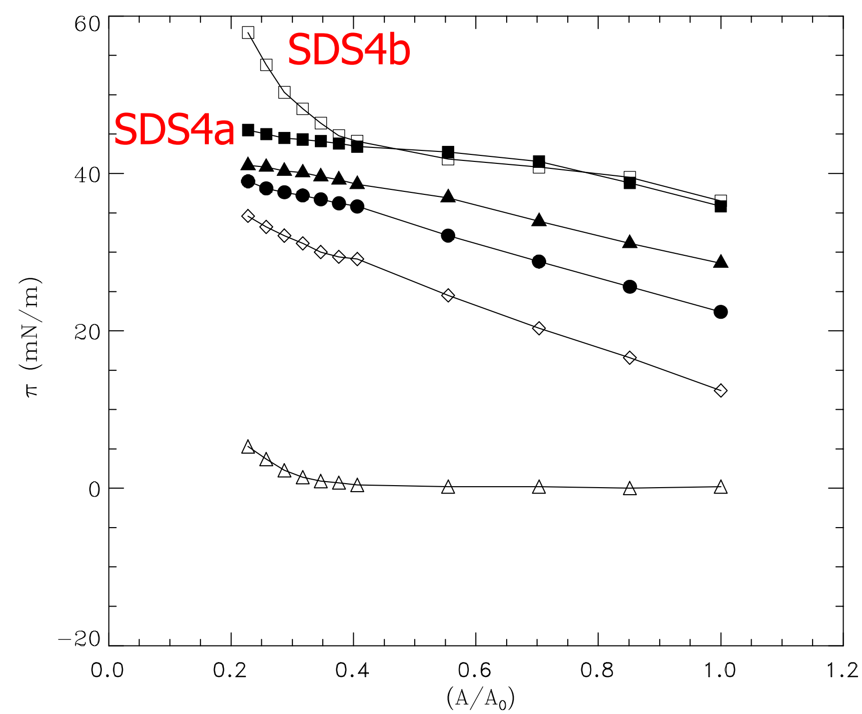
Surface Properties Measurements
Longitudinal wave device



- The horizontal oscillation of barrier generates compression (longitudinal) waves on the surface
- Longitudinal wave causes the fluctuation of surface tension
- Capillary waves were used to measure longitudinal waves

Surface Tension -- SDS

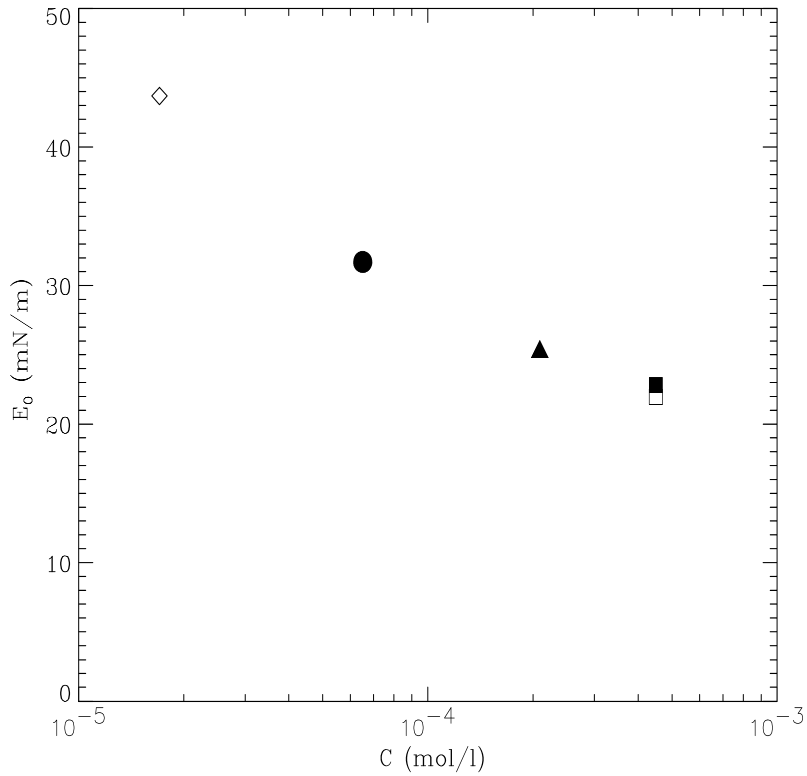


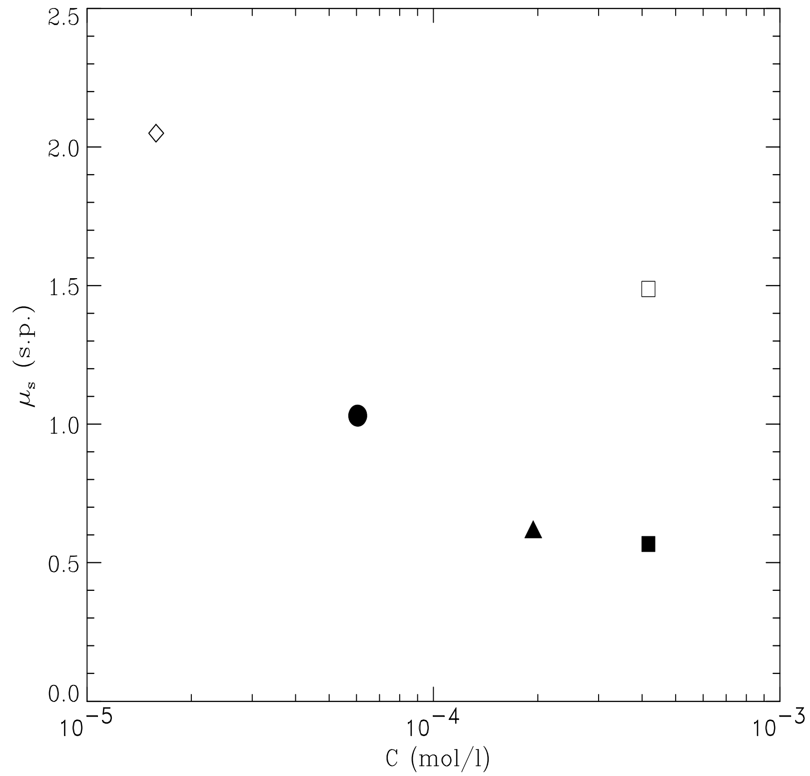


- The ambient surface tension versus the concentration of SDS (left) and the surface pressure isotherm versus the compression area (right).
- The open squares and the black squares measured in the highest concentration of SDS correspond to SDS4a and SDS4b, respectively.

SDS

The Gibbs elasticity (E_0) and surface viscosity (μ_s)

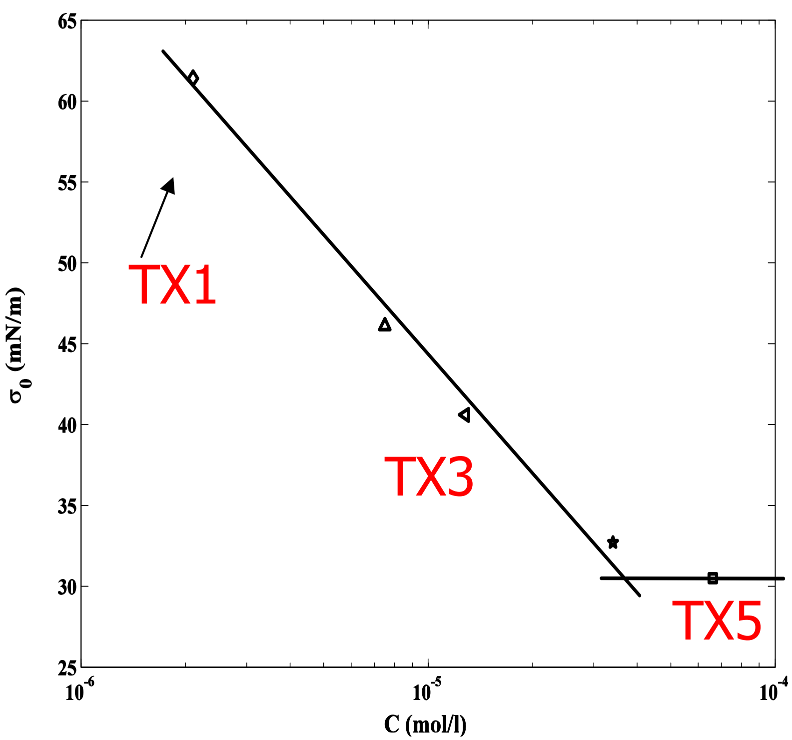


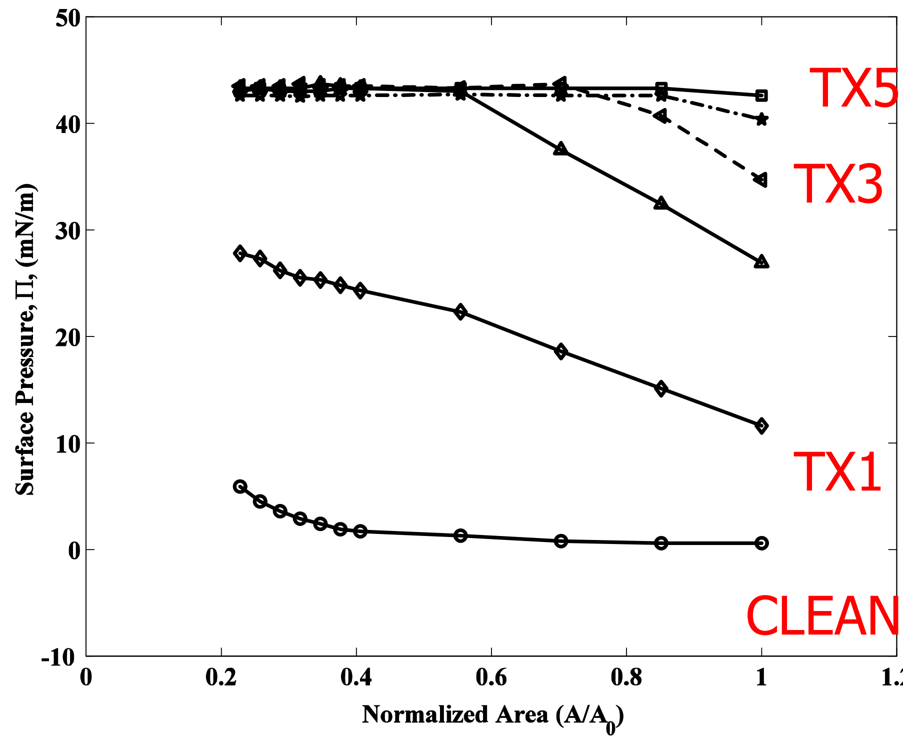


The Gibbs elasticity (left) and surface viscosity (right) vs. the bulk concentration of SDS.

The open square and the black square correspond to SDS4a and SDS4b, respectively .

Surface Tension -- Triton X-100

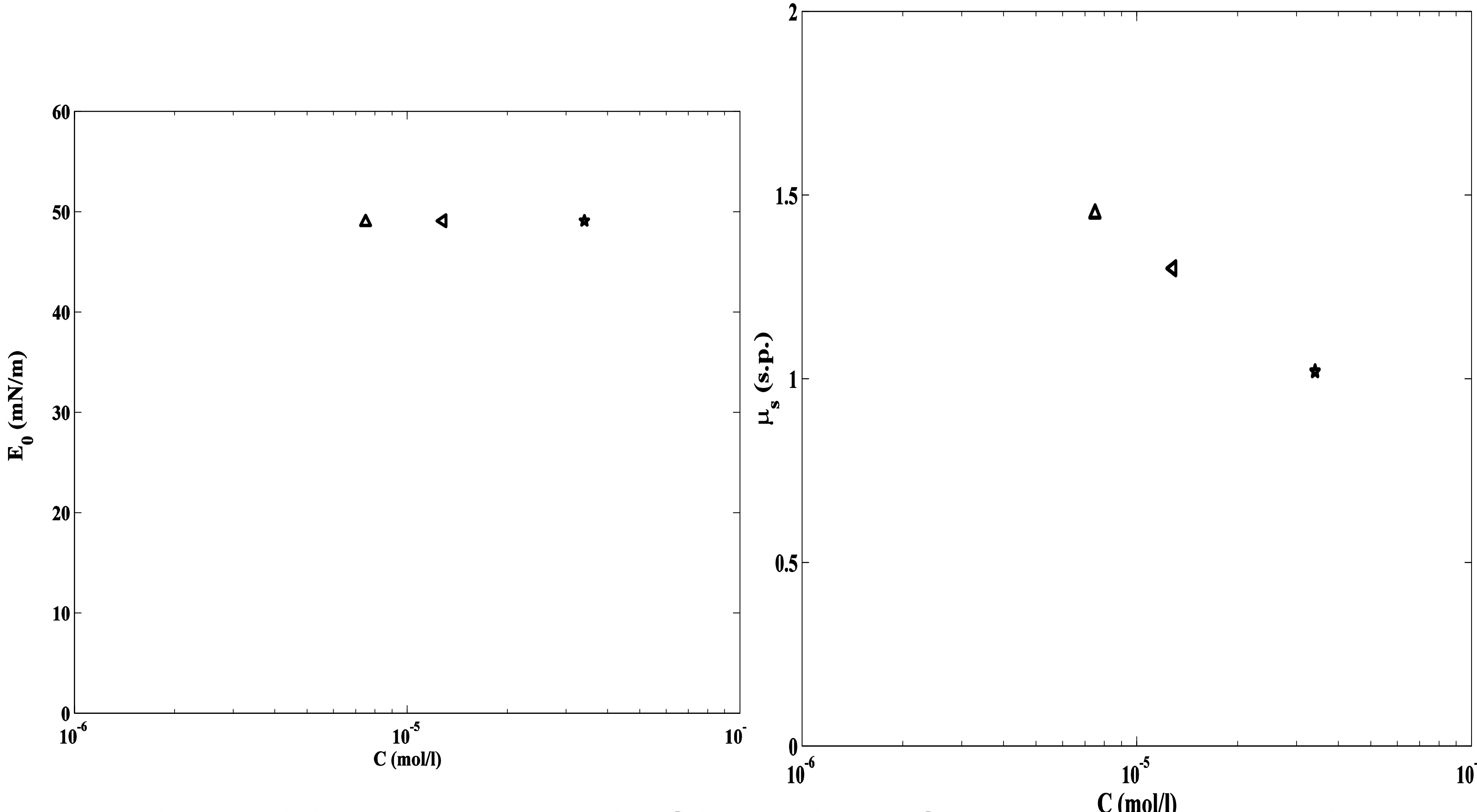




The ambient surface tension versus the concentration of Triton X-100 (left) and the surface pressure (σ_{clean}- σ) versus the compression area (right)

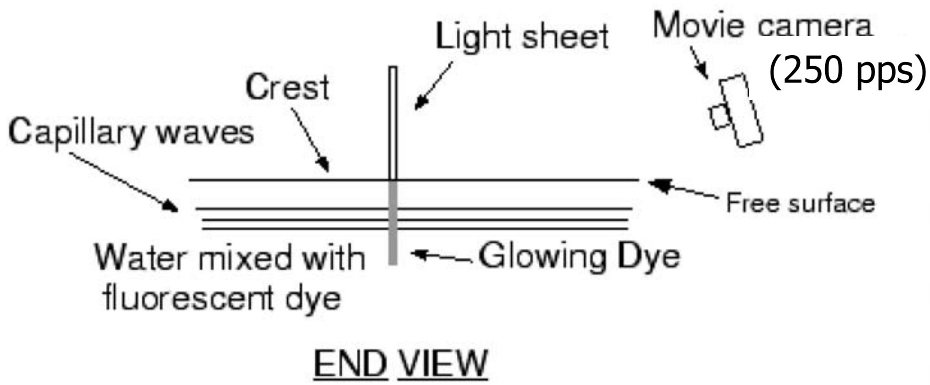
Triton X-100

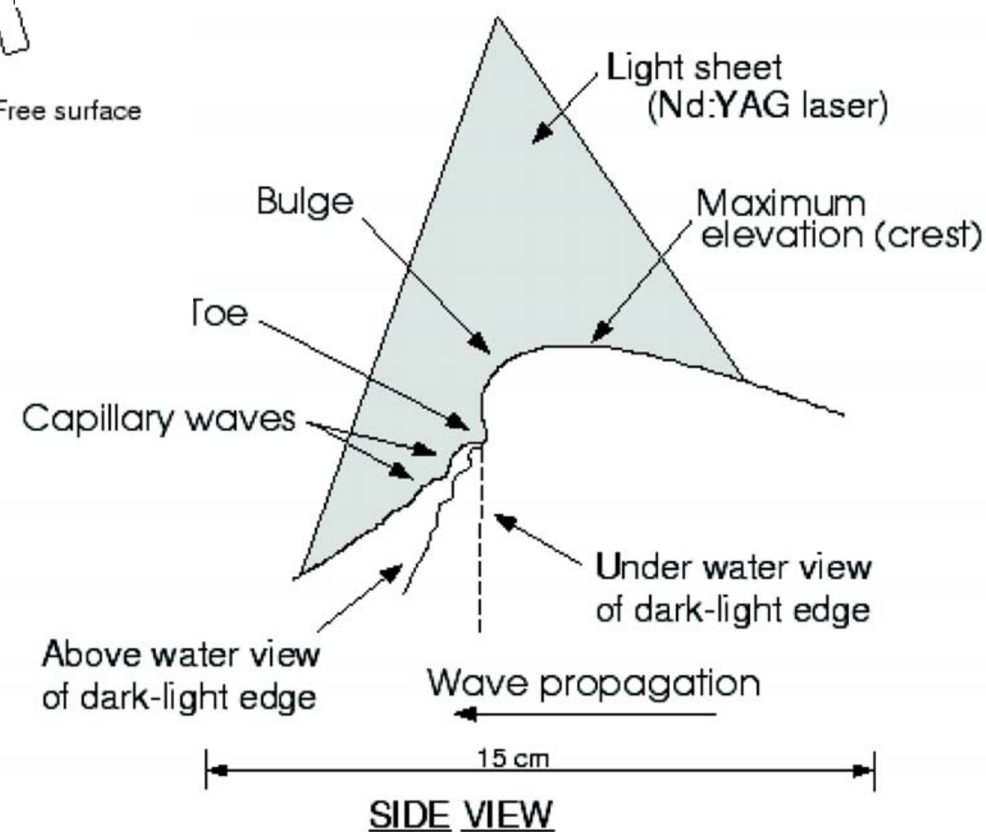
The Gibbs elasticity (E_0) and surface viscosity (μ_s , sum of shear and dilational viscosities)



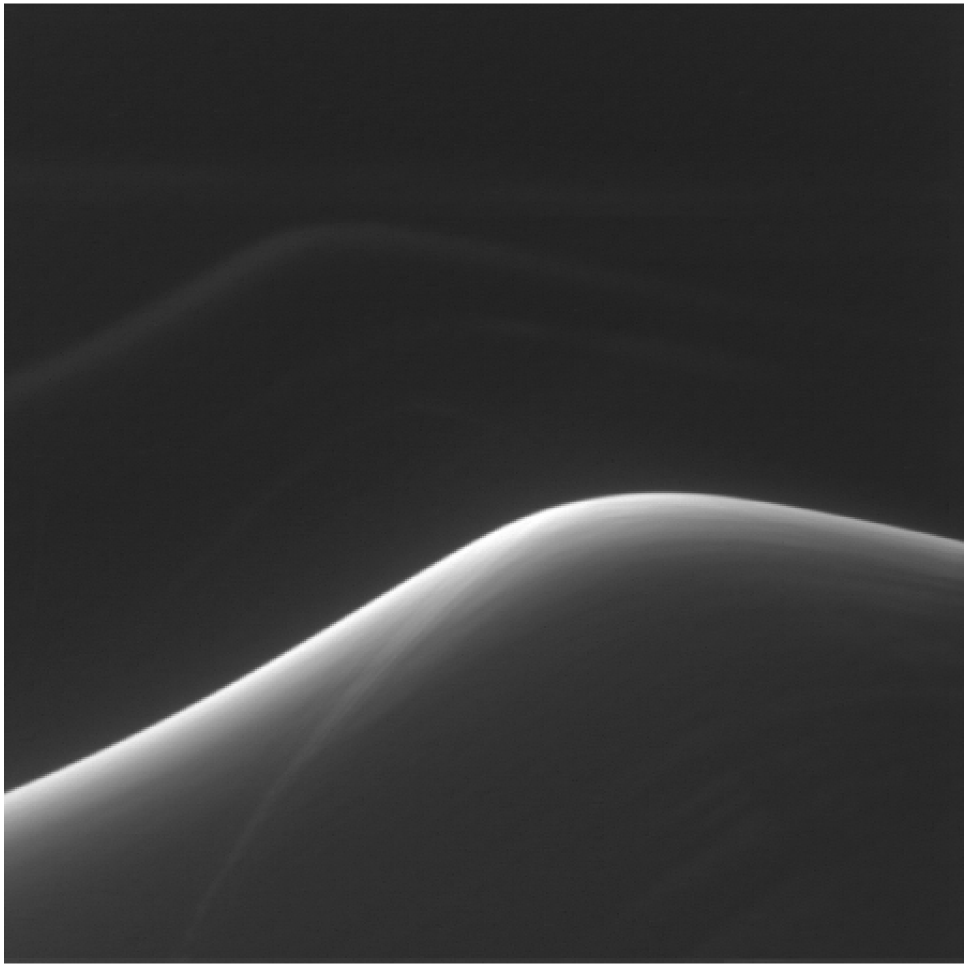
The Gibbs elasticity (left) and surface viscosity (right) versus the bulk concentration of Triton X-100

Crest Profile History Measurements





The breaker in "clean" water

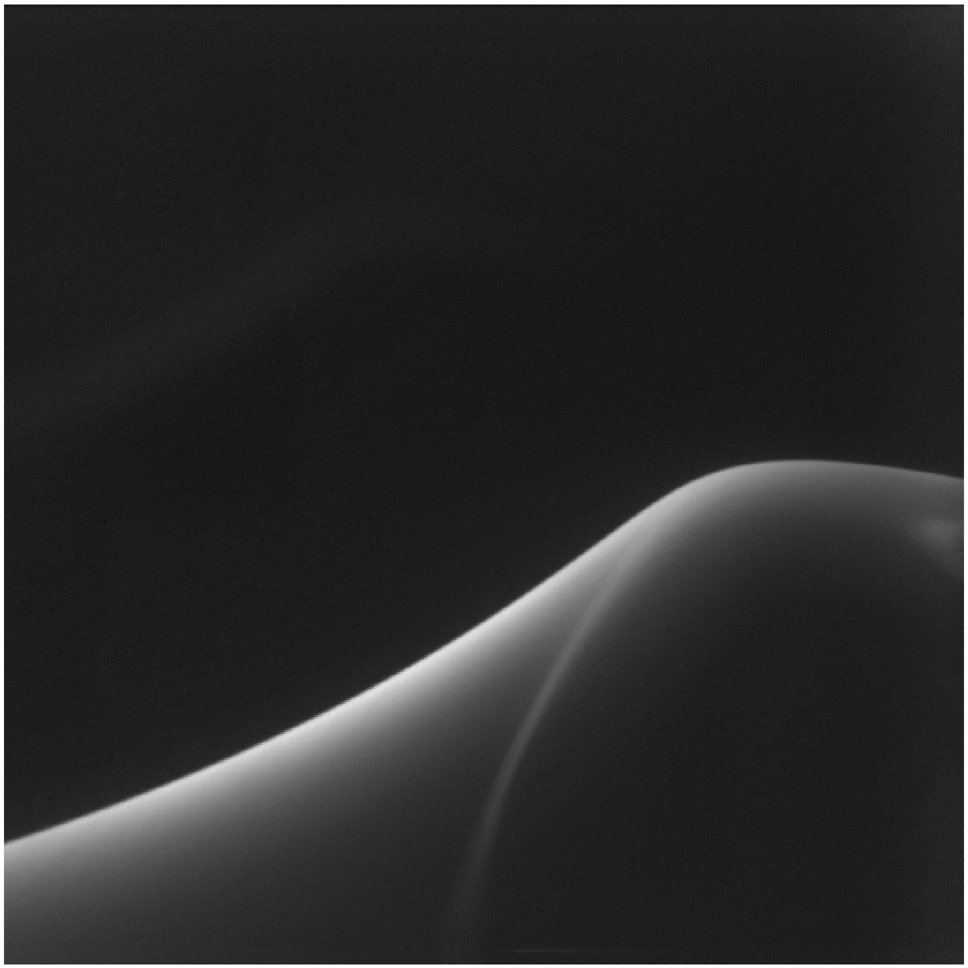


- Wave parameters:
  - f_0=1.15 Hz
  - A/λ_0=0.0505
- Surface property
  - σ_0=73 mN/m

Photographed at 250 fps.

Shown at 10 fps.

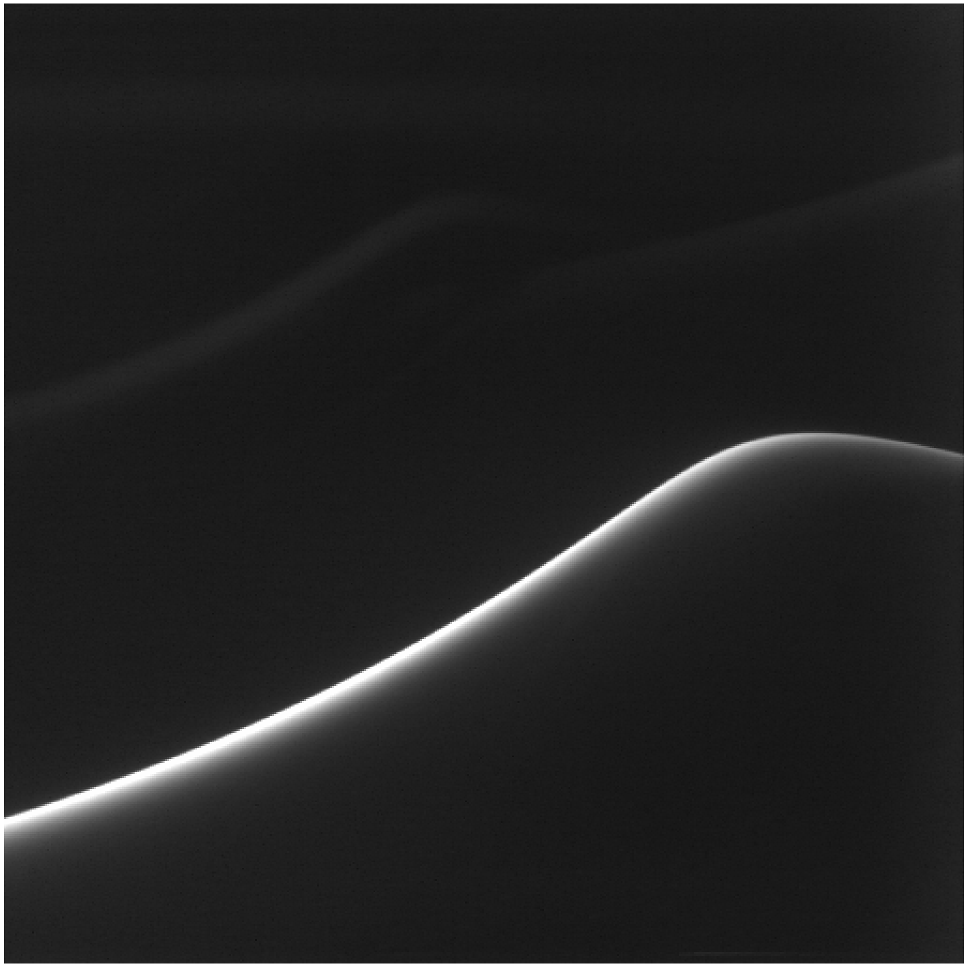
The breaker in TX1
(the lowest concentration of Triton X-100)



- Wave parameters:
  1. f_0=1.15 Hz
  2. A/λ_0=0.0505
- Surface property
  1. σ_0=61.4 mN/m

The breaker in TX5

(The concentration of Triton X-100 is above CMC)



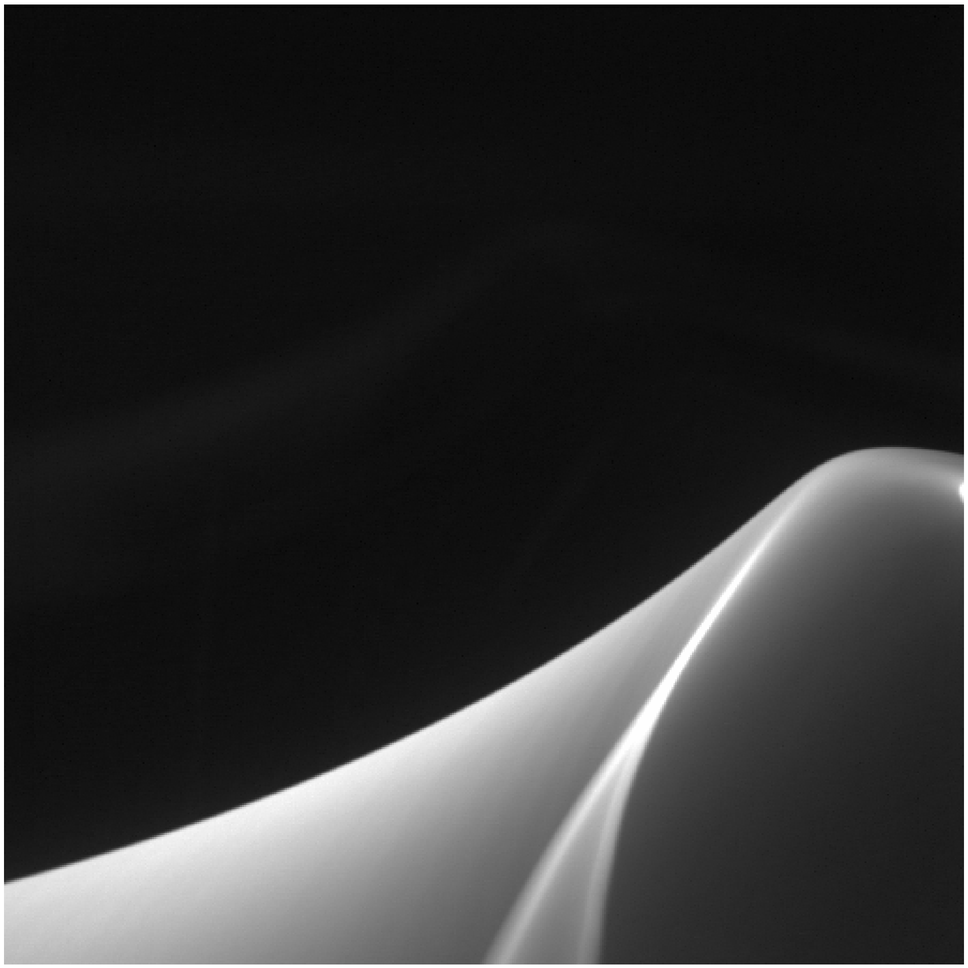
- Wave parameters:

1. f_0=1.15 Hz
2. A/λ_0=0.0505

- Surface property

1. σ_0=30.5 mN/m

The breaker in SDS4a



- Wave parameters:

1. f_0=1.15 Hz
2. A/λ_0=0.0505

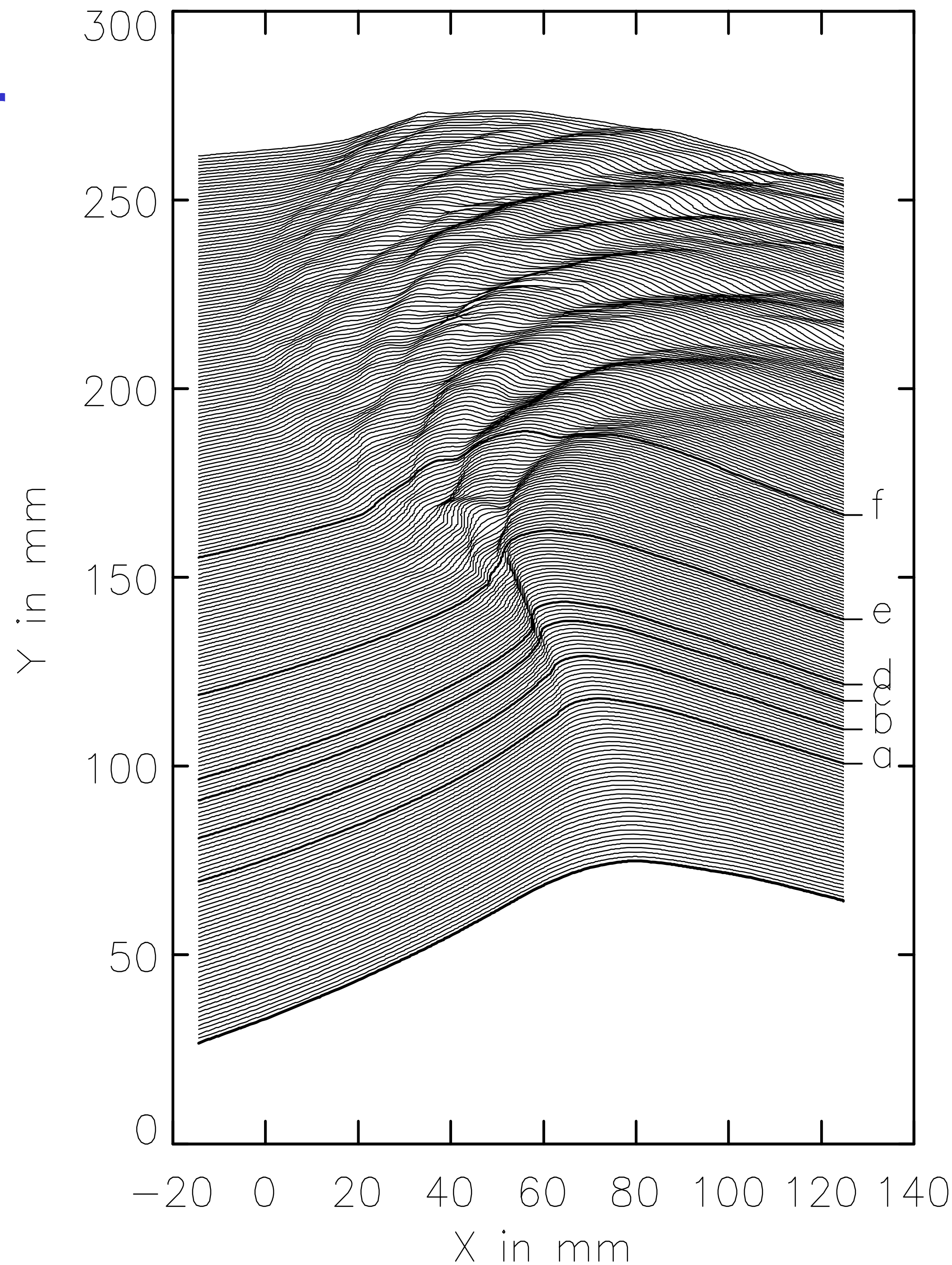
- Surface property

1. σ_0=40.1 mN/m
2. E_0=22.8 mN/m
3. μ_s=0.57 mN.s/m

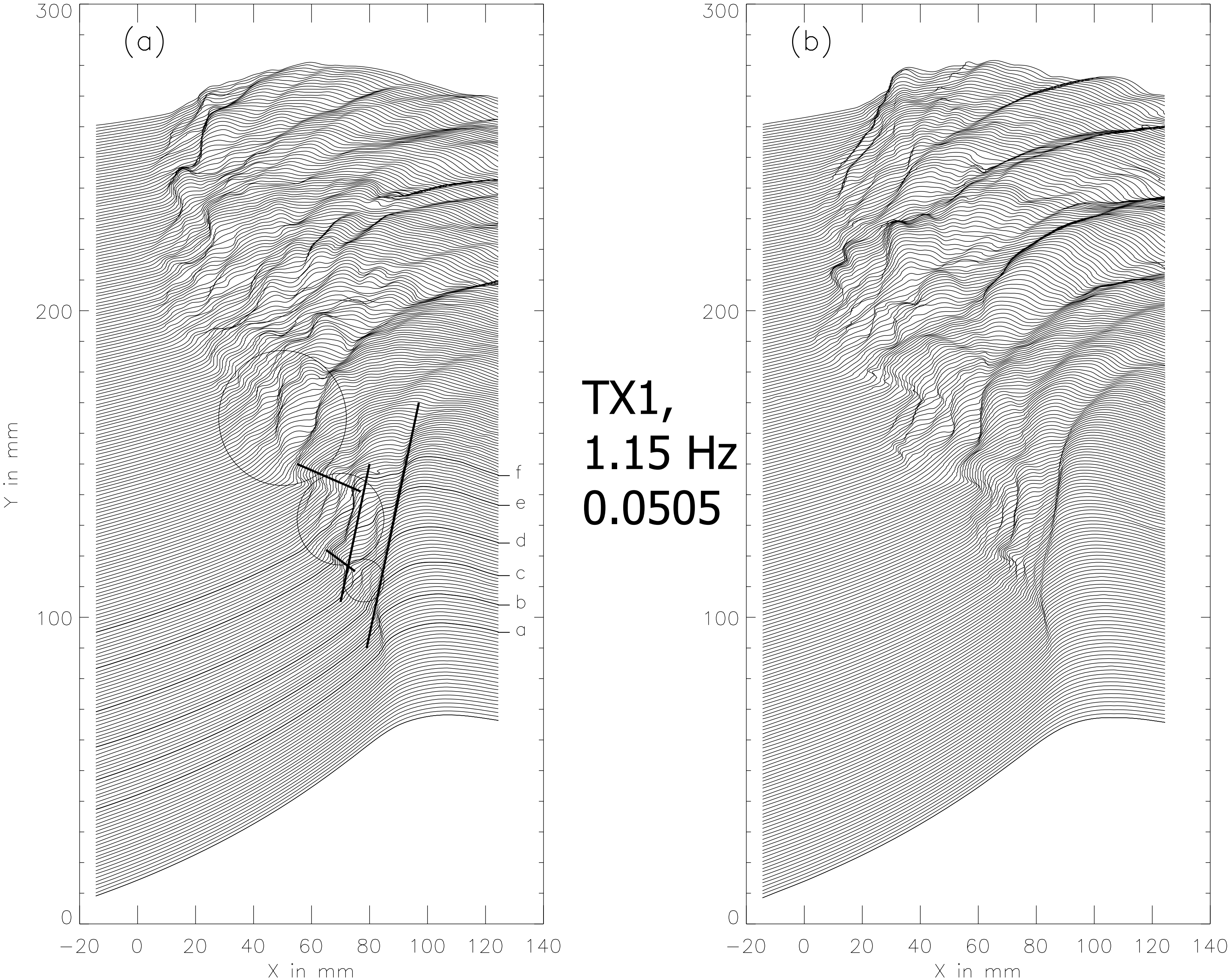
The breaker in SDS4b

- Wave parameters:
1. f_0=1.15 Hz
2. A/λ_0=0.0505
- Surface property
1. σ_0=38.0 mN/m
2. E_0=21.98 mN/m
3. μ_s=1.49 mN.s/m

Clean Water

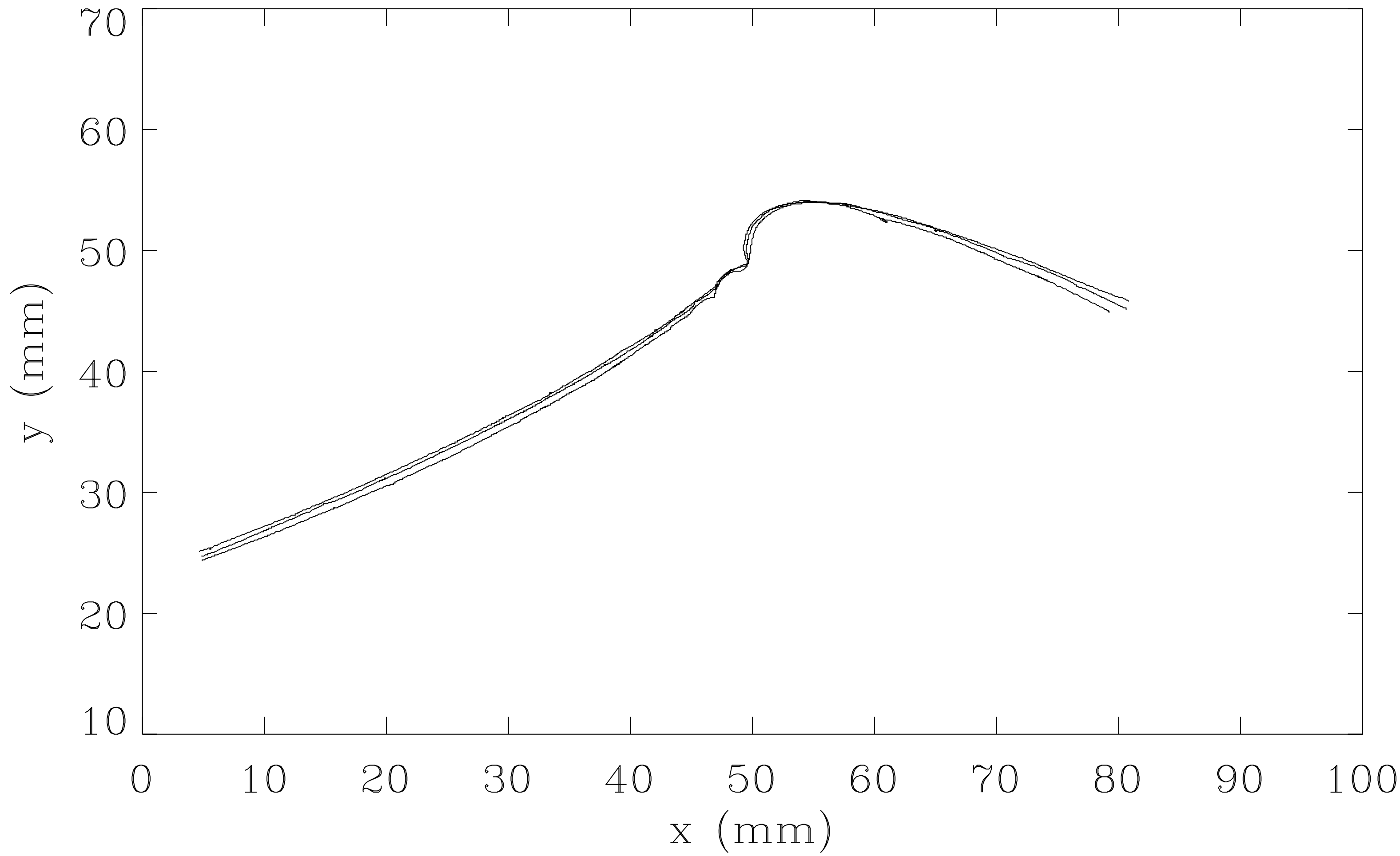


300
250
200
150
100
50
0
−20
0
20
40
60
80
100
120
140
X in mm
Y in mm
f
e
d
c
b
a

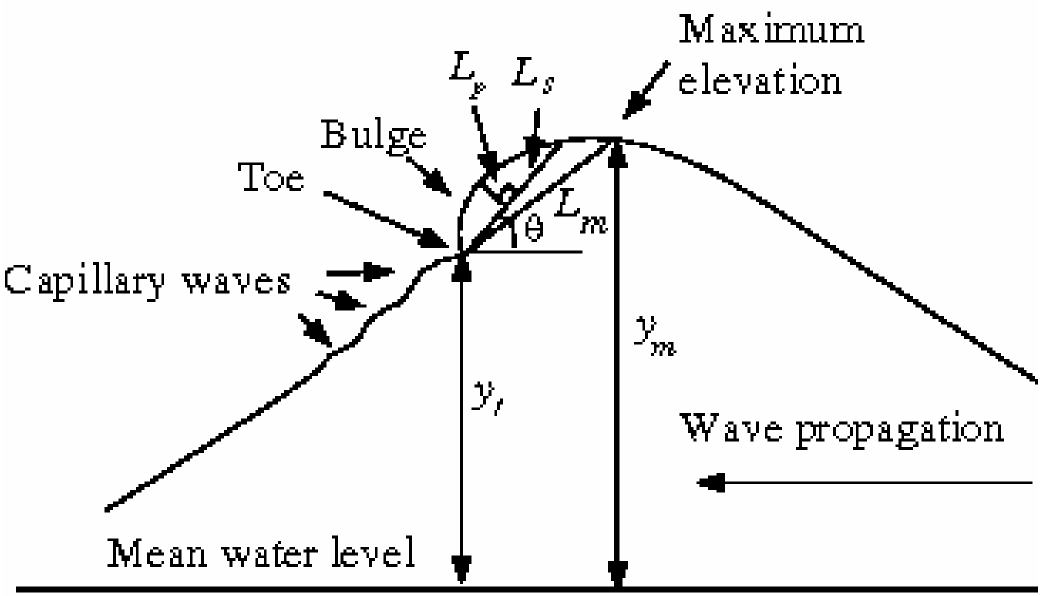


TX1,
1.15 Hz
0.0505

Three weak breakers at the point of transition to turbulent flow: f0 = 1.15, 1.26, and 1.42 Hz



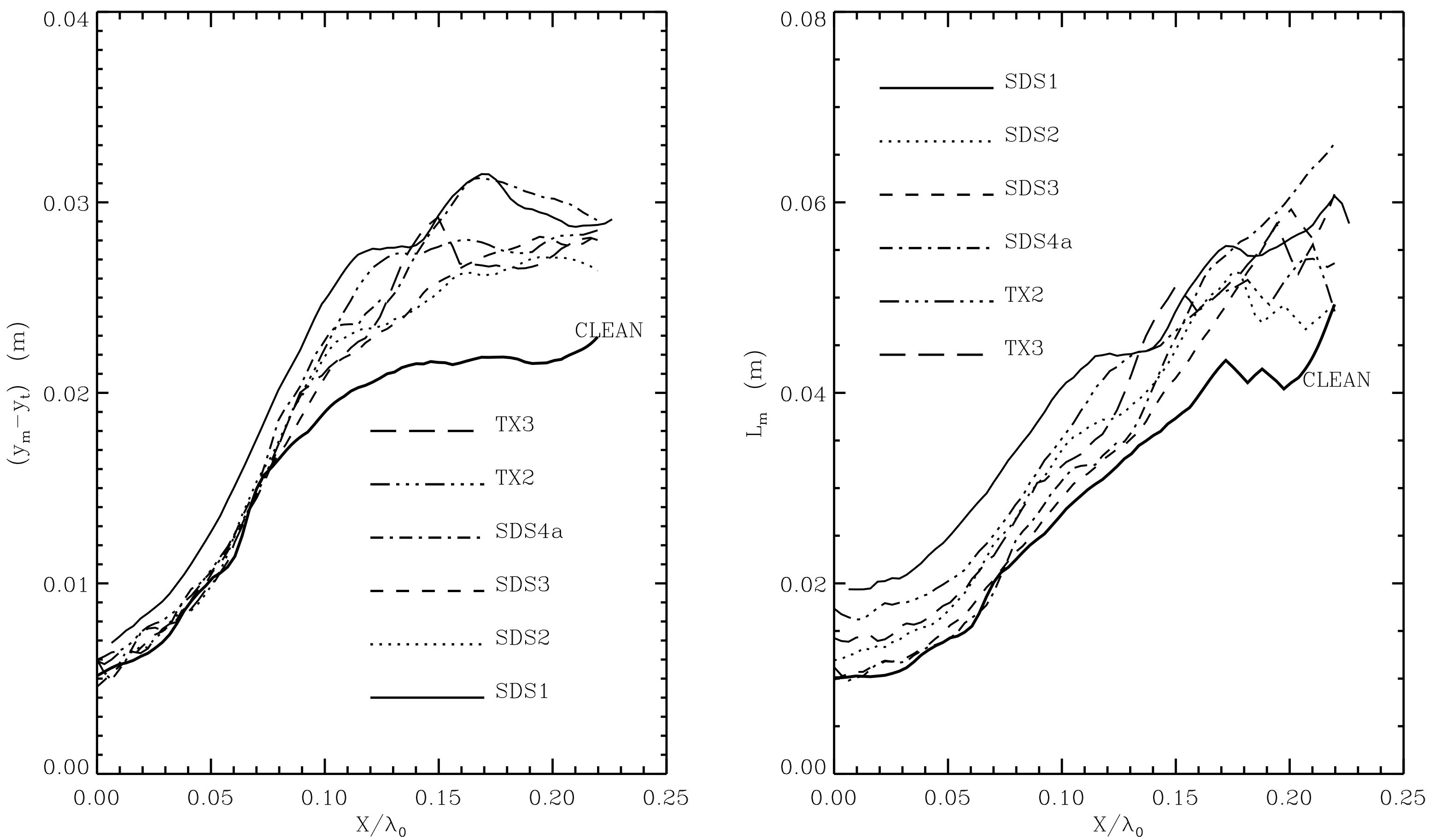
Histories of geometrical paramters



- The crest height, y_m
- The toe height, y_t
- The bulge length, L_m
- The bulge length, L_s
- The bulge thickness, L_p
- The angle, θ

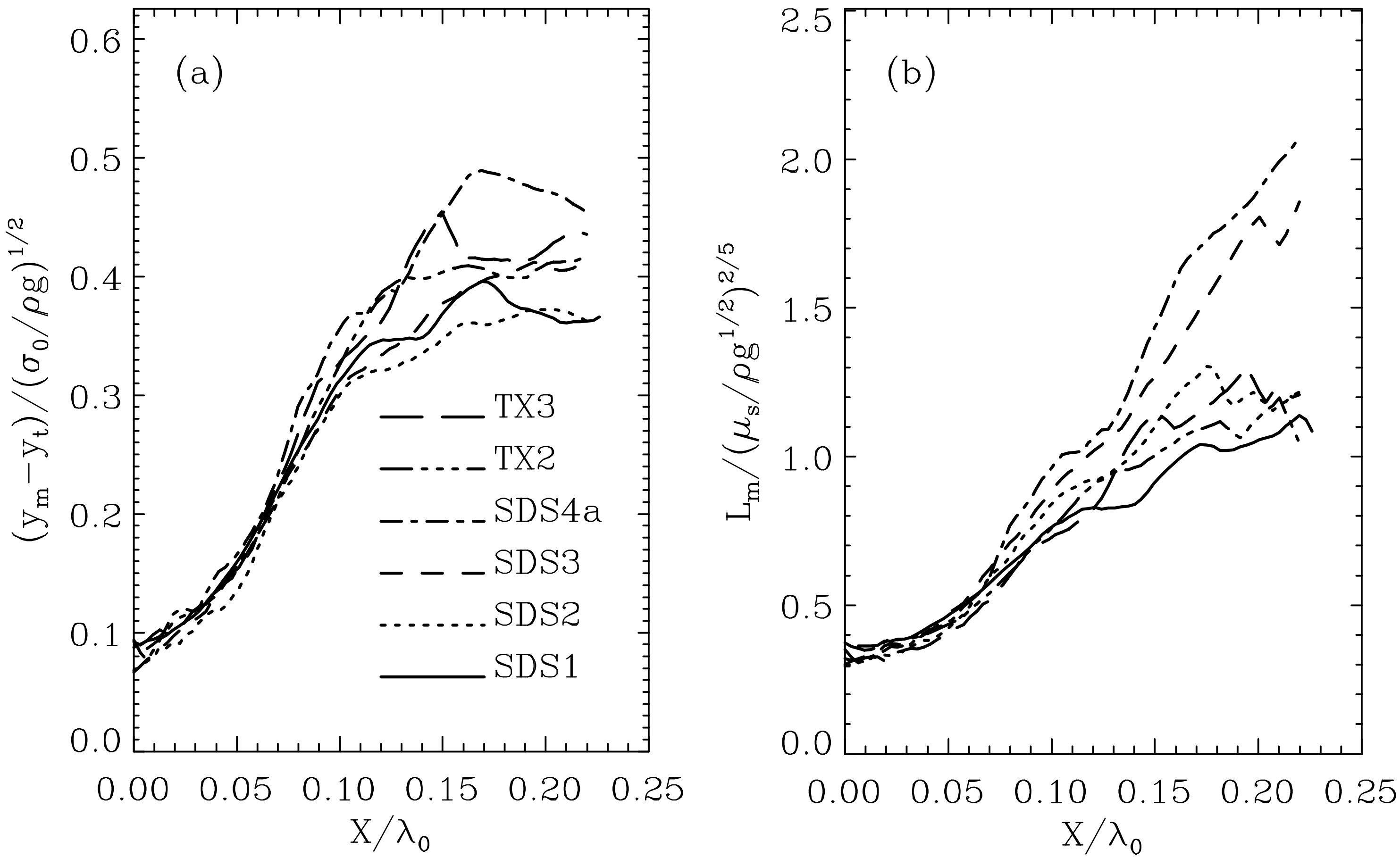
Plot versus dimensionless distance from wave maker, X/λ_0

Histories of Geometric Parameters



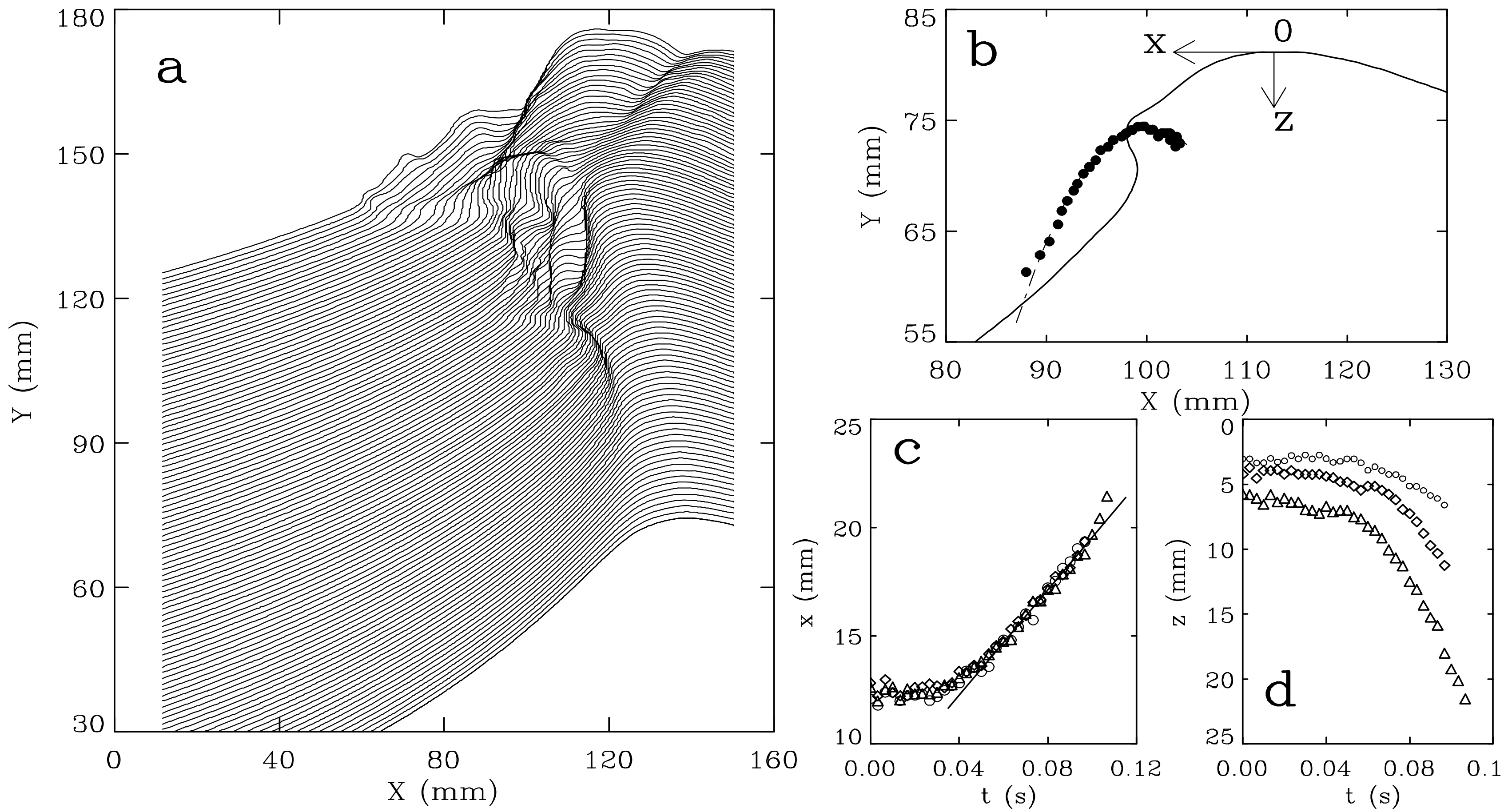
Each curve is an average of 3 to 5 realizations.

Histories of y_m- y_t scaled by capillary-gravity wavelength and L_m scaled by viscosity



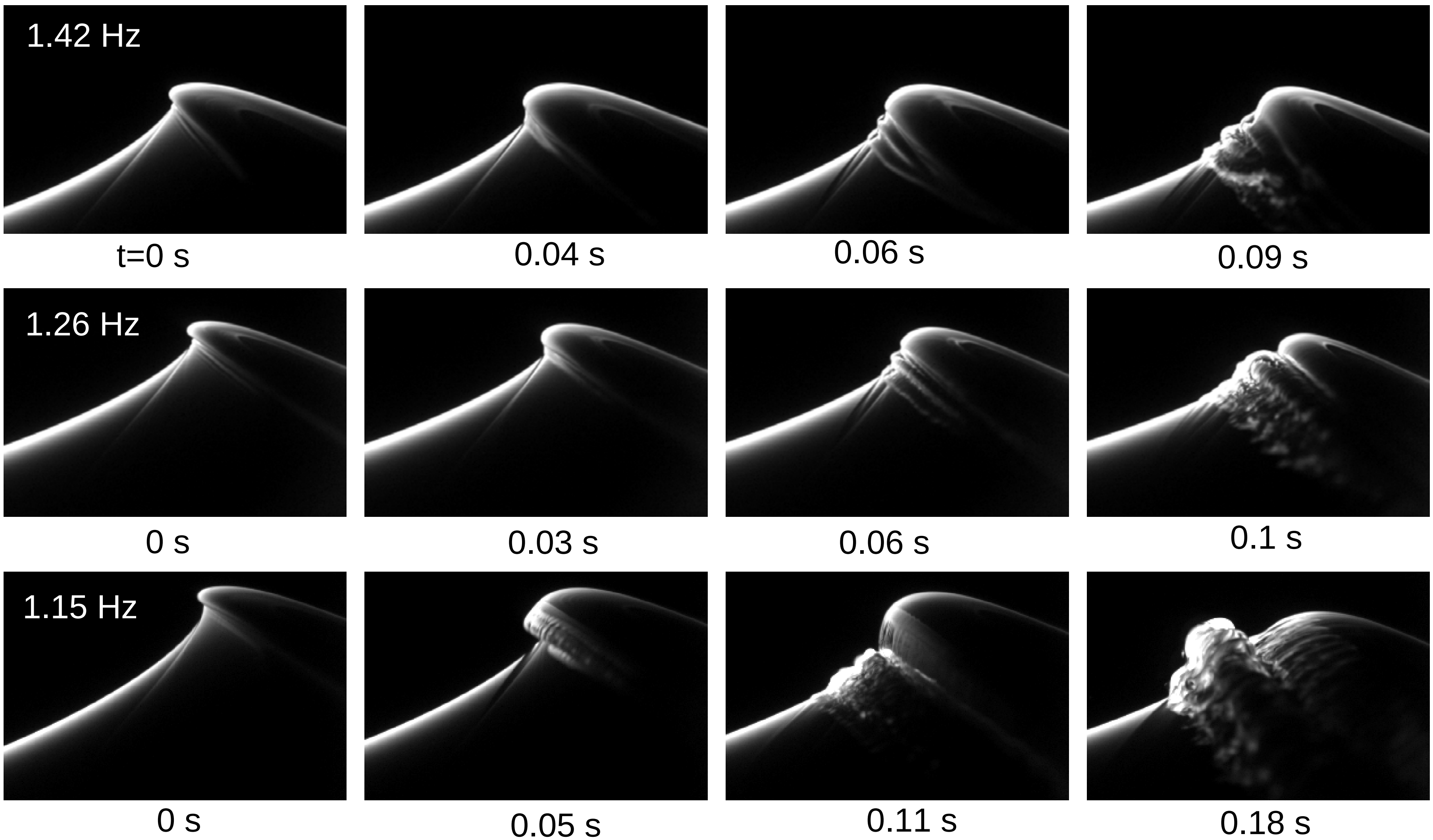
- Capillary-Gravity wavelength is proportional to length wave with minimum phase velocity.

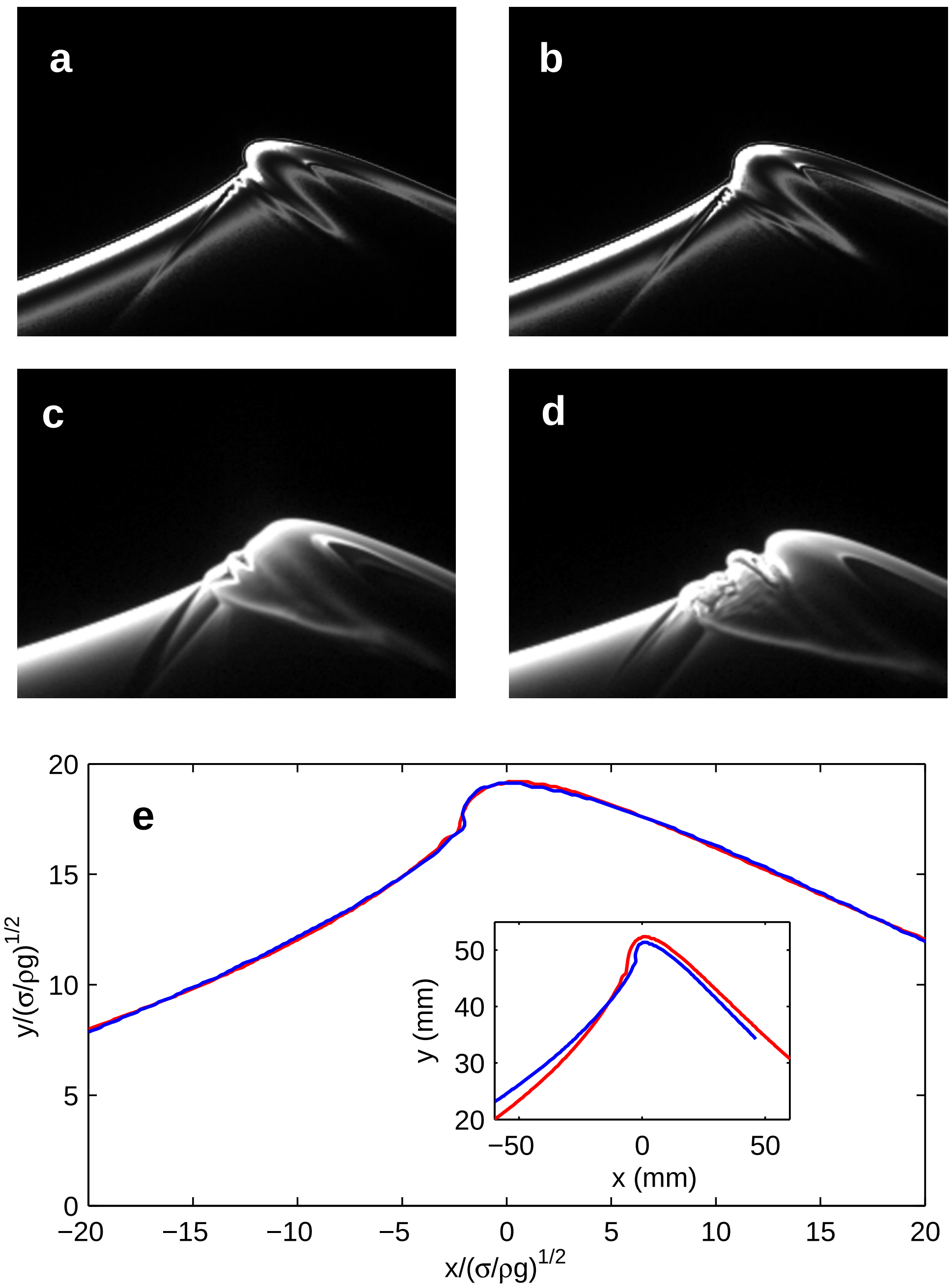
SDS4b: f_0 = 1.15 Hz, A/λ_0 = 0.0505



The vertical acceleration of the jet tip is 6.4 ± 0.8 m/s^2

Three waves with $A/\lambda_0 = 0.0505$ and different frequencies (TX5)

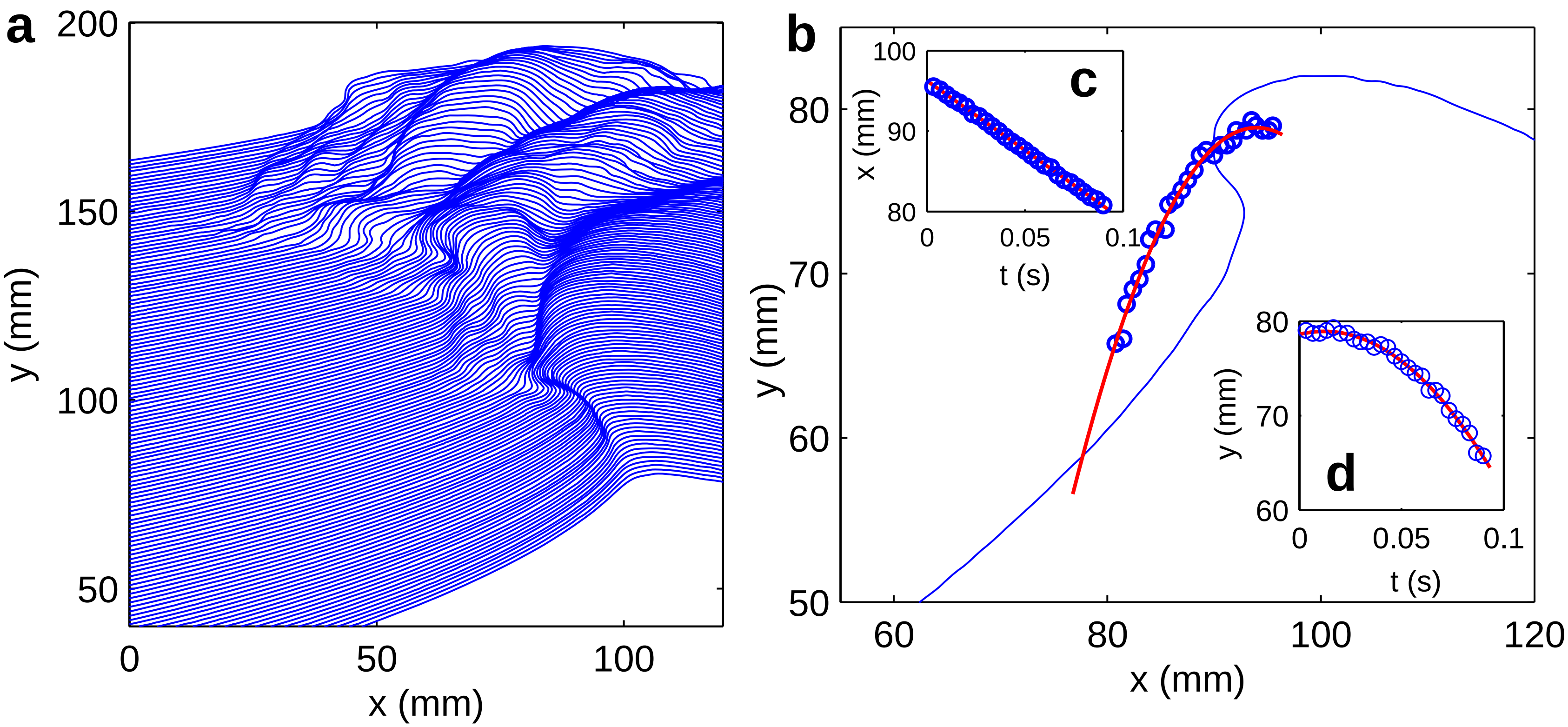




- TX5: CMC
- Weak breaker
- f_0 = 1.42 Hz

- Clean: Red
  σ_0 = 73 mN/m
- TX5: Blue
  σ_0 = 30 mN/m

TX5 f_0 = 1.15 Hz, A/λ_0 = 0.0505



Vertical acceleration of the tip is 4.5 m/s^2

Summary and conclusions

- The capillary waves found upstream of the toe in clean water, nearly disappear for all cases with surfactants below the CMC.
- For most surfactant cases the breaking process is qualitatively the same as in clean water.
- Various measures of the bulge geometry scale with various lengths based on surface properties.
  - The geometrical parameters y_m-y_t and L_s scale with surface tension while L_m scales with surface viscosity

Conclusions Continued

- At the highest concentration of SDS, a jet issues from a point on the bulge just above the toe (this surfactant condition lies in the upper left region of the $E_0 - \mu_s$ plane).
- In Triton X-100 at the CMC, the wave behaves in a manner similar to the clean-water case, but with a lower surface tension. This includes the formation of a jet at the lowest wave frequency used herein.

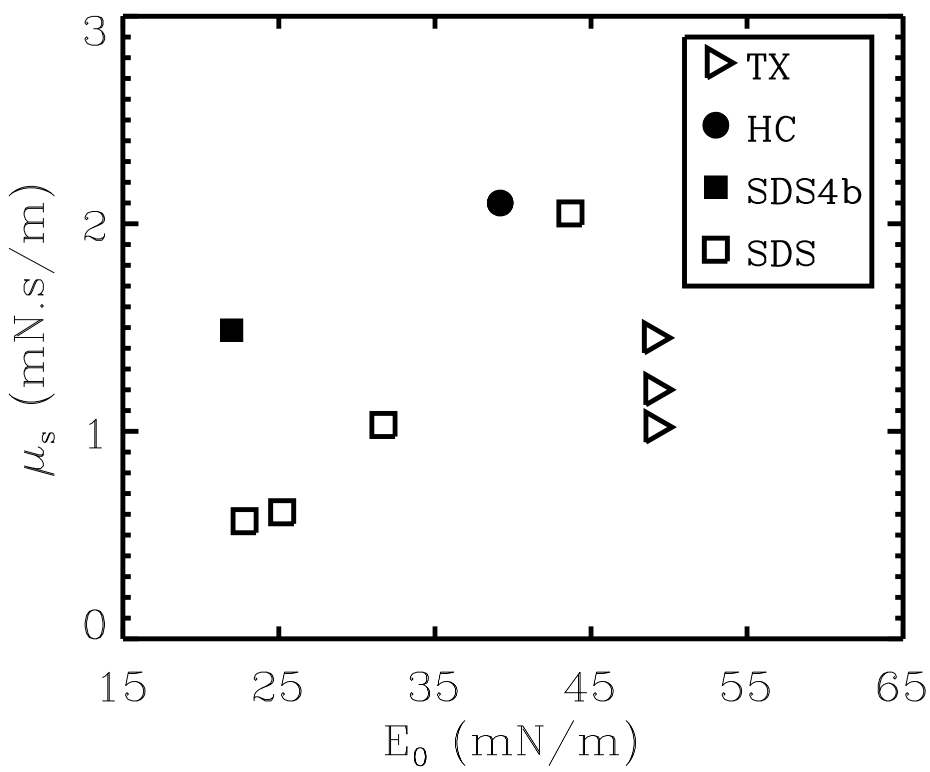
The quantitative modification of the clean water process

- The bulge changes shape, capillary waves disappear and ripples vary
- The geometrical parameters y_m-y_t and L_s scale with surface tension while L_m scales with surface viscosity

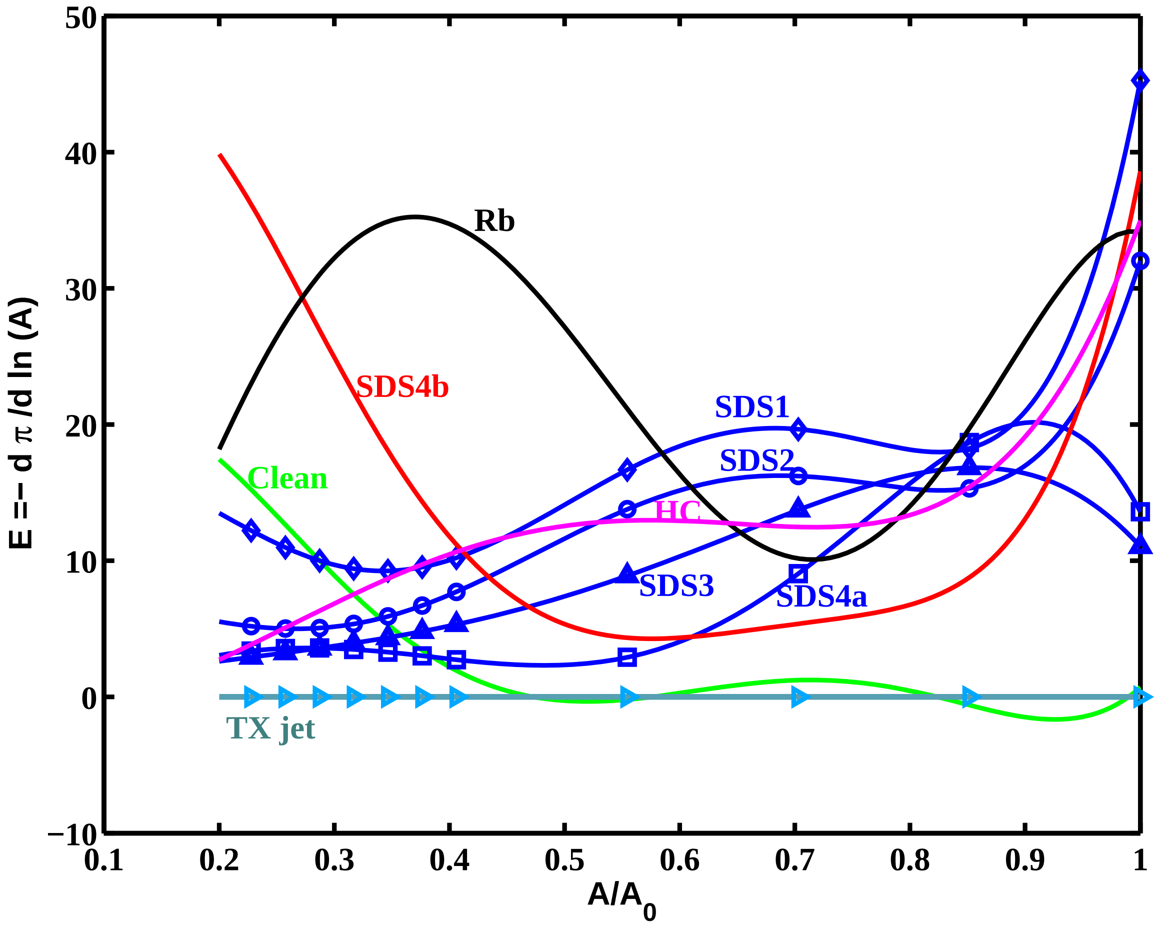
Conclusions

- In low to moderate surfactant concentrations, the breaker changes quantitatively from the clean-water case.
- In high concentrations of SDS, but still below the CMC, when the surface viscosity is high a jet forms from a position below the crest.

The Jet is found in the cases marked by the filled symbols.

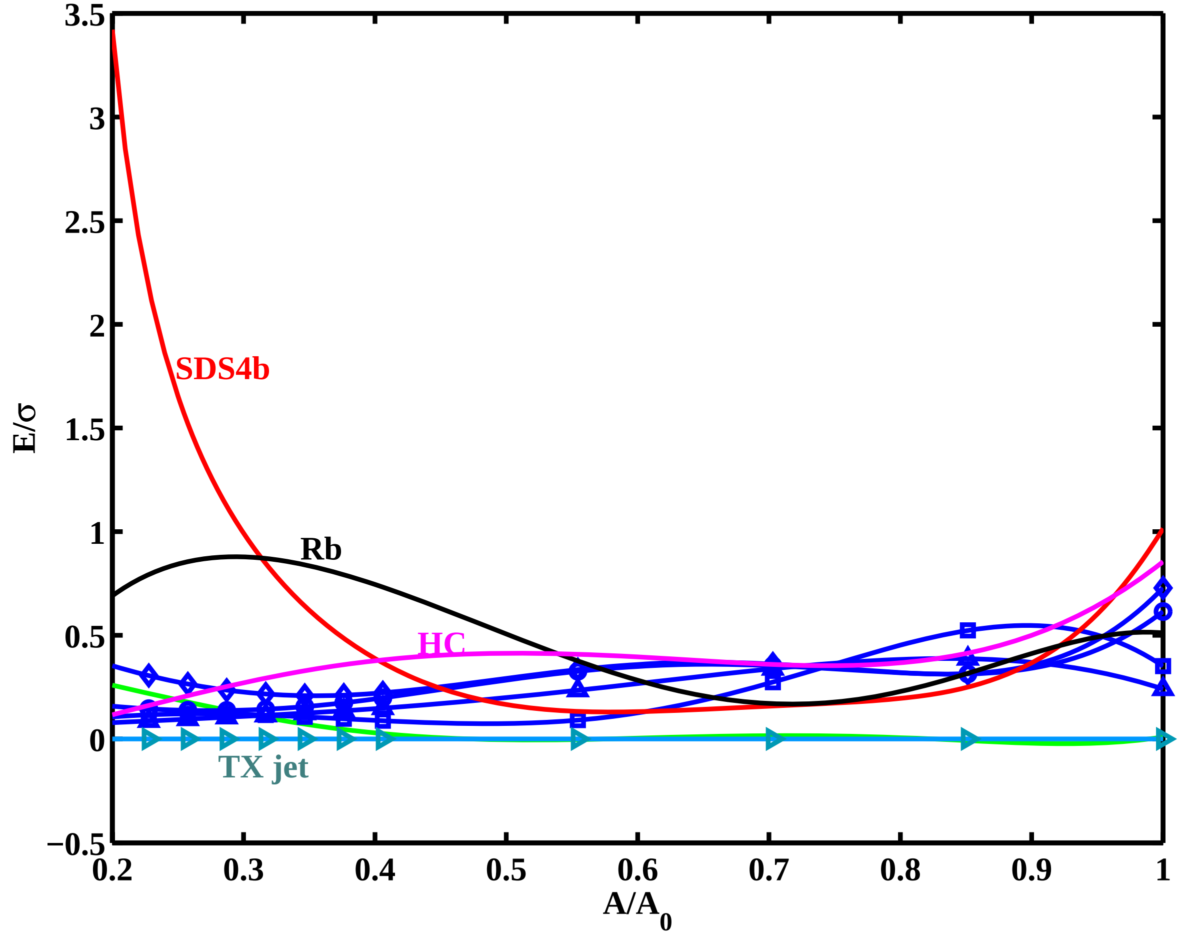


The jet is found in cases Rb, SDS4b, and HC



E is the static elasticity.

The jet is found in cases Rb, SDS4b, and HC

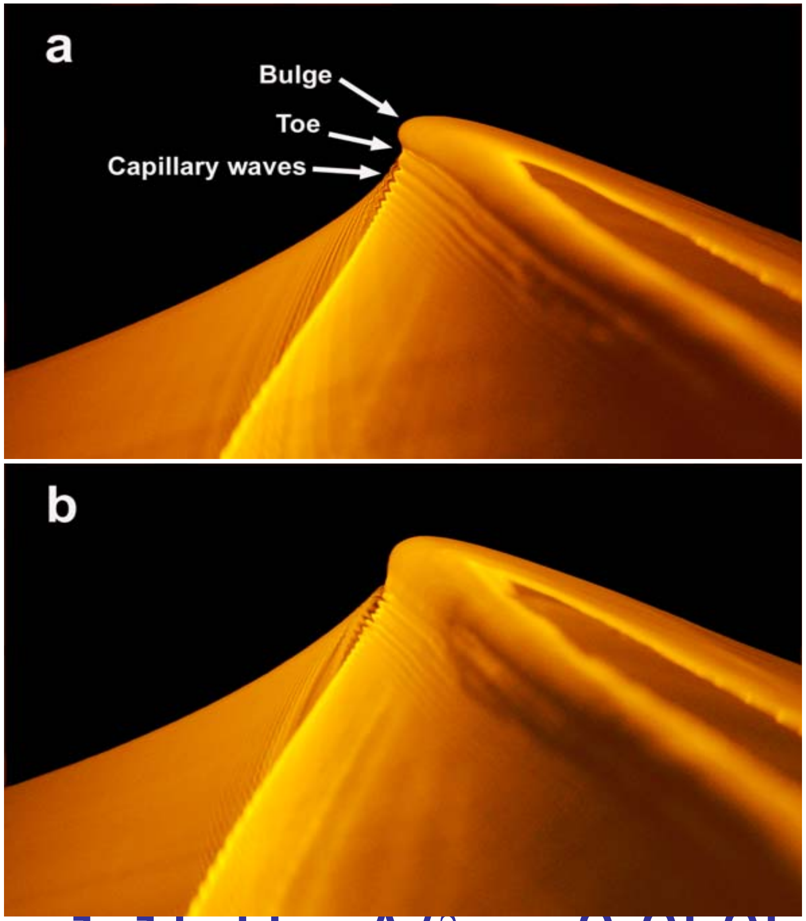


E is the static elasticity

The small plunging jets

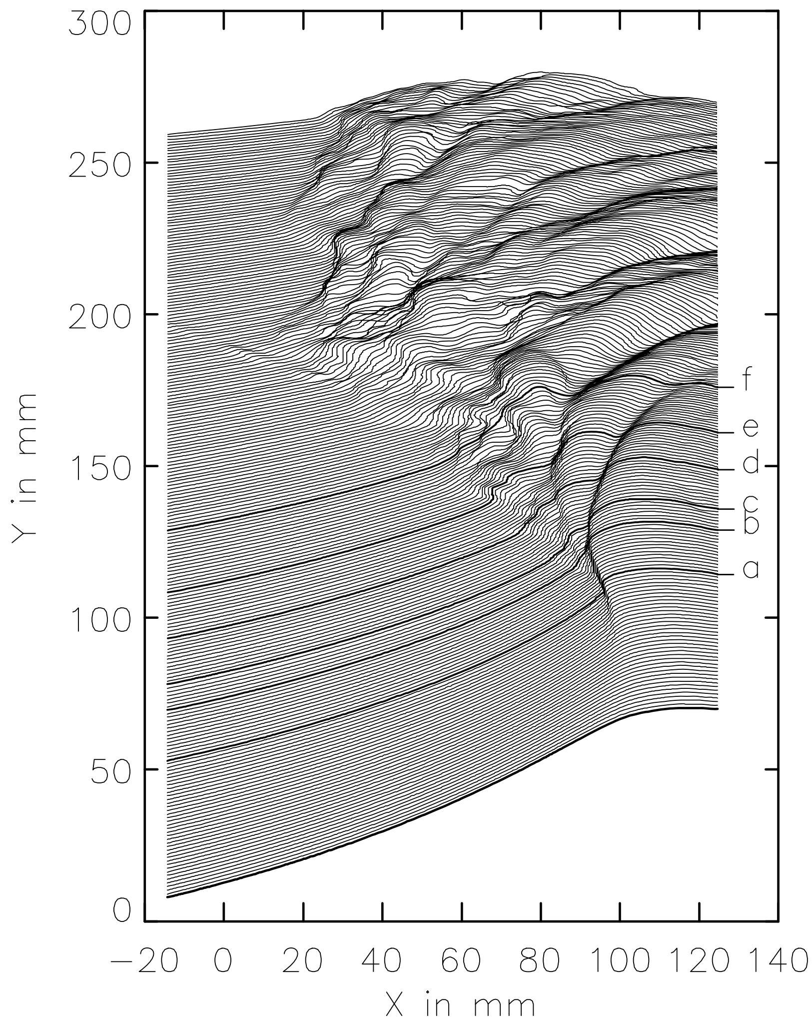
- Occurred in the solution where the concentration of Triton X-100 was above CMC
- Appeared in some of the experiments at the highest concentration of SDS with specific surface dynamic properties.
- The jet tip trajectory is parabolic but the vertical acceleration is less than g

The breaker in clean water

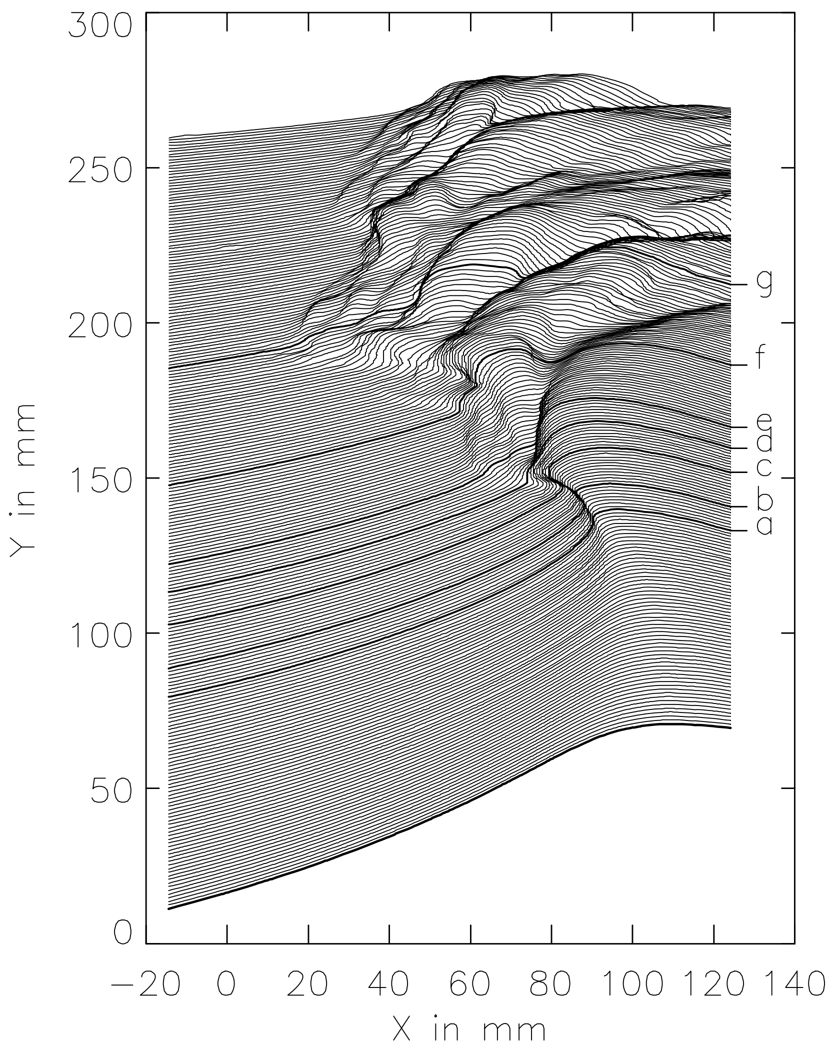


$f_0 = 1.15$ Hz, $A/\lambda_0 = 0.0505$

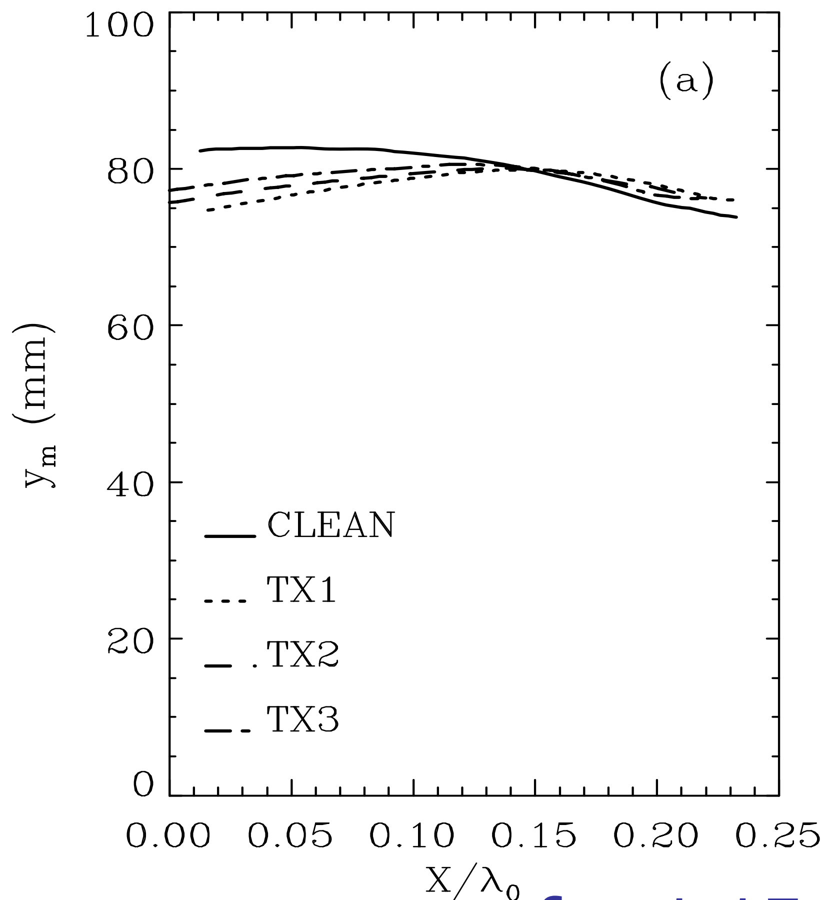
The profile history of the breaker in TX3

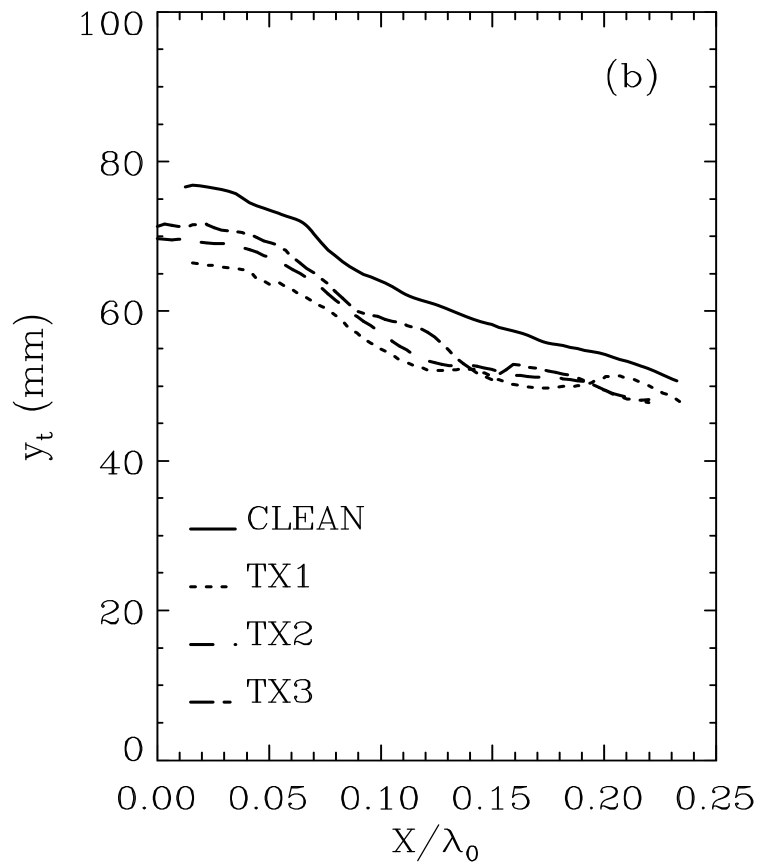


The profile history of the breaker in TX5



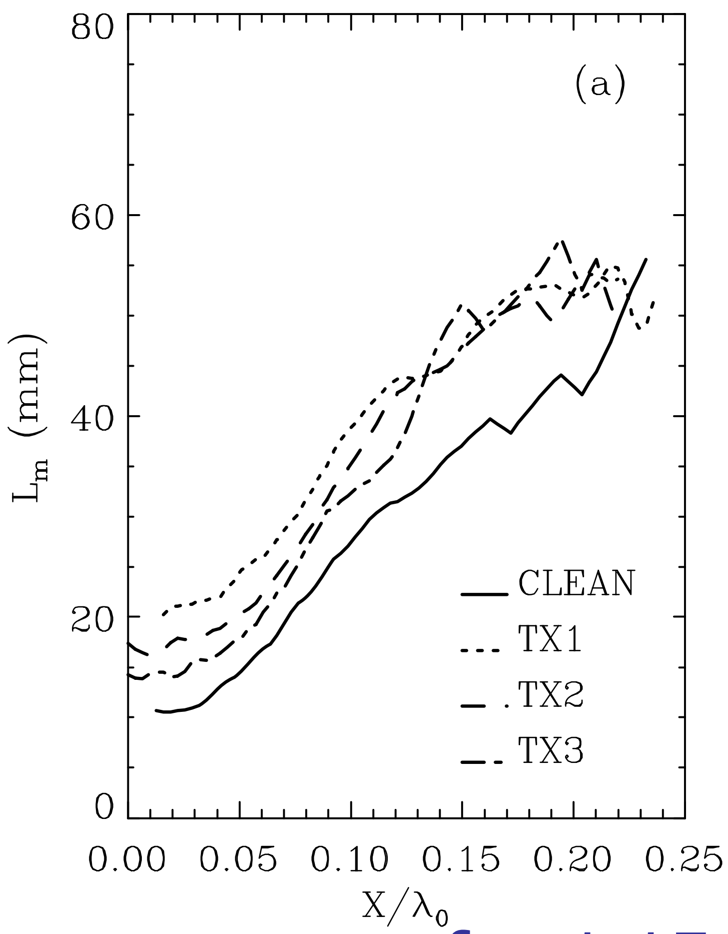
Effect on geometrical parameters when the concentration below CMC. 1, (y_m, y_t)

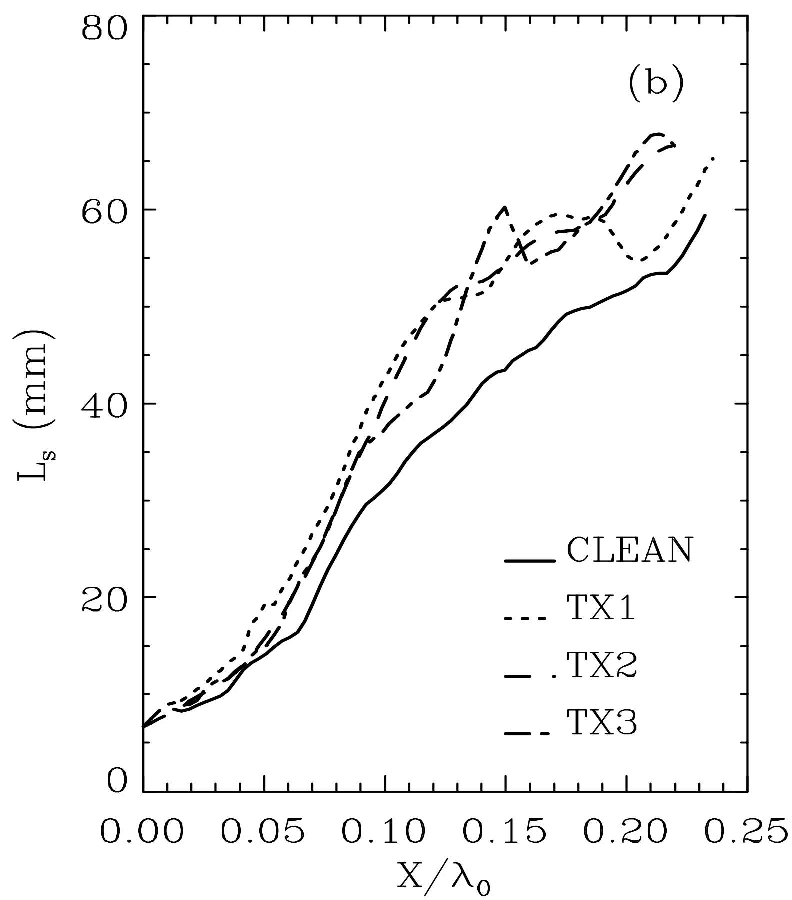




f_0 =1.15 Hz, A/λ_0 =0.0505

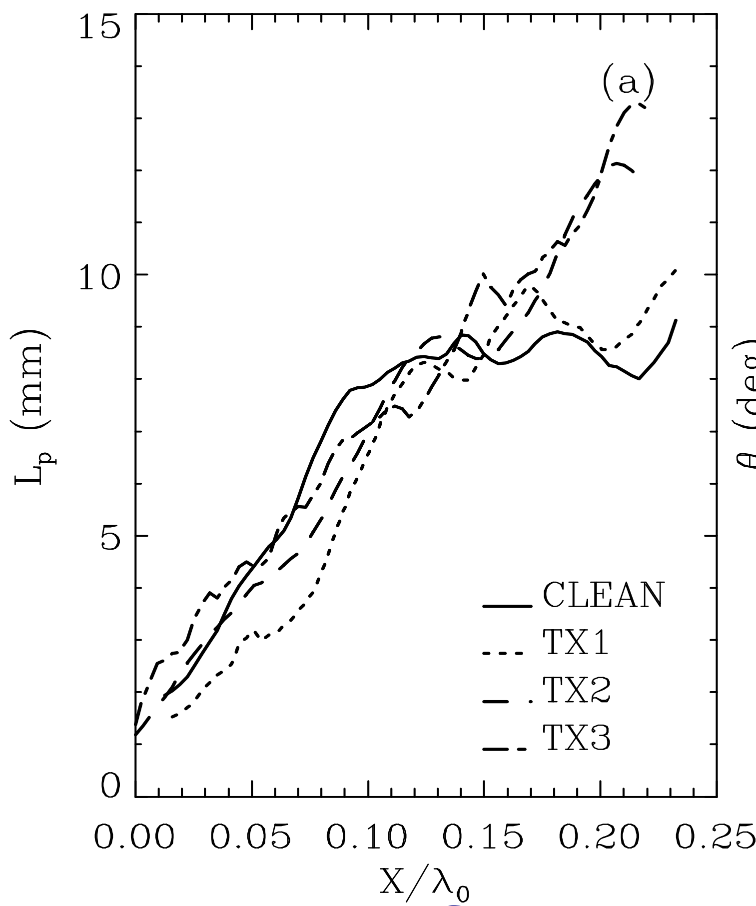
Effect on geometrical parameters when the concentration below CMC. 2, (L_m, L_s)

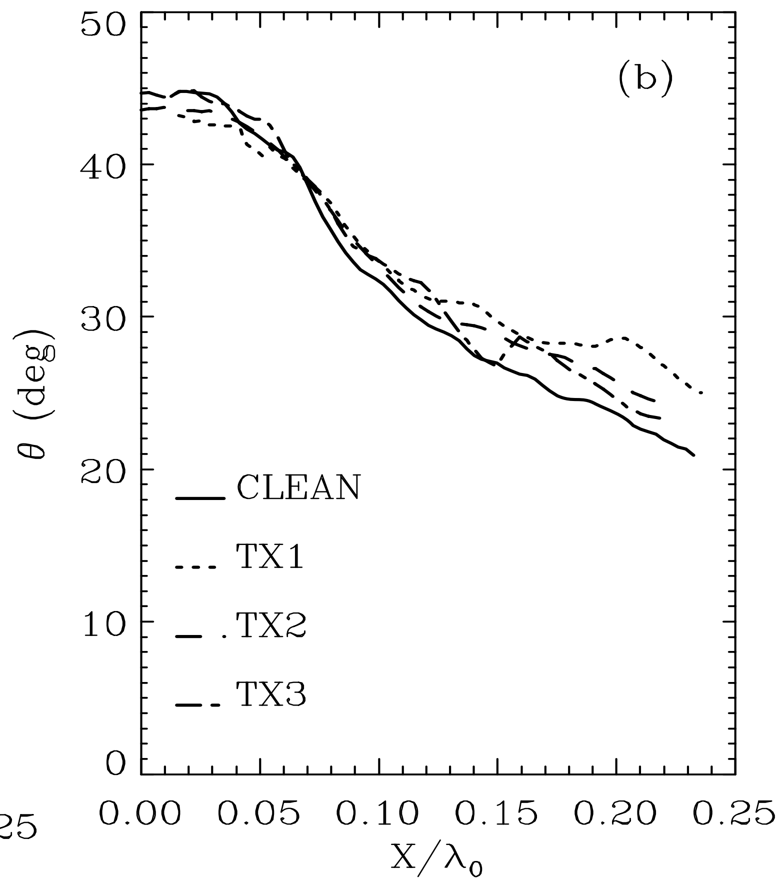




f_0 =1.15 Hz, A/λ_0 =0.0505

Effect on geometrical parameters when the concentration below CMC. 3, (L_p, θ)





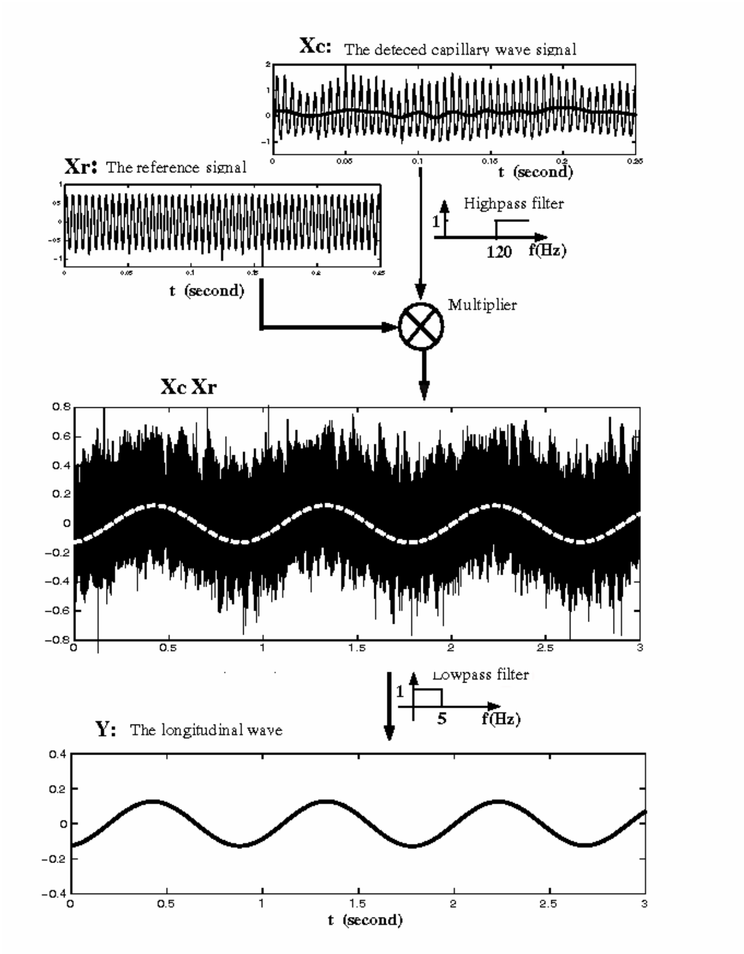
f_0 =1.15 Hz, A/λ_0 =0.0505

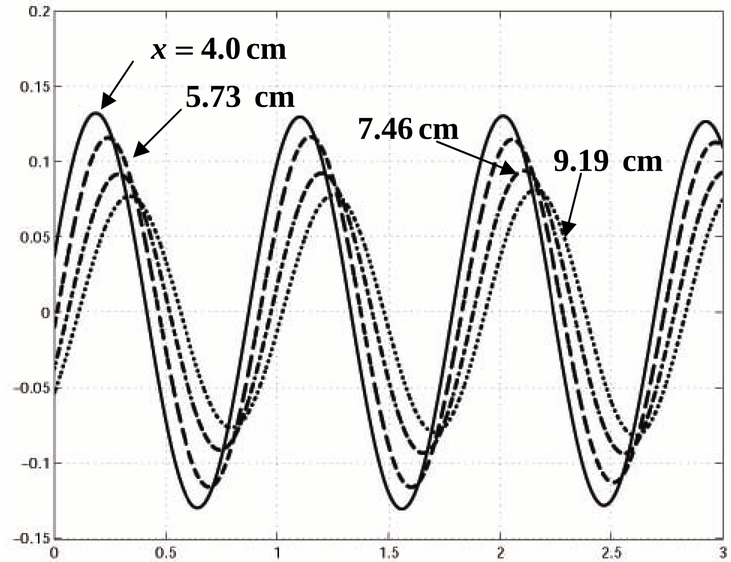
Comparison and scaling analysis

- Comparison of geometrical parameters in TX2 and SDS3, where σ_0 is nearly the same
- Comparison of geometrical parameters, when scaled by their wavelength in TX2 and SDS3.
- The geometrical parameters are non-dimensioned by the length scales derived from the ambient surface tension, Gibbs elasticity and surface viscosity

Longitudinal wave measurement

Sample results





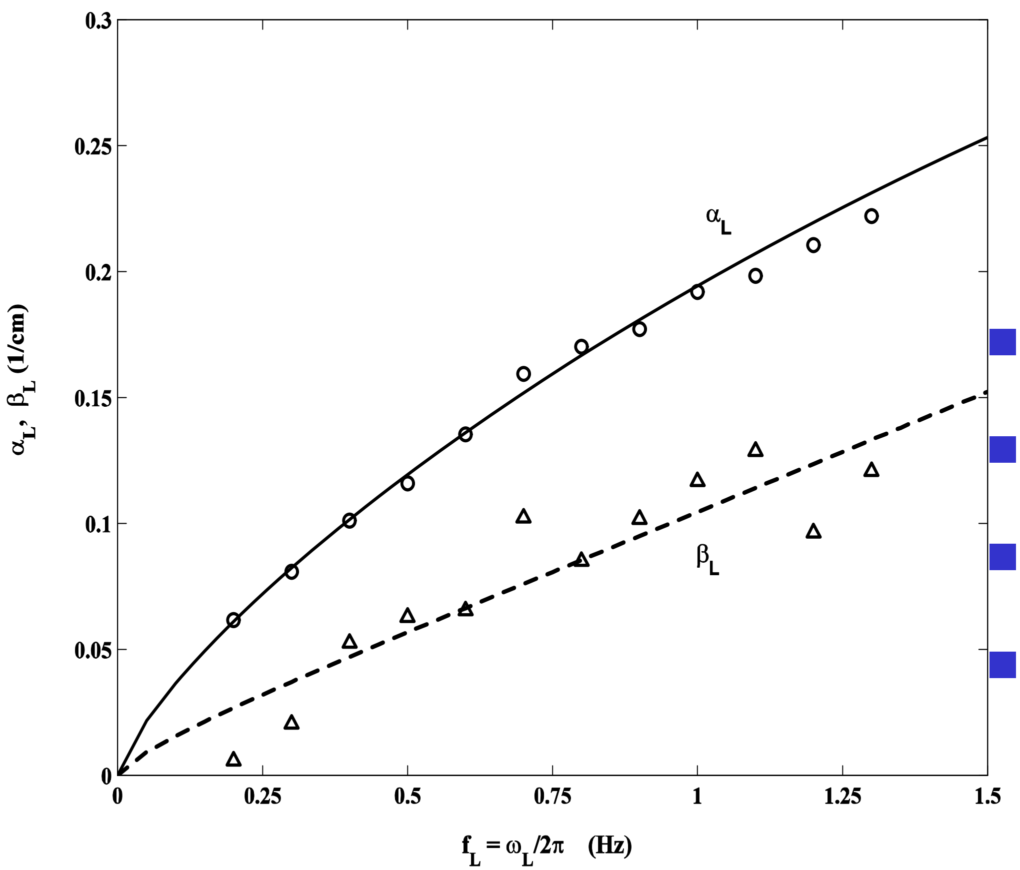
$$\Delta\sigma(x,t) = |\Delta\sigma|_0 \, e^{-\beta_L x} \cos(\alpha_L x - \omega_L t + \Phi_0)$$

$$\Phi = \alpha_L x + \Phi_0$$

$$|\Delta\sigma| = |\Delta\sigma|_0 \, e^{-\beta_L x}$$

Surface Properties Measurements

Gibbs elasticity and surface viscosity



$$k_L^2 = \frac{(\rho\mu\omega_L^3)^{1/2}}{E_0 - i\omega_L\mu_s} e^{i\pi/4}$$

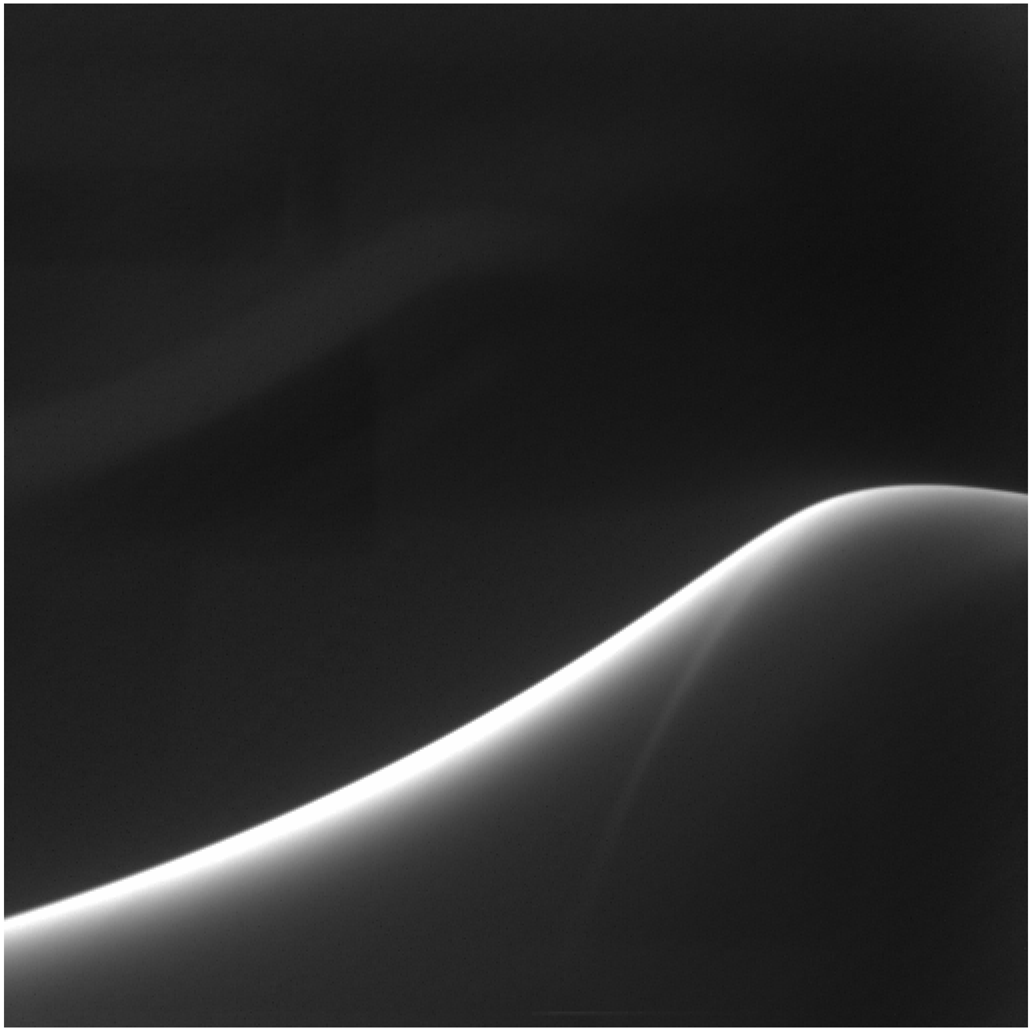
- E_0 = 31.7mN/m
- μ_s = 1.05 (mN.s/m)
- $\varepsilon_{E_0}/\sqrt{N}$=1.057
- $\varepsilon_{\mu s}/\sqrt{N}$=0.153

Effects of Surfactants

- The entire ocean is covered to varying degrees by surfactants.
- Suppression of wavelengths below 40 cm is well documented.
- Gas transfer rate, which scales with mean square slope of shorter waves, is reduced in the presence of surfactants.
- These effects occur even at low surfactant concentrations.

*Cox and Munk (1954), Barger et al. (1970), Hunerfuss et al. (1983), Wu (1998), Tang and Wu (1992), Boch et al. (1999), Uz et al. (2002),

The breaker in TX3
(The concentration of Triton X-100 is below CMC)



- Wave parameters:
1. f_0=1.15 Hz
2. A/λ_0=0.0505
- Surface property
1. σ_0=40.6 mN/m
2. E_0=49.07 mN/m
3. μ_s=1.30 mN.s/m

Plan of Research

- Explore effects of surfactants on weak/short-wavelength mechanically generated breaking waves.
  - Measure crest profile histories.
  - Measure surface dynamic properties.
  - Correlate breaking behavior and measurements with surface property measurements.

Clean-Water Experiments

- Okuda (1982) Internal flow structure of short wind waves
- Ebuchi, Kawamura and Toba (1987) – Fine structure of laboratory wind-wave surfaces
- Duncan, Qiao, Behres and Kimmel (1994) Weak spilling breakers
- Duncan, Qiao, Philomin and Wenz (1999) Crest profile evolution
- Qiao and Duncan (2001) Crest flow field evolution

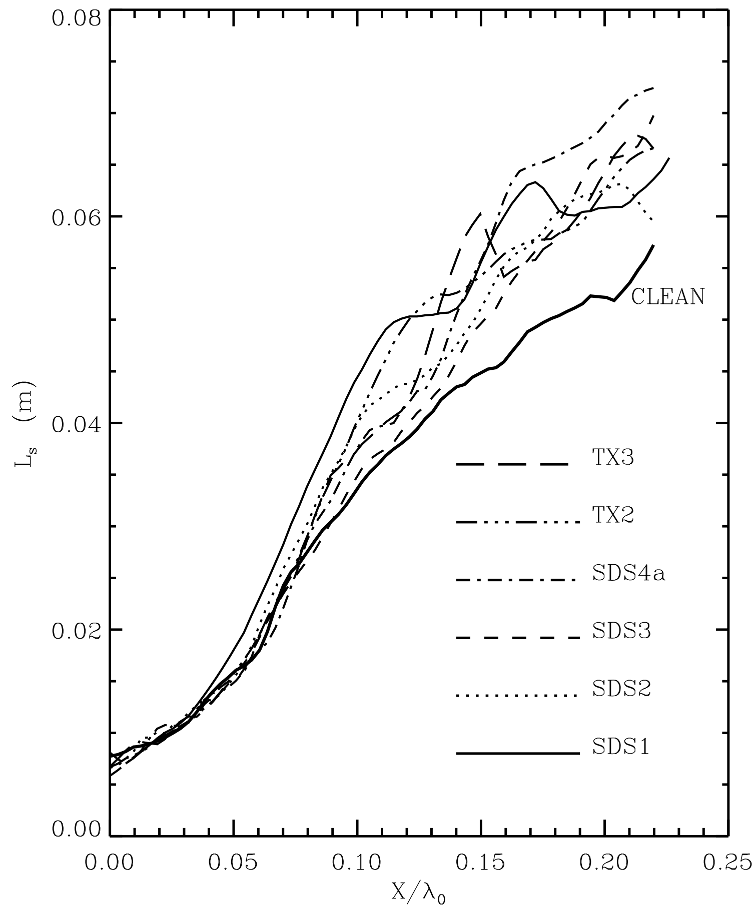
Wave Generation

- Dispersive focusing (Longuet-Higgins (1976) Rapp and Melville (1990))
- Parameters adjusted so that packet focuses to form a weak breaker.
- All generation parameters Froude scaled with average wave-packet frequency.
  - Wedge depth, wedge-motion amplitude, breaking distance.

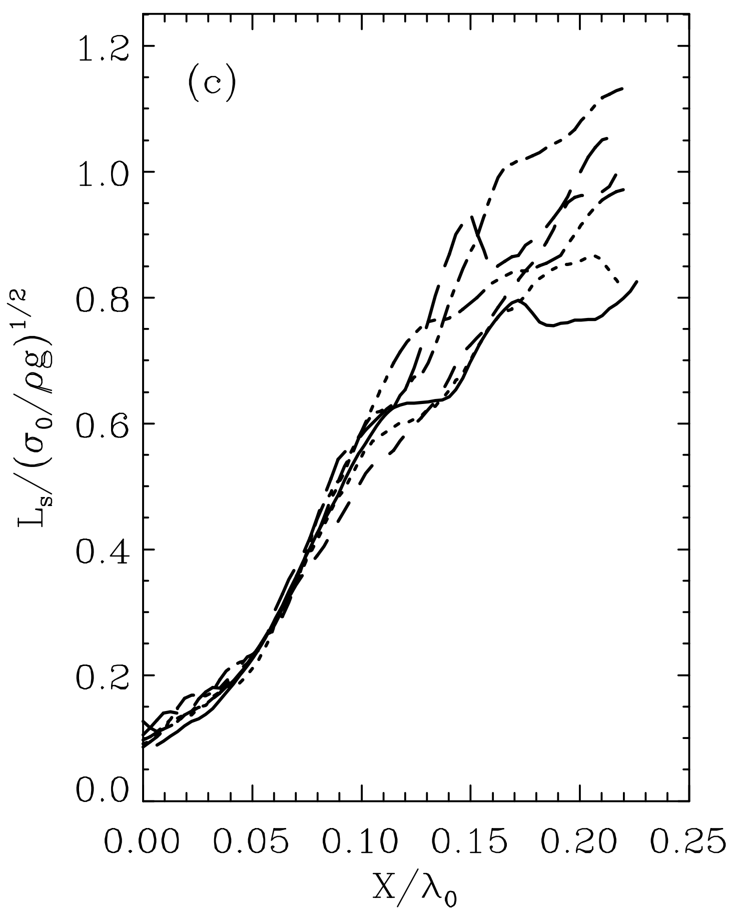
Water Treatment continued

- Surfactant rheology experiments usually done with distilled water in bench top experiments under very clean conditions.
- Present experiments are performed with 5,000 gallons of tap water.
- There are other surfactants in the tank in addition to those intentionally introduced.
- Correlate wave measurements with *in-situ* measurements of dynamic properties not specific surfactants.

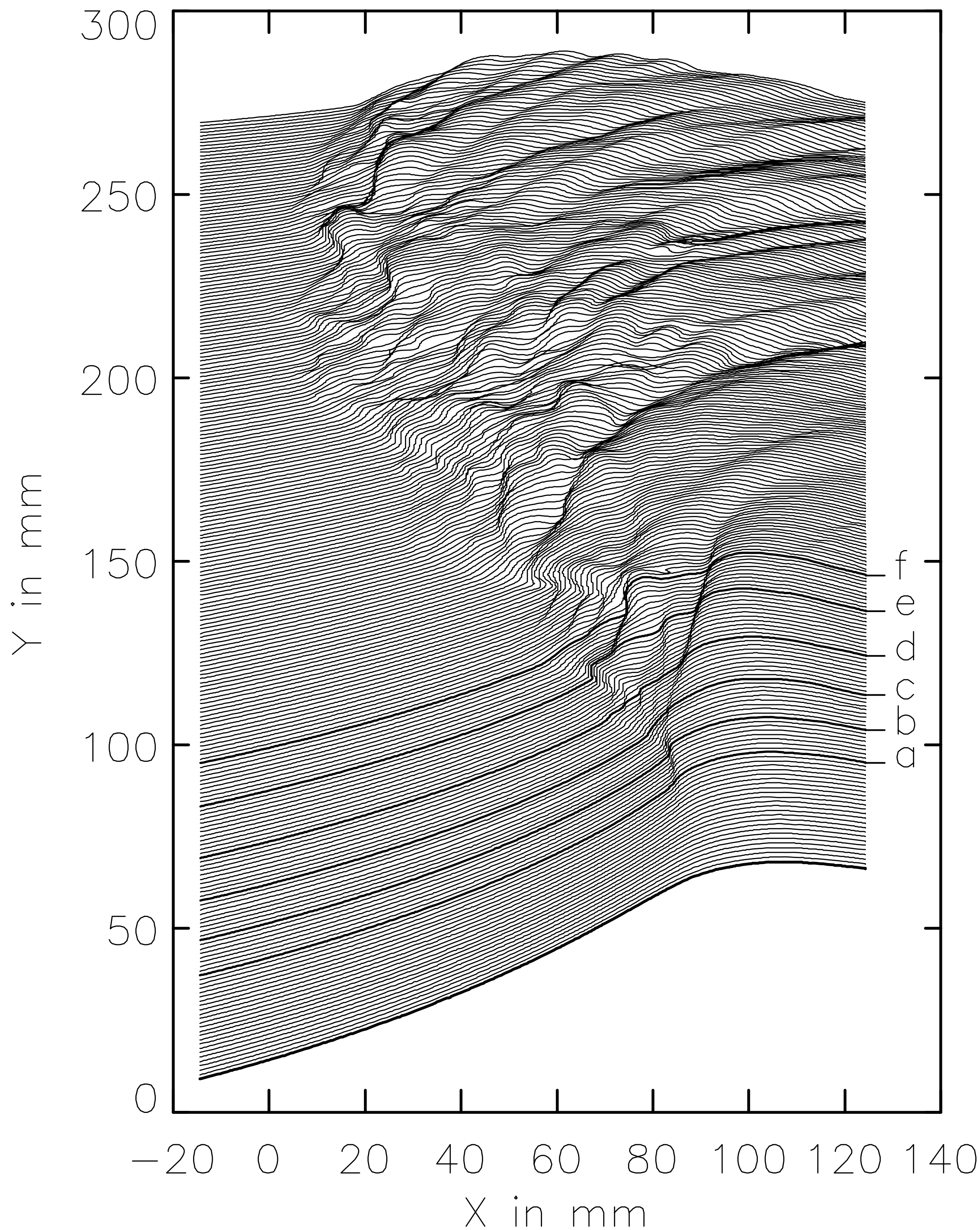
Histories of Geometric Parameters



Histories of L_m Scaled by Gravity-Viscous Wavelength



TX1



300
250
200
150
100
50
0
Y in mm
−20
0
20
40
60
80
100
120
140
X in mm
f
e
d
c
b
a