TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

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Insitute for Process Engineering and Environmental Technology

Lecture 10: Foam Measurement

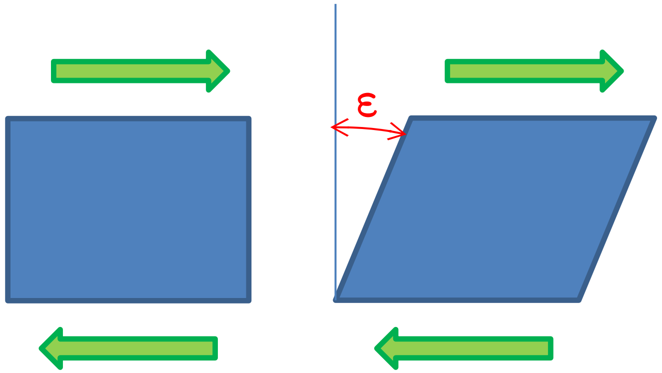
Structure

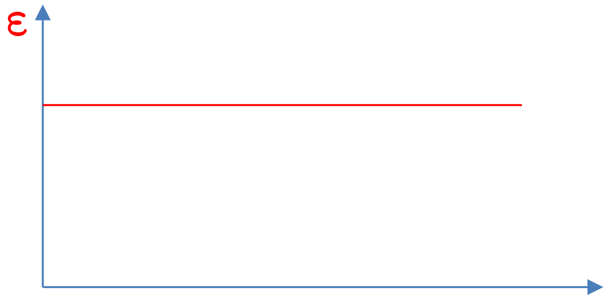
- Review lecture 9
- Optical measurement
- Resistivity measurement
- Radiography/Tomography
- Velocity measurement

Response to stress:

- Elastic body

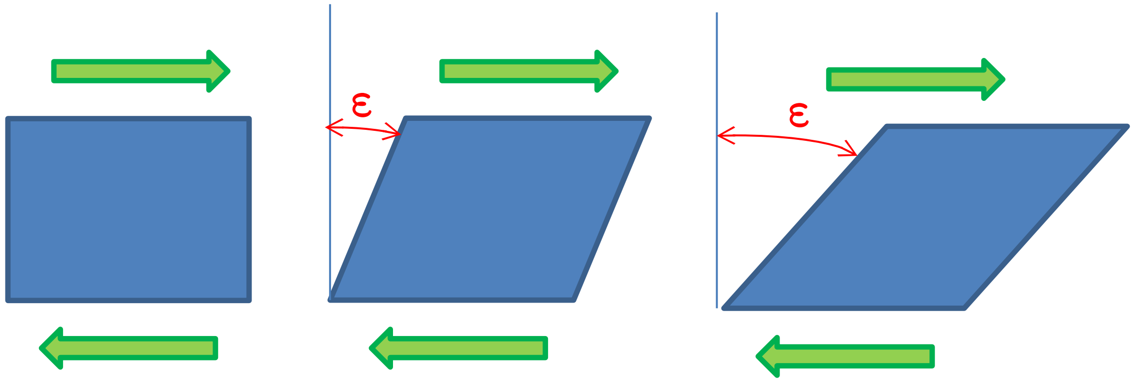
Constant stress → constant strain **angle** ε

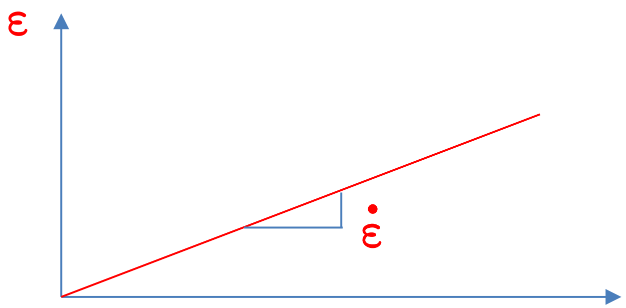


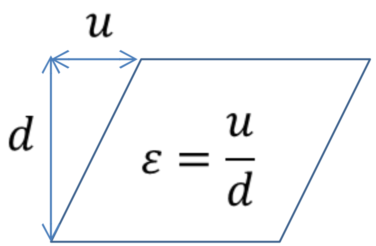


- Newtonian fluid:

Constant stress → constant strain **rate** $\dot{\varepsilon}$

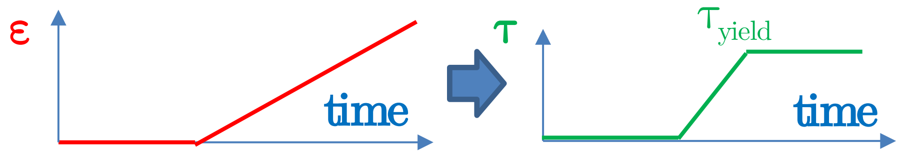


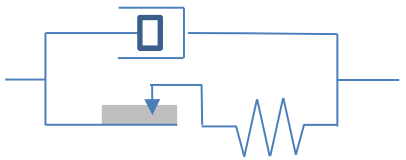


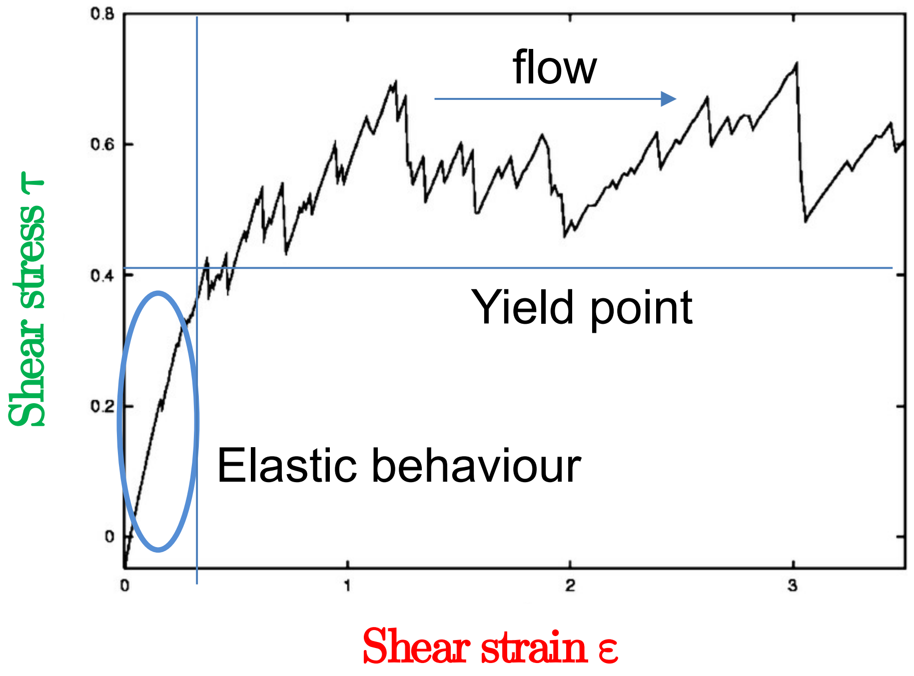


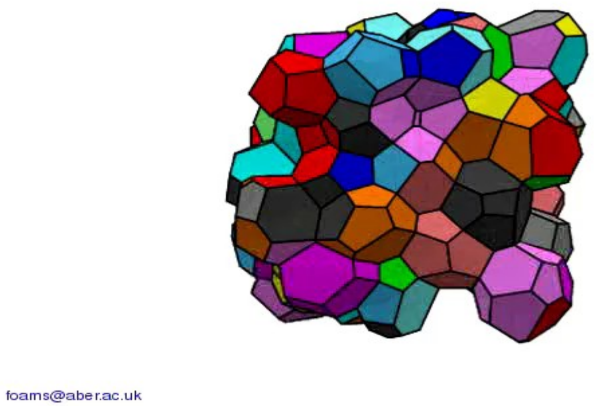
Rheology of foam

- Low strain: elastic behaviour
- Critical yield stress causes bubble rearrangement
- Viscous behaviour at high stress, strain



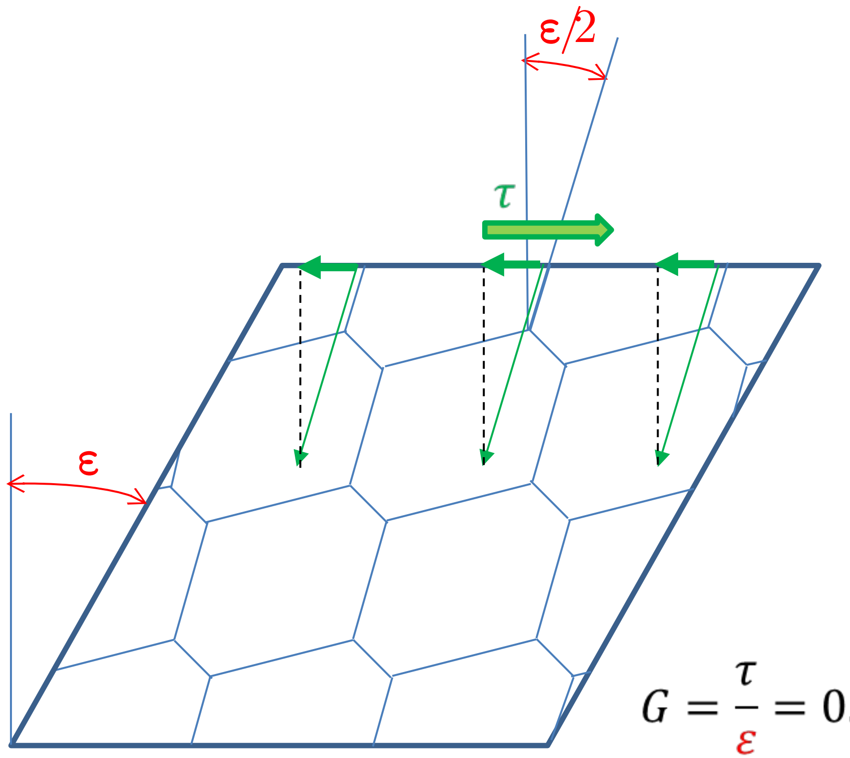






Simple aproach: 2D foam

- Dry, monodisperse 2D foam forms hexagonal pattern
- Shear stress results from surface tension of cutted lamellas

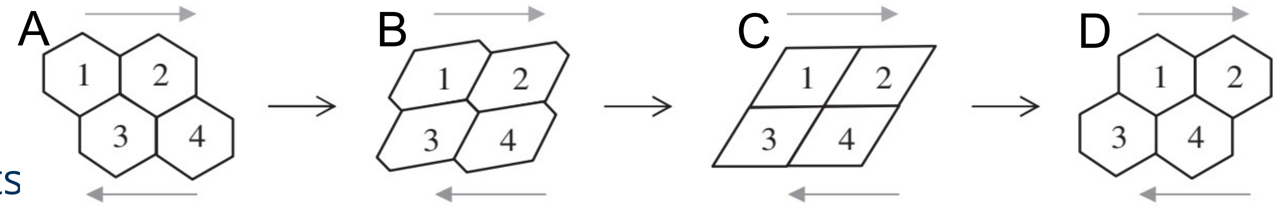


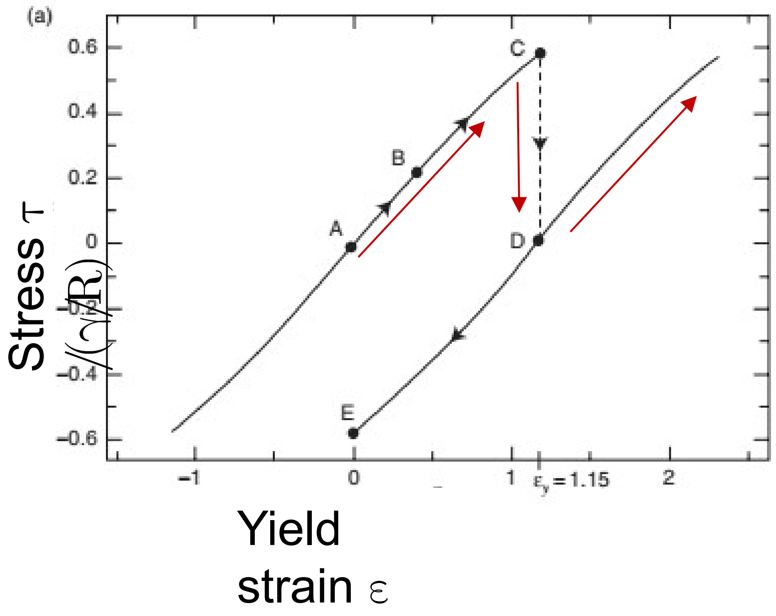
$$G = \frac{\tau}{\varepsilon} = 0.525 \frac{\gamma}{R_e}$$

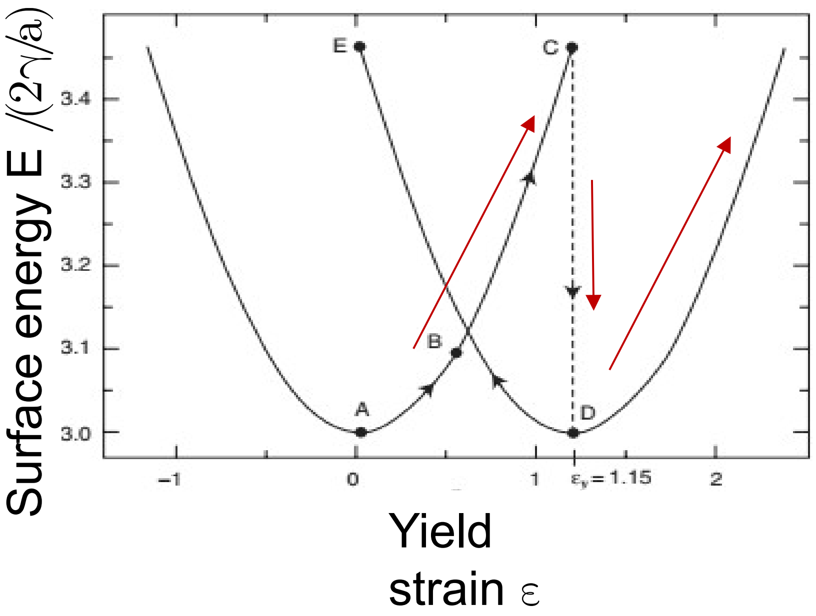
$$G = \frac{\tau}{\varepsilon} = 0.51 \frac{\gamma}{R_e}$$

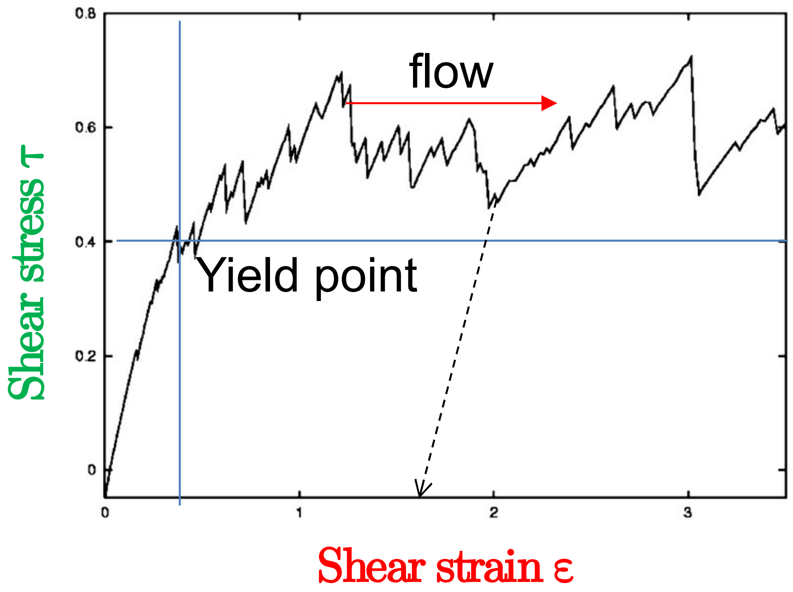
Yield point for 2D foam

- Flow of foam is a sequence of T1 rearangements







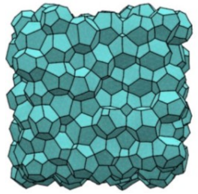


$$\varepsilon_{yield} = 1.15$$

$$\tau_{yield} = 0.603\frac{\gamma}{R_e}$$

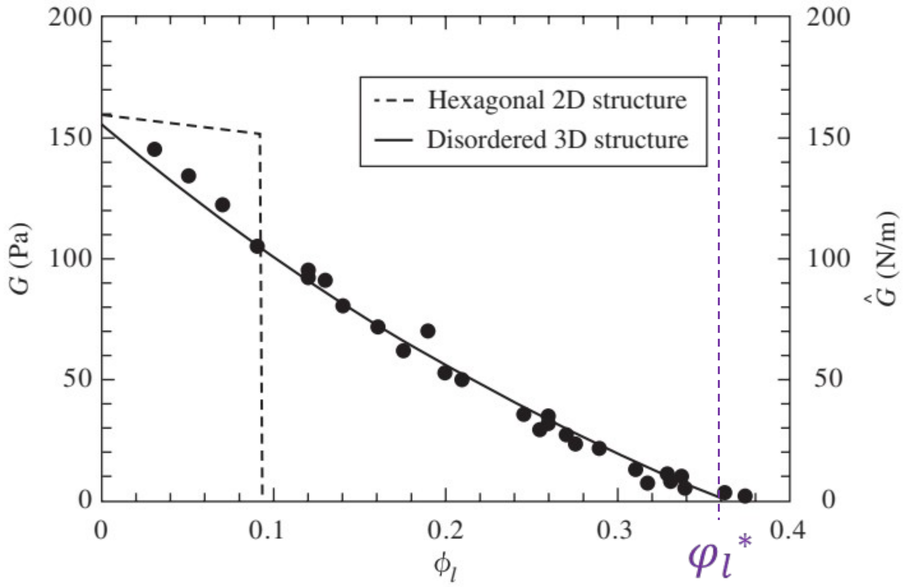
$$\varepsilon_{yield} \approx 0.15\ \dots 0.4$$

$$\tau_{yield} \approx 0.1\ \dots 0.2\frac{\gamma}{R_e}$$

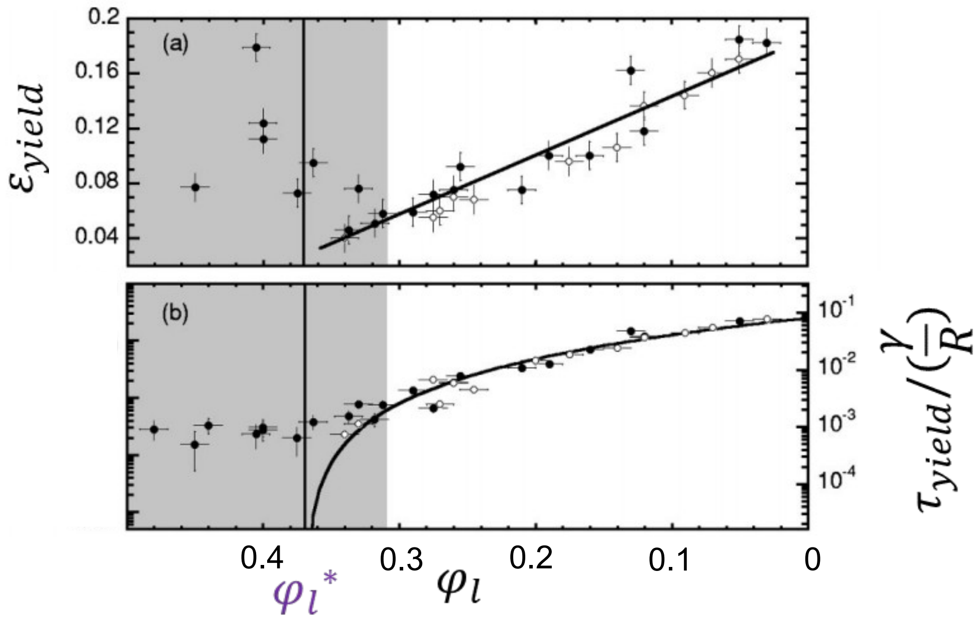


Elastic behaviour of wet foam

- Experimental results: liquid fraction reduces shear modulus
- Loss of rigidity at jamming point (36% liquid fraction)



$$G = 1.4(1-\varphi_l)(\varphi_l{}^* - \varphi_l)\frac{\gamma}{R_e}$$

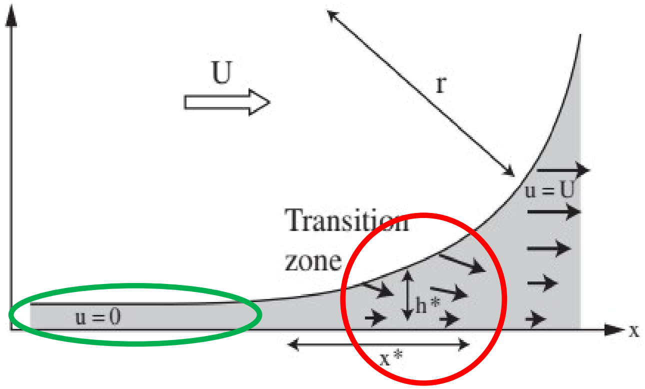


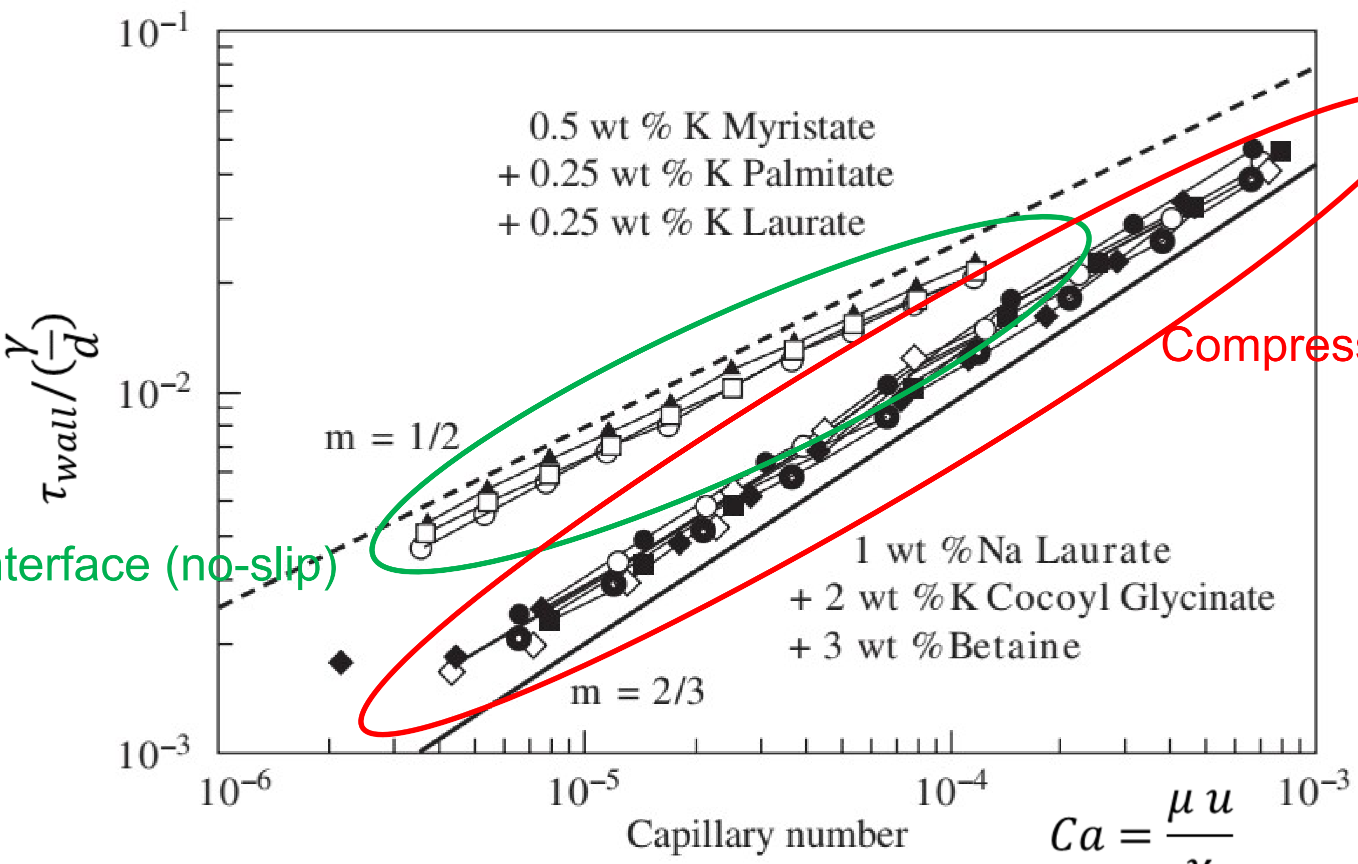
$$\varepsilon_{yield} \approx a_1(\varphi_l{}^* - \varphi_l), \qquad a_1 \approx 0.5\,..\,1.0$$

$$\tau_{yield} \approx a_2\frac{\gamma}{R_e}(\varphi_l{}^* - \varphi_l)^2, \qquad a_2 \approx 0.2\,..\,0.5$$

Role of surface compressibility

- Surface compressibility (mobility) depends on surfactant
- Compressible interfaces result in lower wall stress





$Ca = \frac{\mu u}{\gamma}$

$\tau_{wall} \sim \frac{\gamma}{d} Ca^{1/2}$

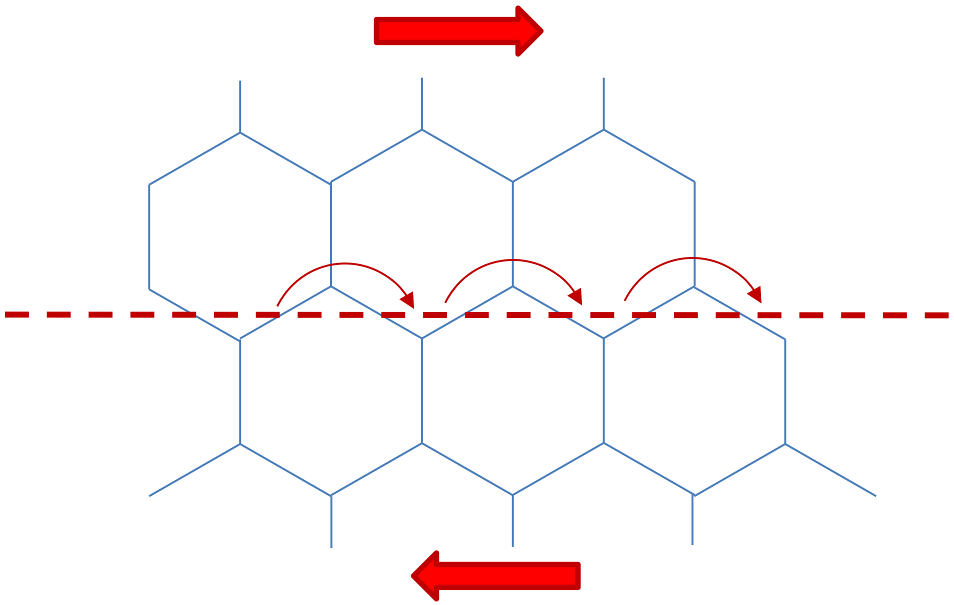
incompressible interface (no-slip)

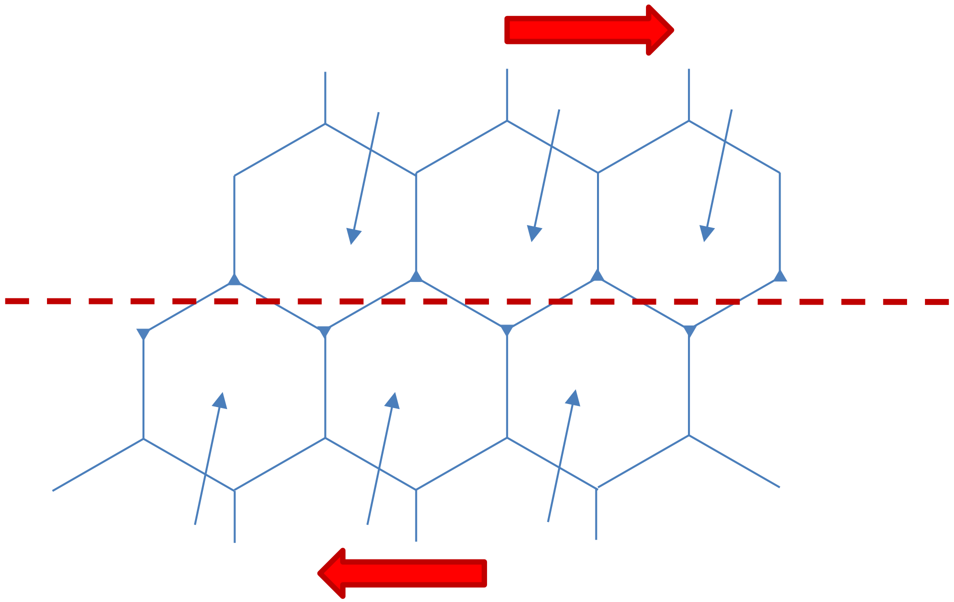
Compressible interface (free-slip)

$\tau_{wall} \sim \frac{\gamma}{d} Ca^{2/3}$

Shear banding

- T1 rearrangements are localized in a single sliding layer (band)?
- Local shear might attract more liquid (dilatancy)
- Locally higher liquid fraction reduces shear modulus, stabilizing shear layer





Rheometer

- Review on foam rheology

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **17** (2005) R1041–R1069 doi:10.1088/0953-8984/17/41/R01

TOPICAL REVIEW

Rheology of liquid foam

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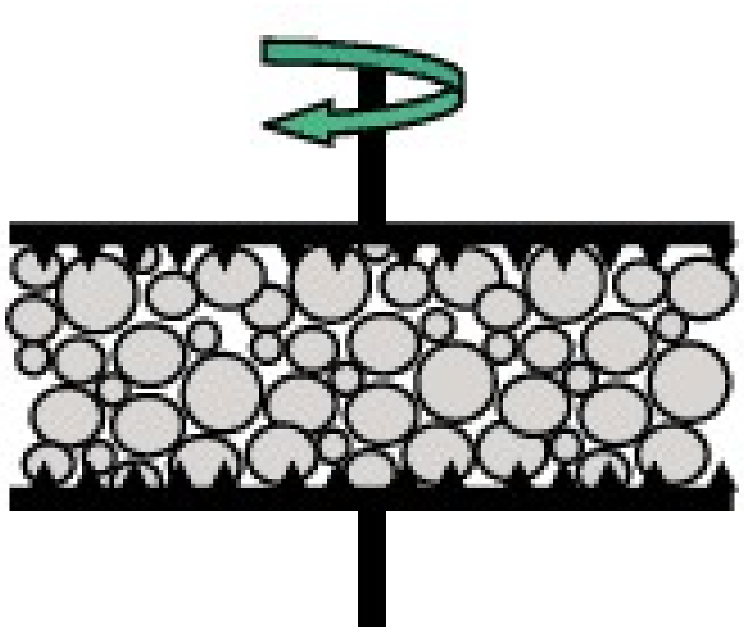
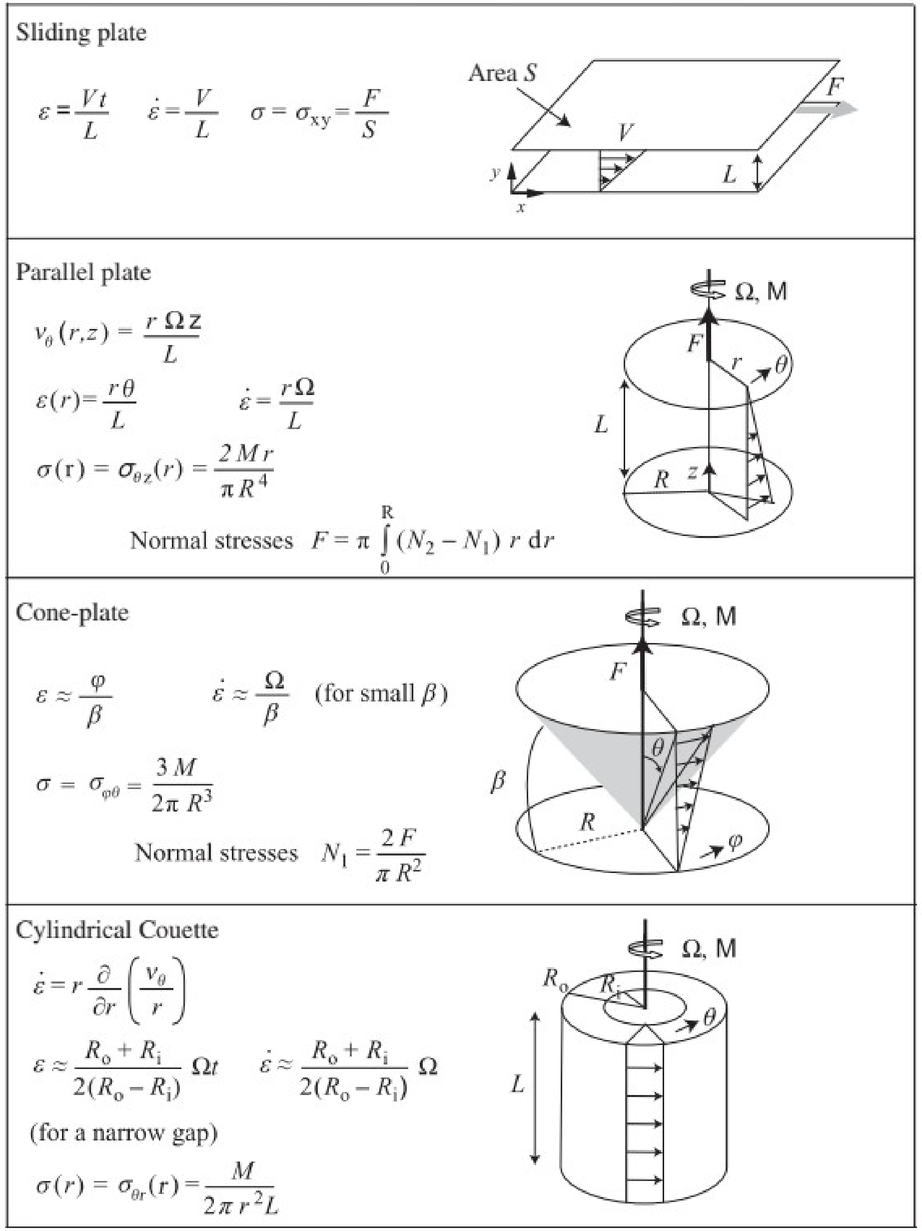
Rheometer

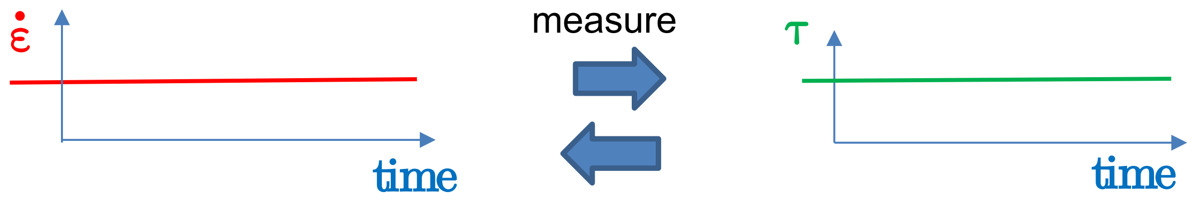
- Measure relation between strain (rate) and stress
- Well defined geometry
- → analytical solution of stress / strain distribution
- Avoid wall slip! → etching grooves, sandpaper





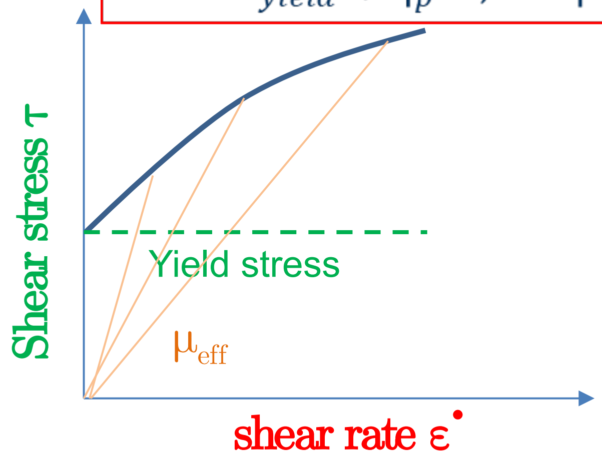
Steady shear

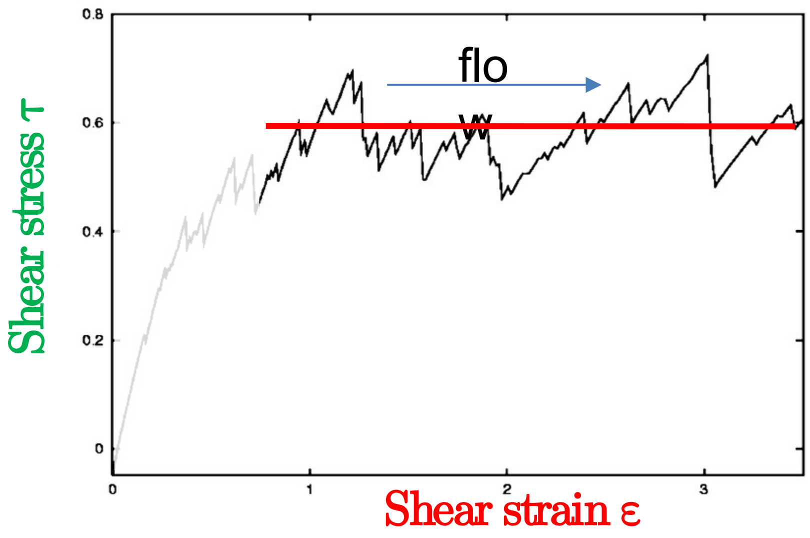
- Set steady shear rate (or steady stress)
- Wait for steady state and measure stress (or shear rate)
- Test different shear rates



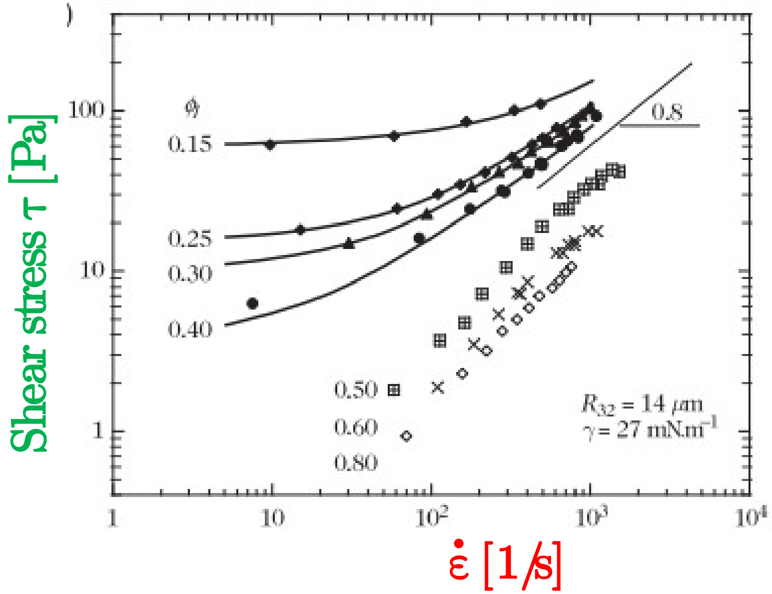
Herschel-Bulkley law

$$\tau = \tau_{yield} + \eta_p \dot{\varepsilon}^{\beta}, \qquad \beta < 1$$



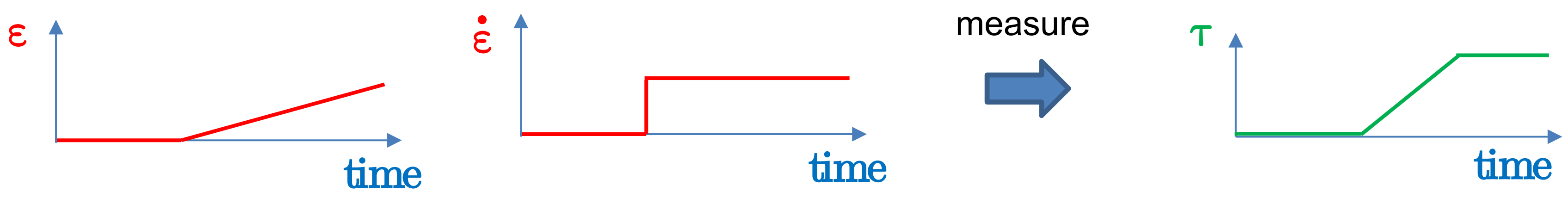


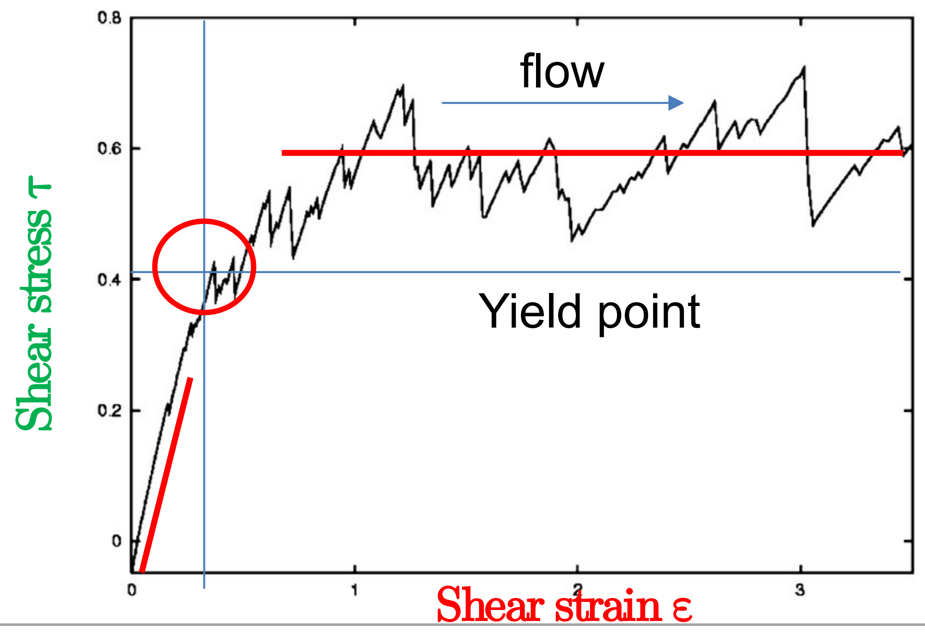
- Effective viscosity $\tau / \dot{\varepsilon}$ in flow state



Shear start-up

- Shear start-up
- Start to shear with constant shear rate, measure corresponding shear stress



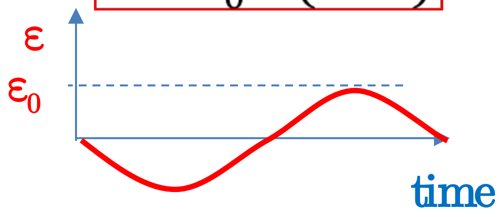


- Elastic shear modulus
- Yield stress

Oscillatory shear

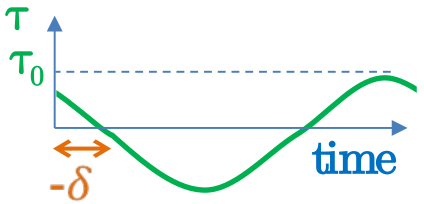
- Sinusoidal strain of amplitude ε_0 and frequency ω
- Wait for steady state and measure resulting stress
- Gives complex shear modulus G*(ω)

$$\varepsilon = \varepsilon_0 \, R(e^{i\omega t})$$



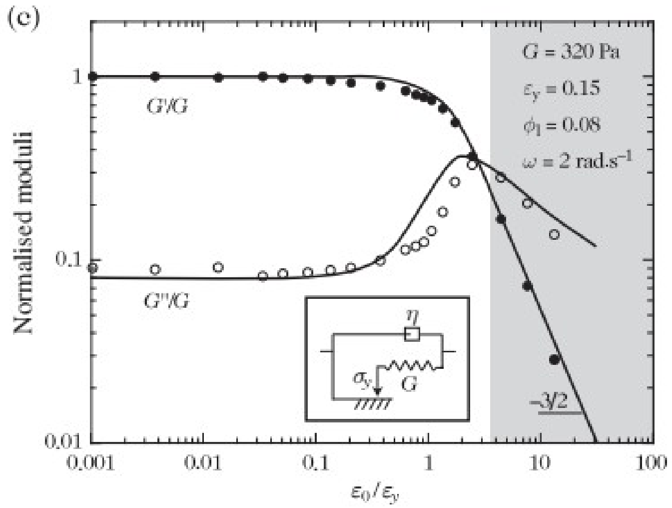
measure

$$\tau = \tau_0 \, R(e^{i\omega t+\delta})$$

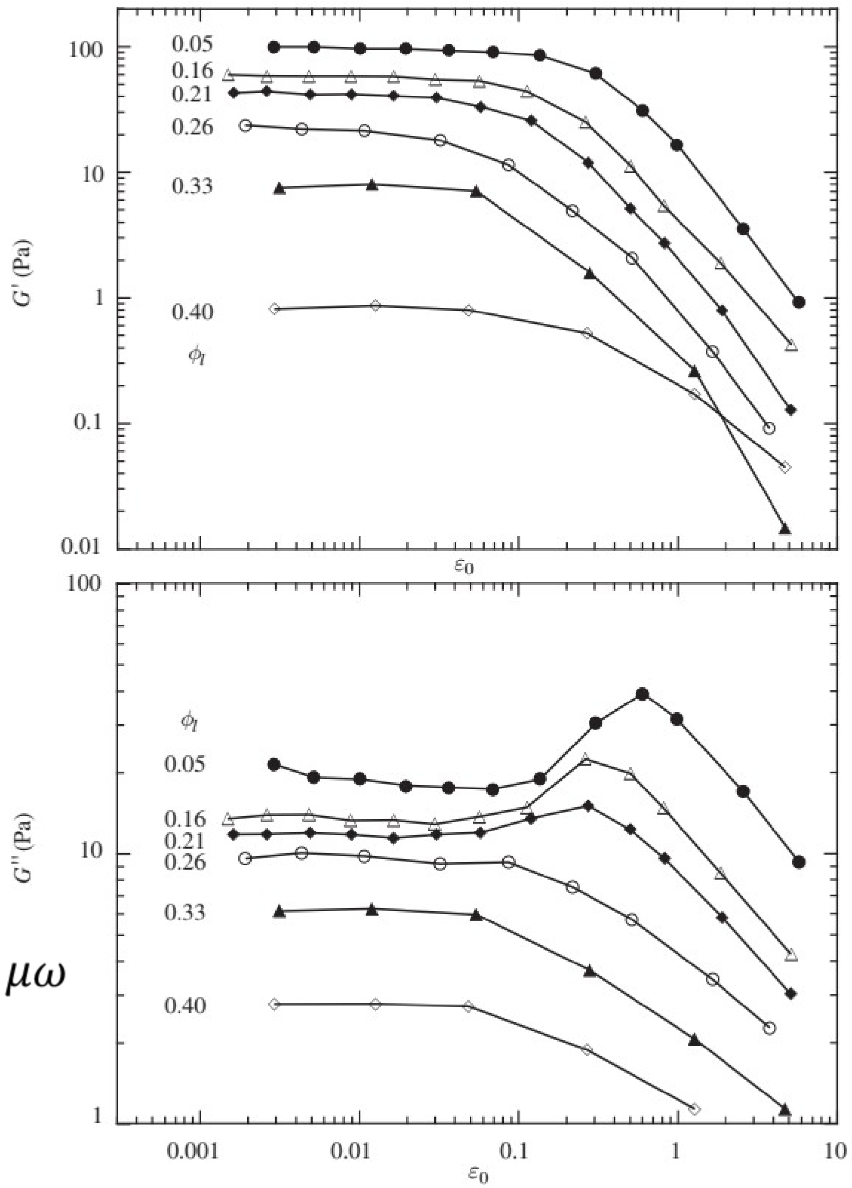


$$\tau = \varepsilon_0 \, R(G^* e^{i\omega t})$$

$$G^* = G' + iG''$$



$$G'' = \mu\omega$$

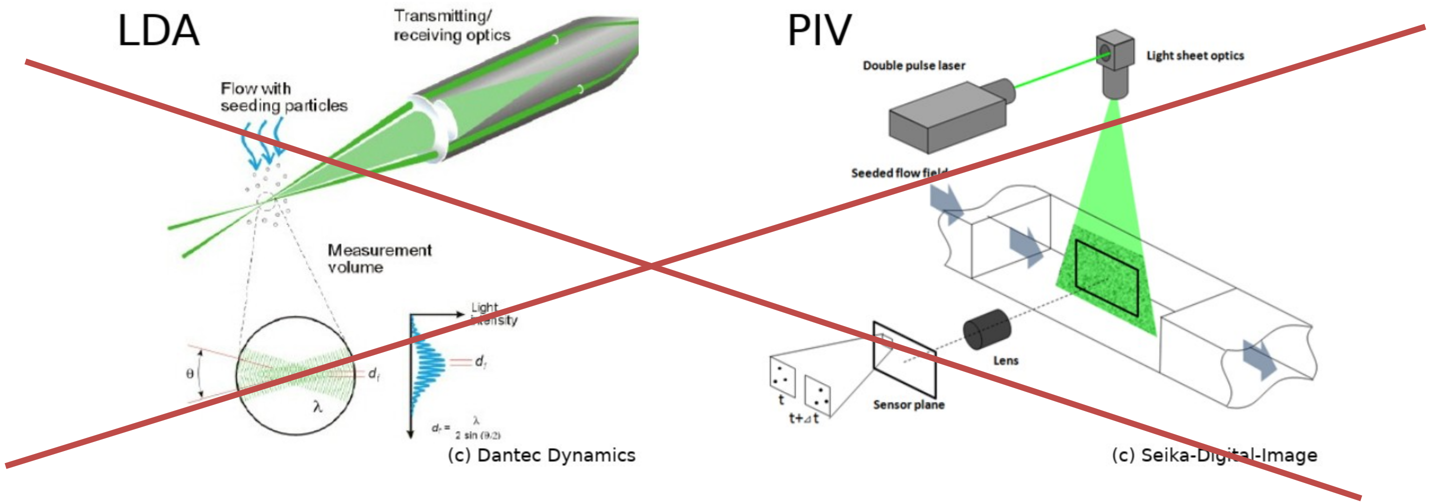


Structure

- Review lecture 9
- Optical measurement
- Resistivity measurement
- Radiography/Tomography
- Velocity measurement

Optical measurement

- Most convenient, but: **Foam is opaque**
- Typically limited to surface of a foam cluster
- Many established measurement techniques are not applicable

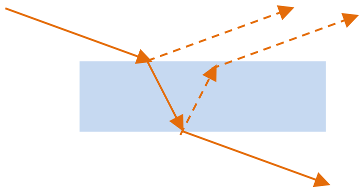


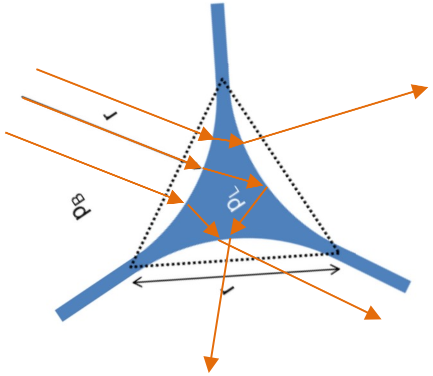
(c) Dantec Dynamics

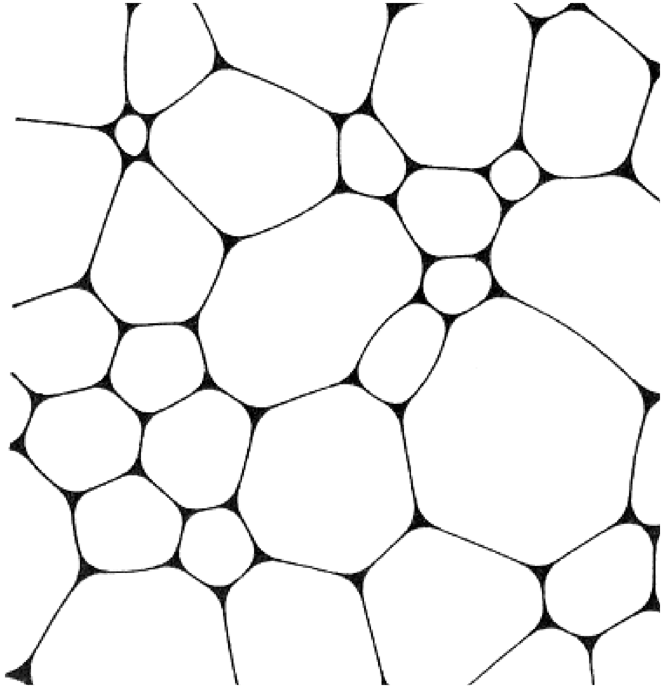
(c) Seika-Digital-Image

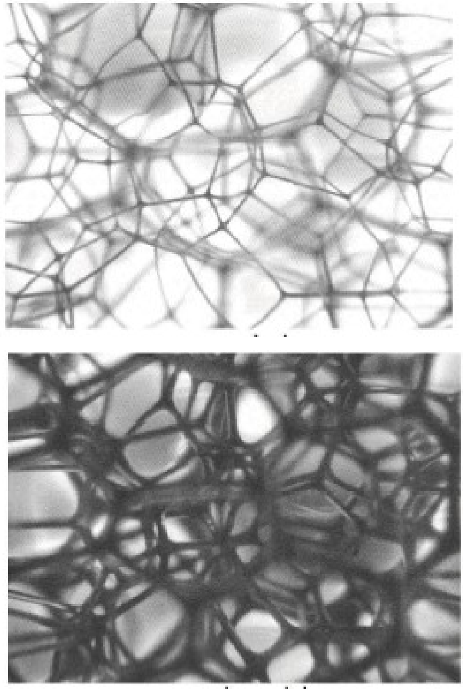
Light refraction

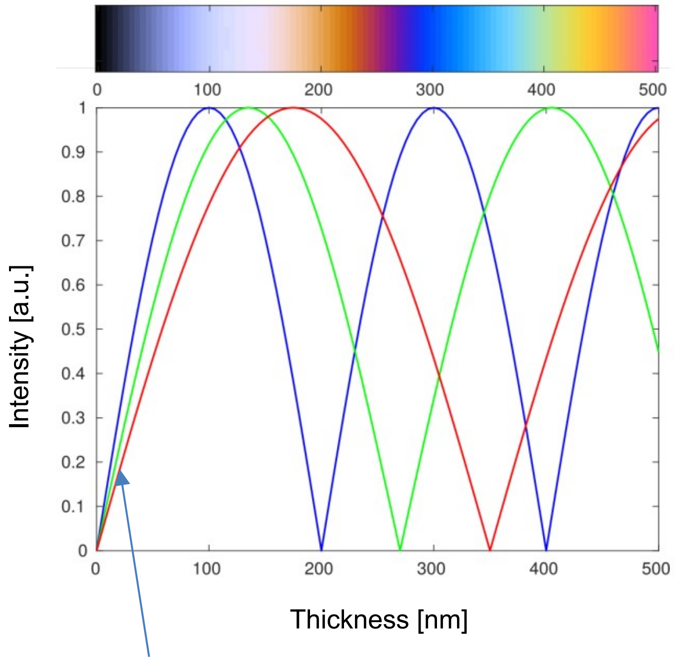
- Thick lamellas – partially reflected, CBF lamellas – no reflection
- Light is refracted/reflected by Plateau borders





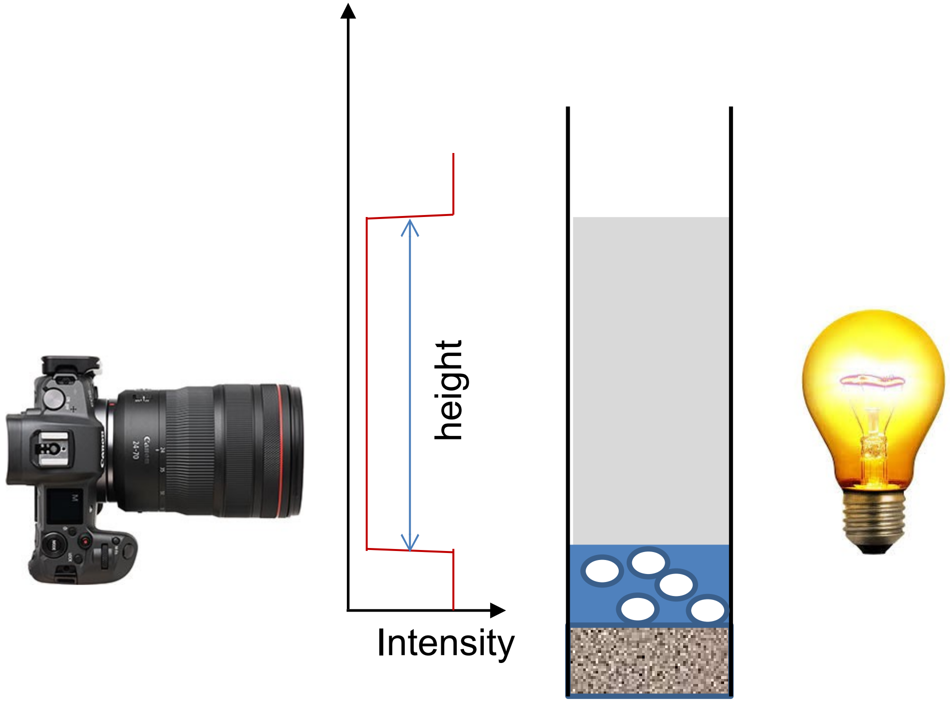


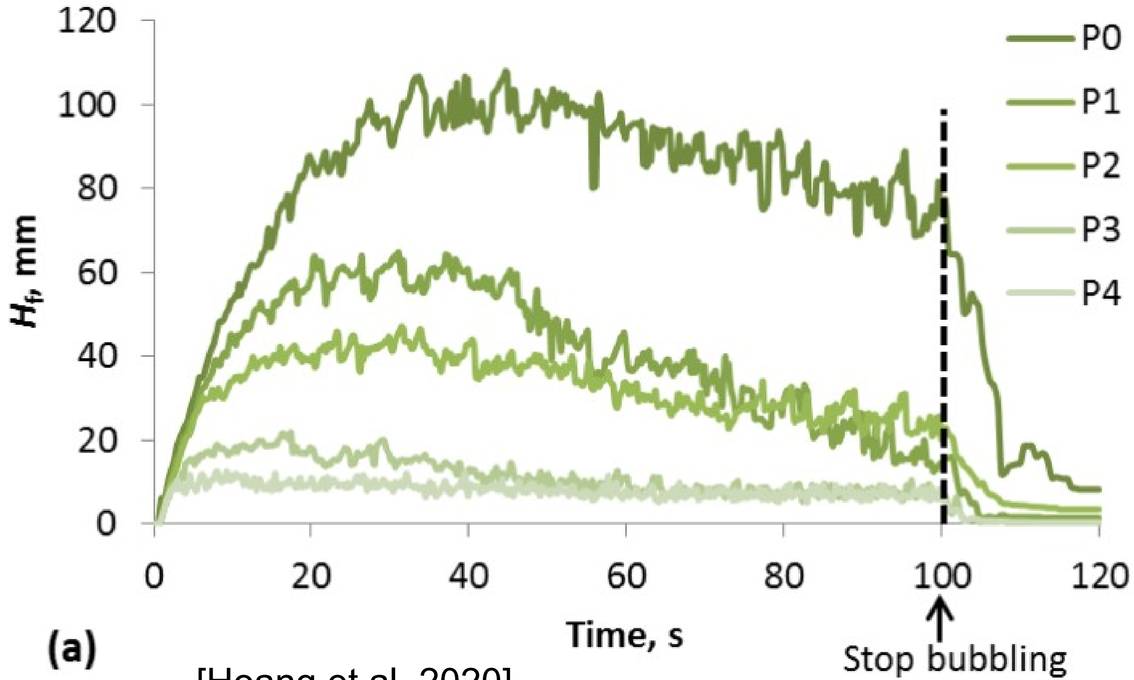




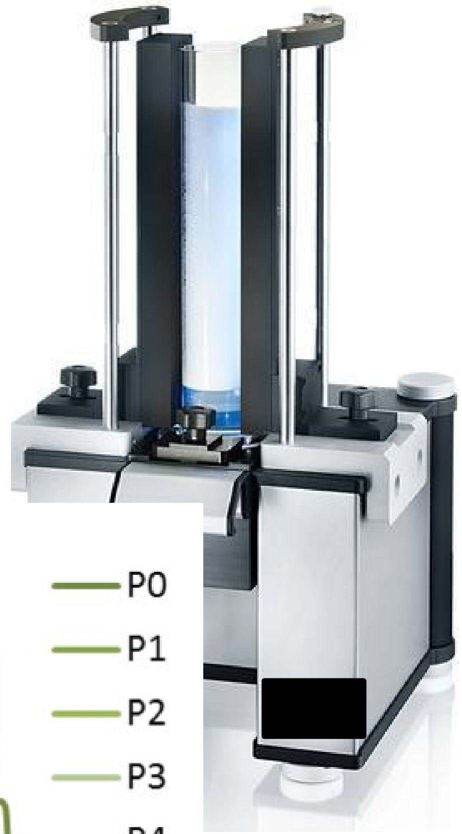
Foam height

- Automated measurement of foam height, using transmittency
- Commercialized in foam test devices



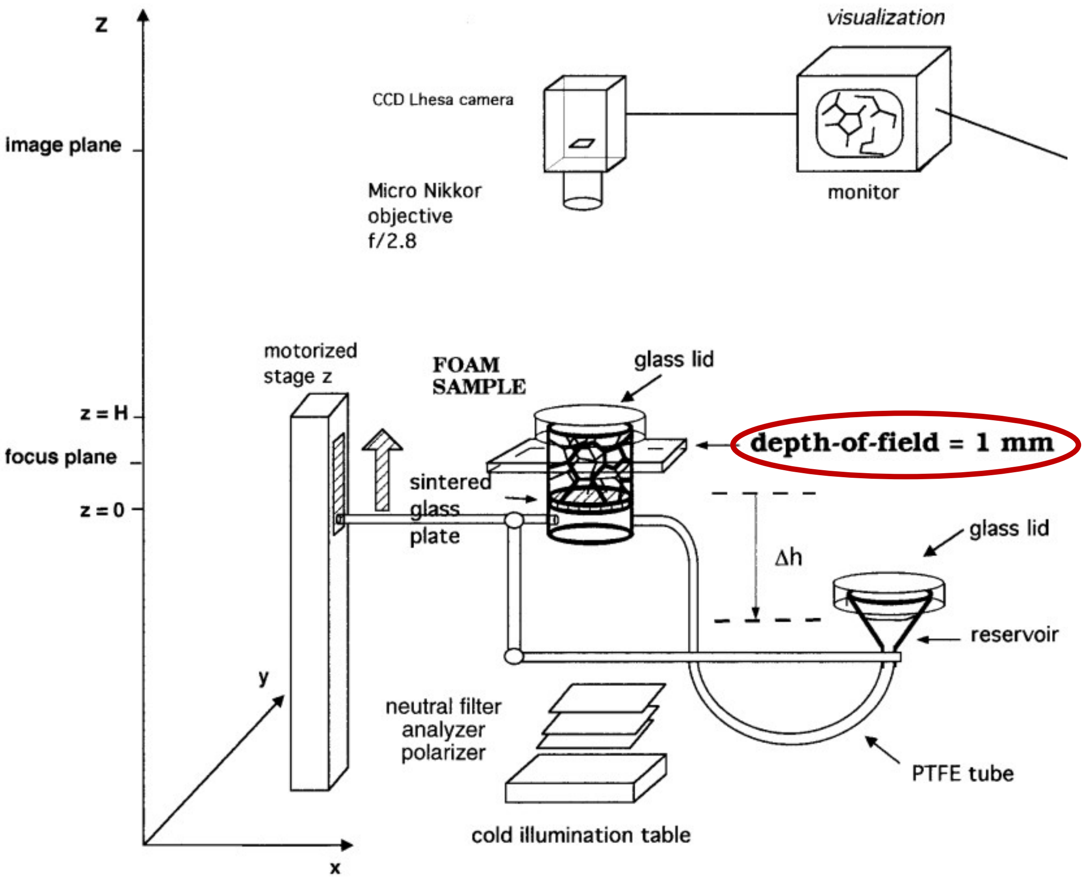


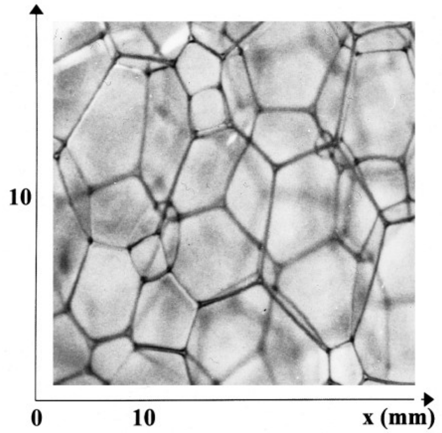
[Hoang et al. 2020]

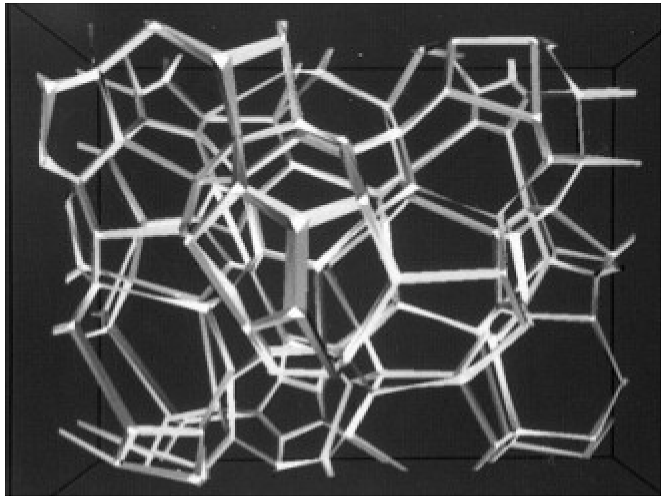


Optical tomography

- Reconstruction of Plateau border structure
- Suitable only for dry foam and lass than 10 bubble diameter thickness



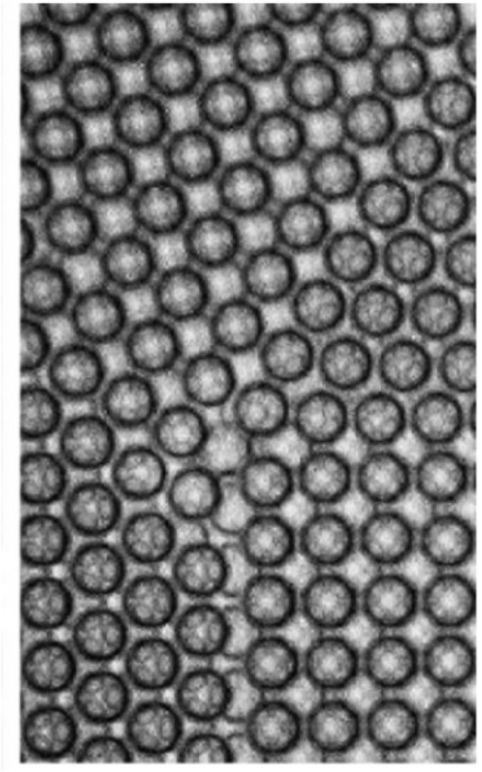


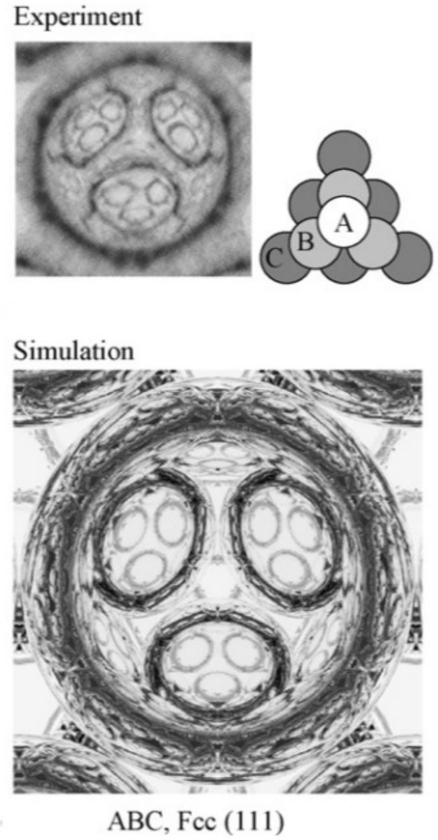


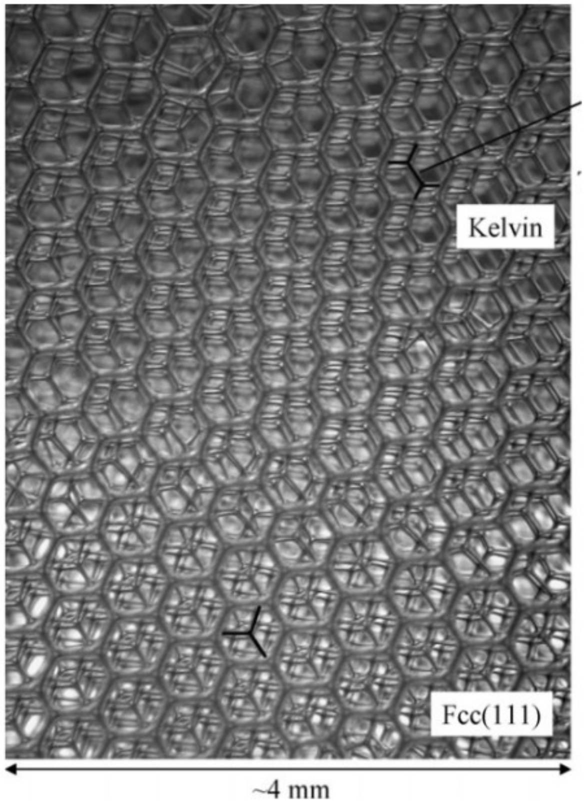
[Monnereau & Vignes-Adler, 1998]

Optical tomography near the boundary

- Careful image processing yields crystalline structure
- Comparison with ray-tracing to tell apart FCC and HCP



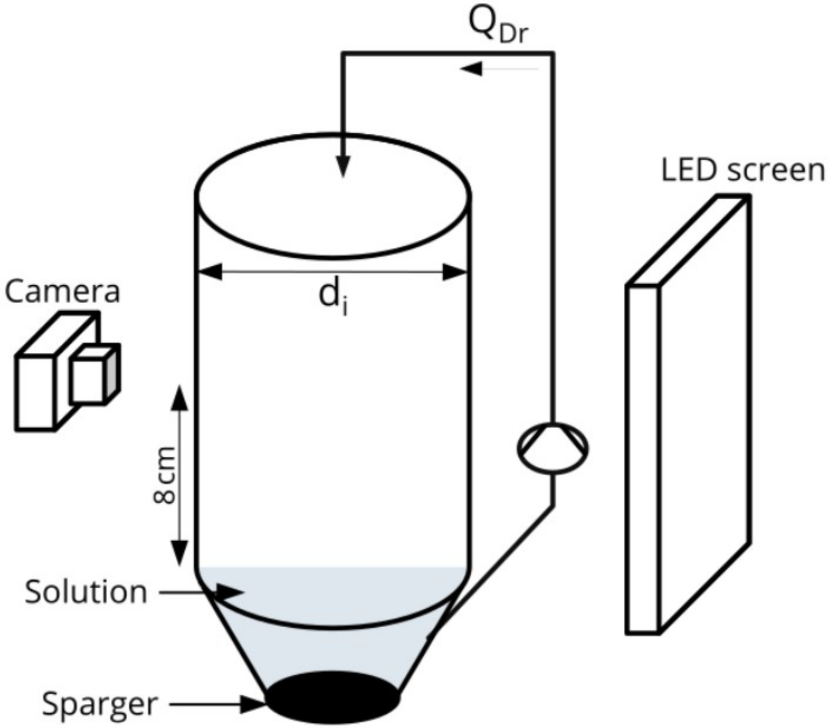


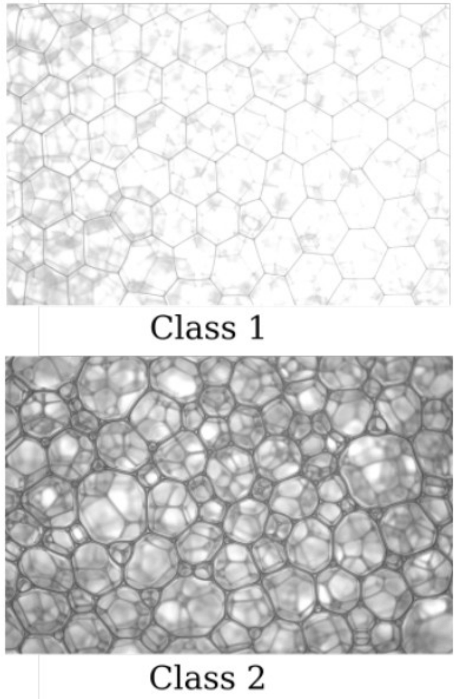


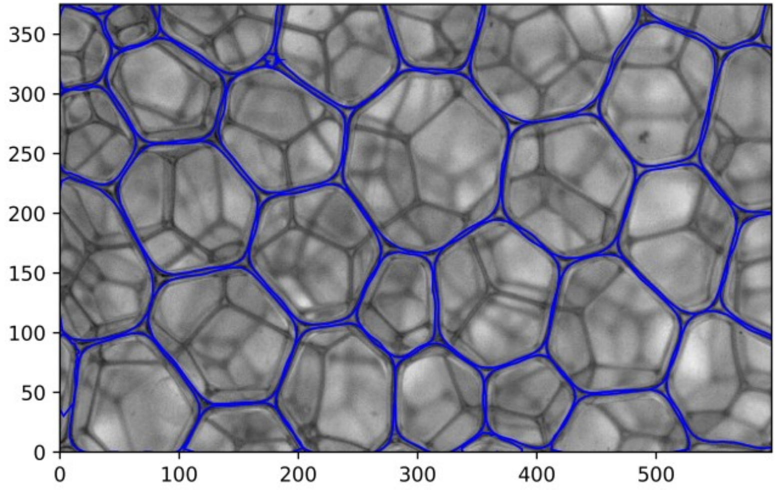
[Van der Net et al. 2006]

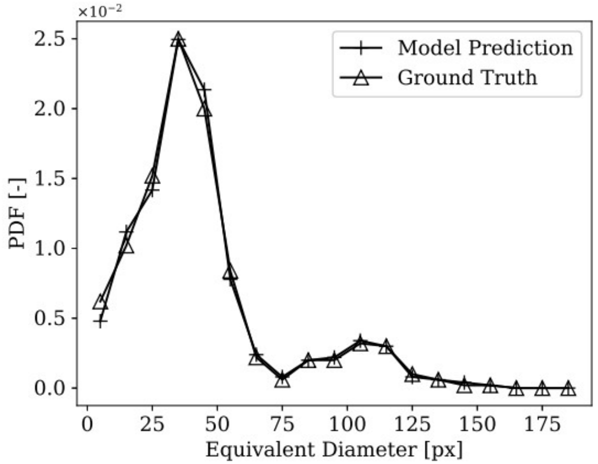
Optical measurement of foam surfaces

- Pictures of wall-bounded foam show a lot of structure
- Neural Network approach to segment bubbles





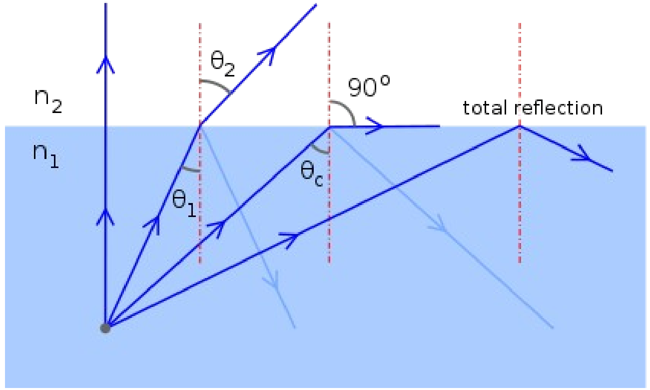


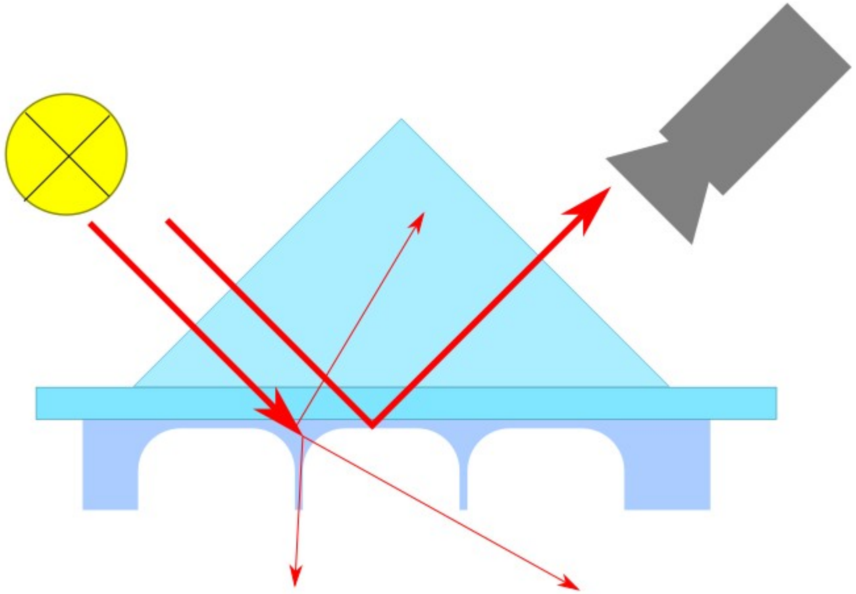


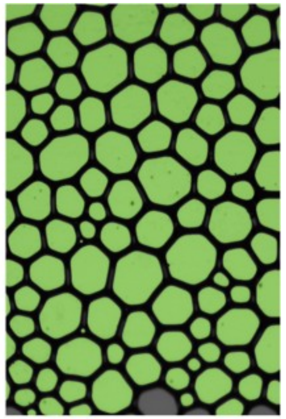
[Knüpfer & Heitkam 2022]

Optical measurement of foam surfaces

- Enhanced image contrast using total internal reflection
- Lamellas appear bright, Plateau borders appear dark

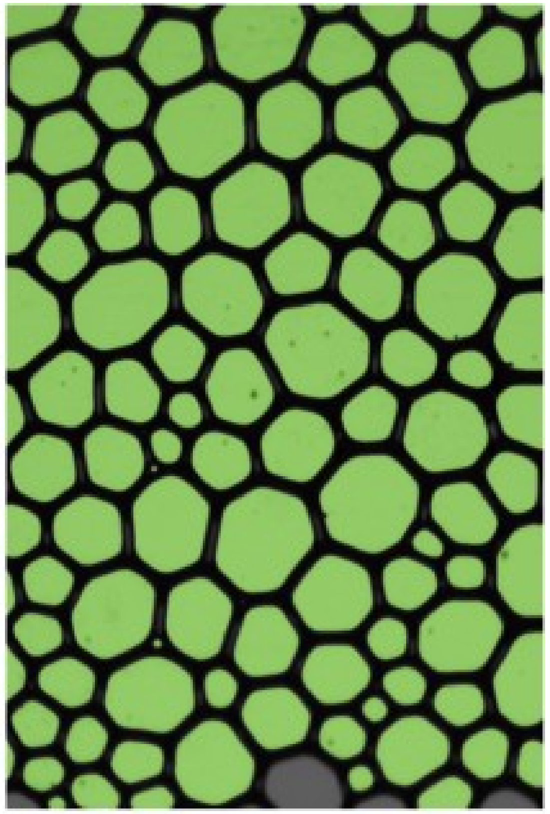


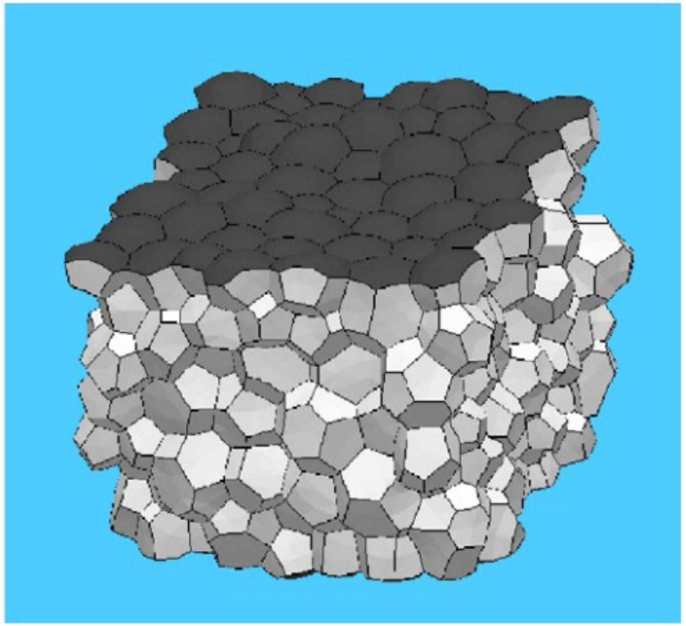


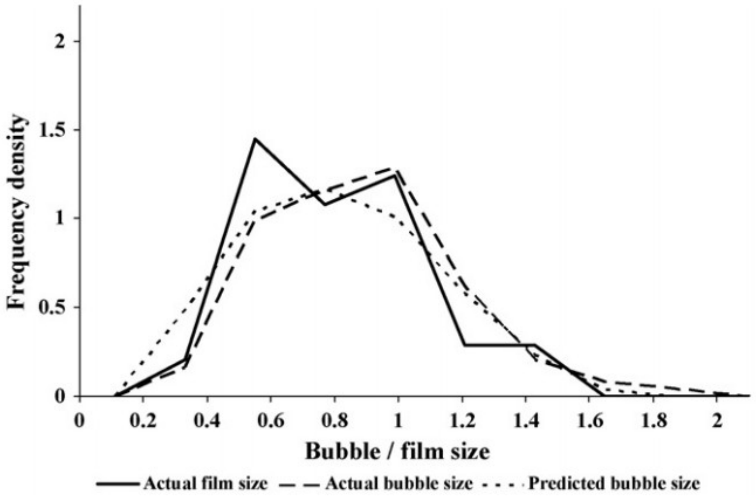


Bubble size measurement

- Segmentation algorithm (discussed in lecture 3) → Lamella size
- Relation between lamella size and bubble size from Surface Evolver
- Recomputation algorithm in [Wang & Neethling 2008]



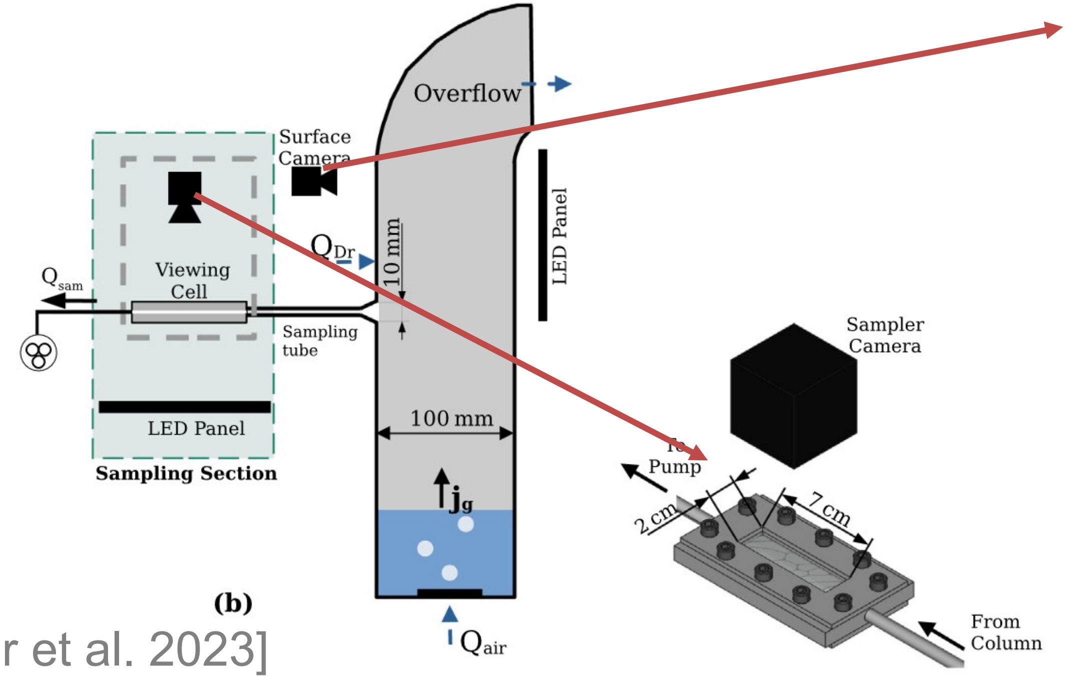


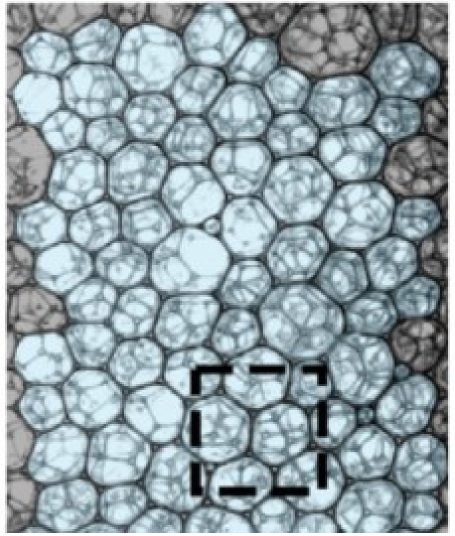


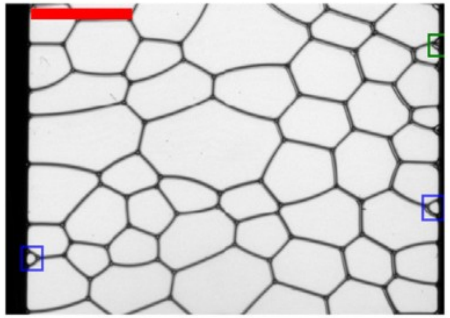
[Wang & Neethling 2008]

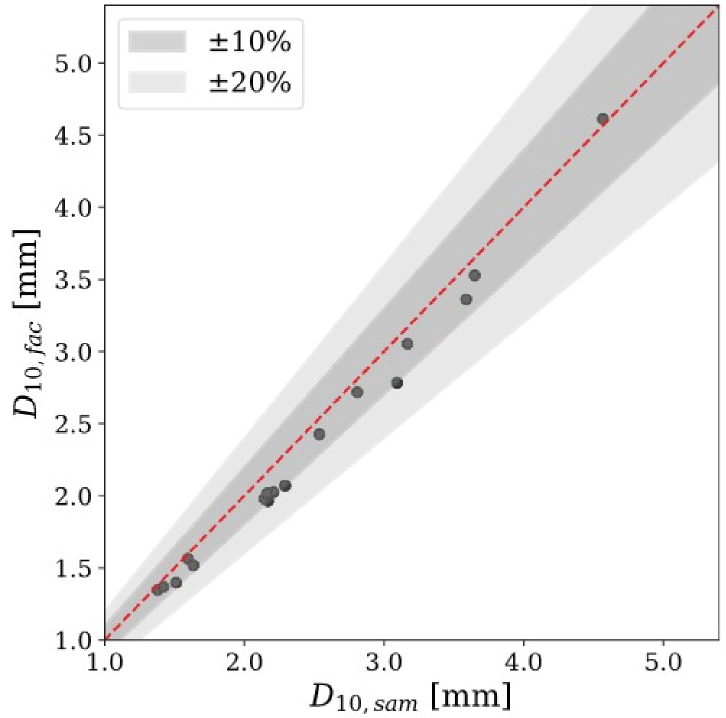
Bubble size measurement

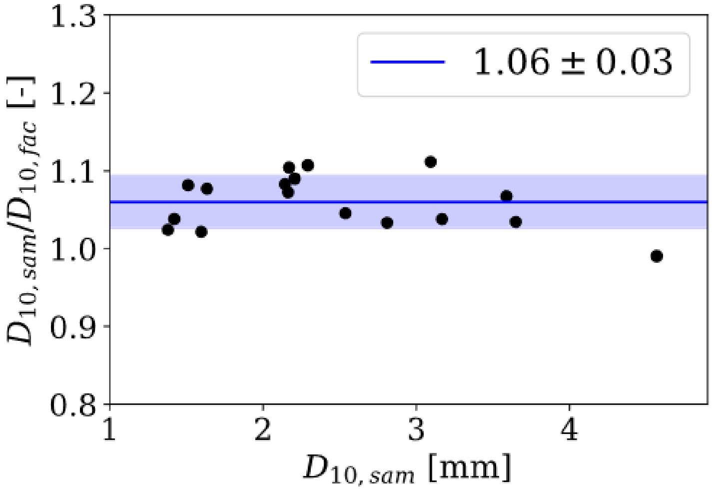
- Direct measurement with two methods:
- Surface segmentation vs bubble extraction
- Surface segmentation underestimates by 6%







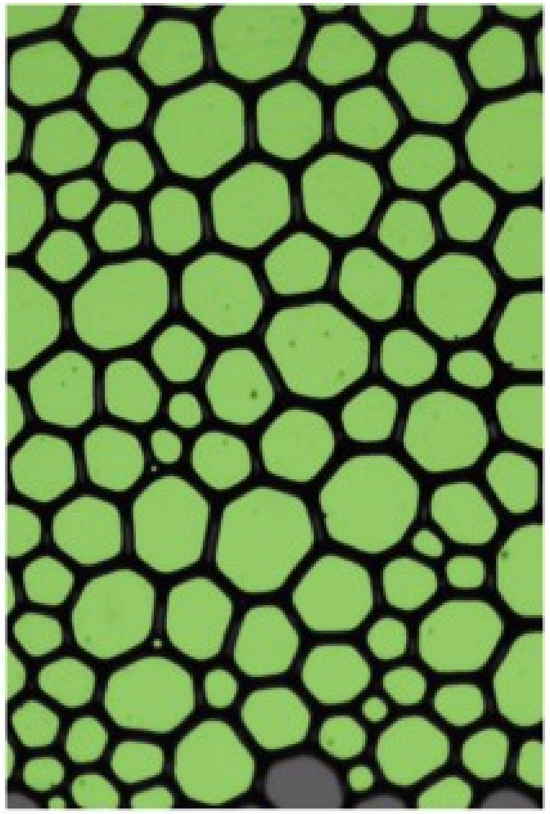


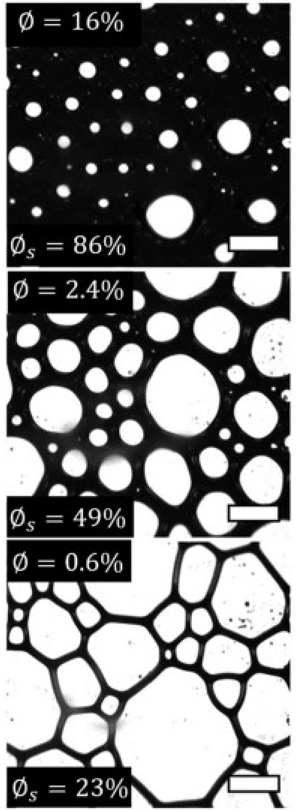


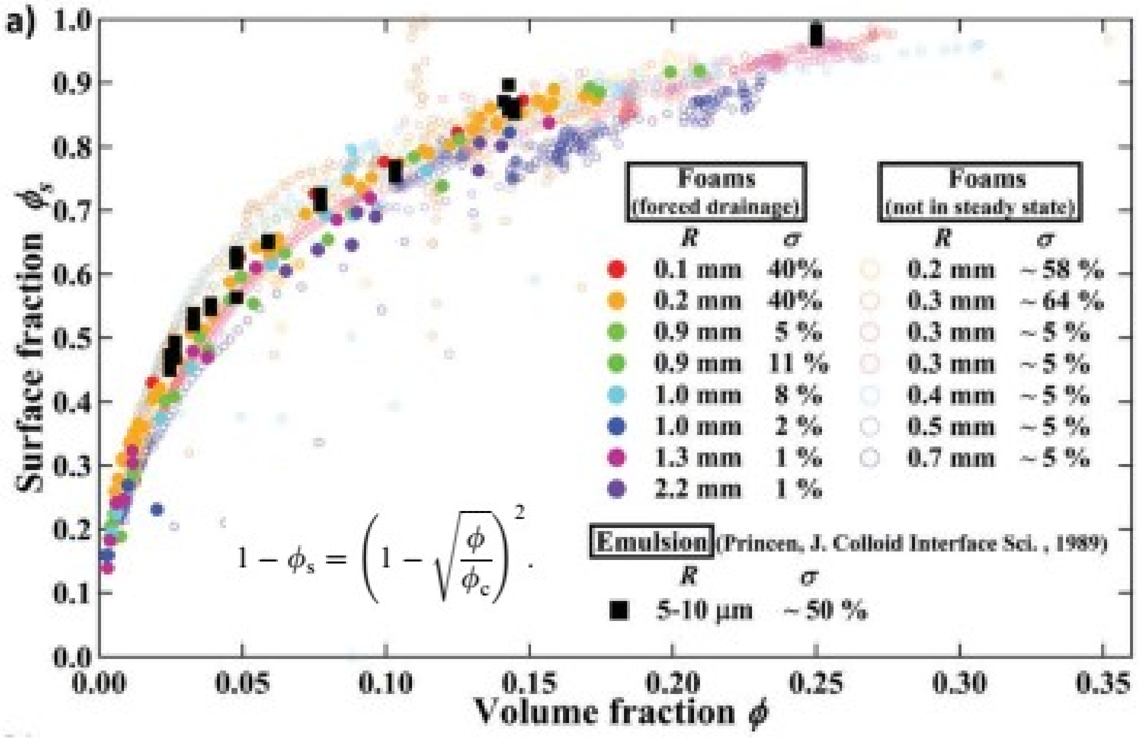
[Knüpfer et al. 2023]

Liquid fraction measurement

- Segmentation algorithm (discussed in lecture 3) → Lamella surface area fraction φ_s
- Relation between lamella size and bubble size from Surface Evolver



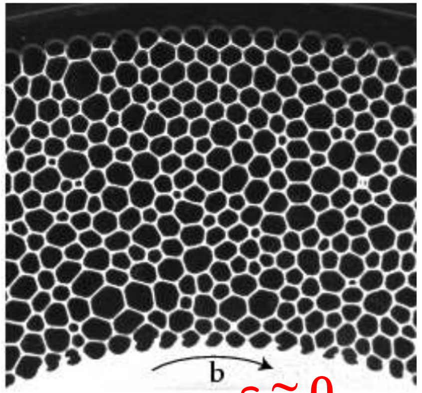




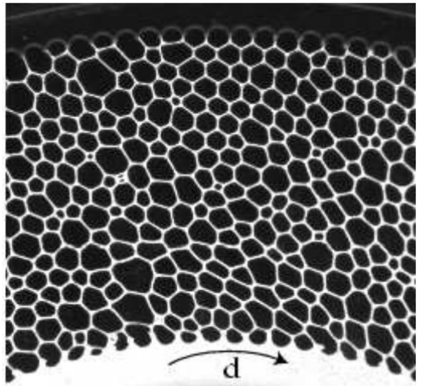
[Forel et al. 2016]

Stress (deformation)

- Segmentation algorithm (discussed in lecture 3) → Aspect ratio and orientation of bubbles
- Local anisotropic stress distribution

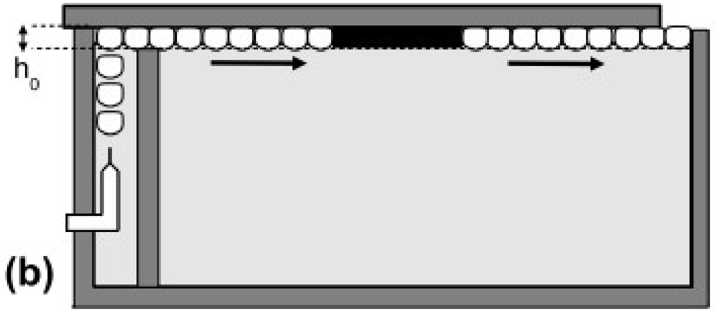


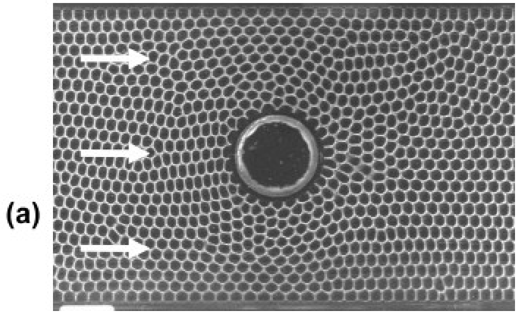
$\varepsilon \approx 0$

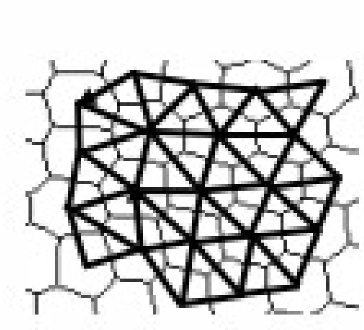


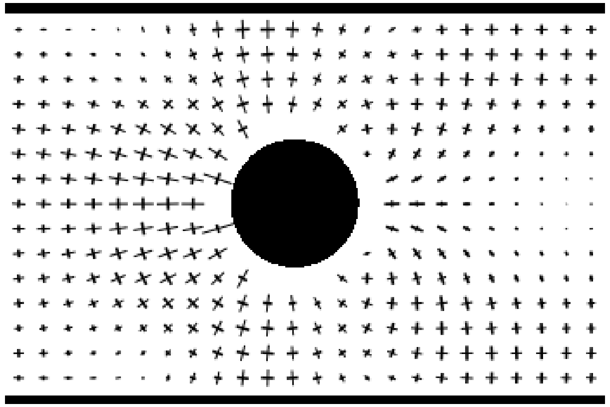
$\varepsilon > \varepsilon_{yield}$

[Janiaud & Graner 2004]









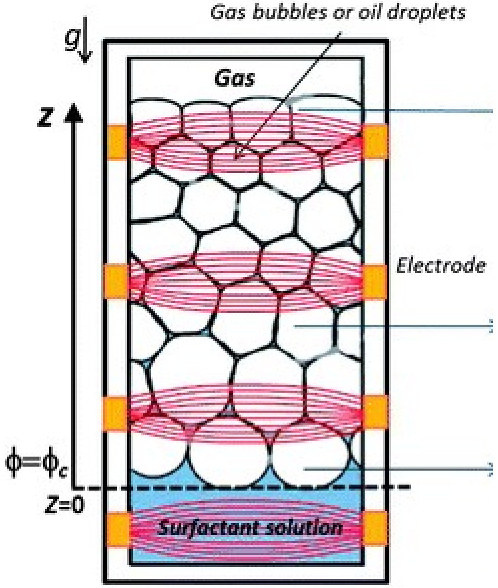
[Dollet & Graner 2006]

Structure

- Review lecture 9
- Measurement of foam rheology
- Optical measurement
- Resistivity measurement
- Radiography/Tomography
- Velocity measurement

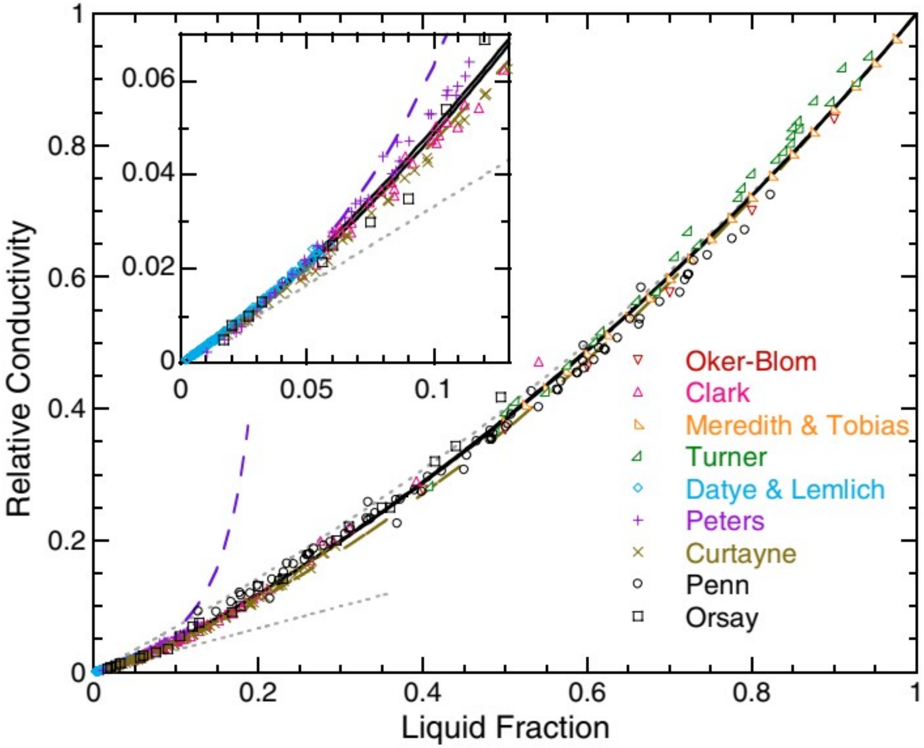
Liquid fraction ←→ resistivity

- Gas has zero conductivity – current is transported by Plateau border network
- Conductivity is a good measure for liquid fraction



$$\frac{\sigma_{foam}}{\sigma_{liquid}} = \varphi_l \frac{2\,(1 + 12\,\varphi_l)}{6 + 29\,\varphi_l - 9\,\varphi_l^{\,2}}$$

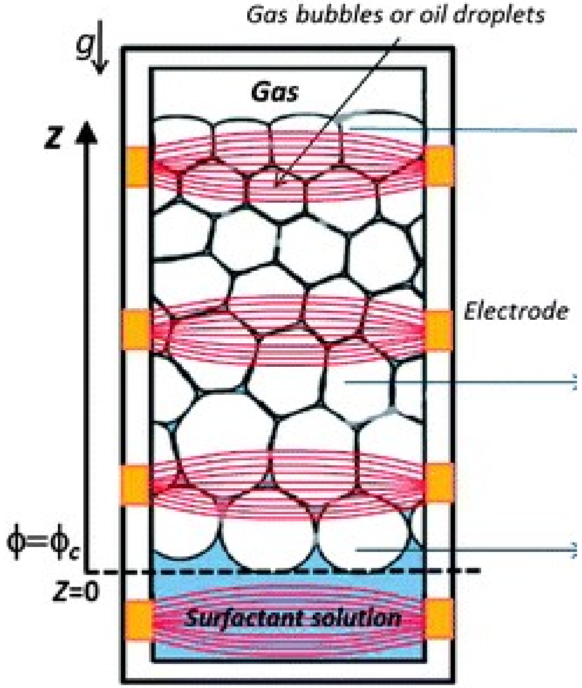
$$\varphi_l = \sigma \frac{3\,(1 + 11\,\sigma)}{1 + 25\,\sigma + 10\,\sigma^2}, \sigma = \frac{\sigma_{foam}}{\sigma_{liquid}}$$



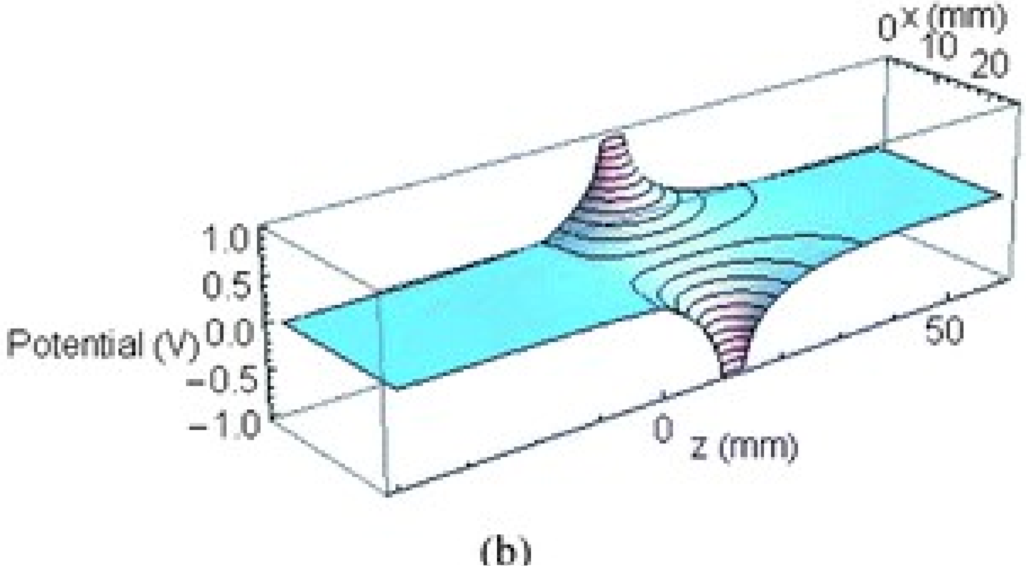
[Feitosa et al. 2005]

Liquid fraction ←→ resistivity

- Shape of electric field over-weights volume close to electrodes
- Larger electrodes are preferred



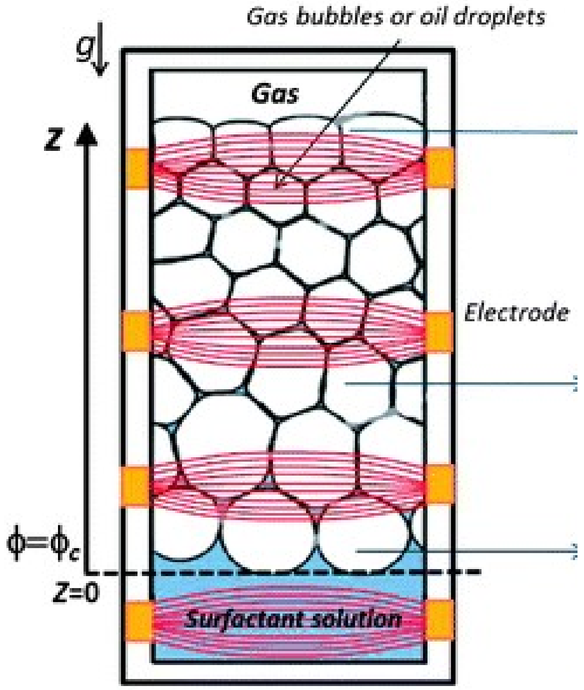
$$R \sim \frac{1}{\sigma}\frac{L}{A}$$

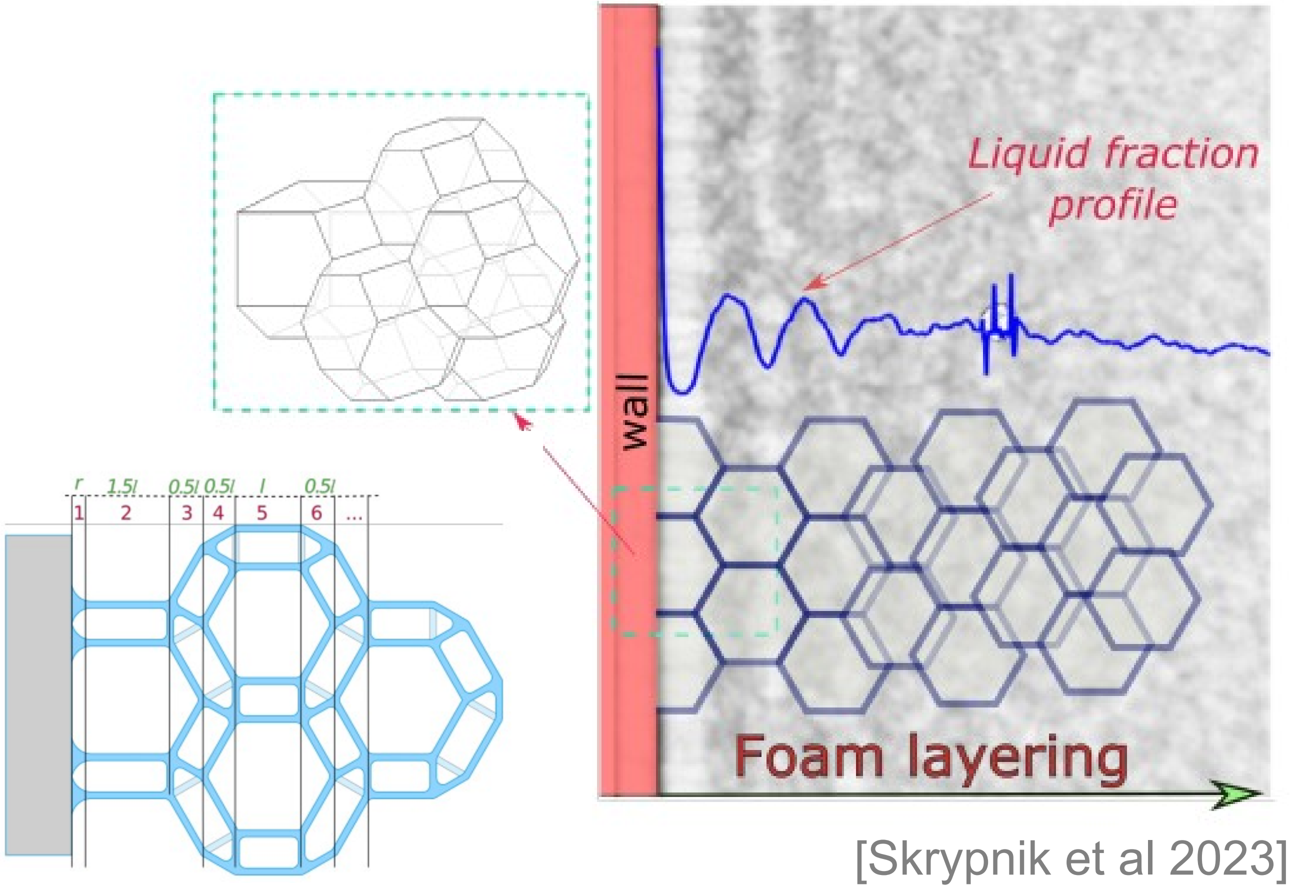


[Maestro et al. SM 2013]

Liquid fraction ←→ resistivity

- Liquid fraction layers at wall
- Influence of electric conductivity???

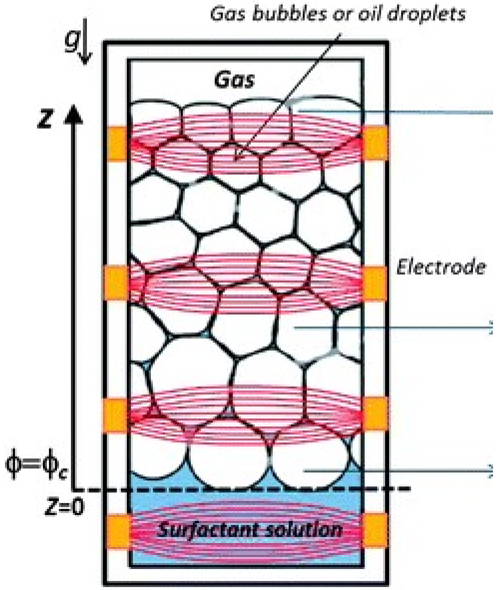


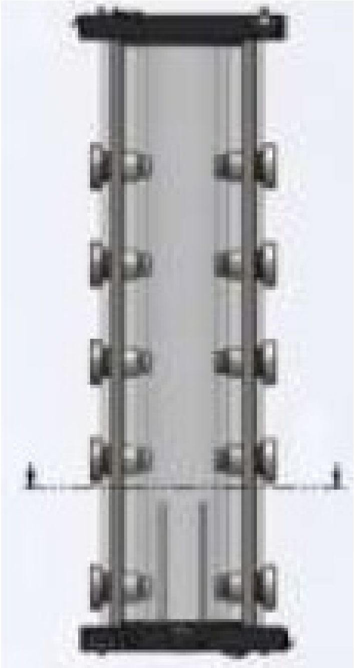


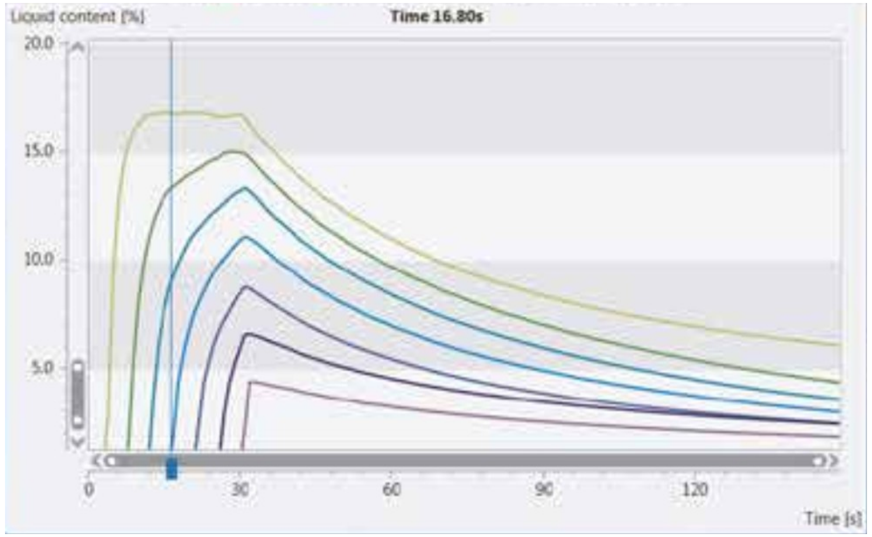
[Skrypnik et al 2023]

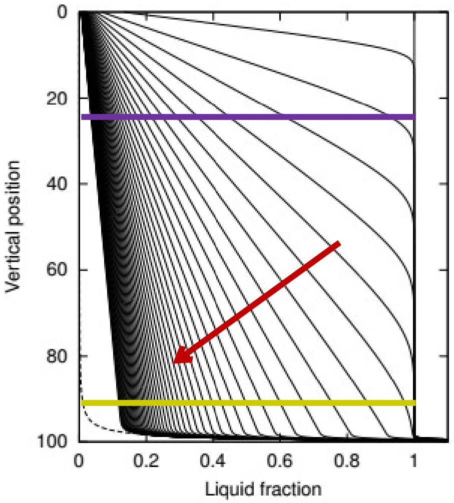
Liquid fraction ←→ resistivity

- Commercialized for liquid profile measurement
- Liquid profile yields drainage resistance





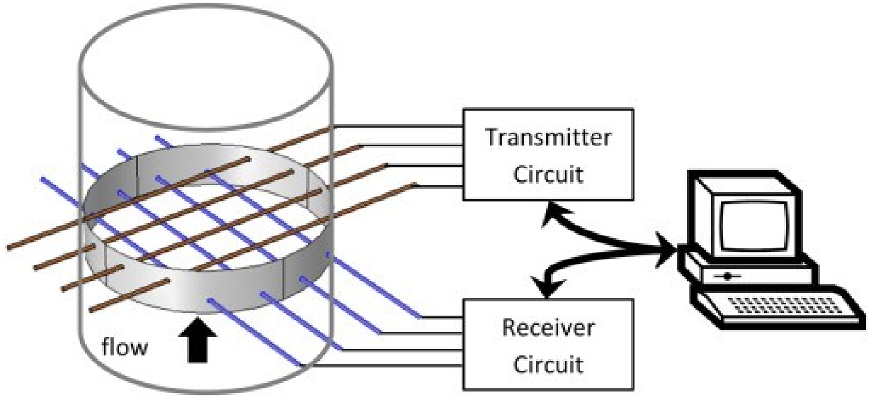


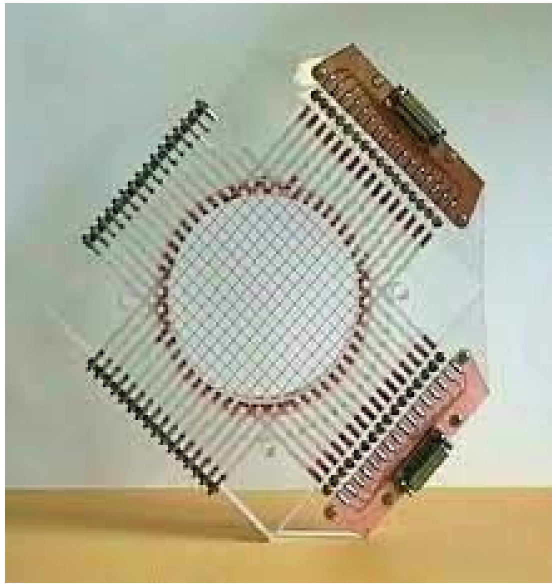


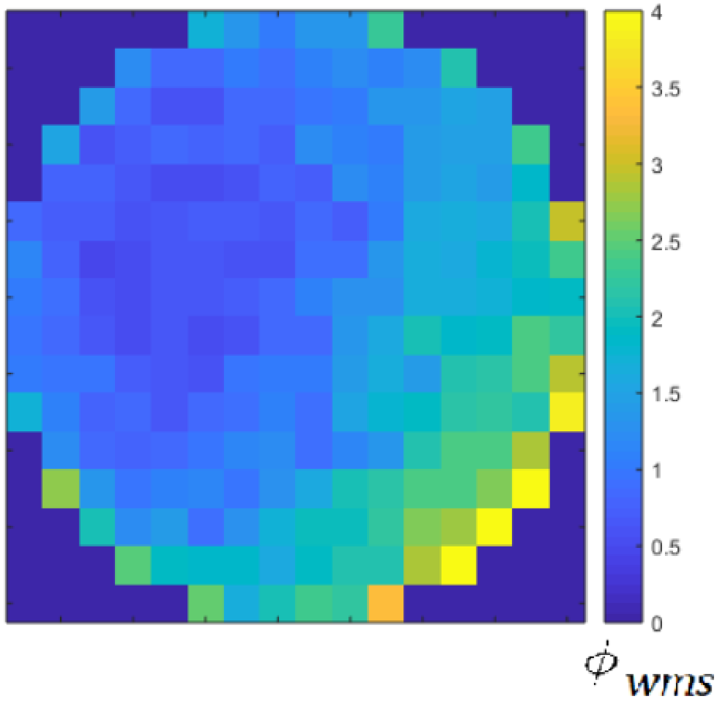
[Hoang et al. 2020]

Wire-Mesh sensor

- Measurement at crossing points between two arrays of wires
- Current injection in one electrode pair → el. Potential on all electrodes



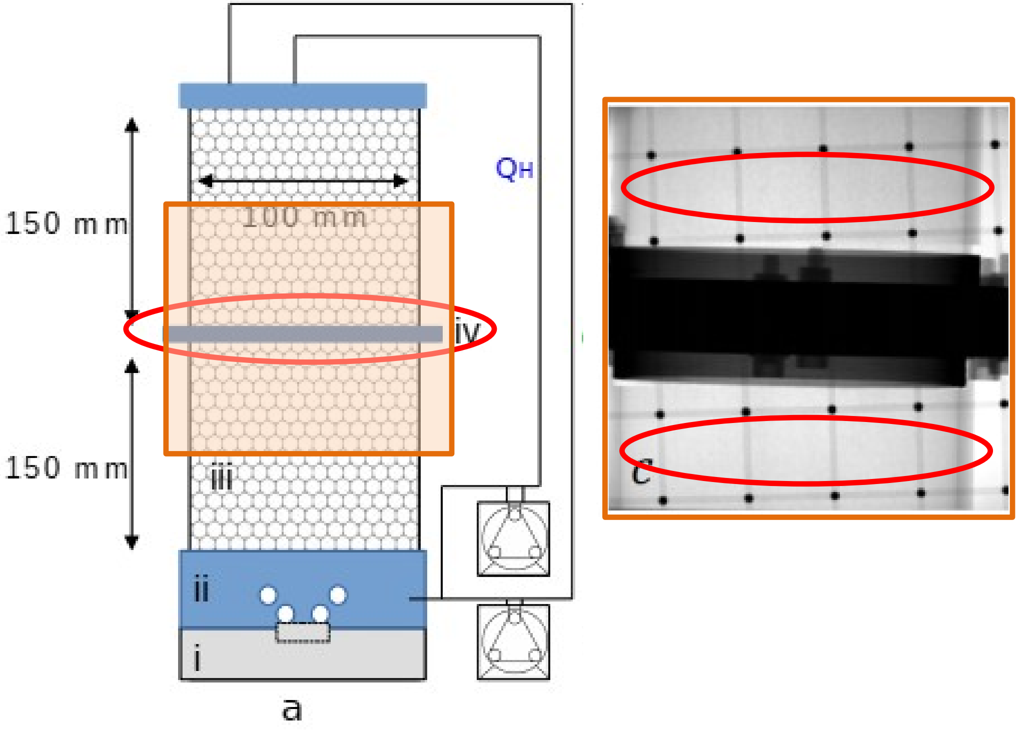


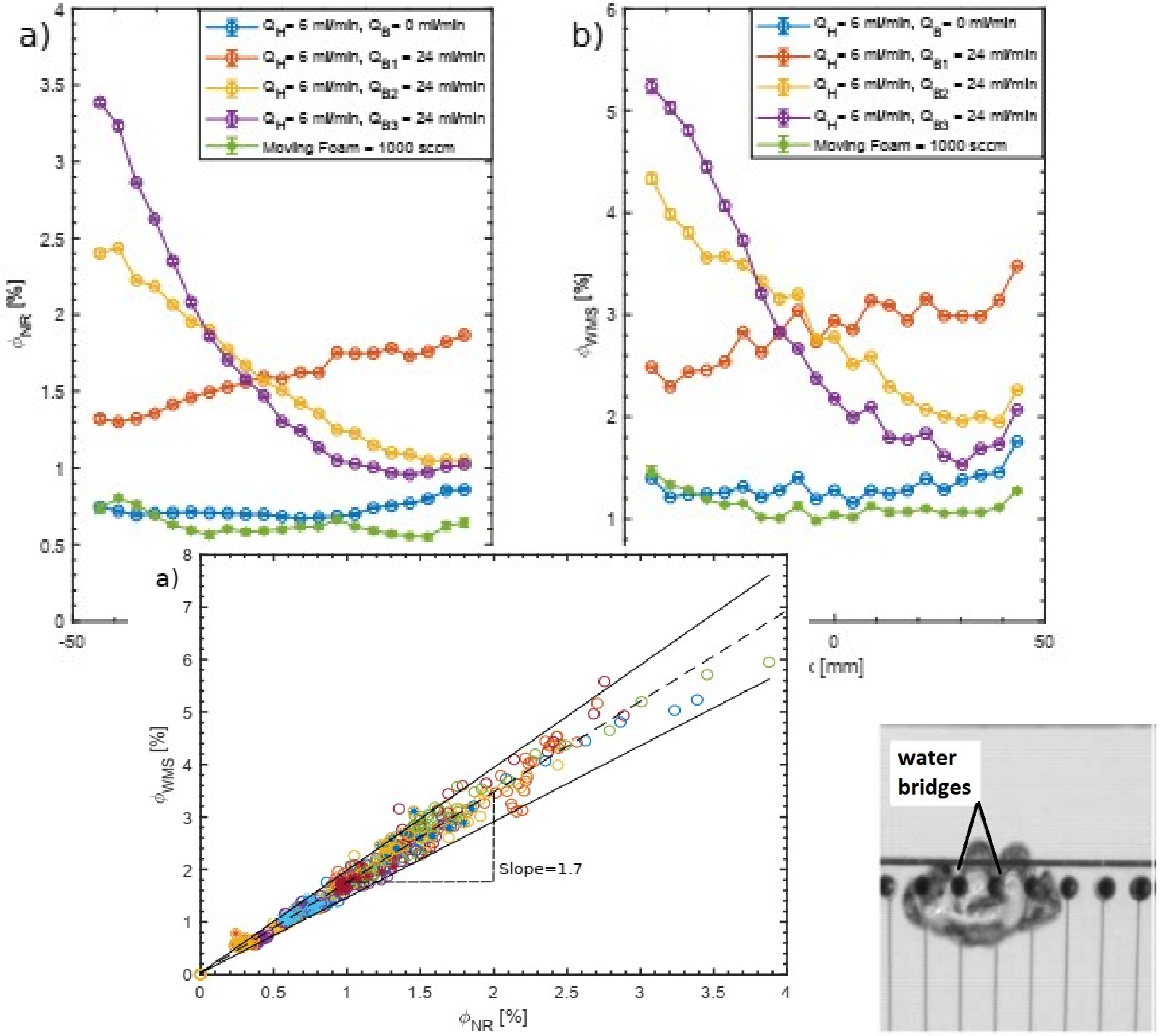


[Ziauddin et al. 2022]

Calibration of Wire-Mesh

- Wire-Mesh sensor for liquid fraction in foam

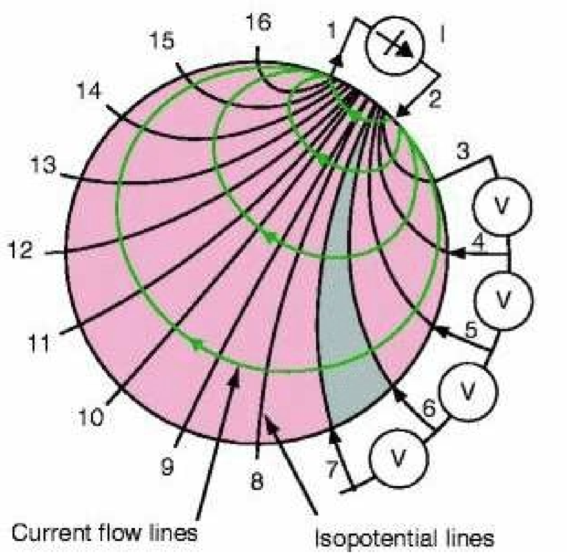


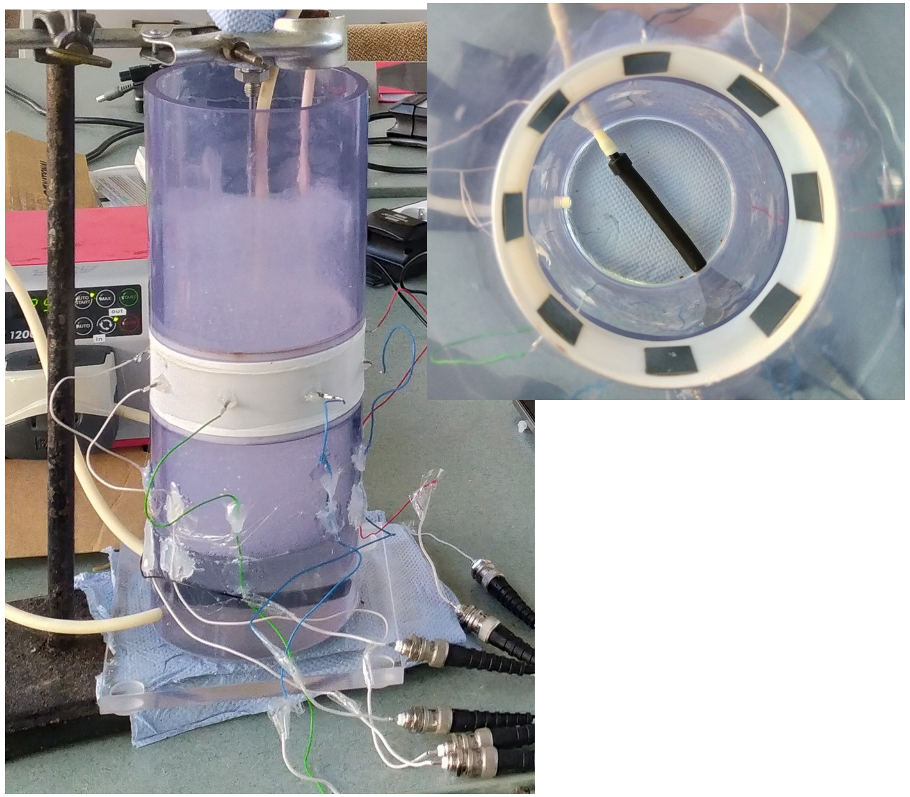


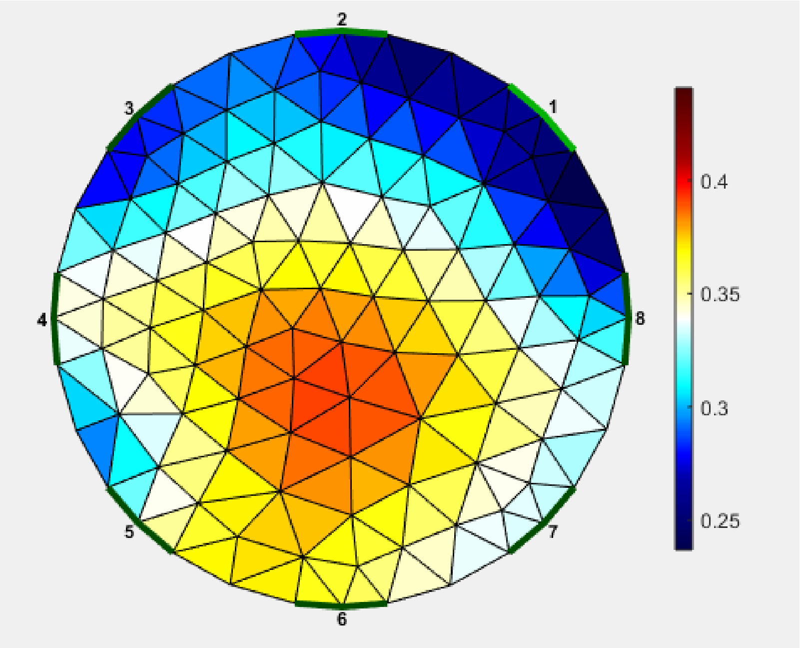
[Ziauddin et al., Journal of Physics: Condensed Matter , 2022]

Electric resistance tomography

- Set of electrodes along the circumference
- Current injection in one electrode pair → el. Potential on all electrodes
- → Highly nonlinear, complex reconstruction process

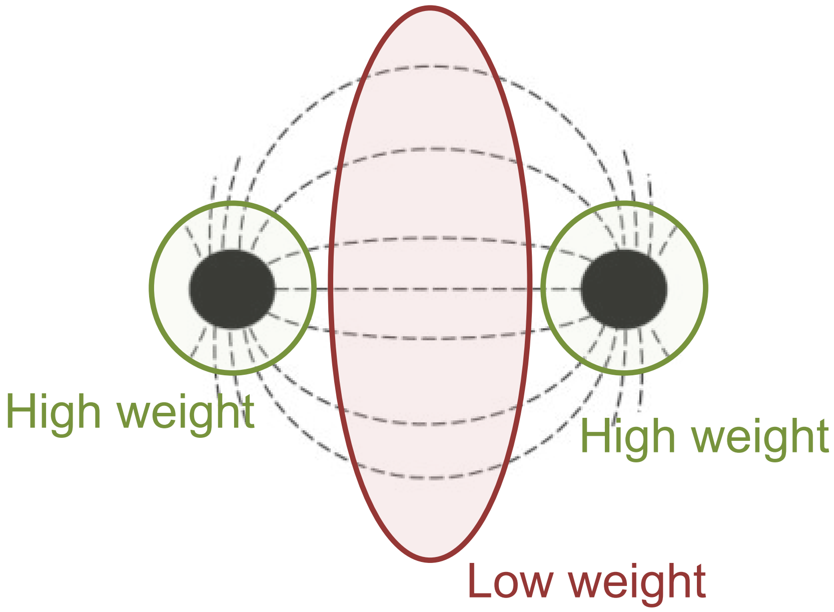


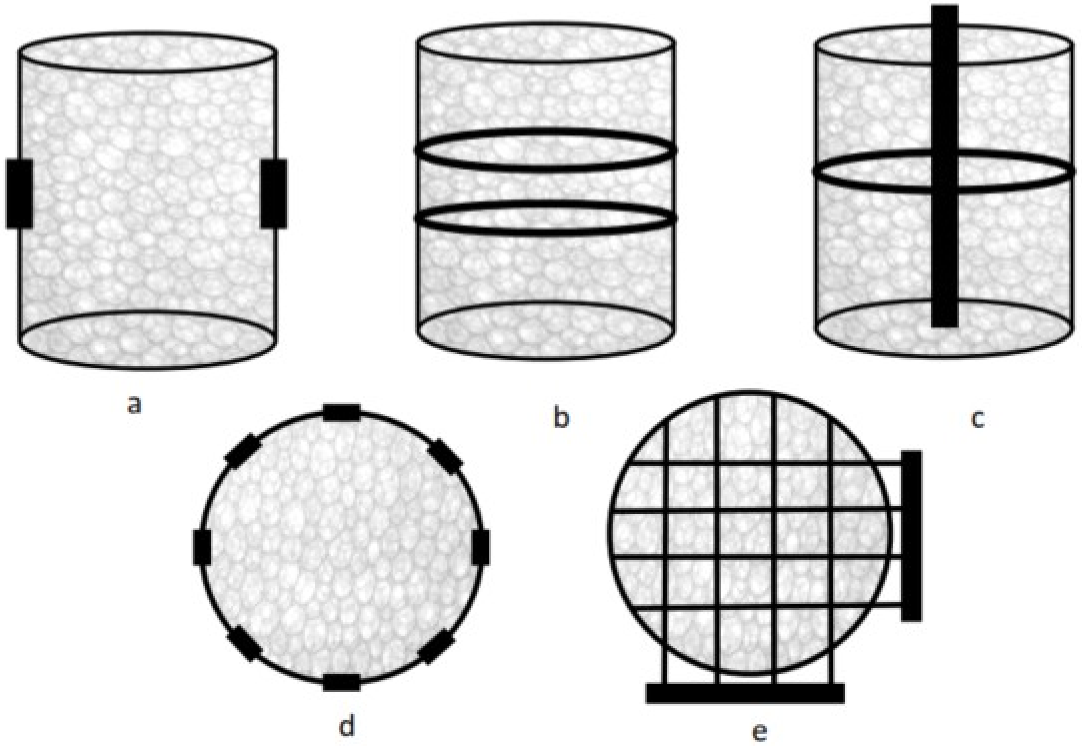




Electrode Arrangements

- Many arrangements possible
- Focus on different zones, weighted according to local current density





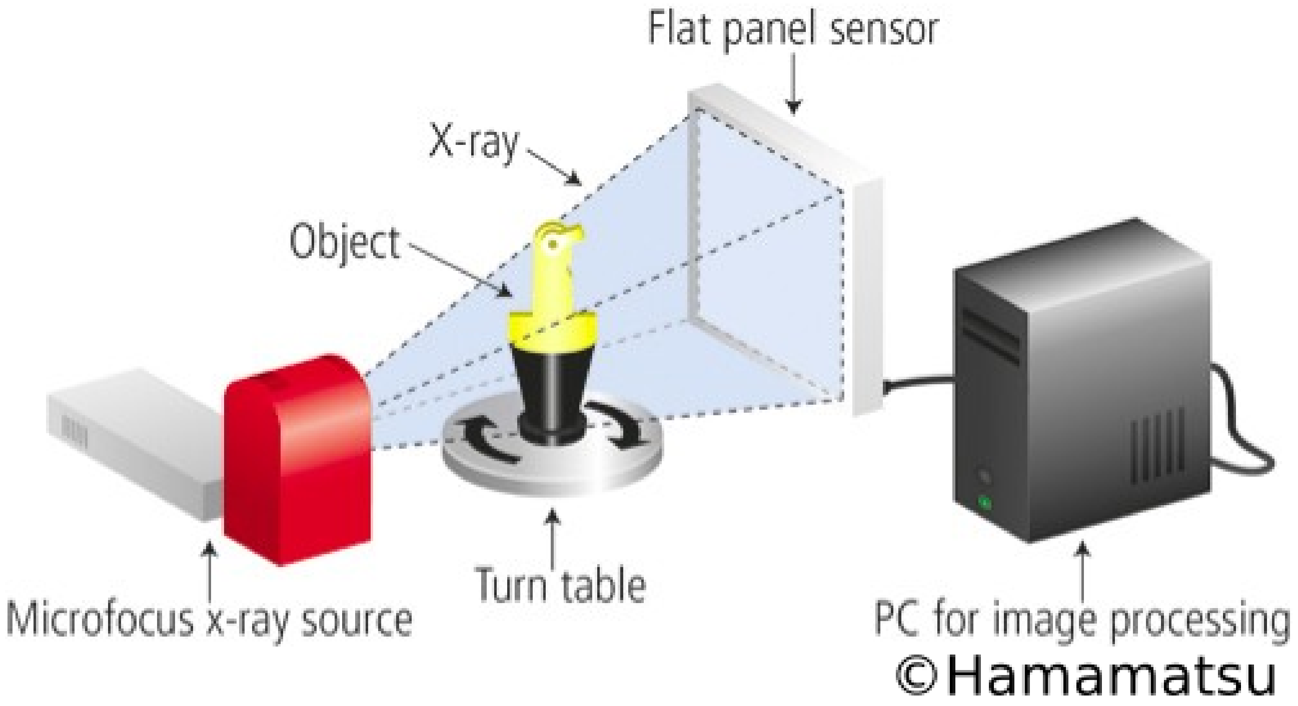
Structure

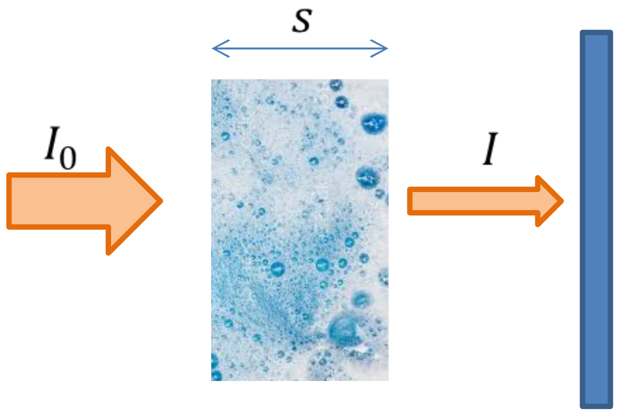
- Review lecture 9
- Measurement of foam rheology
- Optical measurement
- Resistivity measurement
- Radiography/Tomography
- Velocity measurement

Radiography

- Radiation source and detector
- Radiation is attenuated by measurement object → Beer-Lambert law

$$\frac{I}{I_0} = e^{-(\sigma s)}$$





[Wang & Cilliers 1999]

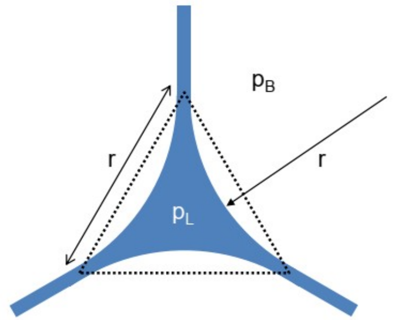
Exercise: Attenuation

- How strong is the relative attenuation of different foam samples
- X-ray, 150 keV: “NIST Standard Reference Database 126” → $\frac{\sigma}{\rho} = 0.0575\ \frac{cm^2}{g}$ $\frac{I}{I_0} = e^{-(\sigma s)}$

- (a) Block of shaving foam, 10 cm thickness, D_b=0.1mm, φ_l=10%

- (b) Plateau border (transversal oriented) of soap foam, D_b=5mm, φ_l=0.1%

Decoration theorem: $\varphi_l \approx 0.72 \frac{r^2}{{R_e}^2}$



Exercise: Attenuation

- X-ray, 150 keV: "NIST Standard Reference Database 126" → $\frac{\sigma}{\rho} = 0.0575 \frac{cm^2}{g}$ → $\sigma = 0.0575 \frac{1}{cm}$

- (a) Shaving foam, 10 cm thickness, D_b=0.1mm, φ_l=10%

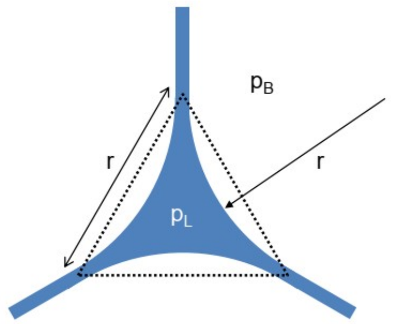
$$\frac{I}{I_0} = e^{-(\sigma s)} = e^{-(0.0575\,/cm\,\cdot\,10\,cm\,\cdot\,10\%)} = 94.4\% \qquad \frac{\Delta I}{I_0} = 5.6\%$$

- (b) Plateau border (transversal oriented) of bath tub foam, D_b=5mm, φ_l=0.1%

Decoration theorem: $\varphi_l \approx 0.72 \frac{r^2}{{R_e}^2}$

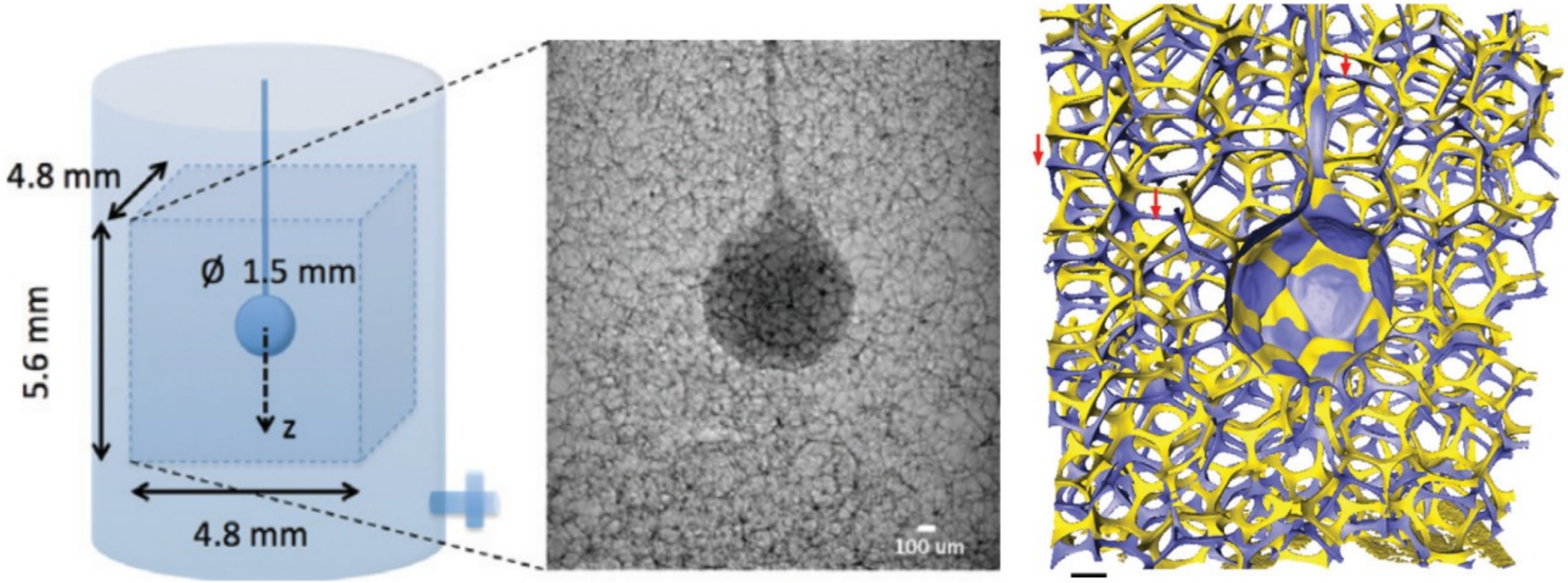
$$r = R_e \sqrt{\frac{\varphi_l}{0.72}} \approx 0.093\,mm$$

$$\frac{I}{I_0} = e^{-(\sigma r)} = e^{-(0.0575\,/cm\,\cdot\,0.0093\,cm)} = 99.946\% \qquad \frac{\Delta I}{I_0} = 0.054\%$$



X-ray tomography

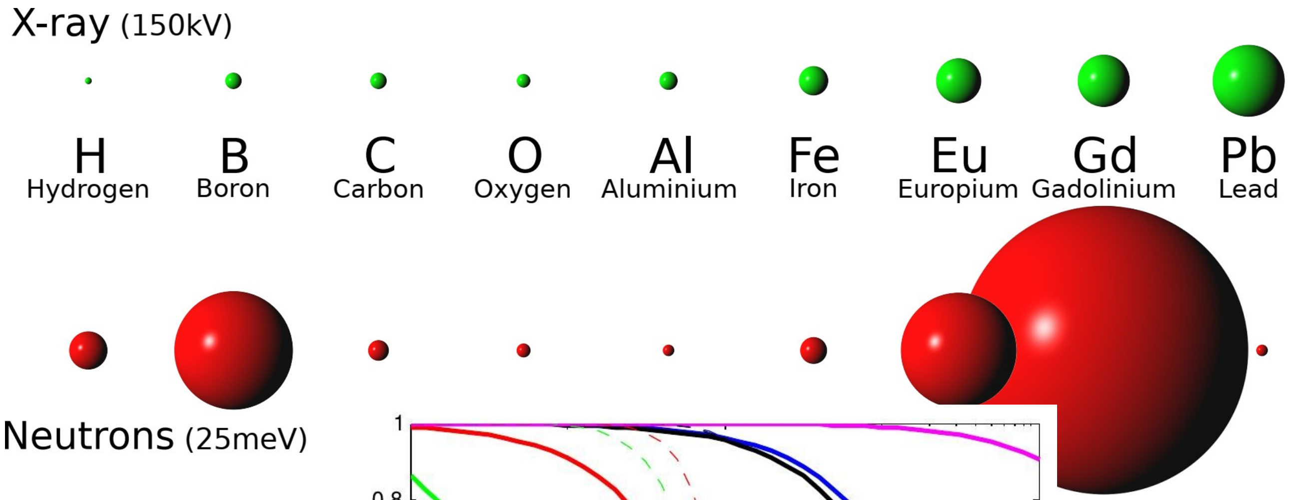
- High-Intensity radiation from synchrotron source -> better contrast
- Very precise measurement requires long exposure
- → Small measurement volume, small velocities

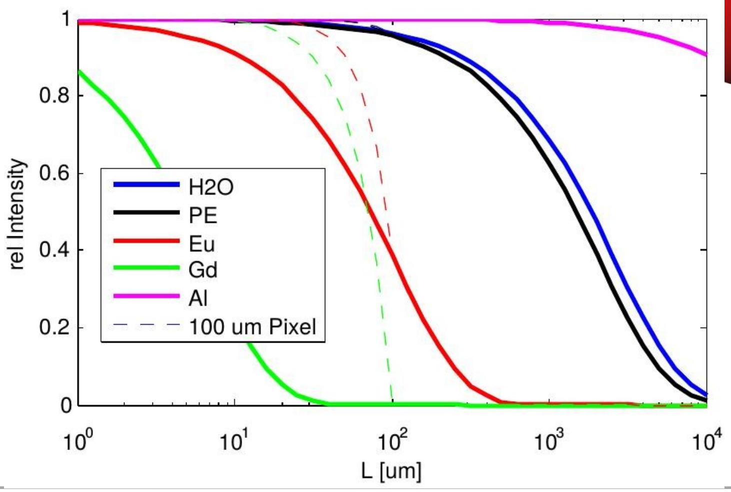


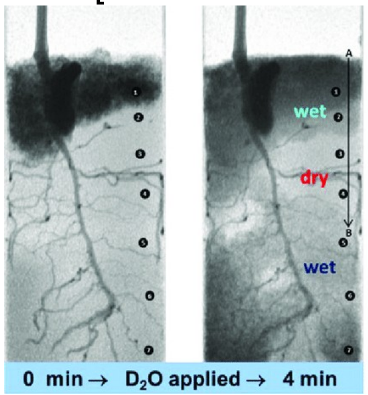
[Raufaste et al. EPL 2015]

Neutron radiography

- Neutron sources with sufficient neutron flux are rare
- Unique attenuation properties







[Paul Scherrer Institut]

Exercise: Attenuation

- X-ray, 150 keV: “NIST Standard Reference Database 126” → $\frac{\sigma}{\rho} = 0.0575\,\frac{cm^2}{g} \rightarrow \sigma = 0.0575\,\frac{1}{cm}$

$$\sigma_{neutron} = 3.74\,\frac{1}{cm}$$

- (a) Shaving foam, 10 cm thickness, D_b=0.1mm, φ_l=10%

$$\frac{I}{I_0} = e^{-(\sigma s)} = e^{-(0.0575\,/cm\;\cdot\;10\,cm\;\cdot\;10\%)} = 94.4\%$$

$$\frac{\Delta I}{I_0} = 5.6\%$$

$$\frac{\Delta I}{I_0} = 97.6\%$$

- (b) Plateau border (transversal oriented) of soap foam, D_b=5mm, φ_l=0.1%

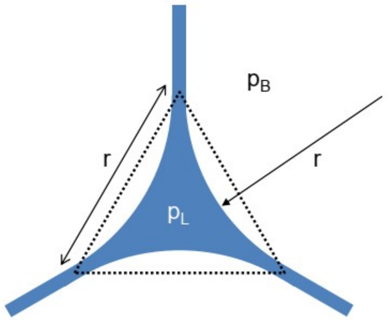
Decoration theorem: $\varphi_l \approx 0.72\,\frac{r^2}{{R_e}^2}$

$$r = R_e\sqrt{\frac{\varphi_l}{0.72}} \approx 0.093\,mm$$

$$\frac{I}{I_0} = e^{-(\sigma r)} = e^{-(0.0575\,/cm\;\cdot\;0.0093\,cm)} = 99.946\%$$

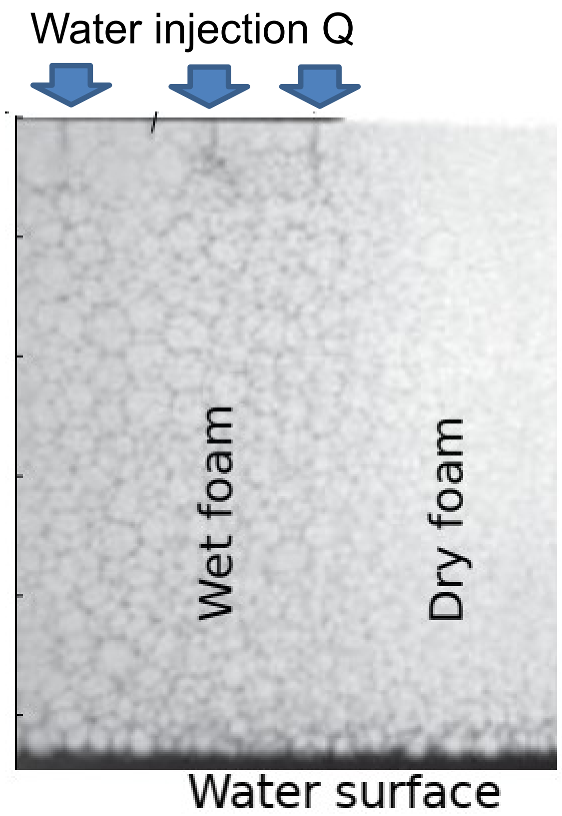
$$\frac{\Delta I}{I_0} = 0.054\%$$

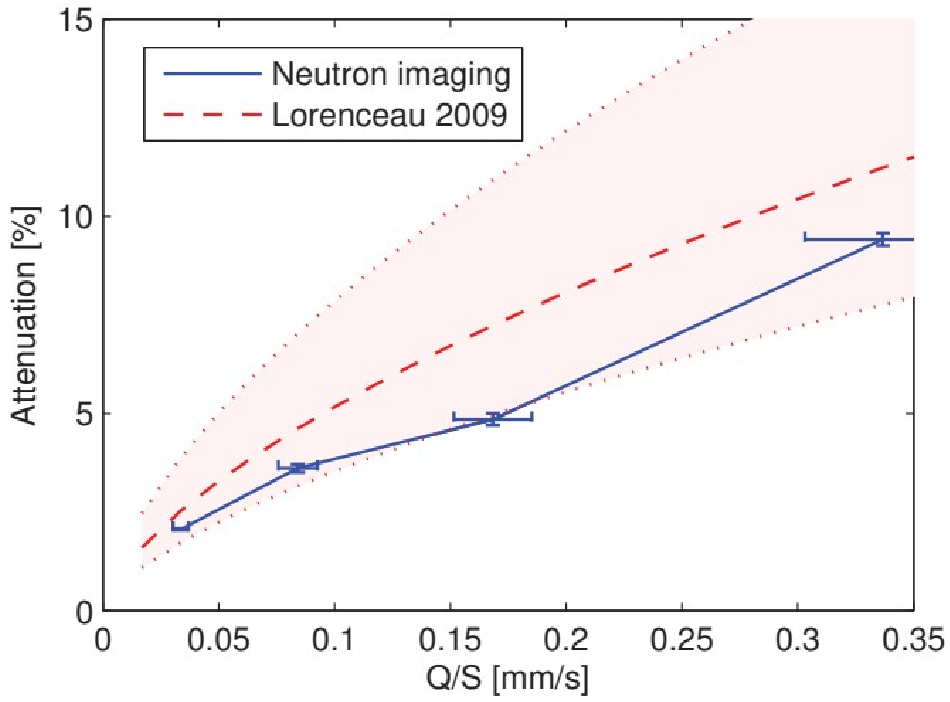
$$\frac{\Delta I}{I_0} = 3.5\%$$



Neutron radiography of liquid fraction

- Forced drainage setup in neutron radiography
- Plateau borders visible
- Liquid fraction can be quantified

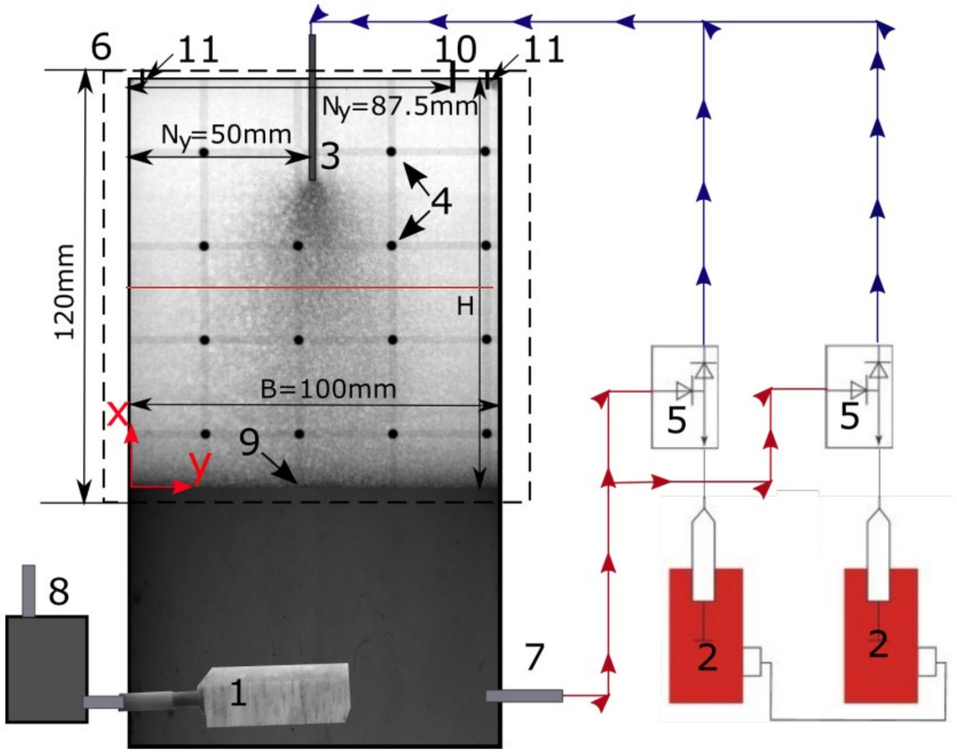


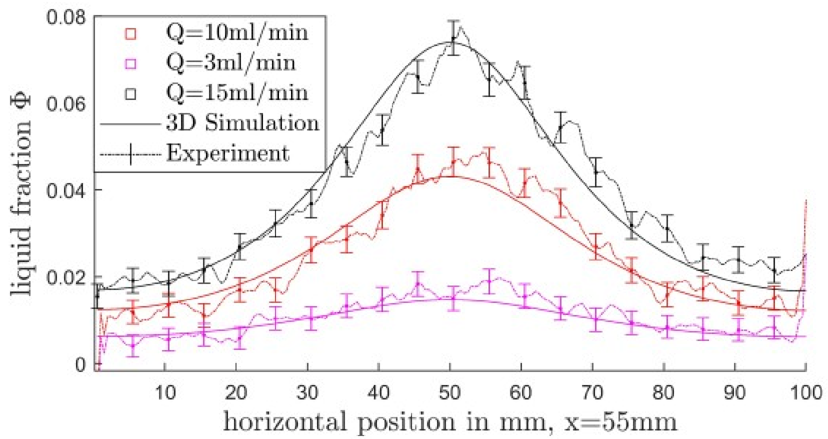


[Heitkam et al. 2018]

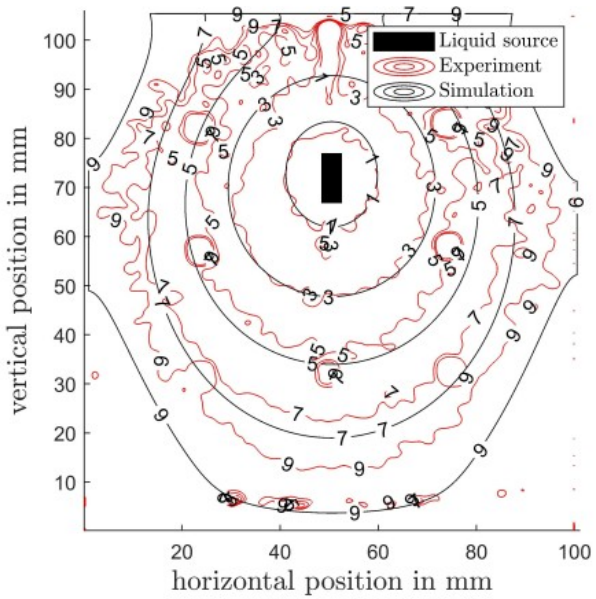
Neutron radiography of liquid fraction

- Measurement of liquid fraction distribution
- Unsteady, 2-dimensional distribution investigated
- Comparison to drainage equation





(a) Front positions with $Q = 6\text{ml/min}$



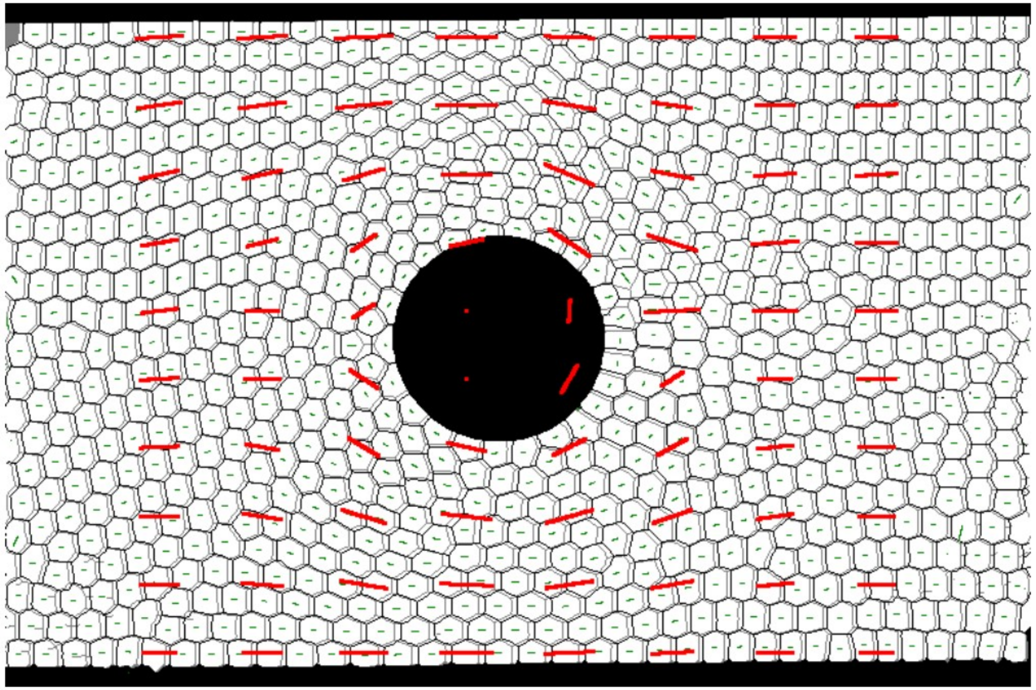
[Walzel et al. 2022]

Structure

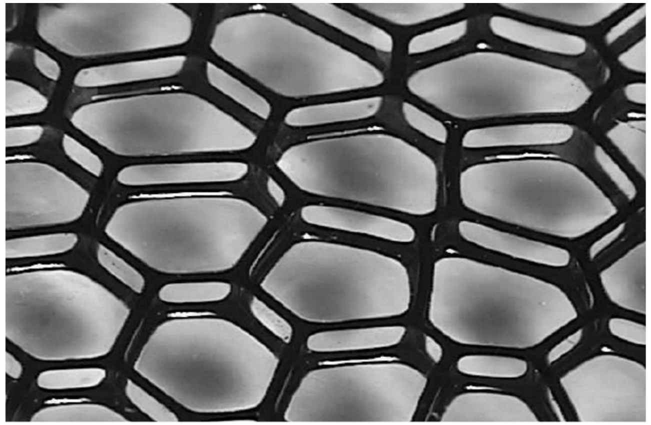
- Review lecture 9
- Measurement of foam rheology
- Optical measurement
- Resistivity measurement
- Radiography/Tomography
- Velocity measurement

Optical velocity measurement

- Consecutive images with defined time shift Δt analysed
- A: Segmentation → shift of each bubble center position Δx_i → velocity $u_i = \Delta x_i / \Delta t$



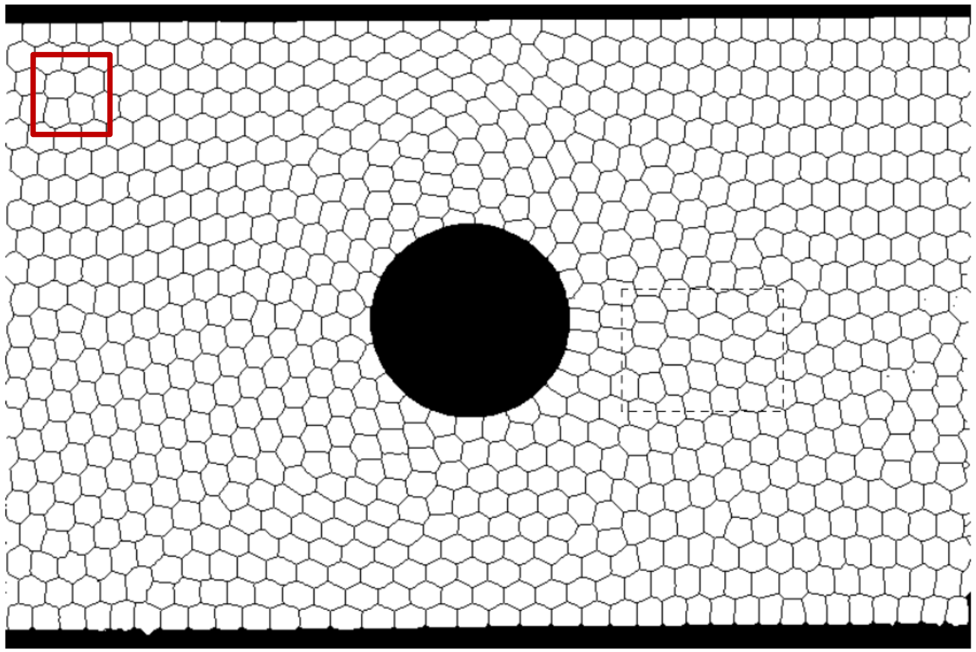
[B. Dollet]

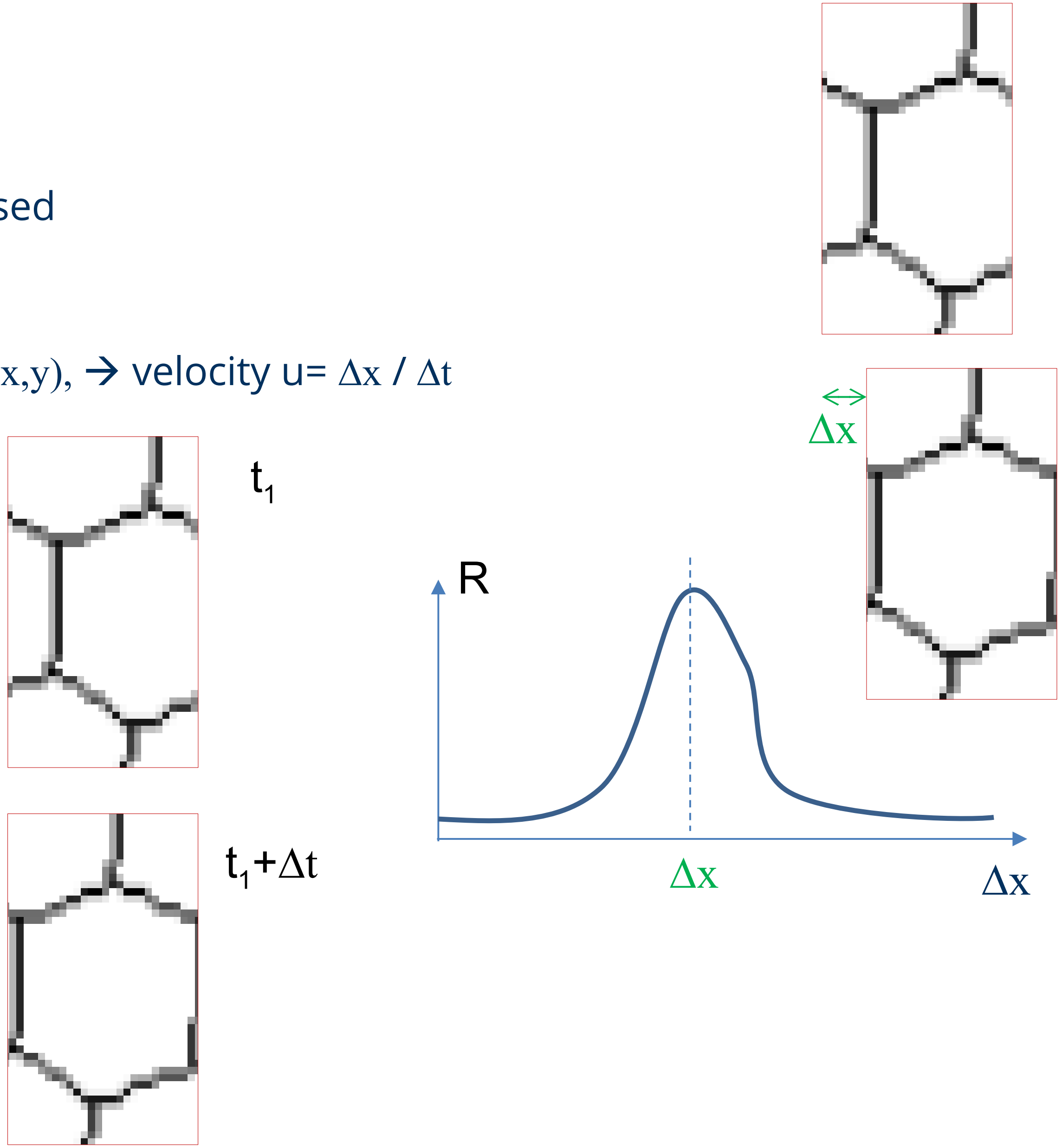


(c) Eric Janiaud

Optical velocity measurement

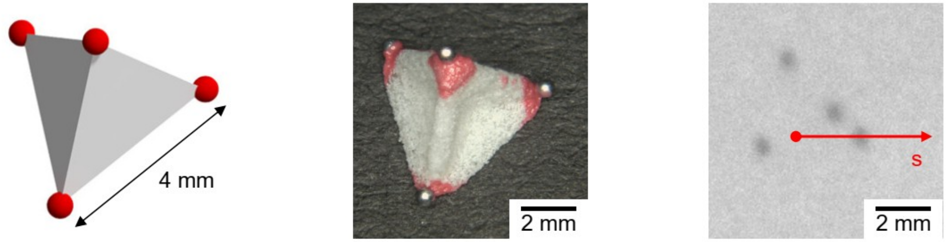
- Consecutive images with defined time shift Δt analysed
- B: PIV-Algorithm → interrogation windows
- → cross-corelation of consecutive images yields Δx (x,y), → velocity $u = \Delta x / \Delta t$



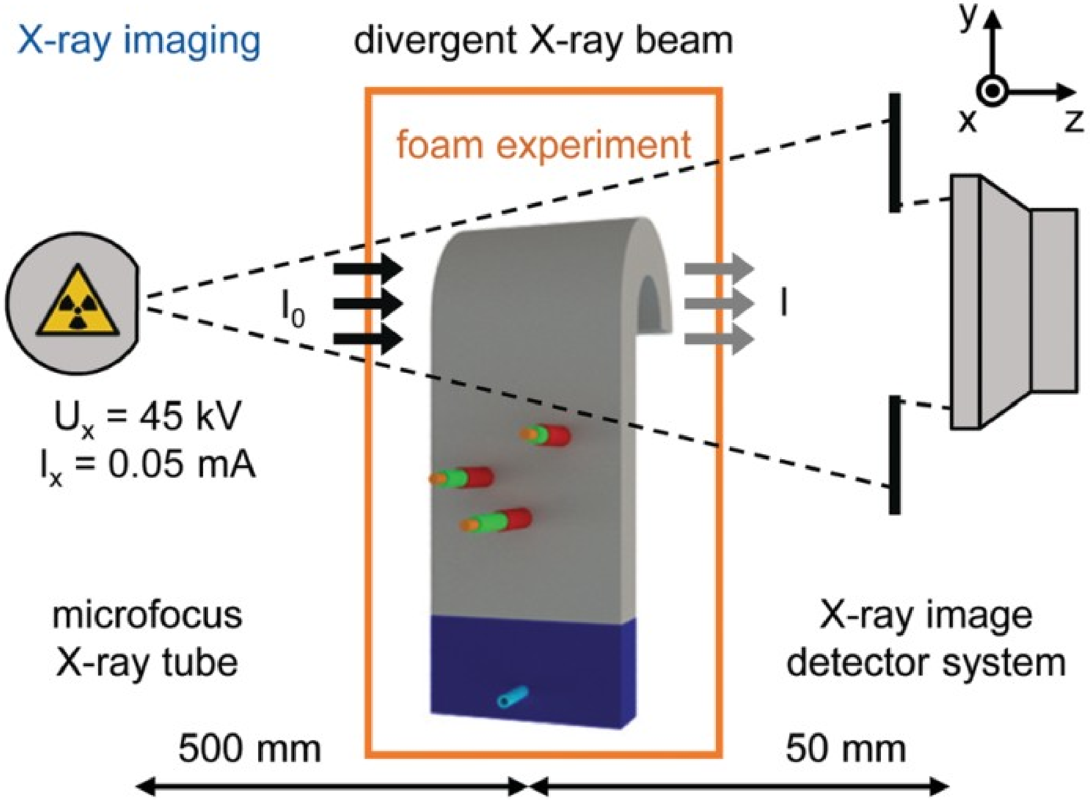


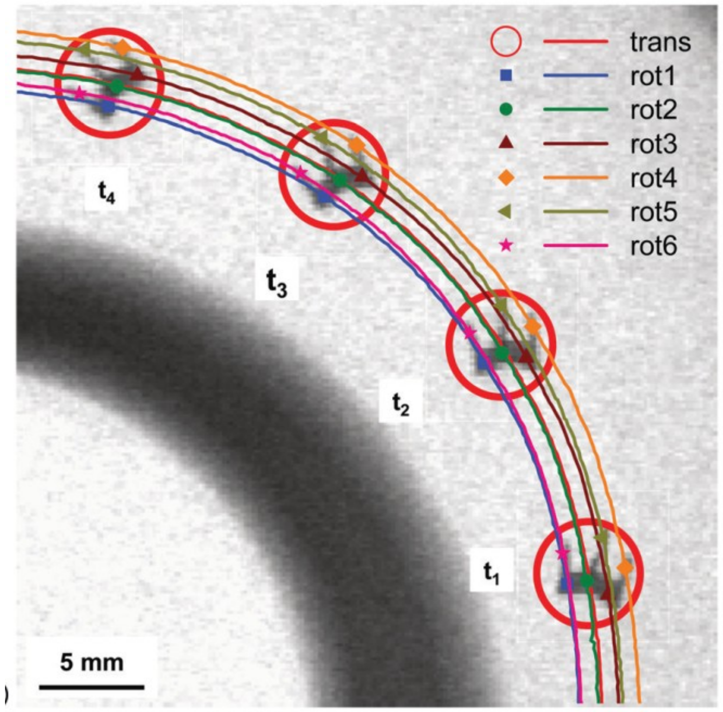
Xray-Particle Tracking Velocimetry

- 3D-printed particles with metal content, sticking in foam
- Tracking of particles yields velocity and vorticity of the foam flow



(a) CAD concept (b) close-up image (c) X-ray image of tracer T1





[Lappan et al. 2020]

Velocity U

$$\mathbf{X}^{\mathbf{i}} = \frac{1}{4}\sum_{j=1}^{4}\mathbf{X}_{\mathbf{j}}^{\mathbf{i}}$$

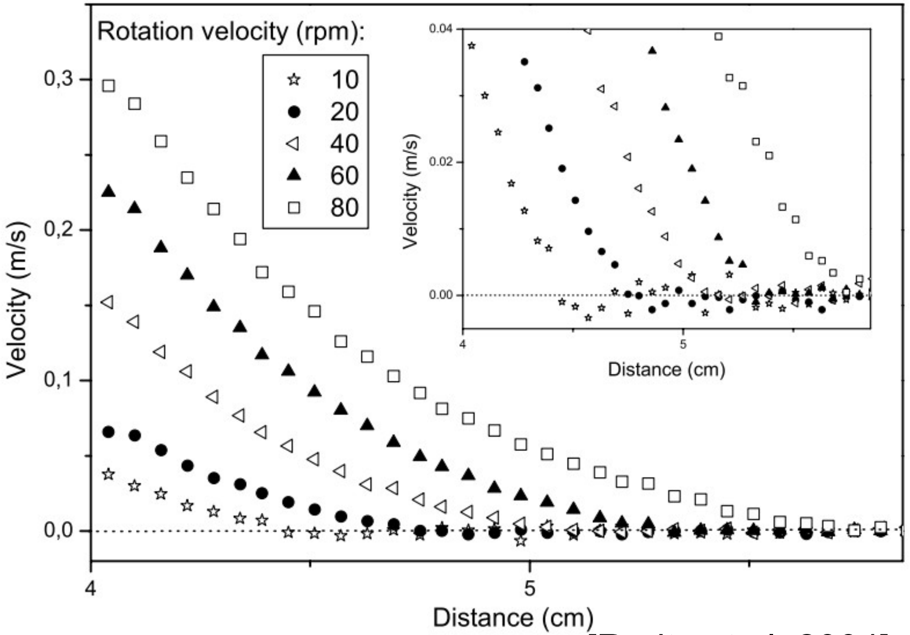
$$\mathbf{U}^{\mathbf{i}} = \frac{\mathbf{X}^{\mathbf{i+1}} - \mathbf{X}^{\mathbf{i-1}}}{2\cdot\Delta t}$$

Rotation ω

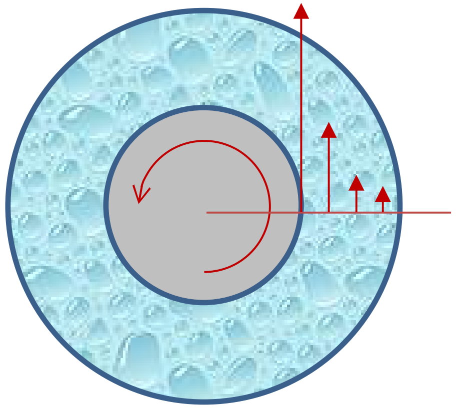
$$\omega_g^i = \frac{\alpha_g^{i+1} - \alpha_g^{i-1}}{2\cdot\Delta t}$$

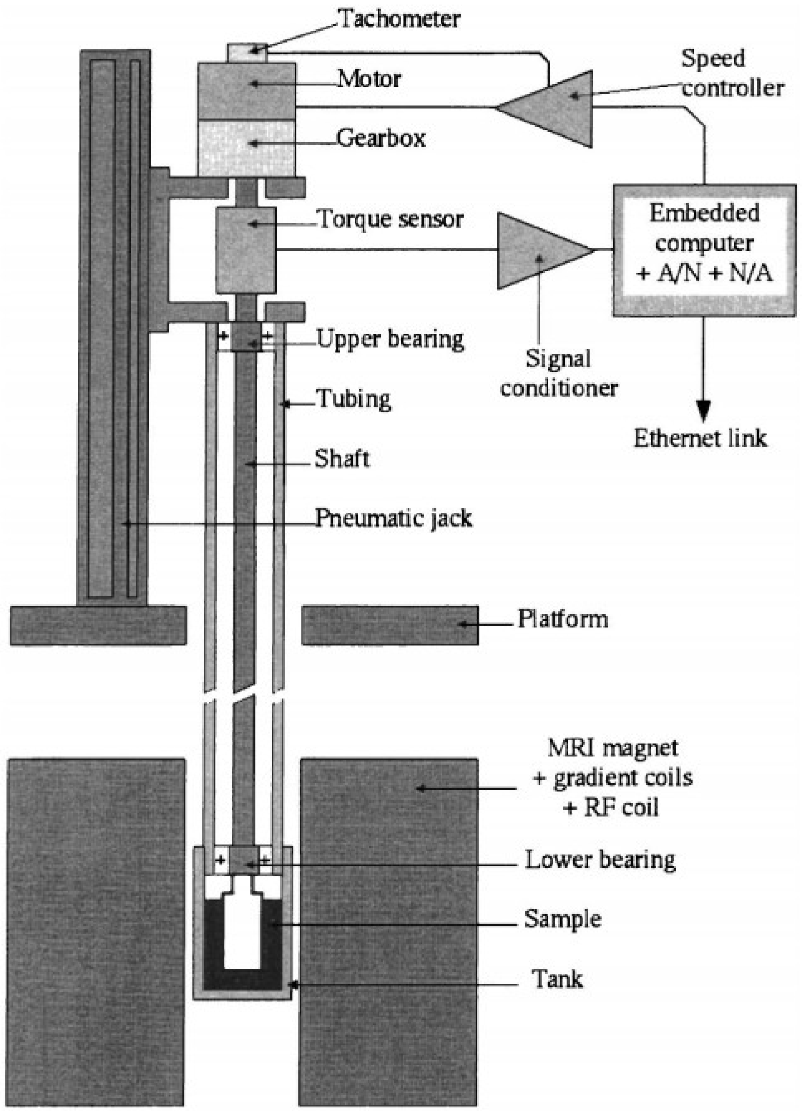
Magnetic Resonance Imaging (MRI)

- Couette rheometer placed inside NMR, filled with shaving foam
- Velocity (of liquid phase) vs position measured by NMR
- 90 sec measurement time



[Rodts et al. 2004]

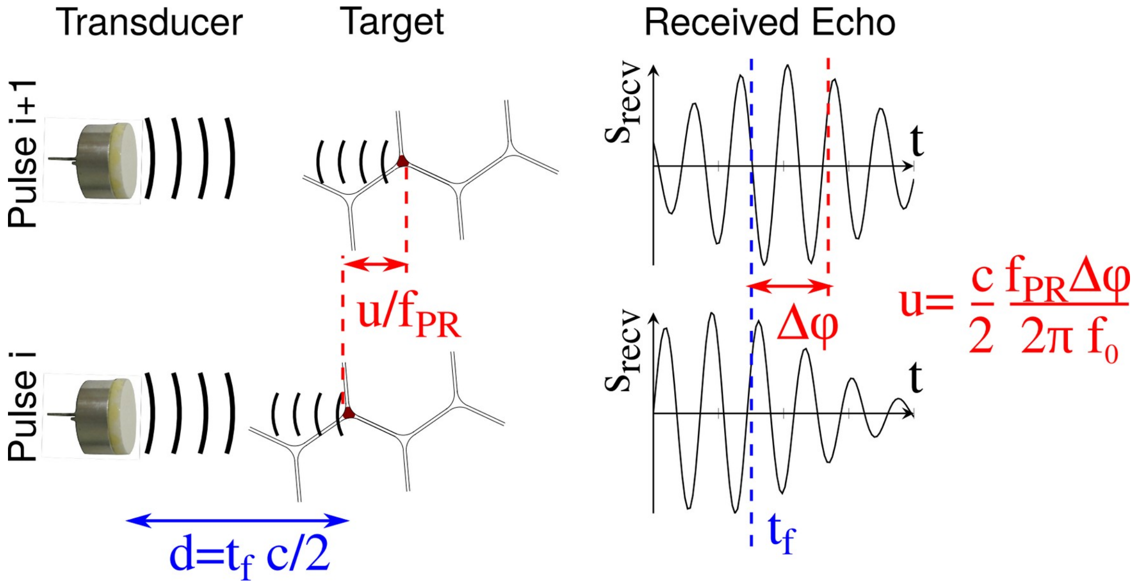


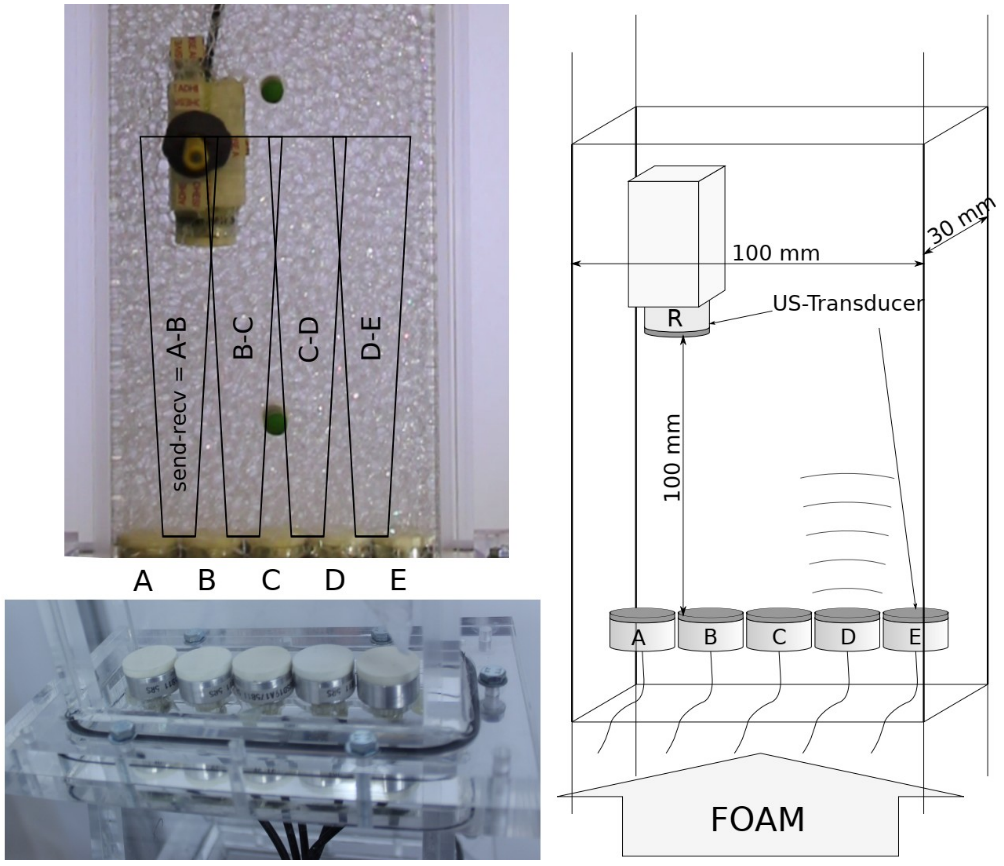


[Raynaud & Moucheront 2002]

Ultrasound Doppler velocimetry

- Pulse reflection at moving target → Doppler frequency shift
- Time of flight yields longitudinal position

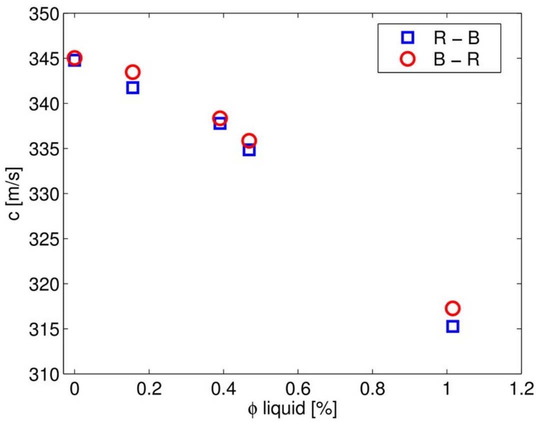


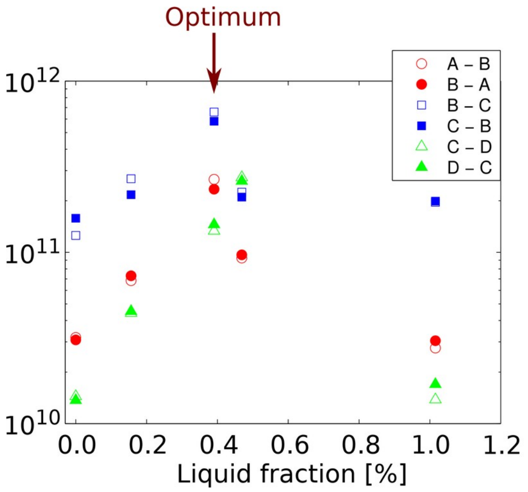


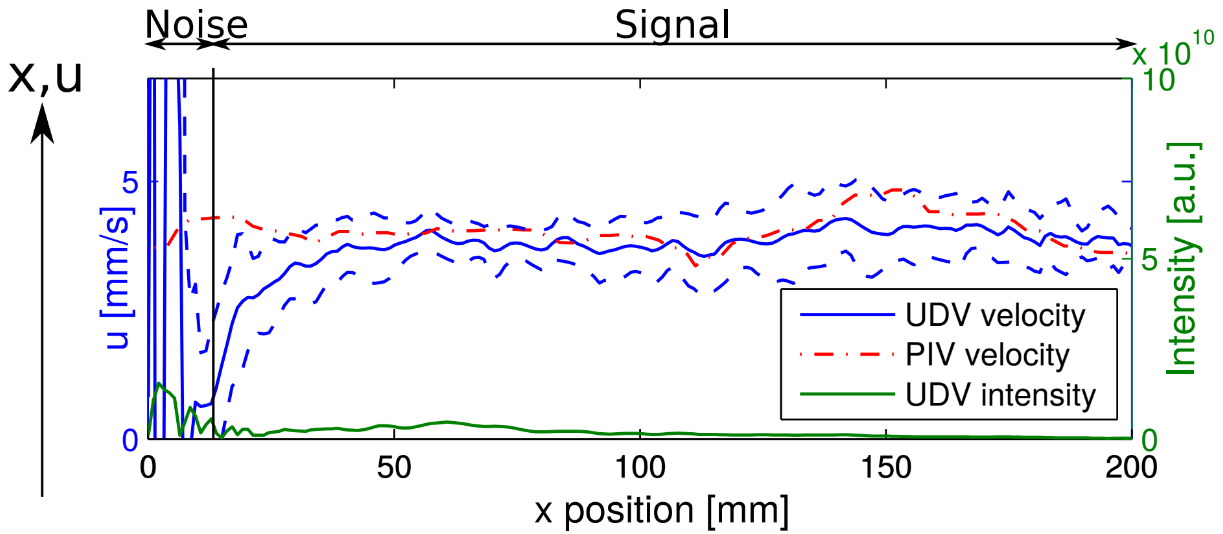
[Nauber et al. 2018]

Ultrasound Doppler velocimetry

- Liquid fraction influences speed of sound and attenuation
- Velocity measurement with 1fps and 10 % uncertainty







[Nauber et al. 2018]