Near-wall phenomena during bubble growth in nucleate boiling

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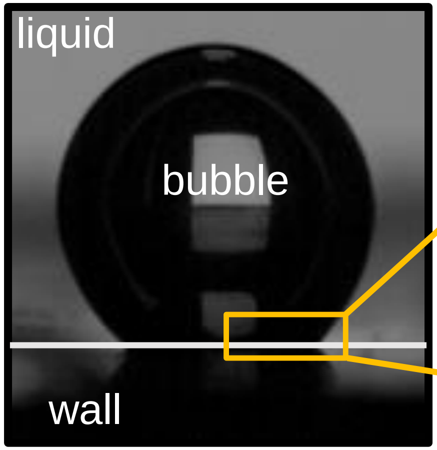
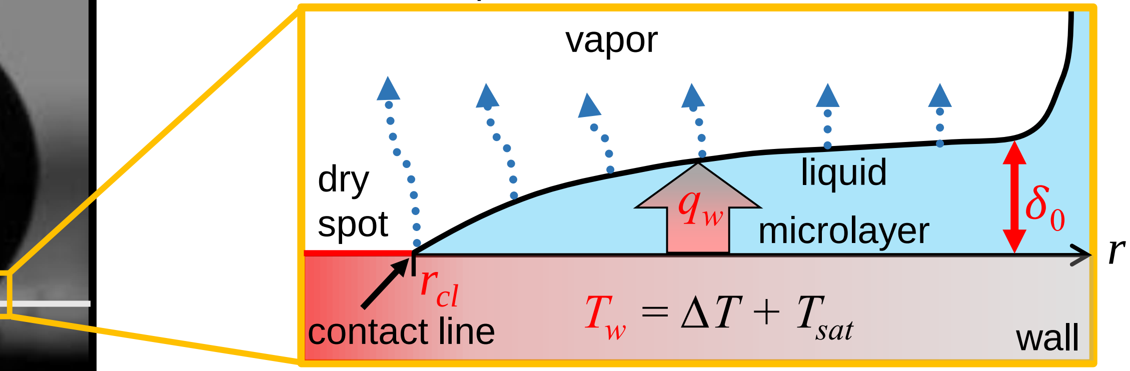
Dry spot and microlayer



Time scale: ms

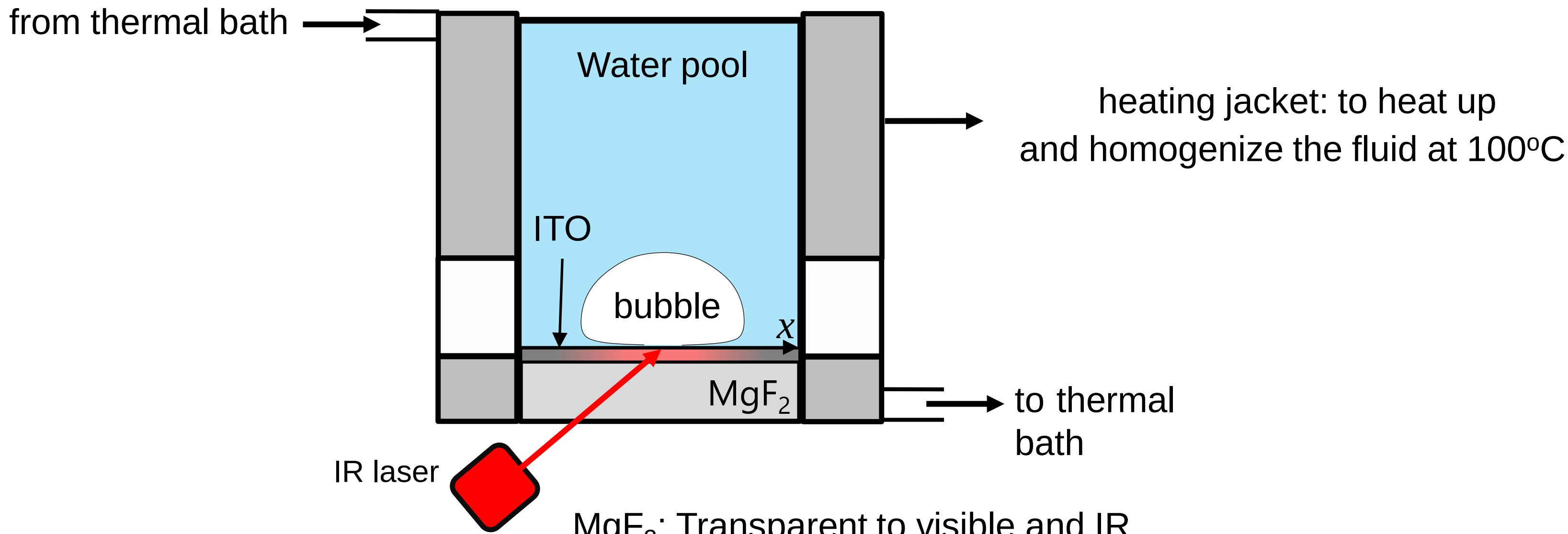
Length scale: mm



Length scale: µm

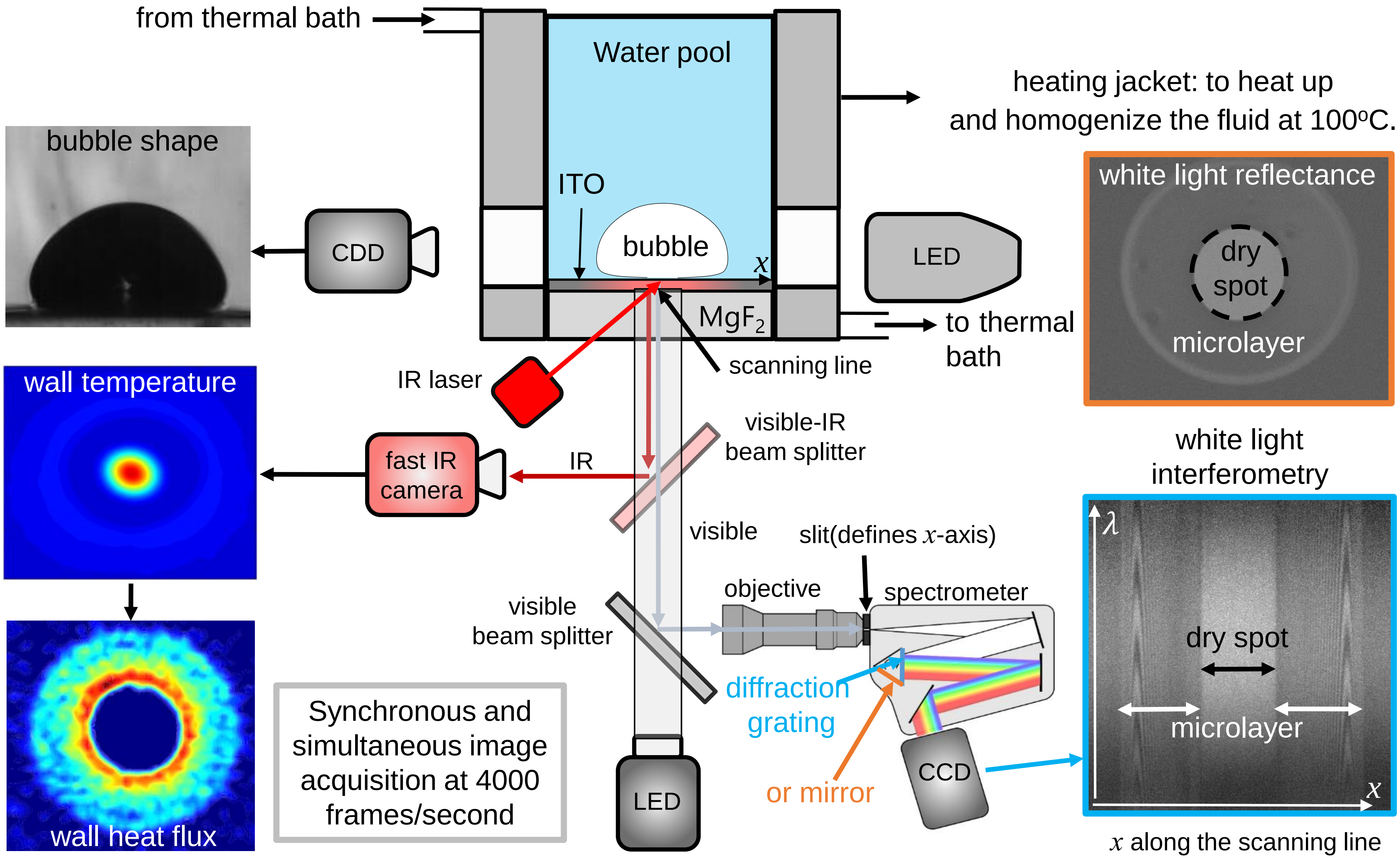
- Microlayer has low thermal resistance (µm liquid layer) leading to high heat fluxes; contributes to bubble growth.
- Dry spot spreading contributes to the wall dewetting → boiling crisis.
- Parameters of interest:
  - Initial microlayer thickness $\delta_0(r)$
  - Wall temperature distribution $T_w\,(r,t)$
  - Wall heat flux distribution $q_w\,(r,t)$
  - Contact line dynamics $r_{cl}(t)$

Pool boiling setup

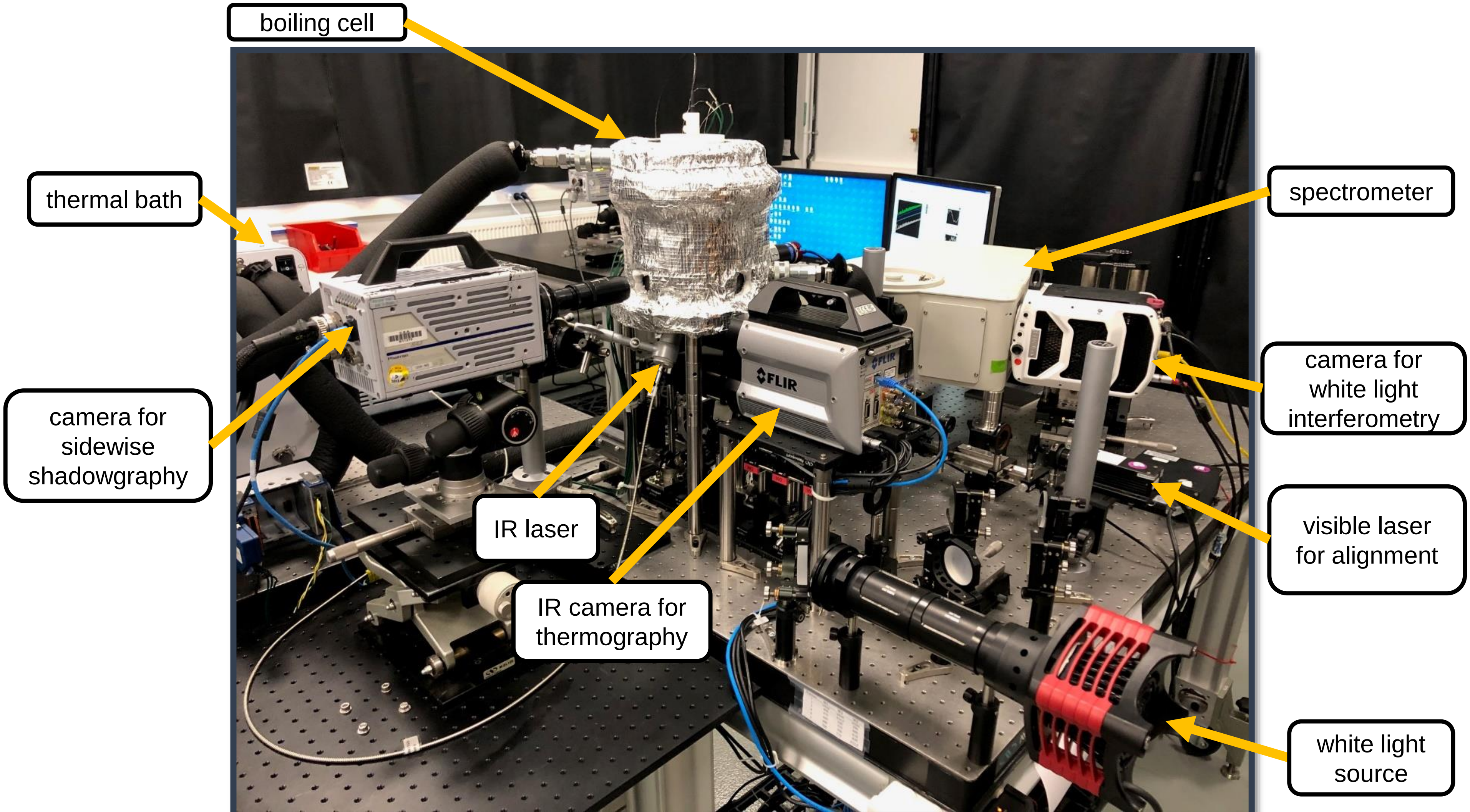


MgF_2: Transparent to visible and IR
ITO: Transparent to visible but opaque to IR.

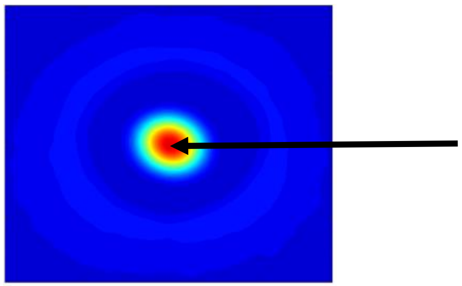
Optical techniques



Pool boiling experimental installation

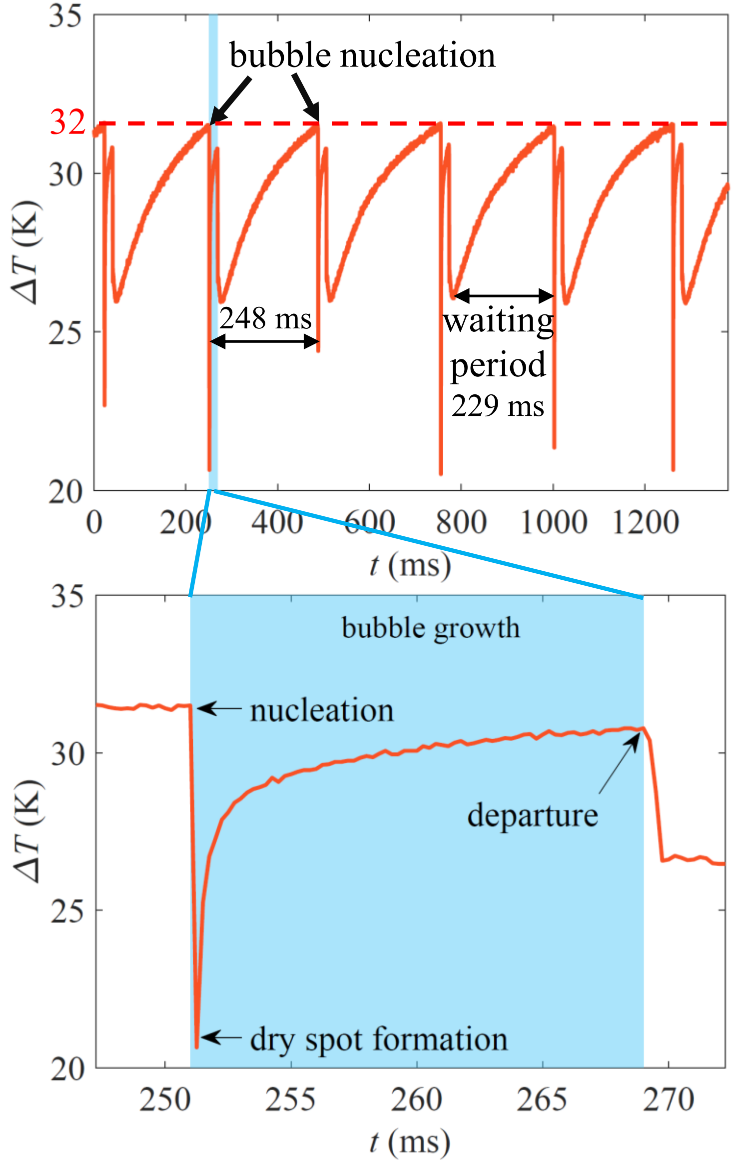


Bubble nucleation, growth and departure



$$\Delta T = T_w - T_{sat}$$

Measured at the nucleation point



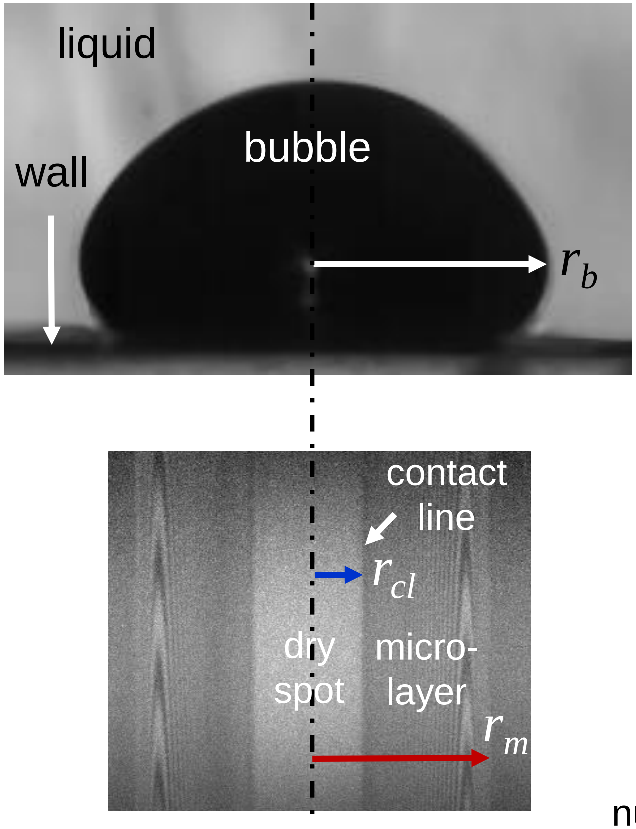
Repetitive boiling cycles

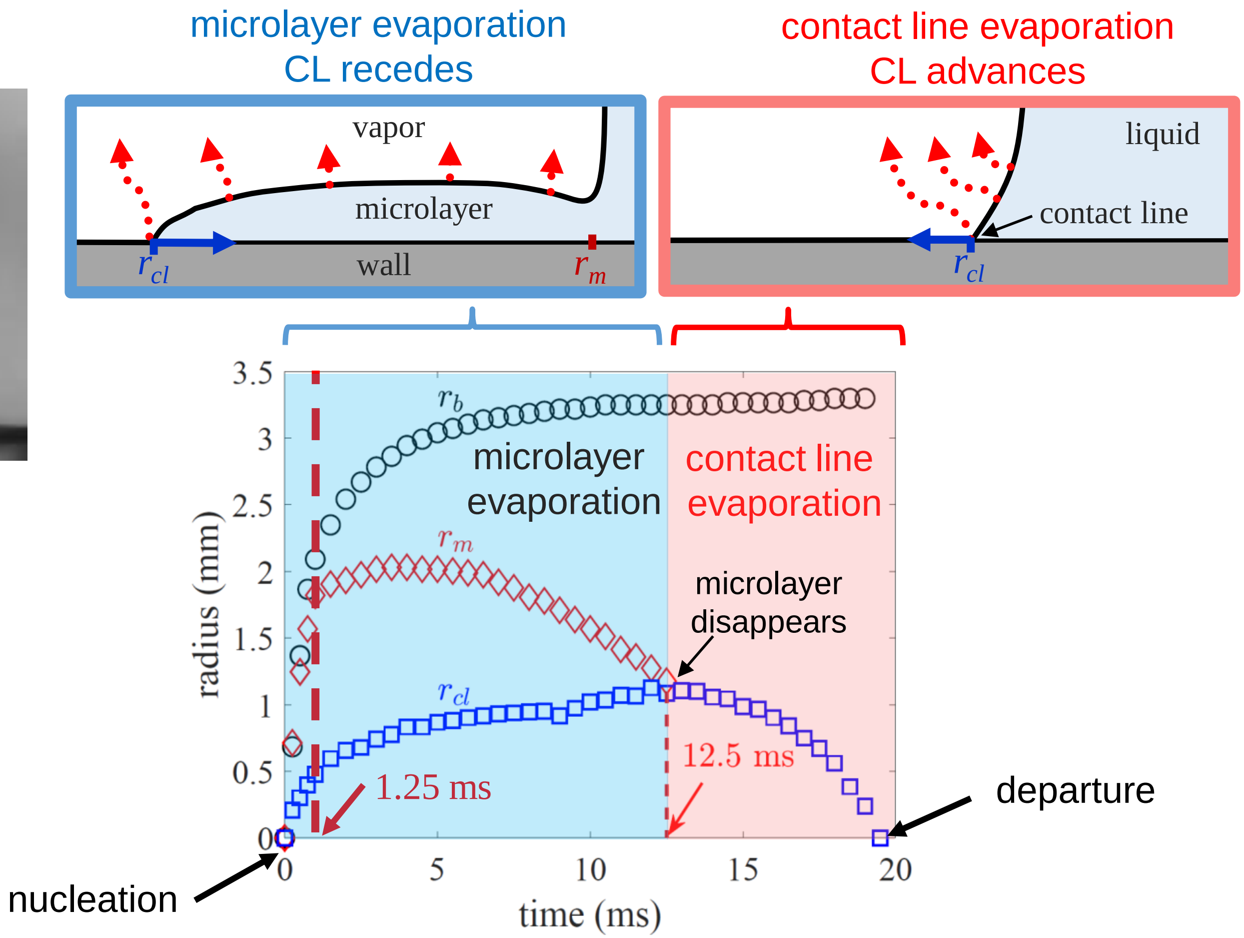
Typical pattern of nucleation, growth and departure

19 ms of bubble growth

The analysis of only one bubble growth cycle is sufficient.

Bubble, dry spot and microlayer radii

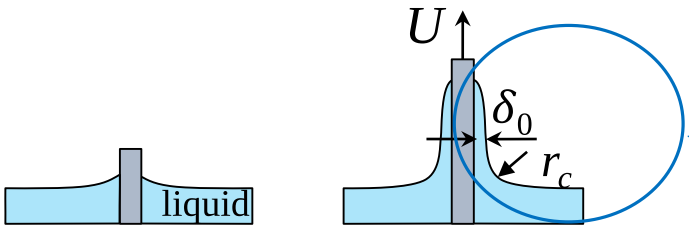




- Because of the localized heating mode, the microlayer is fully formed very quickly, in 1.25ms
- Microlayer disappears because of its length reduction and not by evaporation. CL recedes while bubble edge advances. (Tecchio et. al., JFM, 2024)

Microlayer as a Landau-Levich film

Microlayer formation is similar to the film coating (Tecchio et. al., JFM, 2024)



$\delta_0 = 1.337 r_c Ca^{2/3}$ (Landau & Levich, 1942)

$Ca = \frac{\mu U}{\sigma}$: capillary number

r_c : radius of interface curvature near the film

For a bubble:

- $U = \frac{dr_b}{dt}$
- one can assume that $r_c \propto r_b$ ($r_c = \beta r_b$)

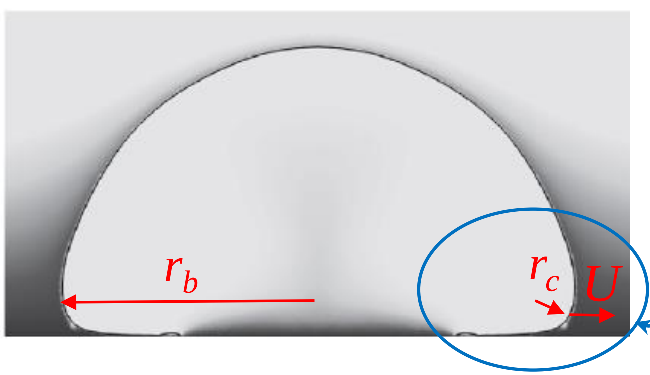
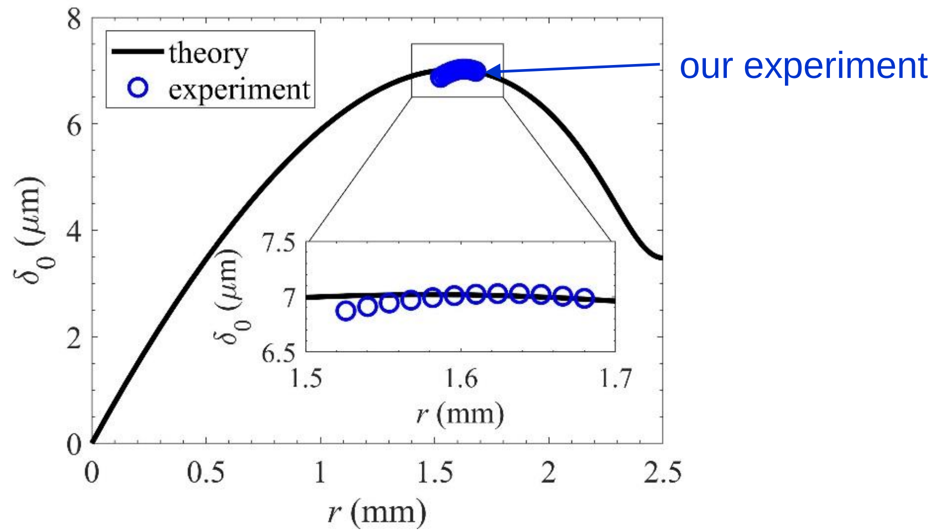


Image from Urbano et. al., (2018)

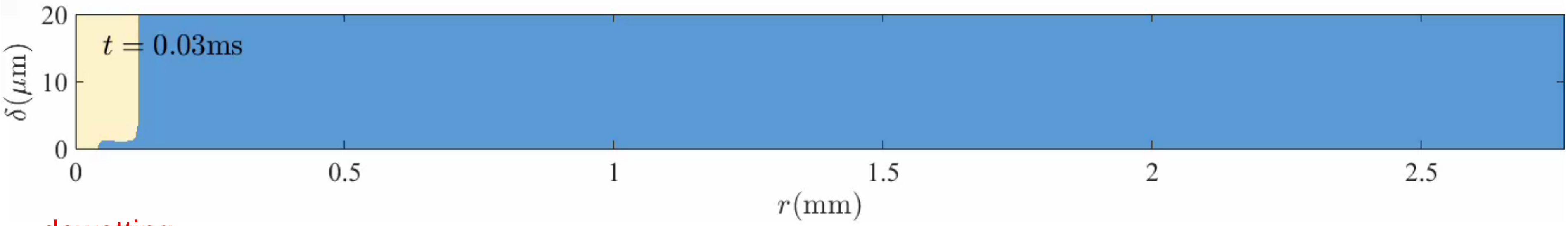
β=0.084 is chosen to fit the **amplitude** of experimental data



- We could measure only a part around the maximum because of slope limitation of interferometry (~0.4º)
- Such a simple theory captures correctly the experimental **position** $r \approx 1.6$ mm of maximum
- Maximum appears because r_b grows while U decreases with t

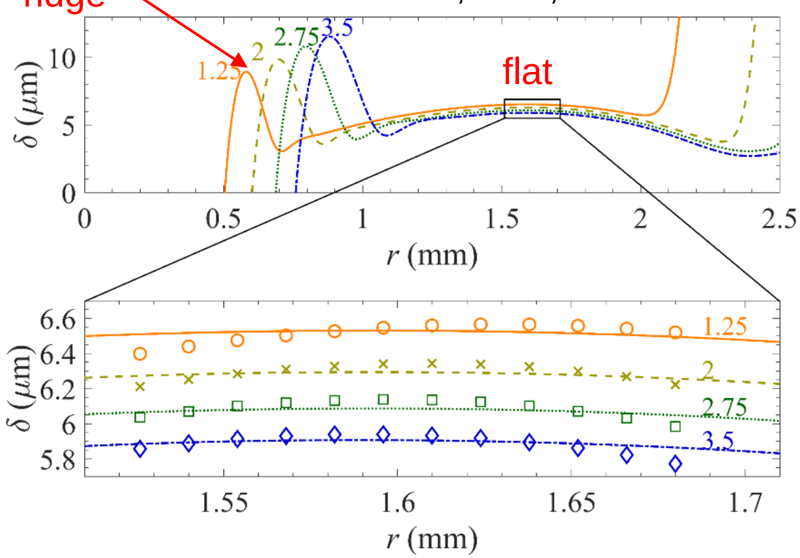
Microlayer with dewetting and evaporation

Simulation based on the 2D lubrication approach accounting for the evaporation and contact line dynamics (Zhang and Nikolayev, JFM, 2022)



dewetting ridge

Tecchio et. al., JFM, 2024



lines: numerical

characters: experiment

Dewetting ridge

- Formed because of high viscous shear in the film and fast contact line receding. Liquid from the previously wetted area accumulates in a ridge.
- Grows in time because of fast contact line receding.
- Dewetting ridge appears in many recent microlayer simulations (Urbano et al. 2018, Giustini, 2024, Bureš & Sato, 2021)
- Ridge was never detected by interferometry because of the slopes higher than critical (~0.4º) .

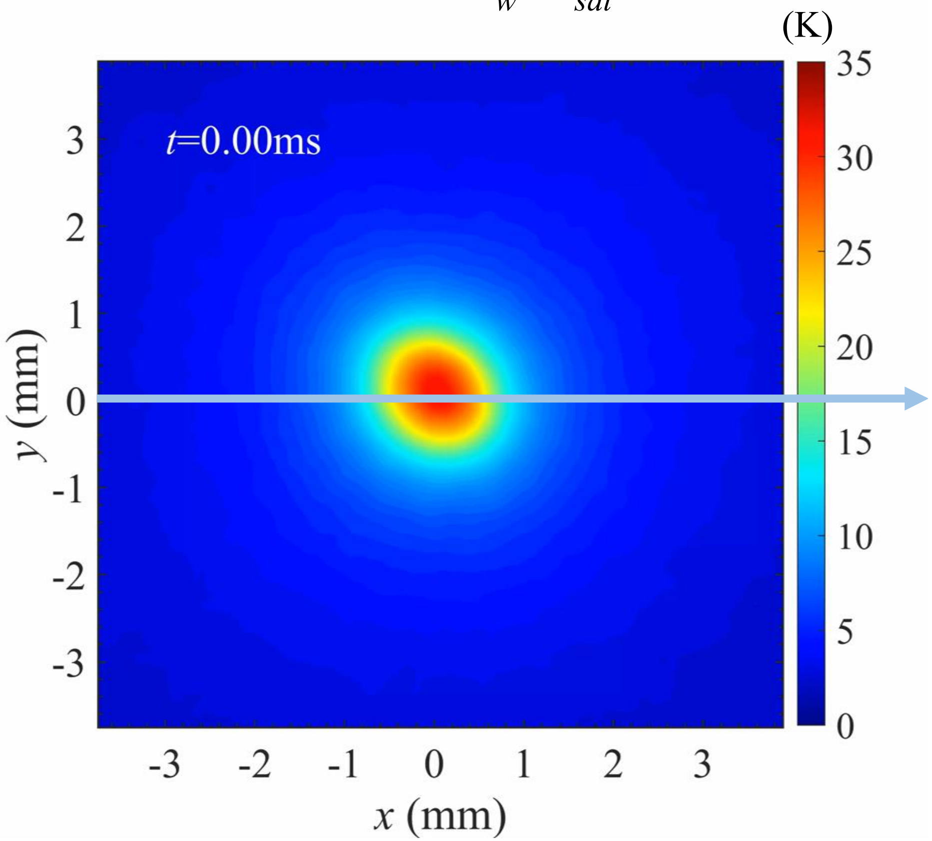
Flat microlayer

- Viscosity and surface tension control the microlayer profile deposited by the receding meniscus.
- Thins over time due to microlayer evaporation only.
- Small slopes produce detectable fringes.

Wall temperature

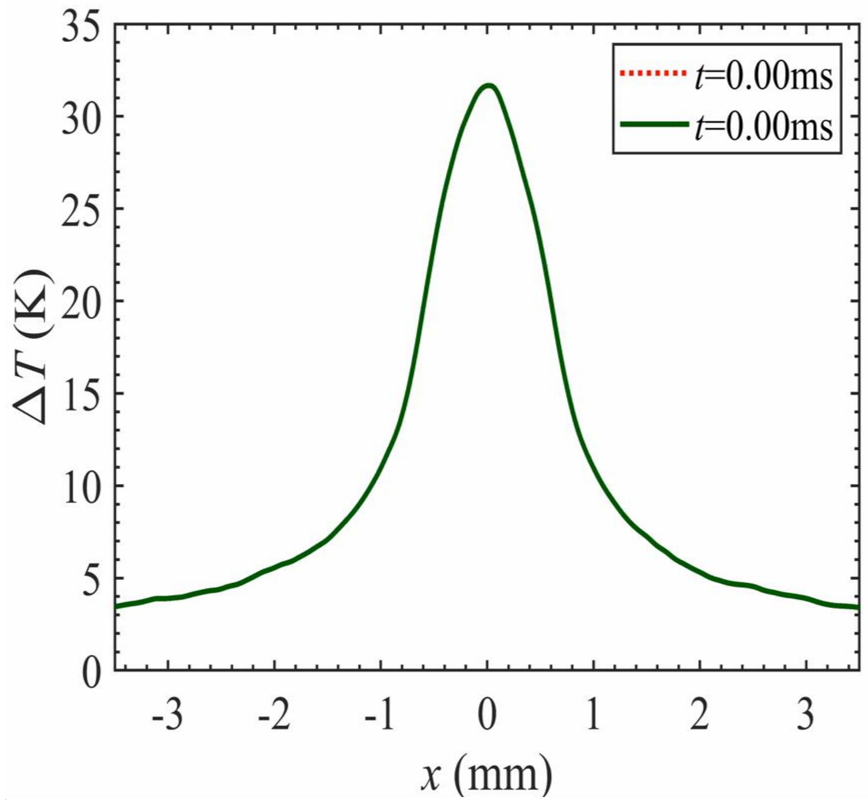
Wall superheating temperature: 2D distribution

$$\Delta T = T_w - T_{sat}$$



Inner circle: Contact line
Outer circle: Microlayer ending or contact line

Wall superheating temperature: Profile



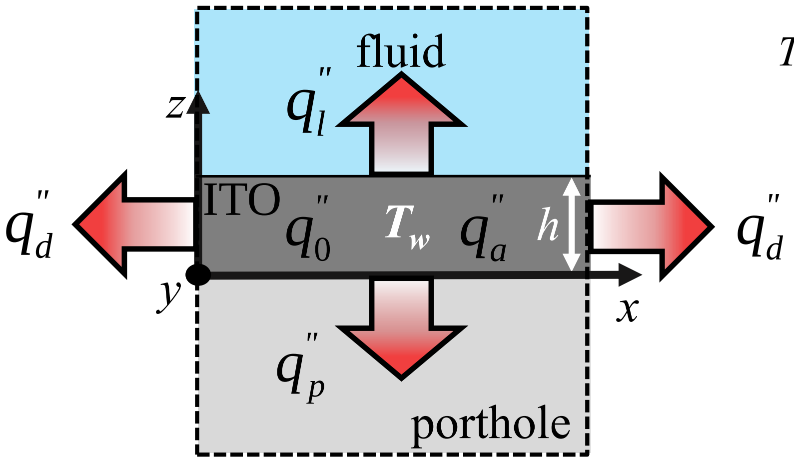
microlayer | dry spot | microlayer

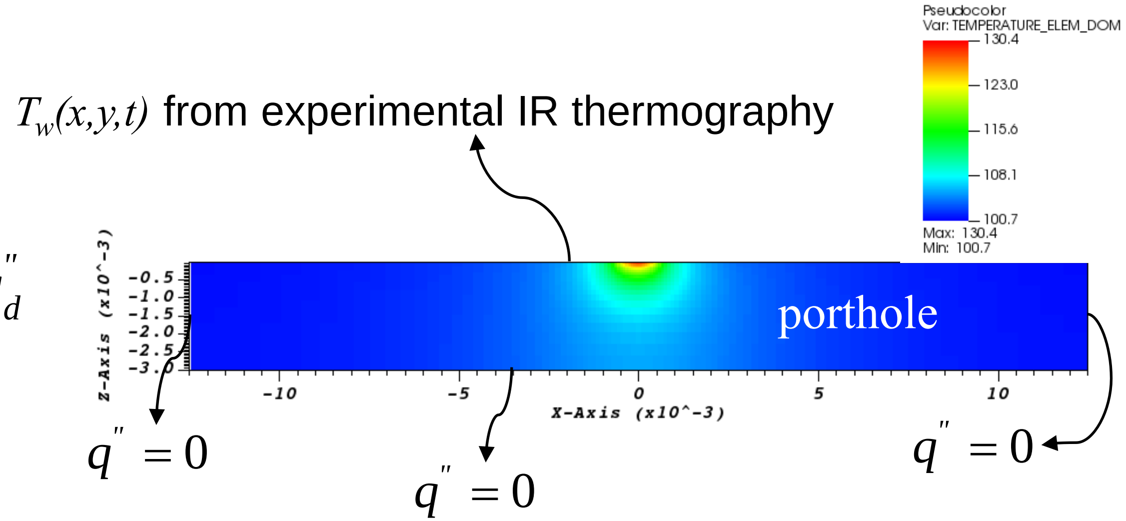
Wall heat flux reconstruction

$$q_l'' = q_0'' + q_p'' + \underbrace{hk_w\left(\frac{\partial^2 T_w}{\partial x^2} + \frac{\partial^2 T_w}{\partial y^2}\right)}_{q_d''} - \underbrace{h\rho_w c_w \frac{\partial T_w}{\partial t}}_{q_a''}$$

Valid everywhere on the ITO film (dry spot and microlayer)

(Kenning and Yan, IJHMT, 1996)





q_0'' : Heat flux on the ITO film given by the IR laser.

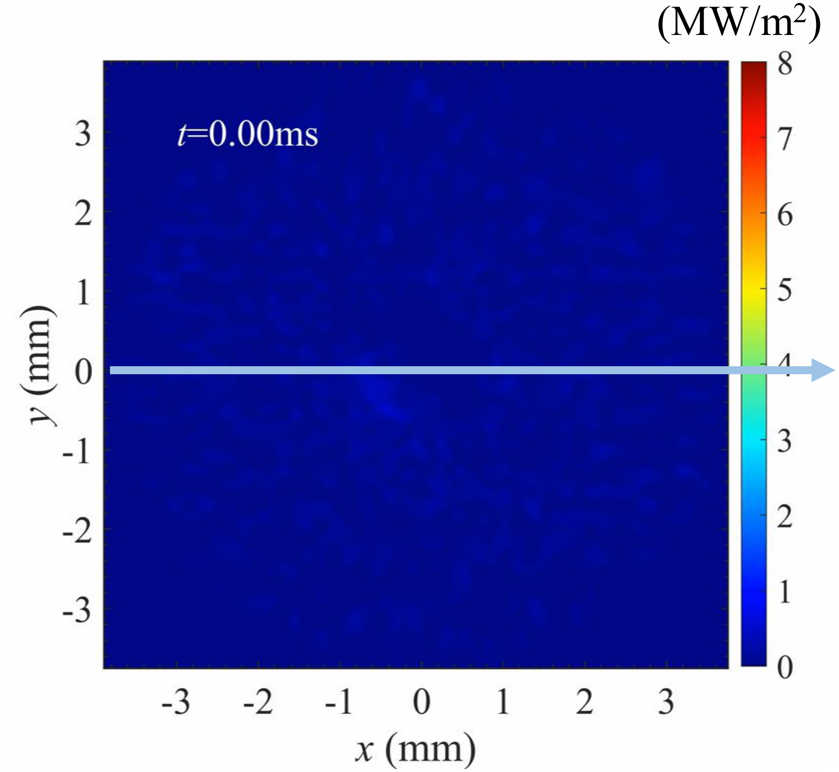
q_p'' : Heat flux at the porthole/ITO interface. Solved numerically (transient heat diffusion).

q_d'' : Radial heat diffusion through the ITO film.

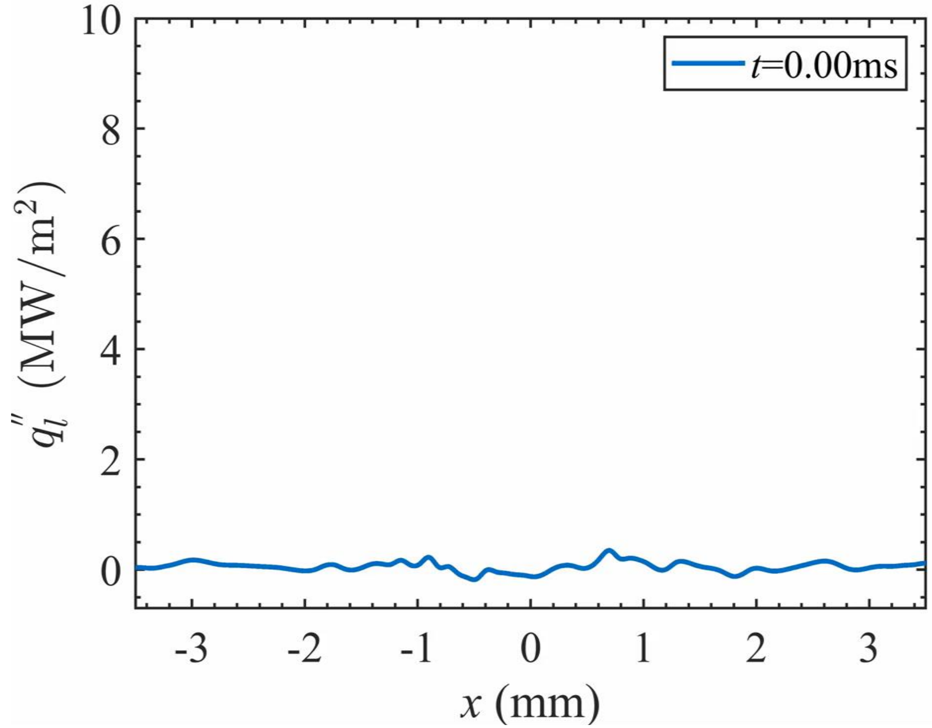
q_a'' : Heat accumulation in the ITO film as internal energy.

Reconstructed wall heat flux

Wall heat flux: 2D distribution



Wall heat flux profile



Inner circle: Contact line
Outer circle: Microlayer ending or contact line

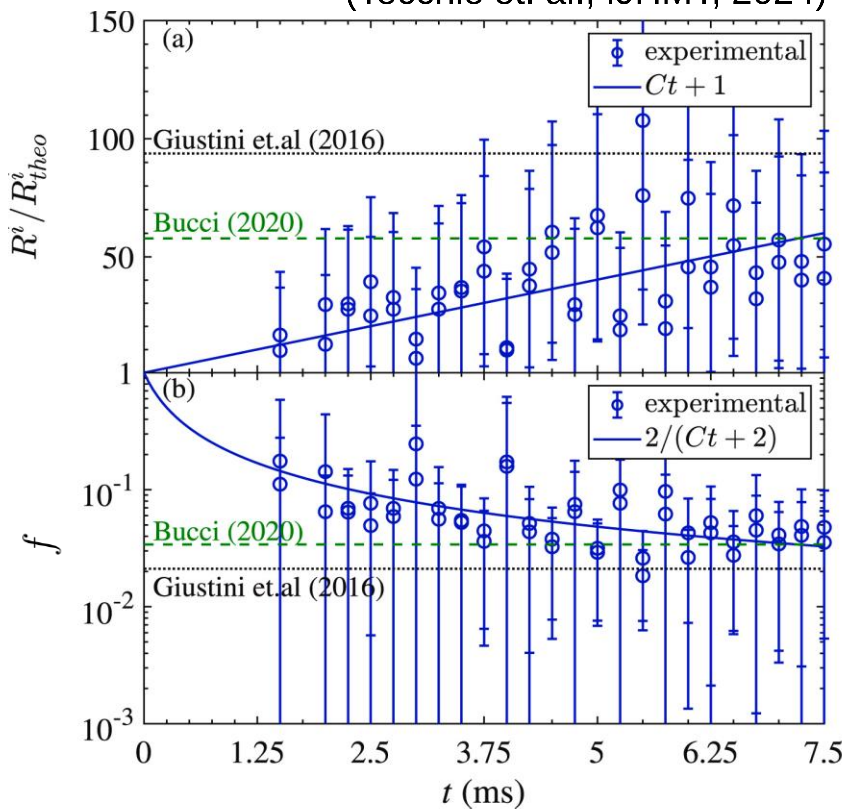
microlayer	dry spot	microlayer

Interfacial thermal resistance

Determined theoretically by the limited velocity of vapor :

$$R^i = \frac{2-f}{2f}\frac{T_{sat}\sqrt{2\pi\mathbb{R}_g T_{sat}/\mathbb{M}}}{\mathcal{L}^2\rho_v} \qquad f = 1 \longrightarrow R^i = R^i_{theo}$$

(Tecchio et. al., IJHMT, 2024)



- Accumulation of impurities at the interface promote an increase of interfacial thermal resistance

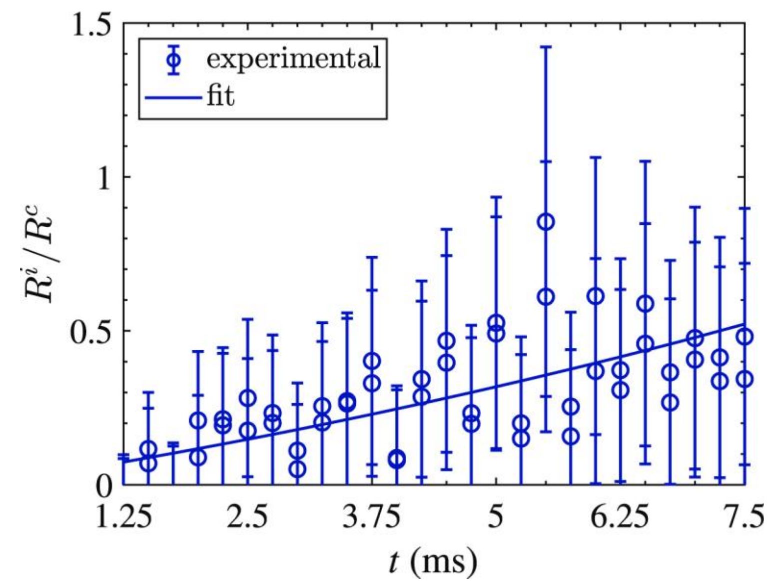
Determined experimentally using the heat flux expression in the microlayer:

IR thermography

Wall heat flux

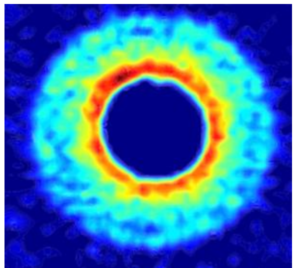
WLI

$$q_l'' = \frac{\Delta T}{\underbrace{\delta/k_l}_{R^c} + R^i} \Longrightarrow R^i$$



- R^c decreases because of microlayer evaporation while R^i increases. The ratio R^i/R^c only increases.

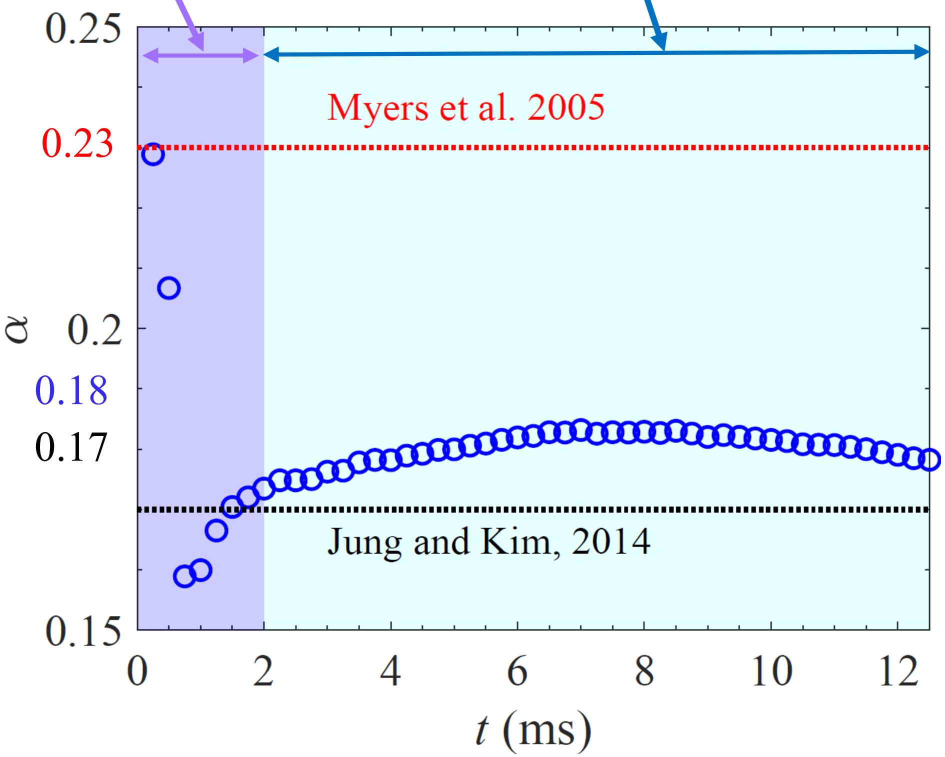
Contribution of microlayer evaporation to bubble growth



$$\alpha = \frac{\boxed{\text{Heat flux integrated over the microlayer}}}{\boxed{\text{Latent heat corresponding to bubble volume increase}}}$$

Rapid bubble growth. Contact line inside hot spot

Bubble growth slows down. Contact line moves away from the hot spot



Microlayer evaporation contribution to bubble growth is about 18% (lower limit) (Tecchio et. al., IJHMT, 2024)

Concluding remarks

- The experimental apparatus is able to measure, synchronously and simultaneously, the microlayer thickness, extents of dry spot and microlayer, wall temperature and bubble macroscopic radius. The wall heat flux is reconstructed.
- We show experimentally that the microlayer can be seen as thin film deposition by the bubble edge.
- Microlayer thinning is a result of its evaporation.
- Excessive interfacial resistance is measured and seems to be a result of water contamination.
- Microlayer evaporation contributes 18% to the overall bubble growth.

Thank you for your attention!

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