Advanced computational methods and diagnostics for two-phase flow and heat transfer

Jacopo Buongiorno

Associate Professor of Nuclear Science and Engineering
Massachusetts Institute of Technology
(617)253-7316, jacopo@mit.edu

Oak Ridge National Laboratory

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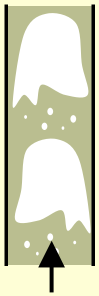
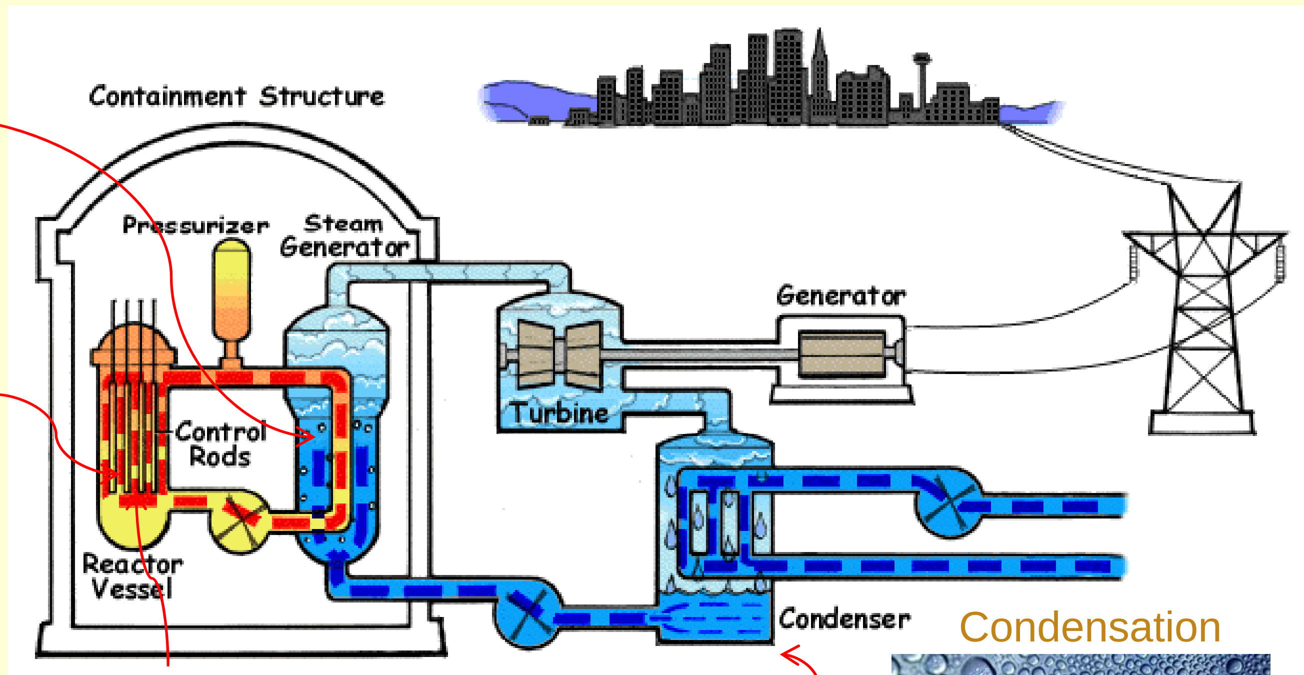
MIT Center for Advanced Nuclear Energy Systems

In LWRs, two-phase flow and heat transfer phenomena are everywhere

Flow boiling

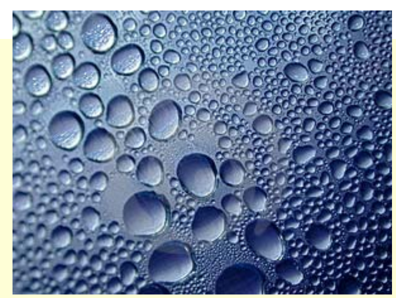




Quenching during LOCAs

Nucleate boiling (including CHF)

Condensation



Nuclear, the old way

Current codes (e.g., RELAP, TRACE, VIPRE) are based on the two-fluid six-equation model:

Mass (k = liquid or vapor)

$$\frac{\partial(\alpha_k \rho_k)}{\partial t} + \frac{\partial(\alpha_k \rho_k v_k)}{\partial z} = \Gamma_k$$

Interfacial exchange terms specified by constitutive relations

Momentum

$$\frac{\partial(\alpha_k \rho_k v_k)}{\partial t} + \frac{\partial(\alpha_k \rho_k v_k^2)}{\partial z} = -\alpha_k \frac{\partial P}{\partial z} - \frac{\tau_{w,k} p_{w,k}}{A} - \alpha_k \rho_k g \cos\theta + \Gamma_k v_k + F'''_{i,k}$$

Energy

$$\frac{\partial[\alpha_k \rho_k (h_k + \frac{v_k^2}{2})]}{\partial t} + \frac{\partial[\alpha_k \rho_k v_k (h_k + \frac{v_k^2}{2})]}{\partial z} = \frac{q''_w p_{w,k}}{A} + \alpha_k \rho_k v_k g \cos\theta + \Gamma_k (h_k + \frac{v_k^2}{2}) + F'''_{i,k} v_k + Q'''_{i,k}$$

Nuclear, the old way (2)

Current codes are (relatively) fast, BUT

- Numerical errors are not easily quantified
- Employ empirical constitutive equations applicable only in narrow operating ranges
- Are unsuitable for multi-dimensional analysis
- Assume unphysical sharp transitions between flow regimes
- Assume idealized geometry of interface between phases

Nuclear, the old way (3)

This approach has resulted in the adoption of "supersized" margins, which are effectively a measure of ignorance of key phenomena such as DNB, two-phase flow, multi-dimensional natural circulation, etc.

Over-conservatism is hurting nuclear economically in the competition vs coal, gas and renewables

The path forward

- Higher computing power makes it possible to adopt fully-implicit smooth solution schemes, which should make numerical uncertainty negligibly small.
- The onus of accuracy is shifted to the constitutive models.

3 types of constitutive models are possible:

- Purely empirical “models”, e.g., Chen’s correlation (hopefully a thing of the past)
- Mechanism-based semi-empirical models
- “First-principle” models

Semi-Empirical Constitutive Models

Example: the RPI heat flux partitioning model for nucleate boiling

$$q_{tot}'' = q_e'' + q_q'' + q_c''$$

$$q_e'' = \frac{\pi D_b^3}{6} \rho_g h_{fg} f_b N_{SD}$$

$$q_q'' = \left(t_w f_b\right) A_q \frac{2k_l (T_w - T_{sat})}{\sqrt{\pi \alpha_l t_w}}$$

$$q_c'' = A_{1\phi} h_{turb} \left(T_w - T_{sat}\right)$$

Still requires input of:

- bubble departure diameter
- bubble departure frequency
- bubble growth and wait times
- nucleation site density

Generally applicable correlations for these boiling parameters are not available!

“First-Principle” Constitutive Models

Calculate liquid-vapor interface geometry with interface tracking methods

Mass $\nabla \cdot \vec{u} = 0$

Energy $\rho c_p \left[\frac{\partial T}{\partial t} + \nabla \cdot (\vec{u} T) \right] = \nabla \cdot \lambda \nabla T$

Surface tension represented as delta function at interface

Momentum (Navier-Stokes)

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho \nabla \cdot (\vec{u}\vec{u}) = -\nabla P + \nabla \cdot \mu (\nabla \vec{u} + \nabla^{\perp} \vec{u}) + \rho \vec{g} + \sigma \kappa \vec{n} \delta_S$$

Marker function

Marker function defines position and shape of interface

$$\frac{\partial \phi}{\partial t} + \vec{u} \cdot \nabla \phi = 0$$

$$\phi(\vec{r}, t) \equiv \begin{cases} 1 & liquid \\ 0 & vapor \end{cases}$$

Properties

$$\rho = \phi \rho_\ell + (1-\phi)\rho_v \qquad \mu = \phi \mu_\ell + (1-\phi)\mu_v$$

$$c_p = \phi c_{p,\ell} + (1-\phi) c_{p,v} \qquad \lambda = \phi \lambda_\ell + (1-\phi)\lambda_v$$

One-fluid four-equation approach; momentum and energy exchanges are calculated directly by resolving velocity and temperature gradients at the interface

“First-Principle” Constitutive Models (2)

Possible treatments of turbulence in Navier-Stokes equations are same as in single-phase CFD:

- Direct Numerical Simulation (DNS): resolves all time/space scales down to dissipative (Kolmogorov) eddies
- Large Eddy Simulation (LES): low-pass filtered equations, constitutive equation needed for dissipative eddies
- Reynolds stress Averaged Navier Stokes (RANS): uses constitutive model for Reynolds stresses in time-averaged equations

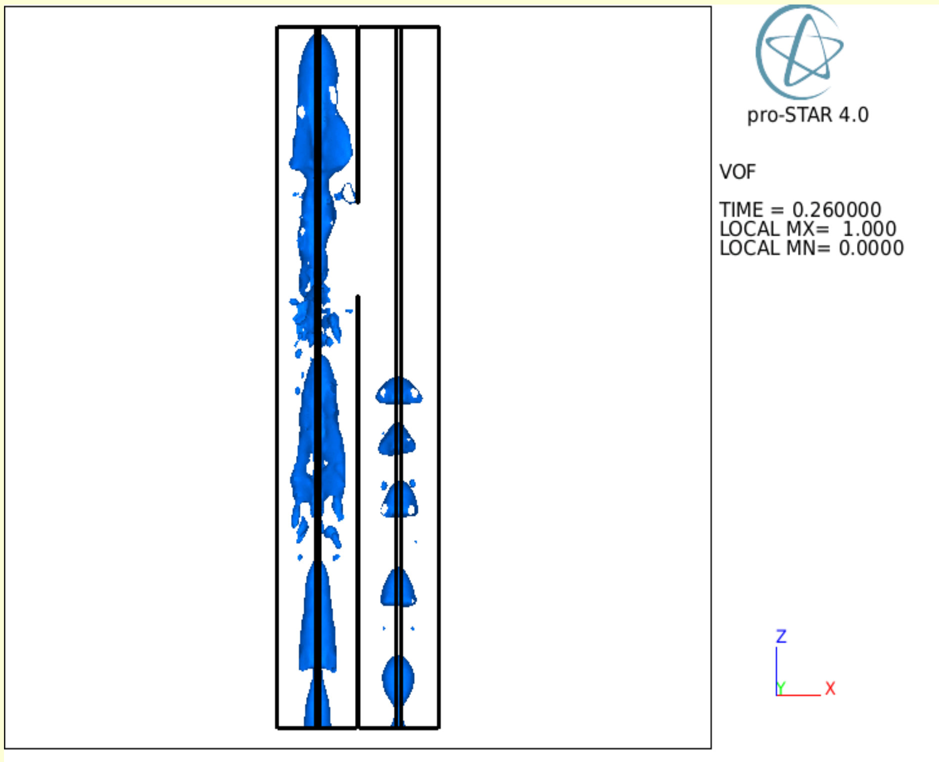
2 main approaches to solution of the marker function equation:

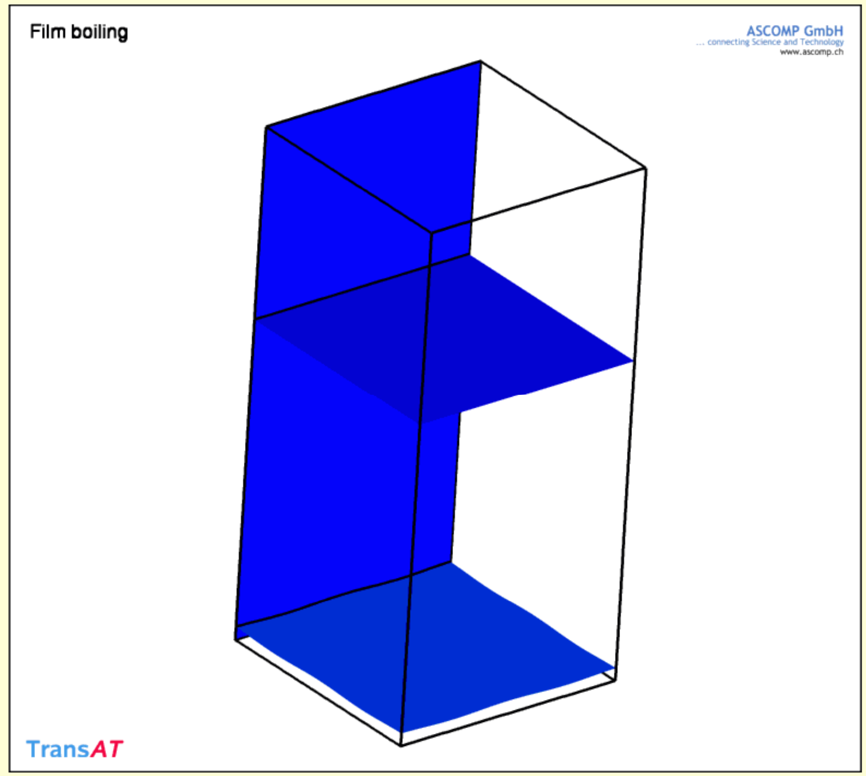
- Volume Of Fluid (VOF): interface is geometrically reconstructed from value of fluid fraction (between 0 and 1) in any given grid element
- Level-set: uses *continuous* marker function; $\phi=0$ contour surface marks the interface
- Front tracking: marker *points* on the interface are tracked
- Smooth particles hydrodynamic (SPH): continuum is discretized into *particles*, followed individually (similar to MD, but larger scale)

“First-Principle” Constitutive Models (3)

Example 1: plug flow
(VOF – E. Baglietto, CD-Adapco)

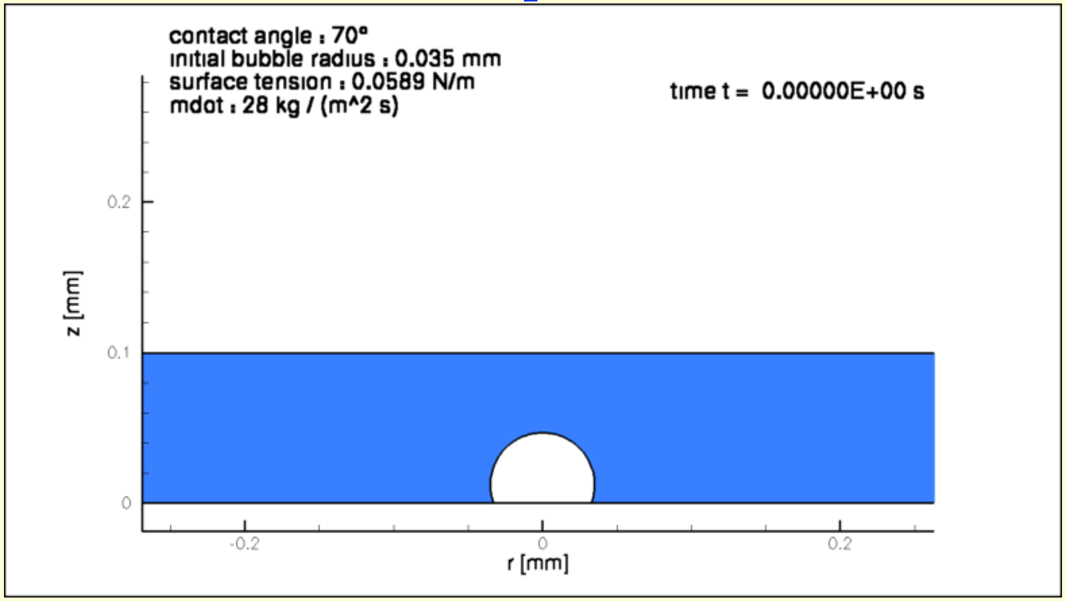
Example 2: film boiling
(level set – D. Lakehal, Ascomp)





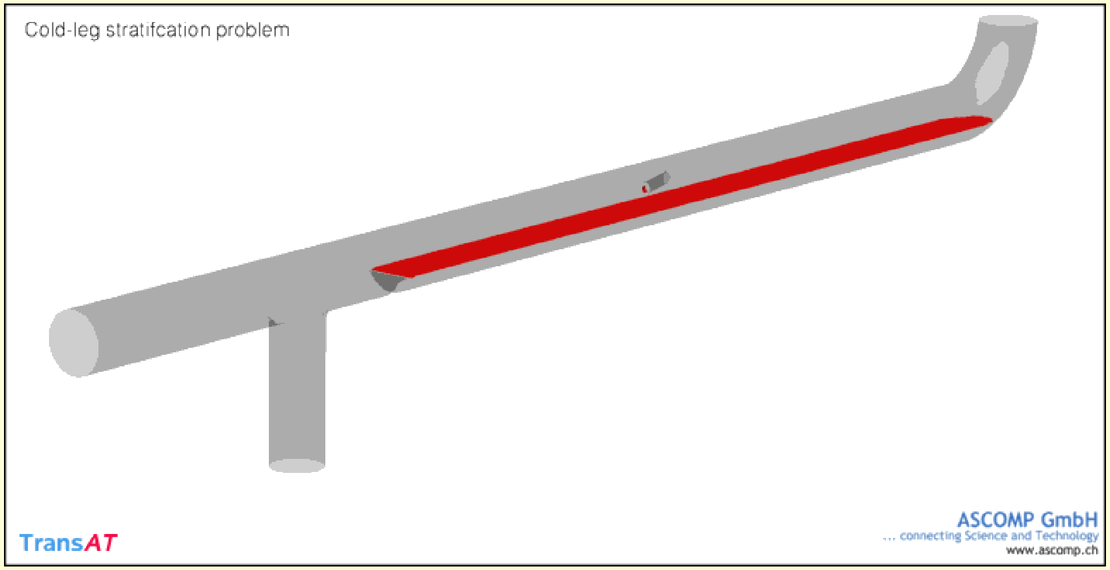
Example 3: small bubble interactions http://users.wpi.edu/~gretar/Movies/b27_def.mpg
(front tracking – G. Tryggvason, WPI)

"First-Principle" Constitutive Models (4)



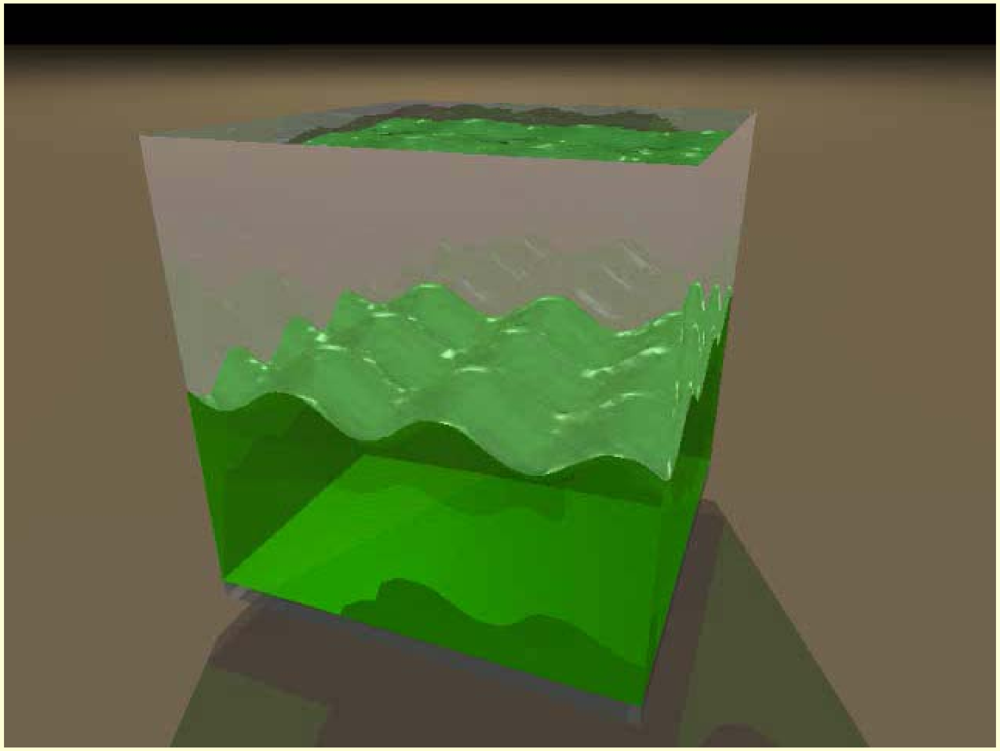
Example 4: bubble growth and burst in high-heat flux nucleate boiling (level set – D. Lakehal, Ascomp)

Example 5: mixing of ECCS water and steam in cold leg after LOCA (level set/LES – D. Lakehal, Ascomp)

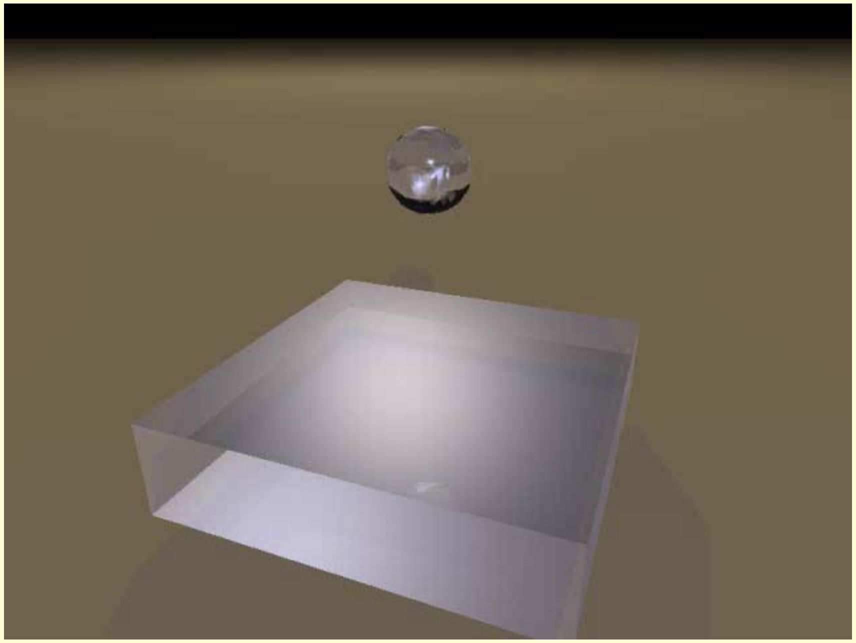


"First-Principle" Constitutive Models (5)

Example 6: Raleigh-Taylor instability
(SPH – J. Williams, MIT)



Example 7:
Droplet impact into thin film
(SPH – J. Williams, MIT)



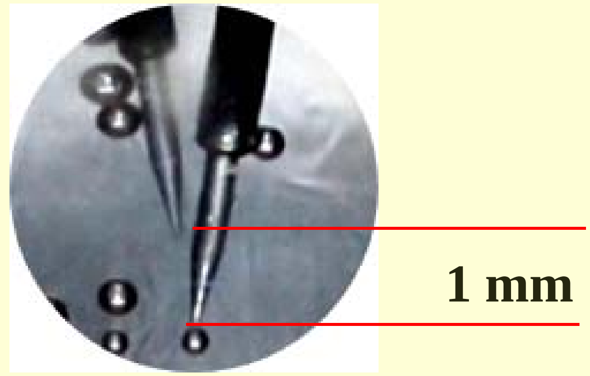
How to validate models that generate such richness of information?

Two-Phase Flow Diagnostics: State-of-the-art

Input for and validation of constitutive models requires advanced two-phase flow diagnostics:

- Multi-sensor conductivity and optical probes (Purdue, Berlin Tech Univ and many others)
- Wire-mesh probe (ETH)
- X-ray tomography (FZD, MHI and others)
- Neutron radiography (JAERI, Kyoto Univ)
- Particle image velocimetry (TAMU, Darmstadt Univ and others)
- NMR (CEA)

Multi-sensor conductivity/optical probes



Sensor is a binary phase indicator.

Number of sensors per probe determines parameters that can be measured:

- 1 sensor: void fraction
- 2 sensors: bubble velocity
- 3 sensors: bubble curvature and interfacial area

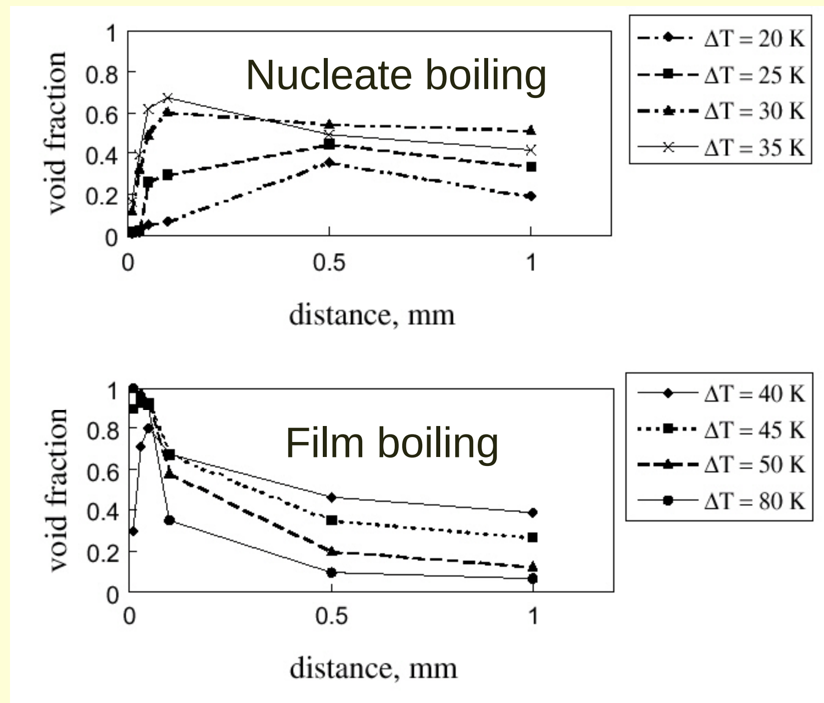
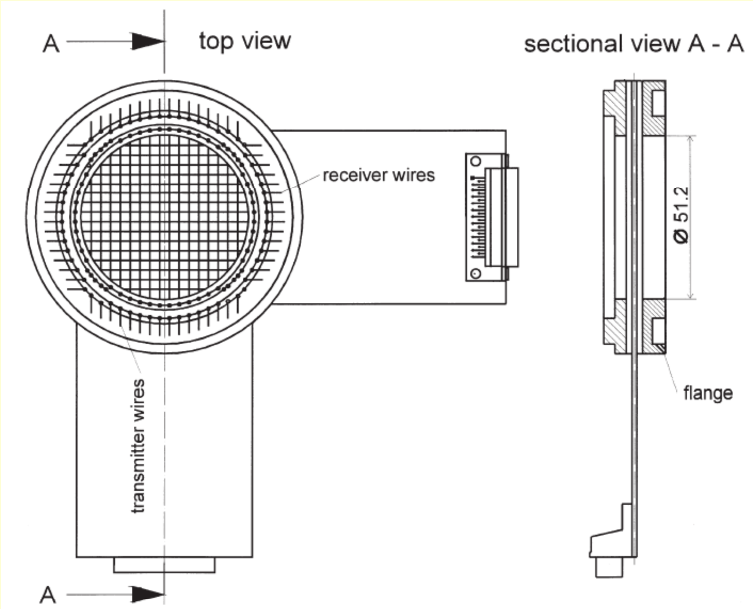


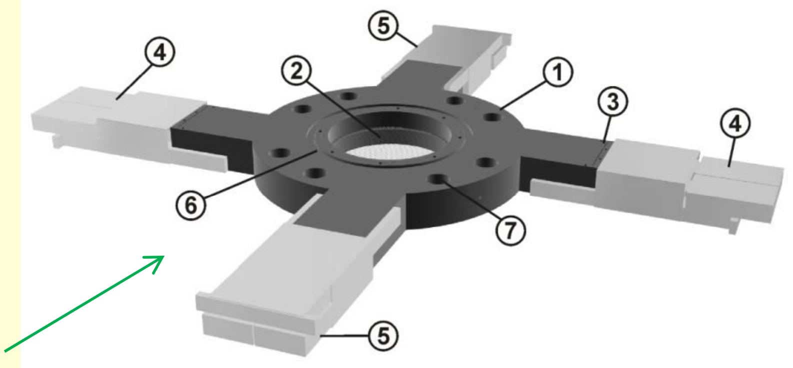
Fig. 15. Time averaged void fraction of FC-72 above heater in different boiling regimes.

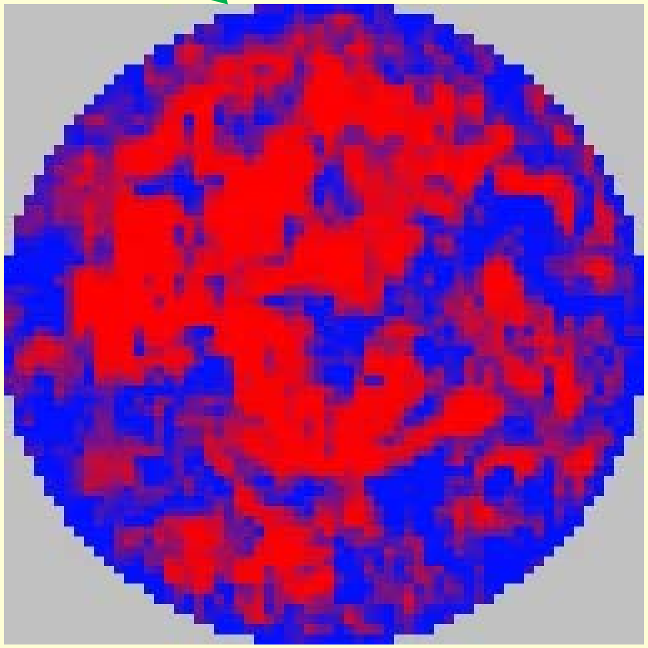
Wire-mesh sensor



Measures electrical conductivity at each wire intersection

Gives instantaneous 2D void fraction distribution across channel (time resolution ~1kHz)

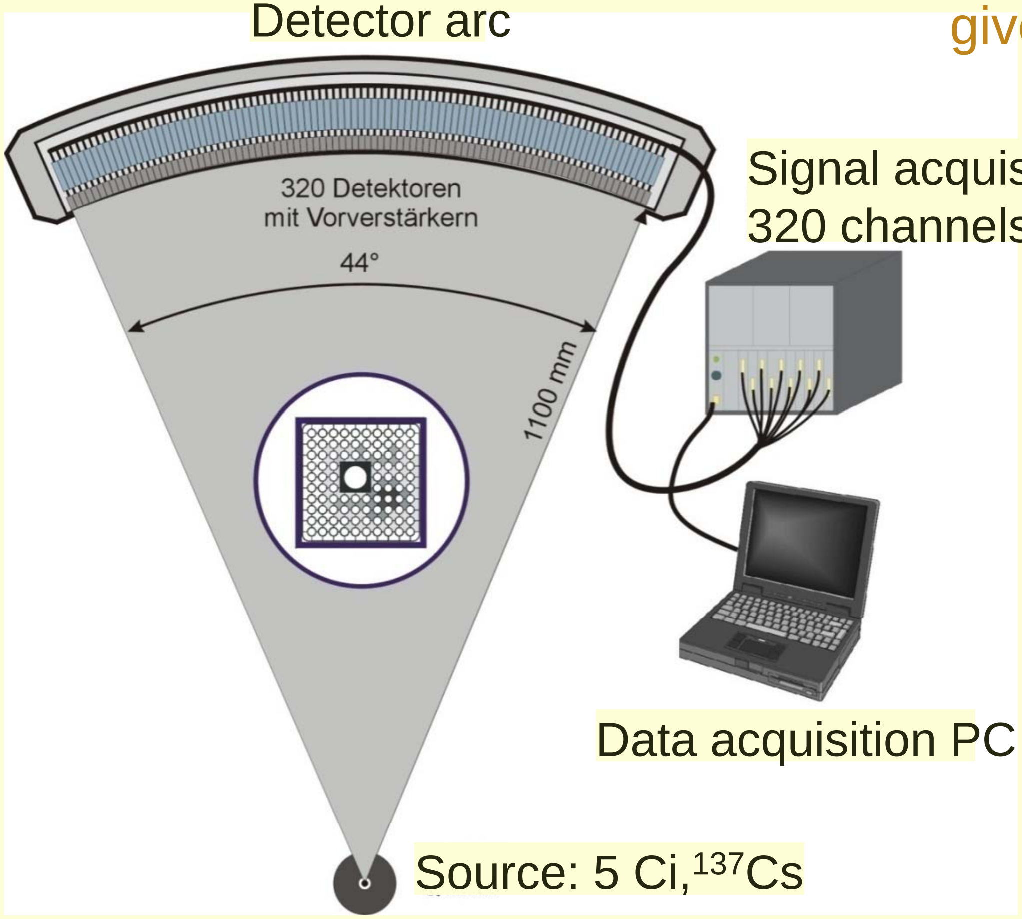


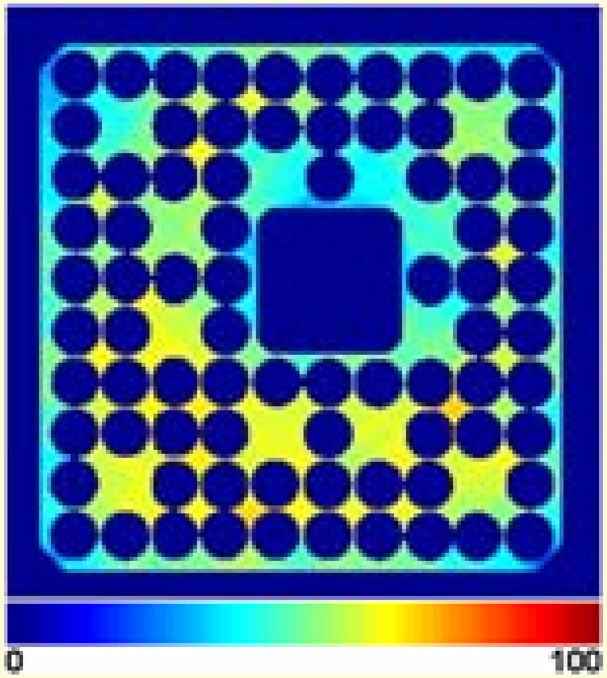


Robust design can be used in high P and T channel; 64 x 64 measuring points, P_{max} = 70 bar, T_{max} = 286 °C, electrode wires ∅ 100 µm

X-ray/γ-ray tomography

Source and detectors are rotated around the test object at high speed, to obtain series of projections , which then can be de-convoluted to give 2D distribution of voids

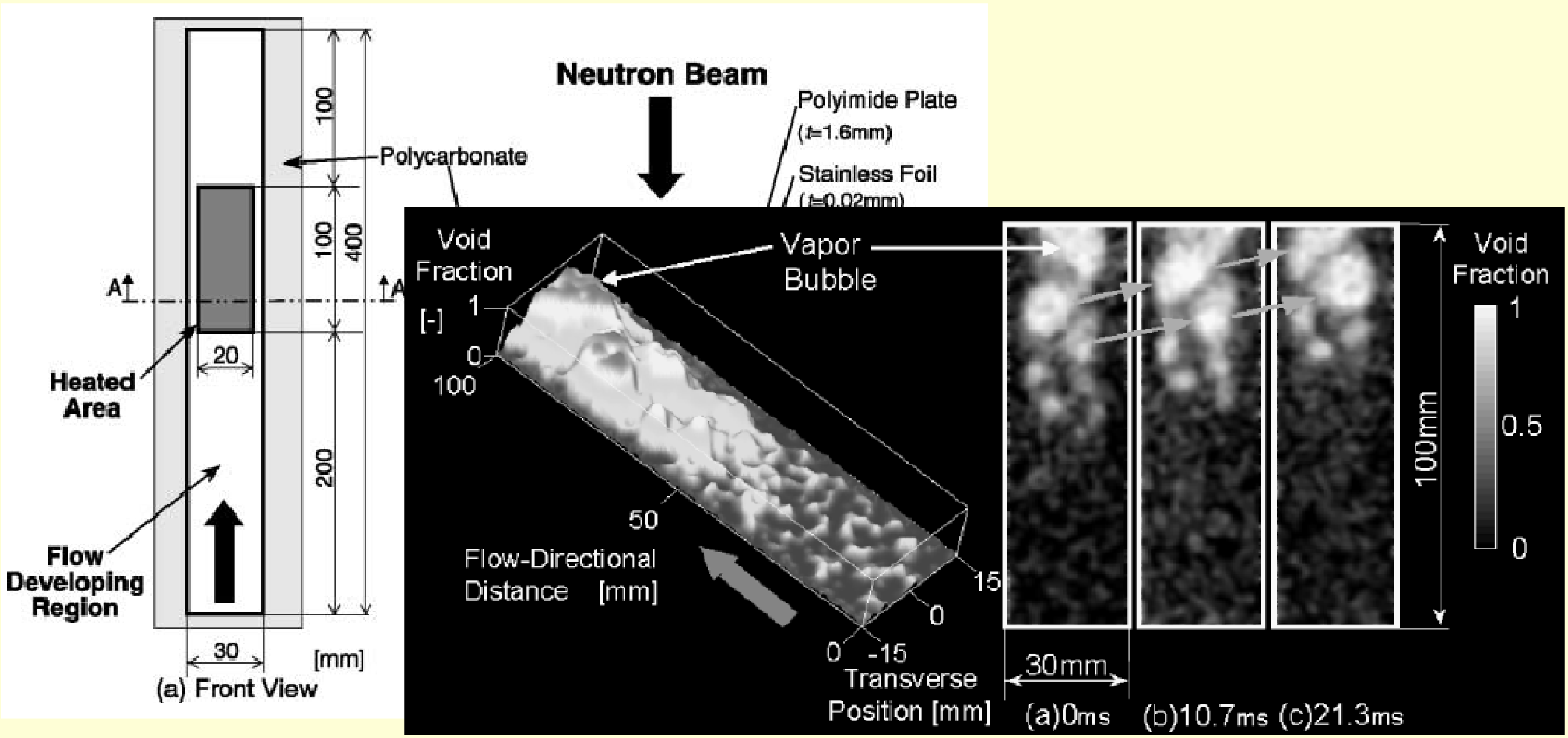




Void fraction

Neutron radiography

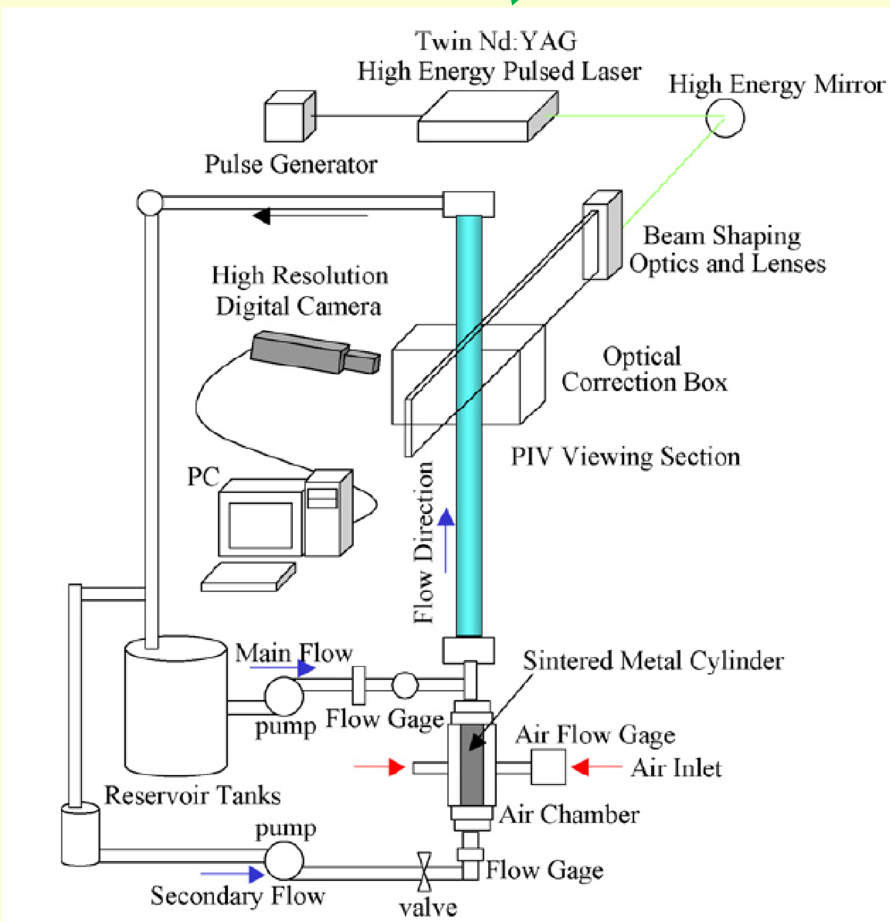
Instantaneous 2D void fraction distributions, averaged over depth of channel

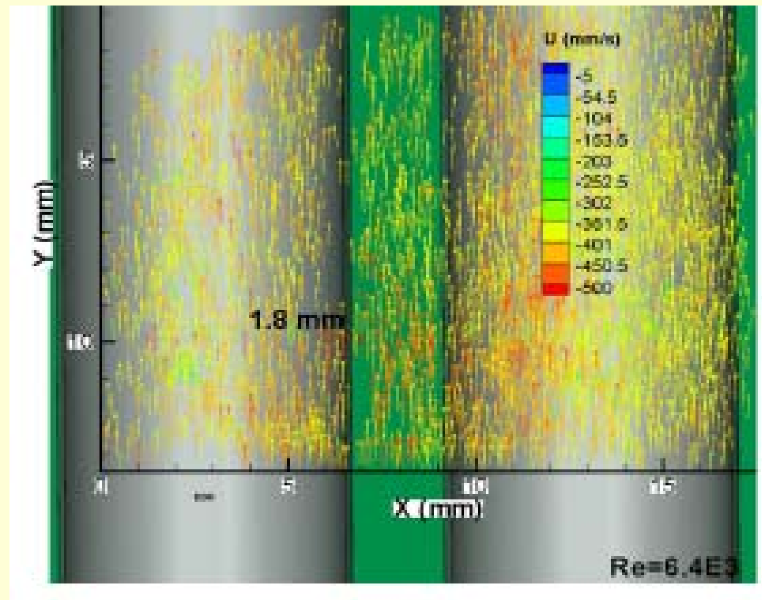


- Radiography quite fast (~kHz), but
- Tomography slow (*test object* needs to be rotated)

Particle Image Velocimetry (PIV)

Neutrally buoyant microparticles are illuminated by laser and tracked by high-speed video camera.

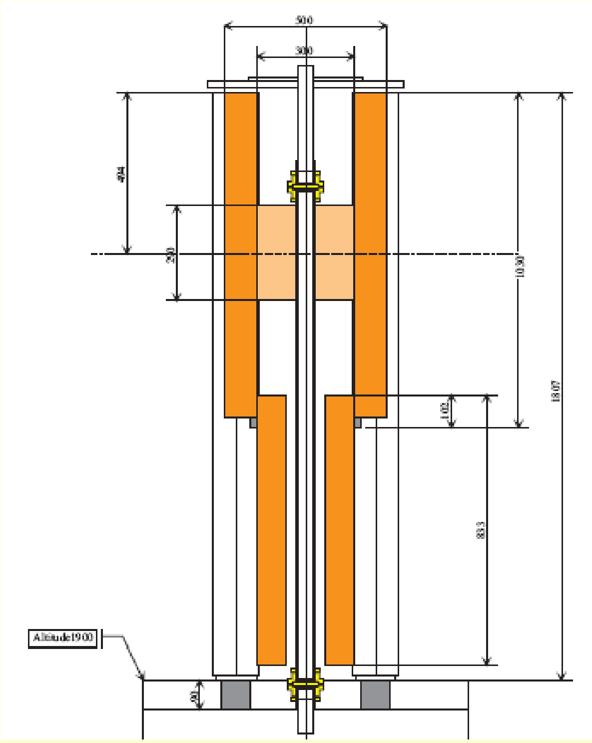


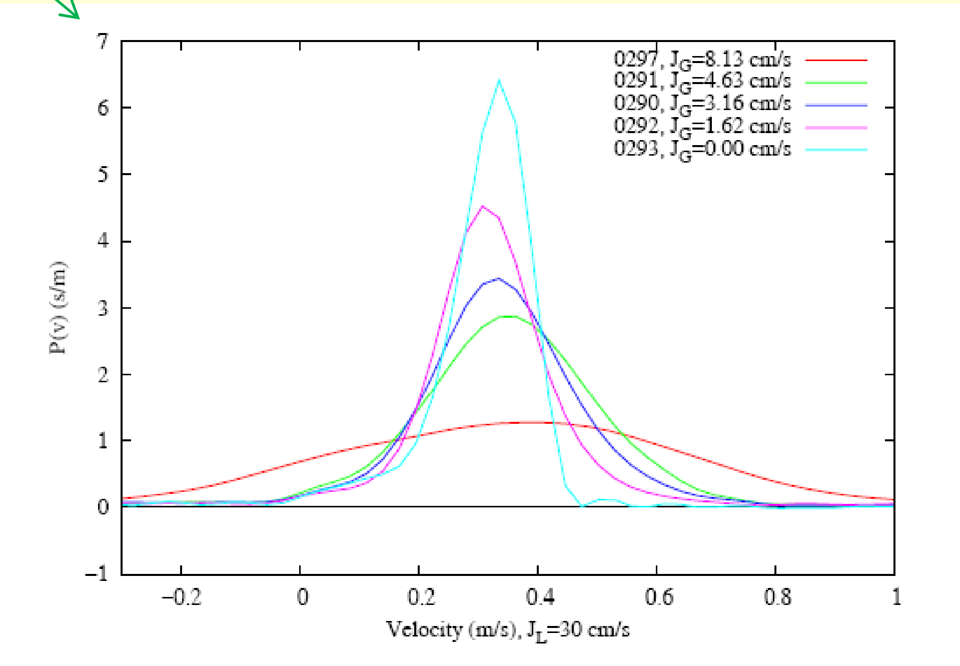


Gives instantaneous 2D velocity distribution in liquid. Useful for turbulence models

Nuclear Magnetic Resonance (NMR)

Magnetically tag fluid and measure displacement gives you velocity distribution (pdf, not spatial)





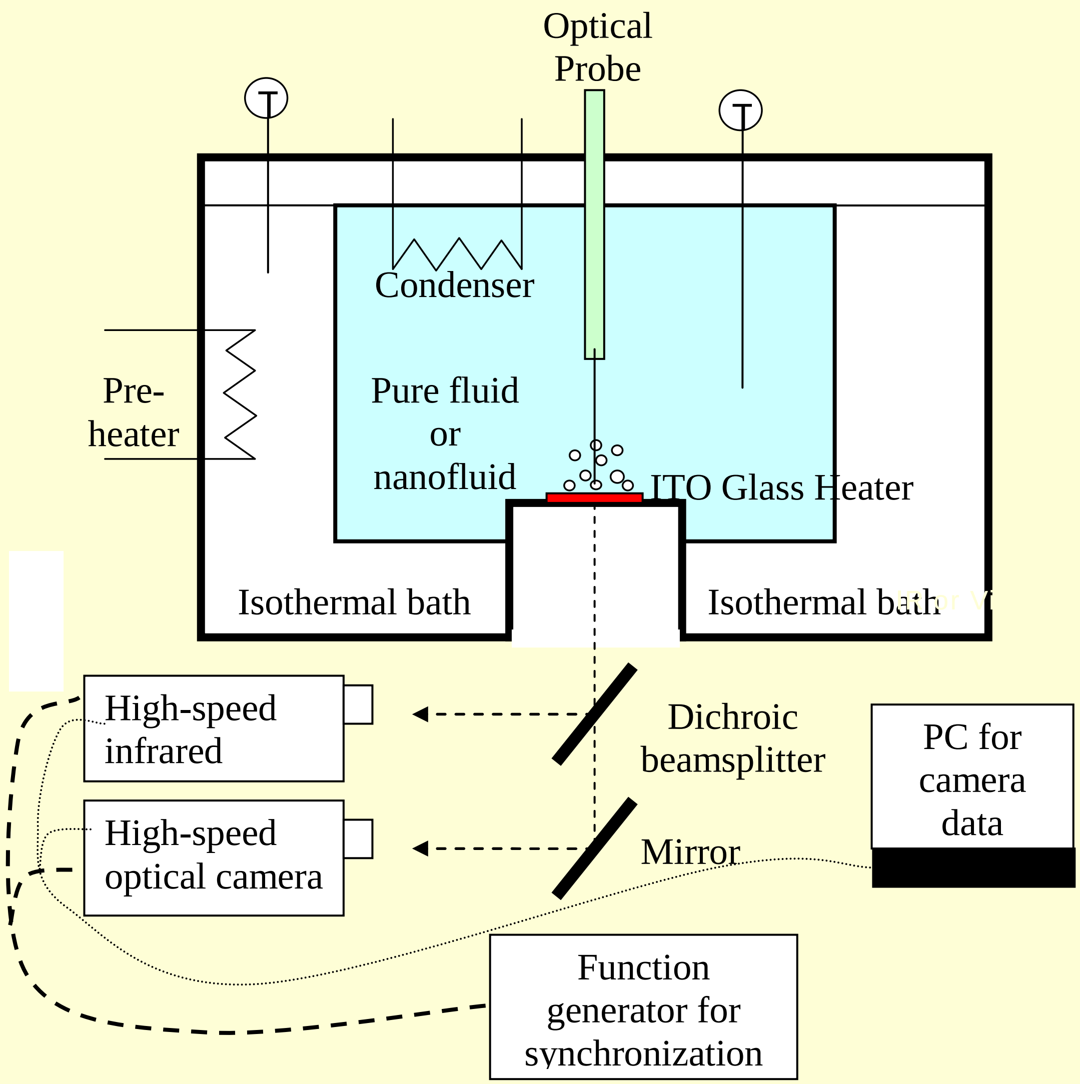
Signal intensity is proportional to average void fraction in channel; requires calibration with single-phase flow having same residence time. Still a long way to go...

Two-Phase Heat Transfer Diagnostics: State-of-the-art

Input for and validation of constitutive models requires advanced two-phase heat transfer diagnostics:

- High-speed IR thermometry (MIT, UCSB)
- High-speed surface phase detection (MIT, U-Tokyo)
- Micro-arrays (U-Maryland)
- Phase shift interferometry (Darmstadt Tech Univ)
- Micro thermocouples (Berlin Tech Univ, Inst Thermo-Fluid Eng Sci Bethlehem PA)

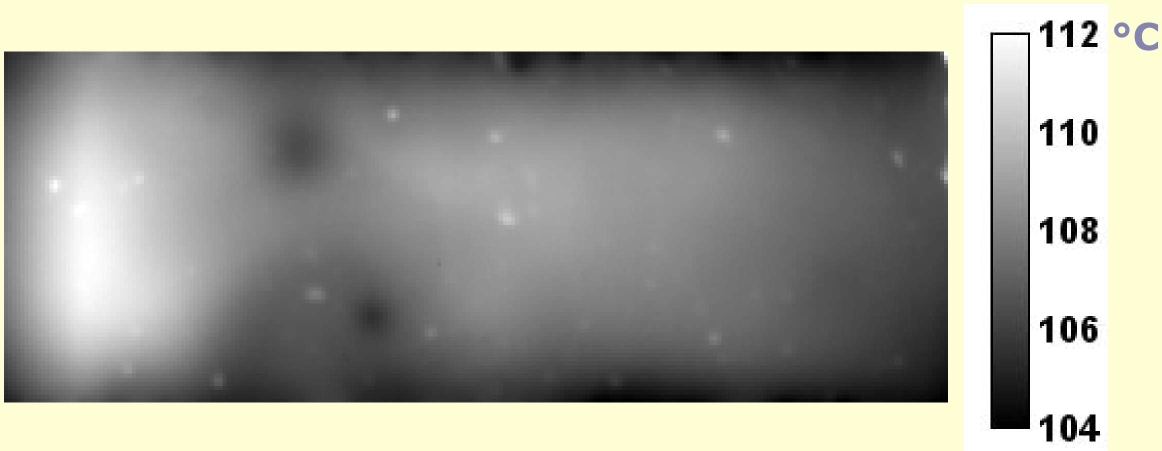
High-Speed IR Thermometry



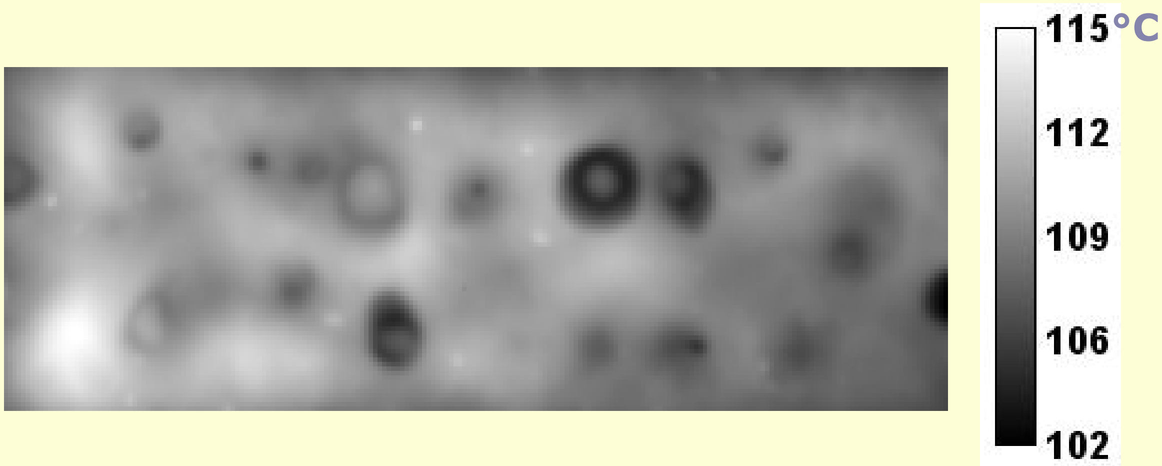
High-Speed IR Thermometry (2)

IR images easily give the *nucleation site density*

DI water
at q″=50 kW/m²
(ΔT_s~8.5°C)

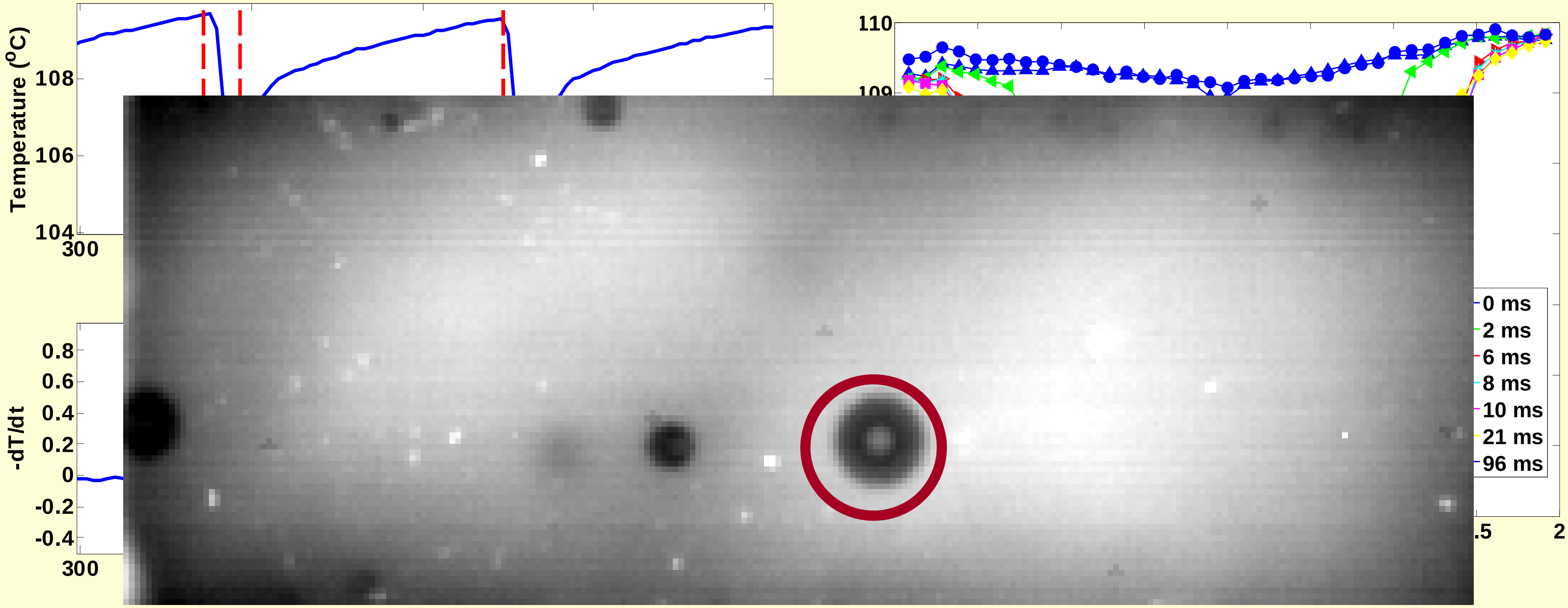


DI water
at q″=250 kW/m²
(ΔT_s~10.3°C)



High-Speed IR Thermometry (3)

IR images give the *bubble frequency, growth time and wait time*

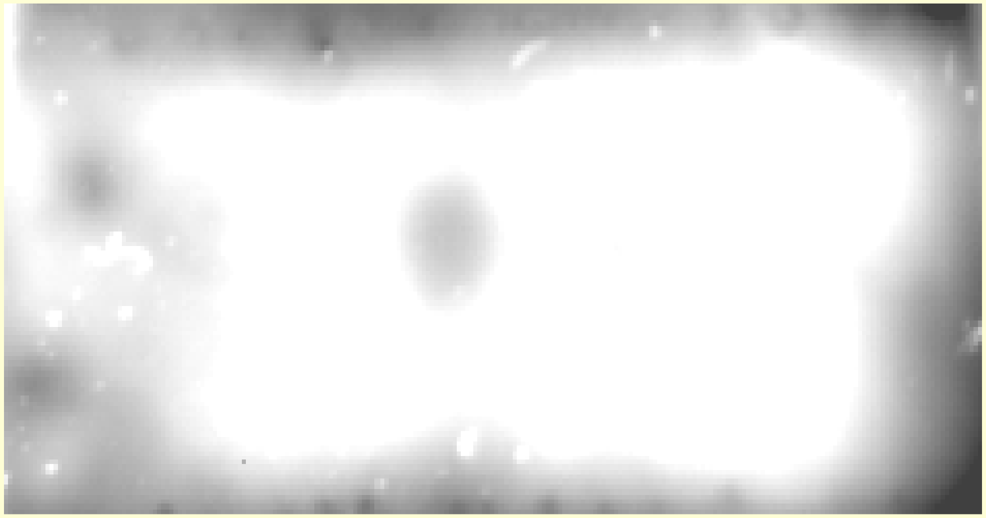


...but also *the spatial temperature distribution* about a nucleation site

High-Speed IR Thermometry (4)

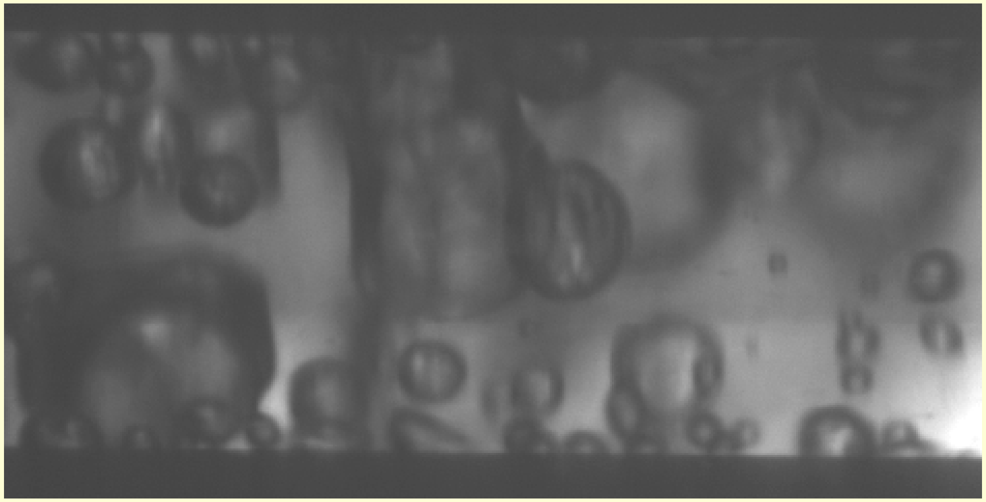
Synchronized with high-speed video camera…

High-Speed IR Data →



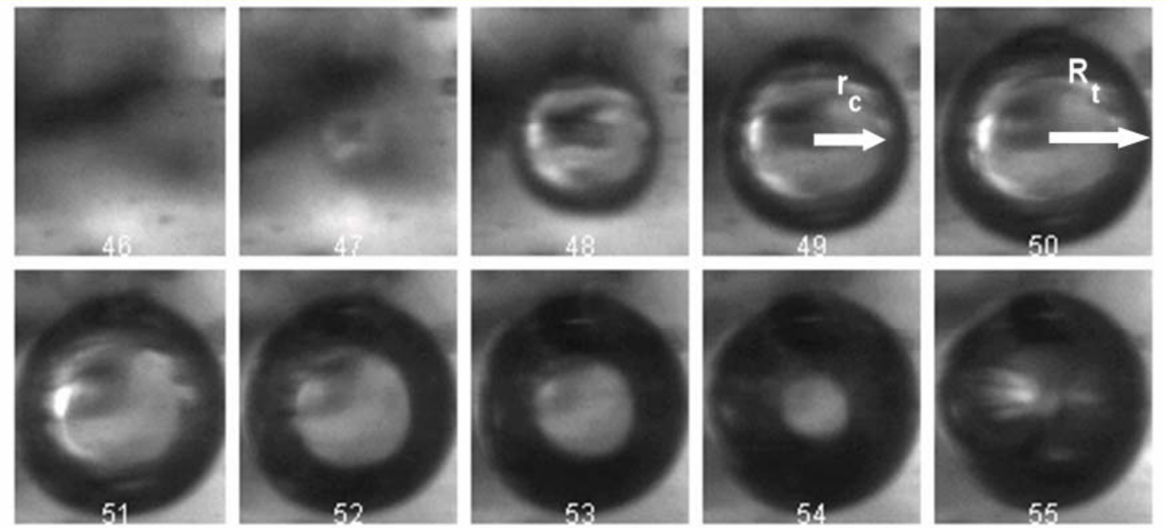
DI water, q”=100kW/m², filmed at 480fps
Playback ~2fps
(1/240 speed)

High Speed Video →



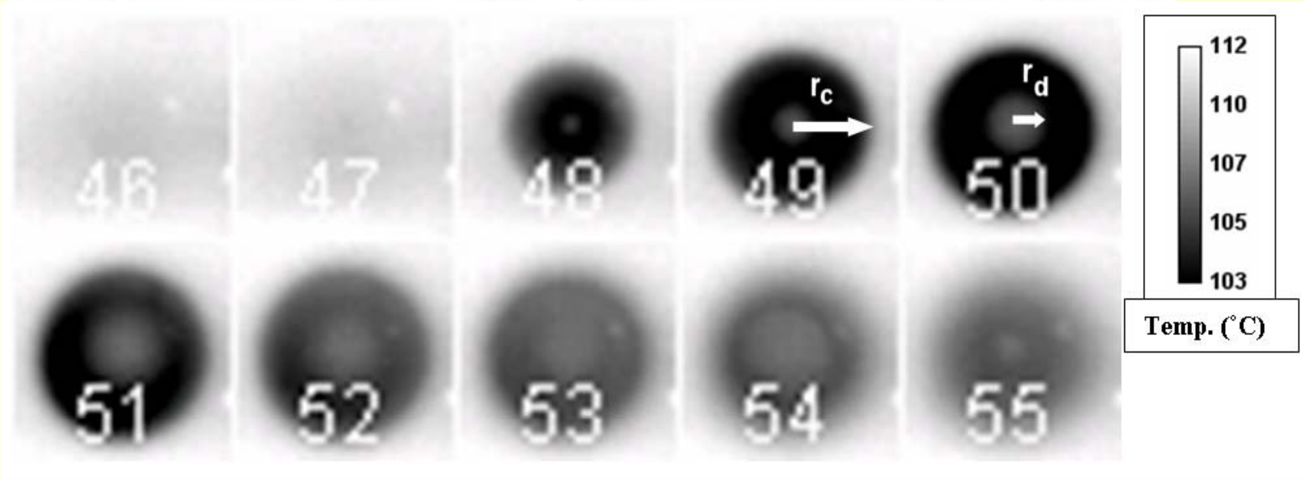
High-Speed IR Thermometry (5)

HSV for a single bubble life-cycle for frames 46-55.



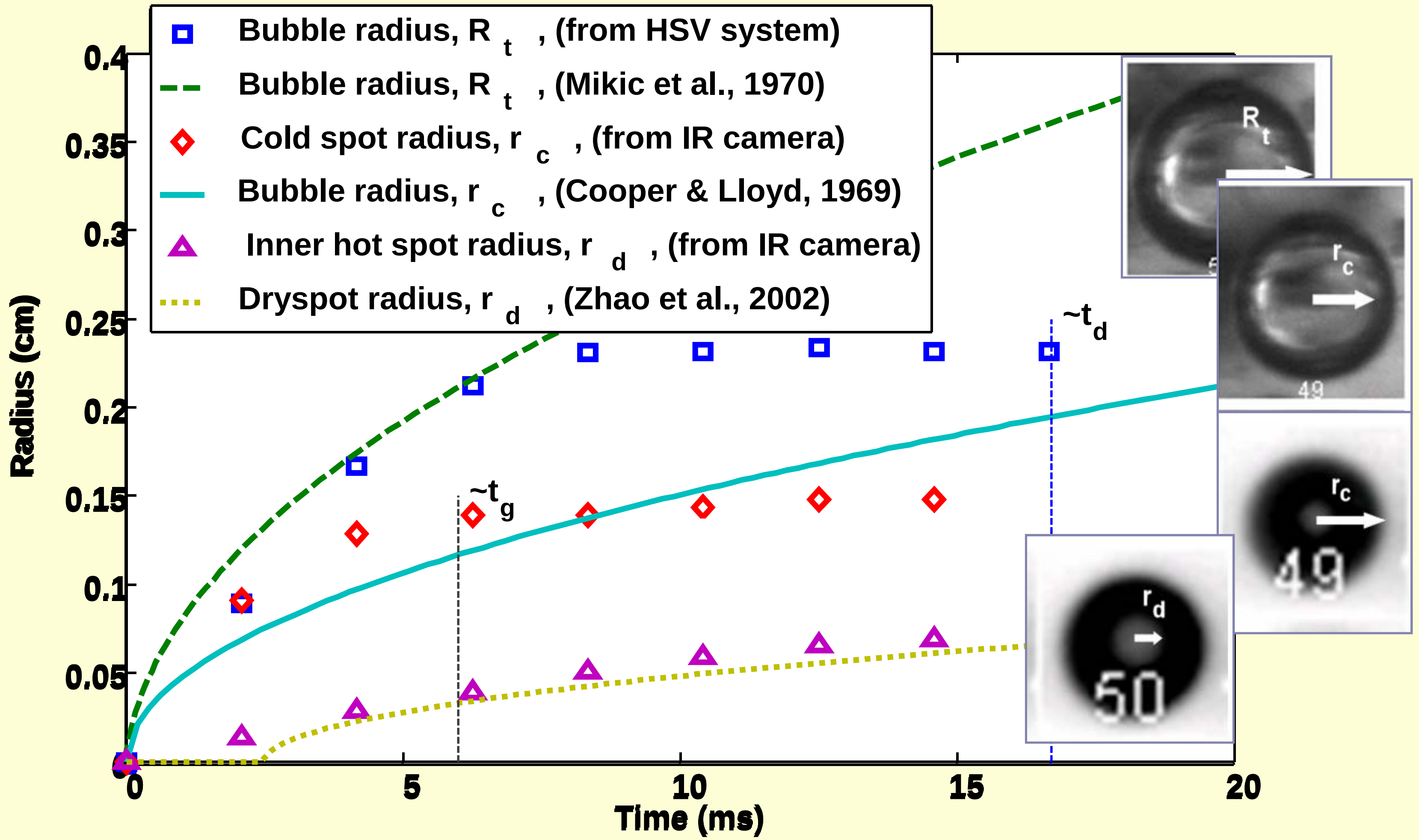
DI water, q”=60kW/m², 480fps

IR data for a single bubble life-cycle for frames 46-55.



High-Speed IR Thermometry (6)

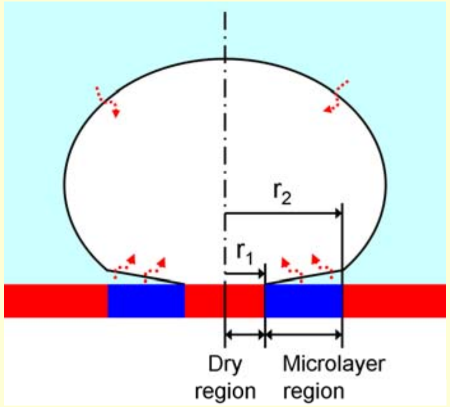
….enables validation of bubble growth theories.



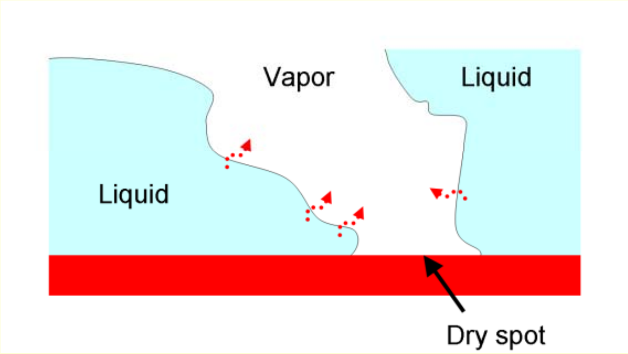
High-Speed Surface Phase Detection

Objective is to detect the <u>triple contact line</u> (liquid-vapor-solid) on the heat transfer surface

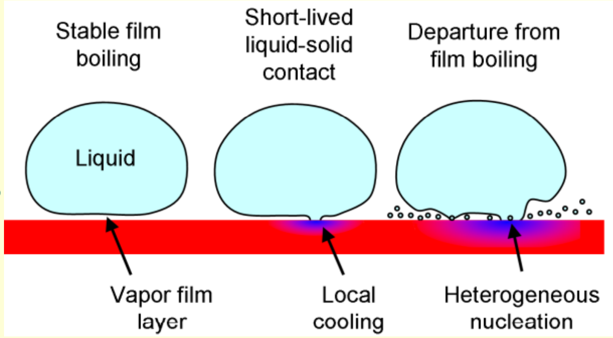
Single bubble nucleation



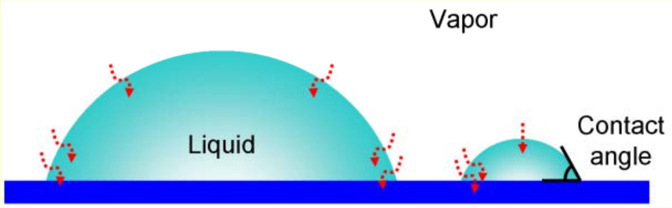
High-heat flux nucleate boiling (including CHF)



Quenching

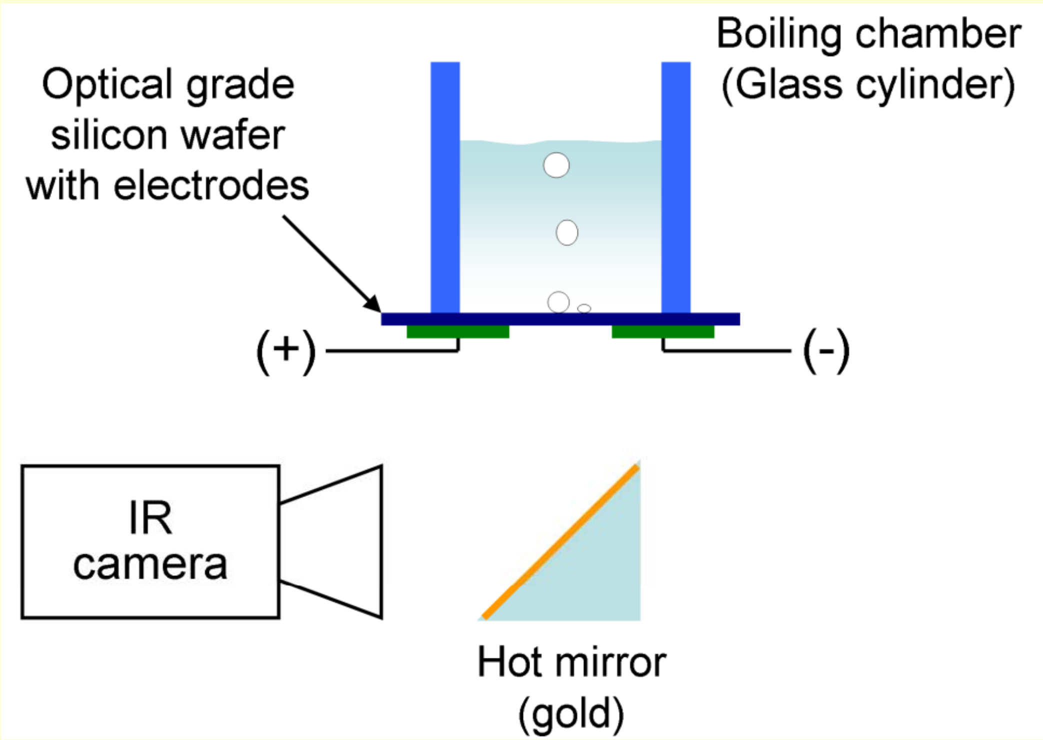


Dropwise condensation



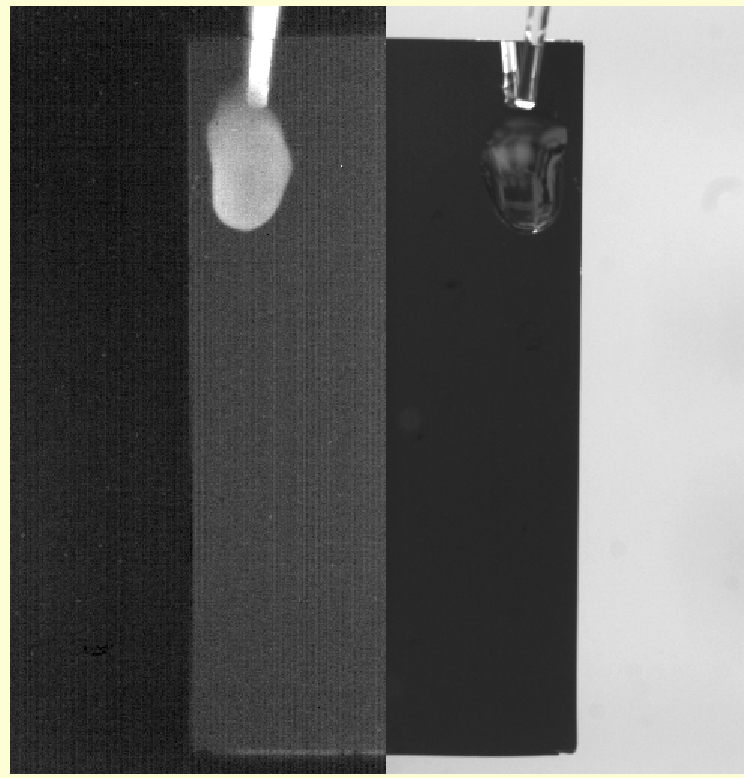
The triple contact line is where heat transfer is the most intense

High-Speed Surface Phase Detection (2)



•IR-transparent heater (Si wafer) with IR-opaque fluid (water)
•Measure temperature to distinguish phases
•Bright (hot) is liquid, dark (cold) is vapor (not intuitive!)

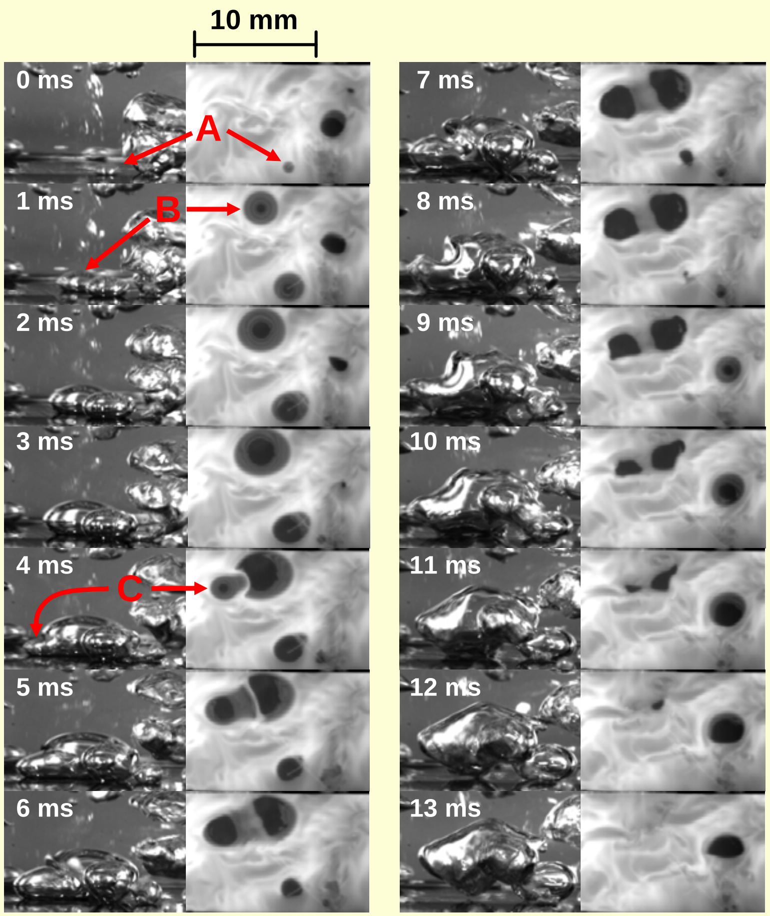
Droplet sliding on surface of Si wafer



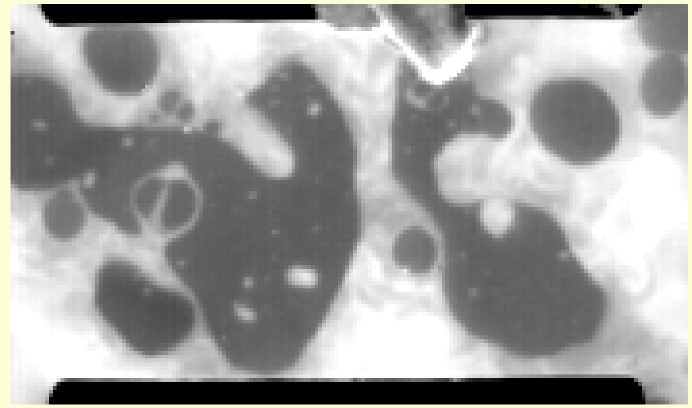
IR (from behind the wafer) HSV (from above the wafer)

MIT paper: Int J Multiphase Flow, submitted 2010

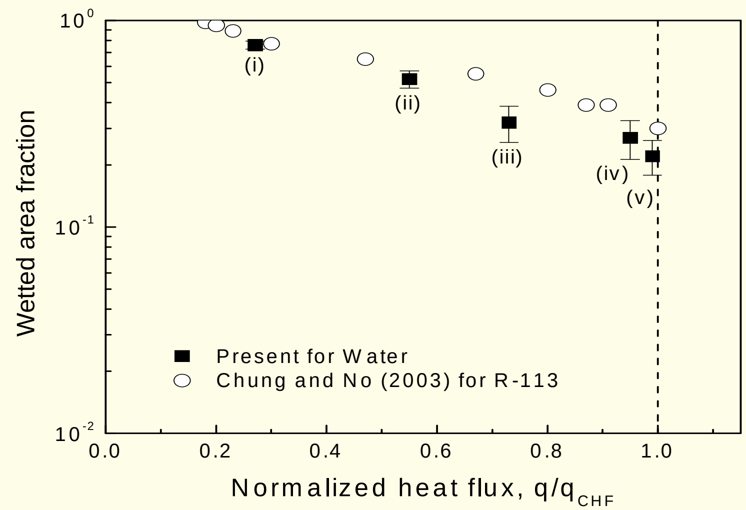
High-Speed Surface Phase Detection (3)



Observation of mushroom bubble formation and detachment in low-heat-flux nucleate boiling

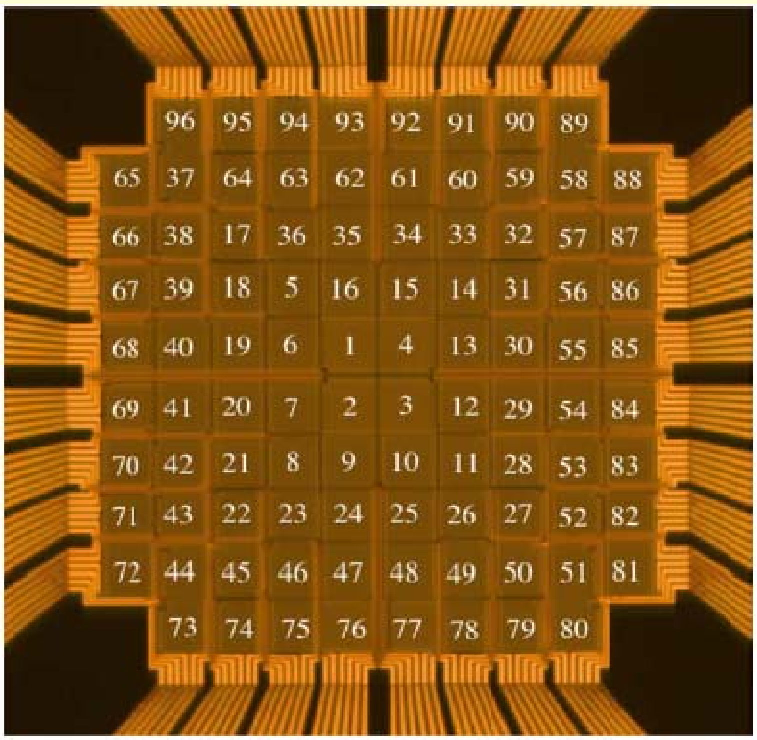


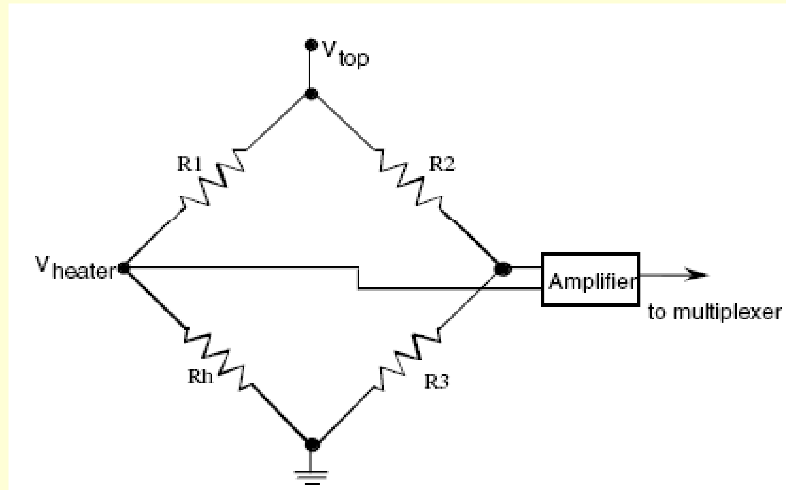
Dynamics of dry patches in high-heat-flux nucleate boiling

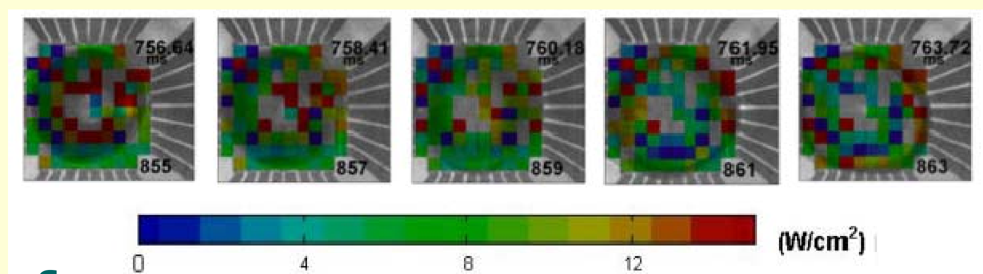


Microarray Heaters

Power input to each micro-heater is electronically controlled to maintain fixed temperature







Main output is local value of heat flux

Phase Shift Interferometry

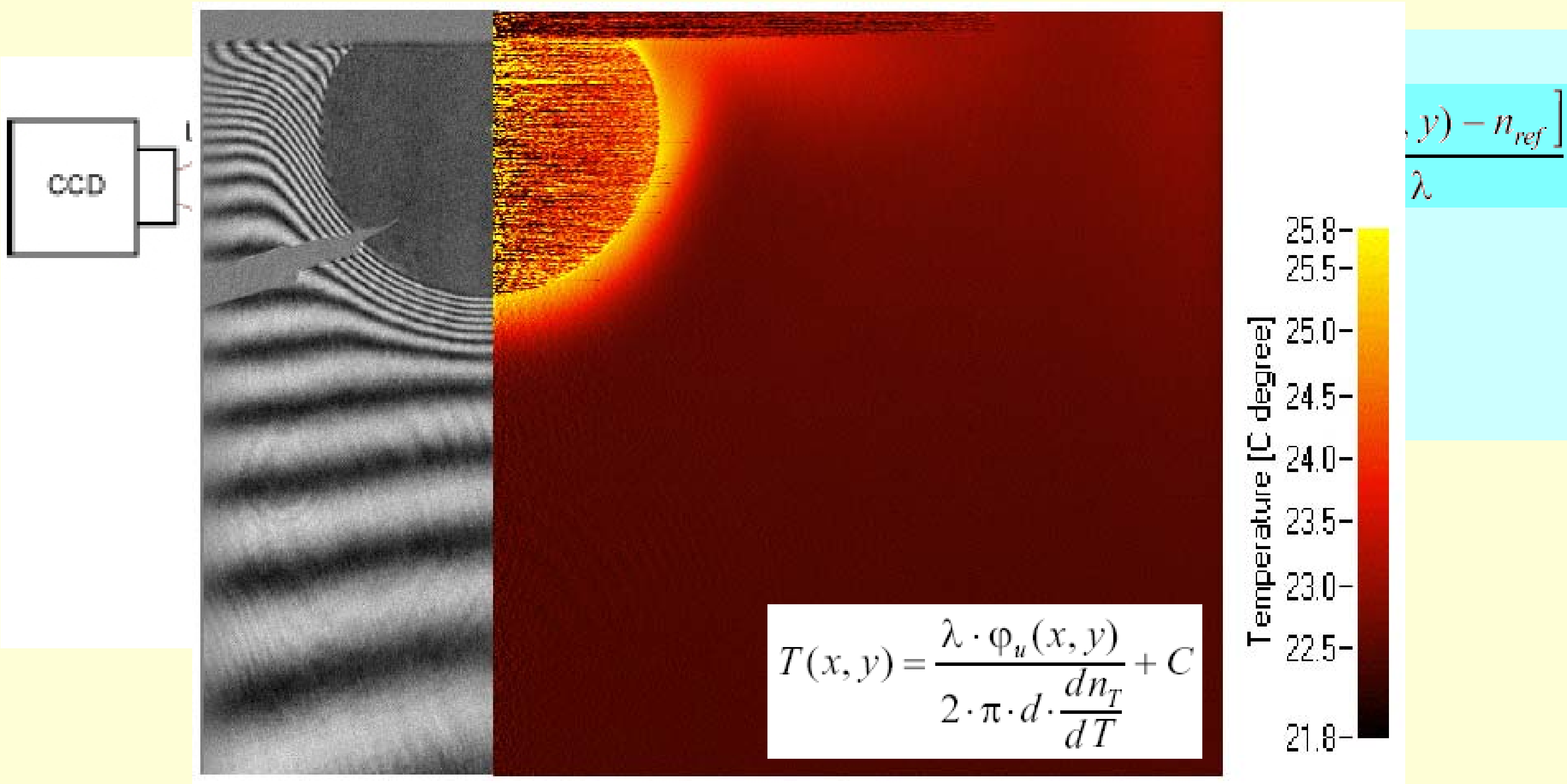


Fig. 3. Local Temperature distribution around a single vapor bubble

Measures temperature *within* fluid

Micro Thermocouples

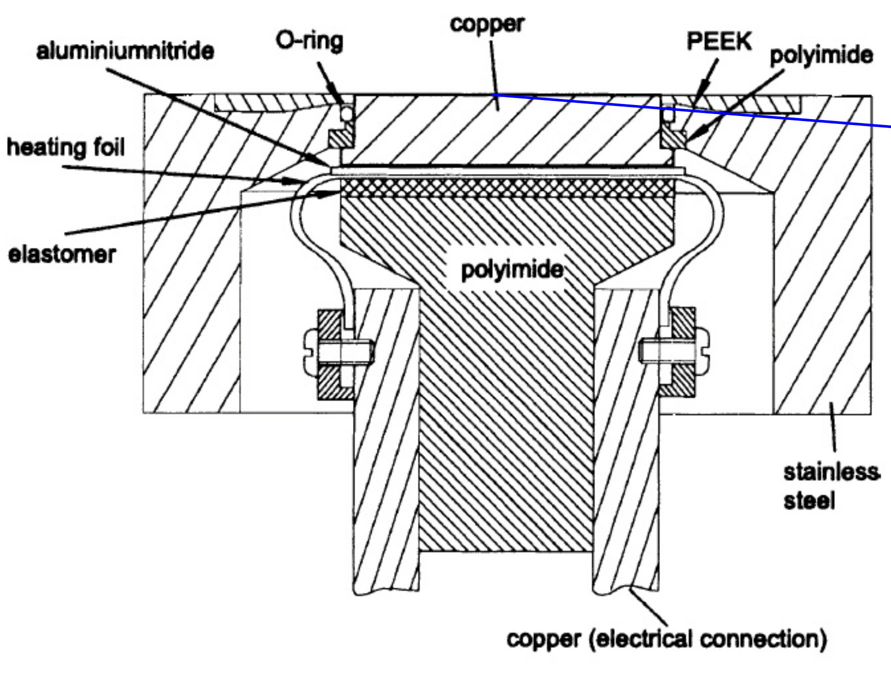


Fig. 2. Heater section.

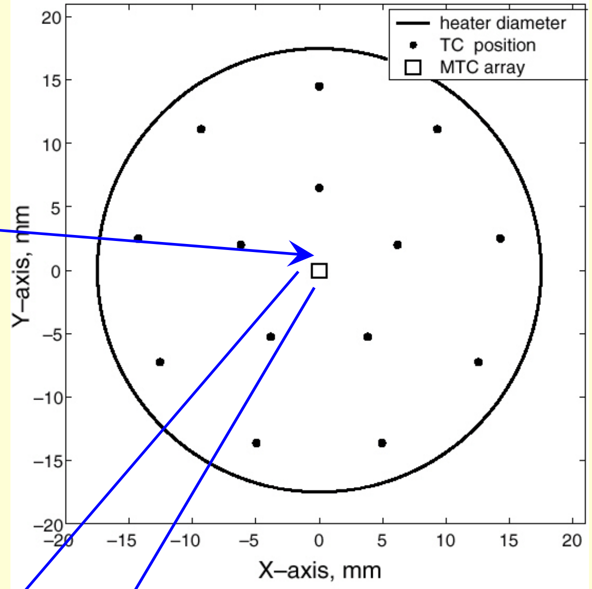


Fig. 3. Positions of sheathed thermocouples.

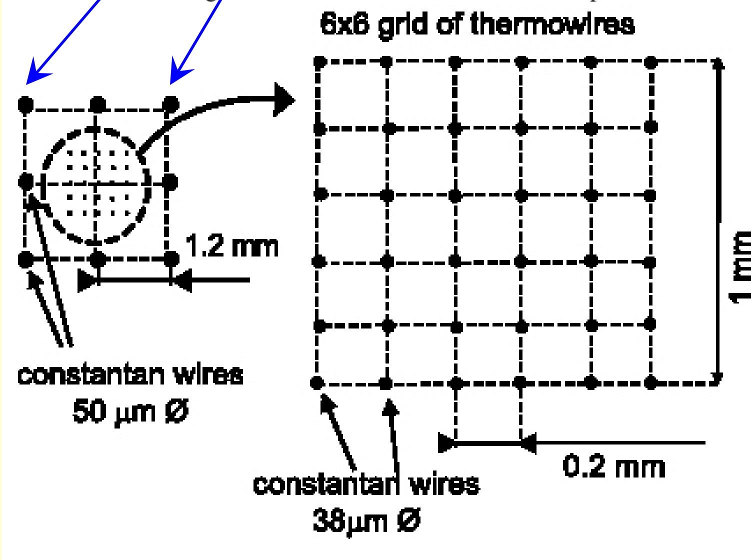


Fig. 6. Designed positions of microthermocouples.

Fine grid of micro-TCs measure temperature a few μm below the surface

Conclusions

- “First-principle” simulation methods that track the interface in two-phase flow and heat transfer are available
- They can be used to generate constitutive relations for current codes, thus reduce uncertainties/cost in nuclear design and safety
- Validation of these information-rich methods requires the use of advanced two-phase flow and heat transfer diagnostics, which are now available!

Acknowledgements

Special thanks to Prof. Michael H. Prasser (ETH) for providing some figures on the advanced diagnostics

- Thank you -

Questions?