2D Surface Phosphor Thermometry In A Shallow Boiling Water Channel

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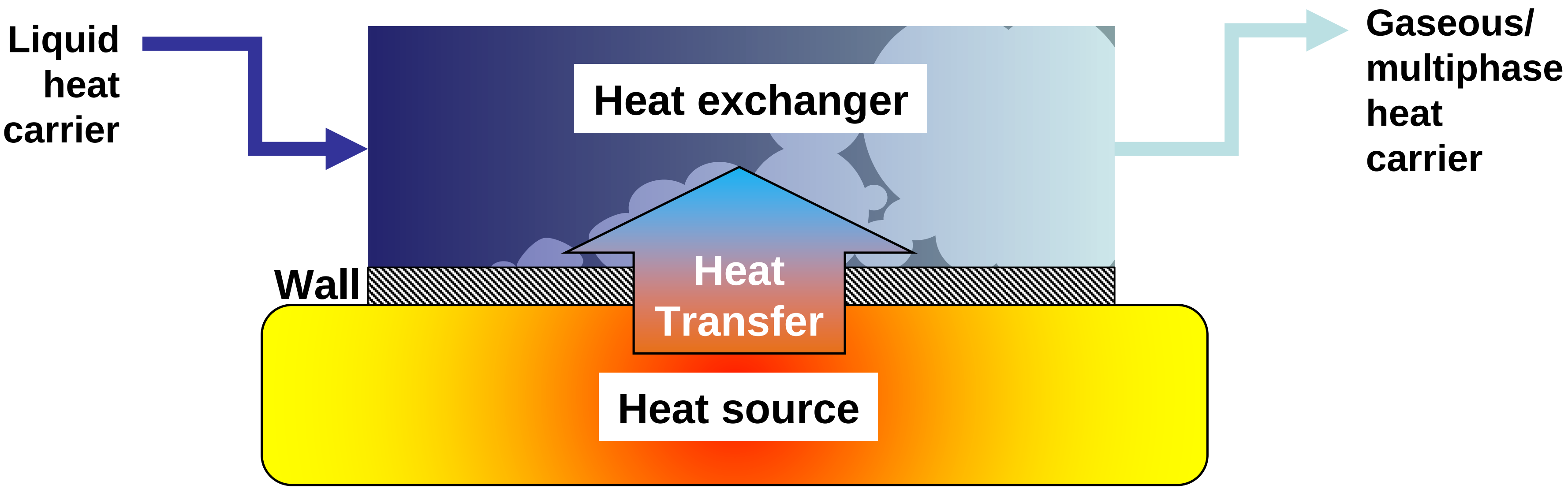
Boiling and heat exchangers

- One design solution for wall cooling is to run a heat carrier fluid in **canals within the wall**
- **Boiling** of the heat carrier is wanted **but** makes **heat transfers** challenging to predict
- Boiling is a complex phenomenon, with different regimes and strong temperature gradients



Final aim : describe experimentally the heat transfer at play in a boiling heat exchanger with forced convection at system scale

Boiling and heat exchangers

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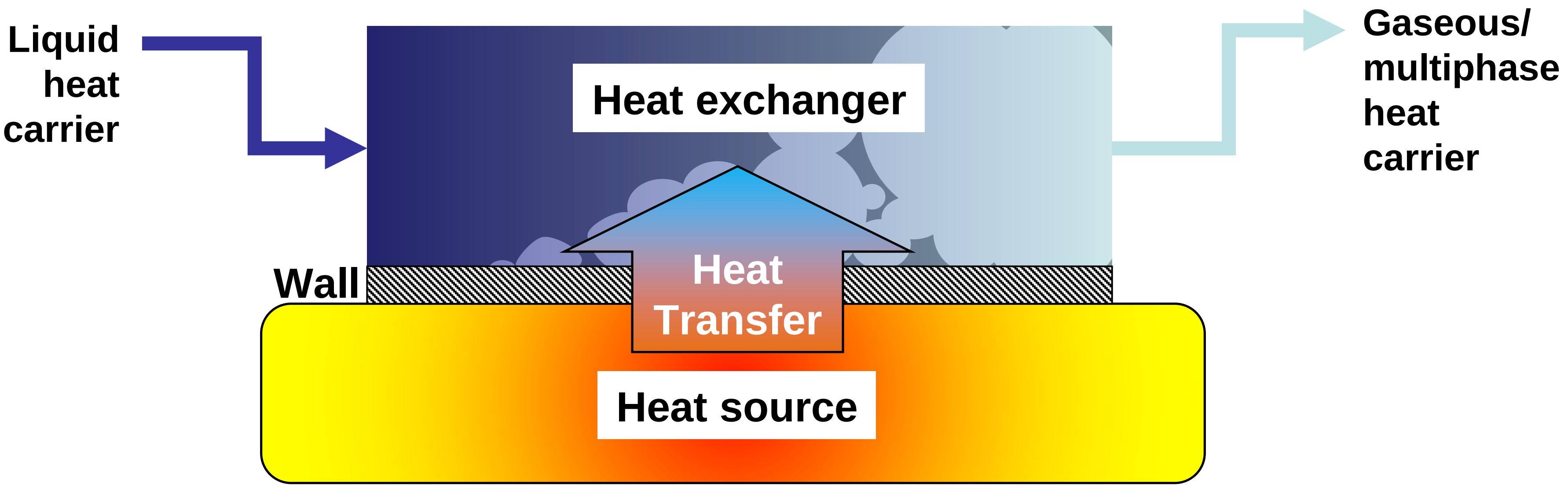


Today's presentation :
obtaining temperature fields on the exchange surface

1. **Experimental setup and flow morphology**

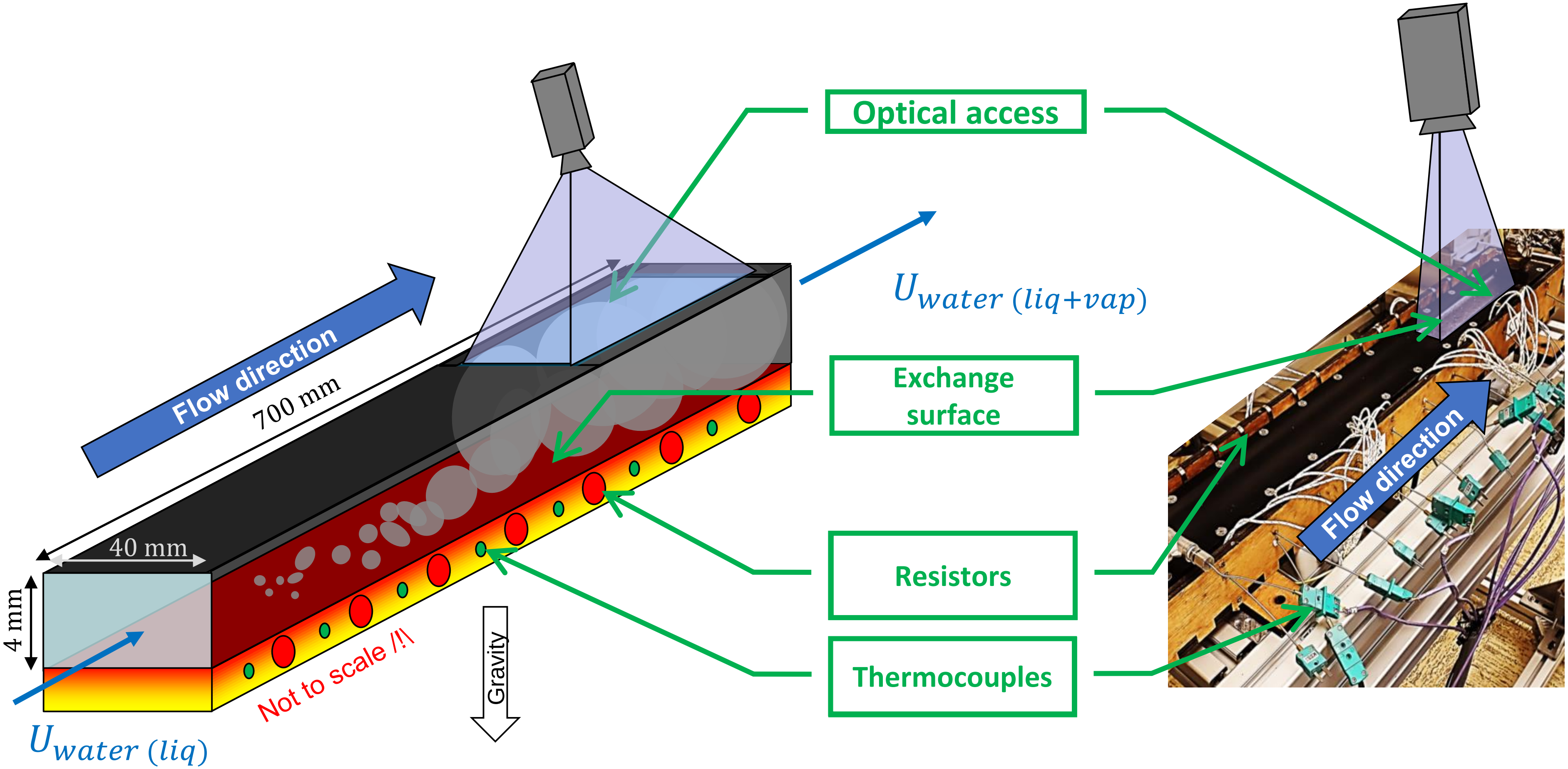
2. **Phosphor thermometry setup**

3. **Results**

4. **Validation**

Multiphase heat exchanger experimental setup – REMED

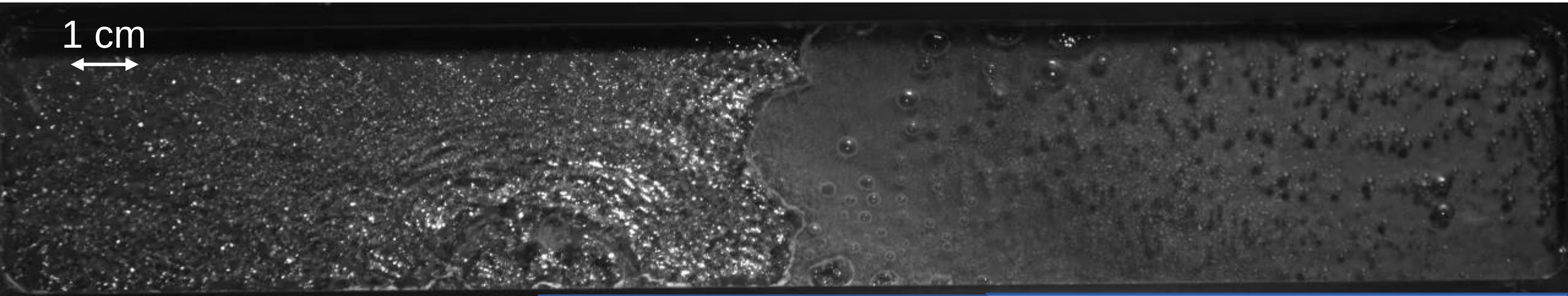
Cooling channel experimental model with **electric heating** and **water** as a coolant



Flow direct visualisation (top view)

Surface heating power density: 0.17 MW/m², flowrate: 31 kg/m²/s, 200 frames/s

Flow direction



III Liquid/vapor mix	II Liquid/vapor frontier oscillation	I Quasi-liquid

Several distinct unsteady flow regimes, small spatial scales

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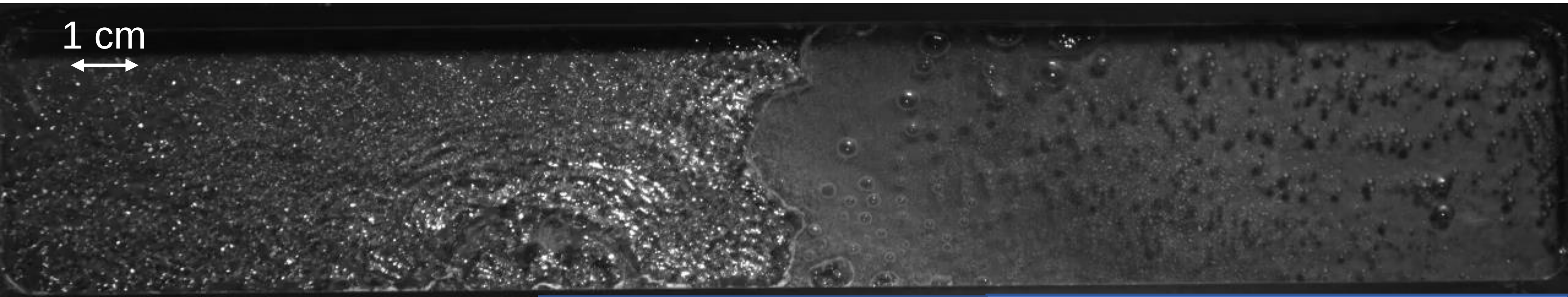

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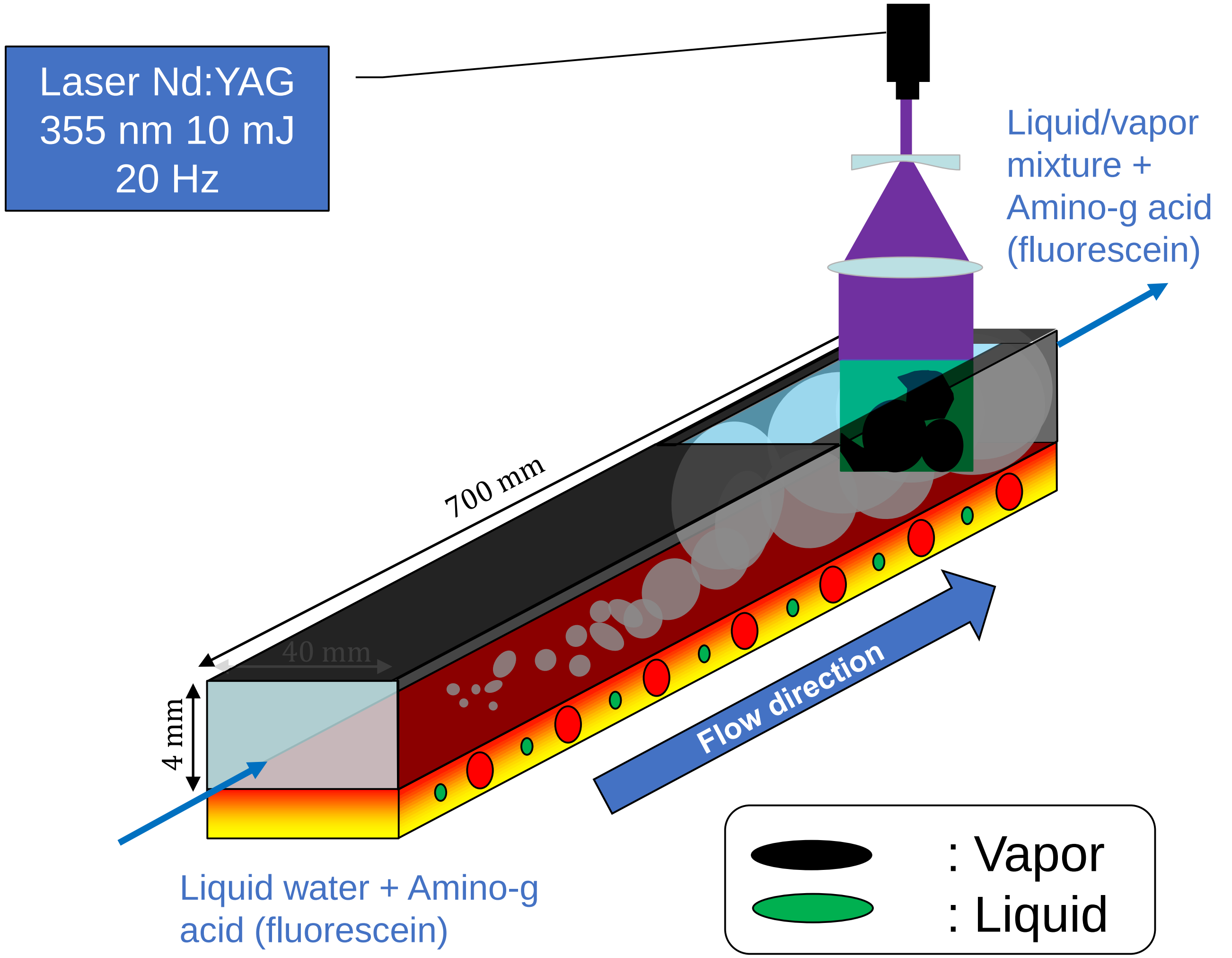
But what about flow stratification?

Uncovering the flow stratification with amino-g PLIF

- $\rho_{vap} \ll \rho_{liq}$
- $I_{fluo_{vap}} \ll I_{fluo_{liq}}$

⇒ Amino-g acid acts as a liquid phase tracer



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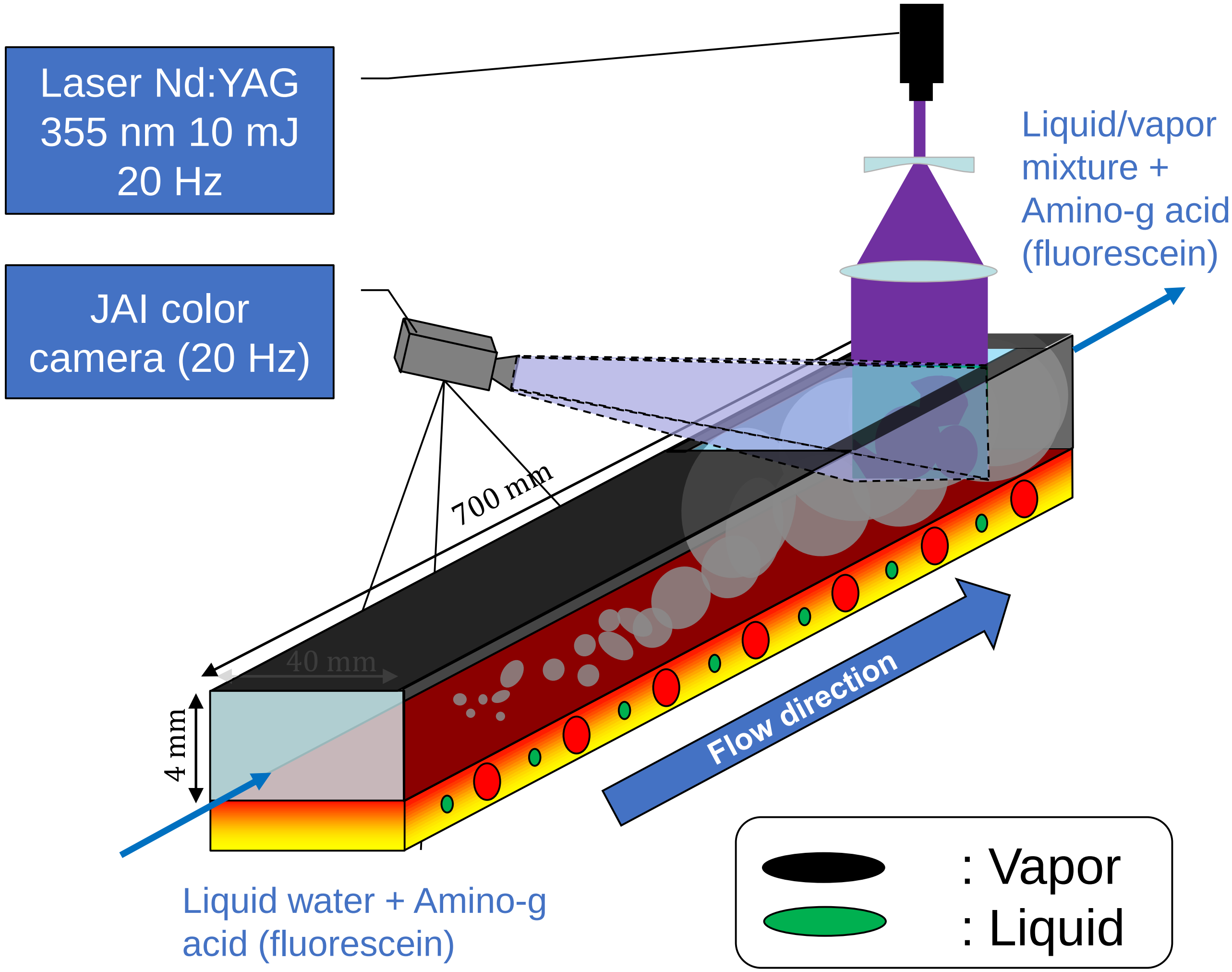
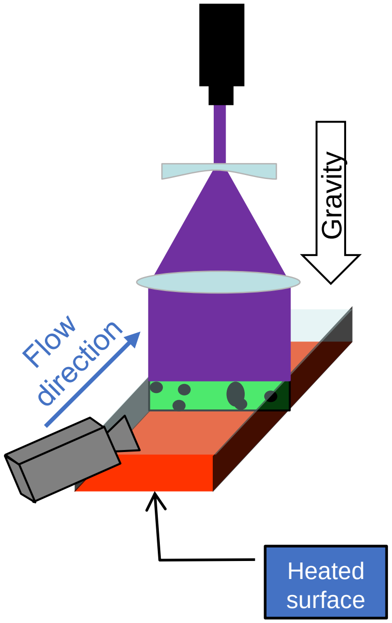
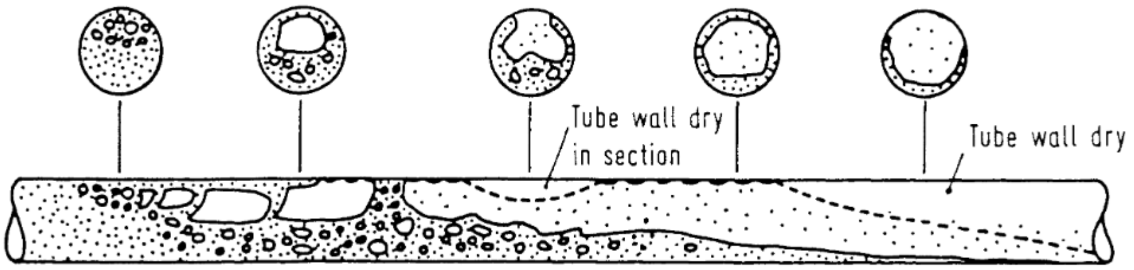


Uncovering the flow stratification with amino-g PLIF

Nucleation regime





Collier, J.G.; Thome, J.R. Convective Boiling and Condensation, 3rd ed., reprint 2001 ed.; The Oxford Engineering Science Series; Clarendon Press: Oxford, UK; Oxford University Press: New York, NY, USA, 2001; p. 38

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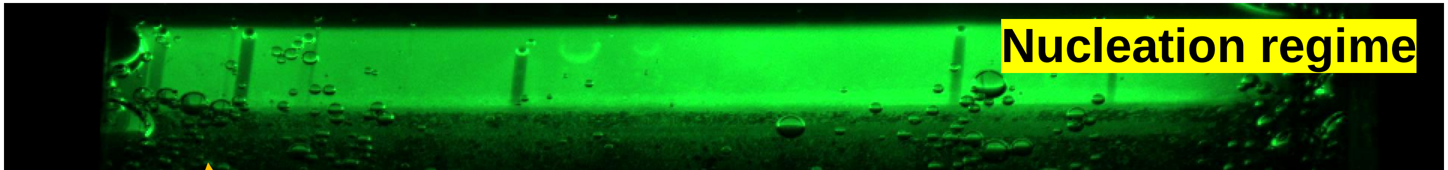

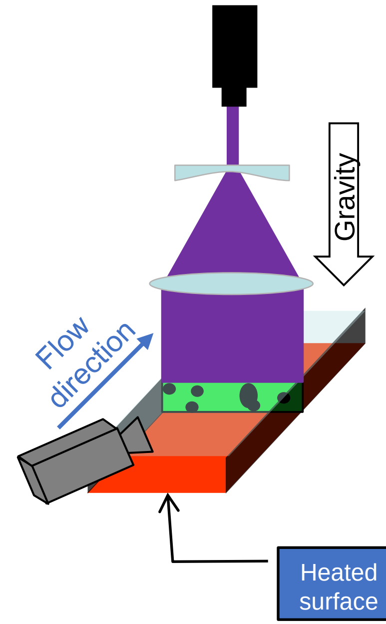

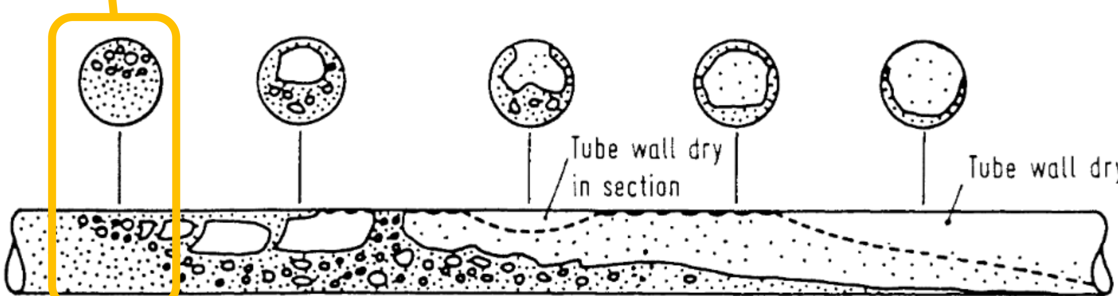

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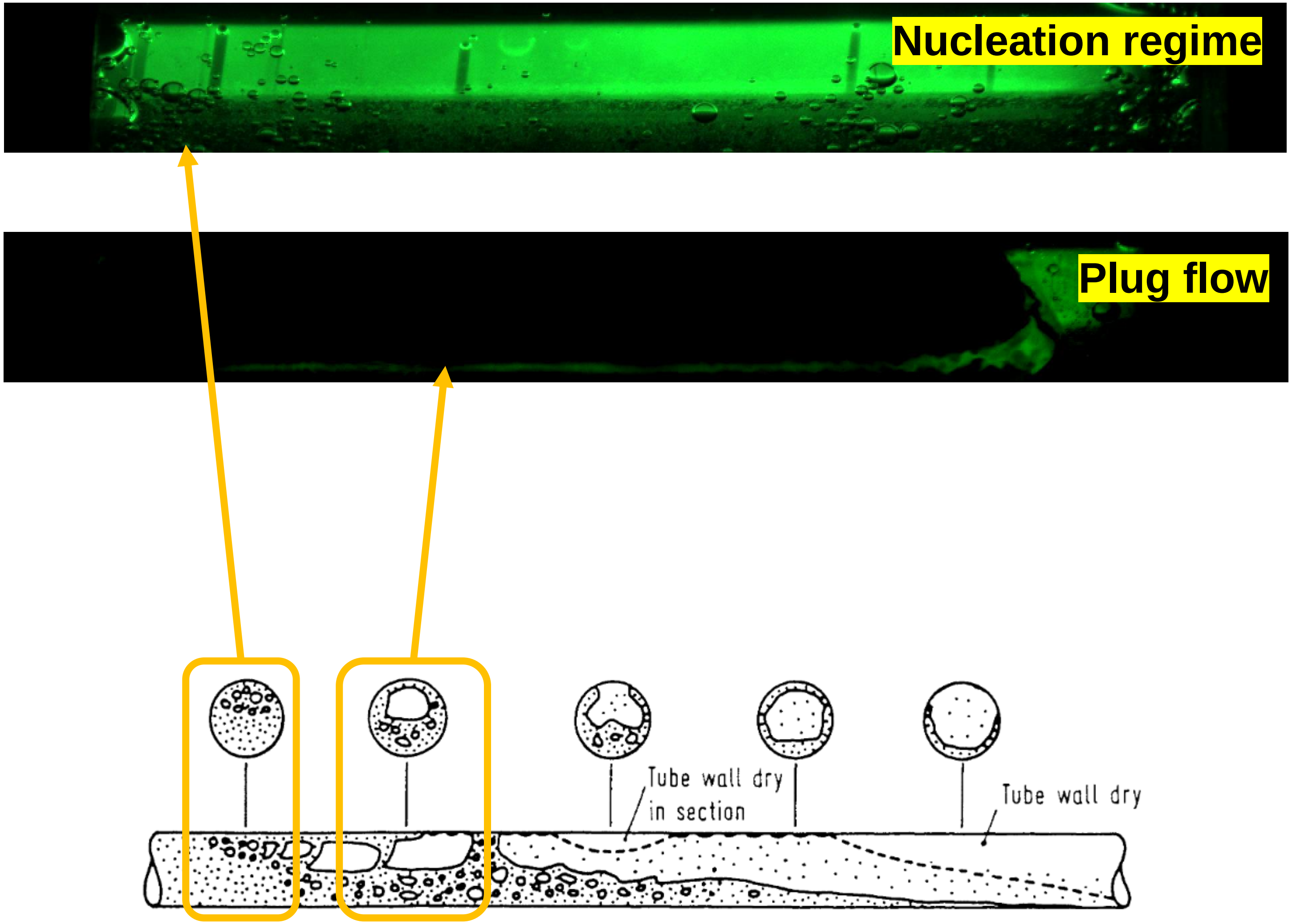

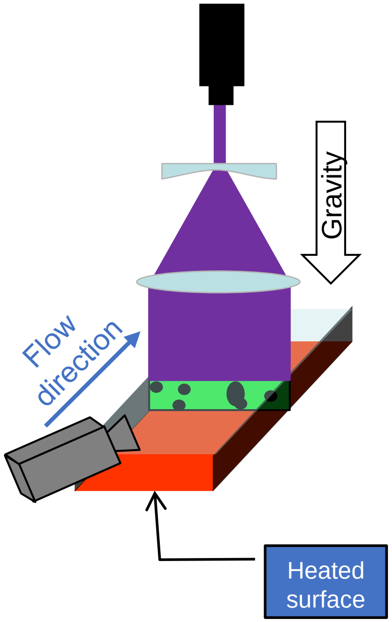

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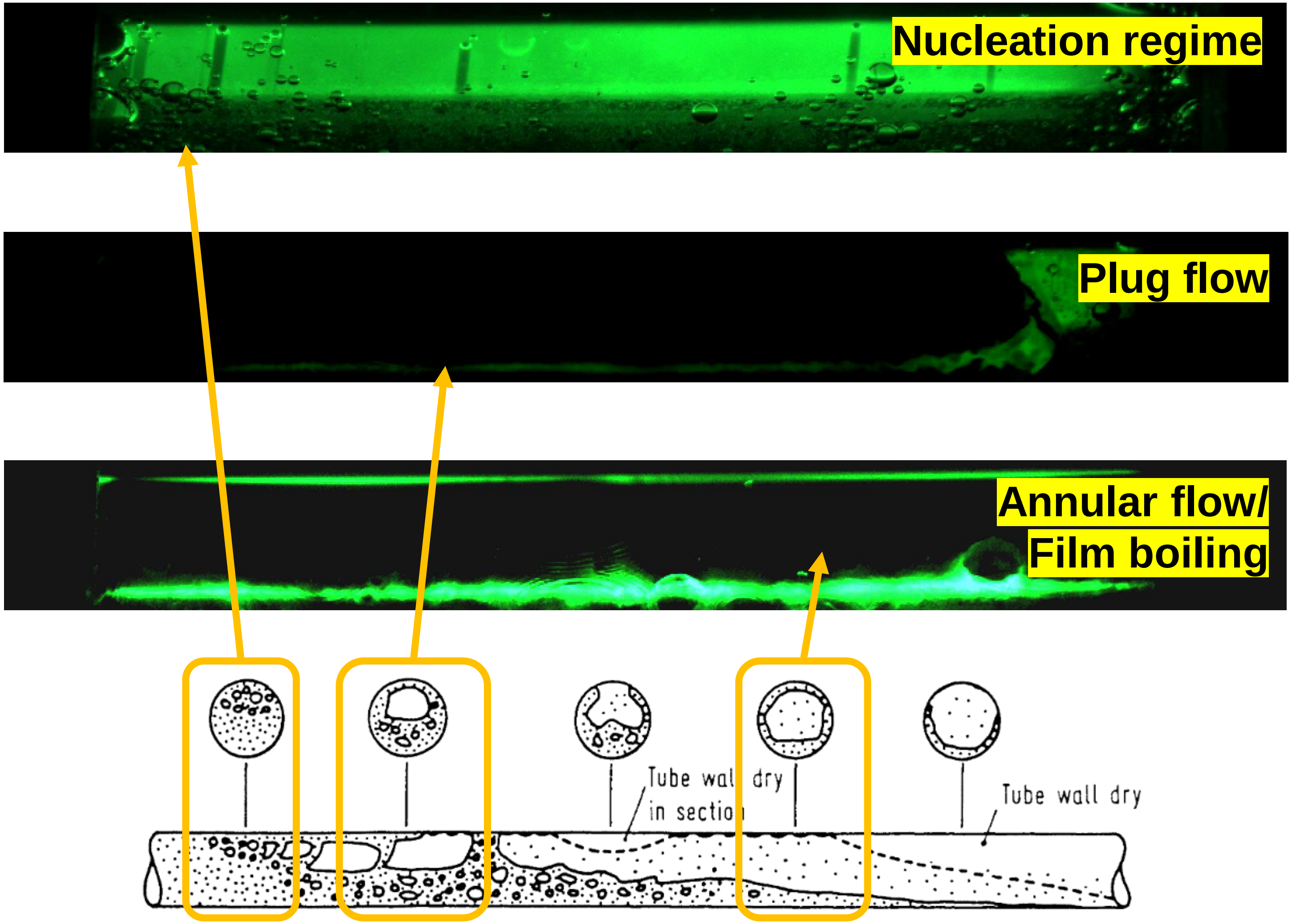

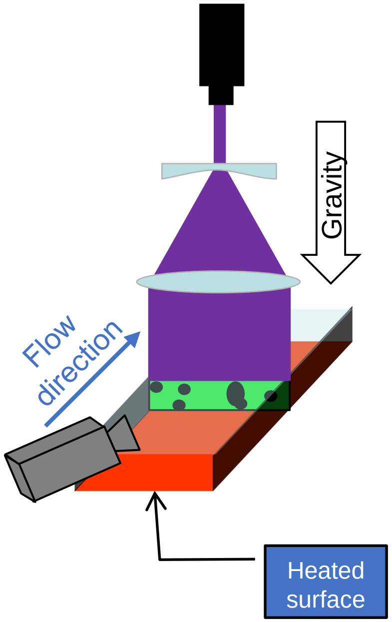

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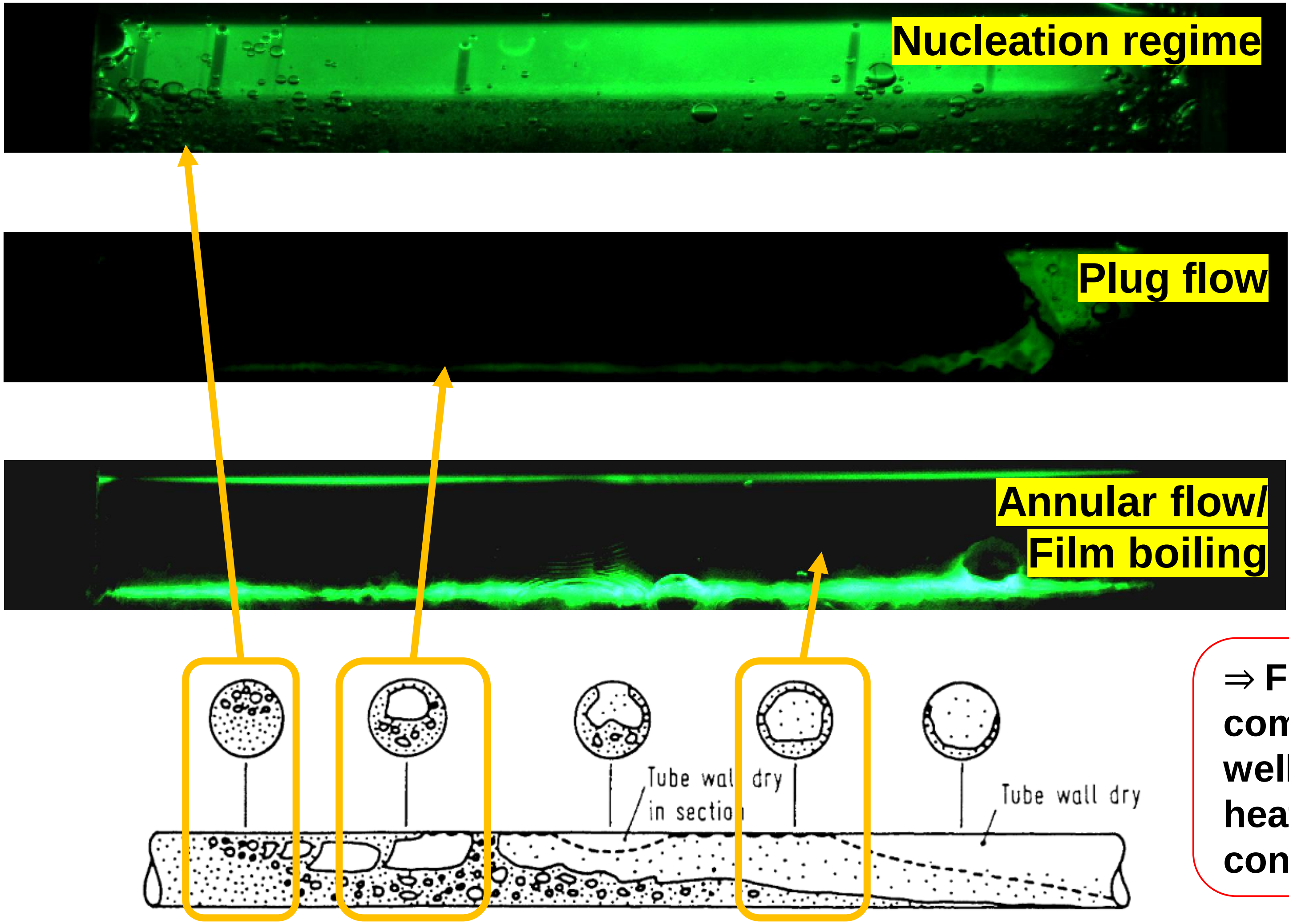

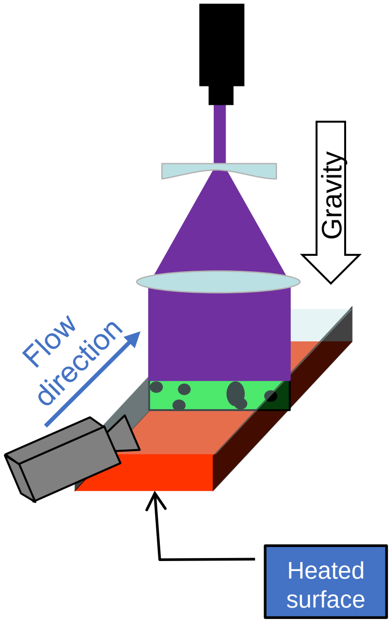

⇒ **Flow regimes are comparable to the well-known horizontal heated pipe configuration**

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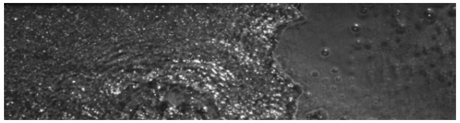
Wall thermometry in multiphase flows

2D unsteady phenomenon



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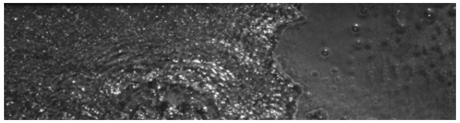
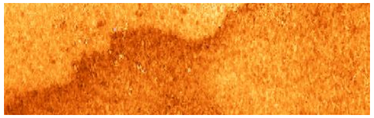


Needs a space- and time-resolved diagnostic



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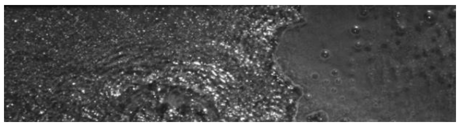

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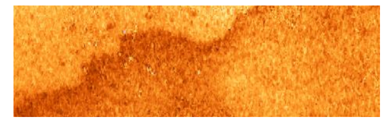

Final aim :
full scale system application

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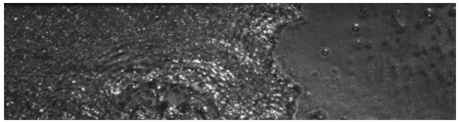

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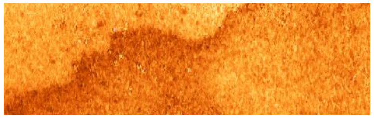

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- No fully transparent apparatus ☹
- No back face measurements ☹
- No surrogate/low boiling point coolant ☹

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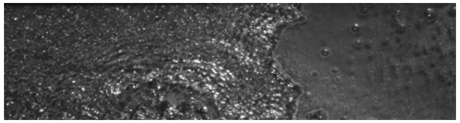

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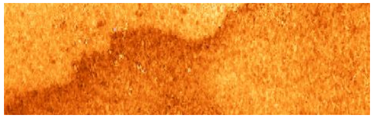

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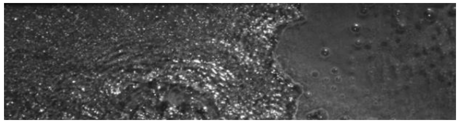

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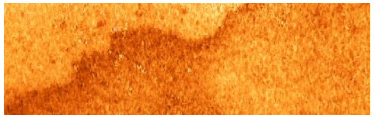

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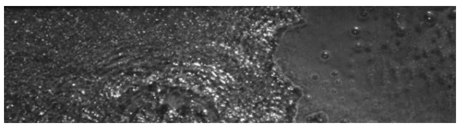

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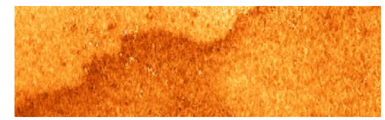

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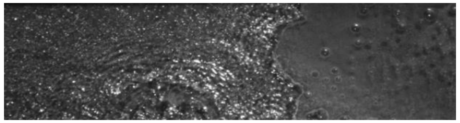

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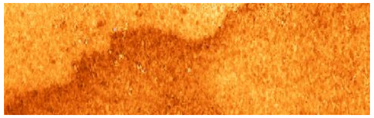

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➔ Phosphor thermometry (JT 52 ☺)!

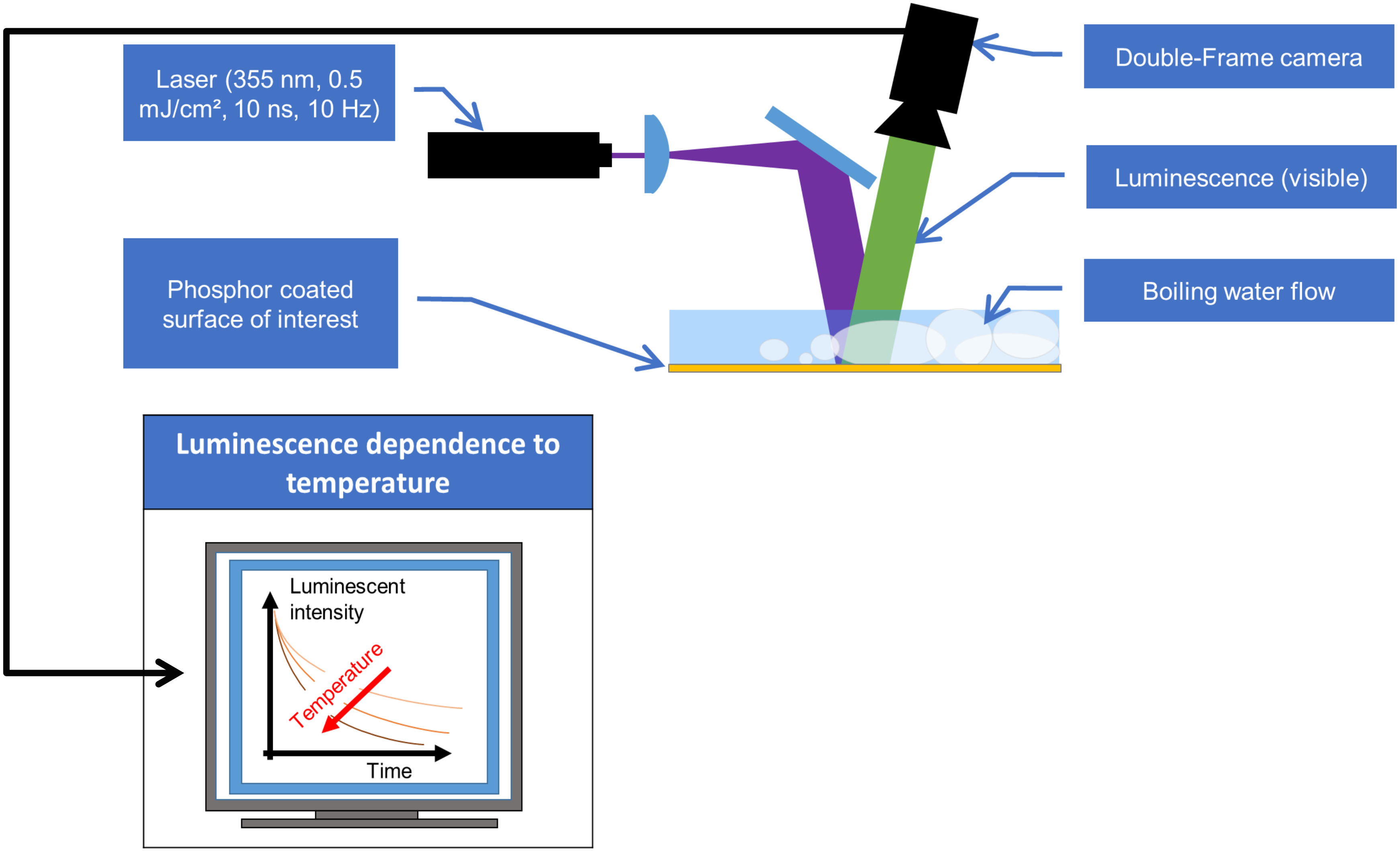
1. Experimental setup and flow morphology

2. Phosphor thermometry setup

3. Results

4. Validation

Lifetime phosphor thermometry



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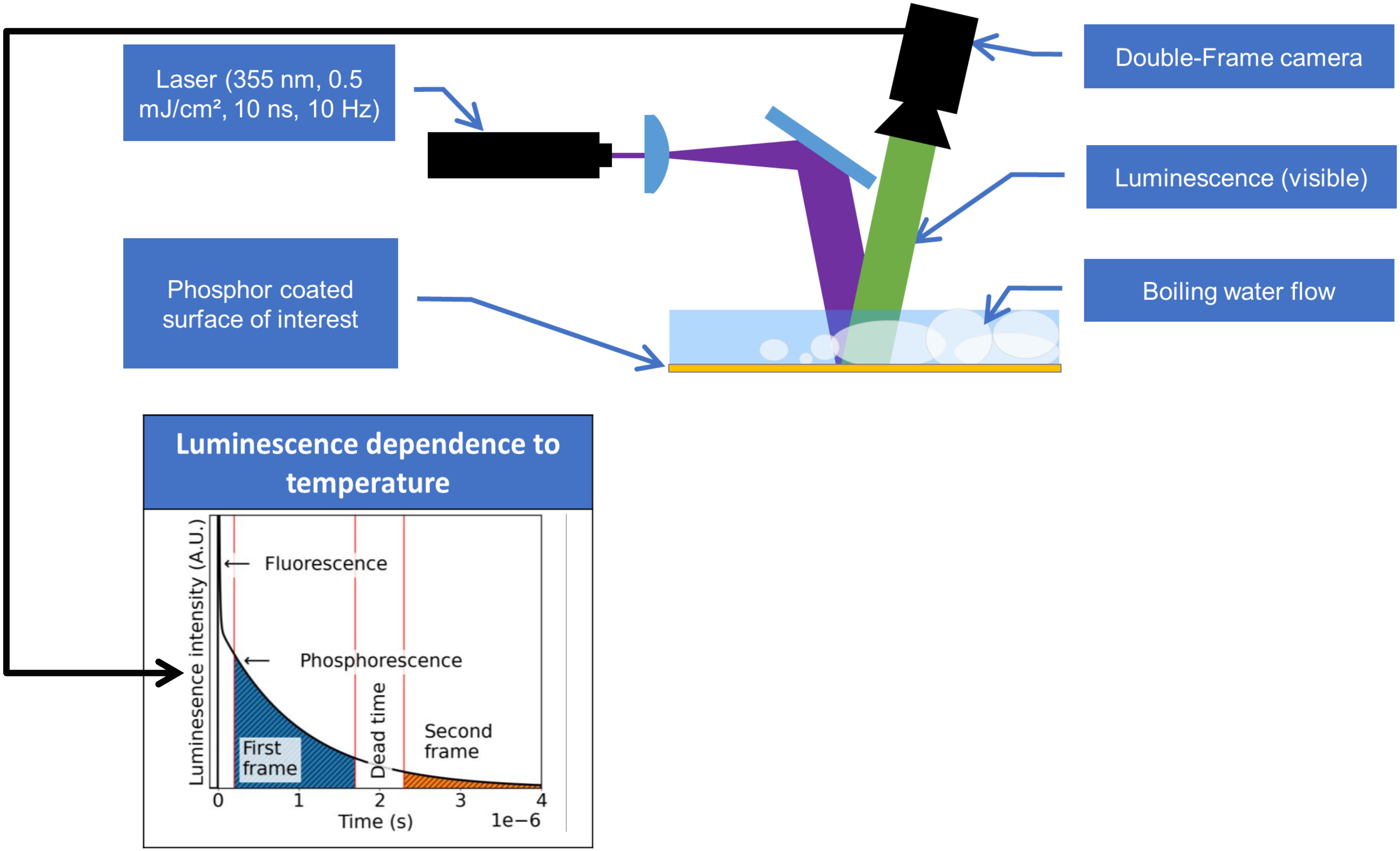

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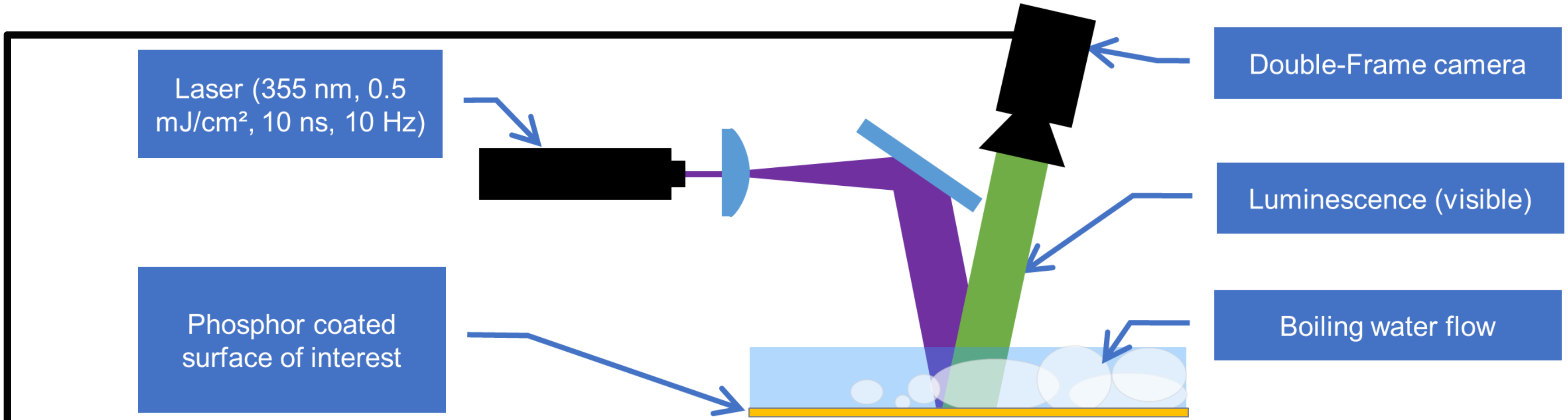

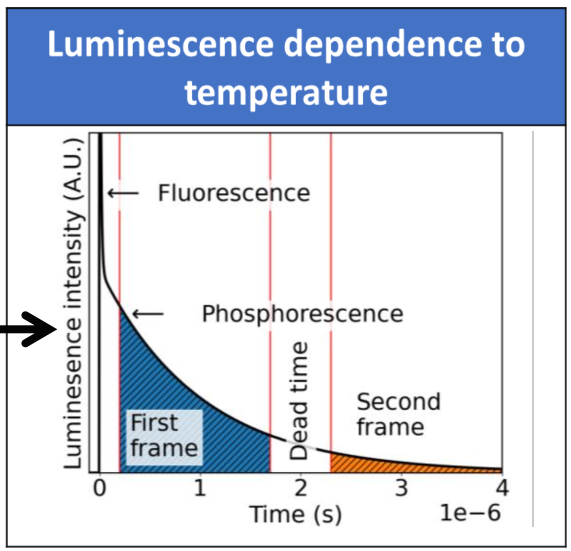

<u>Why lifetime phosphor thermometry ?</u>

- ✓ Space- and time- resolved
- ✓ Limited intrusiveness
- ✓ Resilience to 2-phase flow
- ✓ **Optical path independence**

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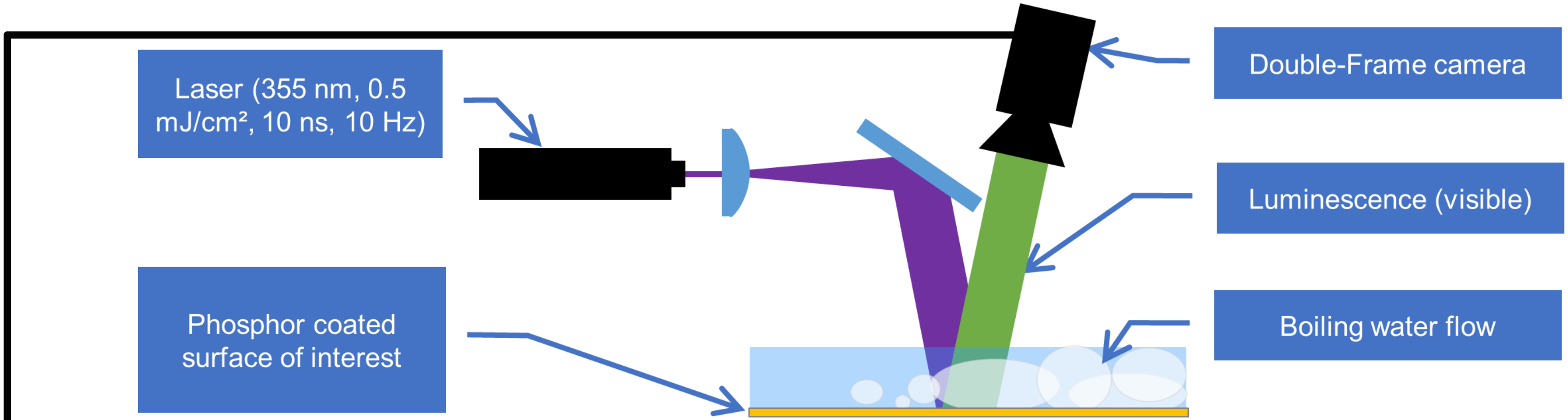

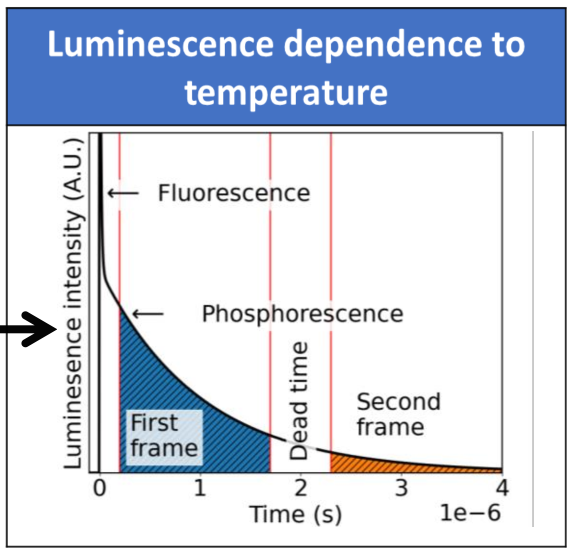

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* typical values for infrared : 5%/K; organic TSPs : 2-10 %/K

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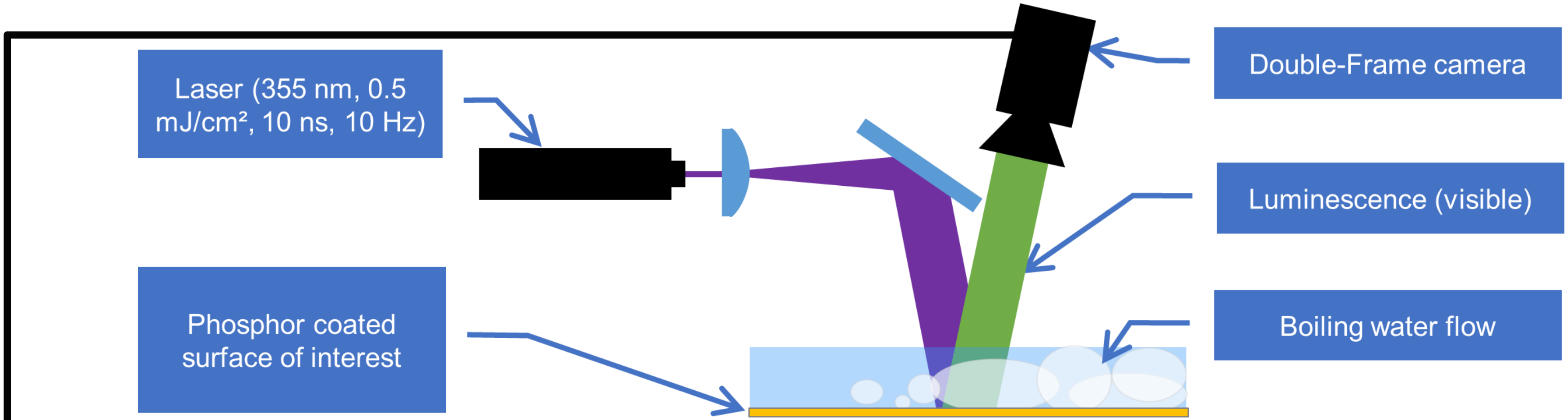

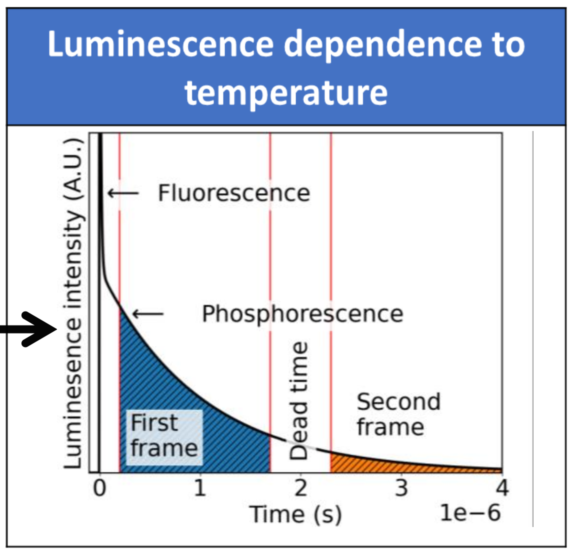

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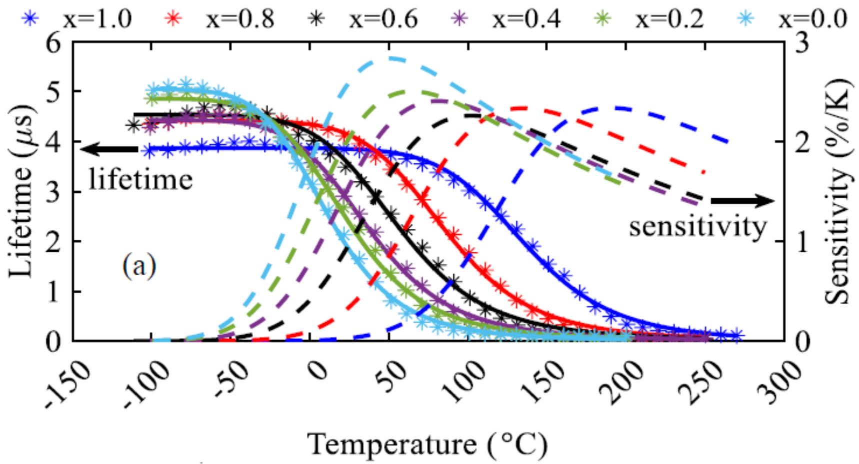
- x **But typical phosphor sensitivities are relatively* low (0.1 – 0.5 %/K) ☹**

⇒ **What if we could maximize the phosphor sensitivity in the vicinity of the boiling point ?**

* typical values for infrared : 5%/K; organic TSPs : 2-10 %/K

Dial-a-range phosphor thermometry : $(Sc_{1-x}Y_x)VO_4{:}Bi^{3+}$

- Developed by Elashry et al. 2023 [4]
- Sensitivity and range are tuned by adjusting the Sc/Y concentrations
- Useful temperature range for $x = 0.8$: **[50, 150] ºC**
- Sensitivity ∈ **[1, 2.5] %/K** ☺



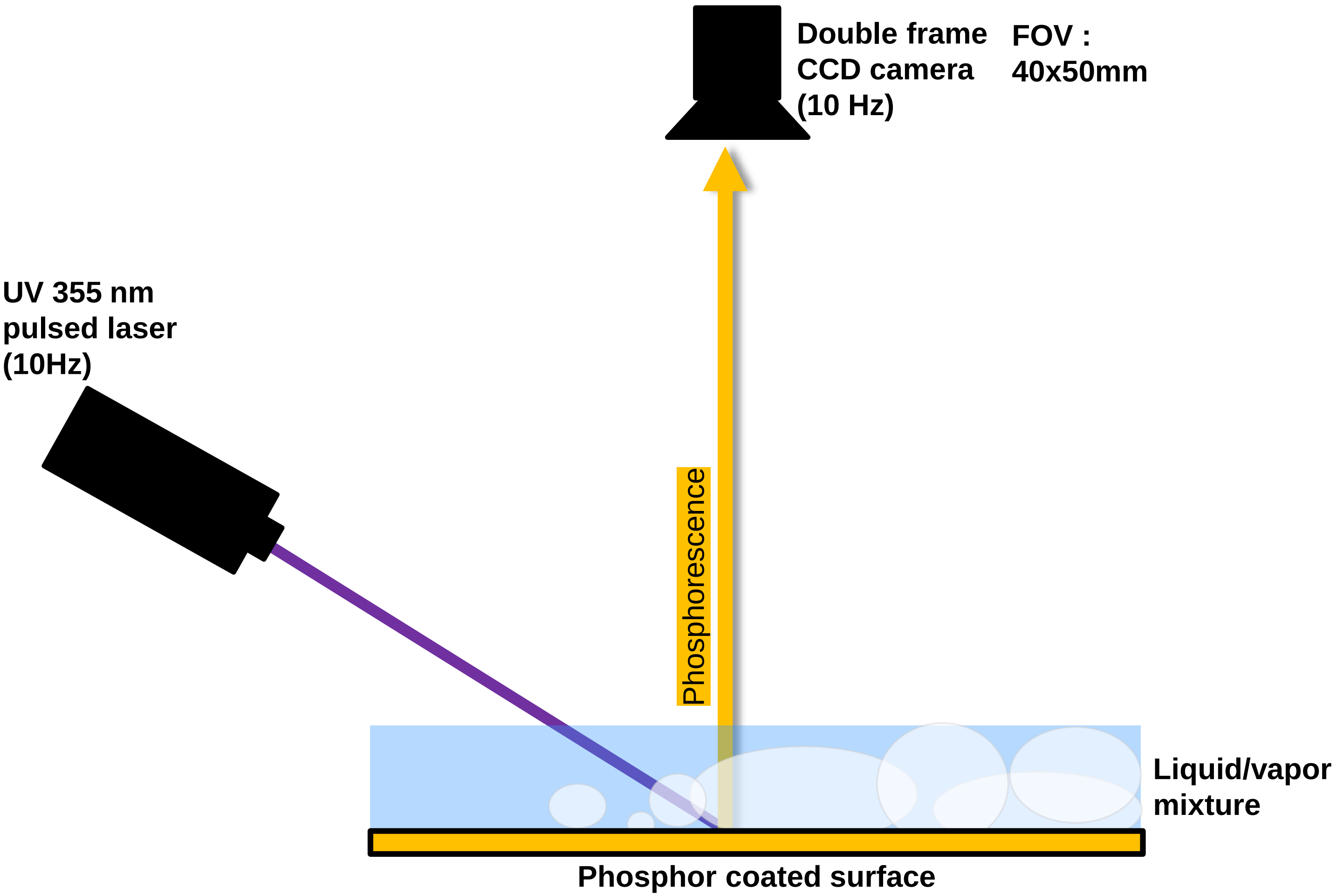
$(Sc_{1-x}Y_x)VO_4{:}Bi^{3+}$ decay time and relative sensitivity temperature dependence [4]

In-house mixing-and-firing chemical synthesis

$(Sc_{0,2}Y_{0,8})VO_4{:}Bi^{3+}$ after firing

[4] M. Elashry, A. Rashed, L. Dalipi, U. Betke, C. Abram, and **B. Fond**, “Bismuth-doped rare-earth orthovanadates as tunable luminescence decay-time thermometers.” Optica Open (preprint)

Synchronous phosphor thermometry and direct visualisation



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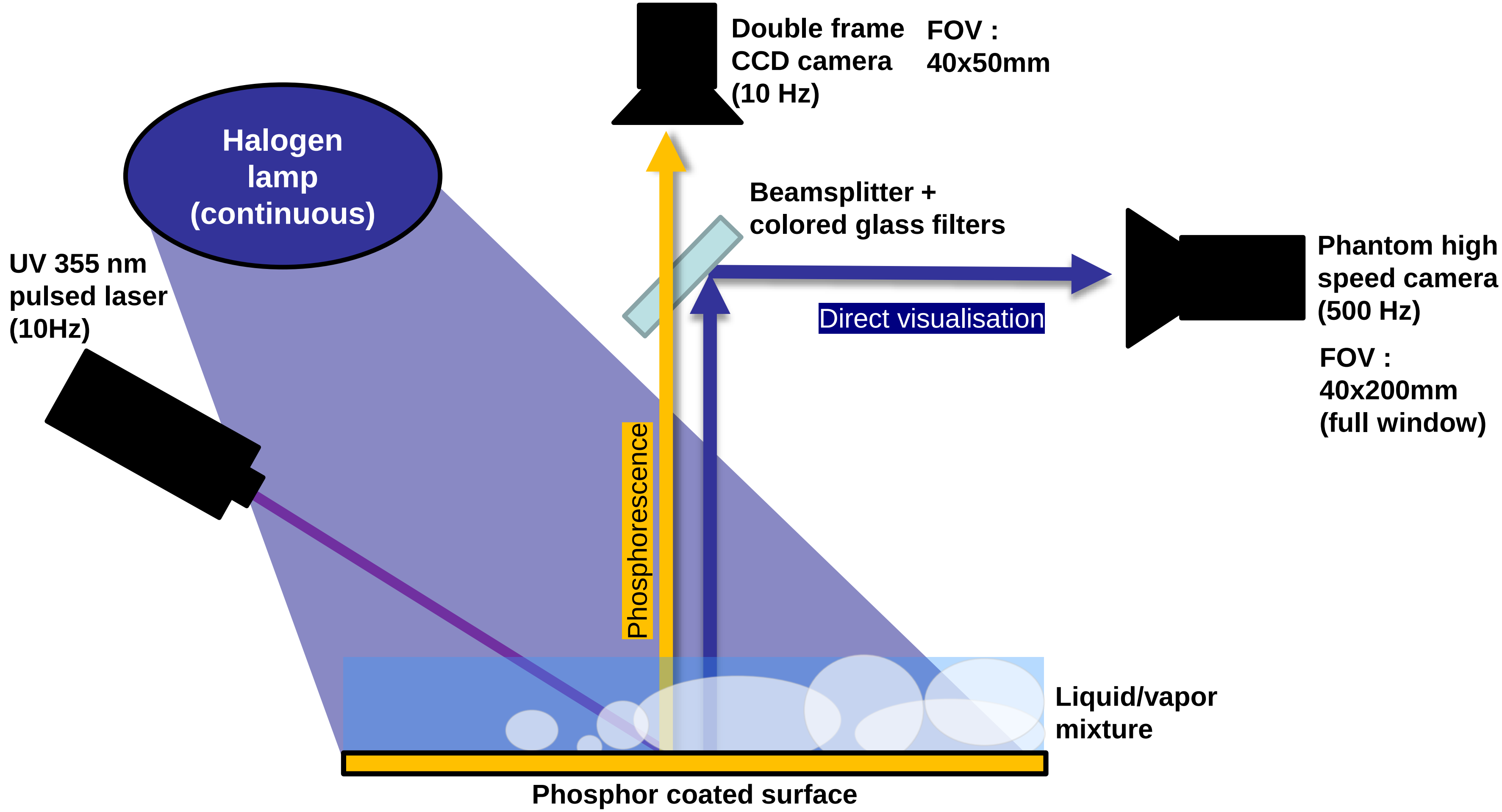

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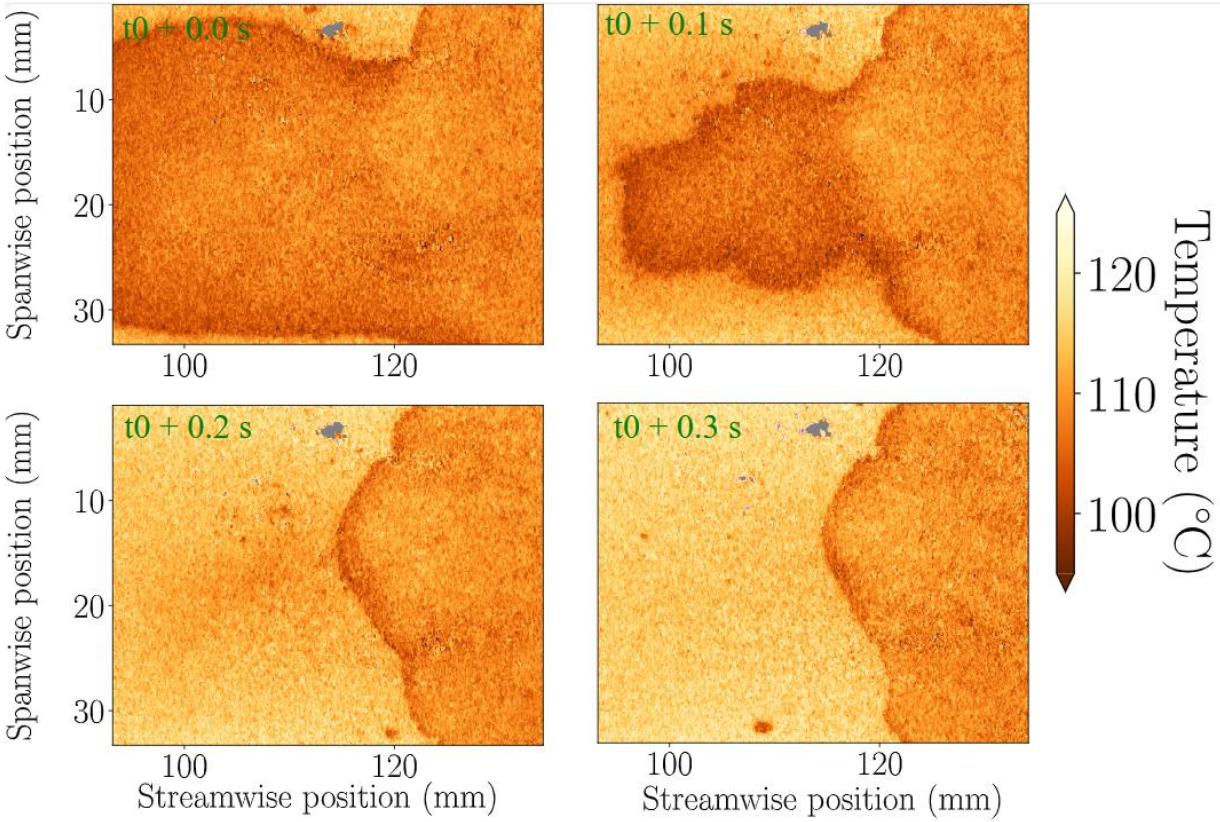
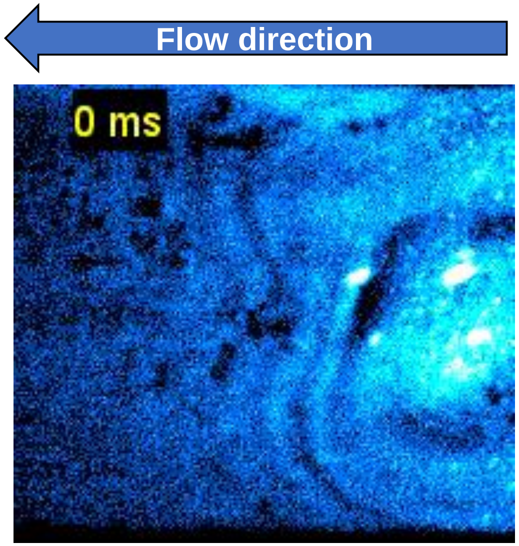
Focus on a single dryout event



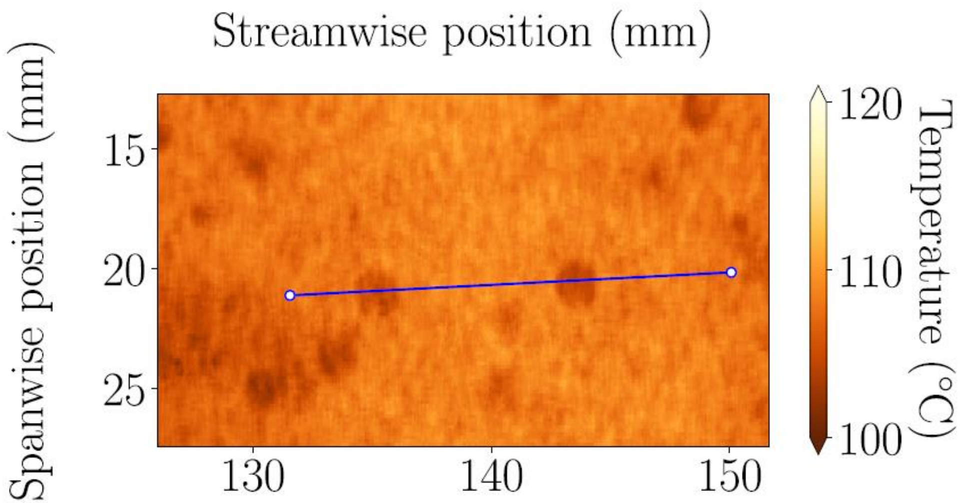
Instantaneous temperature fields during a dryout event

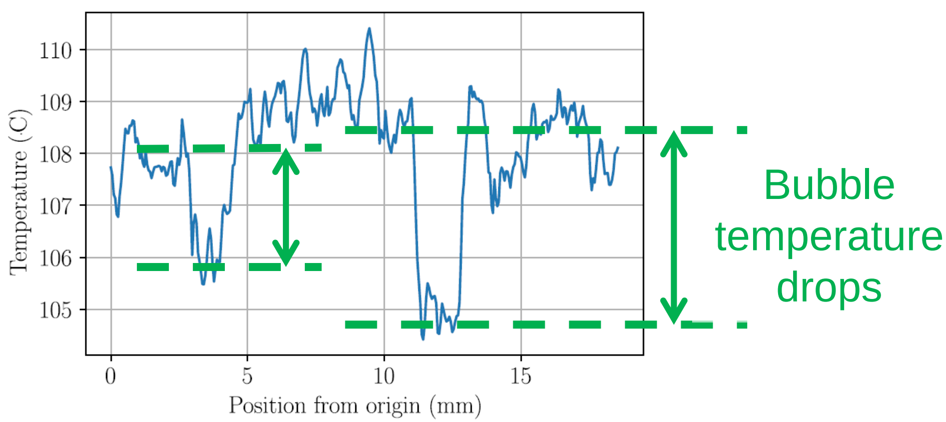


Direct visualisation of the dryout event

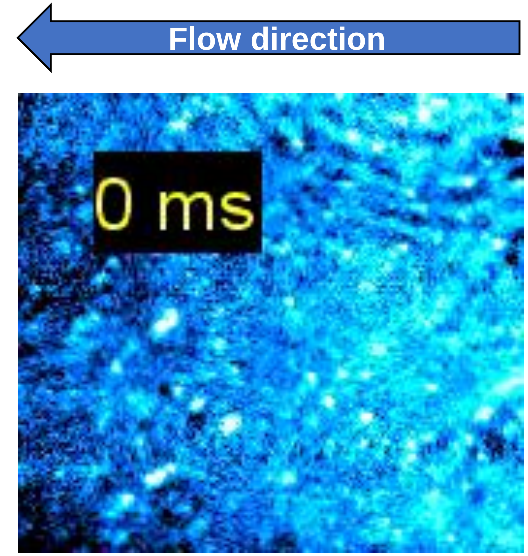
Run ID	12r
Heating power density	0.20 MW/m²
Mass flow rate	19 kg/m²/s
Thermometry framerate	10 Hz
Visualisation framerate	500 Hz

Focus on bubble departure events (annular flow)





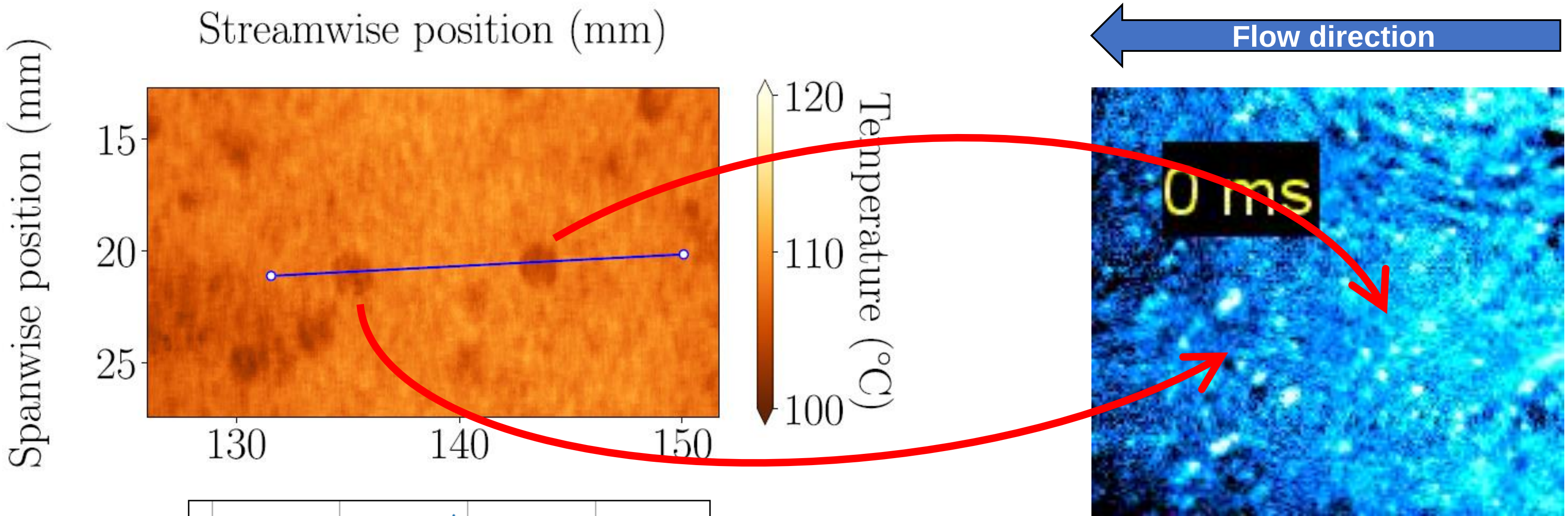
Instantaenous temperature field during a bubble growth event (top), temperature field under 2 bubbles (bottom)

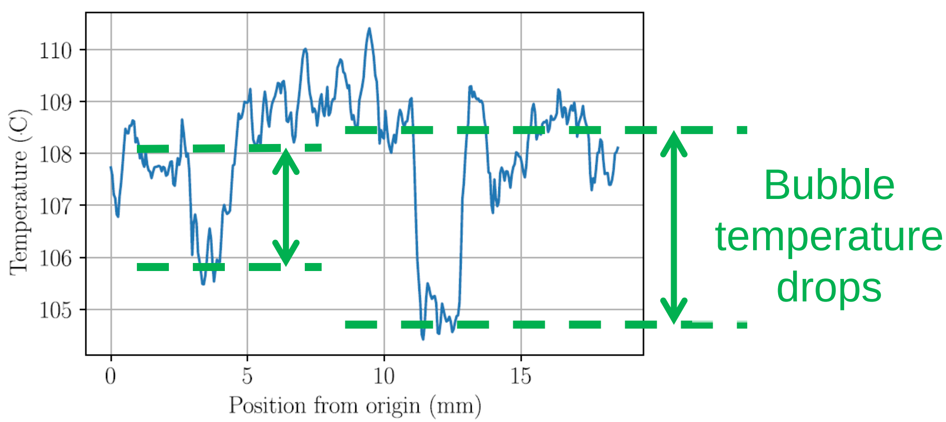


Direct visualisation of the bubble growth event

Run ID	3
Heating power density	0.10 MW/m²
Mass flow rate	13 kg/m²/s
Thermometry framerate	8 Hz
Visualisation framerate	500 Hz

Focus on bubble departure events (annular flow)





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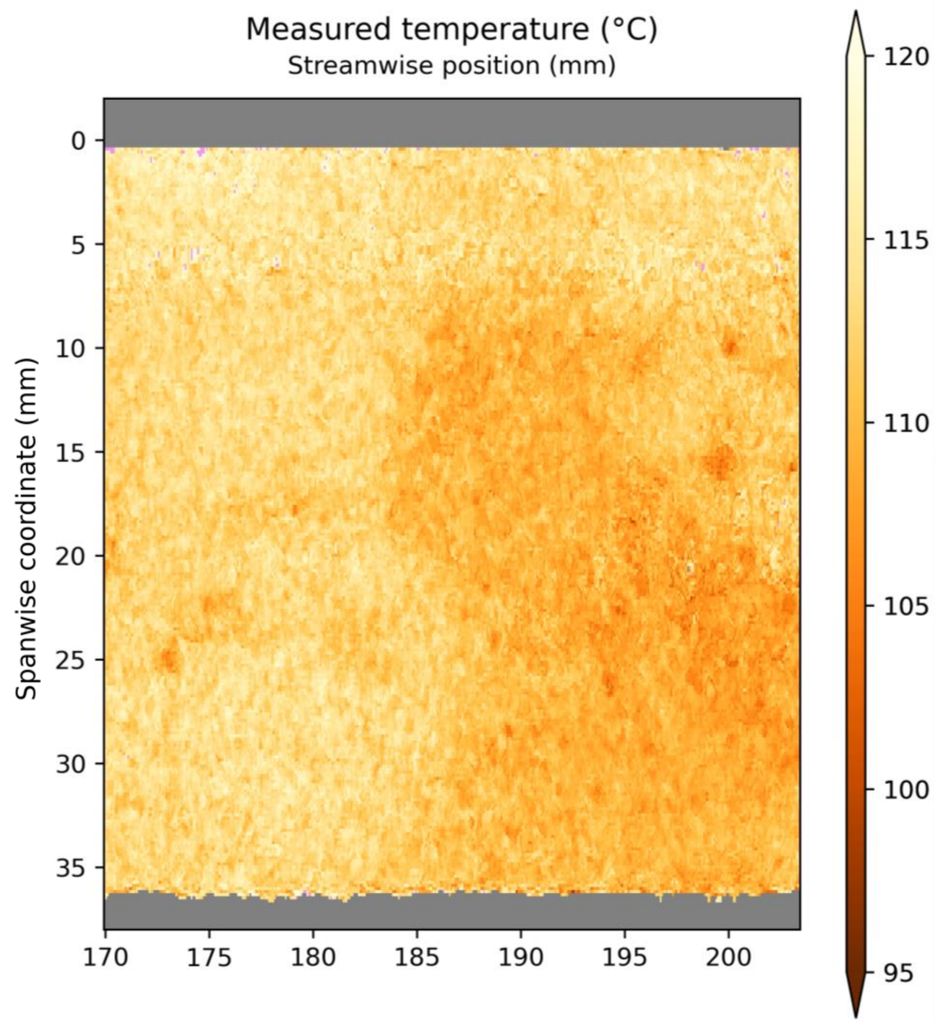
Time-averaging

Run ID	28
Heating power density	0.20 MW/m²
Mass flow rate	32 kg/m²/s
Phosphor thermometry framerate	10 Hz
Acquisition duration	100 s



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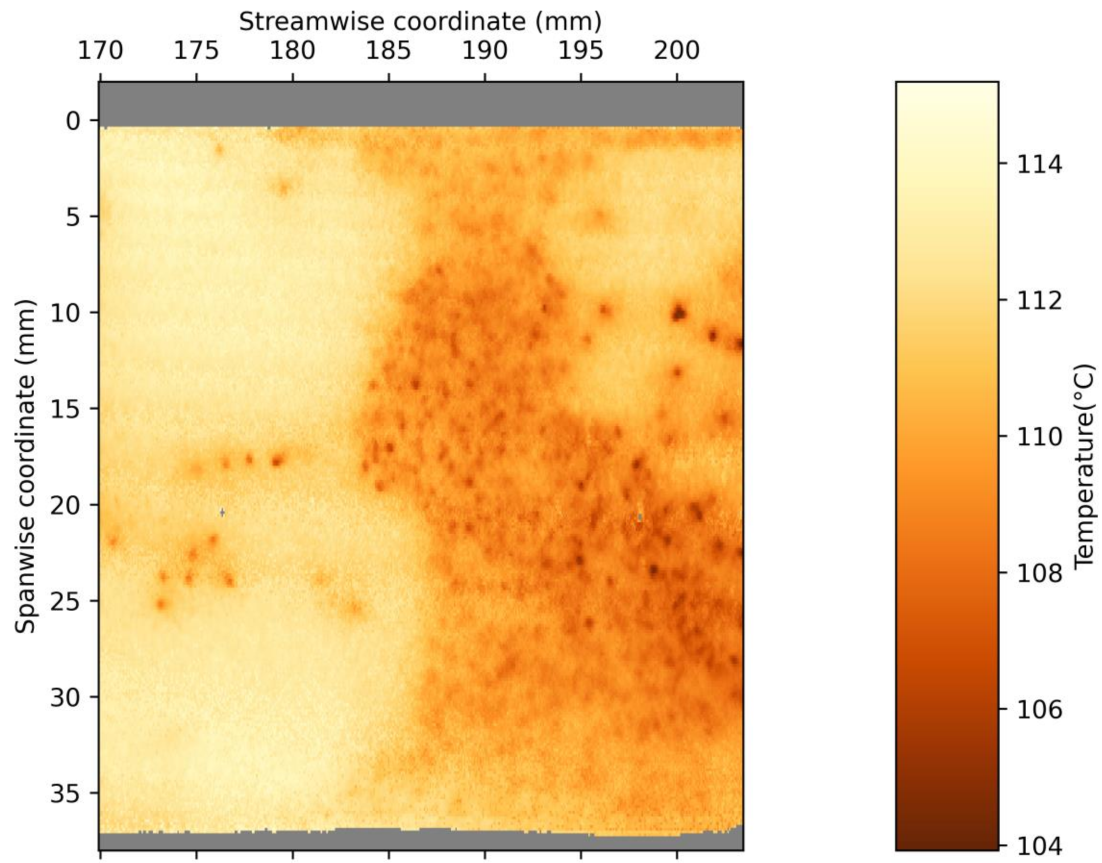
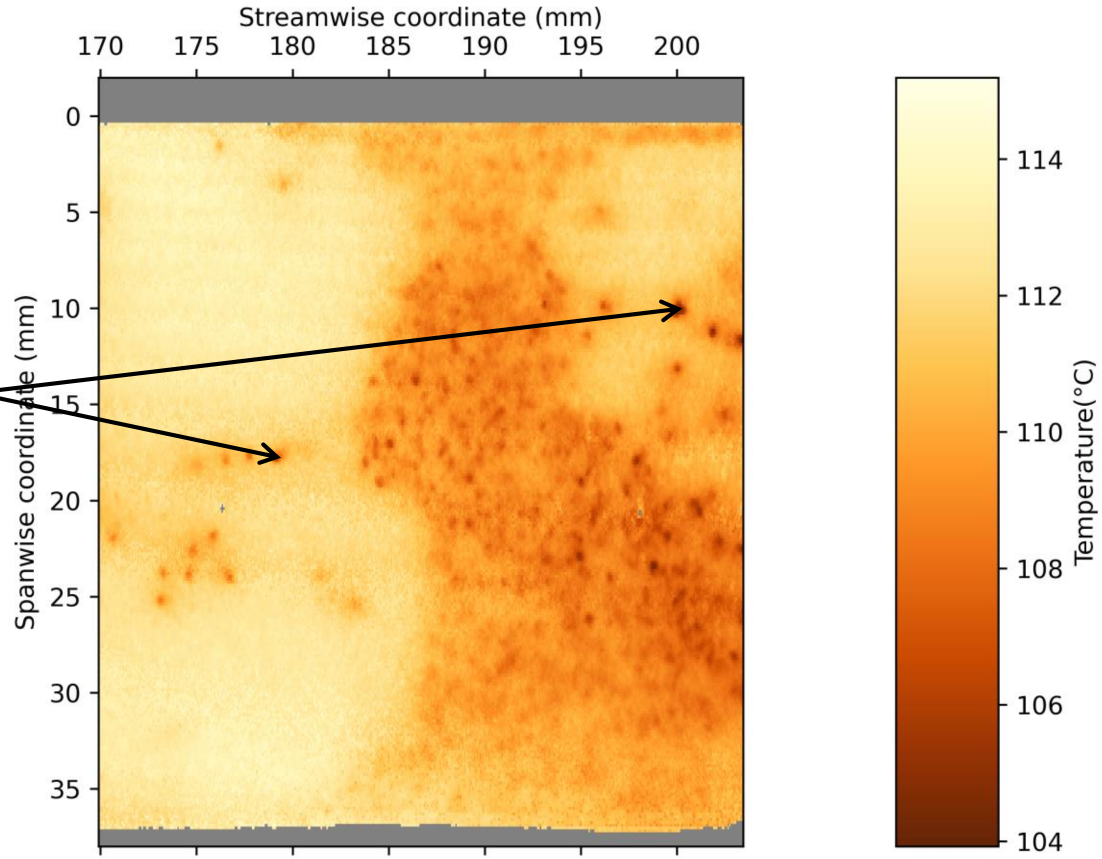
Phosphor thermometry framerate	10 Hz
Acquisition duration	100 s



Average temperature field over 1000 shots, 10 Hz

Time-averaging



Cold spot :
- **favorable bubble formation site**
- **Average overheat : ~5° C**

Run ID	28
Heating power density	0.20 MW/m²
Mass flow rate	32 kg/m²/s
Phosphor thermometry framerate	10 Hz
Acquisition duration	100 s

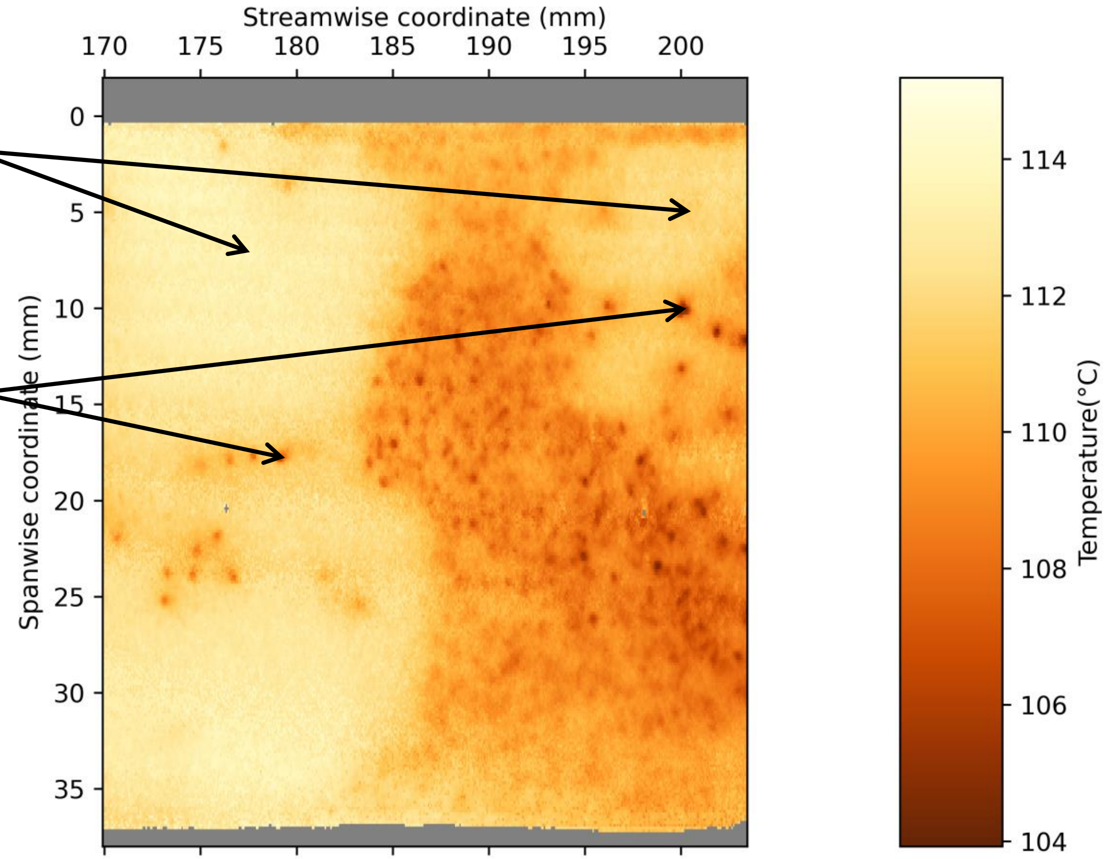
Average temperature field over 1000 shots, 10 Hz

Time-averaging

Hot spots :
- **Low ebullition**
- **Average overheat : ~15° C**

Cold spot :
- **favorable bubble formation site**
- **Average overheat : ~5° C**

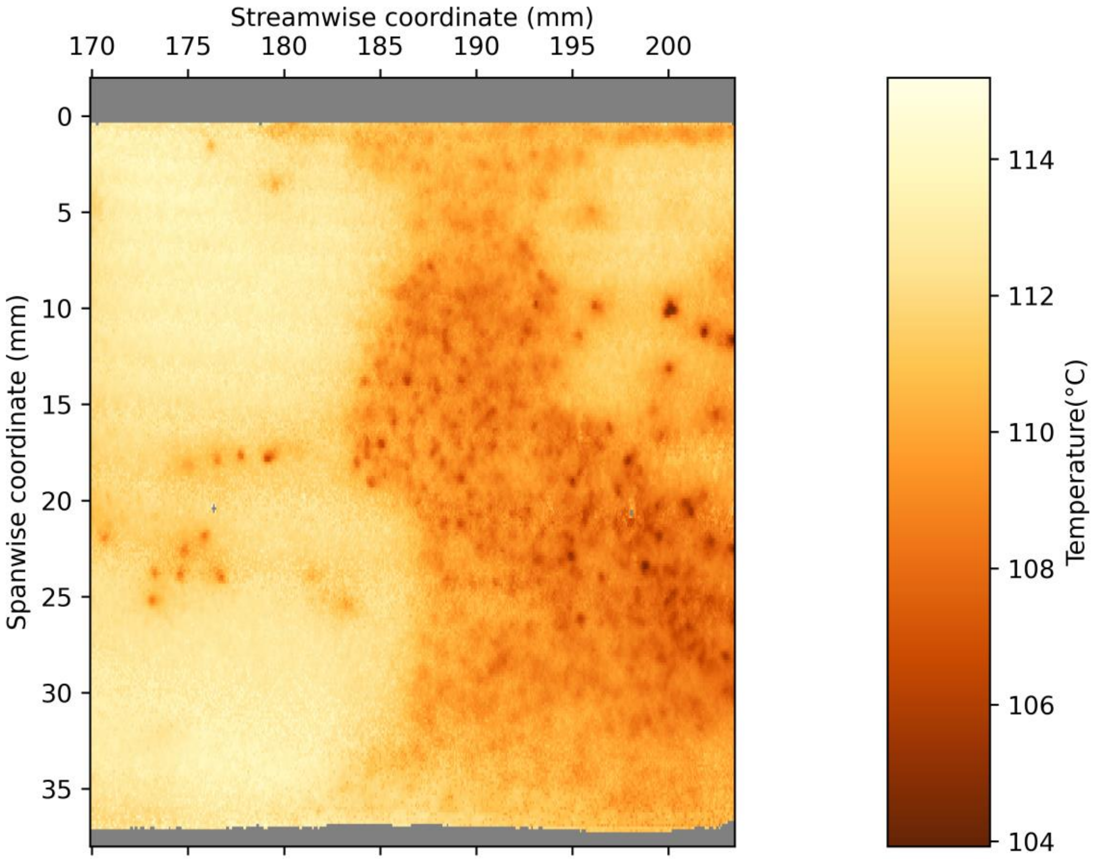
Run ID	**28**
Heating power density	**0.20 MW/m²**
Mass flow rate	**32 kg/m²/s**
Phosphor thermometry framerate	**10 Hz**
Acquisition duration	**100 s**



Average temperature field over 1000 shots, 10 Hz

Time-averaging

- **~1 mm effective spatial resolution**
- **Overheating assessment**
- **Detection of nucleation sites**
- **Detection of favorable/unfavorable zones**



<u>Average temperature field over 1000 shots, 10 Hz</u>

1. Experimental setup and flow morphology

2. Phosphor thermometry setup

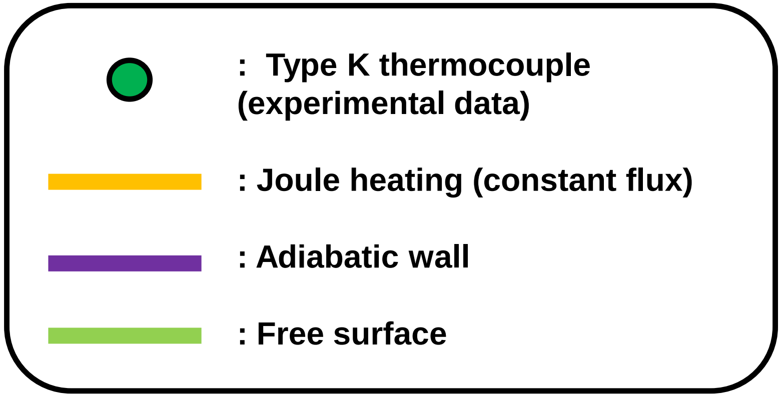
3. Results

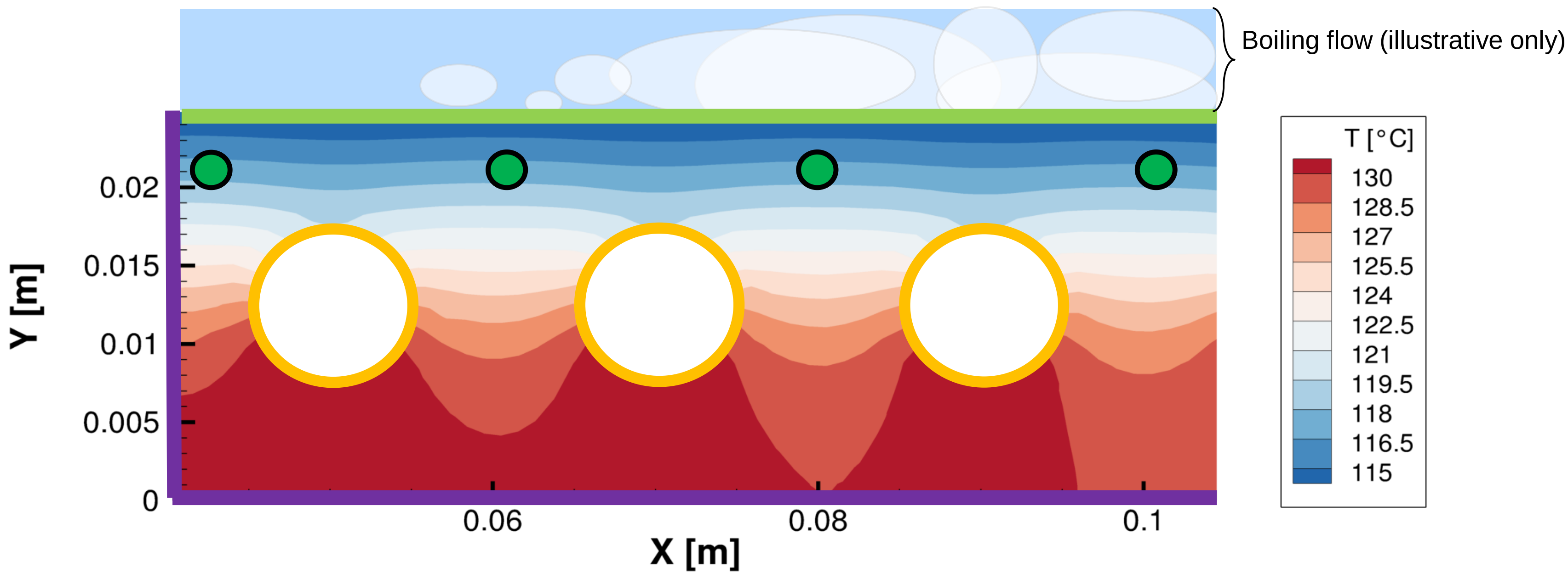
4. Validation

Comparison to thermocouple data (time-averaged)

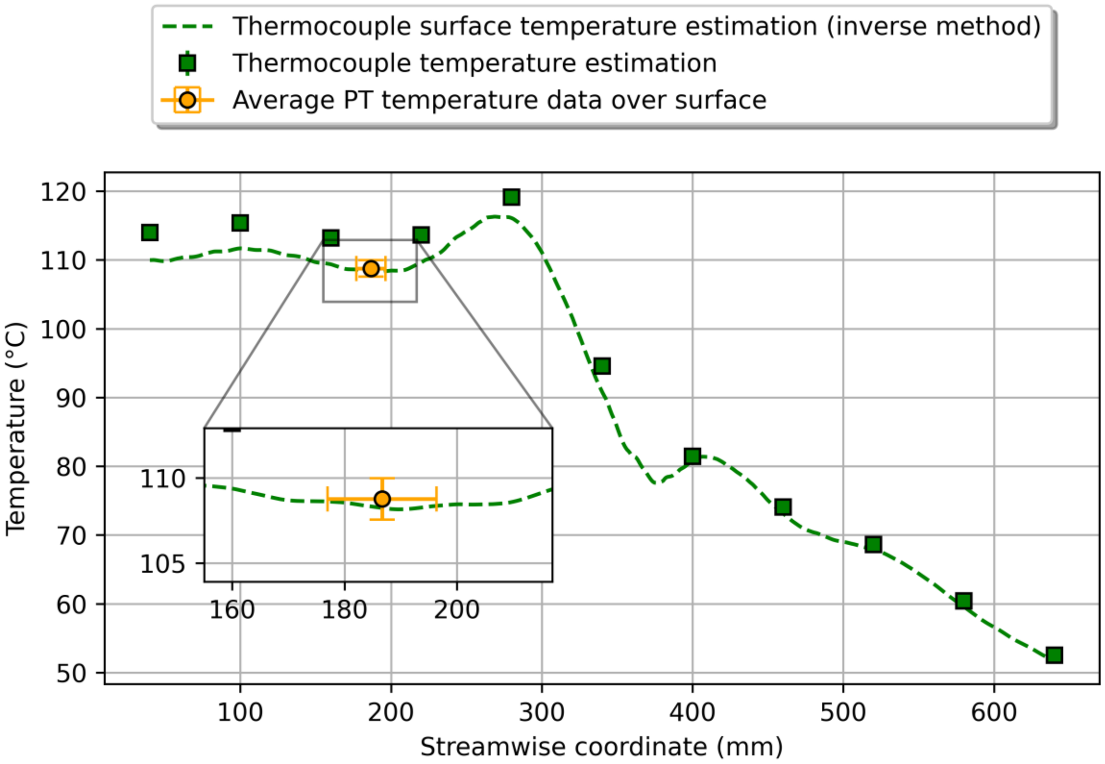
- Surface temperature data can be reconstructed from **<u>sub-surface thermocouples</u>** using **<u>inverse methods</u>**

- This low-resolution data can then be **<u>compared</u>** to the phosphor thermometry data





Comparison to thermocouple data (time-averaged)



Run ID	28
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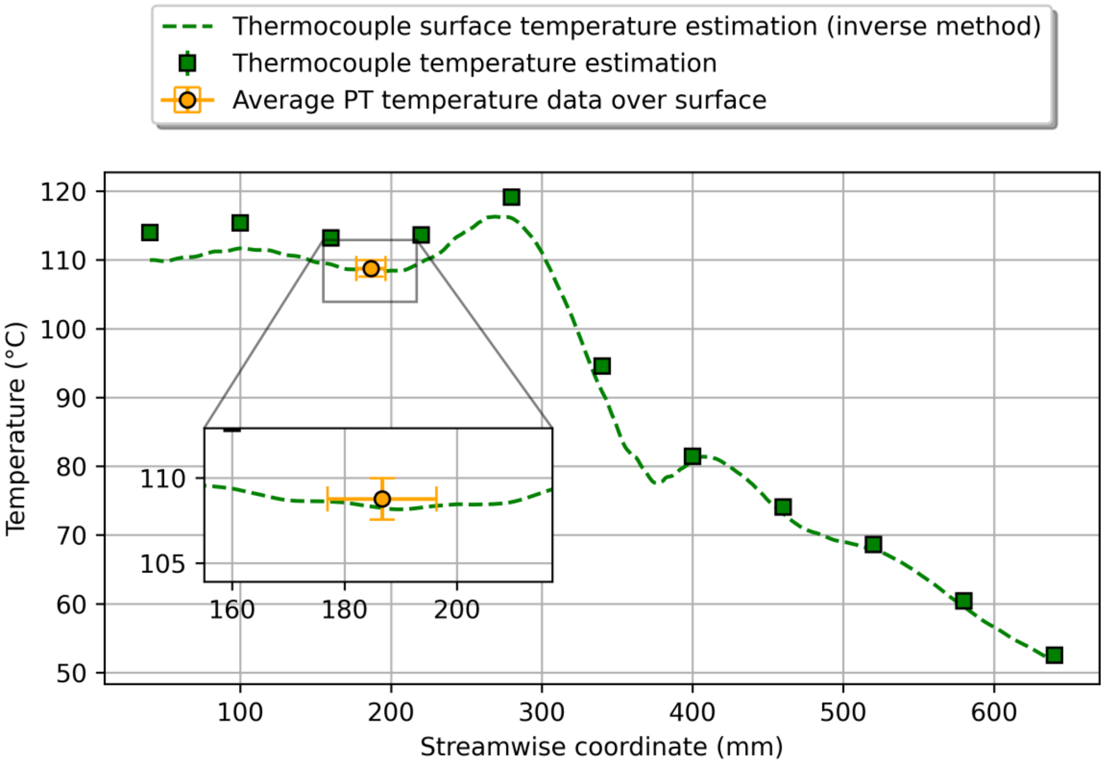

Run ID	28
Heating power density	0.20 MW/m²
Mass flow rate	32 kg/m²/s

- **Good agreement between time- and spaced-averaged temperature data and inverse method data on most runs**
- **Some particular operating conditions (3 out of 15) have a ~3K discrepancy (currently being investigated)**

Assessing the measurement uncertainty through a single bubble

- PT Measurements
  - **<u>At uniform wall temperature</u>** (no heating, system close to thermal equilibrium)
  - **<u>Through vapor bubbles</u>** (generated upstream)

- **The measured temperature field should be quasi-uniform**

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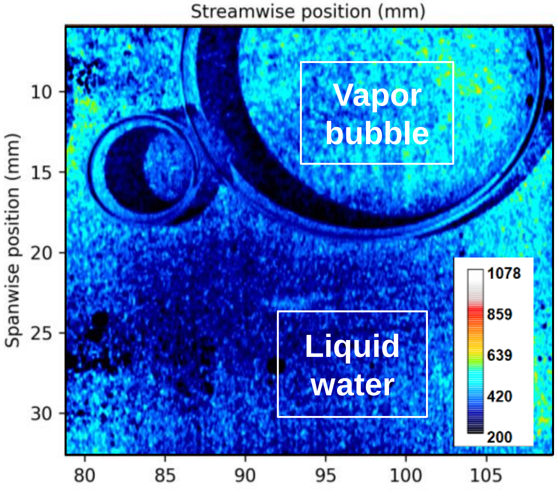
Instantaenous luminescence intensity

First frame (counts)



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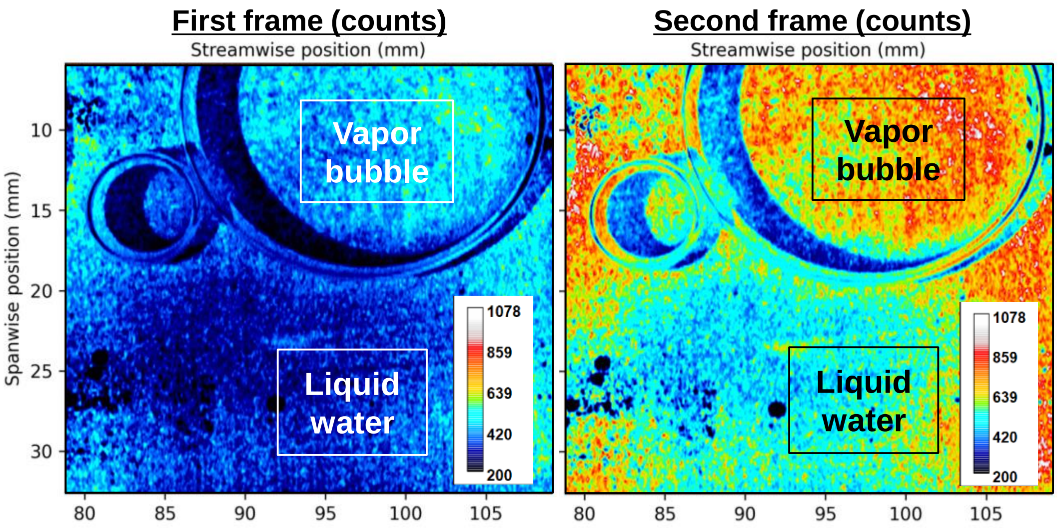

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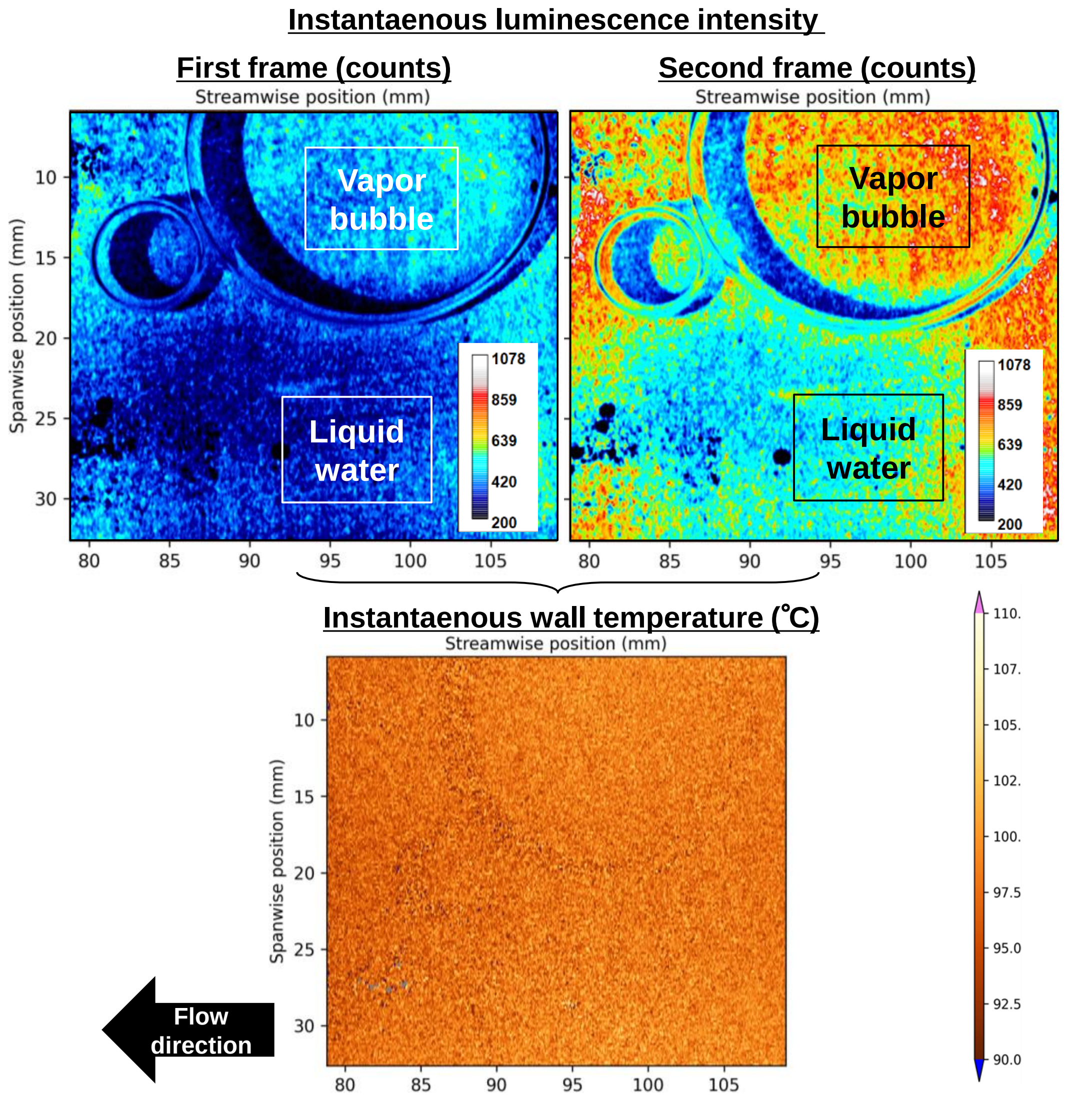

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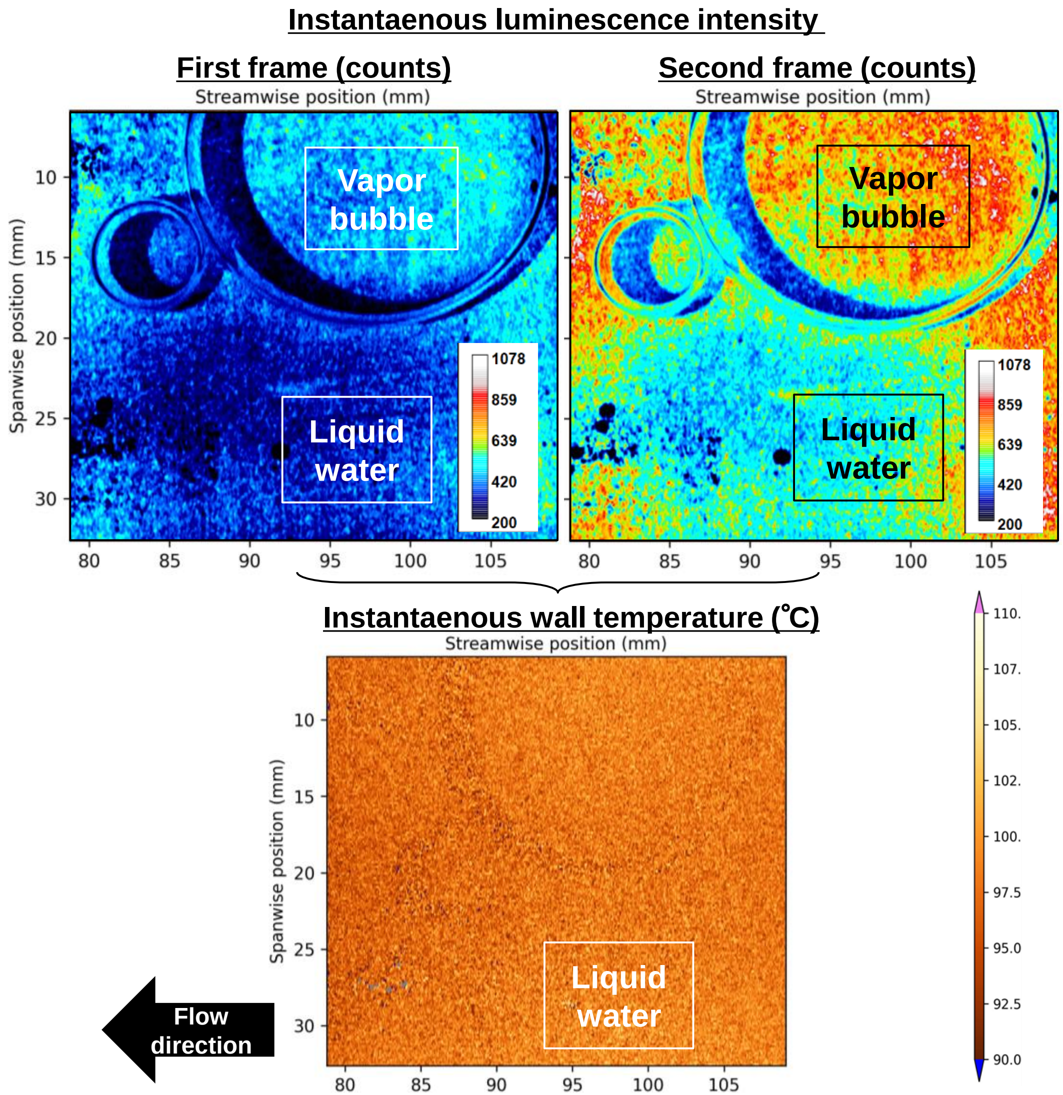

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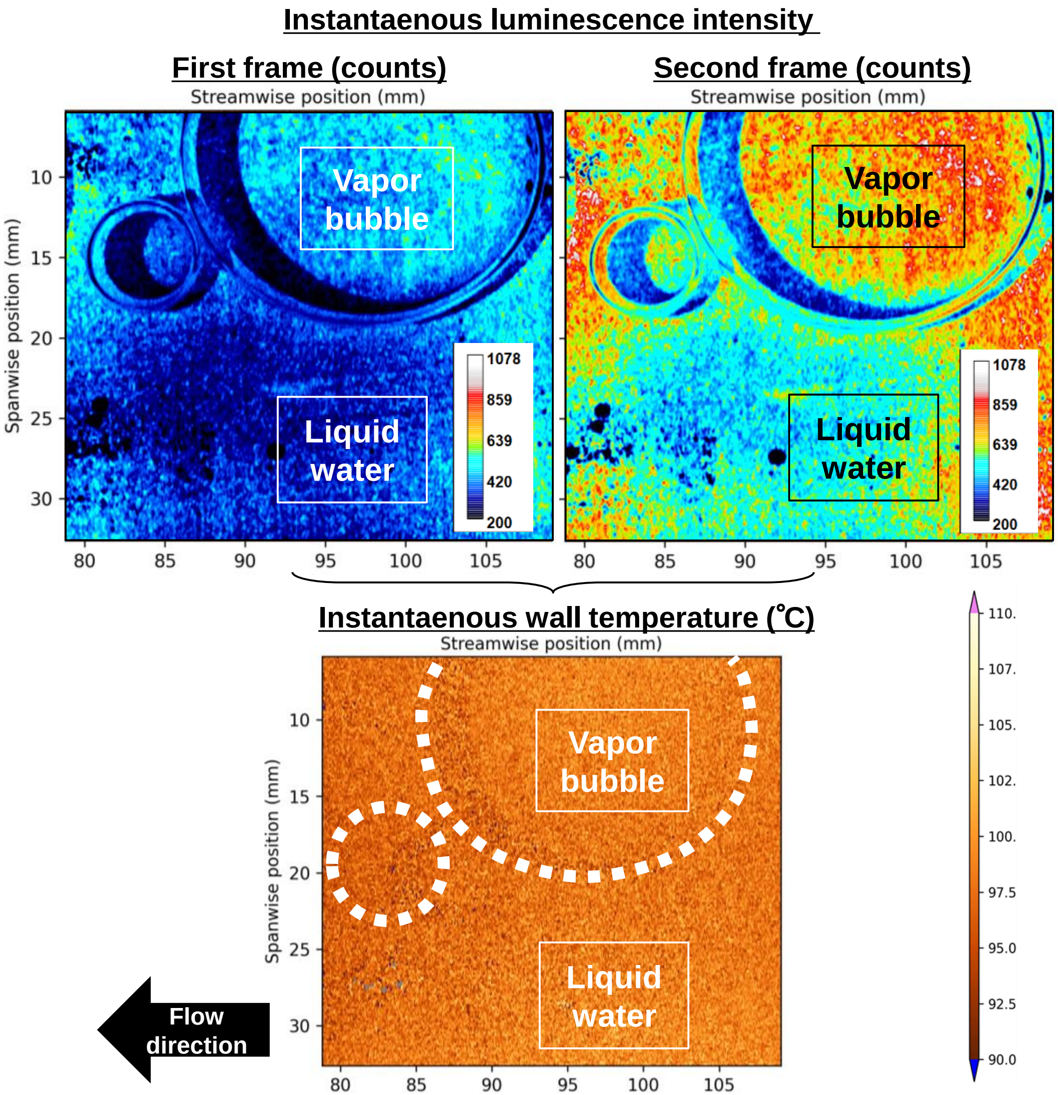

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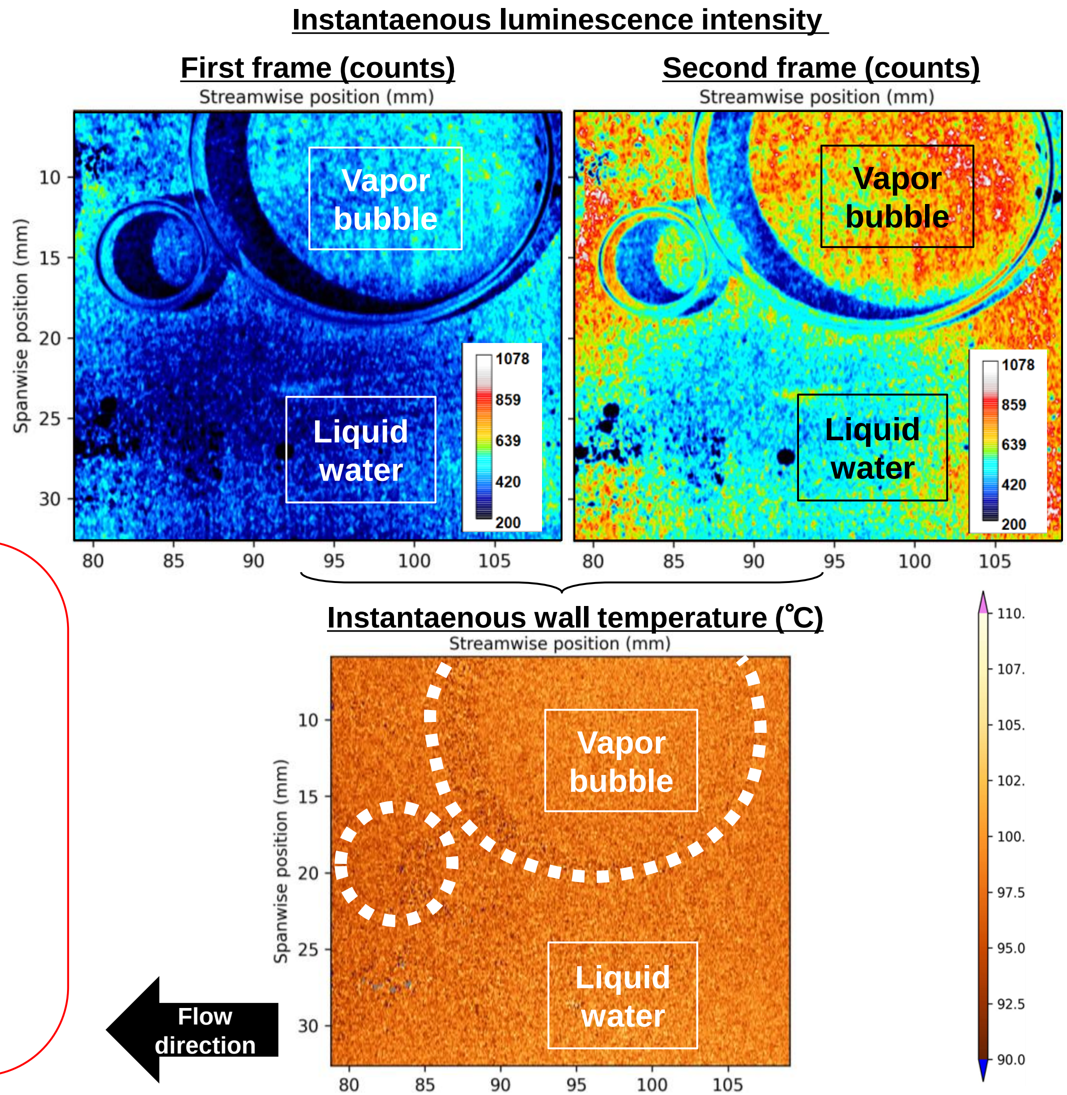

- **As expected the measurement is similar through the liquid and the bubble**
- **Shadows lowers the SNR but do not affect the mean value**
- **Typical single shot σ_θ at uniform temperature : 2 K**

Conclusions and perspectives

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✓A phosphor has been tuned to this application to achieve maximum sensitivity

✓2D unsteady temperature measurements have been acquired **through** a boiling flow with PT for the first time

✓Average temperature fields have been validated against TC data

✓Dryout and bubble growth events have been measured

✓In harsh and/or optically challenging environements, phosphor thermometry can save your life!

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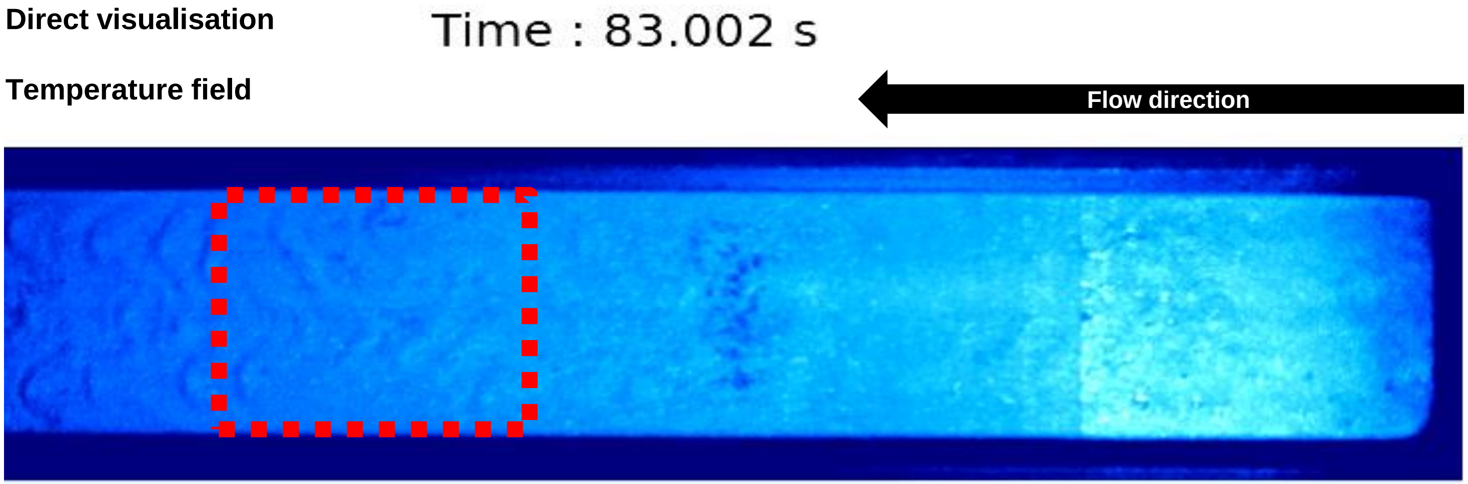
What's next?

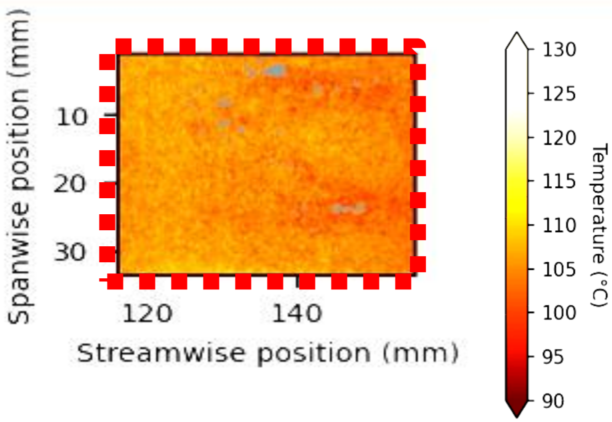
- Heat transfer coefficient fields are currently being estimated
- Application to realistic geometries

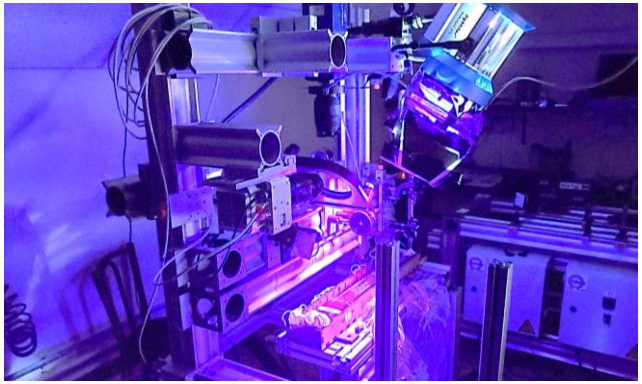
Thank you for your attention!

: Direct visualisation

: Temperature field







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