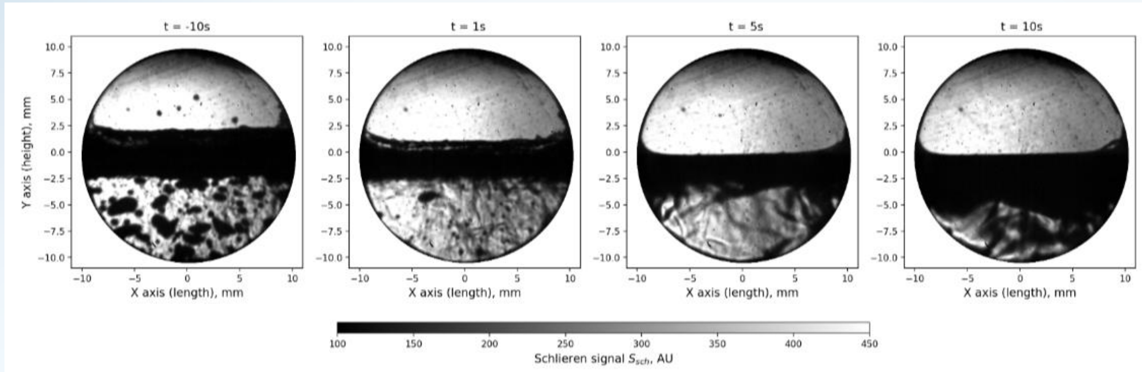


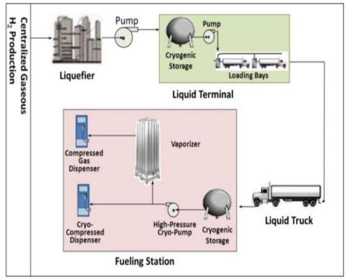
OPTICAL INVESTIGATION OF A LIQUID/GAS INTERFACE IN A CRYOGENIC FLOW

CARACTÉRISATION EXPÉRIMENTALE D'INTERFACE LIQUIDE/GAZ DYNAMIQUE EN CONDITION CRYOGÉNIQUE – APPLICATION AU TRANSPORT D'HYDROGÈNE

Tanguy DAVIN, Saïd IDLAHCEN, Gilles GODARD, Benjamin QUEVREUX, Benjamin DURET, Émilien VAREA (CARNOT Exp.)

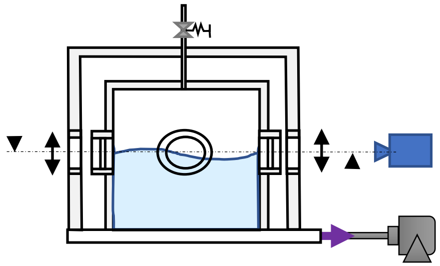
CORIA laboratory, University of Rouen, France

OPTICAL INVESTIGATION OF A LIQUID/GAS INTERFACE IN A CRYOGENIC FLOW



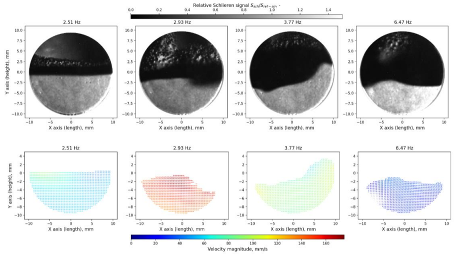
1. Context & objectives

- Hydrogen for transport
- Literature



2. Experimental methodology

- Experimental apparatus
- Experimental characterization
  - A. Direct measurements (P, Qv, T)
  - B. Imaging characterization



3. Results

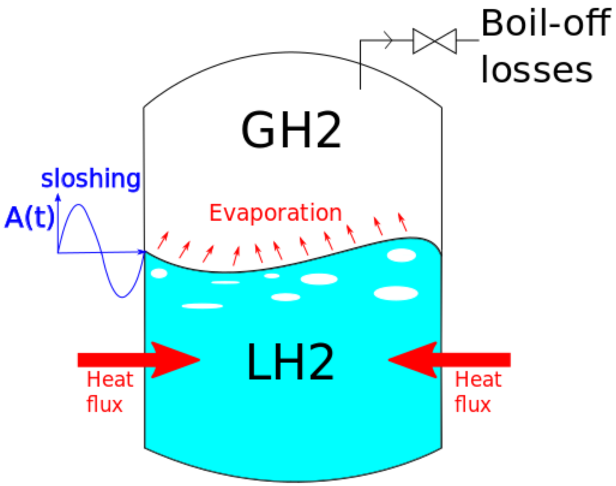
- A - Direct measurements
- B - Imaging characterization

4. Conclusions & Prospects

CONTEXT: HYGROGEN TRANSPORT

Hydrogen as a energy vector for transport

Poor volume energy density → liquid



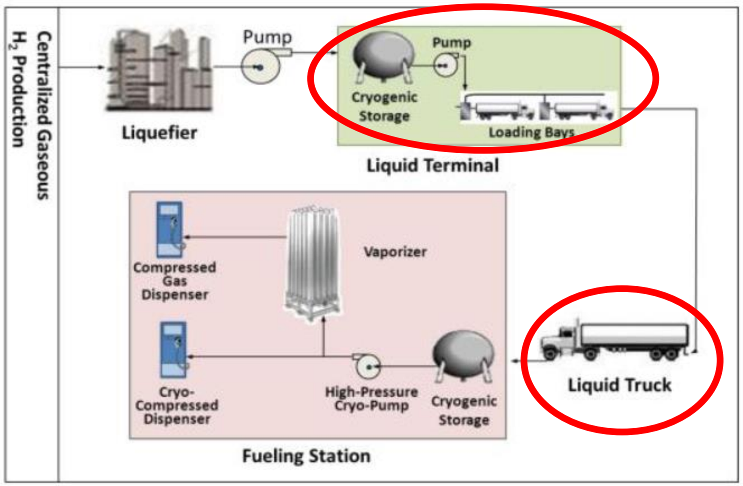
Boil-off representation

LH2 vaporizing in the tank, pressure rise

H2 loss to prevent overpressure

BOIL-OFF

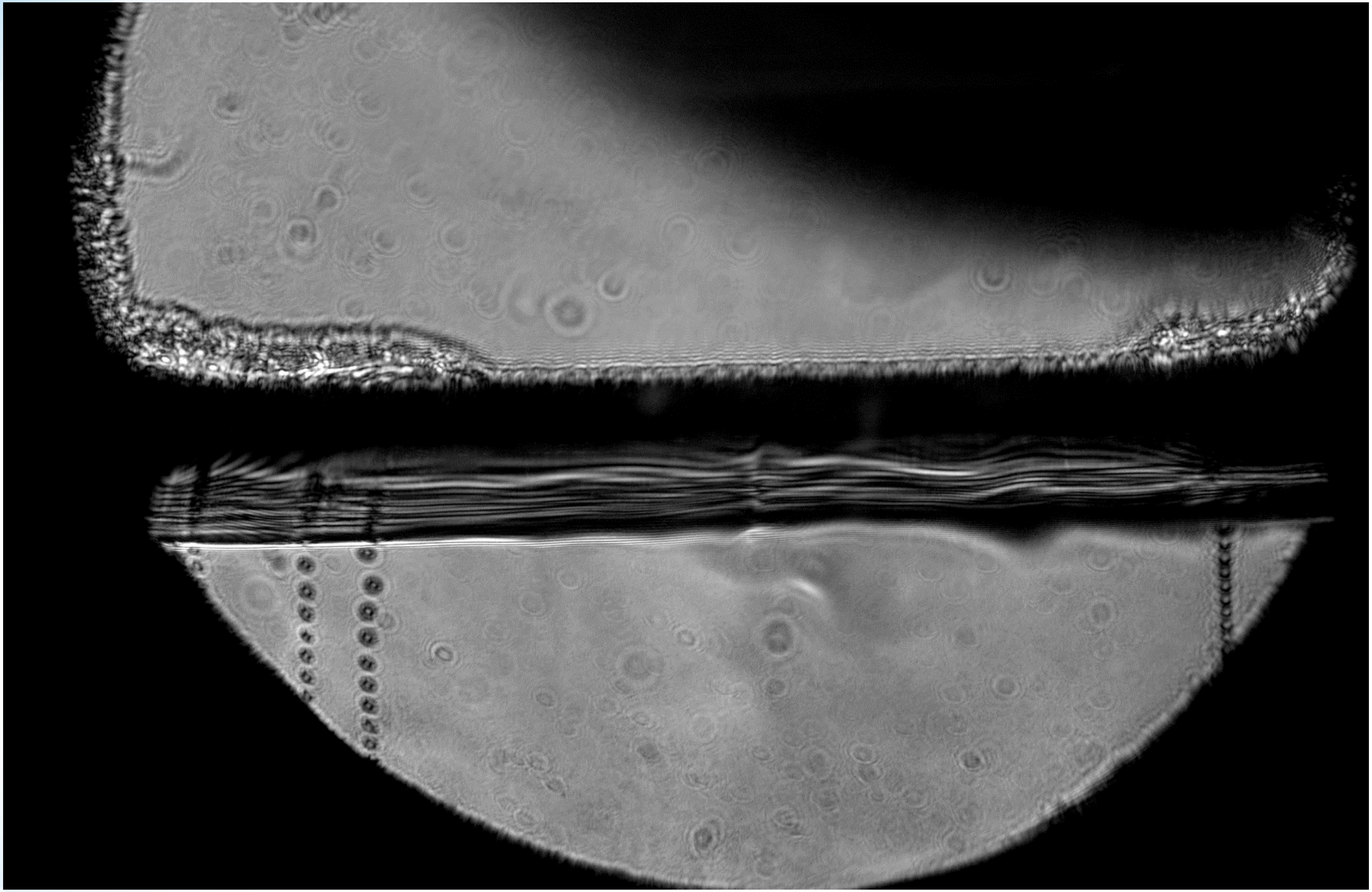
- **Experimental**/numerical **characterization of the phenomenon**
- **Sloshing impact on the phenomenon?**



Network of the Gas/liquid nitrogen transport [1]

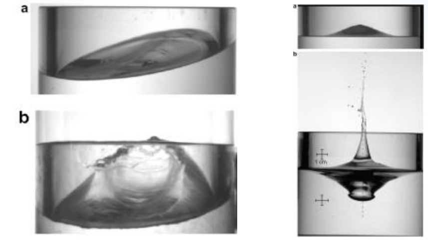
[1] H2020 Project PRESLHY, public deliverable, 2018

WHAT WE ARE AIMING TO CHARACTERIZE…



Transmission visualisation of a N_2 liquid/gas sloshed @6.5Hz (Phantom T4040, 200 Hz-cam, 30fps =speedx0.15) (video)

STATE OF THE ART: BOIL-OFF CHARACTERIZATION



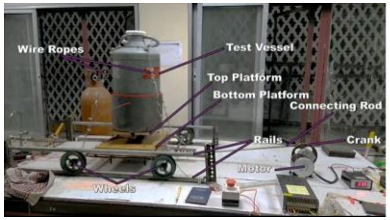
Modes visualization@ Tamb [2]

Limited characterization on cryo-sloshing studies

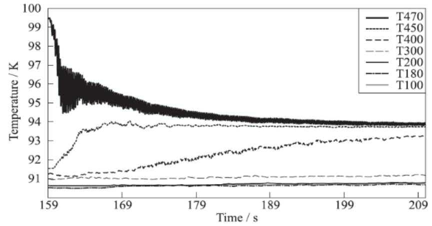
Cryo conds WITHOUT sloshing / At $Tamb$ WITH sloshing
Cryo conds WITH sloshing:

Global meas. (p, Q_v)

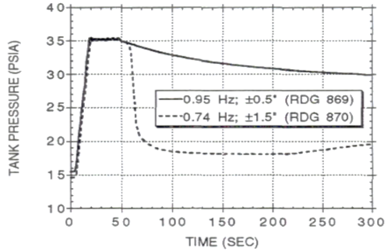
Point meas, T by TCs



Test vessel [3]



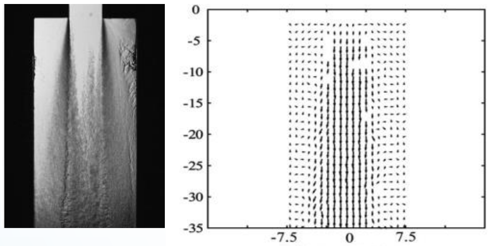
N2 T(t) measurements [4]



N2 P(T) measurements [5]

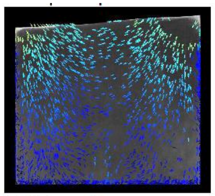
Cryo-flows visualization

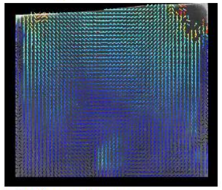
- Most PIV: droplets/bubbles flows


PIV on cavitating He [6]

- The very few studies in the scope…


N2 direct visualization [4]

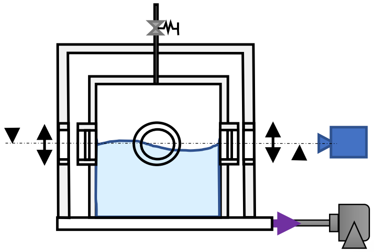

PTV post proc.


PIV post proc.

PIV/PTV in LN2 [7]

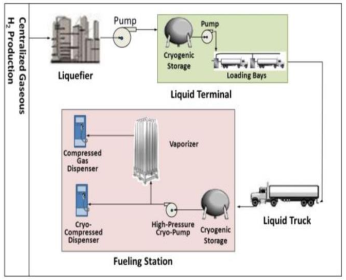
➡ Imaging challenge:

With cryo conds
During sloshing
Fine resolution
Multiple fields



[2] S. P. Das and E. J. Hopfinger, “Mass transfer enhancement by gravity waves at a liquid–vapour interface,” IJMT, 2009
[3] B. Nitin et al., “Experimental evidence of enhanced boil-off in isobaric mobile cryogenic vessels”, IJ Refrigeration, 2023
[4] J. Lacapere et al., “Experimental and numerical results of sloshing with cryogenic fluids”, Progess in propulsion Pys., 2009
(5] M. e. Moran et al., " Experimental results of hydrogen sloshing in a 62 cubic foot (1750 Liter) tank”, AIAA Joint Prop. Conf., 1994
[6] K. Harada et al., “PIV measurements for flow pattern and void fraction in cavitating flows of He II and He I”, Cryogenics, 2006
[7] A. Simonini et al. 2016, “Experimental investigation of Liquid Nitrogen sloshing for space applications”, Space Prop Conf., 2016

OPTICAL INVESTIGATION OF A LIQUID/GAS CRYOGENIC FLOW



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     A. Direct measurements (P, Qv, T)

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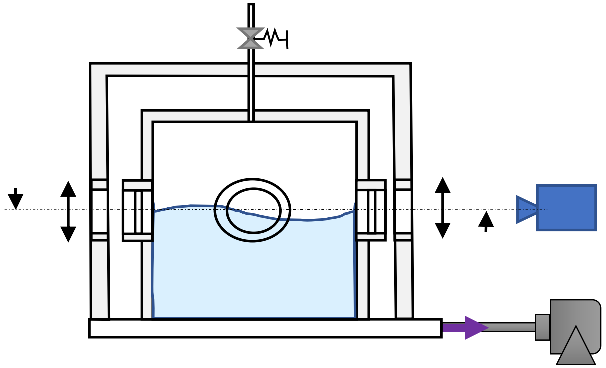

3. Results
   - A - Direct measurements
   - B - Imaging characterization

4. Conclusions & Prospects

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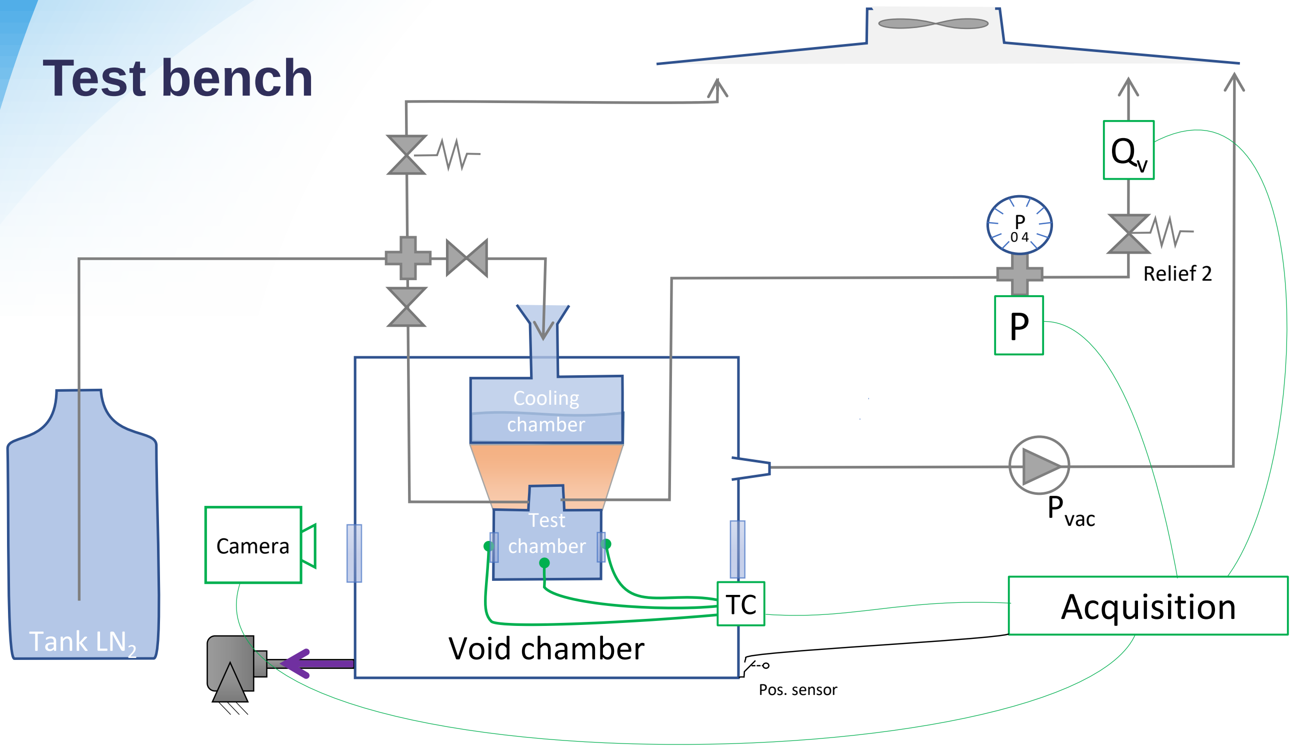
Experimental apparatus

Test bench



Simplified sketch of the test bench

Cryostat

Sloshing parameters:

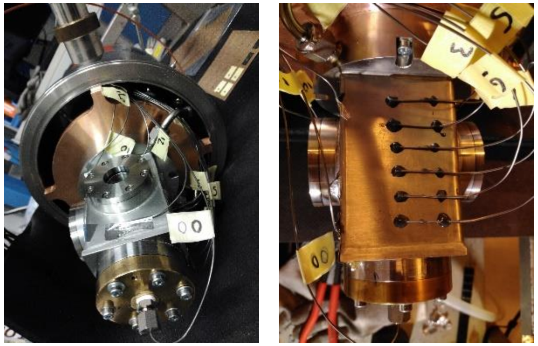
- Frequency ***f***
- (Amplitude ***A***)

We_{liq}	50 - 600
Re	22 000 - 88 000
Bo_A	40 - 680

Characterization system

A. Direct charac: Sensors P, Q_v, T (global)

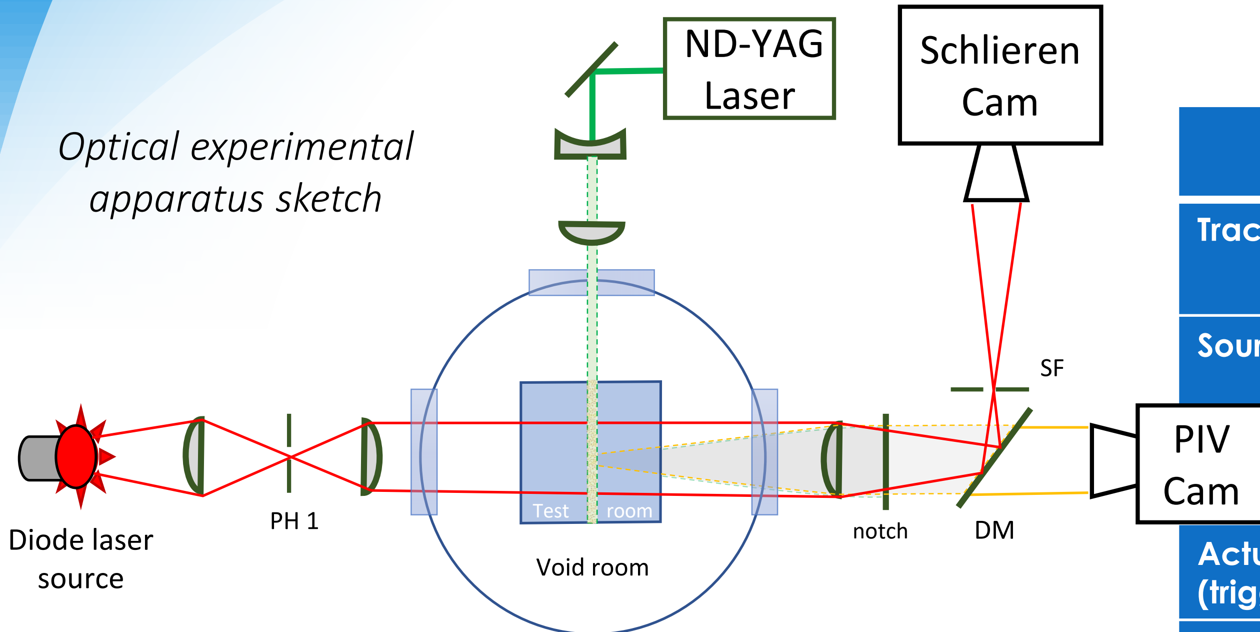
B. Imaging charac Optics (local)



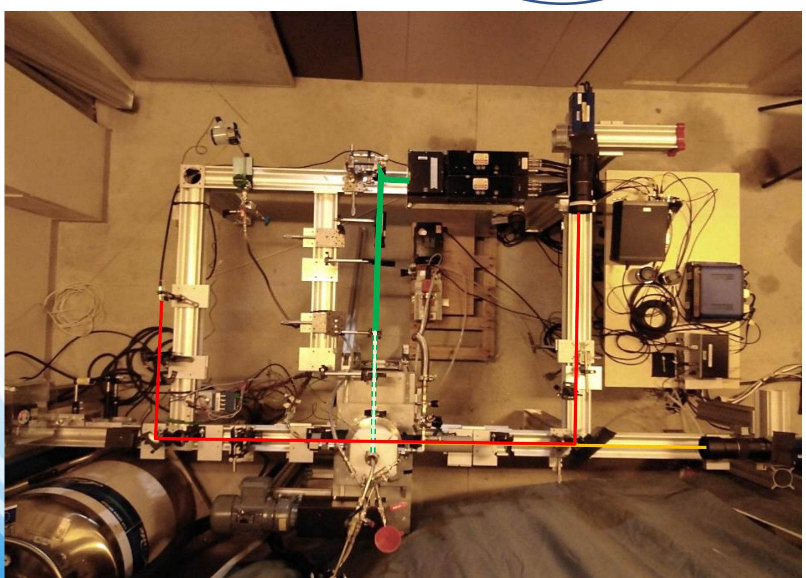
Direct instrumentation

IMAGING SYSTEM: OPTICAL APPARATUS

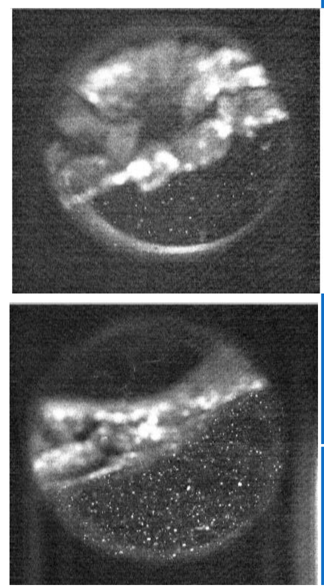
Optical experimental apparatus sketch



	PIV	Schlieren
Tracking	Liquid	Liquid (+gas) Interface
Source	ND-YAG Quantel® 70mJ @ 10Hz/532nm Reduced intensity (QS-delay, Spot expansion)	low-coherence Cavilux® beam @ 500 Hz /640 nm
Actual *f* (trigger)	1.3 – 6.5 Hz	1.3 – 6.5 Hz
Δt double-pulse	2 ms	1 ms (if activated)
Other elements	Particles : Rhodamine Vestosint 2154 $d_{50} = 21$ µm Fluorescent @570nm $\rho_p \sim 1\,020 \frac{kg}{m^3}$; $\rho_{LN_2} \sim 800 \frac{kg}{m^3}$ ⇒ Premixing + dilution at inlet 128x128p², 75-87,5%ov	Spatial filter: Cutter blade ($\overrightarrow{grad}\,n$ sensibility+) variable aperture iris (sensibility-)
Imaging system	Imager Pro X 4M, Nikkor 300 mm FoV ~30x30mm, ~70 pix/mm	Imager Pro X 4M, Nikkor 300 mm FoV ~30x30mm, ~70 pix/mm

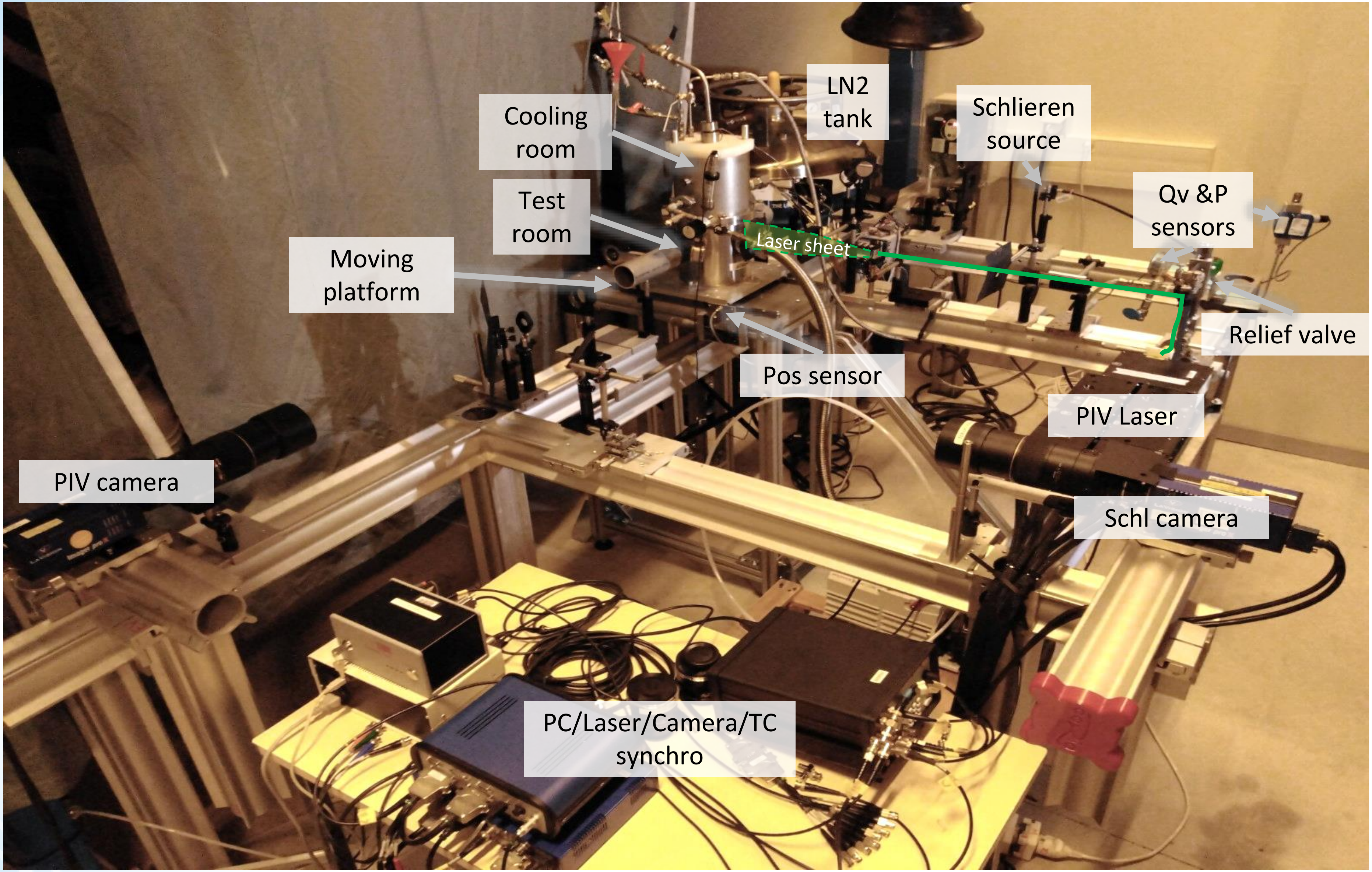


Top view of the actual test bench



Raw PIV images

ACTUAL TEST BENCH



General view of the test bench

OPTICAL INVESTIGATION OF A LIQUID/GAS CRYOGENIC FLOW

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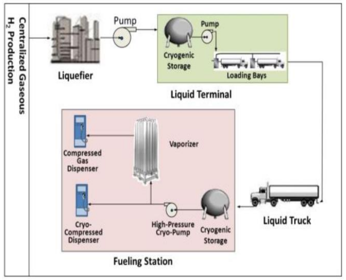

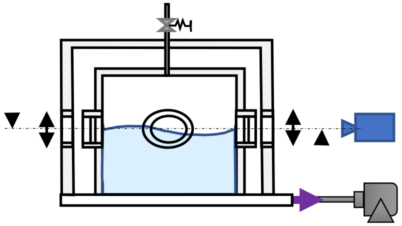

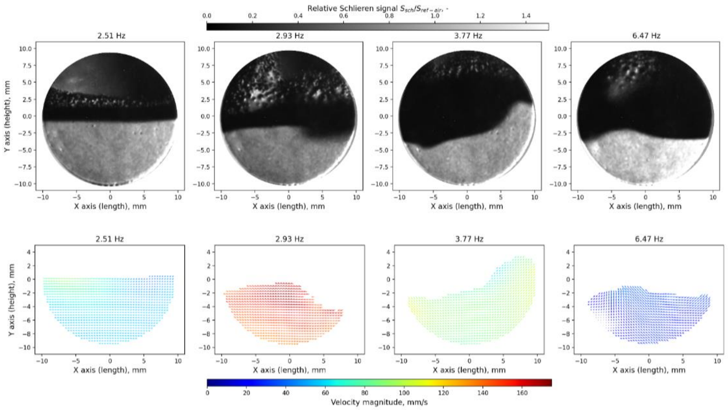

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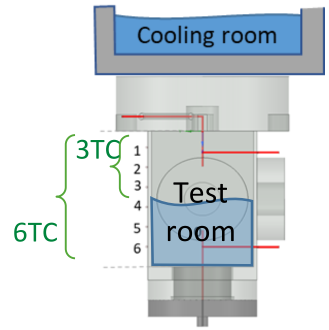
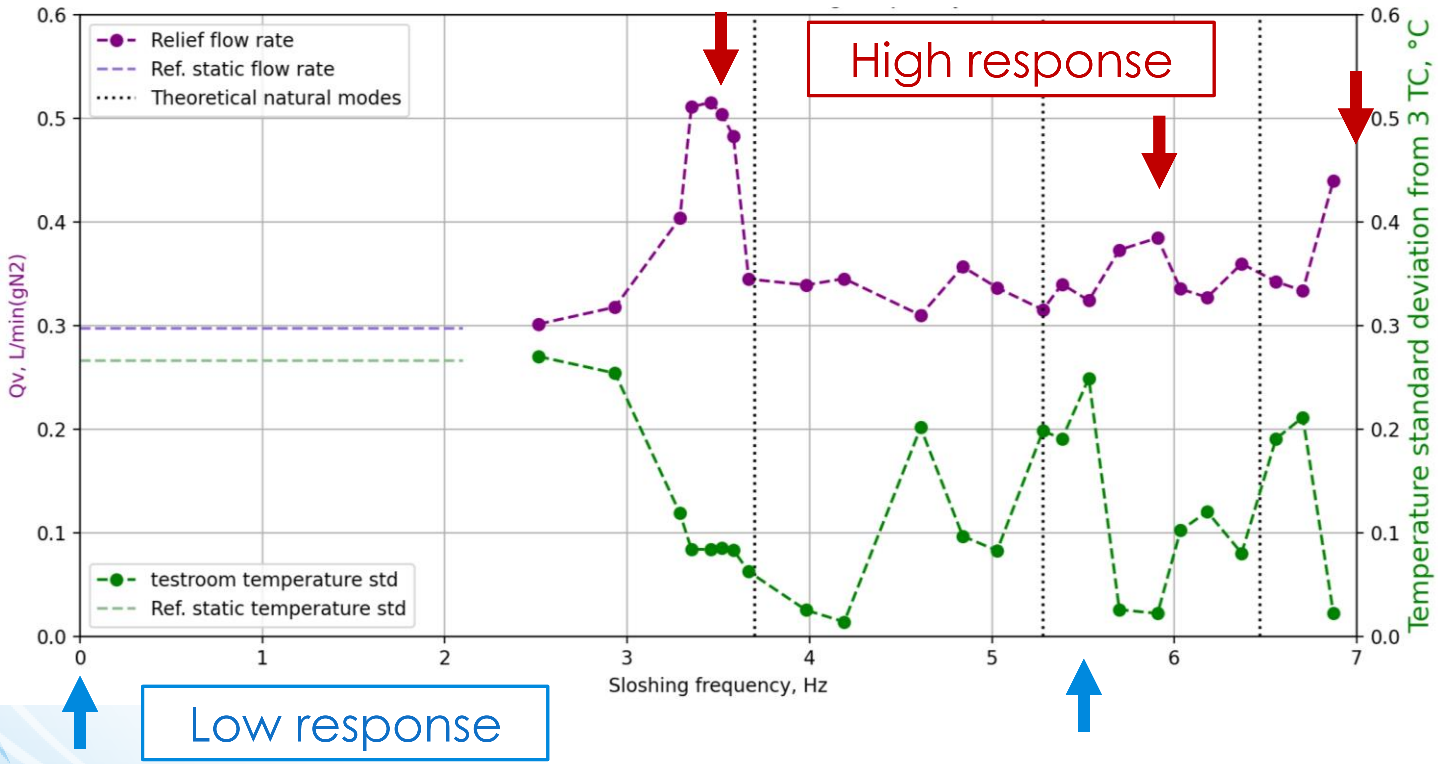
A. Direct characterization: sloshing modes

Frequency modes highlighted by:

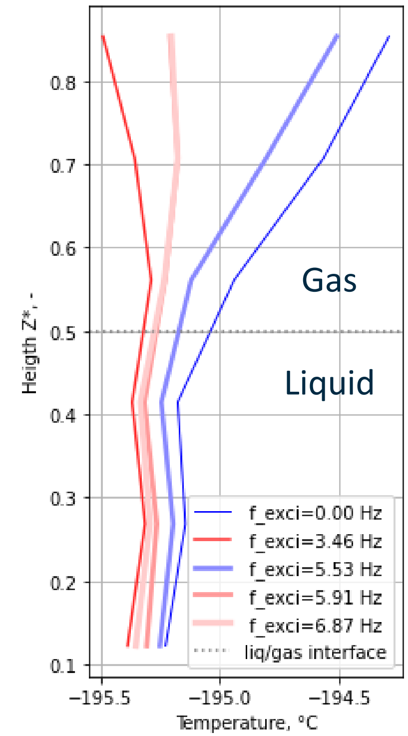
- **Relief flow rate**
- **Testroom temperature distribution**



Gas stratification
Vs. Mixing

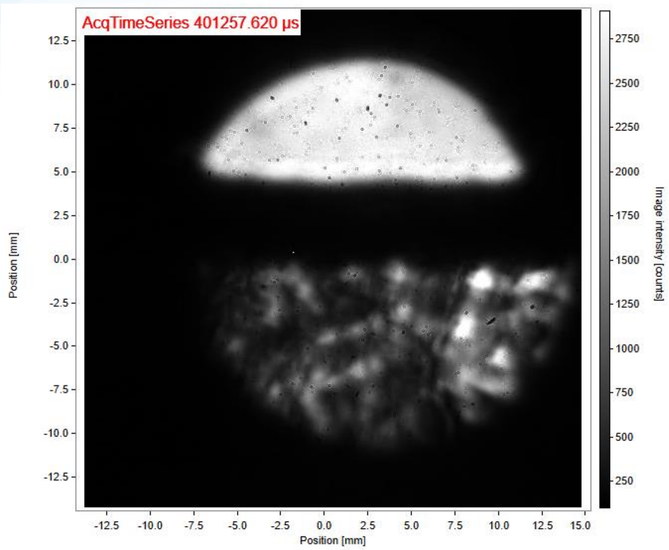


Excitation response of the relief flow rate and the gas testroom temperature distribution @ 1.02 bar

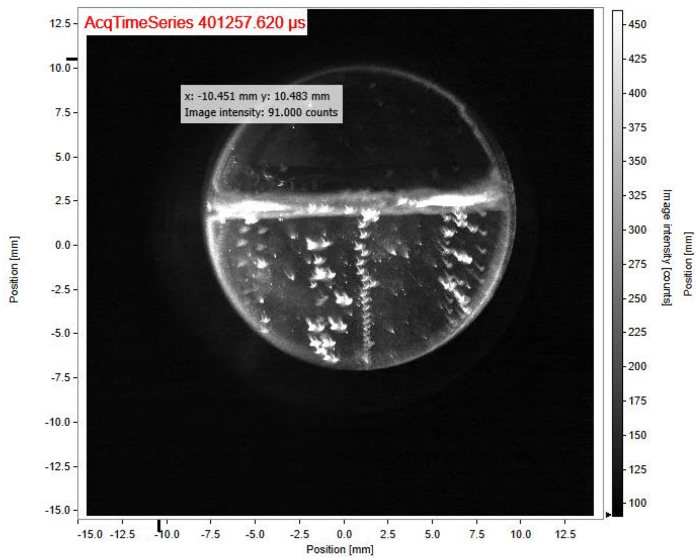


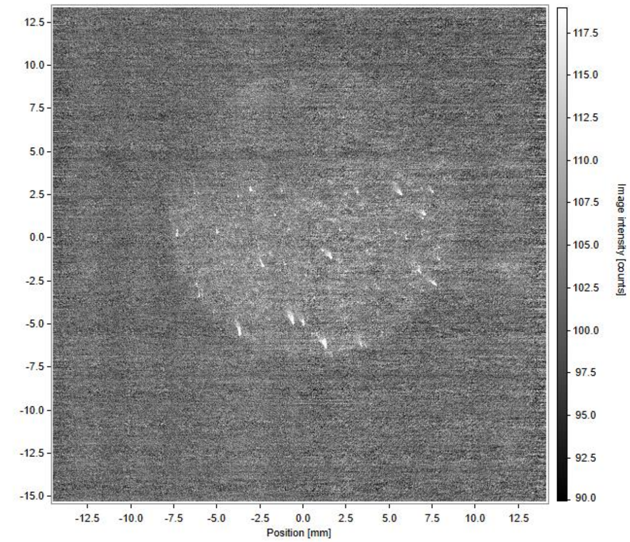
Vertical temperature profiles from 6TCs

B-IMAGING: AN OVERVIEW OF THE RAW DATA (SCHLIEREN & PIV)



Raw Schlieren imaging



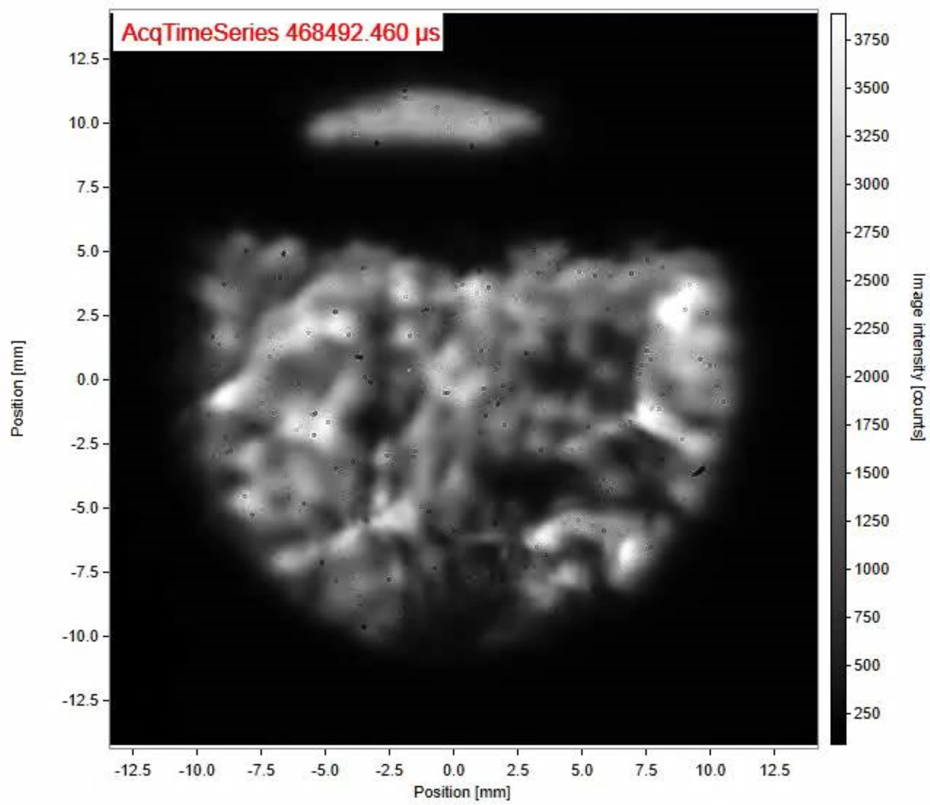


Raw PIV imaging (rhodamine) :
WITH and WITHOUT 532nm filter

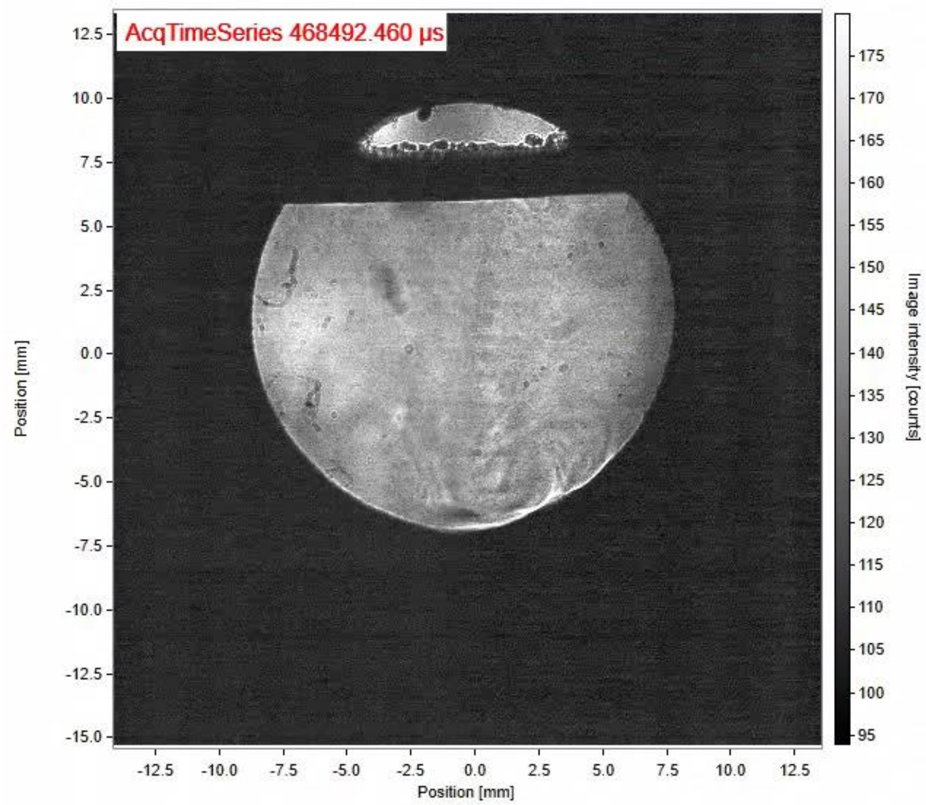
Simultaneous sequences during a slightly bubbling regime

B-IMAGING: SCHLIEREN SENSIBILITY TO SHARPNESS (STATIC)

Time capture of Schlieren during pressurization, simultaneous Schlieren visualizations (t_{real} x100)



Reduced spatial filter (small iris aperture) (video)

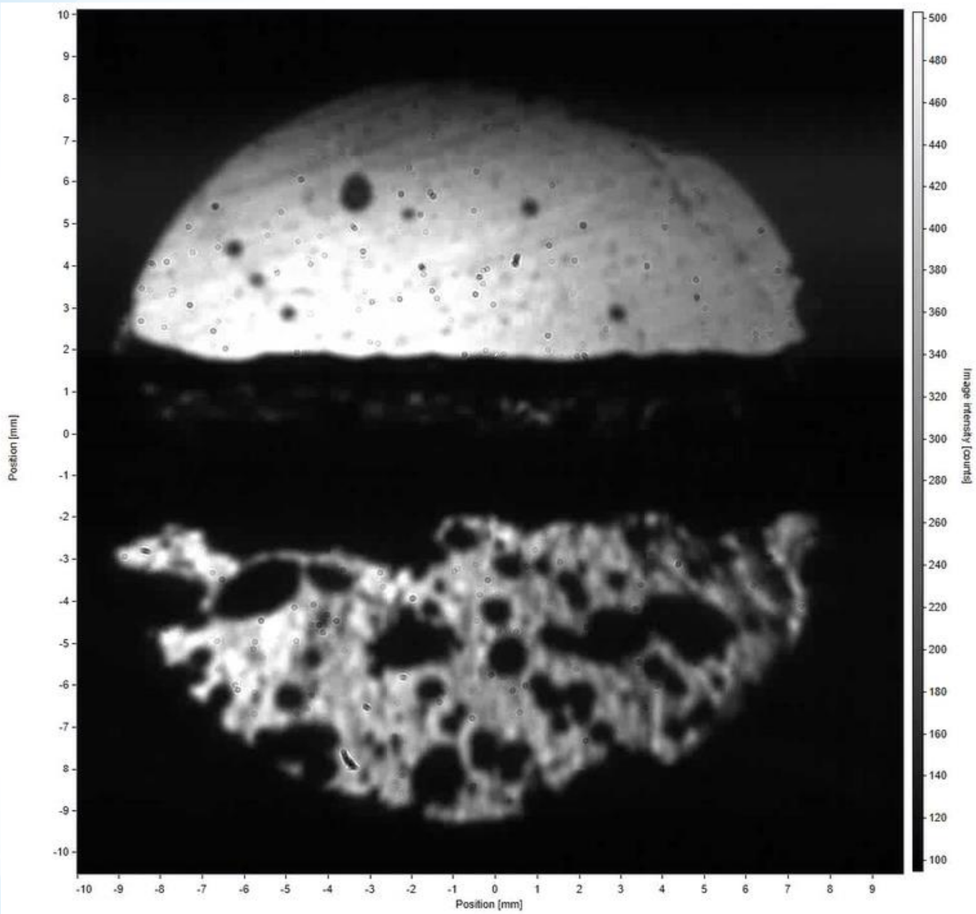


Open Schlieren (no iris nor blade) (video)

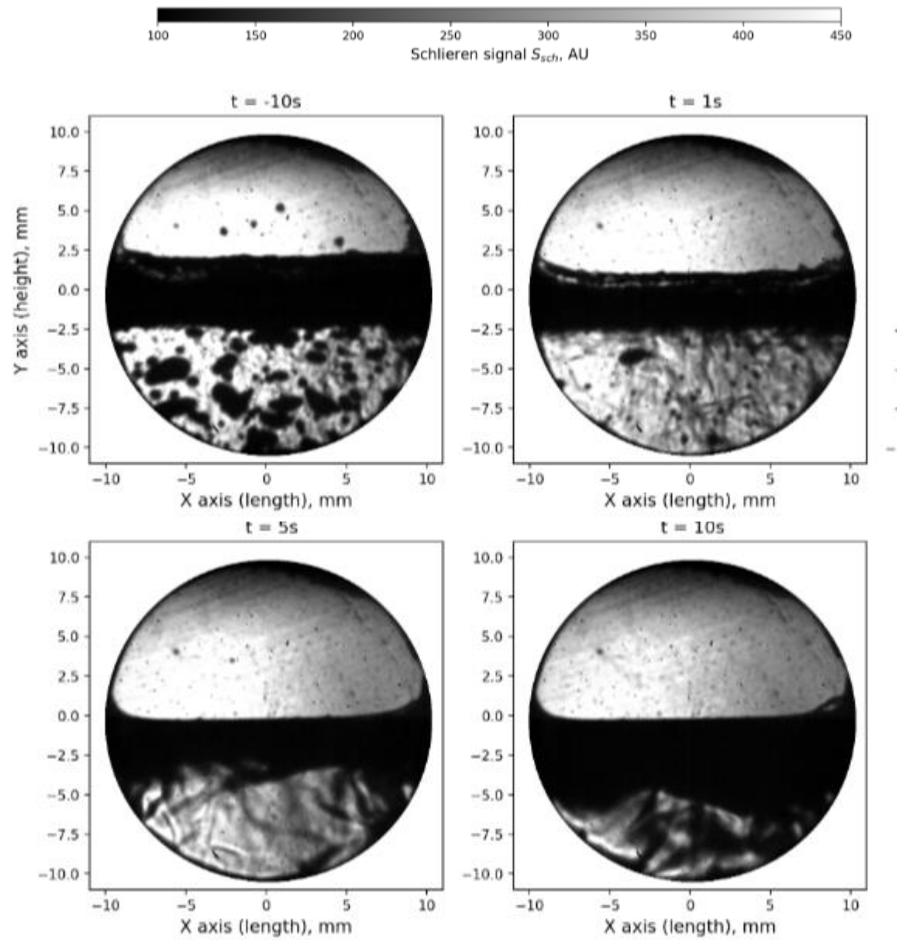
High sensibility for static

Low sensibility for sloshing

B-Imaging: Flow transient state in static conditions (high Schlieren sensibility)

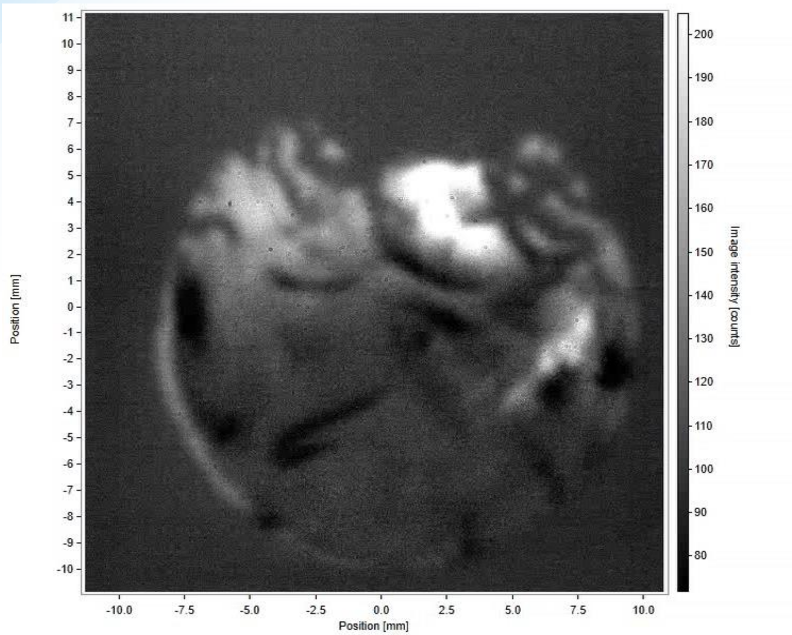


High sensibility Schlieren (cutter blade): Schlieren during pressurization (t ~ 0) (video)

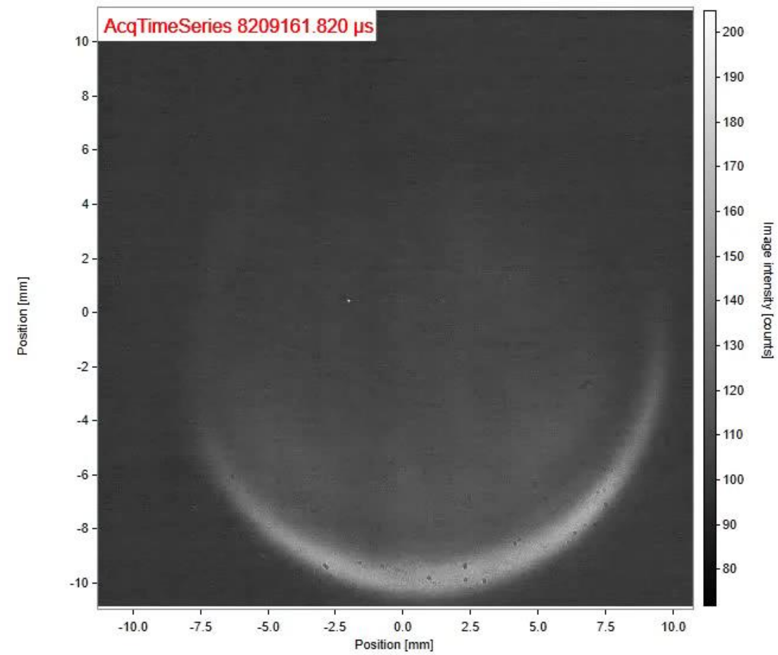


Schlieren images time evolution

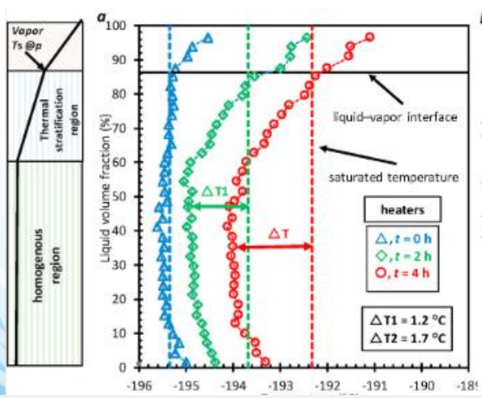
B-IMAGING: FLOW TRANSIENT STATES IN STATIC CONDITIONS



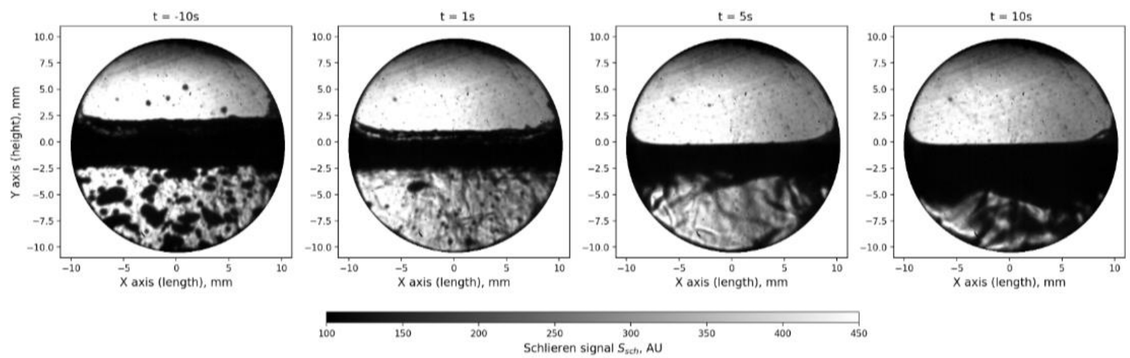
Presurrization, in liquid (video)



Depressurization, in liquid (video)



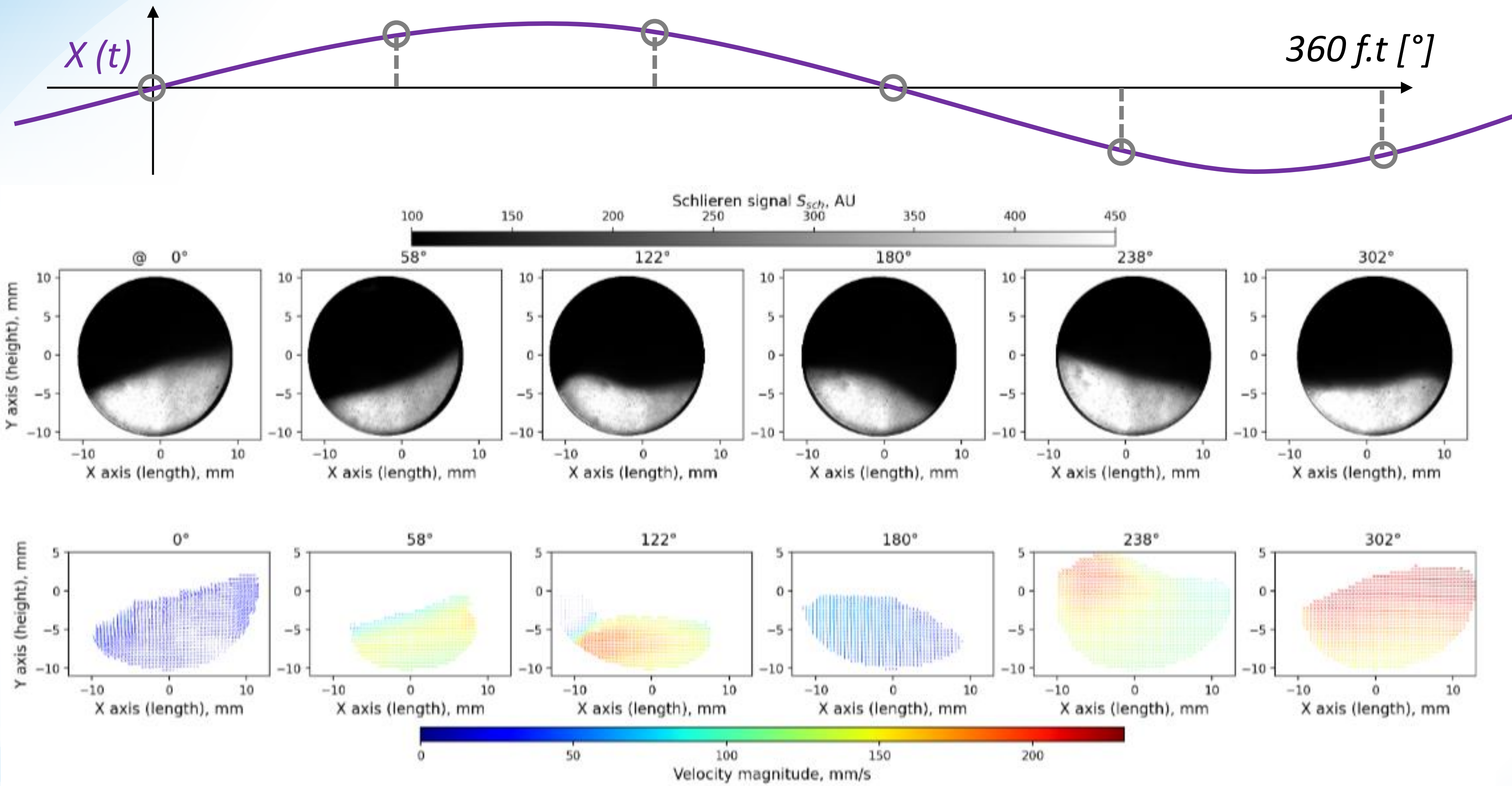
Thermal stratification at surface [8]



Schlieren images time evolution (gas/liq)

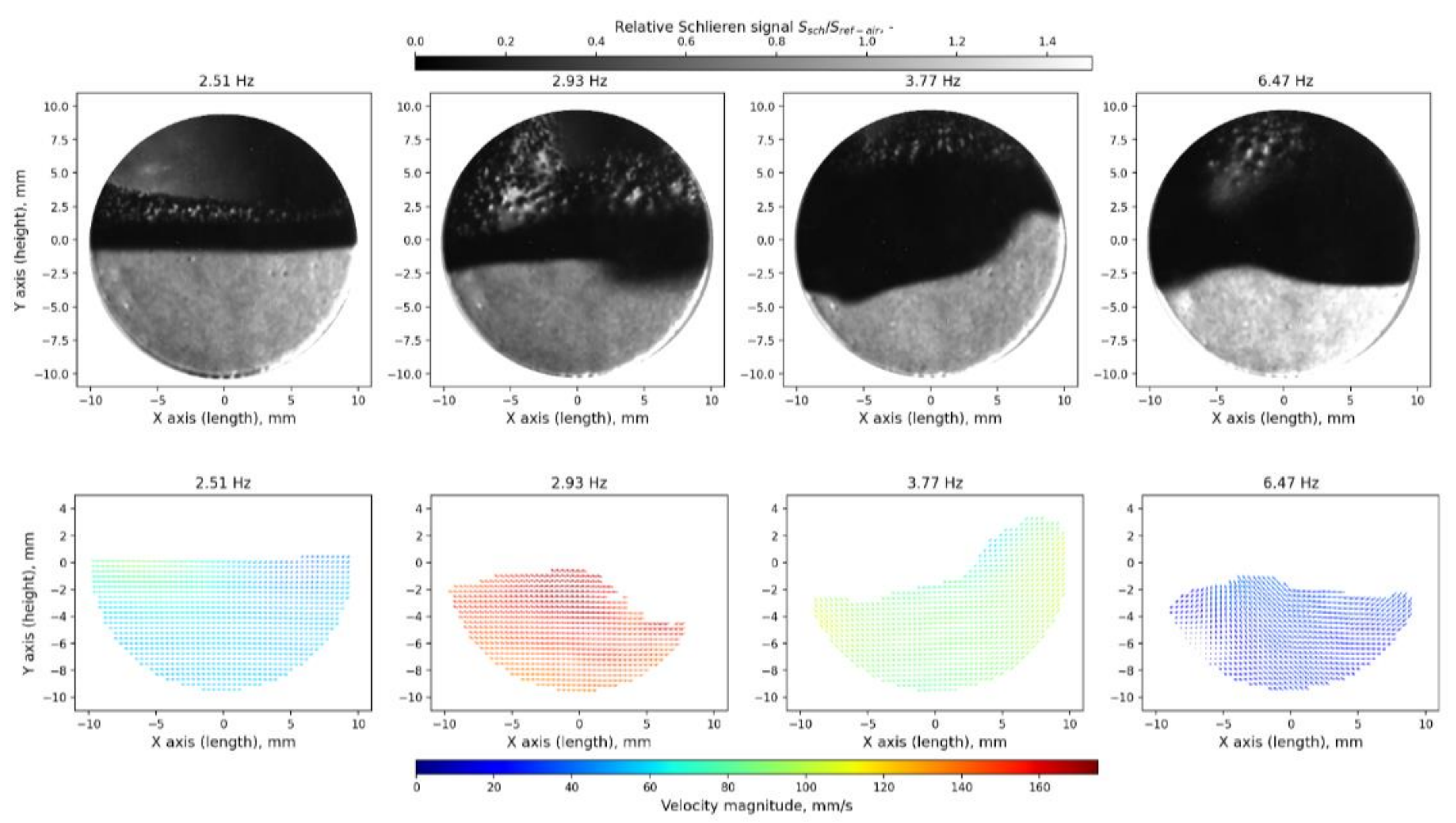
[9] F. Perez et al., Measurements of boil-off gas and stratification in cryogenic liquid nitrogen with implications for the storage and transport of liquefied natural gas,Energy, 2021

B-IMAGING: PHASED MEASUREMENTS ON SINUSOIDAL EXCITATION



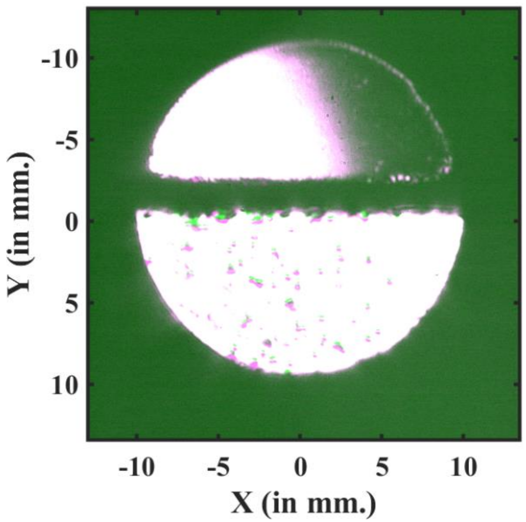
Simultaneous Schlieren (low sensibility) and PIV, t-averaged: 6 positions evenly distributed over the period, fexci = 3.53 Hz, P = 1.8 bar

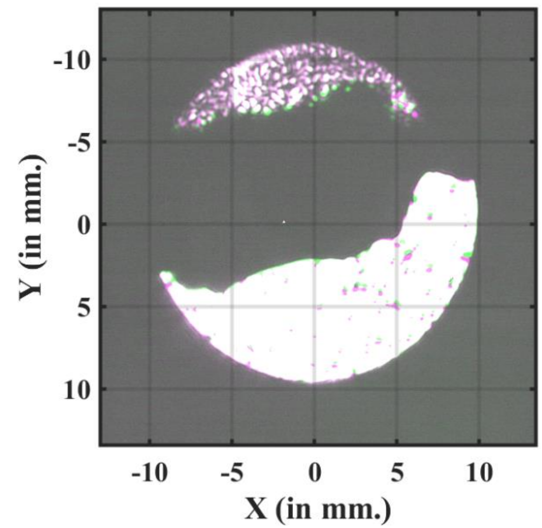
B-IMAGING: PHASED MEASUREMENTS, INFLUENCE OF THE FREQUENCY



Simultaneous Schlieren (low sensibility) and PIV, t-averaged (100 images): influence of the excitation frequency, 0°-phased, P = 1.8 bar

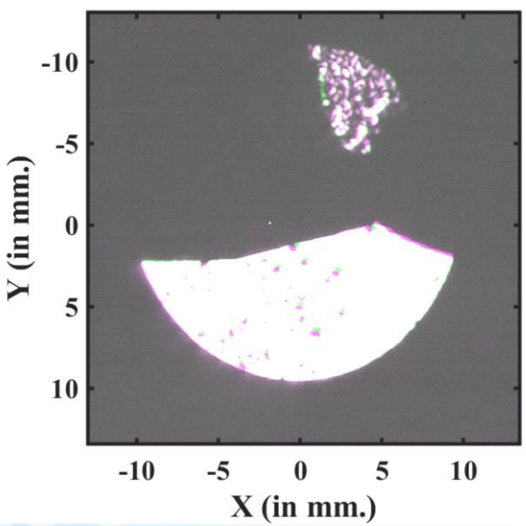
Characteristic images for interface detection: Schlieren low sensibility

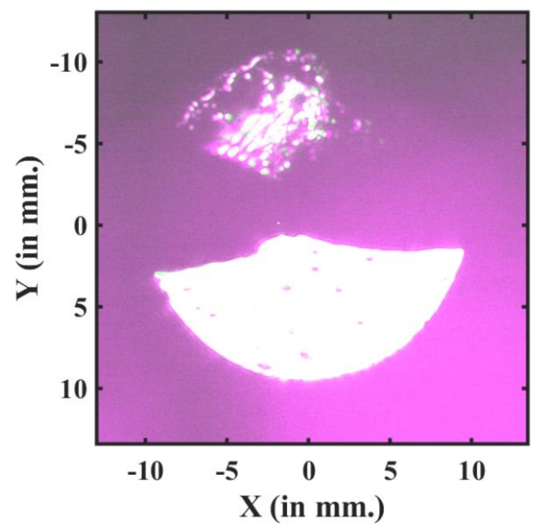




Raw image pairs (fake color)

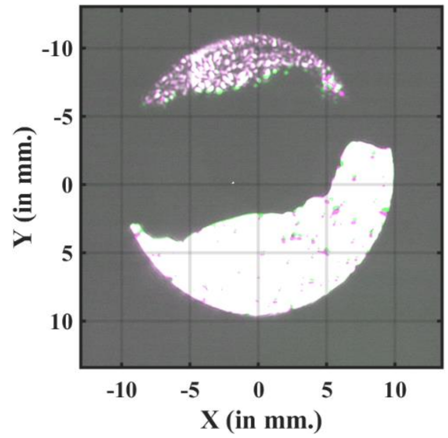
2-pulsed laser beam
Δt=1ms
Duration 0,5 μs

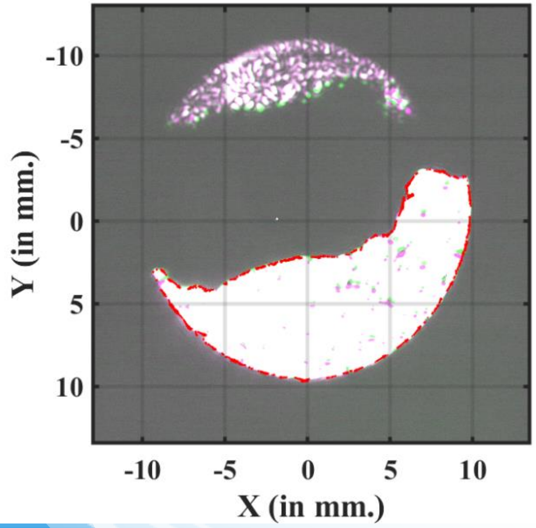


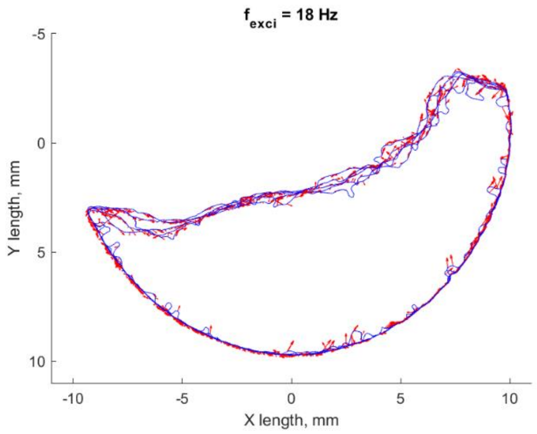


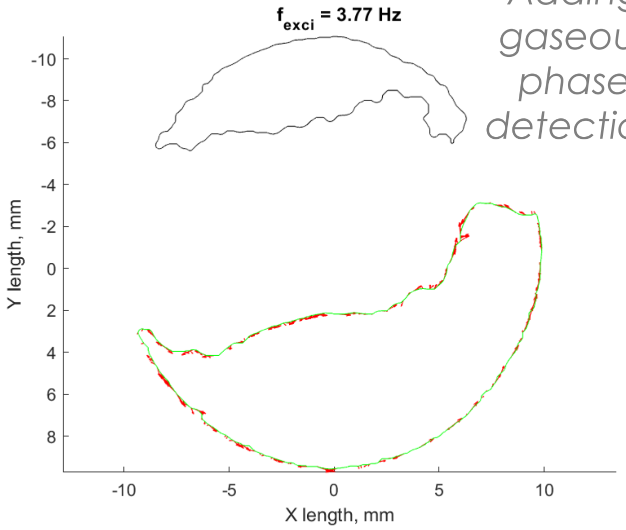
INTERFACE DETECTION AND VELOCITY PROCEDURE

- **Matlab « ultrafast Vmap code »**
  - **Closed contour detection (1or 2 contours)**
  - **Windows correlation @ interface**
    - **32x32pix² (0,5mm)**
    - **Interface speed (2pulses, Δt=1ms)**







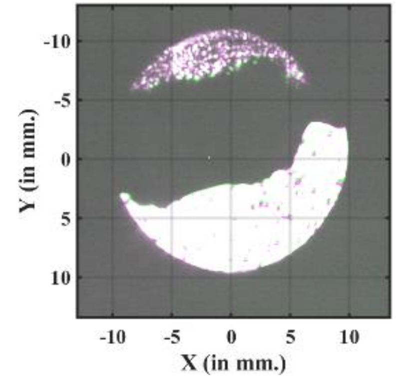


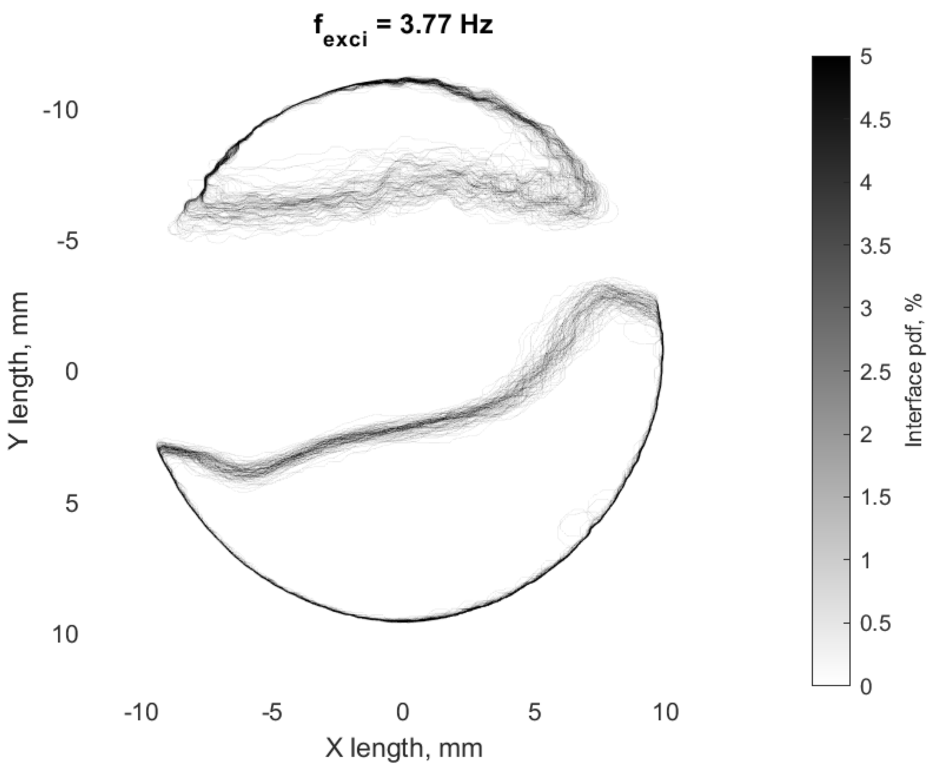
Adding gaseous phase detection

B-IMAGING, INTERFACE PDF

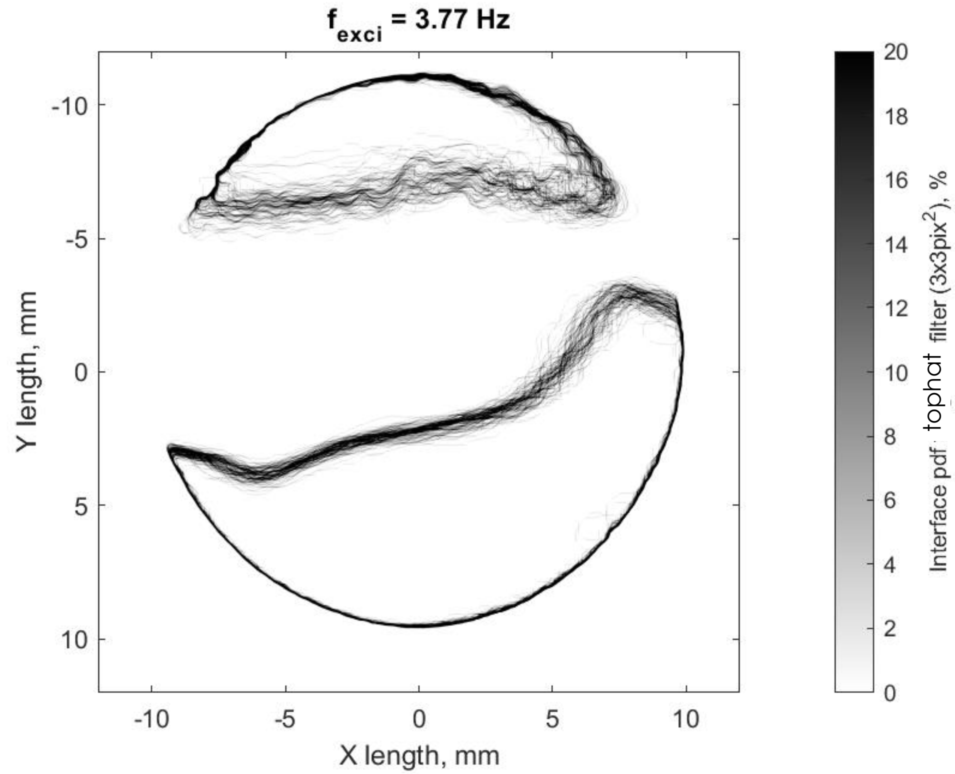
► **Statistics on 100 images**

1 raw image pair (double false color)



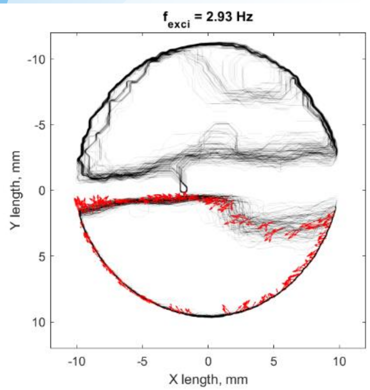


Interface pdf

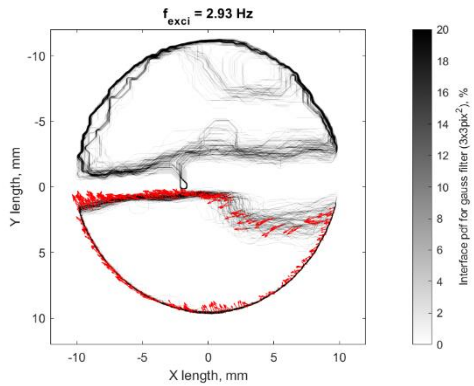


Interface pdf considering a 3x3pix² tolerance (top hat filter)

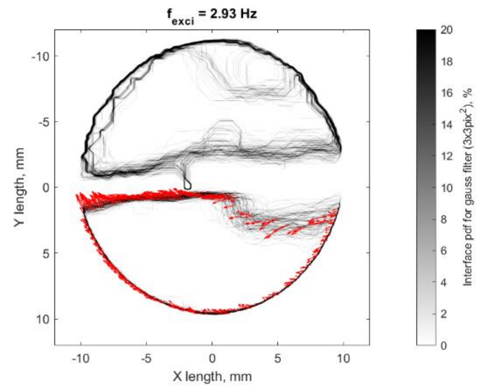
INFLUENCE OF THE INTERROGATION WINDOW FOR CORRELATION



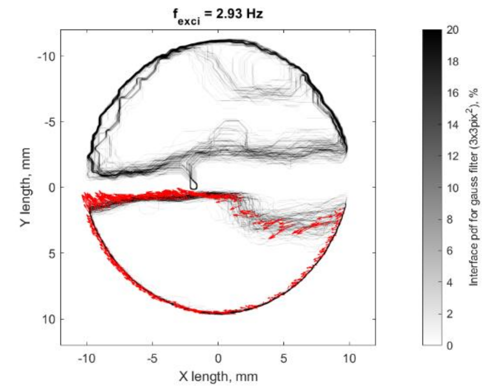
8x8 pix²



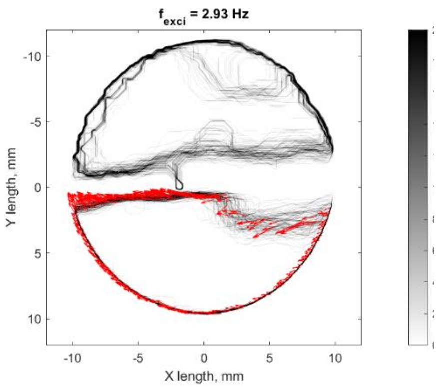
16x16 pix²



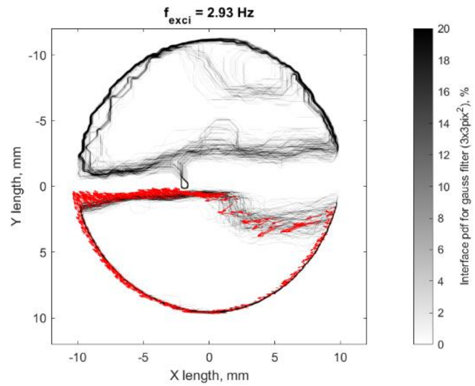
24x24 pix²



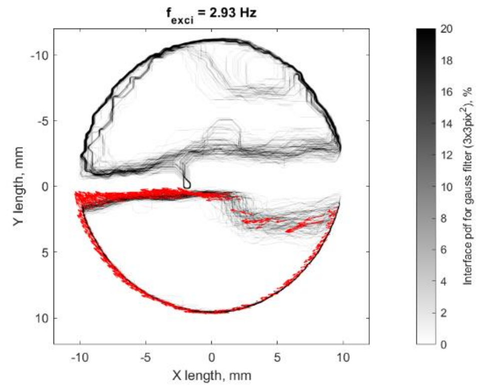
30x30 pix²



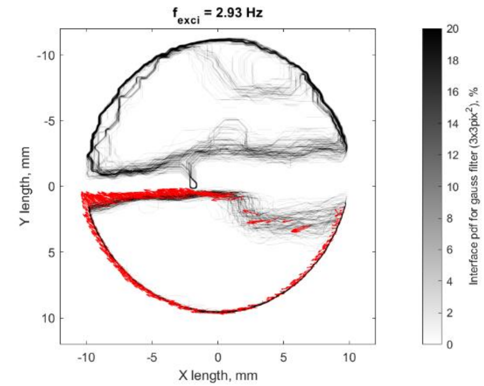
38x38 pix²



46x46 pix²



54x54 pix²



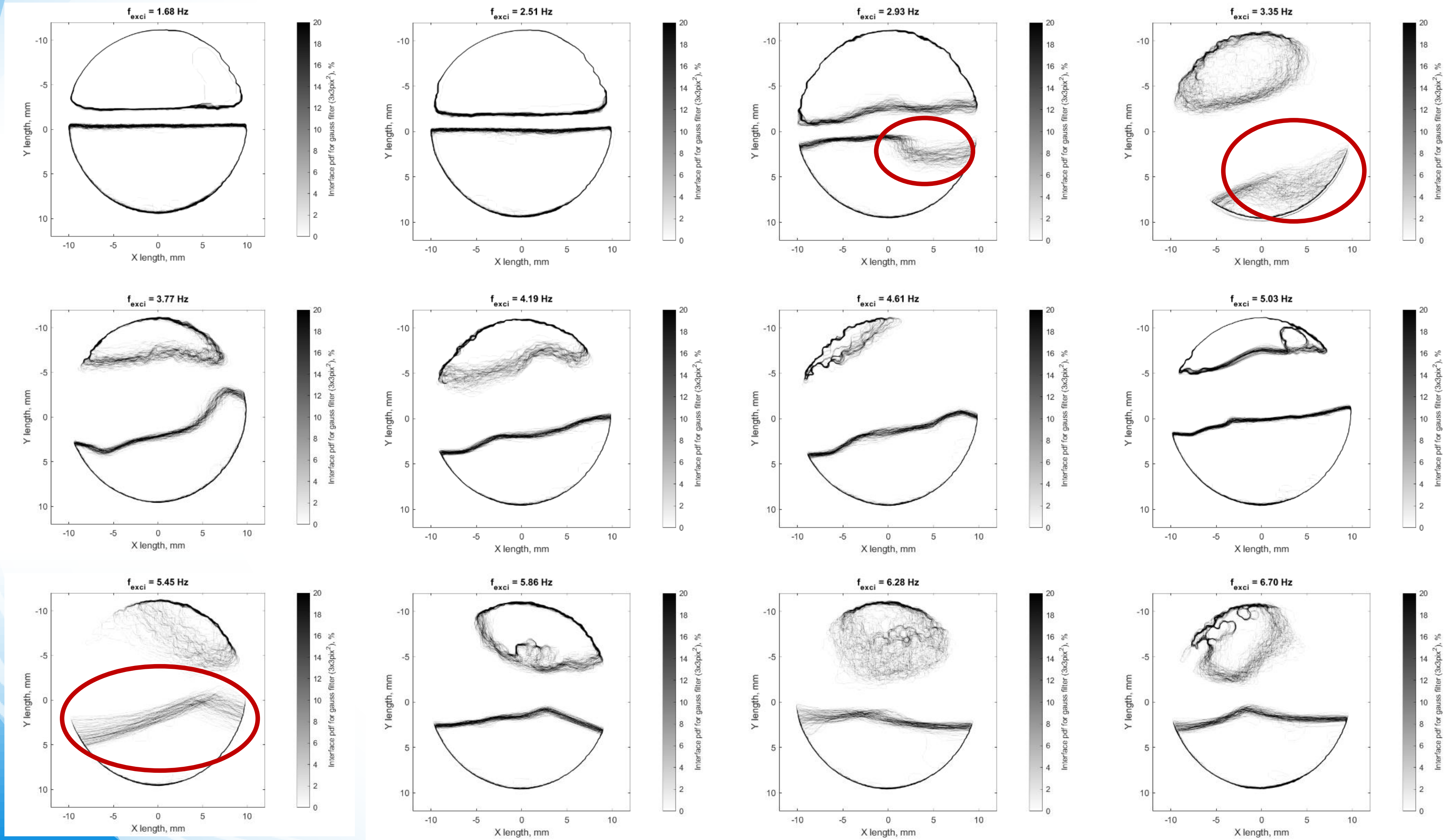
62x62 pix²

Superimposed interface and its velocity for different IW (from 8x8 to 62x62pix²)

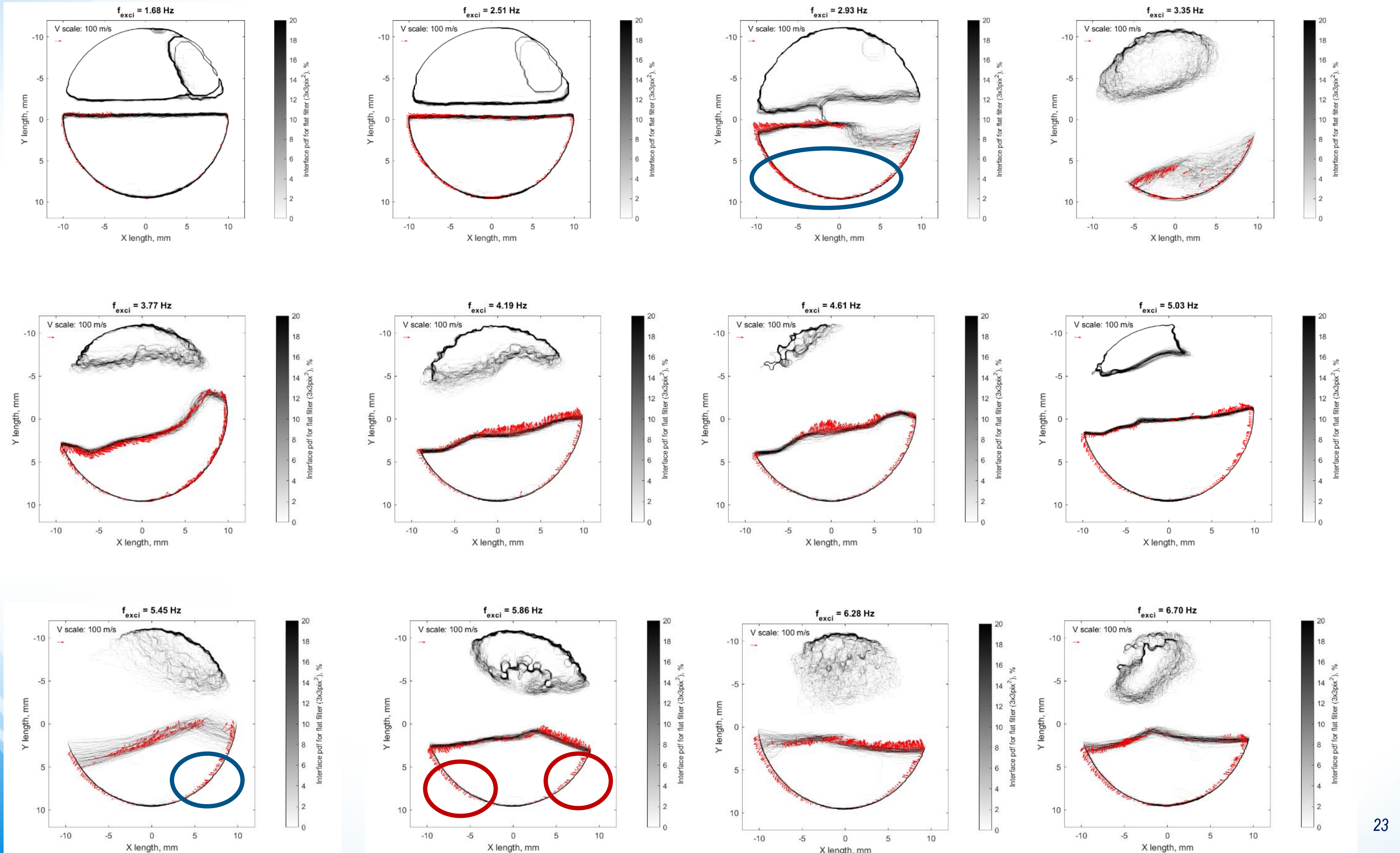
IW 32x32 pix²

STATISTICS RESULTS : INTERFACE PDF

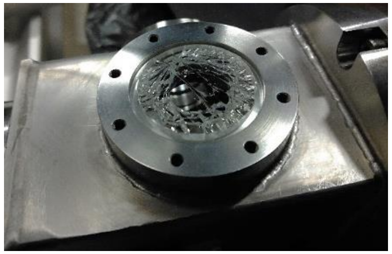
Chaotic interface



STATISTICS RESULTS : INTERFACE PDF AND MEAN VELOCITY

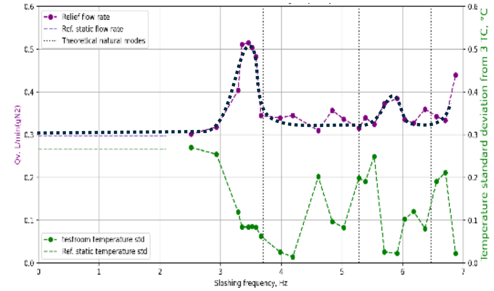


CONCLUSIONS



MEASUREMENTS IN CRYOGENICS CONDITIONS

- **Security, overpressure/void, sealing (breaking portholes), probe sticking, condensation…**

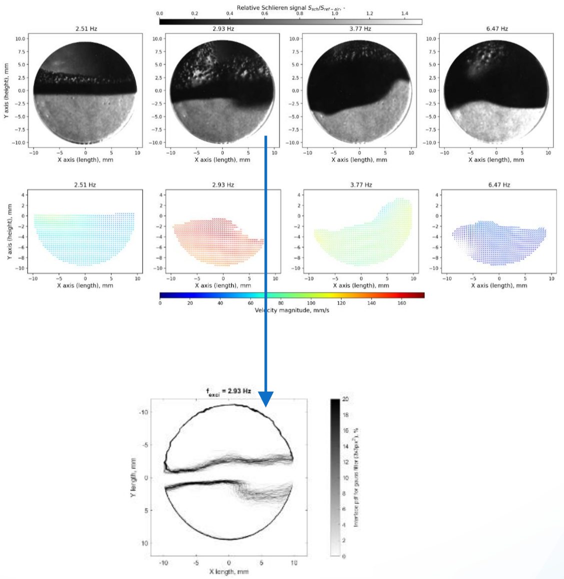


RESPONSE TO THE EXCITATION, IN PARTICULAR MODE #1

FLOW CHARACTERIZATION

Good repeatability .
Chaotic modes

- **PIV for liquid**
  - **Sedimentation/seeding issues (OK for sloshing)**
  - **Interface disrupting laser sheet**
- **Schlieren (various sensibility):**
  - ***n* gradients for stratified/transient flows**
    - **→ sensitive even for ~1K range**
  - **Interface for sloshed flows with issues:**
    - **Optical disturbances (meniscus, in-depth integral)**
    - **Lack of tortuosity for good correlation**

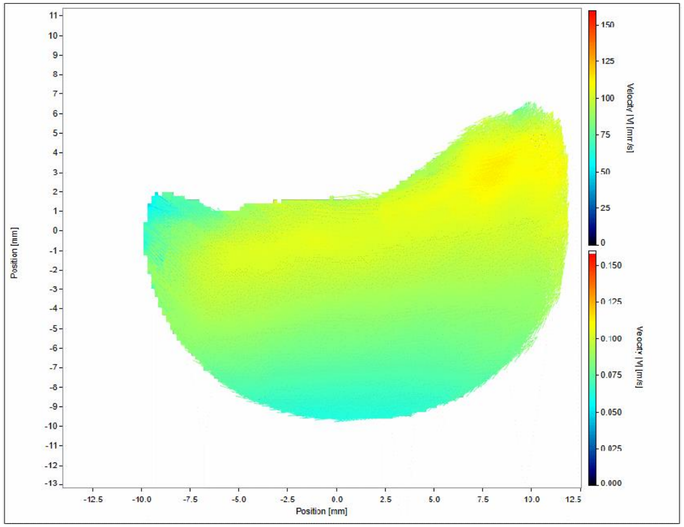


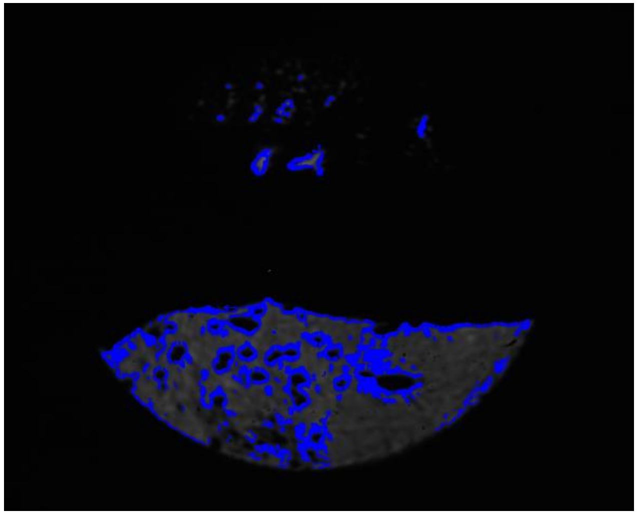
Prospects

Work in progress…

- **Producing more PIV/Schlieren data:**
  - Various <u>amplitude</u>/frequency/positions conditions
  - More images per sequence
- **Getting more from imaging data:**
  - Interfacial density
  - Integration of Schlieren images (static) → temperature
    - Interface @ T_{sat} (P_{sat})
- **Interface: comparison with another algorithm**
  - Interface detection
  - Bubbles/droplet/convective structures detection?

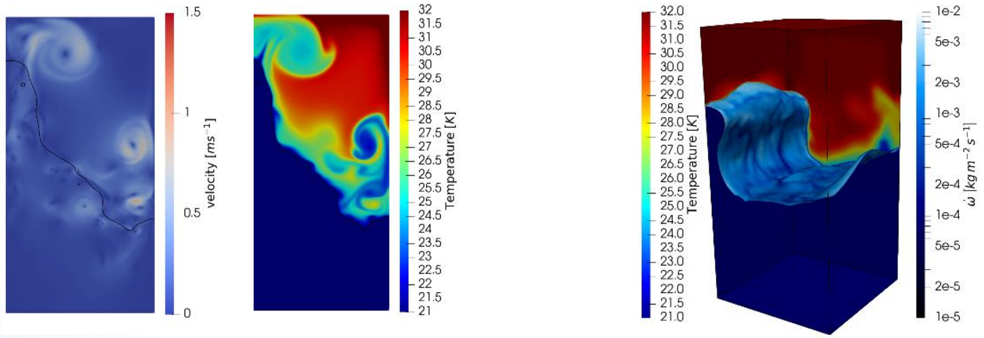
Phased PIV, mode #1 (3.55 Hz), 400 images (video)





FluidCV *[D. Sedarsky/JB. Blaisot/T. Chazelle (+ R. Herrera)*

- **Comparison with model (B. Duret, L. Germes)**

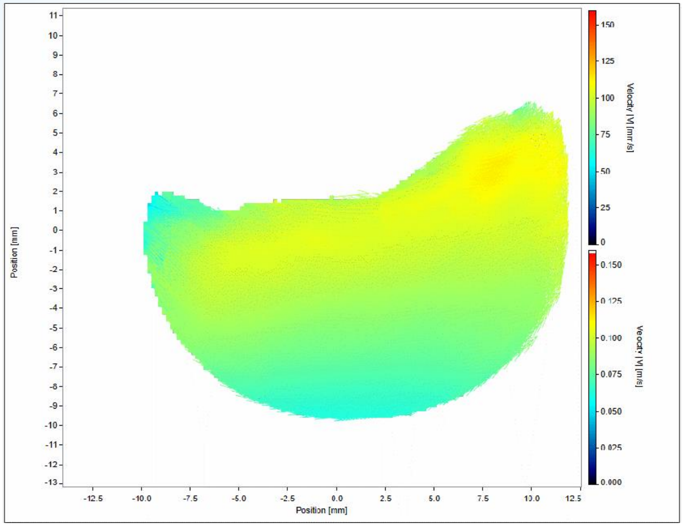


DNS Velocity and temperature fields of sloshed liq/gas hydrogen [9]

Wednesday 10am !

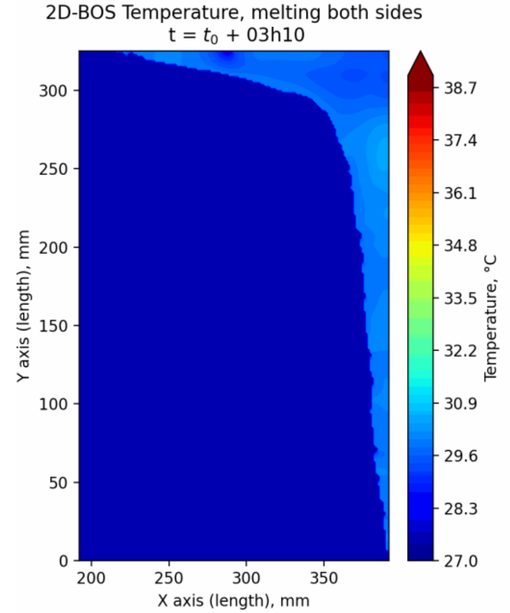
[9] L. Germes M, B. Duret, J. Réveillon, F-X Demoulin and A. Jarry, Direct numerical simulation of sloshing and phase change in LH2 tanks,10th EUCASS 2023, Lausanne, Switzerland

THANKS FOR YOUR ATTENTION



Phased PIV, mode #1 (3.55 Hz), 400 images (video)

? Questions



Another interface study: Unsteady melting test (video)
[COCHERMAT Carnot Project, T. Davin, L. Danaila, E. Varea]

<u>CRYOBALL Carnot project</u>

Num. : Benjamin Duret (project leader), Leandro Germes M.
Exp. : Emilien Varea, Tanguy Davin

<u>Other aknowledgements:</u>

Amauric Jarry (CNES), Davide Duri (CEA-DSBT) for discussions
Workshop (Benjamin Quevreux) for the test bench upgrade
Saïd Idlahcen, Gilles Godard for optics diagnostics…

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