High-speed visualization and X-ray densitometry of cavitation dynamics in a venturi

Saad Jahangir, Willian Hogendoorn, Christian Poelma
PhD Candidate, S.Jahangir@tudelft.nl,
Multiphase Systems (P&E,3mE), TU Delft

Wednesday, 18 Oct 2017

TU Delft

CaFE
Innovative Training Networks

HORIZON2020
Marie Skłodowska-Curie actions

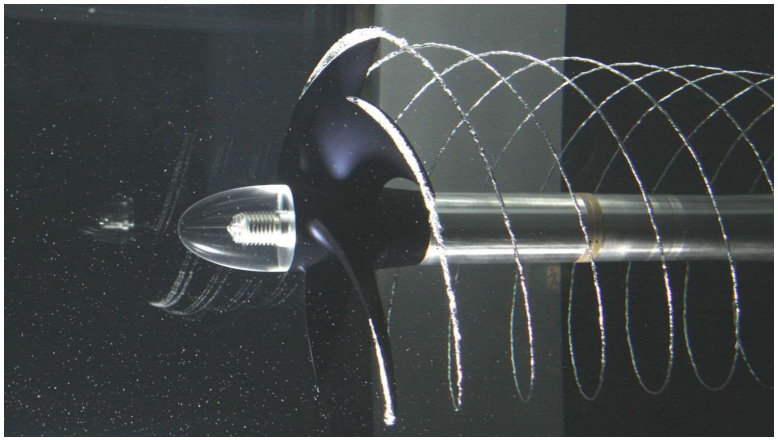
MARIE CURIE ACTIONS

Outline of the presentation

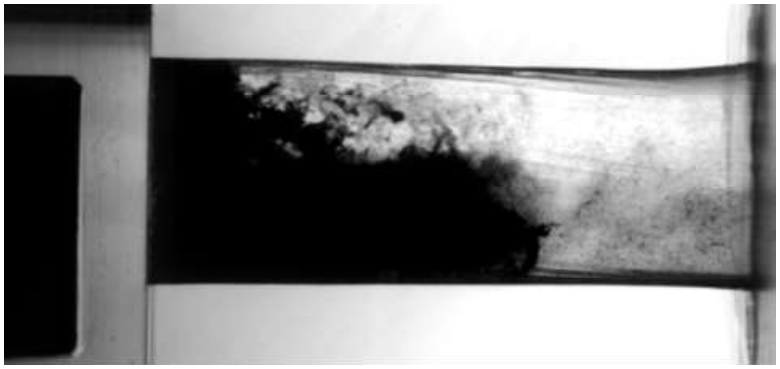
- **Introduction**
- **Shadowgraphy**
- **X-ray densitometry**
- **Conclusions**

Introduction to cavitation

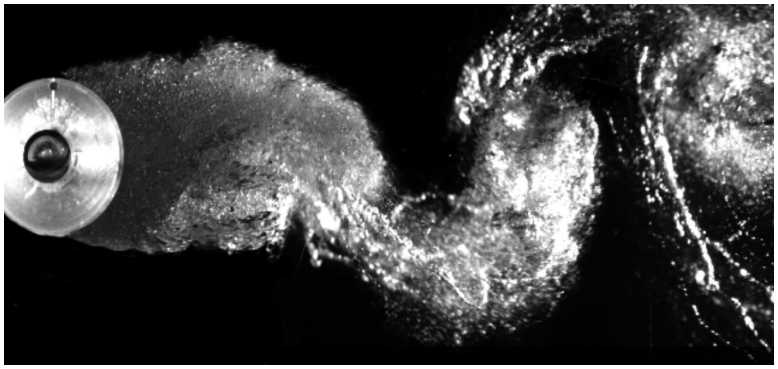
Source: EPFL



Source: Cavitation Research Laboratory/AMC



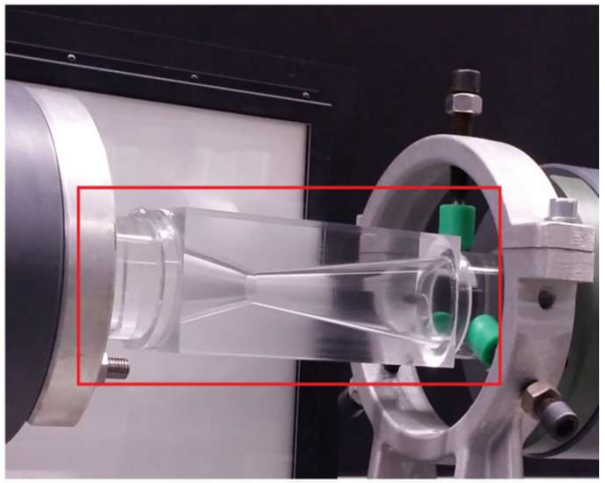
Source: City Uni & Delphi Diesel Systems



Source: Steven Ceccio (University of Michigan)

Cavitation test geometries:

- **Hydrofoil**
- **2D Wedge**
- **3D Axisymmetric venturi**

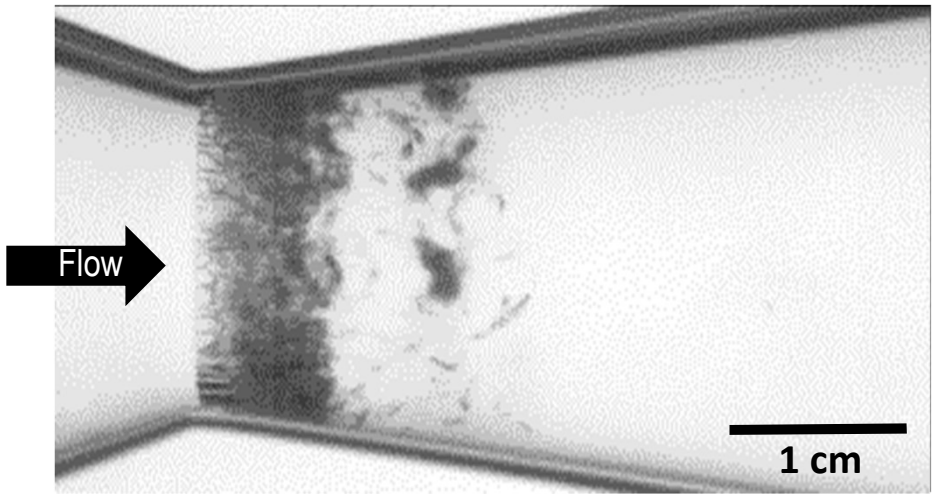


Cavitation regimes:

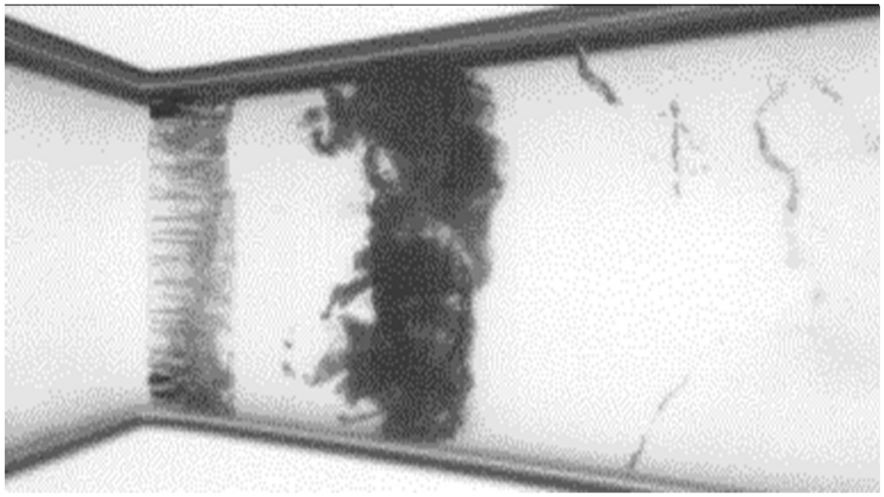
- **Sheet cavitation**
- **Partial cavitation (Type – A)**
- **Partial cavitation (Type – B)**
- **Shear or jet cavitation**

Cavitation regimes:

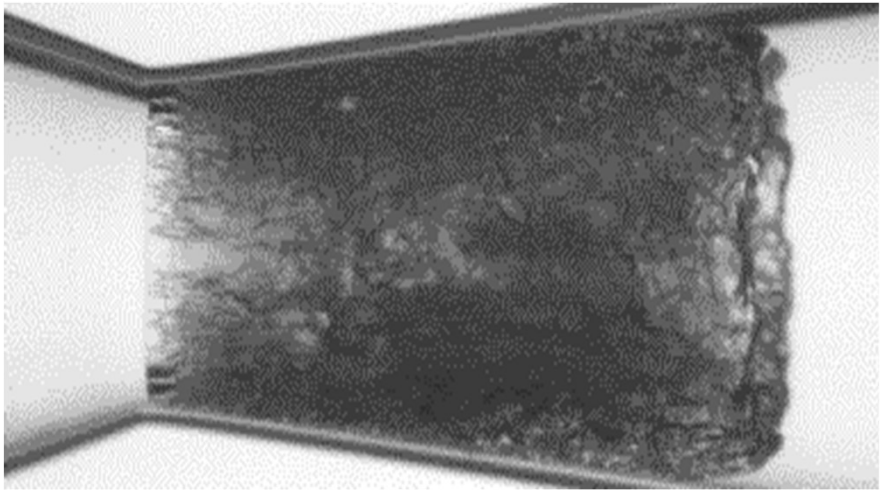
Sheet cavitation



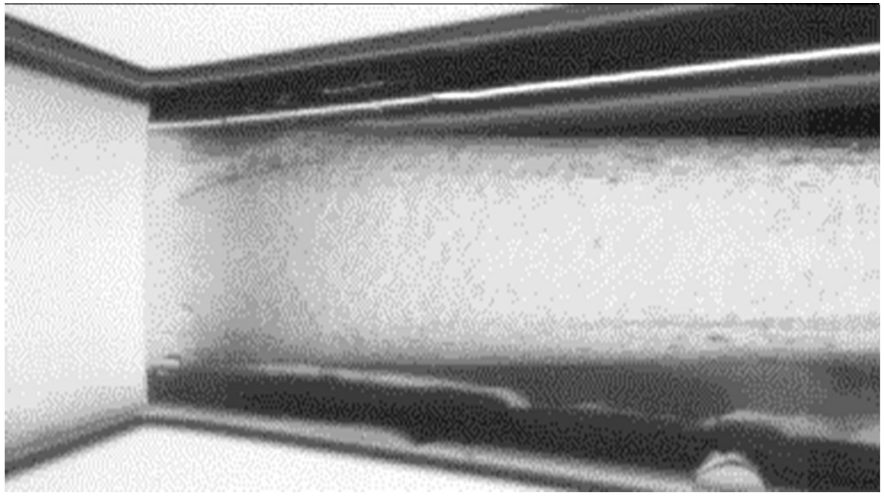
Partial cavitation (Type – A)



Partial cavitation (Type – B)



Shear or jet cavitation



Question to be answered:

- **What physics triggers different cavitation mechanisms and shedding of vapor clouds?**

Analysis of following parameters:

- **Cavity length**
- **Cavity shedding frequency**
- **Cavity growth rate**

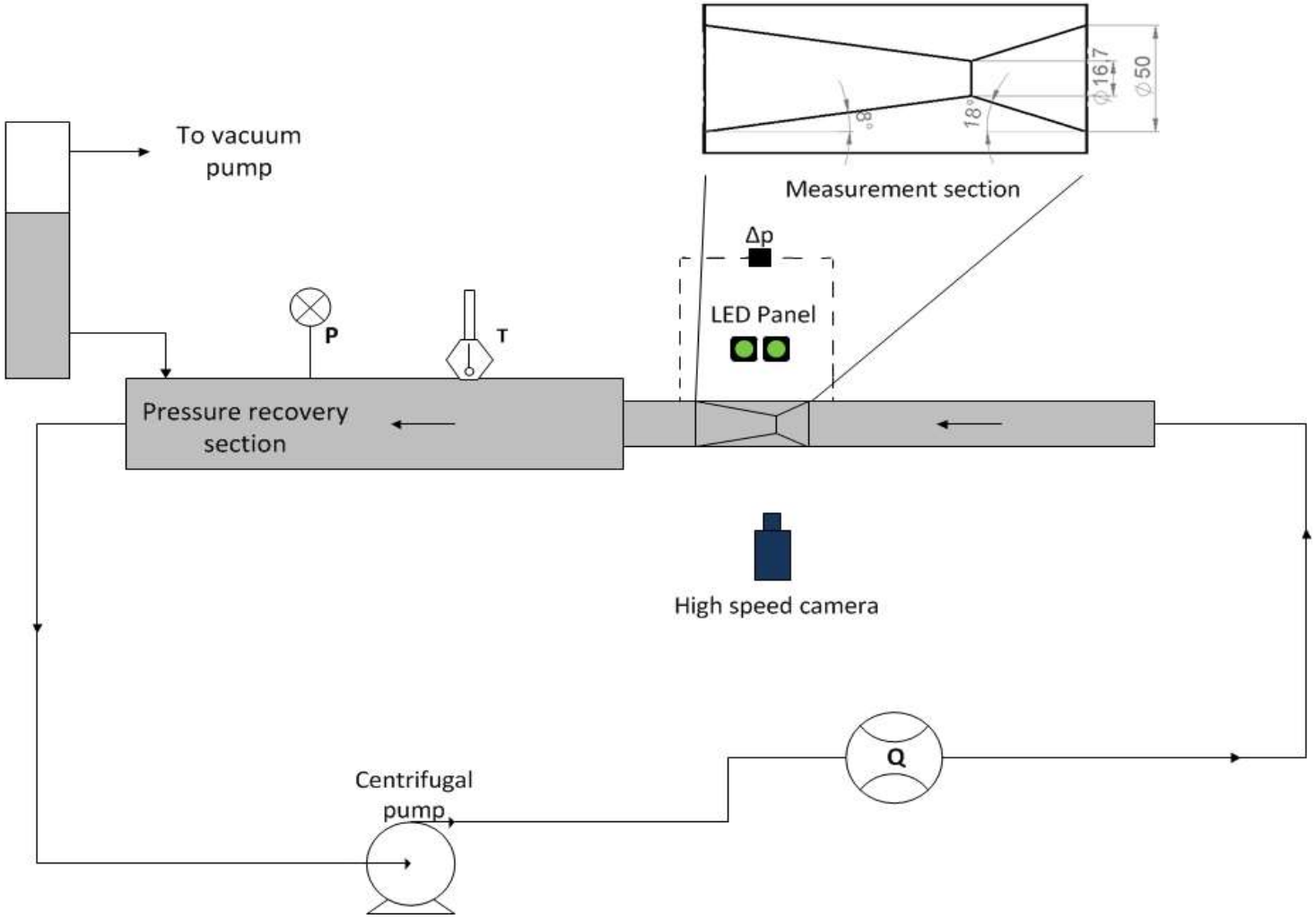
} Shadowgraphy

- **Void fraction**
- **3D shape of cavity**

} X-ray densitometry

- Objectives
- **Shadowgraphy**
- X-ray densitometry
- Conclusions

Experimental setup



Schematic diagram of the pipe flow facility

Filtered water at 45% oxygen content

Dimensional parameters

- **Cavitation number:** $\sigma = \frac{p - p_v}{\frac{1}{2}\rho u^2}$
- **Strouhal number :** $St_d = \frac{f \cdot d}{u}$
- **Reynolds number:** $\mathrm{Re} = \frac{d \cdot u}{\nu} \cong 1 \cdot 10^5 - 3 \cdot 10^5$
- **Pressure loss coefficient:** $K = \frac{\Delta p}{\frac{1}{2}\rho u^2}$

Data processing

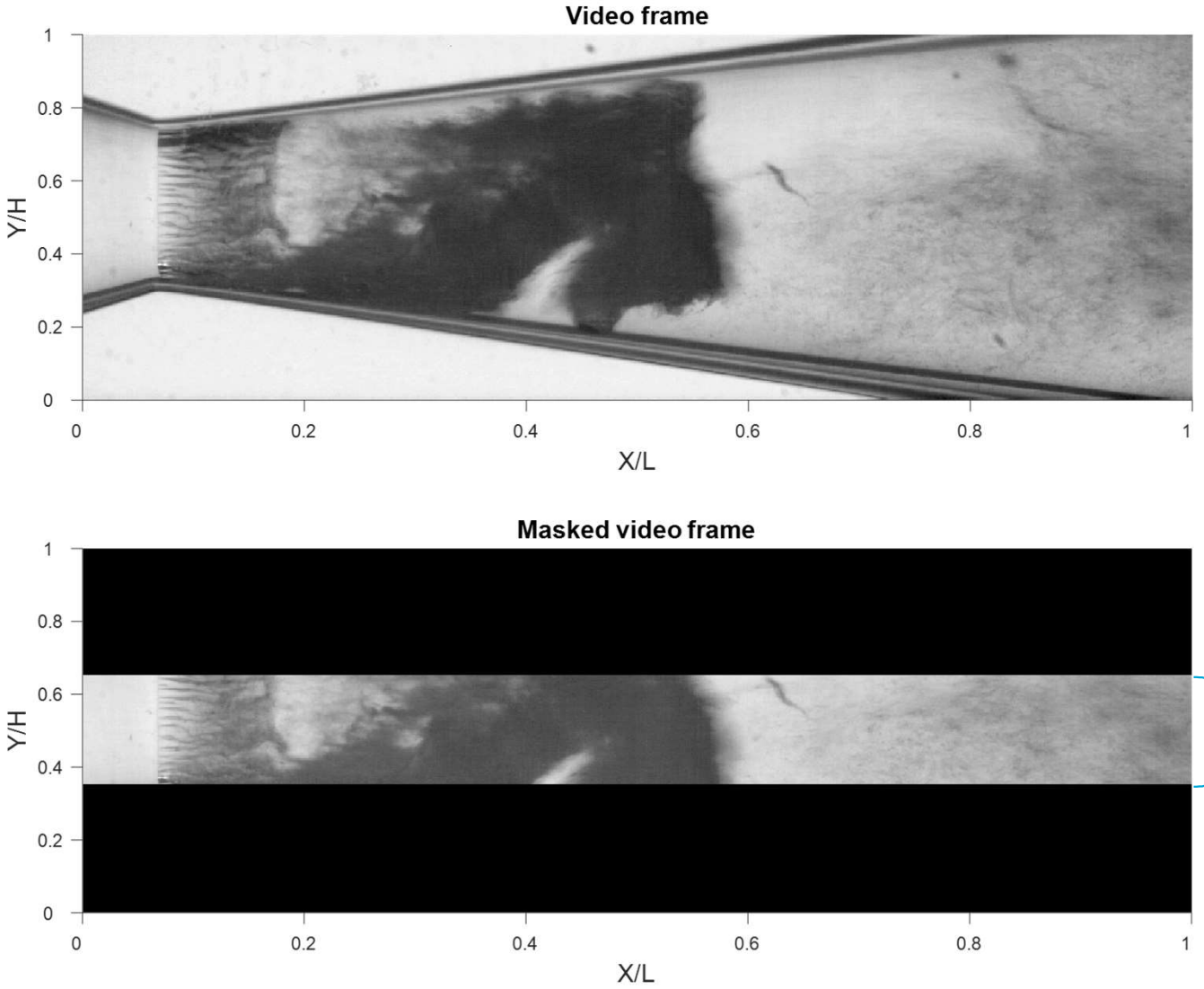
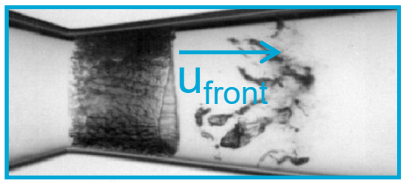
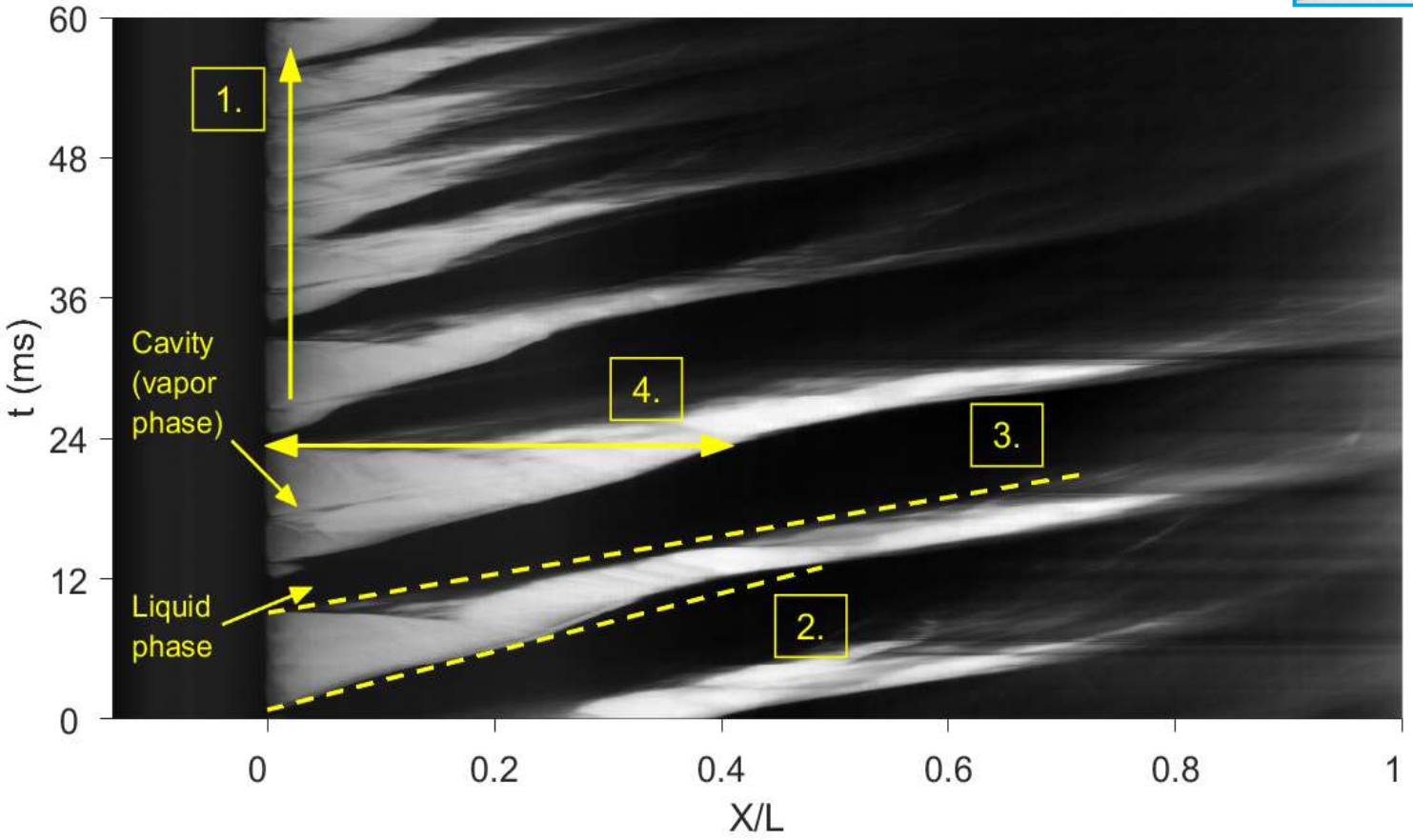


Image masking and averaging

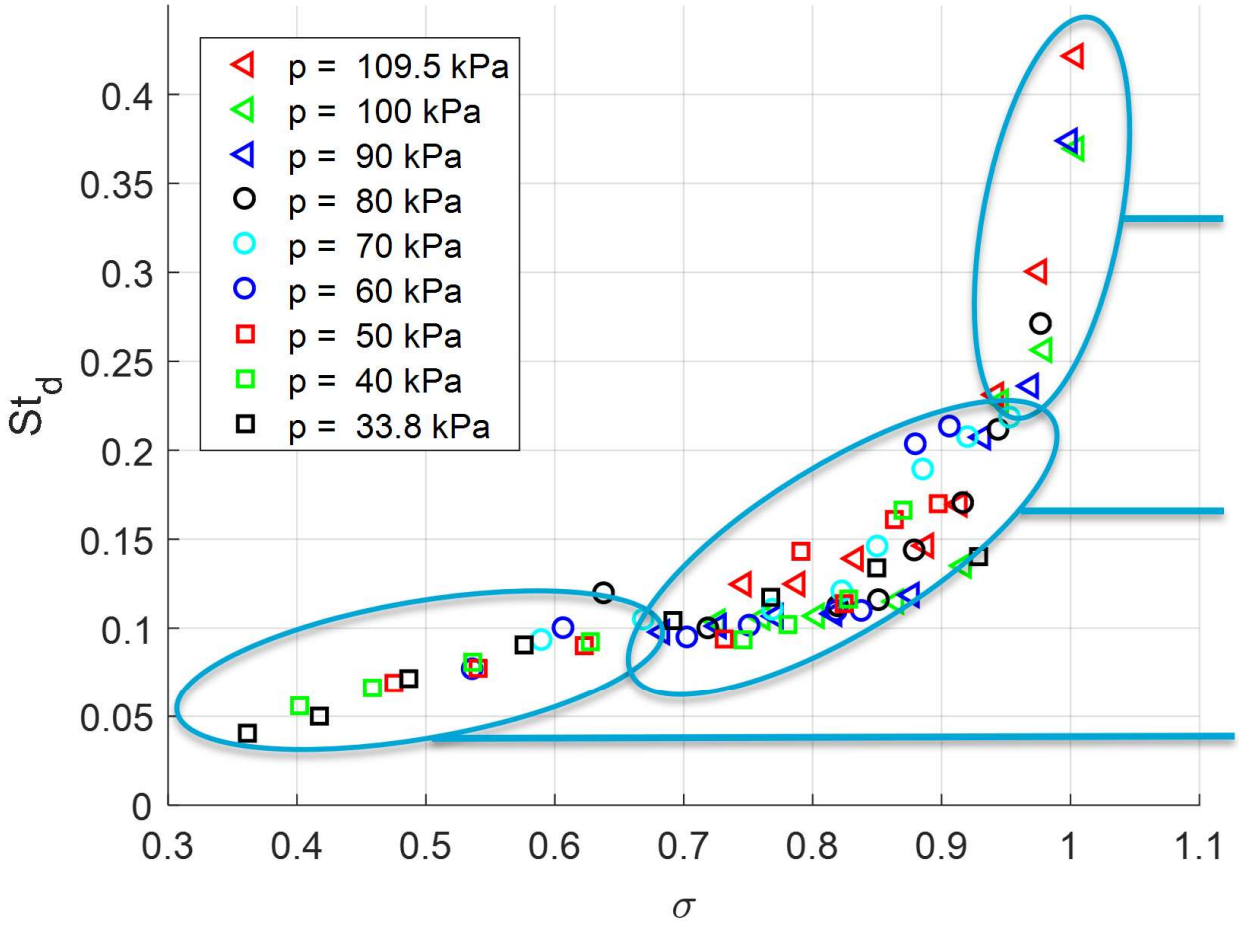
Data processing: x-t diagram





1. Shedding frequency (FFT)
2. Cavity growth rate
3. Advection velocity
4. Cavity length

Measurement results



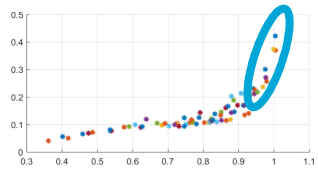
Hypothesis:

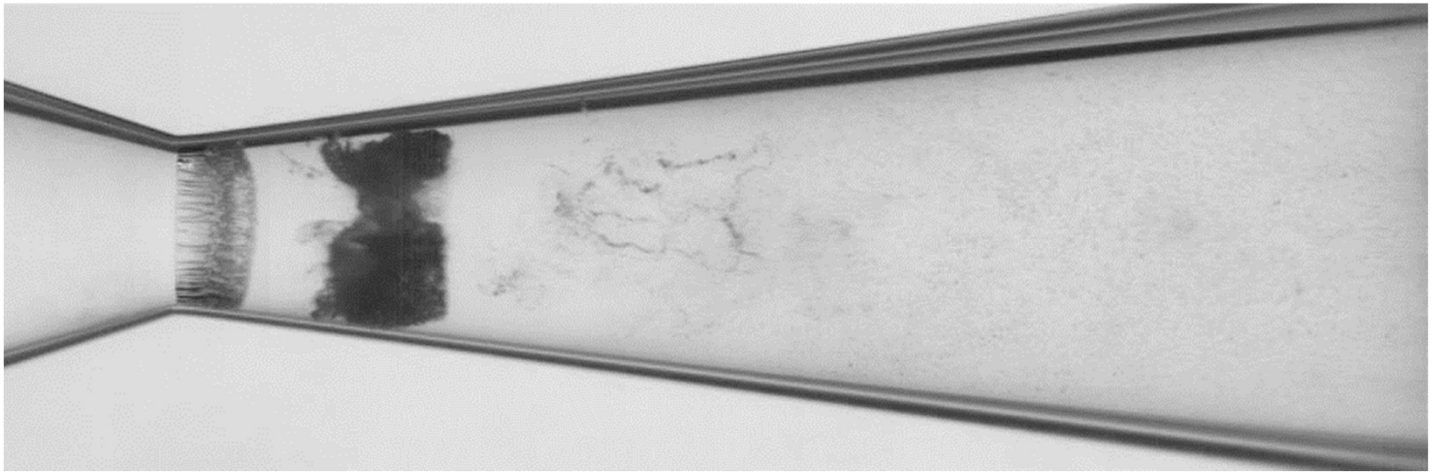
Governed by re-entrant jet mechanism

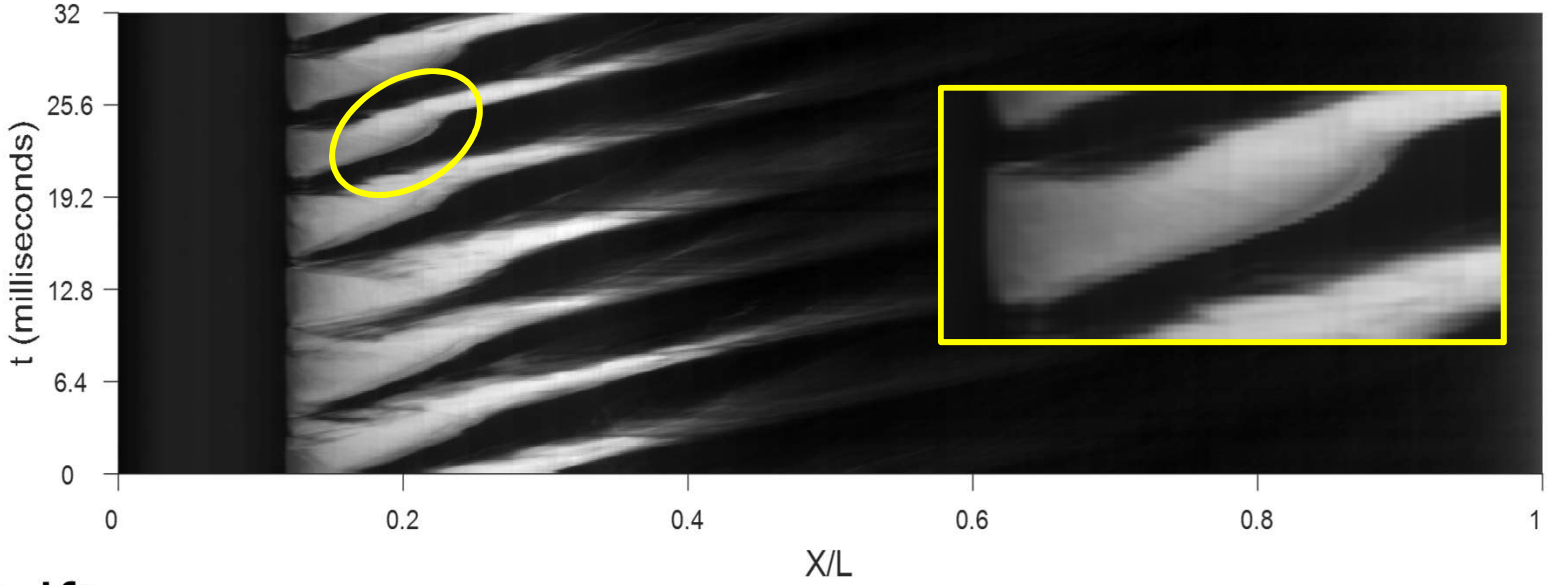
Governed by both mechanisms

Governed by bubbly shock mechanism

Re-entrant jet regime

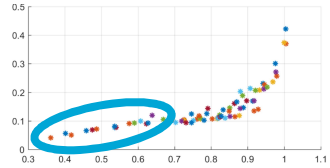


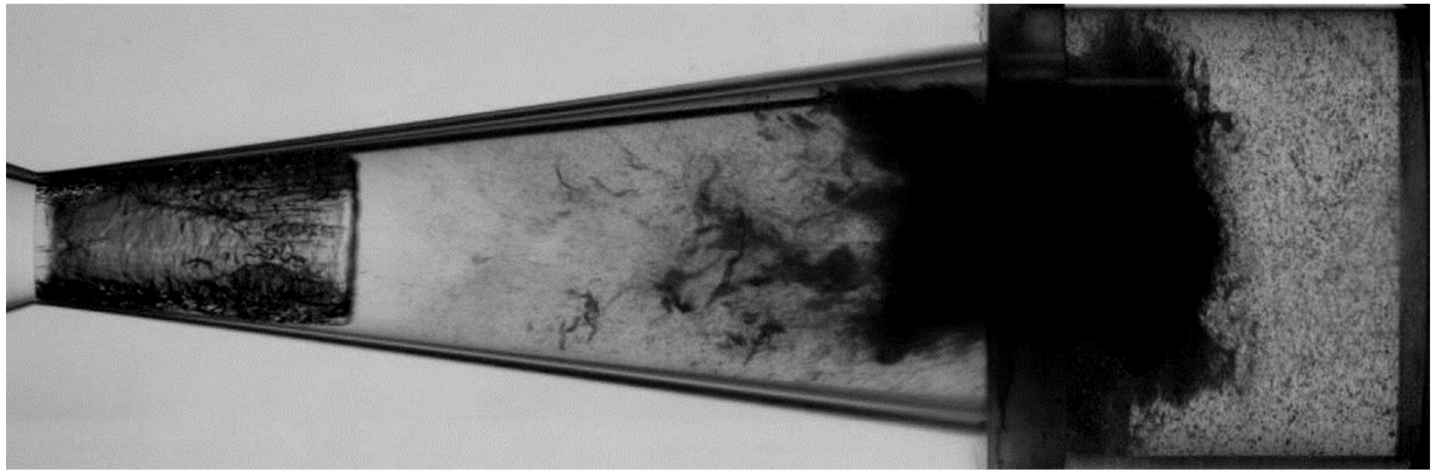


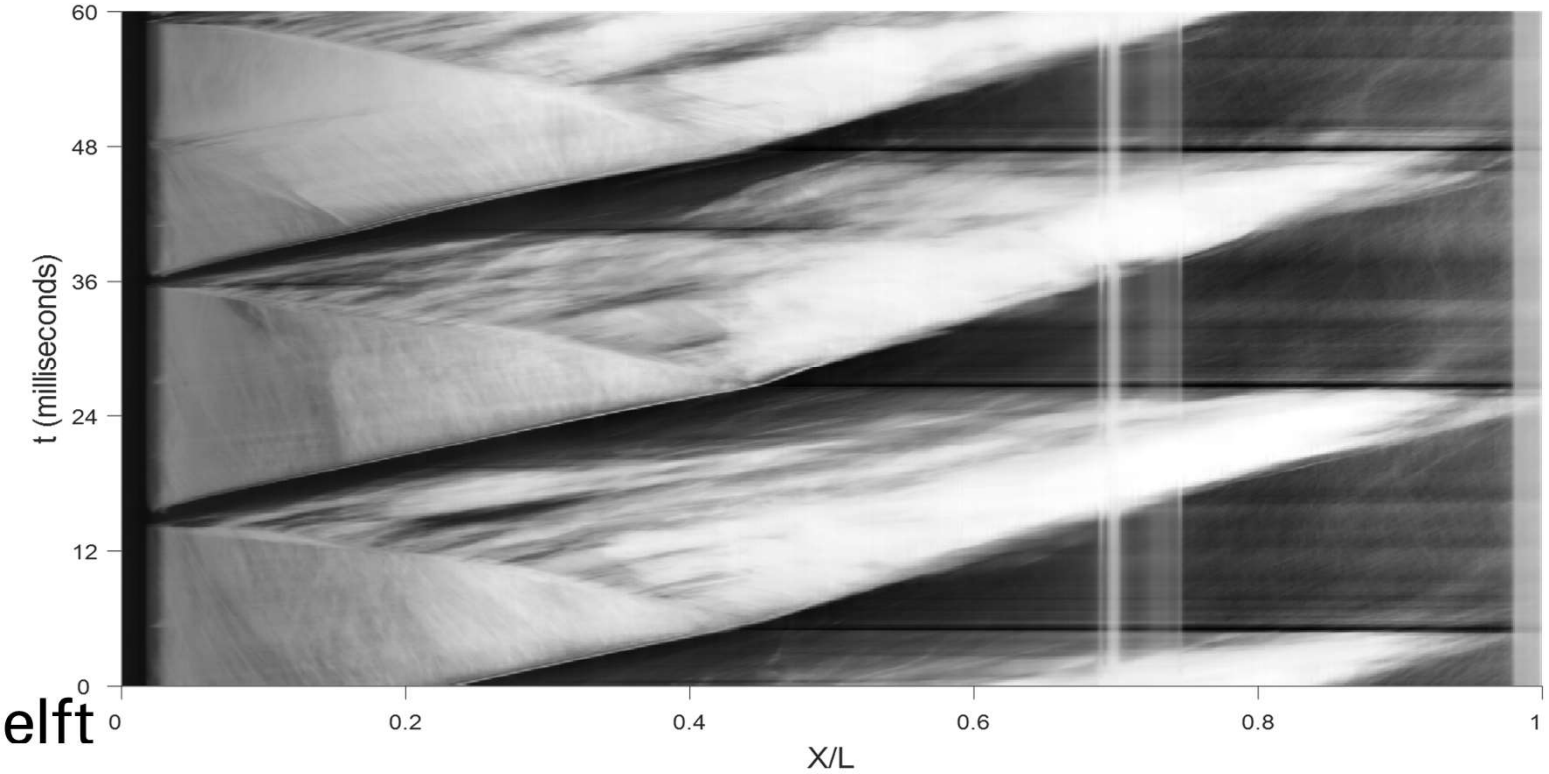


Note: Colors in x-t diagram are inverted

Bubbly shock regime

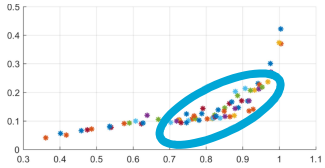


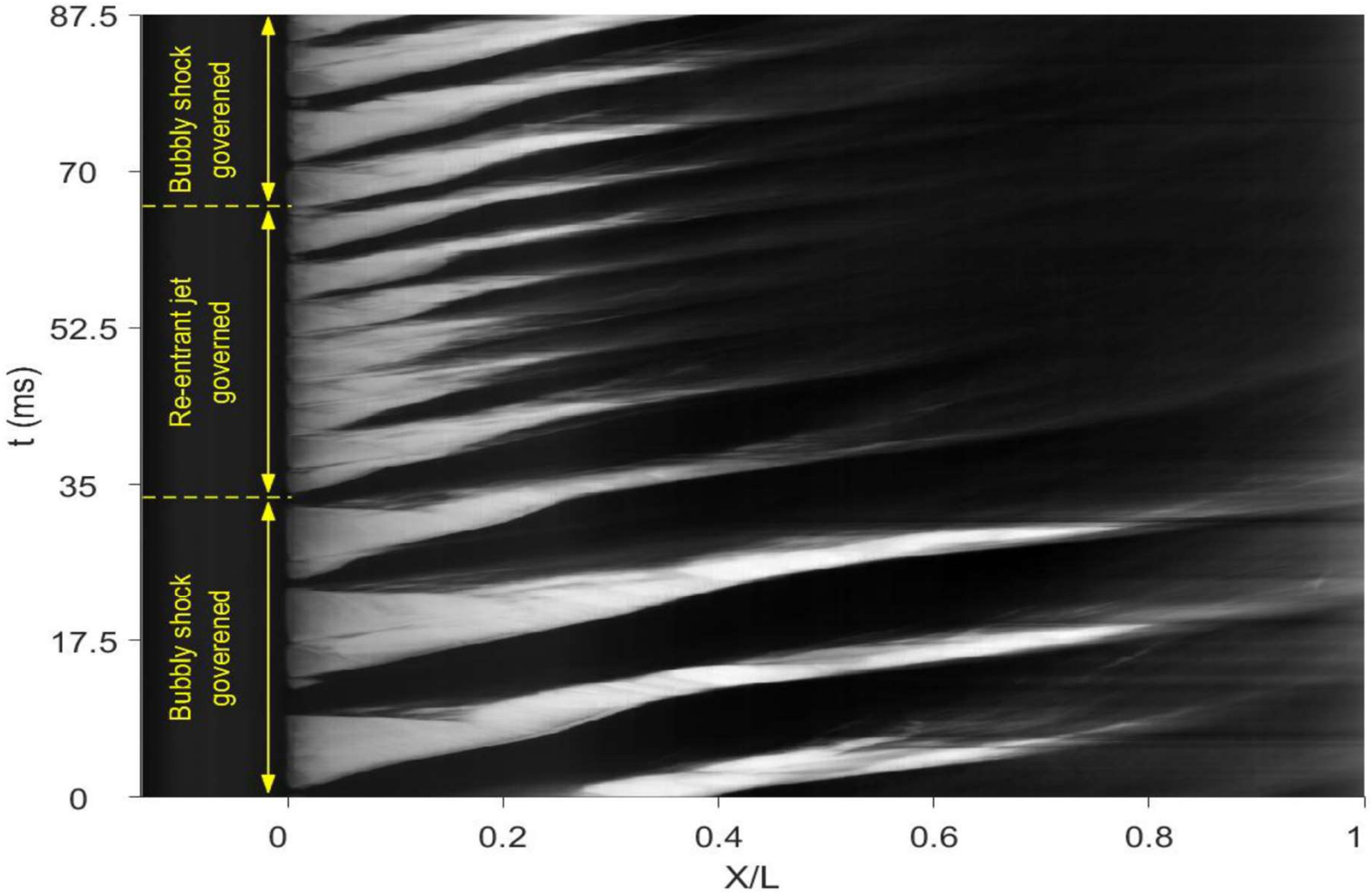




TU Delft

Transition regime





- Objectives
- Shadowgraphy
- **X-ray densitometry**
- Conclusions

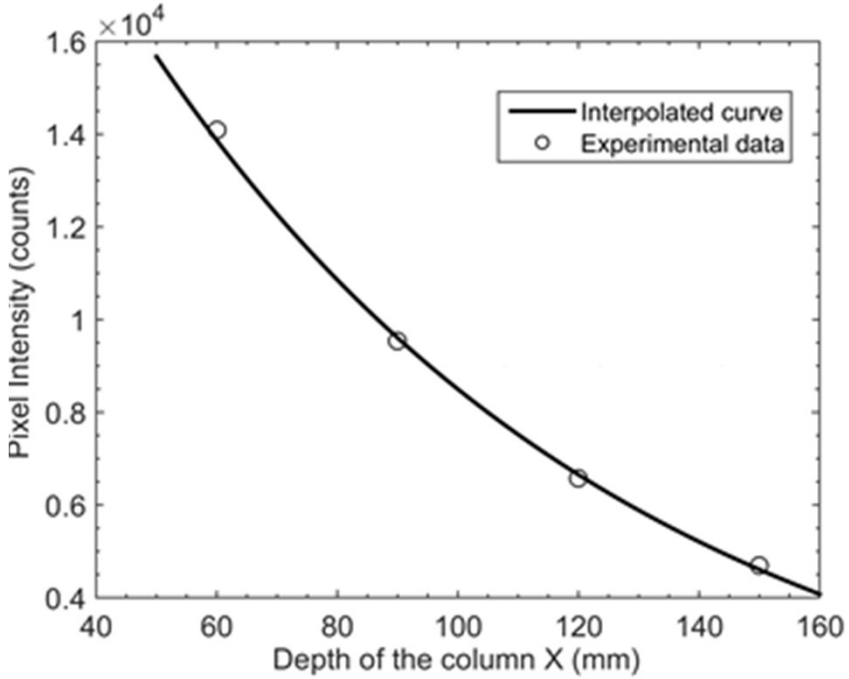
X-ray measurement principle

Beer-Lambert law

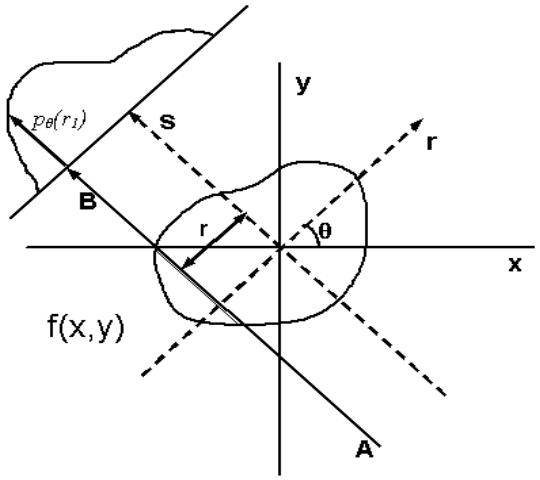
$$\frac{I}{I_0} = e^{-\mu d}$$

$\mu = attenuation\ coefficient\ [cm^{-1}]$
$d = pathlength\ material\ [cm]$

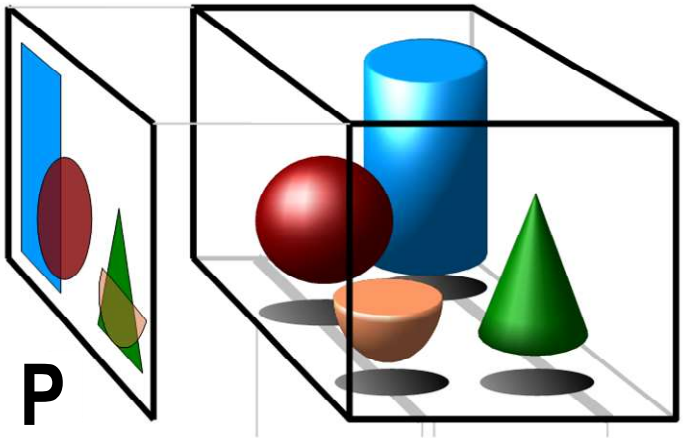
Pixel intensity = pathlength material on that line



X-ray projection



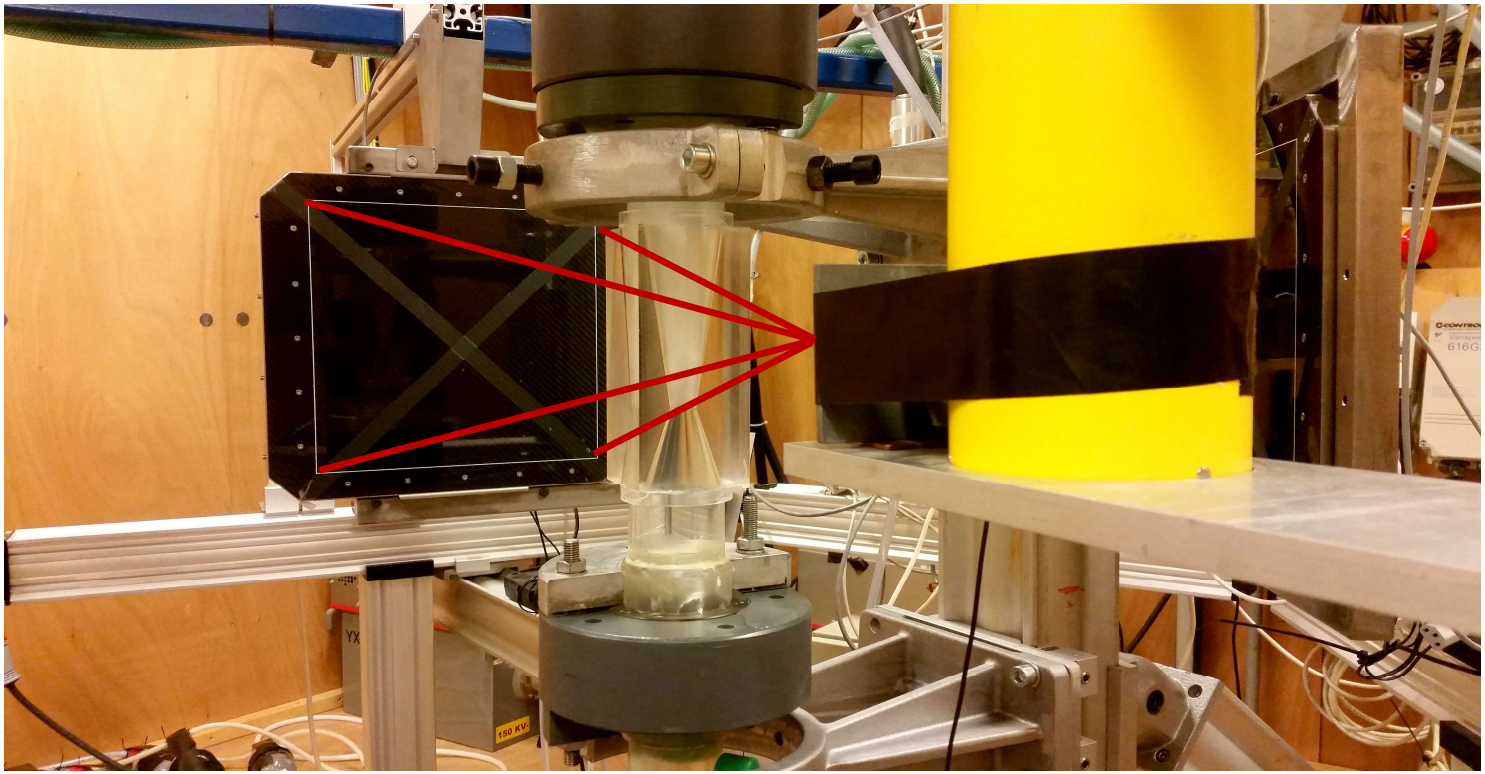
1-D “line” detector



2-D “area” detector

Source: Evert Wagner

X-ray setup



Portable flow loop, Department of Chemical Engineering, TU Delft

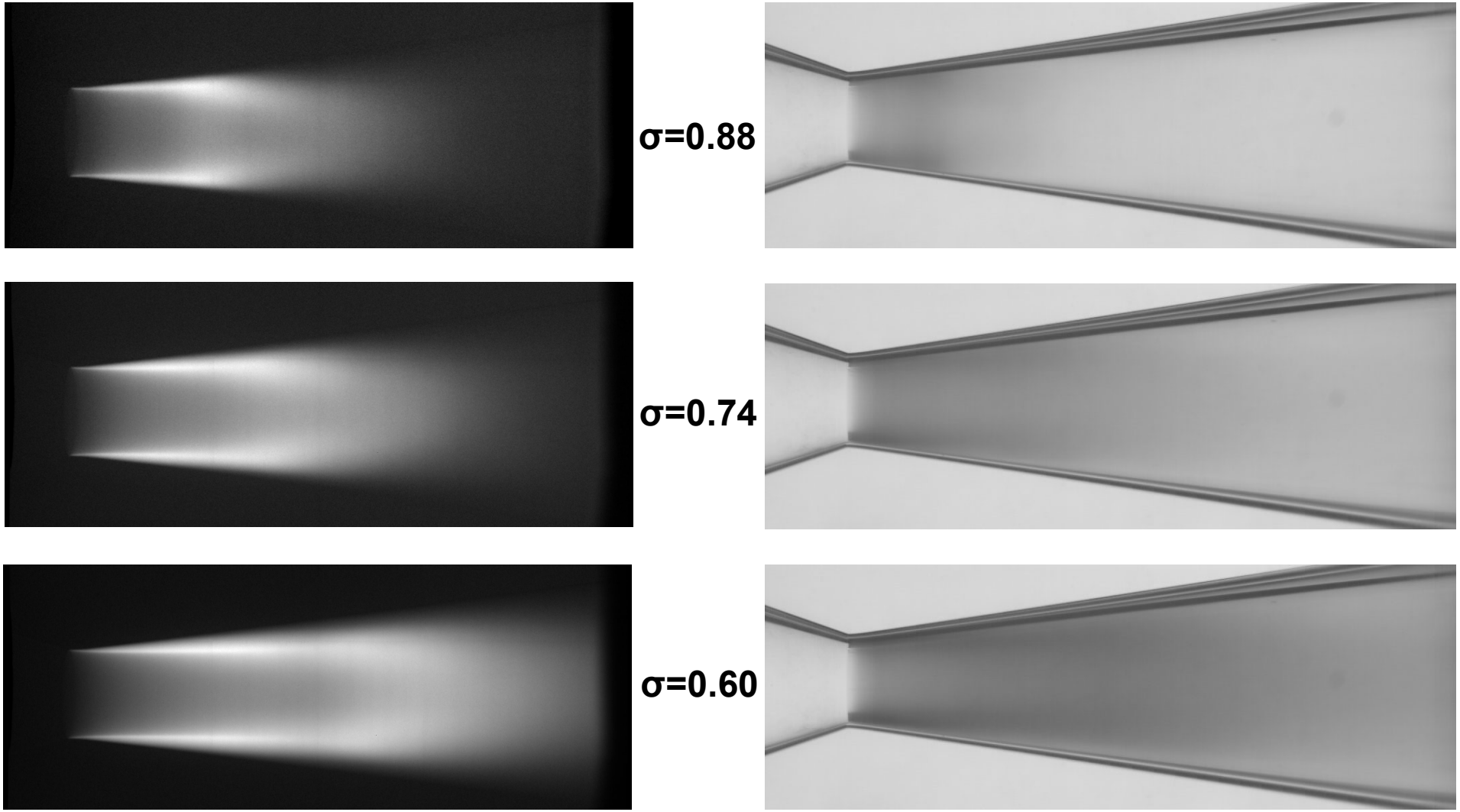
(in collaboration with Prof. Dr. Rob Mudde and Evert Wagner)

Operating conditions:

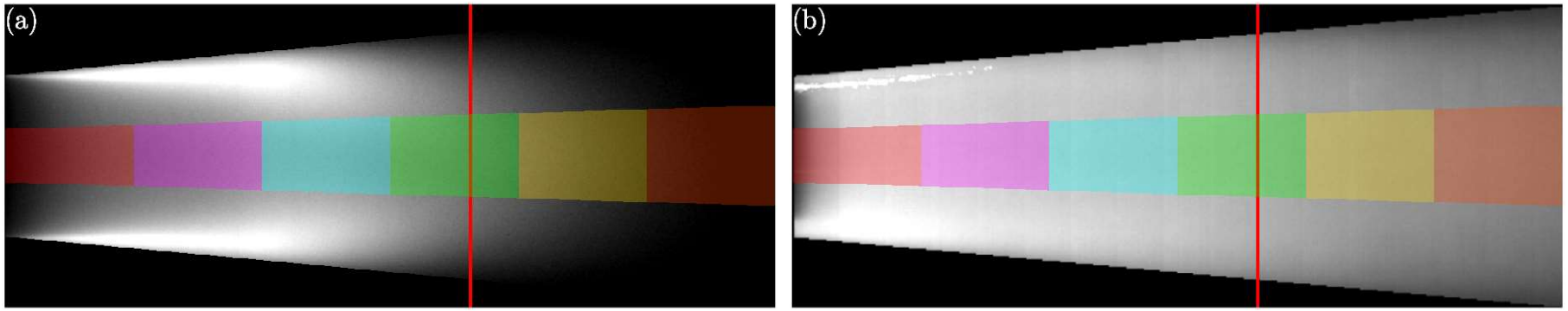
- Source-detector pair used to measure attenuation
- Source was operated at 120 keV and 5-12 mA
- Flat detector CMOS model with 1548 X 1524 pixel array
- Images recorded at 60 Hz

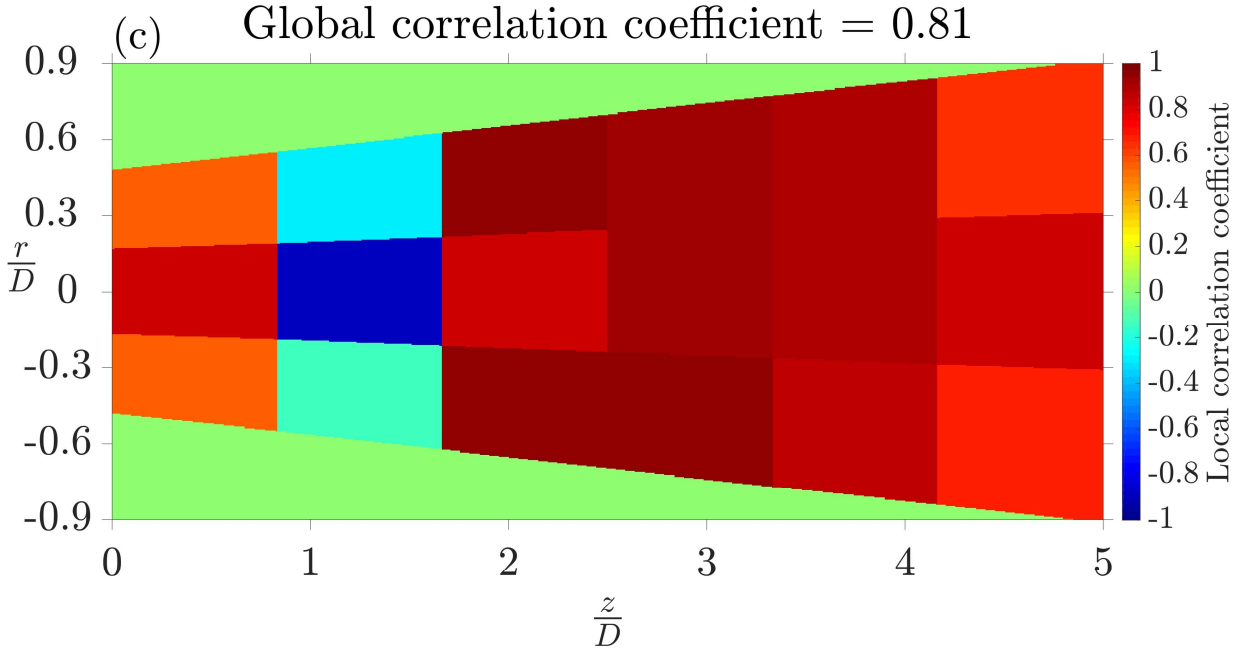
Time-averaged images

X-ray source **High-speed camera**

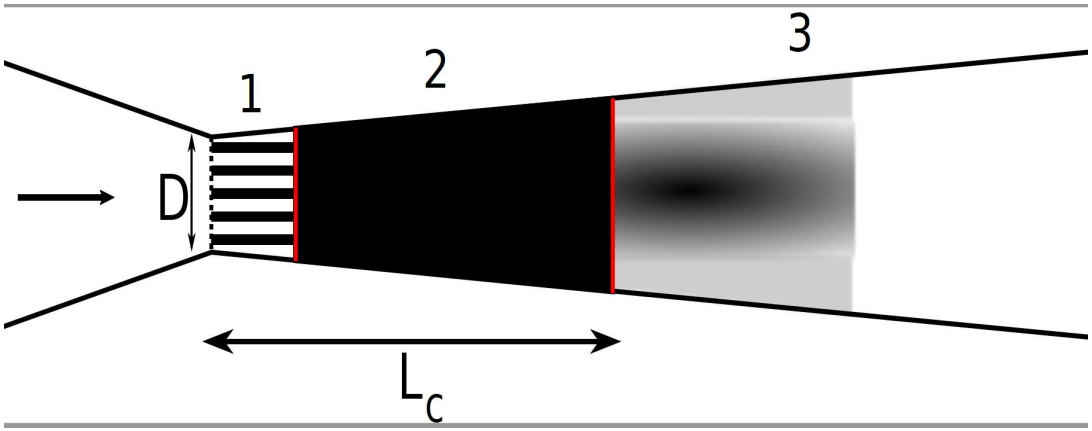


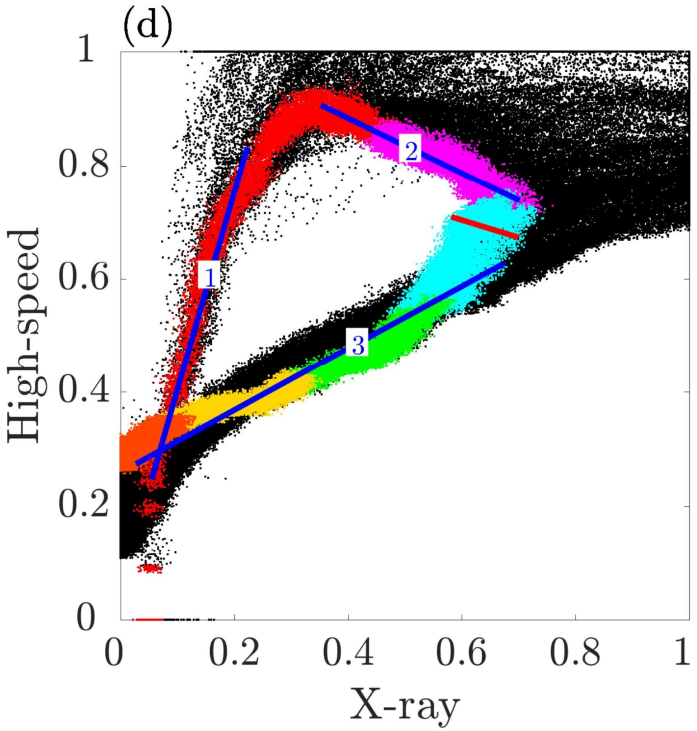
Comparison of x-ray and shadowgraphy images



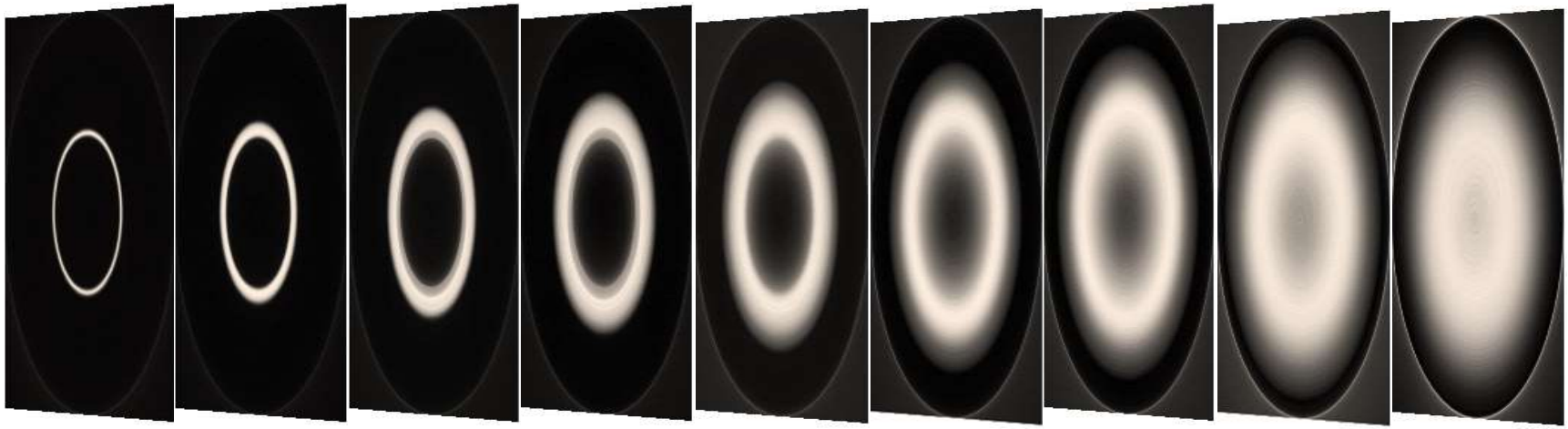


Comparison of x-ray and shadowgraphy images

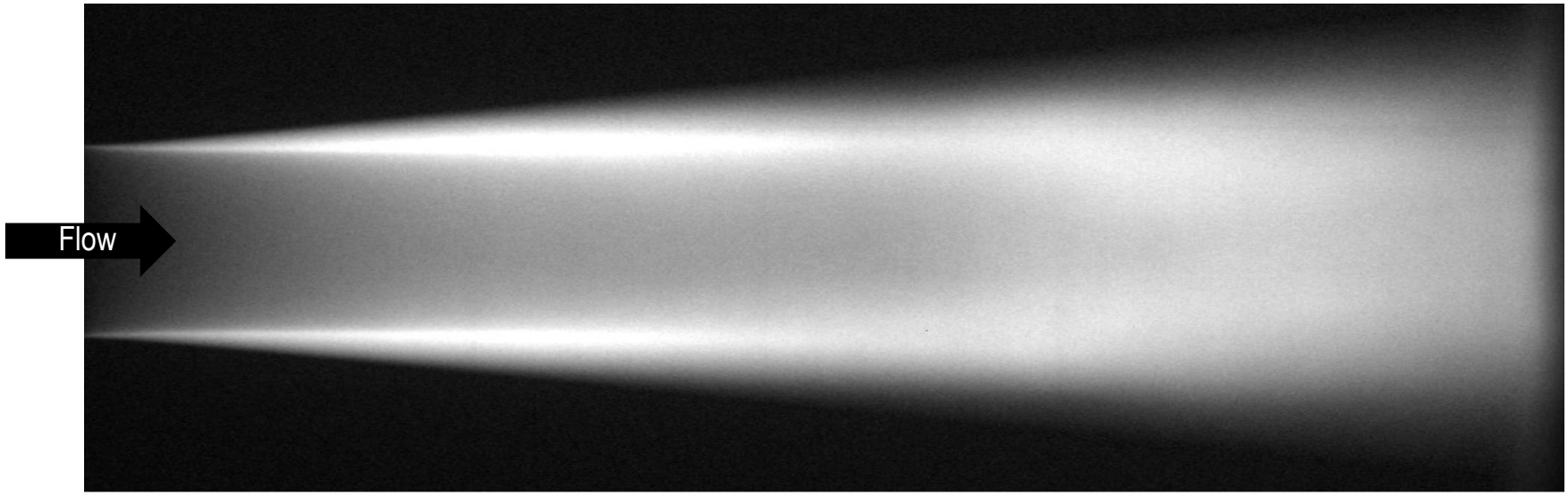




Tomographic reconstruction

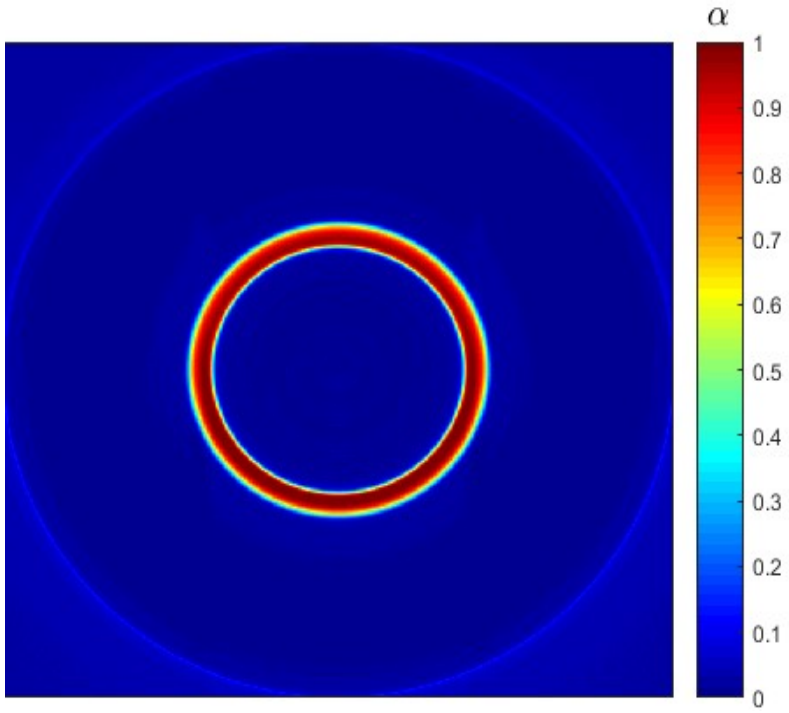


Cut planes

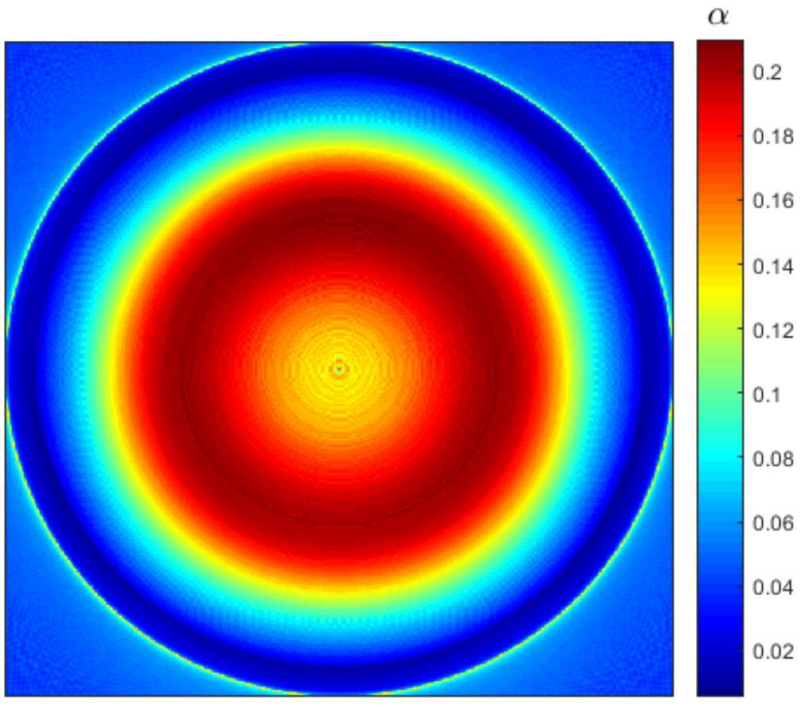


Side view

Void fractions



Near throat of venturi



Downstream of venturi
(Bubble collapse reagion)

Conclusion

- Cavitating flow is investigated and two partial cavitation mechanisms are identified
- Slip-stick behavior is characteristic for re-entrant jet
- Bubbly shock is characterized by shock front
- Both mechanisms are distinguished in a quantitative way by means of X-t diagrams
- X-ray images show intense cavitation near wall region
- Vapor fraction decreases from 94 to 18 percent downstream but vapor cloud grows which results in bubbly water

Acknowledgements

- **Prof. Dr. Ir. Christian Poelma**
  PhD supervisor and promotor

- **Willian Hogendoorn and Amitosh Dash**
  PhD colleagues

- **Prof. Rob Mudde and Evert Wagner**
  X-ray experiments

Thank you!