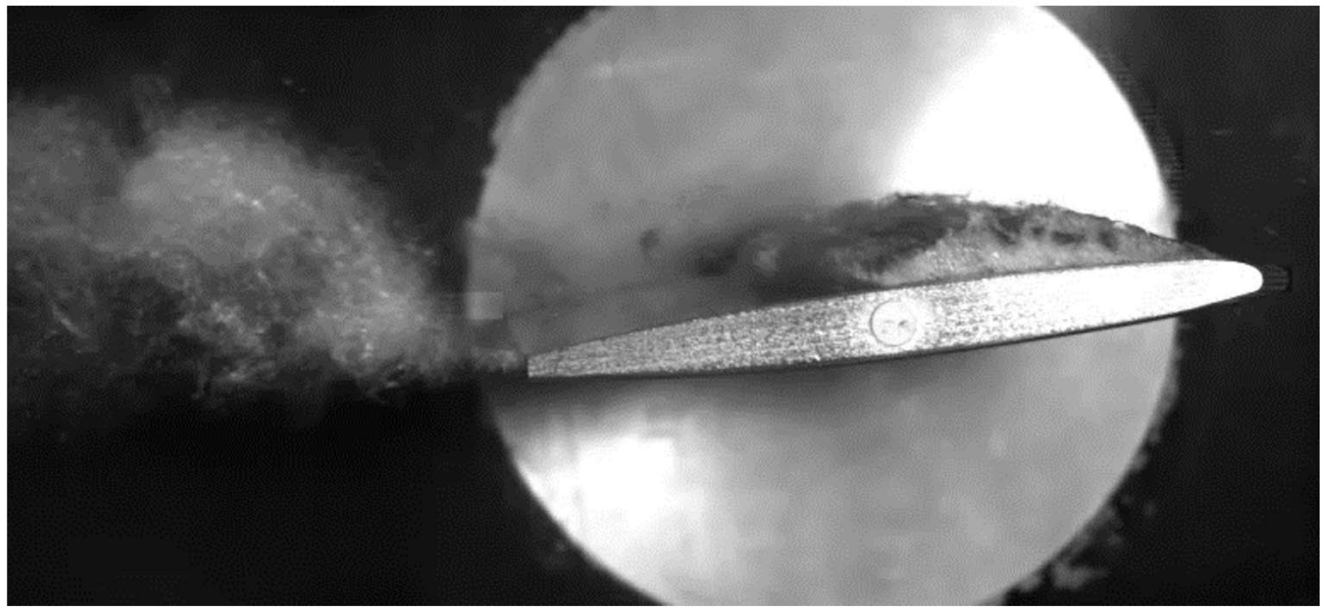
ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE
SECTION DE GENIE MECANIQUE
6th & 8th Semester, Fall 2024

CAVITATION AND INTERFACE PHENOMENA
Chapter 1 : Introduction

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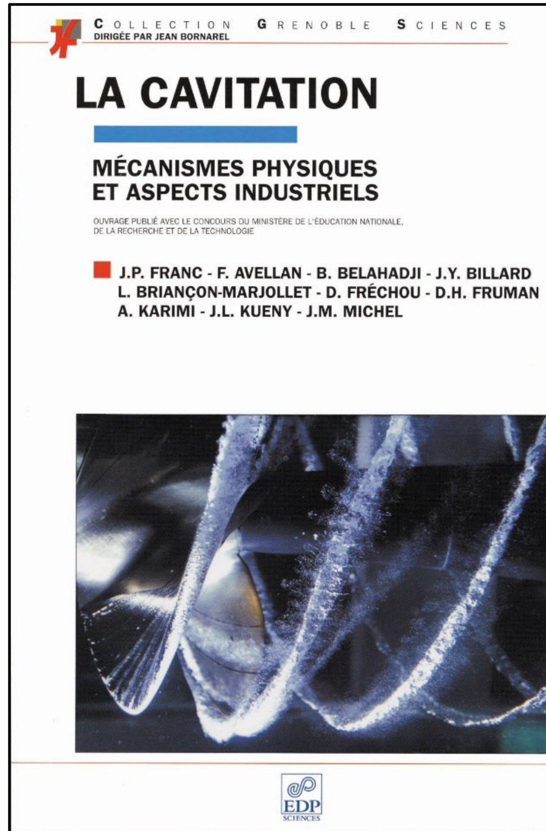
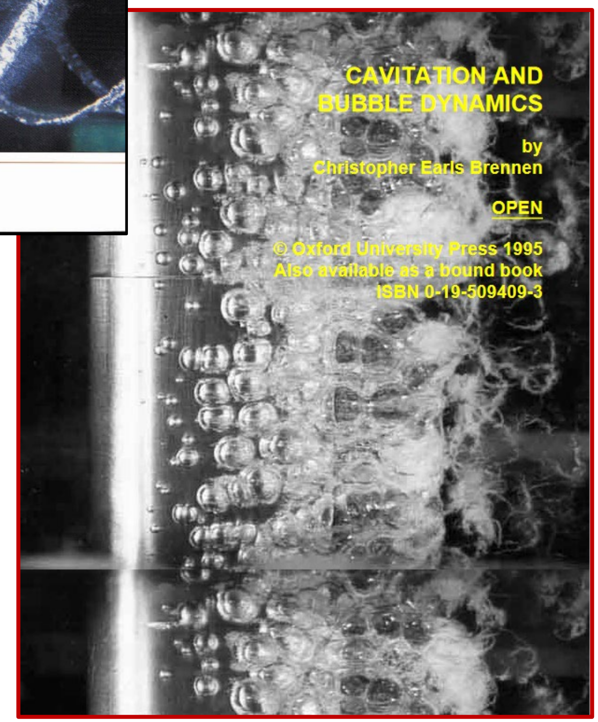
About the course

- *COURSE MATERIAL:*
    - *Slides (PDF format) on Moodle*
    - *Recorded videos on Kaltura*

- *REFERENCES*
    - *La cavitation, J. P. Franc et al., 1995, Presses Universitaires de Grenoble*
    - *Cavitation and Bubble Dynamics C. E. Brennen, Oxford University Press, New York Available here on internet:*





- *EXAM*
    - *Oral (In English or French)*
    - *20 min. preparation + 20 min. questionning*

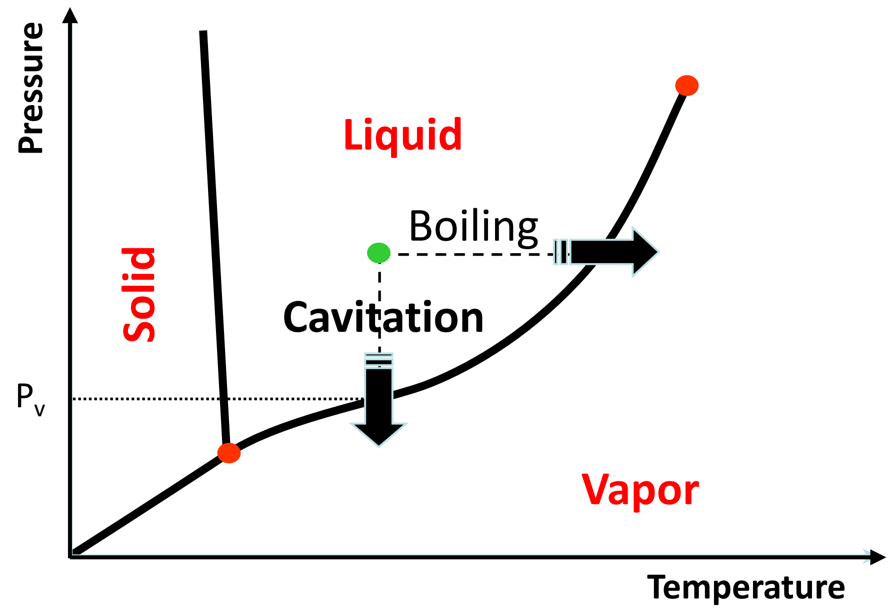
Introduction
What is Cavitation ?

- **Definition:**
  - **The cavitation is the formation of cavities filled with vapor and gas within a liquid due to a pressure decrease without heat exchange**

  - **Cavitation is “different” from boiling, in which vapor is produced by an increase of the temperature at a constant pressure**

- **Cavitation incipience:** $p < p_v(T)$

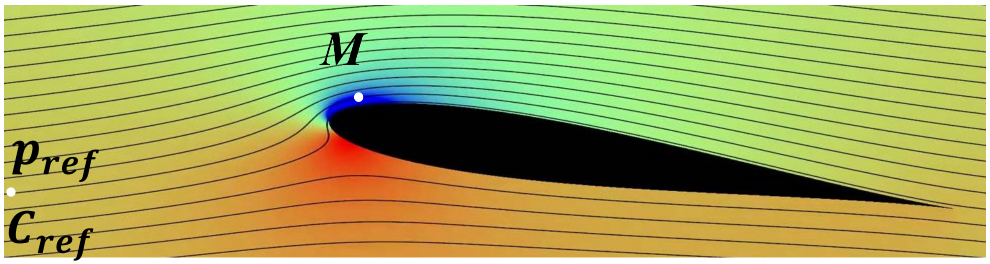
  $p_v(T)$ is the vapor pressure at a given temperature T



Cavitation Incipience

- **Condition for cavitation occurrence in a flowing liquid:**

$$p_M < p_v(T) \Leftrightarrow c_p(M) < -\sigma$$



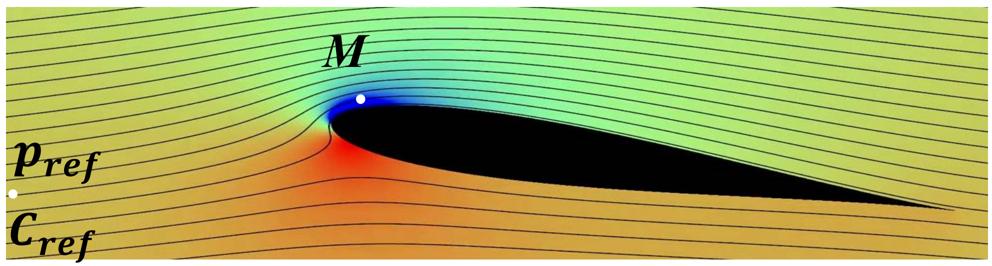
Pressure coefficient: $c_p(M) = \dfrac{p_M - p_{ref}}{\frac{1}{2}\rho C_{ref}^{\,2}}$ **Cavitation number:** $\sigma = \dfrac{p_{ref} - p_v(T)}{\frac{1}{2}\rho C_{ref}^{\,2}}$

- **The cavitation number, σ, represents a non-dimensional margin between the reference pressure and vapor pressure.**

- **The cavitation risk increases when cavitation number decreases:**
  - **Example: To avoid cavitation in its propeller, a submarine always dives before increasing its speed. In fact, the surrounding pressure increases with the submergence and so does the cavitation number.**

Cavitation Incipience

- **Energy Conservation**
  (Bernoulli Equation along a streamline)



$$\frac{1}{2}\rho {C_{ref}}^2 + p_{ref} + \rho g Z_{ref} = \frac{1}{2}\rho {C_M}^2 + p_M + \rho g Z_{ref} + \rho g H_{ref:M}$$

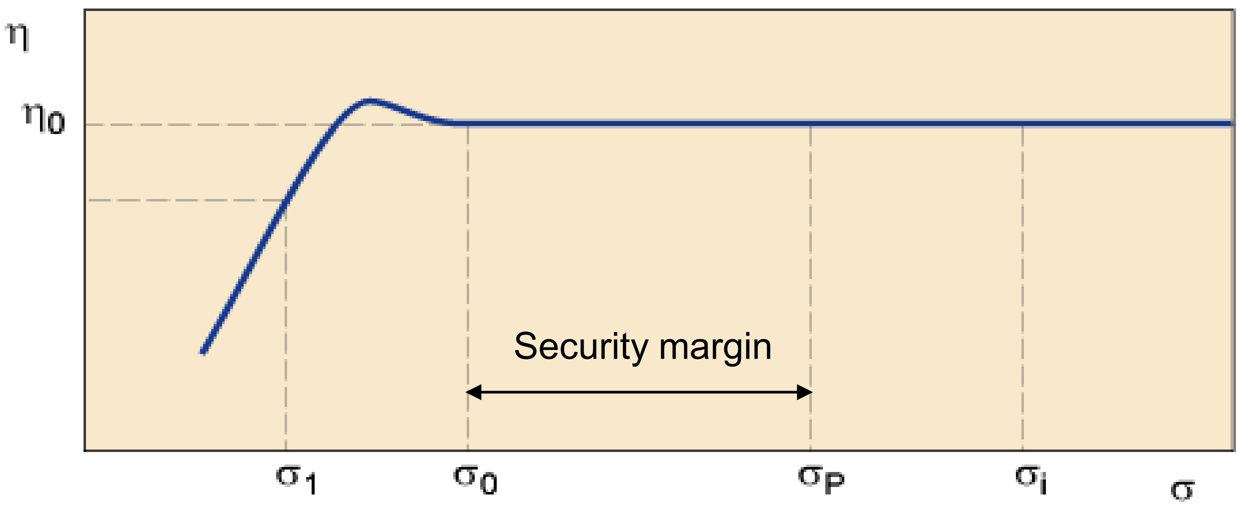
Head losses

→ **Risk of cavitation is increased with:**
- **an increase of flow speed (Venturi, hydrofoil, Vortices, …)**
- **an increase of height (Siphons, …)**
- **An increased head losses (Valves, Diaphragms, …)**

Cavitation Effects

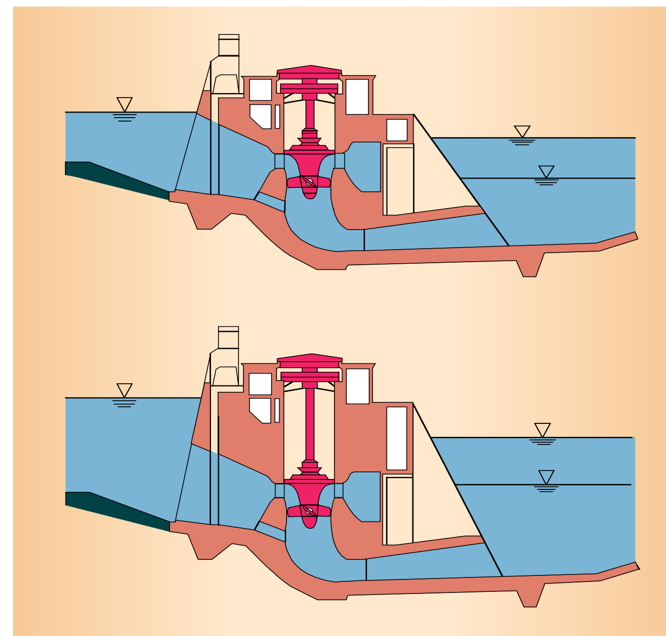
1. Alteration of hydrodynamic performances

- **Typical efficiency curve of hydraulic turbines as a function of cavitation number**



3% drop of efficiency | **Start of efficiency drop** | **Nominal operation** | **Cavitation Incipience**

- **Solution: Increase the submergence (Cost ?)**



As for submarines, a hydraulic turbine may be placed deeper in earth to increase the pressure and avoid cavitation. Nevertheless, this comes with an increase of the construction cost.

Cavitation Effects

2. **Noise and Vibration**
   - Premature cracks of the blades (Turbines, pumps, propellers, …)
   - Hydraulic & Electric stability
   - Passengers comfort (Marine transportation)
   - Submarines discretion

Premature cracks in a 200 MW Pump Turbine

3. **Erosion**
   - Mass loss of runner blades
   - → Periodic Inspections
   - → Costly repairs

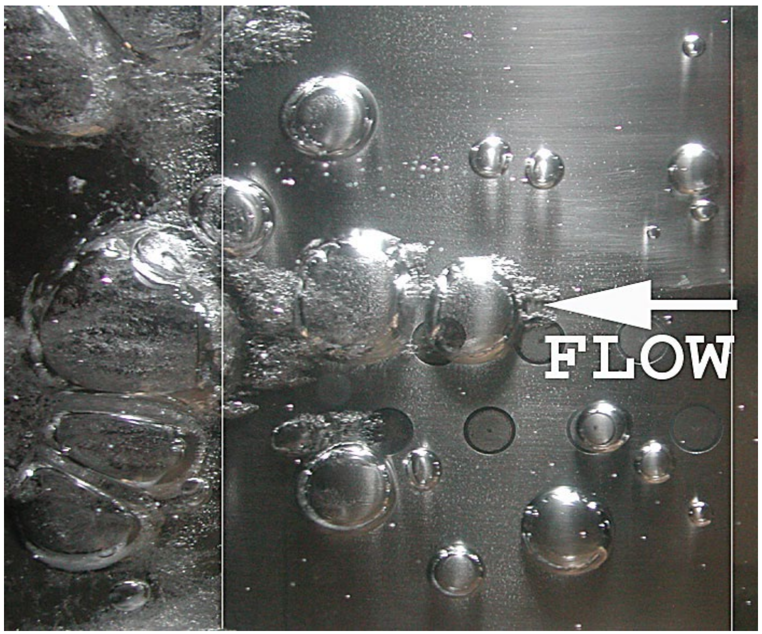
Severe erosion in pump propellers

Nowadays, there is no industrial alloy that can resist to cavitation

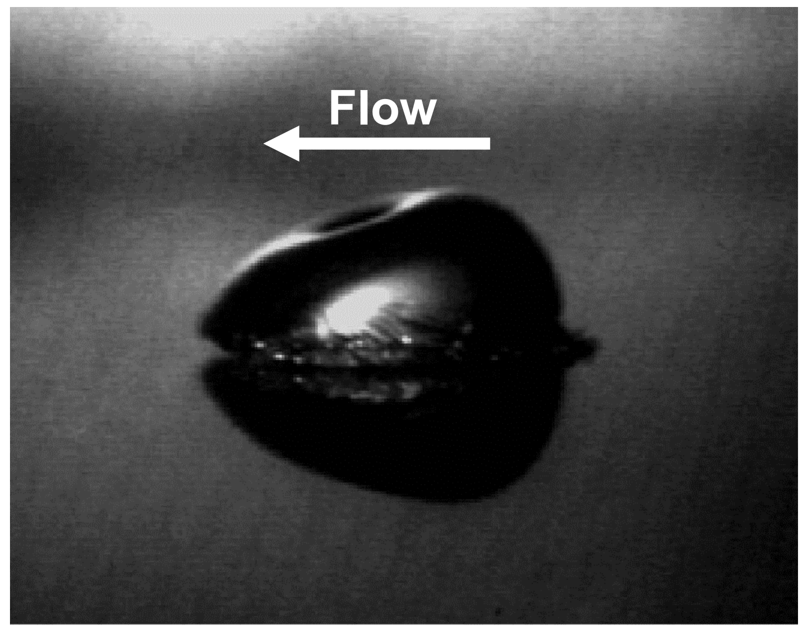
Cavitation Types

- **(1) Bubble Cavitation**

Top view of bubble cavitation on a 2D hydrofoil



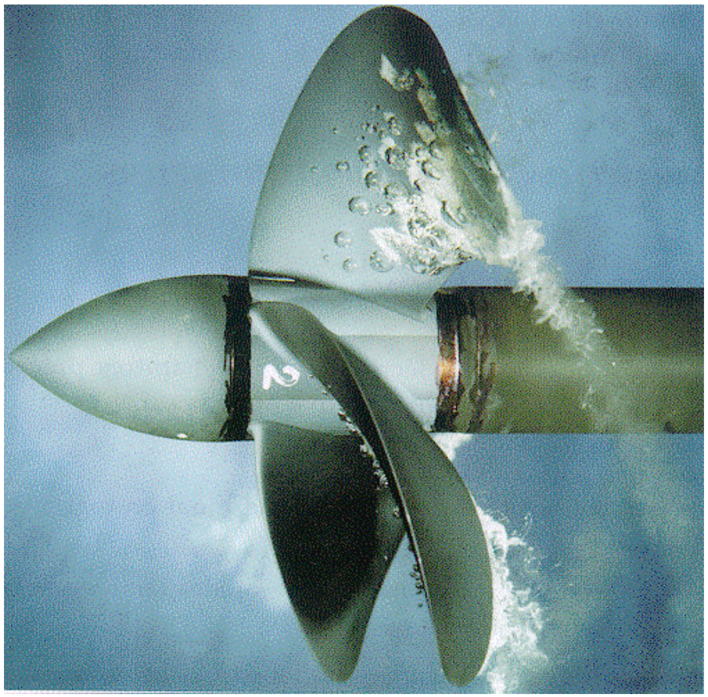
Side view of a cavitation bubble travelling on a 2D hydrofoil suction side



Cavitation Types

- **(1) Bubble Cavitation**

Bubble Cavitation in a marine propeller



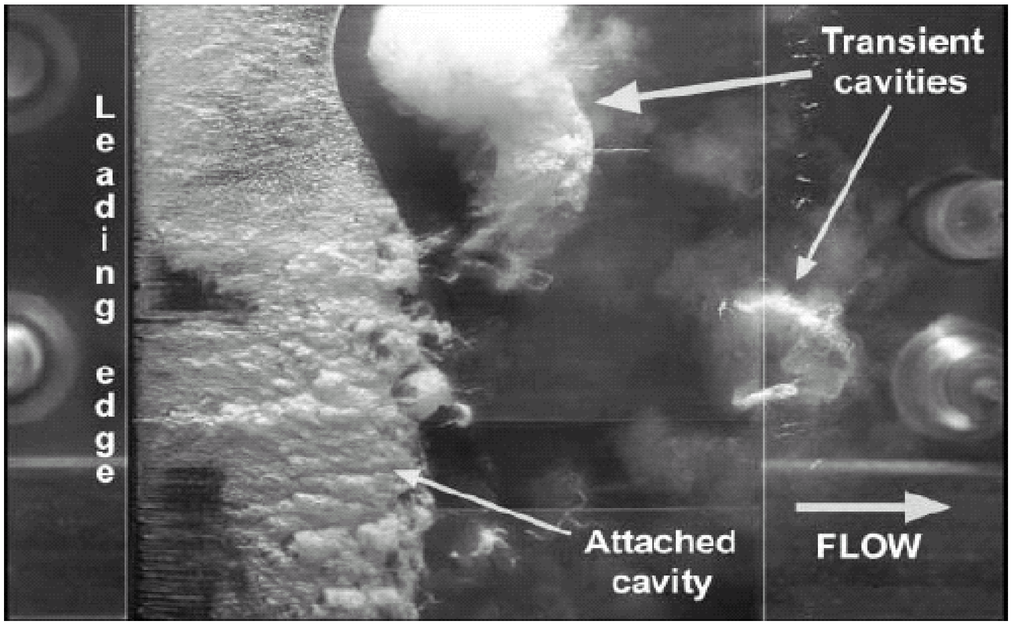
Bubble cavitation in a model of Francis turbine

Cavitation Types

- **(2) Leading edge cavitation**

also known as "*attached cavitation*" or "*inlet cavitation*"

Top view of leading edge cavitation on a 2-D hydrofoil



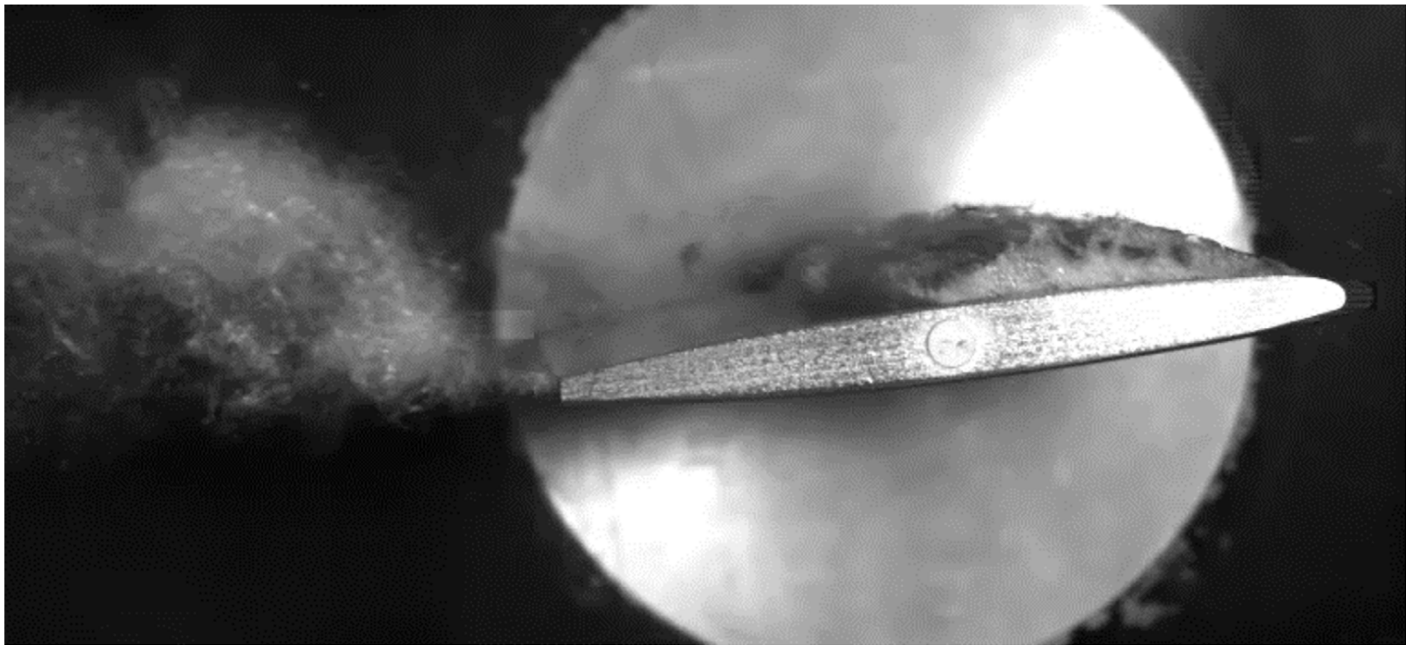
- ***Unstable vapor cavity with a shedding and collapse of transient cavities***
- ***Always associated with severe Erosion in the pressure recovery region***

Cavitation Types

- **(2) Leading edge cavitation**

also known as “*attached cavitation*” or “*inlet cavitation*”

Side view of a leading edge cavitation on a 2-D hydrofoil



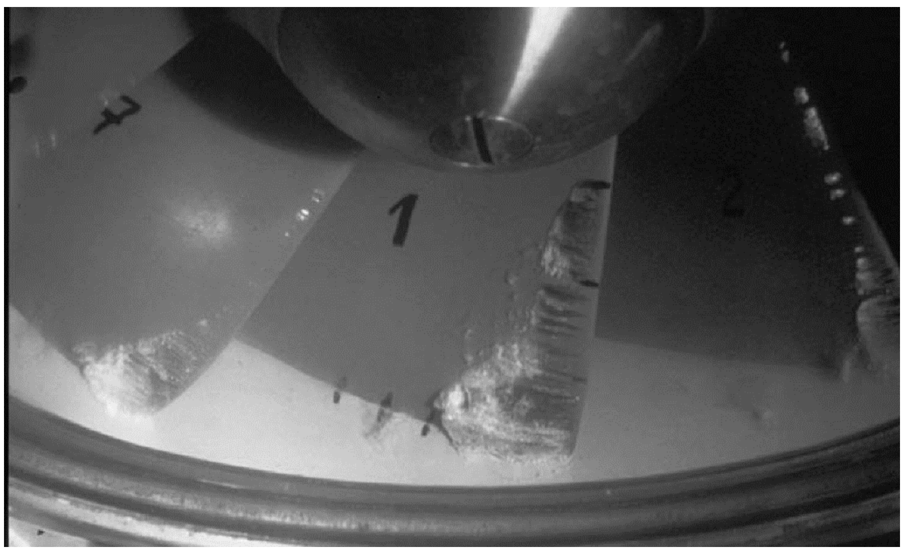
- ***Unstable vapor cavity with a shedding and collapse of transient cavities***
- ***Always associated with severe Erosion in the pressure recovery region***

Cavitation Types

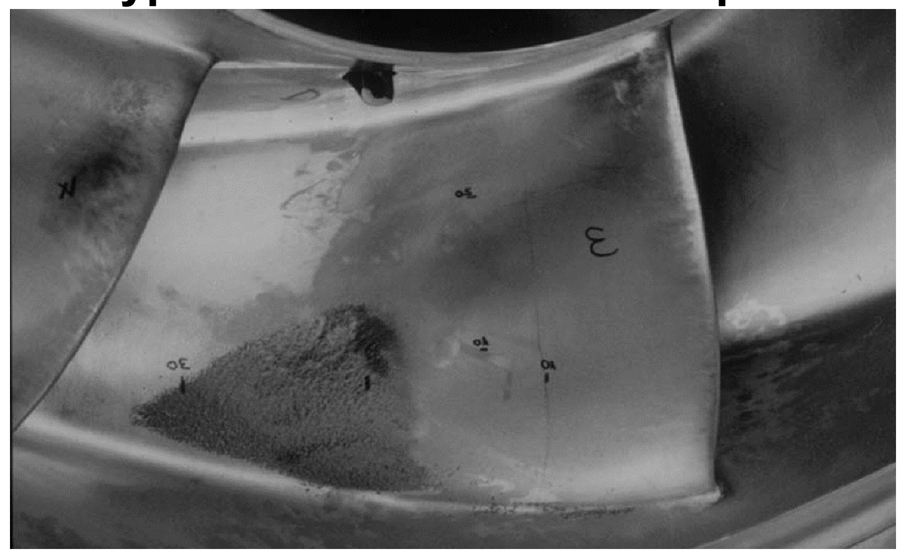
- **(2) Leading edge cavitation**

also known as "*attached cavitation*" or "*inlet cavitation*"

Visualization of cavitation in pump model



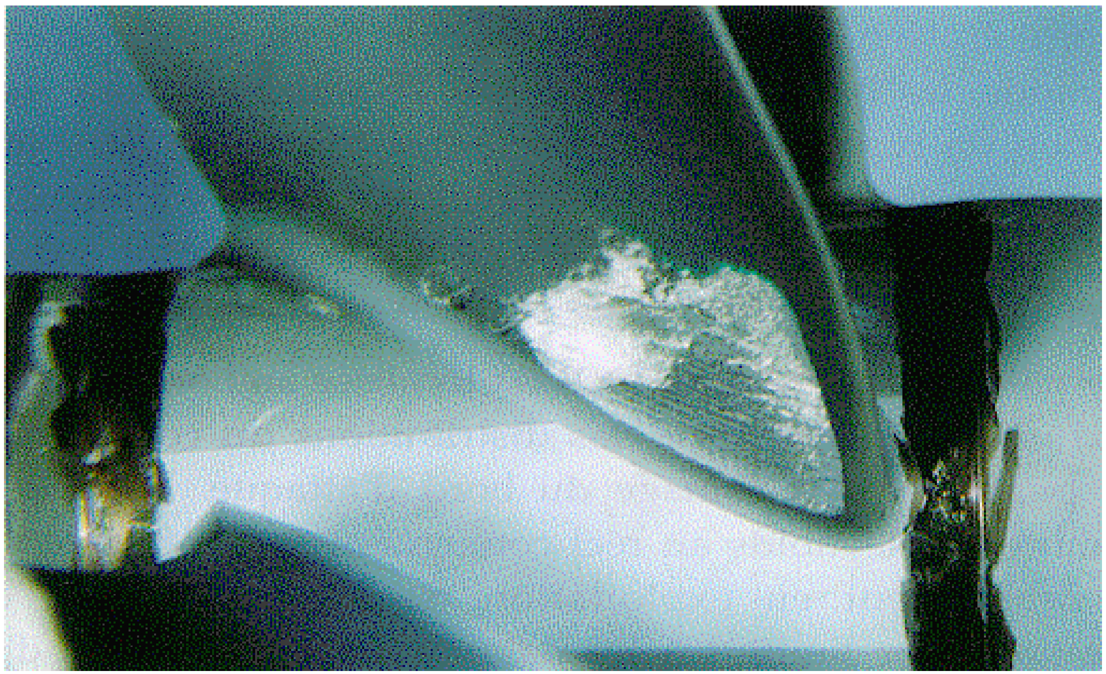
Erosion observed on the corresponding prototype after ~1000 hours of operation



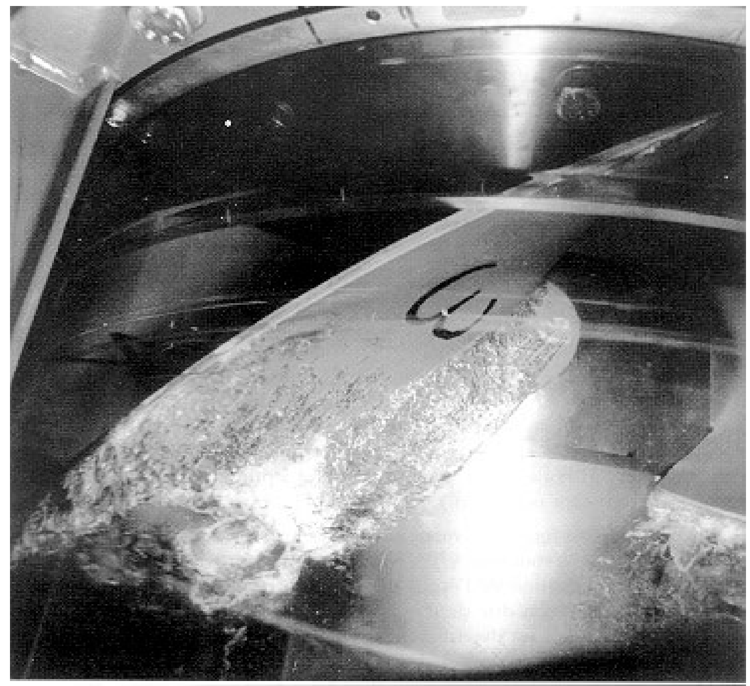
Cavitation Types

• **(2) Leading edge cavitation**
also known as "*attached cavitation*" or "*inlet cavitation*"

Model of marine propeller



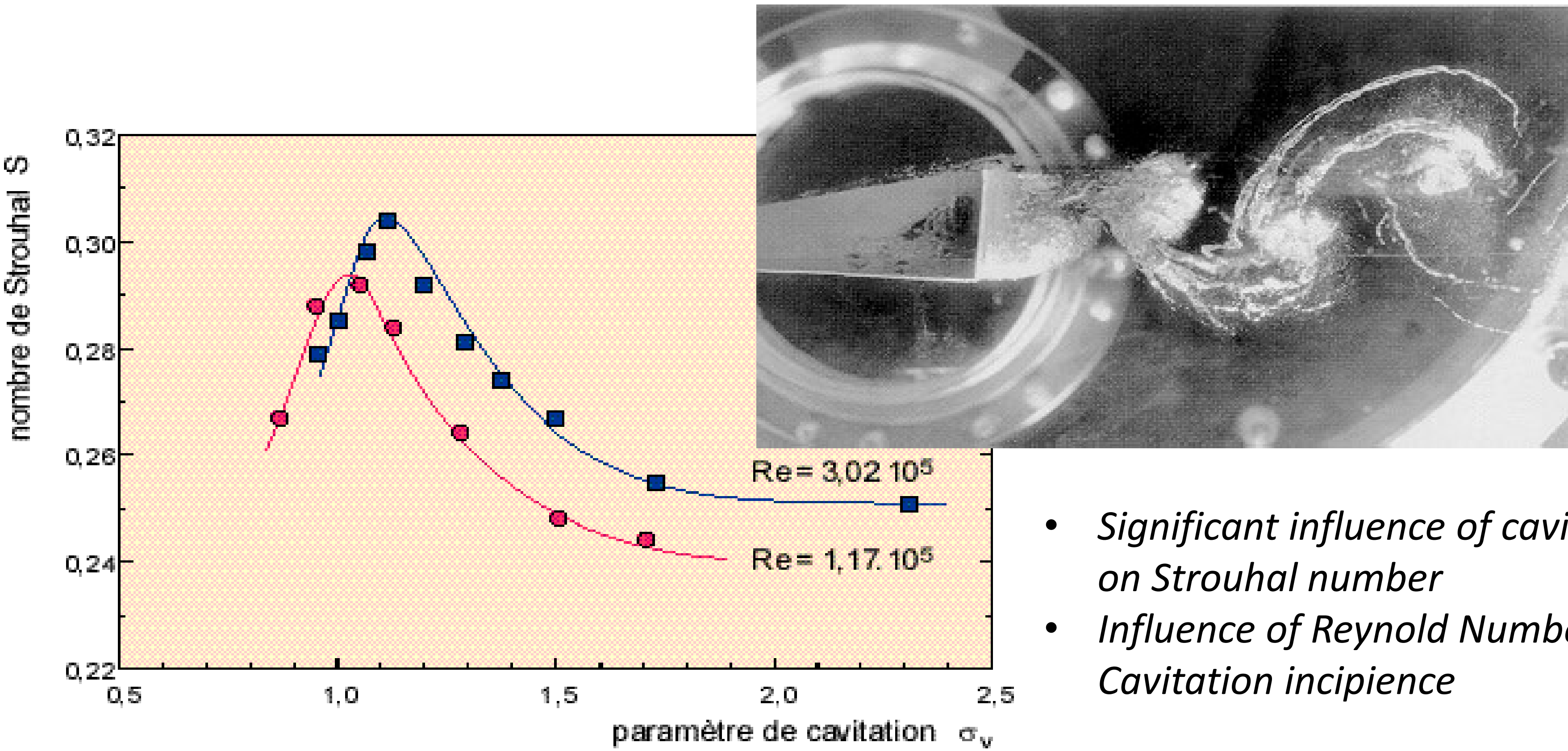
Model of Kaplan turbine



Cavitation Types

- **(3) Vortex Cavitation**
  - **Cavitation may develop in a vortex, due to the low pressure in its core**

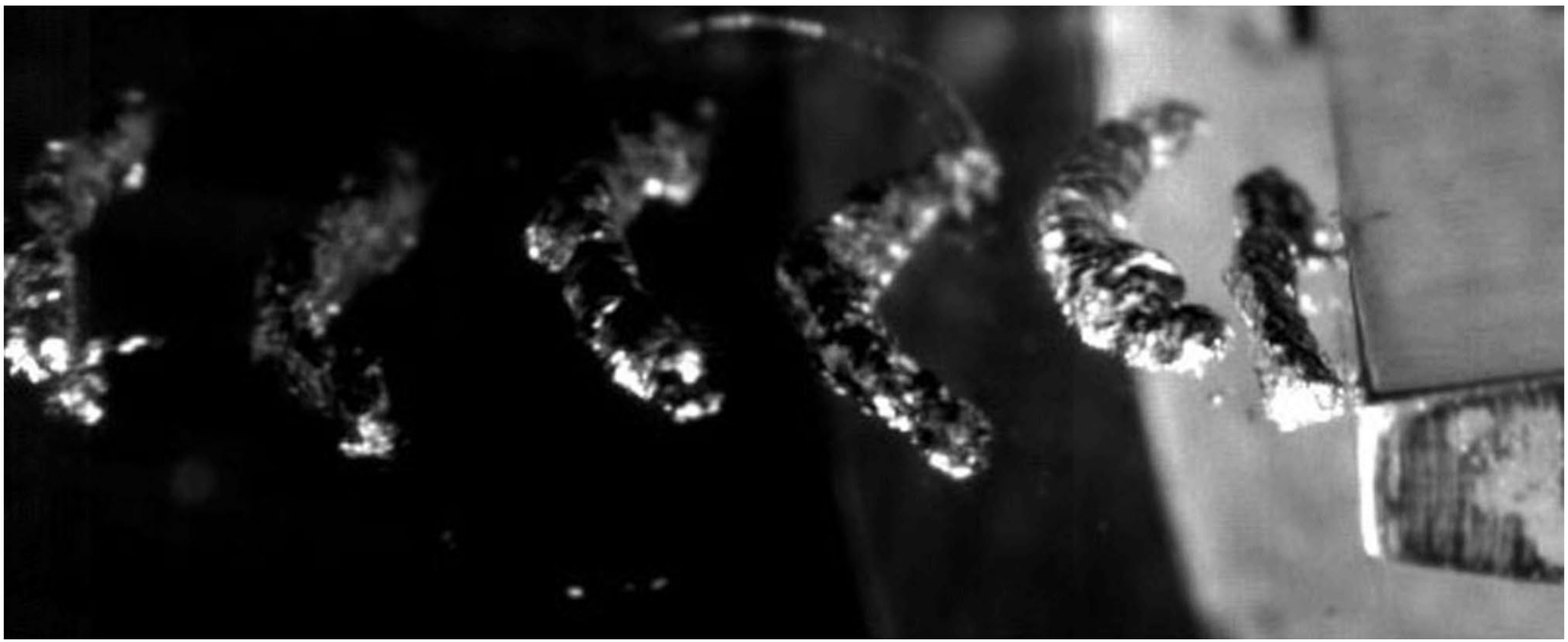
Cavitation in the wake of an obstacle (Von karman Vortices)



- *Significant influence of cavitation on Strouhal number*
- *Influence of Reynold Number on Cavitation incipience*

Cavitation Types

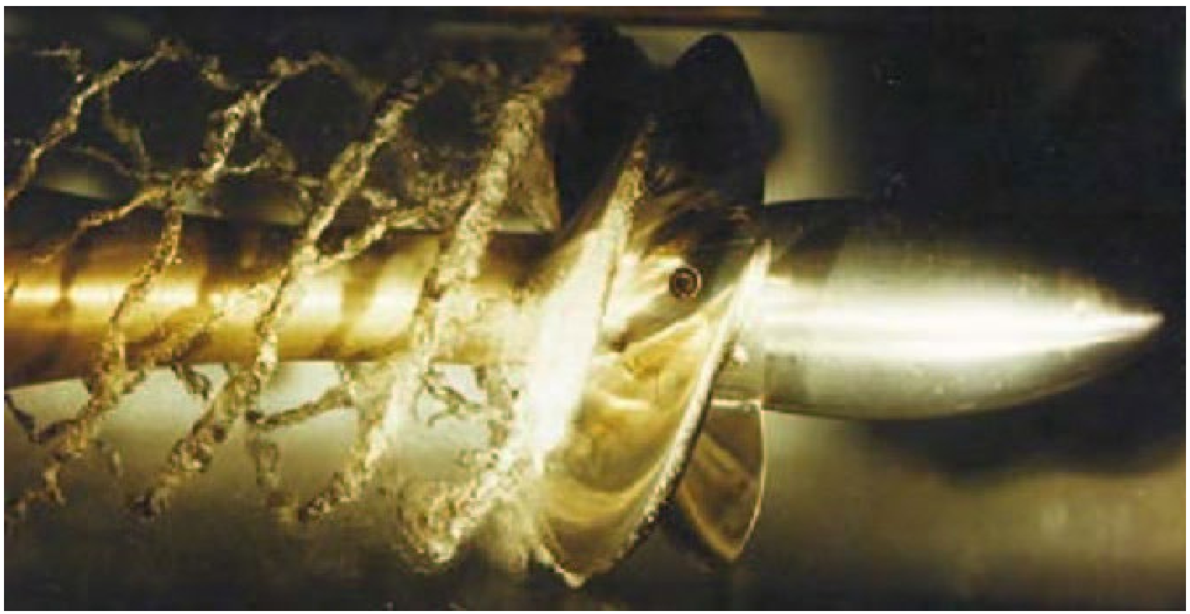
- **(3) Vortex Cavitation**
  - **Cavitation within the wake of a 2D hydrofoil**
    - **Hydro-elastic coupling:**
    Shedding frequency ~ resonance frequency of the hydrofoil (torsional mode)

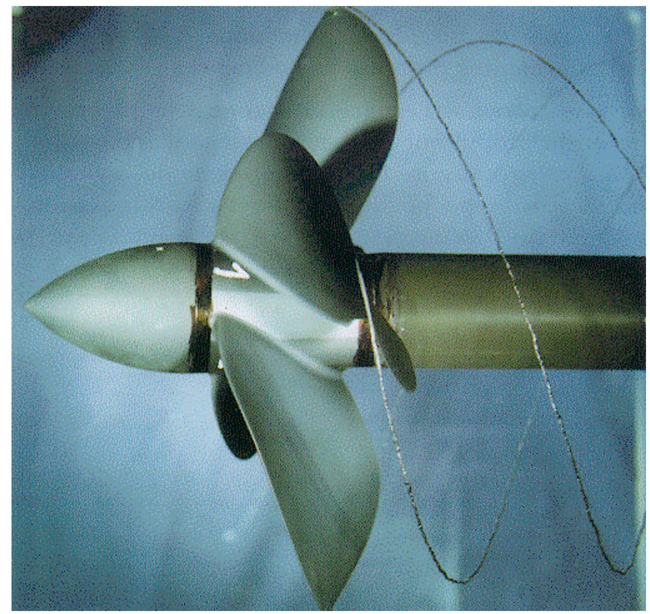


Cavitation Types

- **(3) Vortex Cavitation**

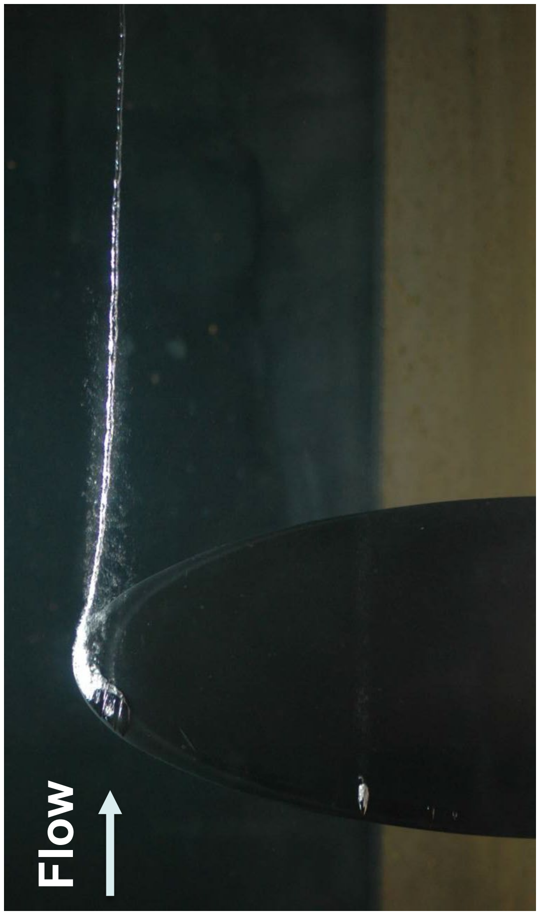
Tip vortex cavitation in marine propellers

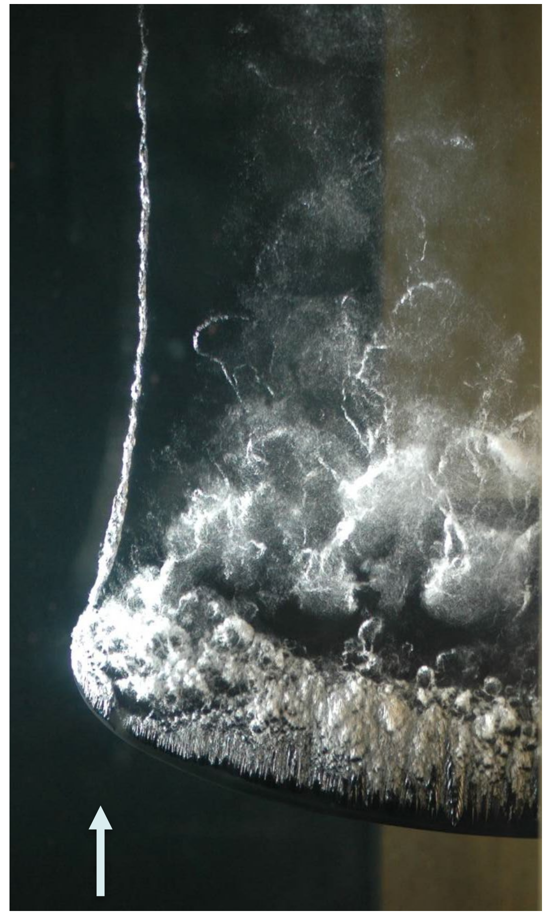




Cavitation Types

- **(3) Vortex Cavitation**
  - **Tip vortex cavitation (TVC): Case of an elliptical hydrofoil**





Cavitation Types

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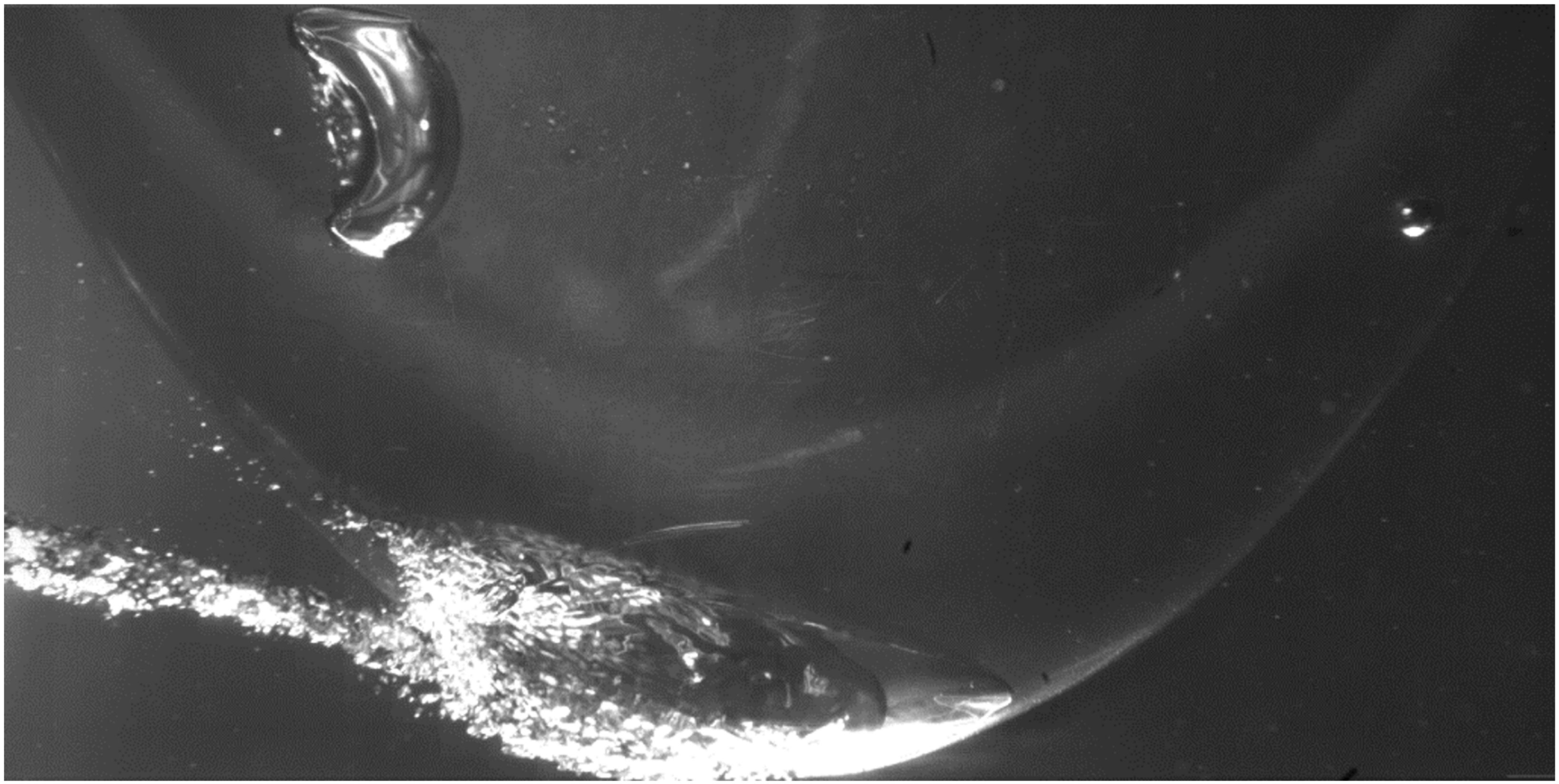
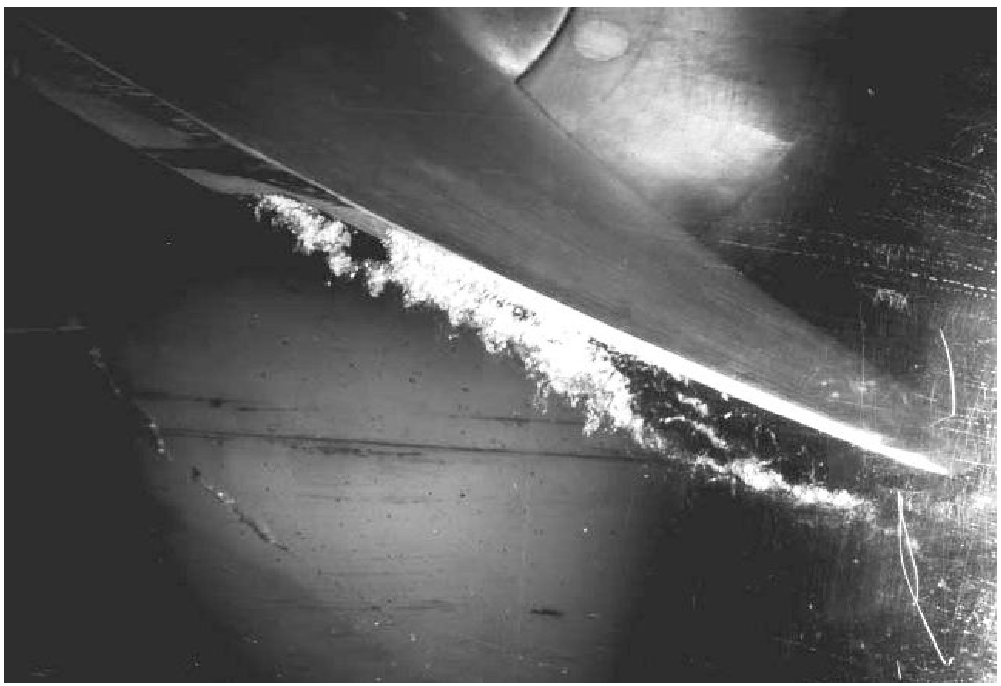


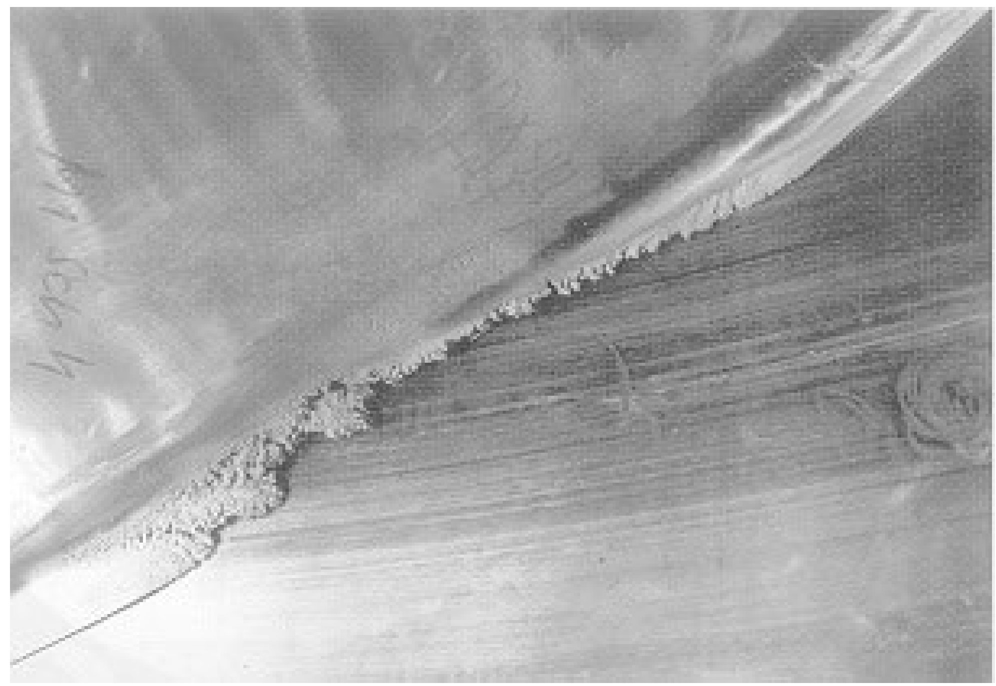
Cavitation Types

- (3) Vortex Cavitation
  - Tip leakage vortex cavitation in Kaplan turbines

Model tests

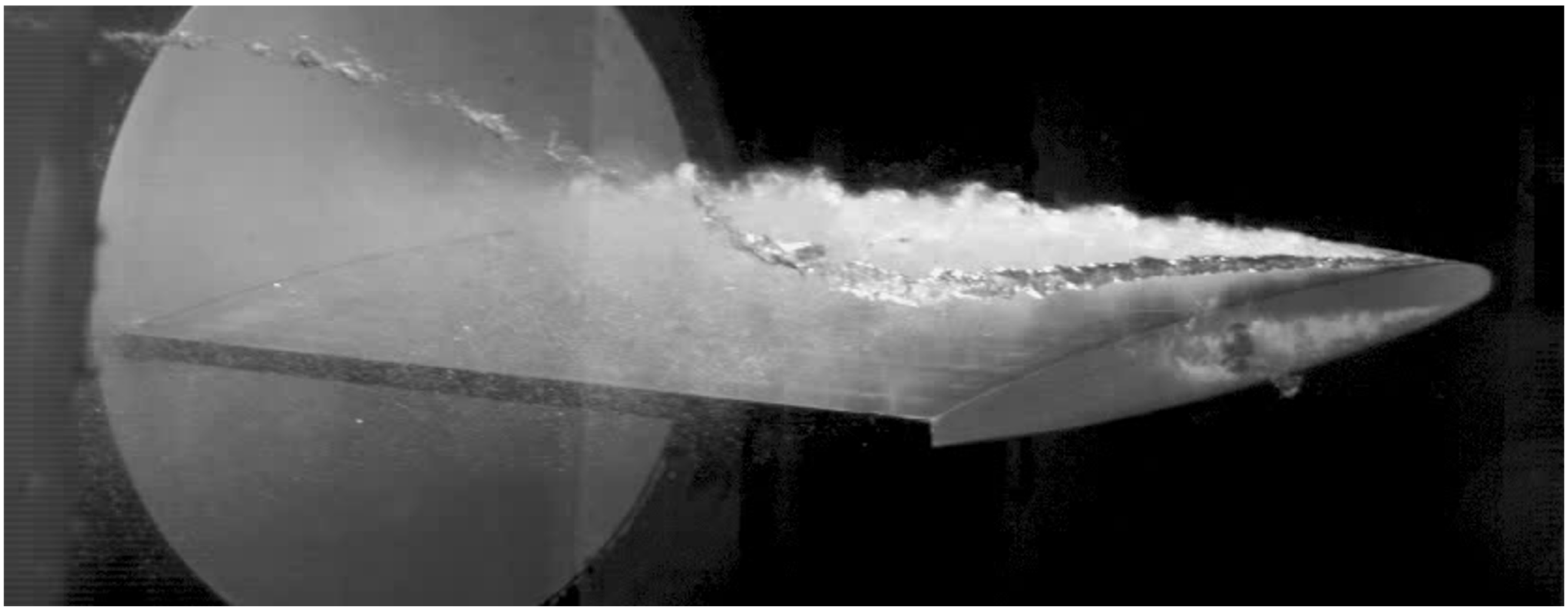


Erosion on prototype blades



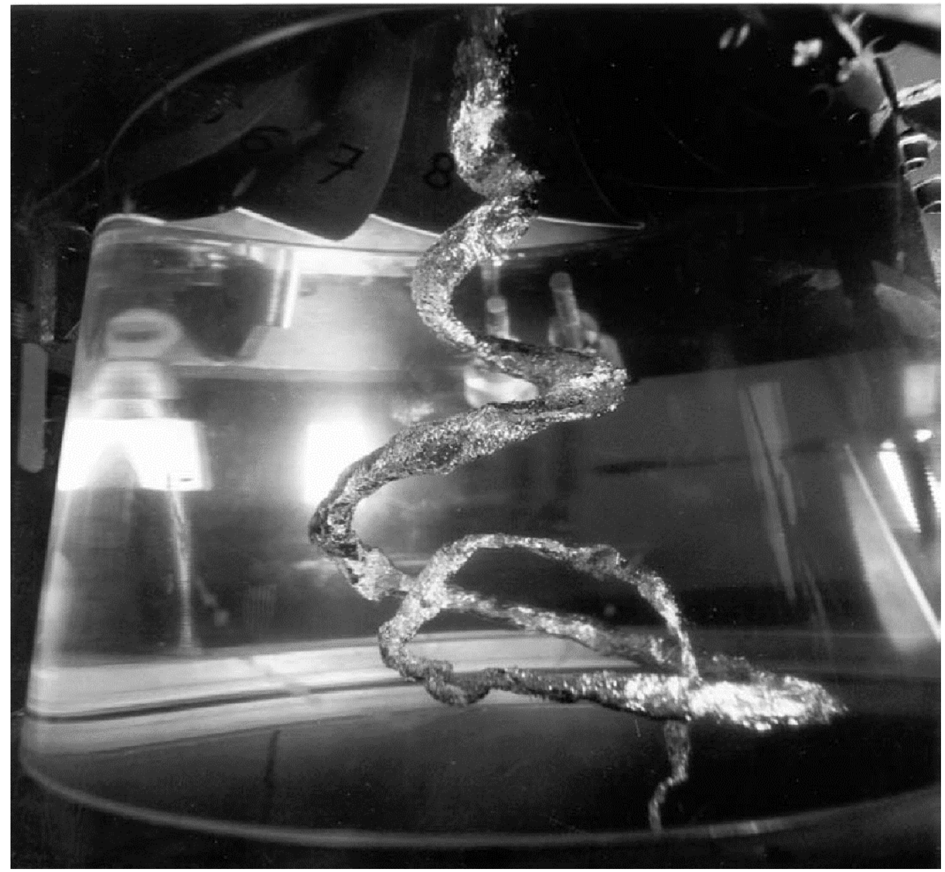
Cavitation Types

- (3) Vortex Cavitation
  - Tip leakage vortex cavitation in Kaplan turbines
    - Simplified case study: Naca009 hydrofoil in EPFL Cavitation Tunnel



Cavitation Types

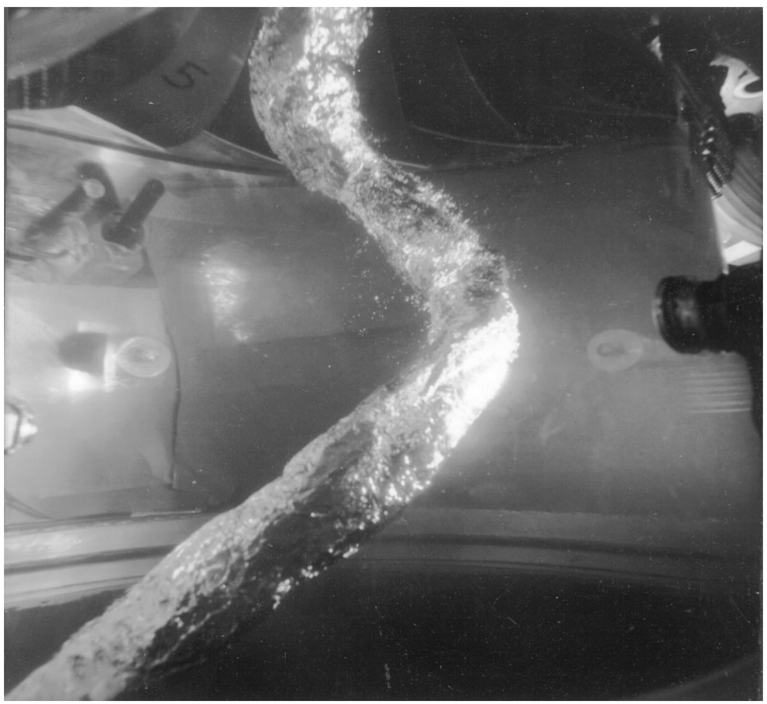
- (3) Vortex Cavitation
  - Vortex Cavitation at the outlet of a Francis turbine (Rope)
  - Due to the residual kinetic moment at part load condition
  - Source of strong hydraulic instabilities (noise and vibration)
  - No erosion



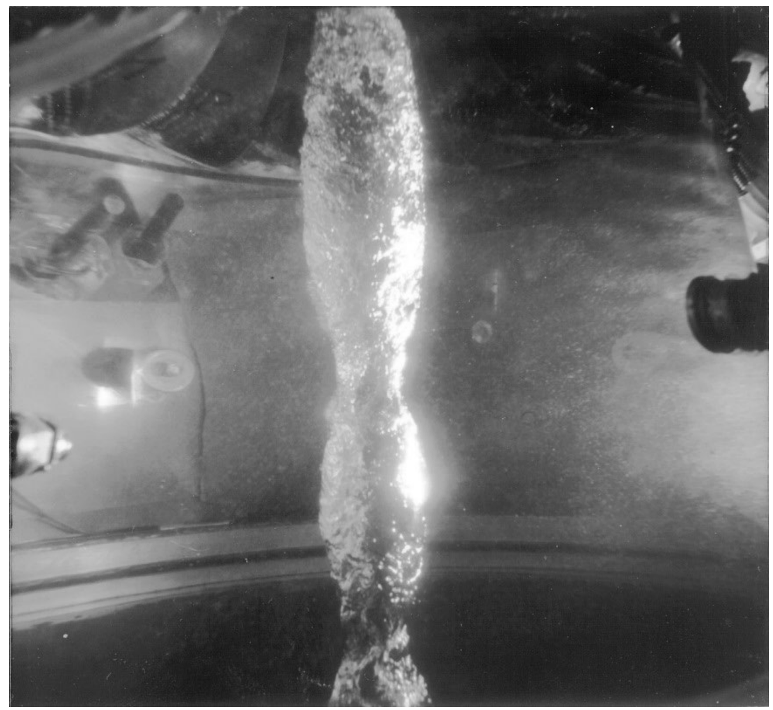
Cavitation Types

- (3) Vortex Cavitation
    - Breakdown of cavitating vortex at the outlet of Francis turbines

Part Load

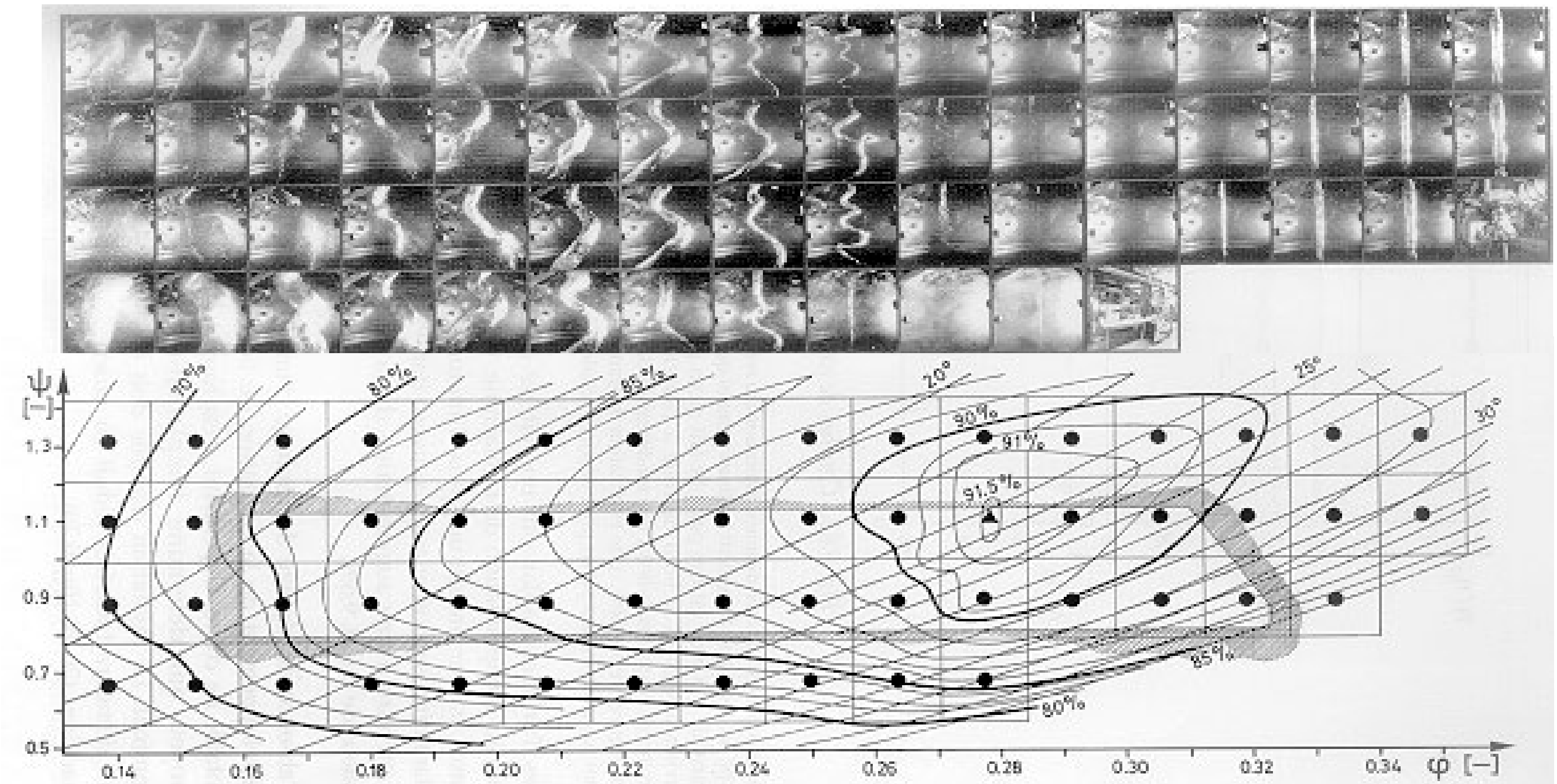


Full Load



Cavitation Types

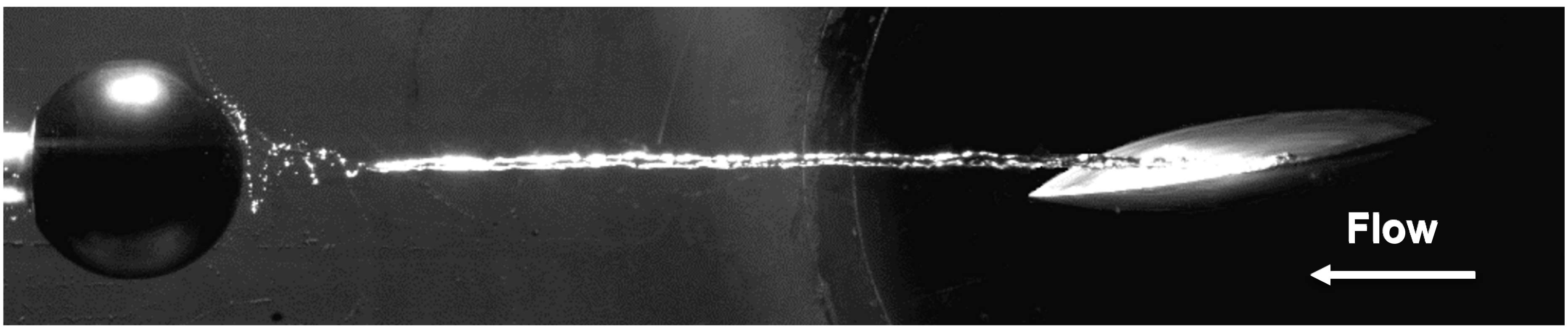
- **(3) Vortex Cavitation**
  - **Rope development in a Francis turbine**
    - **Typical rope shape as a function of operating point (efficiency hill chart)**



Cavitation Types

- (3) Vortex Cavitation

- Vortex Breakdown reproduced in EPFL Cavitation Tunnel
  - Obstacle-induced spiral vortex breakdown
  - Stagnation point → Axial velocity reduction → Vortex breakdown
  - Mechanism of onset and development of the vortex breakdown ?
  - Effect of cavitation on vortex breakdown ?



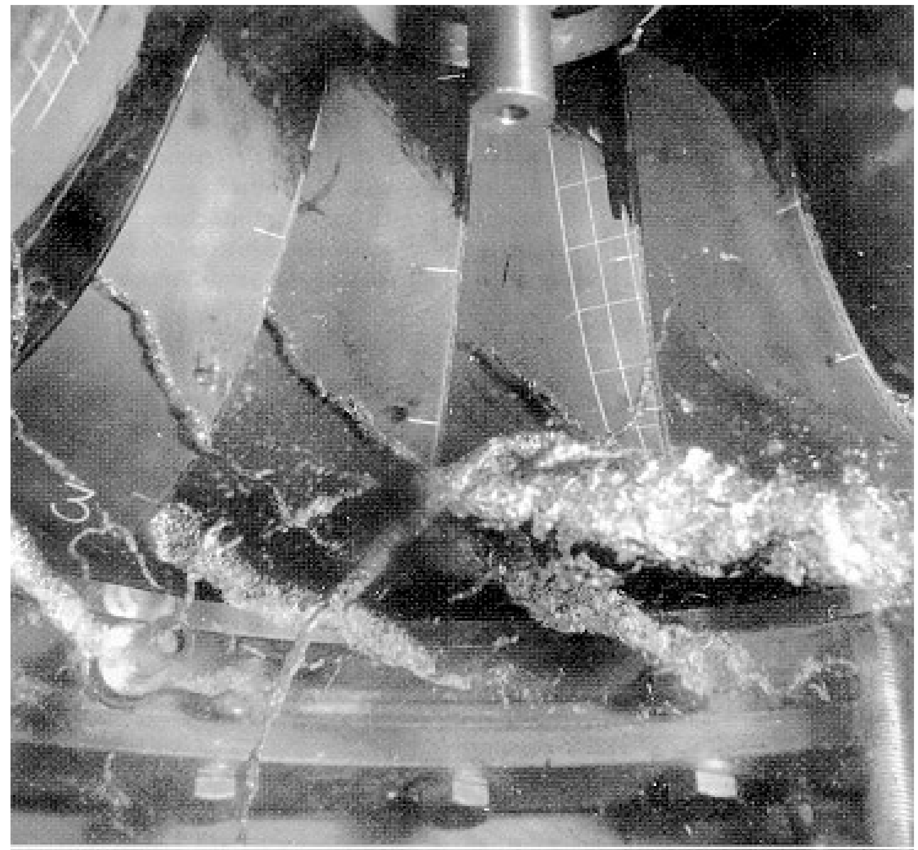
Pasche et al., Experiments in Fluids, 2014 (Master thesis)

Cavitation Types

- (3) Vortex Cavitation

  - Inter-blade vortices
    - Low head Francis turbine
    - Development of cavitating vortices between the blades at part load conditions

  - Highly unstable → strong vibration → Premature cracks of the blades

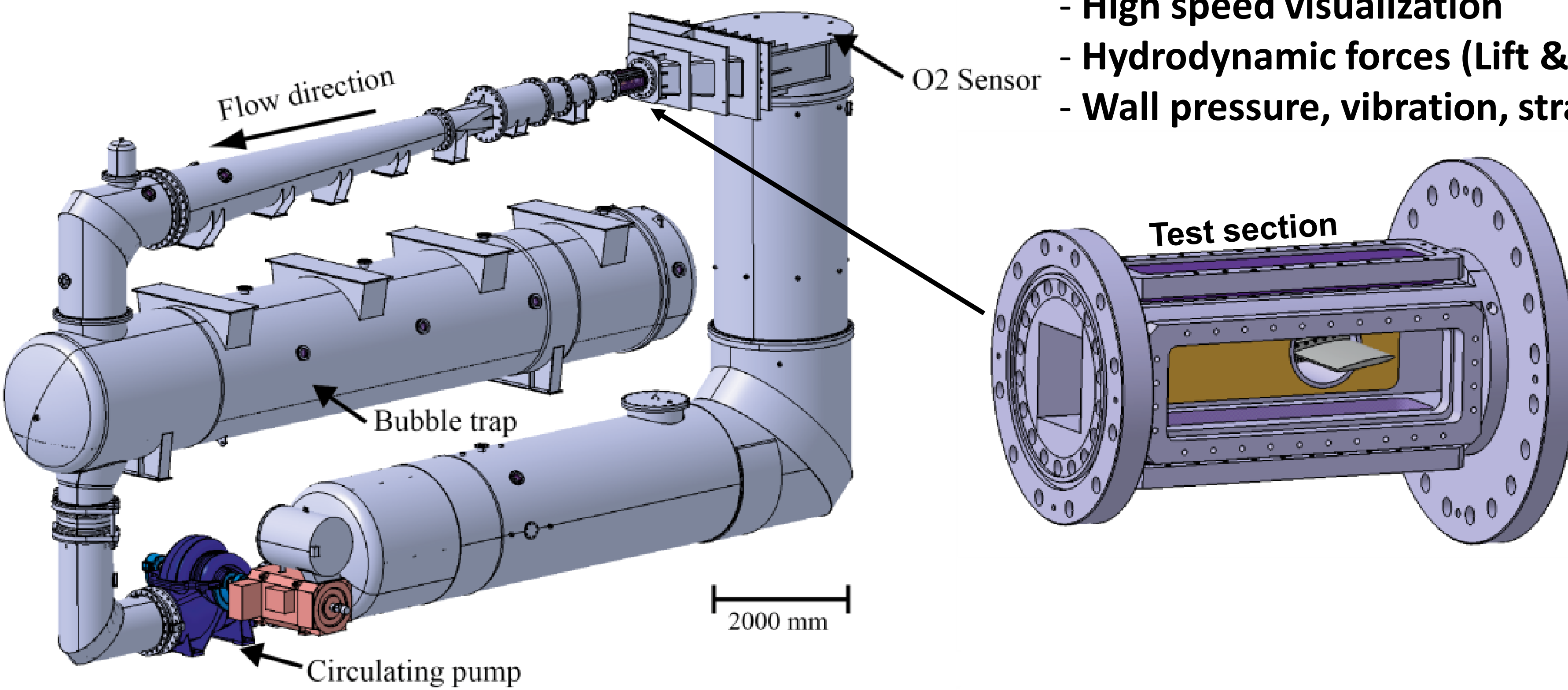


Inter-blade vortices in a Francis turbine model

EPFL Infrastructure for Cavitation Studies

- **High Speed Cavitation Tunnel**
  - **150 x 150 x 750 mm Test Section**
  - **Max Flow Velocity : 50 m/s**
  - **Max Pressure : 20 bar**

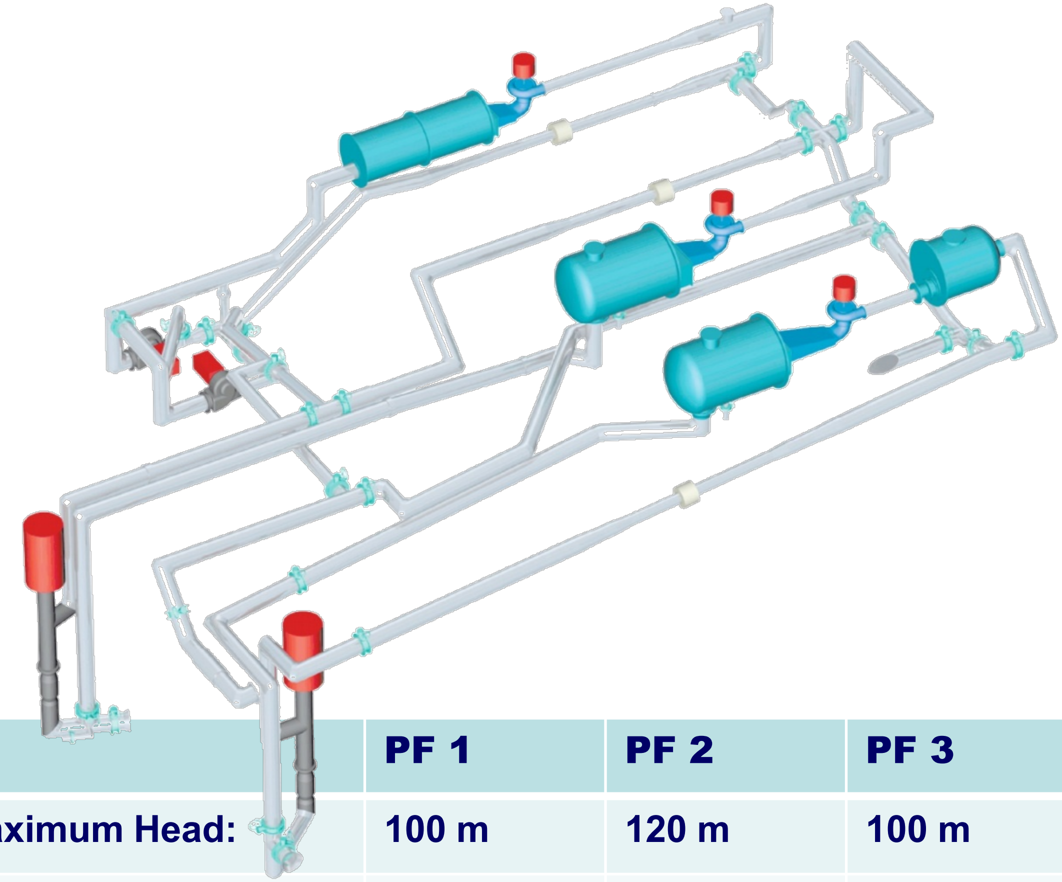
- **Variety of 2D and 3D hydrofoils**
- **State of the art instrumentation:**
  - **Non intrusive techniques for velocity survey (LDV, PIV)**
  - **High speed visualization**
  - **Hydrodynamic forces (Lift & Drag)**
  - **Wall pressure, vibration, strain, …**

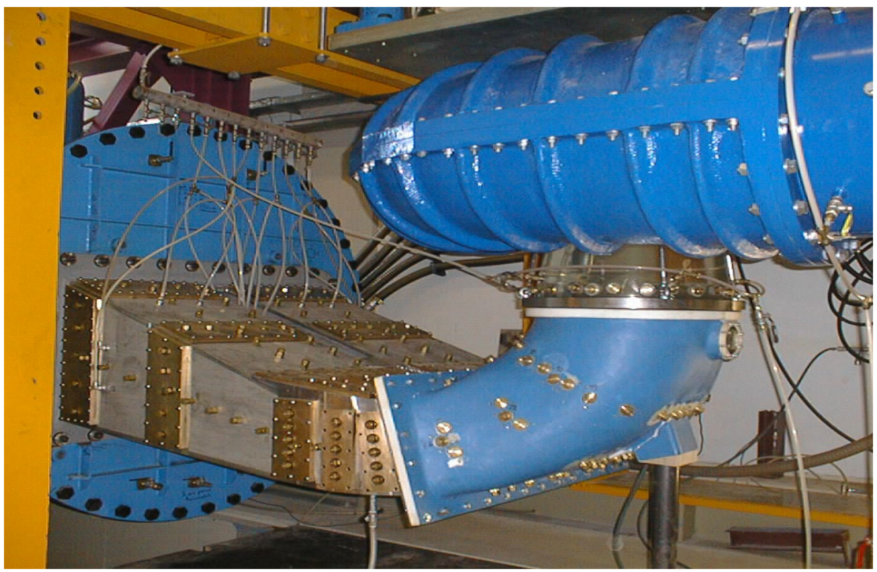


EPFL Infrastructure for Cavitation Studies

- **3 Independent Test Rigs for Turbines and Pumps Models**

- **IEC 60193 Testing Facilities Measurement Accuracy < 2 ‰**



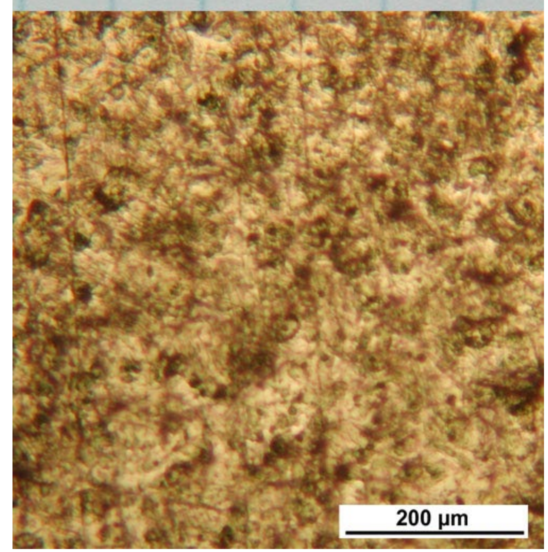


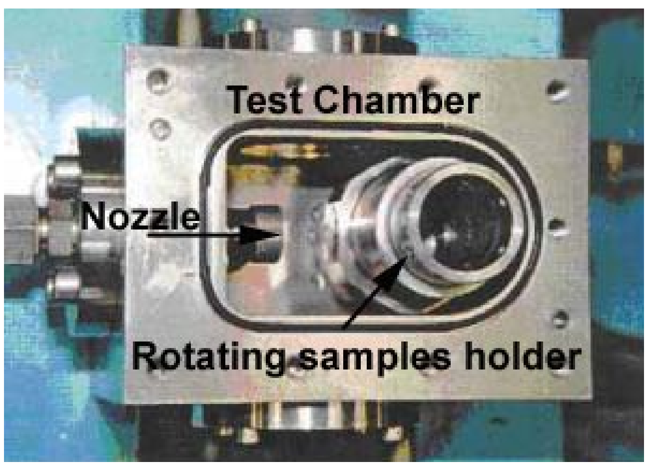
	PF 1	PF 2	PF 3
Maximum Head:	100 m	120 m	100 m
Maximum Discharge:	1.4 m^3/s	1.4 m^3/s	1.4 m^3/s
Generating Power	300 kW	300 kW	300 kW
Pumping Power	900 kW	1’000 kW	2x400 kW
Max Speed	1’500 rpm	1’500 rpm	1’500 rpm

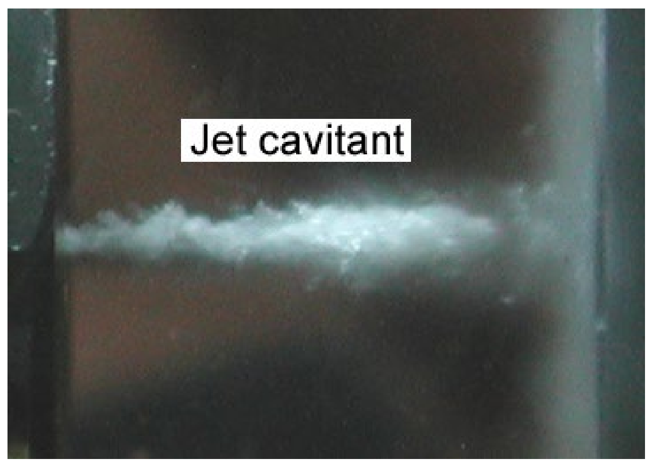
EPFL Infrastructure for Cavitation Studies

- **High speed cavitating jet for erosion tests**
  - **Jet diameter: 0.5 mm**
  - **Jet speed: 200 m/s**
  - **Driving pressure: 300 bar**

  - **Mass loss measurement**
  - **Microscopic observations**

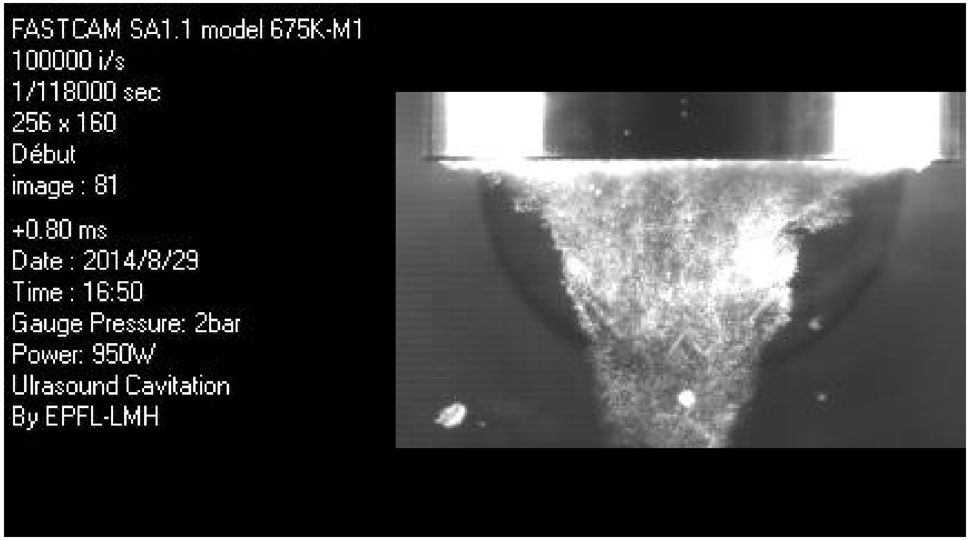




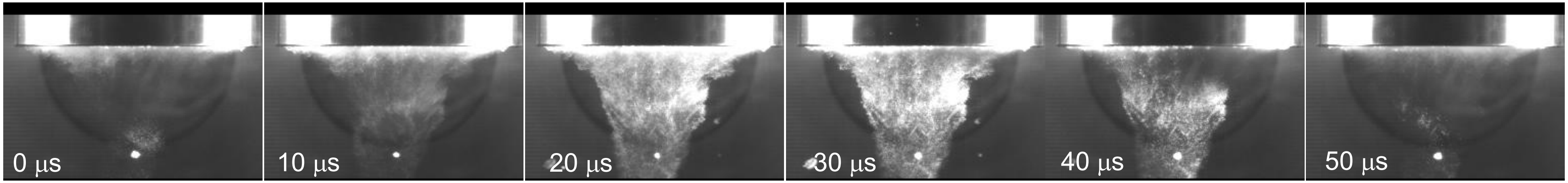


EPFL Infrastructure for Cavitation Studies

- Ultrasound cavitation for erosion tests (Sonication)
    - 5 cm diameter sonotrode: Freq. ~ 20 KHz, Power ~ 1 Kwatt



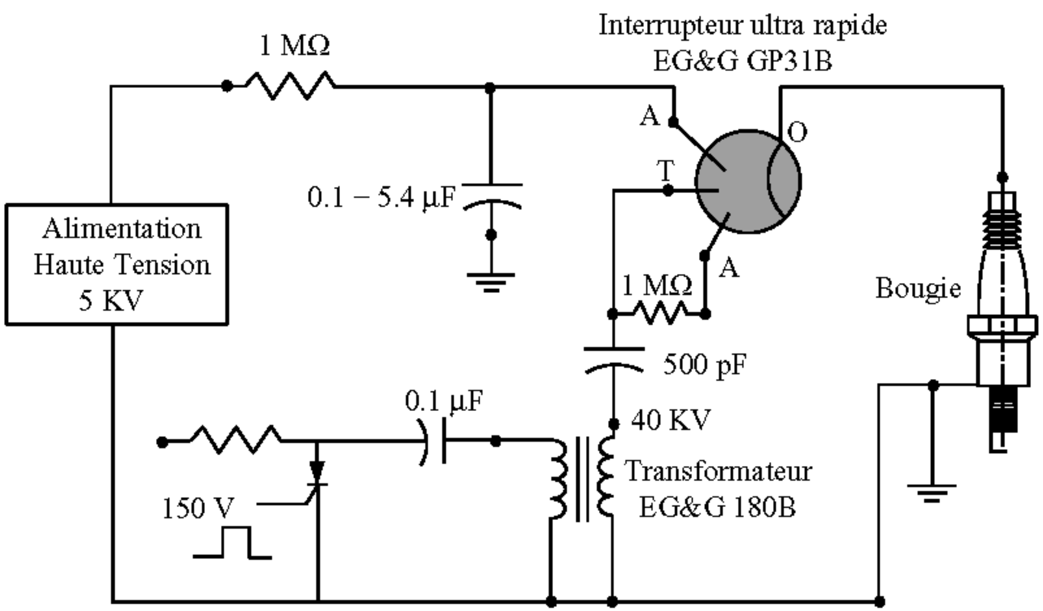
    - High speed visualization of one sonication cycle

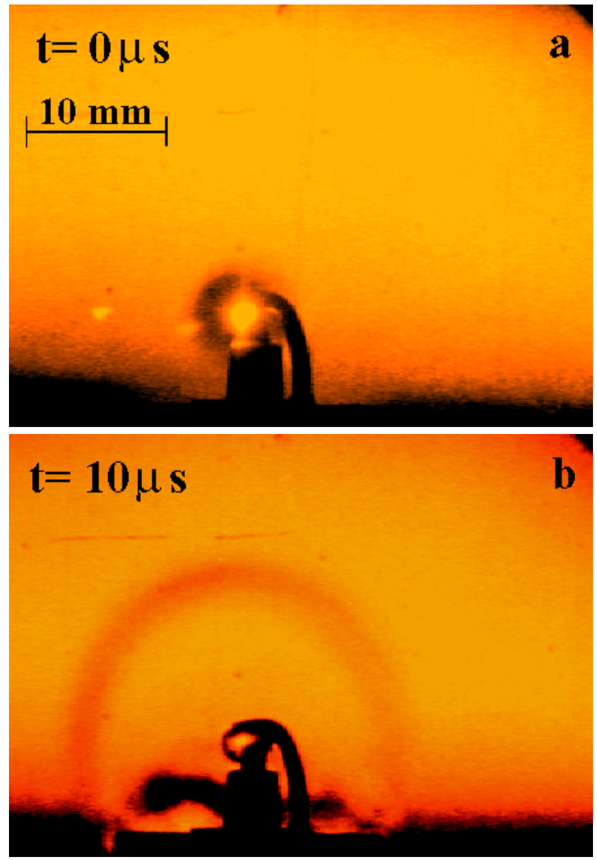


EPFL Infrastructure for Cavitation Studies

- **Spark-induced cavitation bubble in still liquids**
  - **Spark Generator:**

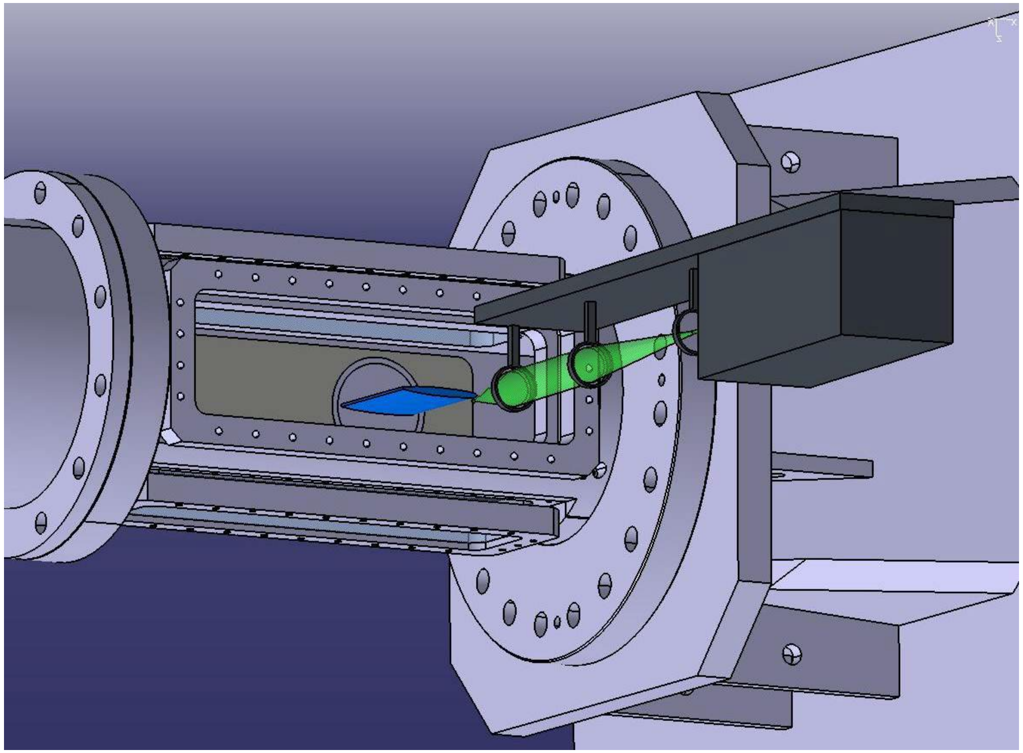
    Electric discharge → Growth & collapse of a ~spherical bubble

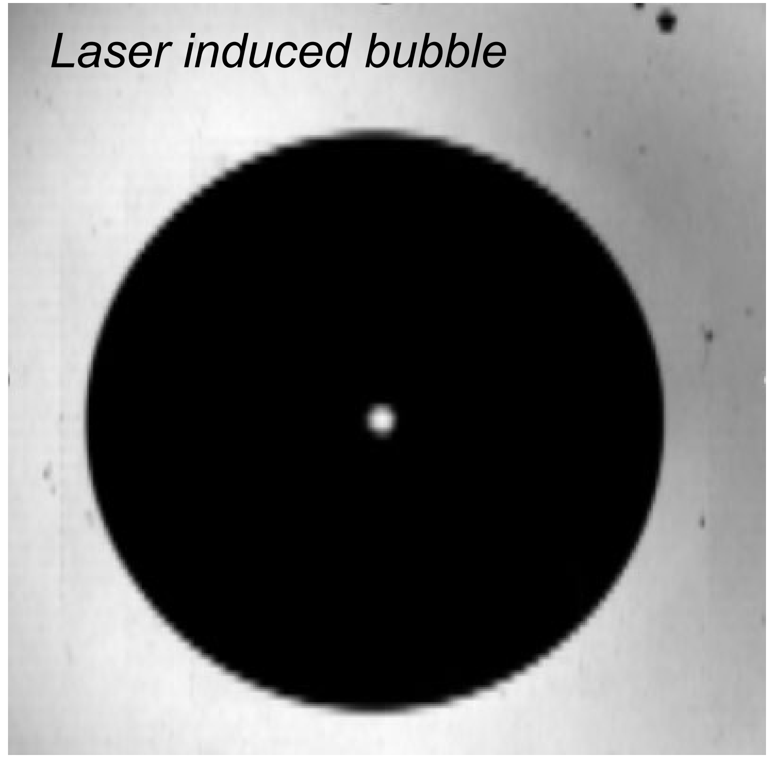




EPFL Infrastructure for Cavitation Studies

- **Laser-induced cavitation bubble in still or flowing liquids**
    - **Focused laser pulse → Growth and collapse of a ~spherical bubble**
    - **Non intrusive (flowing liquids)**





EPFL Infrastructure for Cavitation Studies

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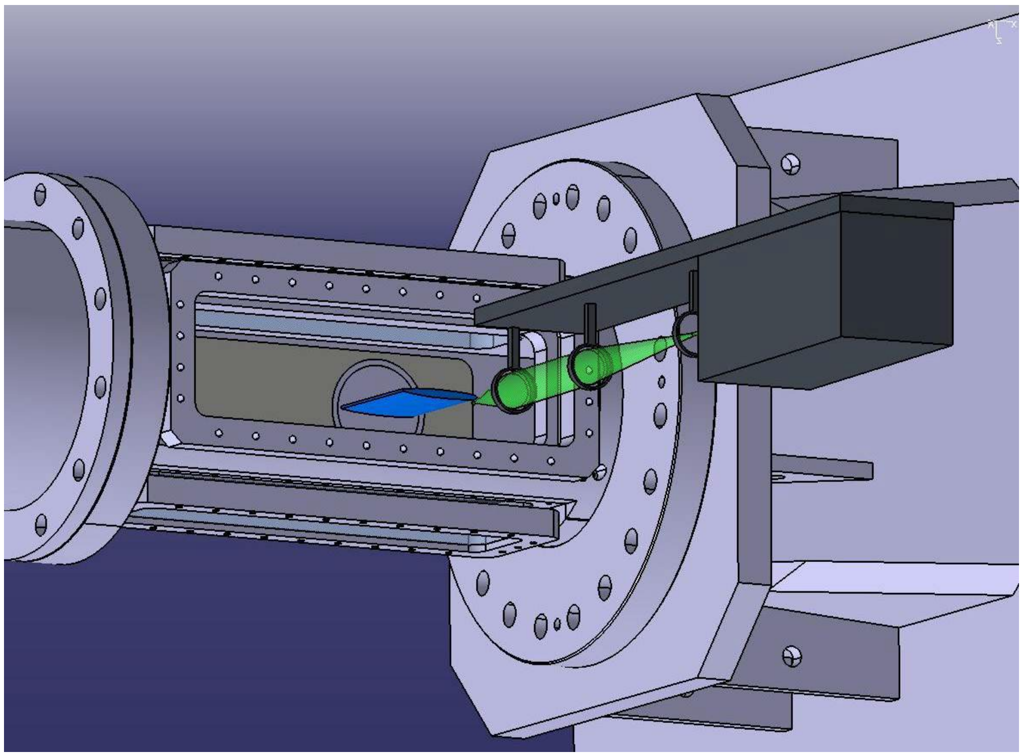


Laser induced bubble

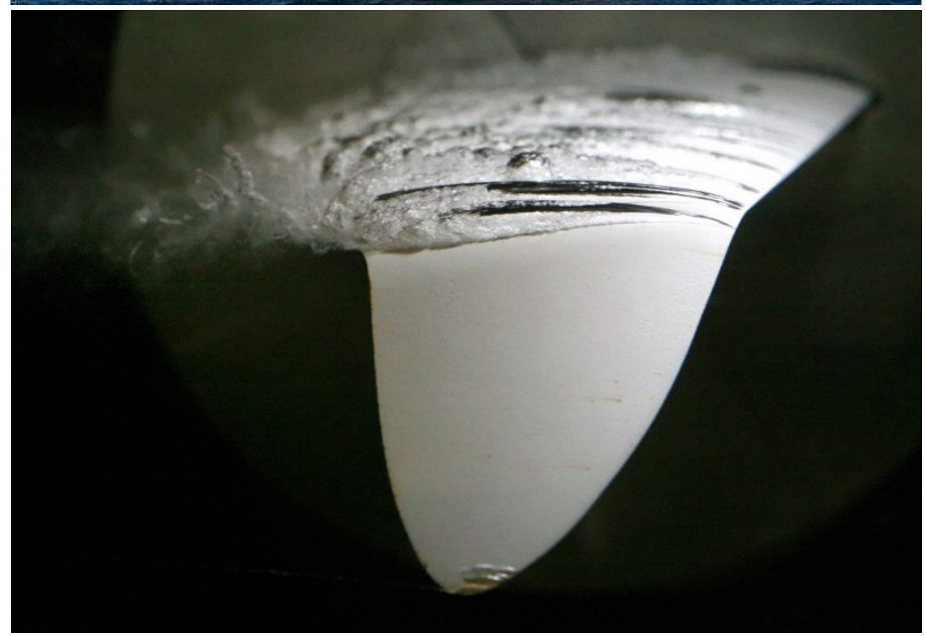
Application: High speed sailing: Hydroptere

- **Partnership EPFL – Hydroptere**
  - **Record speed achieved on Sep. 2010: 55 knots over 1 mile**

- **Major limitation: Cavitation on lifting foils**

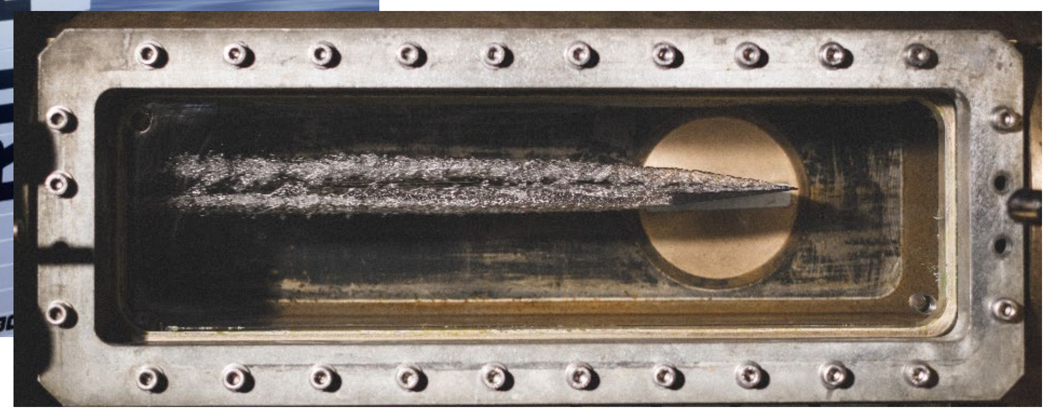
Cavitation may occur in any body moving in water at high-speed (~50 knots).

- **Side view of cavitation development on a reduced scale mode of the Hydroptere lifting foil, tested in EPFL Cavitation Tunnel**



Application: High speed sailing

- Partnership EPFL – SP80 (Ongoing project)
  - Goal: Break the speed record (>80 knots)
  - Innovation: Lifting foils with ventilation and/or super-cavitation

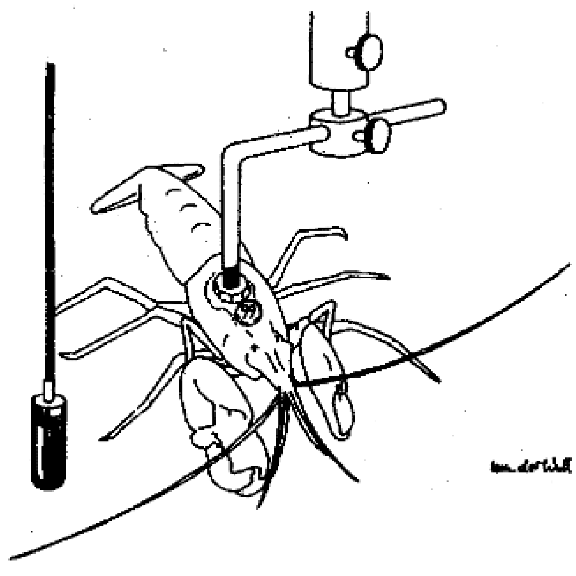


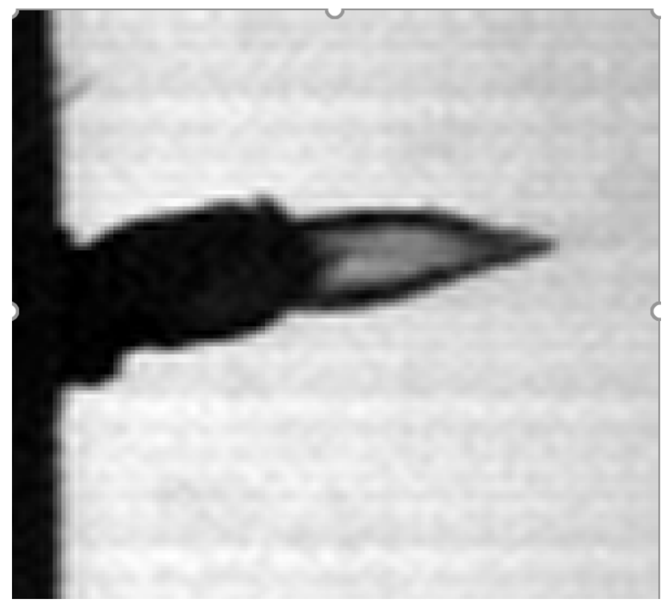
Application:

Cavitation in nature: Snapping (or Pistol) shrimps

Snapping shrimps are the noisiest creatures in the shallow ocean (Mexican Gulf, USA), capable of drowning out submarine sonars by large band noise

High frequency noise is not due to mechanical shock but to cavitation



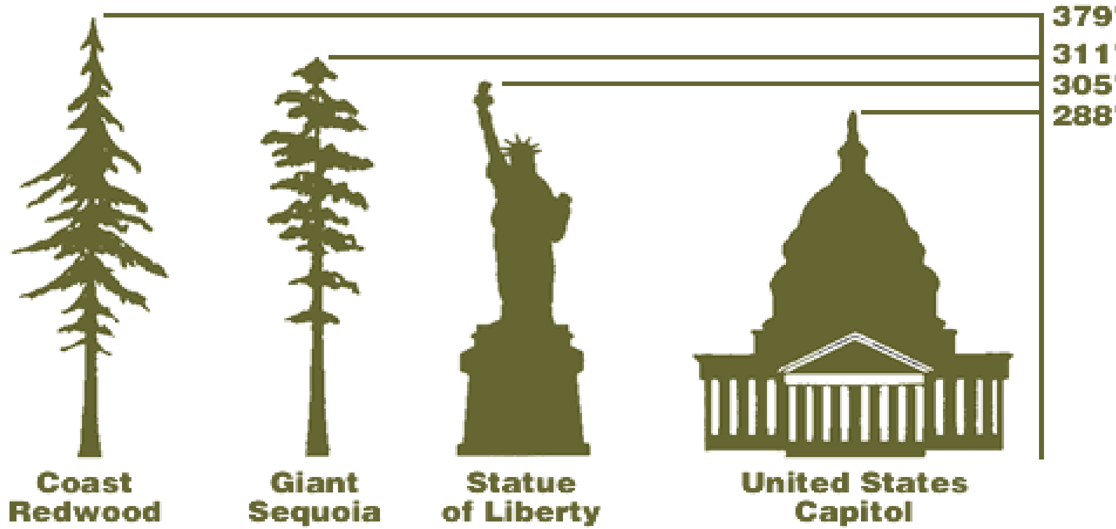


Application:

Cavitation in nature: water ascent in giant trees

- **Giant Sequoia trees may be 115 m high**
- **Historical record: 135 m (Eucalyptus)**

- **Sap (Water + Nutrients) is pumped through tiny pipes (Xylem) from the root to all leaves, without cavitation**
  - **How come ? (open question)**



Application:
Cavitation in nature: Human body

Cracking sound produced by fingers is due to cavitation of the synovial fluid

Source: ”Real-Time Visualization of Joint Cavitation”, Gregory et al, Plos One 2015

Fig 1. The radiofrequency coil inside the clear housing (left). The metocarpophaangeal (MCP) joint of interest centred over the bore of the radiofrequency coil (middle). The participant's hand within the imaging magnet (right).

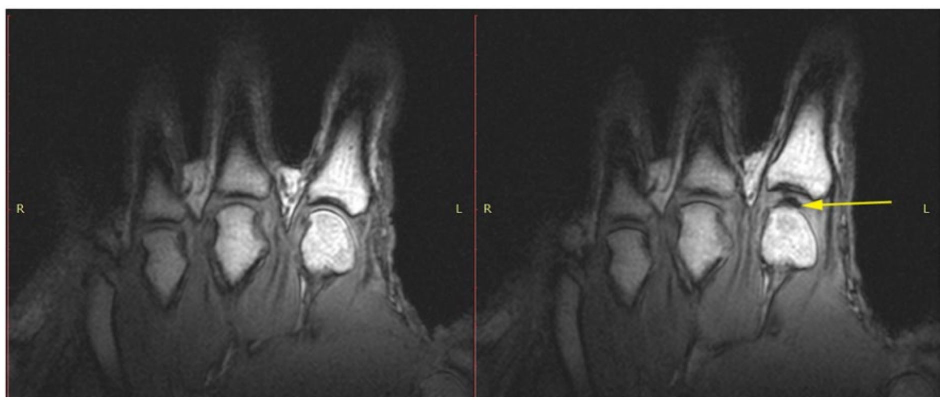


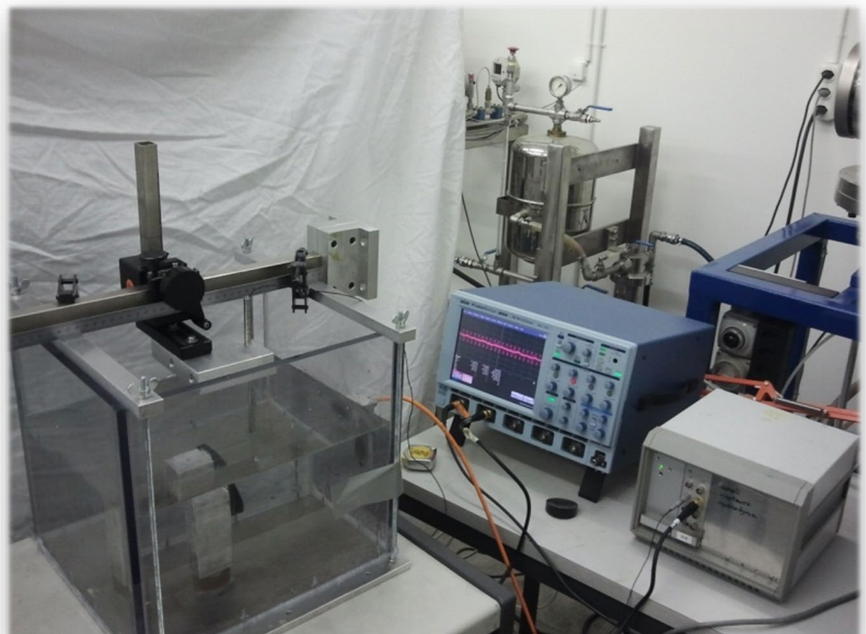
Fig 2. T1 static images of the hand in the resting phase before cracking (left). The same hand following cracking with the addition of a post-cracking distraction force (right). Note the dark, interarticular void (yellow arrow).

Application: Medical

- **"Lipocavitation" to lose weight :**

  Ultrasound induced cavitation within human body is supposed to eliminate fat ?

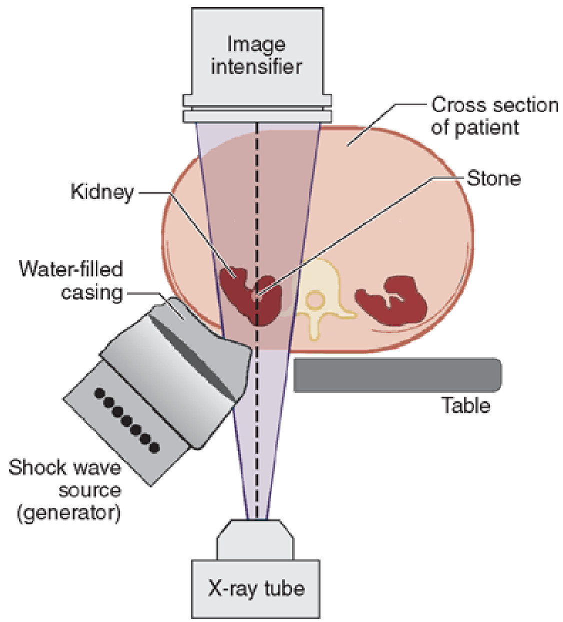
EPFL Semester project:
Cavitation produced by focused ultrasonic waves for non-intrusive adipose tissue lysis
A. Cayron, Th. Curran



Application: Medical

Extracorporeal Shockwave Lithotripsy
The Art of Breaking Kidney Stones

- **Extracorporeal application of single acoustic focused waves.**
- **Early devices used a spark discharge inside an ellipsoidal reflector, wave is re-focused on kidney.**
- **X-ray imaging for monitoring**



Source: Butterworth JF, Mackey DC, Wasnick JD: *Morgan & Mikhail's Clinical Anesthesiology*, 5th Edition: www.accessmedicine.com

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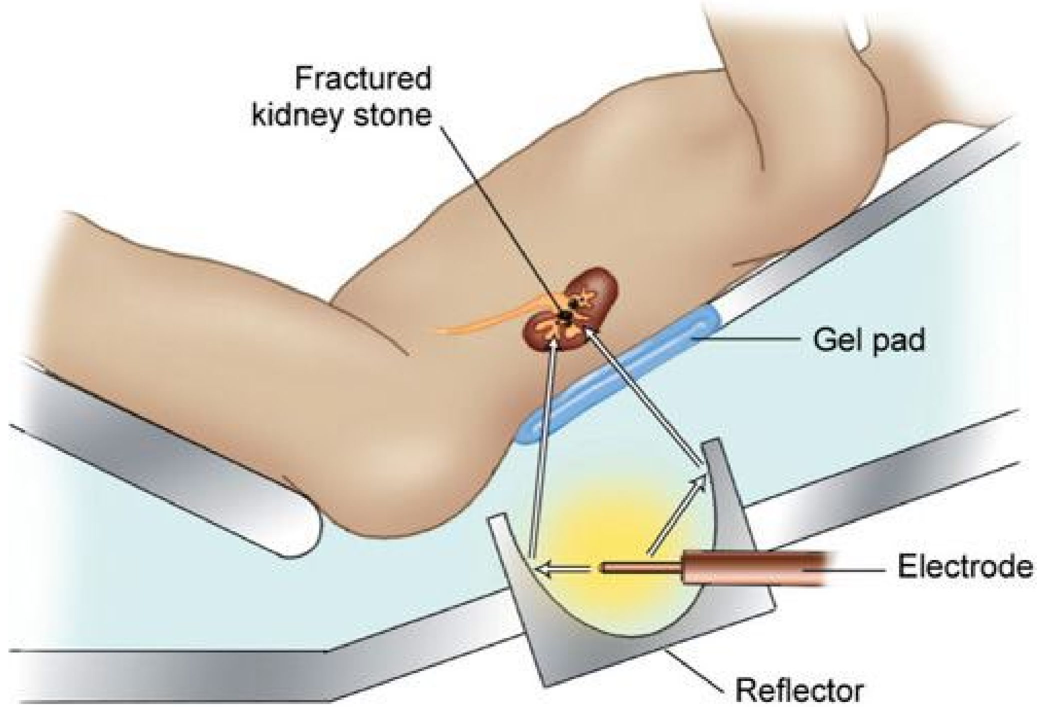
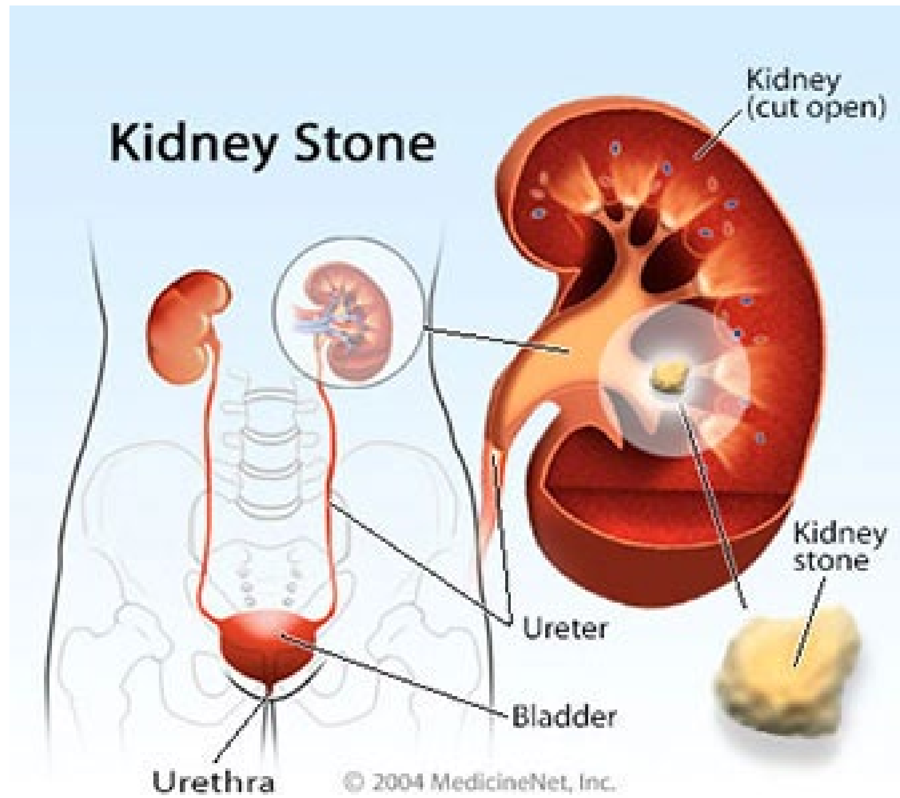


Application: Medical

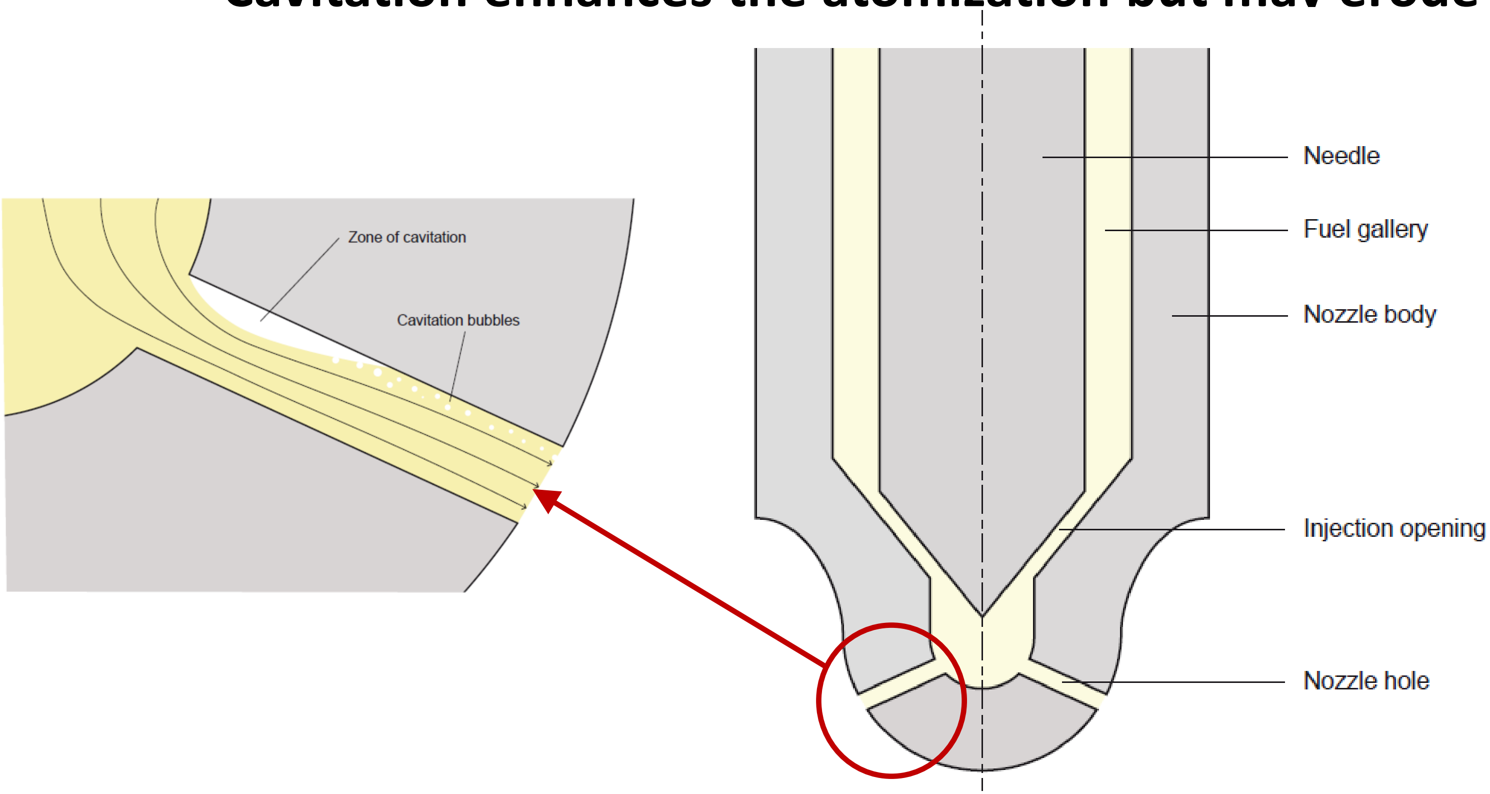
Extracorporeal Shockwave Lithotripsy
The Art of Breaking Kidney Stones

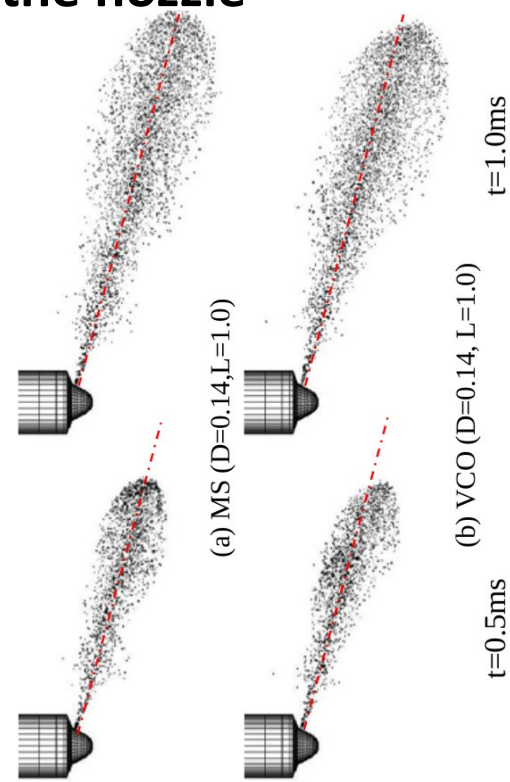
- Single shock waves are administered at heart beat rate
- ~2000-3000 shocks to crush kidney stones of 1-2mm diameter.
- Local anesthesia, ambulant treatment.
- Very few side effects.



Application:
Cavitation issue in Modern Diesel Injectors

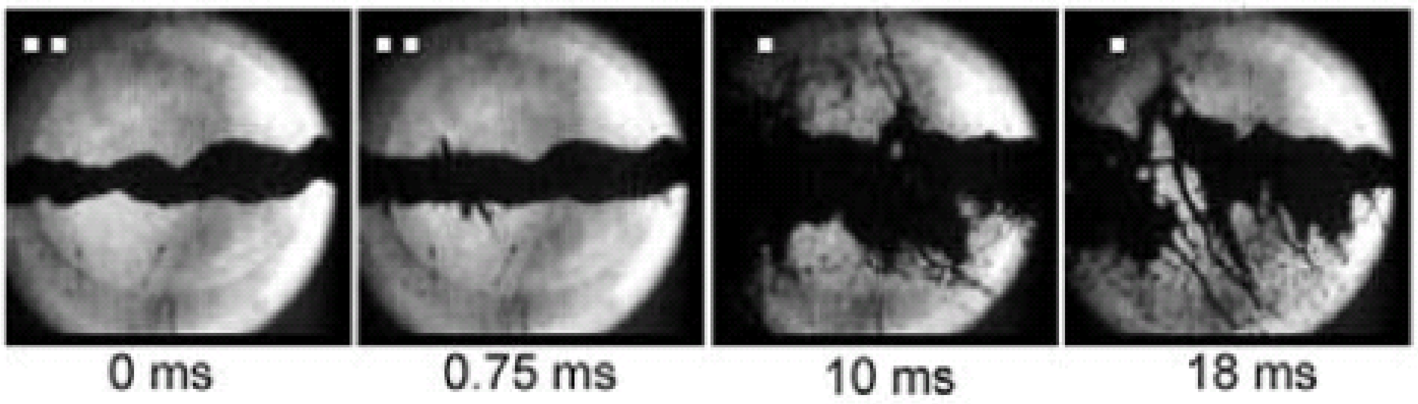
- **High pressure (> 2000 bar), confined nozzles (Diameter < 200 mm):**
- **Cavitation always occurs within the nozzle:**
    - **Cavitation enhances the atomization but may erode the nozzle**





Cavitation in mercury jets with the collaboration of the European Centre for Nuclear Research (CERN), Geneva

The issue: High instabilities observed in the mercury jet, used as metallic target in the CERN neutrino factory

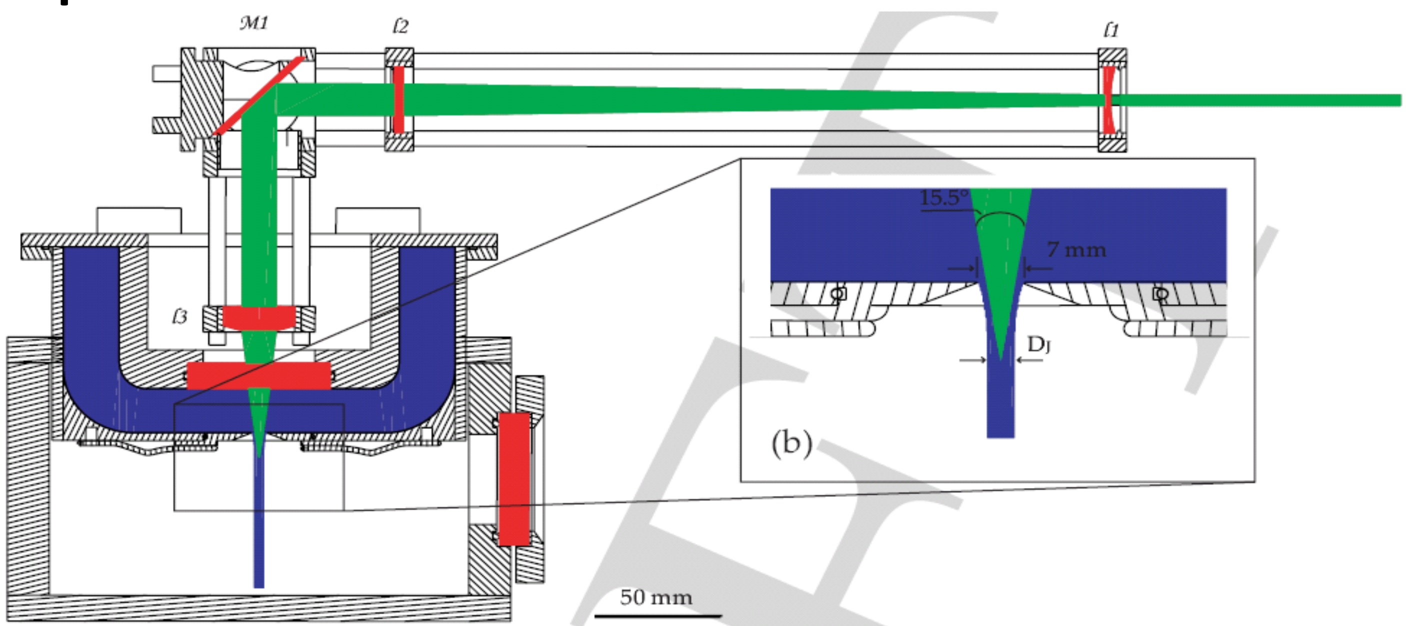


Mercury jet (10 mm diameter) at 2.5 m/s exposed to a pulse of 3.8×10^{12} 24 GeV protons. Photo courtesy of the BNL E951 experiment, first published in Kirk et al. (2001)

Interaction of a cavitation bubble with a cylindrical free surface

Experimental Setup

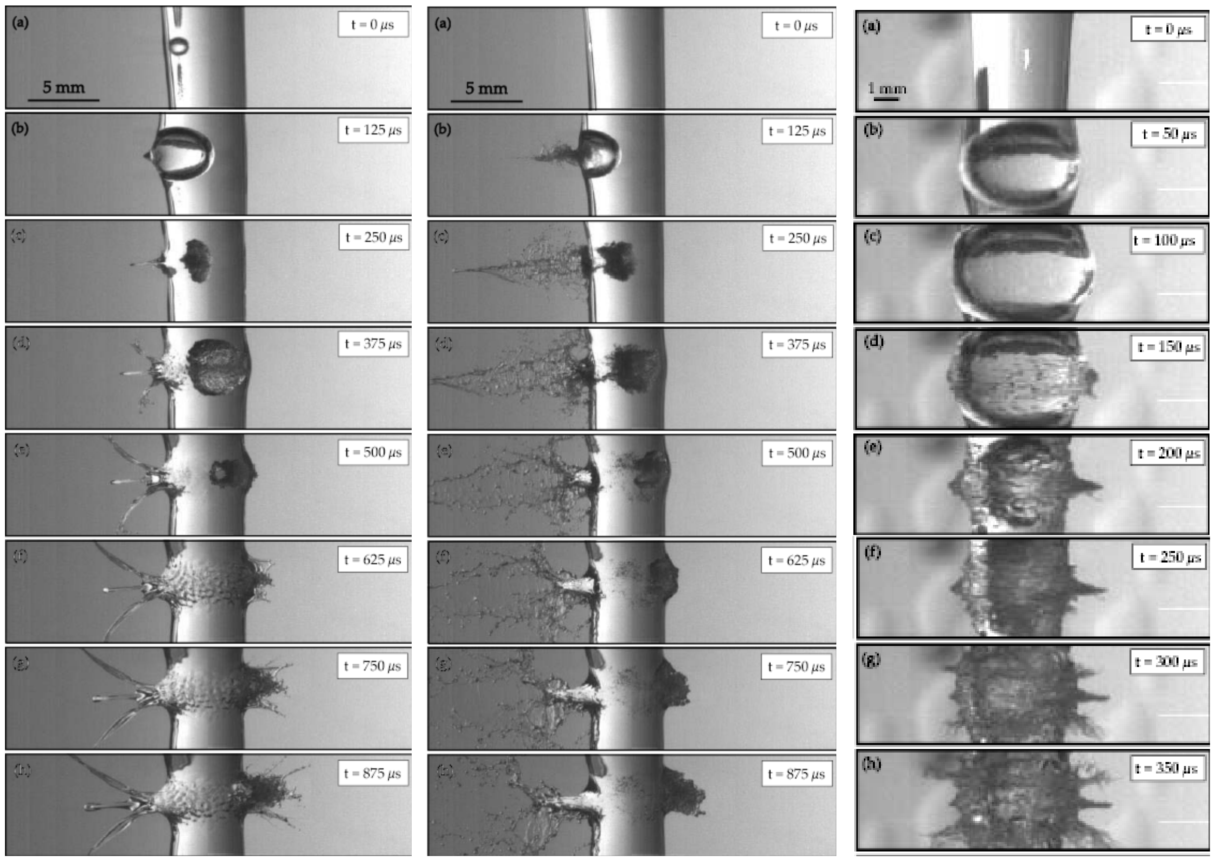
- Single cavitation bubble within a water jet
- Pulsed laser focused in the jet
- High speed visualization



Robert et al., Physics of Fluids Journal, 2007 (Master thesis)

Dynamics of a cavitation bubble within a water jet and its interaction with the free surface

High speed visualization of a laser induced bubble dynamics



Robert et al., Physics of Fluids Journal, 2007 (Master thesis)

Bubble Dynamics in Microgravity

1. Bubble in Drop
2. Effect of gravity induced pressure gradient

D. Obreschkow[2], P. Kobel[3], N. Dorsaz[1], A. de Bosset[1]

C. Nicolier[4] and M. Farhat[1],

[1]Ecole Polytechnique Federale de Lausanne, Lab. of Hydraulic Machines

[2]Physics Dep., Oxford University, United Kingdom

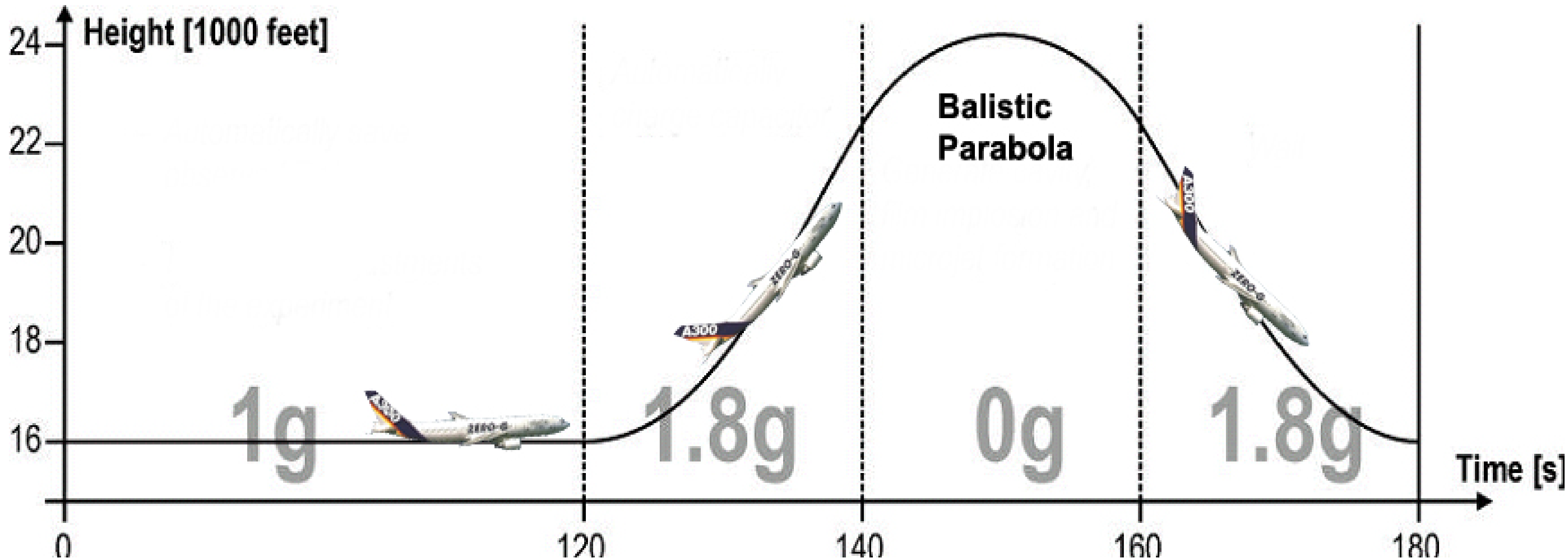
[3]Max Planck Institute for Solar System Research, Katlenburg-Lindau

[4]NASA Johnson Space Center, Houston, Texas, USA

Bubble Dynamics in Microgravity

Parabolic flight maneuver

- **Pull up and pull out phases : 20 sec, ~2g acceleration**
- **Zero- G phase: ~ 20 sec**
- **32 parabolas / flight, 2 minutes rest period between 2 parabolas**
- **Flight duration ~ 4 hours; Total duration of tests: ~10 minutes**



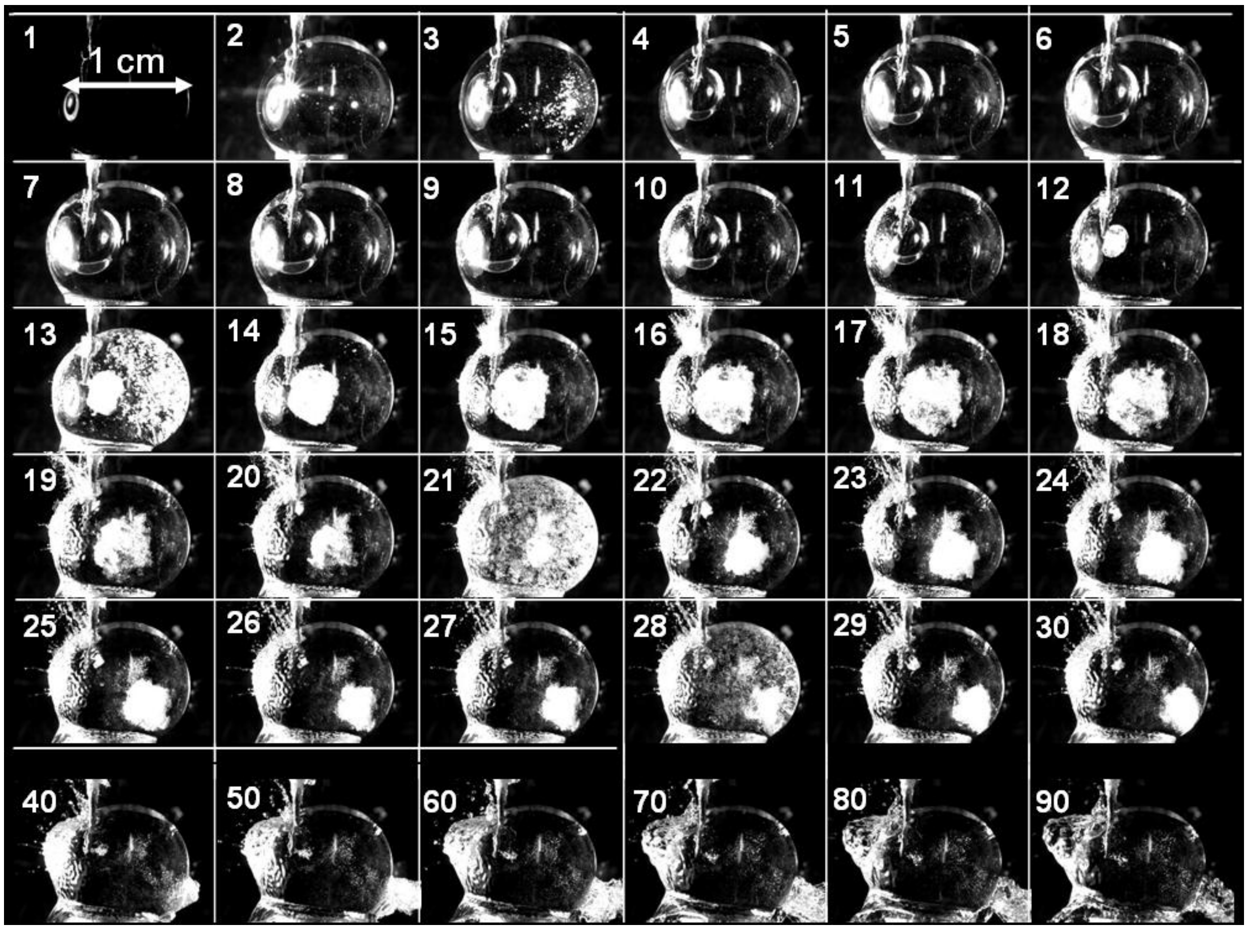
Bubble Dynamics in Microgravity

Experimental Setup: designed and realized at EPFL

- **Student flight campaign: 2005**
- **Professional flight campaigns:**
    - **2006, 2010, 2012, 2013, 2014, 2015, 2017**
- **1st Swiss Parabolic Flight Campaign:**
    - **2015 (Dübendorf)**

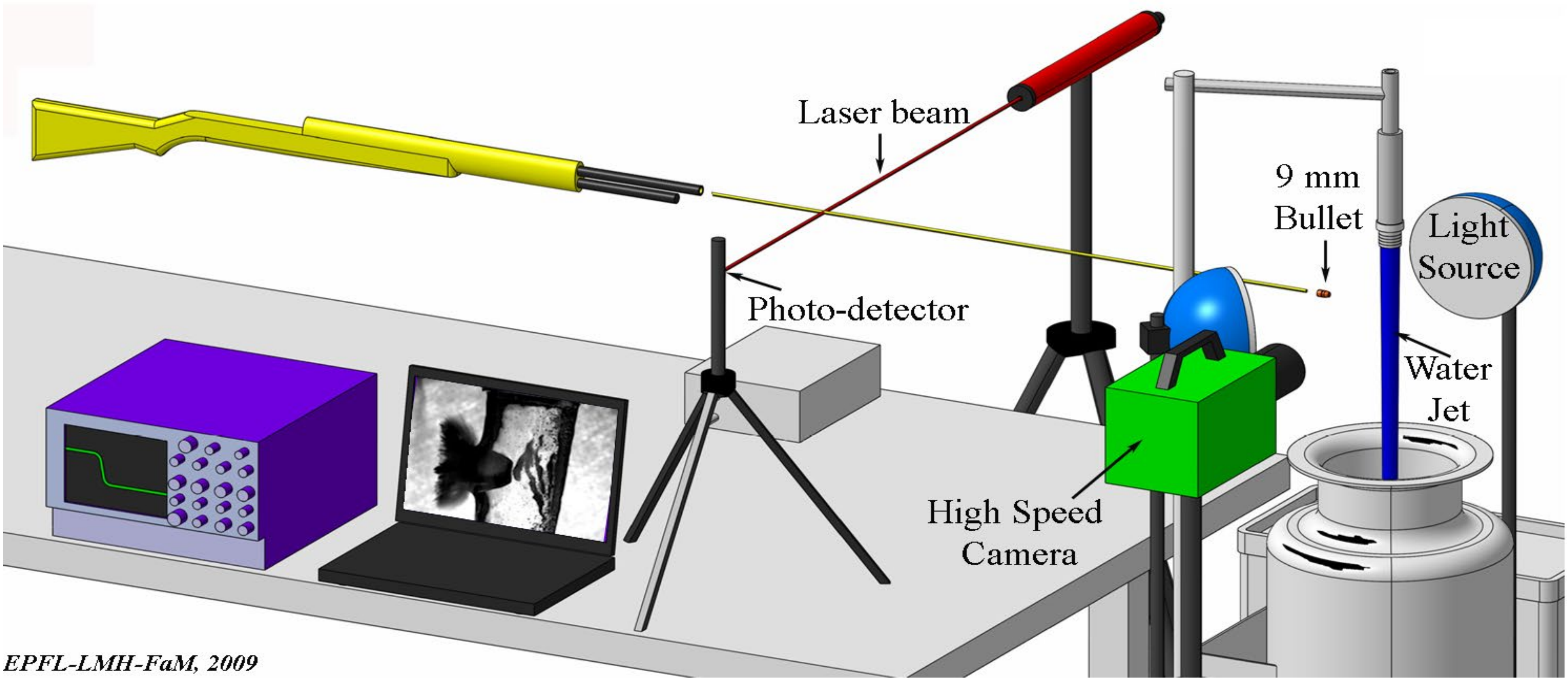
Bubble Dynamics in Microgravity

High speed visualization of a spark generated bubble within a water drop in microgravity (time step=80 μs)



High speed impact of a jet with a solid surface
Collaboration with Swiss Army
Semester Project

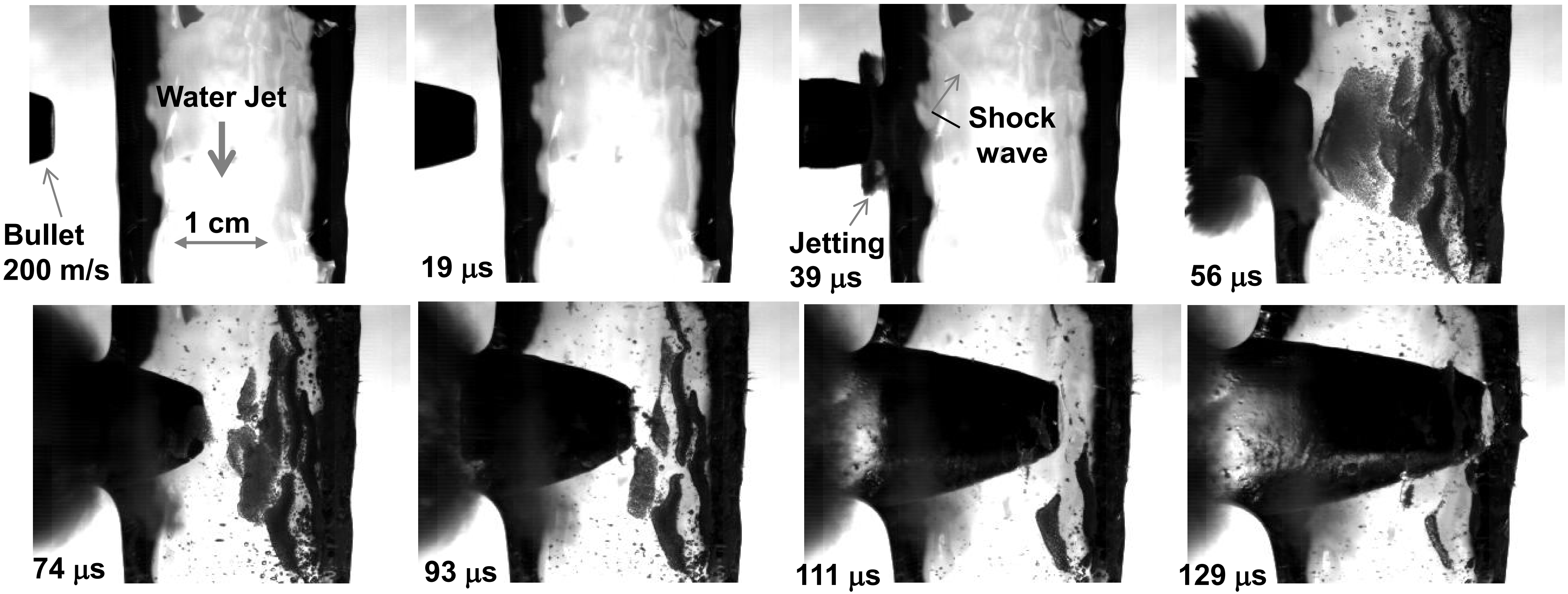
- ✓ **Water jet, having 2.5 cm diameter and ~ 1 m/s**
- ✓ **9 mm bullet, shot at speeds between 200 and 500 m/s (Swiss Army)**
- ✓ **Fast photodiode placed in the bullet path to trigger the camera**



EPFL-LMH-FaM, 2009

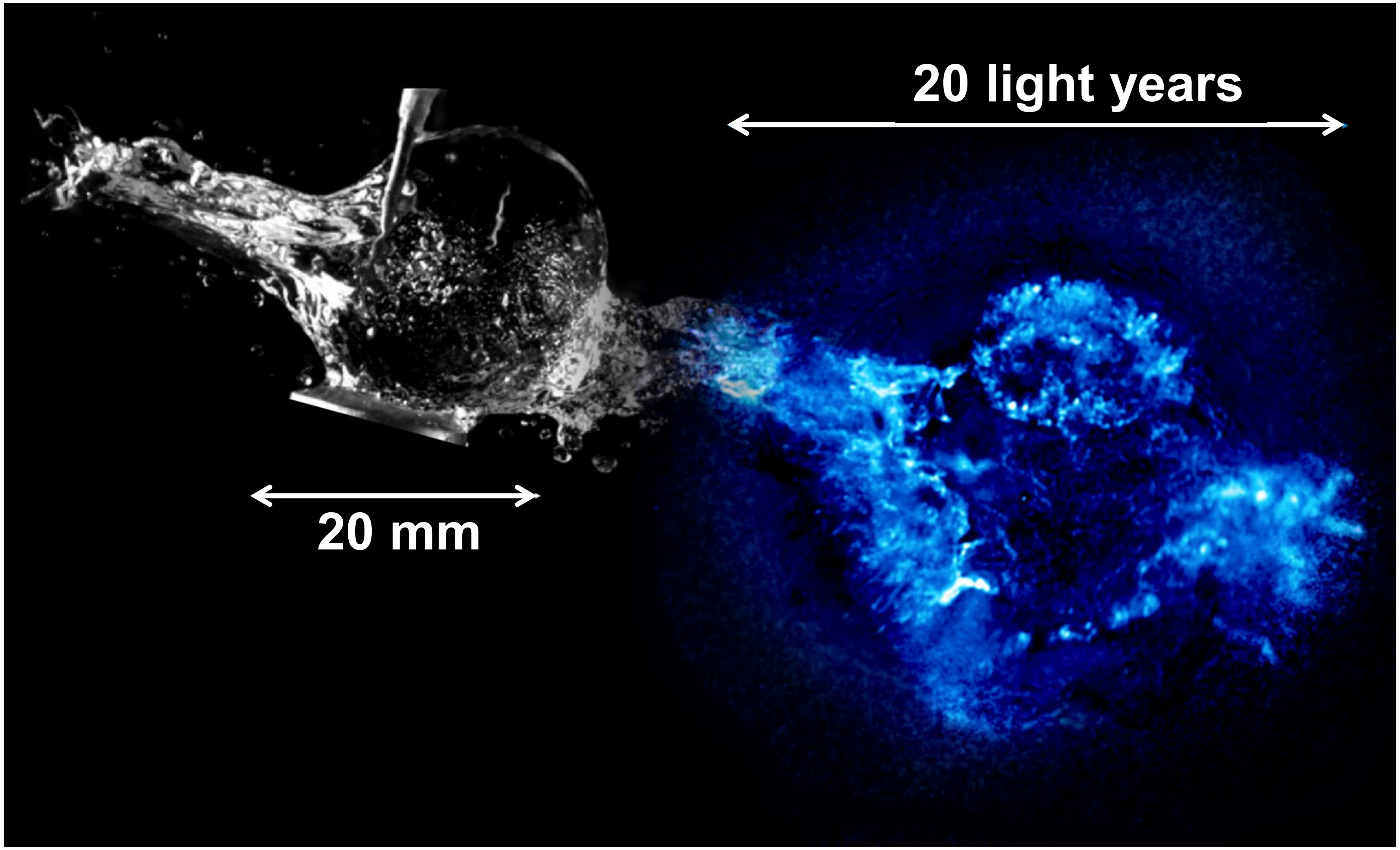
High speed impact of a jet with a solid surface
Evidence of cavitation occurrence

- Bullet velocity : 200 m/s
- 54'000 frames/second



Cavitation Bubble Dynamics within a Liquid Drop

Application: Astrophysics
Similarities with Explosions of giant stars (Supernovae)



CAVITATION AND INTERFACE PHENOMENA: COURSE OUTLINES

Laboratory Visit (High-Speed Cavitation Tunnel, laser induced bubbles, high-speed jet apparatus, Turbines model test rigs, …