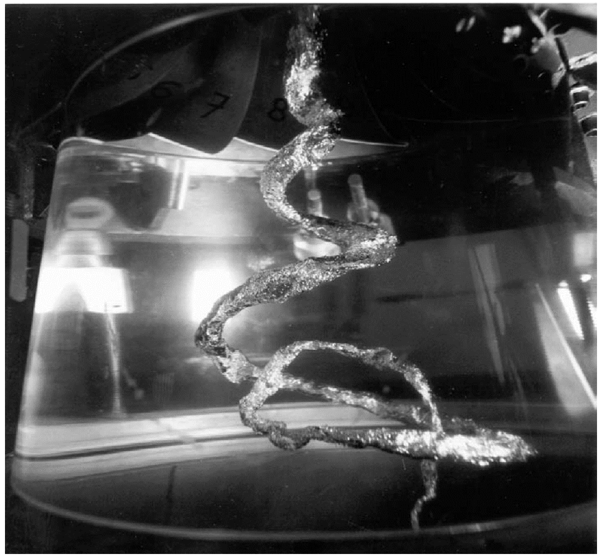
ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE
MECHANICAL ENGINEERING
Bachelor semester 6, Spring 2025

Introduction to Turbomachines
Cavitation in Hydraulic Machines



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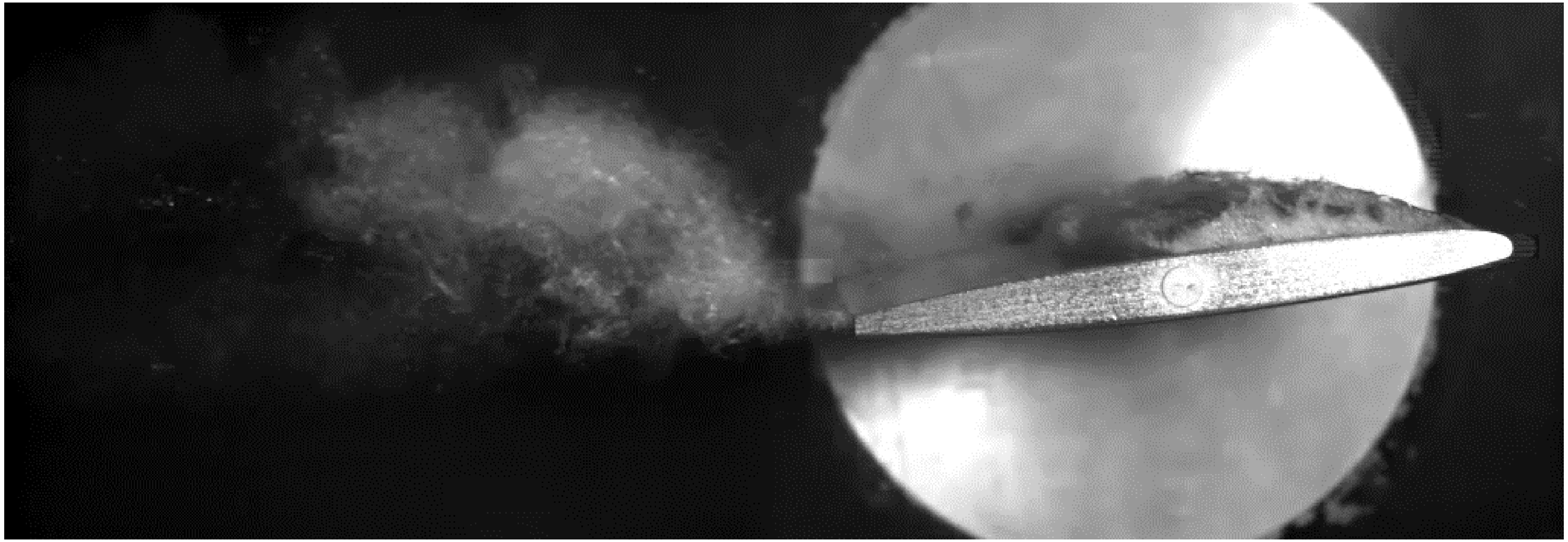
What is Cavitation ?

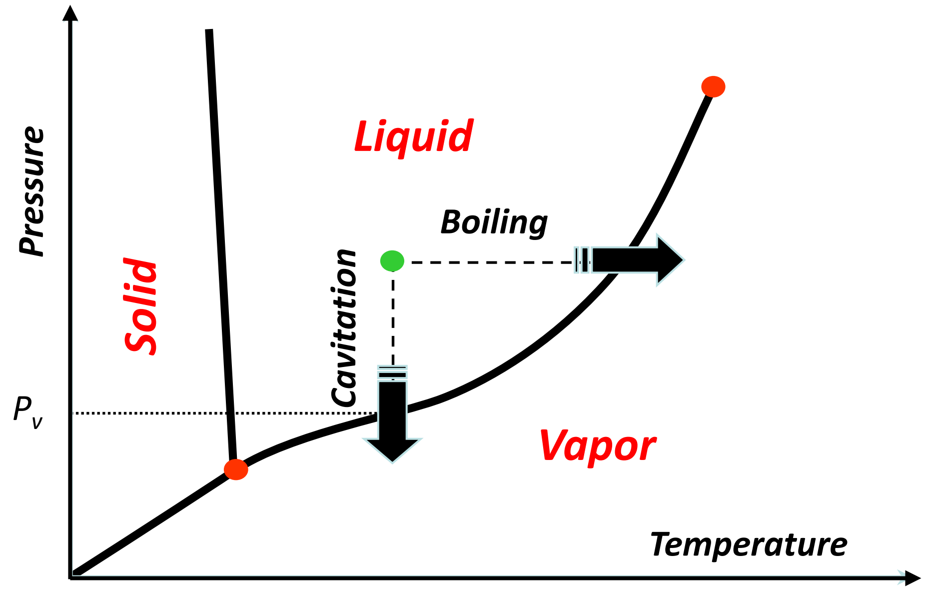


- Dictionary: Cavitation is the formation of cavities filled with vapor and gas within a liquid due to a pressure decrease without heat exchange
- ChatGPT: Cavitation is the formation and rapid collapse of tiny vapor bubbles in a liquid, usually caused by a drop in pressure. It typically occurs in places where liquid is moving quickly, like around a boat propeller, pump impeller, or hydraulic system.

What is Cavitation ?

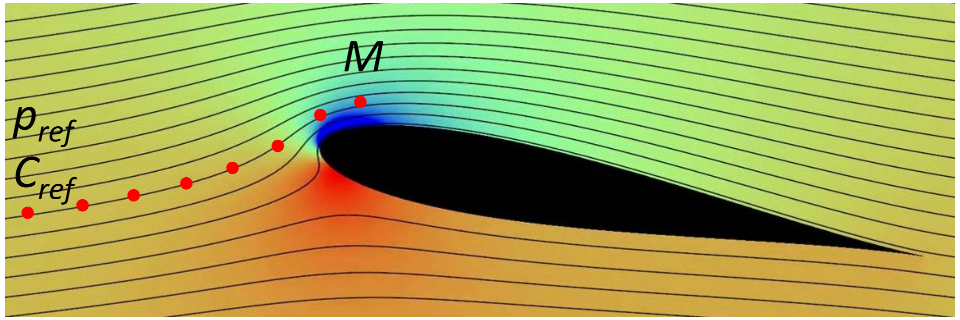
- Cavitation incipience: $p \le p_v(T)$

  p_v is the vapor pressure at a given temperature T



- "Different" from boiling, for which the vaporization is caused by a temperature increase at a constant pressure
  - In flowing liquids, the pressure may evolve much faster than temperature, leading to peculiar phenomena
- Cavitation is a limiting factor for turbomachines designers.

- **Condition for cavitation occurrence:**



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

where $c_p(M)$ is the pressure coefficient and σ is the cavitation number

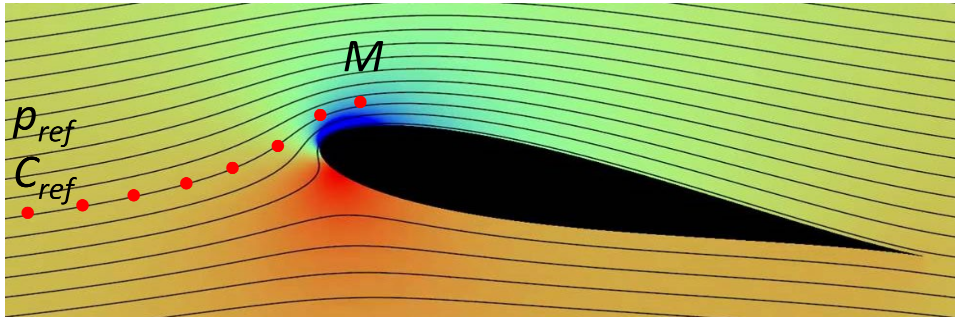
$$c_p(M) = \frac{p_M - p_{ref}}{\frac{1}{2}\rho {C_{ref}}^2} \qquad \sigma = \frac{p_{ref} - p_v(T)}{\frac{1}{2}\rho {C_{ref}}^2}$$

- σ represents a non-dimensional margin between the liquid pressure and vapor pressure

→ The risk of cavitation increases for a decreasing cavitation number

- **Energy Conservation**

  - Bernoulli Equation along a streamline:



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

Head losses

→ Risk of cavitation (excessive drop of pressure at point M) is increased with:

- an increase of flow speed (hydrofoil, Venturi, Vortices, …)
- an increase of height (Siphons, …)
- an increased of head losses (flow past valves, diaphragms, …)

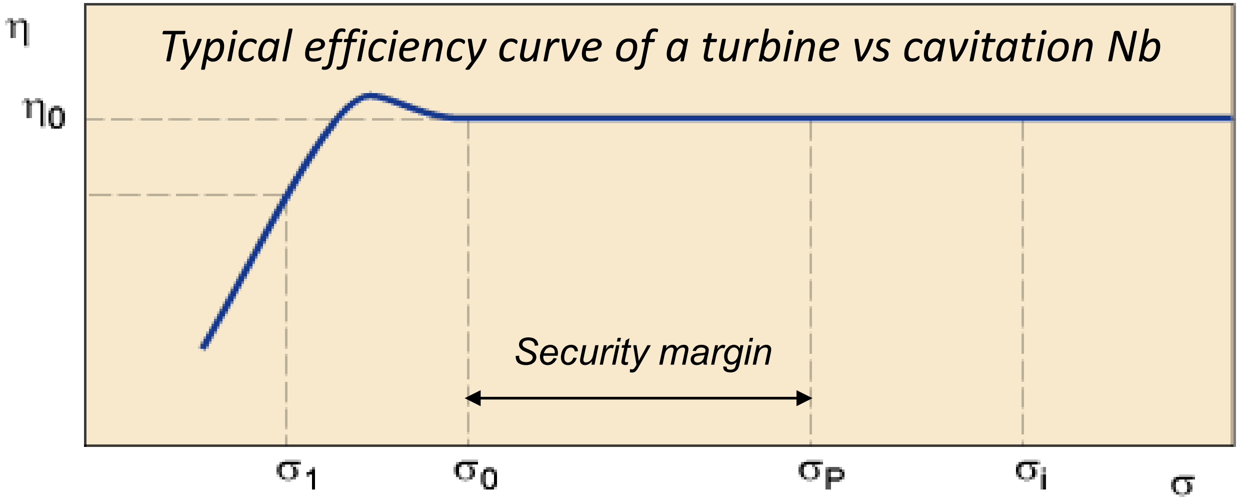
Cavitation Effects

- **Effects of cavitation:**

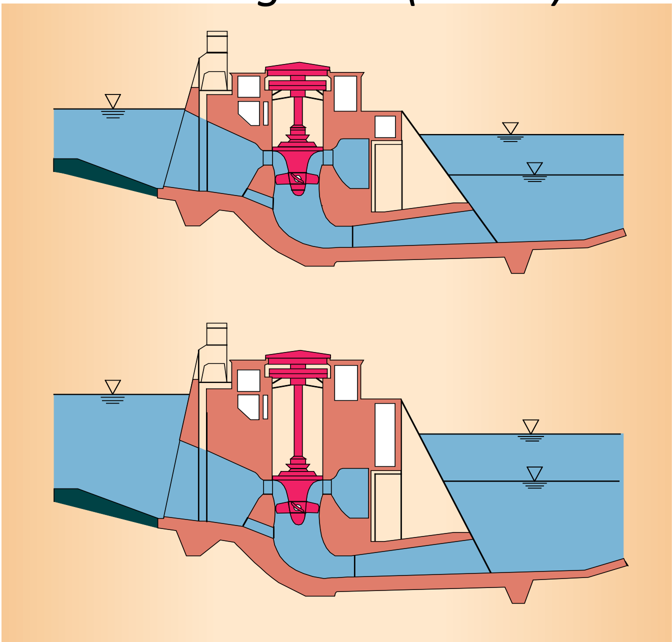
1. Alteration of hydrodynamic performances:

The presence of the gas phase within a flowing liquid causes an increase of drag and a decrease of lift

Solution: Increase of the setting level (Cost ?)



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



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

- **Effects of cavitation:**

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

  3. Erosion
  - *Mass loss of runner blades*

  → Periodic Inspections

  → Costly repairs

Premature cracks in a 200 MW Pump Turbine

Severe erosion in pump propellers

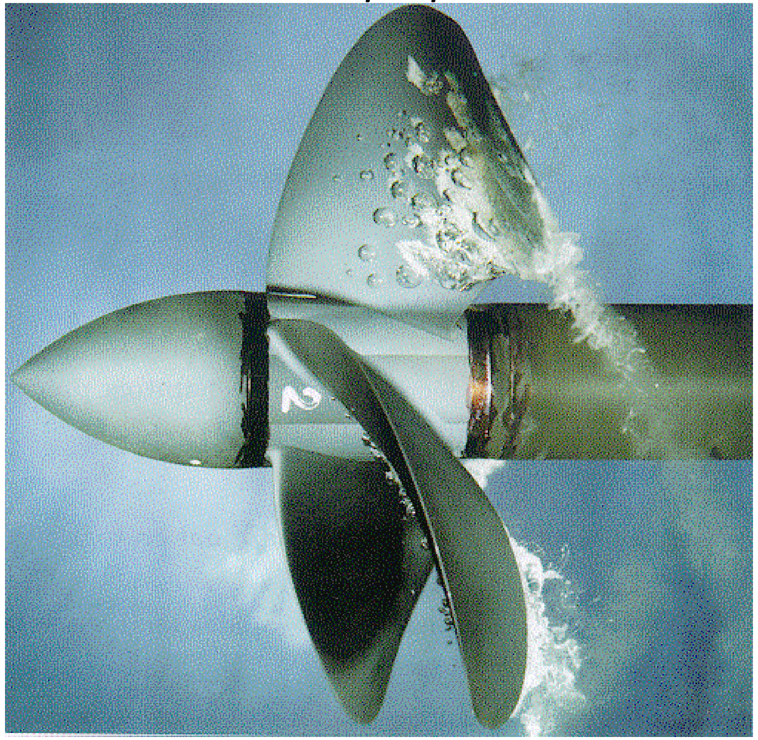
No industrial alloy can resist to cavitation aggressiveness

- **Types of cavitation**

  1. Bubble Cavitation:

  Separated bubbles are generated randomly. They grow in the low pressure zone and condense violently (collapse) as the pressure increases downstream.

Bubble Cavitation in a marine propeller



Bubble cavitation in a model of Francis turbine

Similarity with boiling

- **Types of cavitation**

  2. Leading edge cavitation (also called "attached cavitation" or "inlet cavitation"):

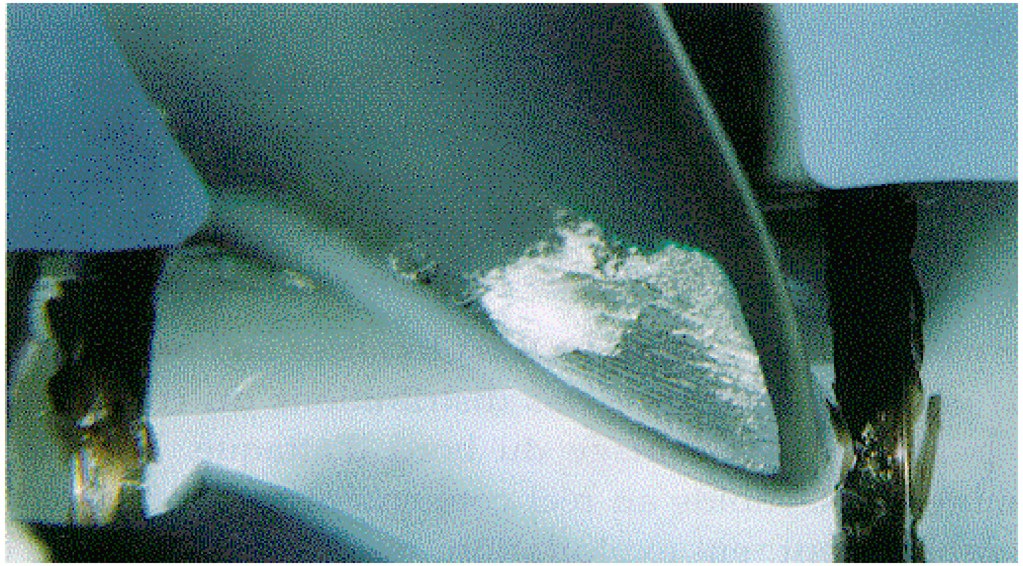
  A main cavity is formed at the leading edge (minimum pressure).

  - Characterized by the shedding of transient cavities that collapse downstream

  - Always associated with severe erosion

Side view of attached cavitation on a 2-D hydrofoil

Model of marine propeller



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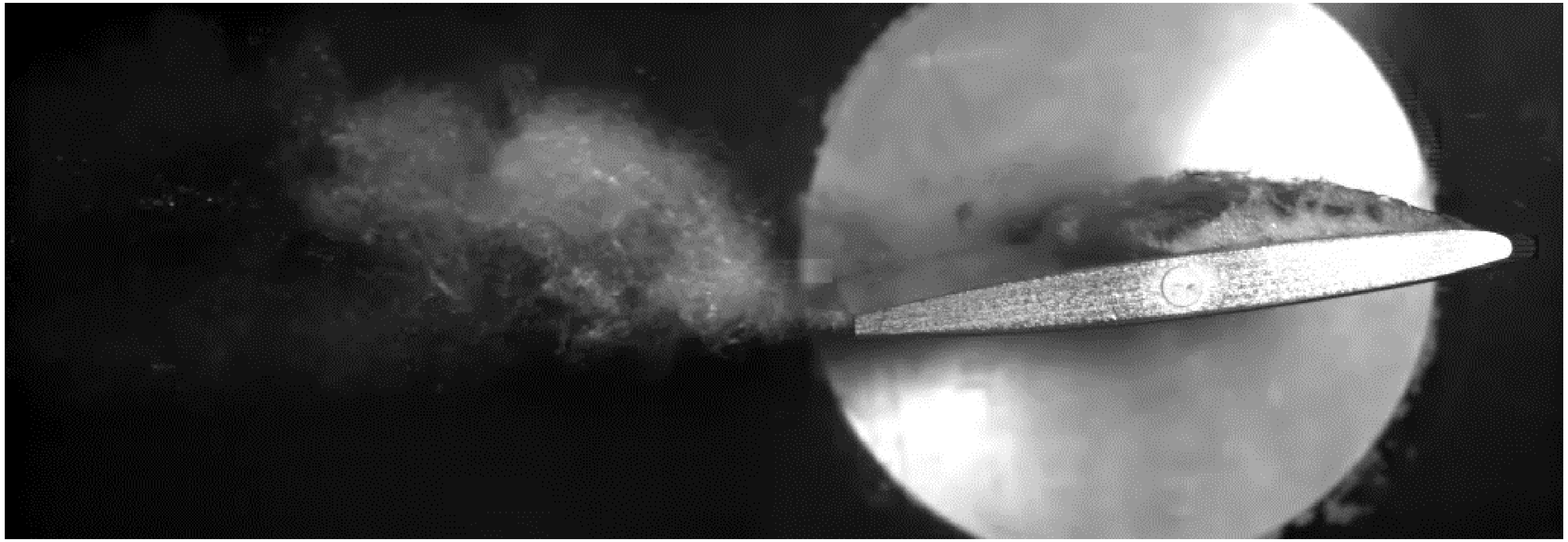
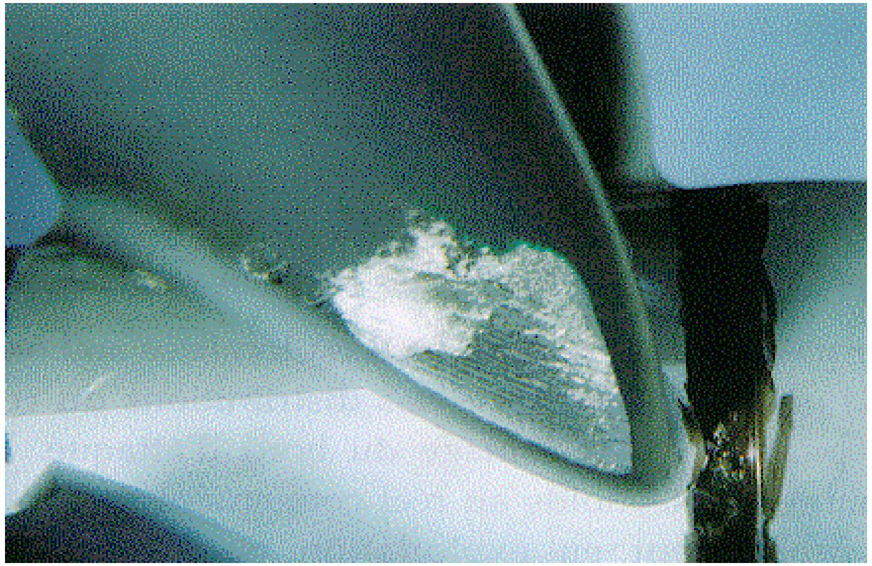


Model of marine propeller



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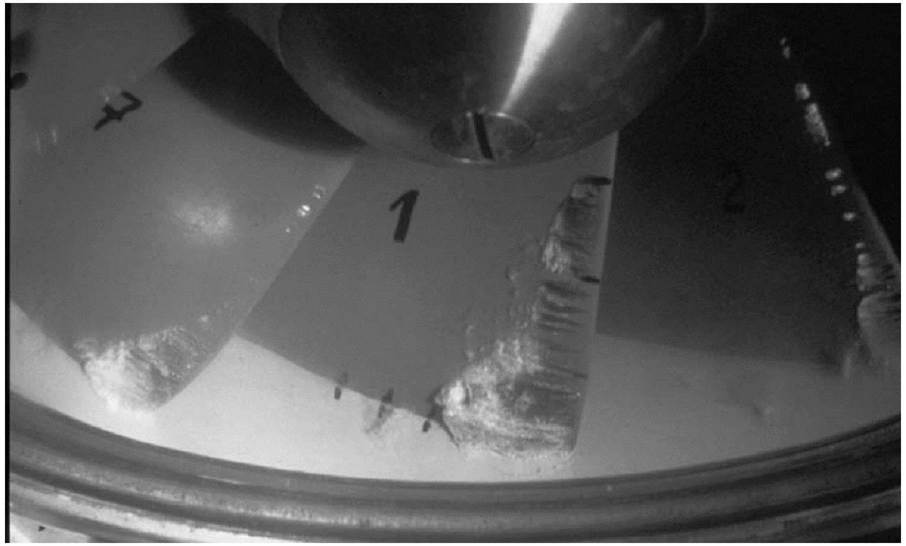
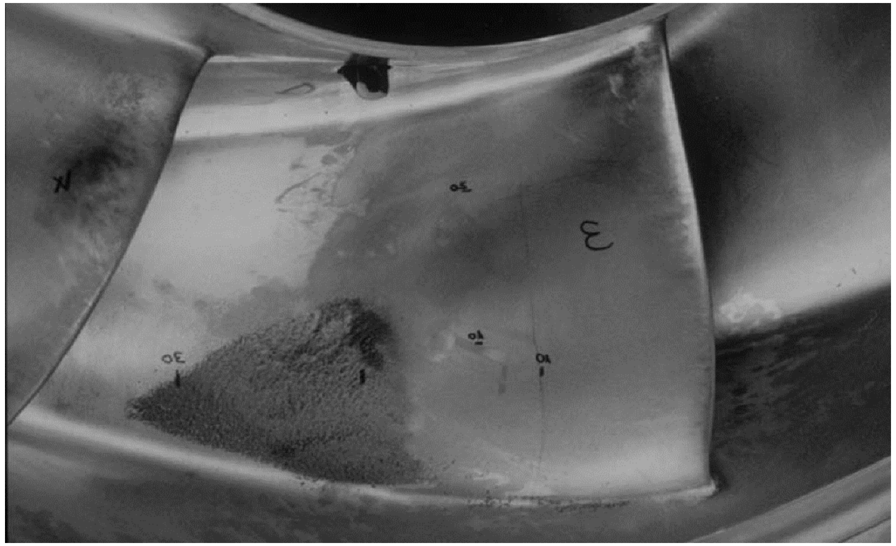
Model and prototype of a storage pump

Visualization of cavitation in pump model



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

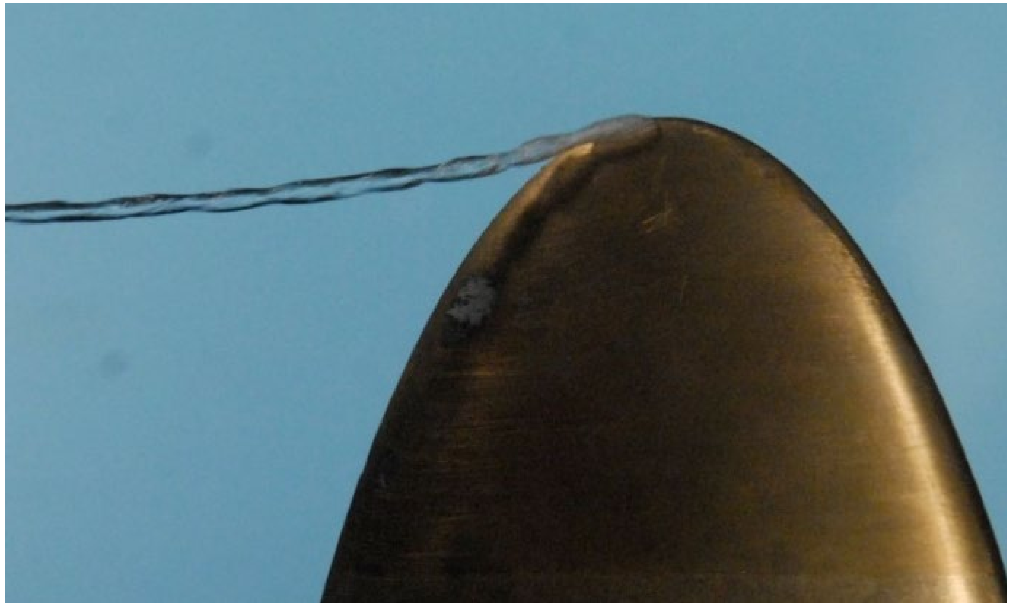


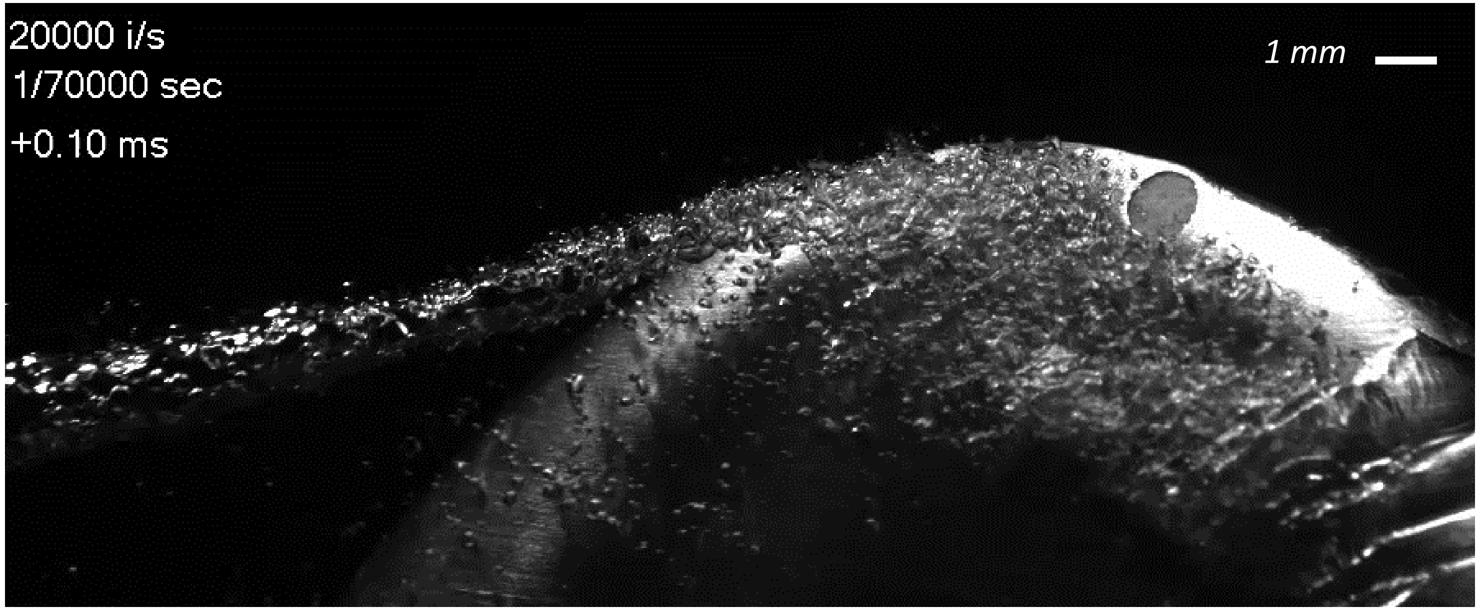
- **Types of cavitation**

  3. Vortex Cavitation

  Develops in a vortex, due to the low pressure in its core

Example: Tip Vortex Cavitation at the tip of an elliptical hydrofoil



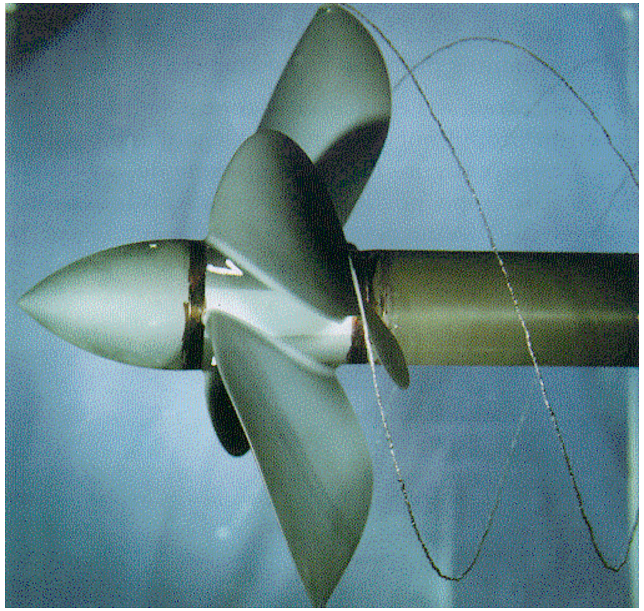


- **Types of cavitation**

  3. Vortex Cavitation

  Develops in a vortex, due to the low pressure developed in its core

Example: Tip Vortex Cavitation in marine propellers

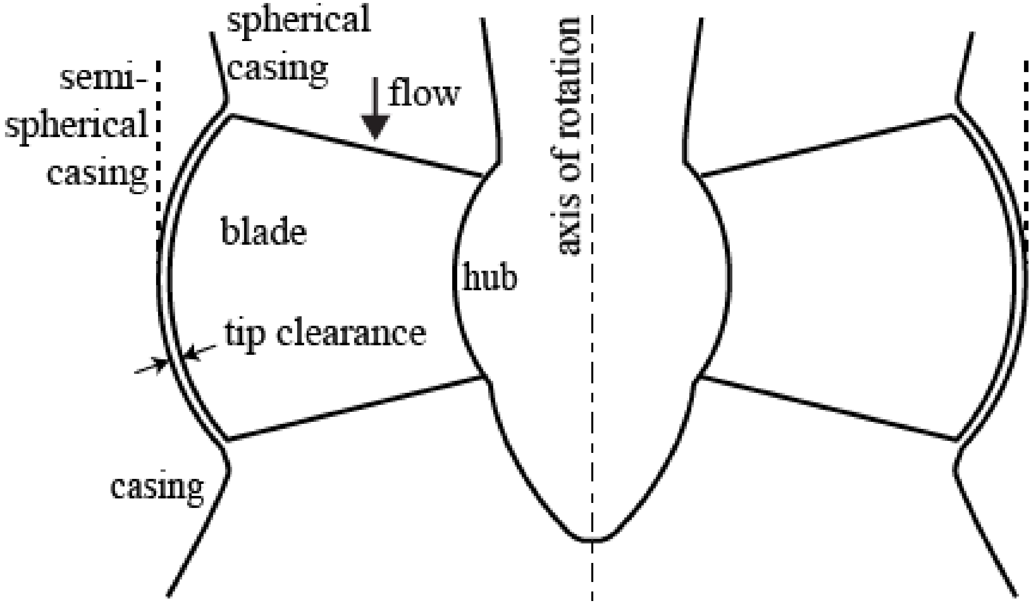


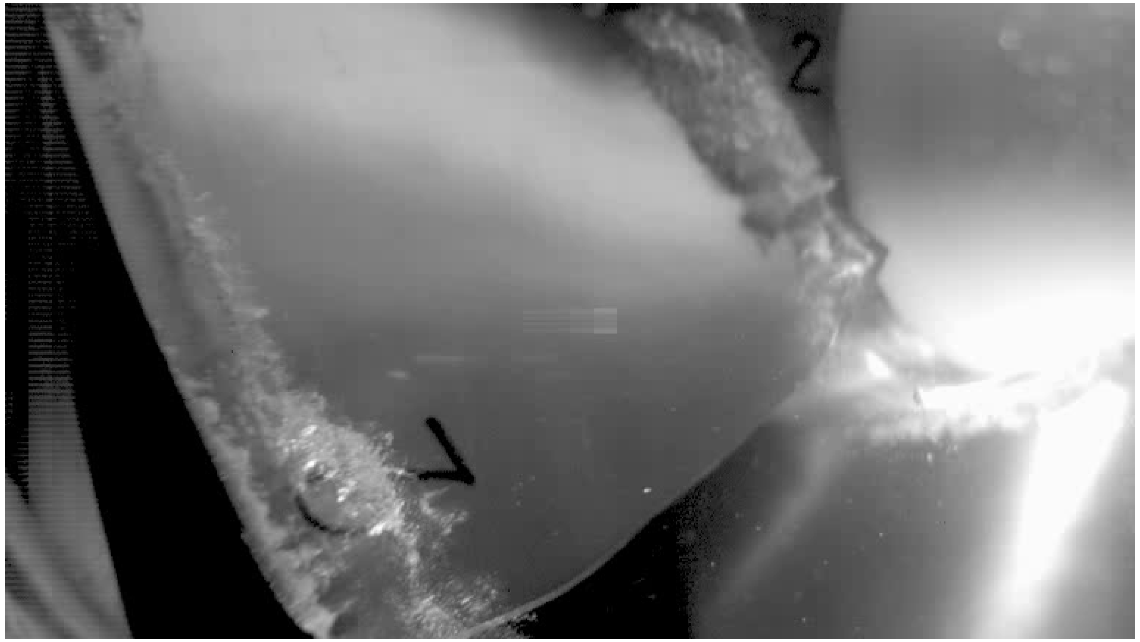
- **Types of cavitation**

  3. Vortex Cavitation

  Develops in a vortex, due to the low pressure developed in its core

Example: Tip Leakage Vortex Cavitation in Kaplan turbines





Cavitation Types

- **Types of cavitation**

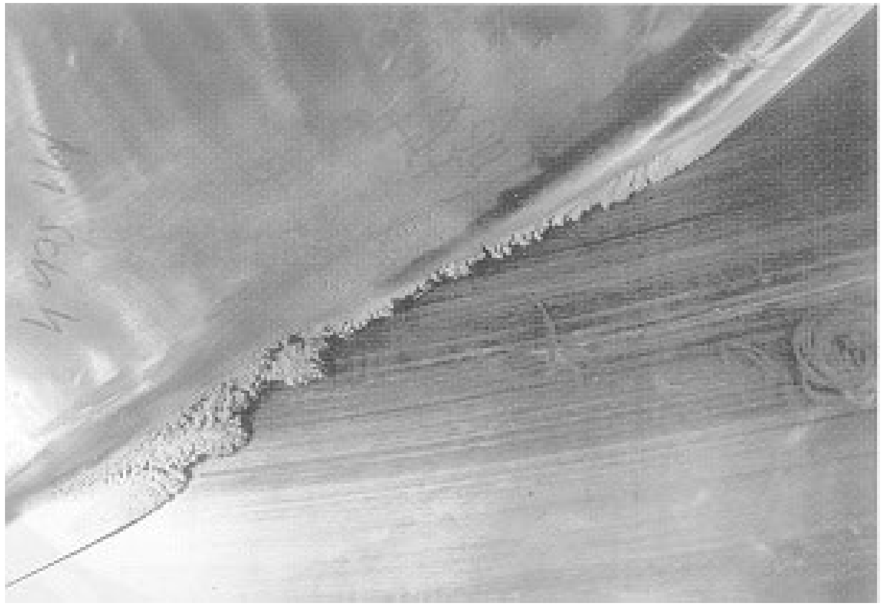
  3. Vortex Cavitation

  Develops in a vortex, due to the low pressure developed in its core

Example: Tip Leakage Vortex Cavitation in Kaplan turbines

Visualization of a cavitating tip leakage vortex in a model of Kaplan turbine

Cavitation erosion in a Kaplan turbine prototype: erosion of the tip of the blades



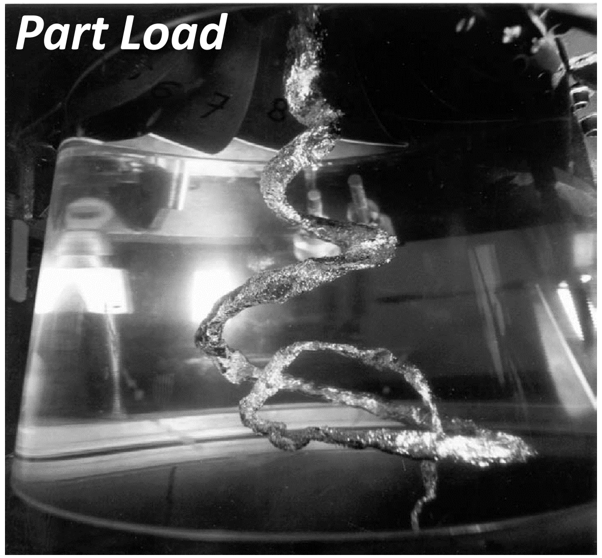
- **Types of cavitation**

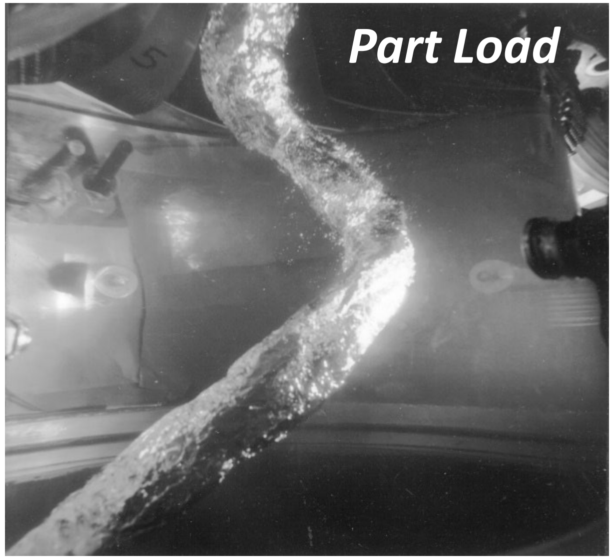
  3. Vortex Cavitation

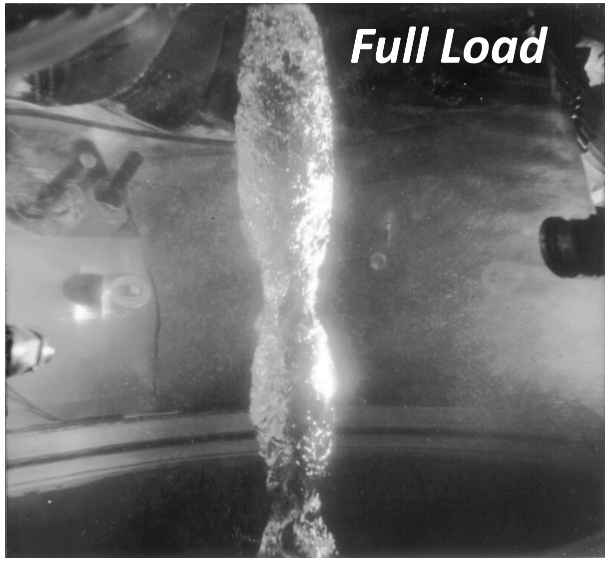
  Develops in a vortex, due to the low pressure developed in its core

Example: Cavitating vortex breakdown at the outlet of a Francis turbine (Rope)

- *Always develops at part load and full load conditions (off-design)*
  - *Source of strong hydraulic instabilities (noise and vibration)*





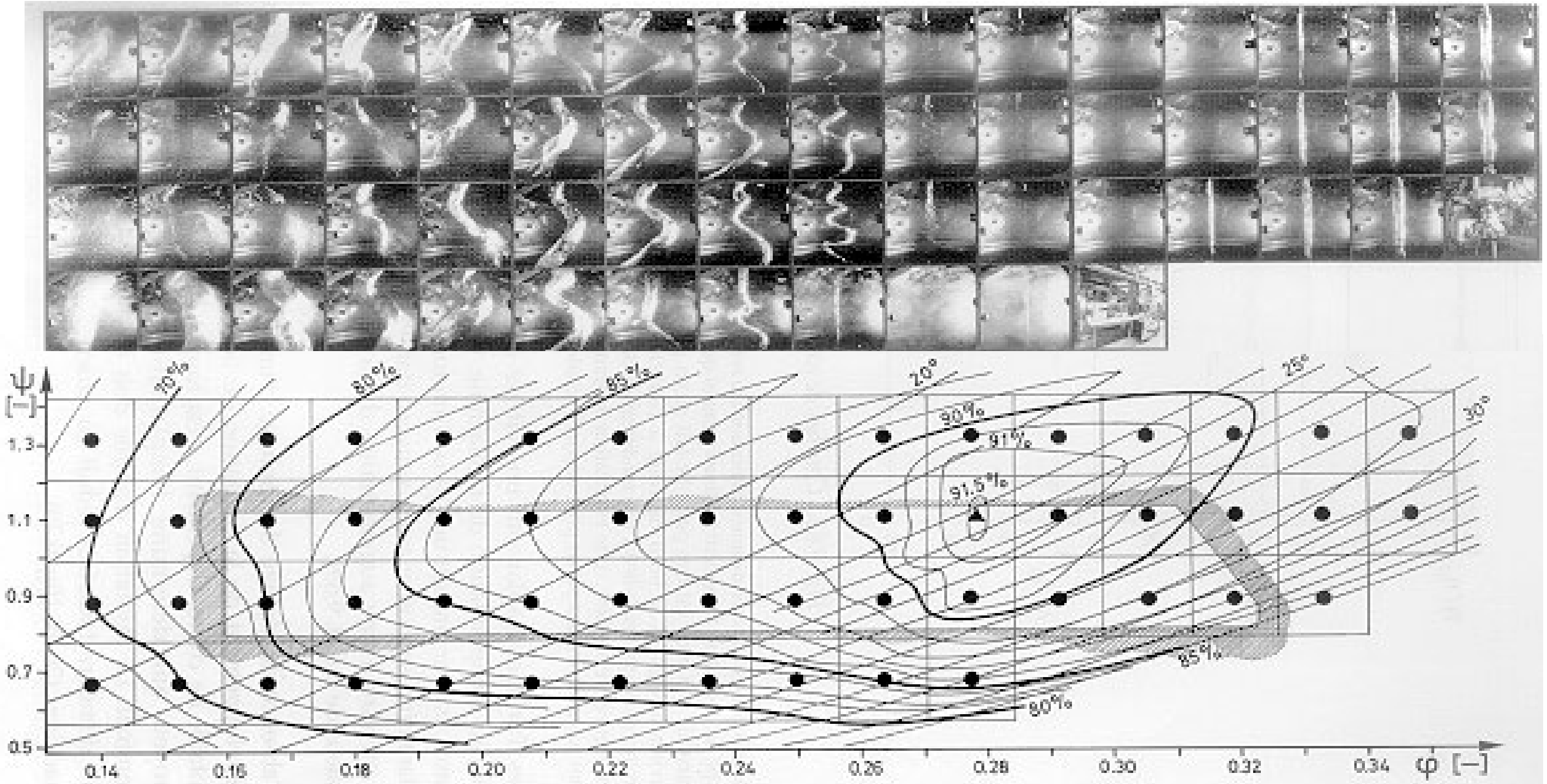


- **Types of cavitation**

  3. Vortex Cavitation

Example: Cavitating vortex breakdown at the outlet of a Francis turbine (Rope)

- ***Rope development in a Francis turbine : Typical rope vs operating point (efficiency hill chart)***

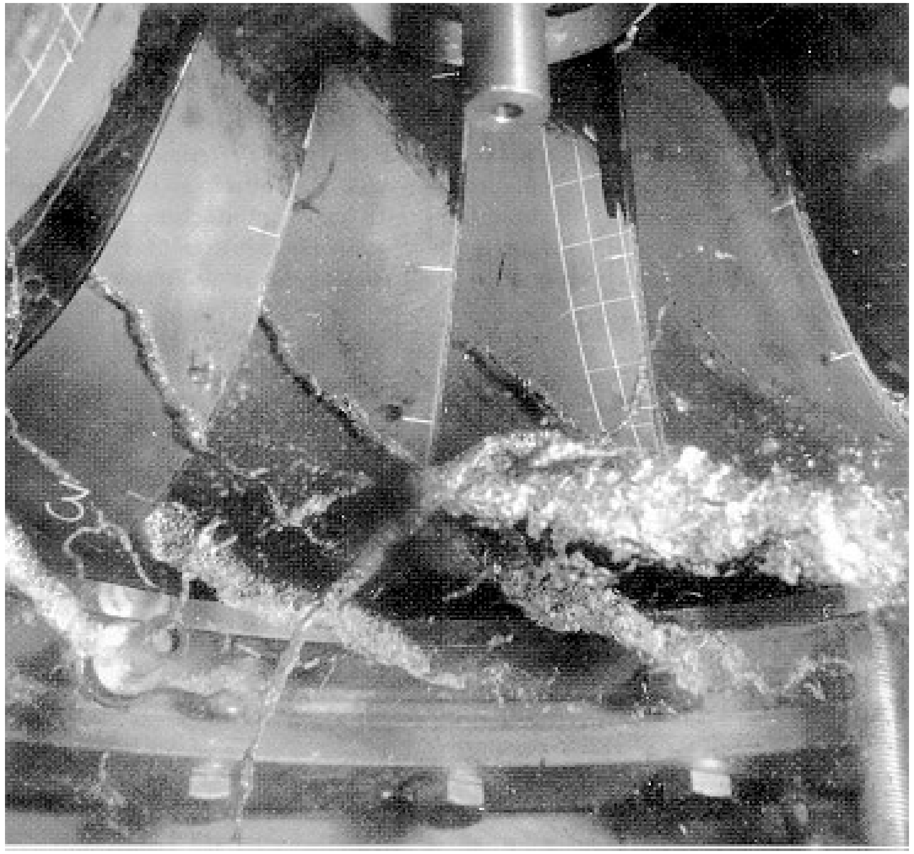


- **Types of cavitation**

  3. Vortex Cavitation

  Develops in a vortex, due to the low pressure developed in its core

Example: Inter-blade vortices in a Francis turbine model



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

- *Highly unstable → strong vibration*

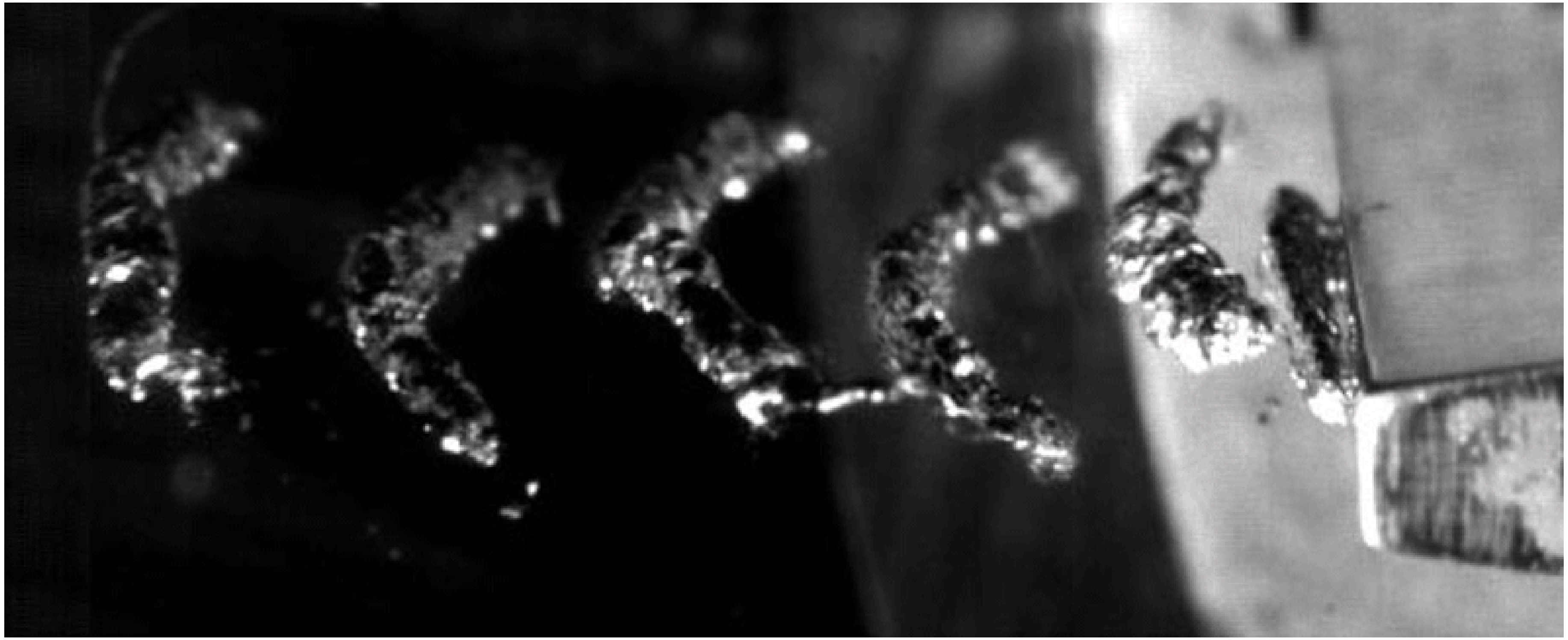
→ Premature cracks of the blades

- **Types of cavitation**

  3. Vortex Cavitation

  Develops in a vortex, due to the low pressure in its core

Example: Cavitation in wake vortices (Kàrmàn vortices) of a blunt trailing edge hydrofoil



Cavitation in High-Speed Sailing Boats

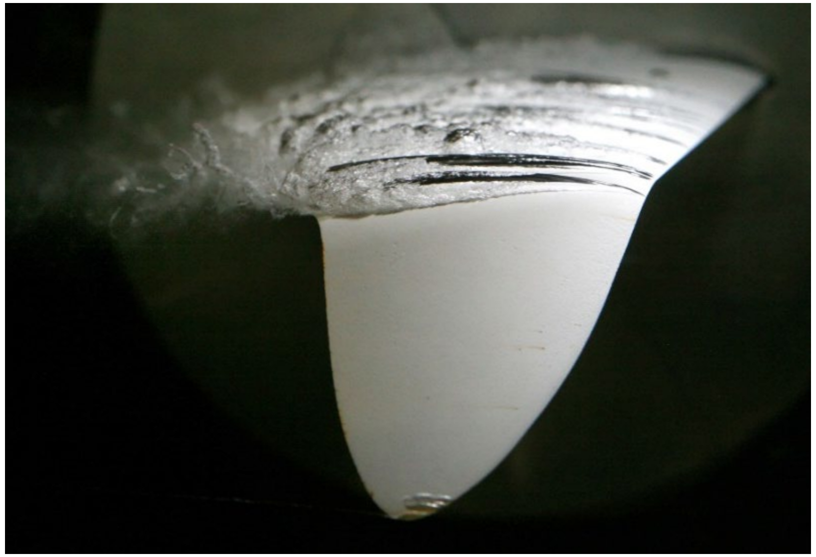
- **The case of high-speed sailing boats**
  Cavitation is the main obstacle that limits the speed of sailing boats

  - *Partnership EPFL – Hydroptere*
  - *Goal: Break the speed record (>50 knots)*
  - *Record speed achieved on Sep. 2010: 55 knots over 1 mile*

  - *Major limitation: Cavitation on lifting foils*

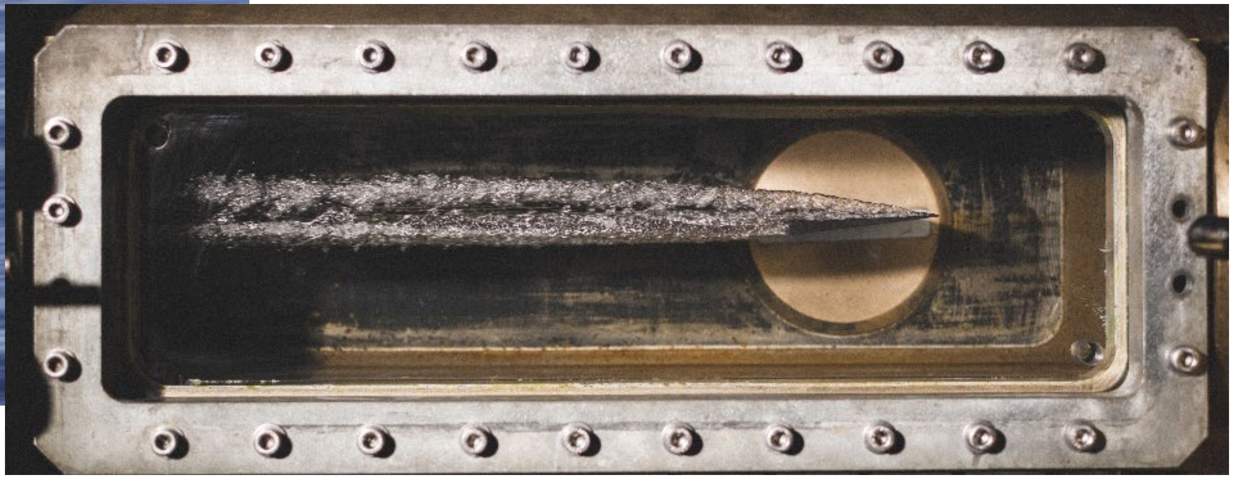
  - *Cavitation may occur in any body moving in water at high-speed (~50 knots). Only few fishes can swim at such speed, for a limited time.*

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



Cavitation in High-Speed Sailing Boats

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

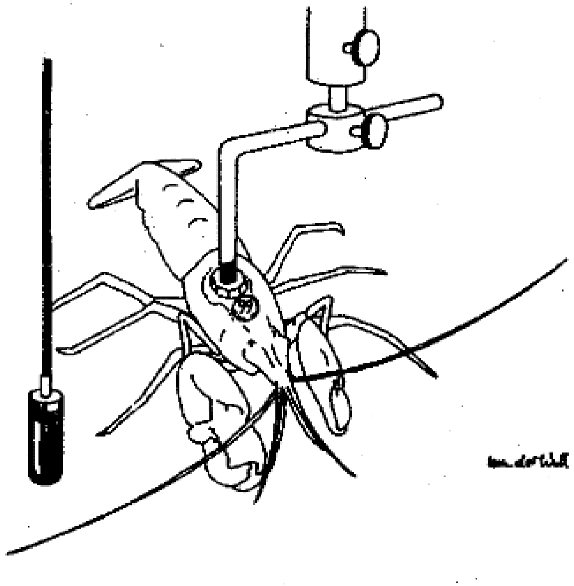
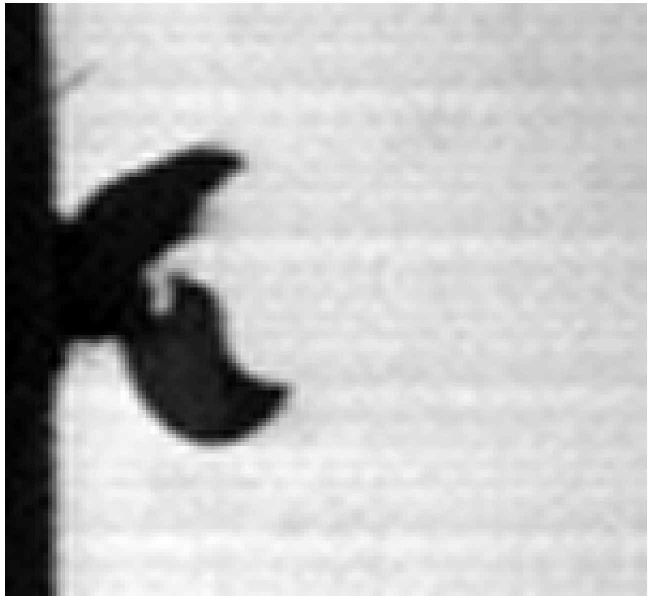


Cavitation in nature

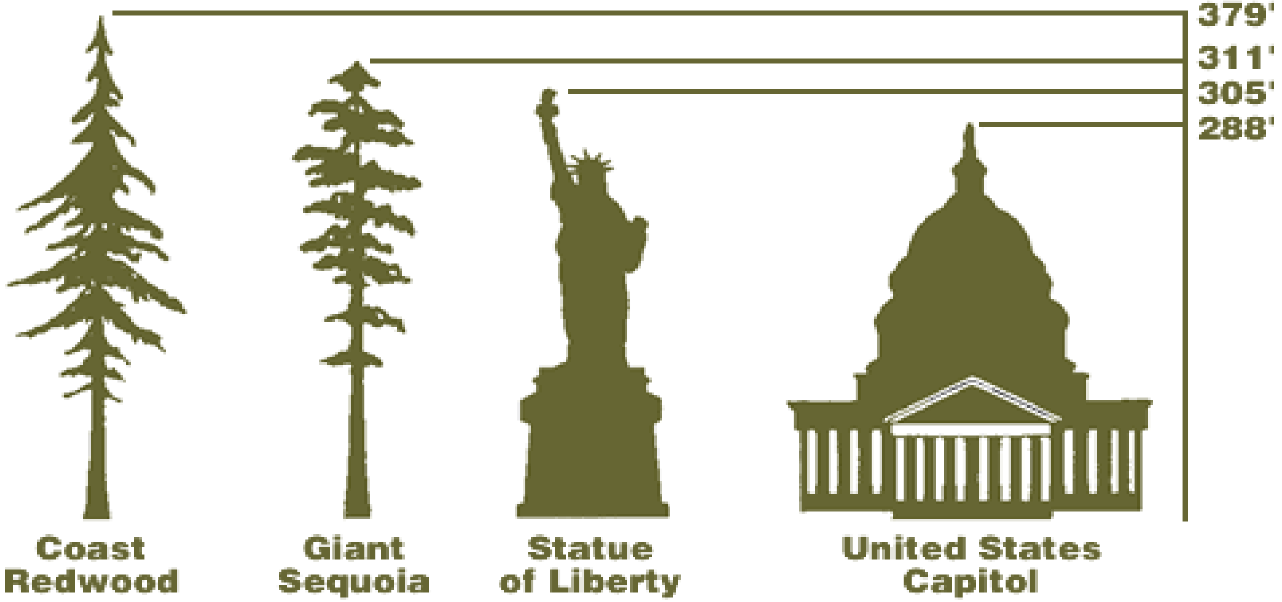
- **Cavitation in nature**
  - ***Snapping shrimps (or Pistol shrimps)***

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 as revealed by high speed visualization

- **Cavitation in nature**
  - ***Water ascent in giant trees***
    - *Giant Sequoia trees may be as high as 115 m (Historical record: 135 m, Eucalyptus)*
    - *Sap (Water + Nutrients) is pumped through tiny pipes (Xylem) from the root to feed every leaf, defying gravity !*
    - *A single giant tree needs ~3000 liter of water everyday*
    - *How can the sap withstand extreme tensions ? (open question)*

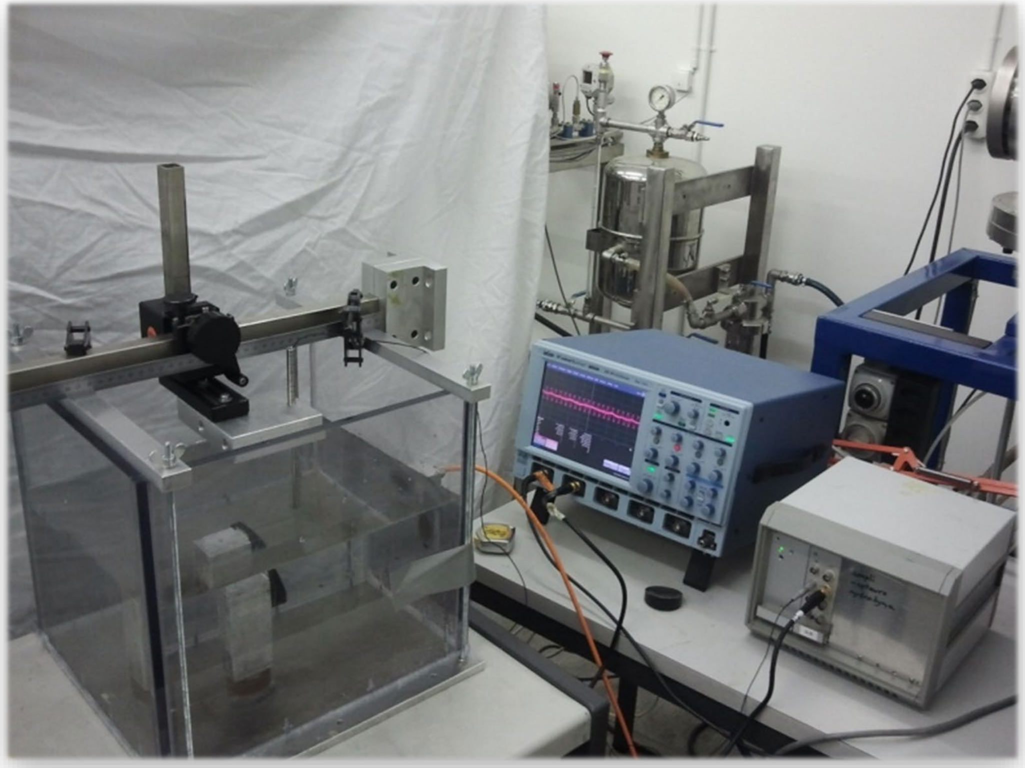


Medical Application

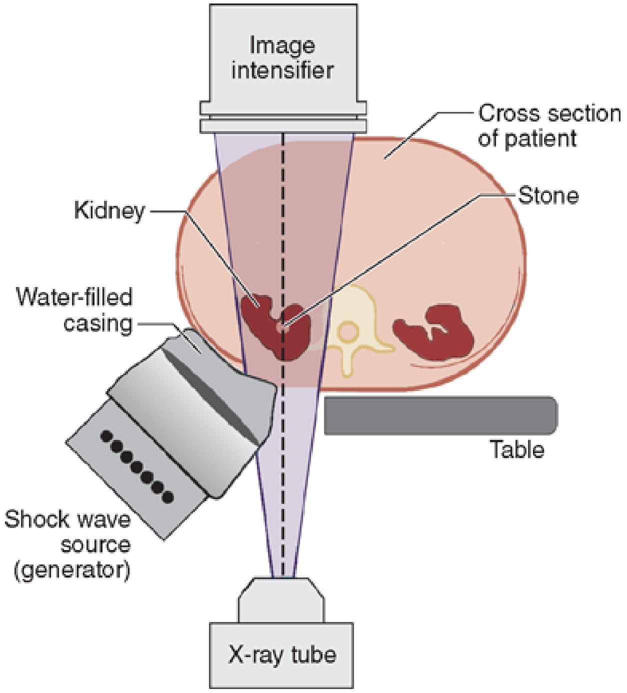
- ***"Lipocavitation" to lose weight :***

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

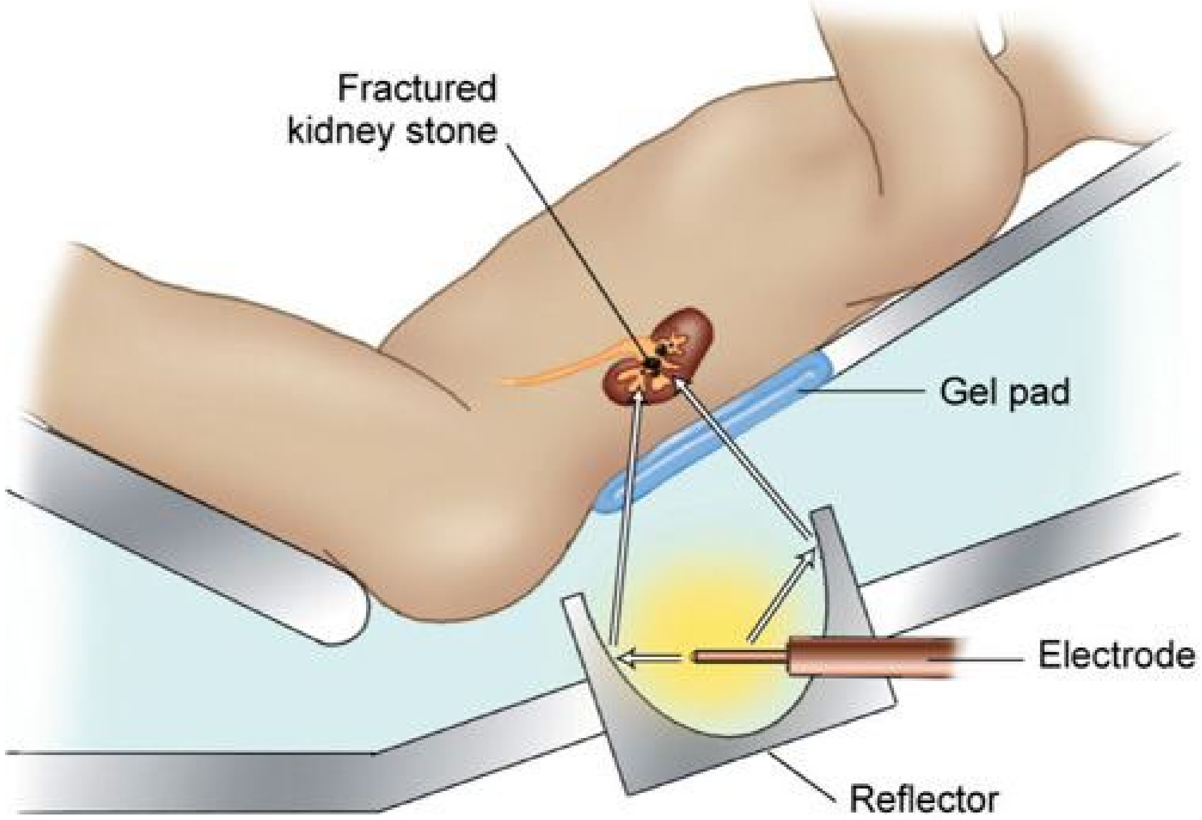
Cavitation produced by focused ultrasonic waves for non-intrusive adipose tissue lysis
A. Cayron, Th. Curran, Semester project, EPFL



- ***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*

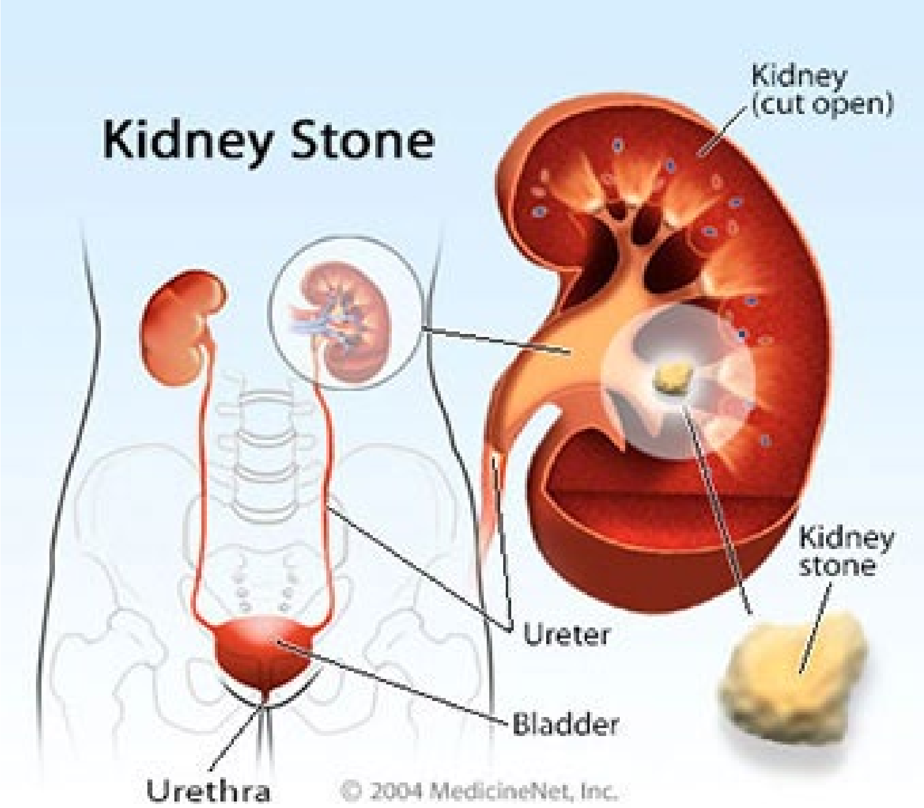


Source: Butterworth JF, Mackey DC, Wasnick JD: *Morgan & Mikhail's Clinical Anesthesiology*, 5th Edition: www.accessmedicine.com



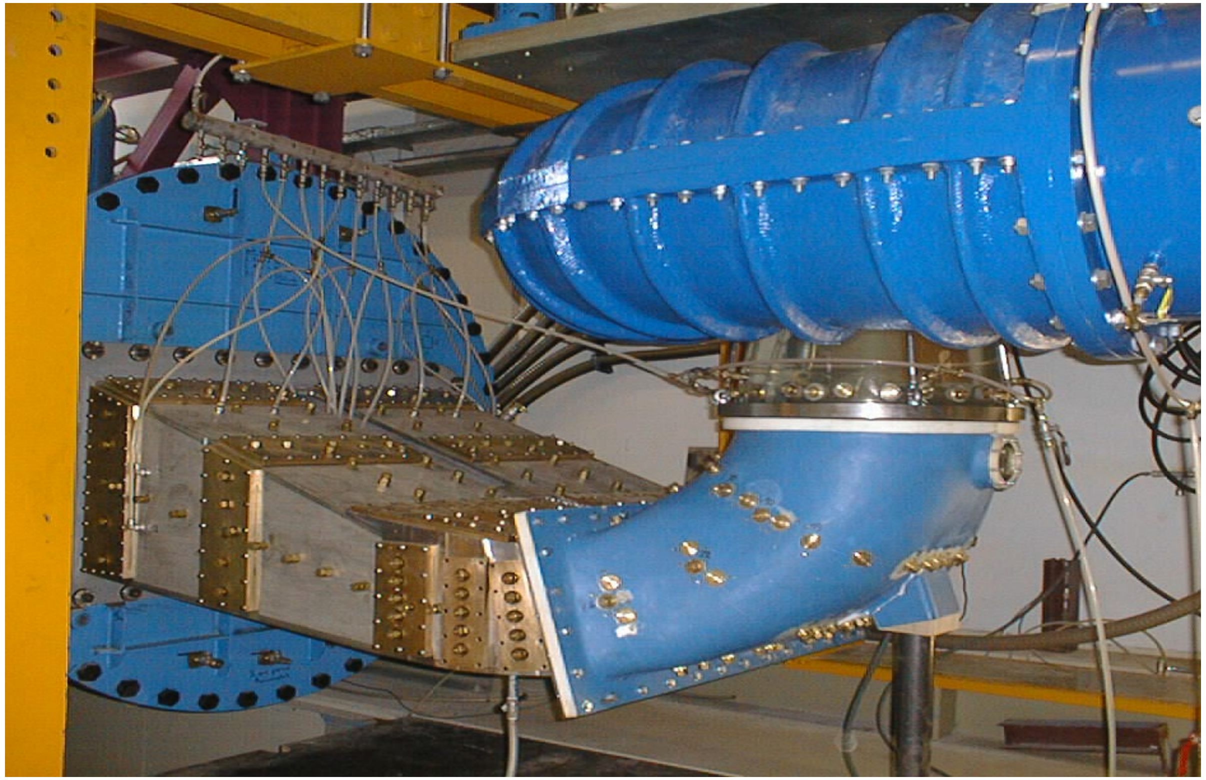
- ***Extracorporeal Shockwave Lithotripsy: The Art of Breaking Kidney Stones***

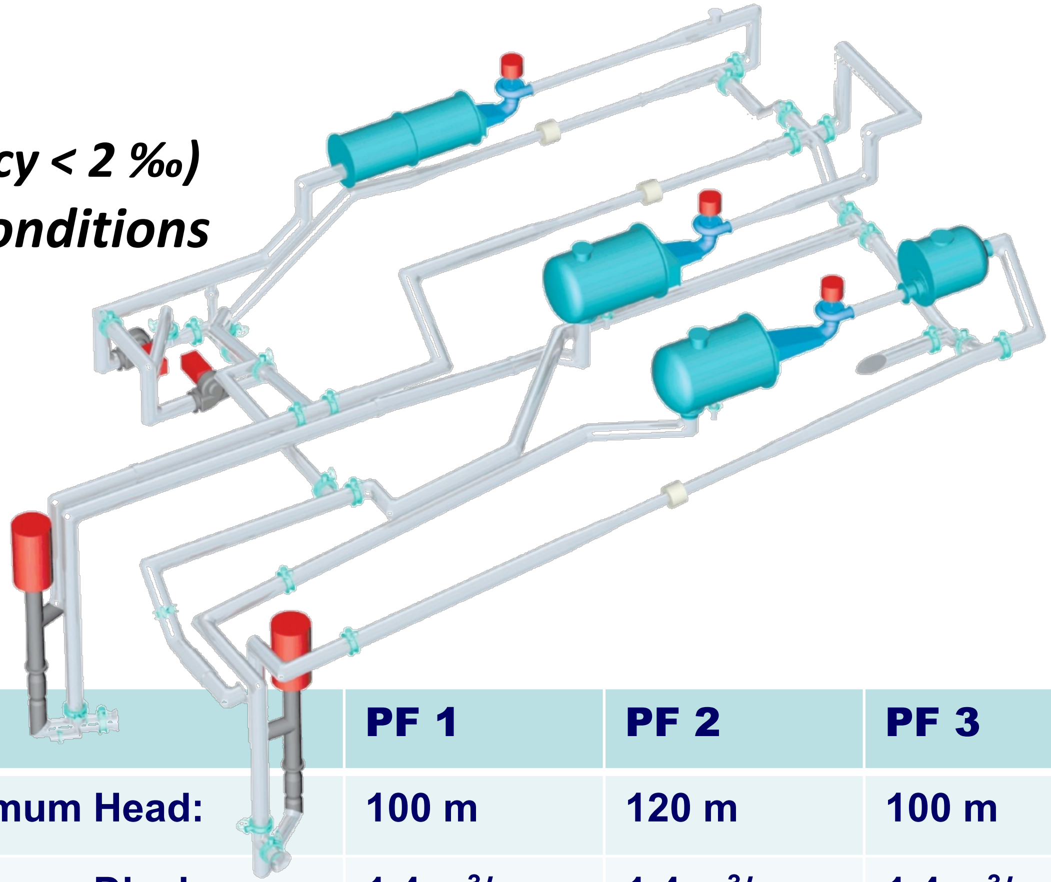
  - *Single shock waves are administered at heart beat rate*
  - *~2000-3000 shocks to crush kidney stones of 1-2mm diameter.*
  - *Local anesthesia, ambulant treatment.*
  - *Very few side effects.*



EPFL Infrastructure for Cavitation Studies

- ***Test Rigs for Turbines and Pumps Models***
  - *IEC 60193 Testing Facilities (Measurement Accuracy < 2 ‰)*
- ***Observation of cavitation occurrence in realistic conditions***
  - *Competitive tests, Acceptance tests*
  - *Research*



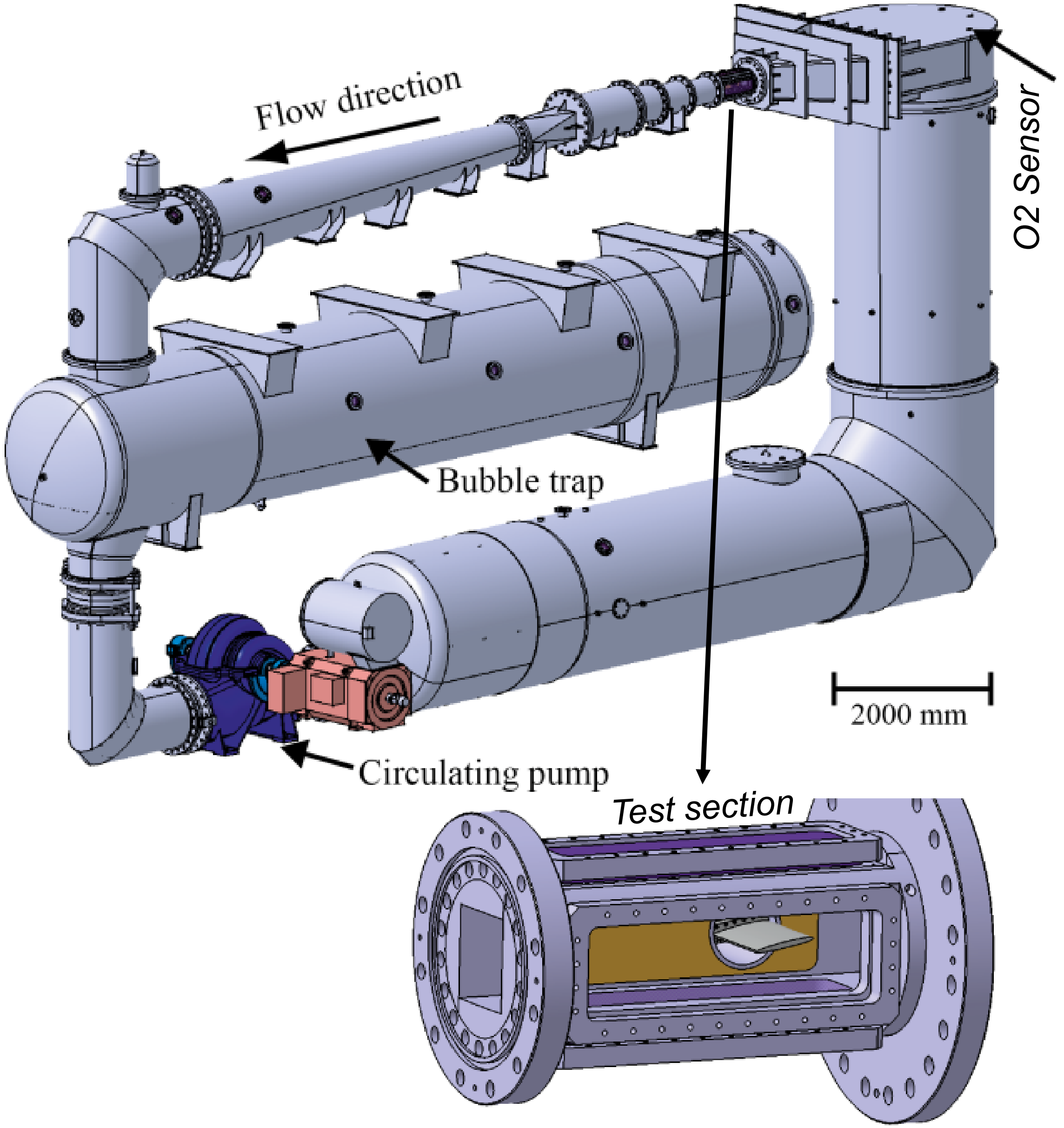


	PF 1	PF 2	PF 3
Maximum Head:	100 m	120 m	100 m
Maximum Discharge:	1.4 m^3/s	1.4 m^3/s	1.4 m^3/s
Generating Power	300 kW	300 kW	300 kW
Pumping Power	900 kW	1’000 kW	2x400 kW
Max Speed	1’500 rpm	1’500 rpm	1’500 rpm

EPFL Infrastructure for Cavitation Studies

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

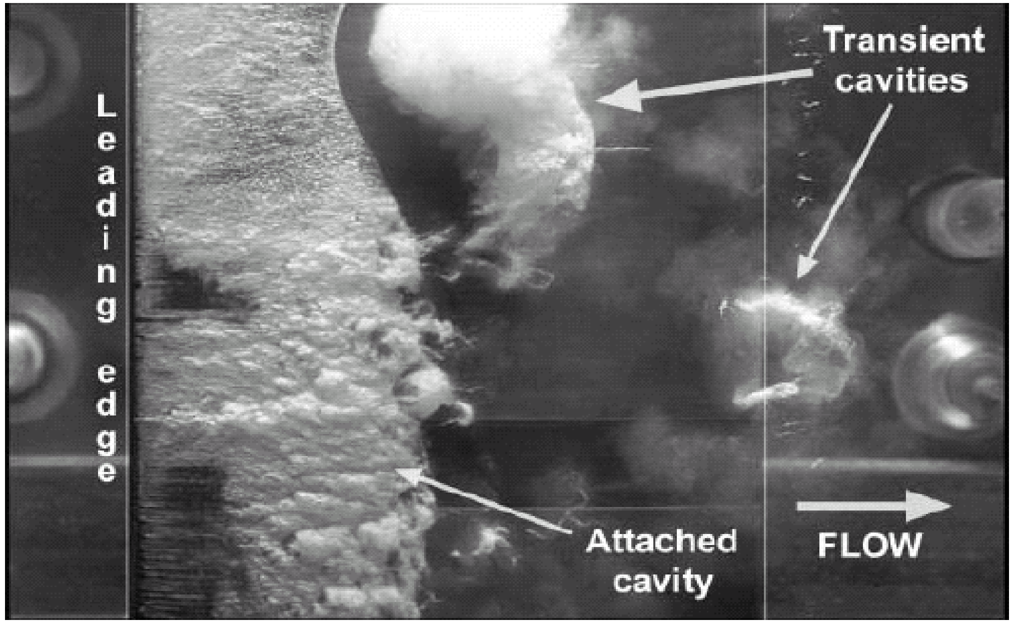
- ***Investigations of cavitating flows in simplified test conditions:***
  - *Variety of 2D and 3D hydrofoils*
    - *@ fixed incidence and variable speed and pressure*
    - *Control of gas content*
  - *State of the art instrumentation:*
    - *Optical techniques for velocity survey (LDV, PIV)*
    - *High speed visualization*
    - *Hydrodynamic forces (Lift & Drag)*
    - *Wall pressure, vibration, strain,*
    - *…*



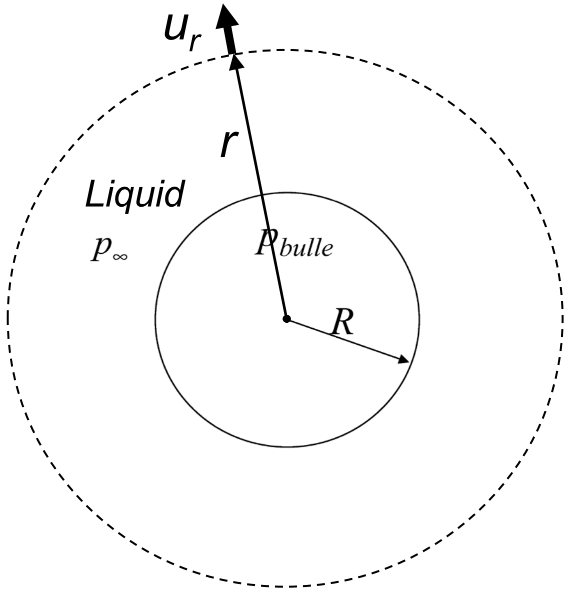
Cavitation erosion

- **Cavitation erosion: Physical mechanism ?**
  - *Case of leading edge cavitation (the most erosive case)*
    - *Main cavity : a mixture of liquid and gas, highly unstable*
    - *Periodic shedding of transient cavities which collapse in the pressure recovery area*
    - *Transient cavities are U-shaped vortices, forming a cloud of tiny bubbles*
    - *Erosion is always observed where the collapse of transient cavities occur*
    - *Unlike bubble cavitation, the transient cavities collapse close to the solid boundary.*

Top view of attached cavitation on a 2-D hydrofoil



- **Cavitation erosion: Physical mechanism ?**
  - *The case of a single cavitation bubble: Rayleigh model (1917)*
  - *Hypotheses:*
    - *Bubble of initial radius R_0, placed in infinite volume of a liquid at rest*
    - *The bubble may be empty ($p_{bubble} = 0$) or filled with vapour only ($p_{bubble} = p_v$)*
    - *Only spherical deformation of the bubble is allowed*
    - *The liquid is supposed Newtonian and incompressible*
    - *We neglect the mass transfer across the bubble interface*
    - *Phase transition is not taken into account*
    - *No surface tension*
    - *No gravity*



  - *Conservation of mass and momentum yields:*

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = -\frac{p_\infty - p_v}{\rho}$$

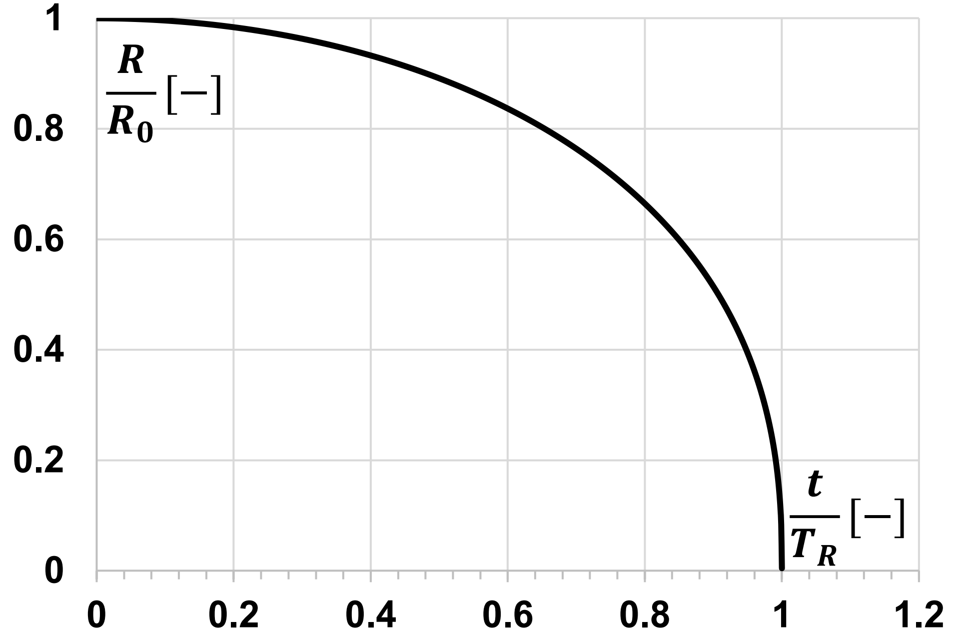
(development out of scope)

- **Cavitation erosion: Physical mechanism ?**
  - *Integration of Rayleigh equation (twice)*

    → *Interface velocity* ($\dot{R}$) *during the collapse and collapse time* (T_R)

$$\dot{R} = \sqrt{\frac{2}{3}\frac{p_\infty - p_v}{\rho}\left(\frac{{R_0}^3}{R^3} - 1\right)} \qquad T_R \approx 0.915 R_0 \sqrt{\frac{\rho}{p_\infty - p_v}}$$

Rayleigh time is the time it takes to a spherical bubble, of initial radius R_0, filled with vapor only to collapse in a liquid of density ρ and a pressure p_∞



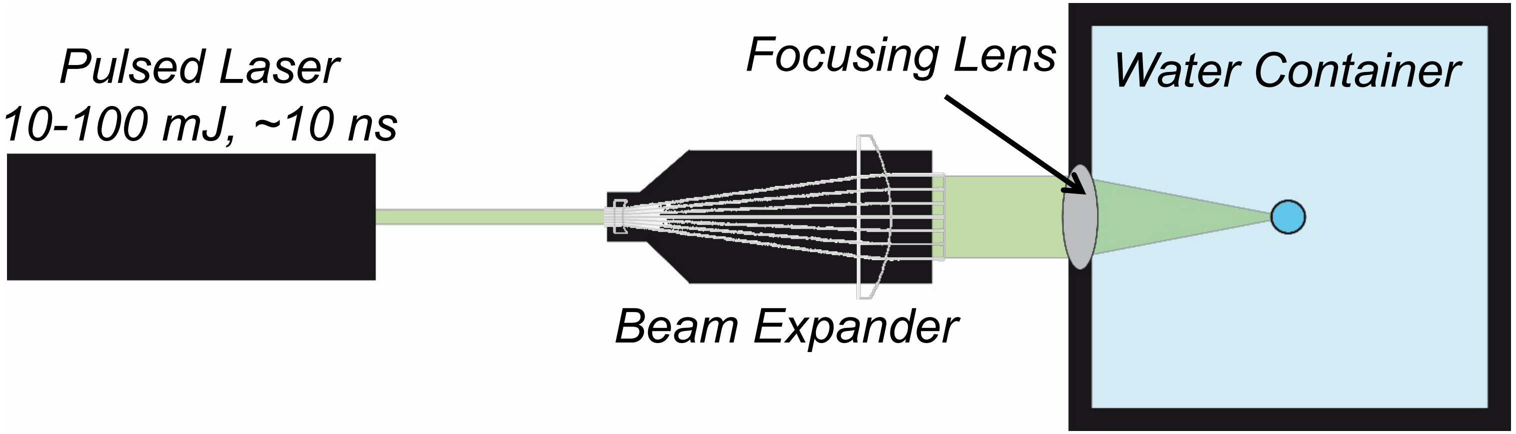
- $\lim_{R \to 0}(\dot{R}) = +\infty$:

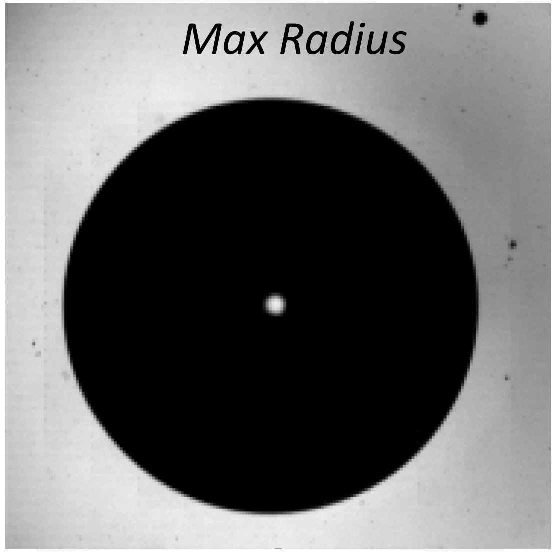
Infinite velocity at the end of the collapse !
Compressibility effect must be taken into account

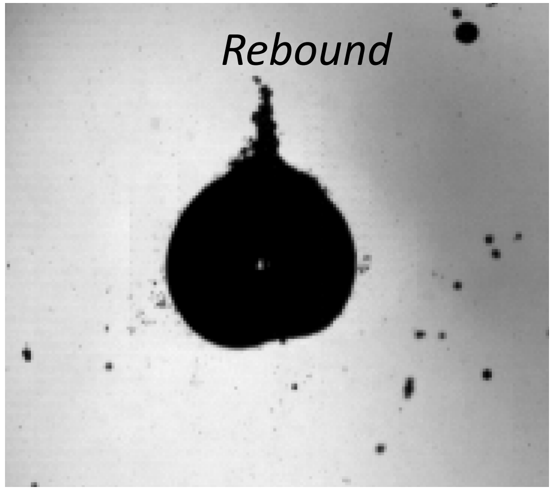
In reality, the velocity is limited by the presence of non-condensable gas within the bubble

- **Cavitation erosion: Physical mechanism ?**
  - *Experimental investigations: Laser induced bubble*
    - *Pulsed laser (~ns duration, 10-500 mJ/pulse)*
    - *Optics: Beam expander + converging lens*
    - *Laser focusing in water → plasma*

      → Rapis growth and collapse of a spherical bubble





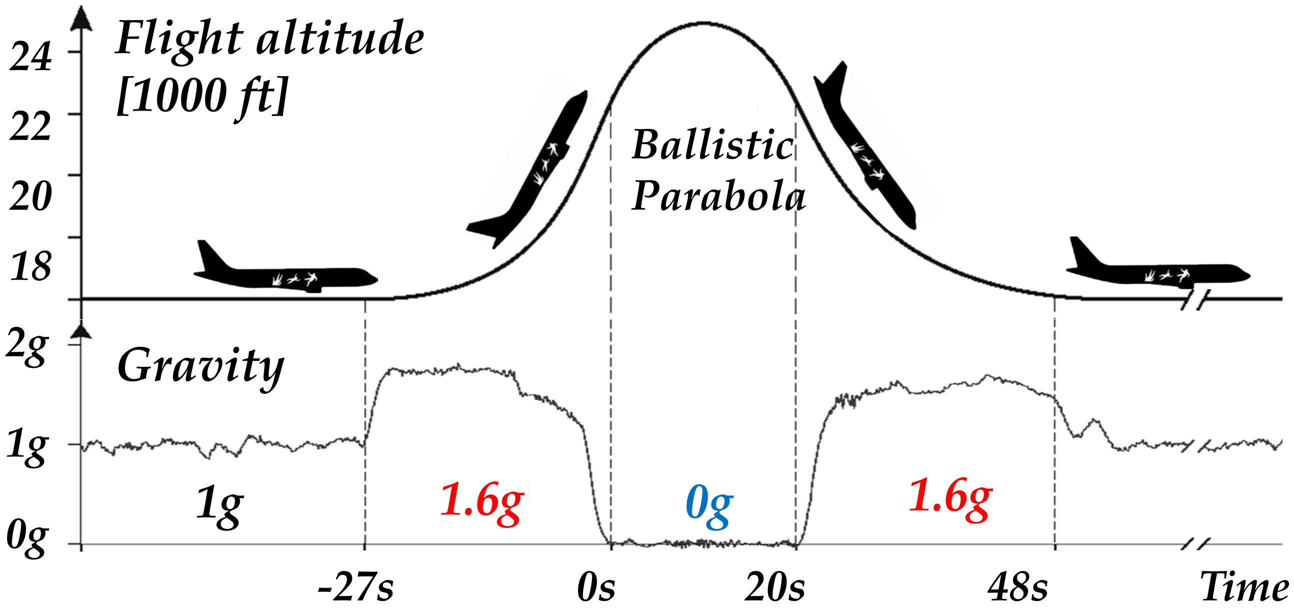


Cavitation erosion

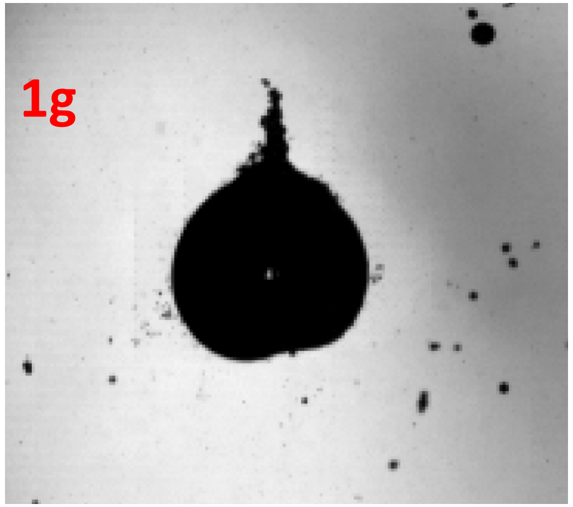
- **Cavitation erosion: Physical mechanism ?**
  - *Experimental investigations: Laser induced bubble*
    - *Pulsed laser (~ns duration, 10-500 mJ/pulse)*
    - *Optics: Beam expander + converging lens*
    - *Laser focusing in water → plasma*

      → Rapid growth and collapse of a spherical bubble

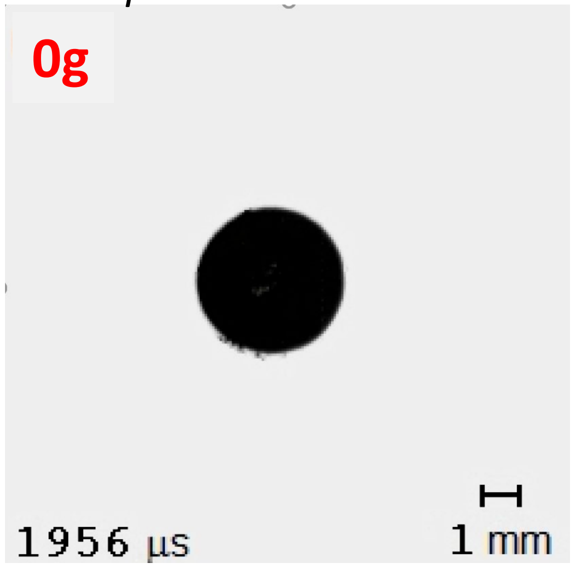
Cavitation bubble dynamics in microgravity (ESA parabolic flights)



Rebound: Upward Jet

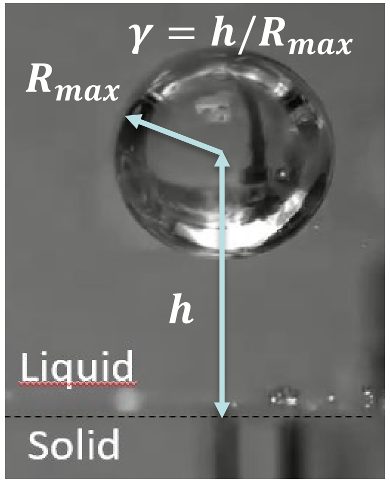


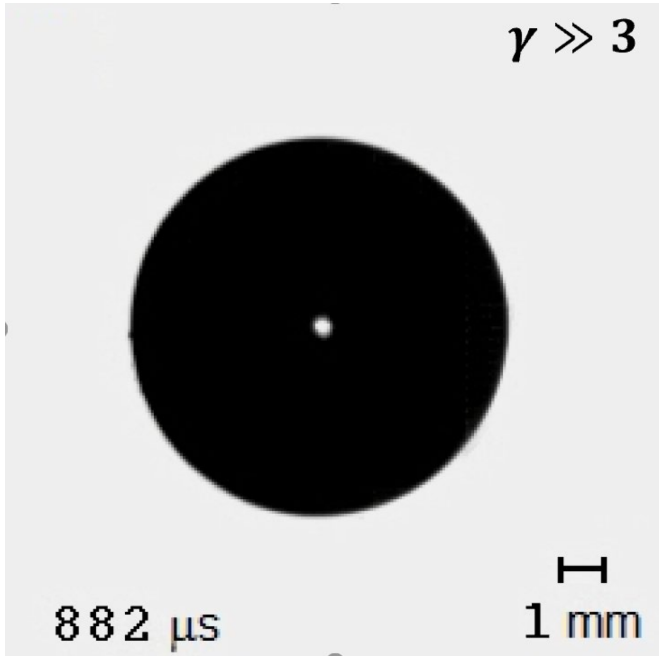
Spherical rebound

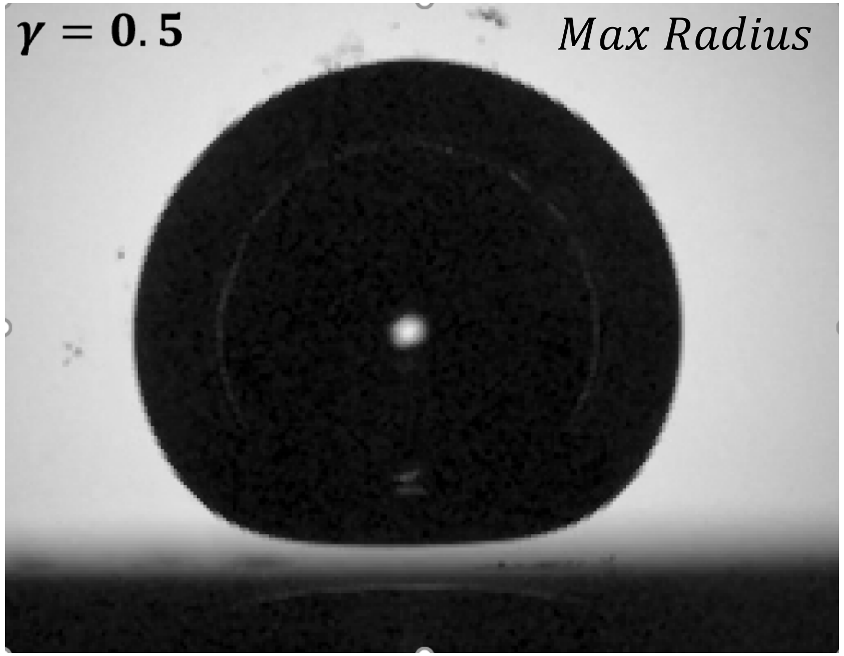


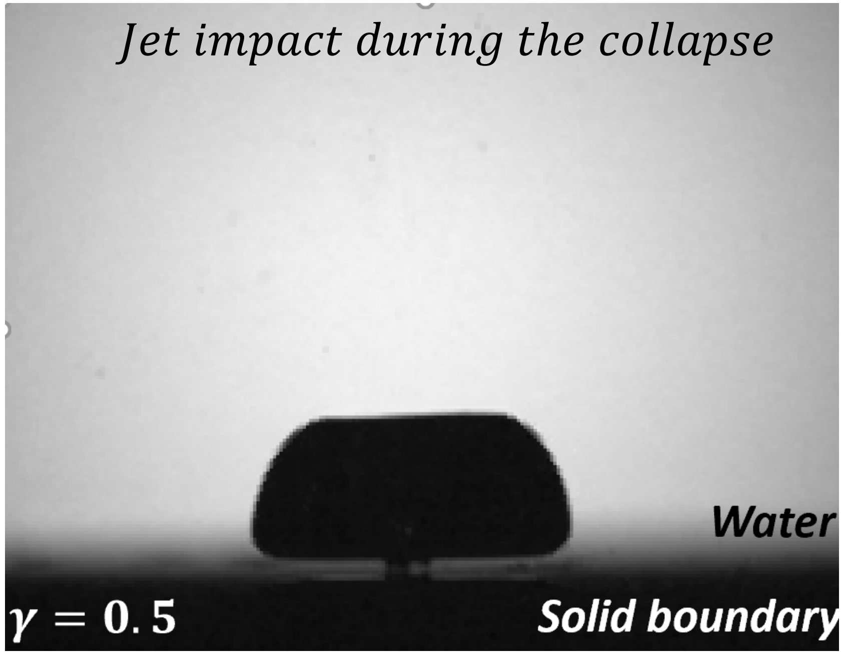
- **Cavitation erosion: Physical mechanism ?**
  - *Micro-jetting induced by the collapse of a bubble in the vicinity of a solid boundary* ($\gamma < 3$)
    - *Development of high-speed micro jet, directed towards the wall*

    Toroidal shape of the rebound bubble
    - *The micro-jet speed may reach 1000 m/s !*

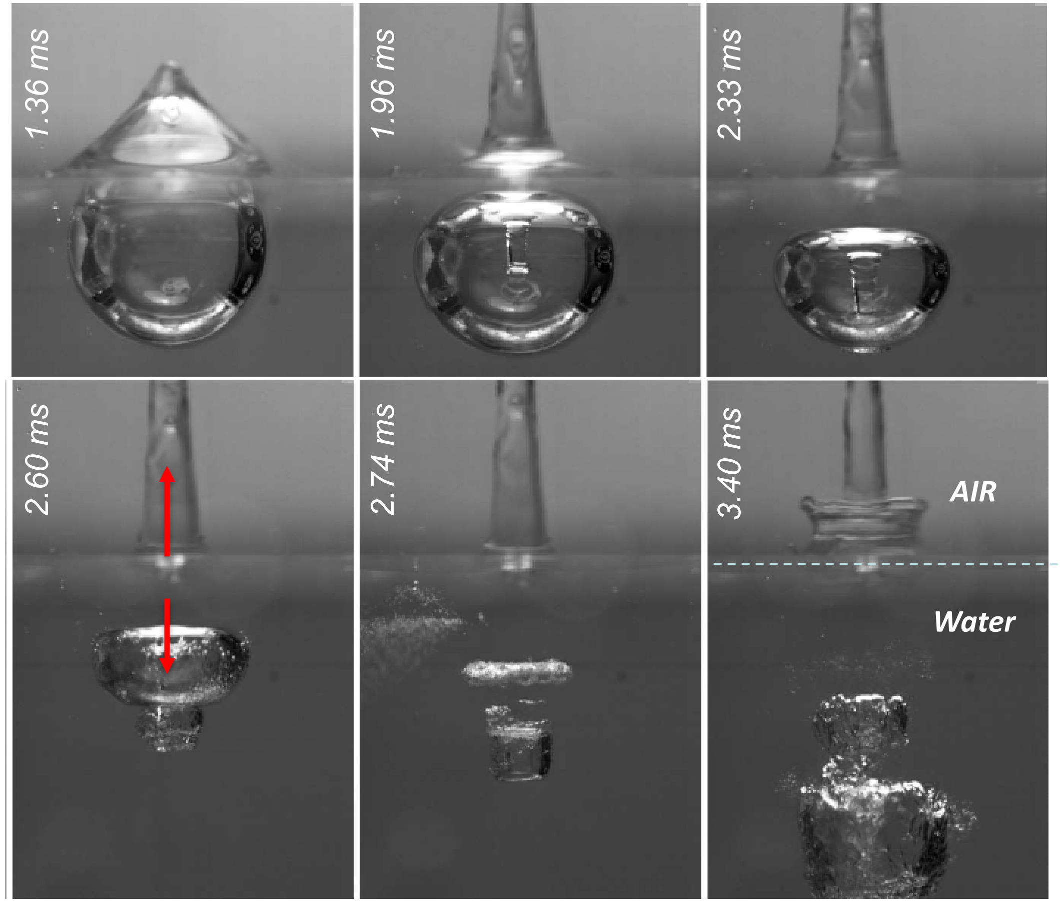


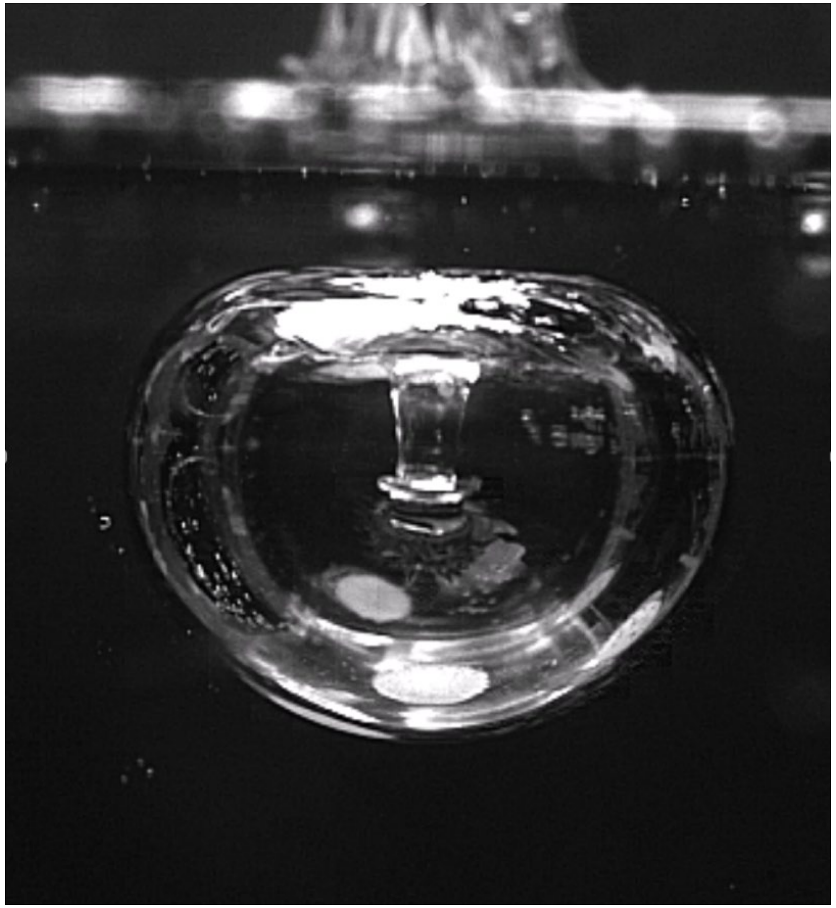




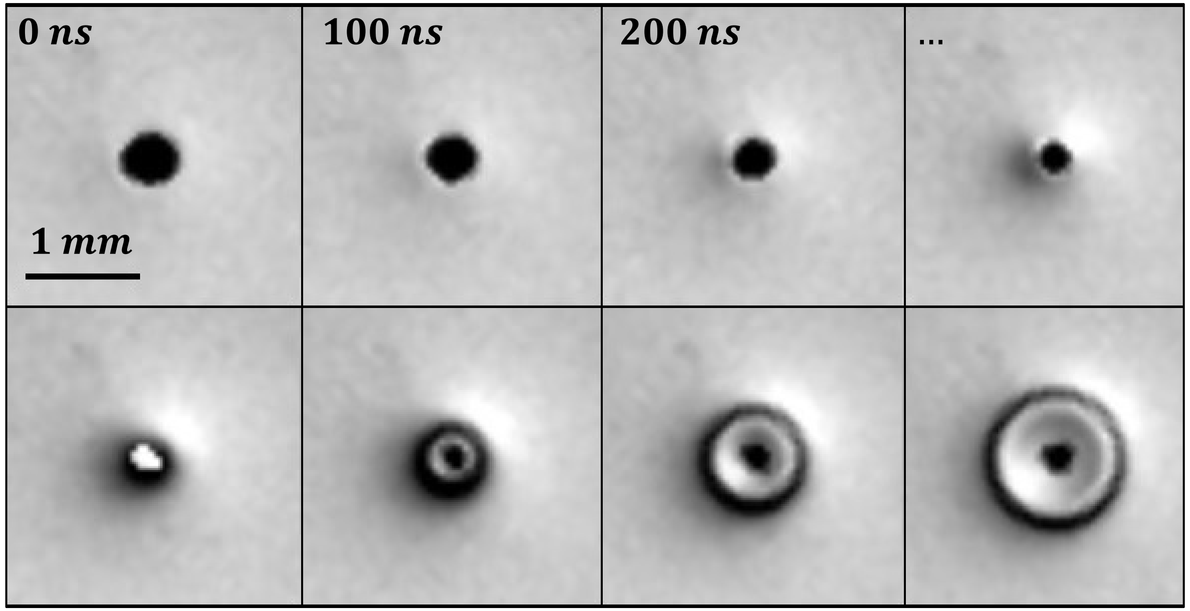


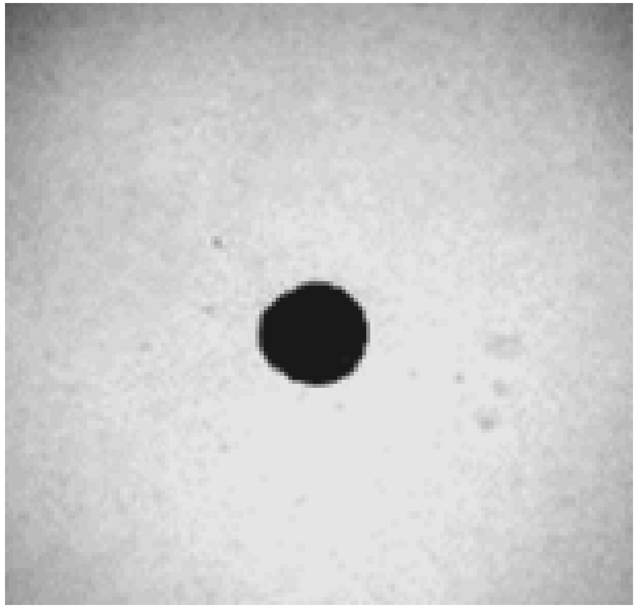
- **Cavitation erosion: Physical mechanism ?**
  - *Micro-jetting induced by the collapse of a bubble in the vicinity of a free surface* $(\gamma < 3)$
    - *Development of 2 high-speed micro jets:*





- **Cavitation erosion: Physical mechanism ?**
  - *Shockwaves induced by the collapse of a cavitation bubble*
    - *Shadowgraph visualization of the last stage of a bubble collapse*
    - $R_{max} = 3.8\ mm$, *10 million frames/second*
    - *Formation of an intense shockwave at the final stage of the collapse*
      Estimation of the shock pressure: ~GPa !

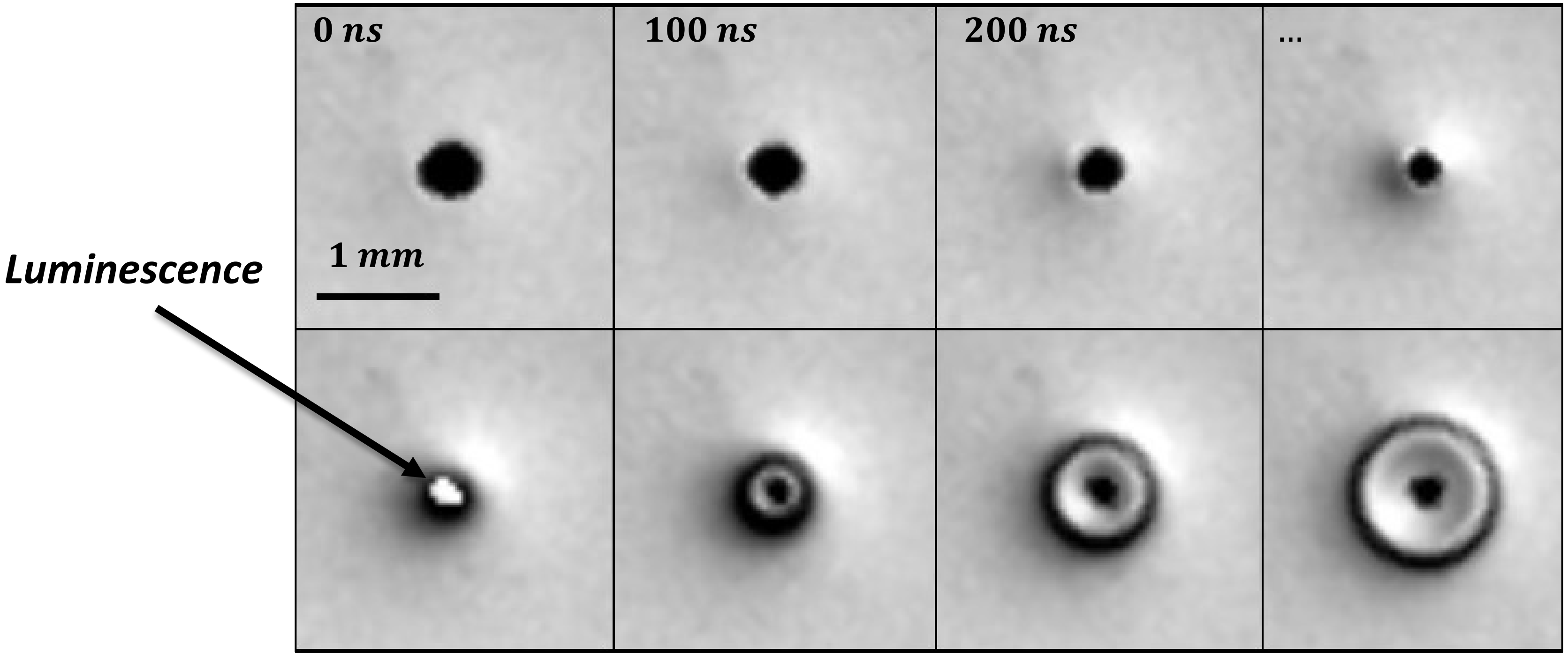




Cavitation erosion is believed to originate from a combined action of shockwaves and micro-jetting

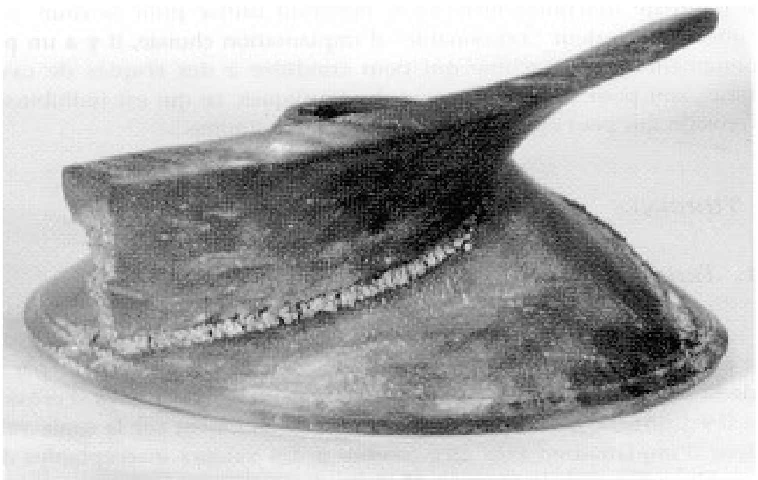
Collapse induced Luminescence

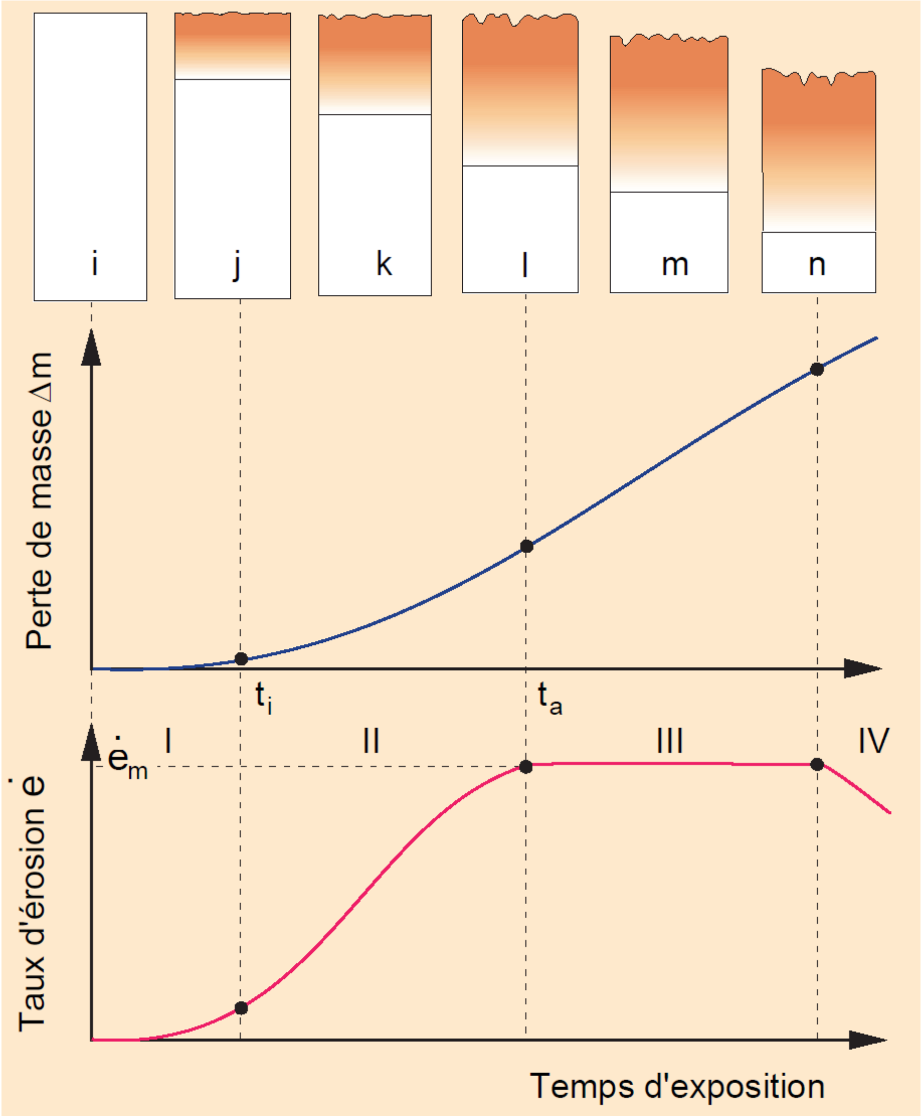
- *Evidence of light emission at the final stage of the collapse of a highly spherical bubble*
  - *10 million frames per second, 50 ns exposure time*
- *Due to a tremendous of pressure (~GPa) and temperature (~ 10'000 K) of the non-condensable gas → Light emission (black body radiation)*



Typical steps of cavitation erosion process:

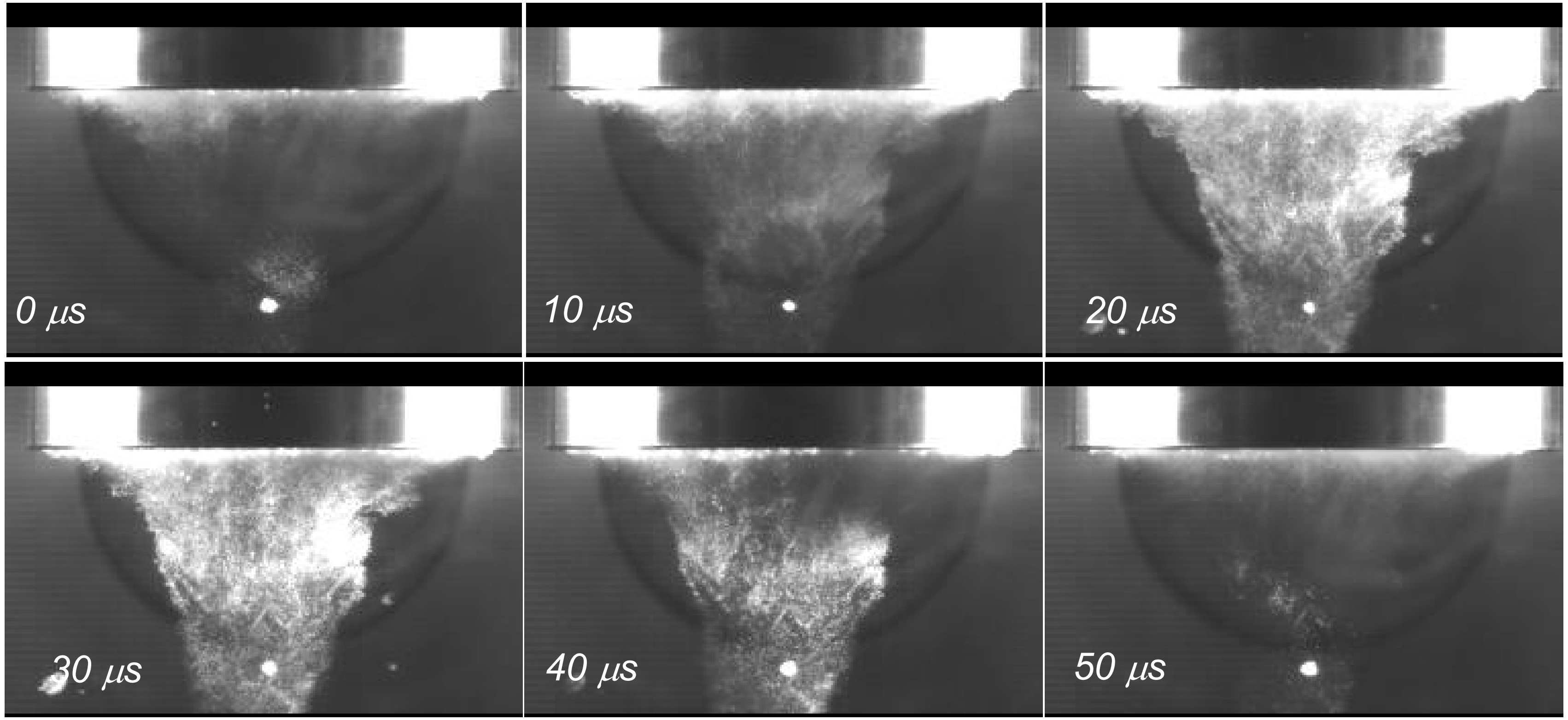
- ***I: Incubation period***
  - ***Surface deformation without mass loss***
- ***II: Acceleration period***
  - ***Increase of mass loss rate***
- ***III: Stationary period***
  - ***The rate of mass loss remains constant***
- ***IV: Deceleration period***
  - ***Decrease of mass loss rate***





Experimental Methods for Cavitation Erosion Tests

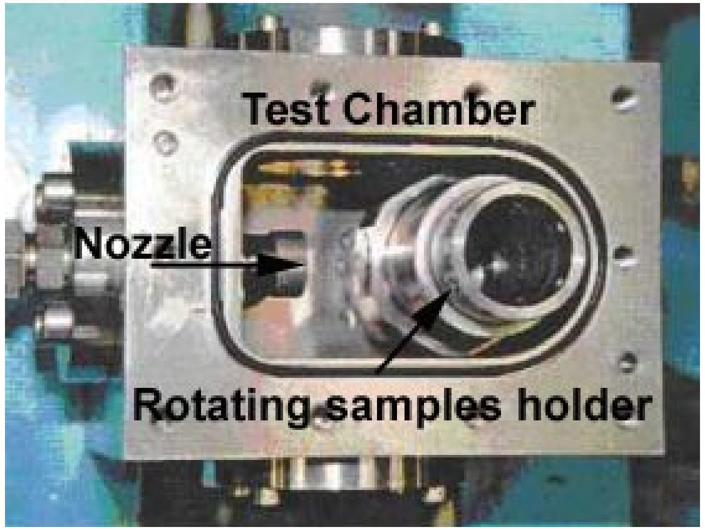
- *Ultrasound cavitation for erosion tests (Sonication)*
  - *5 cm diameter sonotrode: Freq. ~ 20 KHz, Power ~ 1 Kwatt*
  - *High speed visualization of one sonication cycle*

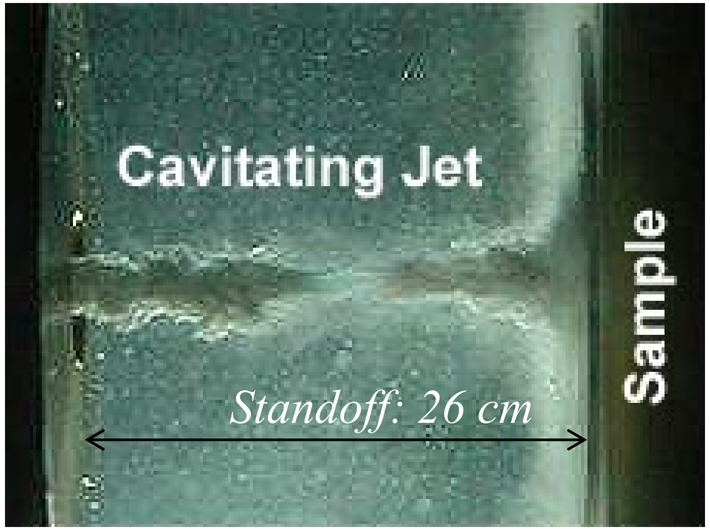


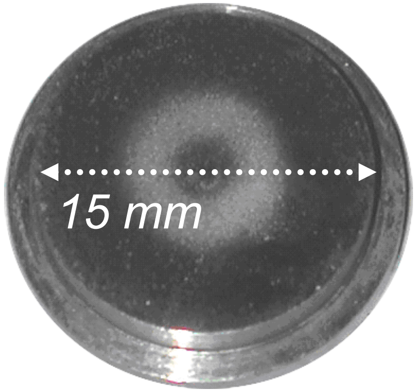
Experimental Methods for Cavitation Erosion Tests

The High-Speed Cavitating Jet

- *High speed immersed water jet impinging on a polished surface (sample)*
- *Upstream Pressure : 300 bar*
- *Nozzle diameter: ~ 0.5 mm → Jet speed: 200 m/s*
- *Downstream pressure is varied to adjust cavitation aggressiveness*





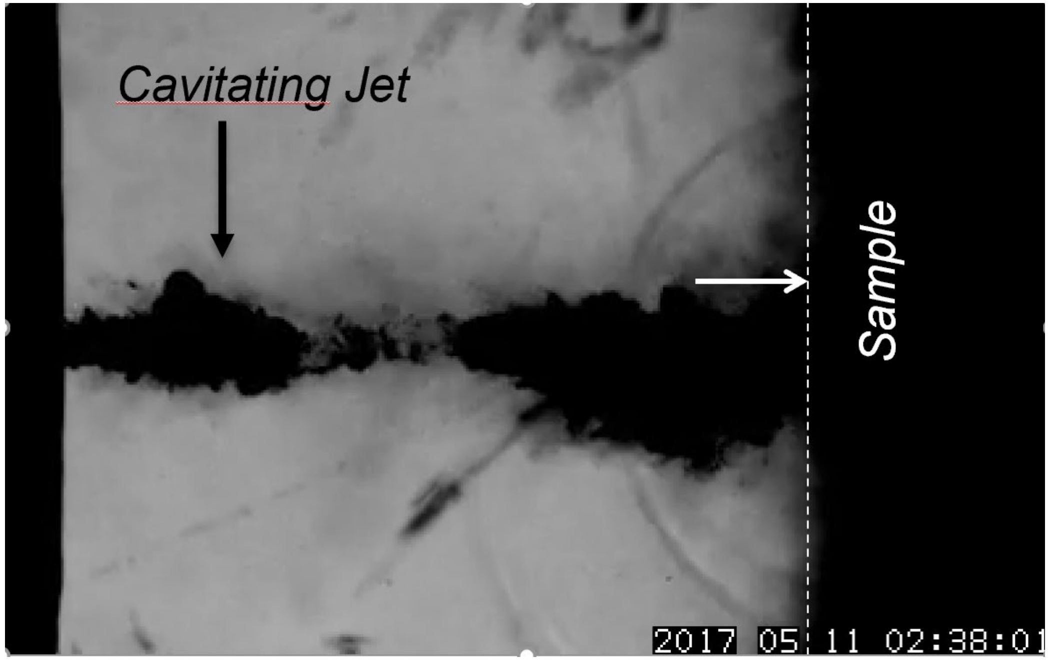


Experimental Methods for Cavitation Erosion Tests

The High-Speed Cavitating Jet

- *High speed immersed water jet impinging a polished surface (sample)*
- *Upstream Pressure : 300 bar. Nozzle diameter: ~ 0.5 mm → Jet speed: 200 m/s*

Shadowgraph visualisation of radiated shockwaves by a high speed cavitating jet (500'000 frames/second, 50 ns exposure time)



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The High-Speed Cavitating Jet

- *High speed immersed water jet impinging a polished surface (sample)*
- *Upstream Pressure : 300 bar*
- *Nozzle diameter: ~ 0.5 mm → Jet speed: 200 m/s*
- *Downstream pressure is varied to adjust cavitation aggressiveness*

- *The mass loss is measured at regular intervals to evaluate the material resistance*

Advantage: Significant erosion may be obtained within few test hours

Exposure: 0 min | *Exposure: 60 min* | *Exposure: 120 min* | *Exposure: 180 min*