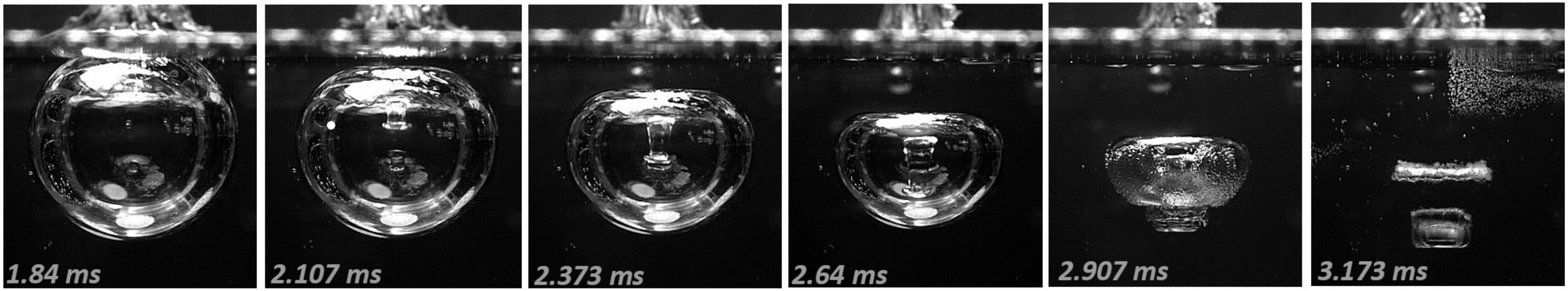
ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE
SECTION DE GENIE MECANIQUE
6th & 8th Semester, Fall 2025

CAVITATION AND INTERFACE PHENOMENA
Chapter 3 : Dynamics of non-spherical cavitation bubbles
3.1 Effect of neighboring surfaces



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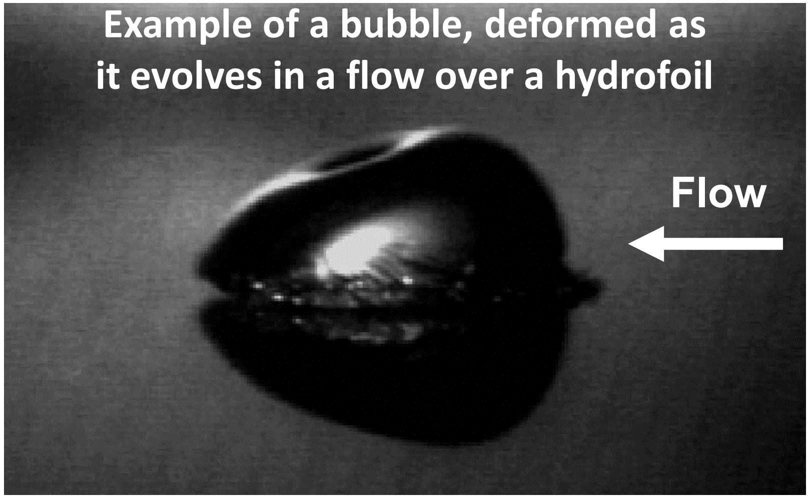
Dynamics of cavitation bubbles
The need for experimental investigations

- **Limitations of analytical models:**
  - **Rayleigh, Rayleigh-Plesset, Keller-Miksis, …**
    - **Spherical bubble, evolving in an infinite liquid volume**
    - **Phase transitions and mass transfer not taken into account**
    - **The last stage of the bubble collapse is poorly modeled**
      - **Thermal effects ? Chemical reactions ?**

- **In real life, bubbles are never spherical and are always deformed by pressure gradients, induced by the flow, neighboring surfaces or gravity field.**

→ ***In thin context, experimentation is necessary to better understand the physical mechanisms and draw empirical rules to predict the dynamics of deformed bubbles.***


Example of a bubble, deformed as it evolves in a flow over a hydrofoil

Dynamics of cavitation bubbles

Experimental techniques for bubble generation

- **Laser-induced bubble (Focusing of a pulsed laser):**
  - **Short pulsed laser (100 fs – 100 ns) in distilled & filtered water**
  - **Plasma[1] generation (ionization) → Increase of absorption coefficient**
    - **Ionization threshold: function of the laser pulse duration (~ 5.5 mJ for 70 ns pulse duration)**
  - **Significant increase of the temperature at the focal point**
    - **→ Vaporization and instantaneous increase of the pressure**
    - **→ Explosive growth of a vapor bubble**
  - **The cavity cools down as it expands and reaches a maximum radius (function of laser energy, Liquid pressure and temperature).**

Follows Successive implosions and rebounds

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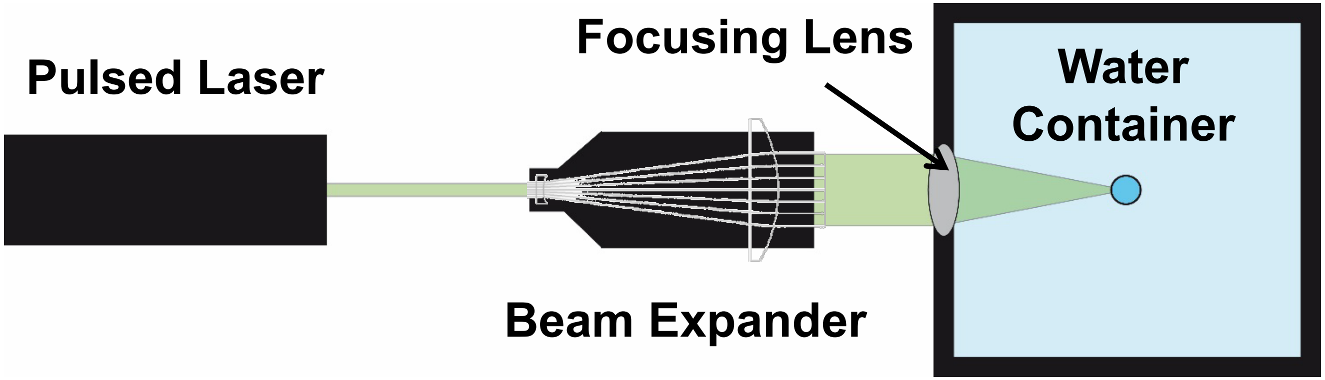
[1] ***Plasma is one of the four fundamental states of mater, made of highly agitated ions and free electrons***

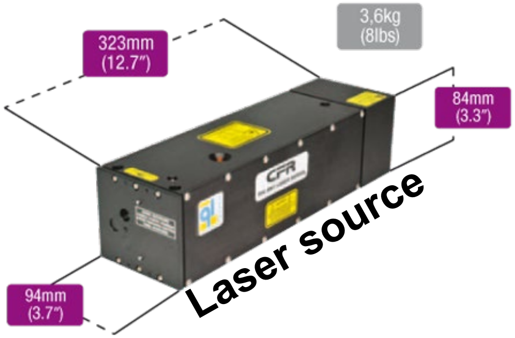
Dynamics of cavitation bubbles

Experimental techniques for bubble generation

Typical setup for a laser induced bubble



- **The laser source:**
  - **Pulsed laser of typically ~10 ns duration**
  - **Energy per pulse in the range 10-200 mJ**
  - **Class IV laser (security !!)**

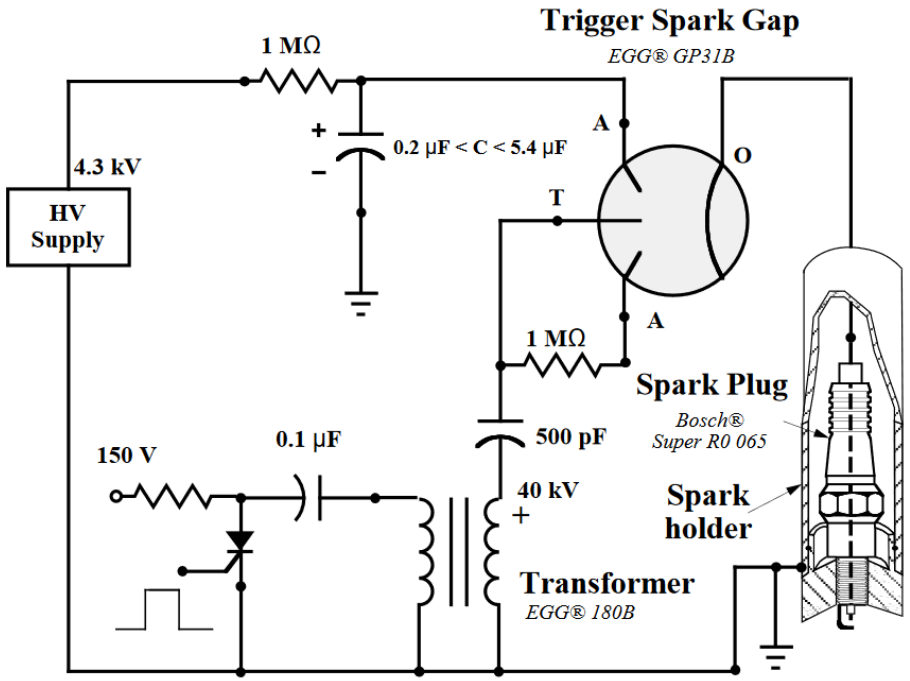


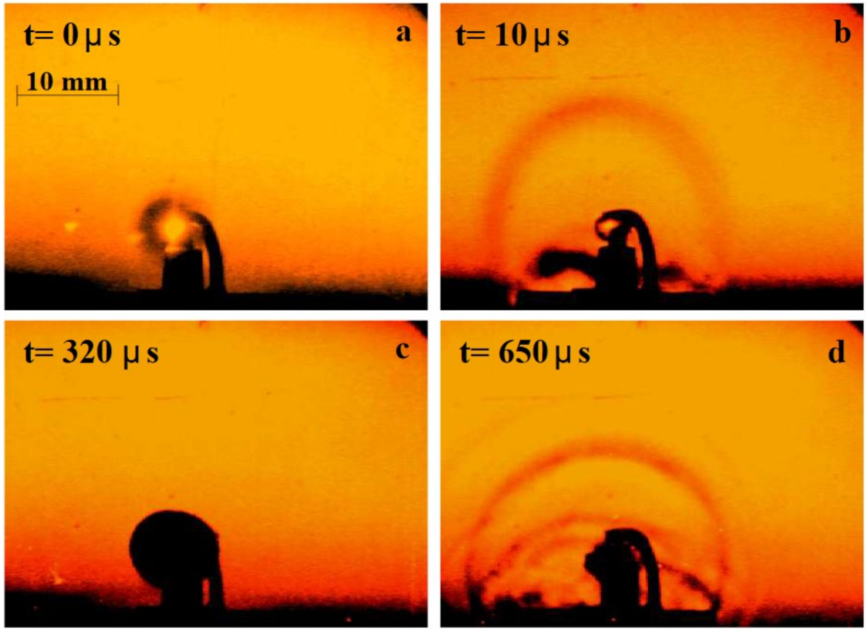
- **The beam expander:**
  - **Galilean type (diverging + converging lenses)**
  - **Dependent on the laser wavelength**
  - **Maybe of fixed or variable magnification factor**

Dynamics of cavitation bubbles

Experimental techniques for bubble generation

- **Alterative to pulsed laser technique (more affordable):**
  - **Electrical discharge between 2 immersed electrodes**
    - **Short electrical pulse (100 ns – 10 ms)**
    - **Process similar to pulsed laser focusing technique**
      - **Ionization → local heating → Growth and collapse of a vapor bubble**
    - **Lower cost but more intrusive technique**

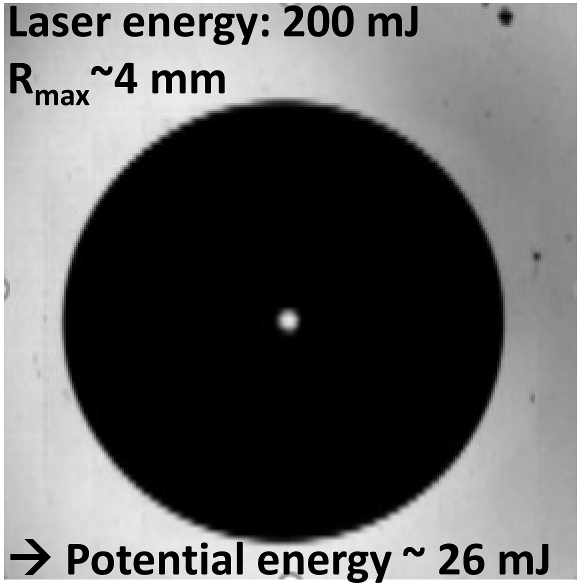




Dynamics of cavitation bubbles

Experimental techniques for bubble generation

Growth and collapse of a laser induced bubble

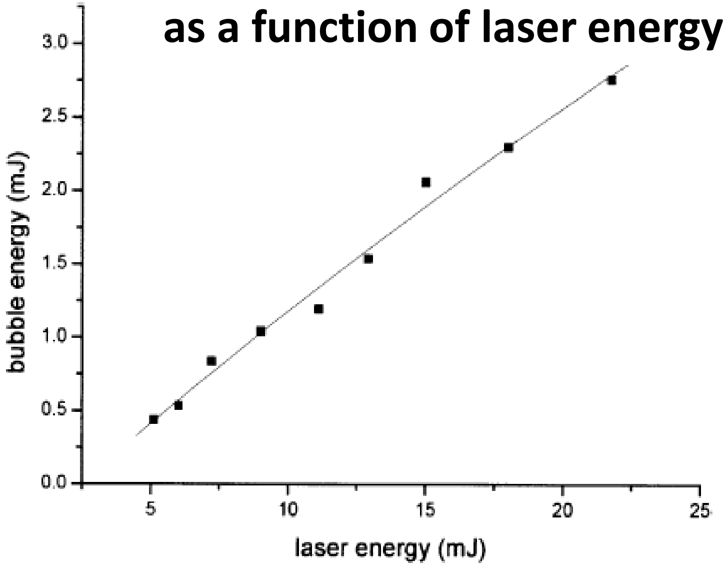


Laser energy: 200 mJ

R_{max}~4 mm

→ Potential energy ~ 26 mJ

Typical bubble energy
as a function of laser energy



1st Remark: The potential energy of the bubble (at its maximum radius) represents only ~13% of laser energy !!

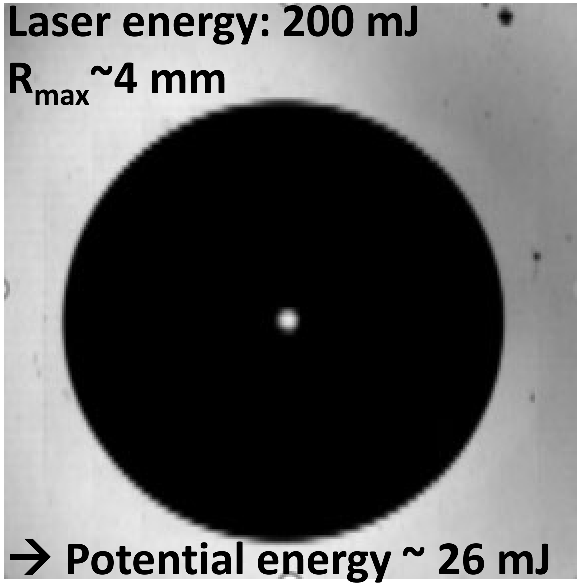
<u>Where does the remaining 87% of the laser energy go ?</u>

This is a difficult question, which will be addressed later

Dynamics of cavitation bubbles

Experimental techniques for bubble generation

Growth and collapse of a laser induced bubble



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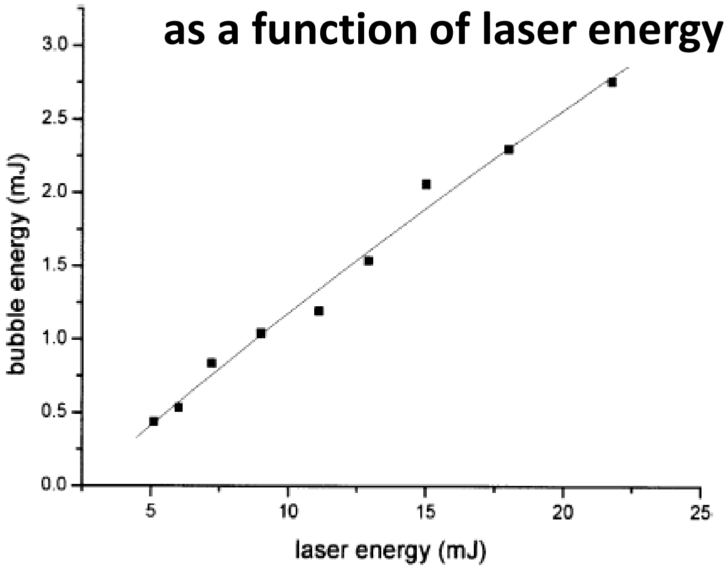
Typical bubble energy as a function of laser energy



2nd Remark: The bubble is generated by local heating → Is it still a cavitation bubble ?

- *Indeed, cavitation is defined as the formation of a bubble filled with vapor and non-condensable gas due to pressure decrease <u>without heat exchange !</u>*

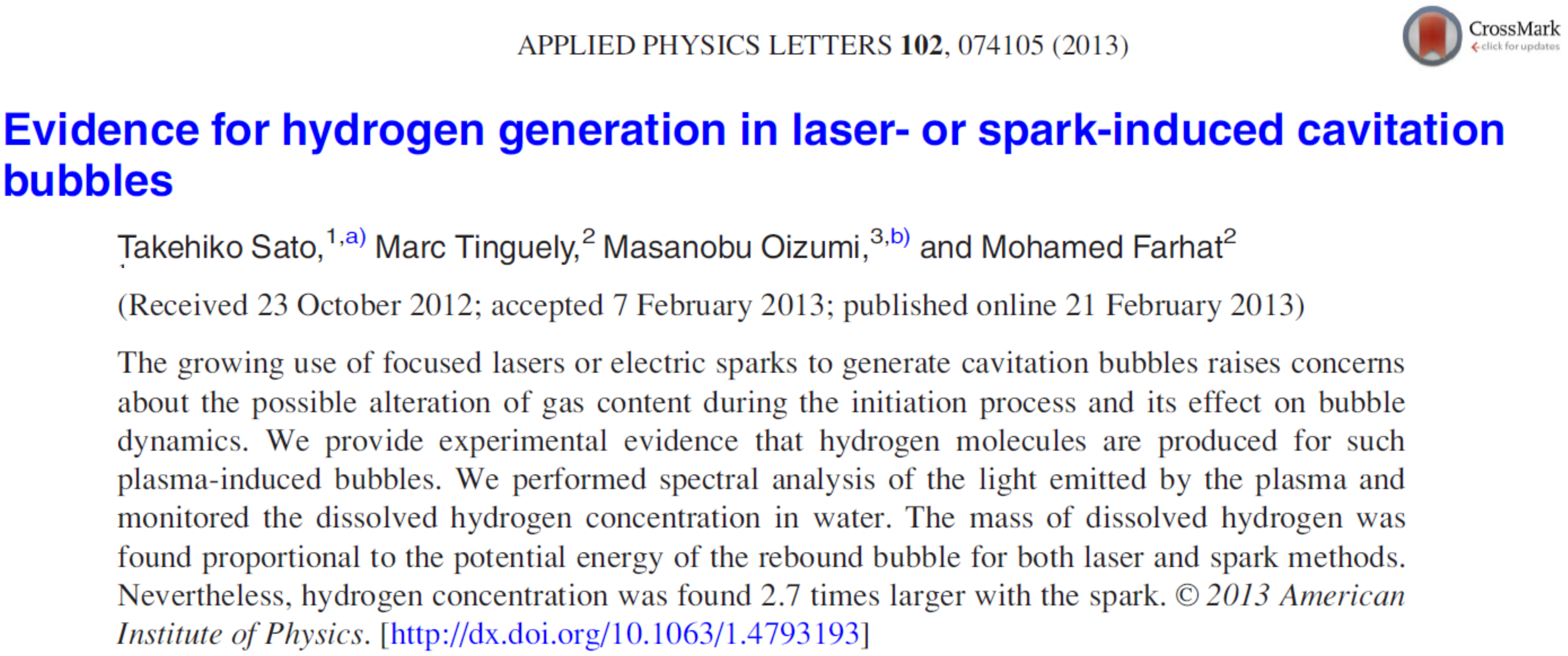
Hypothesis: **Once the bubble has reached its maximum size, it is supposed to be in thermodynamic equilibrium with the liquid → Subsequent events are inertia driven**
→ We assume that a laser-induced bubble behaves as a cavitation bubble

Dynamics of cavitation bubbles

Experimental techniques for bubble generation

- **Effects of plasma on gas content (possible generation of additional gases ?)**
  - **The gas content within a plasma-generated bubble may be altered by the formation of additional hydrogen (dissociation of water molecules)**

    → Effects on bubble dynamics at the final stage of the collapse ?
  - **Reference:**



APPLIED PHYSICS LETTERS **102**, 074105 (2013)

CrossMark

Evidence for hydrogen generation in laser- or spark-induced cavitation bubbles

Takehiko Sato,[1,a)] Marc Tinguely,[2] Masanobu Oizumi,[3,b)] and Mohamed Farhat[2]

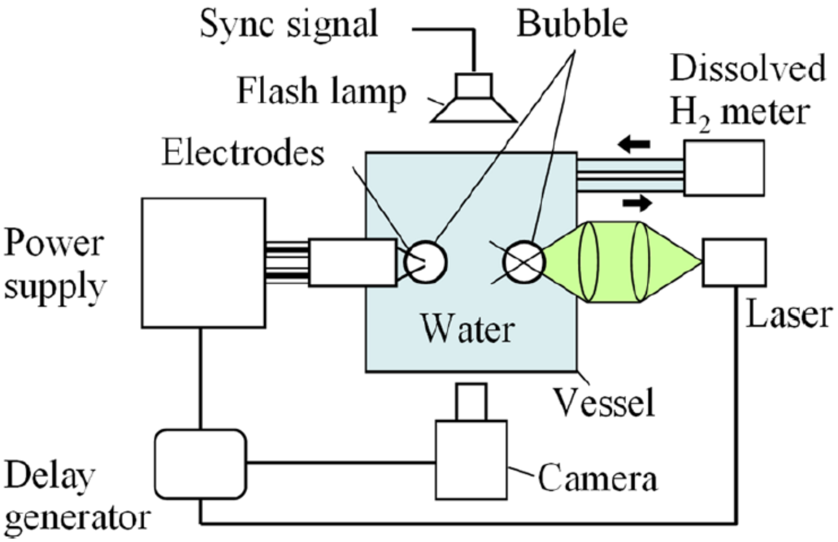
(Received 23 October 2012; accepted 7 February 2013; published online 21 February 2013)

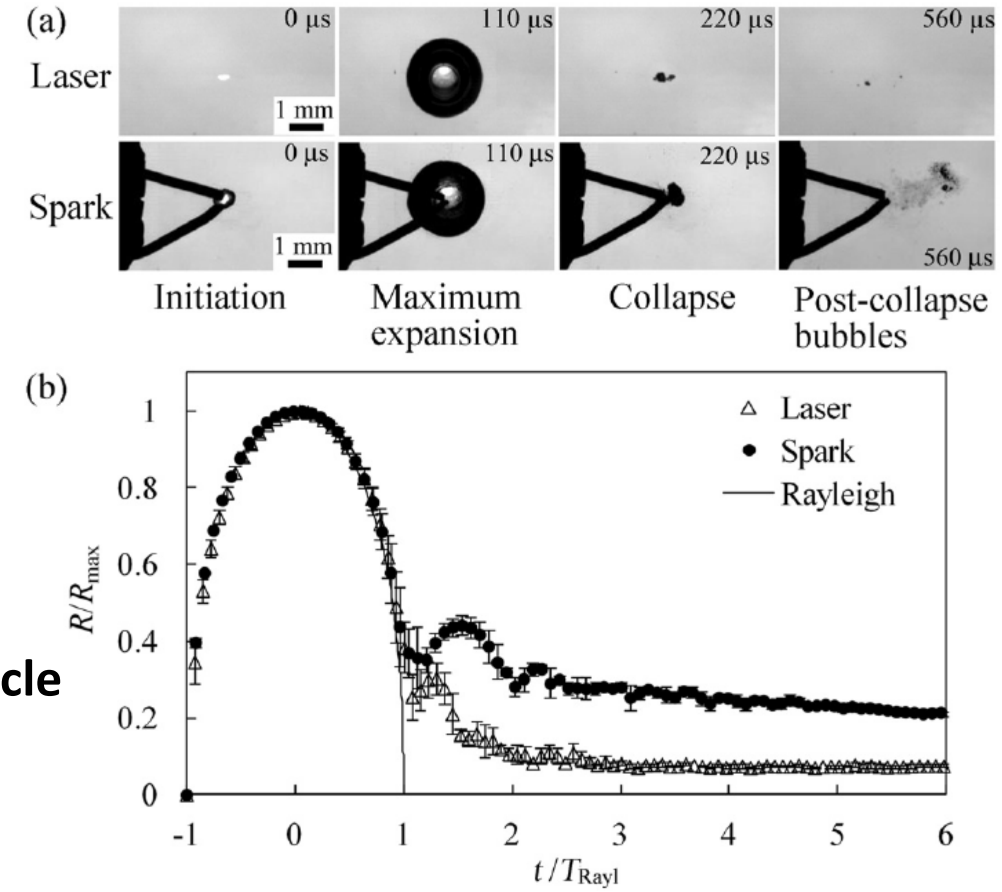
The growing use of focused lasers or electric sparks to generate cavitation bubbles raises concerns about the possible alteration of gas content during the initiation process and its effect on bubble dynamics. We provide experimental evidence that hydrogen molecules are produced for such plasma-induced bubbles. We performed spectral analysis of the light emitted by the plasma and monitored the dissolved hydrogen concentration in water. The mass of dissolved hydrogen was found proportional to the potential energy of the rebound bubble for both laser and spark methods. Nevertheless, hydrogen concentration was found 2.7 times larger with the spark. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4793193]

Dynamics of cavitation bubbles

Experimental techniques for bubble generation

- **Effects of plasma on gas content (possible generation of additional gases ?)**
  - **A laser and spark induced bubbles of similar size are generated within the same container filled with distilled water**



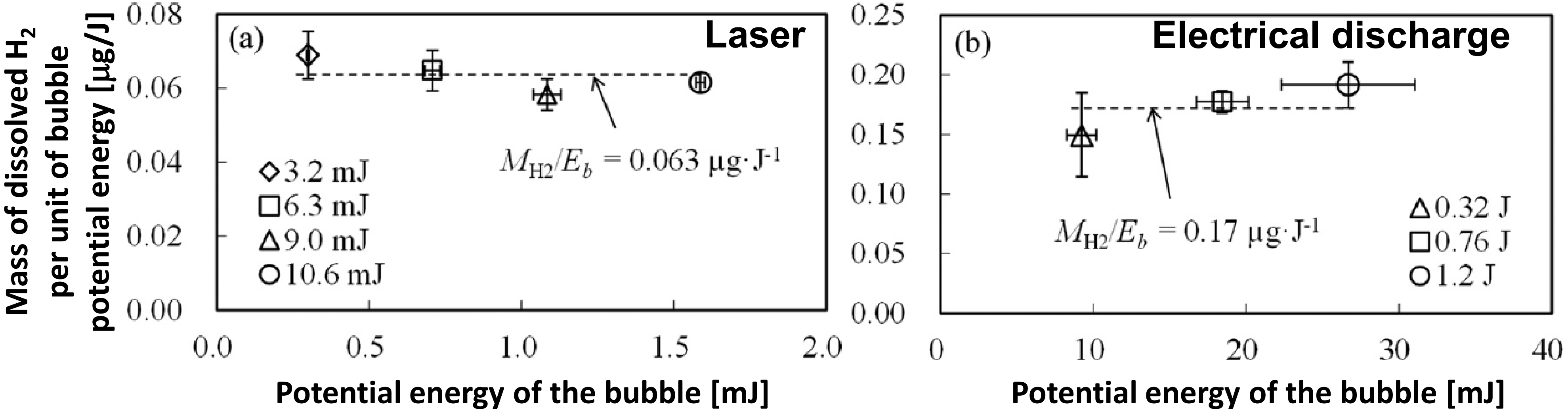


- **The bubbles behaves similarly in the 1st cycle**
  - **Same collapse time**
- **The rebounds are significantly different**
- **Different amount of residual gases**

Dynamics of cavitation bubbles

Experimental techniques for bubble generation

- **Effects of plasma on gas content (possible generation of additional gases) ?**
  - **Amount of Hydrogen generation by laser and spark bubbles**



- **The gas content is indeed affected by the plasma with H2 generation 2.7 times larger with the electrical discharge than laser focusing.**

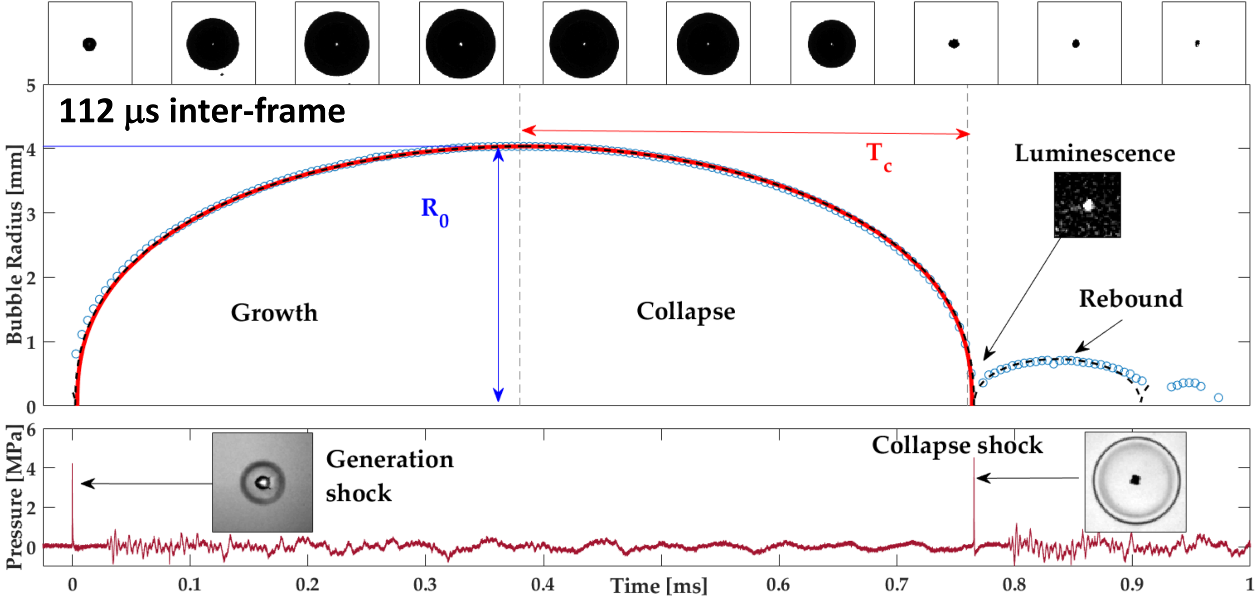
- **Despite the alteration of the gas content by the spark and laser induced plasma, these experimental techniques are growingly used to investigate the cavitation bubble dynamics in a controlled way (for lack of better!)**

Dynamics of cavitation bubbles

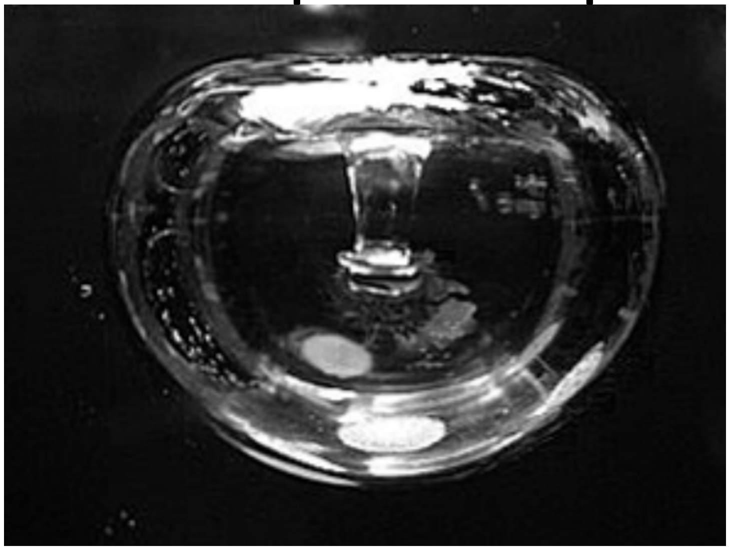
Experimental techniques for bubble generation

- **Key phenomena associated with a laser-induced cavitation bubble:**
  - **Explosive growth with emission of a shockwave**
  - **Deceleration up to $R = R_{max}$**
  - **Bubble collapses and rebounds with the following key phenomena:**
    1. **Shockwave emission (compressibility effects)**
    2. **Light (luminescence), due to extreme heating of the non-condensable gas**
    3. **Micro-jetting, due to bubble deformation**
    4. **Bubble rebound (due to the non-condensable gas)**

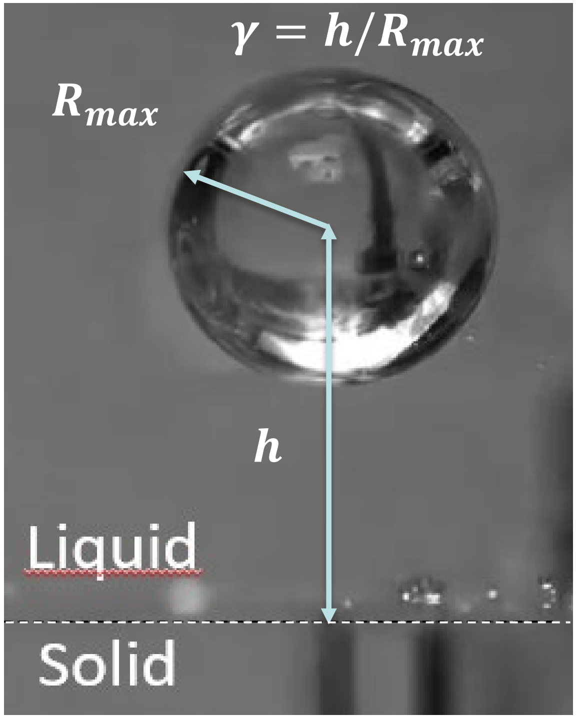
Highly spherical bubble



Example of micro-jetting due to a non-spherical collapse



Dynamic of a cavitation bubble collapse
Effects of a neighboring solid wall



- **Definition: Stand-off parameter γ**

$$\gamma = h/R_{max}$$

R_{max} : *Maximum bubble radius*
h : *Distance between the bubble and the wall*

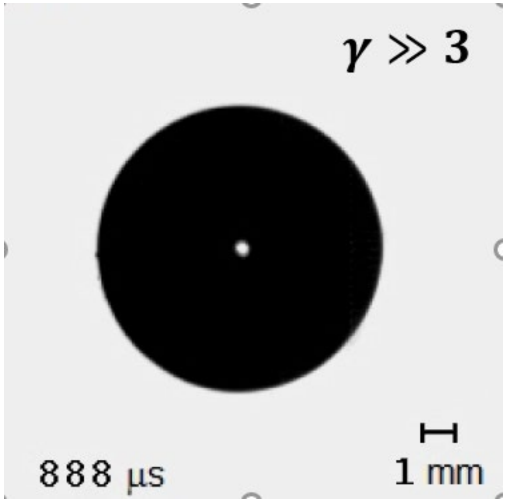
- **The stand-off parameter γ is a non-dimensional number, which characterizes the proximity of a solid boundary**
  - **The effect of the wall on bubble dynamics vanishes as γ increases**

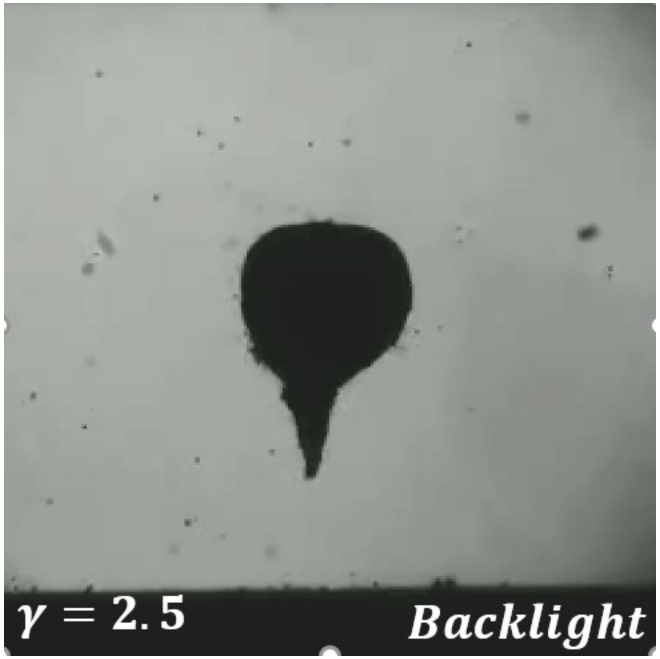
We know from experimentation that (in still liquid and in absence of gravity):

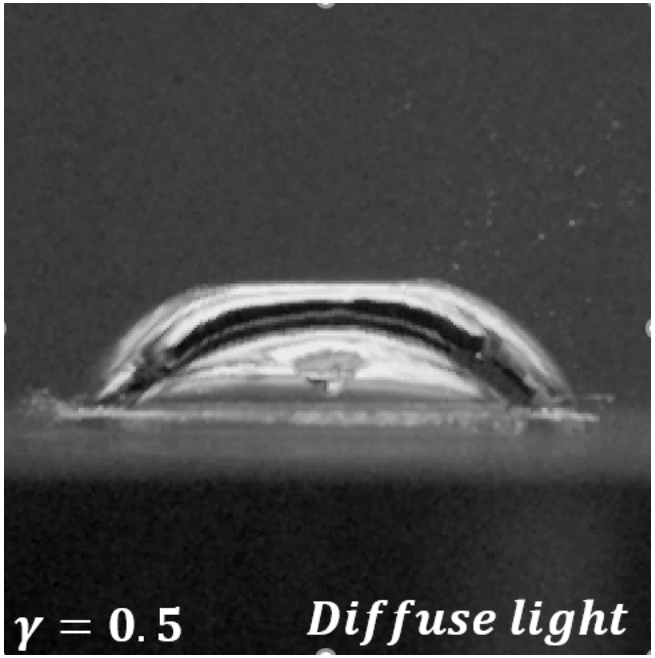
$\gamma \gtrsim 3$ → **the bubble is weakly disturbed and remains almost spherical**

Dynamic of a cavitation bubble collapse
Effects of a neighboring solid wall

- **Bubble far from any boundary $(\gamma > 3)$:**
  → The bubble grows, collapses and rebounds in a spherical way
- **Bubble close to a solid wall $(\gamma < 3)$:**
  → The bubble deforms due to wall-induced pressure anisotropy
  → Development of high-speed micro jet, directed towards the wall
  → Toroidal shape of the rebound bubble

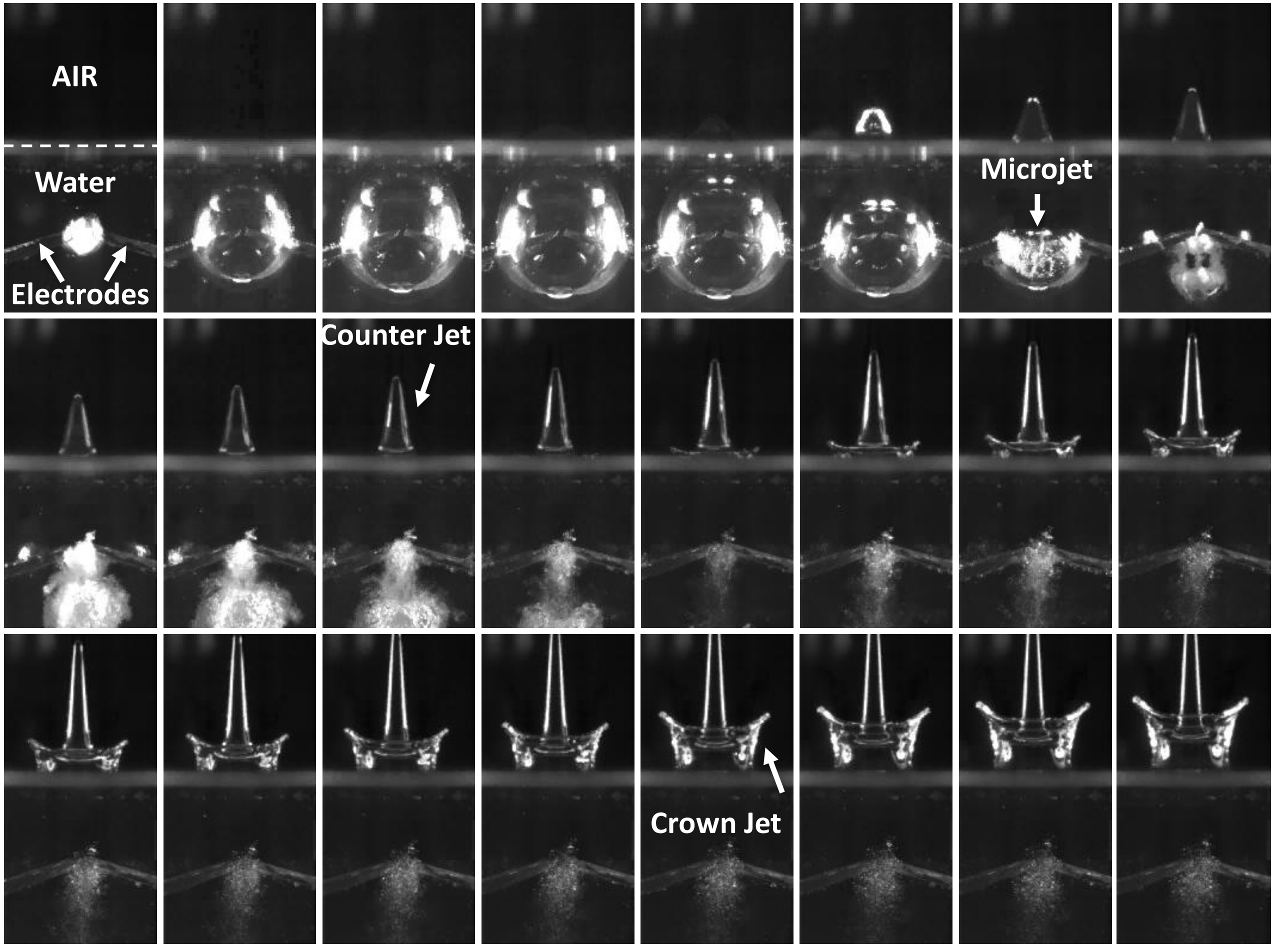






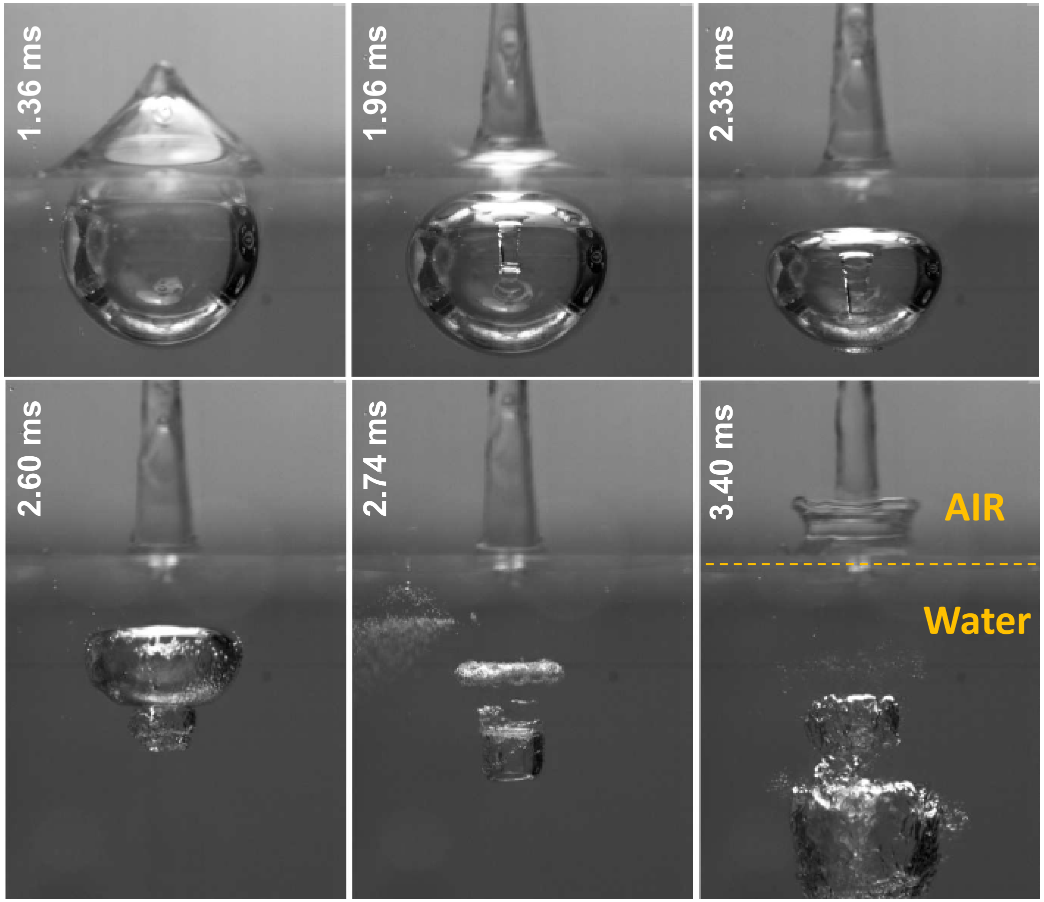
Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface

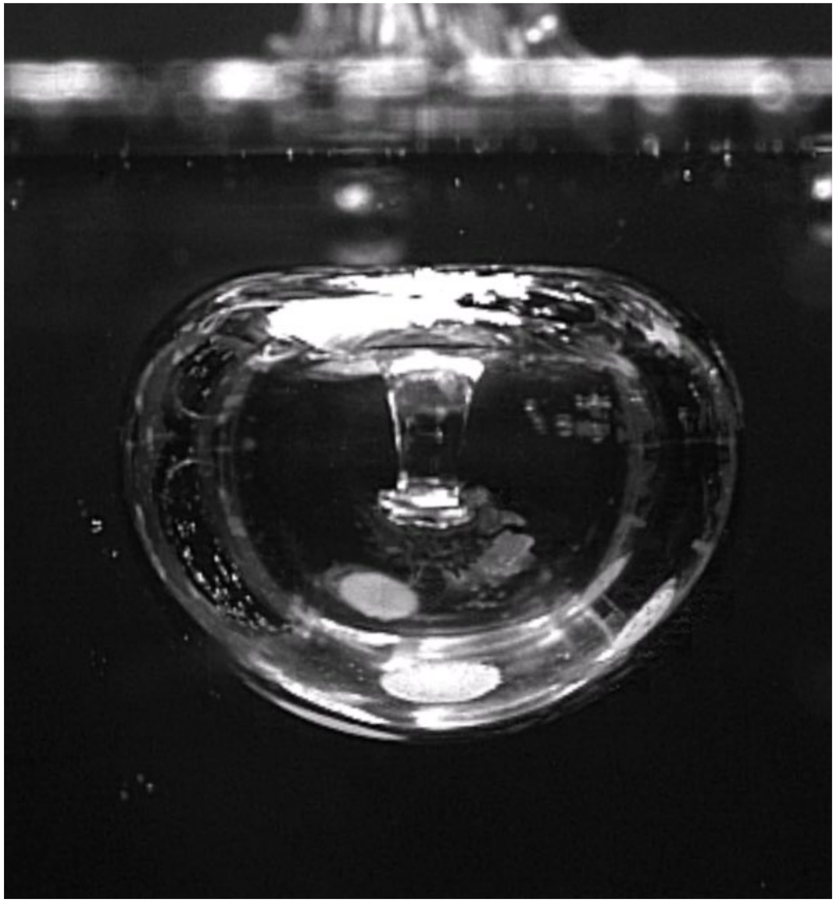
- **Spark-induced bubble, close to the free surface $(\gamma < 3)$**
  - **High-speed jet in the bubble opposite to the free surface (downward)**
  - **Liquid jets out of the free surface (counter jet and, later, a crown jet)**
  - **Unlike solid wall, the bubble moves away from the surface**



Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface

- **Spark-induced bubble, close to the free surface $(\gamma < 3)$**
  - **High-speed jet in the bubble, opposite to the free surface (downward)**
  - **Liquid jets out of the free surface (a counter jet, followed by a crown jet)**
  - **Unlike solid wall, the bubble moves away from the free surface**

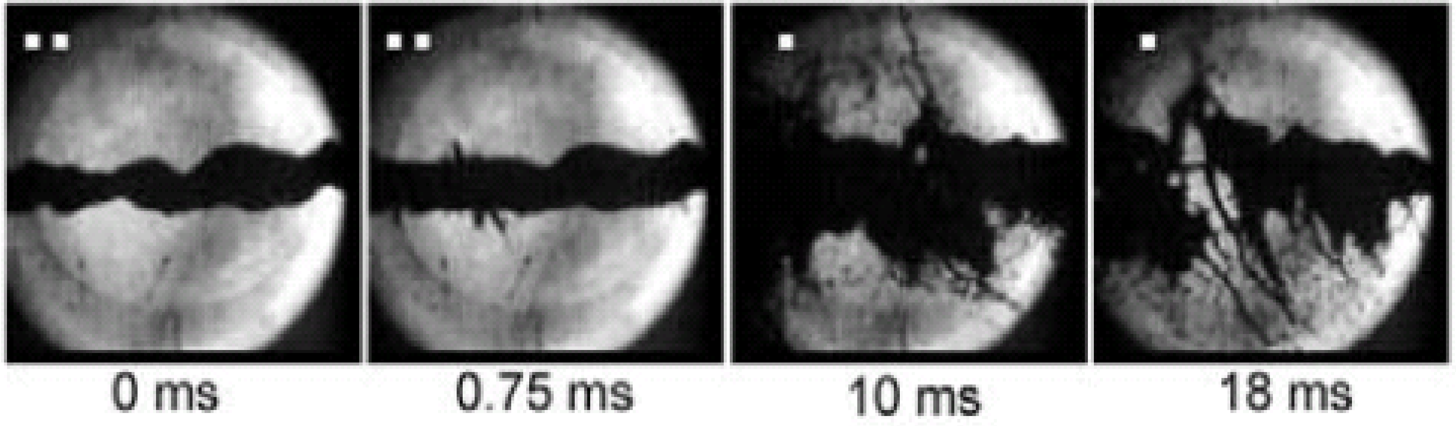




The Inner World of a Collapsing Bubble, O. Supponen et al., Physics of Fluids, 27, 091113 (2015)

Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface

- **Bubble dynamics within a liquid jet**
  - **Master project, E. Robert with the collaboration of CERN (Geneva)**
  - **Problem: Breakup of a mercury jet used as heavy target in Neutrino Factory**



Visualization of the breakup of 10 mm diameter mercury jet, flowing at 2.5 m/s and exposed to a burst of a high energy proton beam (BNL E951 experiment, Kirk et al., 2001)

- **Objective : Investigation of the role of cavitation on the jet breakup ?**

Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface

- **Bubble dynamics within a liquid jet**
  - **Mercury is replaced by water (safer and transparent to laser)**
  - **Experimental setup:**
    - **Pulsed laser for bubble generation (50 mJ energy, 10 ns duration)**
    - **Optical arrangement: Laser is expanded and focused inside the jet**

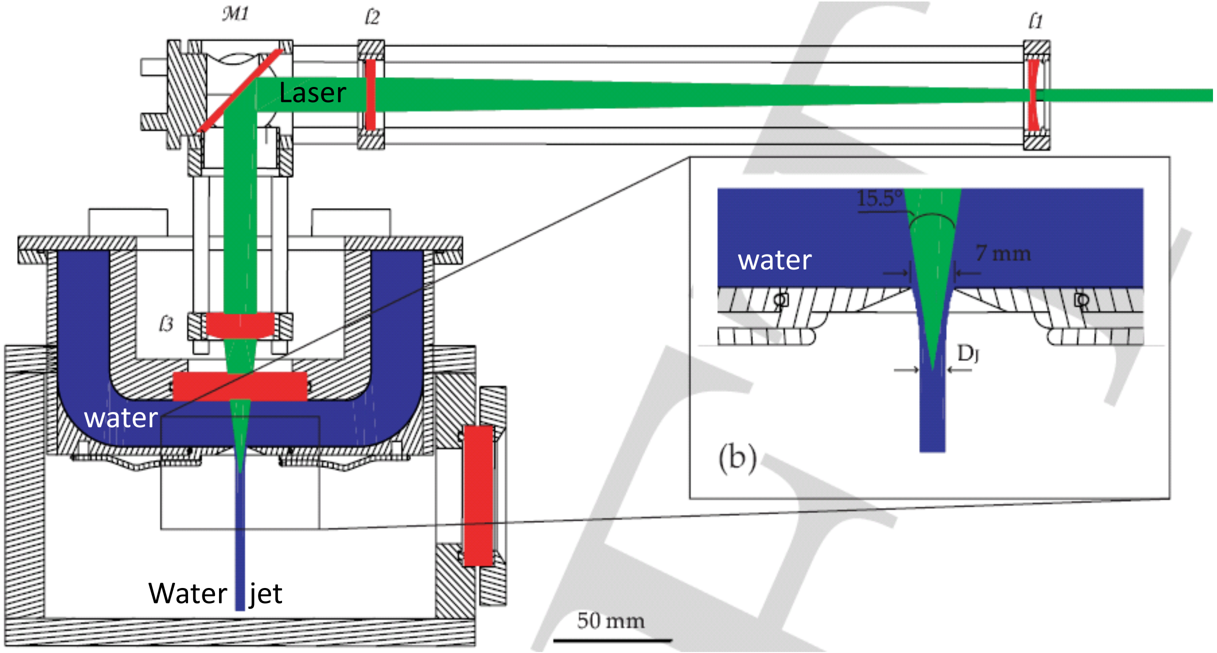
- **Governing parameters**
  - ***Eccentricity:***

$$\varepsilon = \frac{\text{bubble eccentricity}}{\text{jet radius}} = \frac{R_E}{R_J}$$

  - ***Relative radius***

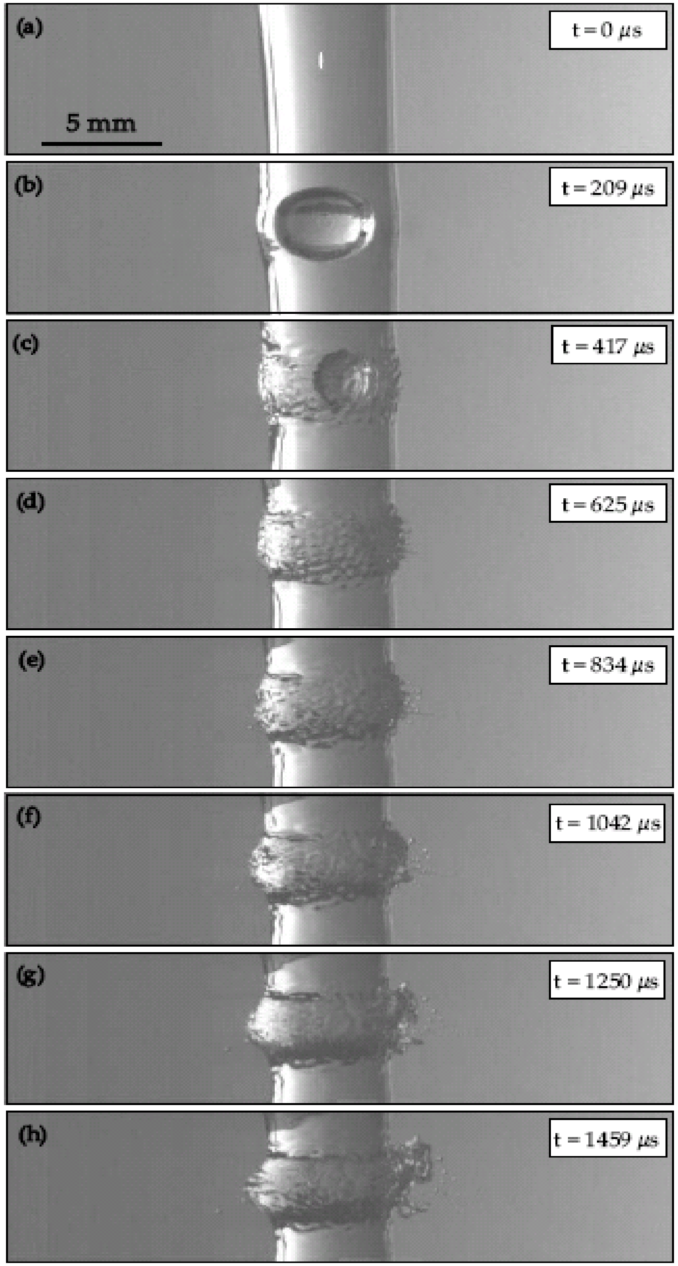
$$\delta = \frac{\text{max. bubble diameter}}{\text{jet diameter}} = \frac{D_B}{D_J}$$

  - ***Driving pressure: p_{atm}***



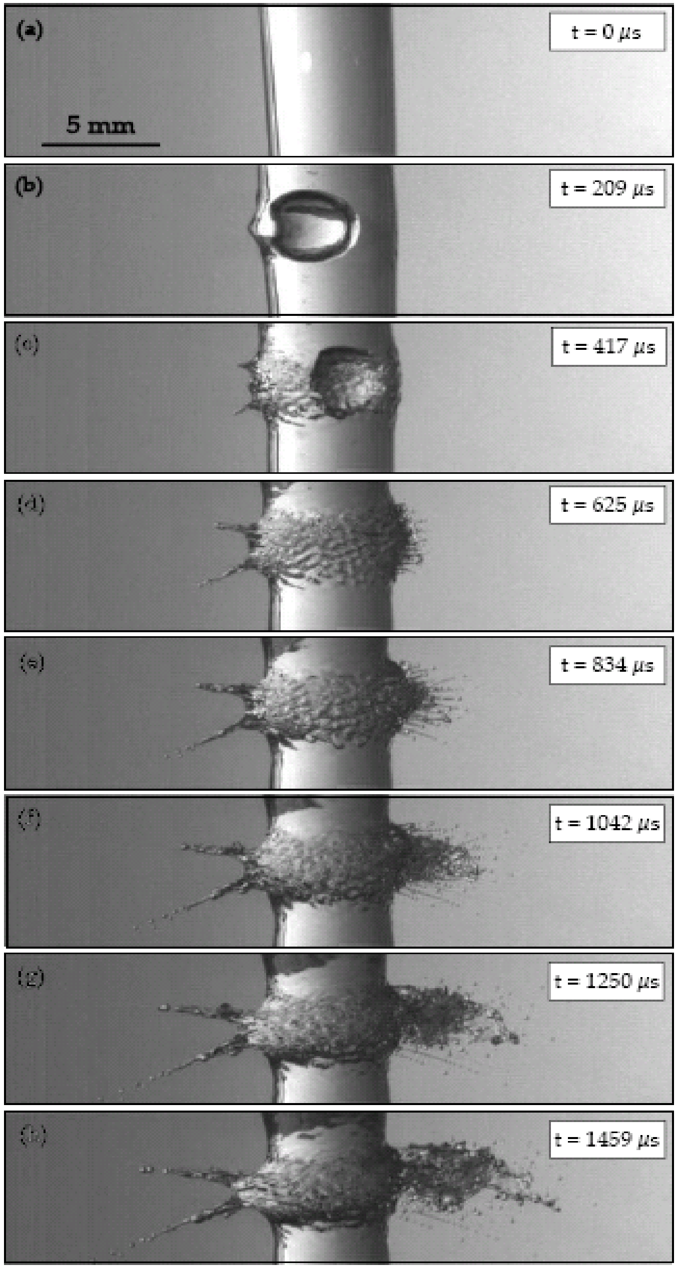
Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface

- **Bubble dynamics within a water jet**
- **Bubble close to the jet axis: ε=0.11; δ=1.06**
  - **The bubble expands more in radial than axial direction → ellipsoidal bubble**
  - **The bubble is slightly displaced after the 1st rebound**
  - **As it rebounds, the bubble is displaced away from the nearest free surface and leads to the formation of a diametrically opposite jet**



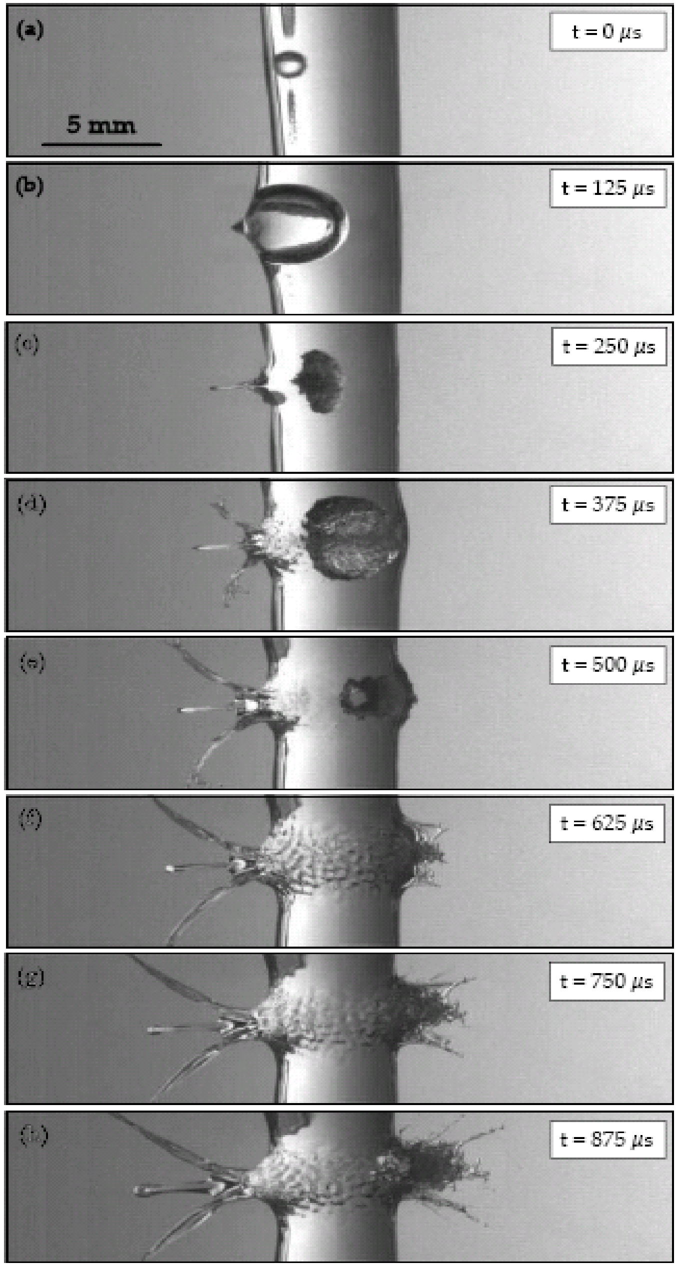
Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface

- **Bubble dynamics within a water jet**
- **Off-center bubble: $\varepsilon=0.31$; $\delta=0.92$**
  - **Weak counter jet**
  - **Stronger "crown" jets and opposite jet**
  - **Crown jet different from the flat free surface case**
  - **As it rebounds, the bubble is displaced away from the nearest free surface and leads to the formation of a diametrically opposite jet**



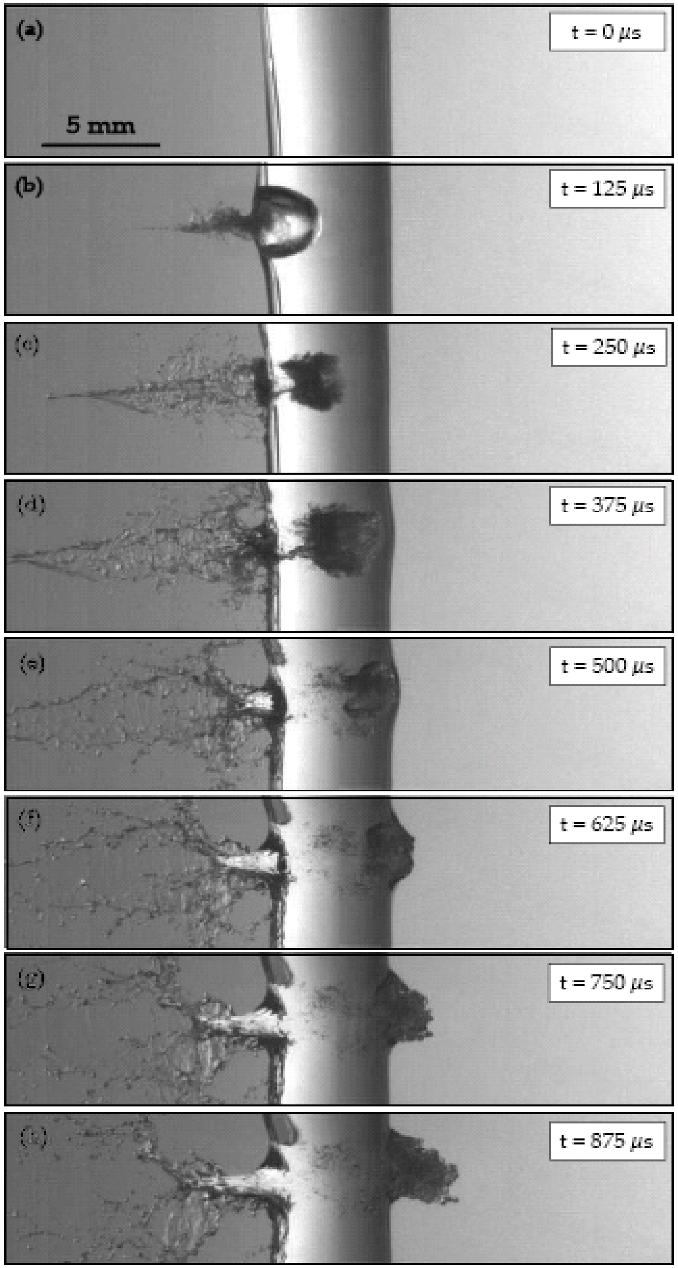
Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface

- **Bubble dynamics within a water jet**
- **Bubble closer to the interface: ε=0.58; δ=0.81**
  - **Stronger counter jet**
  - **Stronger "crown" jet**
  - **As it rebounds, the bubble is displaced away from the nearest free surface and leads to the formation of a diametrically opposite jet**



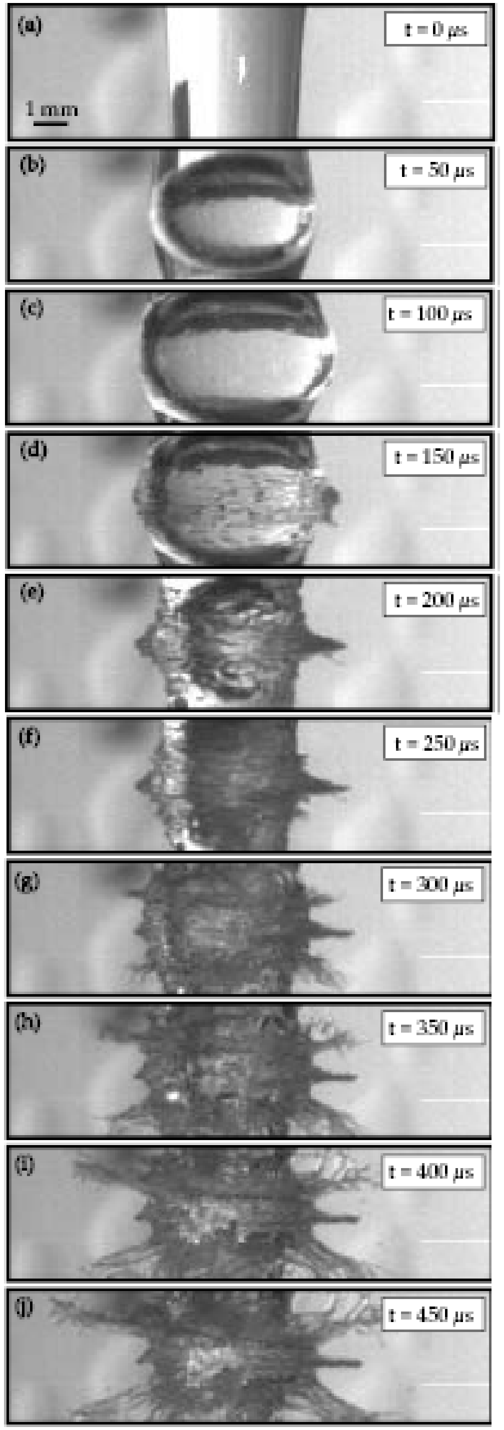
Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface

- **Bubble dynamics within a water jet**
- **Bubble on the interface: $\varepsilon=0.88$; $\delta=0.61$**
  - **The bubble pierces the free surface during its growth**
    - ***The compressed air escapes at high-speed (> 100 m/s)***
  - **Opposite jet**
  - **No crown jet**



Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface

- **Bubble dynamics within a water jet**
- **Bubble larger than the jet: ε=0.09; δ=1.42:**
  - **Centered Bubble grows beyond the water jet diameter.**
  - **The bubble pierces the free surface, leading to a water Jet Breakdown (Similar to Mercury Jet experiment)**

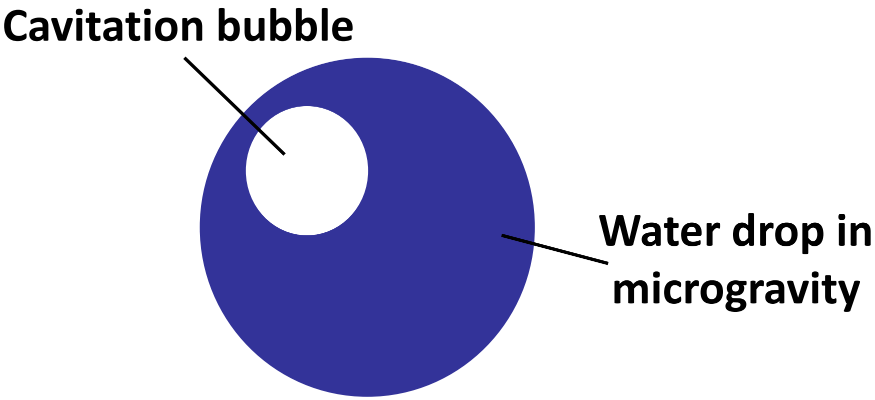


Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface

Bubble dynamics within a water drop (in microgravity)

ESA: European Space Agency

Principle of the experiment



D. Obreschkow[2], P. Kobel[3], N. Dorsaz[1,] A. de Bosset[1], C. Nicolier[1,4] and M. Farhat[1],
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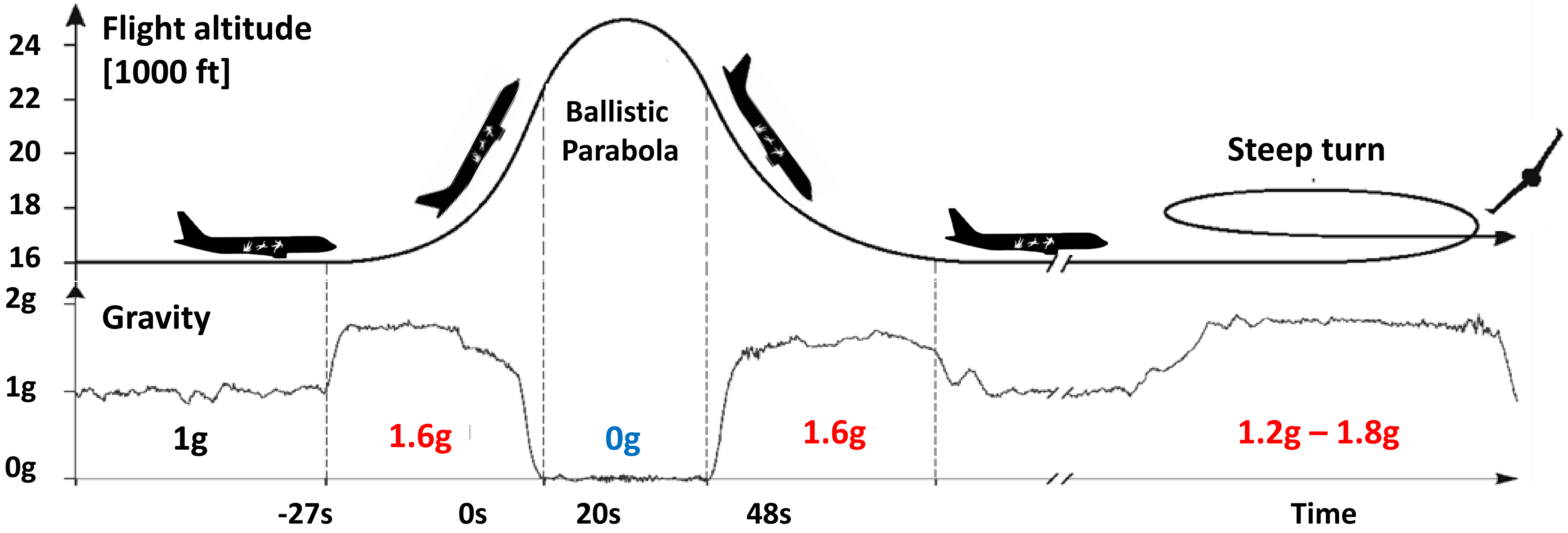
[2]Physics Dep., Oxford University, United Kingdom
[3]Max Planck Institute for Solar System Research, Katlenburg-Lindau
[4]NASA Johnson Space Center, Houston, USA

Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

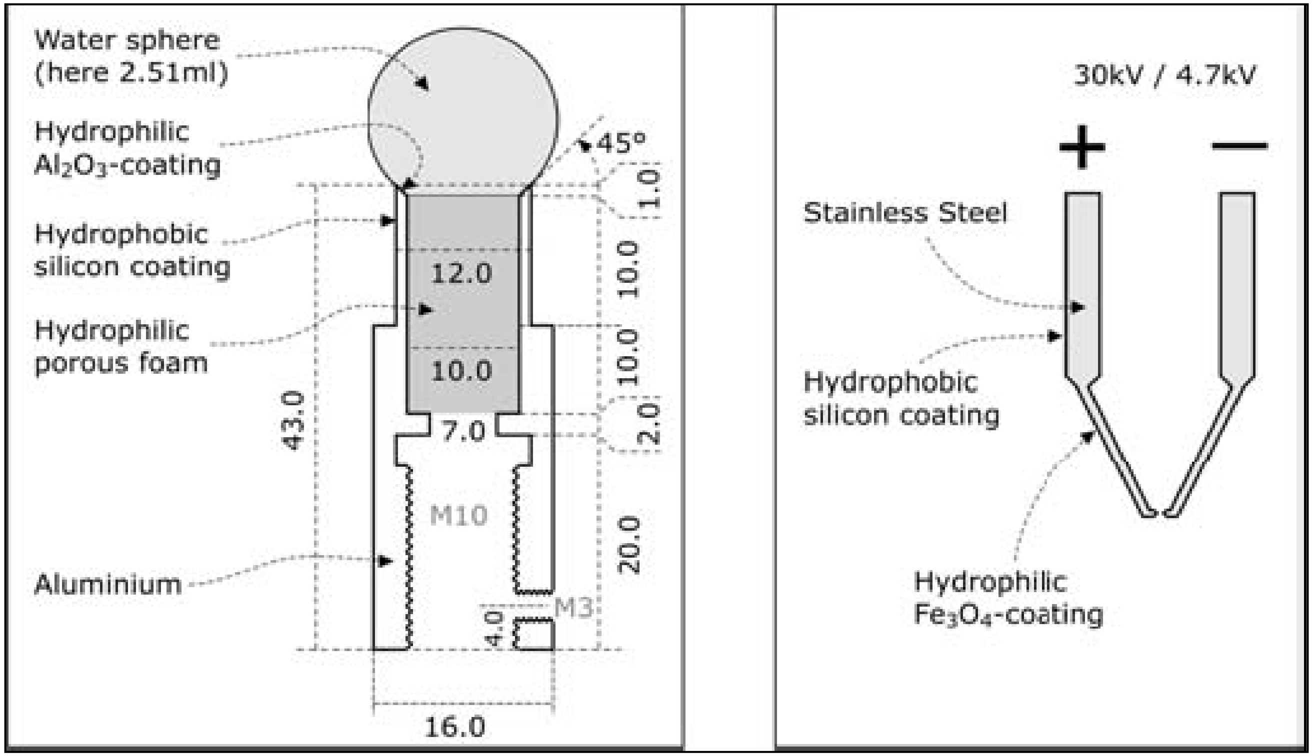
- **Parabolic flight maneuver**
  - **Pull up and pull out phases : 20 sec, ~2g acceleration**
  - **Zero- G phase: ~ 20 sec**
  - **32 parabolas / flight, 2 minutes rest period between 2 parabolas**
  - **2 flights per campaign are performed (total: 20 minutes in microgravity)**



Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

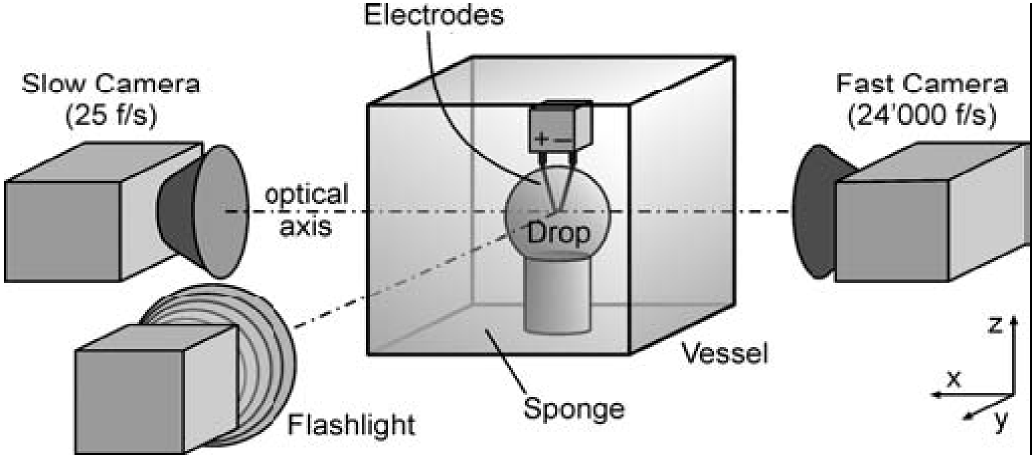
- **Bubble and drop generation in microgravity**
  - **The drop is expelled through injector filled with foam by a micro pump**
  - **Fast electric discharge between 2 electrodes**
  - **Optimization of physical properties of material (injector & electrodes)**

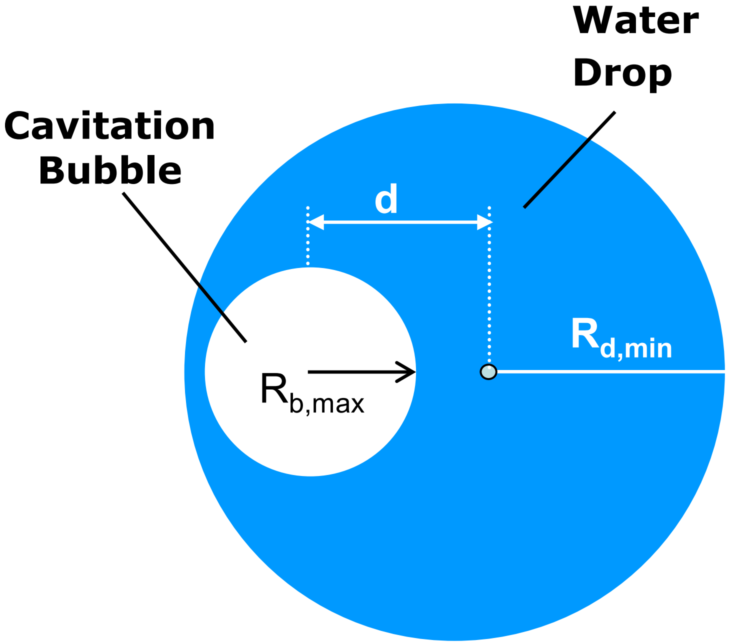
    To avoid interaction with the water drop



Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

- **Visualization of bubble dynamic:**
  - **High-Speed Digital Camera (Photron, up to 120'000 frames/sec)**
  - **Xenon flash lamp (11 ms duration)**

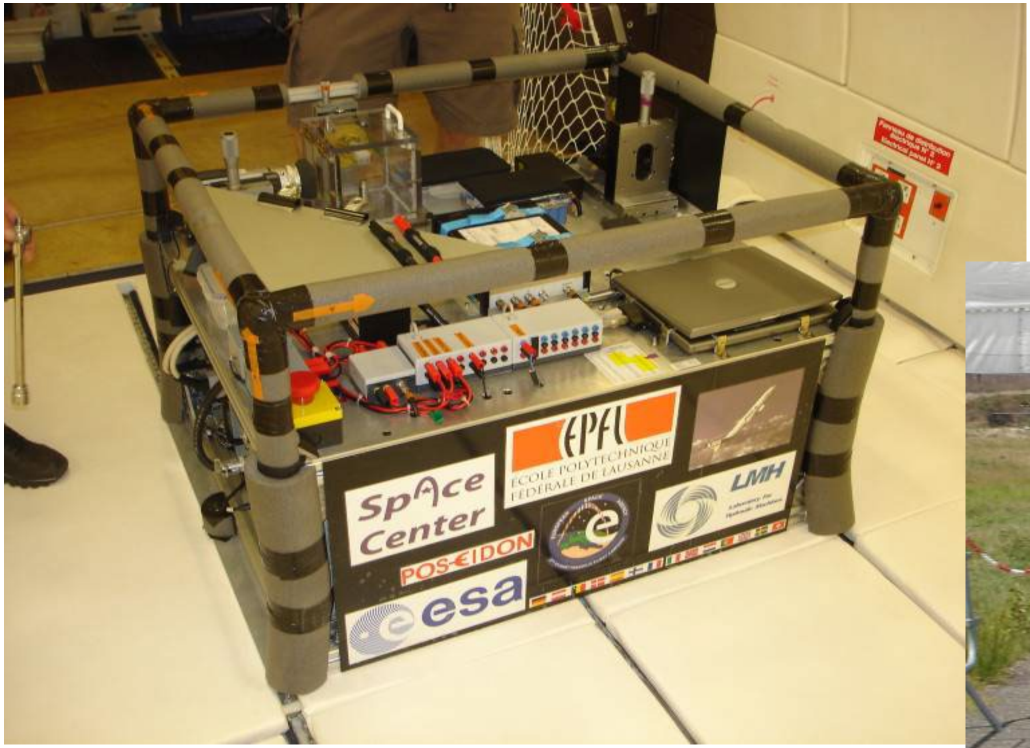




- **Governing parameters:**
  - **Relative radius:** $\alpha = \frac{R_{b,max}}{R_{d,min}}$
  - **Bubble Eccentricity:** $\varepsilon = \frac{d}{R_{d,min}}$

Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

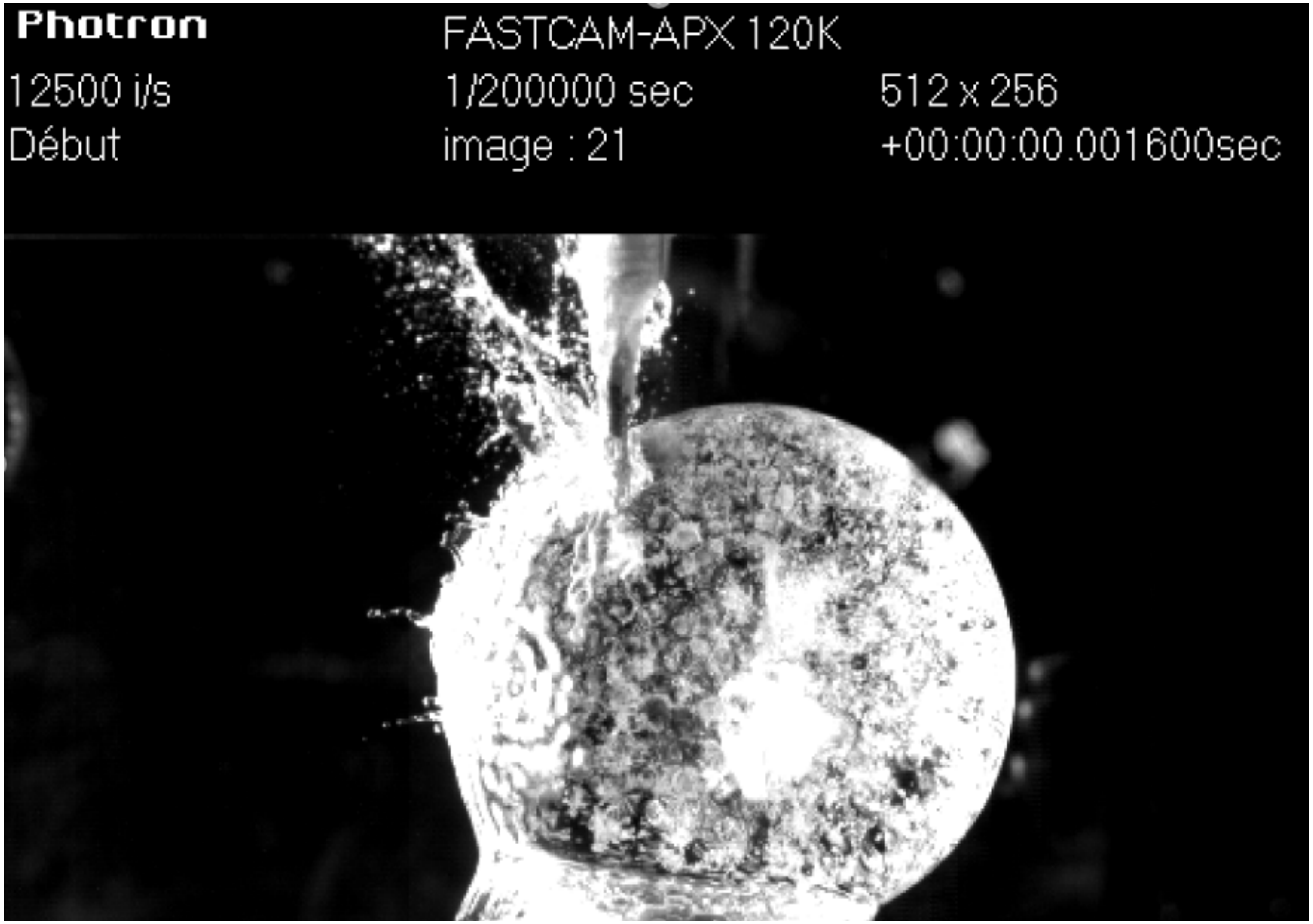
- **Microgavity experiments:**
  - **The experimental setup attached to the airplane floor – EPFL students team**



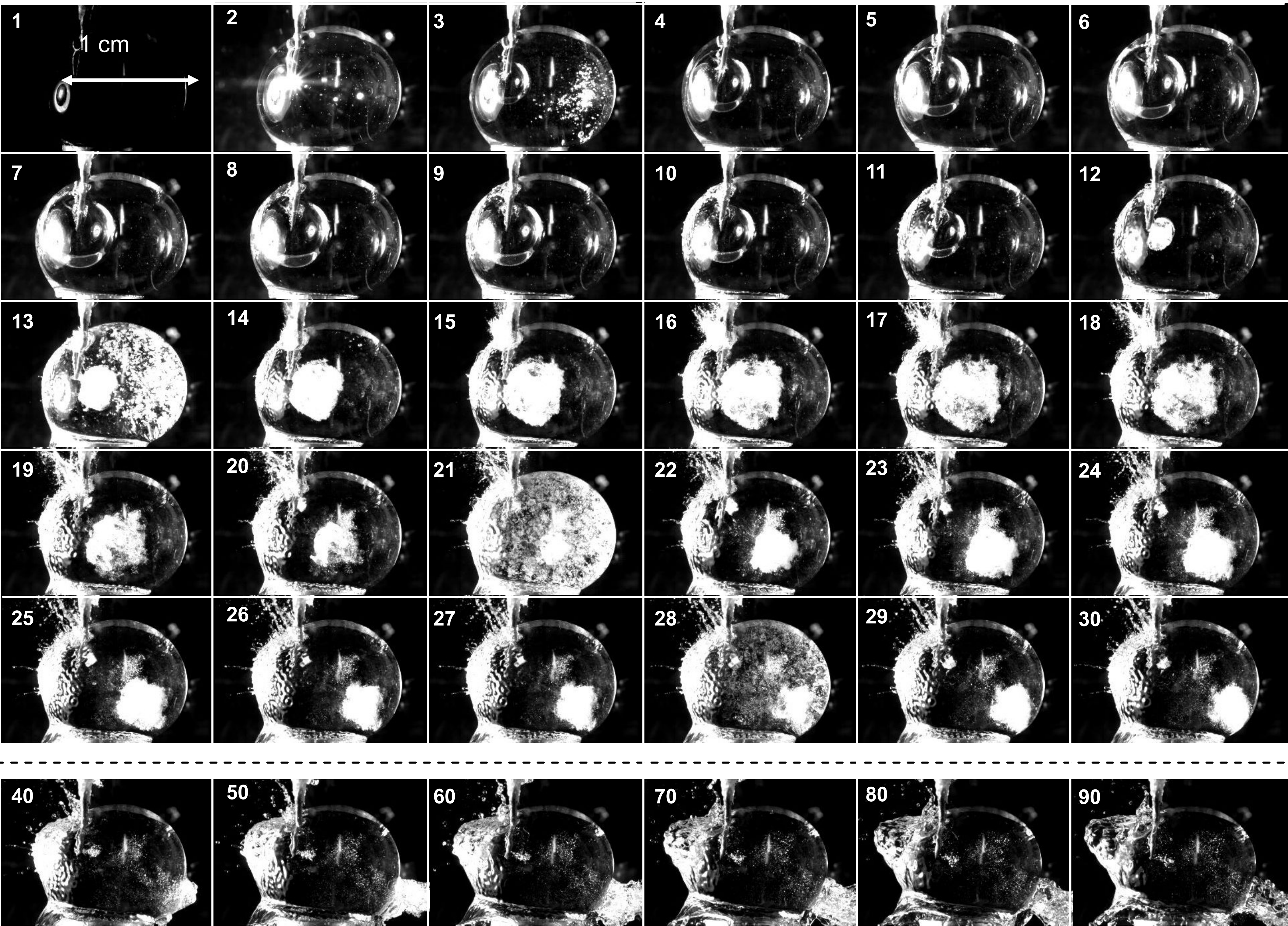
EPFL team of students – ESA 8th SPFC

Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

- **High speed visualization:**
  - **Relative radius: α = 0.3; Bubble Eccentricity: ε = 0.45; 6250 frames/sec**



6250 frames/sec **Frames N° 3, 13, 21 and 28: transient cluster of short-lived bubbles**

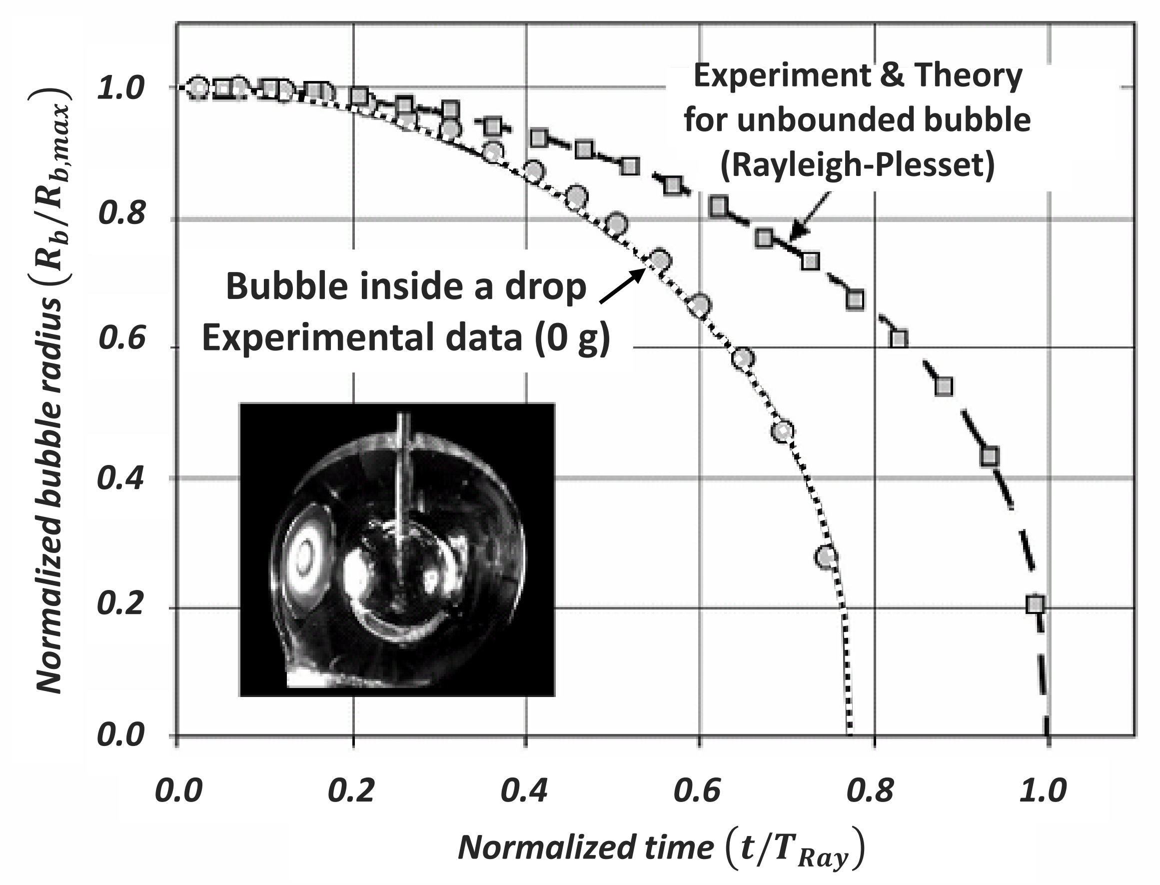


Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

- **Bubble ~ in the center of the drop: $\alpha = 0.5; \varepsilon = 0$**

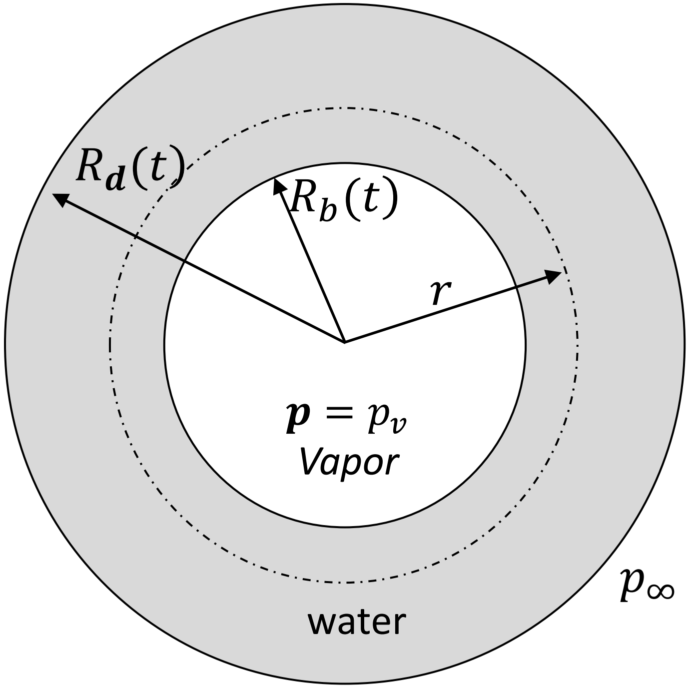
→ **The bubble radius deviates from the Rayleigh-Plesset prediction**

→ **Significant shortening of the collapse time compared to Rayleigh time**



Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

- **Mathematical model:**
  - **Hypotheses : Similar to Rayleigh model**
  - **Mass conservation:**



$$\vec{\nabla}\vec{U} = 0 \implies \frac{\partial(r^2 u_r)}{\partial r} = 0$$

$$\Rightarrow u_r = \frac{R_b^2 \dot{R}_b}{r^2} \qquad \forall r \in [R_b, R_d]$$

Moreover, the initial water volume remains constant, which leads to:

$$R_d^3 = R_{d,min}^3 + R_b^3 \qquad \forall t$$

where $R_{d,min}$ is the minimum radius of the water drop (corresponding to $R_b = 0$)

Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

- **Mathematical model:**
  - **Energy conservation:**

$$\begin{cases} E_{kin} = 2\pi\rho \dot{R}_b^{\,2} R_b^{\,3}(1-\lambda) & \lambda = R_b(t)/R_d(t) \\ E_{pot} = \dfrac{4\pi R_b^{\,3}}{3}\Delta p & \Delta p = p_\infty - p_v \end{cases}$$

$$\dot{E}_{kin} + \dot{E}_{pot} = 0$$

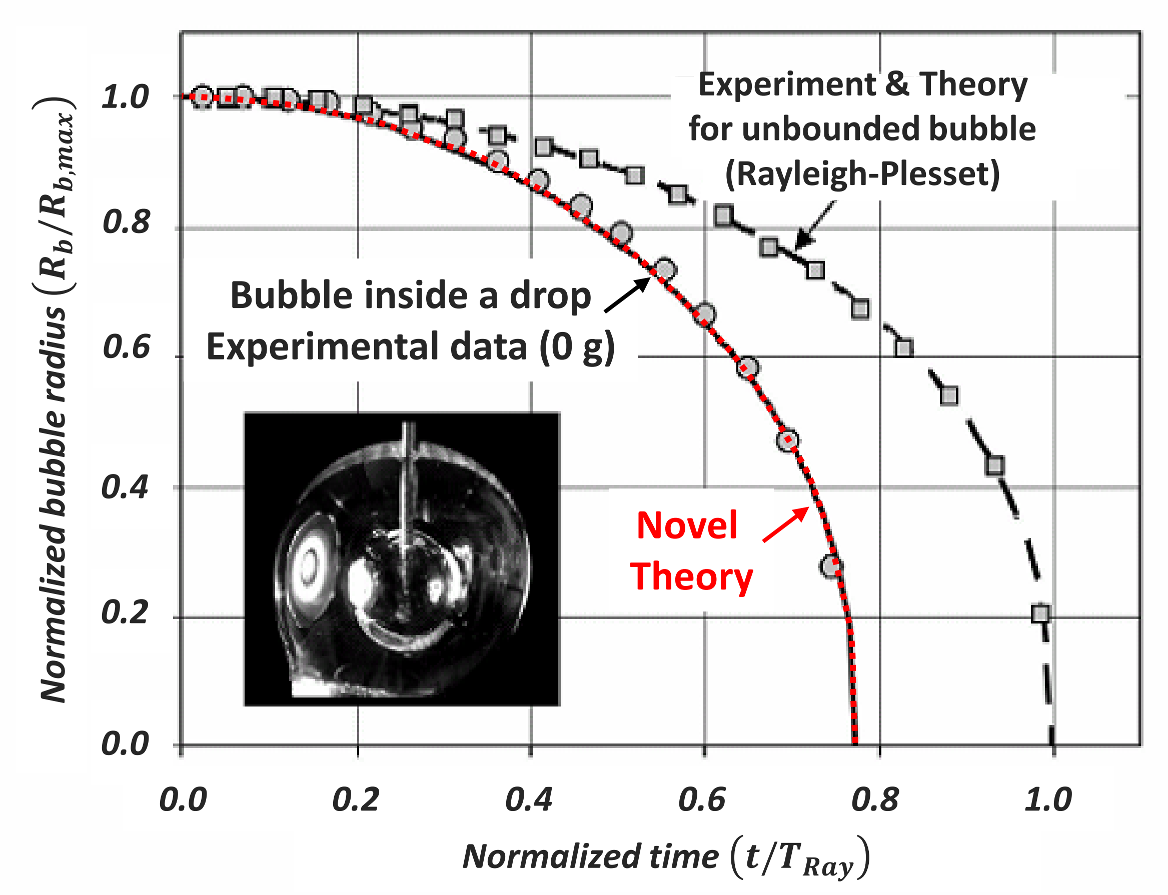
$$\ldots \Rightarrow \quad \frac{3}{2}\dot{R}_b^{\,2} + R_b\ddot{R}_b - 2\lambda\dot{R}_b^{\,2} - \lambda R_b\ddot{R}_b + \frac{1}{2}\lambda^4\dot{R}_b^{\,2} = \frac{-\Delta p}{\rho}$$

$$R_d \to \infty \Rightarrow \frac{-\Delta p}{\rho} = \frac{3}{2}\dot{R}_b^{\,2} + R_b\ddot{R}_b \qquad (Rayleigh)$$

Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

- **Bubble ~ in the center of the drop: $\alpha = 0.5; \varepsilon = 0$**
- **Excellent agreement with experimental data**

$$R_b(0) = R_{b,\max} \quad \mathit{and} \quad \dot{R}_b(0) = 0$$



Experiment & Theory for unbounded bubble (Rayleigh-Plesset)

Bubble inside a drop Experimental data (0 g)

Novel Theory

Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

- **Collapse time for a bubble with arbitrary relative radius α:**

$$E_{kin} + E_{pot} = \frac{4\pi R_{b,\max}^3}{3}\Delta p \Rightarrow \dot{R}_b = -\sqrt{\frac{1}{1-\lambda}\frac{2\Delta p}{3\rho}\left(\frac{R_{b,\max}^3}{R_b^3}-1\right)}$$

$$T_{collapse} = \xi(\alpha) R_{b,\max}\sqrt{\frac{\rho}{\Delta p}}$$

$$with:$$

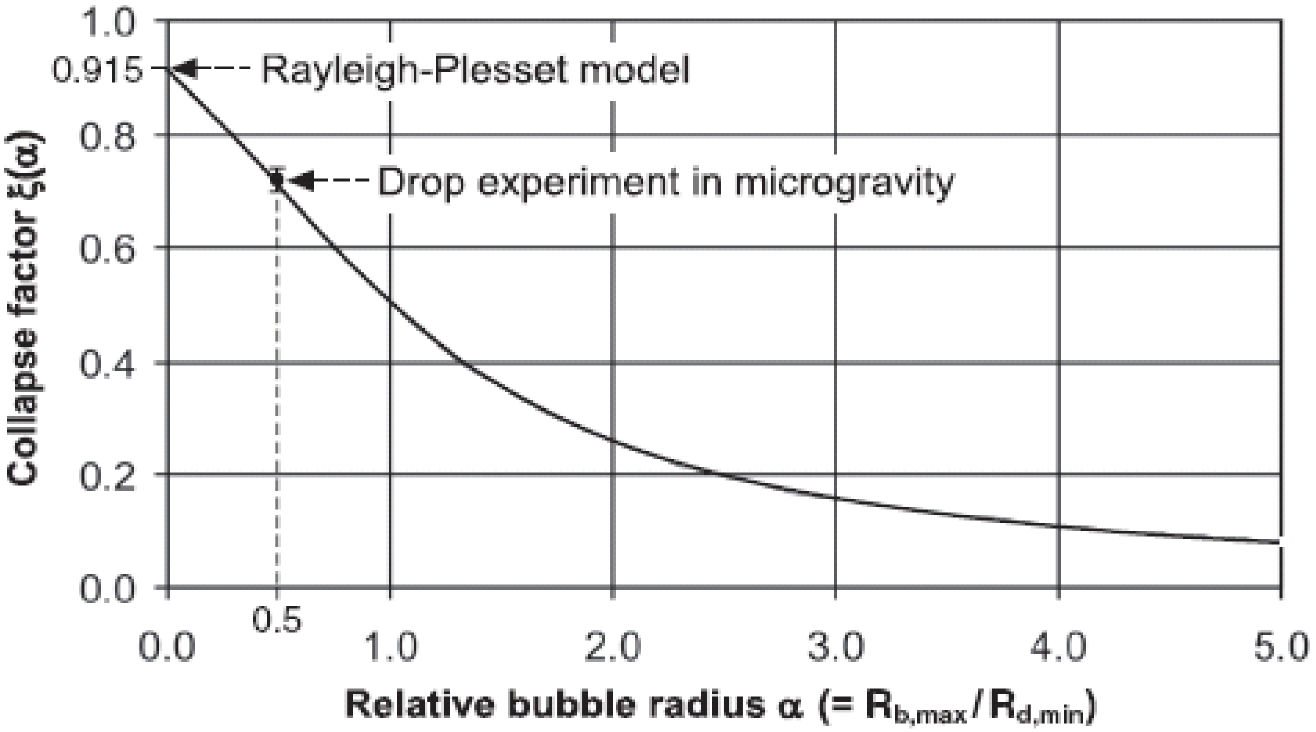
$$\alpha = \frac{R_{b,\max}}{R_{d,\min}} \quad and \quad \xi(\alpha) = \sqrt{\frac{3}{2}}\int_0^1 \sqrt{1-\frac{s}{\left(\alpha^{-3}+s^3\right)^{1/3}}}\left(\frac{1}{s^3}-1\right)^{-\frac{1}{2}} ds$$

where s substitutes $R_b/R_{b,\max}$.

Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

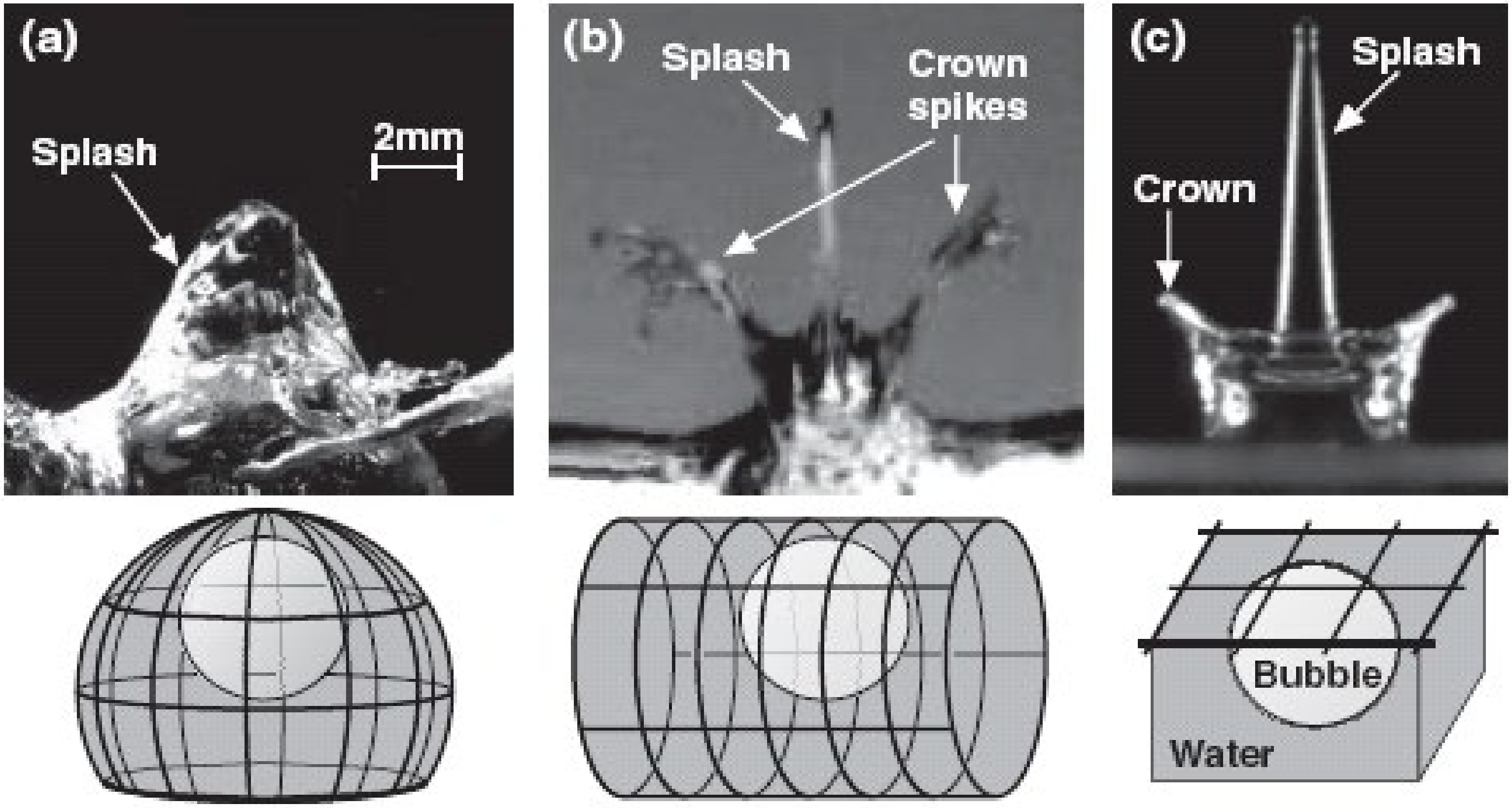
- **Collapse time for a bubble with arbitrary relative radius α:**

$$\begin{cases} \xi(\alpha = 0) = 0.915 & (Rayleigh - Plesset) \\ \lim_{\alpha \to +\infty} \xi(\alpha) = 0 & Drop\ stability\,? \end{cases}$$



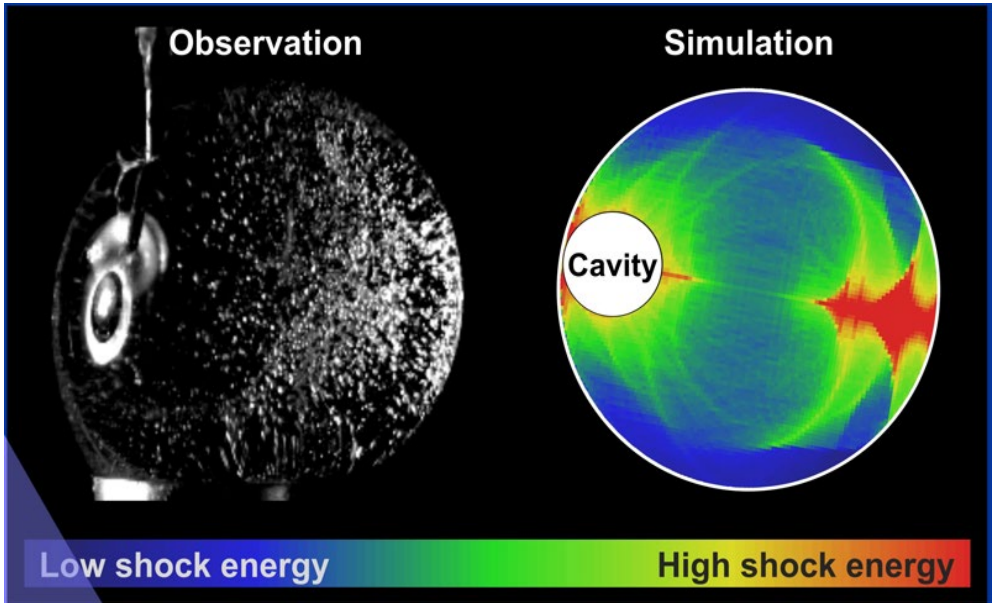
Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

- The counter jet produced by a bubble in a drop:
  - Significant broadening for similar standoff coefficient ε
  - No crown jet is observed



Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

- **The Shock Waves Confinement:**
  - **Mist of short lived bubbles following each collapse of the main bubble**
  - **Due to a strong Interaction of primary and reflected shock waves with micro sized nuclei within the water drop**
  - **Micro bubbles distribution agrees well with prediction of shock waves energy focusing**
  - **Hardly observable on ground based experiments (flat free surface)**



Dynamic of a cavitation bubble collapse
Effects of a neighboring free surface (case of a bubble in a water drop)

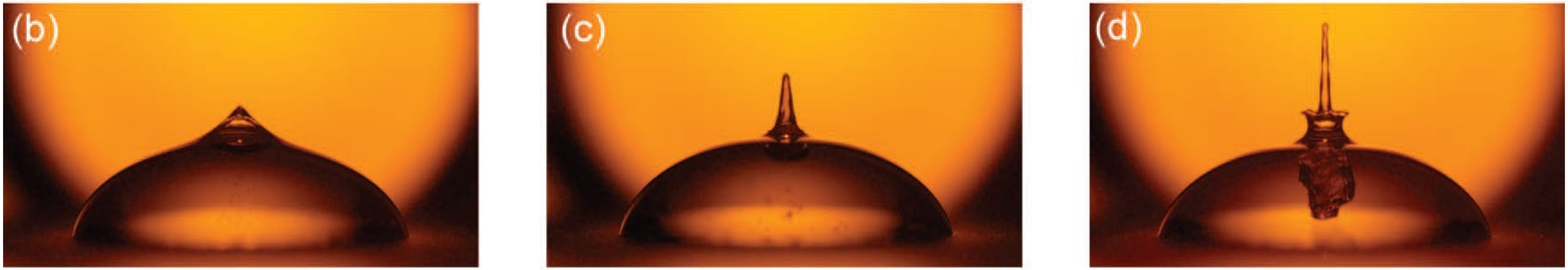
- **Related publications:**

Confined Shocks inside Isolated Liquid Volumes - A New Path of Erosion?, D. Obreschkow, N. Dorsaz, P. Kobel, A. de Bosset, M. Tinguely, J. Field, M. Farhat, Physics of Fluids Letters*, 2011.*

Techniques for Generating Centimetric Drops in Microgravity and Appl. to Cavitation Studies, Kobel, D. Obreschkow, A. de Bosset, N. Dorsaz, M. Farhat, Experiments in Fluids, 2009.

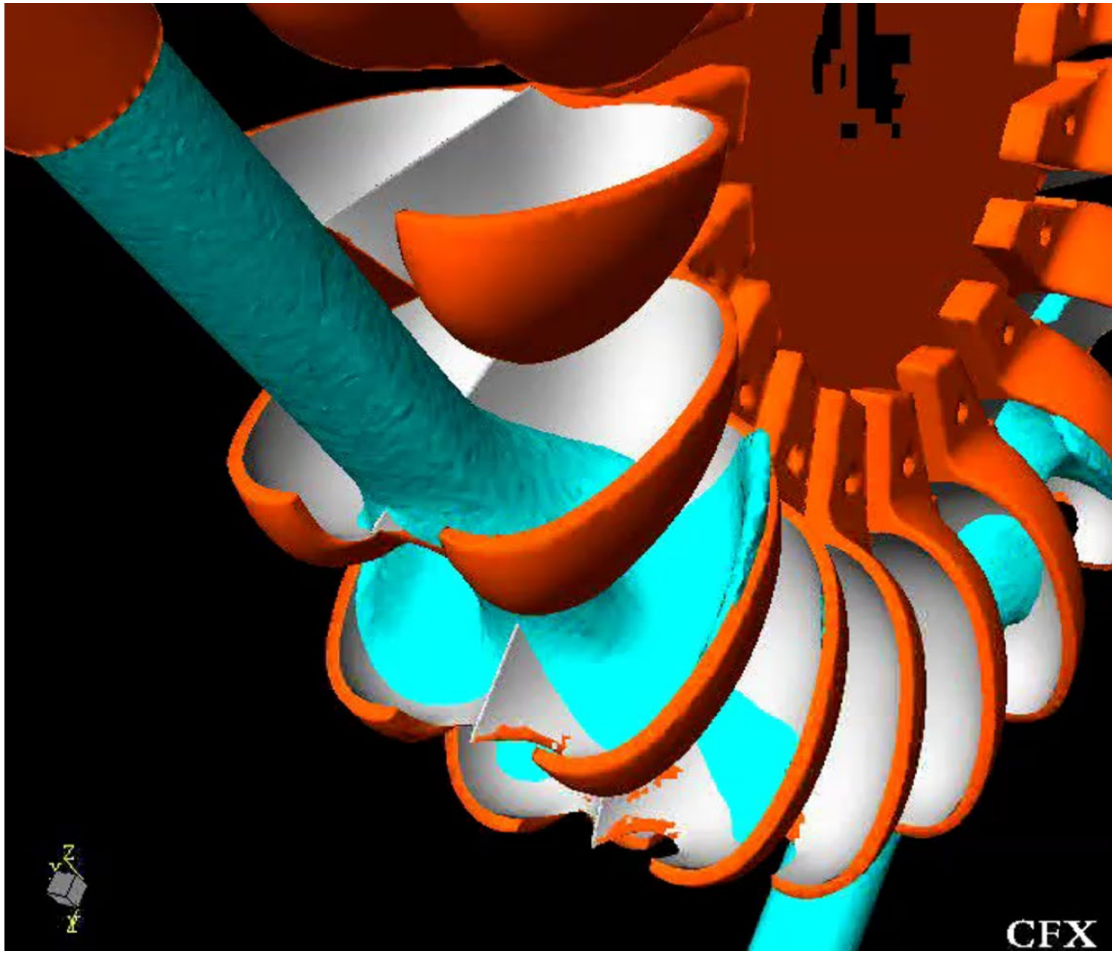
Cavitation Bubble Dynamics inside Liquid Drops in Microgravity, D. Obreschkow, P. Kobel, N. Dorsaz, A. de Bosset, C. Nicollier, M. Farhat, Physical Review Letters, 97, 094502, 2006.

Cavitation within a droplet, L. Heijnen,P. Quinto-Su, X. Zhao, C. Dieter Ohl, Phy. of Fluids, 2009



Cavitation bubble in confined liquid
Application to Hydraulic Machines

- **Erosion due to drop/jet impact on Pelton turbine buckets**
  - **Pelton turbines are action turbines, made of a set of buckets and subjected to the action of one or multiple jets**



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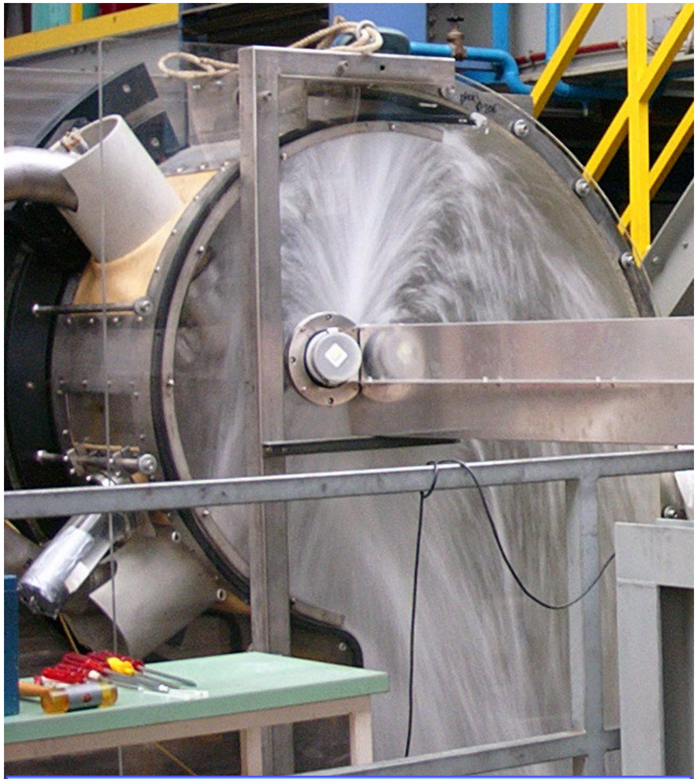
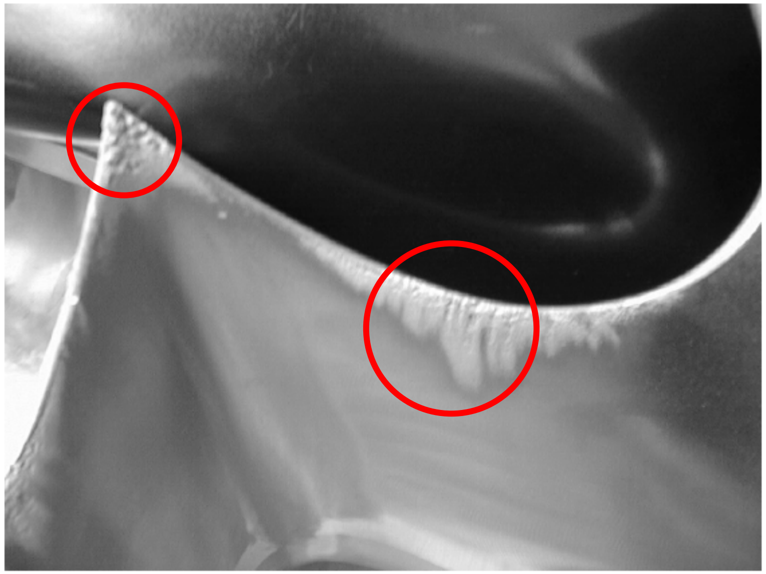


Model tests of a reduced scale model of Pelton Turbine

Cavitation bubble in confined liquid
Application to Hydraulic Machines

In Pelton Turbines, erosion is believed to originate from high-speed impact of the jet/droplets with the buckets



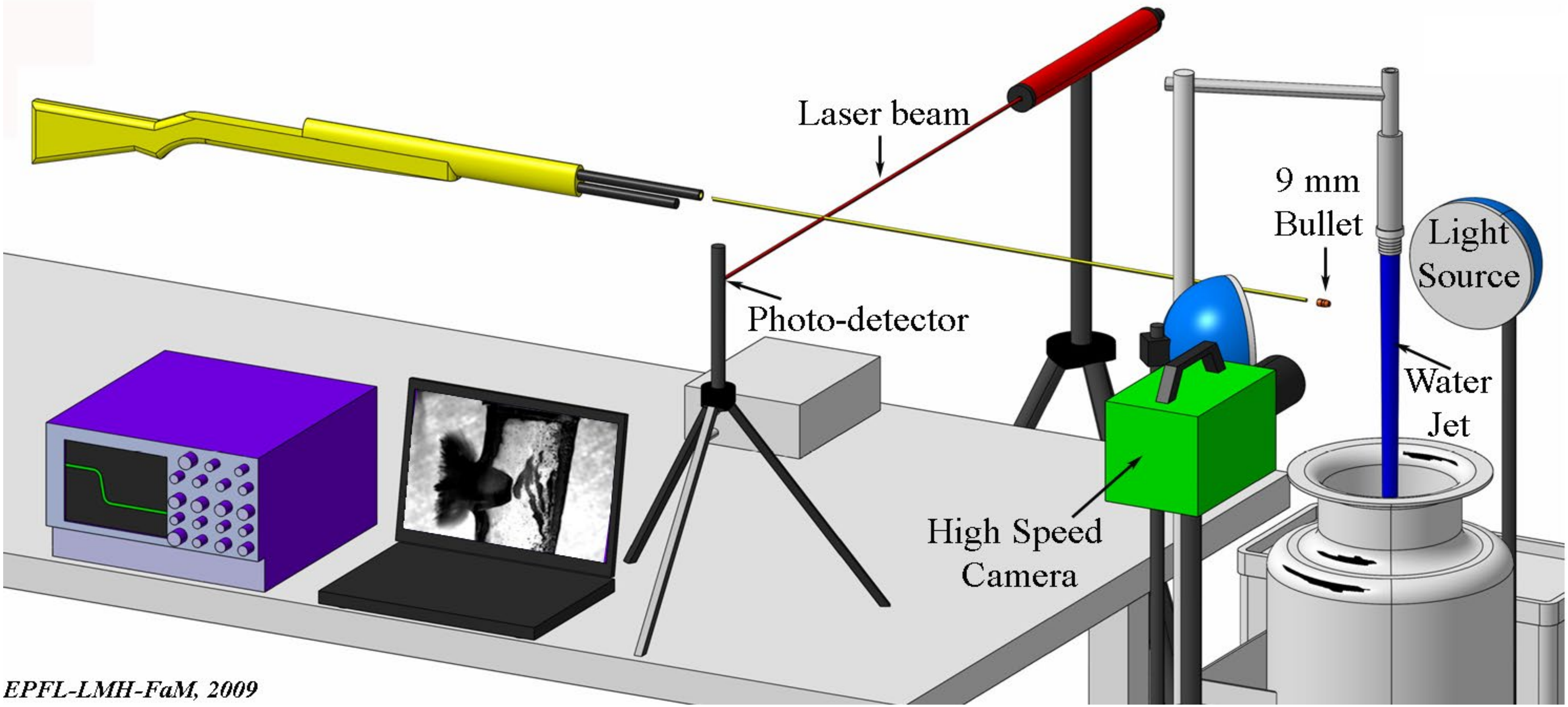
- Erosion is similar to cavitation erosion (Role of cavitation ?)

- Experimental evidence ?
  - How to realize a high speed impact of a solid on a liquid jet/drop ?
  - Safety ? Precision ? Repetitivity ?

  → Collaboration with Swiss Army (use of ballistic facilities)

Cavitation bubble in confined liquid
High speed impact of a jet with a solid surface

- **Water jet, having 2.5 cm diameter and ~ 1 m/s velocity**
- **9 mm bullet, shot at speeds between 200 and 500 m/s (Swiss Army)**
- **Fast photodiode for camera triggering**

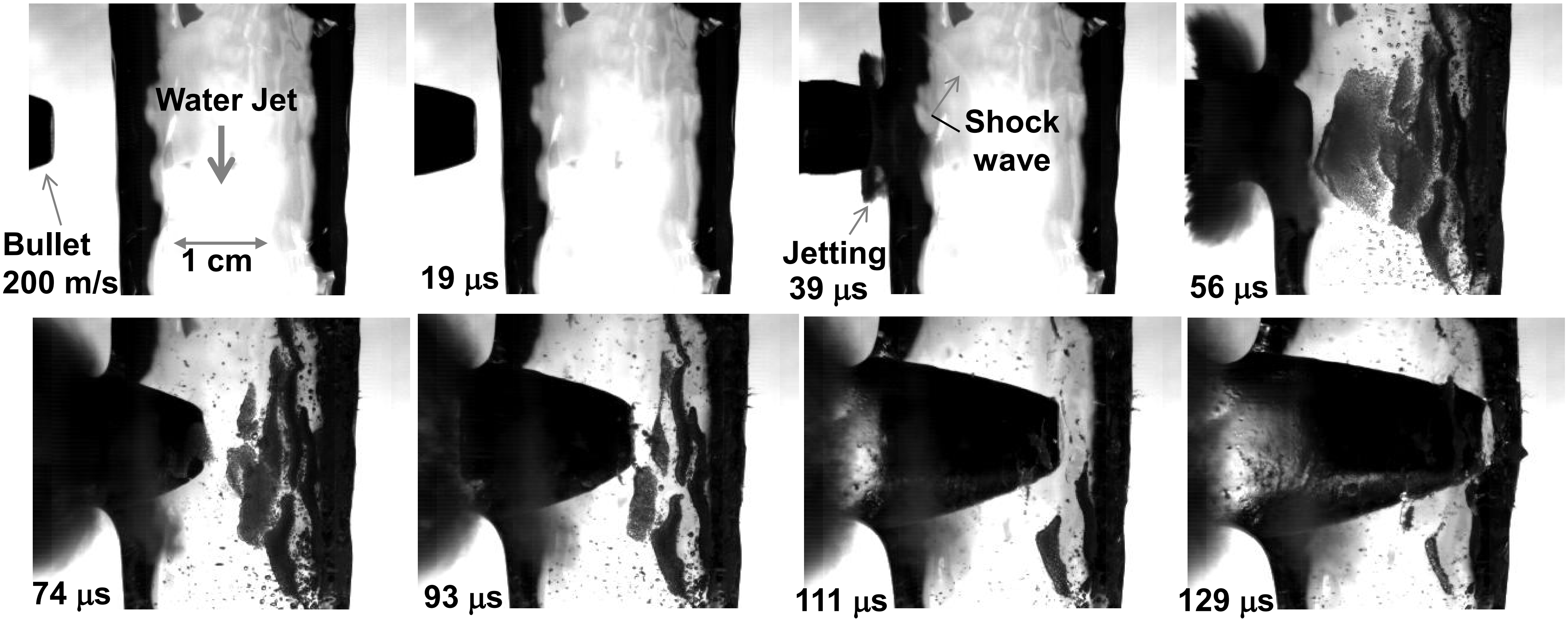


EPFL-LMH-FaM, 2009

Cavitation bubble in confined liquid
High speed impact of a jet with a solid surface

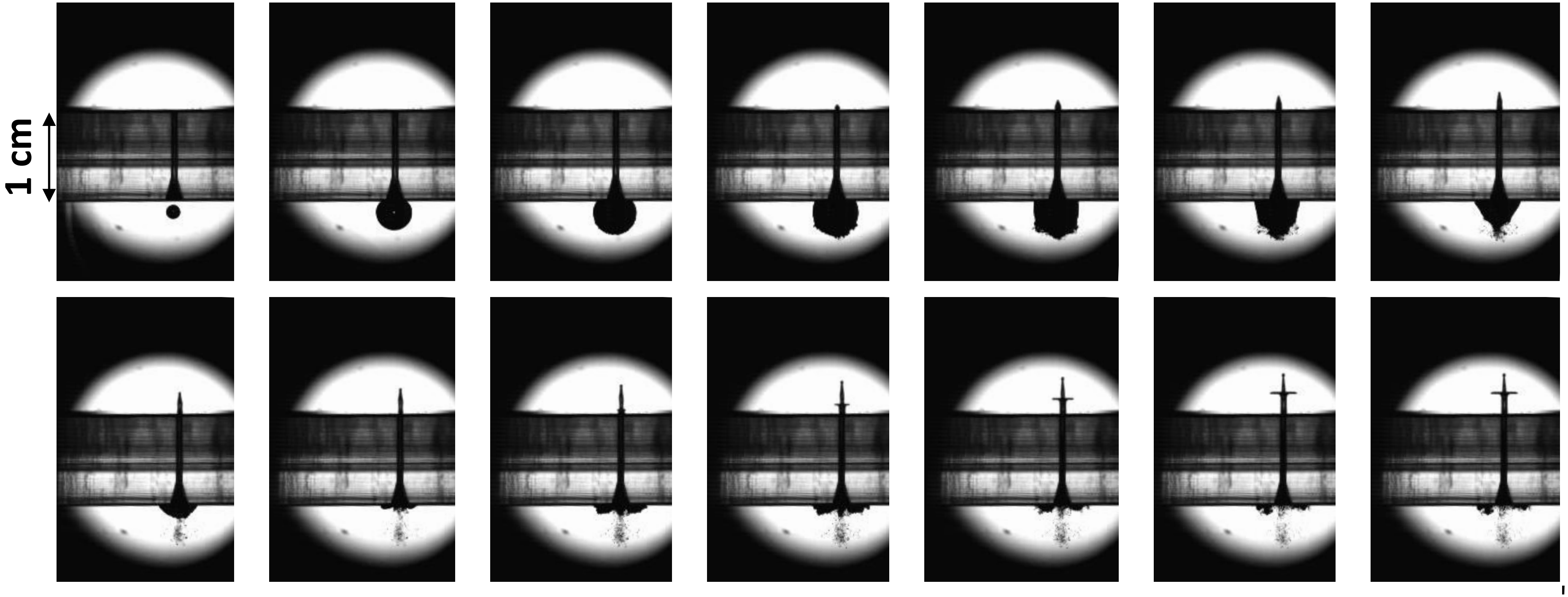
- **9 mm Bullet, hitting a 2.5 cm water jet at a velocity of 200 m/s**
- **High speed visualization: 54’000 frames/second**

→ *Evidence of cavitation occurrence due to shockwave confinement*



Dynamic of a cavitation bubble collapse

- **Application: Laser induced bubble as a non-intrusive micro-pump**
  - **A laser induced bubble, generated near a 1 cm thick plate with a 1 mm hole**
  - **The collapse-induced microjet propels the liquid upward, through the hole & beyond**



Cavitation Bubble Dynamics within a Liquid Drop

Application: Astrophysics

Similarities with Explosions of giant stars (Supernovae)