X-ray visualized interfaces in high-speed sprays

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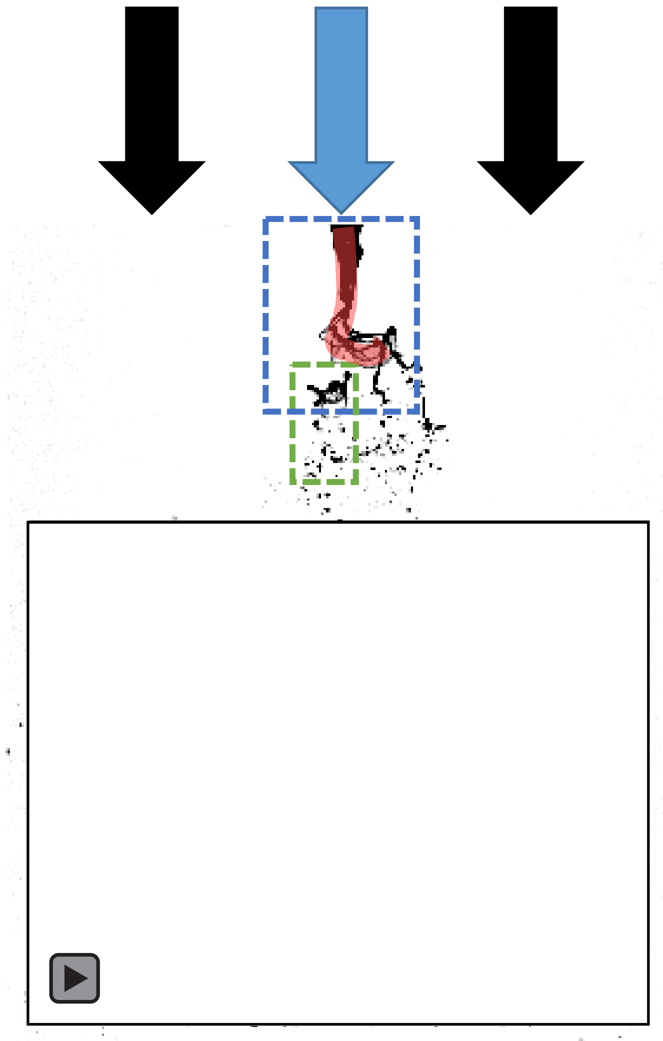
Atomization

- Liquid-gas flows are critical in engineering process innovation and intensification
- Liquid sprays are critical for combustion systems, manufacturing, heat management, chemical processing, painting, e. g.:
  - Liquid fuel sprays
  - Liquid metal atomization
  - Spray cooling and coating
  - Pharmaceutical, food, consumer products
  - Fire safety
  - Ship wake and sea spray

Gas-assisted Atomization Phenomena

gas liquid gas



Near field

Mid field

O. Desjardins' group
L. Vu et al., IJMF 2023

Assisted atomization: breaking of a liquid jet into a spray (droplet cloud) by a gas co-flow

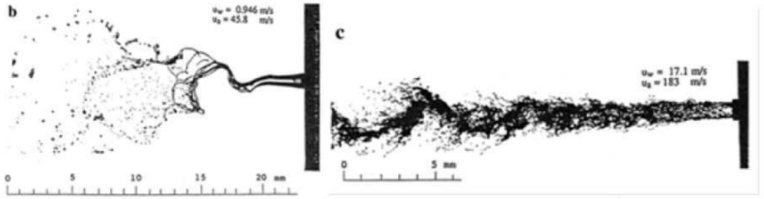
Spray formation:
- Interfacial instabilities
- Primary break-up

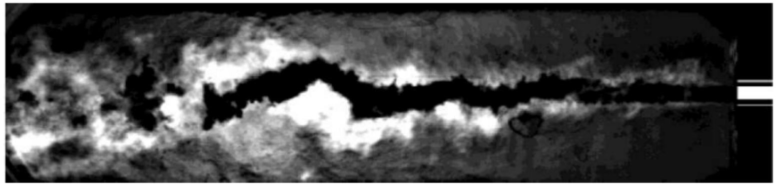
Drops/ligaments in turbulence:
- Secondary break-up
- Turbulent dispersion

Droplets in turbulence:
- Turbulent dispersion
- Evaporation

FLAPPING

Farago & Chigier, 1992



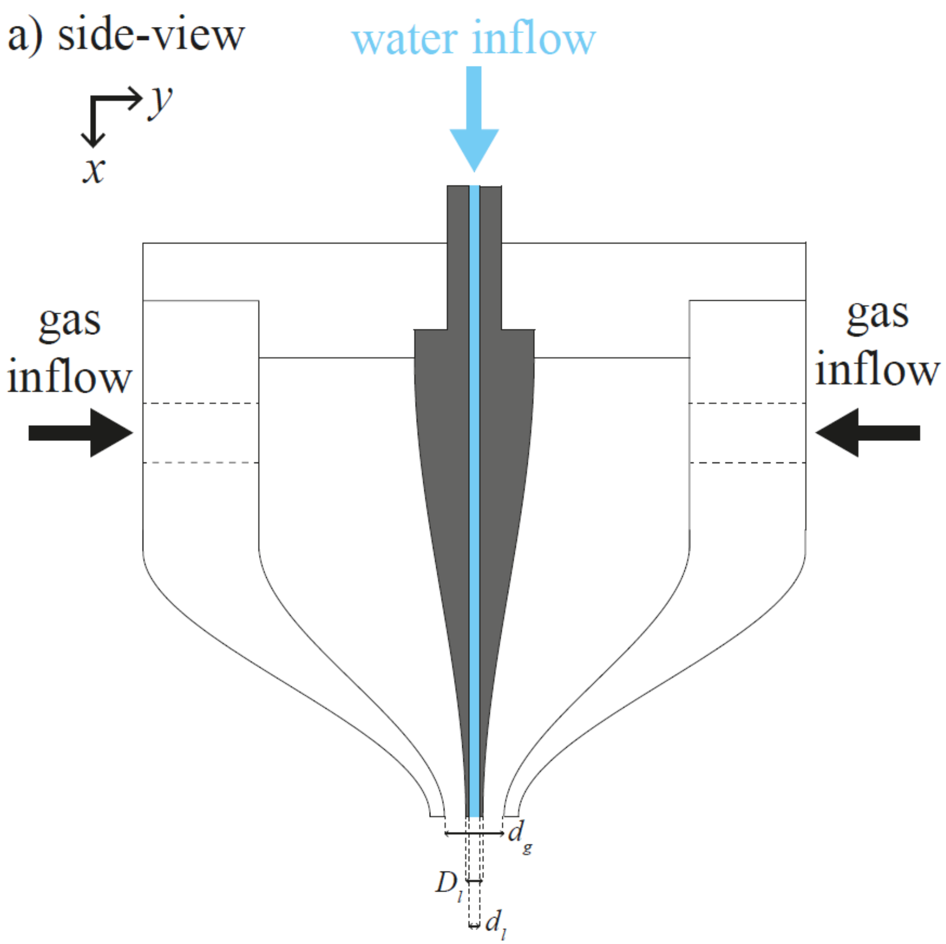


Cryogenic, *Locke at al. 2010*

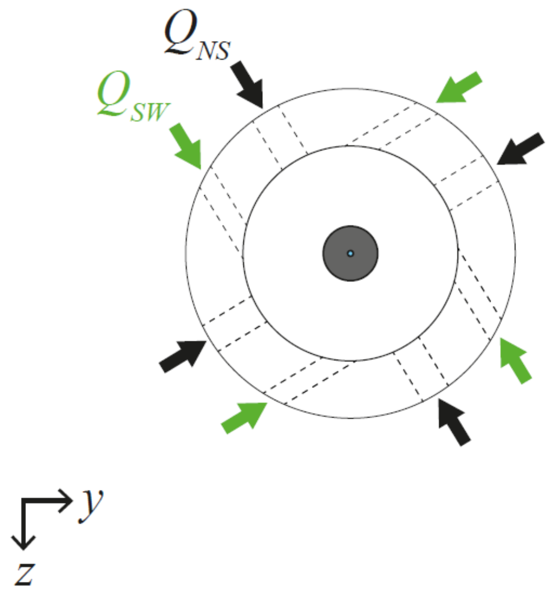
- Frequency well modeled (Delon et al., 2018)
- Flapping affects the cascade of mechanisms, up to droplet spatiotemporal distributions
- Dimensionality and role of swirl

Effect for high-speed sprays

$$Q_{Total} = Q_{SW} + Q_{NS} = cst$$

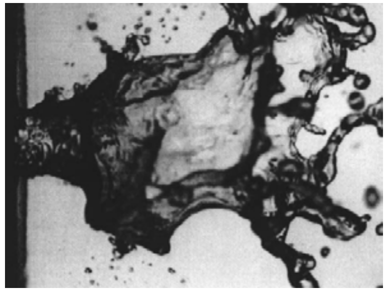


b) top-view



$$SR = \frac{Q_{SW}}{Q_{NS}}$$

Threshold of angular to longitudinal momenta ratio

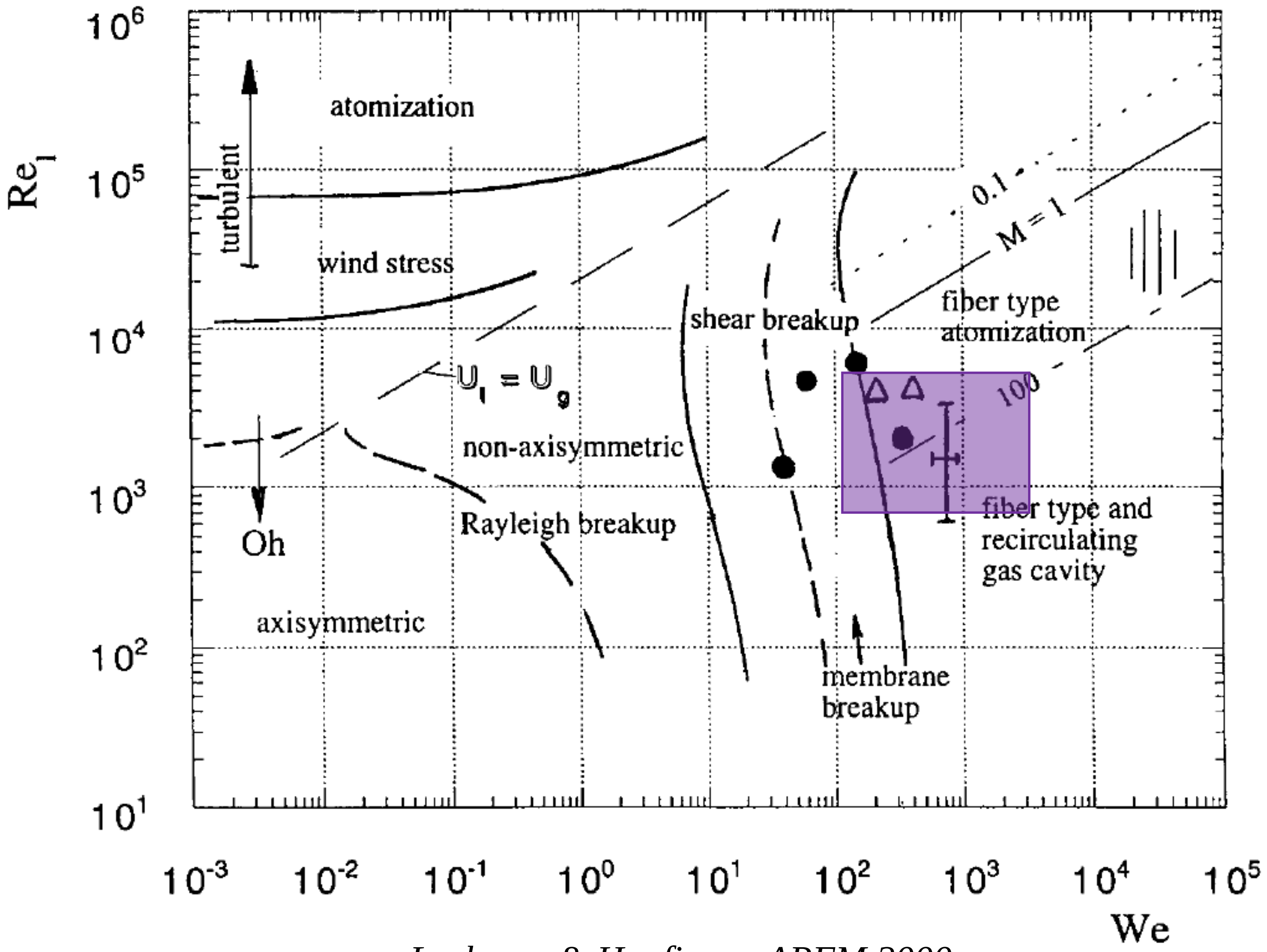


Lasheras & Hopfinger ARFM 2000

Control parameters: liquid flow rate, no-swirl and swirl gas flow rates ➔ Re_l, Re_g, SR

Weber number $We_g = \frac{\rho_g {u_g}^2 d_l}{\sigma}$ Gas-to-liquid dynamic pressure ratio $M = \frac{\rho_g u_g^2}{\rho_l u_l^2}$

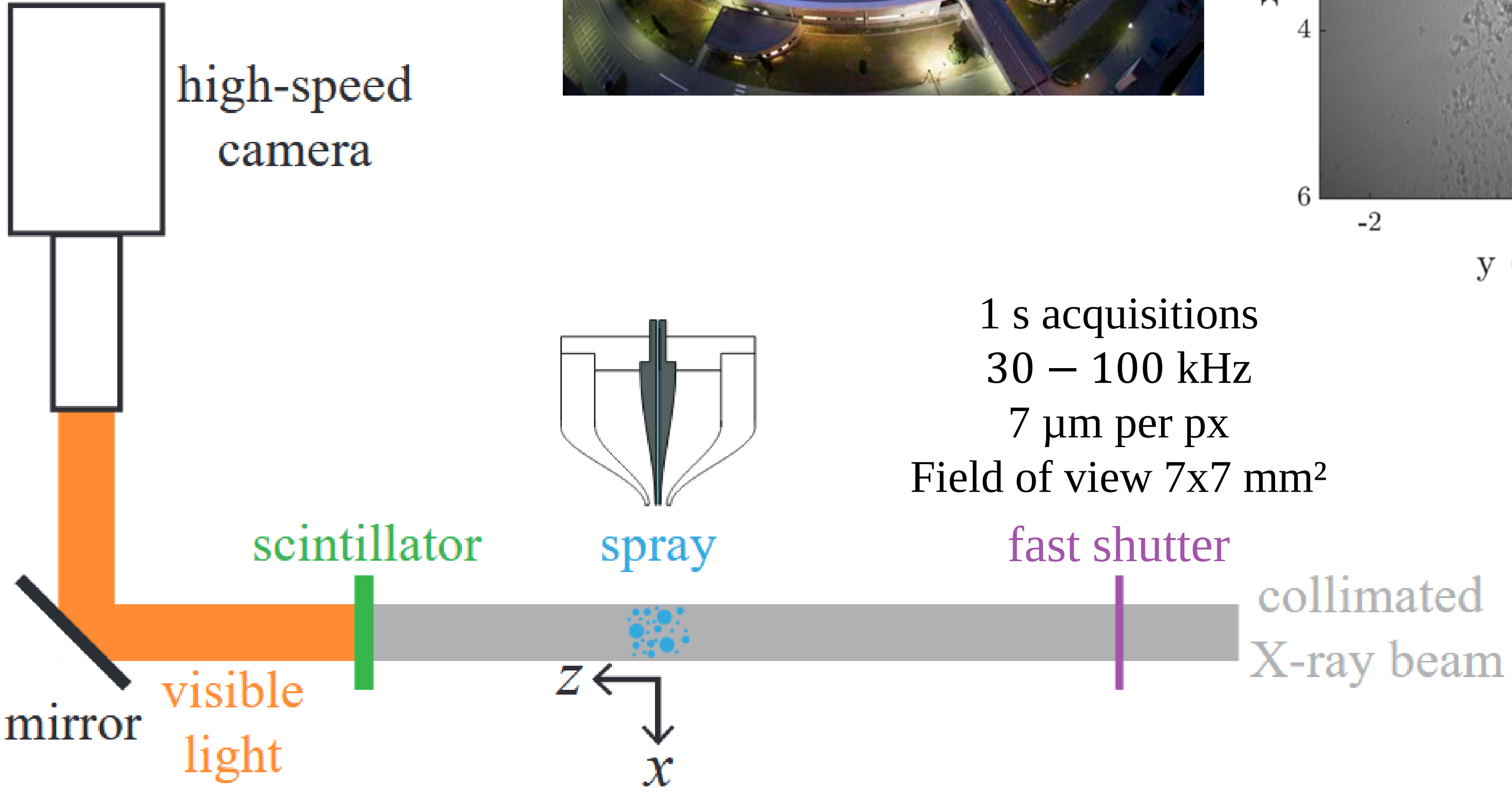
Qualitative spray formation pictures in the near-field

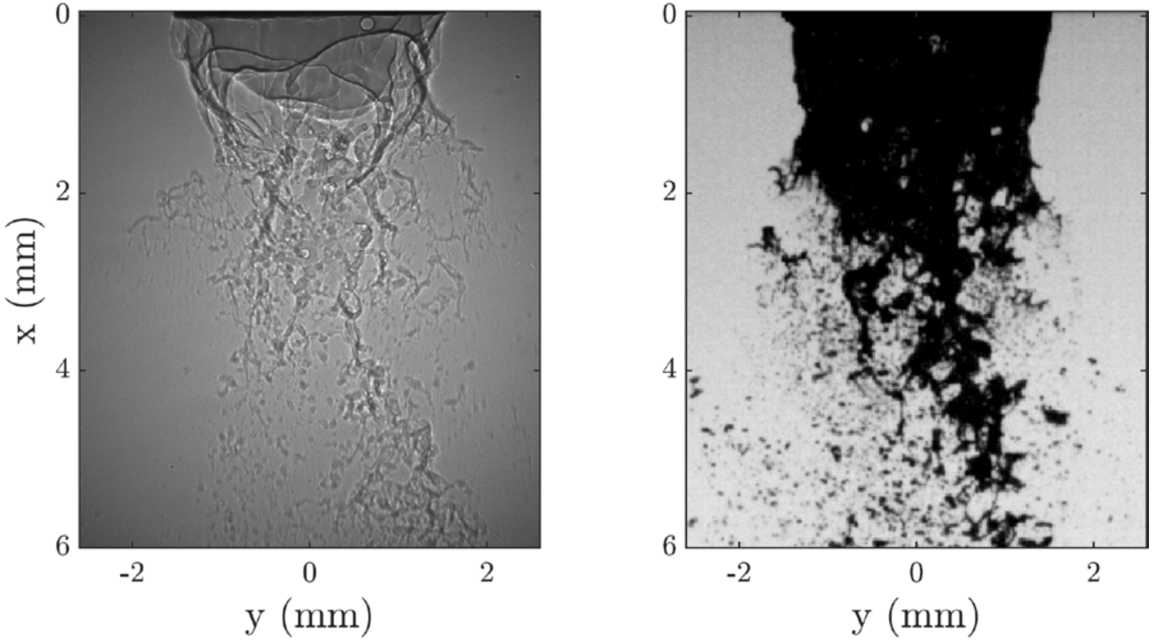


Lasheras & Hopfinger, ARFM 2000

Synchrotron X-ray high-speed imaging

A. Rack
ID19





1 s acquisitions
30 – 100 kHz
7 µm per px
Field of view 7x7 mm²

$800 < Re_l < 5000$

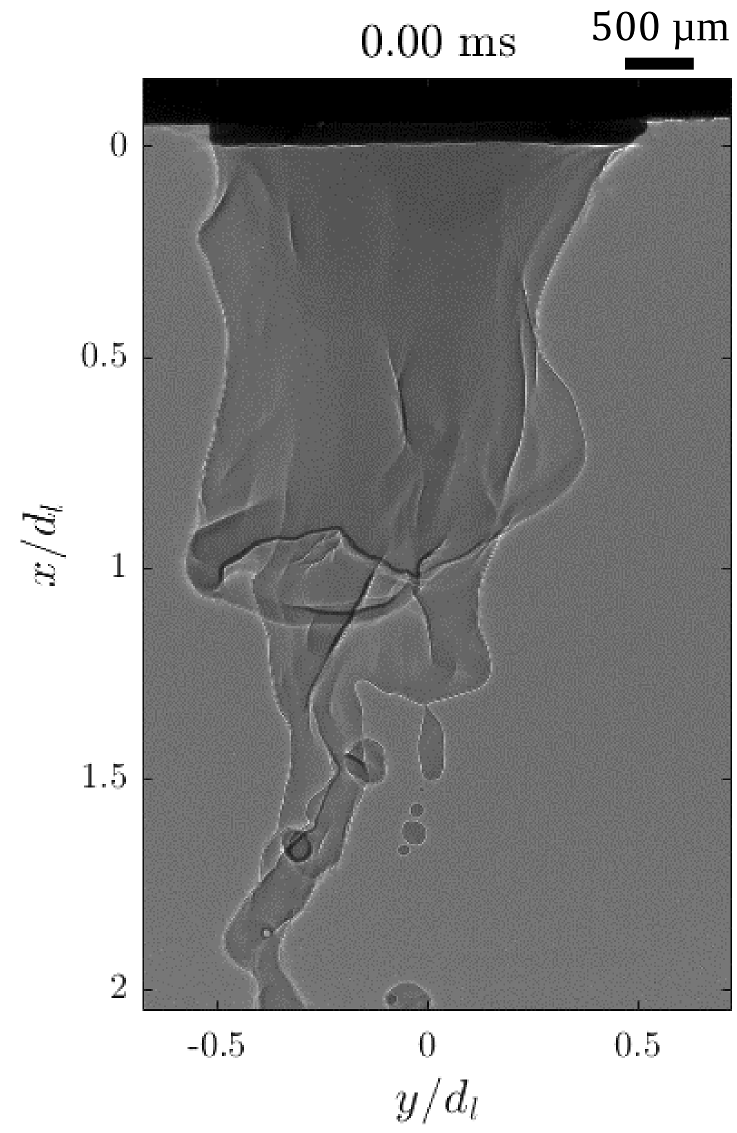
$2\ 10^4 < Re_g < 2\ 10^5$

$30 < We_g < 3200$

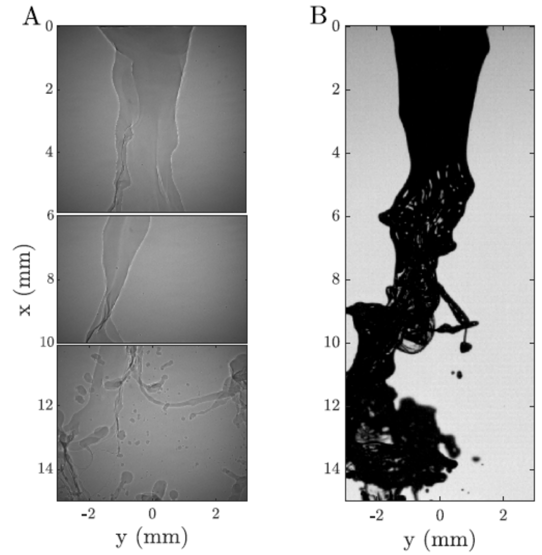
$5 < M < 700$

Intact core

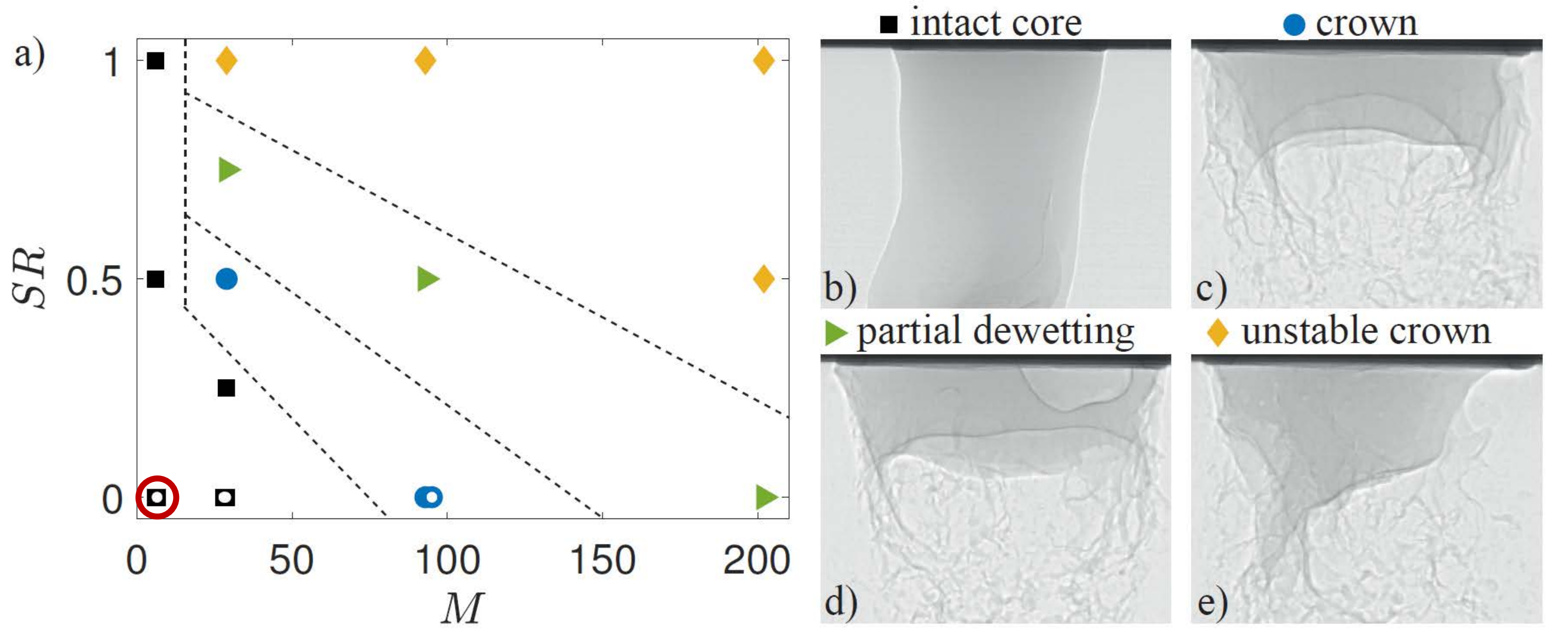
$Re_l = 800$ $We_g = 45$



- No gas penetrated within the liquid jet's core
- Strong signature of flapping
- Formation of bags
- Localized Kelvin-Helmholtz perturbations
- Liquid structure reattachments encapsulate large air pockets
- Full wetting of the liquid nozzle with high curvature as the liquid jet is accelerated

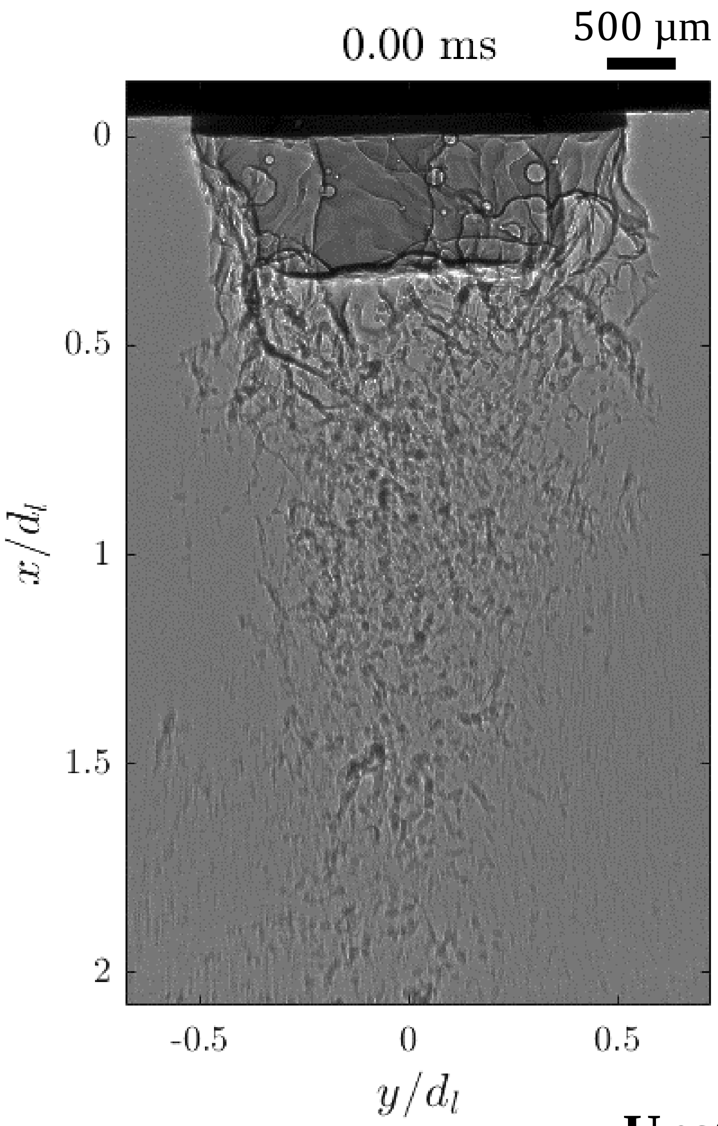


Machicoane et al., IJMF 2019



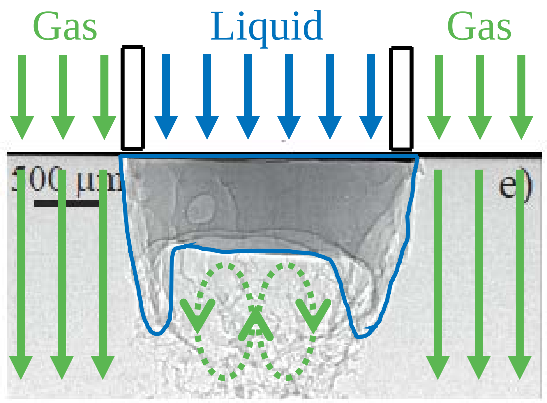
Stable and unstable liquid crown

$Re_l = 1100 \quad We_g = 800$



Machicoane et al., IJMF 2019

$Re_l = 1100, We_g = 1350$

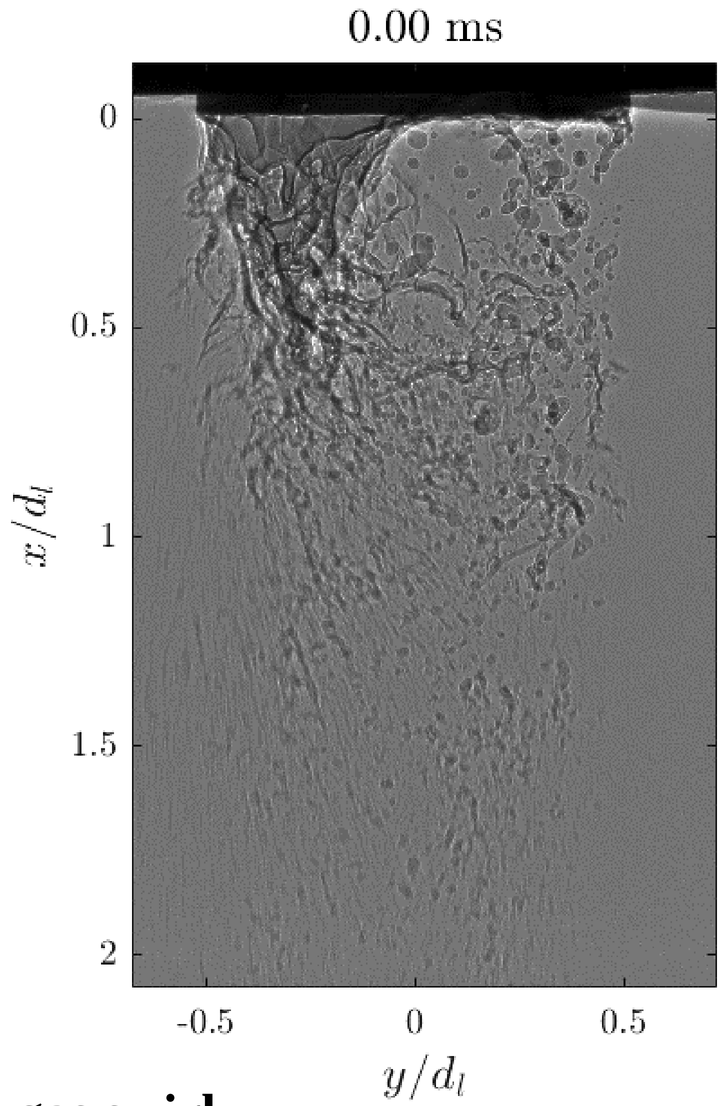


Crown

with gas swirl

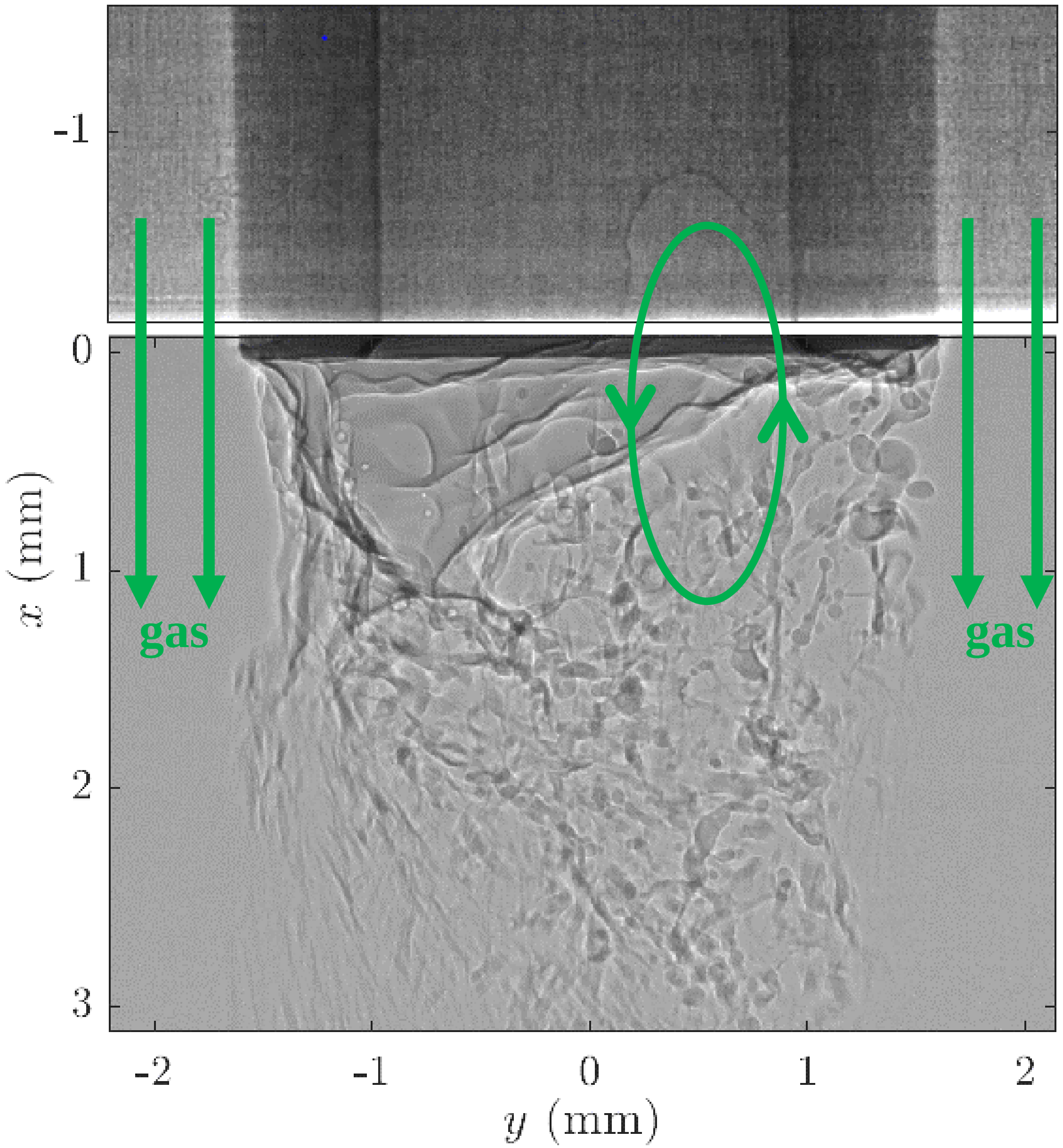
➔ Unstable crown

$Re_l = 800 \quad We_g = 1100$



Unstable crown at extreme *M* values, without gas swirl

Visualization inside the liquid nozzle

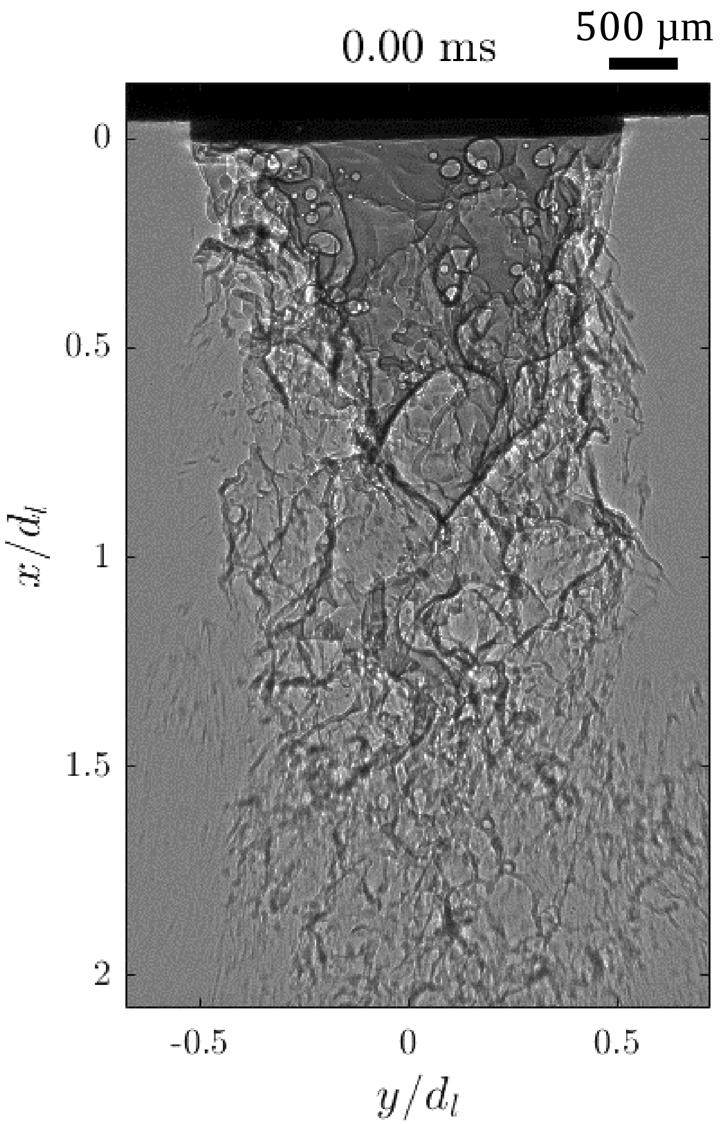


Inside the nozzle

Outside of the nozzle

Transition between intact liquid core and crown

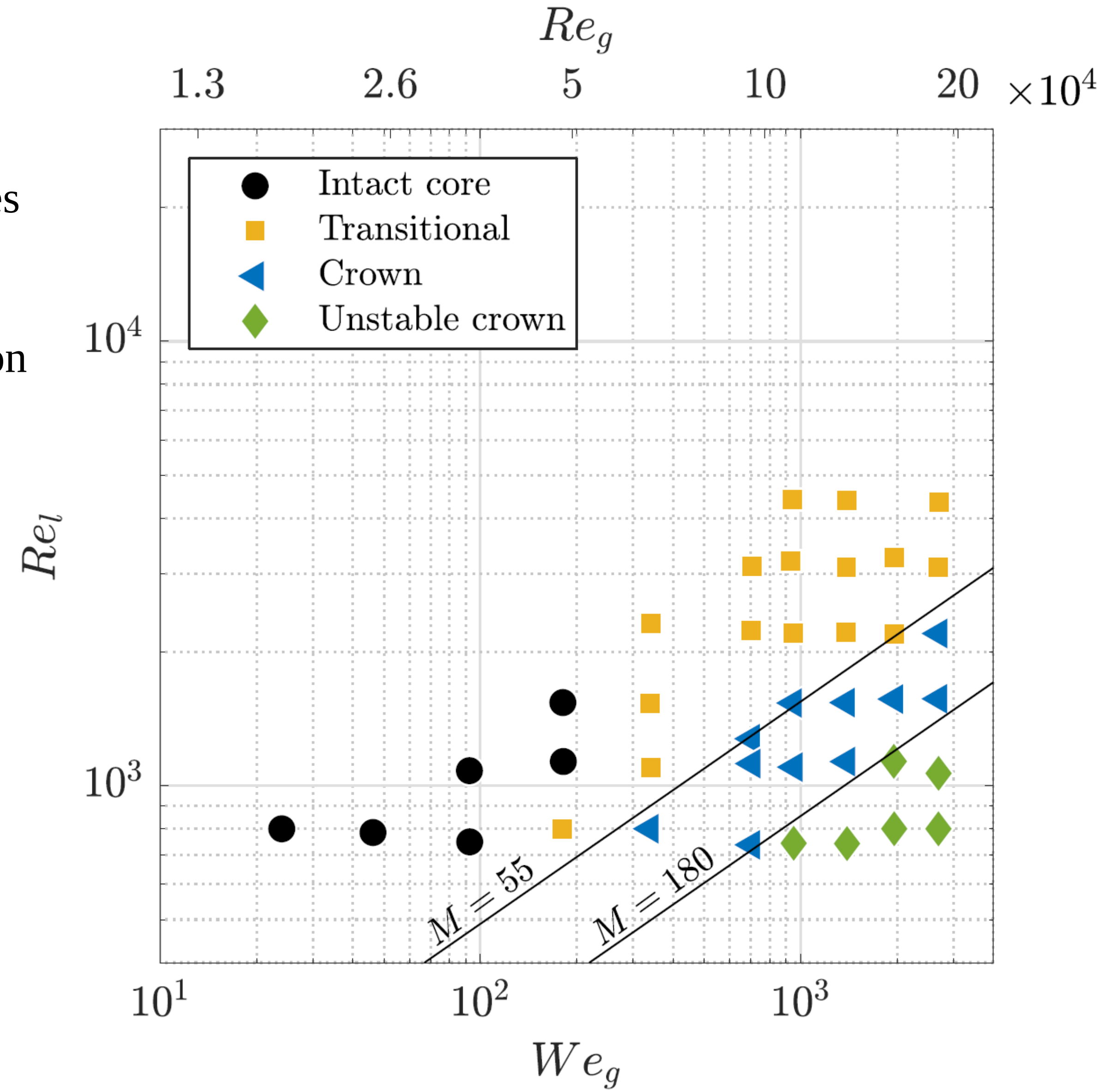
$Re_l = 3100 \quad We_g = 800$



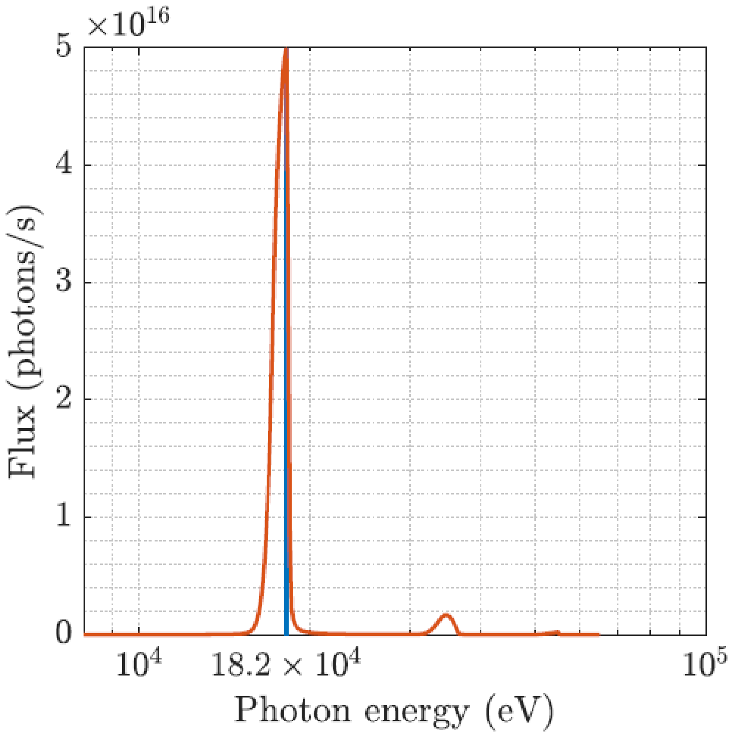
- Many overlapping interfaces
- Many smaller-scale gas recirculations
- « Perforated core » transition between intact core and crown

$$M = \frac{\rho_g u_g^2}{\rho_l u_l^2}$$

Kinetic energy arguments seem in good agreement for transition to crown and unstable crown



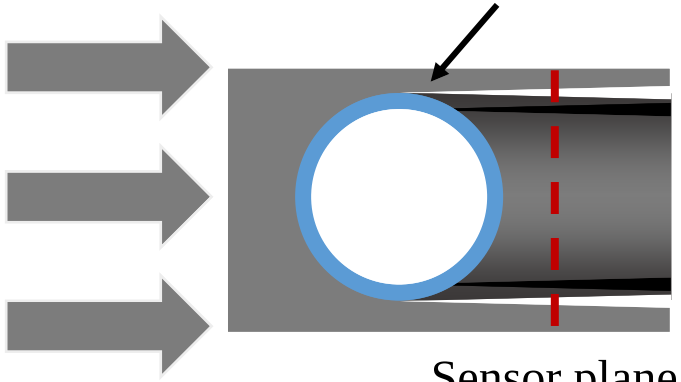
ANKA Phase: from intensity to liquid thickness



Incoming X-ray beam
energy spectrum

X-ray absorption by the liquid jet follows Beer-Lambert's law

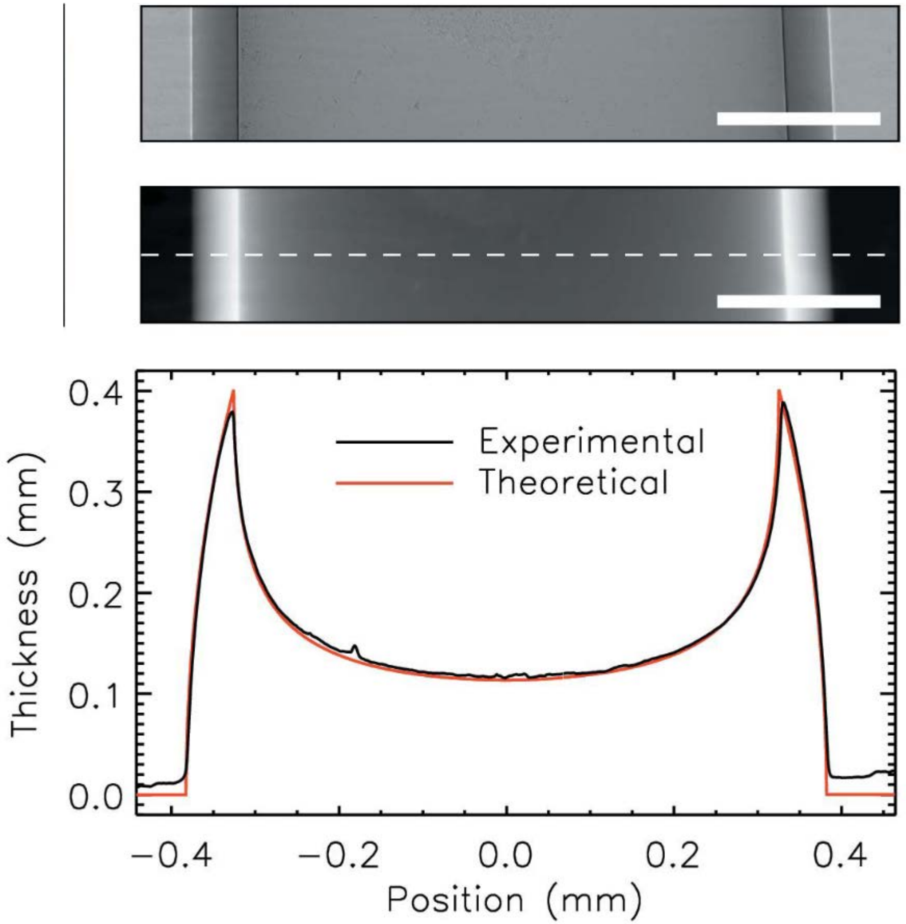
➔ Equivalent path lenght (EPL)



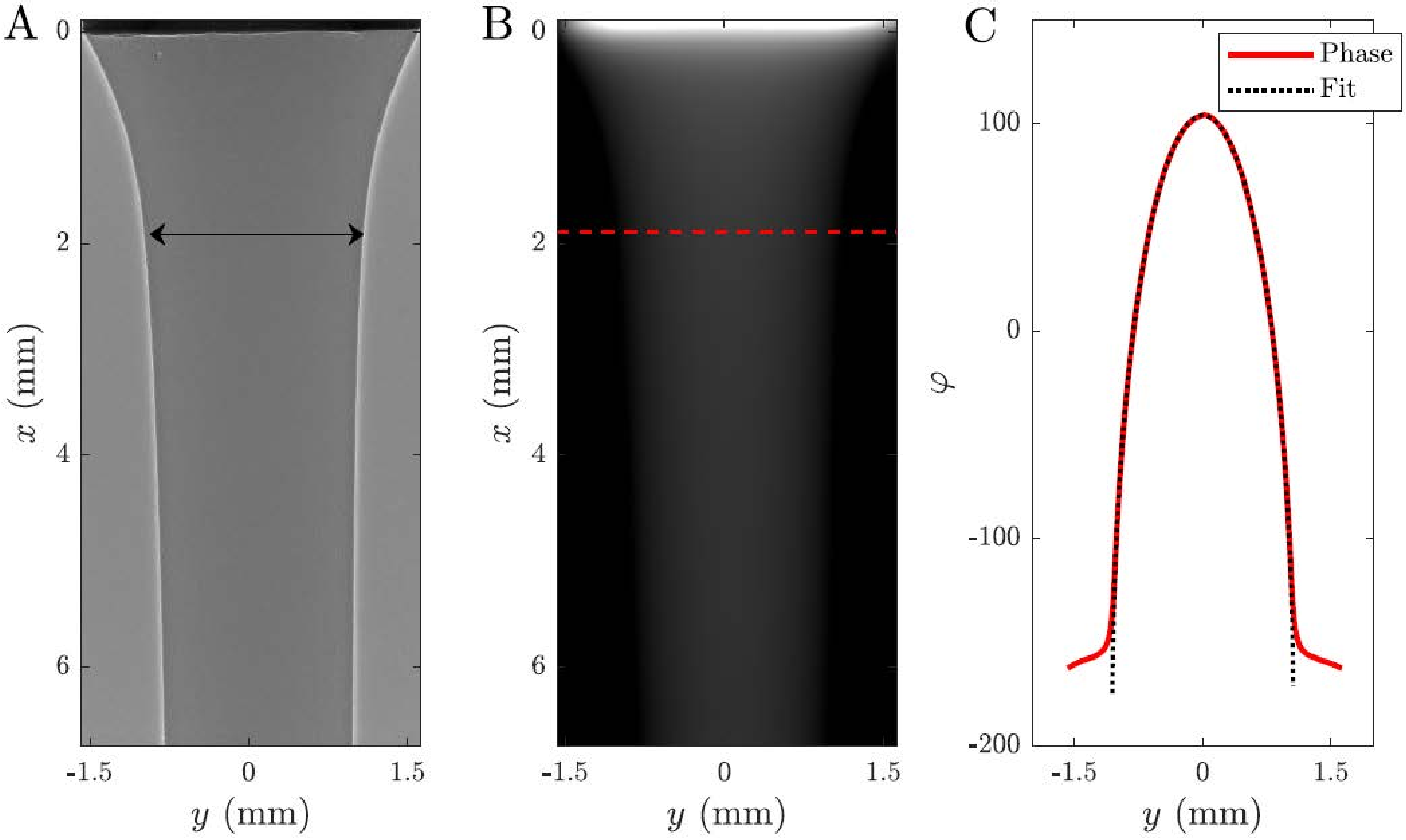
$$\frac{I(x,y,t)}{I_0(x,y)} = \int e^{-\mu(\lambda)h(x,y,t)} d\lambda$$

- Remove interferences $f(x,y,\lambda)$
- Retrieve phase map ϕ
- Convert into EPL map

Weitkamp et al.
J. of Synchrotron Radiation 2011

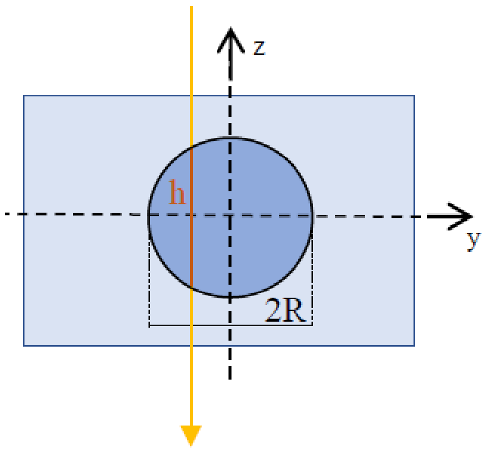


Normalized radiograph
Phase map
EPL



X-ray absorption by the liquid jet follows Beer-Lambert's law

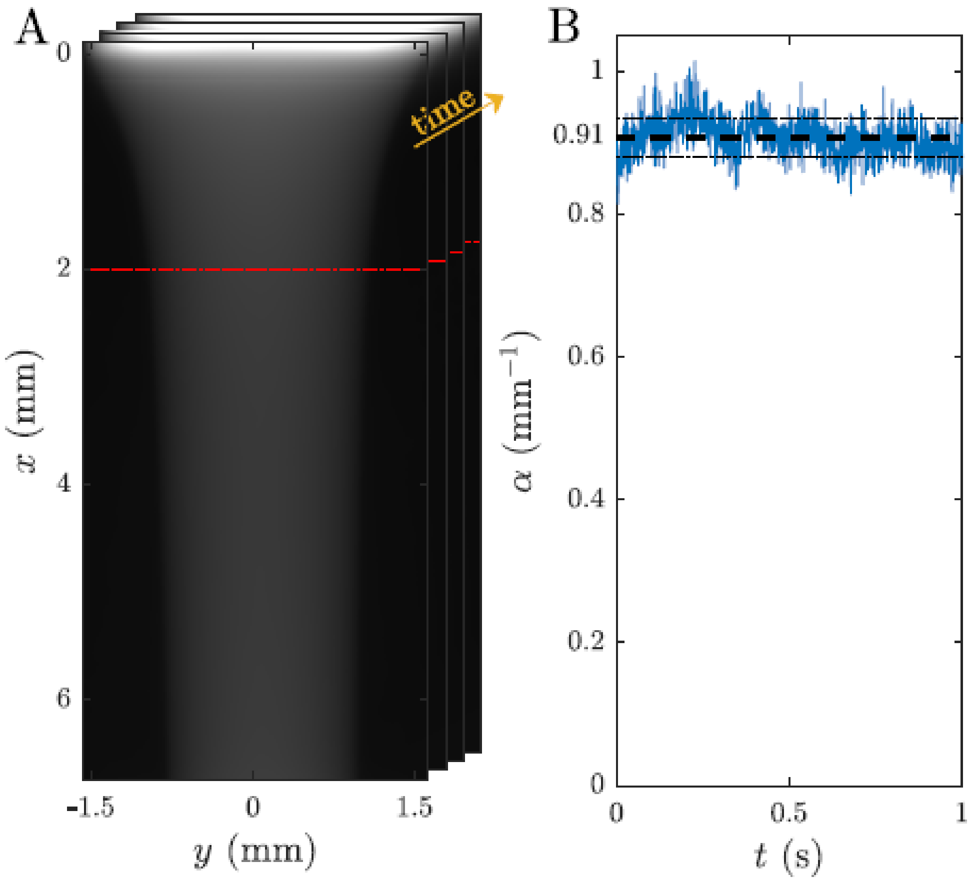
➔ Equivalent path lenght (EPL)

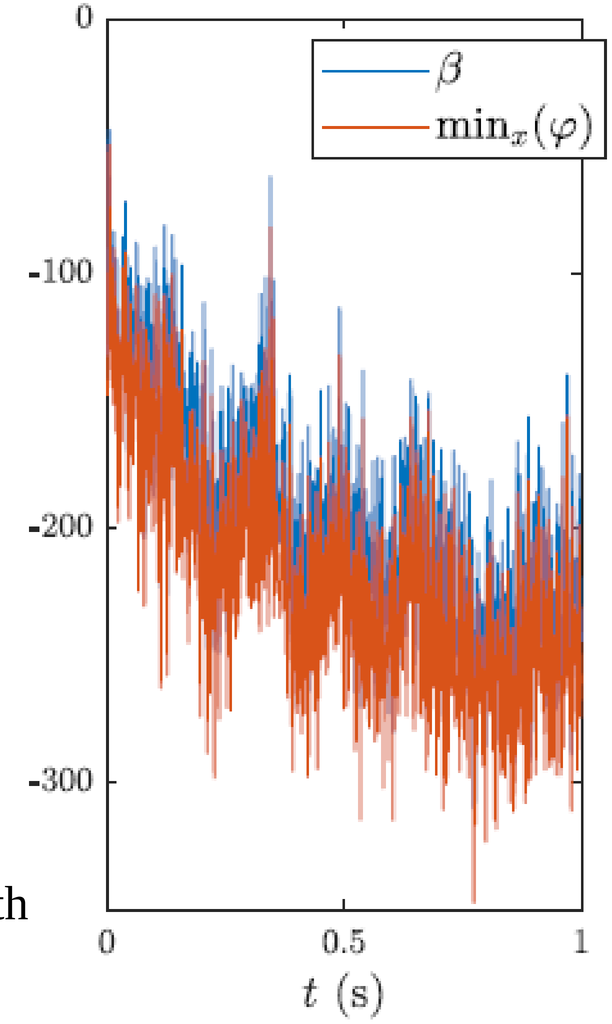


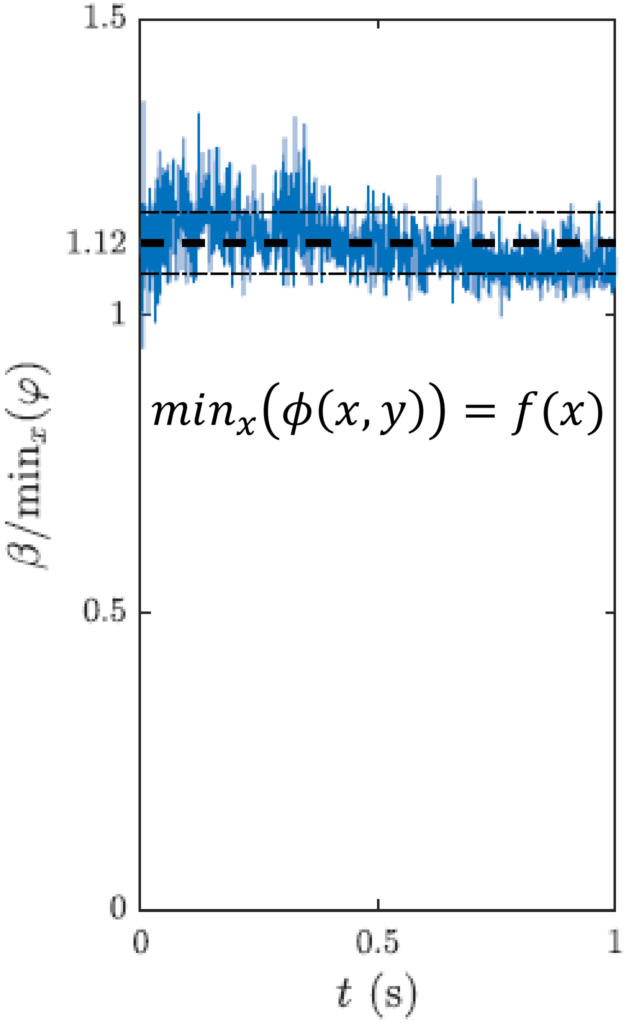
$$\phi = \alpha h(y) + \beta$$

$$h(y) = 2R\sqrt{1-(y/R)^2}$$

➔ Calibrate for the coefficient α and β (non-monochromatic, spatial and temporal inhomogeneities…)

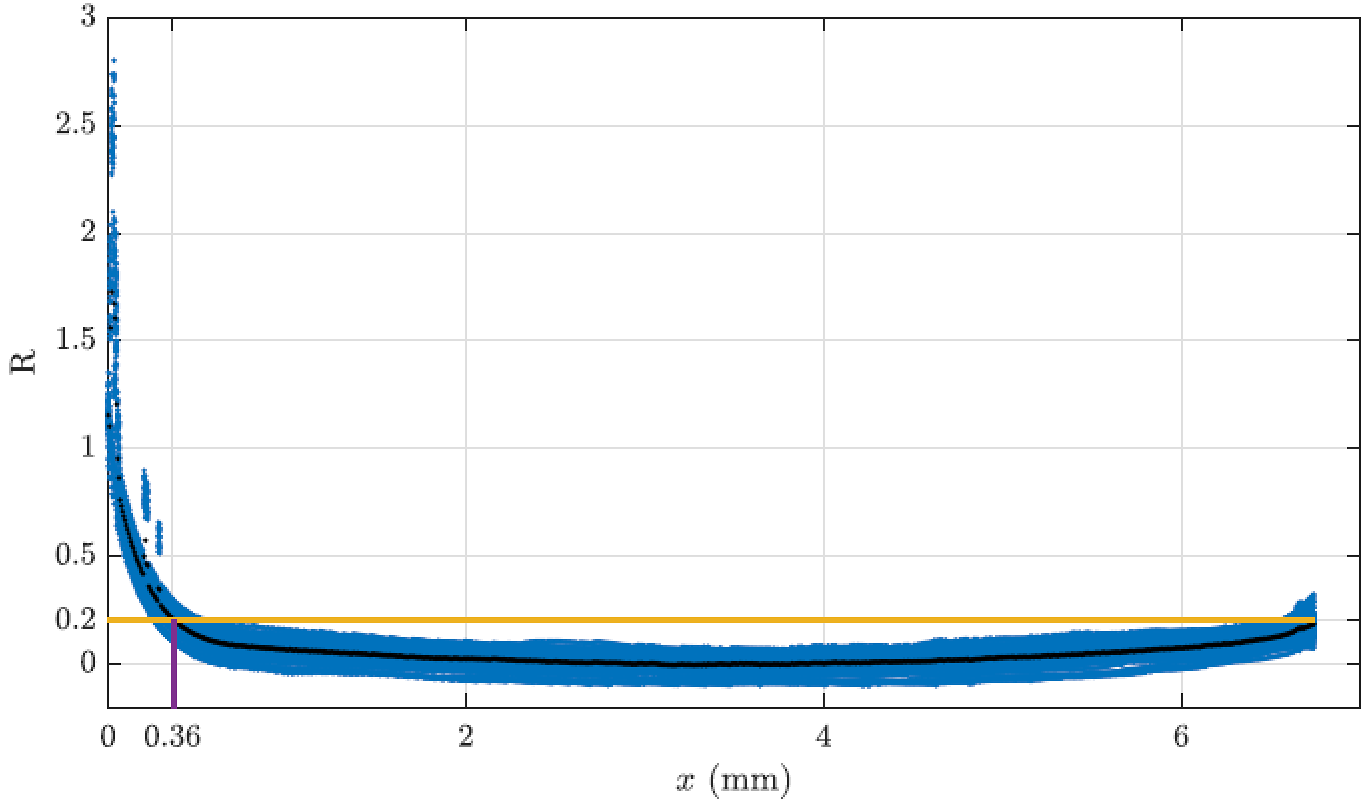


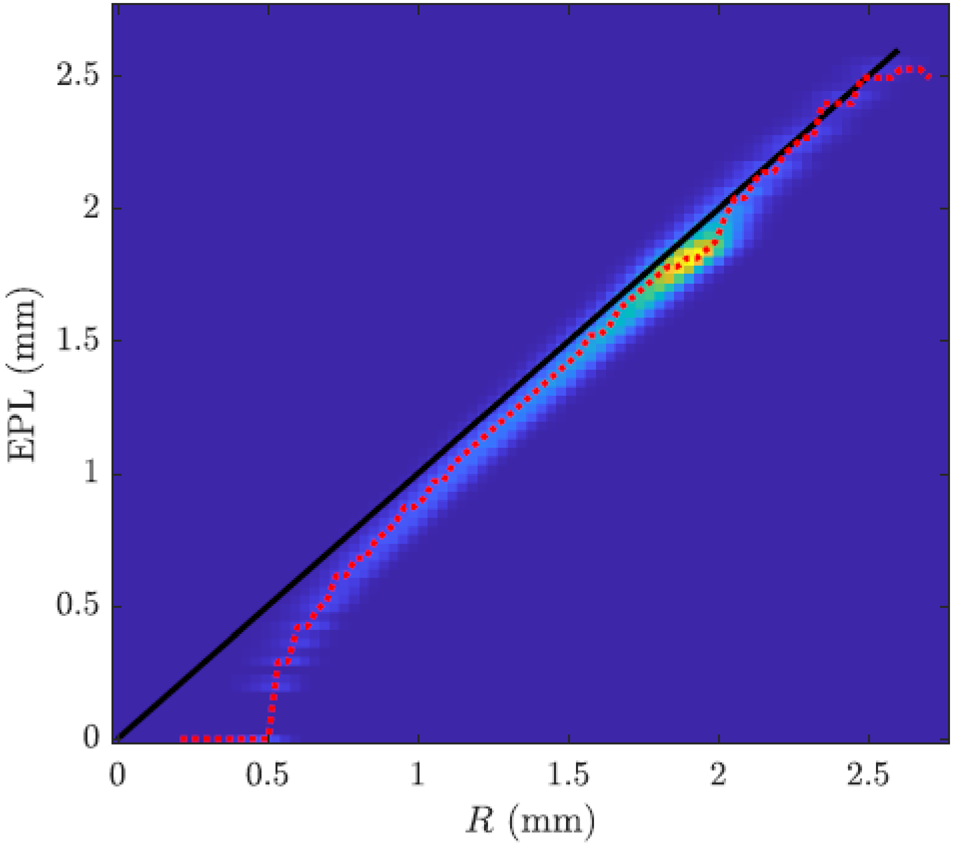




α, β depend on the sample and on the X-ray wavelength

➔ $\alpha = 0.91$ mm^{-1} and $\beta = 1.12\, min_x(\phi)$ for what follows





2D PDF: EPL vs fitted radii

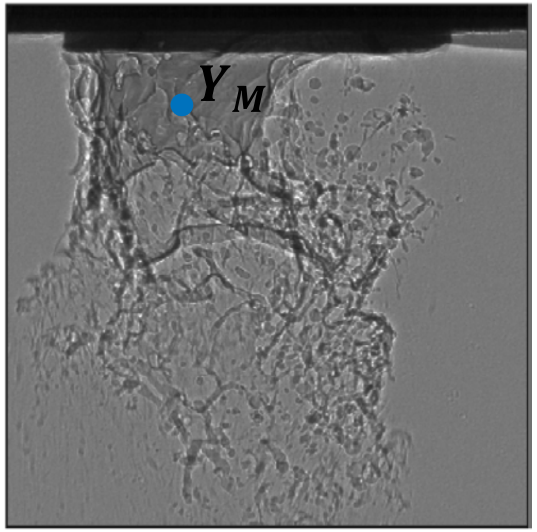
Longitudinal cut along the liquid jet

Limitations of the uncertainties' evaluation

- Nozzle glare (ANKA Phase is for a single material)
- Interference patterns due to X-ray scattering by interfaces limit the probing of small radius values

➔ For $x > \frac{D_l}{10}$ and for $EPL > 1$ mm, approximately 10% accuracy (~ 20% for smaller thicknesses?)

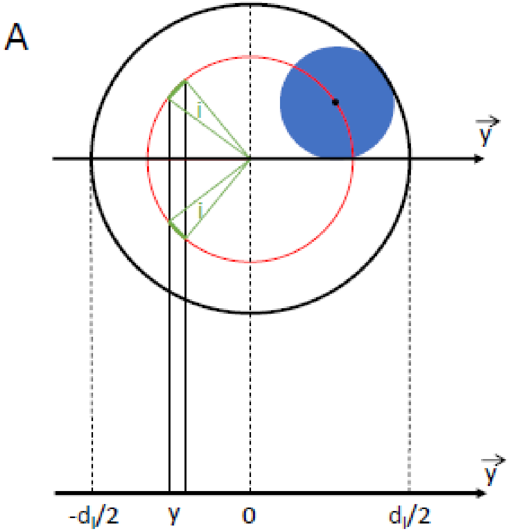
Transverse center of mass of the liquid core

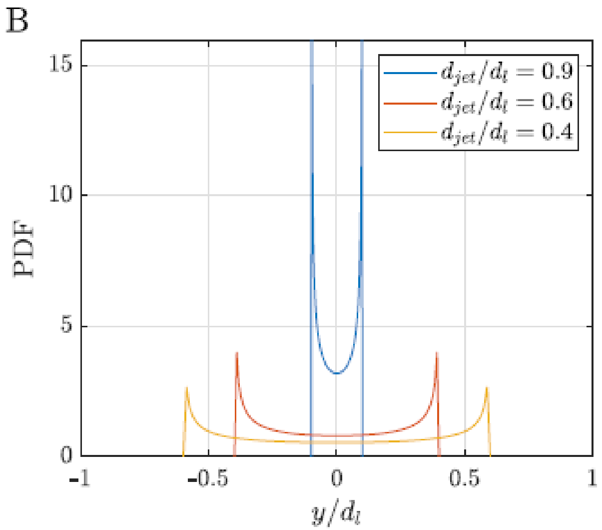


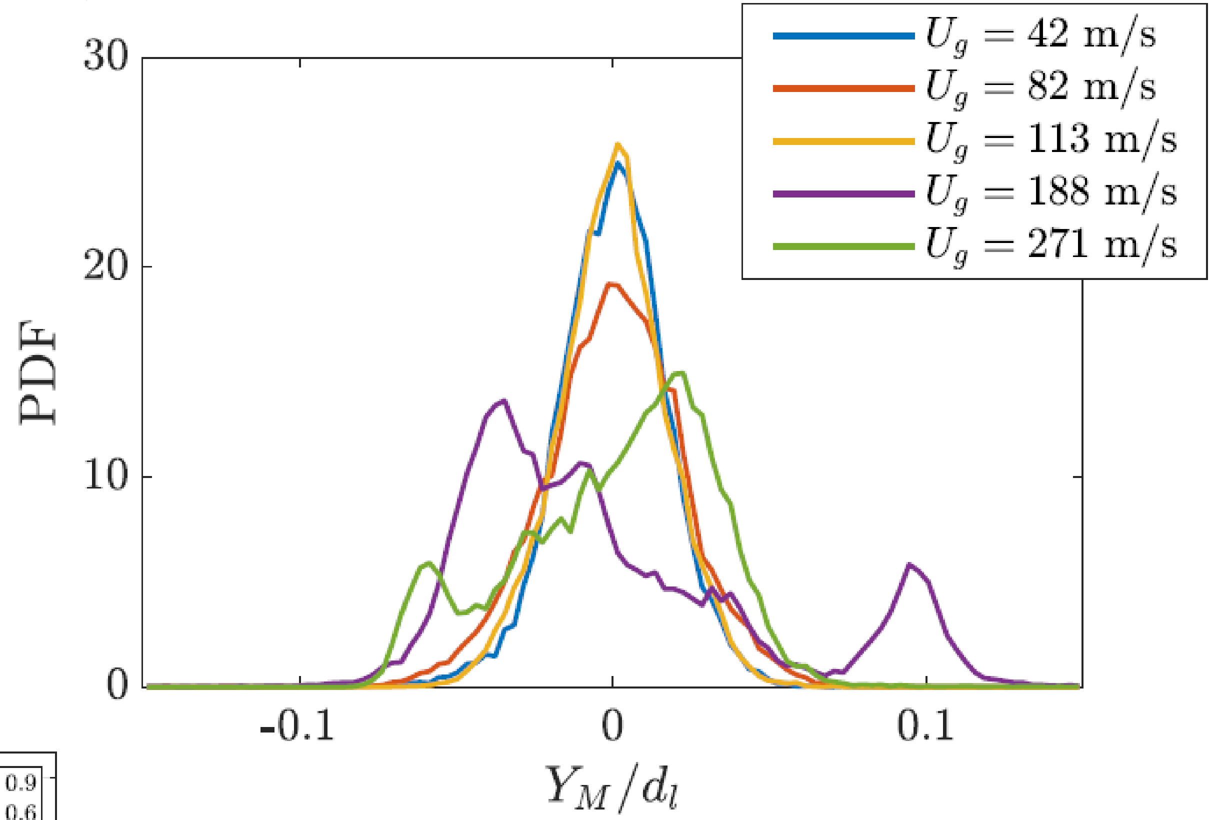
Center of mass along y

$Re_l = 800$

$40 < We_g < 2000$







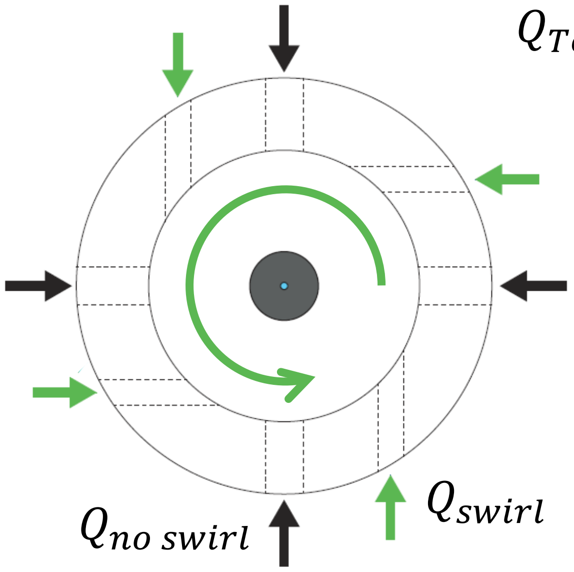
Simple model of the unstable liquid crown

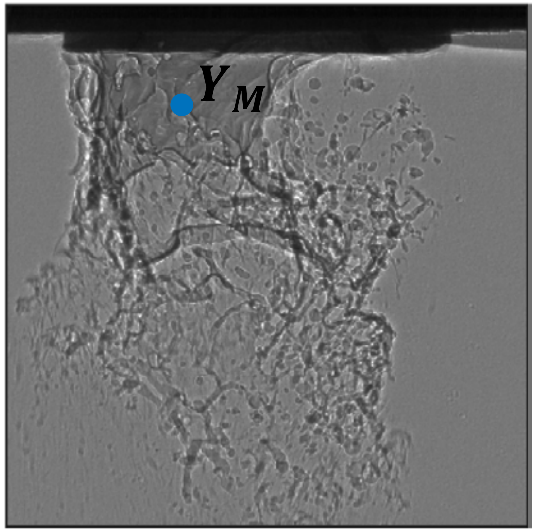
- Circular cross-section
- Anchored at a given distance from the nozzle's axis d_{jet} that is varied
- Qualitatively explains the shape of the PDF

Temporal dynamics of the unstable crown and role of swirl

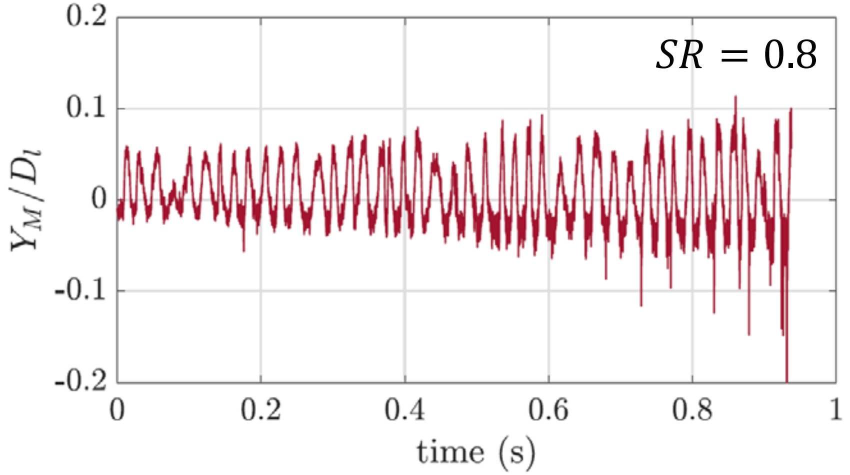
$Q_{Total} = Q_{SW} + Q_{NS} = cst$ $\quad$ $SR = Q_{swirl}/Q_{no\ swirl}$

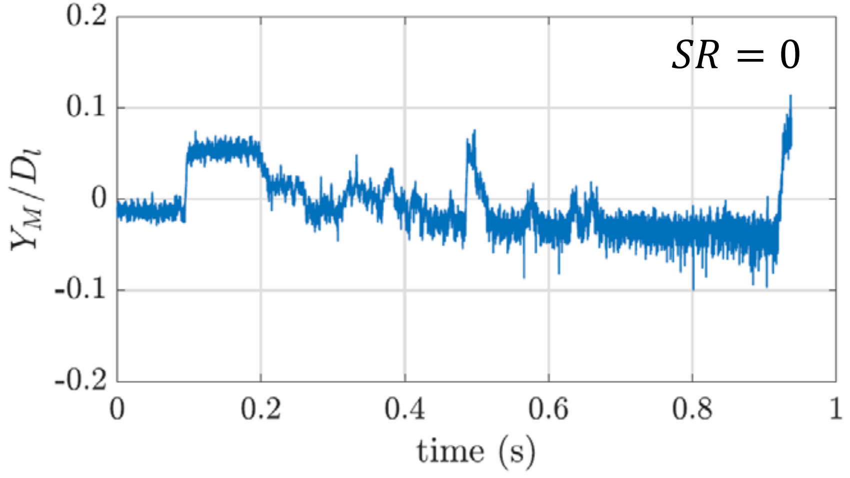
$Re_l = 800$ $\quad$ $We_g = 950$

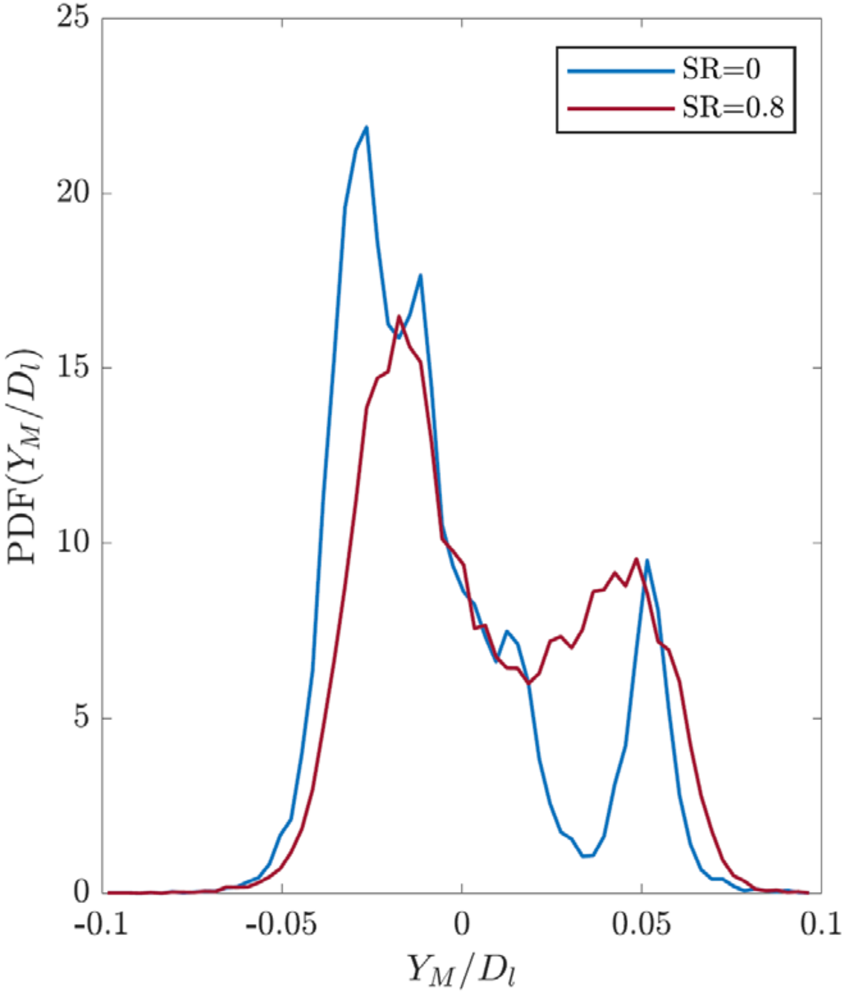




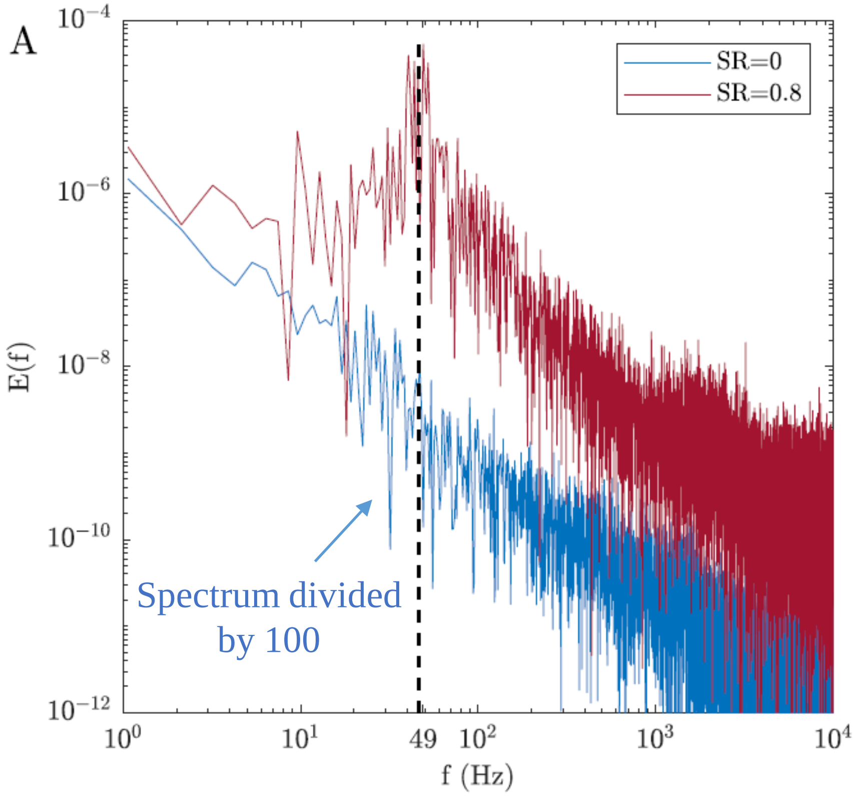
Center of mass along y

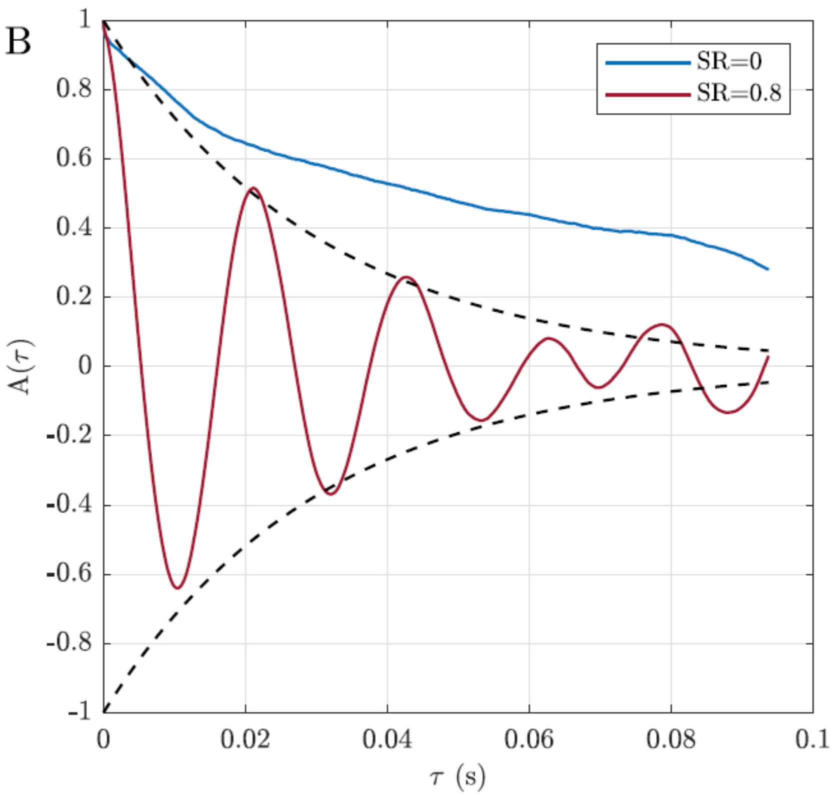






Temporal dynamic of the unstable crown





$Re_l = 800$ $We_g = 950$

- Strong periodicity signature with swirl
- Mean residence time on the side is twice the oscillation period

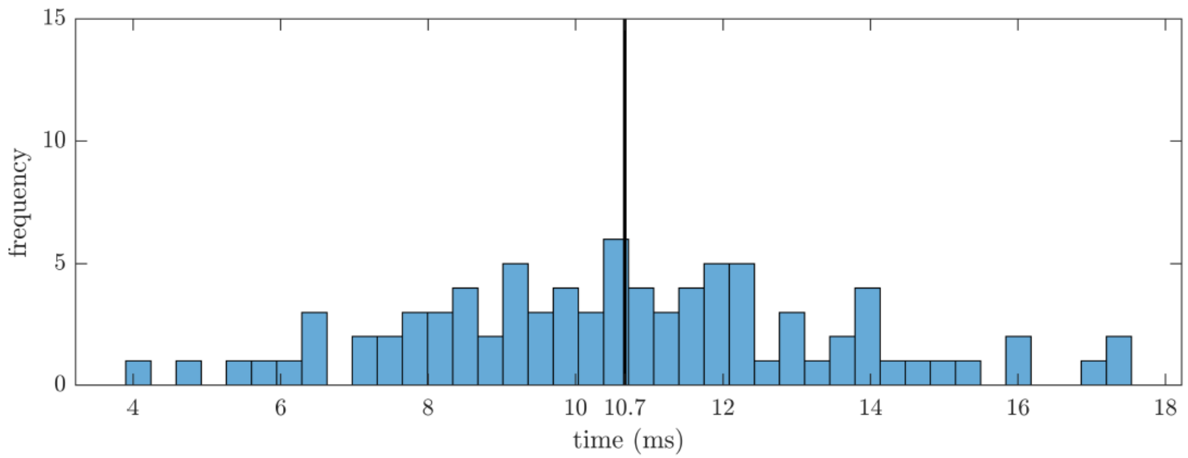
- Without swirl, onset of a slow dynamic which would required longer acquisition to investigate

- Decorrelation of the liquid core center of mass is orders of magnitude slower than that of the liquid core length

$SR = 0.8$

Bin the signal into « left », « right », and « center »

➔ Histogram of the residence times spent « on the side »



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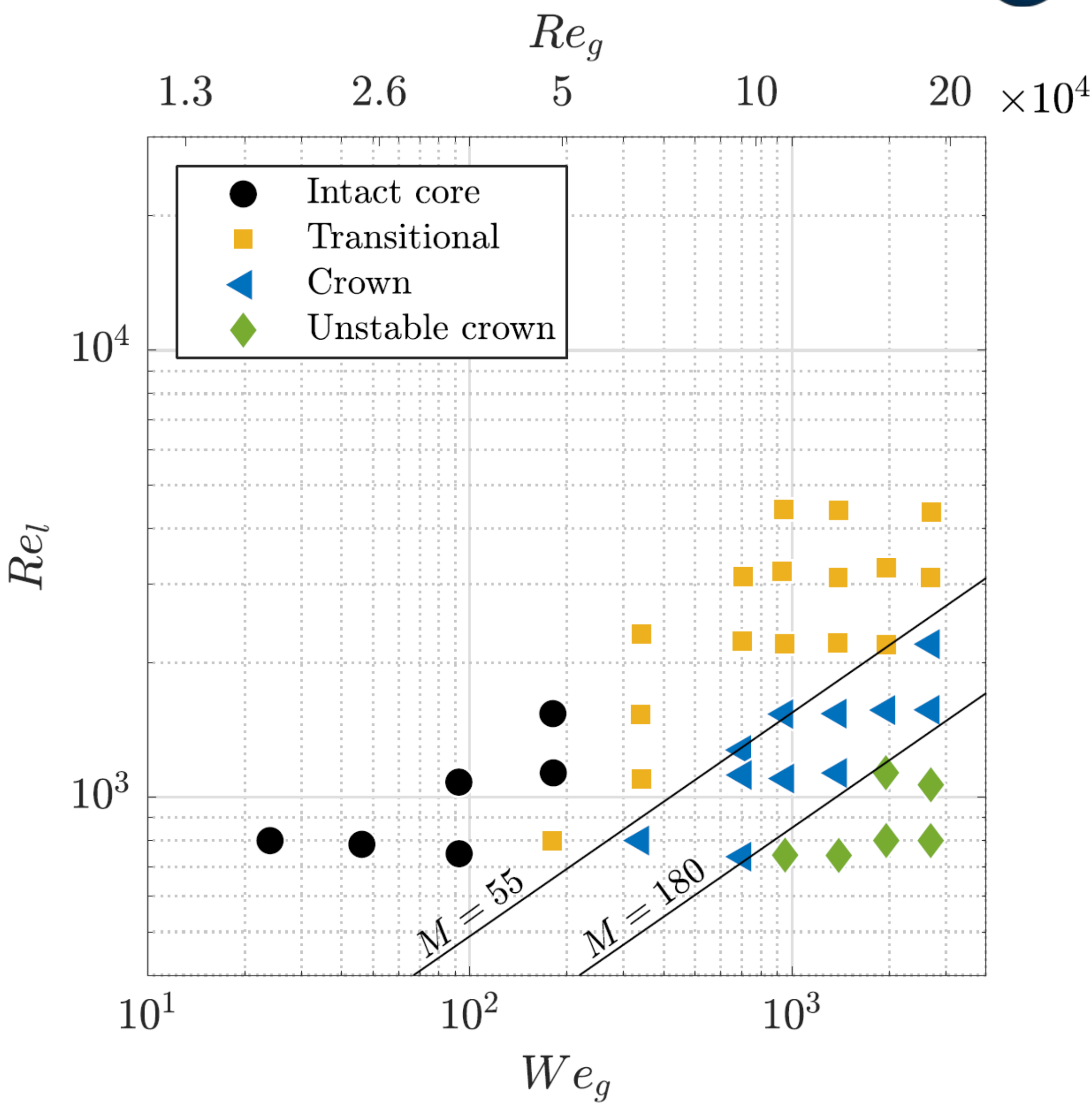
- Proposed a method to retrieve liquid path using X-ray
- At higher We_g, liquid core undergoes transitions, up to unstable crown, even without gas swirl
  - Intact liquid core
  - Transitional liquid core
  - Liquid crown
  - Unstable liquid crown
- Gas swirl leads to
  - Earlier onset of unstable crown (i.e. at lower We_g)
  - Much more frequent motions of the gas recirculation
  - Similar PDF for center of mass
- Open questions
  - Regime map (Re_l, We_g, SR)
  - Characteristic frequency of the liquid core motions with and without swirl



(see *Kaczmarek et al., IJMF 2022* for flapping and role of swirl at lower We_g)