Spatial-temporal measurement of fragments and ligaments in secondary atomization via high-speed DIH

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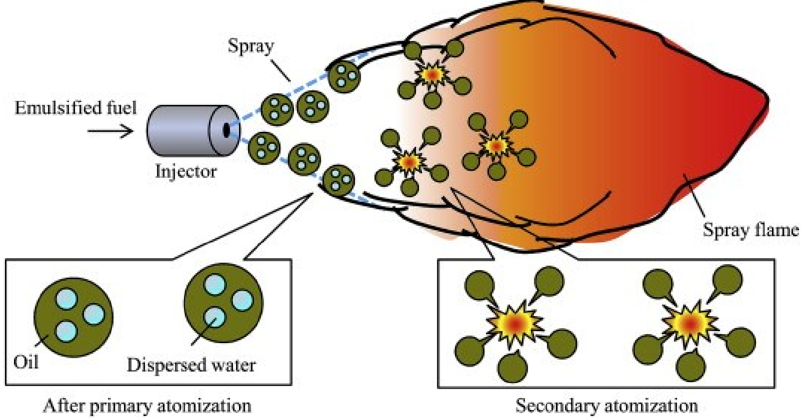
Background

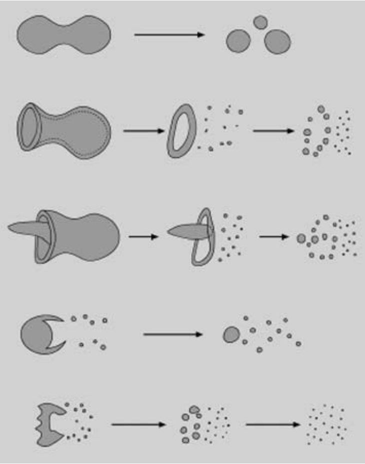
Liquid atomization has wide applications in liquid fuel combustion, agriculture spray, food processing, etc. Secondary atomization determines the final size and velocity.

Spray in engine

Energy , 35 (2) :806-813, 2010



Secondary atomization



Breakup regimes

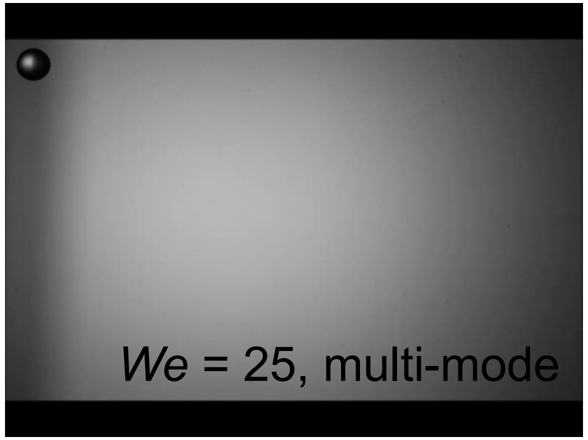
Vibrational, We < ~11

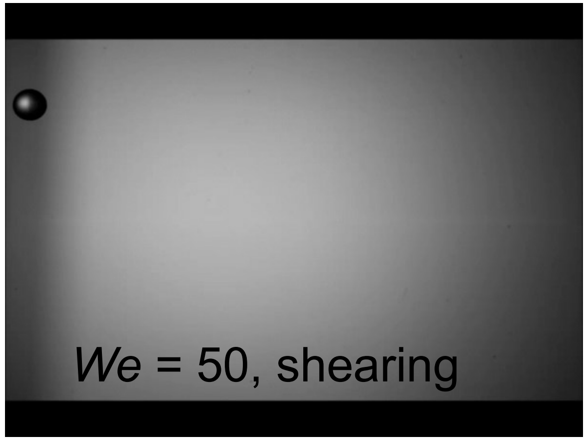
Bag, ~11<We<~35

Multimode, ~35<We<~80

Shearing, ~80<We<~350

Catastrophic, We>~350

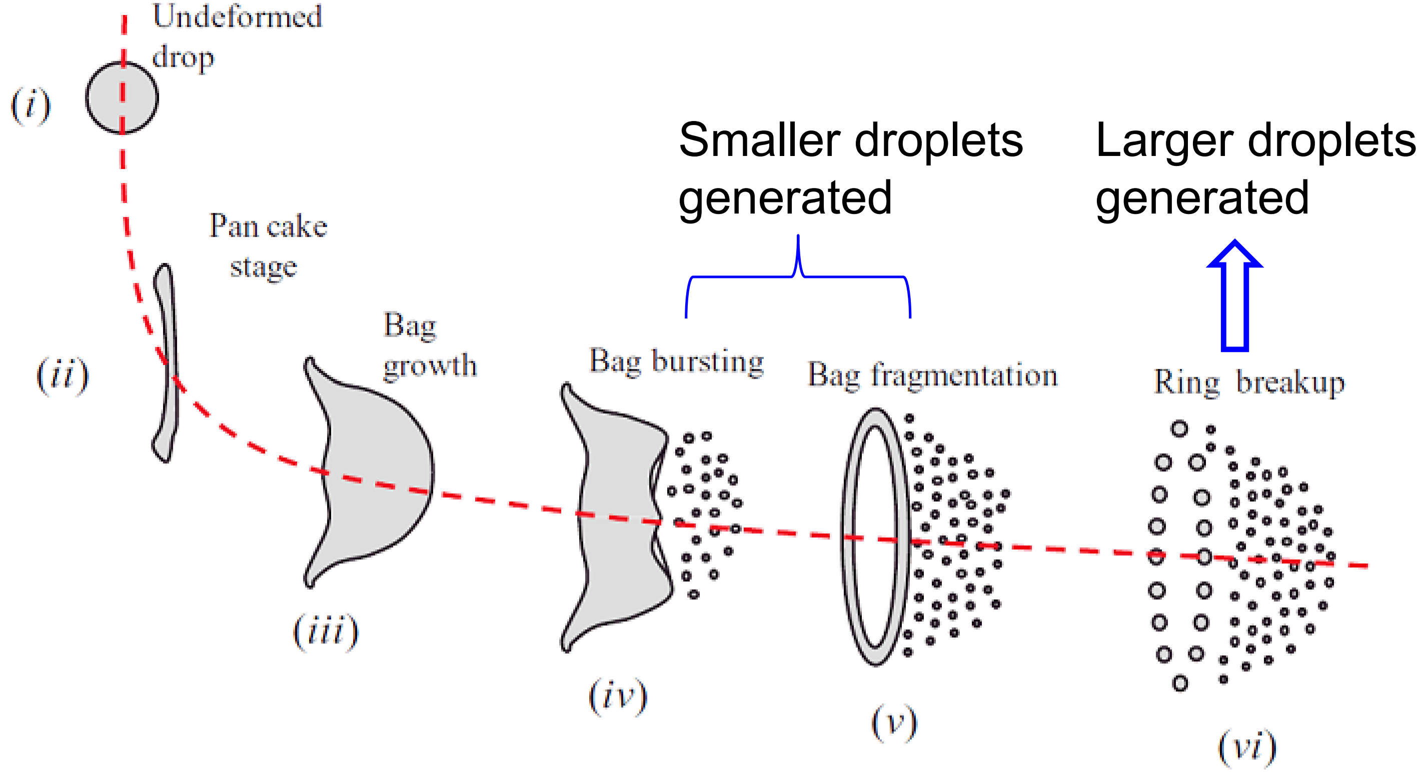




(videos)

Motivation

- Quantify 3D fragments and ligaments and their evolution in during secondary atomization.



Phys. Fluids 26, 072103 (2014)

- In bag and multi-mode (bag-stamen) breakup
  - Establish onset of secondary atomization
  - Two stages: bag rupture and rim disintegration
  - Droplet size and velocity are important parameters
  - Complicated 3D rim

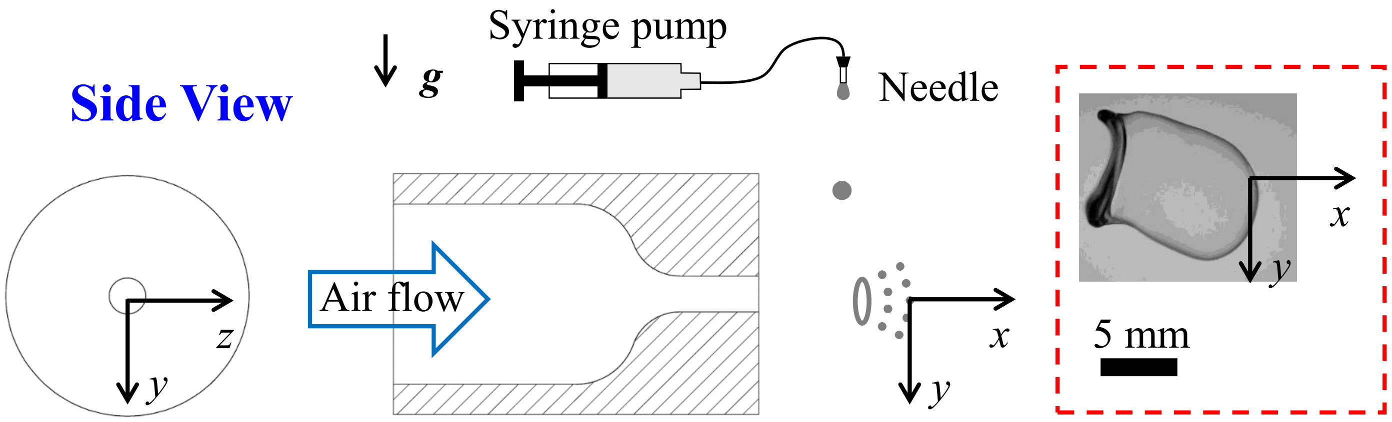
Weber number: $We = \dfrac{\rho_g u_0^2 d_0}{\sigma}$,

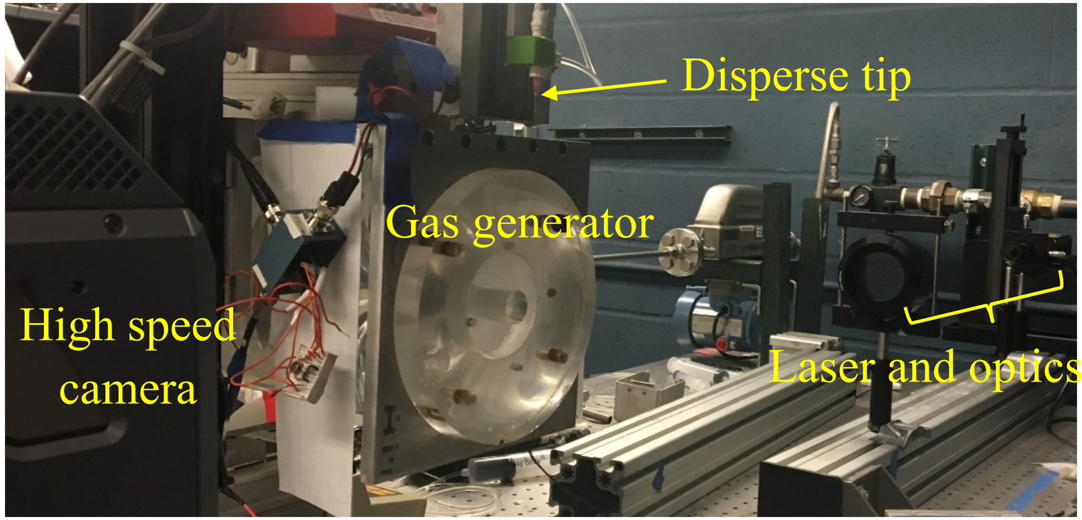
ρ_g – gas density u_0 – relative velocity

d_0 – drop diameter σ – surface tension

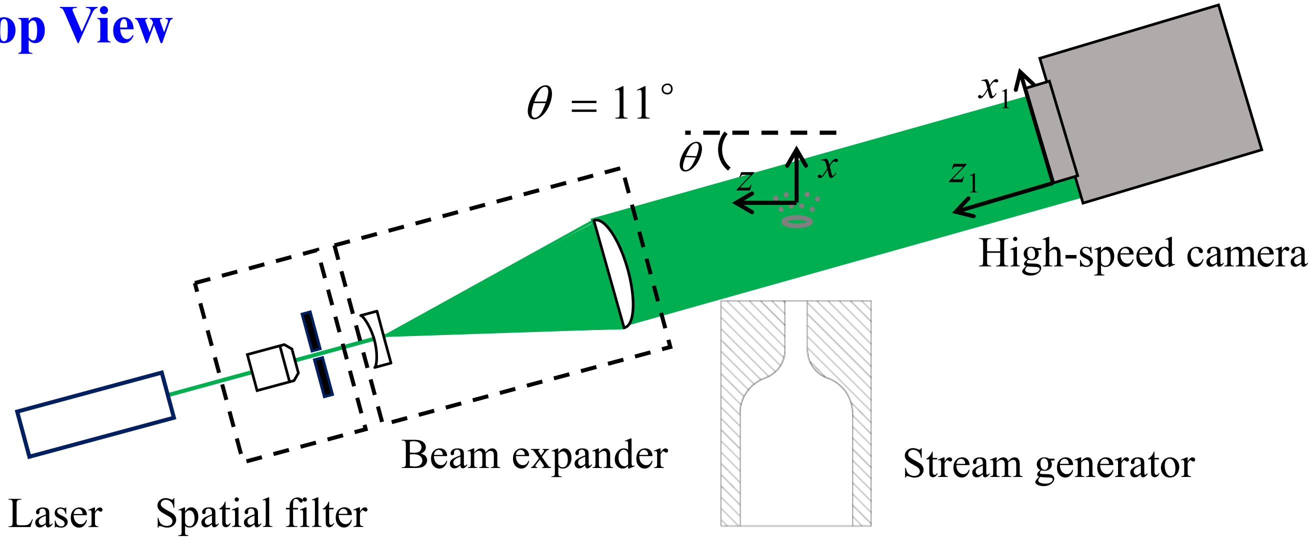
Experimental setup

Side View





Top View



- A tilted illumination to reduce overlap
- Use the bag burst point as start of time t_0 and origin of coordinates.

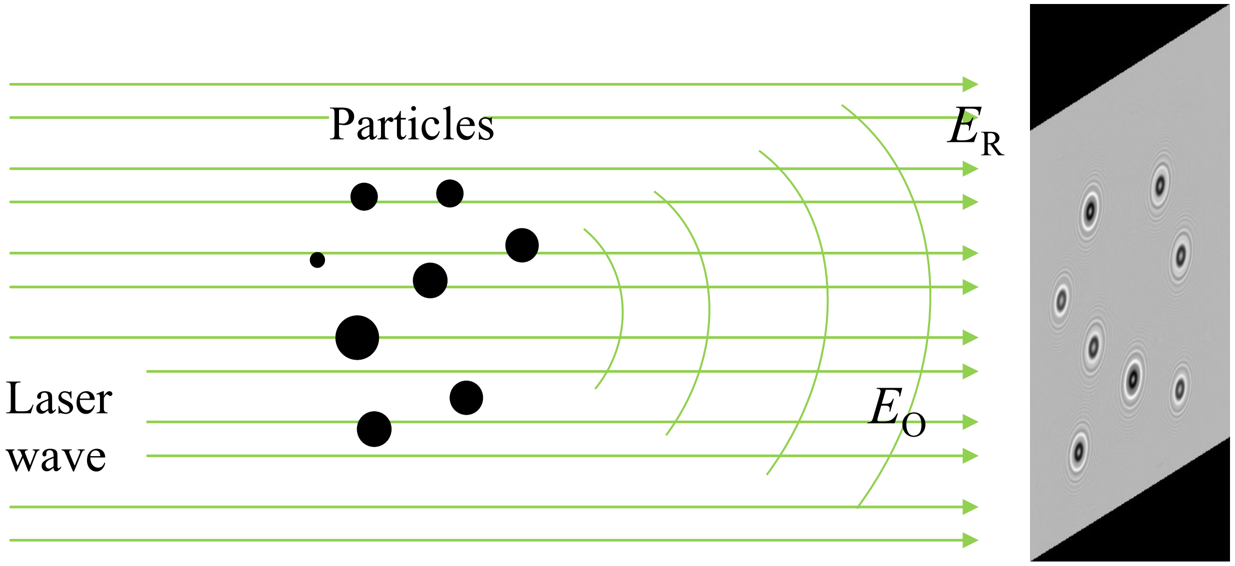
Frame rate: 20 kHz

Ethanol drop, $\sigma = 0.0244$N/m,

$\rho_a = 1.177$kg/m^3, $d_0 = 2.34 \pm 0.02$mm

$We = 11$, bag breakup, $We = 25$ for multi-mode breakup in experiments

Method: Digital in-line holography (DIH)

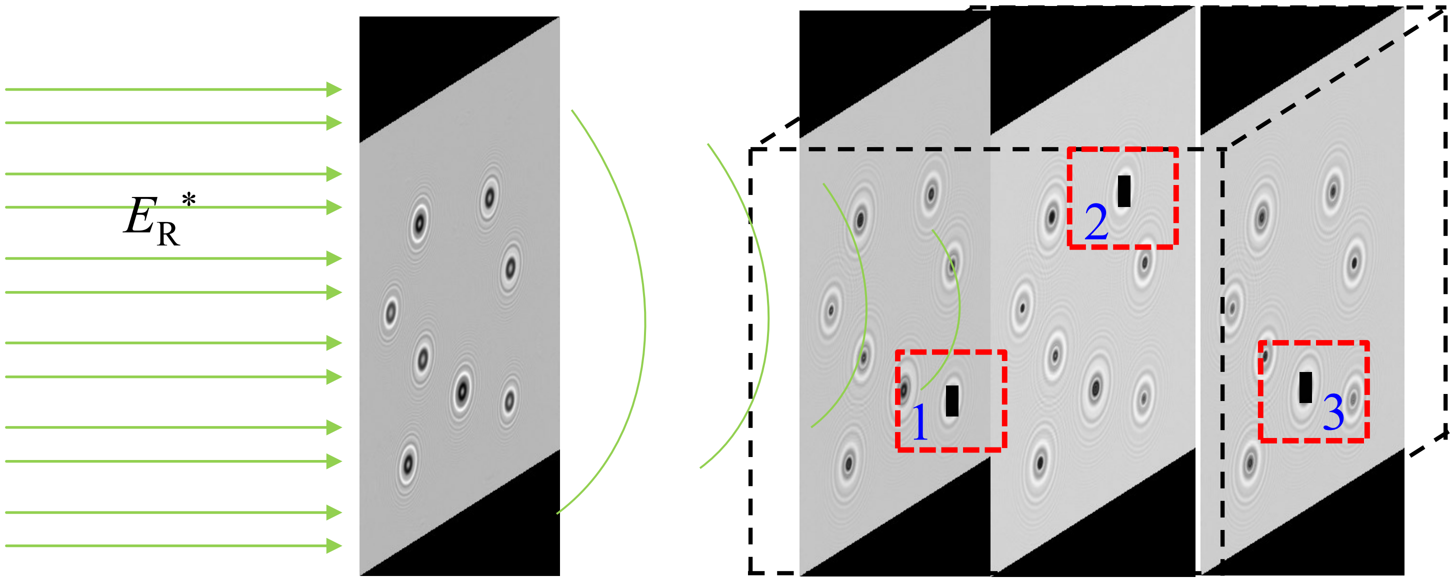


Recording

$$I_H = |E_O + E_R|^2 = I_O + I_R + E_O E_R^* + E_O^* E_R$$

E_O is object wave that is scattered by particles (at the recording plane)

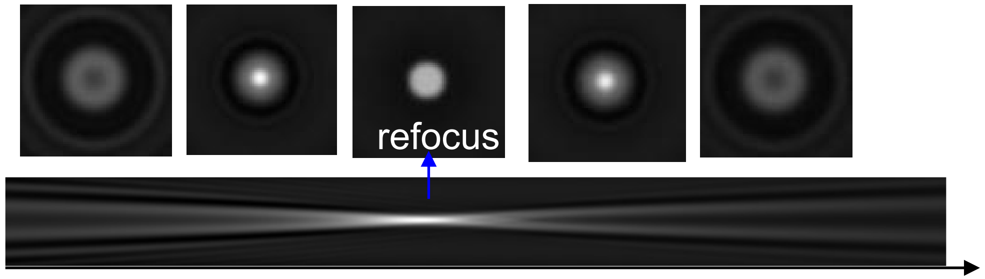
$E_R = 1$ is undisturbed reference wave



Reconstruction

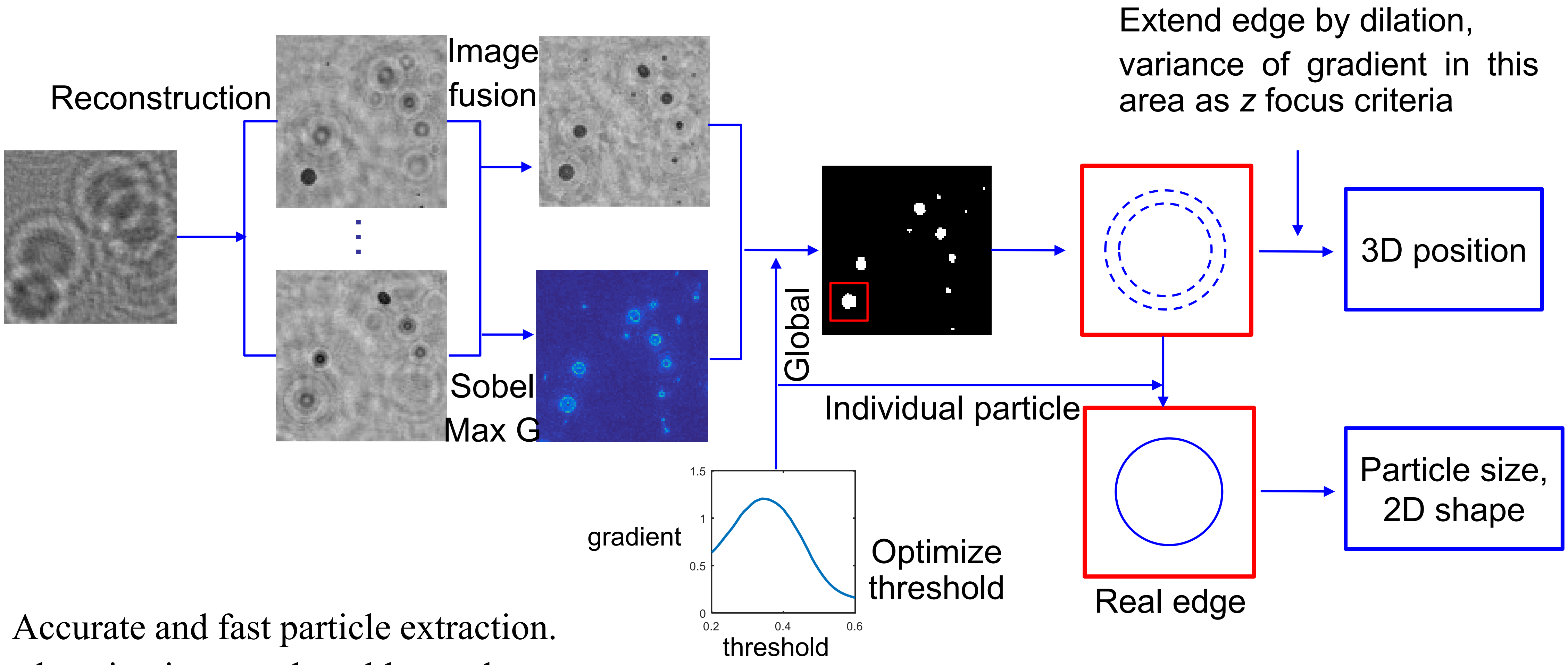
$$E_R^* I_H = E_R^* I_O + E_R^* I_R + E_O E_R^* E_R^* + E_O^* I_R$$

DC term: $E_R^* I_O + E_R^* I_R$; virtual image: $E_O E_R^* E_R^*$; real image: $E_O^* I_R$



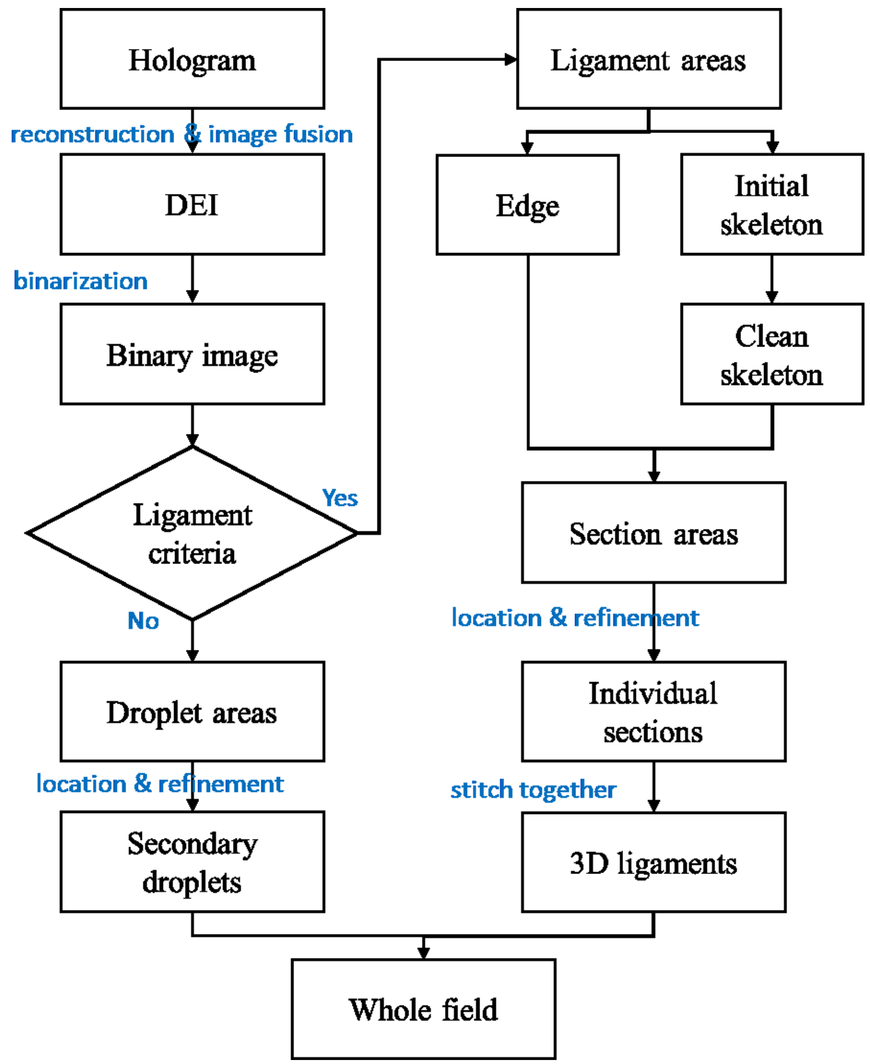
Back propagation along depth position (z)

Method: Particle extraction

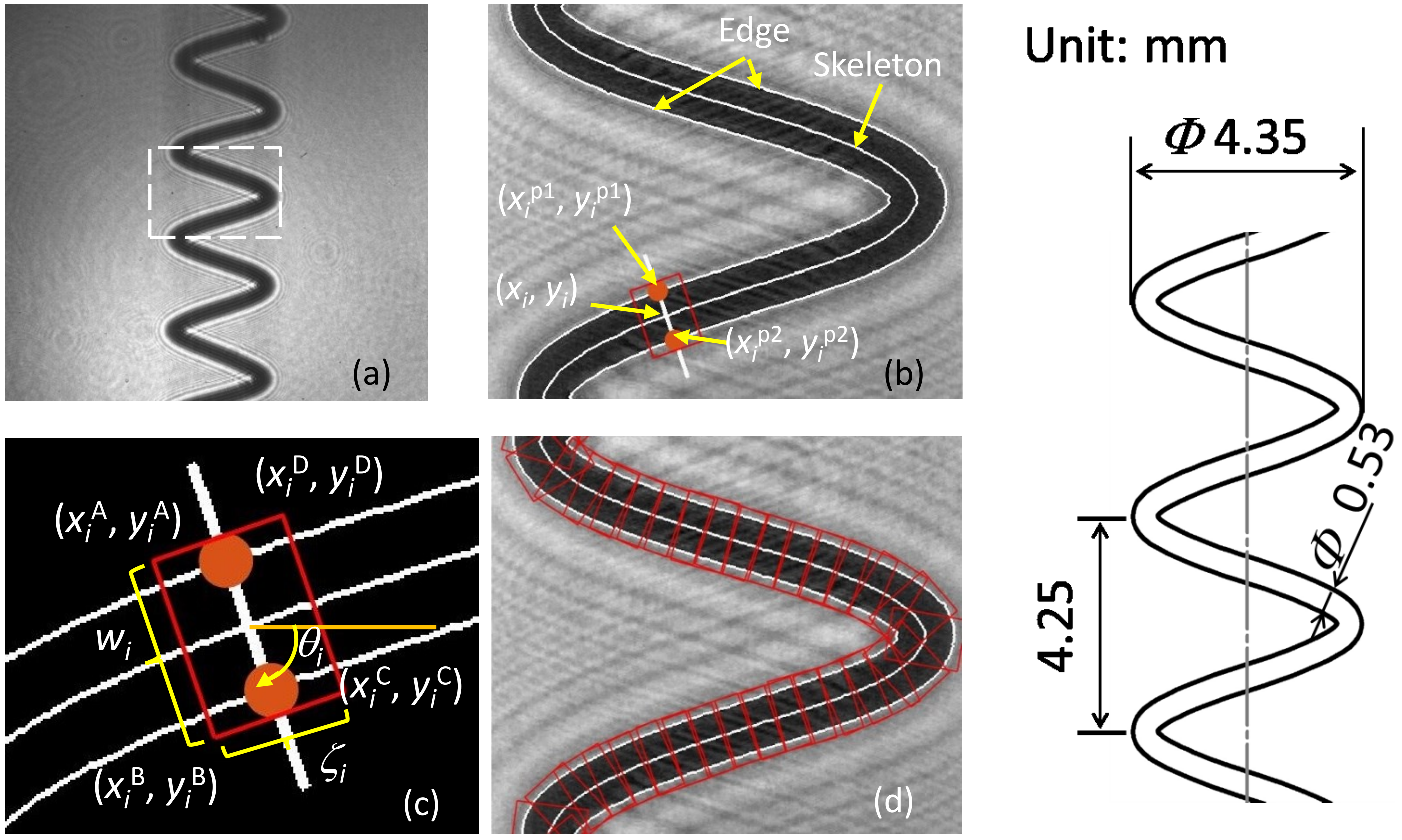


- Accurate and fast particle extraction.
- *z* location is not vulnerable to edge errors.

Method: Ligament extraction



Steps to extract ligaments and fragments

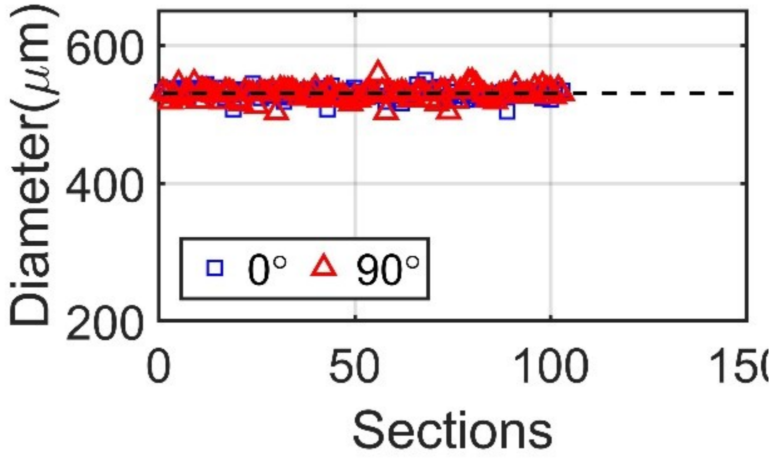


Helical spring demonstration

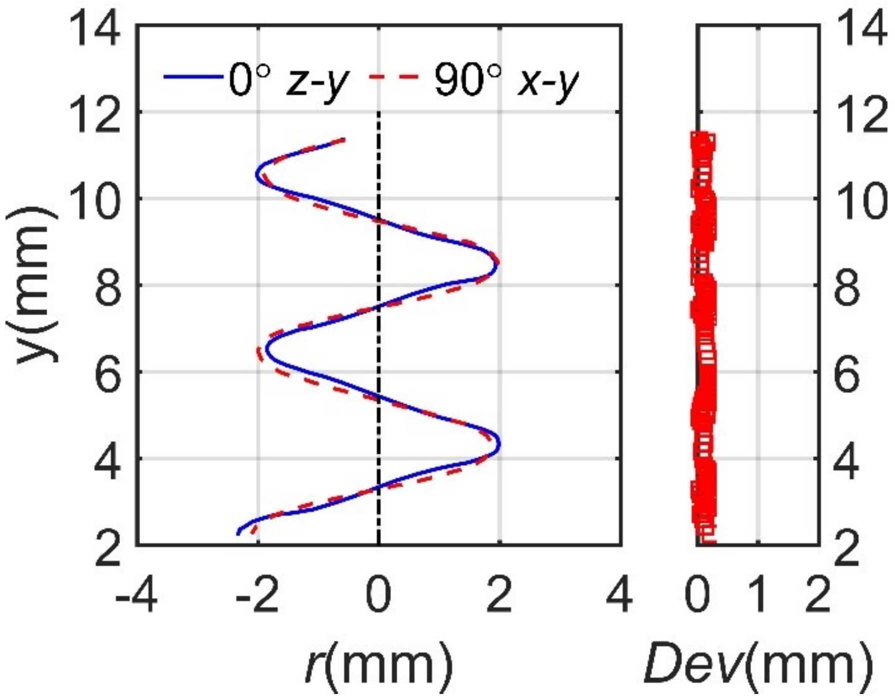
- Obtain edge and skeleton
- Determine local section in the red box
- Locate z position of local section as an individual particle
- Stitch local sections to be an entire ligament

Results: Calibration

Spring calibration



Diameter uncertainty

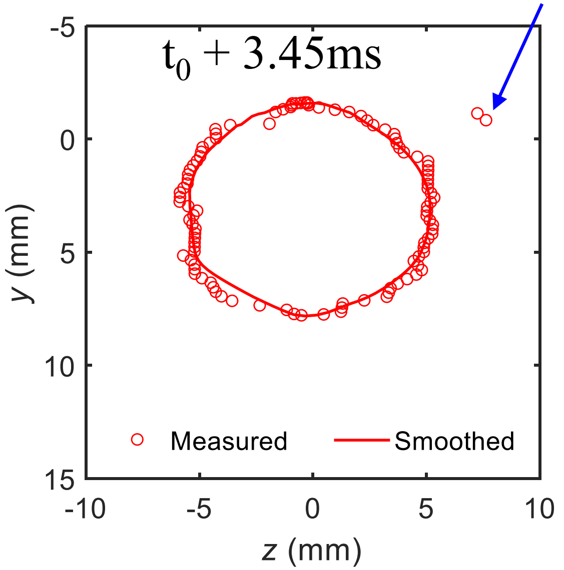


z position uncertainty

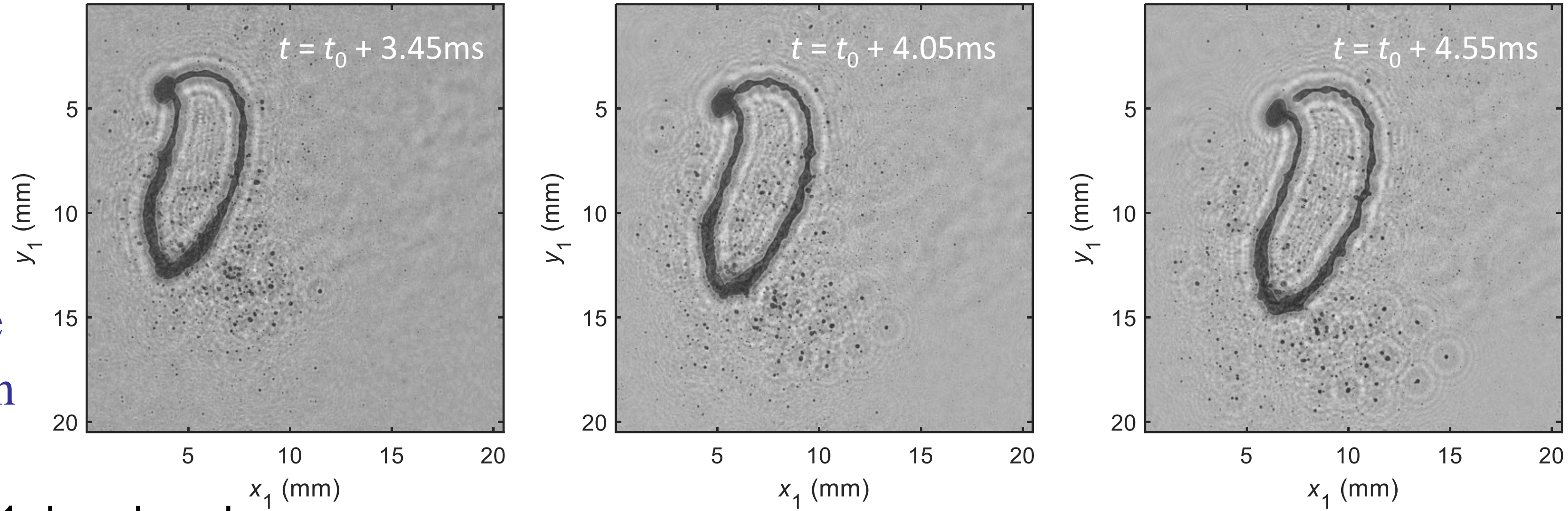
- Diameter error is about ±1 pixel
- Raw z location error is about ±10 pixel
- Robust local linear regression is applied to smooth the z position and remove outlier.

Results: Ligament extraction

Removed outliers

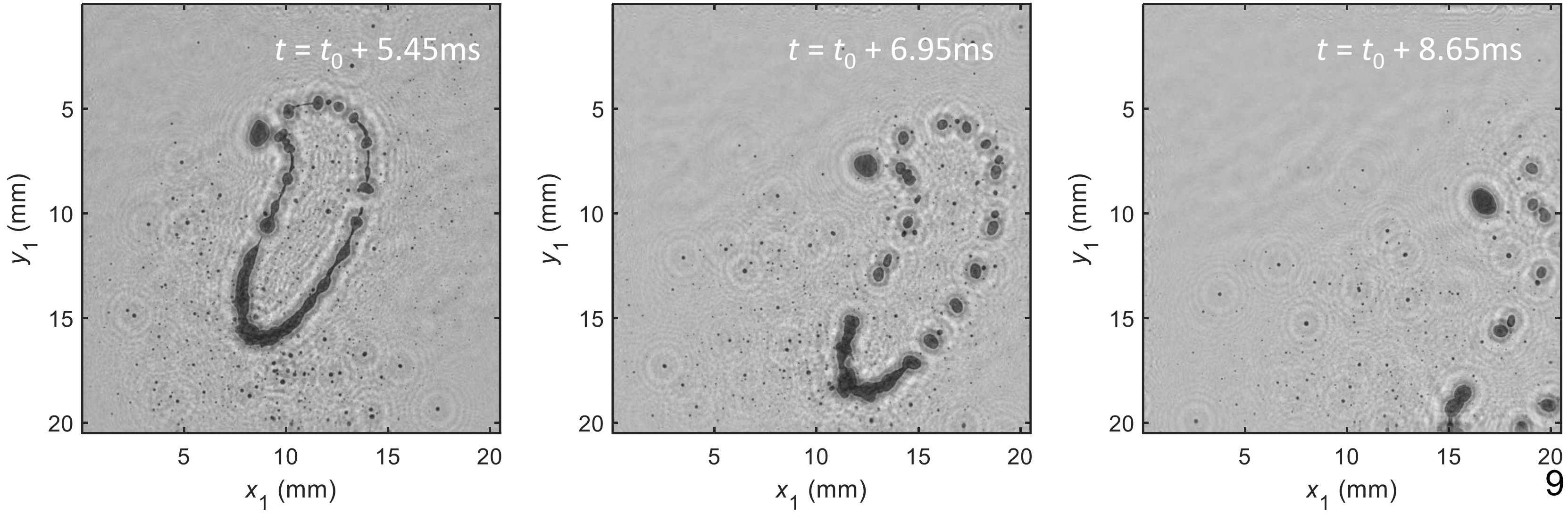


Accurate
z location



We = 11, bag breakup

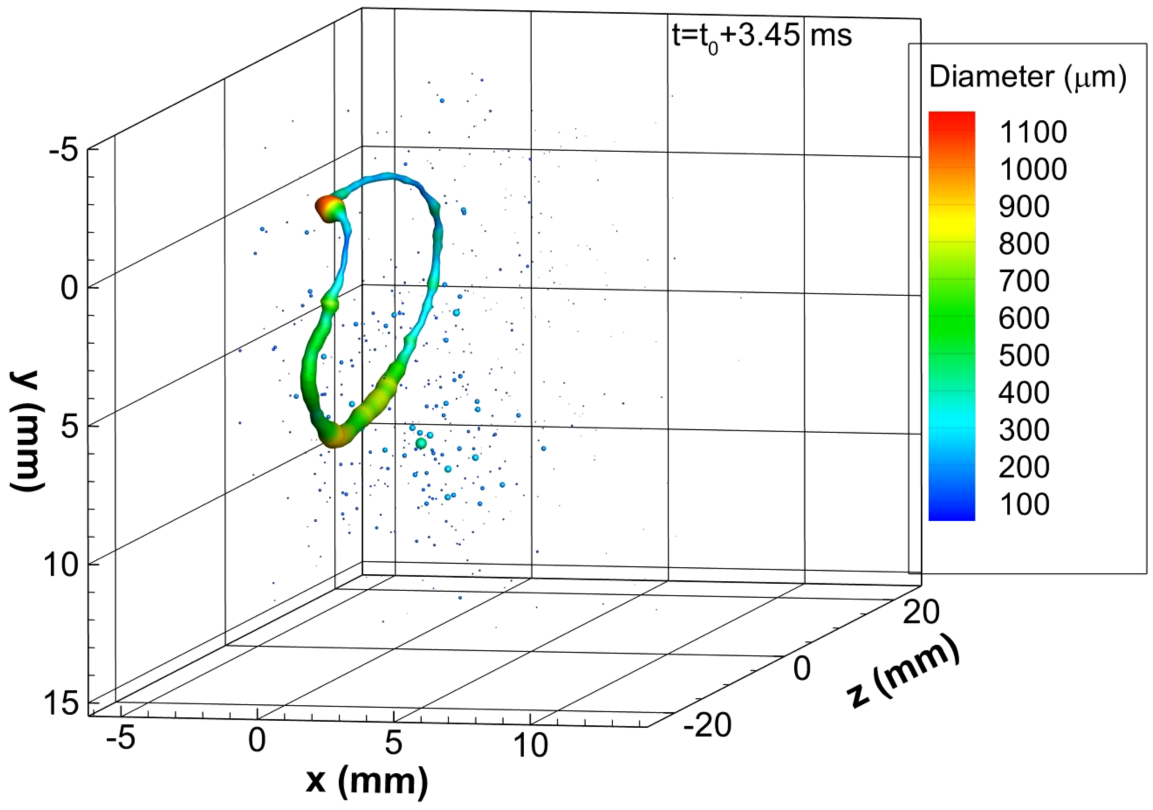
Depth-of-field extended images



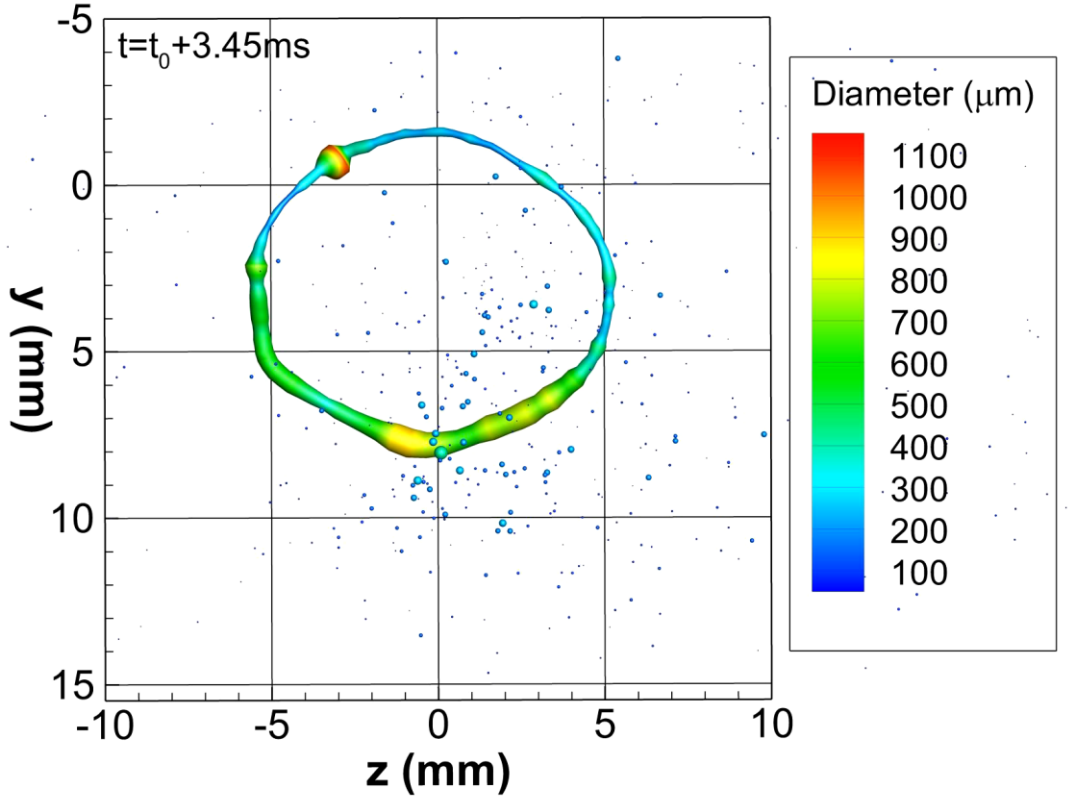
- Optimal threshold ensures accurate size
- z smoothness improves local z position accuracy
- Ligament evolution are obtained form sequential holograms

Results: Ligament evolution

Rim/ligaments are reconstructed and 3D visualized during 5ms after bag burst (15 selected frames)

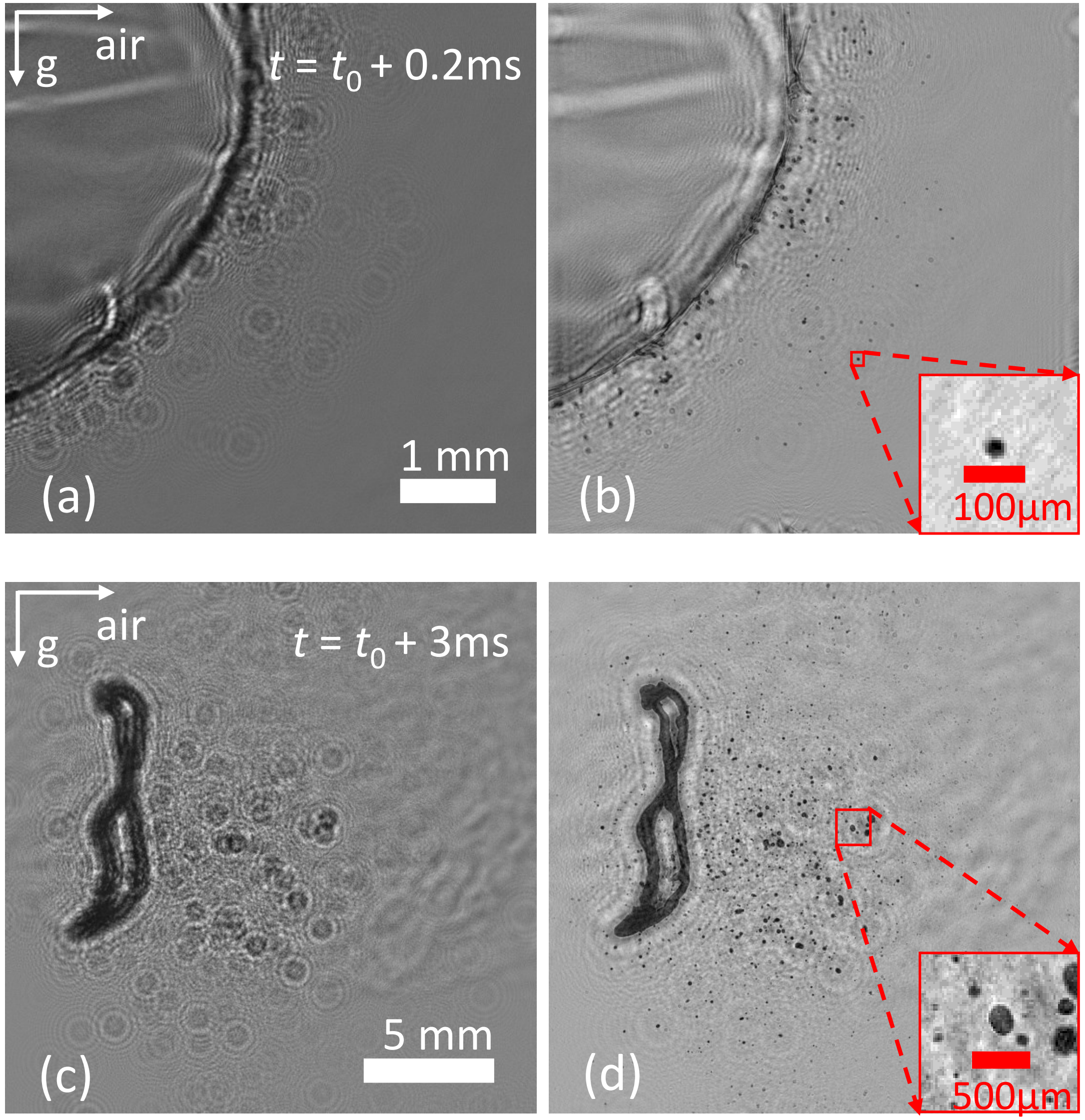


3D view (video)



z-*y* view (video)

Results: Fragment extraction



A magnifying lens is used for droplets at bag burst

Bag burst:

- Small droplets (< 30µm)
- 3.64X (5.5µm pixel size)
- Within ~0.5ms after tip burst.
- Higher velocity (up to 9m/s)

Bag fragmentation:

- Larger droplets (50-300µm)
- 1X (20µm pixel size)
- 0.5-4ms after tip burst.
- Lower velocity (< 5m/s)

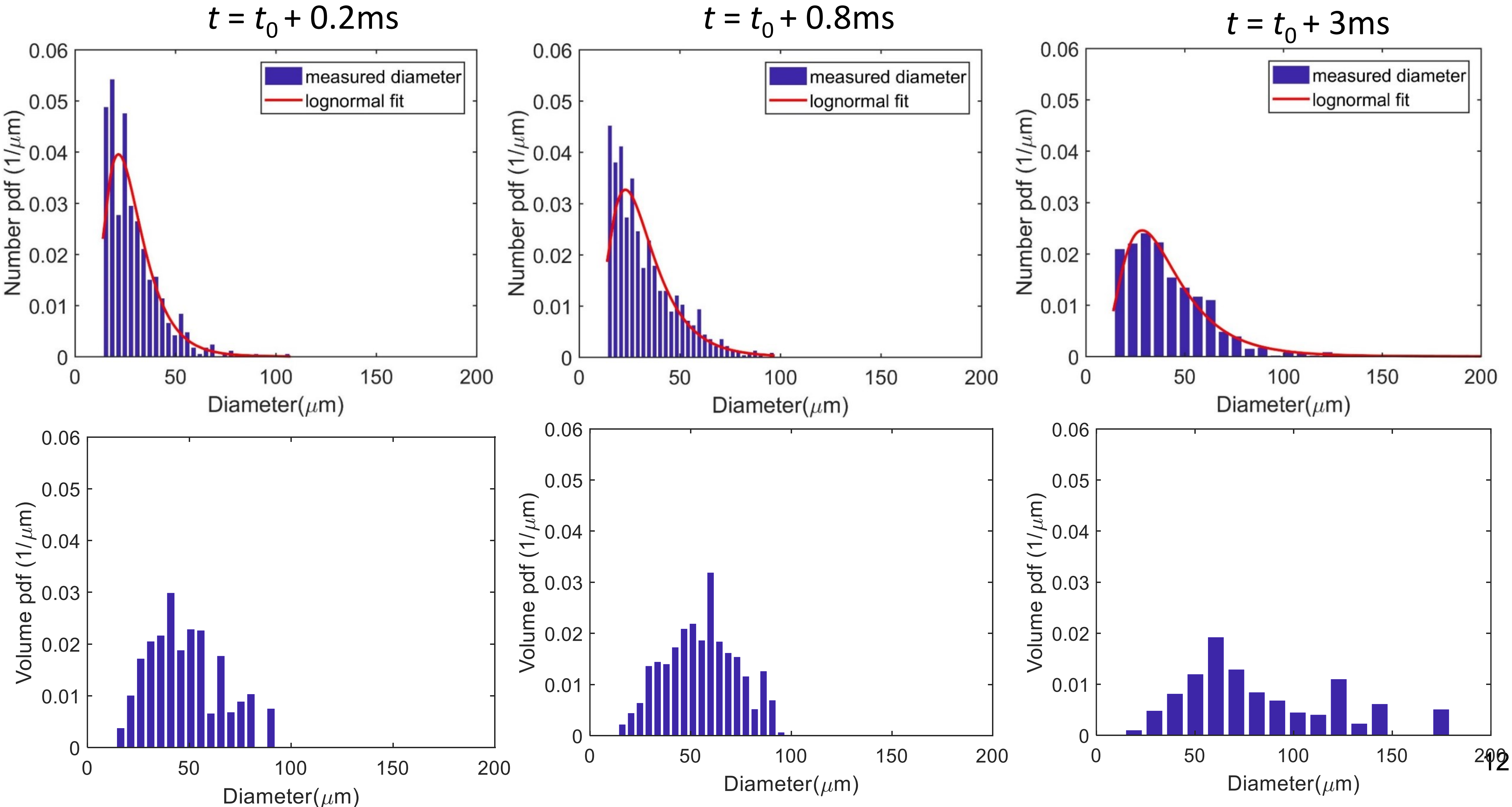
Rim breakup:

- Even larger droplets (may be >500µm)
- Not detailed in our study

Results: Fragment size

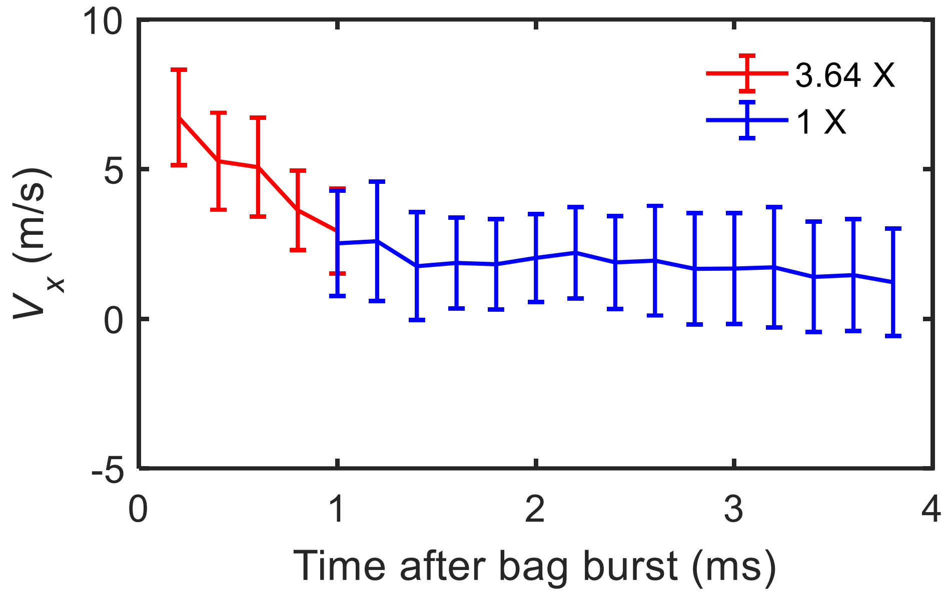
Number PDFs

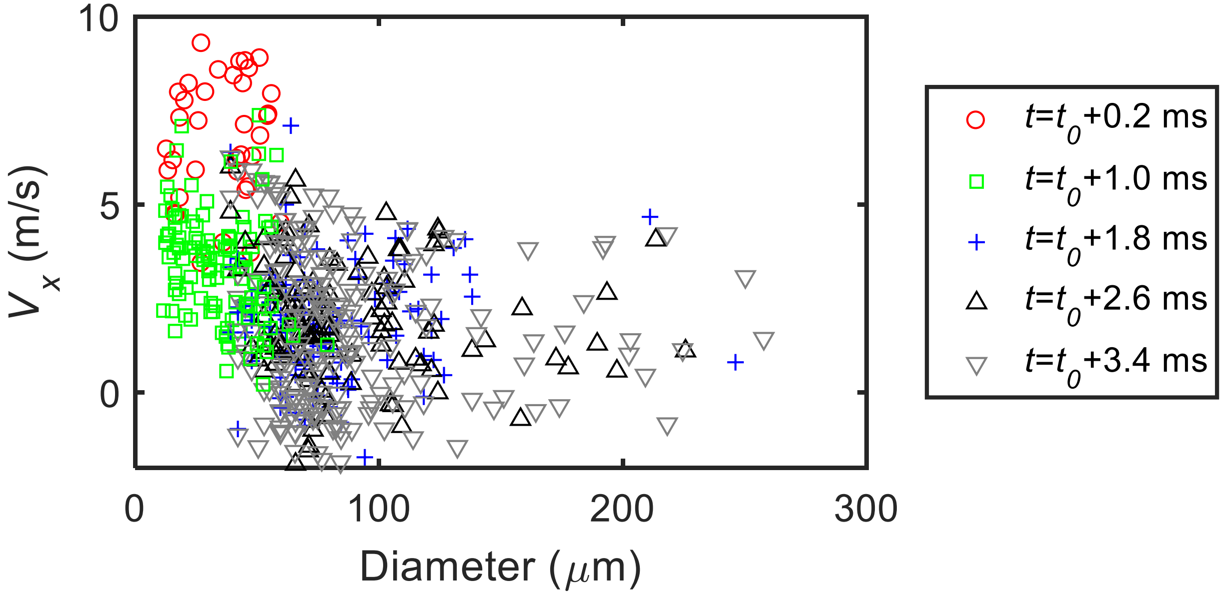
Volume PDFs

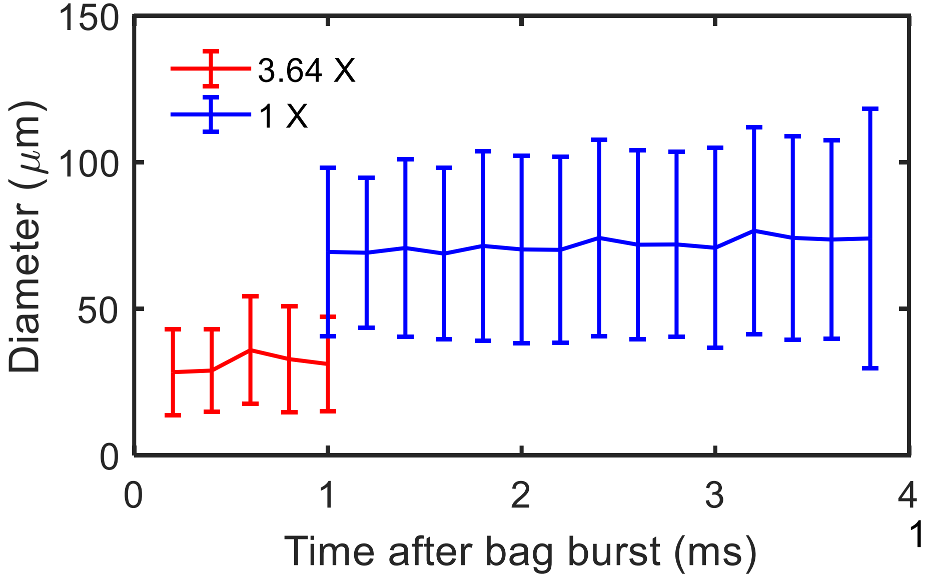


Results: Fragment evolution

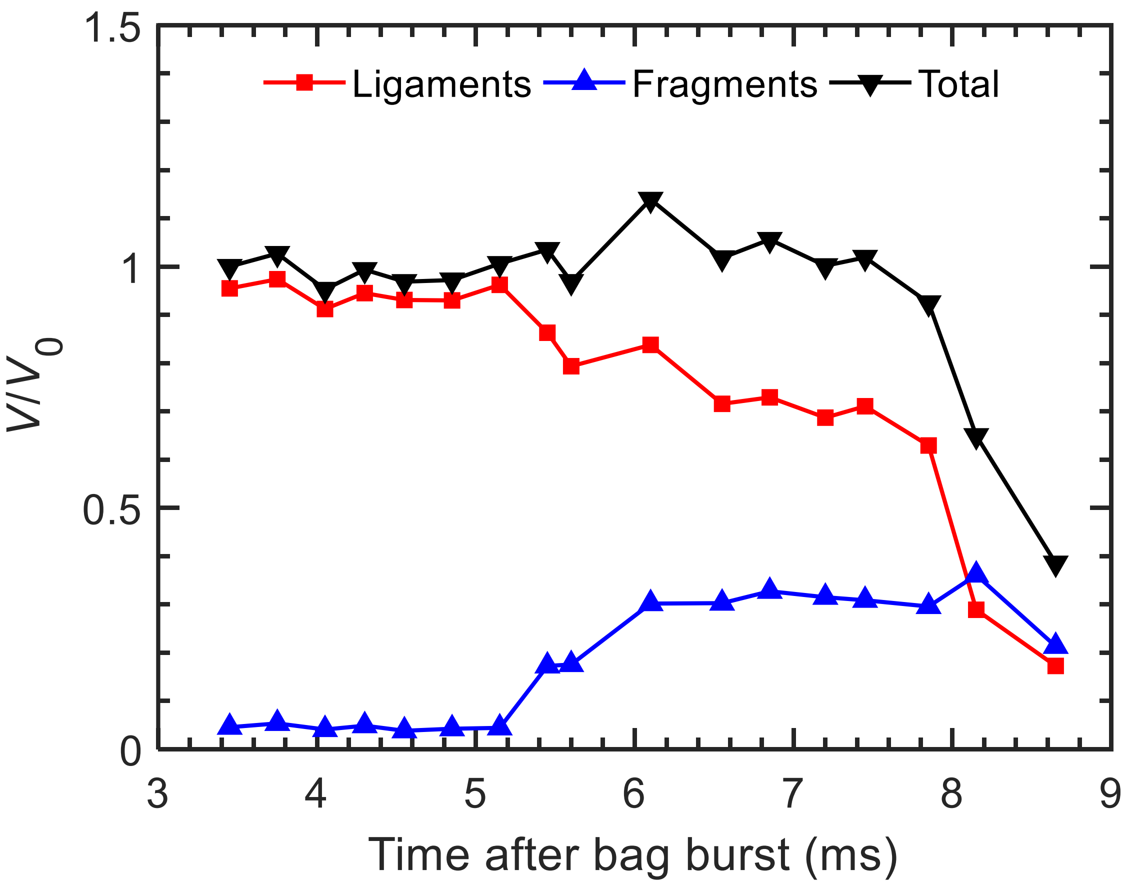
- Droplets move faster at bag burst, slower at bag fragmentation. Even negative velocities appear because of back propagation of the bag wall.
- Velocity shows strong relevance to time and weak relevance to diameter. The time span is too short for droplet acceleration with drag force. Initial velocity plays a more important role.
- Higher magnification is able to detect more smaller droplets but include less larger droplets. Lower magnification exclude droplets smaller than 50μm. Thus there is a diameter gap.





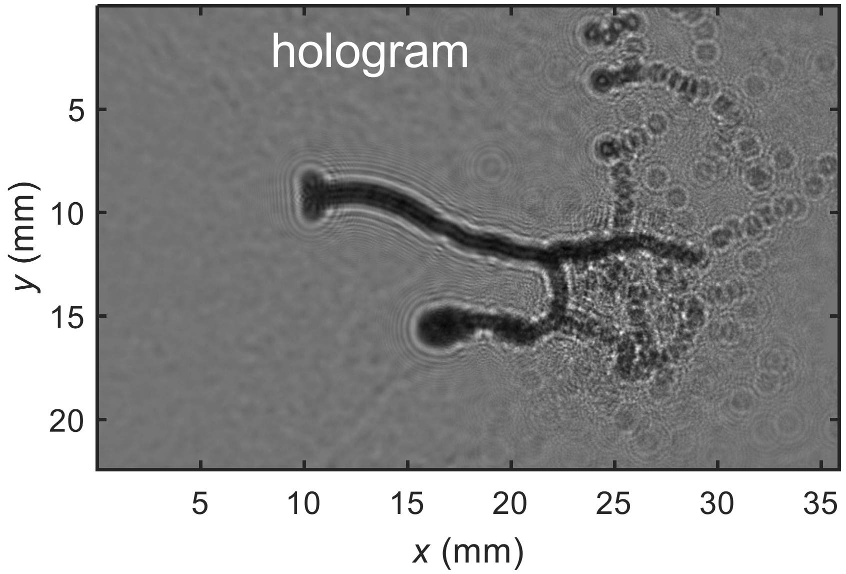


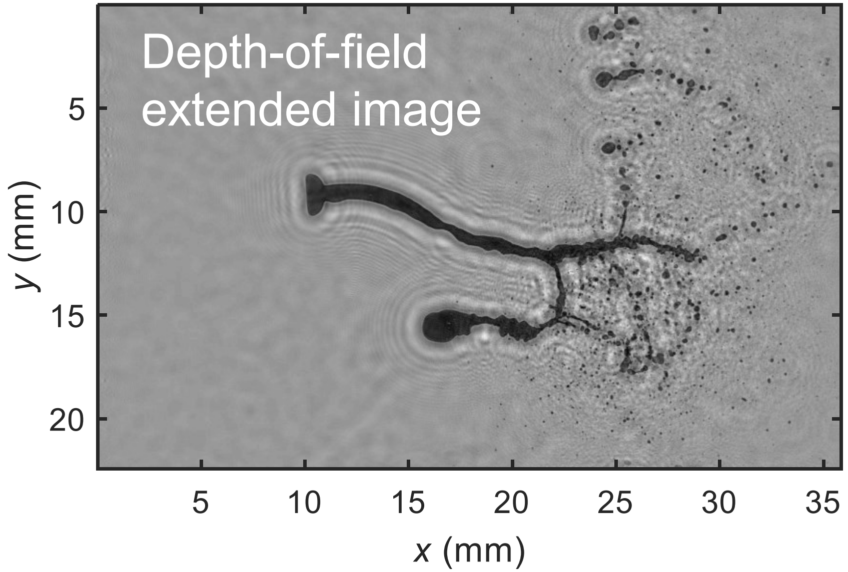
Results: Ligament-fragment volume



- Ligament and fragment volume is relatively stable before rim breakup.
- Rim/ligament volume transfers to fragments after rim breakup.
- Total volume of about the initial volume despite fluctuation caused by uncertainty

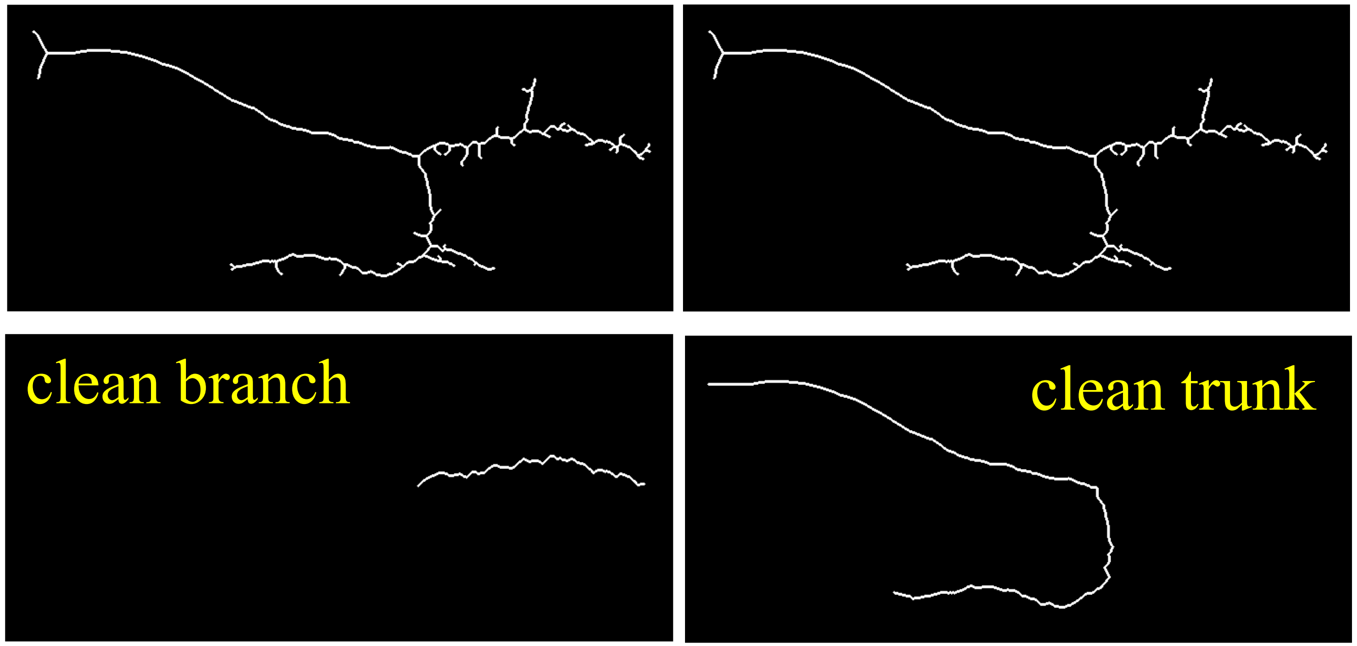
Results: Multi-branch ligaments





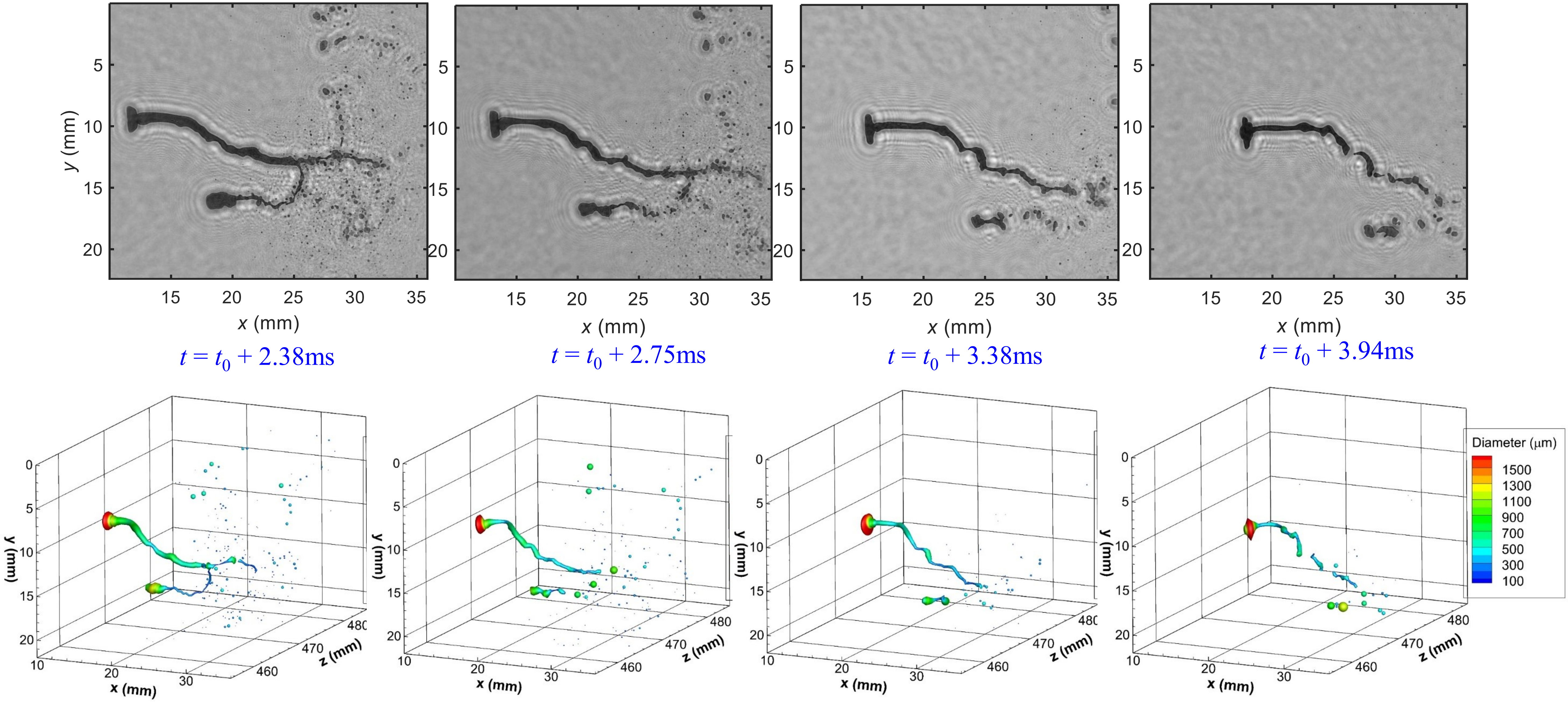
We = 25, Multi-mode breakup

- Ligament criteria: Major axis length > 2mm, aspect ratio > 5 or solidity < 0.5
- Remove the spurs
- Separate branches and save them
- Deal with each branch and stitch them together



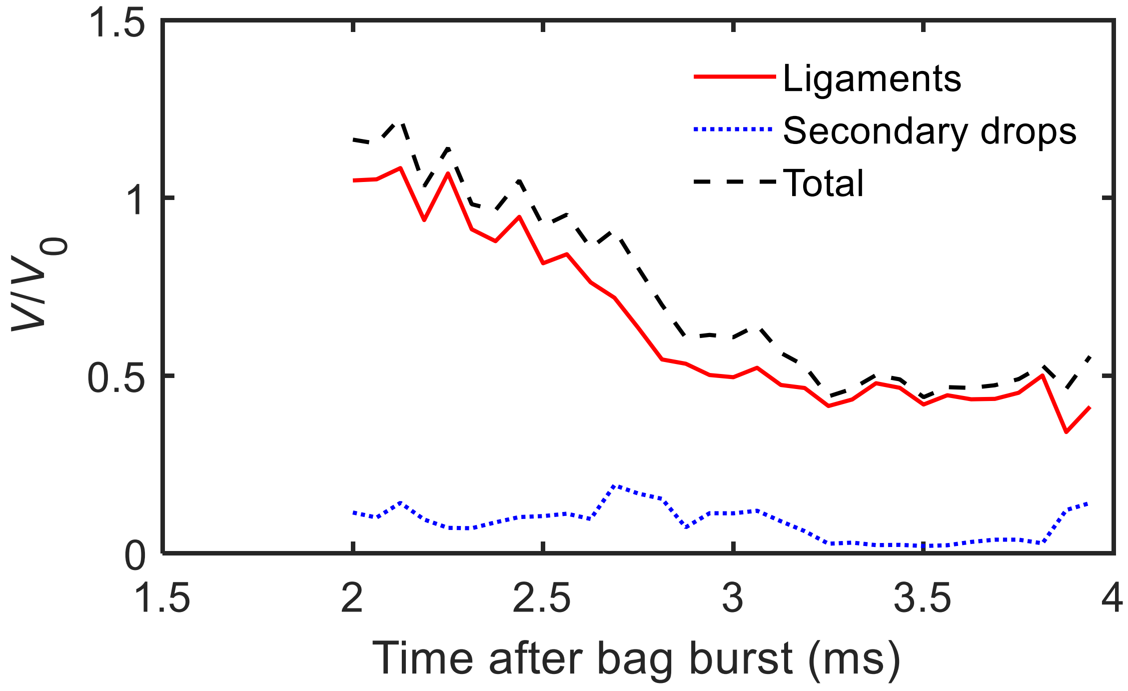
Measurement of multi-branch ligament is an improvement.

Results: Multi-branch ligaments



Results: Multi-branch ligaments

Volume evolution is studied from 32 frames during 1.94ms



Relatively large uncertainty (up to 17%) is probably due to

- Bag residues may be recognized as compact ligament
- Overlap problem
- 5% size error will lead to ~14.5% volume error

Conclusions

1. 3D morphology and evolution of rims and ligaments in bag and multi-mode breakup is measured using an automatic algorithm.
2. With a small tilted angle, overlap problem is to some extent avoided.
3. Time-resolved size and velocity of fragments are analyzed by using two magnification for different stages.
4. Volumes of rim/ligament and secondary droplets add up to nearly 100%, despite some fluctuation caused by measurement uncertainty.
5. Analytical work is expected to explain the interesting results (e.g. multi-modal size distribution and back-propagation of fragments) in the future.

Thank You for Your Attention!