
Metal powder production using supersonic injector with swirl

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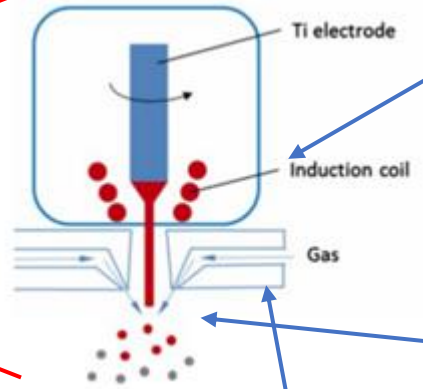
Jean-Pierre Bellot, IJL

Nicolas Rimbert, LEMTA

Electrode induction melting Inert Gas Atomisation



Atomization Tower



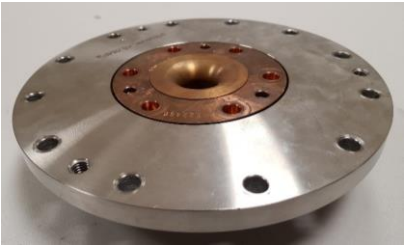
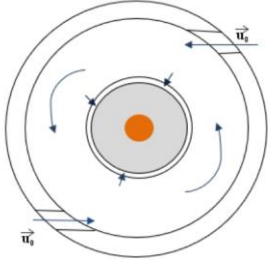
Contacless Induction Fusion



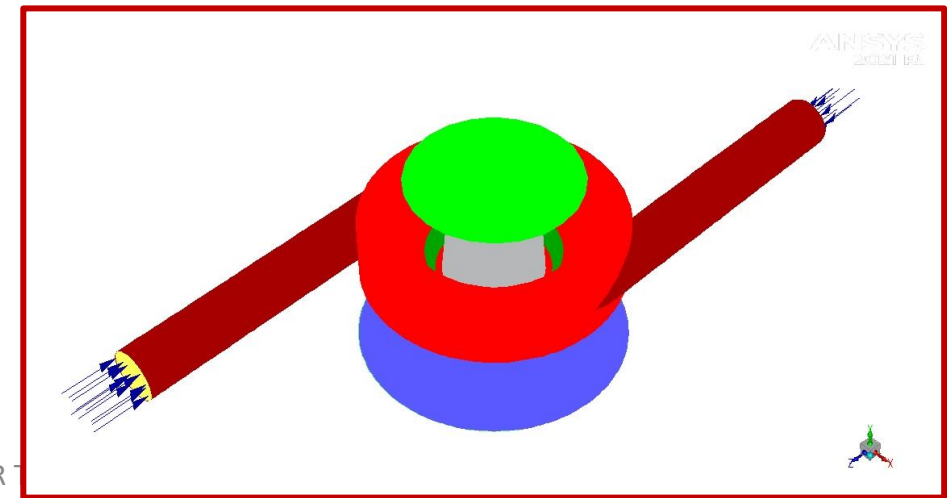
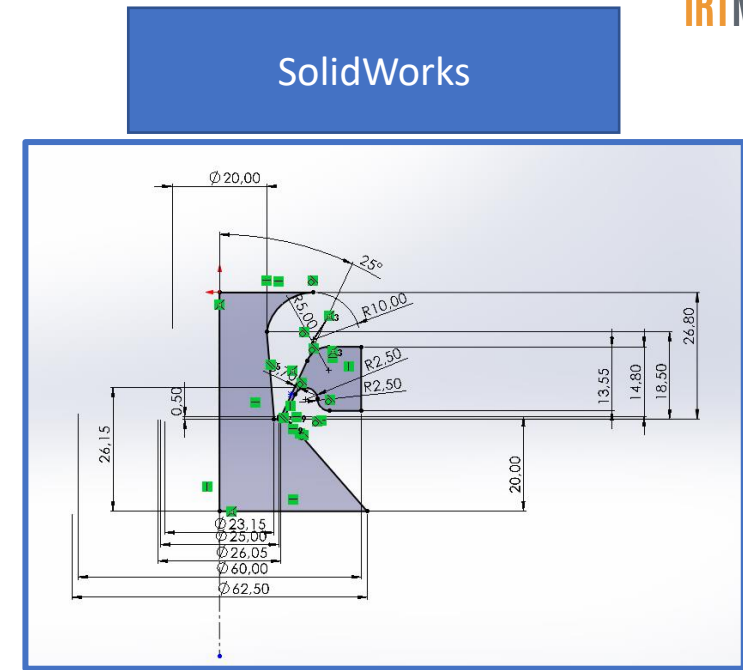
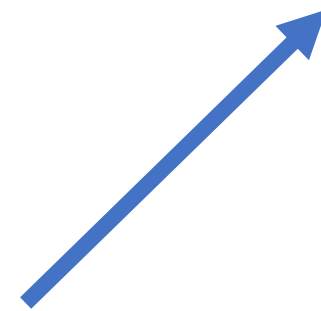
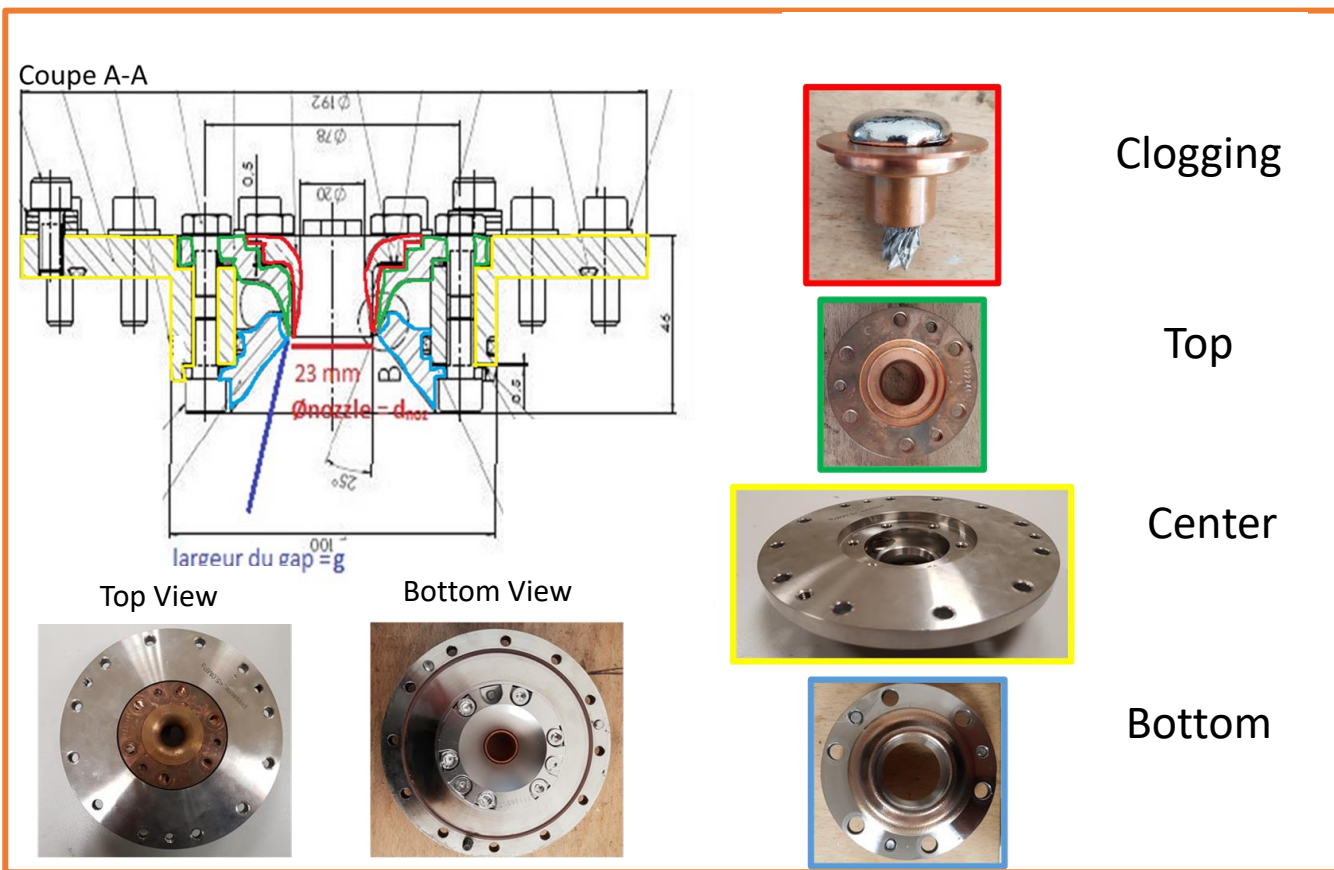
Parameters



Titanium Alloy

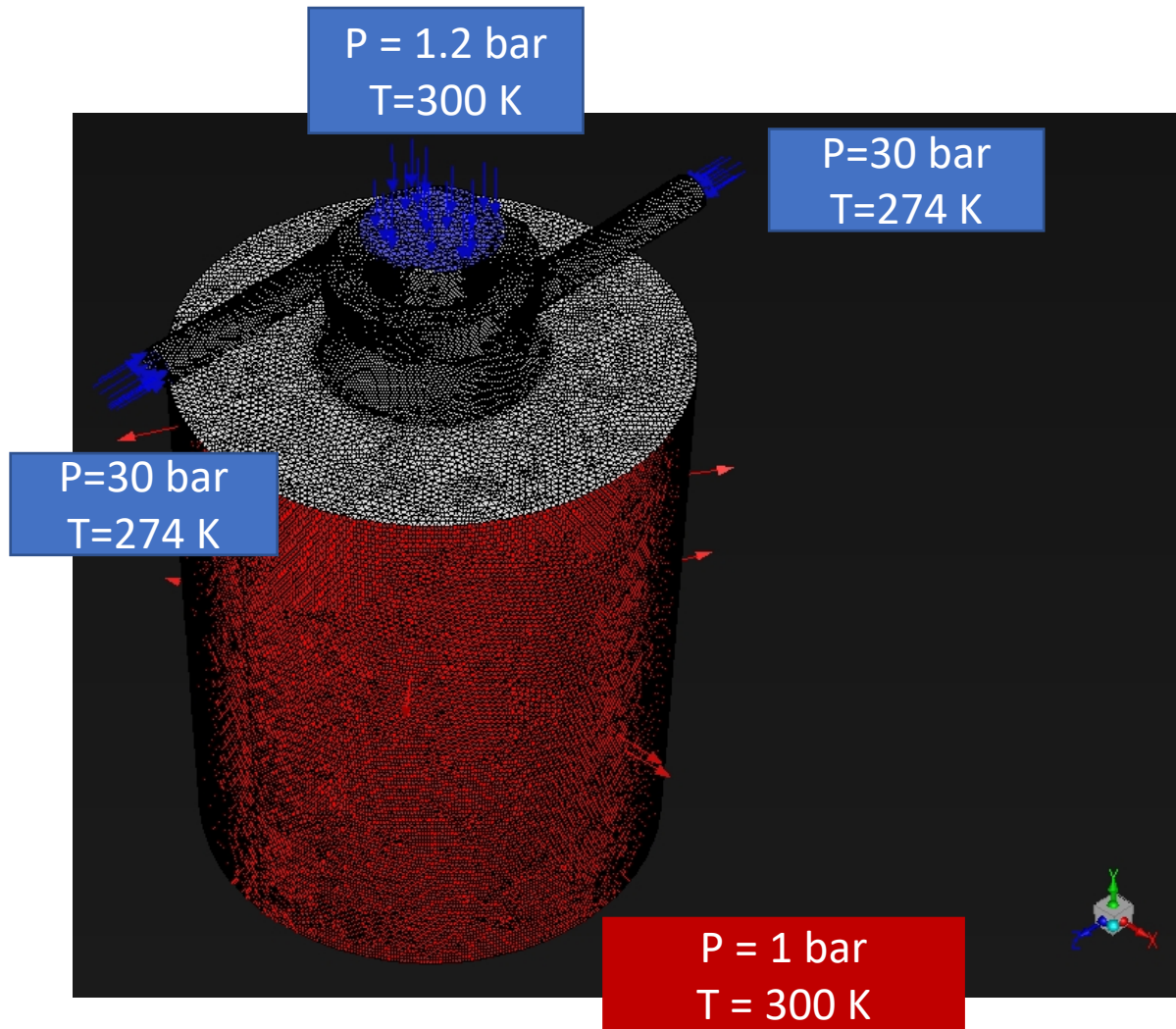


Computer Aided Design



B. Qaddah, P. Chapelle, JP Bellot, J. Jourdan, N. Rimbert, A. Deborde, R. Hammes, A. Franceschini
Swirling supersonic gas flow in an EIGA atomizer for metal powder production: numerical investigation and experimental validation **Journal of Materials Processing Tech.** 311, 117814 (2023)

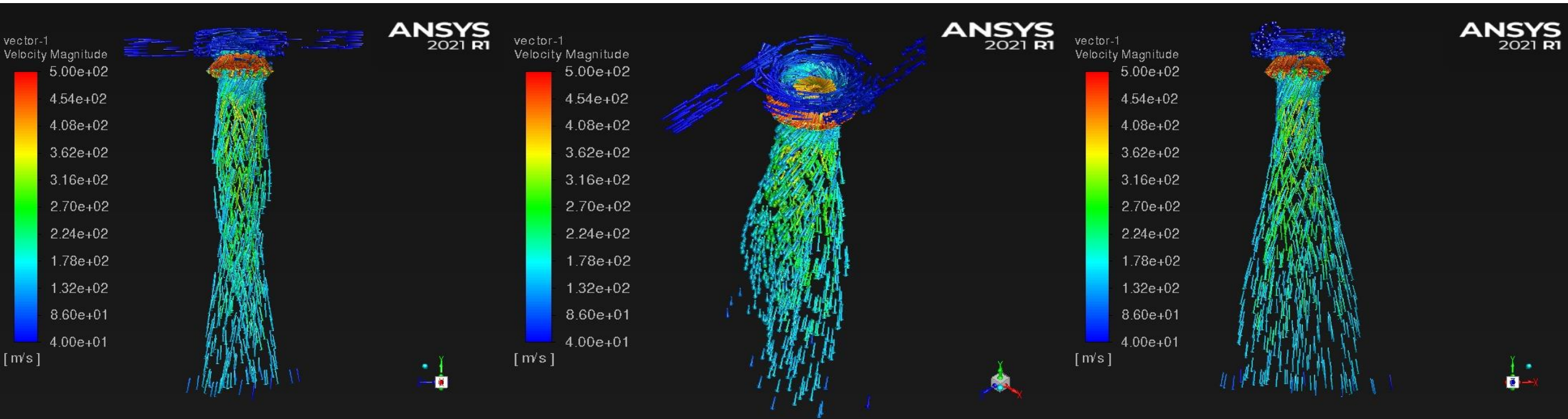
CFD: Meshing and Boundary Condition



- **ANSYS Fluent Configuration**

- $D_{\text{cylinder}} = 150 \text{ mm}$
- $H_{\text{cylinder}} = 200 \text{ mm}$
- Mesh number inside the nozzle
 - 1.12 millions cells
- Mesh number
 - 5.25 millions cells
- Gas = Argon
- Compressible Navier-Stokes equation (RANS)
- k-w SST turbulence model
- Steady State

Swirled Flow



YZ View

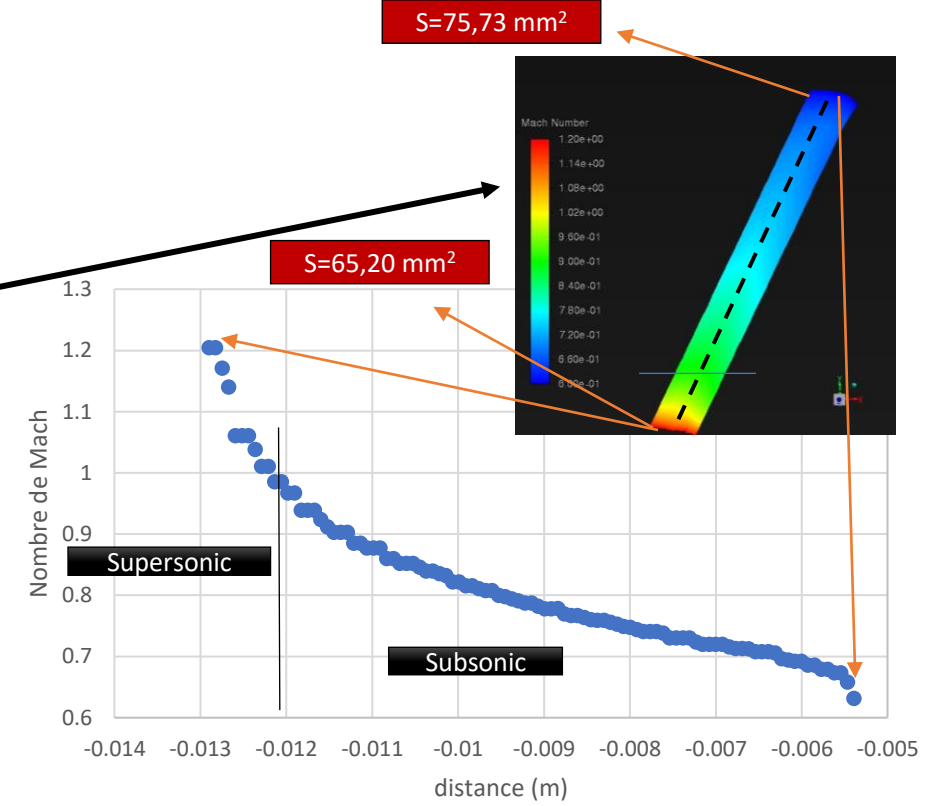
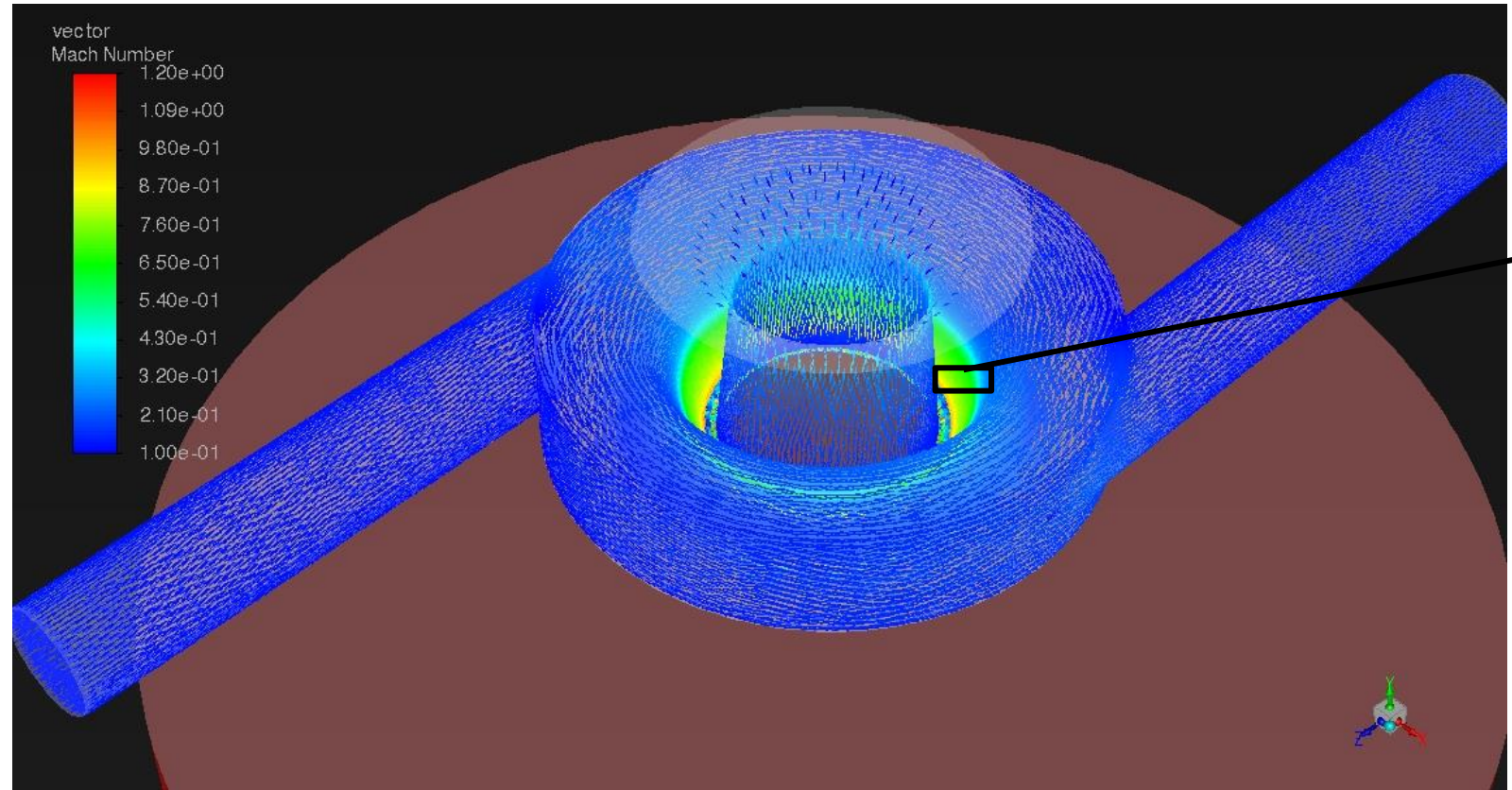
3D

XY View

Swirl number

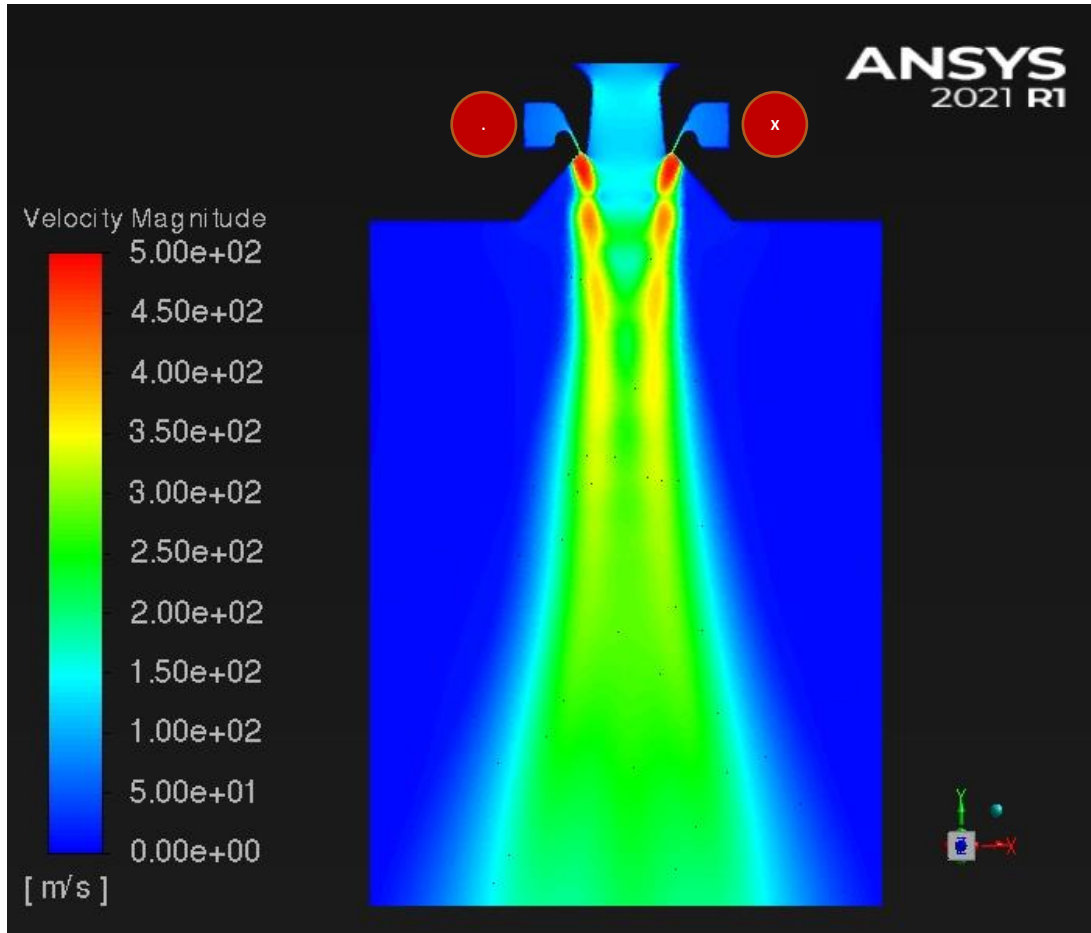
$$\omega = \frac{u_{tan}}{u_{ax}} = 0.34$$

Transition to Supersonic

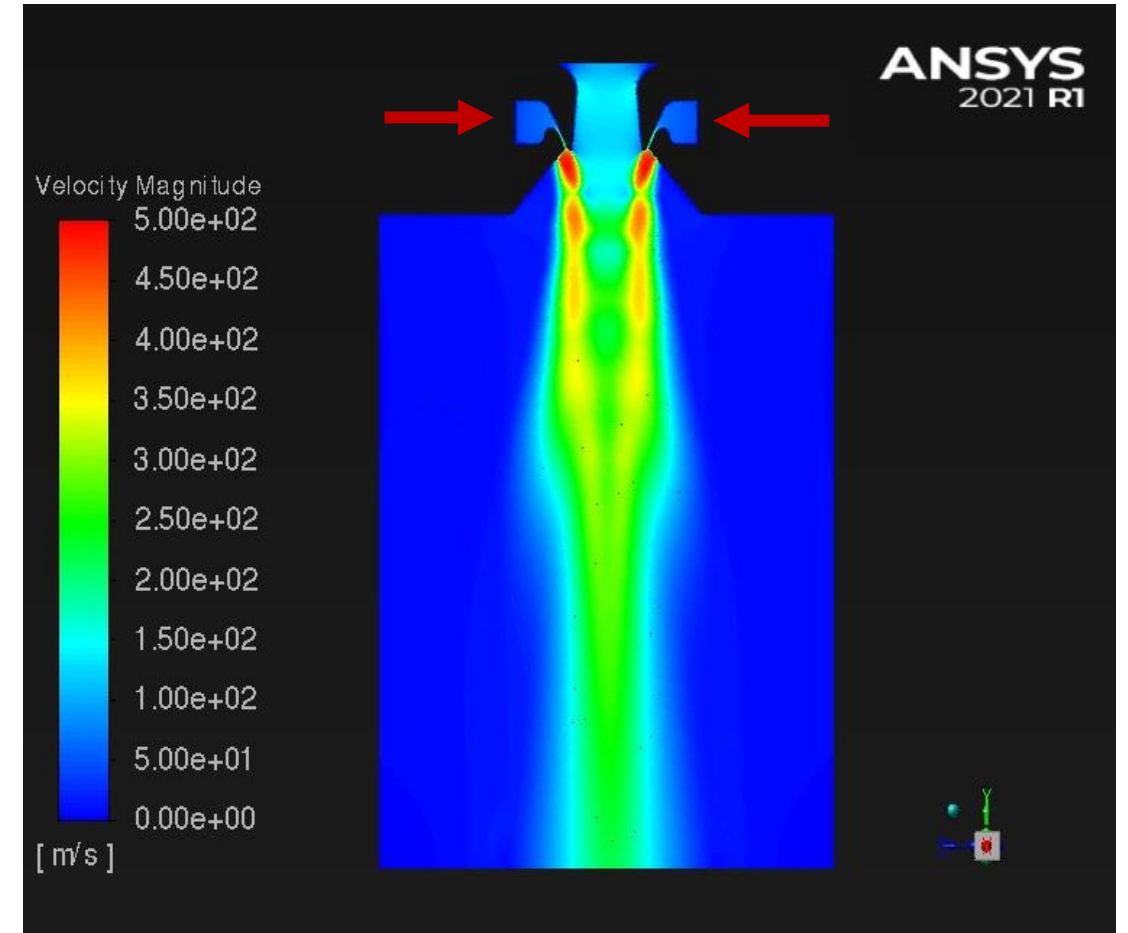


$$\text{Mach Number } M = \frac{U_g}{\sqrt{\gamma RT}}$$

Loss of Symmetry

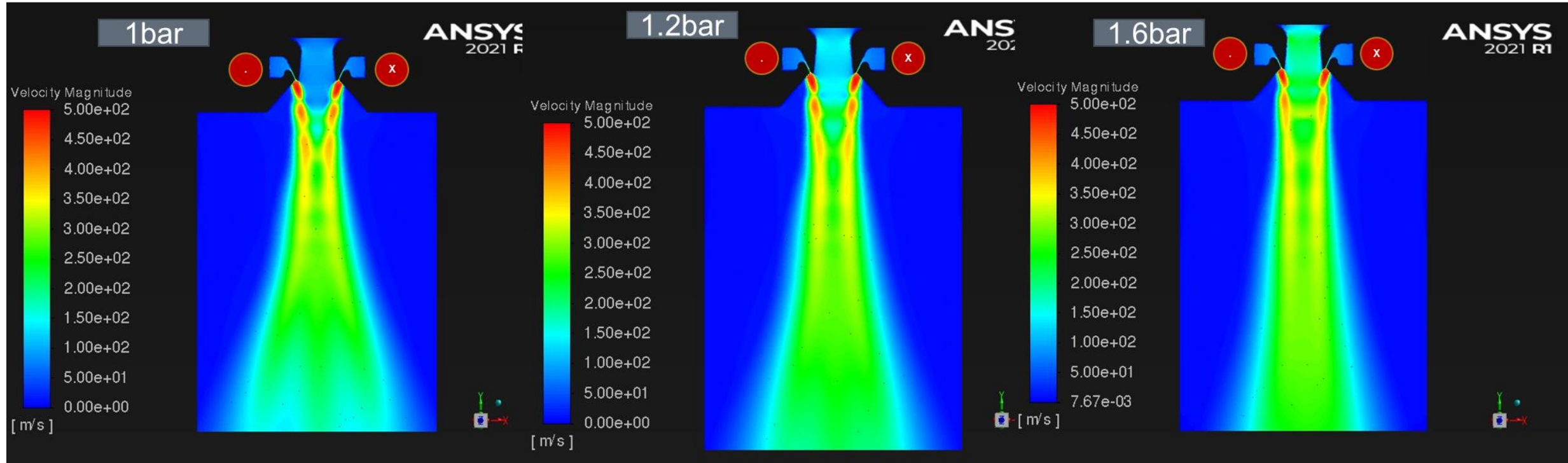


XY plane (Orthogonal to inlets)



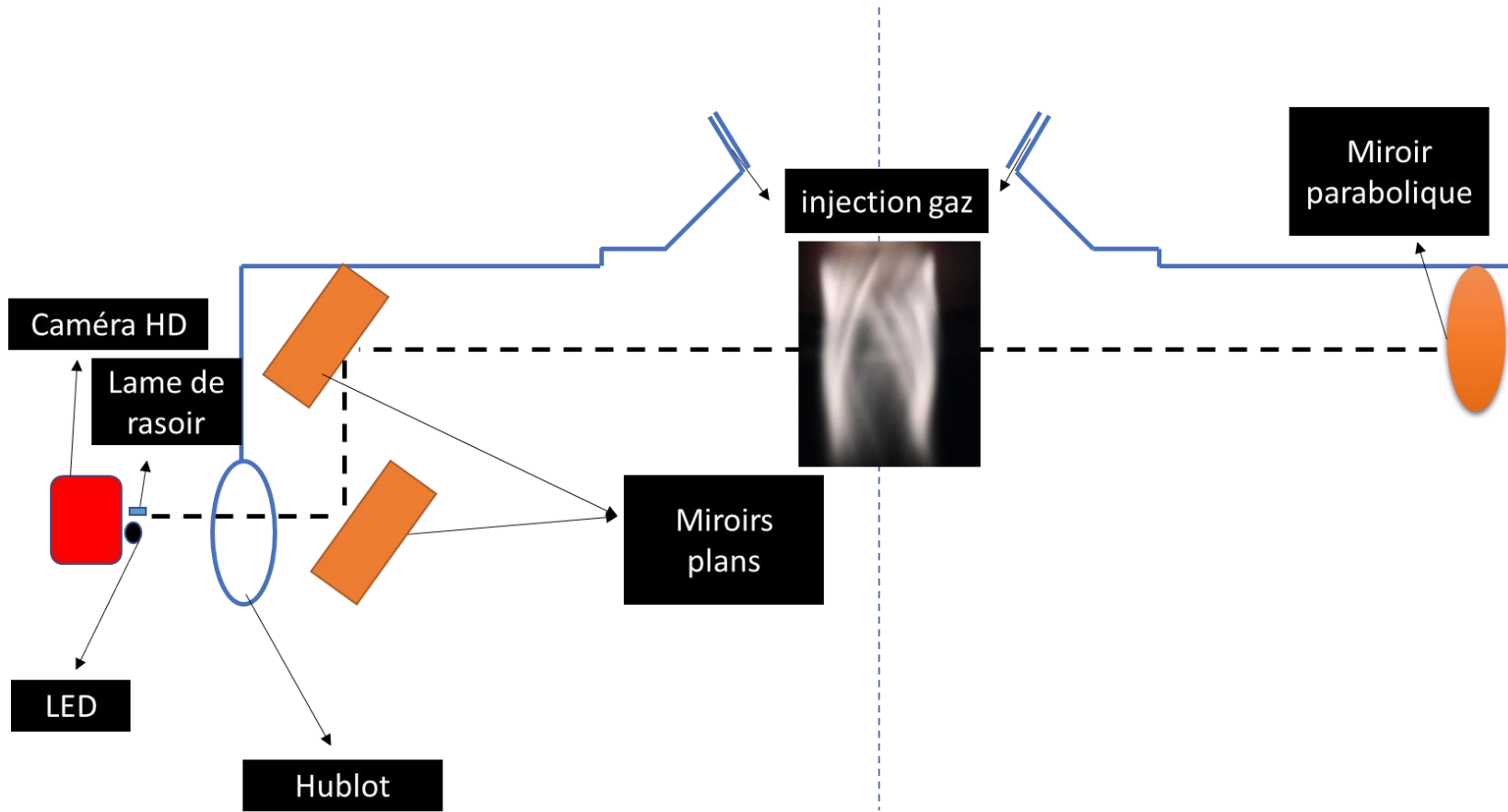
YZ plane (parallel to inlets)

Fusion Chamber Pressure Difference Influence



a.k.a. PDI

Schlieren SetUp



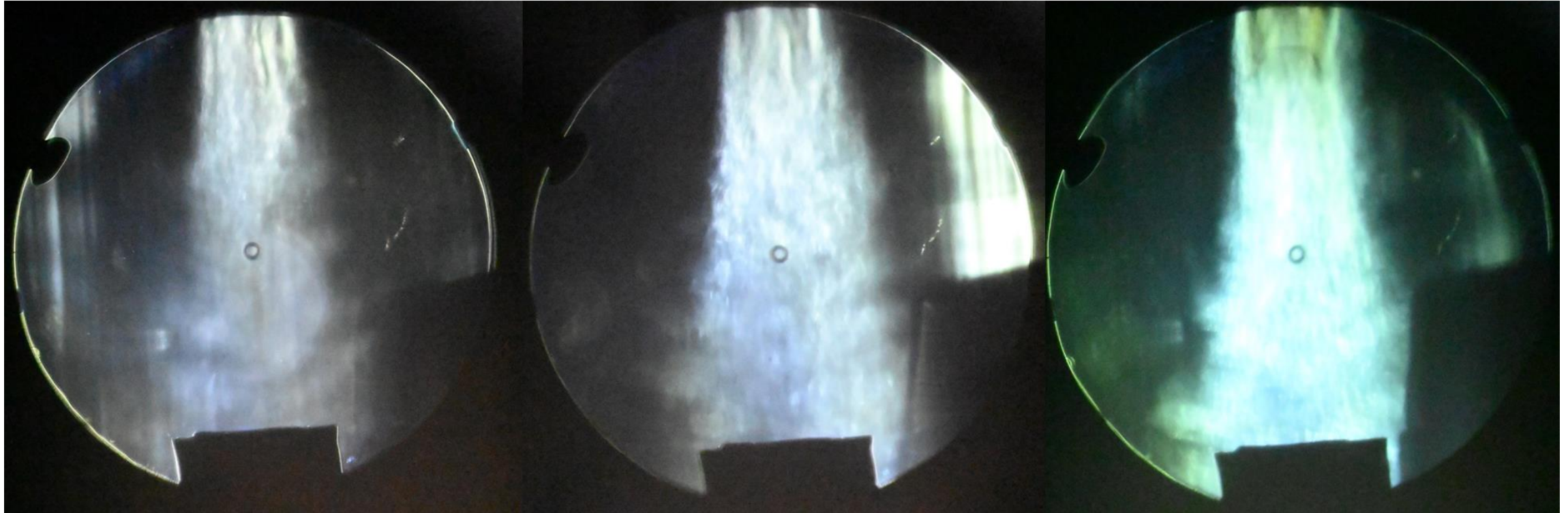
Installation expérimentale – vue du bas de la tour EIGA

Experimental Results

20 bar

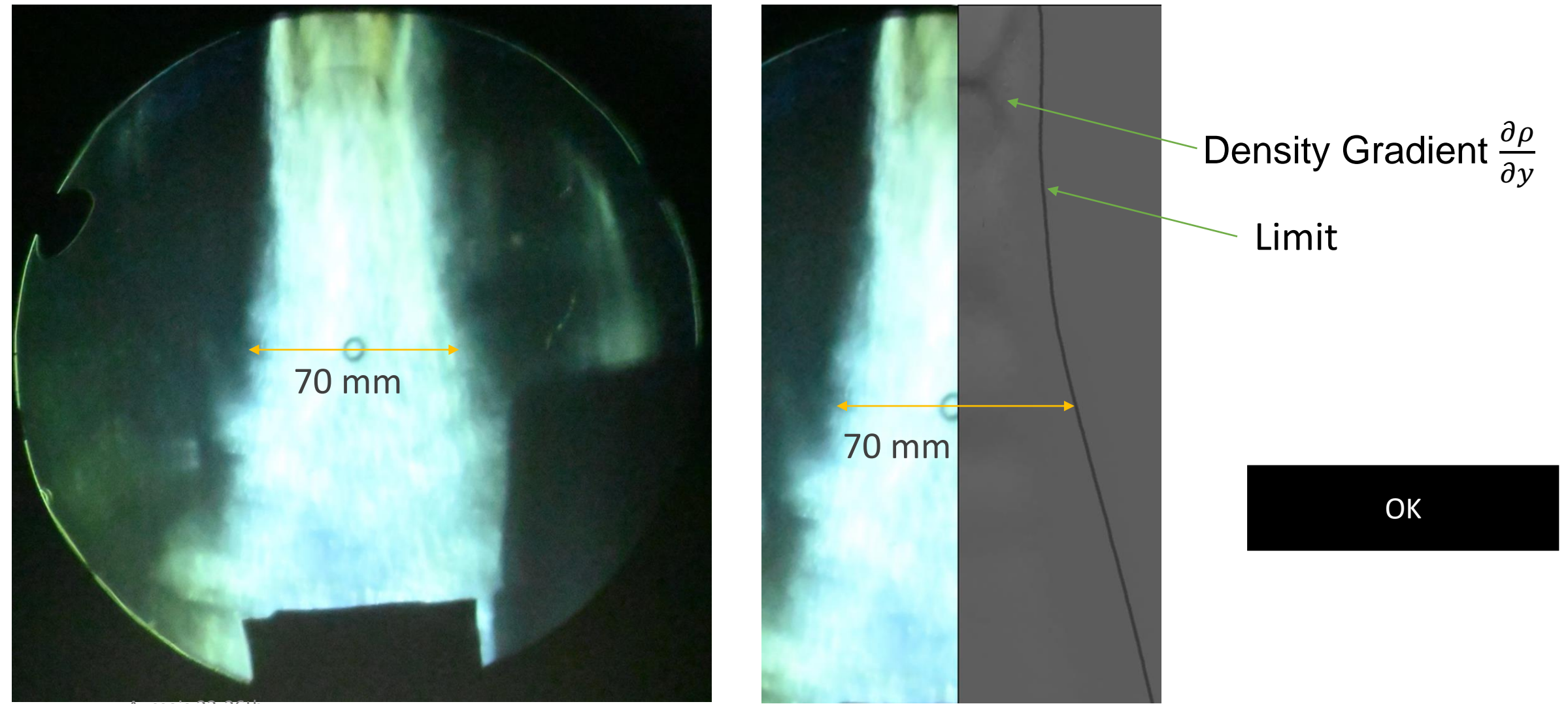
30 bar

45 bar



Vibrations....

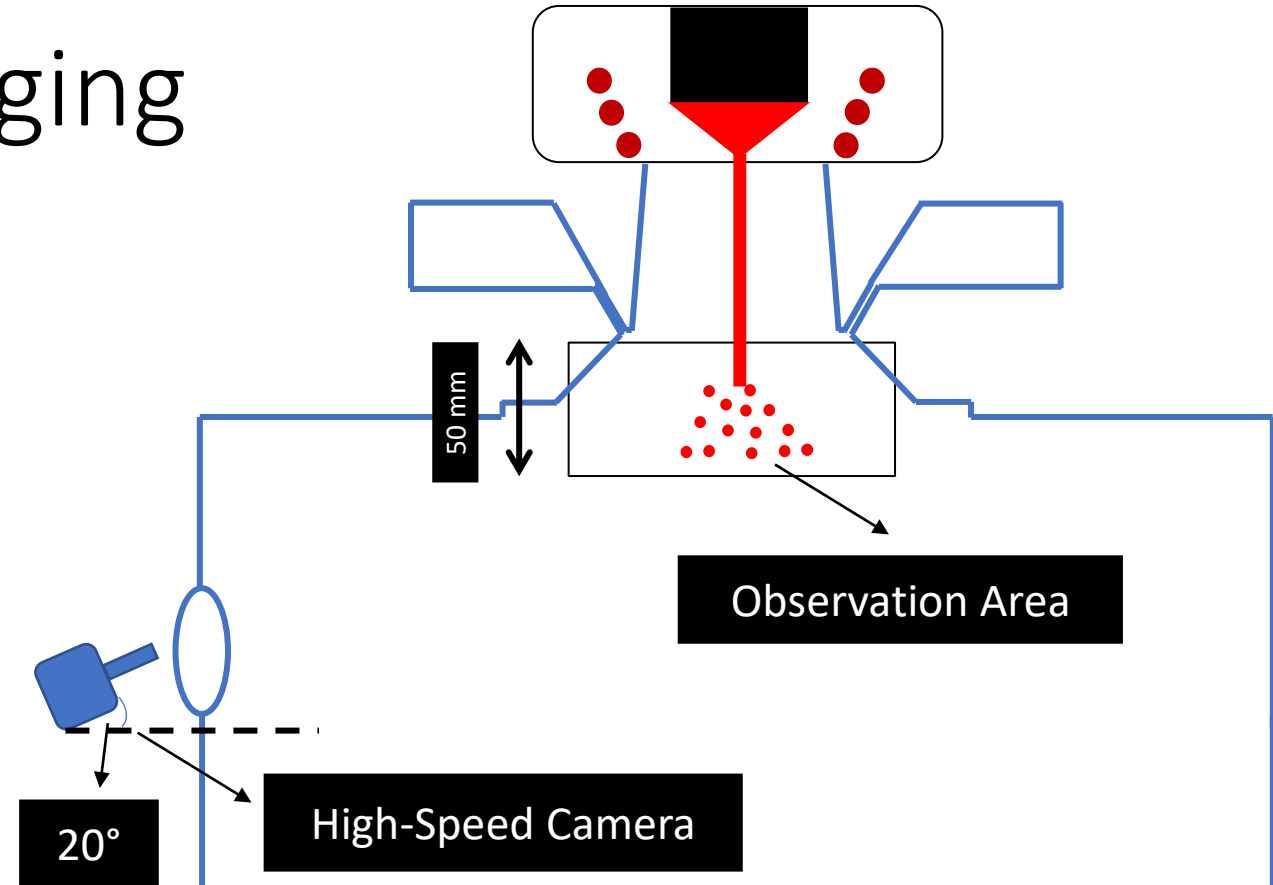
Comparison with CFD



High-Speed Video Imaging

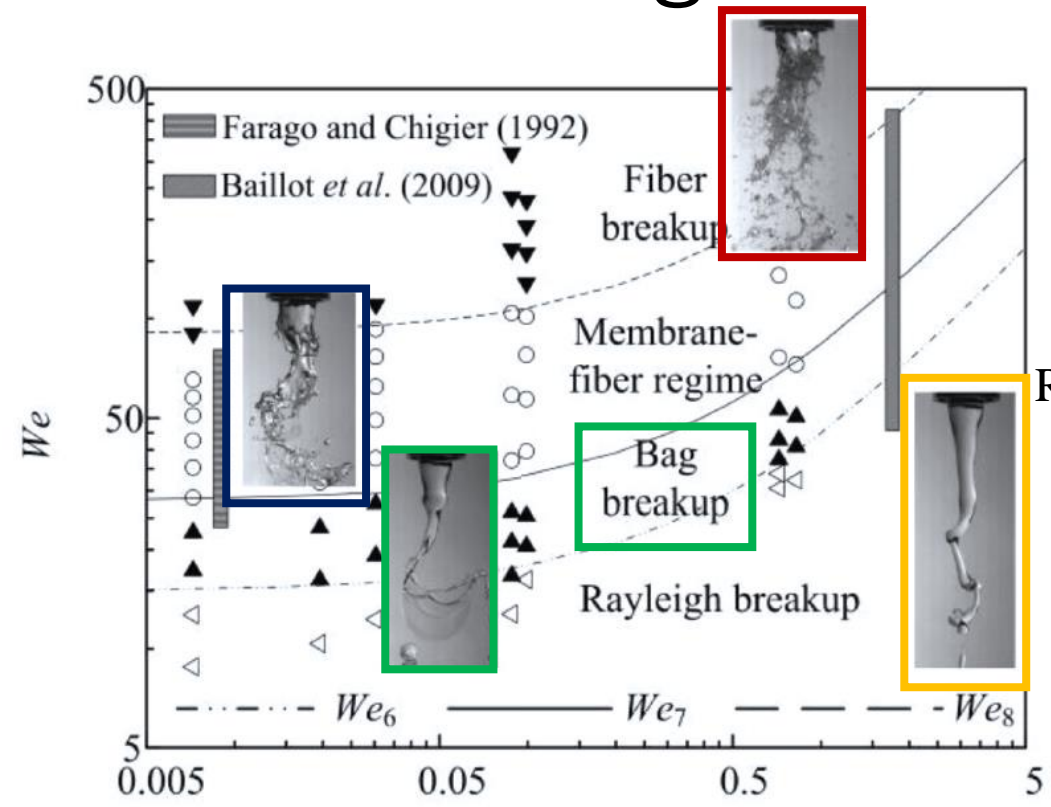


High-Speed Camera



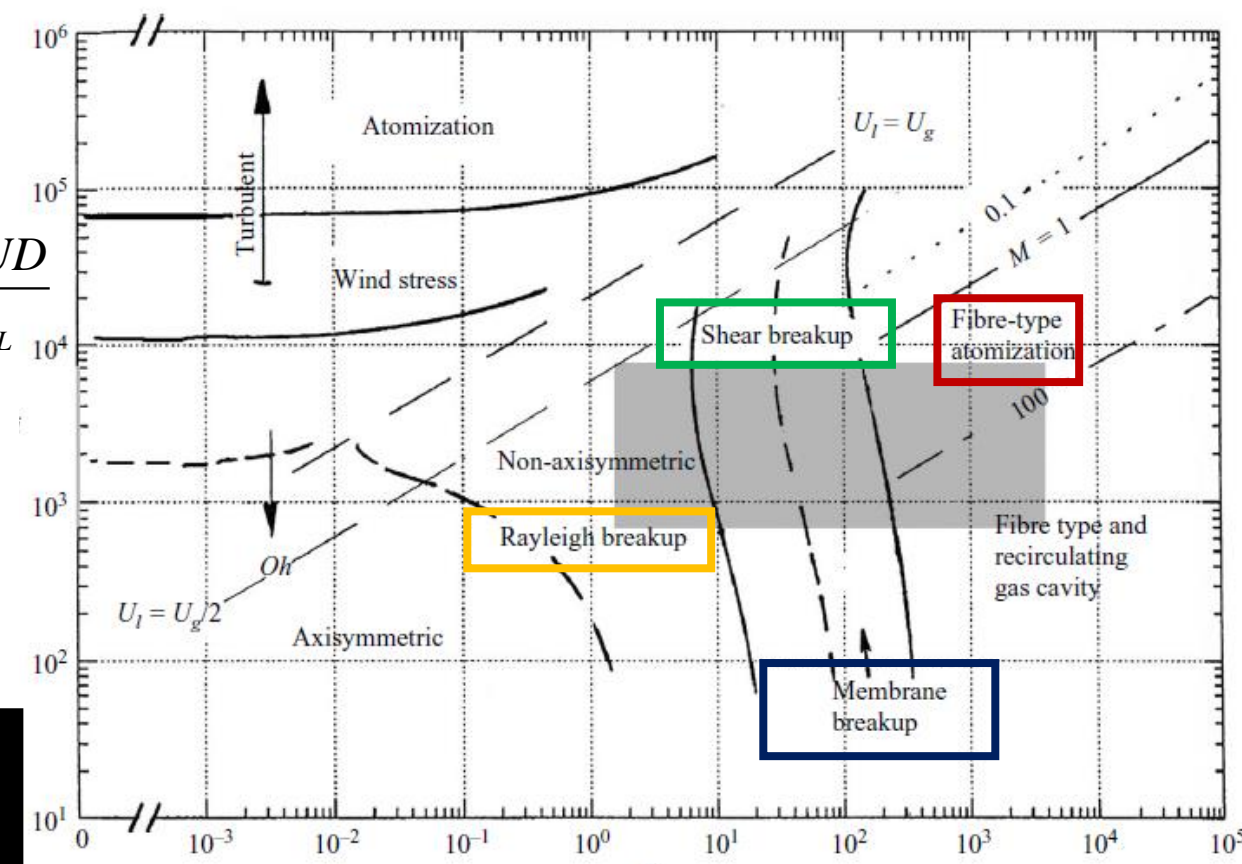
B. Qaddah, P. Chapelle, J-P. Bellot, J. Jourdan, G. Kewalramani, A. Deborde, R. Hammes, N. Rimbert *Primary and secondary breakup of molten Ti64 in an EIGA atomizer for metal powder production* **Powder Technology** 119665 (2024)

Airblast Fragmentation Classification



$$Re_L = \frac{\rho_L U D}{\mu_L}$$

Hopfinger 2000



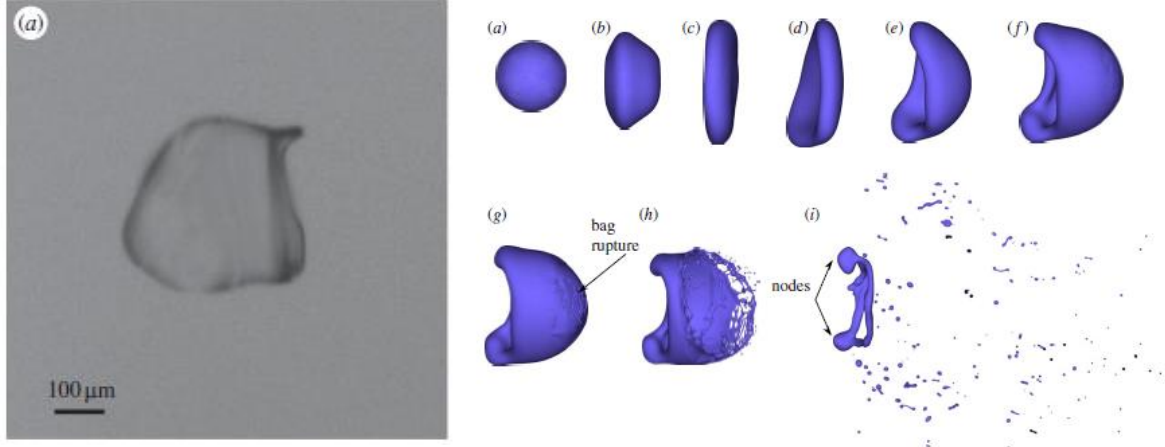
$$We = \rho_G \frac{U^2}{\sigma} D$$

- 4 Mechanisms:
- Fiber breakup
 - Membrane-fiber breakup
 - Bag breakup
 - Rayleigh breakup

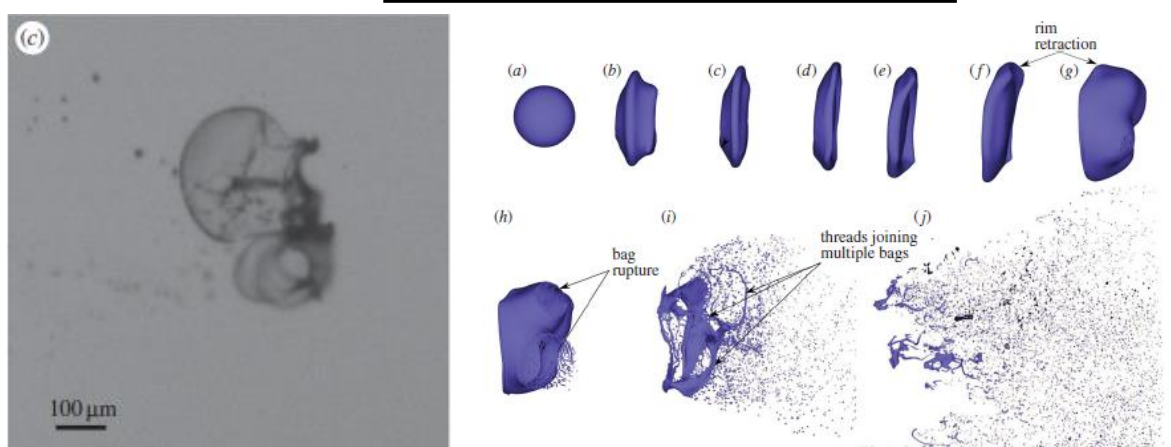
Zhao and Liu 2020

Drop: some DNS Results by Jain et al. (2015)

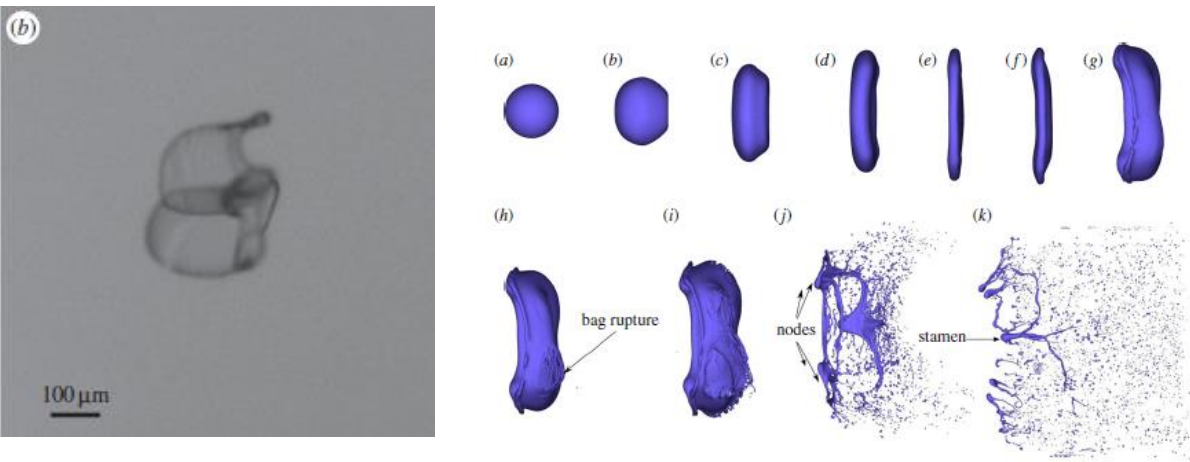
Bag breakup. We=20



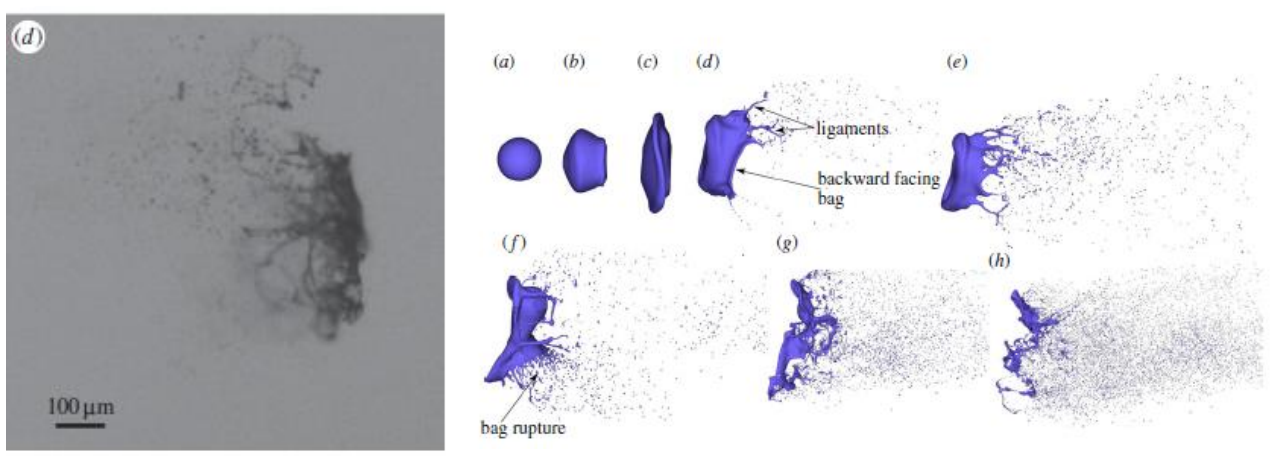
Multi-Bag breakup. We=80



Bag-stamen breakup. We=40



Shear breakup. We=100



Secondary atomization classification

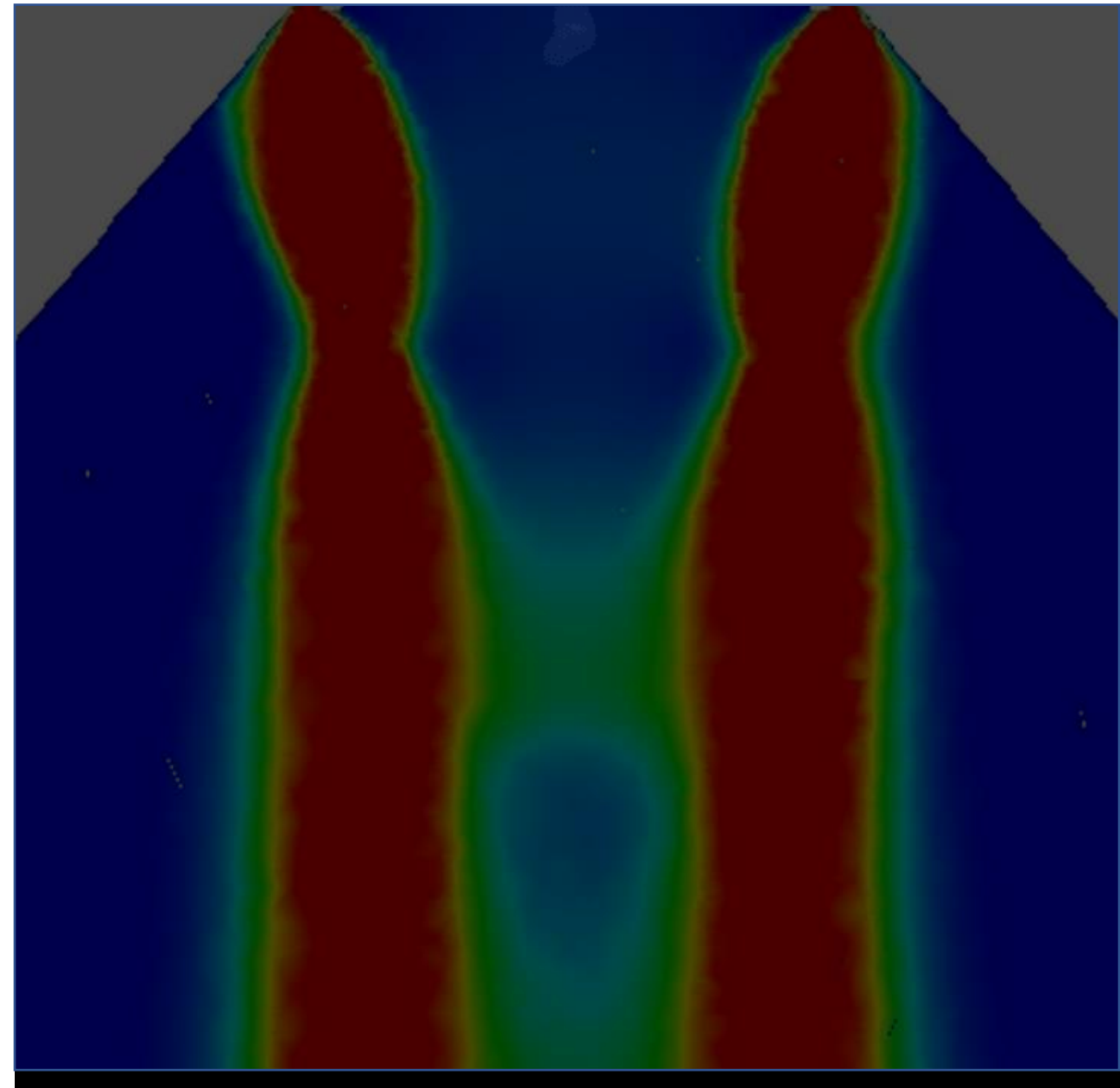
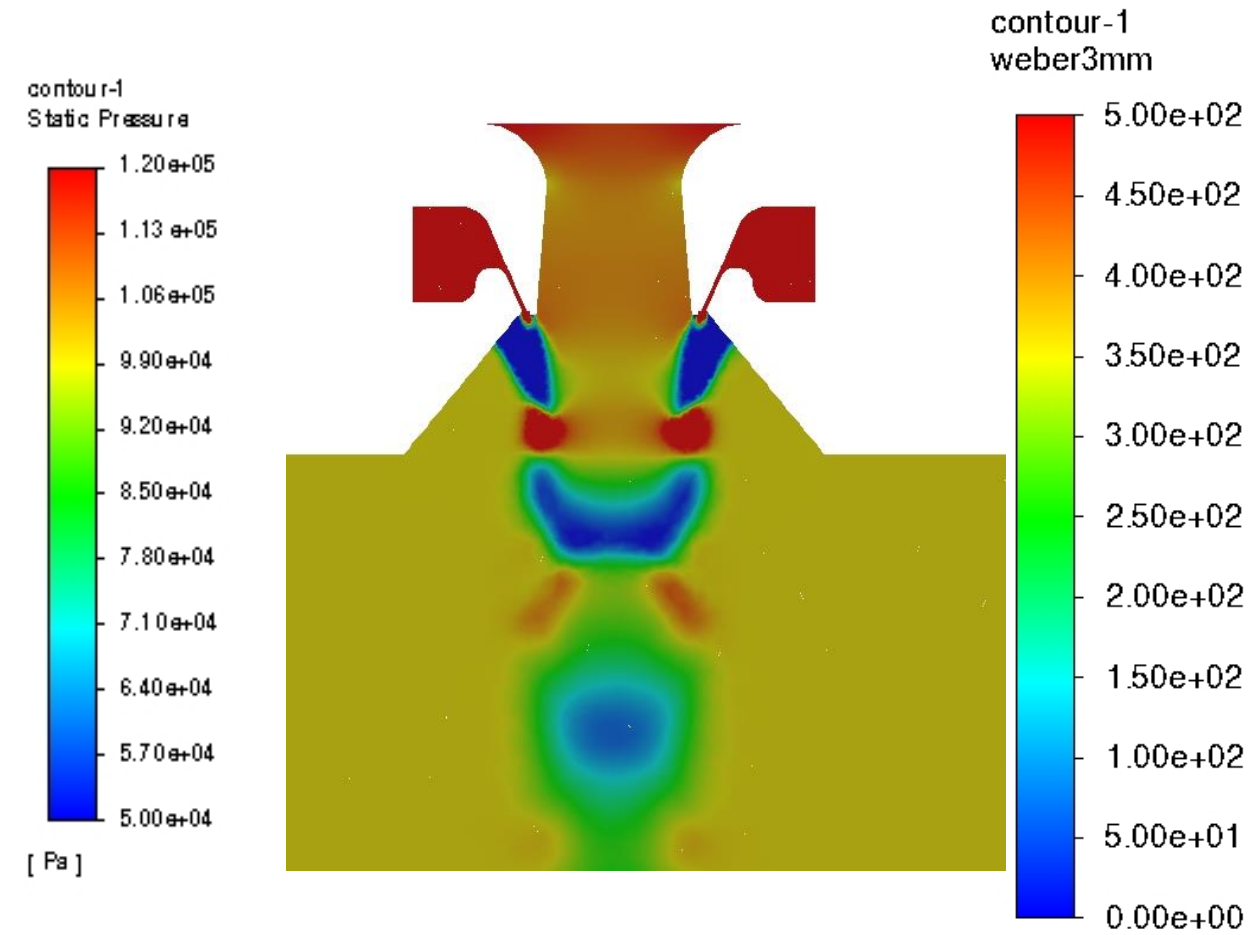
Breakup regime	1	2	3	4	5	6	7
Vibrational	$We < 12$	$We < 10$	$We < 11$	$We < 13$			$We < 12$
Bag	$12 < We < 50$	$10 < We < 18$	$11 < We < 35$	$13 < We < 35$	$13 < We < 18$		$12 < We < 24$
Bag-stamen	$50 < We < 100$	$18 < We < 30$					$24 < We < 45$
Bag-plume			$35 < We < 80$	$35 < We < 80$	$18 < We < 40$		$45 < We < 65$
Multibag			(multimode)	(multimode)		$28 < We < 41$	$65 < We < 85$
Plume-shear					$40 < We < 80$		
Sheet (Shear) thinning	$100 < We < 350$	$We > 63$		$80 < We < 800$			$85 < We < 120$
Catastrophic	$We > 350$			$We > 800$			

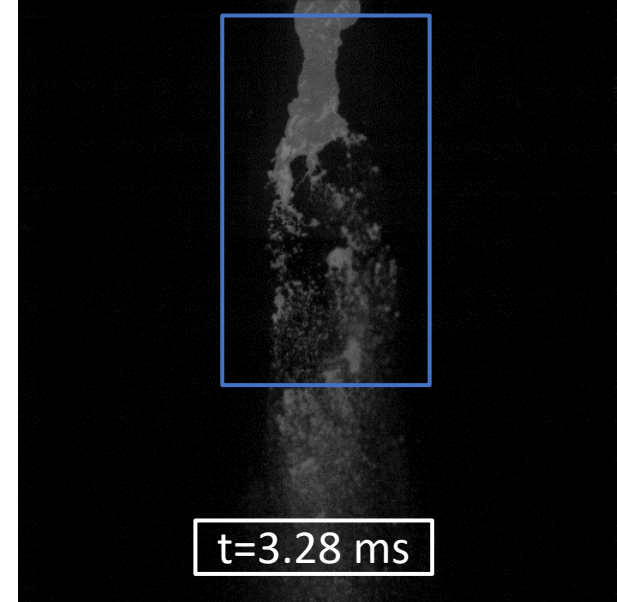
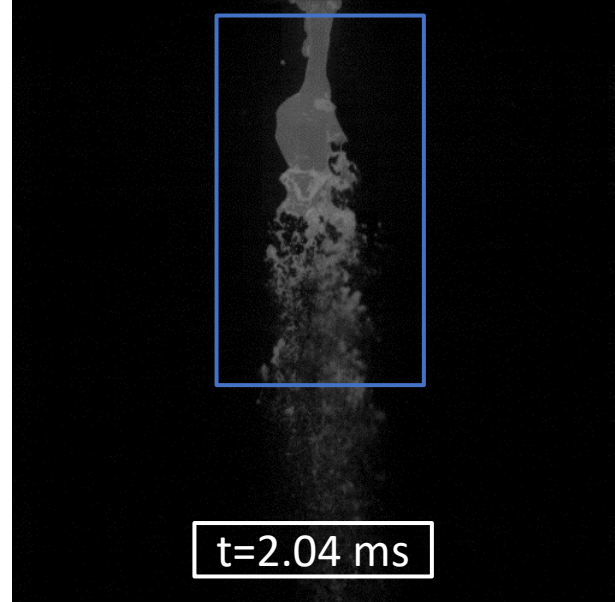
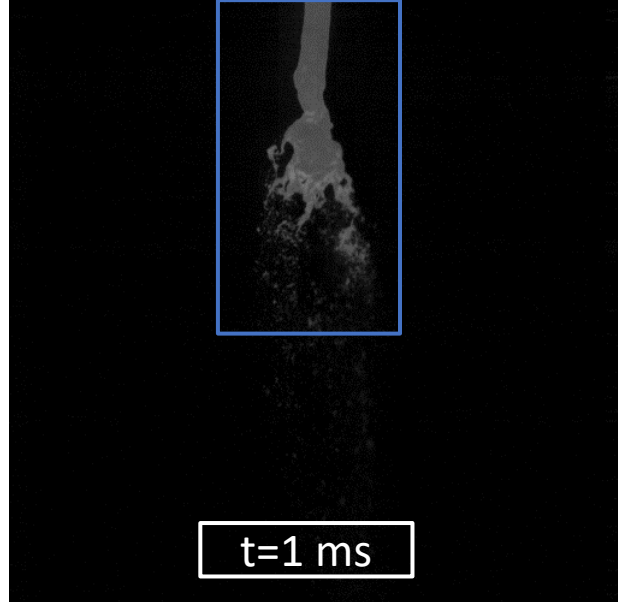
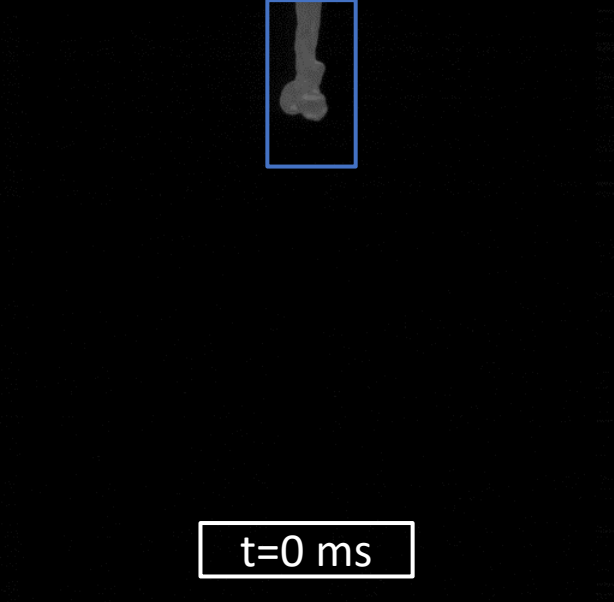
1. Pilch and Erdman (1987), 2. Krzeczowski (1980), 3. Hsiang and Faeth (1995), 4. Chou et al. (1997), 5. Dai and Faeth (2001), 6. Cao et al. (2007), 7. Jain et al. (2015)

Secondary Atomization:

- $We < 13$ Vibrational Breakup)
- $We = 10 - 50$ Bag Breakup
- $We = 20 - 100$ Bag Breakup Stamen
- $We = 20 - 80$ Dual or Multi bag Breakup
- $We > 63$ Shear Breakup

40 bars, PDI 200 mbar

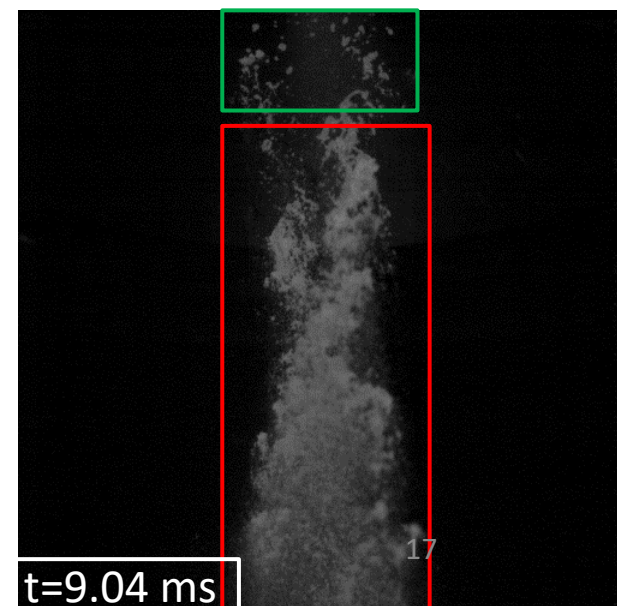
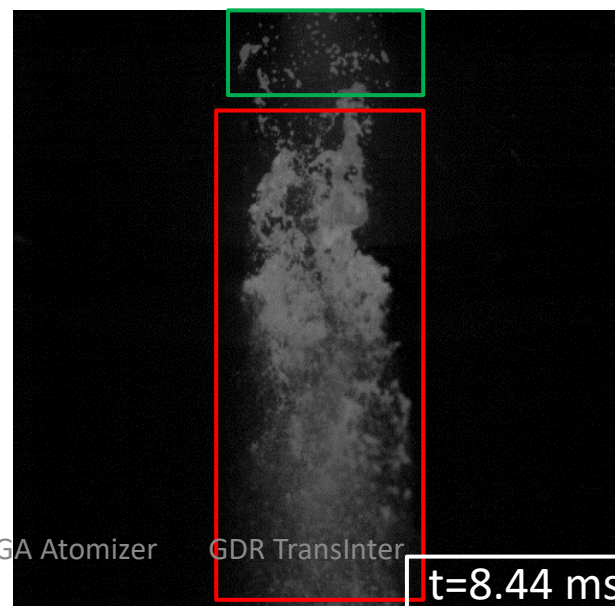
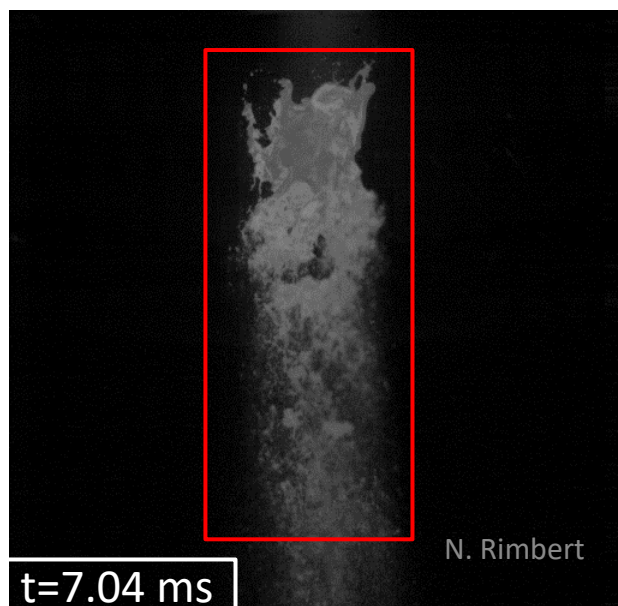
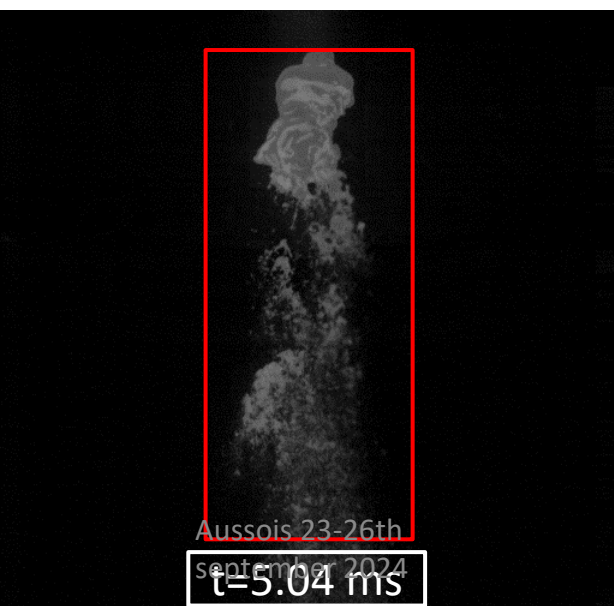


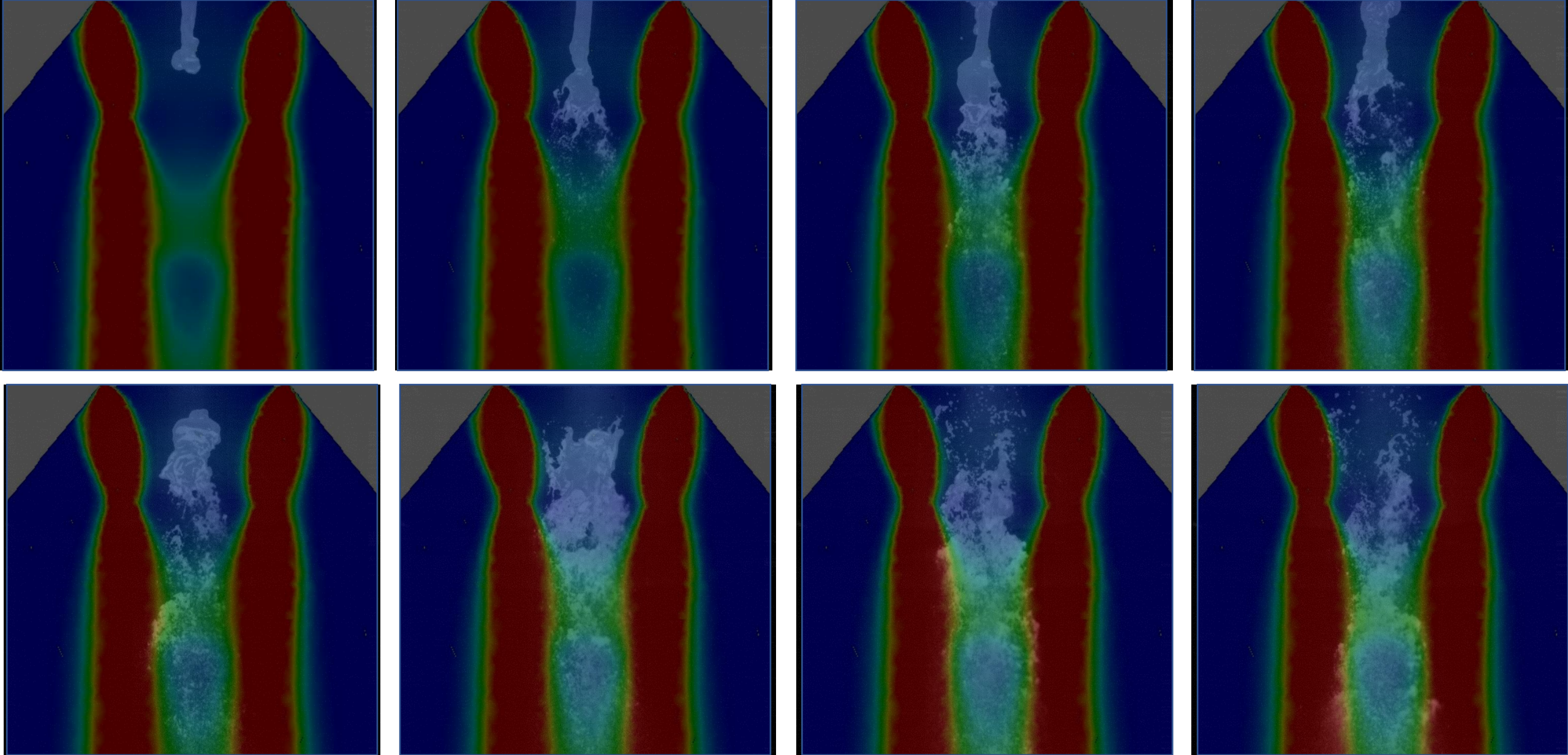


Fiber breakup
Primary atomization
 $D_m=3\text{mm}$. $We = 66$

Shear Breakup
 $D_m=5-7\text{mm}$. $We = 100 - 150$

Powder goes
upstream!





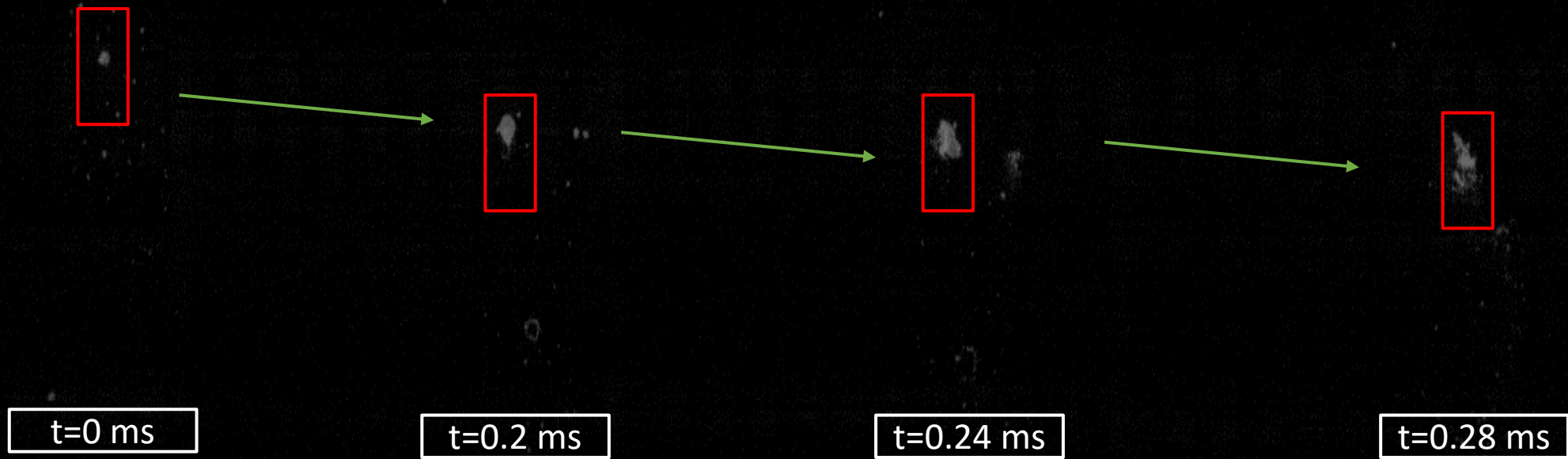


t=0 ms

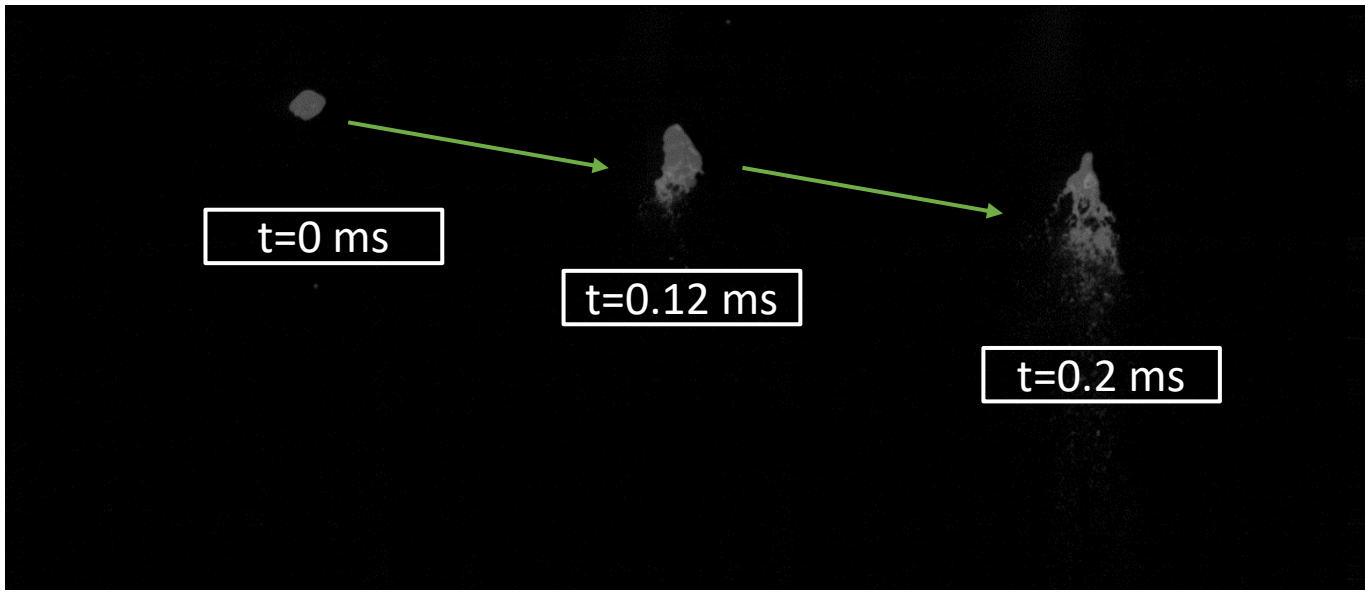
t=0.08 ms

t=0.16 ms

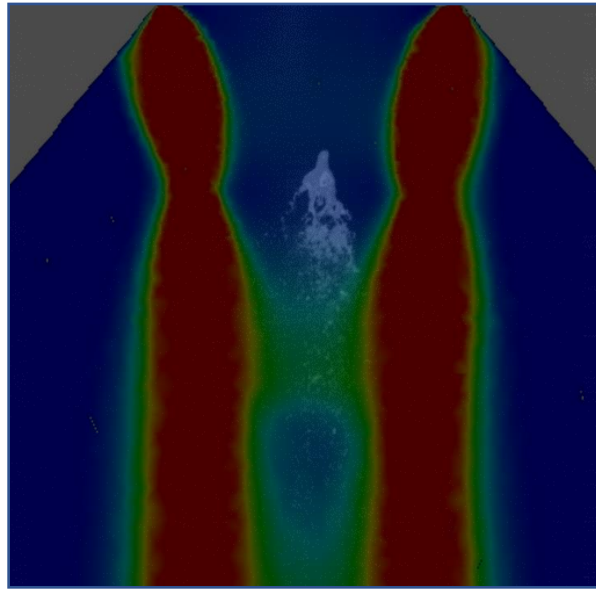
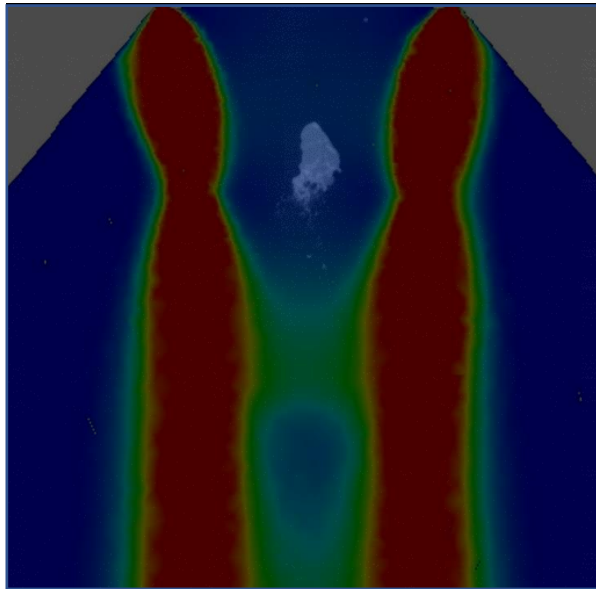
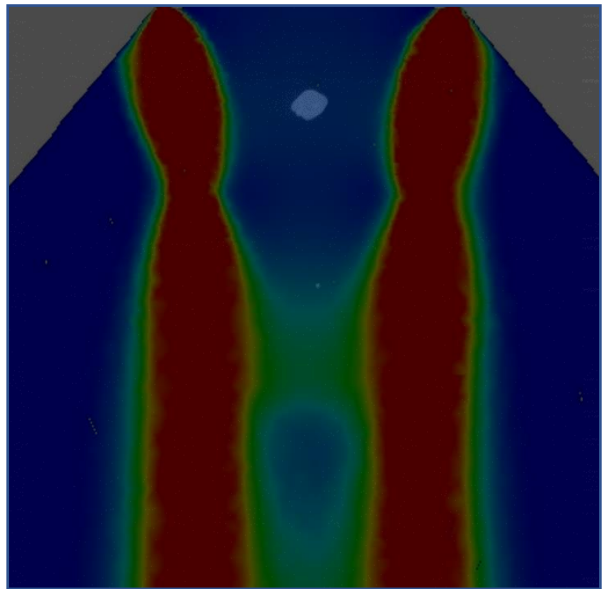
Dm=0.5-1 mm. We<30
bag breakup



Dm=0.5 mm. We = 9-13
bag breakup



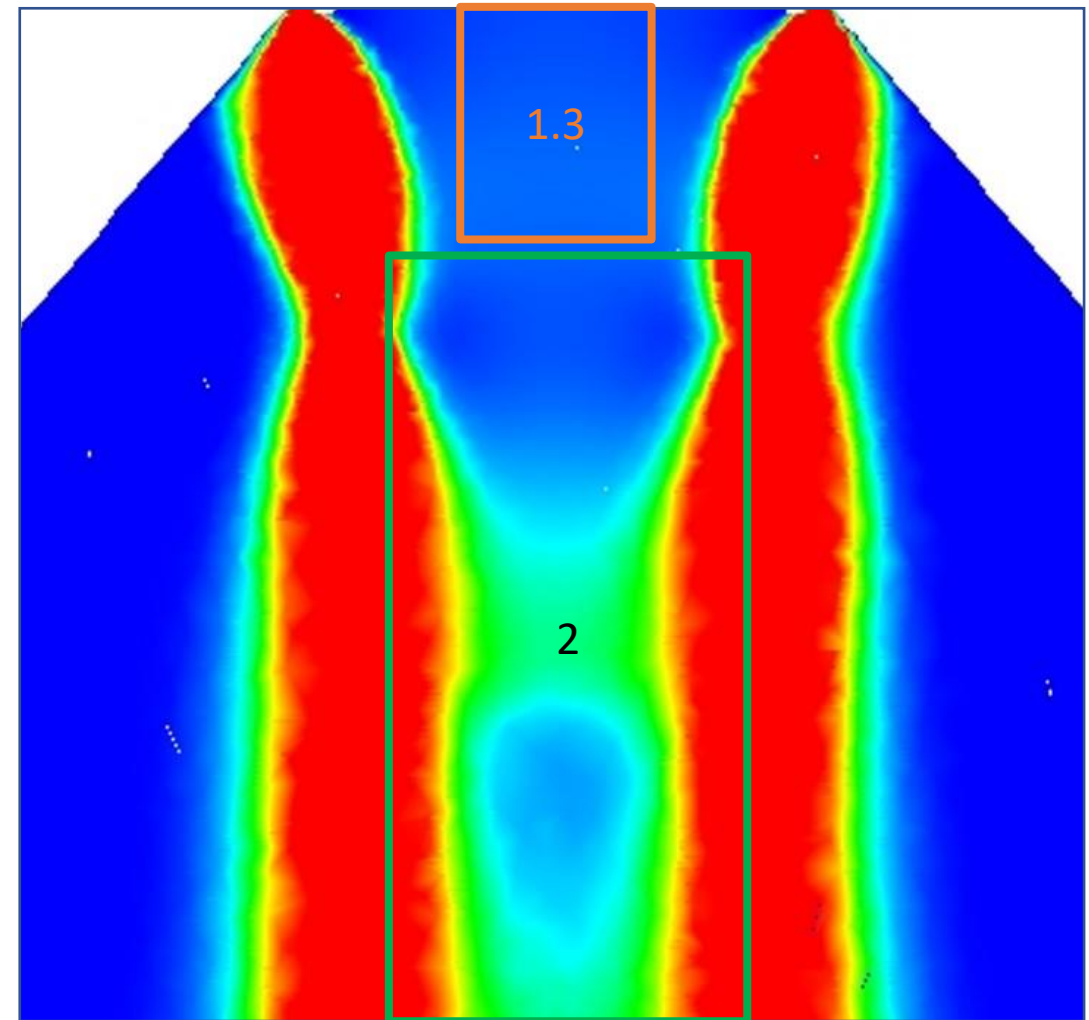
Shear breakup
 $D_m = 2\text{ mm}$. $We = 50$



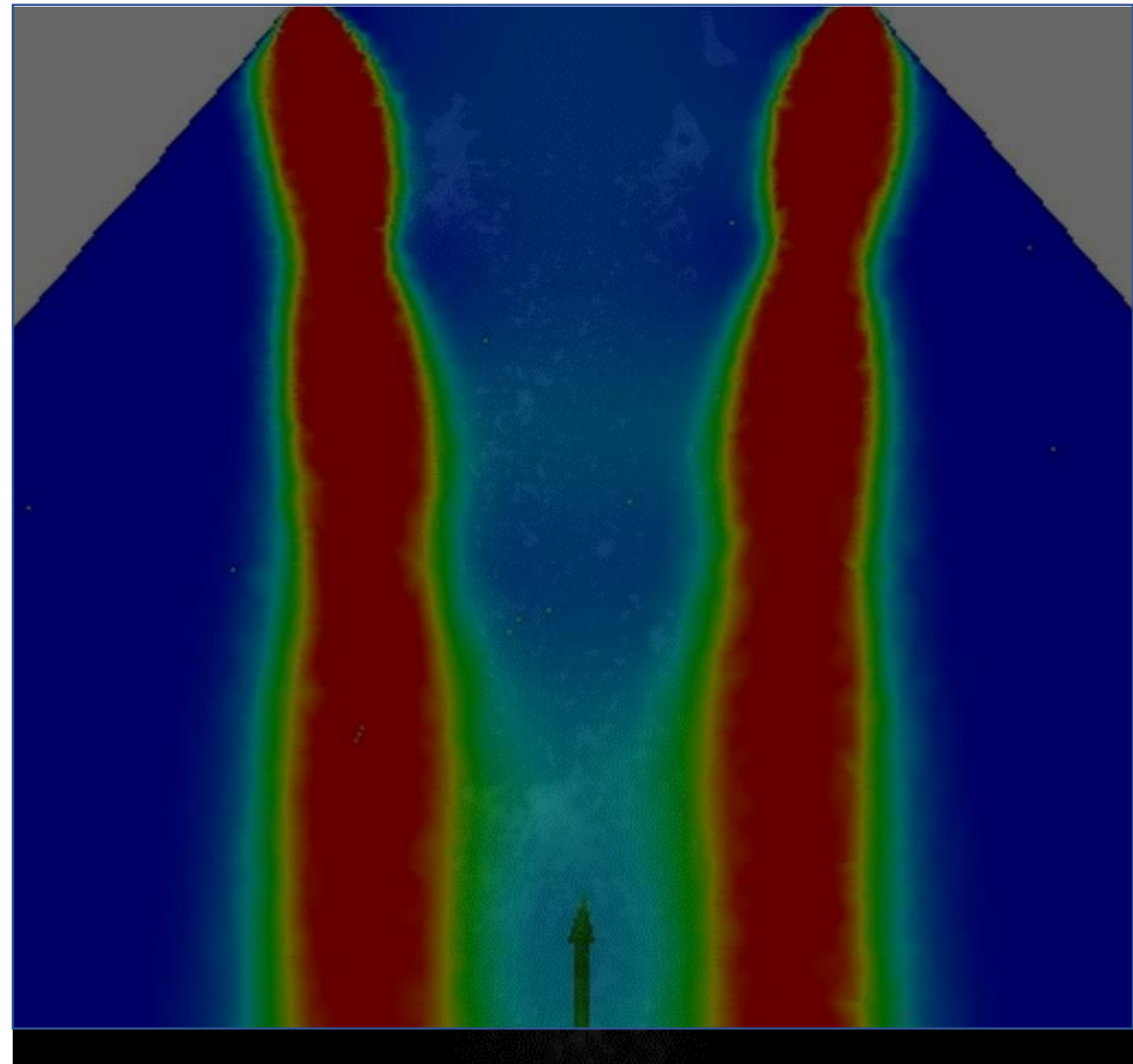
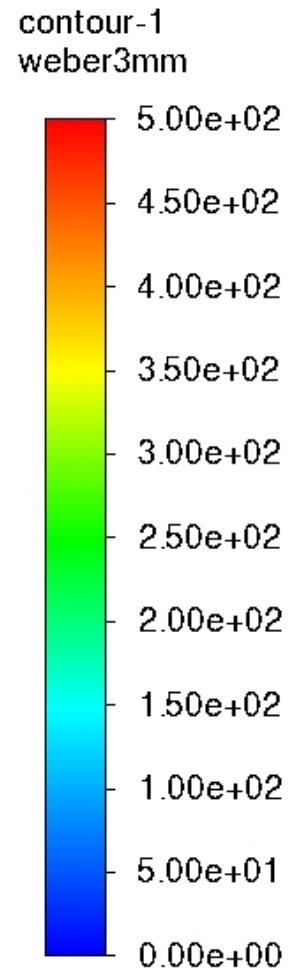
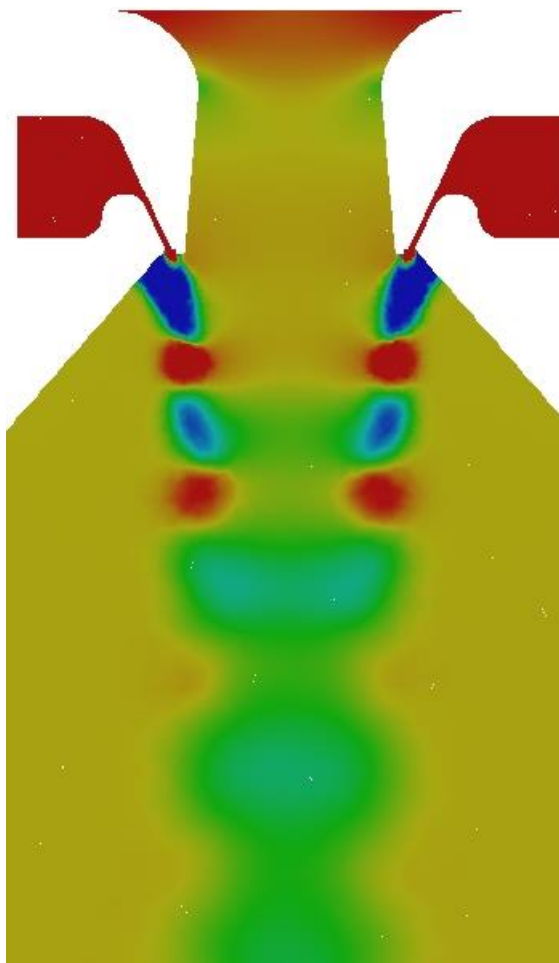
Atomization Areas 40 bar

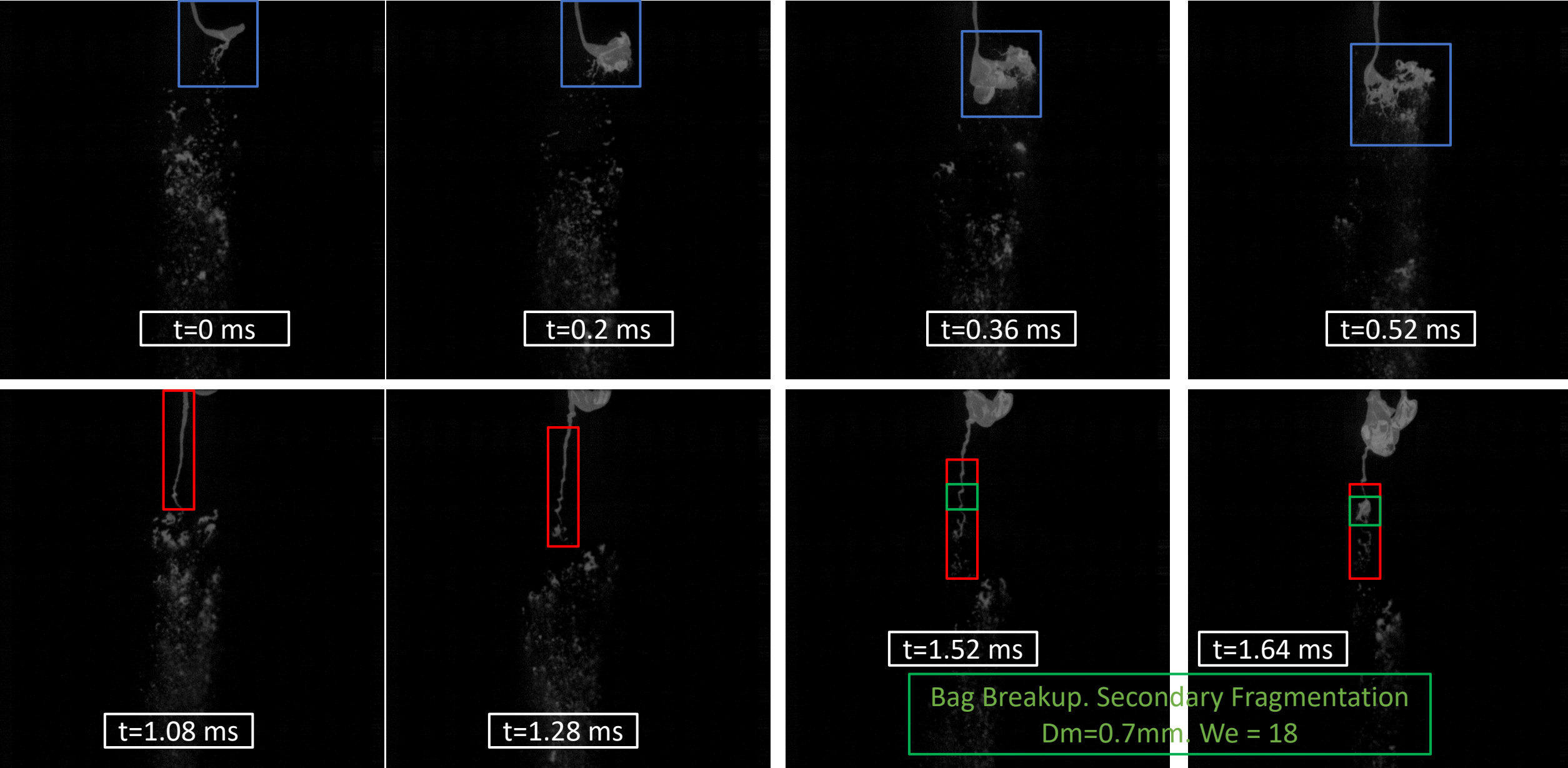
- 1) Fiber breakup
- 2) Shear breakup
- 3) Bag breakup: When powder goes upstream

Note: Very Intermittent jet



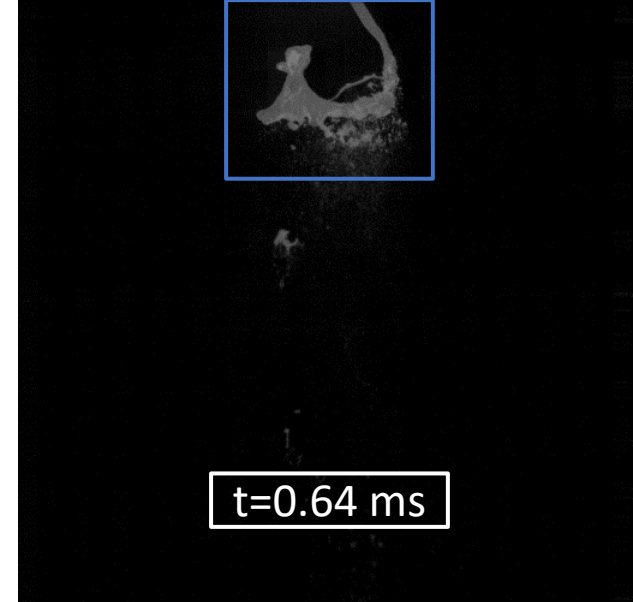
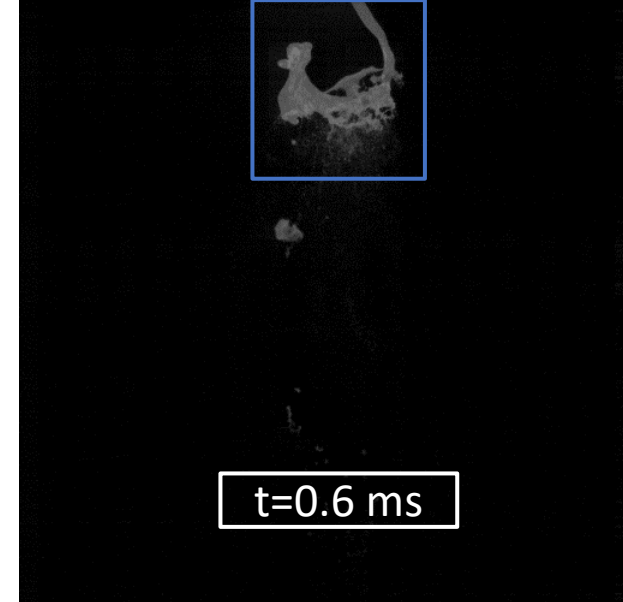
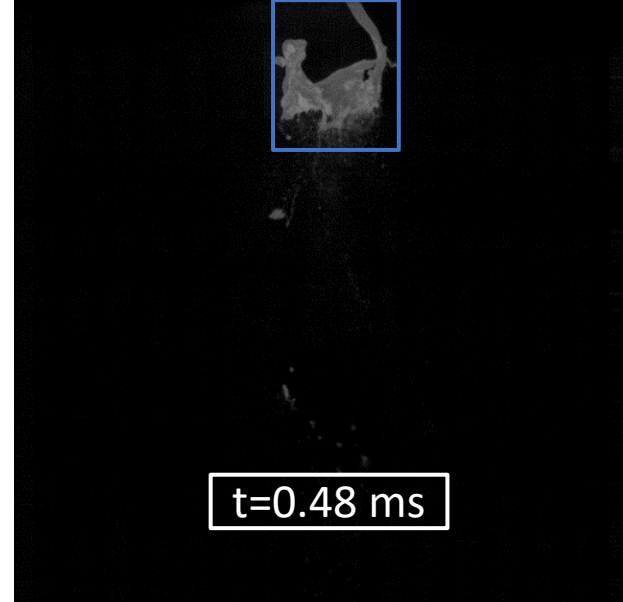
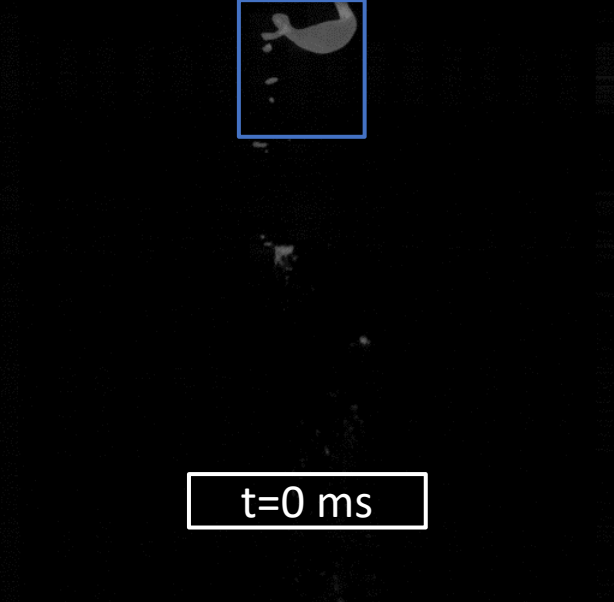
30 bar, PDI 200 mbar





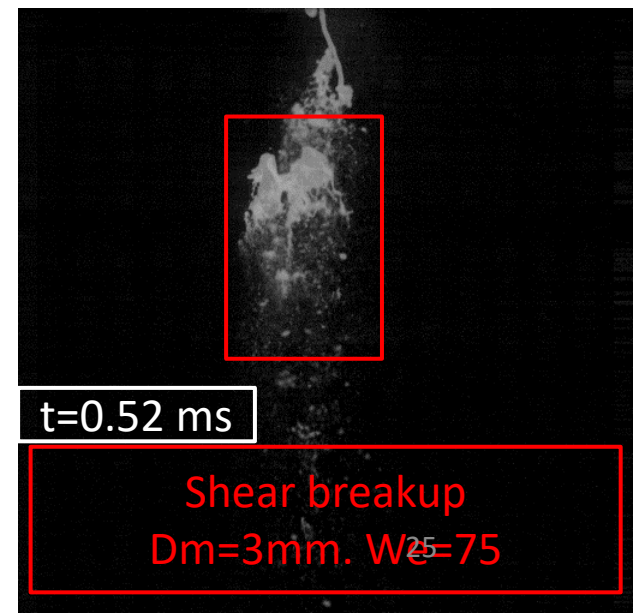
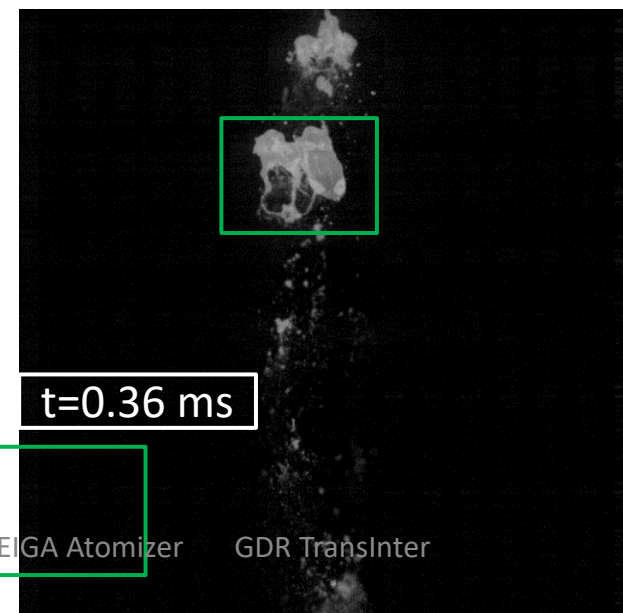
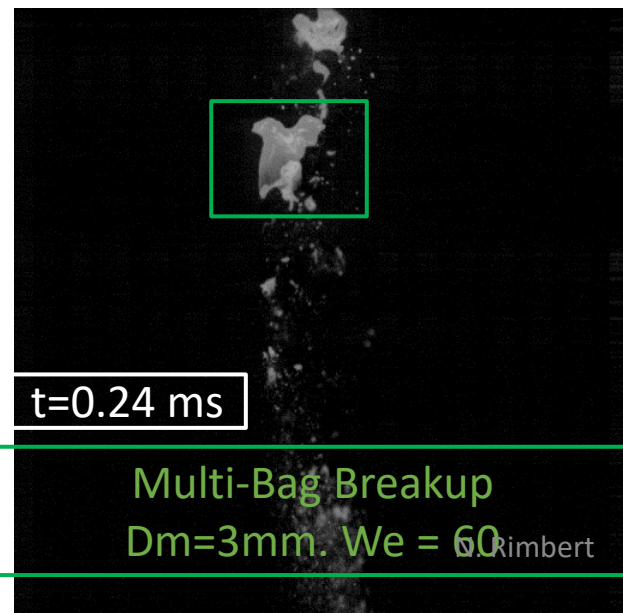
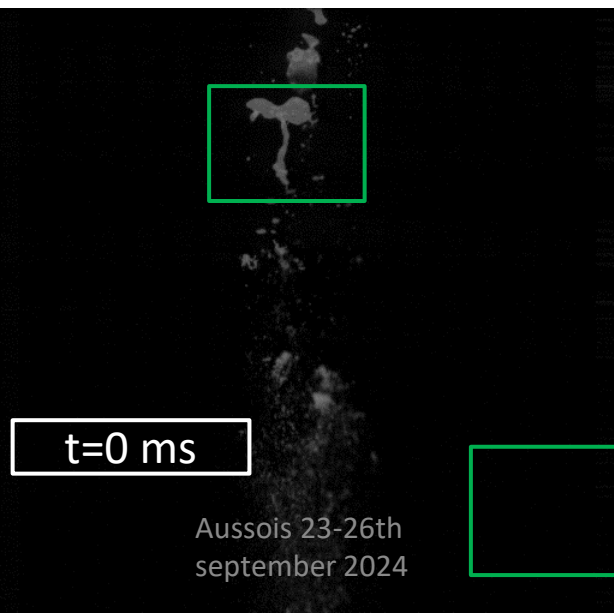
Rayleigh breakup
 Primary atomization
 $D_{m_Fil} = 0.3-0.4\text{mm}$. $We = 6-8$

Bag breakup. Primary atomization
 $D_{m_Fil} = 0.7\text{ mm}$. $We = 14$
 $D_{m_drop_attaché} = 4.5\text{ mm}$. $We = 100$



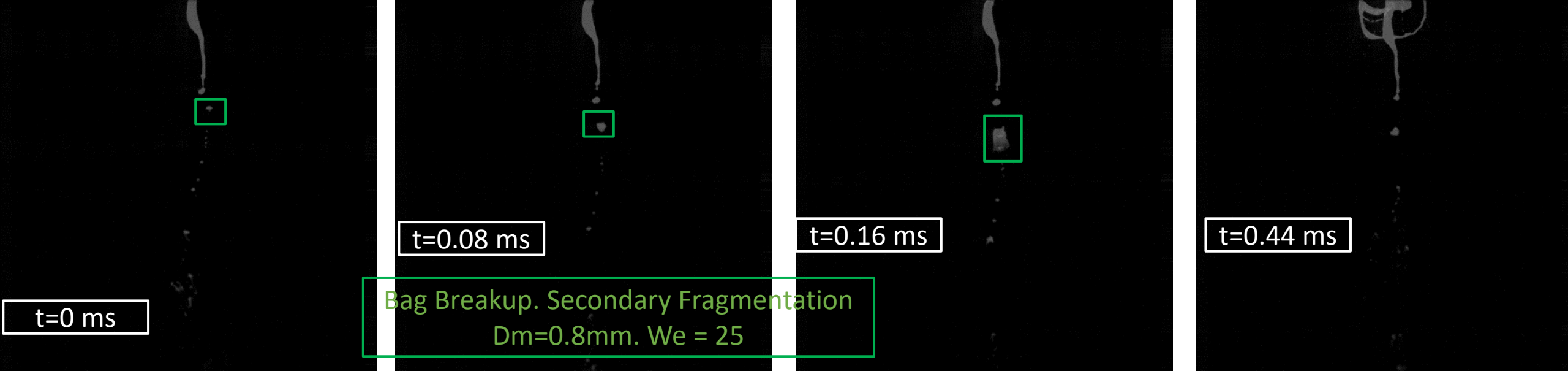
Bag breakup
Primary atomization

Attention au mouvement inversé
Filament métallique dominé par
l'écoulement gazeux



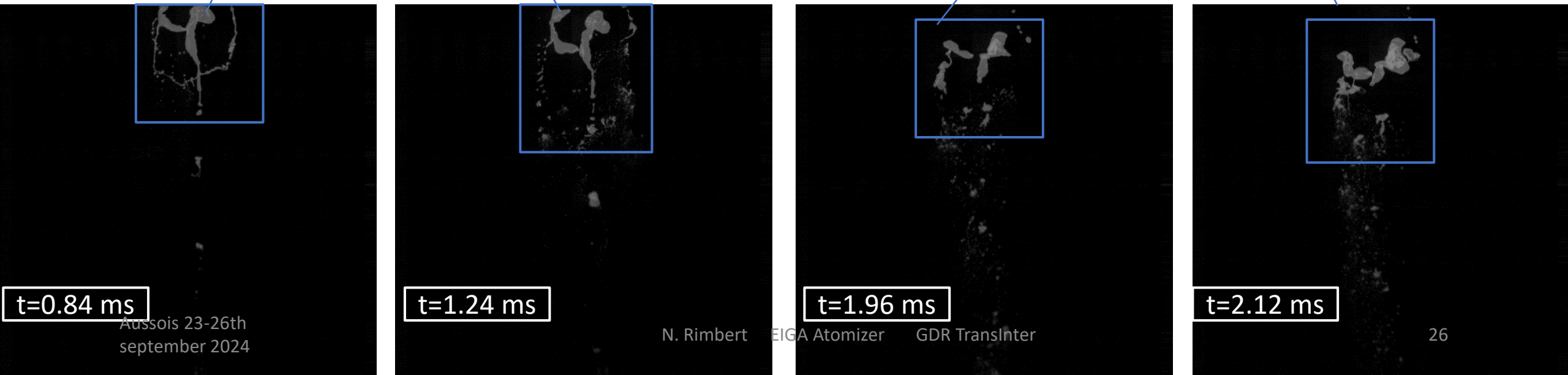
Multi-Bag Breakup
Dm=3mm. We = 60

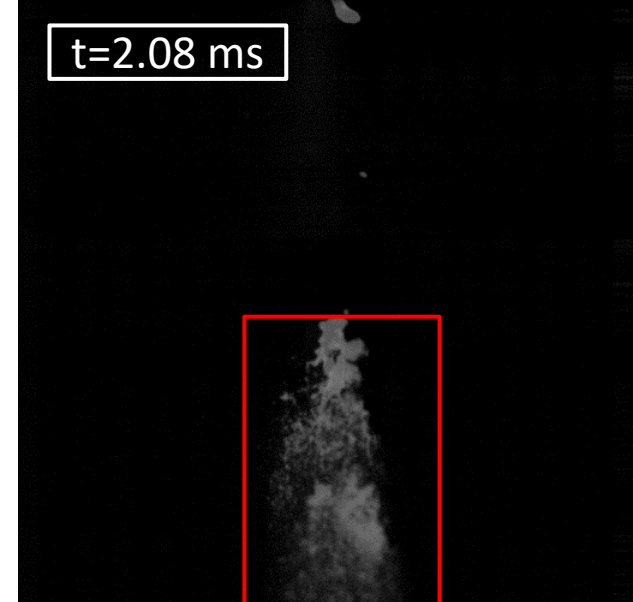
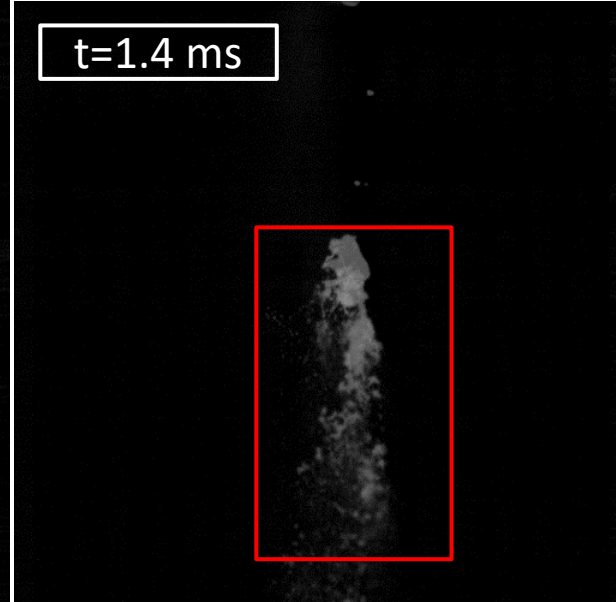
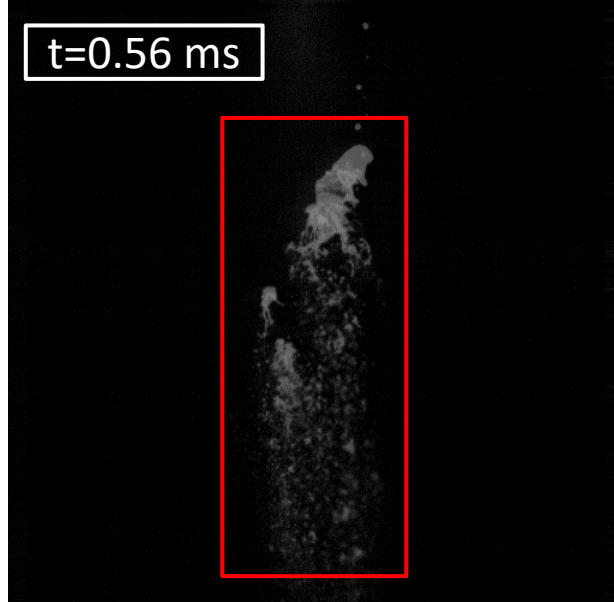
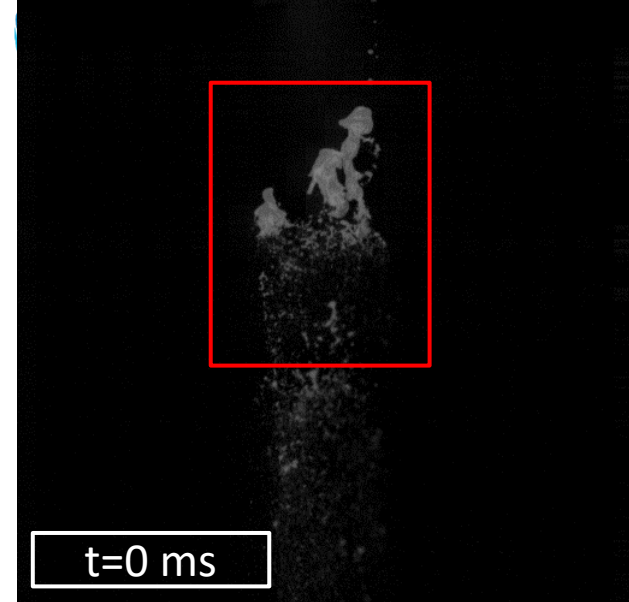
Shear breakup
Dm=3mm. We = 75



Bag breakup
Primary atomization

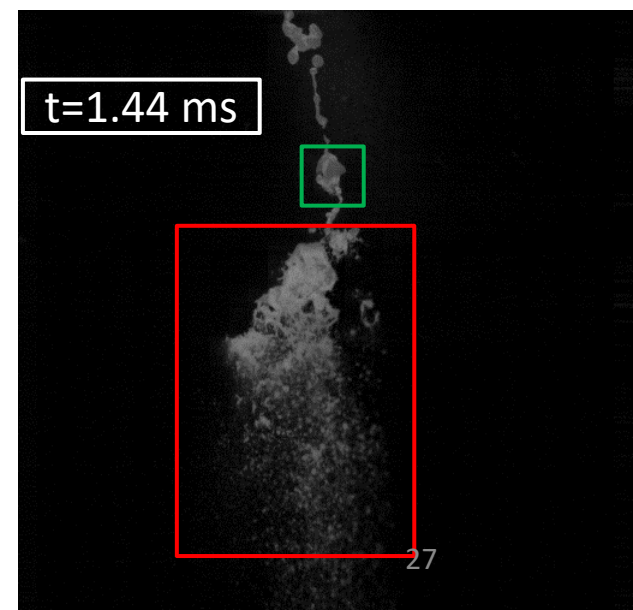
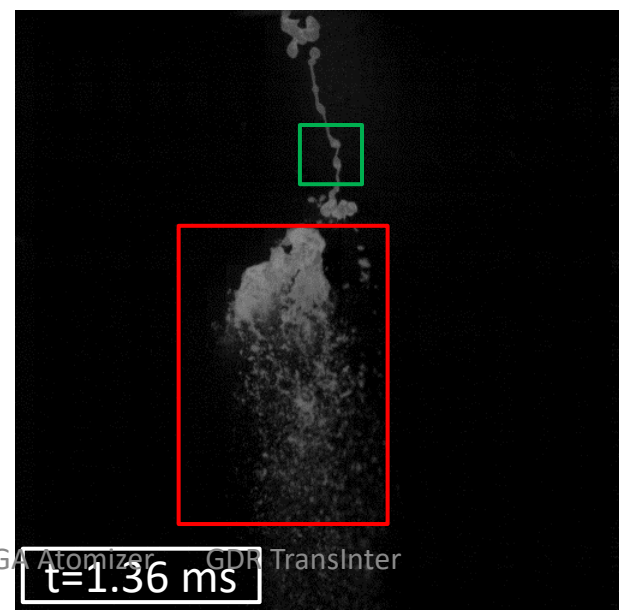
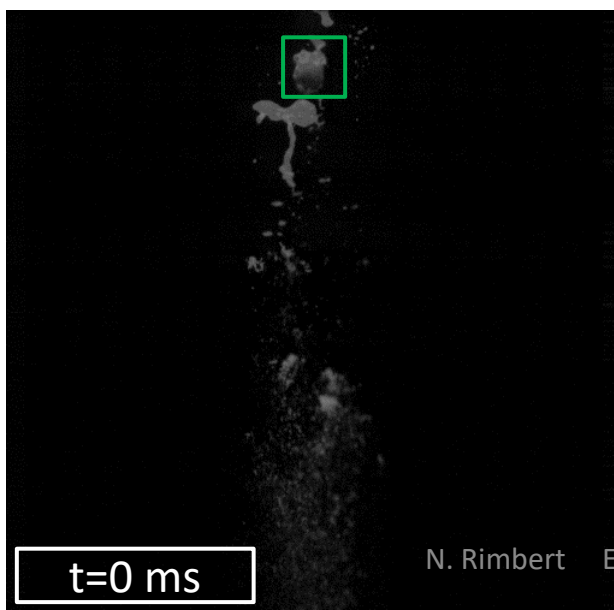
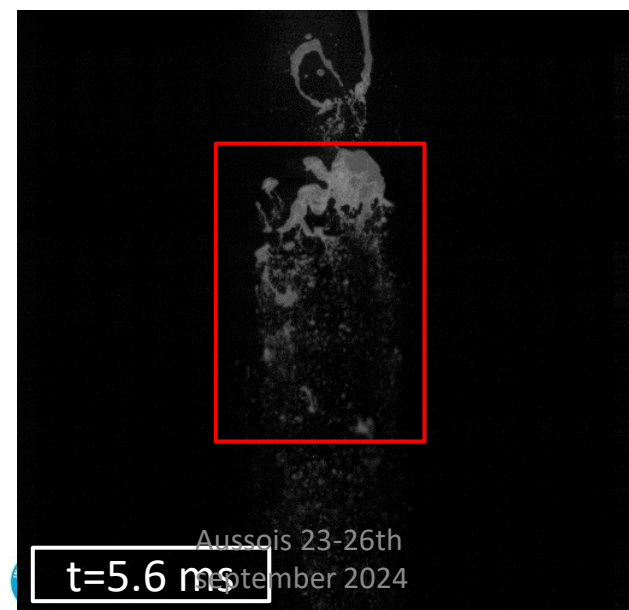
Multibag breakup
Secondary fragmentation
Dm = 3mm. We = 60





Shear breakup
Secondary fragmentation
 $D_m=3\text{mm}$. $We=90$ Atomisation !

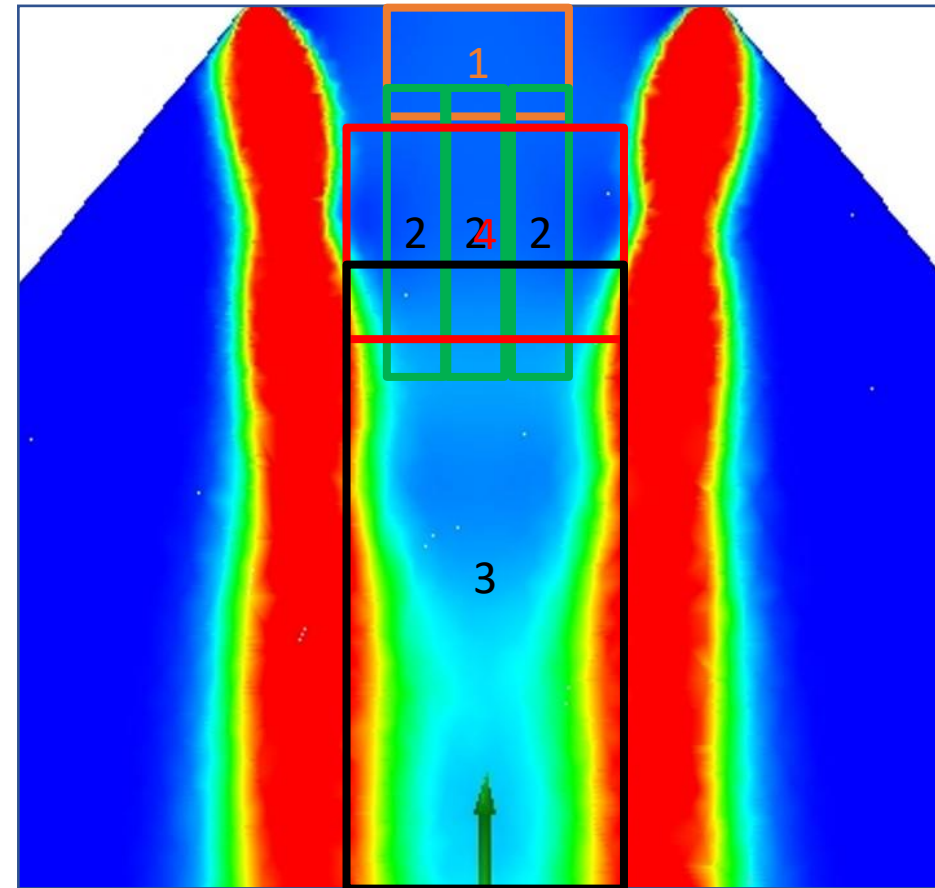
Bag Breakup
 $D_m=0.5\text{mm}$. $We = 14$



Atomization Areas: 30 bar

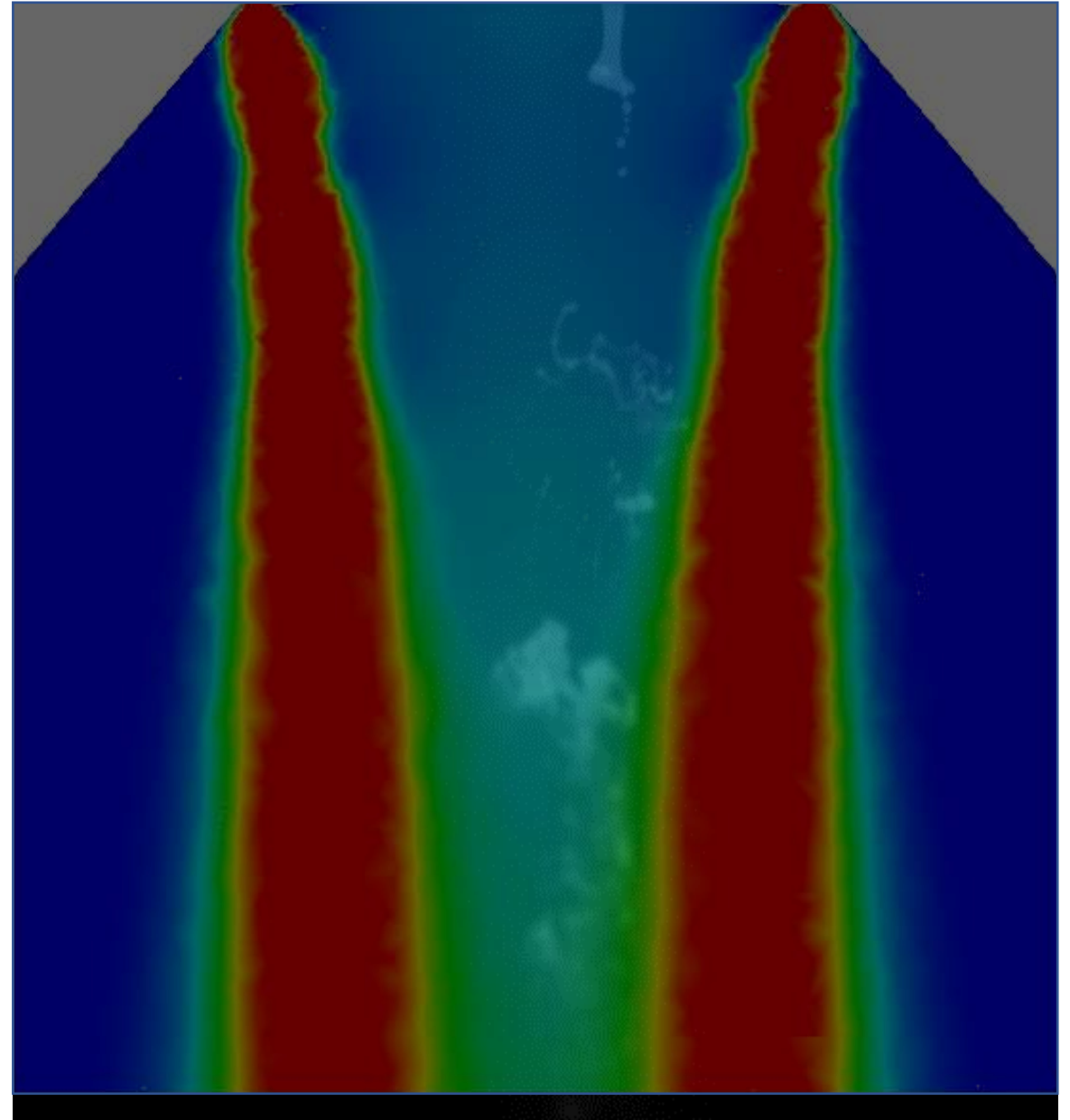
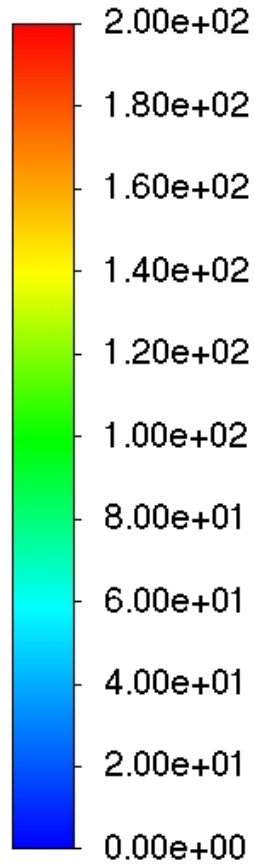
- 1) Fiber breakup
- 2) Rayleigh breakup
- 3) Shear breakup
- 4) Bag breakup

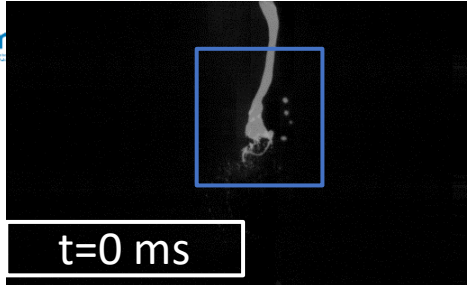
Note: Intermittent jet



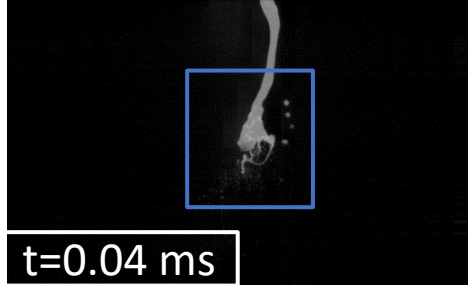
20 bars PDI 200 mbar

contour-1
weber-2mm



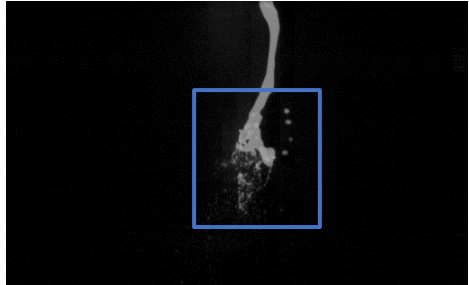


t=0 ms



t=0.04 ms

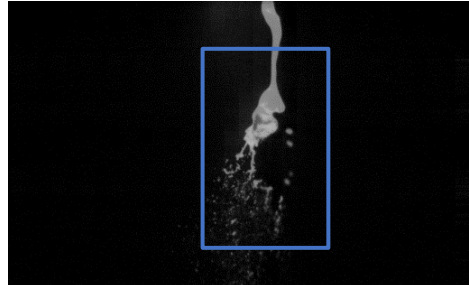
Bag breakup
Primary atomization
 $D_{Fil}=1 - 1.3 \text{ mm. } We = 20 - 30$



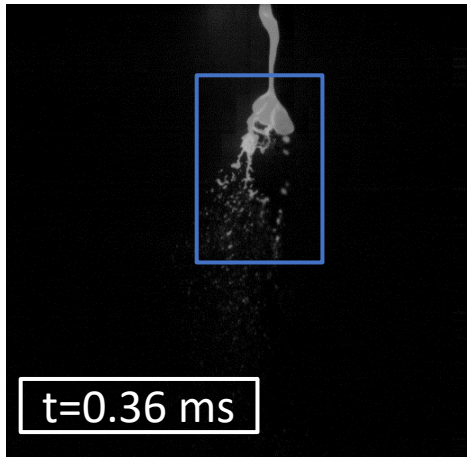
t=0.12 ms



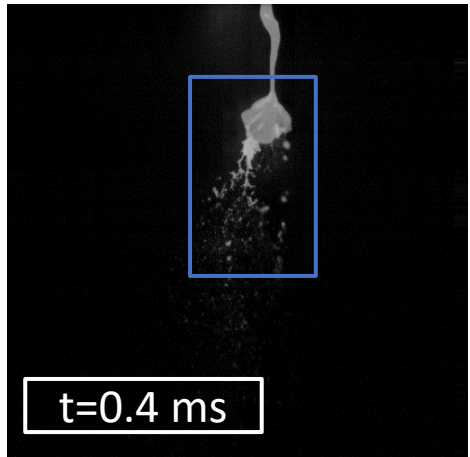
t=0.16 ms



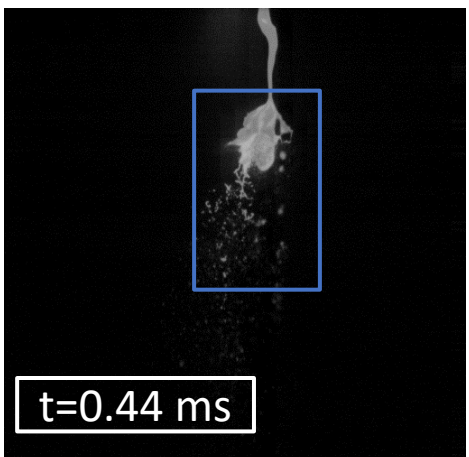
t=0.32 ms



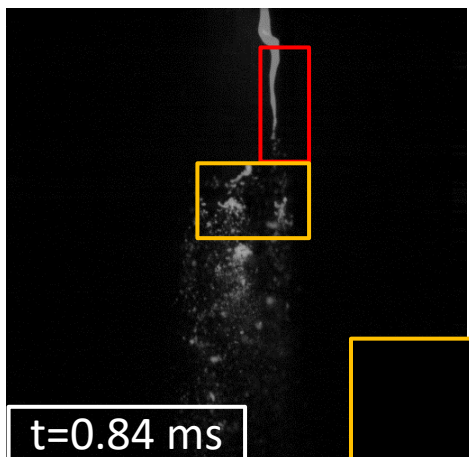
t=0.36 ms



t=0.4 ms

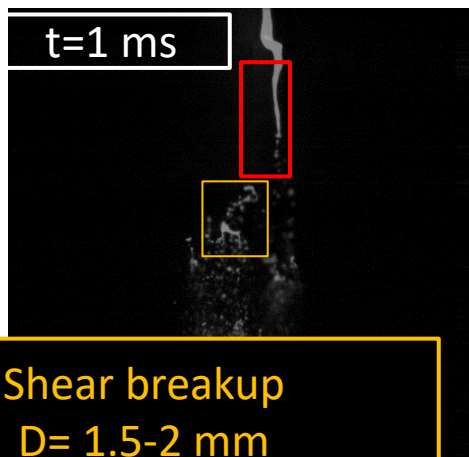


t=0.44 ms

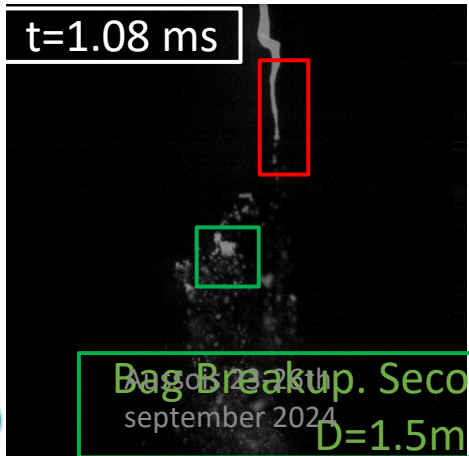


t=0.84 ms

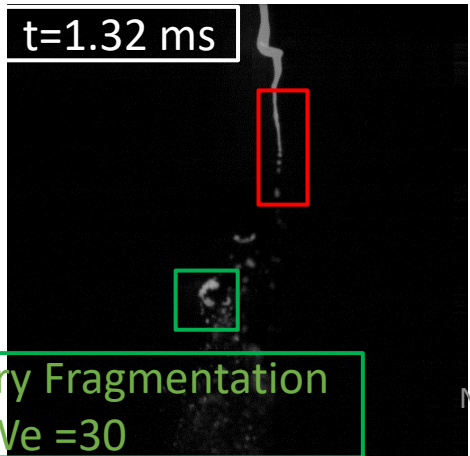
Shear breakup
 $D = 1.5-2 \text{ mm}$



t=1 ms

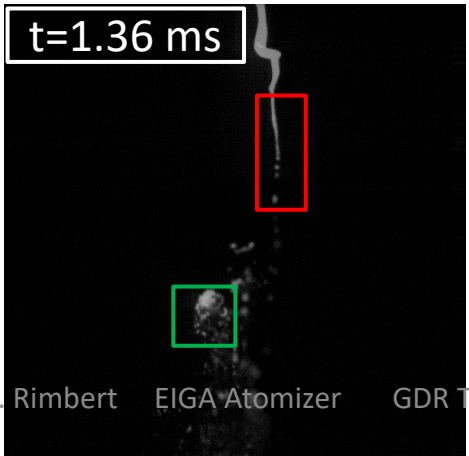


t=1.08 ms

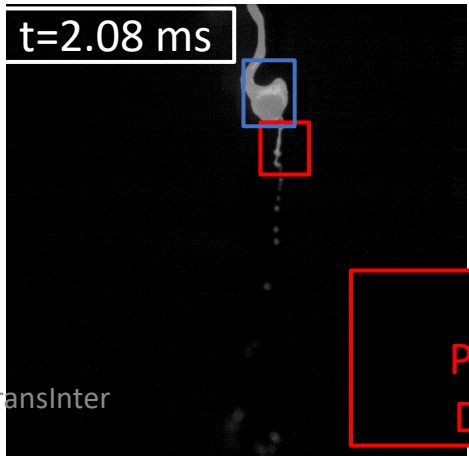


t=1.32 ms

Bag Breakup. Secondary Fragmentation
 $D=1.5\text{mm. } We = 30$

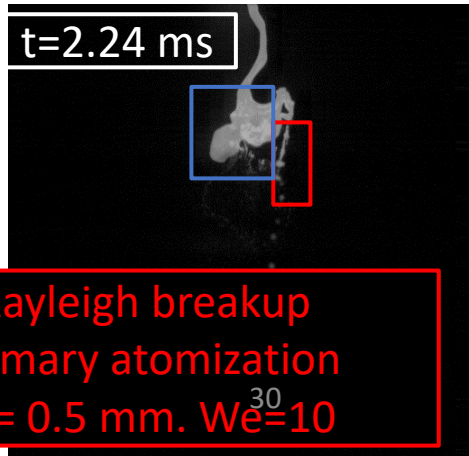


t=1.36 ms

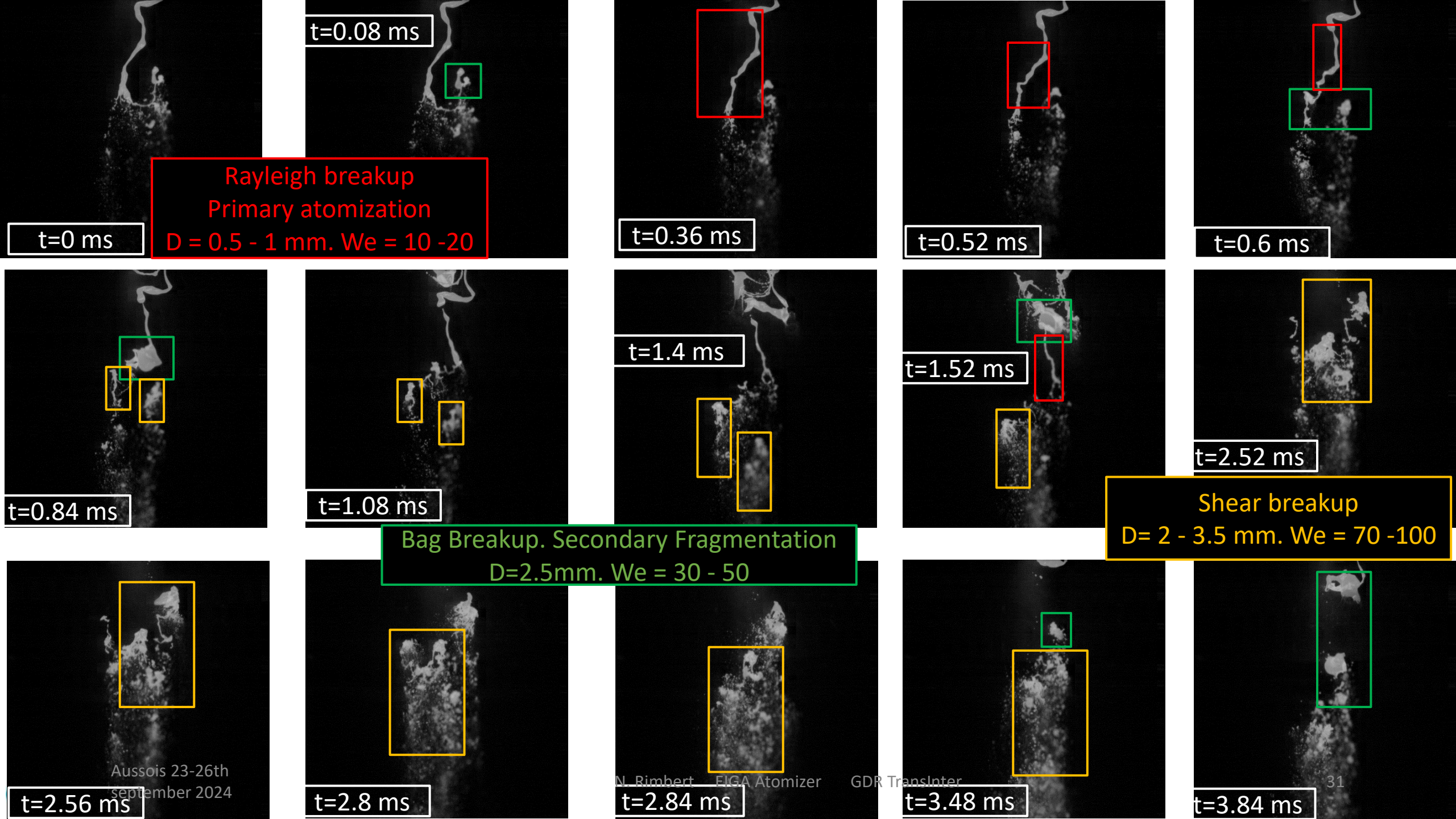


t=2.08 ms

Rayleigh breakup
Primary atomization
 $D = 0.5 \text{ mm. } We=10$



t=2.24 ms



t=0.08 ms

Rayleigh breakup
Primary atomization
D = 0.5 - 1 mm. We = 10 -20

t=0 ms

t=0.36 ms

t=0.52 ms

t=0.6 ms

t=0.84 ms

t=1.08 ms

t=1.4 ms

t=1.52 ms

t=2.52 ms

Bag Breakup. Secondary Fragmentation
D=2.5mm. We = 30 - 50

Shear breakup
D= 2 - 3.5 mm. We = 70 -100

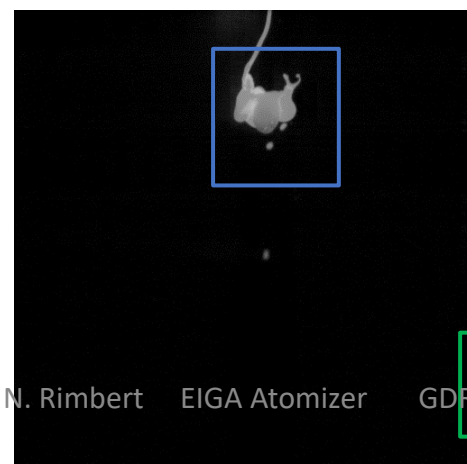
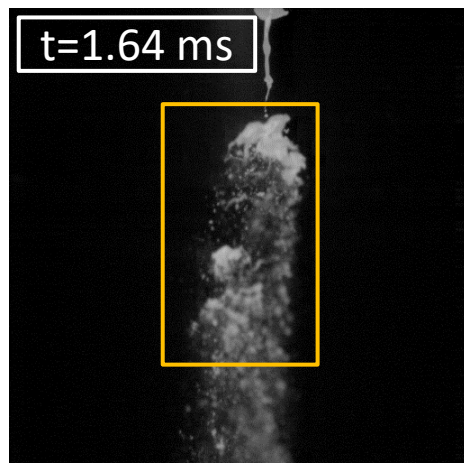
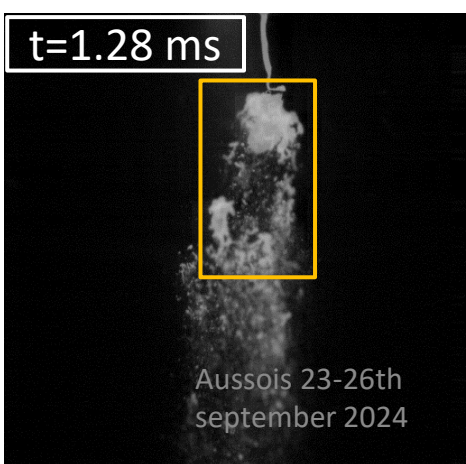
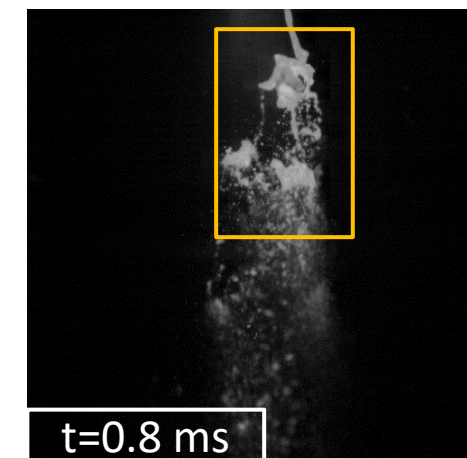
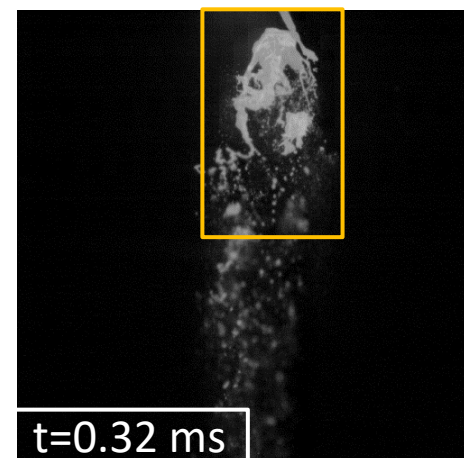
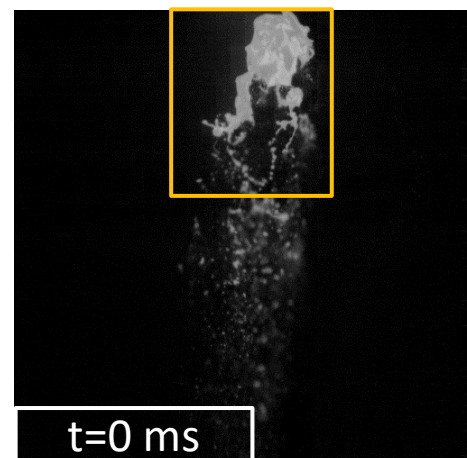
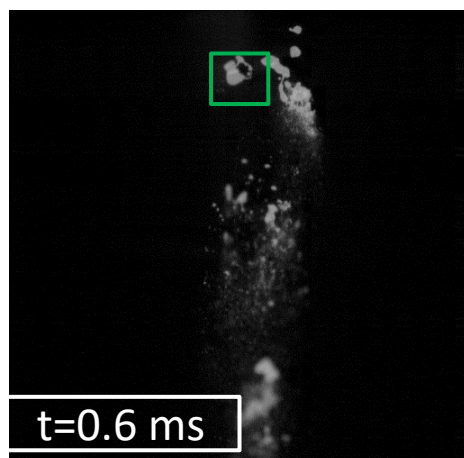
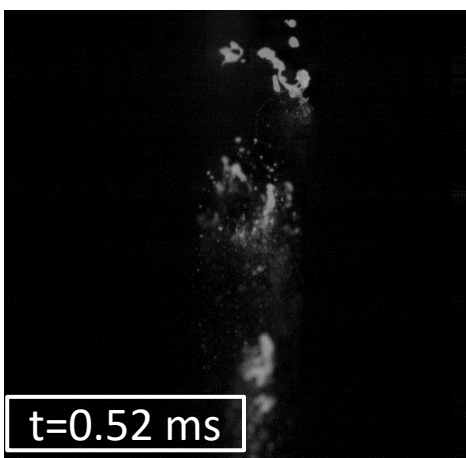
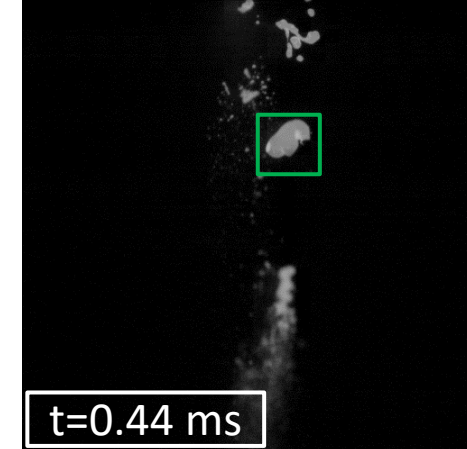
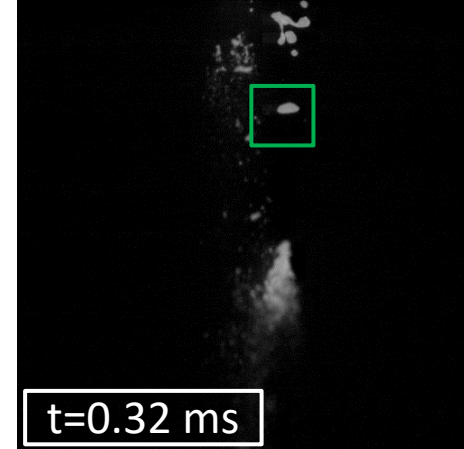
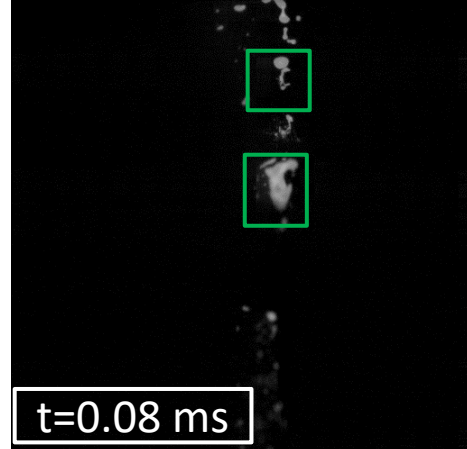
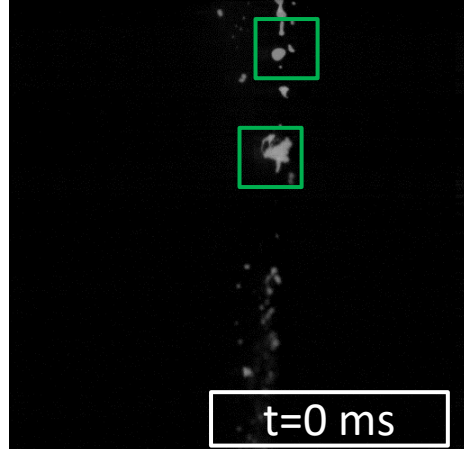
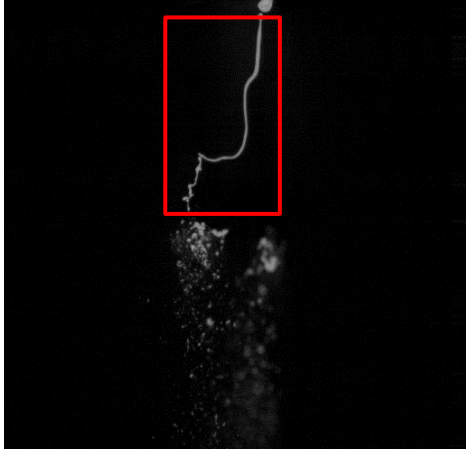
t=2.56 ms

t=2.8 ms

t=2.84 ms

t=3.48 ms

t=3.84 ms



Bag breakup. Primary atomization. $D_{Fil}=1\text{ mm}$
 $We = 30$

Rayleigh breakup. $D = 0.5\text{ mm}$. $We = 10$

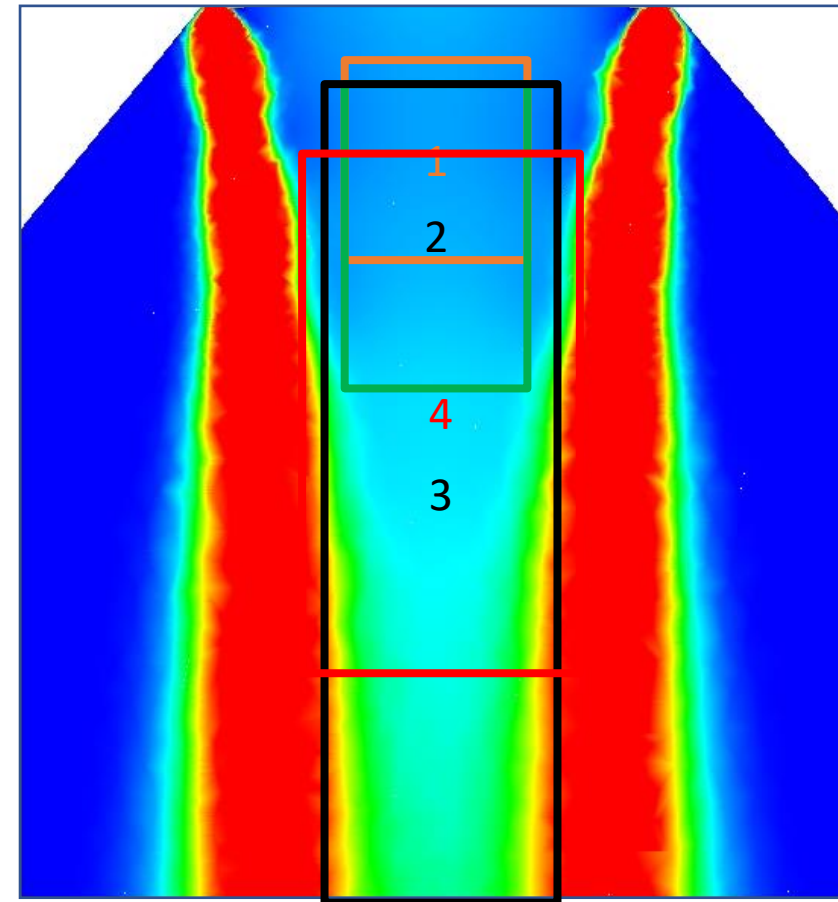
Shear breakup. $D= 2 - 4\text{ mm}$. $We = 70-120$

Bag Breakup. Secondary Fragmentation. $D=2.5\text{mm}$
 $We = 20 - 60$

Atomization Areas: 20 bar

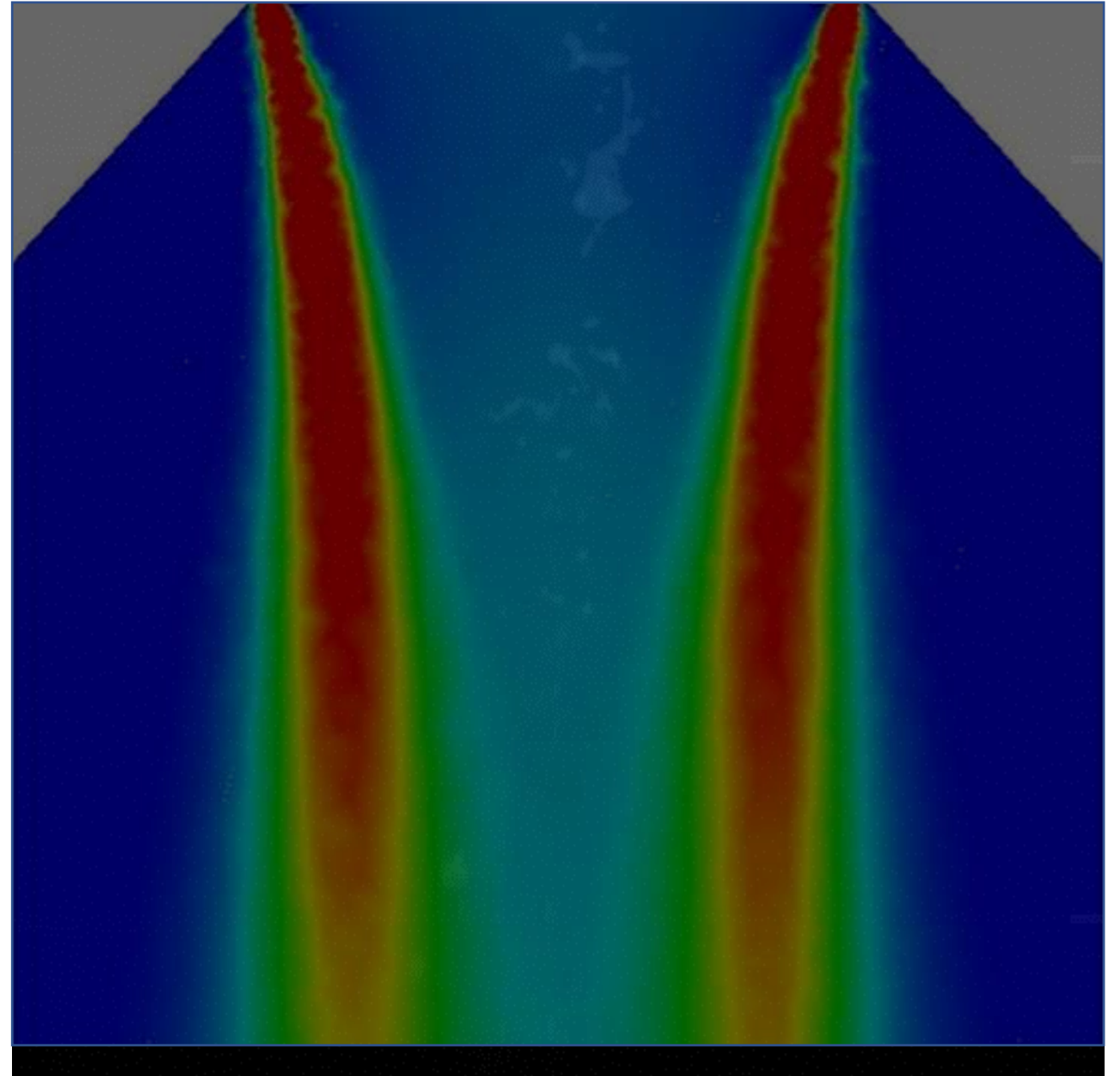
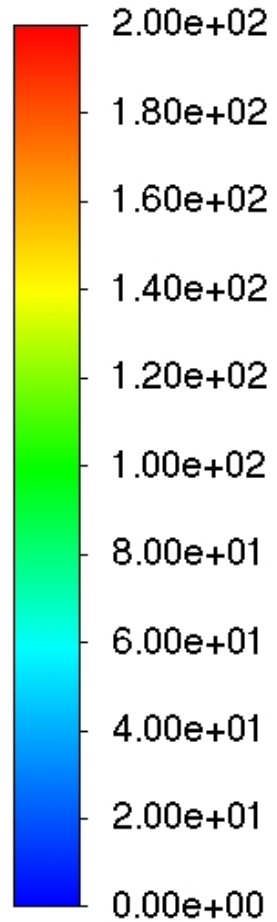
- 1) Fiber breakup
- 2) Rayleigh breakup
- 3) Shear breakup
- 4) Bag breakup

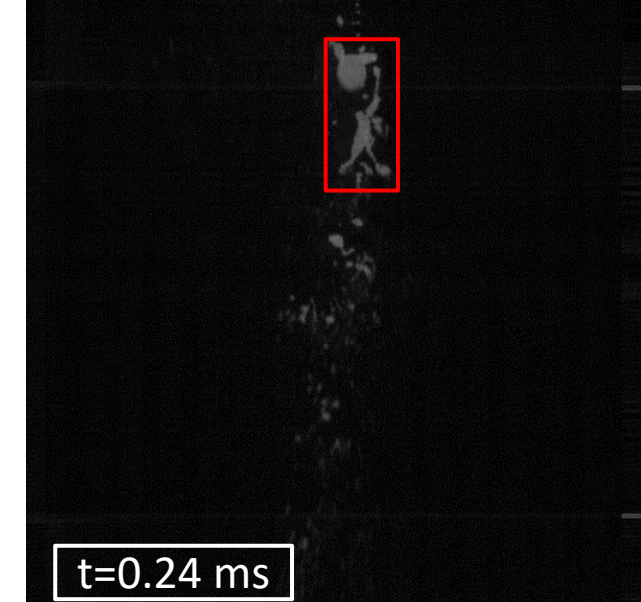
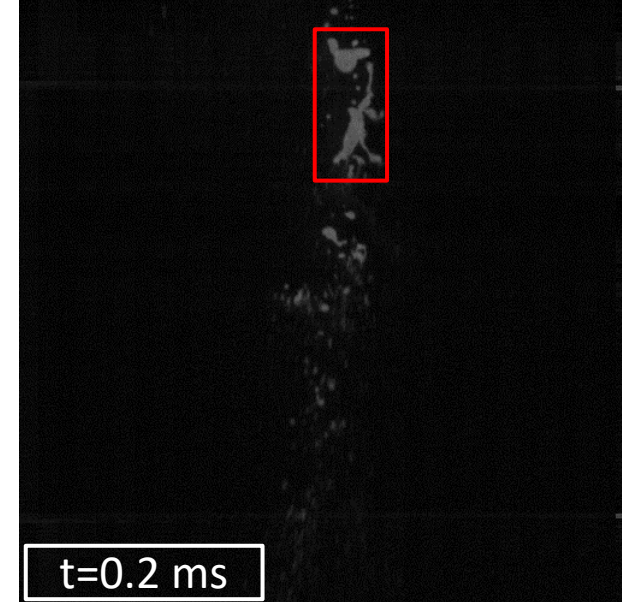
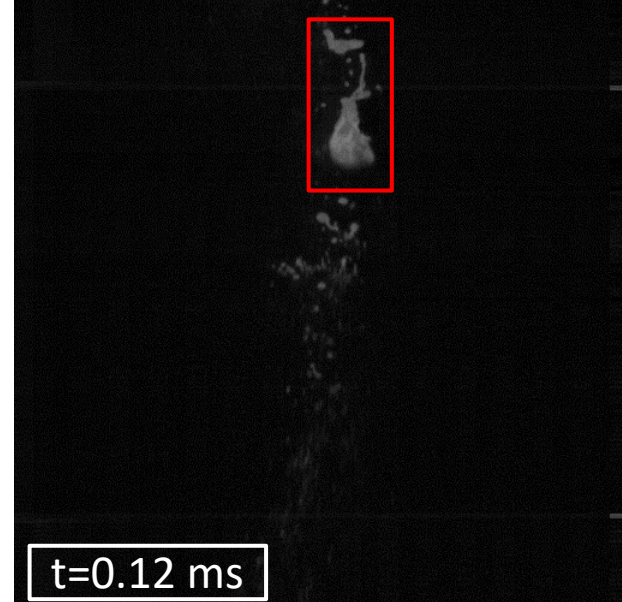
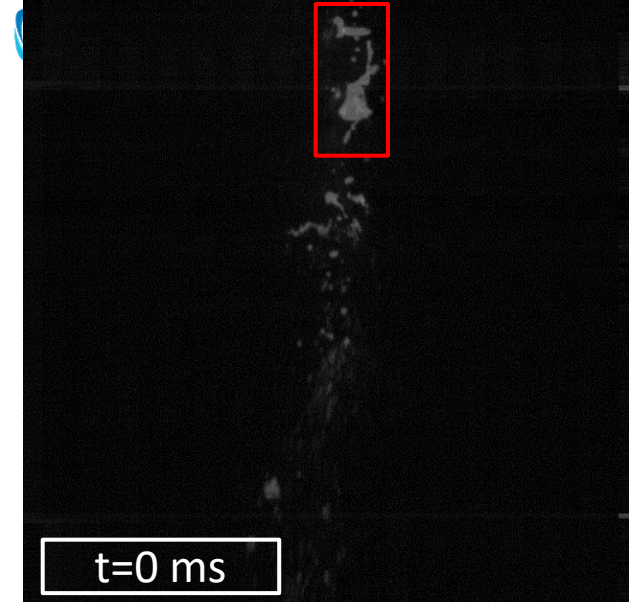
Note: Intermittent jet



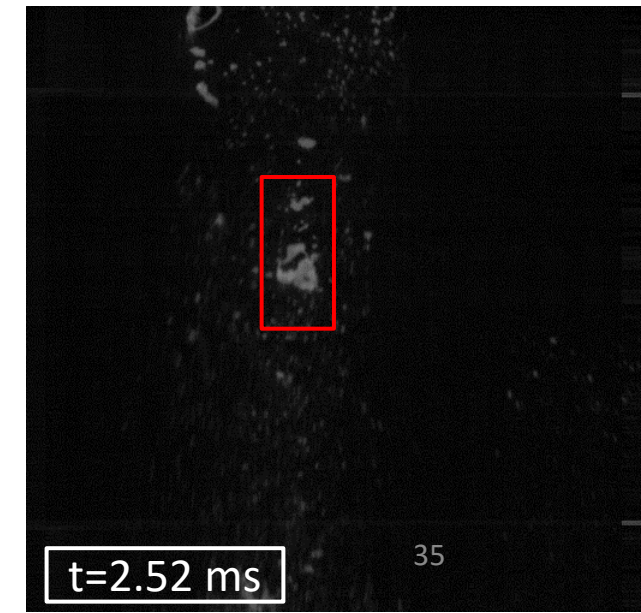
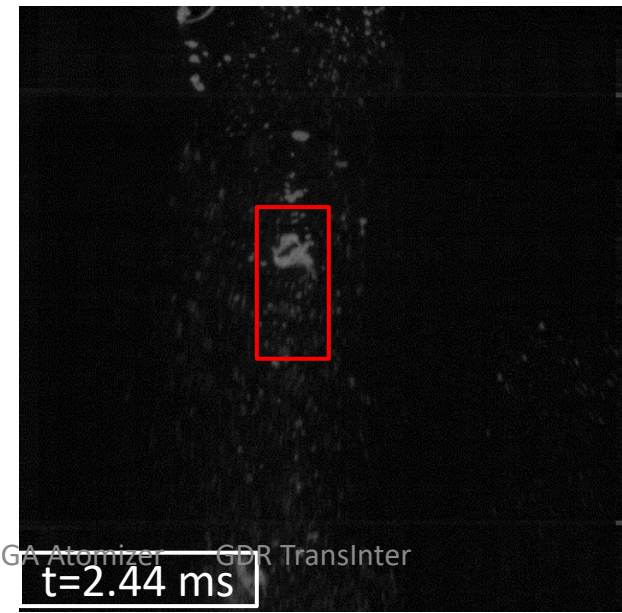
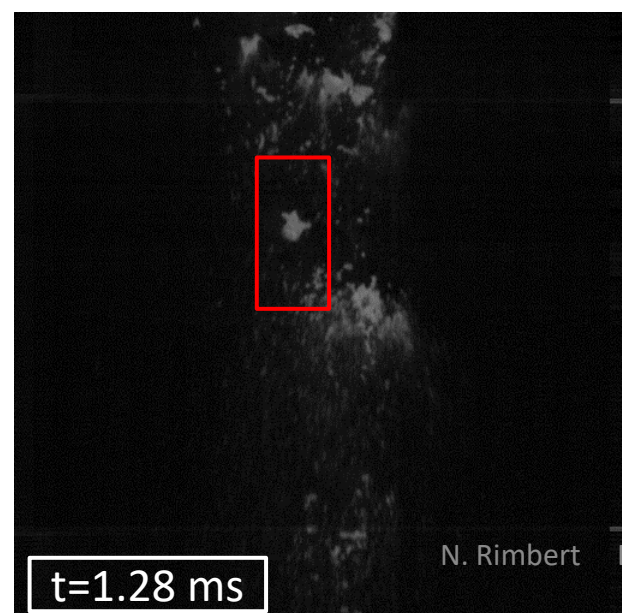
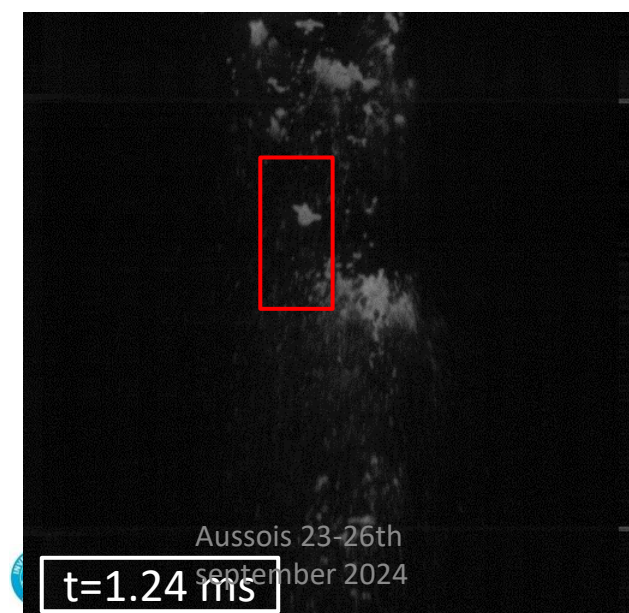
10 bar, PDI 200mbar

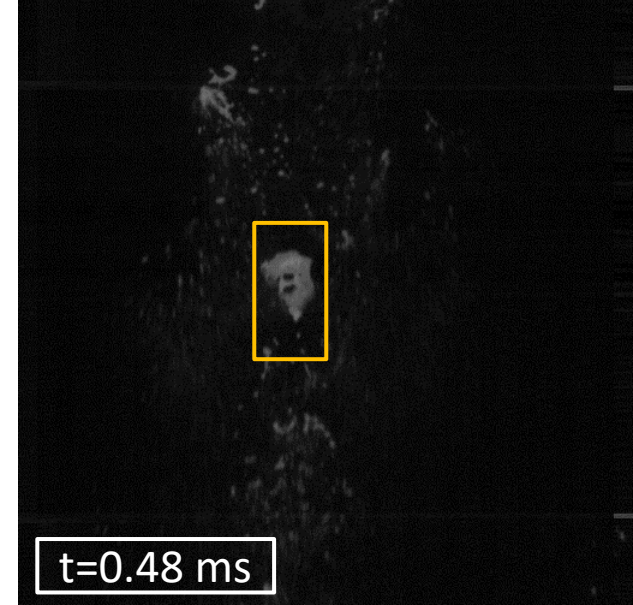
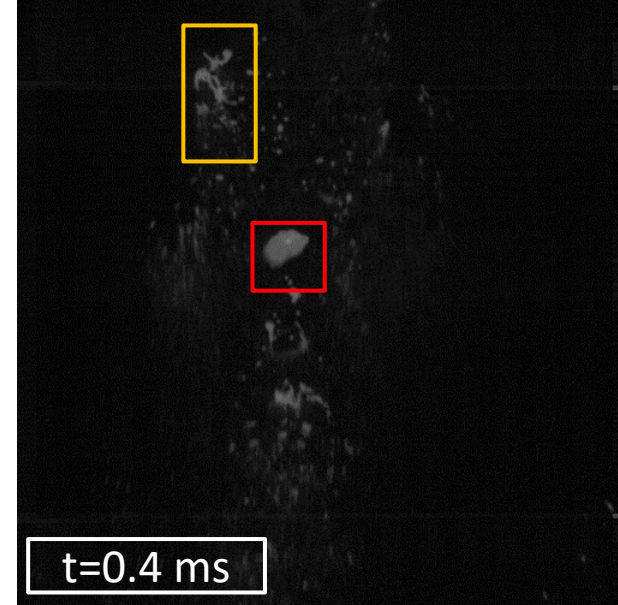
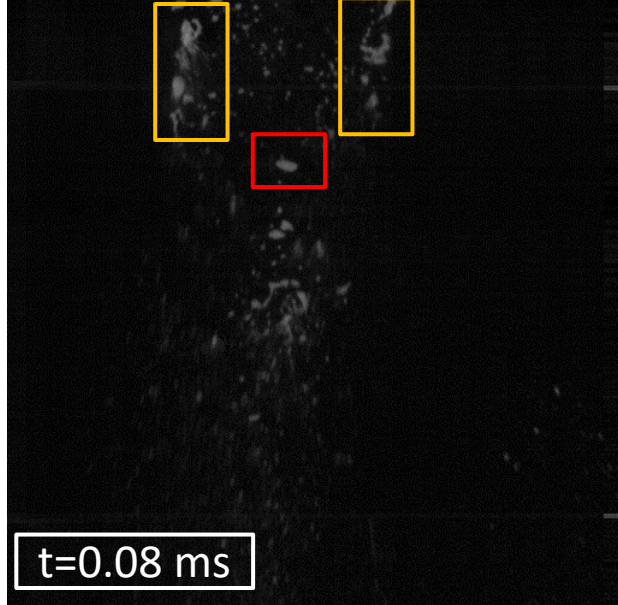
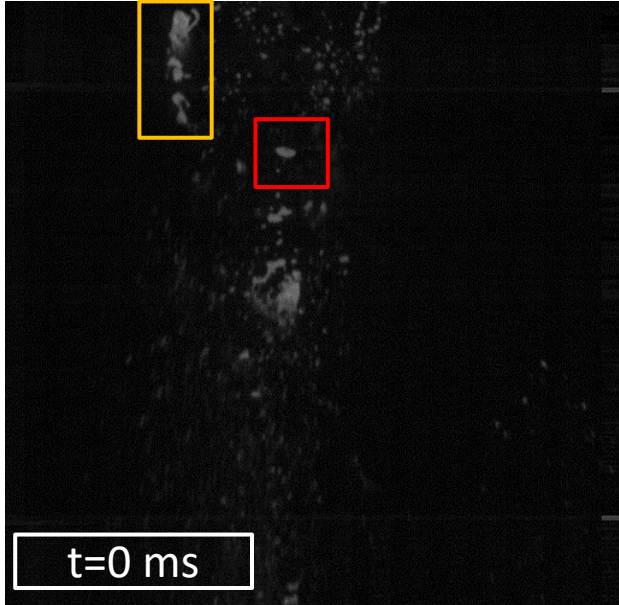
weber-2mm





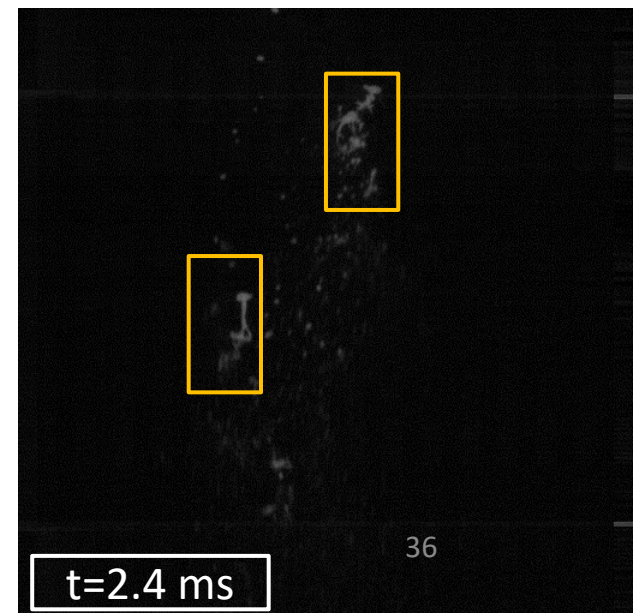
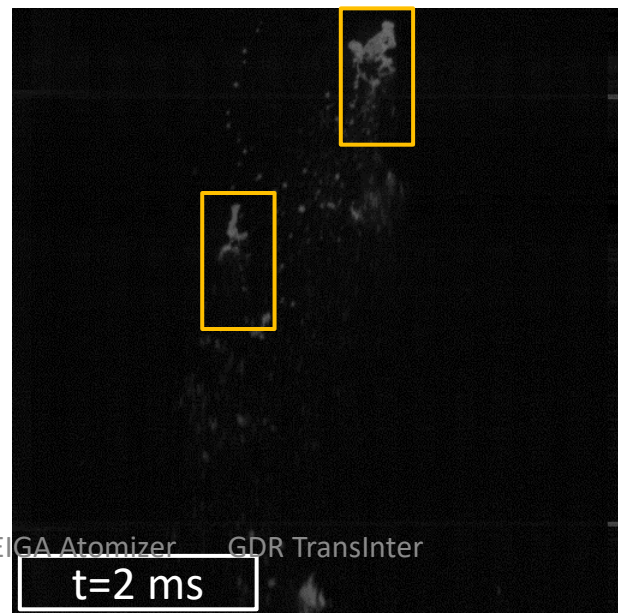
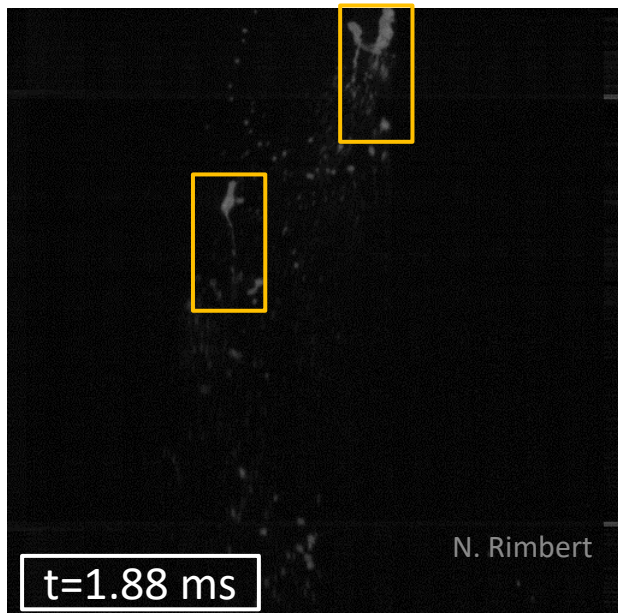
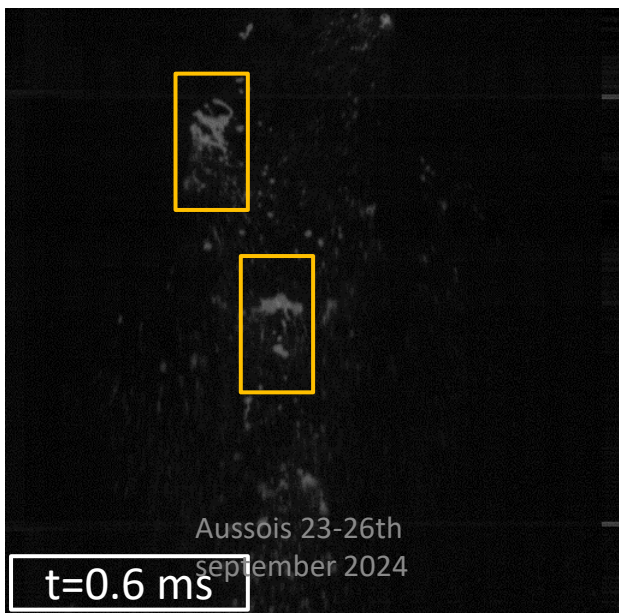
Bag Breakup. Secondary Fragmentation.
D=1-2.5mm. We = 20 - 40

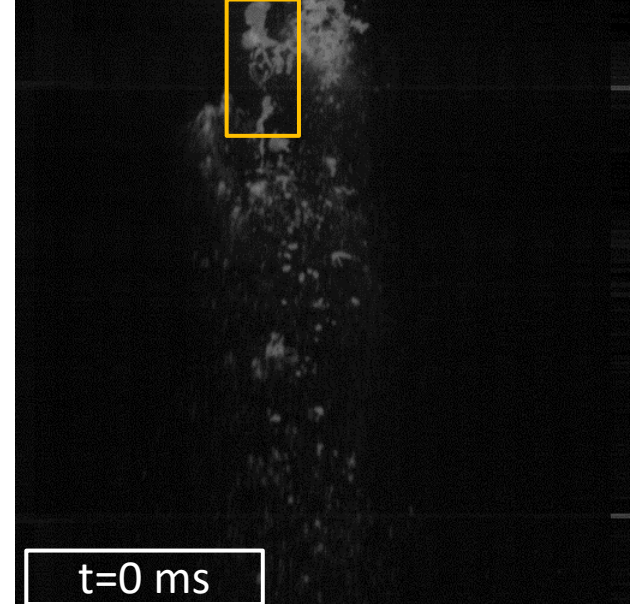
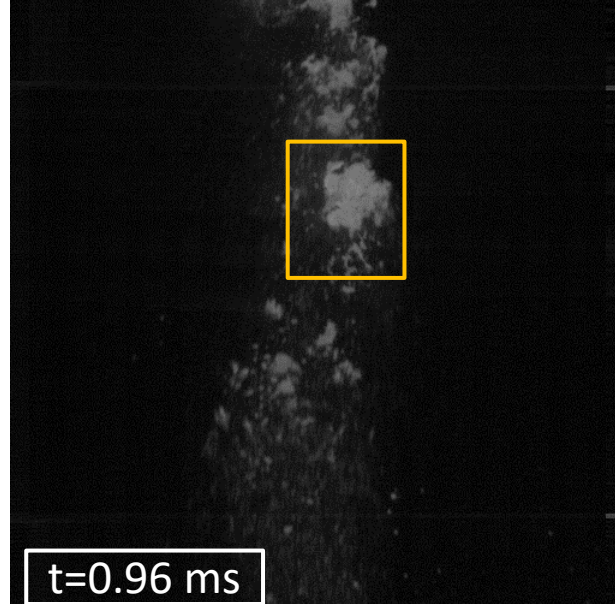
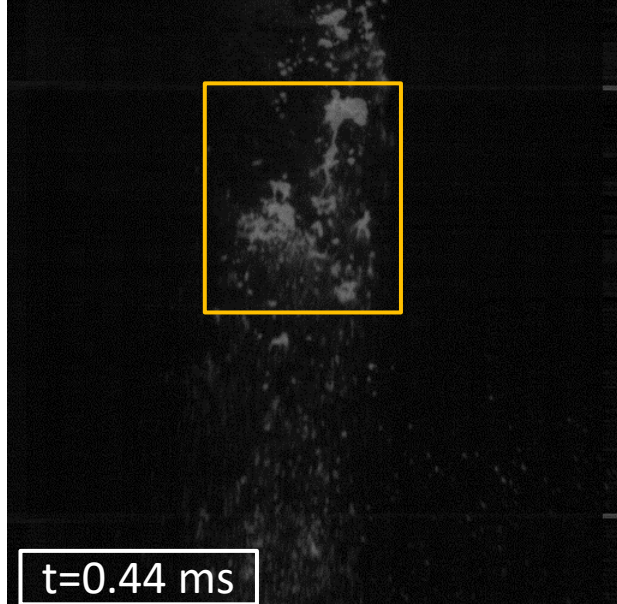
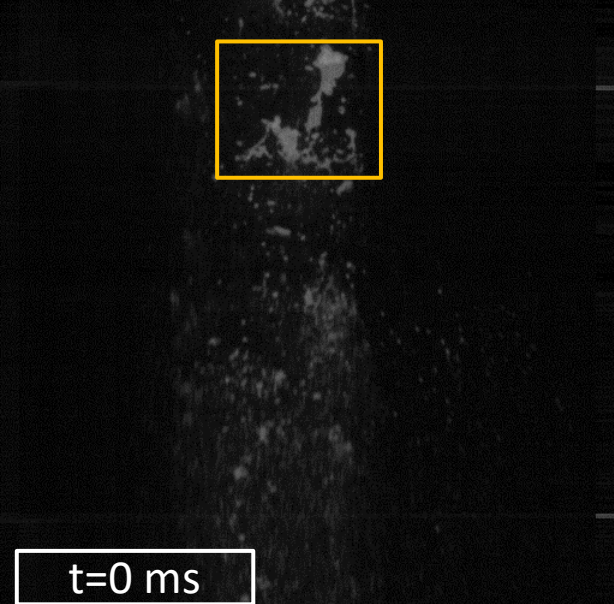




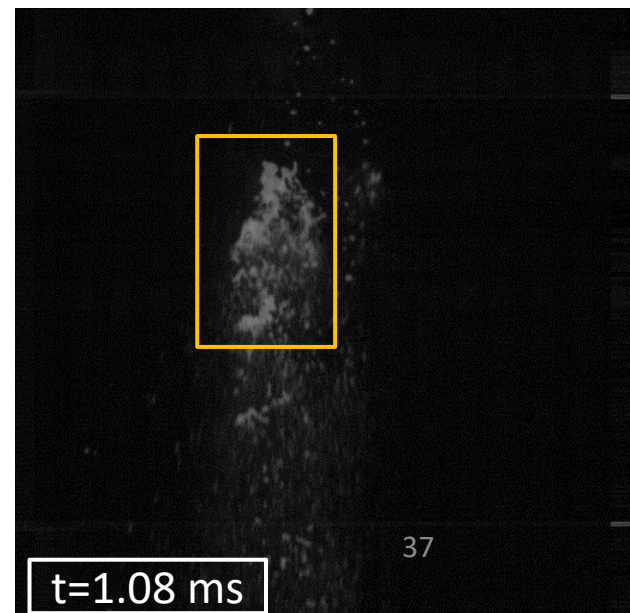
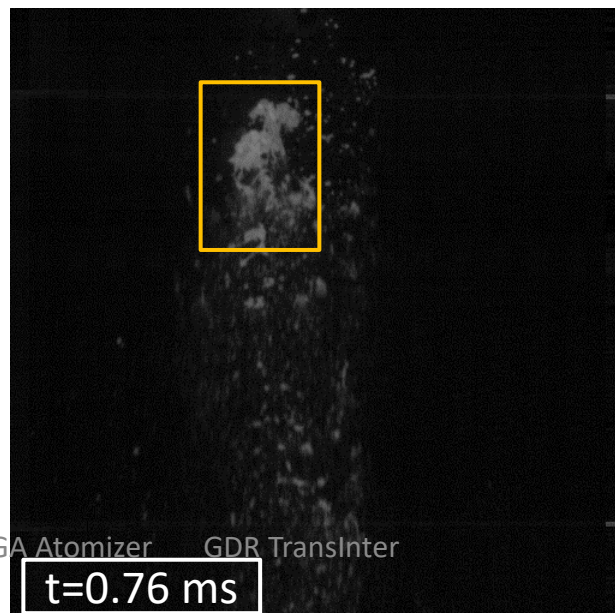
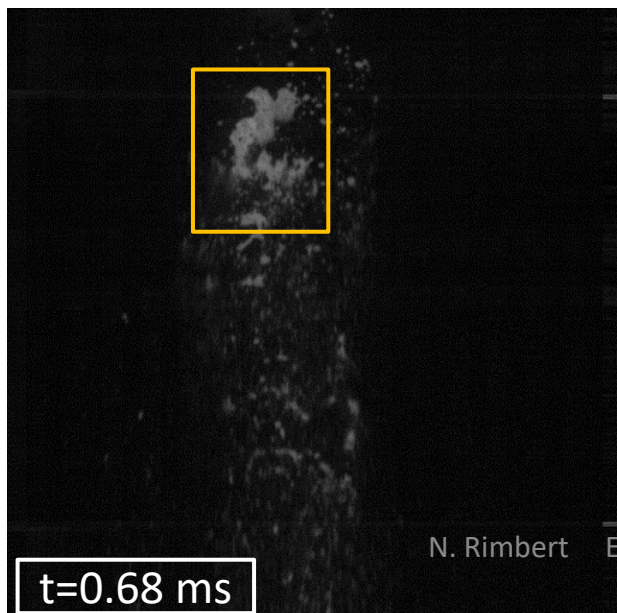
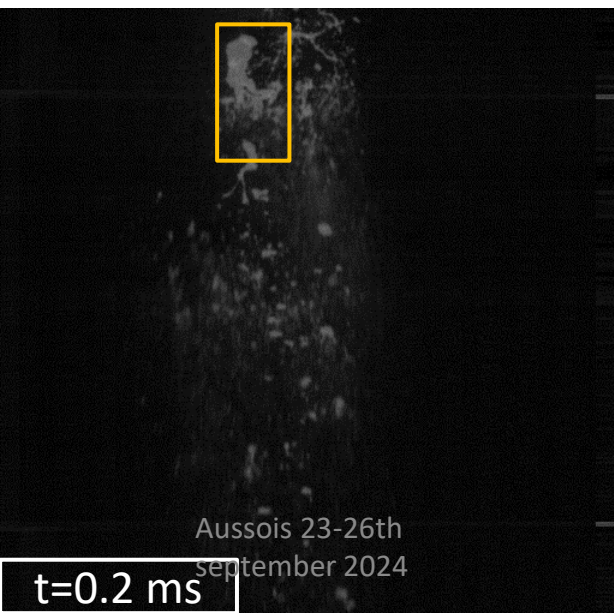
Bag Breakup. $D=1.2$ mm.
 $We = 25$

Shear Breakup. $D=1-2.5$ mm. $We = 60 - 100$





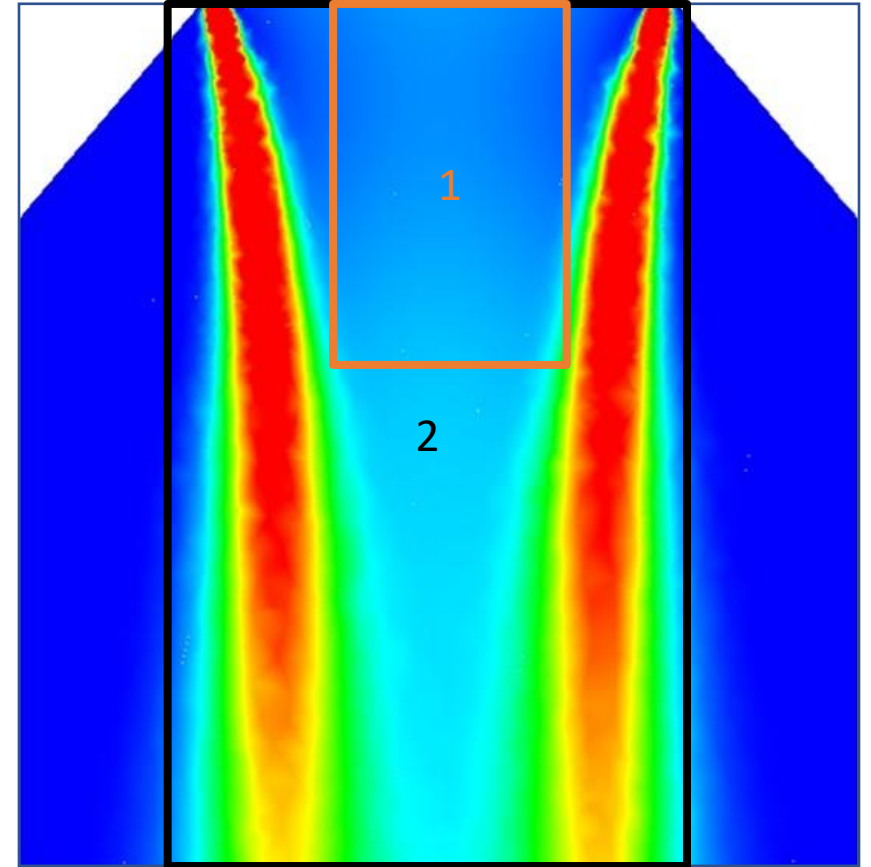
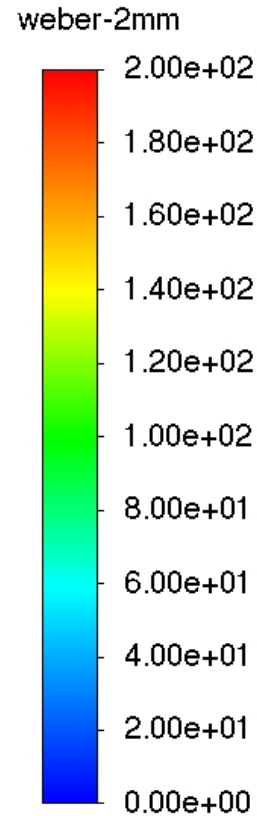
Shear Breakup. $D=1.5-2.5\text{mm}$. $We = 60 - 100$



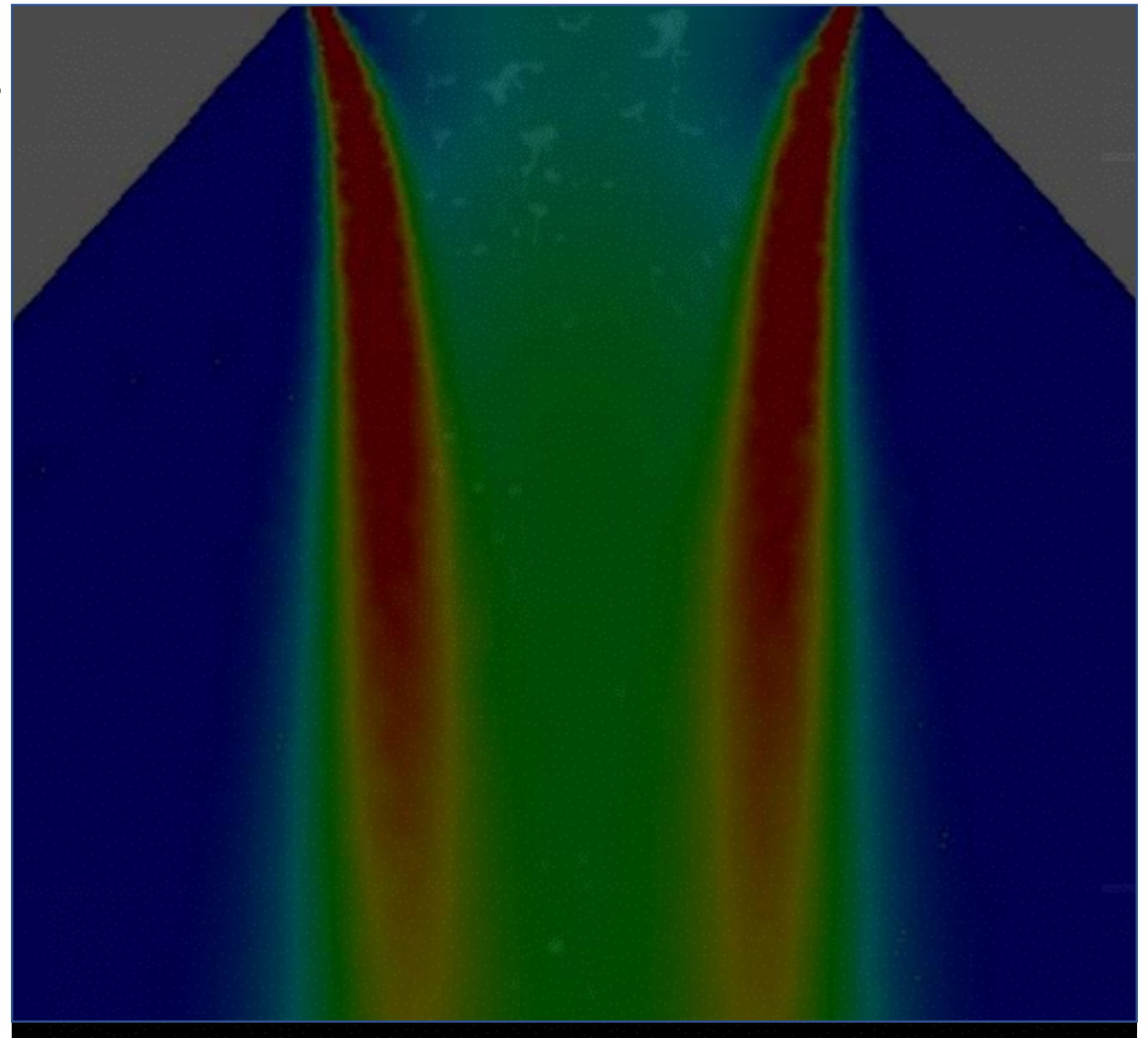
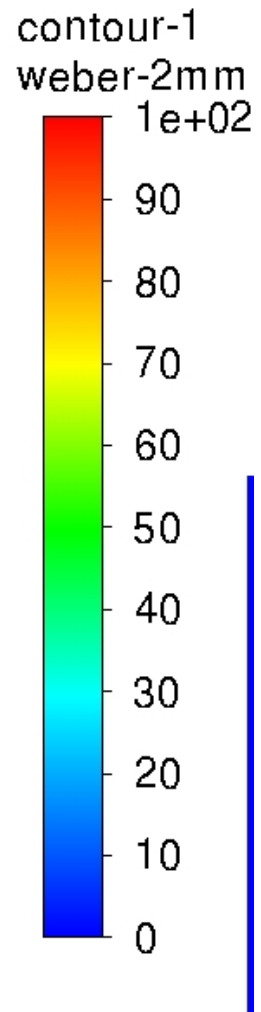
Atomization Areas: 10 bar

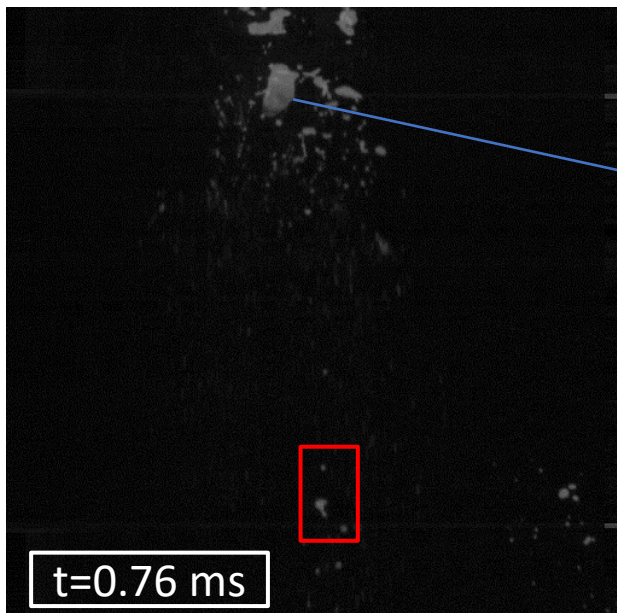
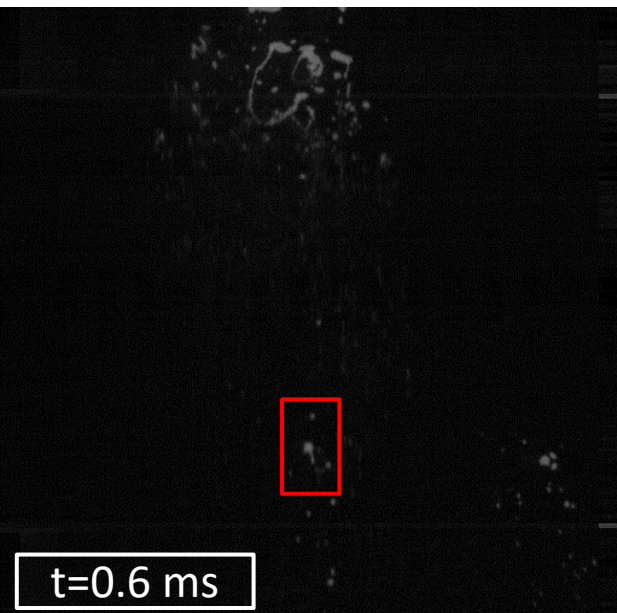
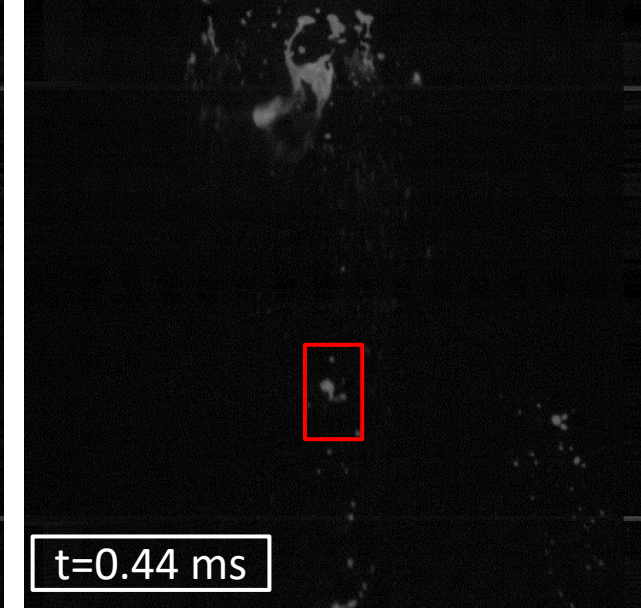
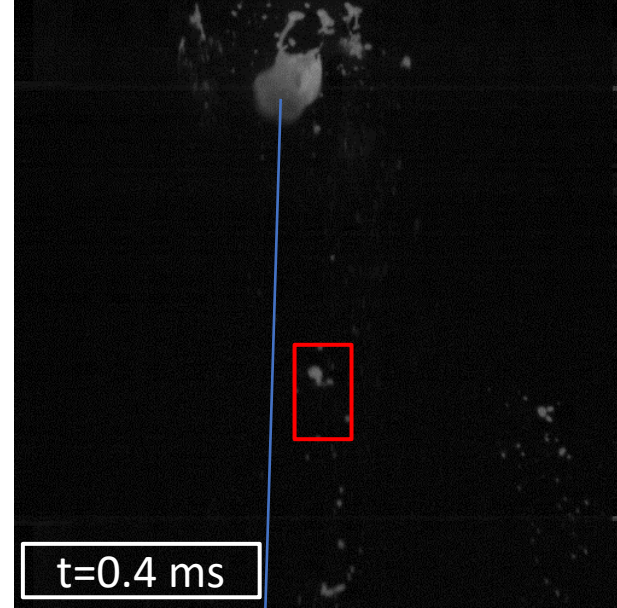
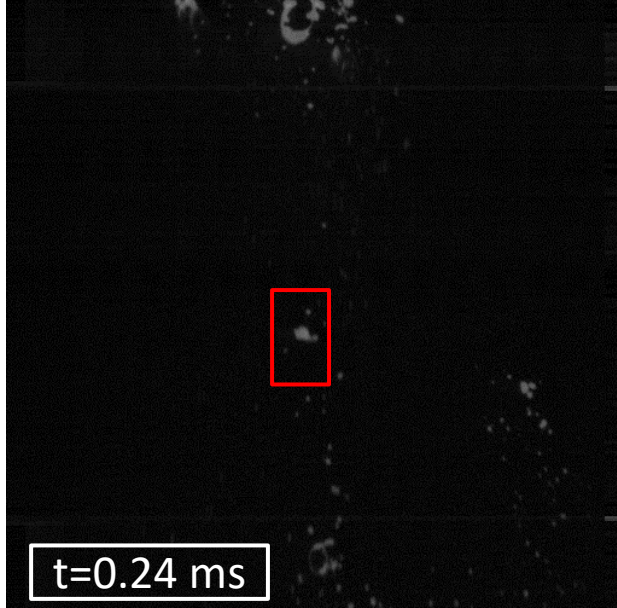
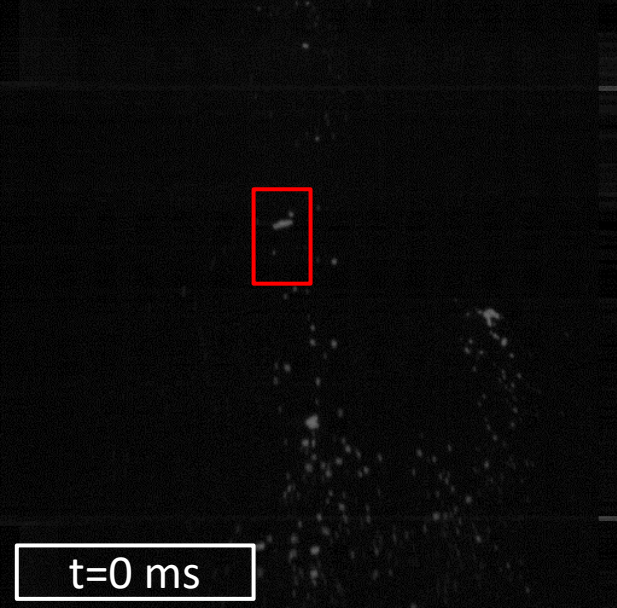
- 1) Bag breakup
- 2) Shear breakup

Note: Continuous jet



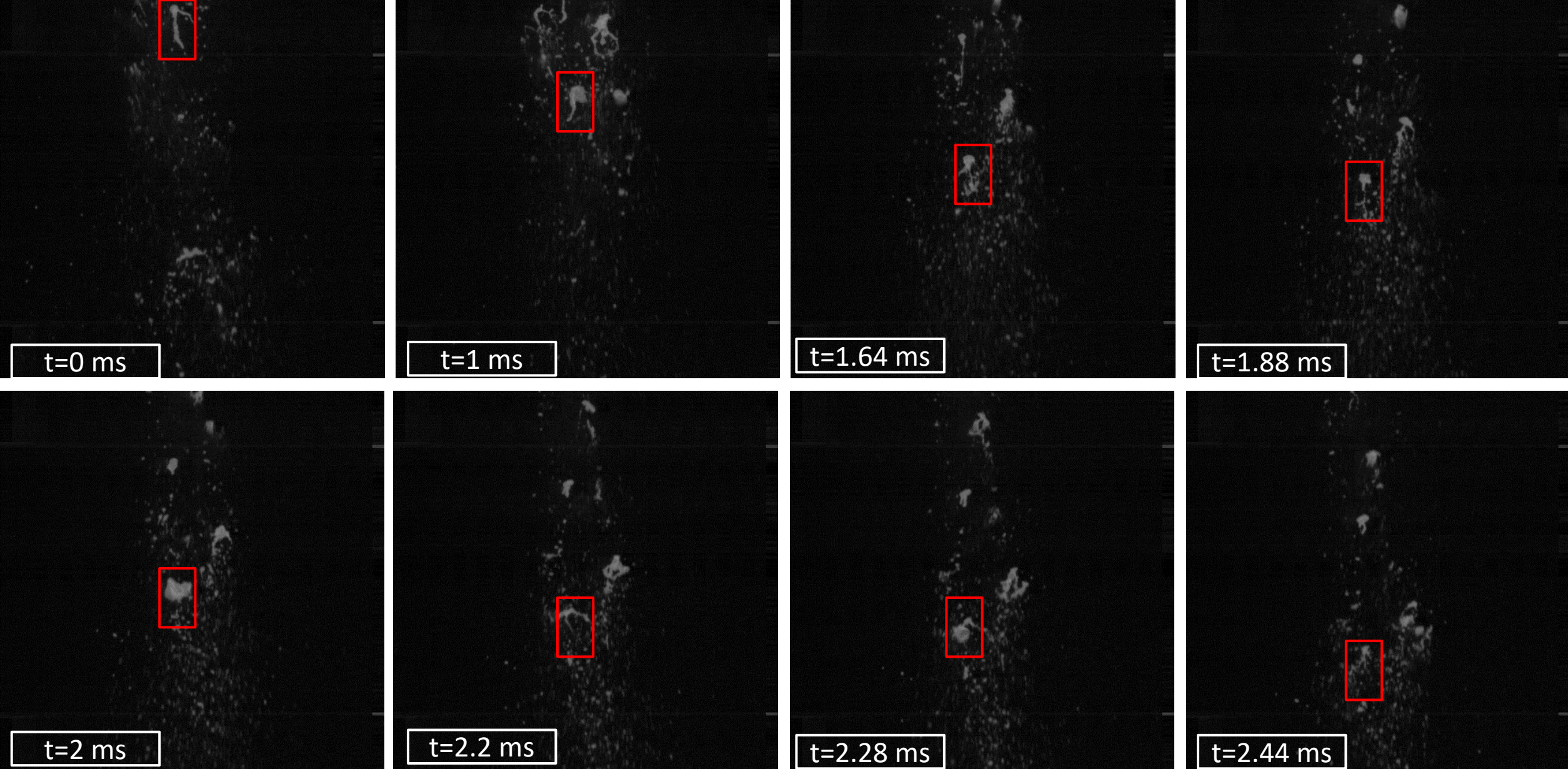
5 bar, PDI 200 mbar





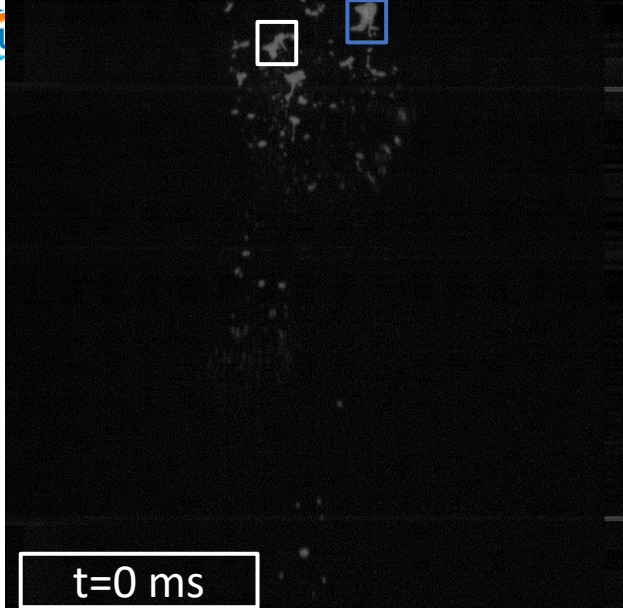
Bag Breakup
 $D_m=1.5\text{mm}$. $We=20-30$
 $U=0.8\text{m/s}$

$D_m=0.5\text{ mm}$. $We > 10$
Vibrational bk
 $U=1\text{ m/s}$

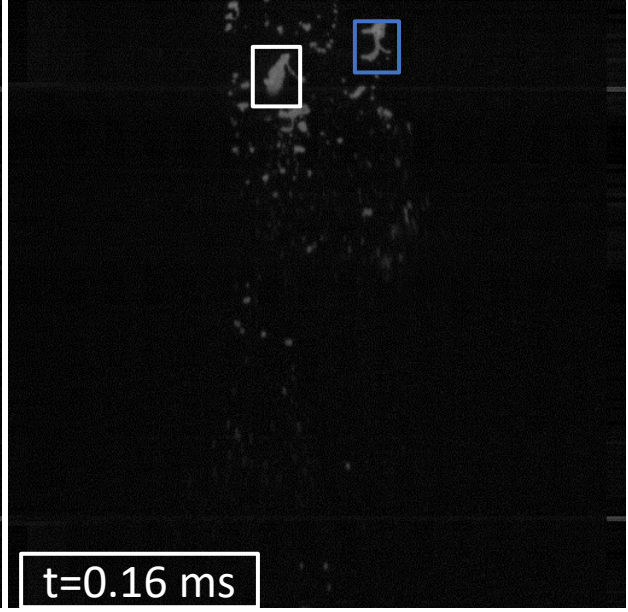


Dm=1.8-2.3 mm. We=30-50
Bag bk ou Multi Bag bk
U=0.7 m/s

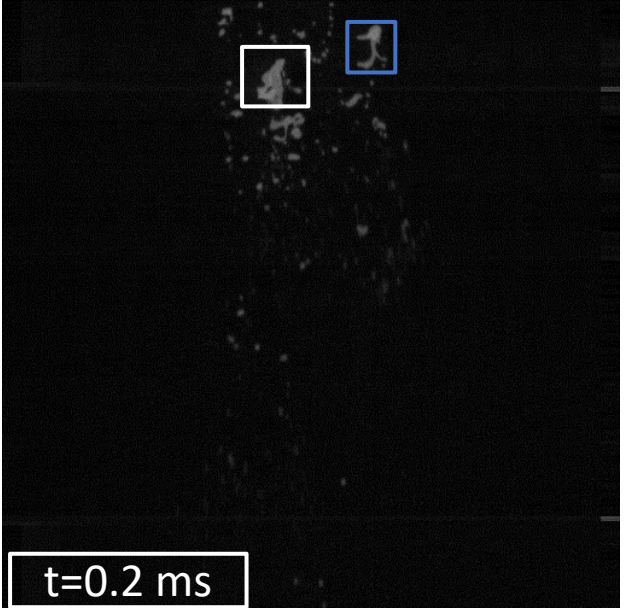
N. Rimbert EIGA Atomizer GDR TransInter



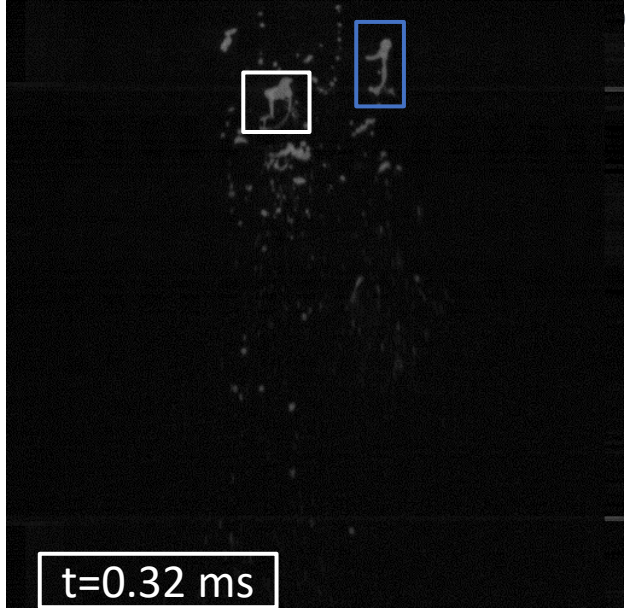
t=0 ms



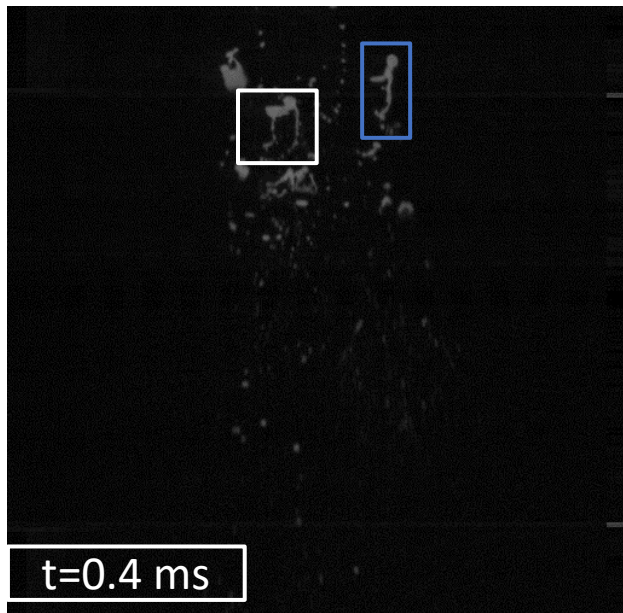
t=0.16 ms



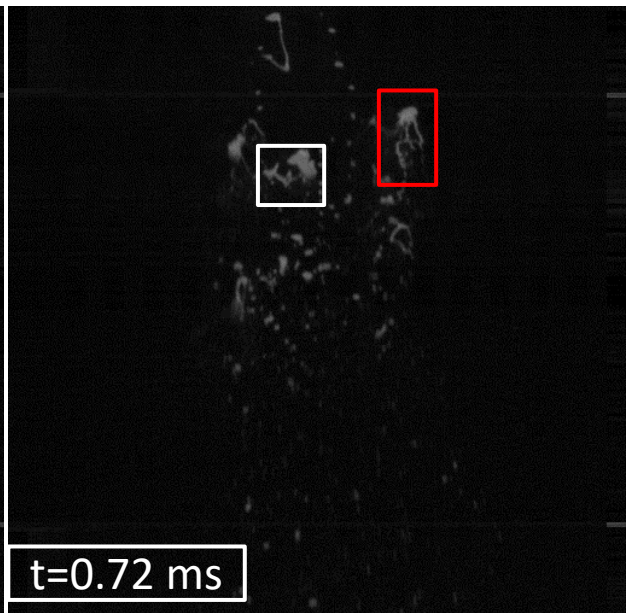
t=0.2 ms



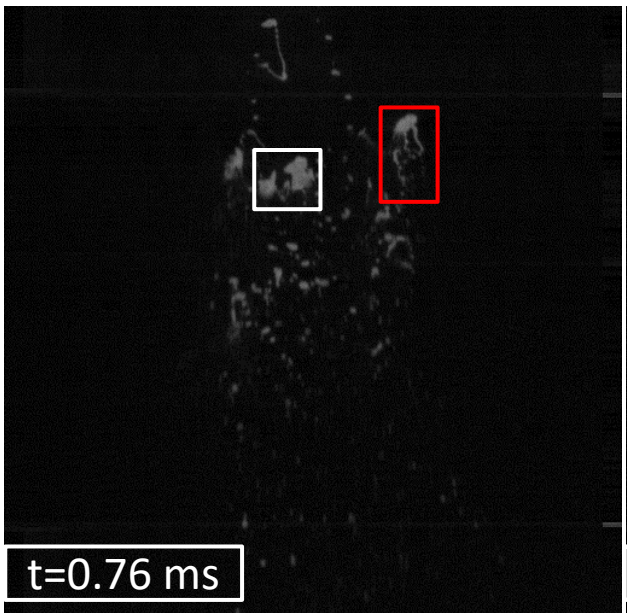
t=0.32 ms



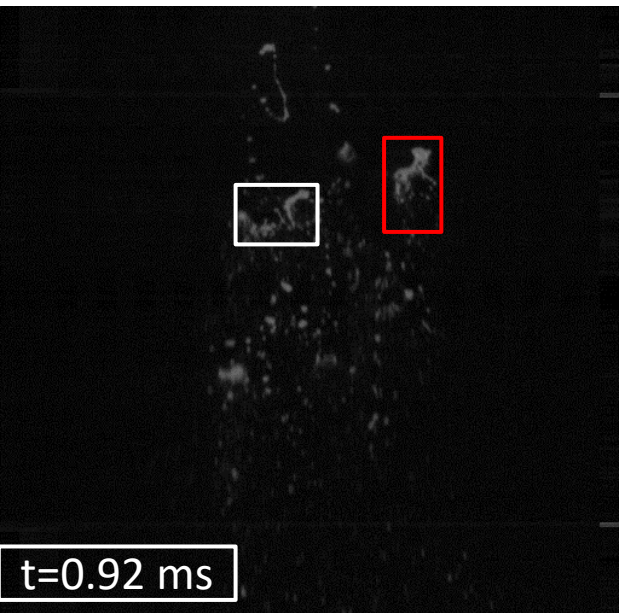
t=0.4 ms



t=0.72 ms



t=0.76 ms



t=0.92 ms

Dm=1.5-2 mm. We=30-50
Bag Breakup Stamen
U = 0.51 m/s

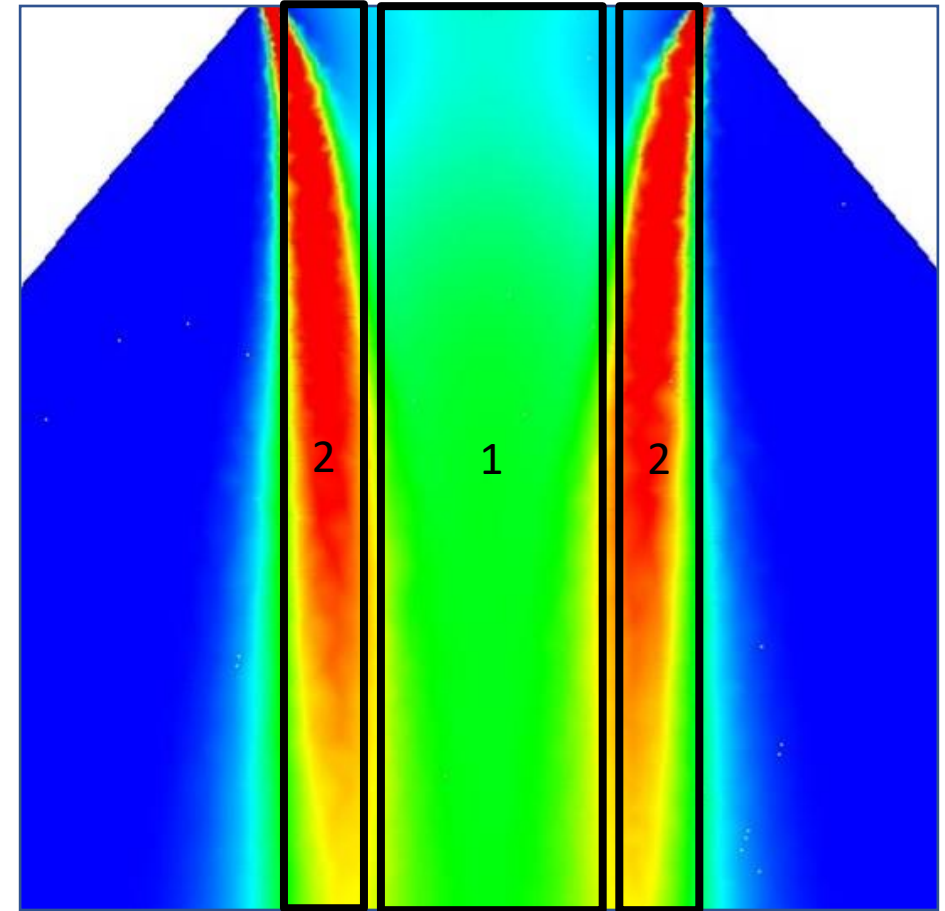
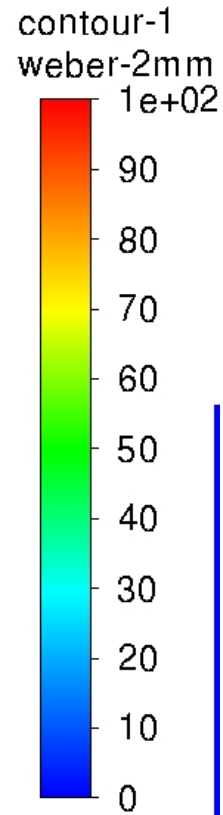
Dm=1.5-2 mm. We=70-100
JellyFish ou Shear bk
U=0.85m/s

Dm=1.5-2 mm. We=20-40
Bag Breakup to shear breakup
U=0.53 m/s

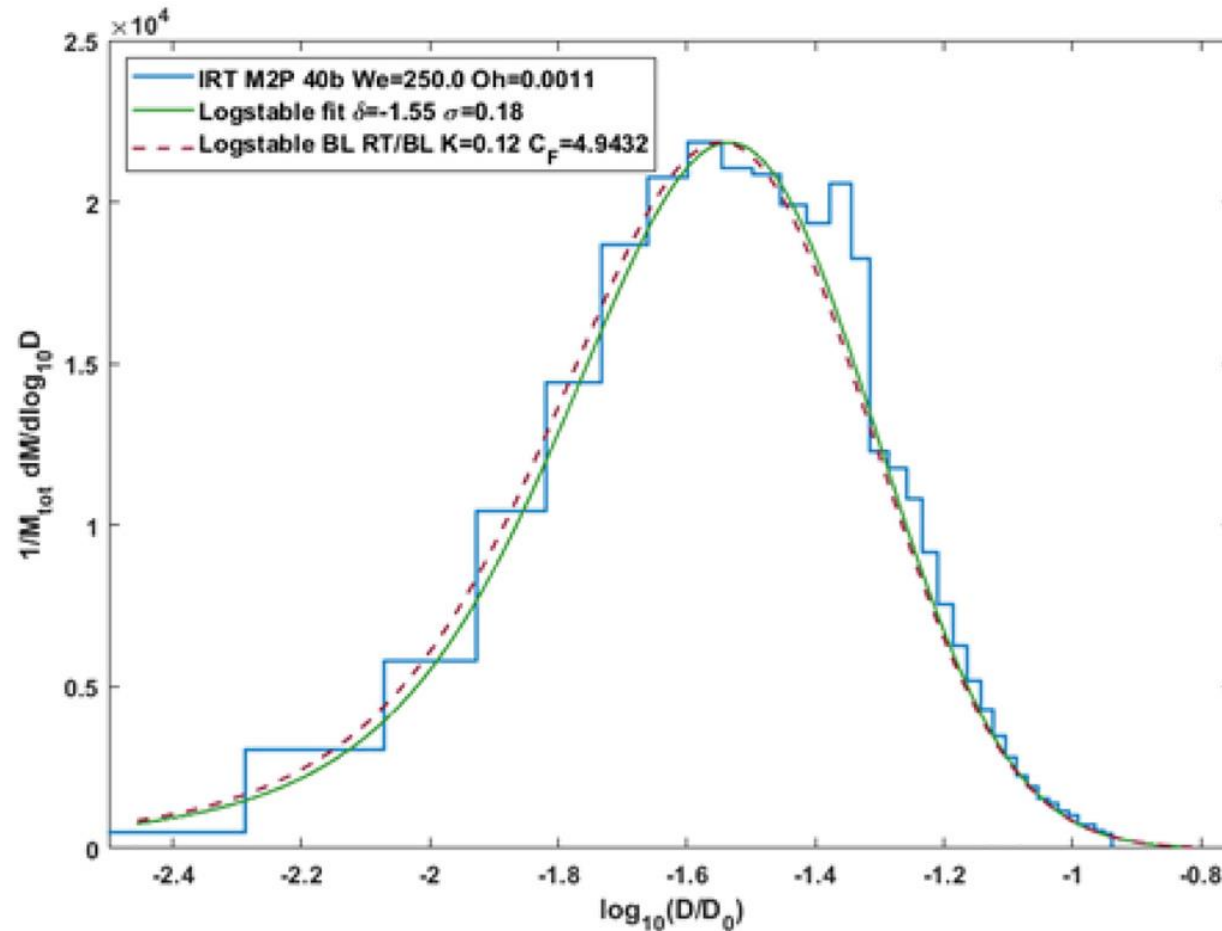
Atomization Areas: 5 bar

- 1) Bag breakup
- 2) Shear breakup

Note: Continuous jet



Mass PDF



Mass/Volume Log-Stable Distribution

Rimbert N., Séro-Guillaume O. *Log-Stable laws as asymptotic solutions to a fragmentation equation: application to the distribution of droplets in a High Weber number Spray* **Phys. Rev. E.** 69, (2004) 056316

N. Rimbert, M. Hadj-Achour, B. Ji, G. Kewalramani, A. Labergue, Y. Dossmann, M. Gradeck, P. Piluso, R. Meignen *Mass log-stable distribution of fragments in liquid-liquid jet fragmentation based on a two-step cascade between viscous shear instability and Rayleigh-Taylor instability* **Int. J. Mult. Flow** 167, 104518 (2023)

Conclusion

- Influence of Injection Pressure
 - Change in dominant regime
 - Bag Breakup
 - Shear Breakup
 - Fiber breakup
 - Rayleigh breakup
 - Transition from continuous to intermittent jet
 - Understanding the fusion process
- Influence of Pressure Difference (PDI) (not shown)
 - Can explain clogging...
- Mass PDF