Experimental Study of Liquid-Liquid Fragmentation

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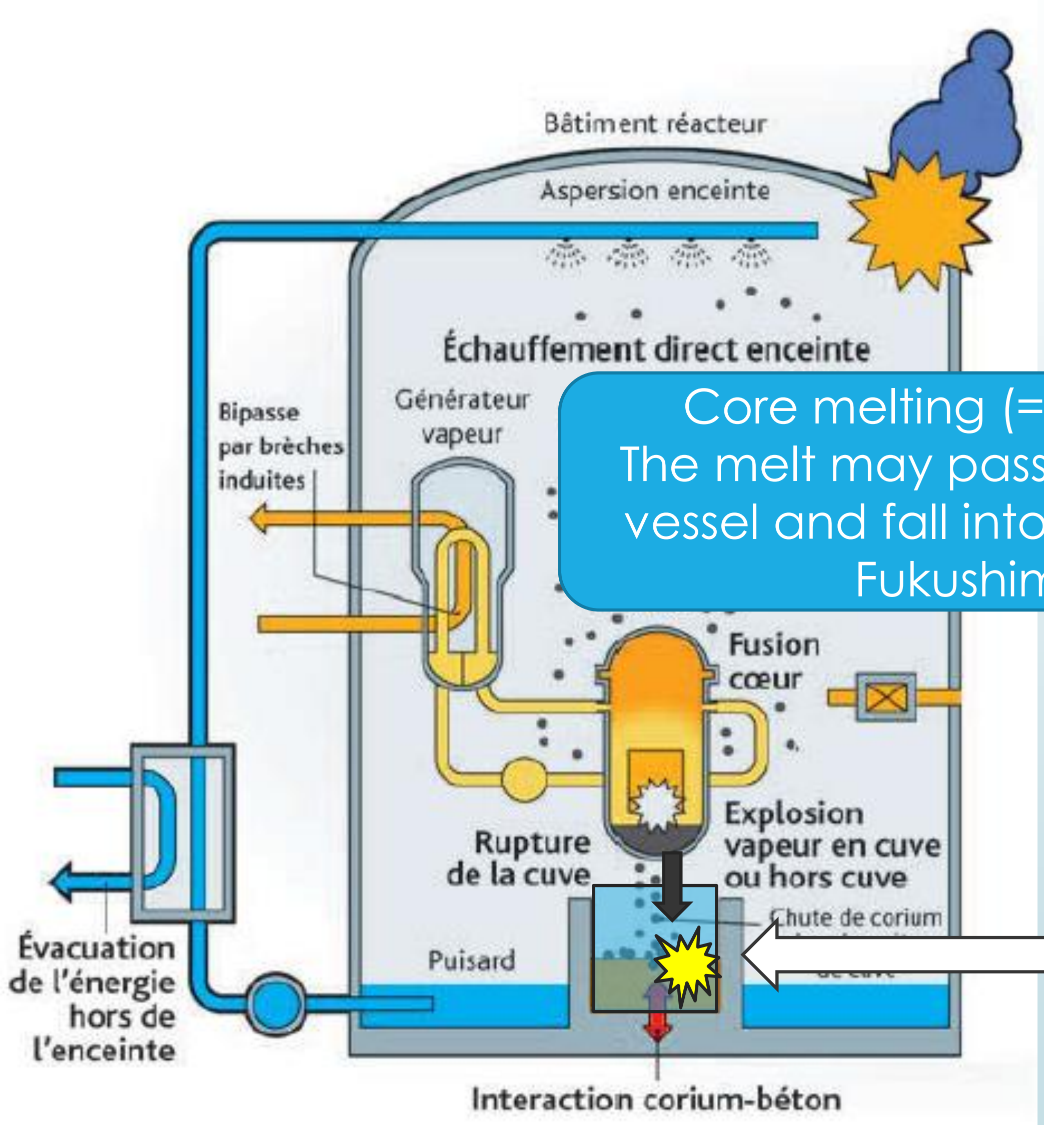
The Project



Source: Livre d'accidents graves IRSN

Core melting (=> corium ~3000 K)
The melt may pass through the reactor vessel and fall into the reactor pit (e.g. Fukushima Daiichi)

Steam explosion risk in mitigation strategies with water in the reactor pit (In-Vessel Retention)

Simplifying Assumptions

- Gas-liquid atomization has been studied a lot!
- Liquid-liquid atomization is easier!
- No vapour!
- The goal: understand the mechanism!

Experimental Facility

- Electromagnetically controlled injector:
- Pneumatic pressure control
- Cargille fluid (transparent) is injected in water tank of 50x50x40 cm^3

	ρ (kg/m3)	μ (Pa-s)
Water	998.2	1.05
Cargille	1896.52	26.02

- Surface tension $\sigma = 0.0265$N/m
- Jets with nozzle diameter 1,2,3 and 4 mm with various injection pressure are produced

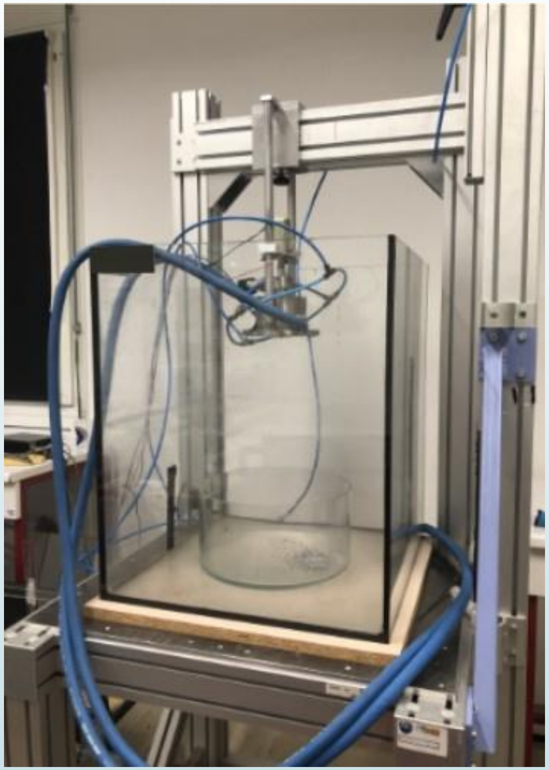
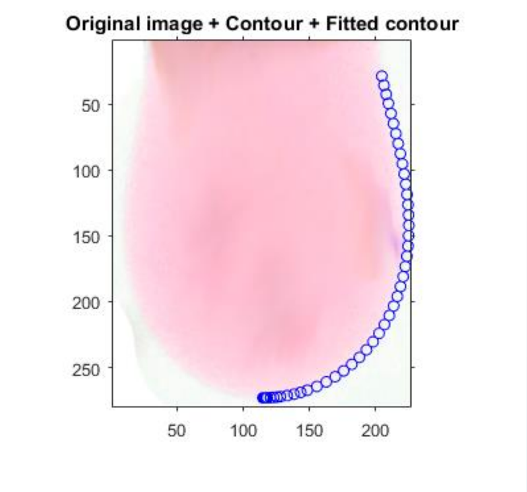
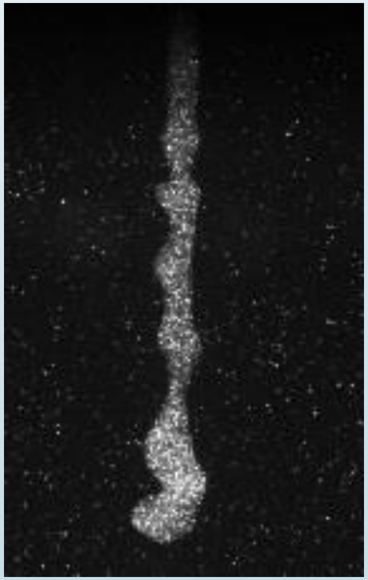


Figure:Experimental setup 'JaLad'

Cargille Fluid

- Density
  - $\rho = 1896.52\ kg/m^3$
- Viscosity
  - $\mu = 26.02$ mPa.s
- Optical index
  - n = 1.3330 (id. eau)
- Surface tension
  - $\sigma = 0.0265 N/m$
- Pyrrométhene 597
  - Fluorescent Dye





Cargille Fluid/Laser Sheet

- Laser sheet 532nm
- Camera records images with9000 fps with lens of 150mm focus length (aperture F2.8)
- Images with pixel size of 99.5 µm
- Pyromethene 597-8C9 dye with absorption coefficient
- a = 5.25 · 10−4L/(mol · cm)at 524nm

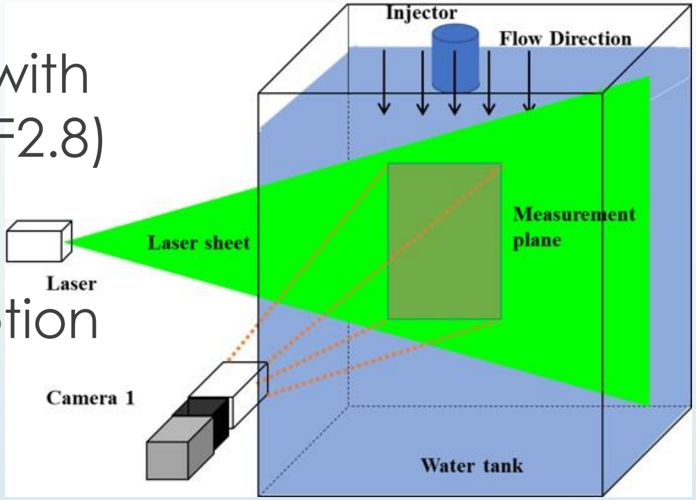


Table 1 Velocity (in m/sec), Diameter, Reynolds number (Re) and Weber number (We) for various jets.

Exp:	U_0	Re	We	Exp:	U_0	Re	We	Exp:	U_0	Re	We
D2V1	1.92	295	279	D2V2	2.96	455	663	D2V3	5.46	838	2248
D3V1	1.62	375	300	D3V2	3.13	764	1245	D3V3	5.96	1375	4027
D4V1	1.72	530	449	D4V2	3.05	938	1408	D4V3	5.90	1813	5256

Non Dimensional Numbers

- Weber number

$$We_C = \frac{\rho_C U_\infty^2 2R_0}{\gamma}$$

- Ohnesorge number (or viscosity group)

$$Oh = \frac{\mu_L}{\sqrt{2R_0 \rho_L \gamma}}$$

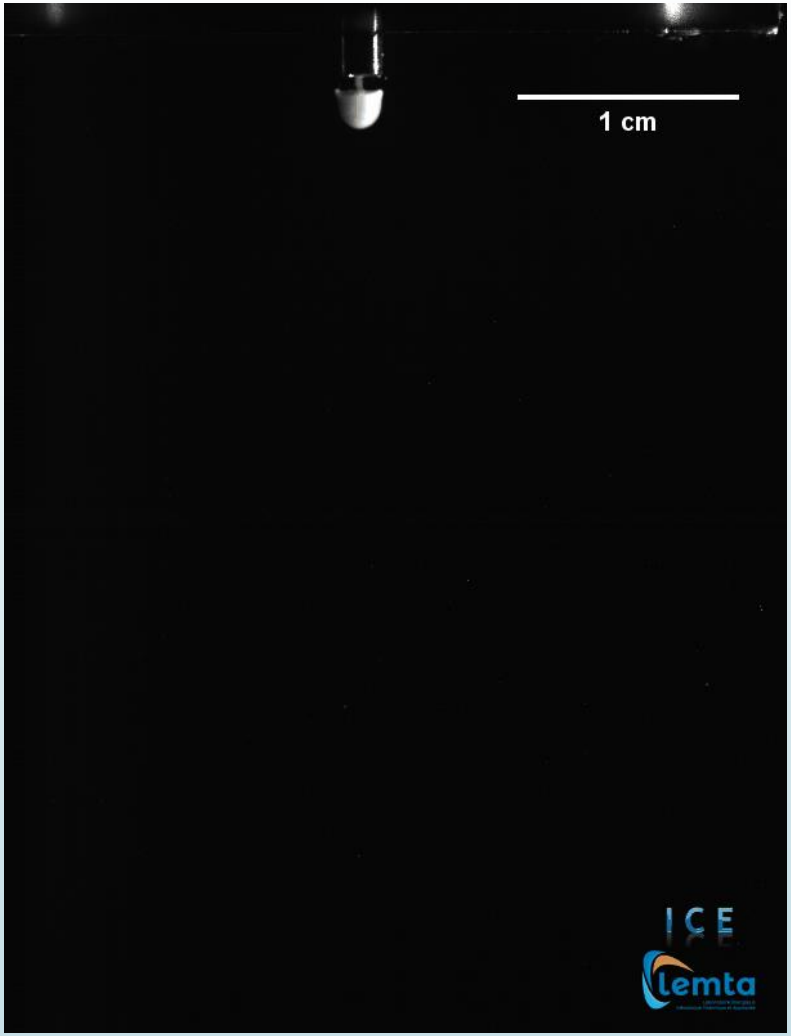
- Density ratio

$$\rho_R = \frac{\rho_L}{\rho_C}$$

- Viscosity Ratio

$$\mu_R = \frac{\mu_L}{\mu_C}$$

Experimental Results



1 Lagrangian Analysis

Tracks

Tracks is a commercial software

Filtering and Calibration → Detection → Tracking

- To reduce noise in images
  - background subtraction
- Multiscale threshold method
  - in-homogeneous lighting and absorption effects.
- Droplet identification
  - clouds contour detection method

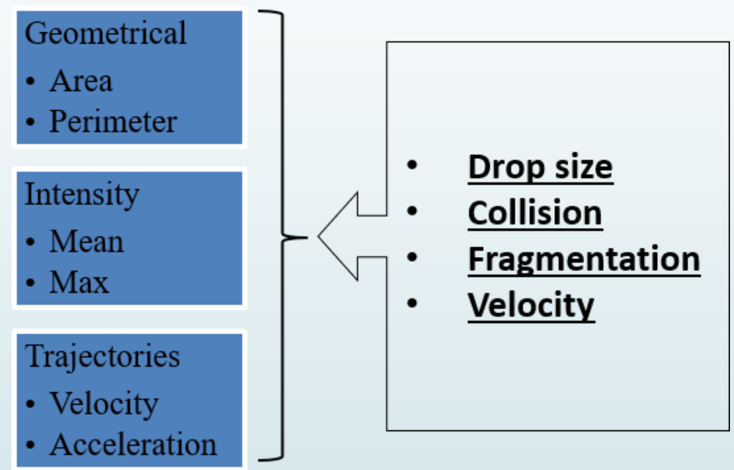
Tracks

Drops are tracked with a predictive tracking algorithm using Kalman filtering method

For each ID, detection

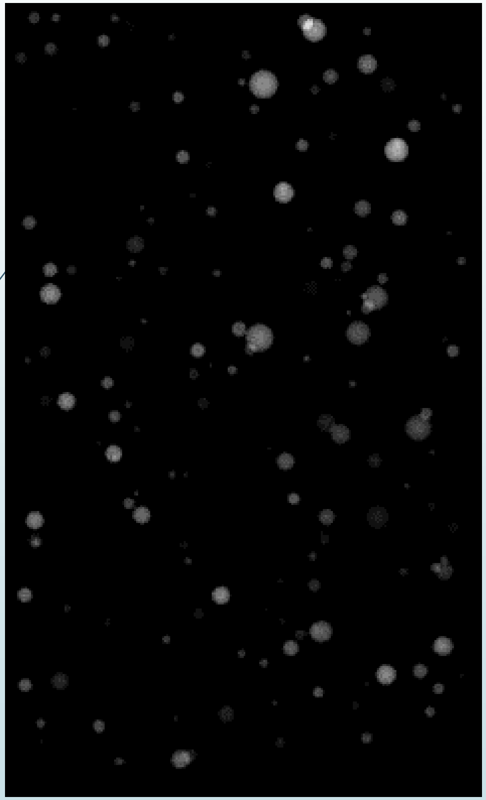
we may have various information.

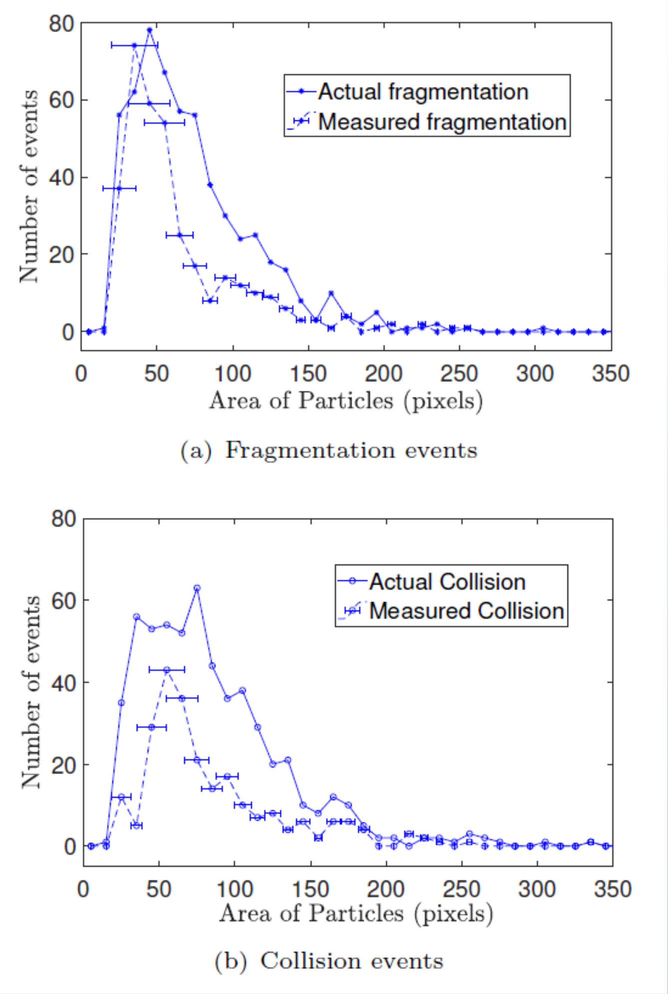
This information for ID is processed to identify events.



- For identifying collision and fragmentation constraints on
  - Change in Area $\frac{dA}{A}$
  - Velocity Jump $\frac{dV_{mag}}{V_{mag}}$
  - Compactness $C = \frac{4\pi \text{Area}}{\text{Perimeter}^2}$

Synthetic Data for Validation





(a) Fragmentation events

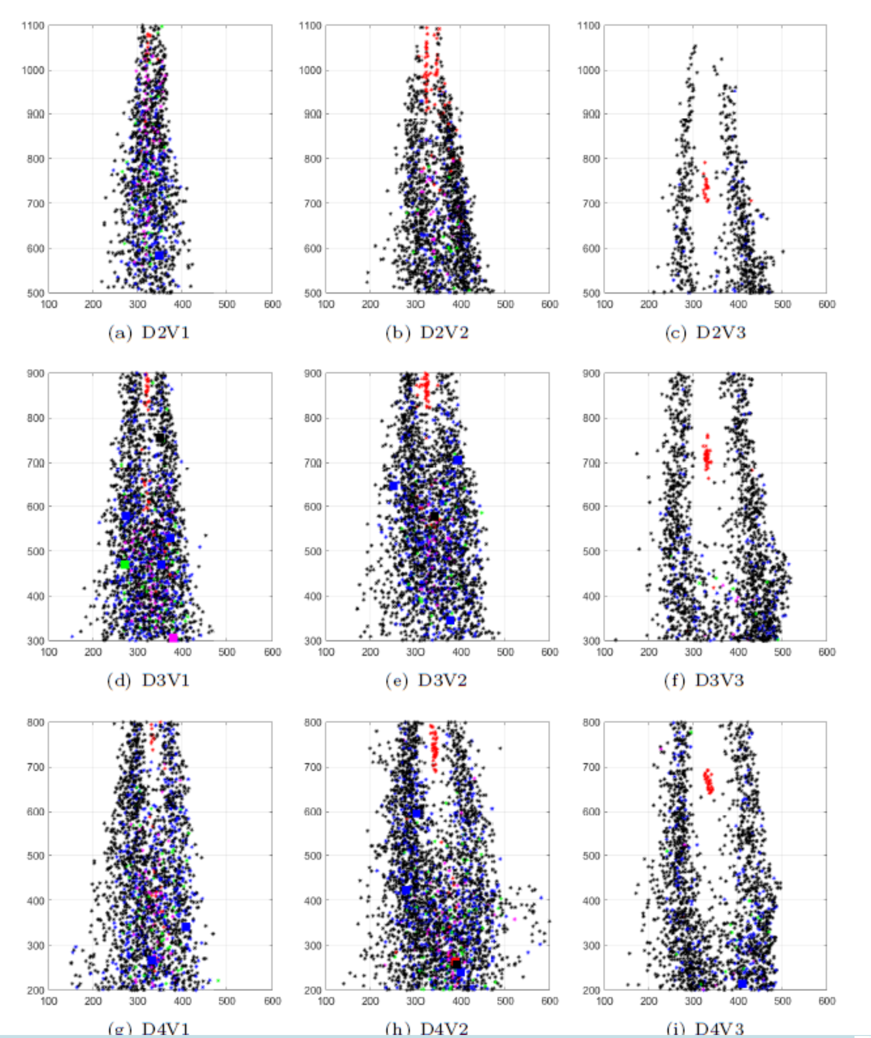
(b) Collision events

Fragmentation Results

Primary and Secondary fragmentation results:

- ❑ Square Symbol for secondary fragmentation
- ❑ Star for Primary Fragmentation
- Blue for size 20- 100 pix.
- Black for size 100- 500 pix
- Green for size 500- 1000 pix
- Magenta for size 1000- 5000 pix
- Red for size 5000 pix and above

Horizontal axis represents pixels in radial direction and vertical axis represents pixels in axial direction

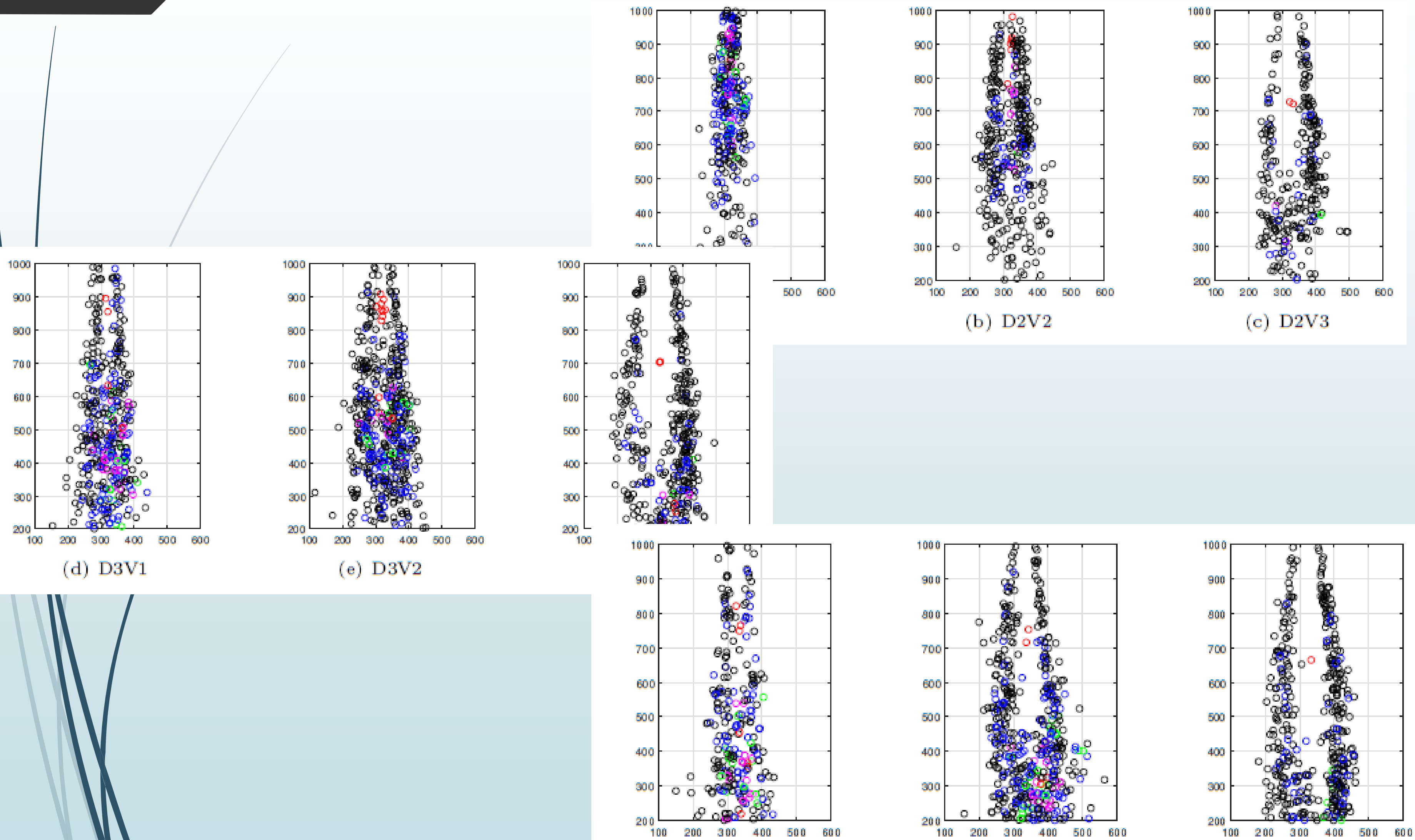


(a) D2V1 (b) D2V2 (c) D2V3

(d) D3V1 (e) D3V2 (f) D3V3

(g) D4V1 (h) D4V2 (i) D4V3

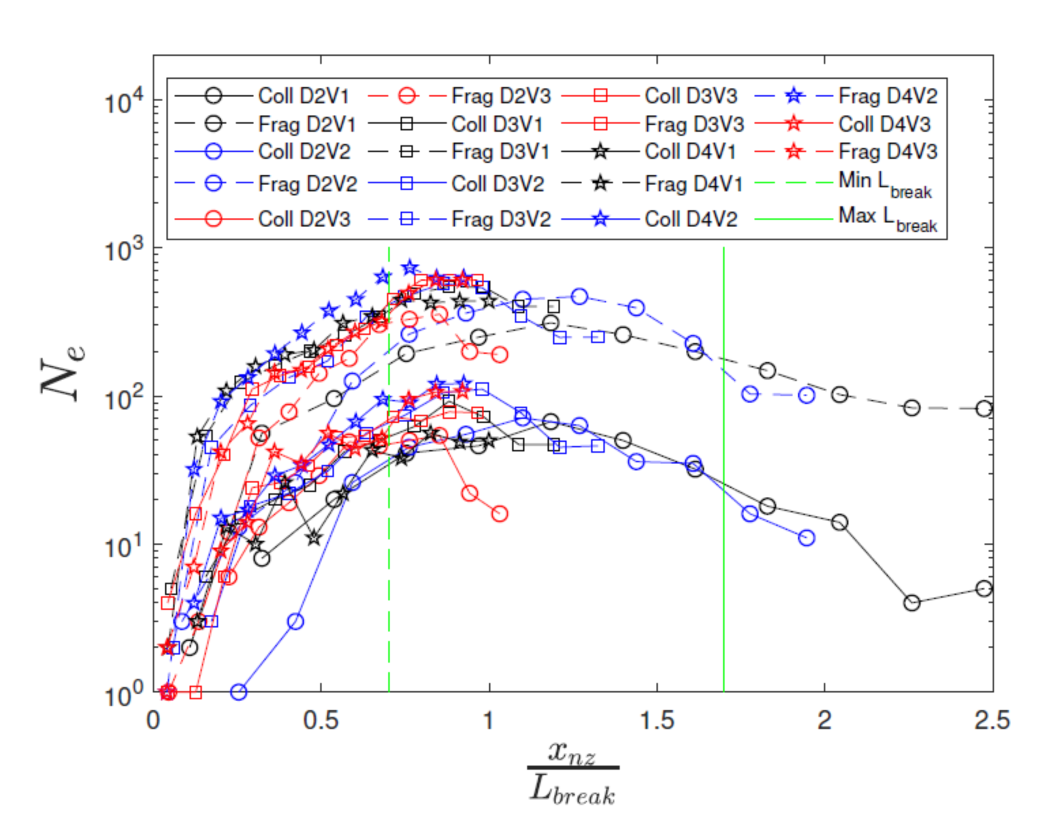
Collision results



(b) D2V2 (c) D2V3 (d) D3V1 (e) D3V2 (g) D4V1 (h) D4V2 (i) D4V3

Fragmentation vs. Collision

- Fragmentation are ten time more frequent than collision
- Submitted to experiments in Fluids…

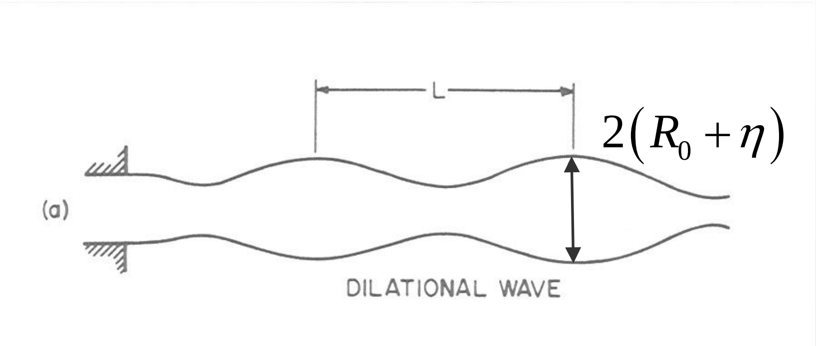


2 Eulerian Analysis and Instability Identification

List of Instabilities

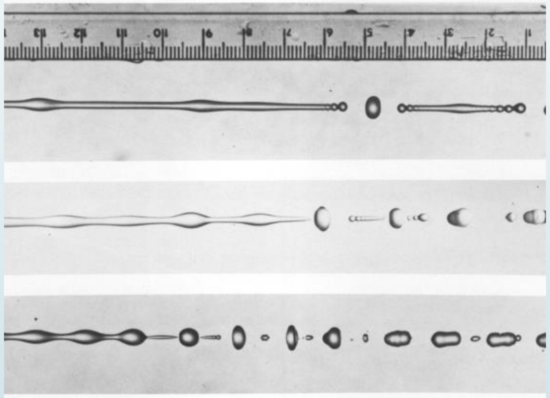
- Rayleigh-Plateau (1873)

$$kR_0 = 0.697$$



$$\eta = \eta_0 e^{(\sigma t + ikx)}$$

Lefebvre (1989)



Van Dyke (1982)

List of Instabilities

- Planar Kelvin-Helmholtz (1871)

$$\frac{R_0}{\lambda_{KH,\max}} = \frac{1}{1+\rho_R^{-1}} \frac{We}{12\pi}$$

- Weber (1931)

$$\sigma^2 + \sigma \frac{3\mu_L k^2}{\rho_L R_0^2} = \frac{\gamma}{2\rho_L R_0^3}\left(1-k^2\right)k^2 + \frac{\rho_C}{\rho_L}\frac{U}{2R_0^2}k^3 \frac{K_0(k)}{K_1(k)}$$

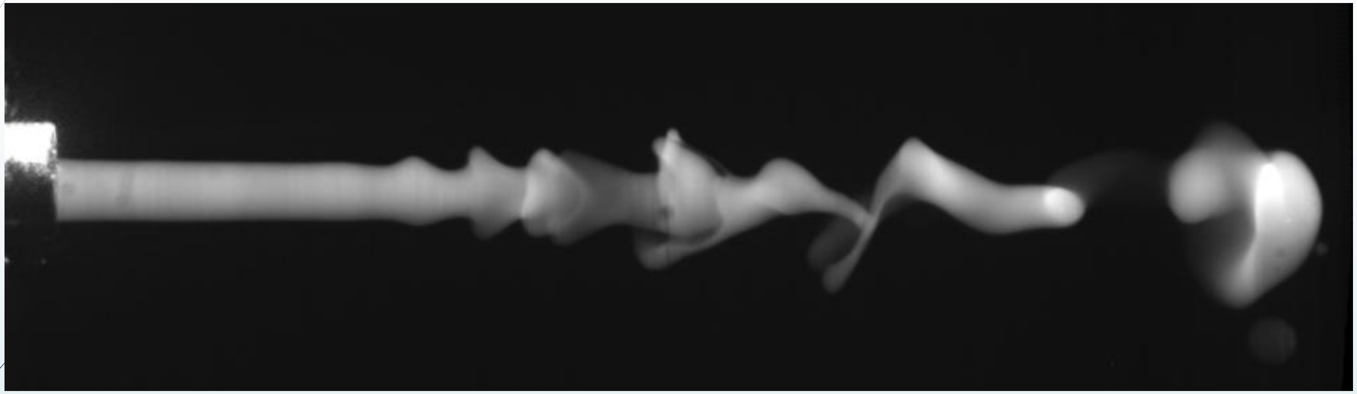
- Reitz (1987)

$$\frac{\lambda}{R_0} = 9.02 \frac{\left(1+0.45 Oh^{0.5}\right)\left(1+0.4T^{0.7}\right)}{\left(1+0.87 We_C^{1.67}\right)^{0.6}} \qquad T = Oh\sqrt{We_C}$$

- Entov-Yarin (1984)

$$k_{EY,\max} = \left(\frac{8}{9}\frac{\rho_L R_0^2}{\mu_L^2}\left(\rho_C U_0^2 - \frac{\gamma}{R_0}\right)\right)^{1/6}$$

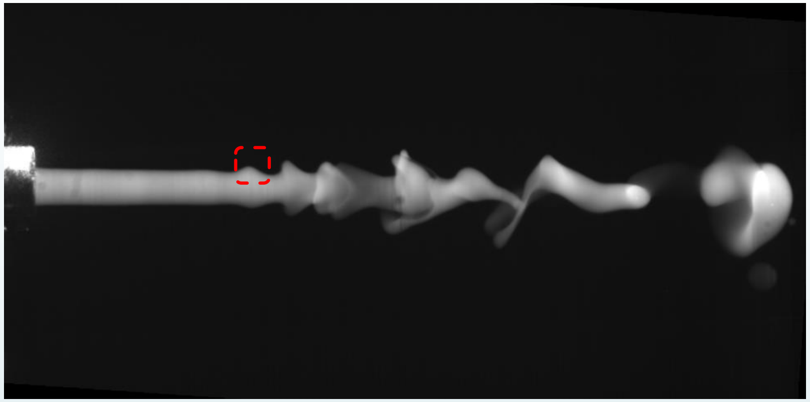
Eulerian Analysis

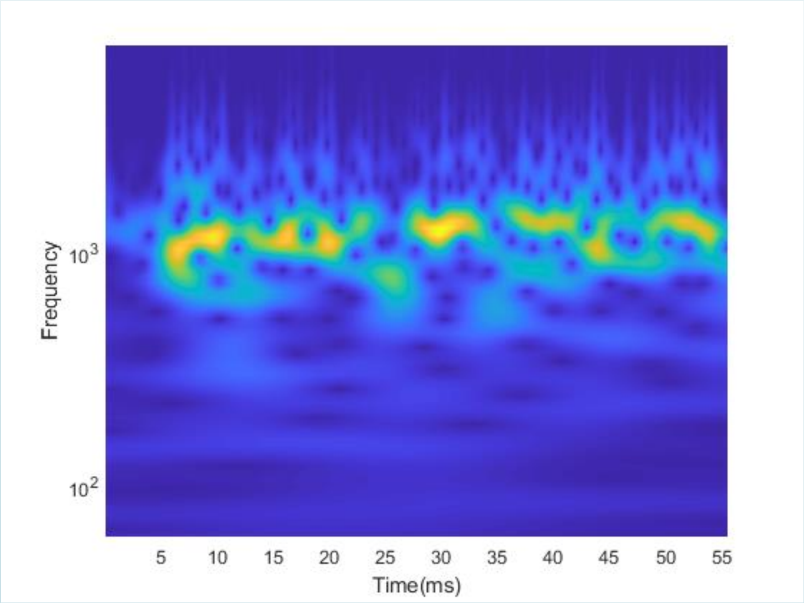


- Cargille fluid
  - D_j= 1mm
  - U=1.91 m/s
- Focus on the edge of the cross section of the jet
  - Spatial resolution: 22.1 µm/pixel
  - Frame rate: 14000fps

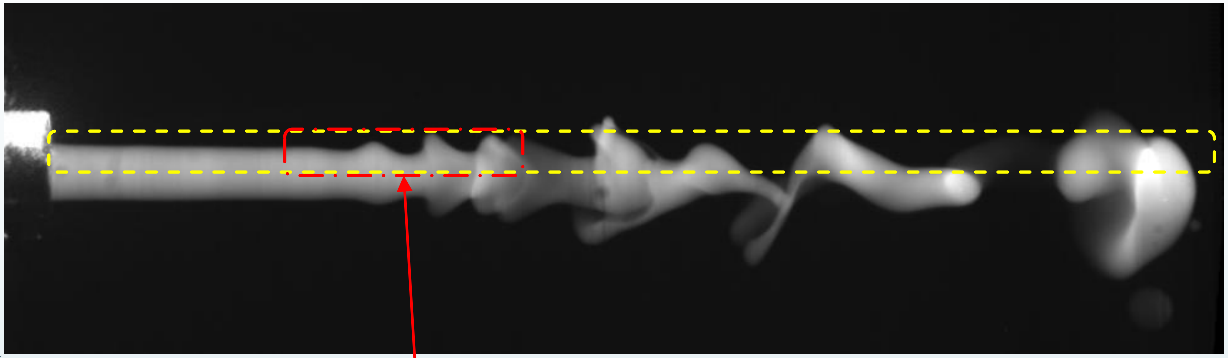
Analysis on Temporal frequency

- A sample region of 10*10 pixels is selected
- A Wavelet analysis is done for 1000 frames
- The result shows a fairly stable temporal frequency

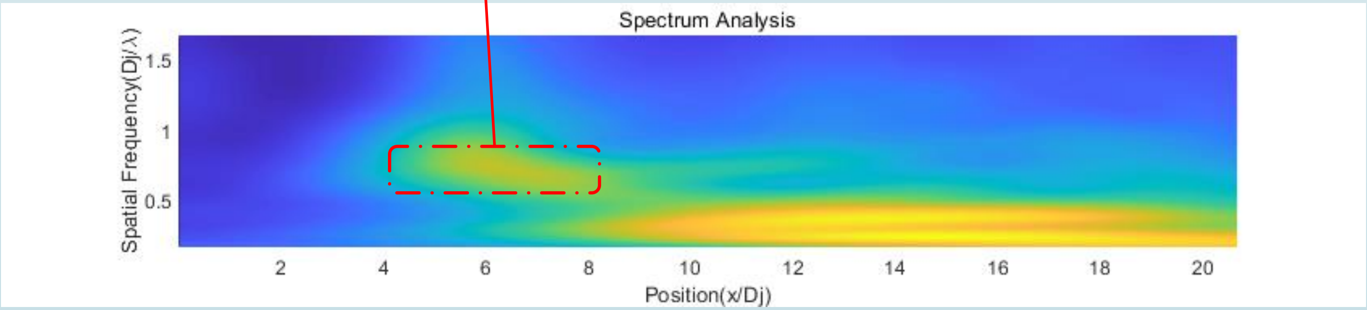




Analysis on Spatial frequency

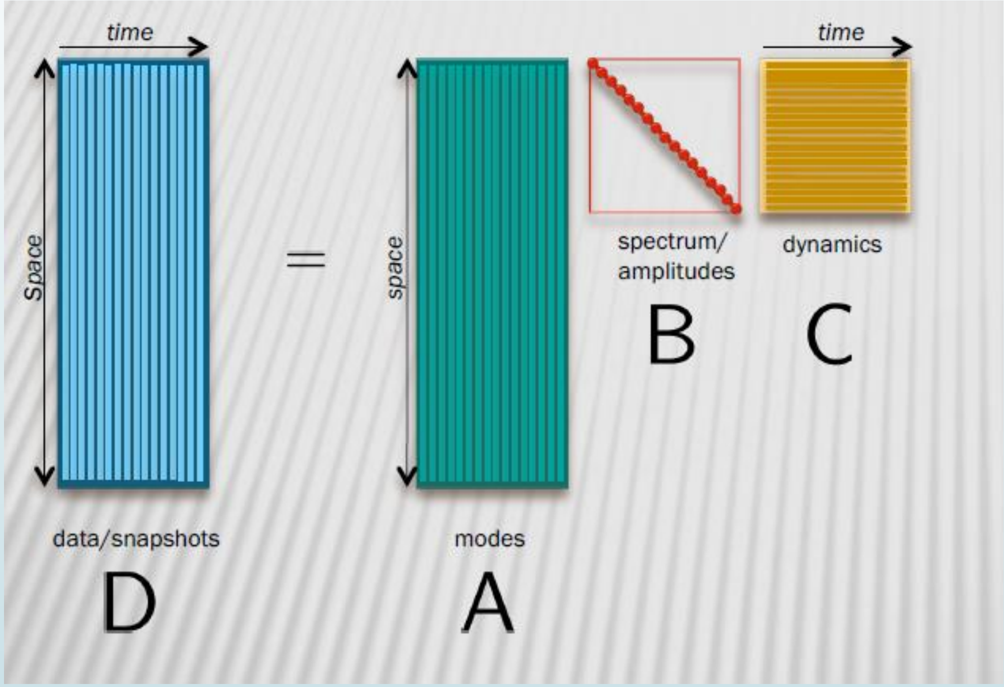


- A sample region of 20*900 pixels is selected
- A Wavelet analysis is done on spatial frequency for 300 frames



Dynamic Mode Decomposition

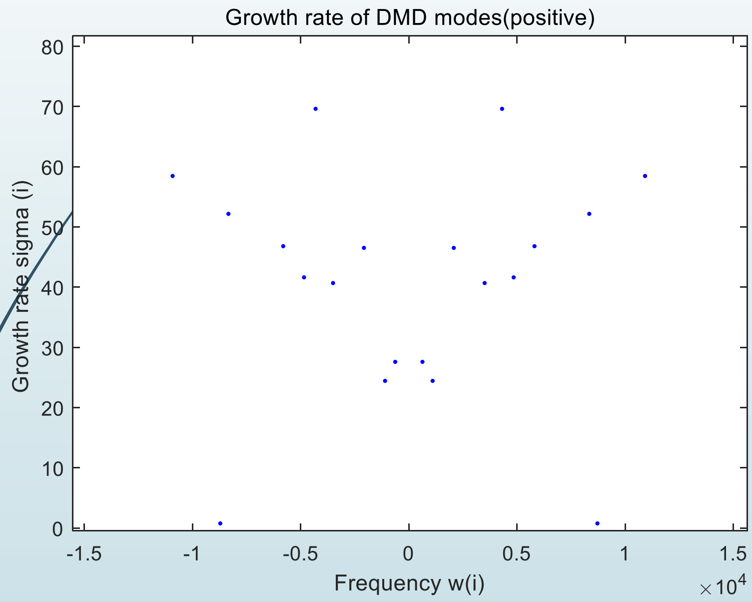
- Data Driven Method
  - Similar to POD (Proper Orthogonal Decomposition)
- D = A B C

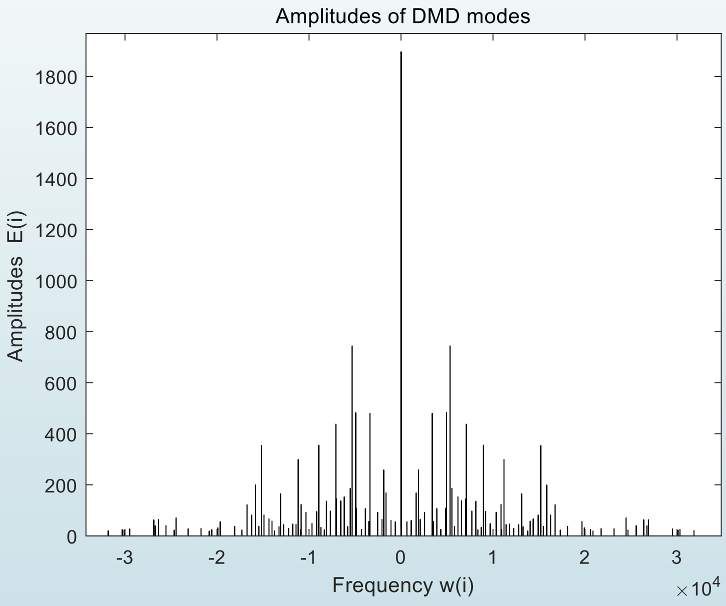


Source: P. Schmidt

DMD Analysis (1)

- Results of DMD analysis





DMD Analysis (2)

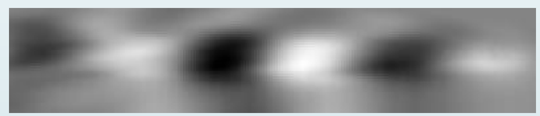
- Modes with positive growth rates are extracted:

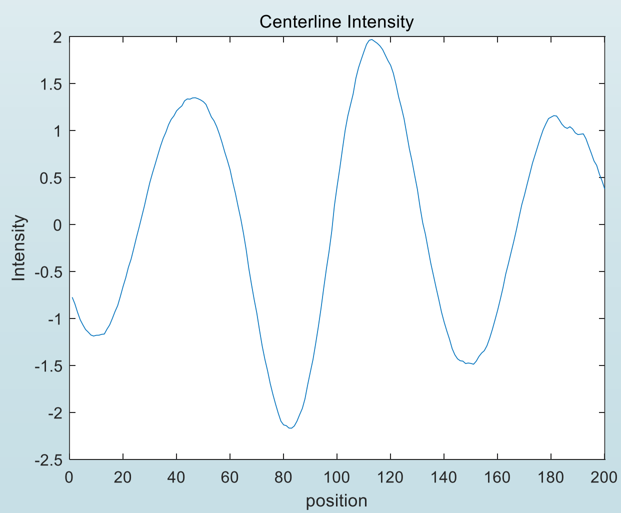
Mode	Growth Rate (s-1)	Amplitude	Frequency (Hz)
41	41.6	109	4846
61	46.5	65	2076
67	24.4	61	1099
71	40.7	57	3505
75	27.6	55	629
93	46.8	37	5809
99	0.8	34	8718
113	69.6	26	4311
117	58.5	25	10921
121	52.2	24	8341

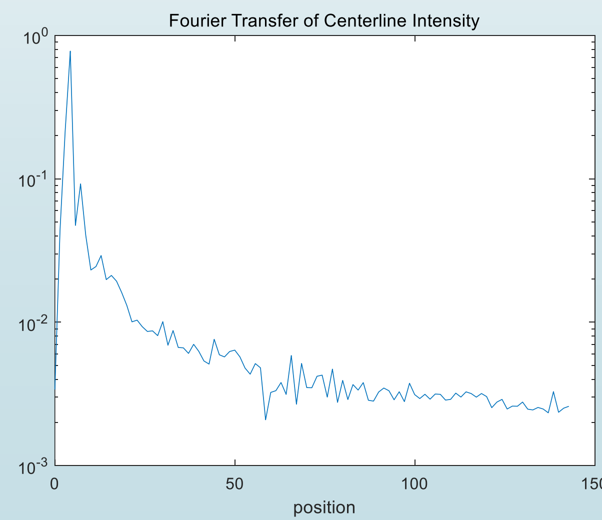
DMD Analysis (3)

- Intensity map of different modes are extracted
- A Fourier transform is done for the centerline
- The non dimensional spatial wavenumber and wavelength can be found

Mode: 41 growth rate: 41.6 amplitude: 109 frequency: 21



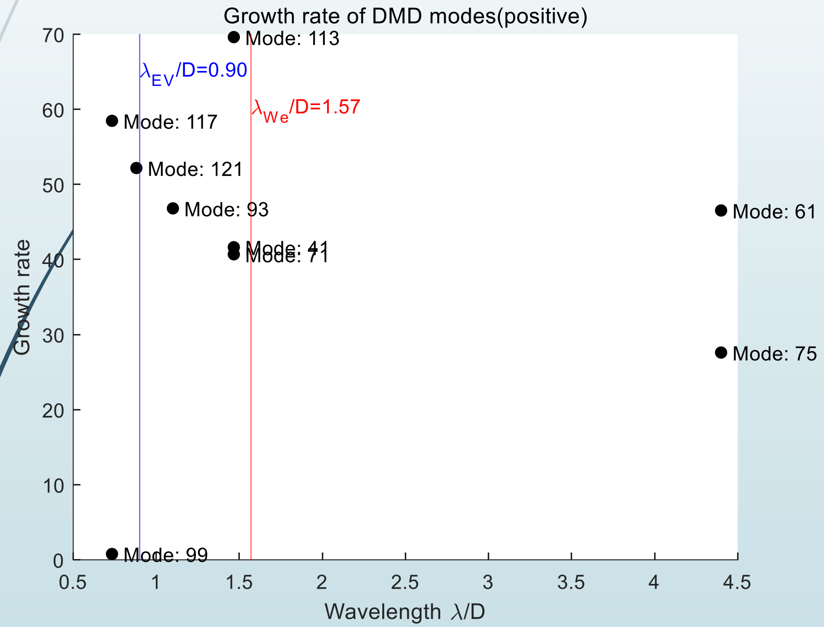


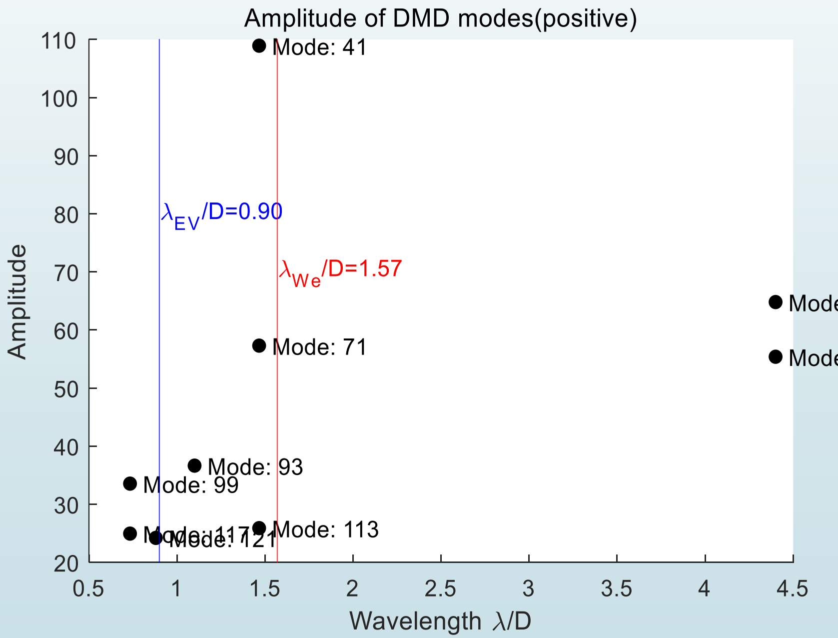


DMD Analysis (4)

- Comparing instability with the result from DMD

D (mm)	P (bar)	U (m/s)	Re_L	We_C	λ_T/D	λ_{We}/D	λ_{EY}/D	λ_{KH}/D	λ_{SS}/D	λ_{LK}/D	λ_R/D
1	1	1.69	128	108	0.056	1.571	0.900	0.132	0.156	0.142	0.154





- The Weber instability model and Entov-Yarin instability model fits best with this result

Conclusion

- Fragmentation dominates over collision
- Instability mechanisms are the root
  - Weber Instability and Entov-Yarin Bending Instability
  - Other atomizer, other instability

Thanks for your attention!