Experimental study on the scattering of regolith due to thruster pulse injection to celestial surface

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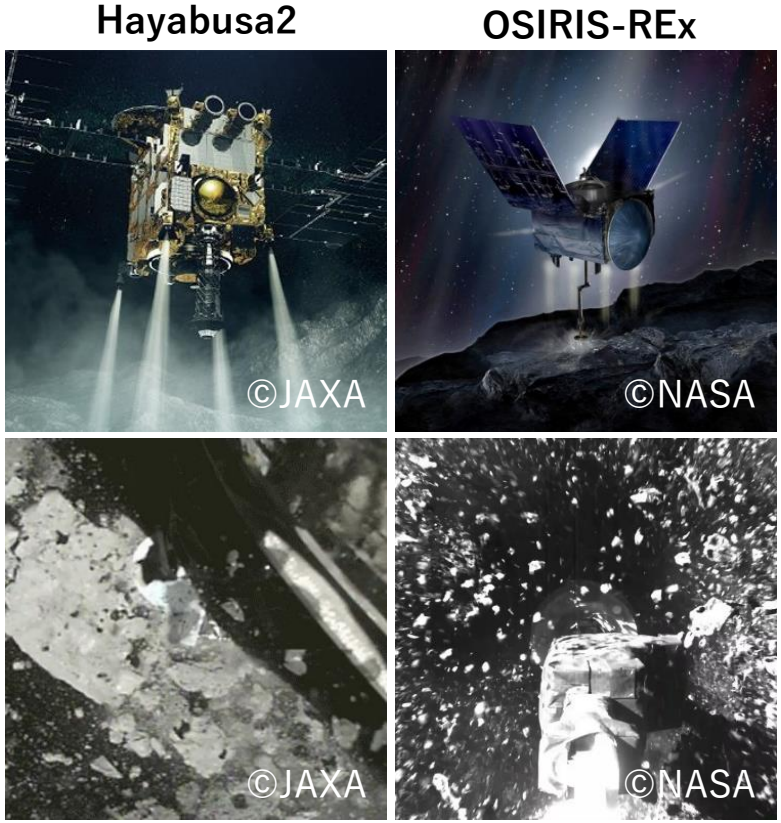
Background

- **Touchdown on the surface of celestial bodies**
  - ➢ Regolith scattering by thrusters was observed
    - ✓ Deterioration of the spacecraft's optical system performance
    - ✓ Decrease in solar cell power generation



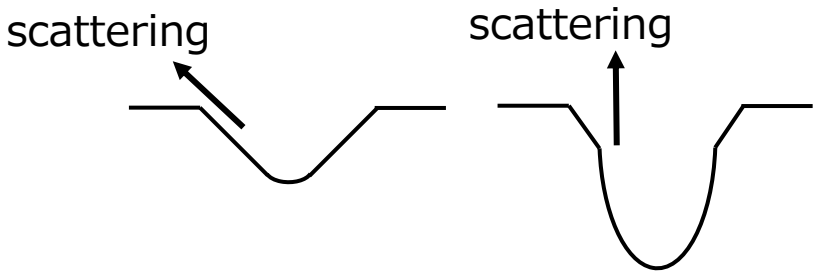
The scene of the landing on asteroid Ryugu in 2019

The scene of the landing on asteroid Bennu in 2020

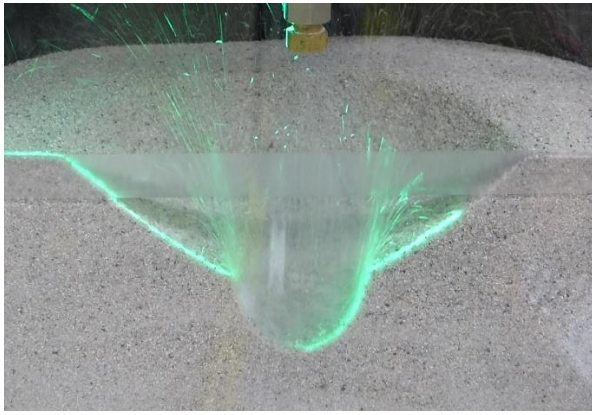
Need to study the regolith scattering caused by thruster injection

Previous research

- **Gas jetting into a container filled with sand**
  - Focusing on the crater wall and scattered particles
    - ✓ Regolith scatters along the wall angles



Crater cross-section visualization experiment[1]



➠ **Results from continuous injection**

  - However, in actual operation...

➠ **Adjusting thrust through pulse injection**

↳ Pulsed jetting method with alternating jetting and stopping

➠ **Need to study regolith scattering by pulse injection**

[1] Kentaro Watanebe, “The scattering of regolith due to thruster injection to celestial surface,” Master's thesis at the Graduate School of Integrated Science and Technology, Shizuoka University, 2021

Objective

- **Proposing pulse injection conditions to suppress scattering counts**

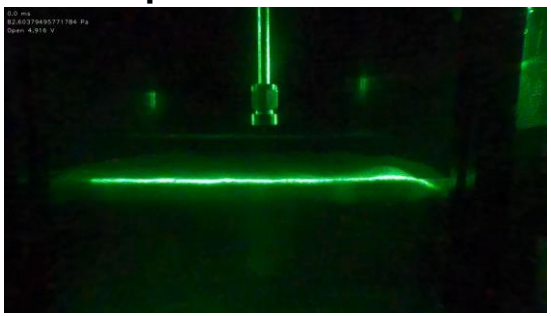
Contents for this time

- The investigation of regolith scattering phenomenon during pulse injection
  - ✓ Comparative experiment between pulse injection with equalized momentum per cycle and continuous injection. (Experiment I)
  - ✓ Additional experiments based on the findings from Experiment I (Experiment II ～)
- Proposing optimal pulse injection conditions for each celestial body based on the identified characteristics
  - ✓ Moon, Mars, and microgravity celestial bodies

Equipment and Method

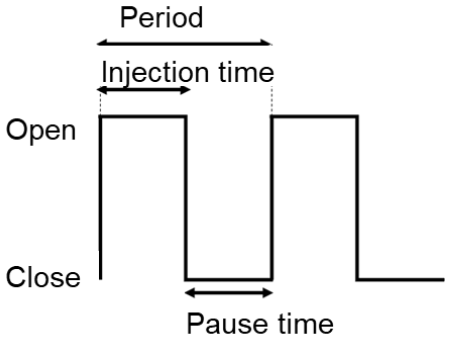
- **Experimental equipment**
  - Visualization panel & Line Laser
    - ✓ Visualization of crater and regolith

Experimental Movie

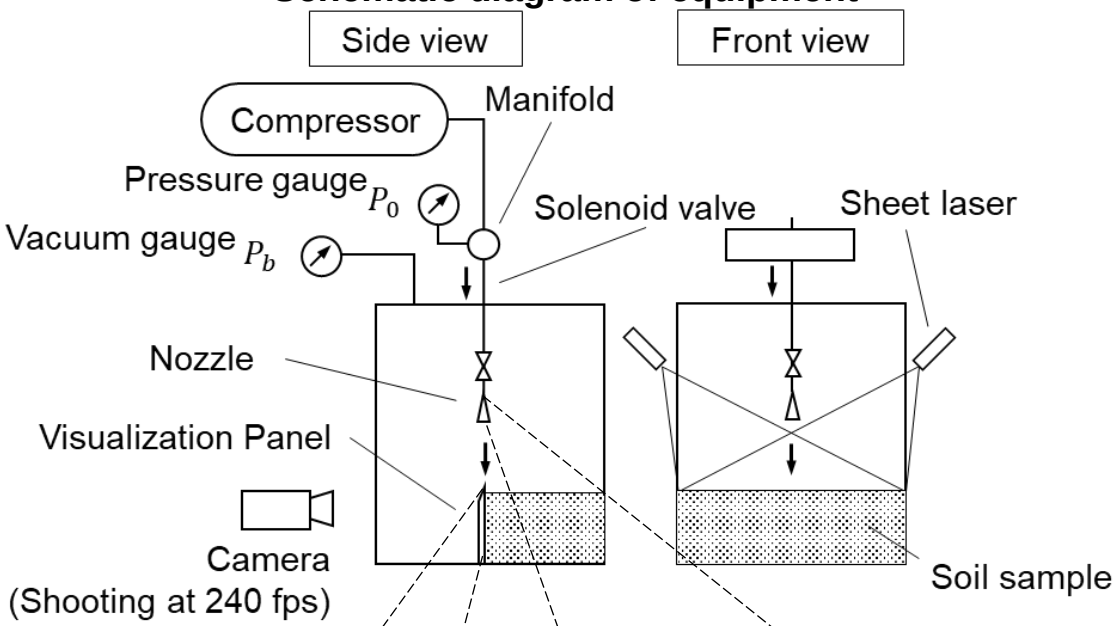


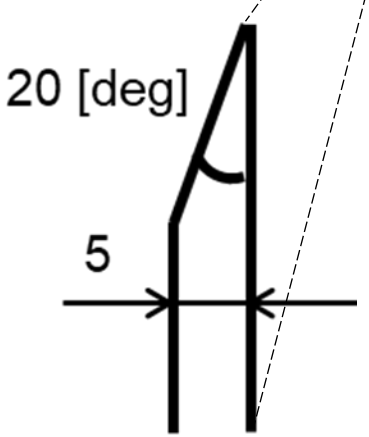
- **Pulsed injection**
  - Solenoid valve opens and closes periodically

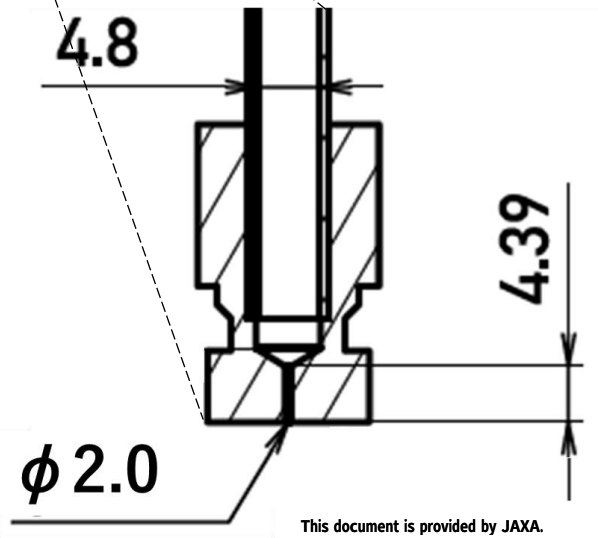
$$\text{Duty} = \frac{\text{Injection time}}{\text{Period}}$$



Schematic diagram of equipment







Momentum of injected gas

What governs the momentum of injected gas?

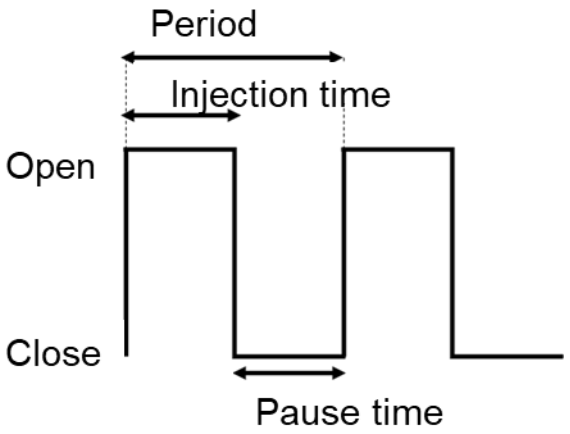
- **Momentum of injected gas per cycle p**

$$p = \rho U^2 A d_u$$

ρ: Density
U: Velocity
A: Area
d_u: Duty ratio
p: Momentum

$$\text{Duty} = \frac{\text{Injection time}}{\text{Period}}$$

Pulse waveform



➢ **Speed of moving fluid U**

Back Pressure $P_b \cong 100$ Pa

$$\frac{P_b}{P_0} < 0.528$$

hold

Flow velocity U is constant at the speed of sound $M = 1$

Manifold Pressure $P_0 \geq 150$ kPa

➢ **Gas Density ρ**

$$\rho = \rho_0 \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{1}{\gamma - 1}}$$

Gas density in manifold ρ_0

$$\rho_0 = \frac{m}{V} = \frac{P_0}{RT}$$

- Flow velocity $\boldsymbol{U}$ is **constant** at the speed of sound
- Momentum per cycle is **proportional** to $\boldsymbol{P_0, A, d_u}$

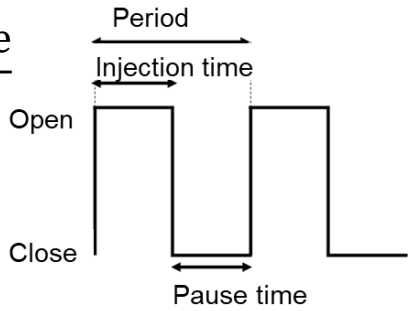
Condition - Expt. I

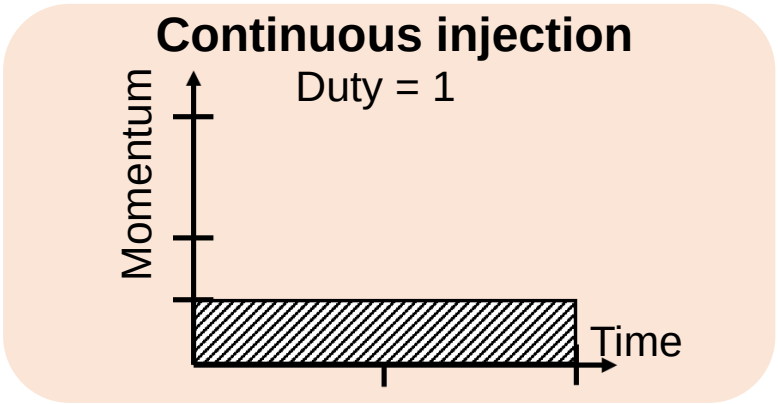
- **Momentum per cycle is equaled**
  - Benchmarking continuous injection
  - Adjust the following during pulse injection

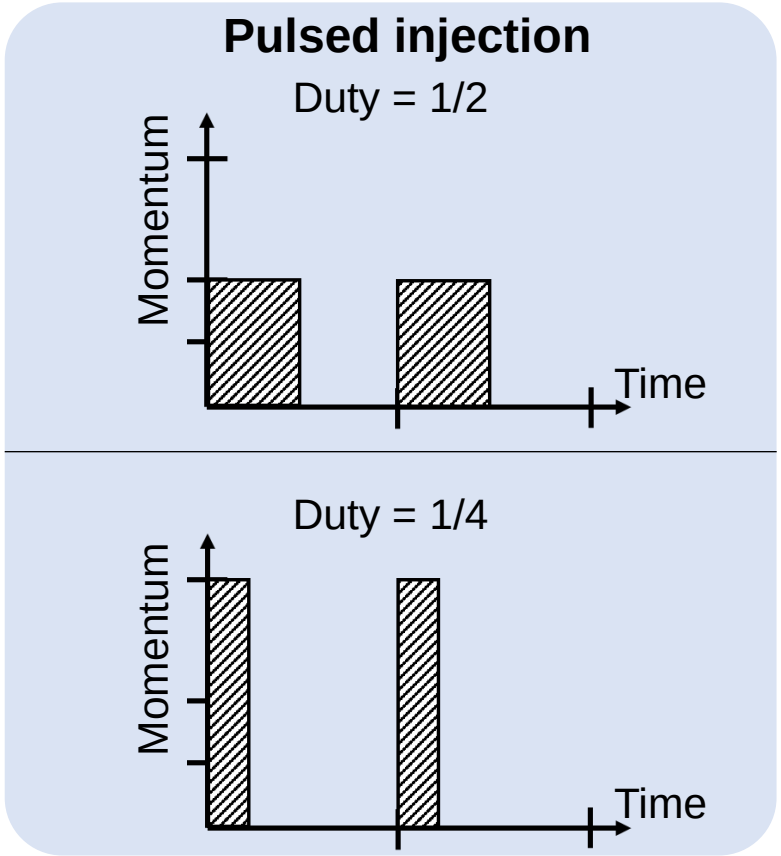
Expt. I-I Nozzle diameter

Expt. I-II Manifold pressure

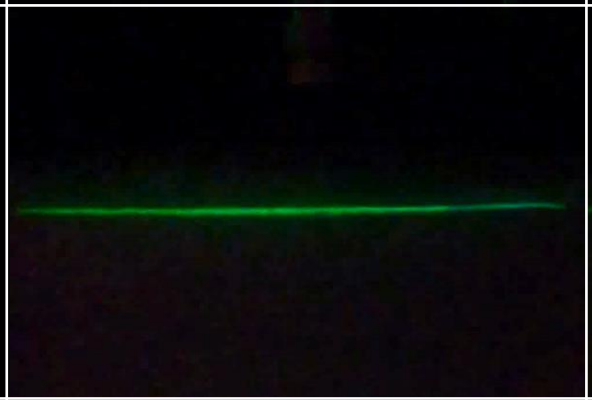
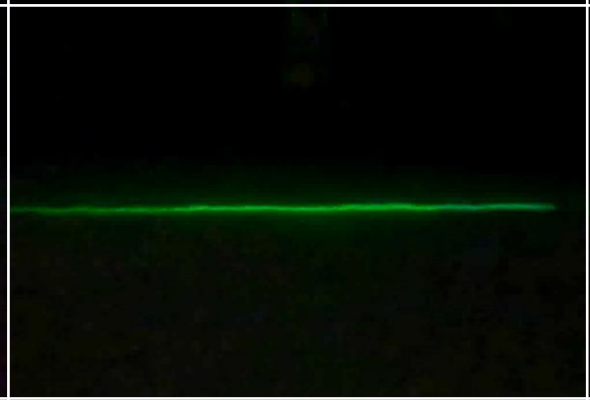
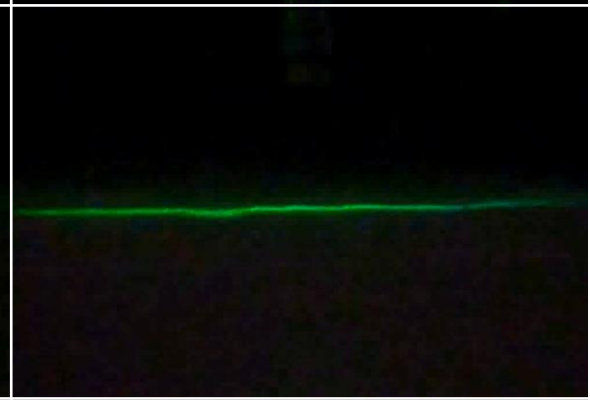
$$\text{Duty} = \frac{\text{Injection time}}{\text{Period}}$$

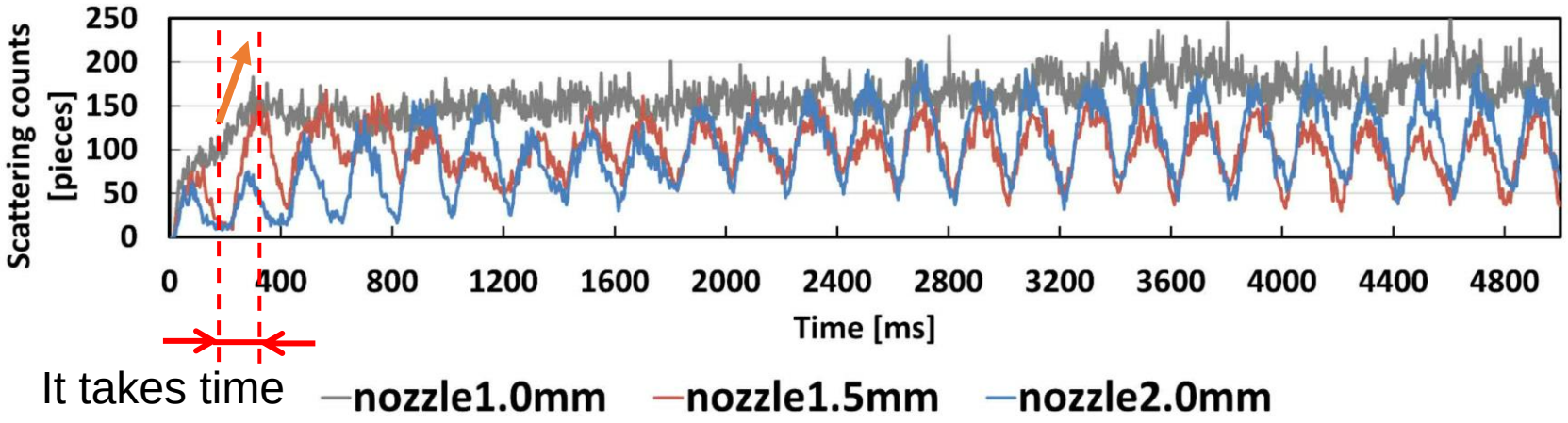






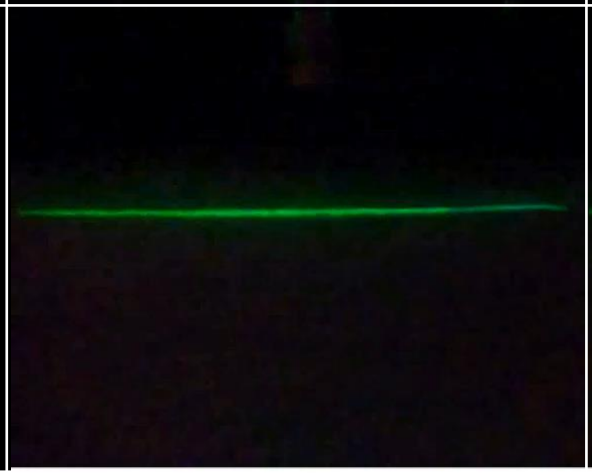
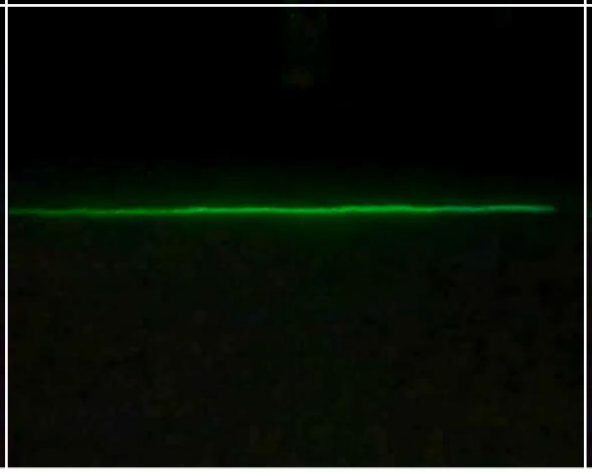
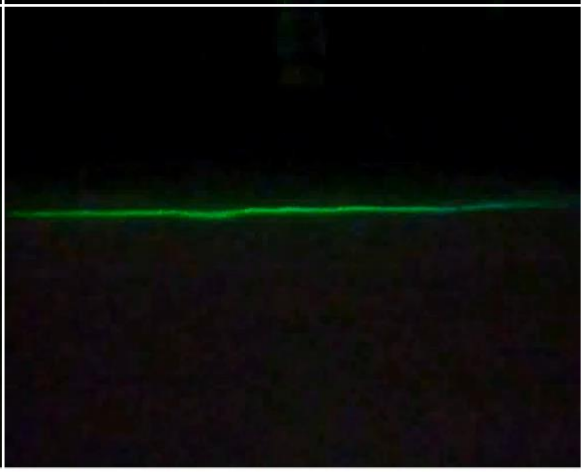
Expt. I-I Result - Nozzle is changed Momentum is equaled

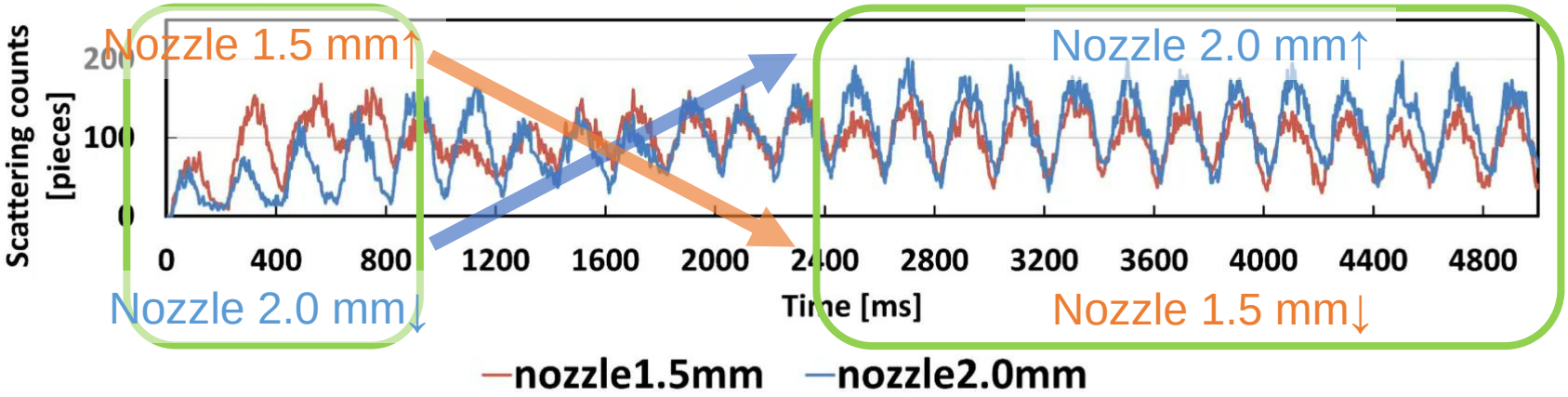
Method	Continuous	Pulsed	Pulsed
Nozzle	1.0 mm	1.5 mm	2.0 mm
Duty [-]	1	$1/1.5^2 \cong 0.44$	1/4=0.25
Movie *White dot ↓ Sand			
Backfilling	No	Complete	Complete



- **Scattering counts : Continuous > Pulsed**

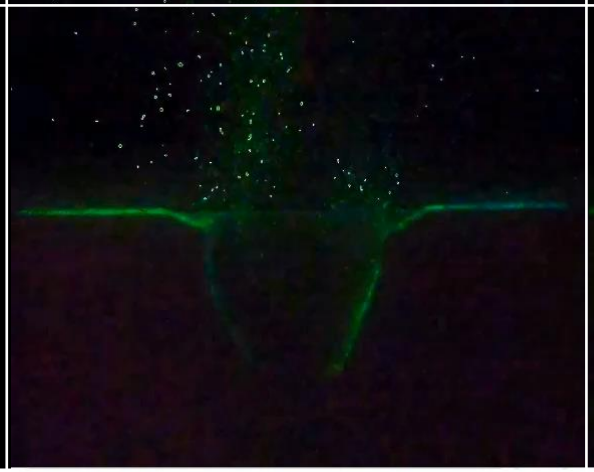
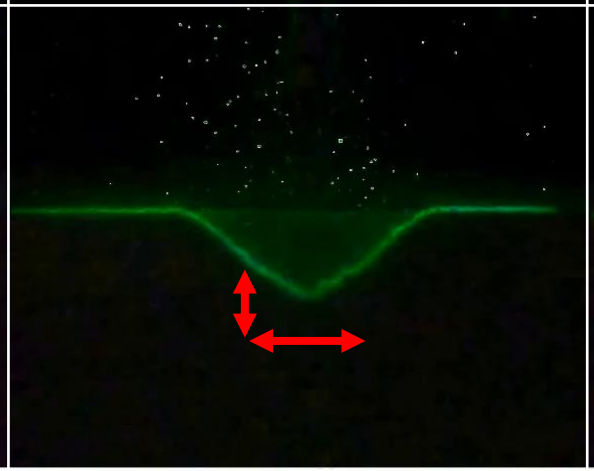
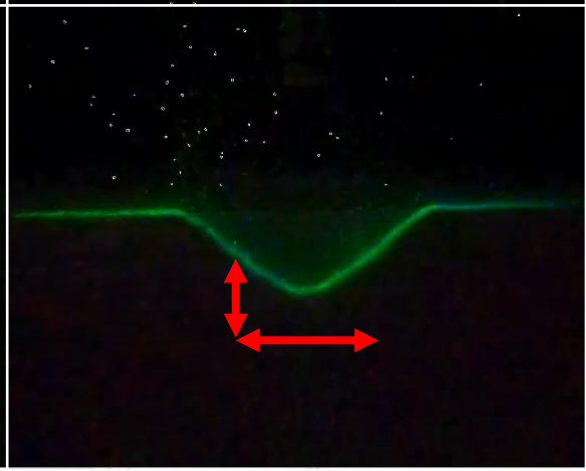
Expt. I-I Result - Nozzle is changed Momentum is equaled

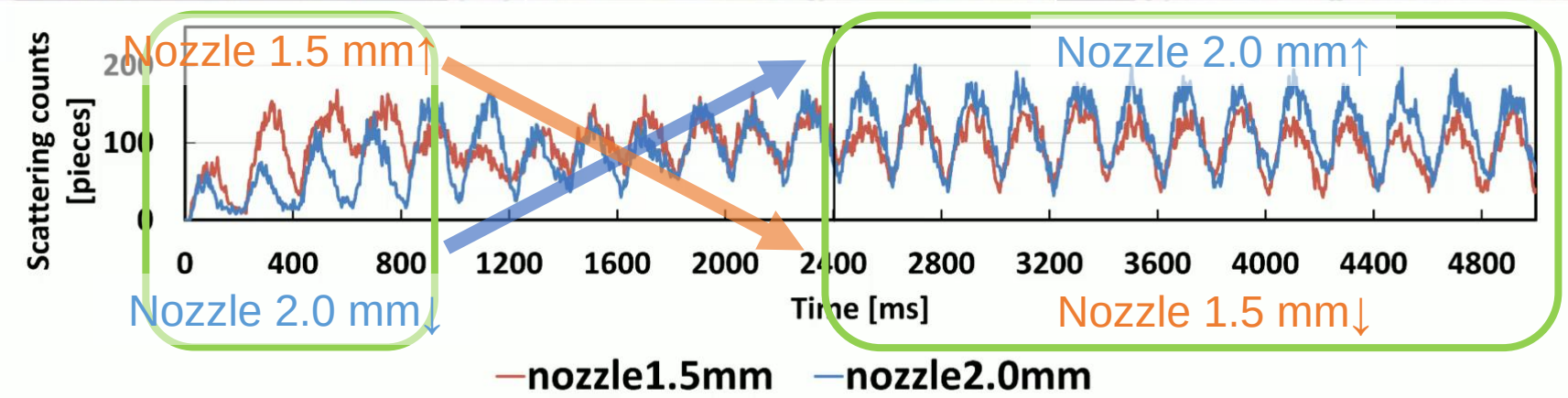
Method	Continuous	Pulsed	Pulsed
Nozzle	1.0 mm	1.5 mm	2.0 mm
Duty [-]	1	$1/1.5^2 \cong 0.44$	1/4=0.25
Movie *White dot ↓ Sand			



- **Reversal phenomenon between the red line and the blue line**
  - ➢ Crater growth stage : Longer injection time → deeper → Scatters more

Expt. I-I Result - Nozzle is changed Momentum is equaled

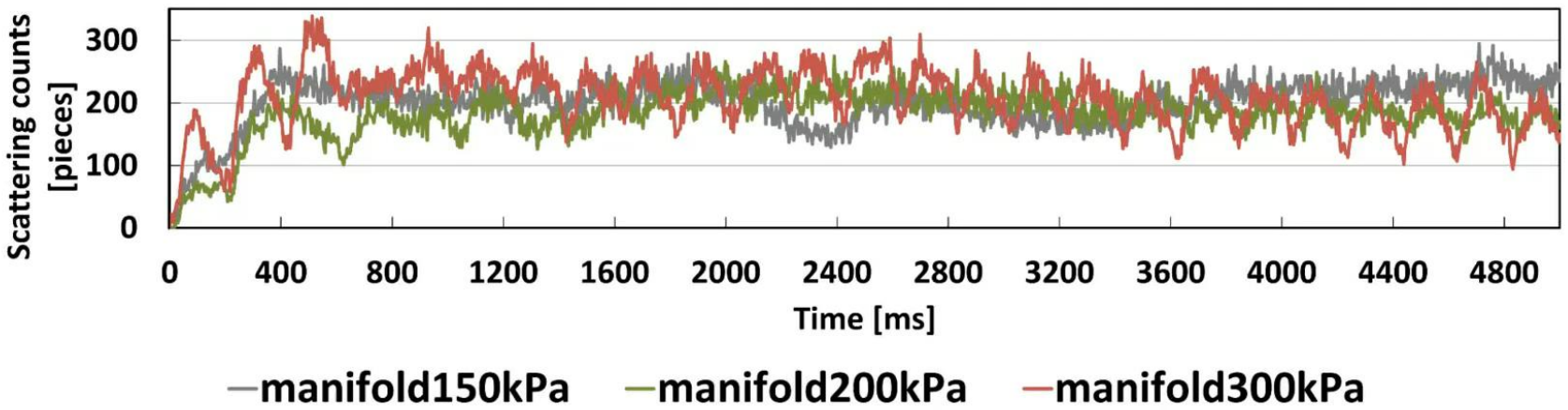
Method	Continuous	Pulsed	Pulsed
Nozzle	1.0 mm	1.5 mm	2.0 mm
Duty [-]	1	$1/1.5^2 \cong 0.44$	1/4=0.25
Movie *White dot ↓ Sand			



- **Reversal phenomenon between the red line and the blue line**
  - ➢ Crater growth stage : Longer injection time → deeper → Scatters more
  - ➢ Crater stagnation stage : Size of the inner crater is larger → Scatters more

Expt. I-II Result - Manifold is changed Momentum is equaled

Method	Continuous	Pulsed	Pulsed
Manifold	150 kPa	200 kPa	300 kPa
Duty [-]	1	3/4	1/2
Movie *White dot ↓ Sand		①Backfilling is incomplete	②Slightly bright



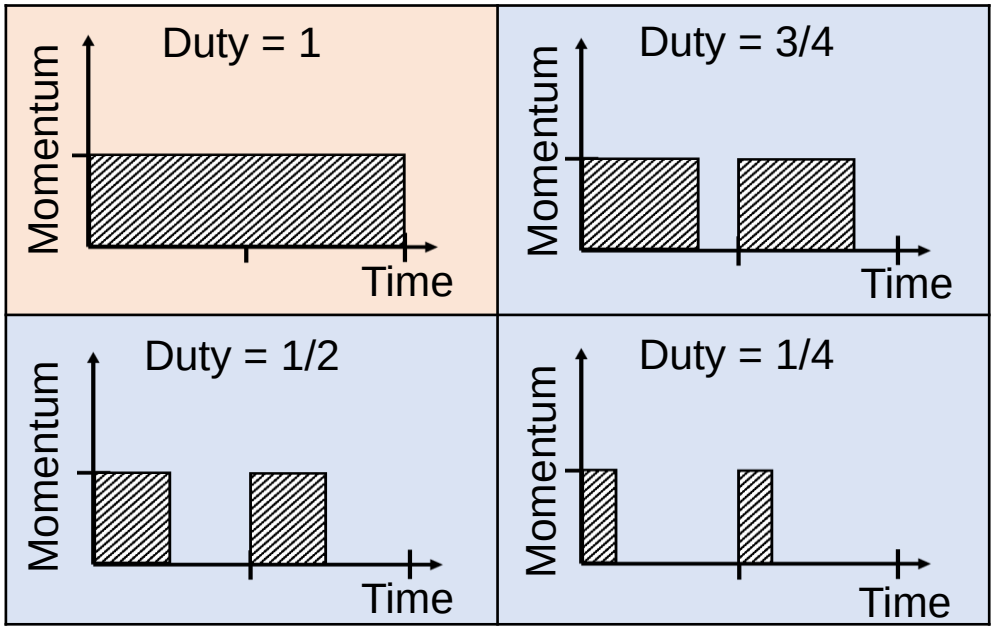
- **Scattering counts : Continuous ≅ Pulsed**
  - ①Because the backfilling process is incomplete
    ②Experimental error → Bright under certain condition

Experiment II

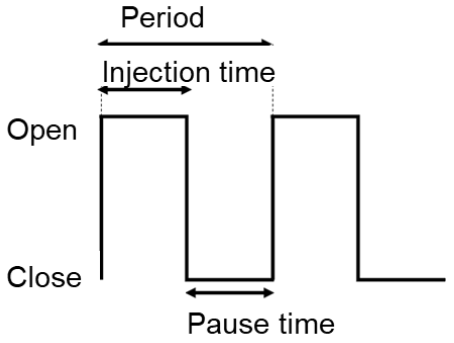
- Experiment I → **Backfilling** has a significant impact on the results
  - The following parameters are considered to influence backfilling
    - ① The valve opening/closing time
    - ② Gravity

In Experiment II, the focus is on **the valve opening/closing time**

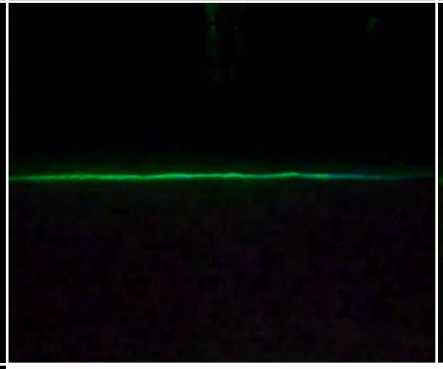
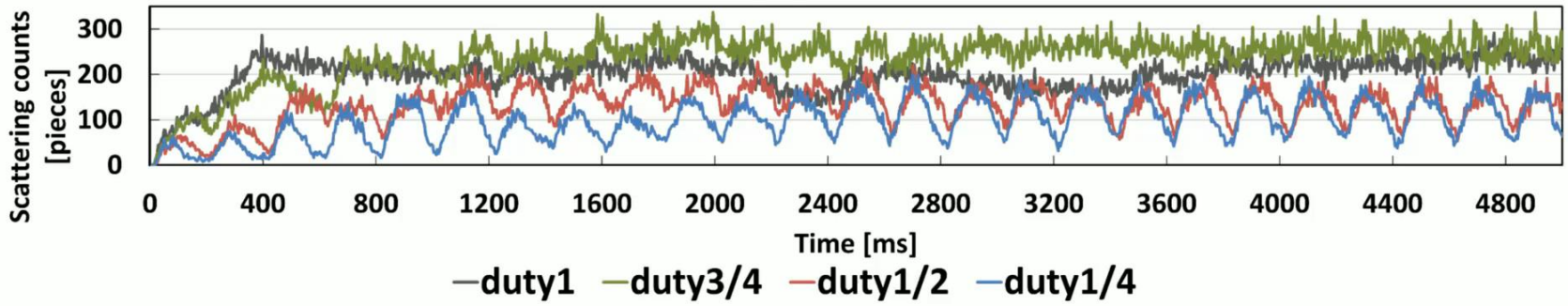
- **Conditions**
  - Change only the valve opening/closing time
  - Period = 200 ms



$$\text{Duty} = \frac{\text{Injection time}}{\text{Period}}$$

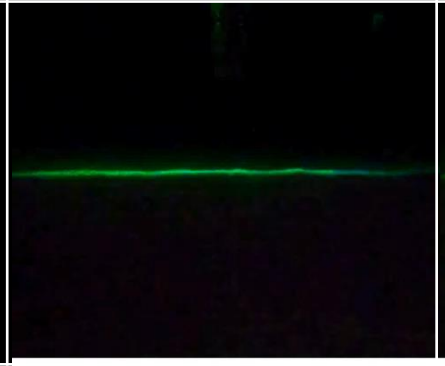
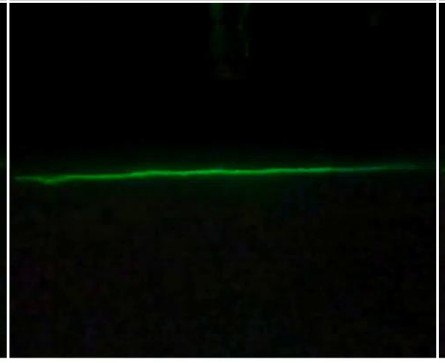
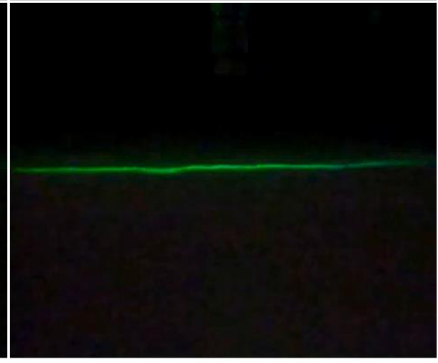


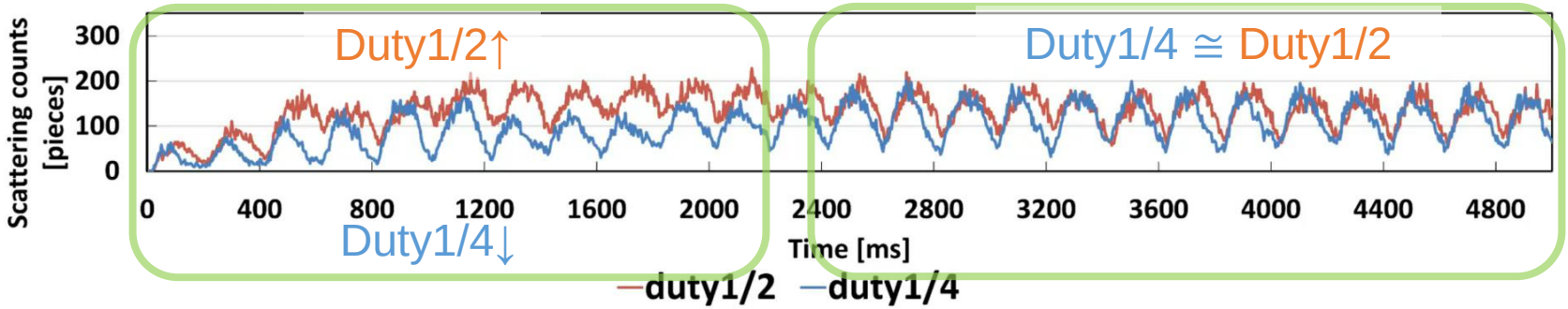
Expt. II Result - Duty is changed

Method	Continuous	Pulsed	Pulsed	Pulsed
Duty [-]	1	3/4	1/2	1/4
Movie *White dot ↓ Sand				
Graph				
Backfilling	No	Imcomplete	Complete	Complete

- **The time required for backfilling is approximately <u>100 ms</u>**
- **Scattering counts : <u>Duty3/4 > Duty1</u> > Duty1/2 ≅ Duty1/4**
  - ➢ During the unstable phase of backfilling in progress → Next injection → Scatters more

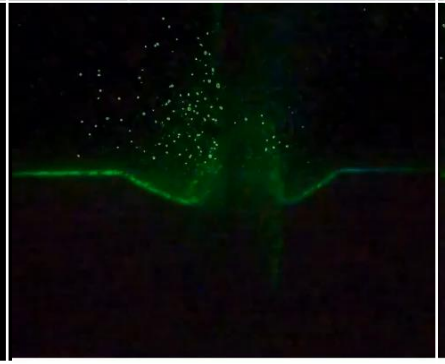
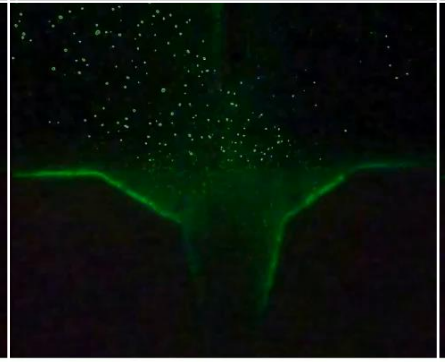
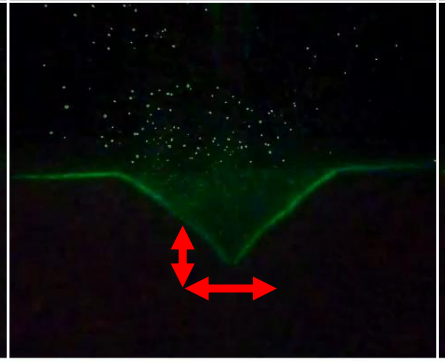
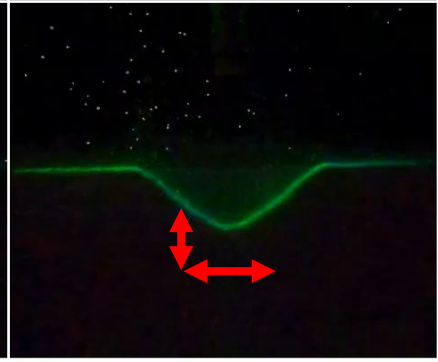
Expt. II Result - Duty is changed

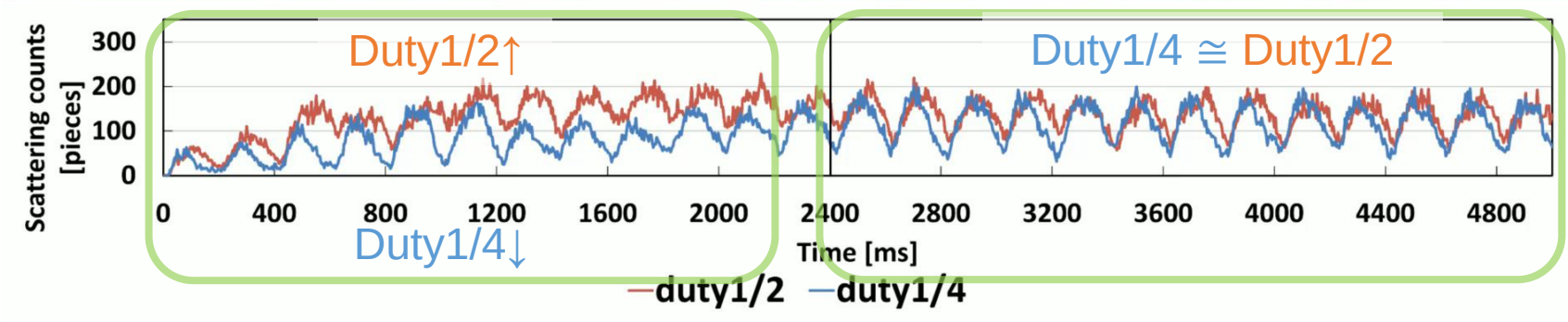
Method	Continuous	Pulsed	Pulsed	Pulsed
Duty [-]	1	3/4	1/2	1/4
Movie *White dot ↓ Sand				



- **Scattering counts : Duty1/2 ≅ Duty1/4**
  - ➢ Crater growth stage : Longer injection time → deeper → Scatters more

Expt. II Result - Duty is changed

Method	Continuous	Pulsed	Pulsed	Pulsed
Duty [-]	1	3/4	1/2	1/4
Movie *White dot ↓ Sand				



- **Scattering counts : Duty1/2 ≅ Duty1/4**
  - ➢ Crater growth stage : Longer injection time → deeper → Scatters more
  - ➢ Crater stagnation stage : Size of the inner crater is equal → Scatter same

What condition is better?

To reduce scattering…

- **Required condition**
  - ✓ Valve closure time ≥ The time for completion of backfilling

- **Conditions based on different situations**
  - ➢ If continuing to jet in the same location...
    - ✓ Yes → Small nozzle
    - ✓ No → Short valve opening time
  - ➢ If you want to match the same flow rate as continuous injection (Manifold pressure or Nozzle diameter)
    - ✓ Nozzle diameter is changed

Conclusion

- **Experiment I**
  - Experiment I-I
    - ✓ Condition : Nozzle is changed & Momentum is equaled
    - ✓ Results of Scattering counts : Continuous > Pulsed
  - Experiment I-II
    - ✓ Condition : Manifold pressure is changed & Momentum is equaled
    - ✓ Results of Scattering counts : Continuous ≅ Pulsed
  - Discussion
    - ✓ Backfilling has a significant impact on the results
- **Experiment II**
  - The time required for backfilling is approximately 100 ms
  - Scattering counts : Duty3/4 > Duty1 > Duty1/2 ≅ Duty1/4
  - Discussion
    - ✓ During the unstable phase of backfilling in progress → Next injection → Scatters more
    - ✓ Crater growth stage : Longer injection time → deeper → Scatters more
    - ✓ Crater stagnation stage : Size of the inner crater is equal → Scatter same

Future works

- **Ensuring reproducibility**
  - Improvement of experimental apparatus
    - ✓ Sheet laser
  - Performing multiple experiments
- **Consideration of microgravity experiments**
  - Investigating the relationship between backfilling and gravity
- **Quantitative evaluation of crater morphology**
  - Measurement of maximum wall slope angle and crater size