POSTER 1-SO-10

Studies on laser-produced plasma EUV generation by using fast-supplying cryogenic Xe targets

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Abstract

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In this paper, we report characterizations of fast-supplying cryogenic Xe targets, a rotating-drum solid Xe layer target [1] and a cryogenic Xe capillary jet target [2], for laser-produced plasma EUV sources. Xe is useful for mitigating debris deposition on multilayer mirrors, but improvement of its EUV conversion efficiency (CE) is one of important issues. Dependences of CE on a delay time of double laser pulses and drum rotation were investigated by using the drum target. The physical mechanism of improving CE will be discussed. Stability of solid target layer which may be broken due to pileup effects of laser-induced shock-wave and target heating was investigated at simulation experiments conducted by using double pulse laser irradiation. A cryogenic Xe capillary jet was successfully generated in vacuum. The capillary jet target is useful for reducing target consumption and debris generation in vacuum without reducing CE. A forming process of the capillary jet target was investigated by using numerical calculations.

[1] T. Mochizuki, et al.: 2nd Int. EUVL Symposium, 7F, Antwerp, Belgium, 30 Sep. ~ 2 Oct., 2003.
[2] T. Inoue, et al.: 3rd Int. EUVL Symposium, SoP19, Miyazaki, Japan, 1 ~ 4 Nov., 2004.

Optimum plasma conditions is required for improving EUV conversion efficiency (CE).

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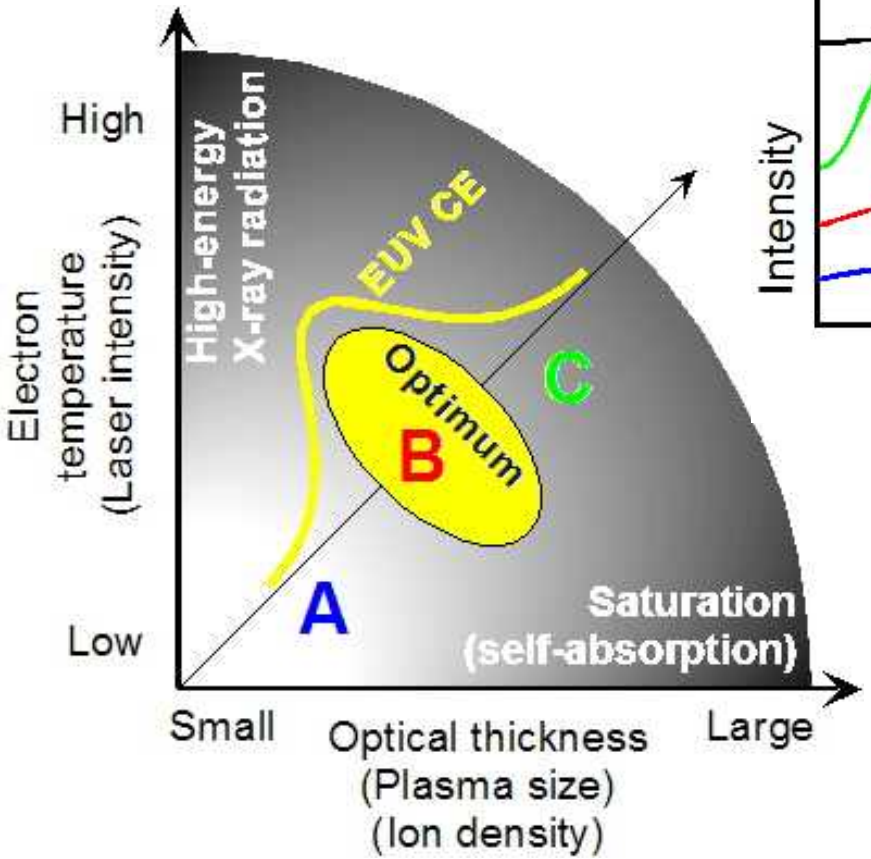

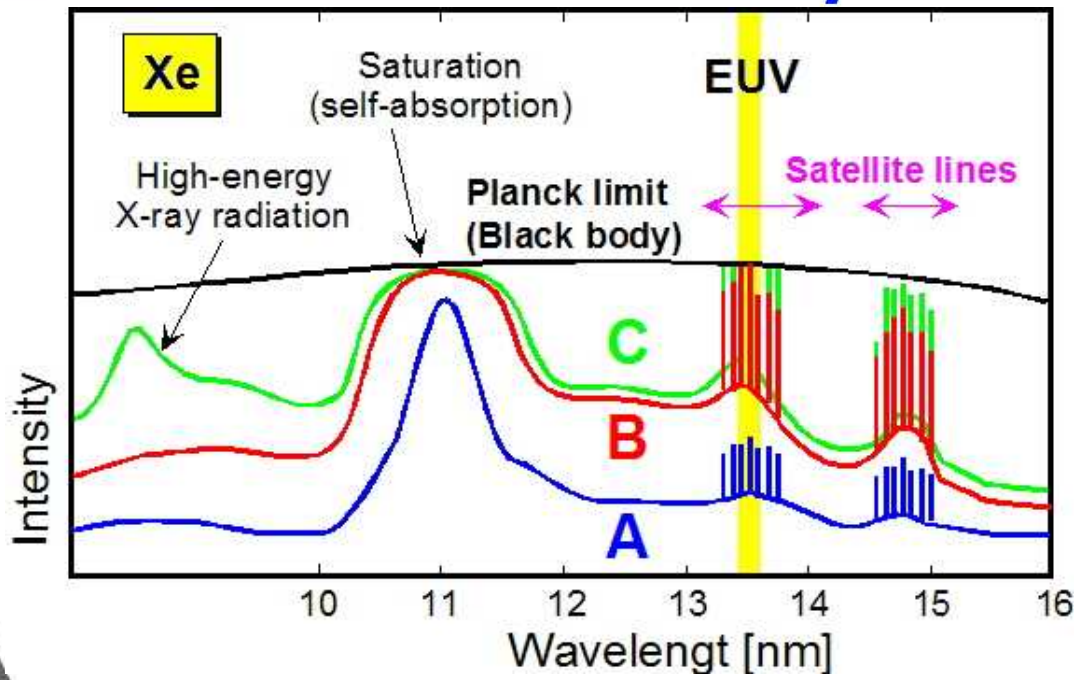

Plasma conditions

Size, ion density, electron temperature, …

Laser conditions

Wavelength, pulse energy, pulse width, intensity, focus spot size, ….

Target conditions

Material, shape, size, surface condition, …

1. Rotating-drum solid Xe layer target

Solid-Xe drum

System profile

Rotating cryogenic drum system can supply solid Xe layer for 1 J / 10 kHz laser irradiation.

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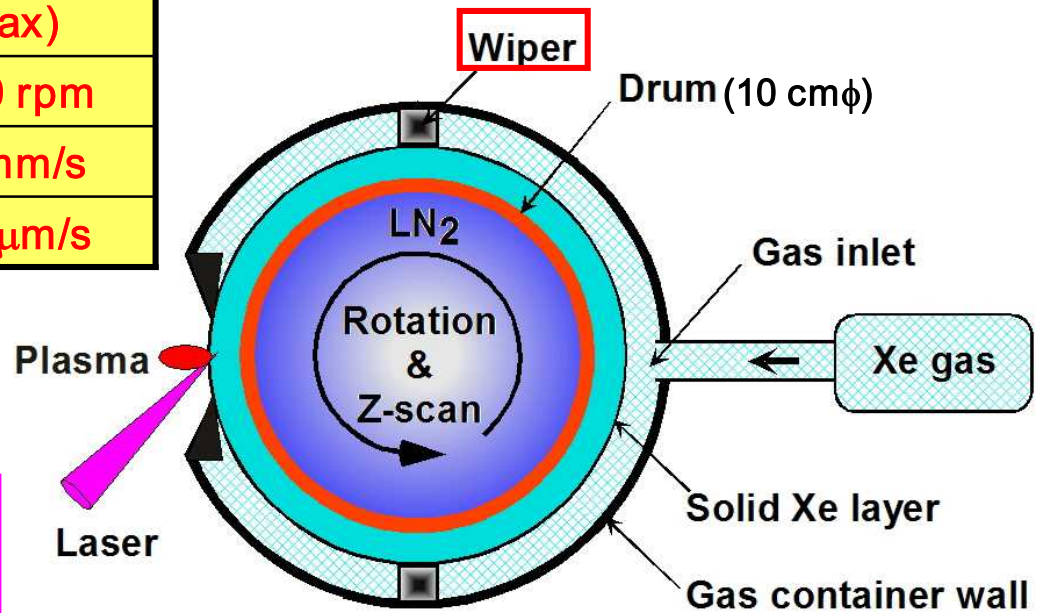
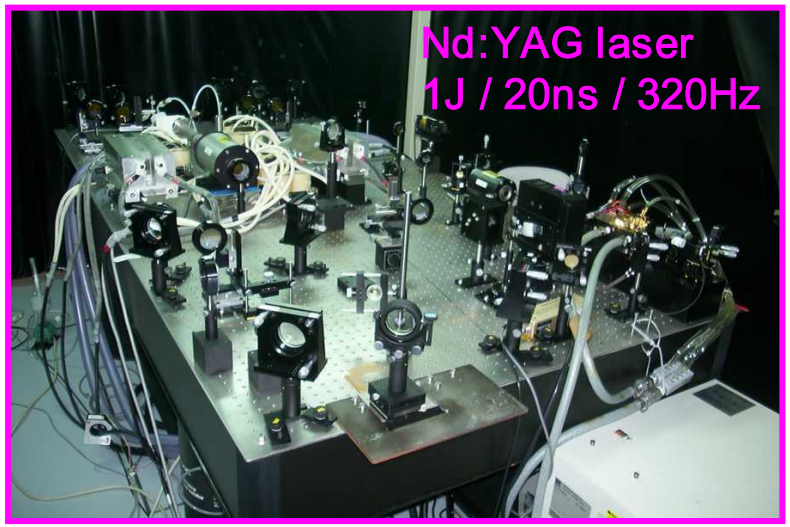
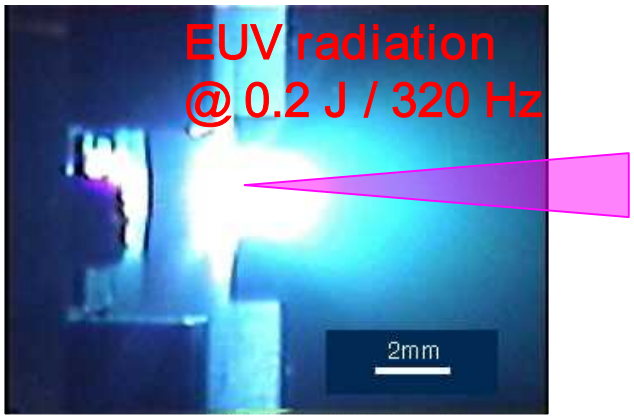
	Required 1 J / 10 kHz	Performance (Max)
Rotation speed	573 rpm	1000 rpm
Z-scan speed	5.7 mm/s	10 mm/s
Crater recovery	14 μm/s	160 μm/s

Wiper is very important to obtain the stability and the rapid recovery

Cross-section view of the drum system







Contents (1)

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(1) Dependences on delay time of double-pulse laser irradiation

- Time-integrated EUV image
- EUV conversion efficiency
- Spectrum

(2) Target rotation effect

- Time-integrated EUV image
- EUV conversion efficiency
- Spectrum
- Ion signal and ion energy distribution

(3) Target exfoliation due to pileup of shock-wave

- Observation of exfoliation with double-laser irradiation
- Theoretical studies on propagation of shock-wave

Experimental setup

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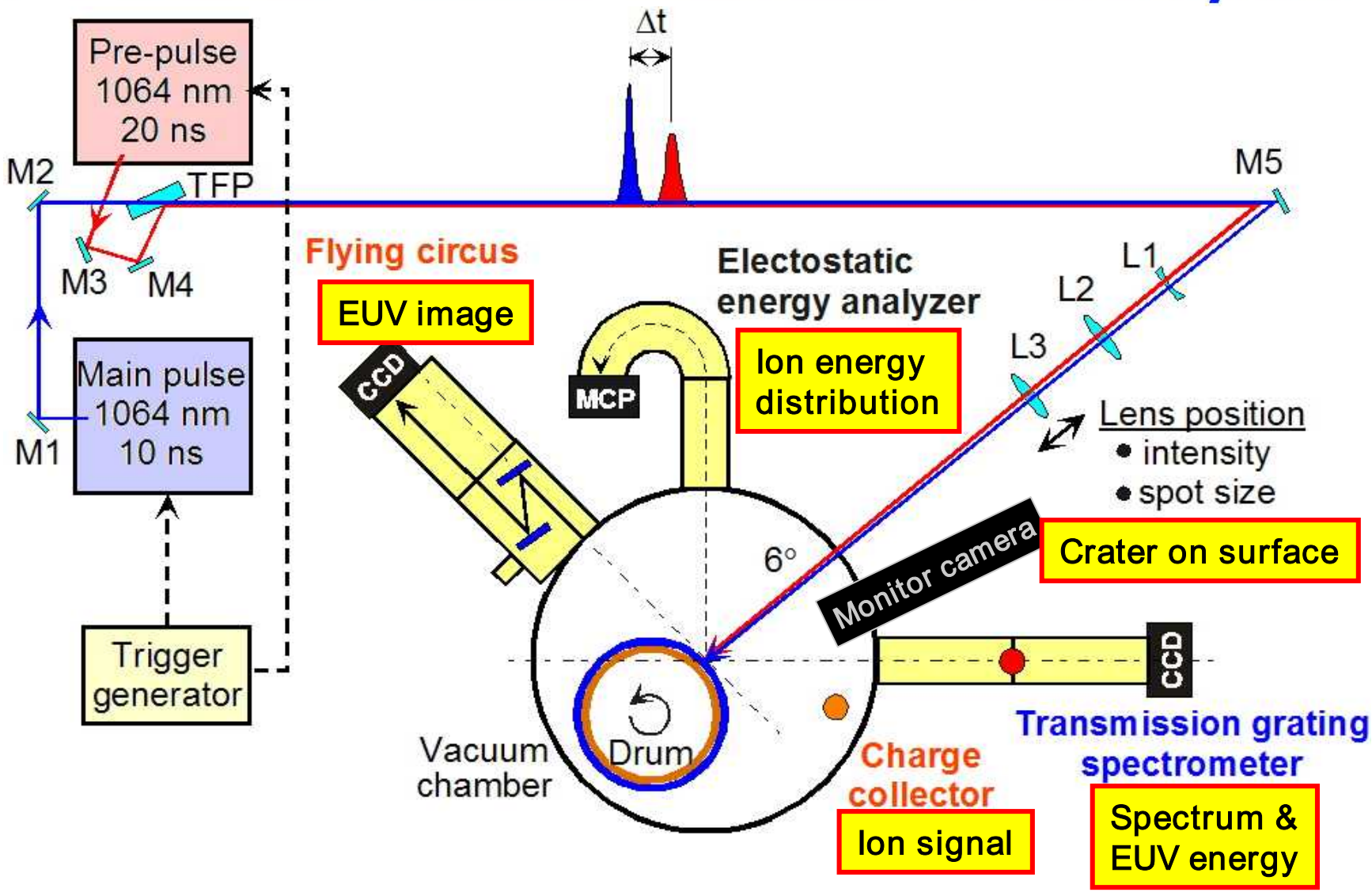


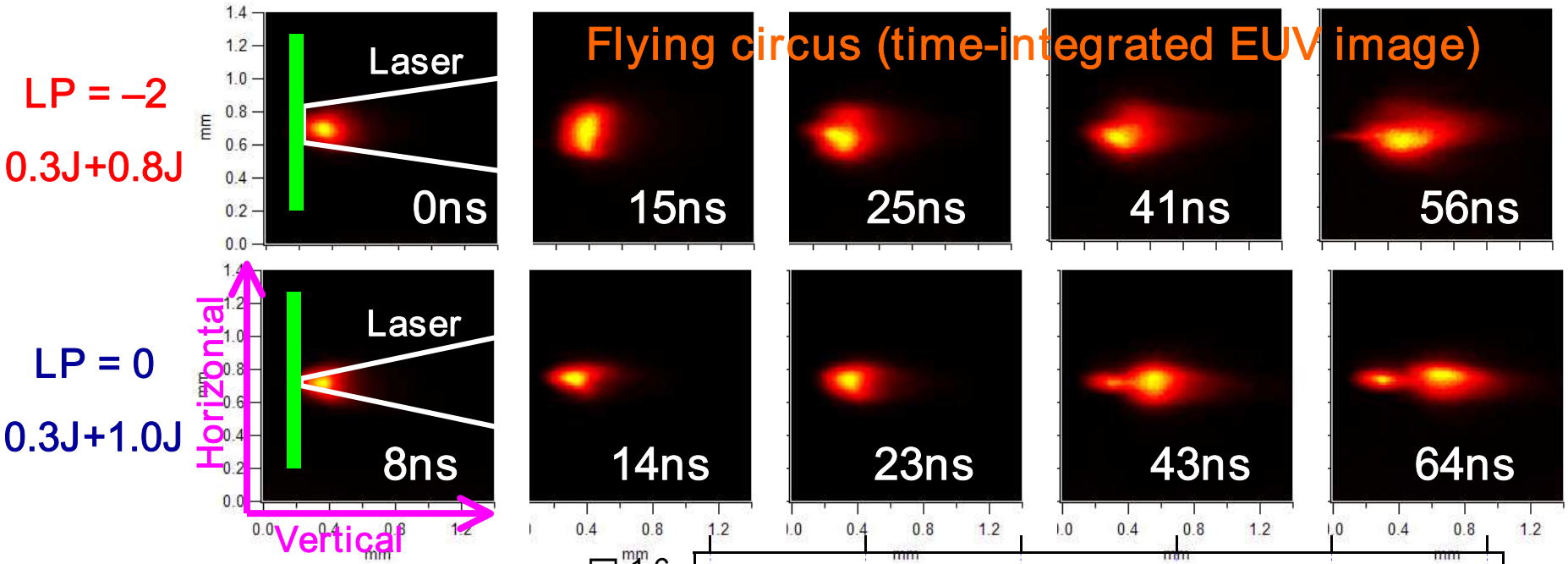
Solid-Xe drum

Double pulse

EUV emission size increased with double-pulse delay time.

Rest target

LASTI/UH



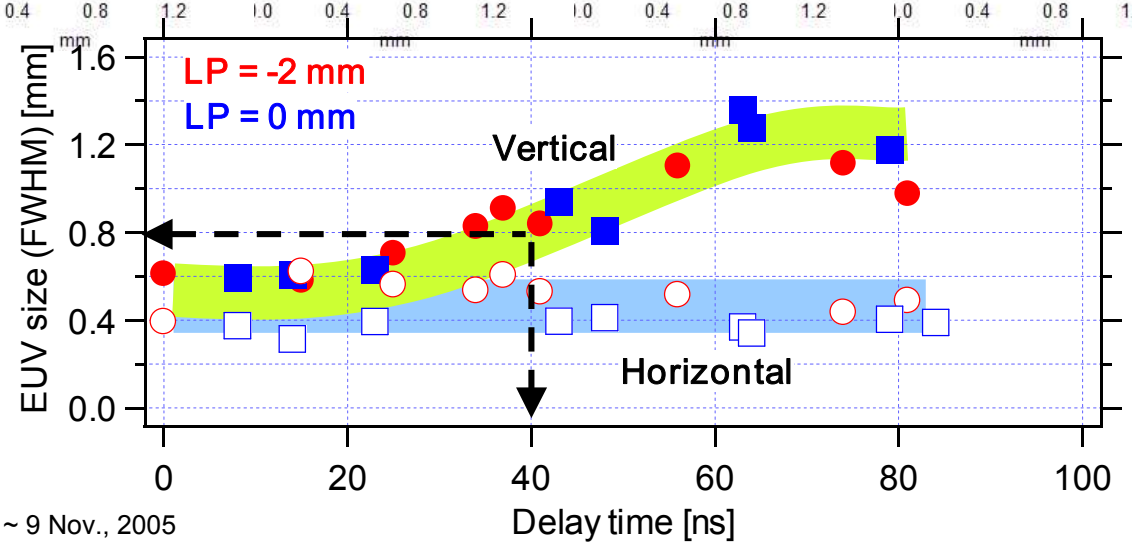
EUV source limitation

Etendue < 3.3 mm^2*sr

Solid-angle : $\Omega = 2\pi$ sr

Source size : D < ~ 800 $\mu m\phi$

→ Delay time < 40 ns



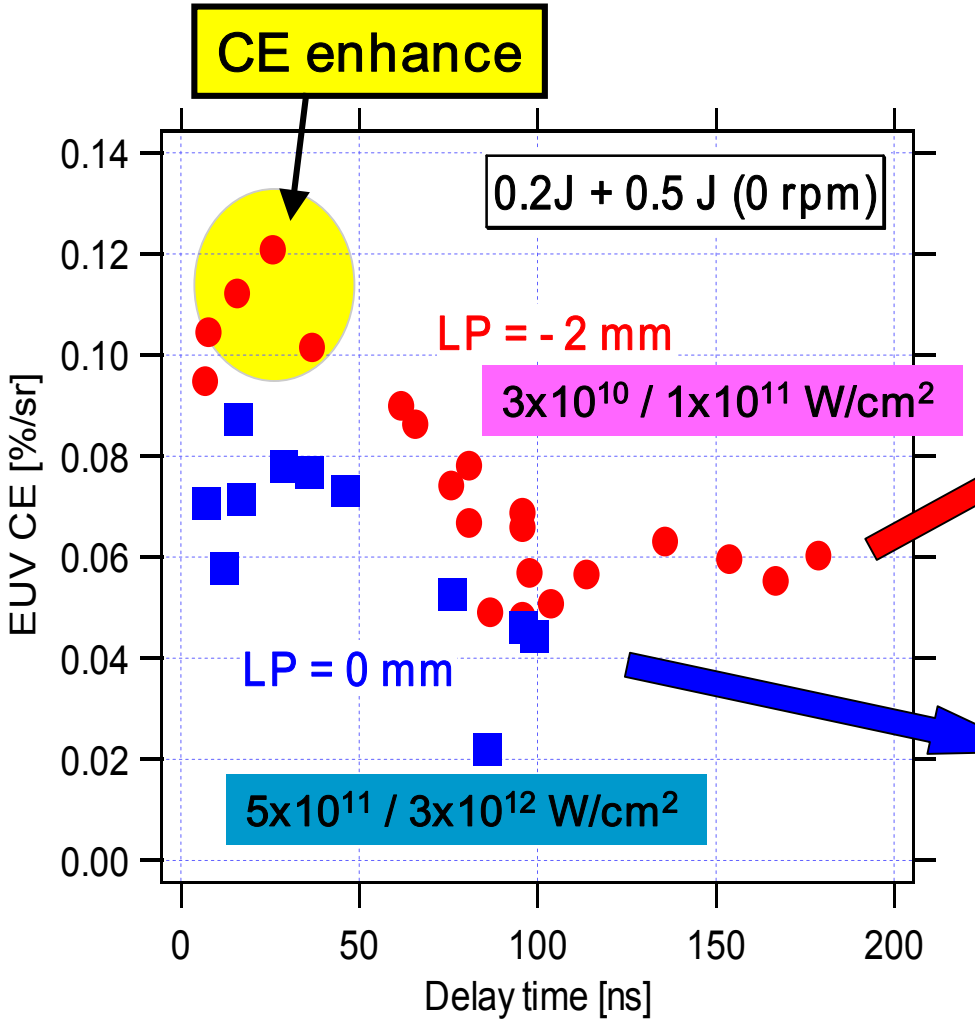
Solid-Xe drum

Double pulse

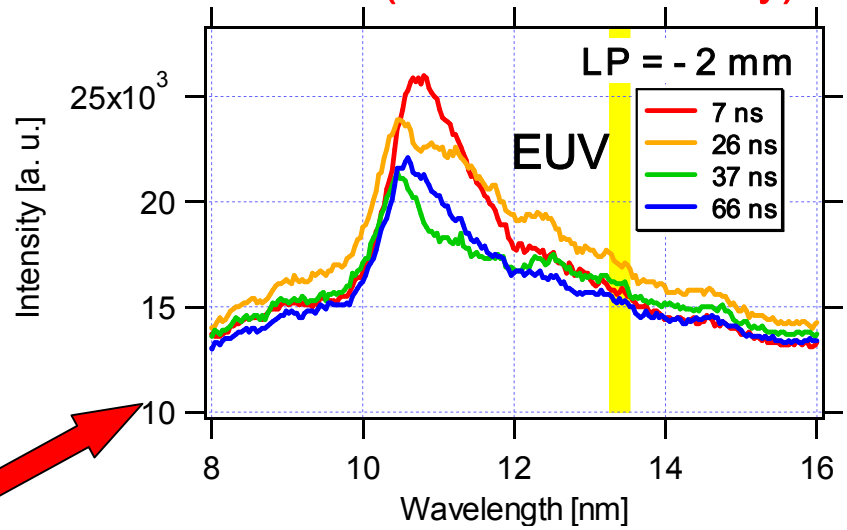
EUV conversion efficiency (CE) depended on double-pulse delay time.

Rest target

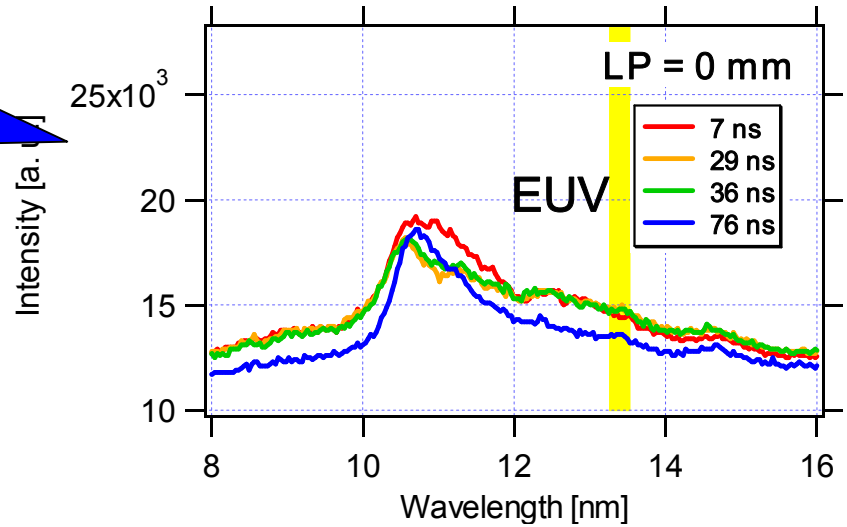
LASTI/UH



LP = –2 mm (Low laser intensity)



LP = 0 mm (High laser intensity)



Solid-Xe drum

Rotation effect

EUV images indicate long scale-length plasma was created in the case of rotating target

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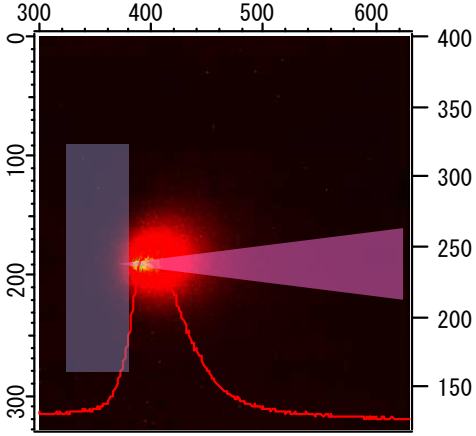
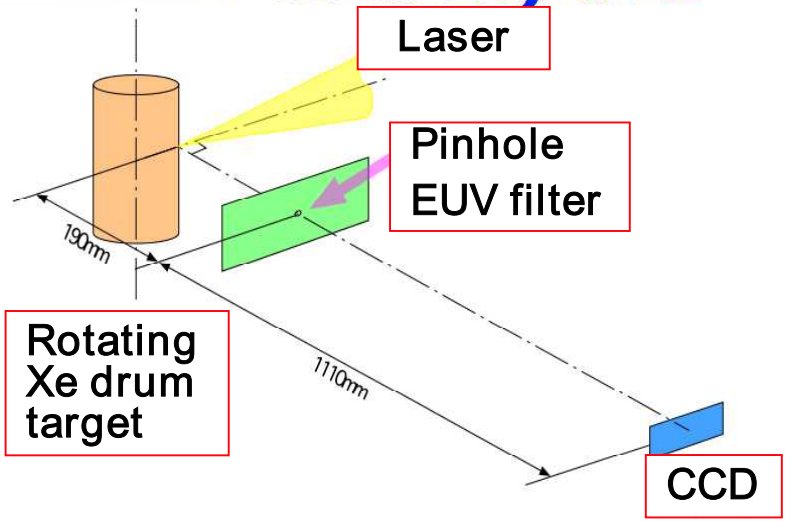
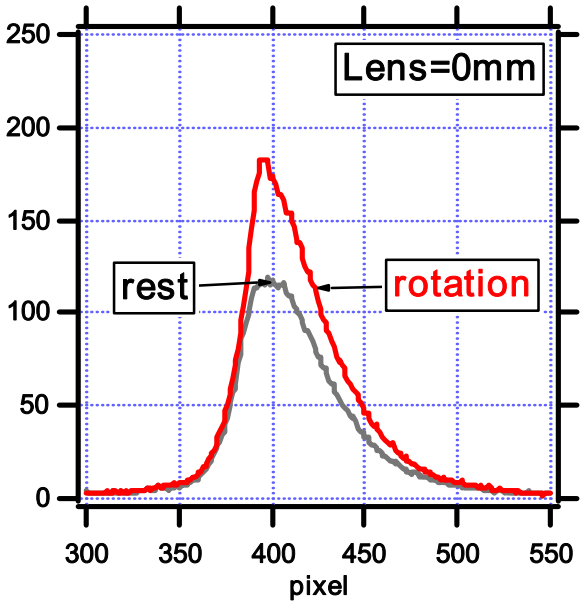
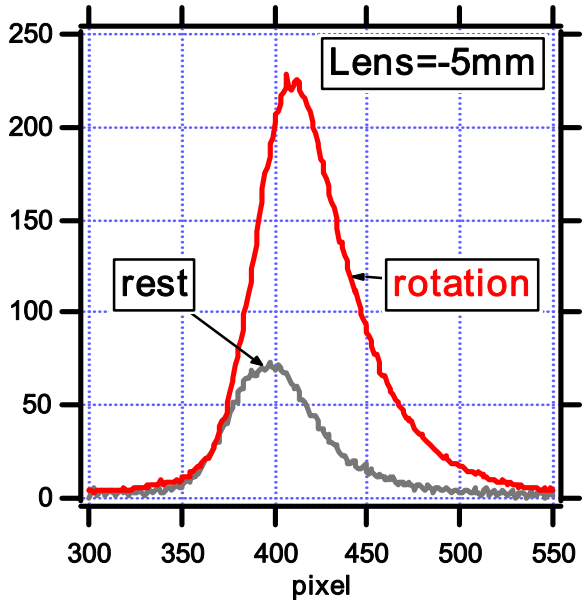


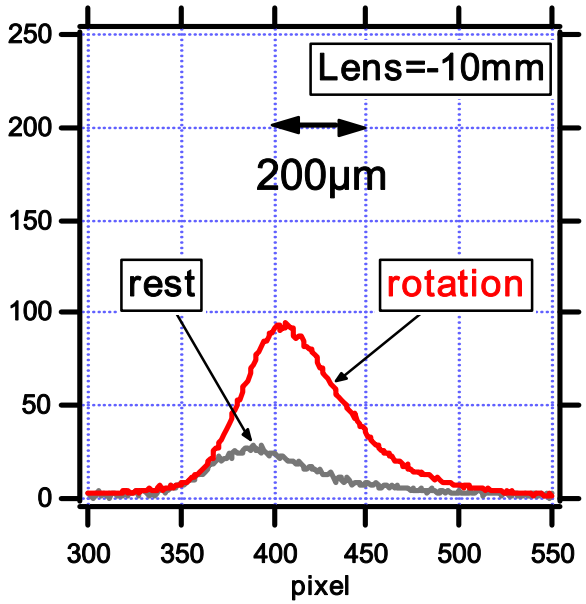
EUV emission profiles in the target normal direction

(1 pixel = 4.1 μm)





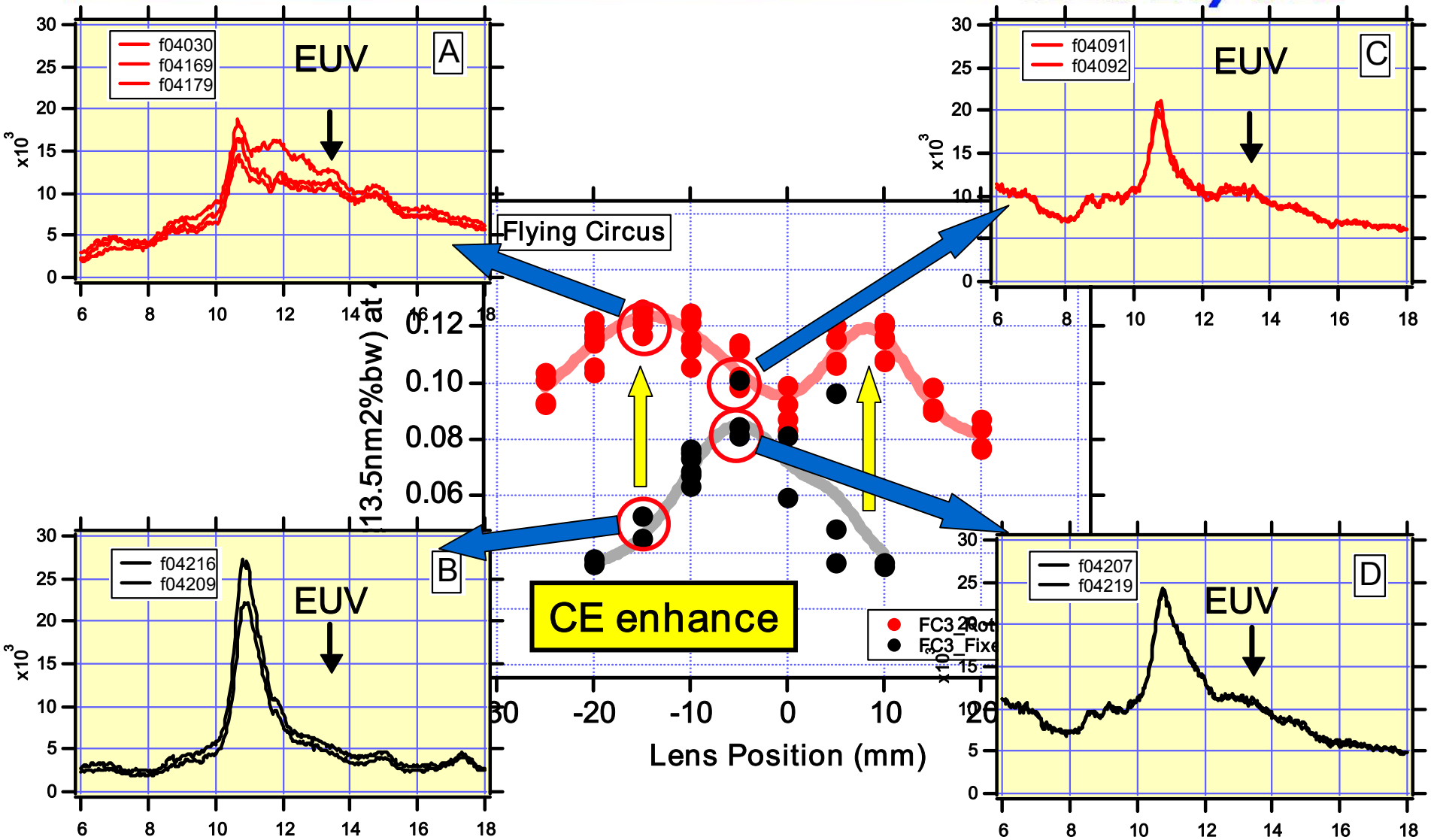




Solid-Xe drum

Rotation effect

EUV spectrum changes at high CE condition on the rotating target



Solid-Xe drum

Rotation effect

Fast Xe ions with kinetic energy of > 2 keV decreased due to surface gas at > 10 rpm.

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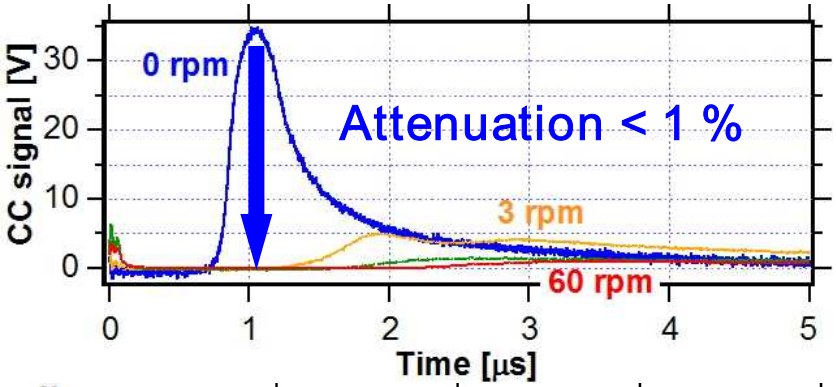
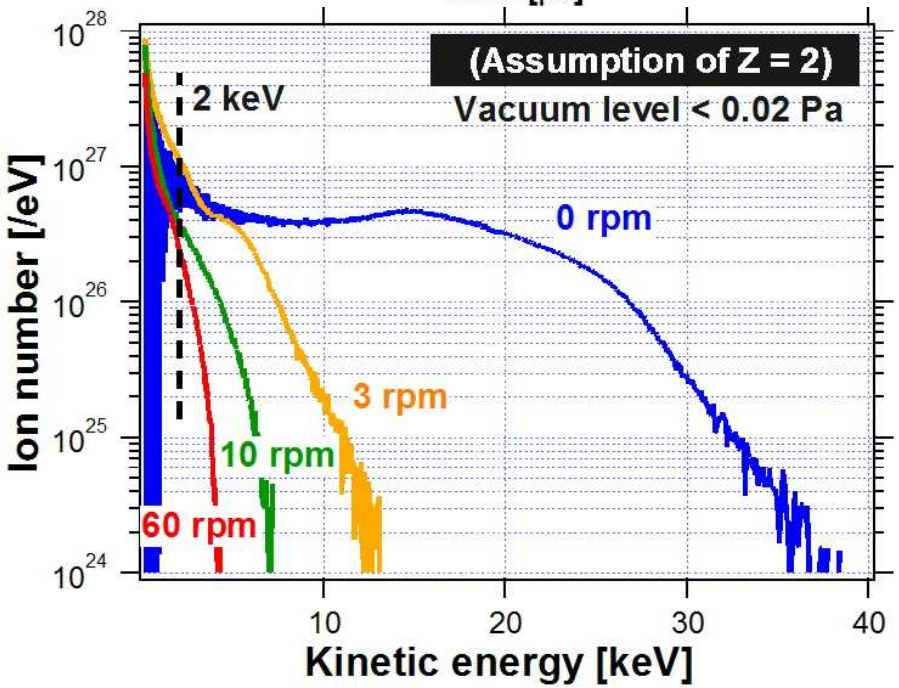
Charge collector (CC)

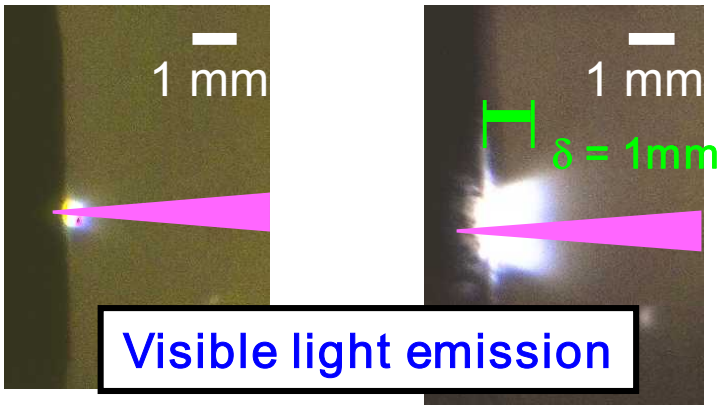




Surface gas condition was estimated.
Thickness ~ 1 mm
Pressure > 83 Pa
EUV absorption rate < 1.6 %
(by using μ = 34358 cm^2/g : NIST data)

Rest target

Rotating target



$$\text{Collision-less rate} \quad \eta = \exp(-\delta/\lambda) = 1\ \%$$

$$\text{Mean free path} \quad \lambda = \frac{1}{\sqrt{2}\cdot n\cdot \pi\cdot D_{Xe}^2} = 220\mu m$$

$$\text{Moleculer density} \quad n = \frac{N_A}{22.4\,L}\cdot\frac{83\,Pa}{1\,atm} = 2.2\times10^{16}\,cm^{-3}$$

Solid-Xe drum

Rotation effect

Energy distribution of ions were measured by using electrostatic energy analyzer.

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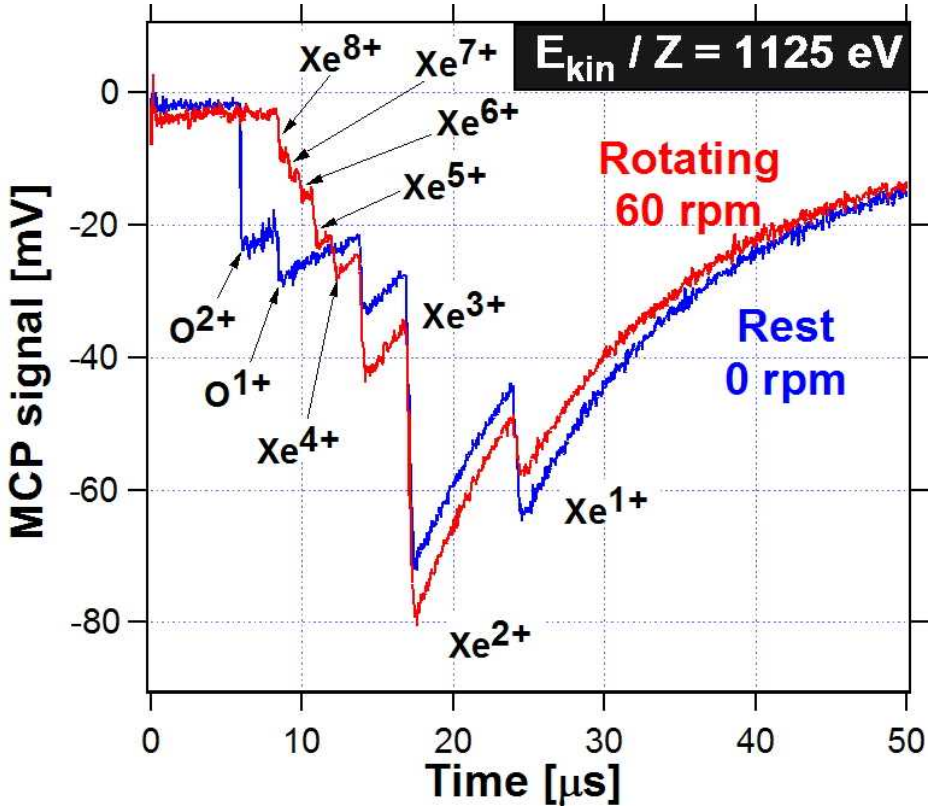
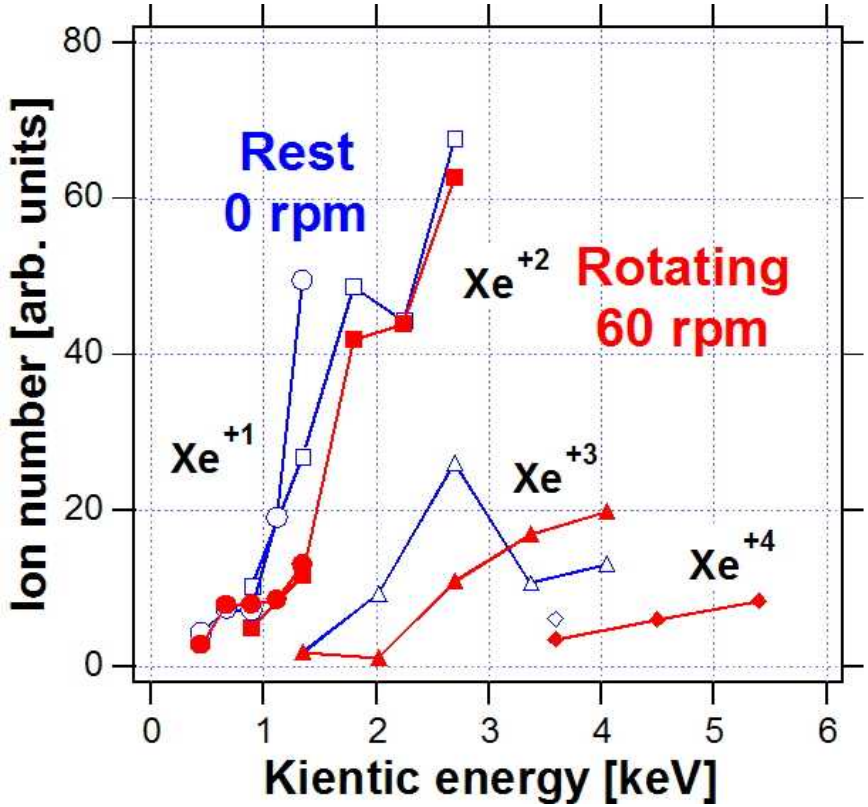
Electrostatic energy analyzer with a MCP detector





- O_2 contamination on solid-Xe target was removed by rotating drum.
- Xe^{8+} ions were observed in rotating target.
- Xe^{2+} ions were the main charge state in rotating target.

Solid-Xe drum

Target exfoliation

Exfoliating due to pileup of shock-waves was observed by irradiating double laser pulses.

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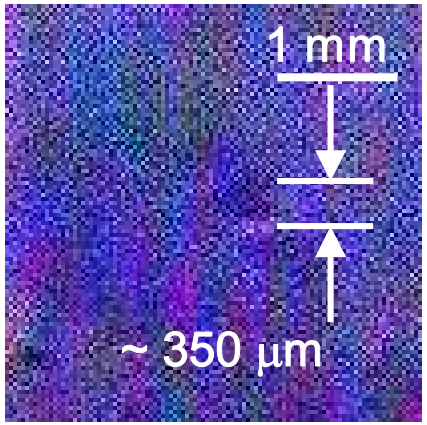
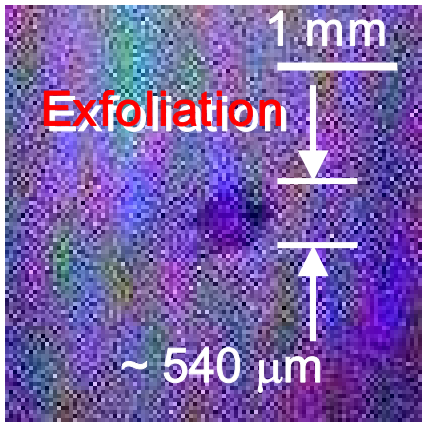
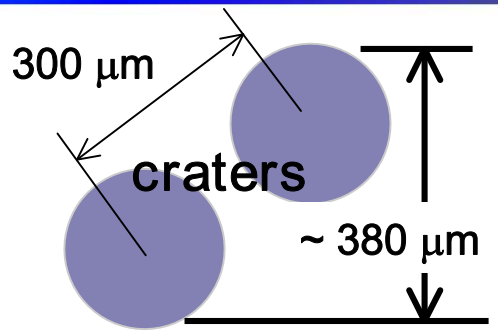
Δt = 2 μs



Δt = 0.5 μs

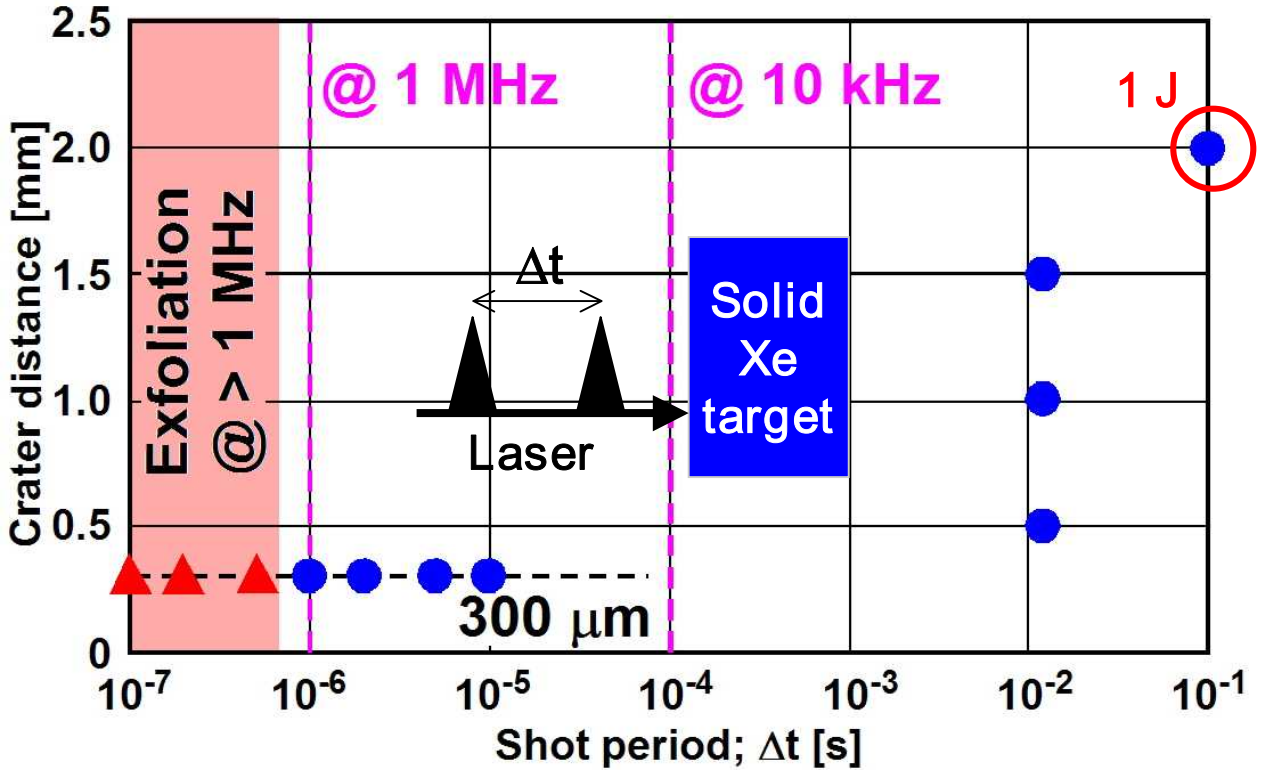




Exfoliating condition

@ 0.5 J, 100 μmϕ spot, 300 μm pitch

f_L > 1 MHz (Δt < 1 μs)



Solid-Xe drum

Target exfoliation

Exfoliating condition (f_L > 1 MHz) was explained theoretically. (Absorption coefficient η = 1.3 %)

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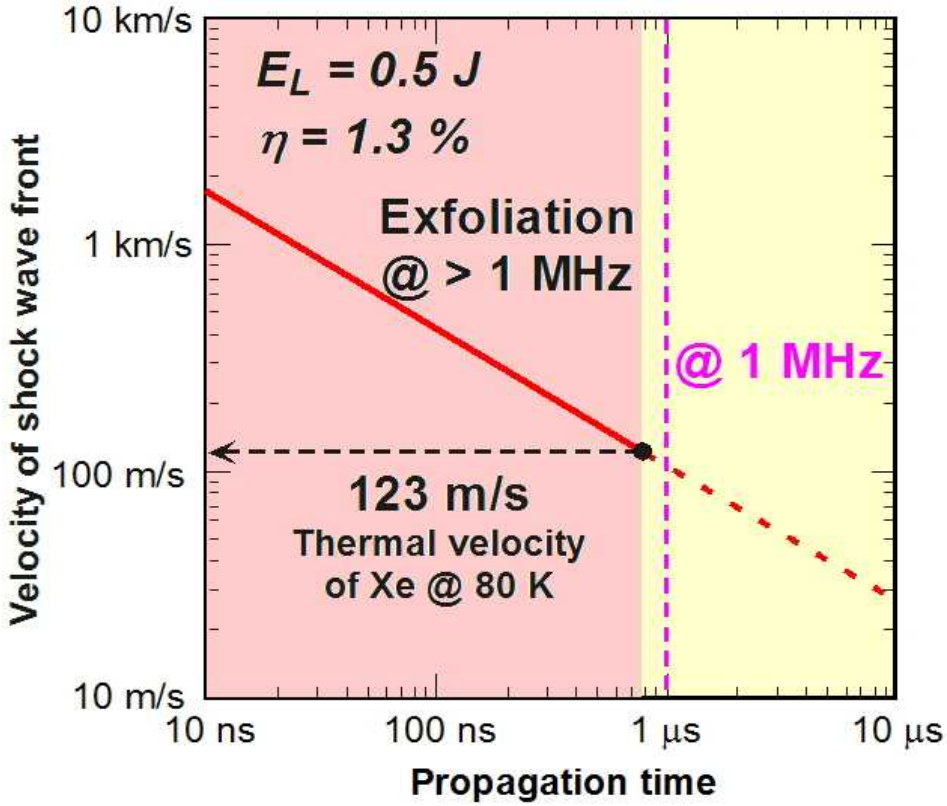
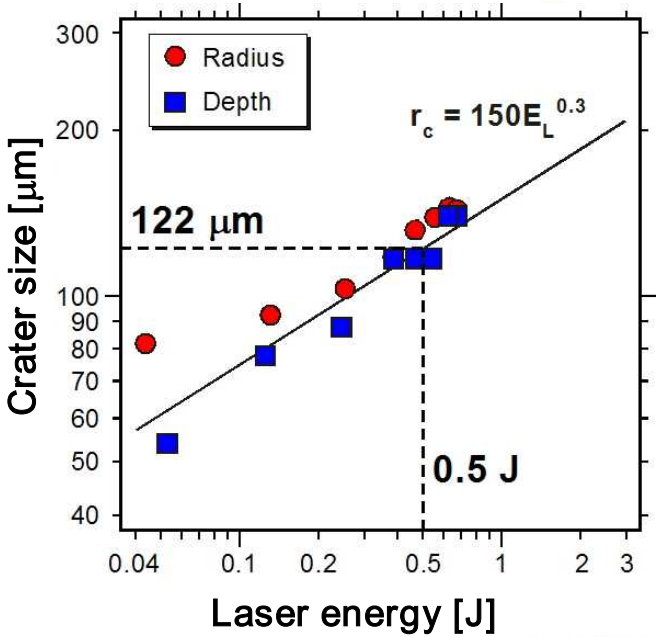
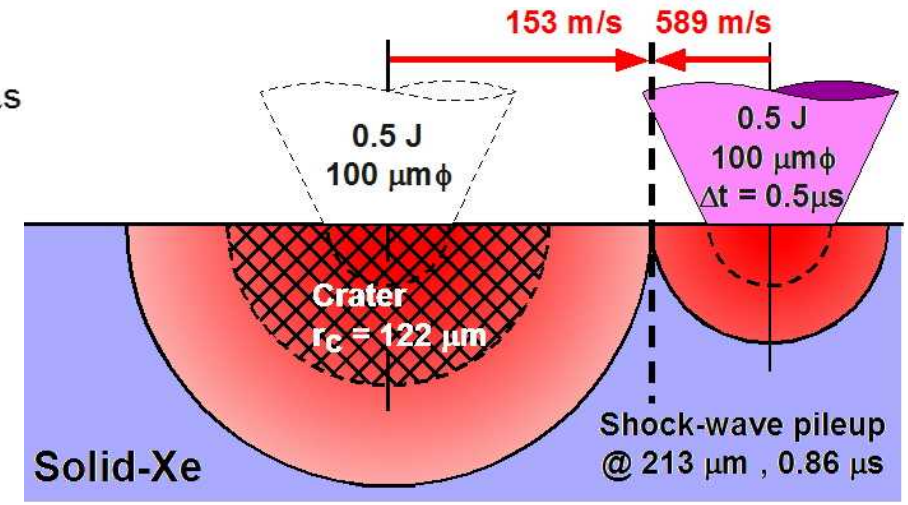


Shock wave propagation





Absorption coefficient η was evaluated with the dependence of crater size on laser energy.

Summary & Future works (1)

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(1) Dependences on delay time of double-pulse laser irradiation

- EUV emission size increased with double-pulse delay time.
- Spectrum change and CE enhancement were explained with modification of plasma due to pre-formed plasma.

(2) Target rotation effect

- In rotating target,CE enhancement due to generation of a long scale-length plasma was estimated from time-integrated EUV images.
- Fast Xe ions (> 2 keV) significantly decreased at > 10 rpm due to a gas layer (curtain) generated near the target surface.

(3) Exfoliation of solid-Xe target due to pileup of laser-induced shock wave was studied experimentally and theoretically.

Future works:

Time-resolved EUV images will be obtained to understand double-pulse and rotating effects on CE enhancement in detail.

2. Cryogenic Xe capillary jet target

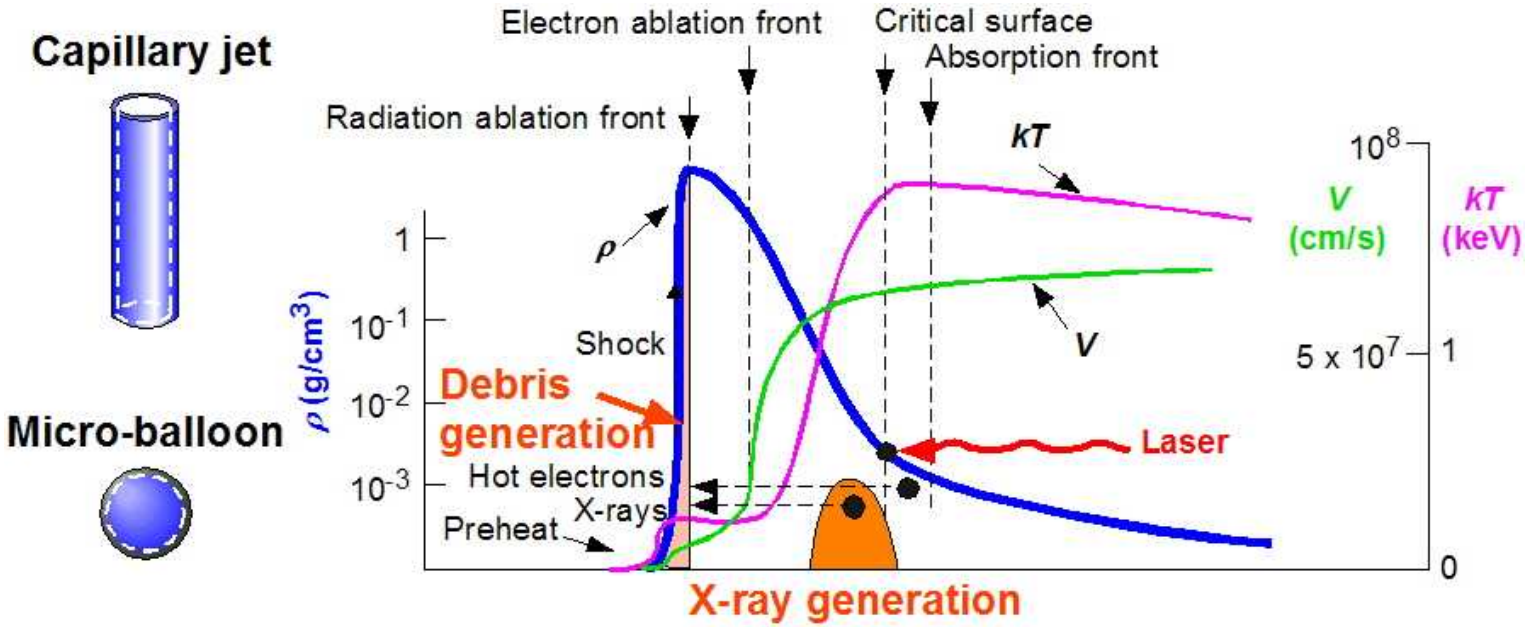
Xe capillary jet

Concept 1

"Capillary jet" and "micro-balloon" targets are useful to decrease Xe consumption and debris.

LASTI/UH

Problem of high power EUV source	Influence
Xe consumption increases. →	• Vacuum level is lowered. • EUV is absorbed by the target material. • High pumping speed is required.
Debris generation increases. →	• Collector mirror is damaged. • Lifetime of collector mirror is shorter. • Cost of EUV source increases.



I.C.E. Turcu, and J.B. Dance: "X-ray from laser plasmas".

Xe capillary jet

Concept 2

Optimum plasma and plasma confinement effect are important for improving effective CE.

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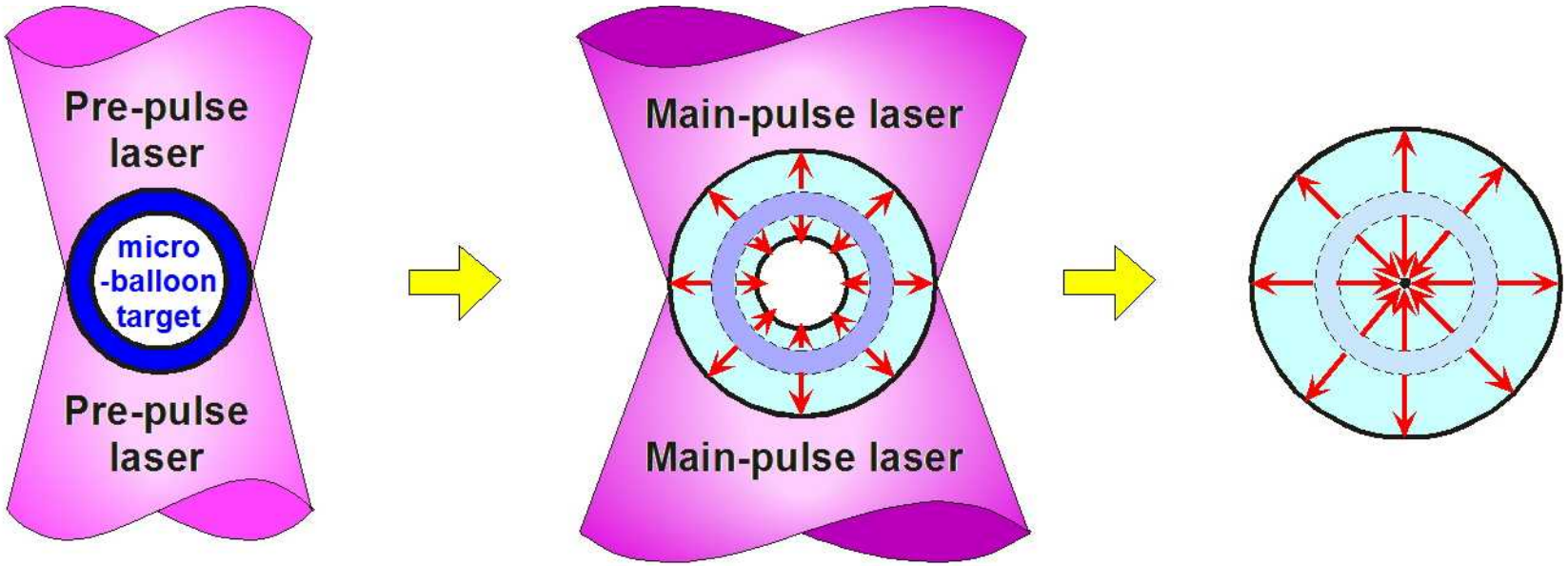
(1) A micro-balloon target is uniformly pre-heated by pre-pulse lasers.

(2) The optimum plasma for EUV generation is uniformly heated by main-pulse lasers.

(3) Plasma confinement effect elongates EUV emission lifetime, and improves effective CE.



D_{out} = 50 ~ 200 μmϕ
Wall = 0.1 ~ 5 μm
$n_{ion} = 1.38 \times 10^{22}$ /cm^3

D_{out} ~ 800 μmϕ
(Etendue ~ 3.3 mm^2*sr)
$n_{ion} = 10^{18} \sim 10^{19}$ /cm^3

Contents (2)

LASTI/UH

(1) Developing a cryogenic Xe capillary jet target

- Forming of Xe capillary jets by using annular nozzles

(2) Theoretical studies on forming condition of a Xe capillary jet

- Calculation of durations for forming processes
  - ✓ Freezing duration due vaporization-induced cooling
  - ✓ Brake-up duration due to fluid instability
  - ✓ Expanding duration of target wall due to inner gas
- Discussion on improving methods of nozzle for increasing jet velocity

Xe capillary jet

Exp. setup

Experimental setup for generating cryogenic Xe capillary jet targets in a vacuum chamber

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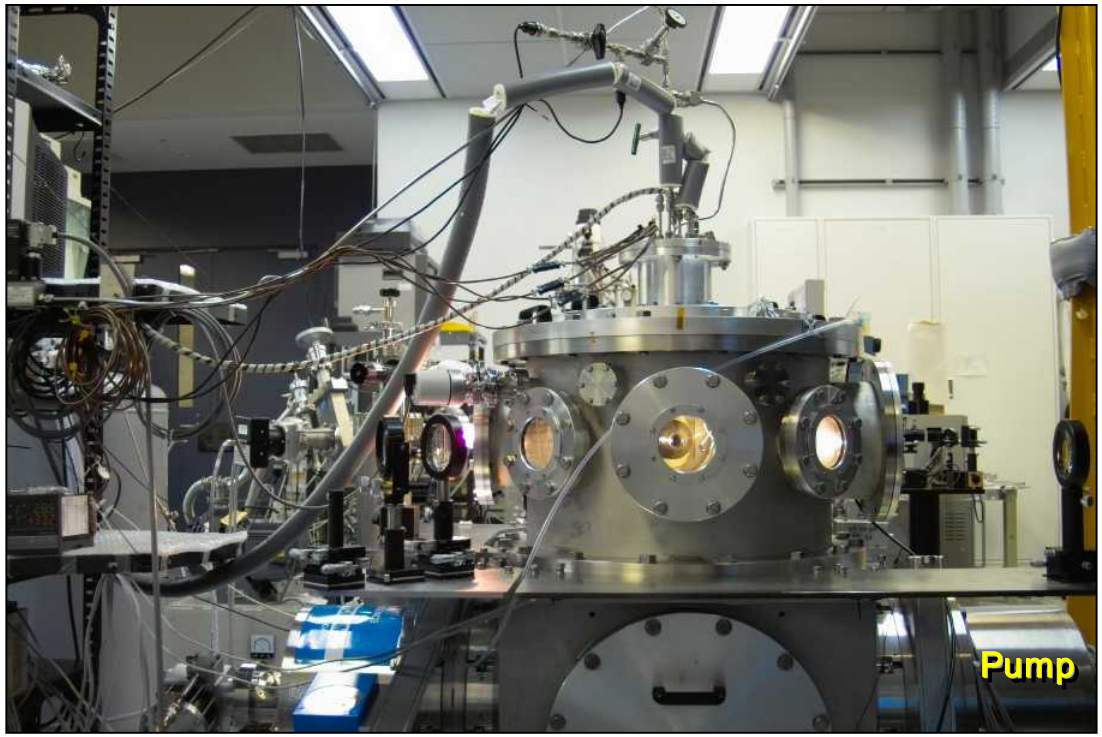
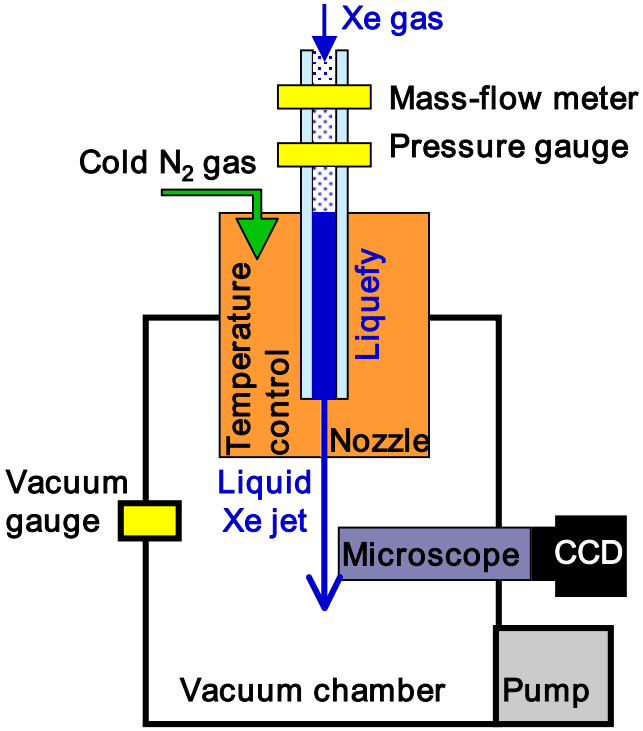
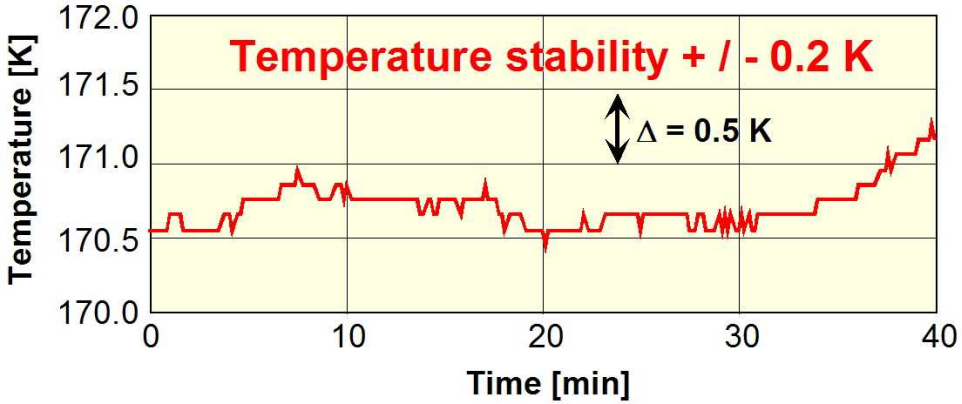
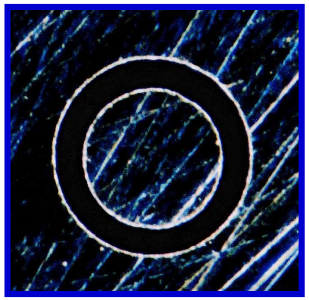






Annular nozzle



Xe capillary jet

Experiment

Cryogenic Xe capillary jet targets were generated in a vacuum chamber.

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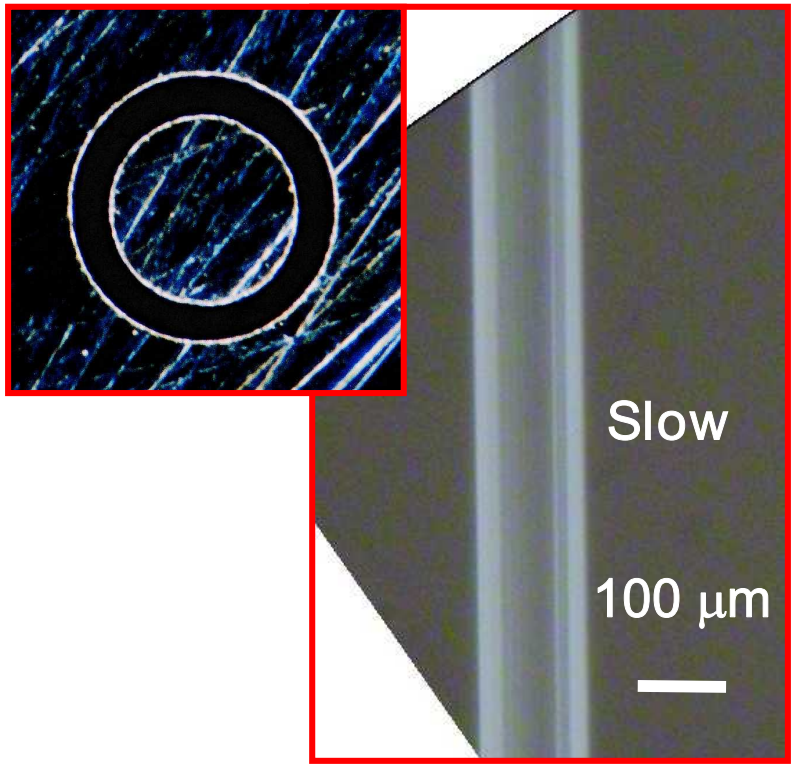
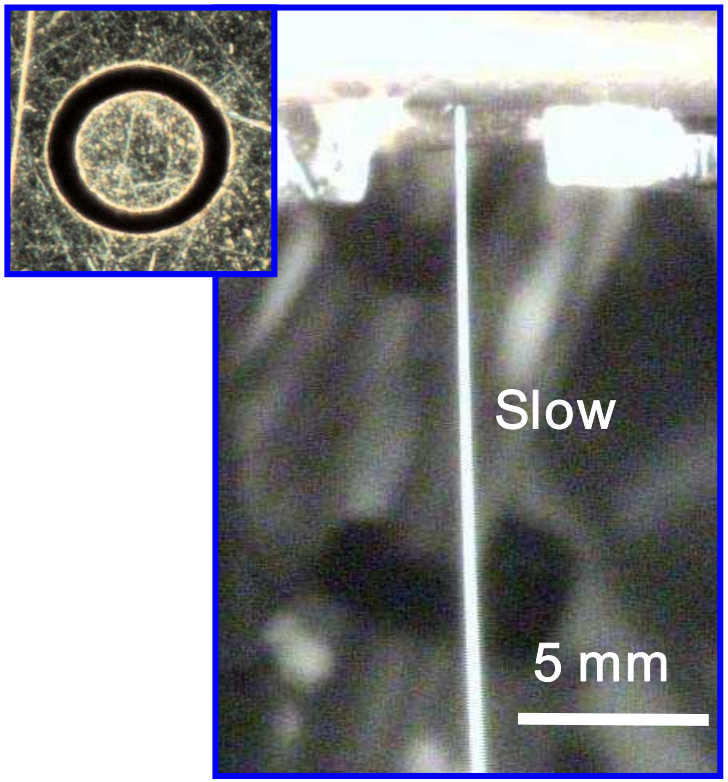
150 / 110 μmϕ

163 ~ 173 K, ~ 0.65 MPa



100 / 70 μmϕ

170 ~ 175 K, 0.05 ~ 0.6 MPa



- Jet velocity was evaluated to be ~ 0.4 m/s (solid filament).
- Spray jets were generated at > 190 K and > 1 MPa.

Xe capillary jet

Forming Model

Forming models of a cryogenic Xe capillary jet target in vacuum

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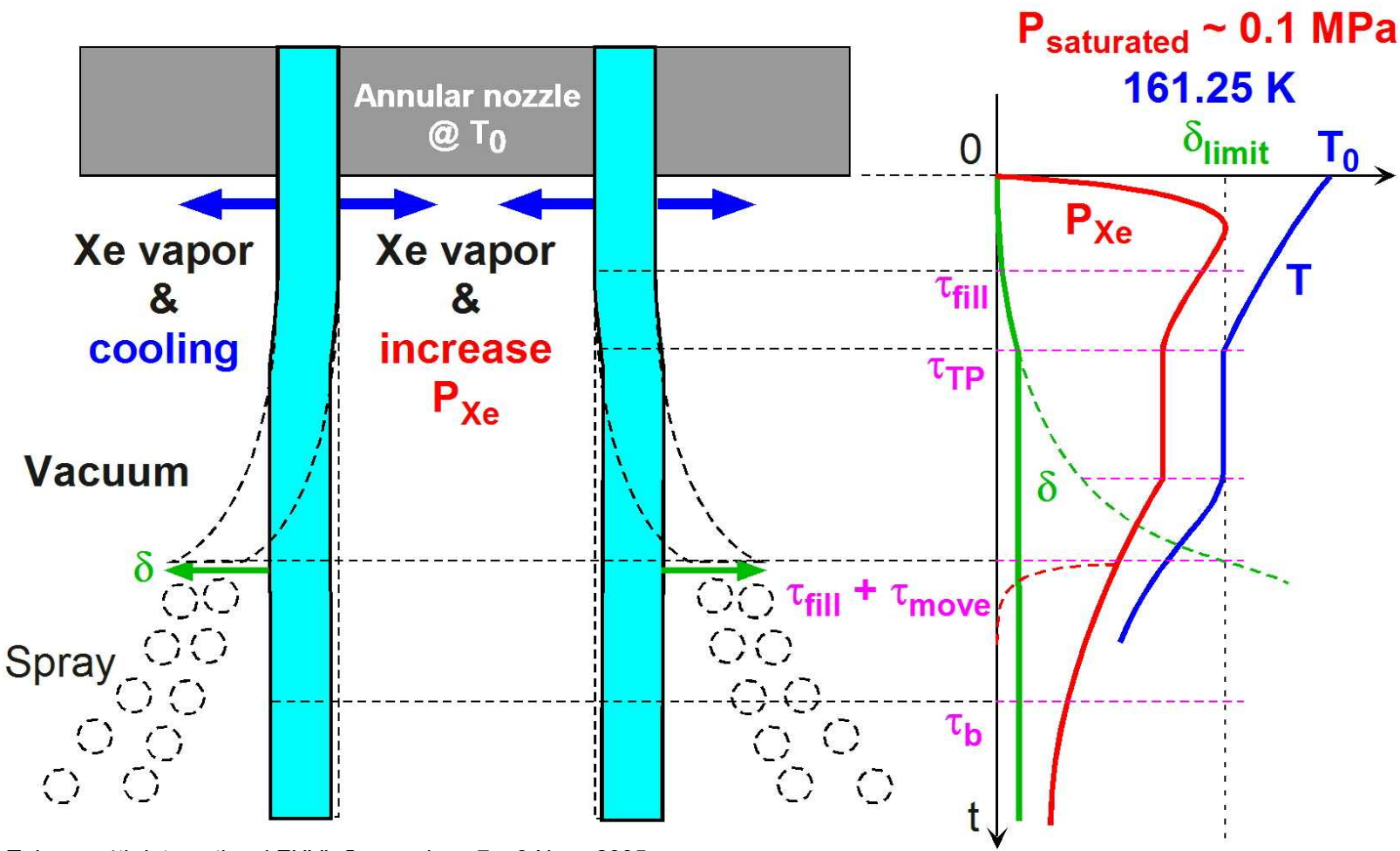
Forming condition : $\tau_{TP} < \tau_{fill} + \tau_{move} < \tau_b$



Xe capillary jet

Forming Model

Cryogenic Xe jet is stabilized by cooling effect before it breaks-up due to fluid instability.

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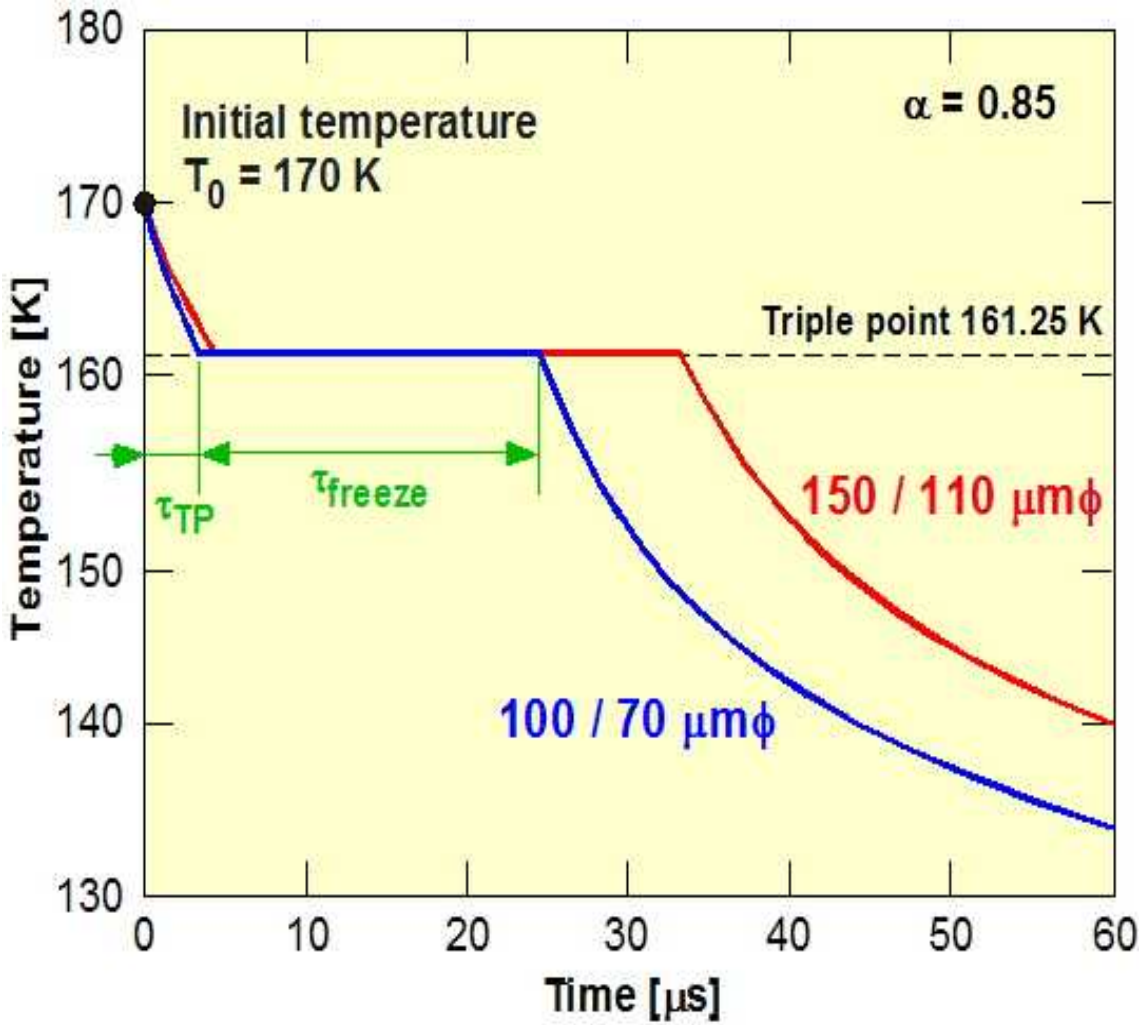


1) Duration for reaching TP :

τ_{TP} = 4.4 μs / 3.2 μs

2) Duration for freezing

τ_{freeze} = 29 μs / 21 μs

3) Break-up duration @ T_0

τ_b = 1300 μs / 800 μs

$$\tau_b = 12\left[\sqrt{\frac{\rho \cdot \delta^3}{\sigma}} + \frac{3 \cdot \mu \cdot \delta}{\sigma}\right]$$

τ_{TP} , τ_{freeze} < τ_b

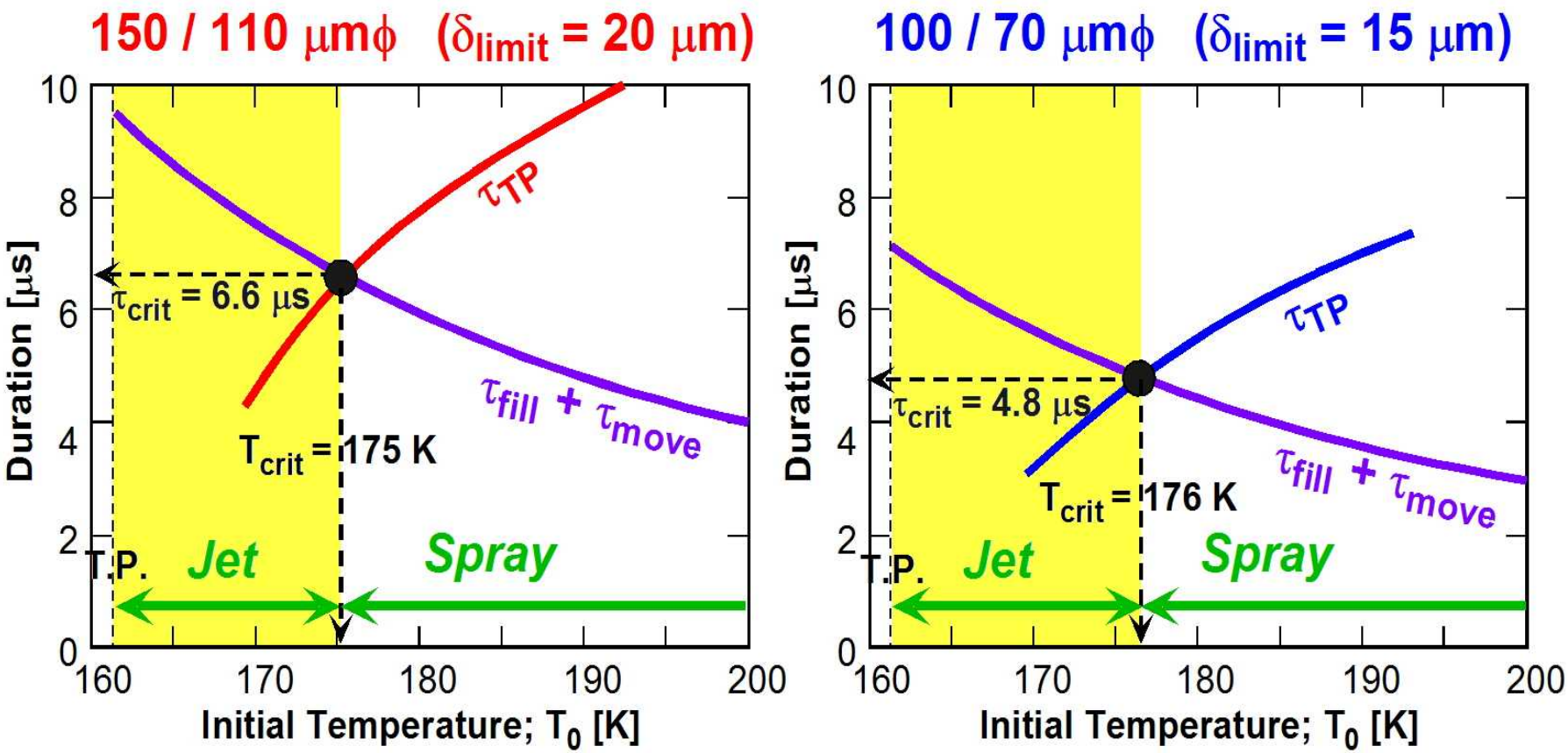
Xe capillary jet

Forming Model

Forming condition of cryogenic Xe capillary jet is satisfied at initial temperature T_0 < 175 K.

LASTI/UH

Forming condition : $\tau_{TP} < \tau_{fill} + \tau_{move} < \tau_b$



Xe capillary jet

Forming Model

Generating Xe capillary jet targets at > 180 K requires δ < 5 μm and D_{out} > 100 μmϕ.

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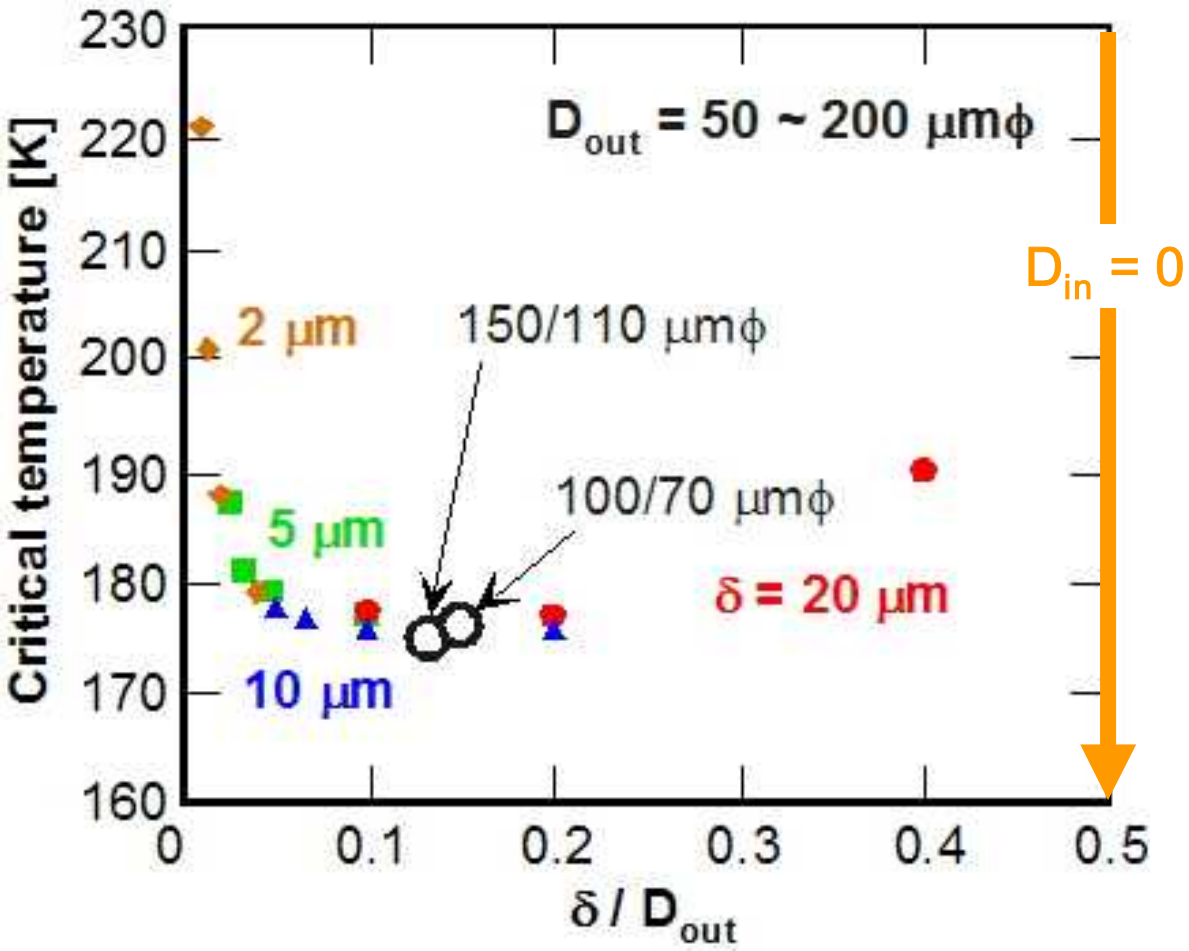

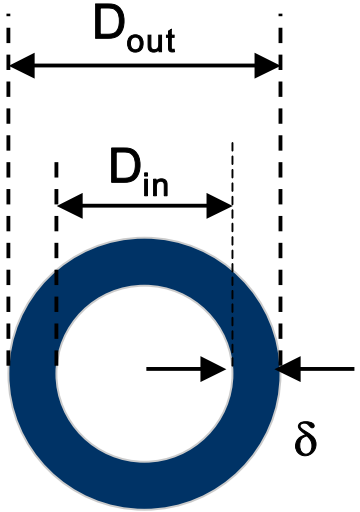

Annular nozzle

Xe capillary jet

Forming Model

Velocity of thinner Xe capillary jets (δ = 5 μm) can reach to ≥ 30 m/s @ ≥ 1.35 MPa.

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Bernoulli equation

$$v_B = \sqrt{\frac{2 \cdot \Delta P}{\rho(T_0)}}$$

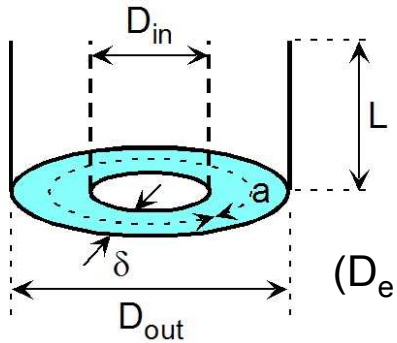
Nozzle parameter

δ = 5 μm

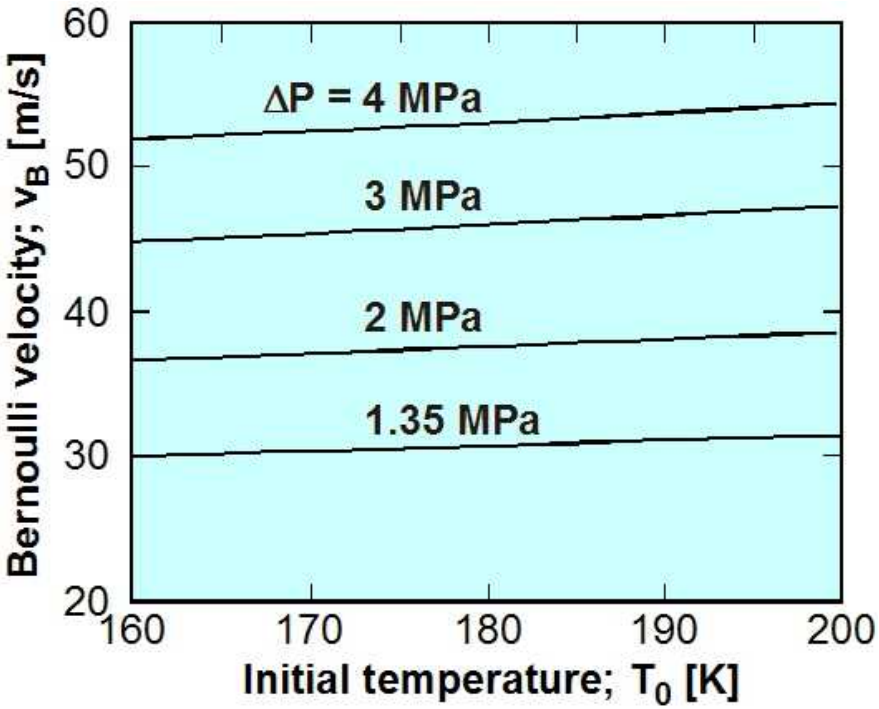
L = 20 μm

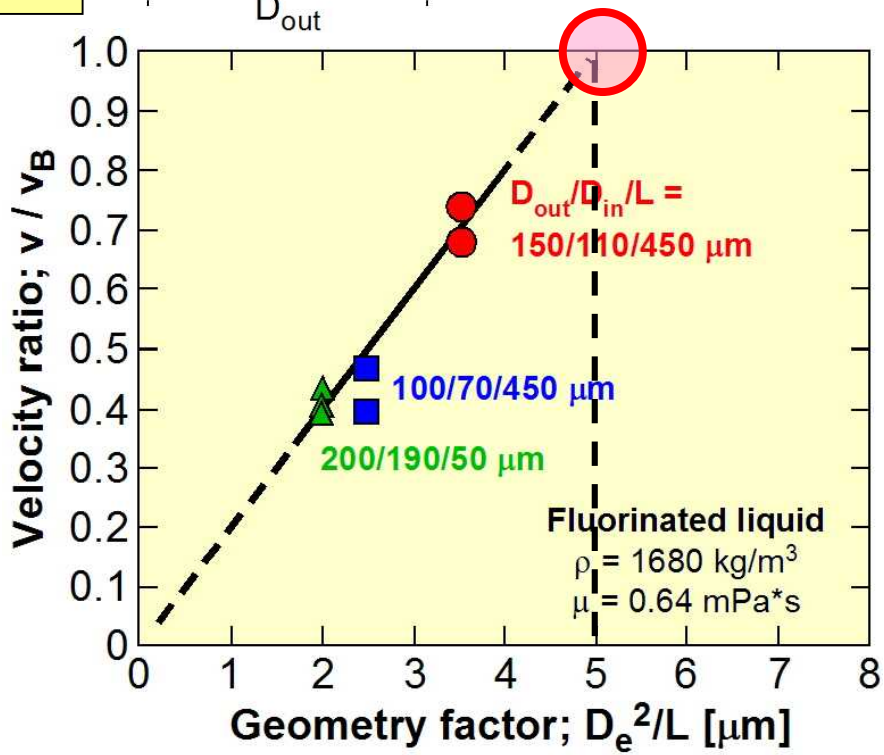
D_e^2/L = 5 μm

Velocity ratio ~ 1



($D_e = D_{out} - D_{in} = 2\,\delta$)





Summary & Future works (2)

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(1) Developing a cryogenic Xe capillary jet target

- A cryogenic Xe capillary jet (solid filament) was generated by using an annular nozzle at a cooling temperature of < 175 K.
- The obtained velocity of the Xe capillary jet was ~ 0.4 m/s.

(2) Theoretical studies on forming condition of Xe capillary jet

- Forming condition of a Xe capillary jet in vacuum was studied considering evaporation-induced cooling effect and expanding target wall due to inner gas pressure.
- A thinner capillary jet was useful for increasing operation temperature and jet velocity.

Future works:

Thinner capillary jet (δ < 5 μm) will be tested to increasing jet velocity at a higher temperature and pressure.

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