SoP19

Fast continuous supply of Cryogenic Xe targets for LPP-EUV source

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3rd International EUVL Symposium
Miyazaki, JAPAN, 1 ~ 4 Nov., 2004

Abstract

In this paper, we report characterization of the **rotating cryogenic drum** which supplies a **solid Xe layer** continuously to the laser focus point [1]. We studied stability of solid Xe layer and emission of debris under high repetition-rate laser irradiation. As alternative targets, we are developing **mass-limited targets** which are formed by using liquid Xe flowing out through a nozzle. Formation of **capillary (hollow filament) targets** and **droplet targets** are reported. **Micro-balloon target** is discussed as a future advanced target.

[1] T. Mochizuki, A. Shimoura, K. Fukugaki, T. Inoue, S. Miyamoto, and S. Amano, 2nd International EUVL Symposium, 7F, Antwerp, Belgium, 30 Sep. to 2 Oct., 2003.

This work was performed under the auspices of Leading Project performed by MEXT.

Comparison of cryogenic Xe targets for 1J/10kHz laser

Key points: high density target, fast-continuous supply, and stability

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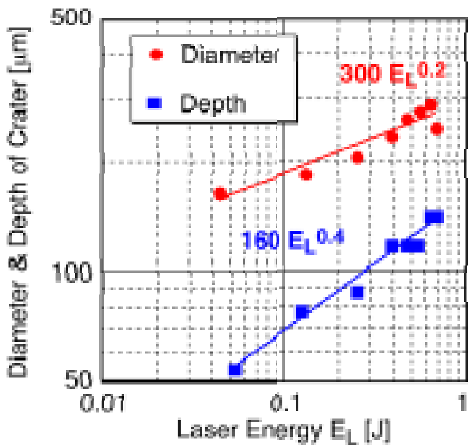
Solid Xe layer target

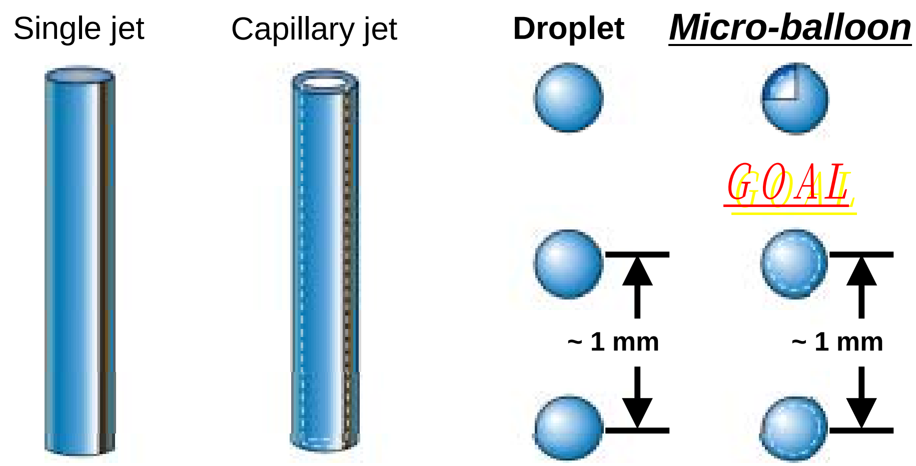
1 J / 10 kHz laser irradiation at 300 μm pitch
Crater size : D = 300 μmϕ, depth = 160 μm
Drum diameter : 10 cmϕ
Drum rotation speed : 573 rpm (10 cmϕ drum)
Recovery speed : 10 μm/s (5 cm z - slide)

Crater size depends on laser energy.



Mass-limited targets

D_{out} = 150 μmϕ, D_{in} = 130 μmϕ, t = 10 μmt, v = 50 m/s
Targets are irradiated by a **1J / 10 kHz laser** <u>every 5 mm or 5 droplets.</u>
No-expanded target material can be collected and recycled.
Re is reduced for capillary and micro-balloon, and they are more stable.
Micro-balloon target is a future advanced target for LPP-EUV source.



Supplying method	Target type	Xe consumption rate [SLM] @ 1 atm	Required pumping speed [L/s] @ 0.5 Pa
Rotating cryogenic drum system	**Solid Xe layer**	**2.58 (100 %)**	**8700**
Liquid flowing from nozzle	Single jet	25.03 (970 %)	85000
	Capillary jet	6.23 (241 %)	21000
	Droplet	**2.50 (97 %)**	**8500**
	Micro-balloon	**0.87 (34 %)**	**3000**

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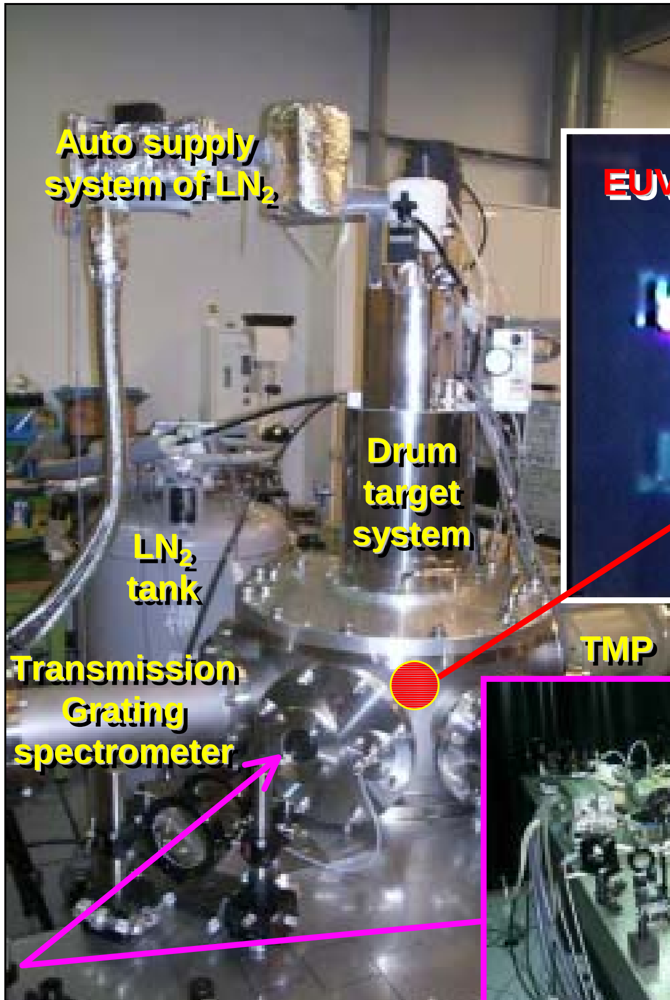
Rotating cryogenic drum system can supply solid Xe layer for 1 J / 10 kHz laser irradiation.

573 rpm and 10 μm/s are required for 1 J / 10 kHz laser irradiation.

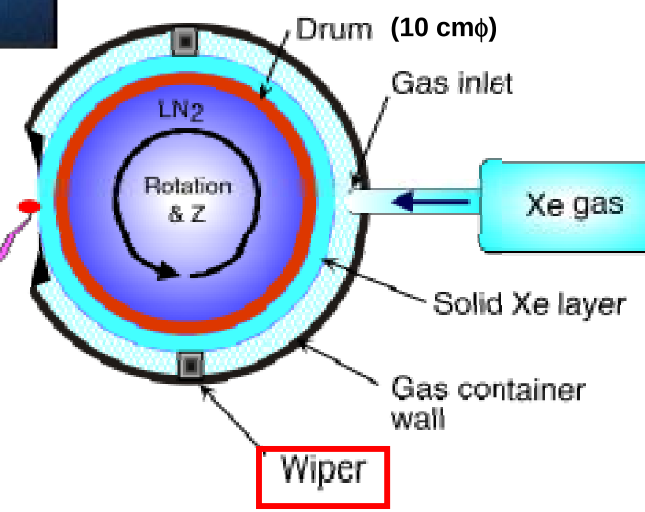


The maximum thickness of solid Xe layer : **500 μm**

Vibration of solid Xe layer
60 μm @ ? 1000 rpm

Recovery speed of crater on solid Xe layer
150 μm/s @ ? 1000 rpm

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



Cross-section view of the drum system

Shock wave contributed to exfoliation of solid Xe layer at Δt < 1 μs, much shorter period than laser pulse separation.

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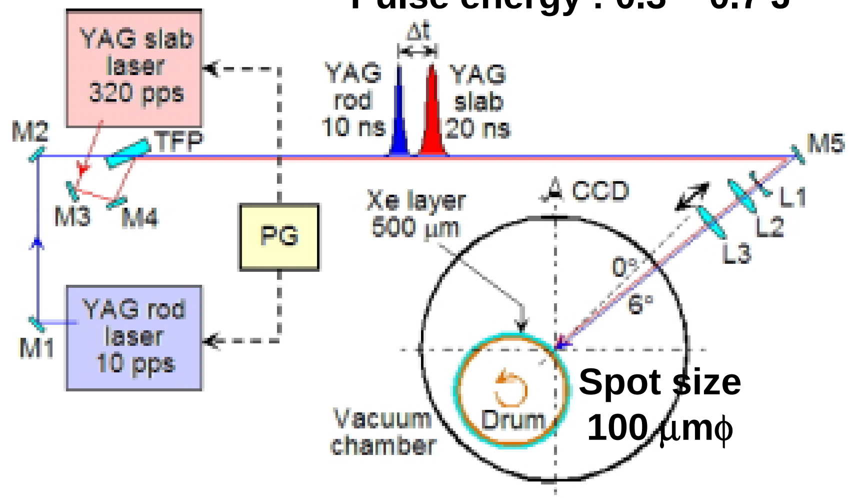
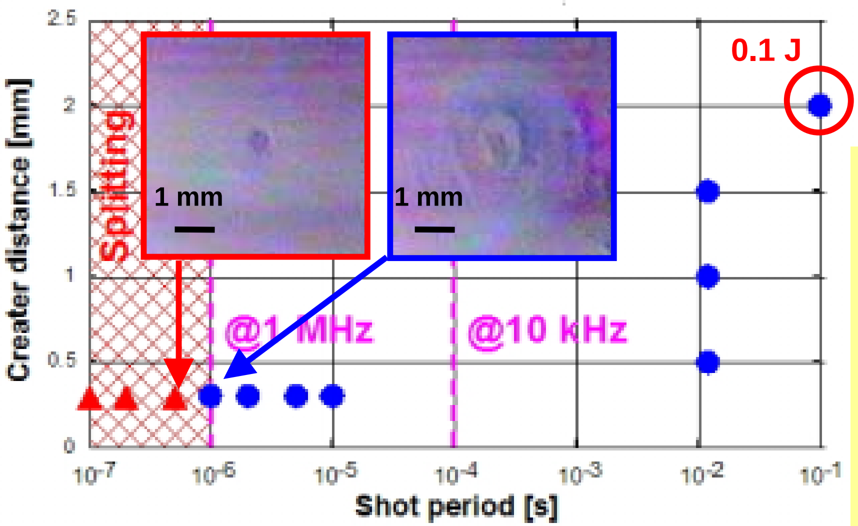
Experimental

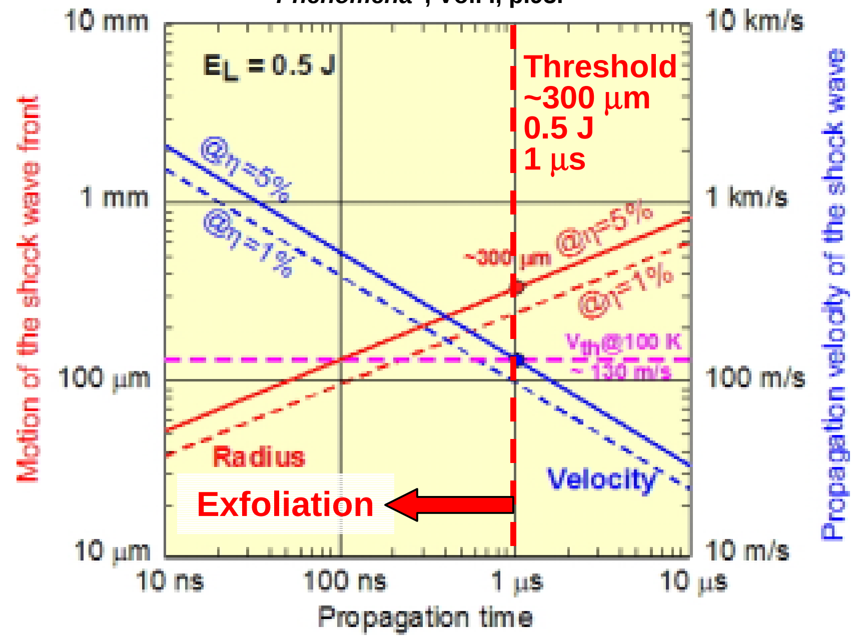
Pulse energy : 0.3 ~ 0.7 J





Calculation

Ya. B. Zel'dovich and Yu. P. Raizer: ***"Physics of Shock Wave and High-Temperature Hydrodynamics Phenomena"***, Vol. I, p.93.



Experimental Results

- For distance of **300 μm**, shock wave contributed to exfoliation of solid Xe layer at **Δt < 1 μs** for pulse energy of **0.3 ~ 0.7 J.**

Calculation Results

- Calculation results was in good agreement with the experimental results.

Stable EUV emission was obtained at 320 Hz. Contamination of Xe was not observed on a Si wafer.

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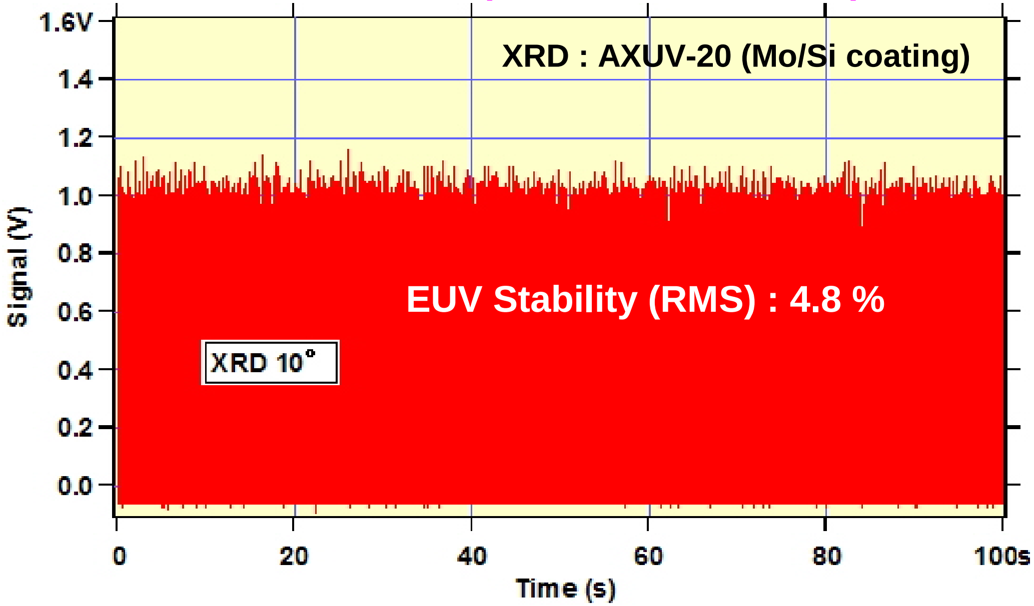
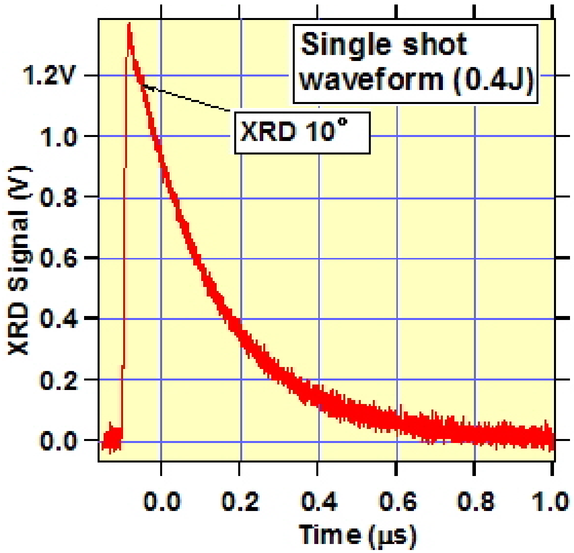
4.8 % Stability of EUV radiation power was obtained by rotating drum at 200 rpm.

Nd:YAG laser 1ω / 60 W (320 Hz / 0.2 J / 20 ns)



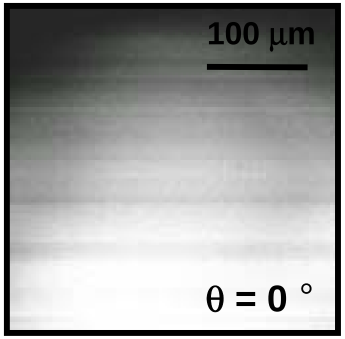


Debris on a Si wafer were observed for Xe and Cu.

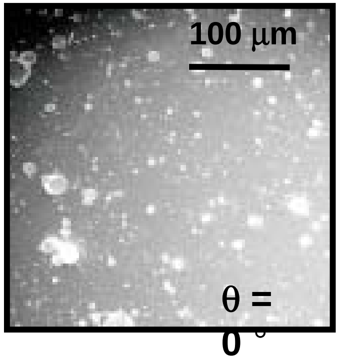
Contamination of Xe was not observed on a Si wafer.

Nd:YAG laser 1ω / 10 W (10 Hz / 1 J / 20 ns)

Xe solid target
200 shots



Cu bulk target
500 shots



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Expansion scheme of LPP for micro-balloon target

Formation of the optimum plasma is required to improve CE.

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EUV conversion efficiency will be improved because of the following model.

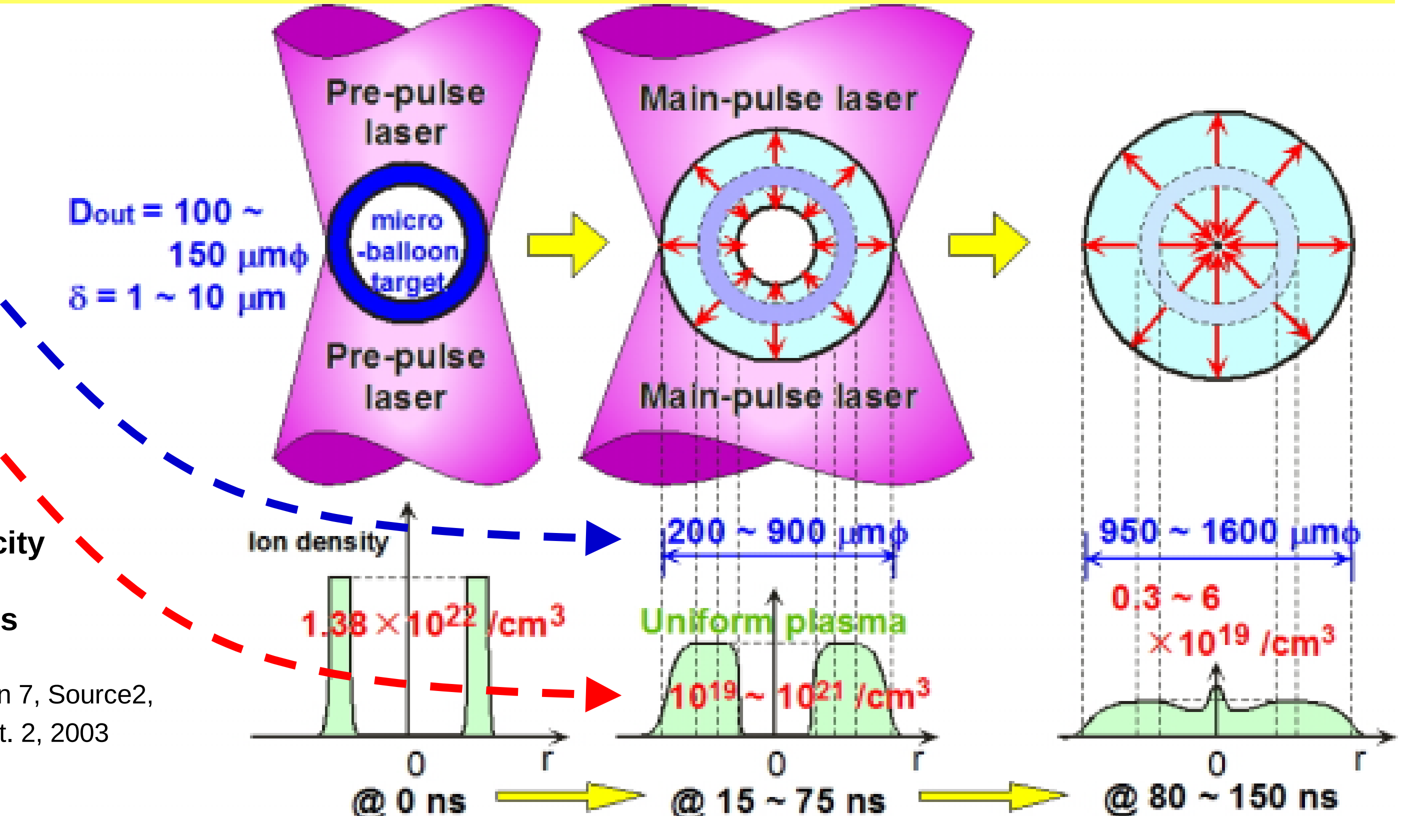
- A micro-balloon target is irradiated uniformly by multi pre-pulse laser beams.
- Uniform plasma with required plasma size (< 800 μmϕ) and the optimum density for EUV radiation ($10^{18} \sim 10^{20}$ /cm^3) is formed, then multi main-pulse laser beams irradiate the uniform plasma.
- Plasma confinement by inertial force accumulates kinetic energy of plasma, then the energy is converted gradually into radiation energy. EUV radiation time will be longer than the laser pulse-duration.

Nd:YAG laser
λ = 1064 nm
τ = 10 ns

Required plasma size
D < 800 μmϕ
(Etendue < 3.3 mm^2・sr)
(Collection angle = 2π)

Optimum ion density[1]
n_{ion} = $10^{18} \sim 10^{20}$ /cm^3

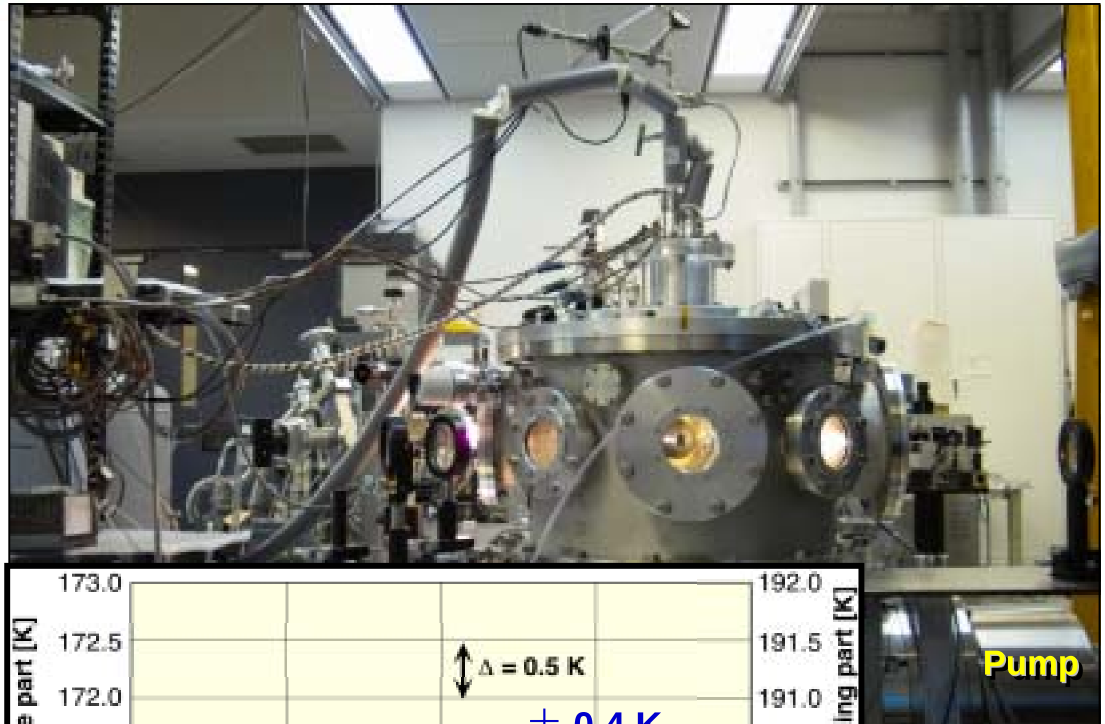
Plasma expansion velocity
v_{out} = ~5×10^3 m/s
v_{in} = v_{out}/10 = ~5×10^2 m/s

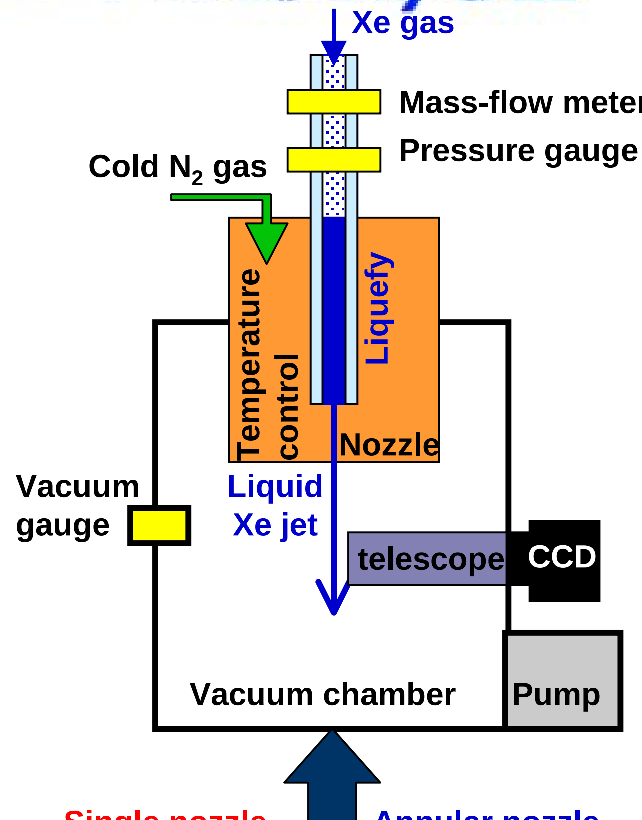


[1] K. Nishihara: EUV03, Session 7, Source2, Antwerp, Belgium, Sep. 30 – Oct. 2, 2003

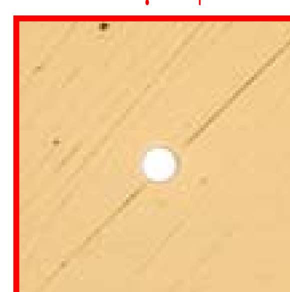
Experimental setup for cryogenic Xe filament targets

Sufficient temperature stability of ± 0.2 K was obtained.





Single nozzle
40 μmϕ



Annular nozzle
150 μmϕ / 110 μmϕ

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Cryogenic Xe capillary jet was generated at P_{Xe} = 0.65 MPa, T = 175 ~ 190 K, and Vac. = 2 ~ 4 Pa.

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Xe single jet

Diameter : 40 μmφ

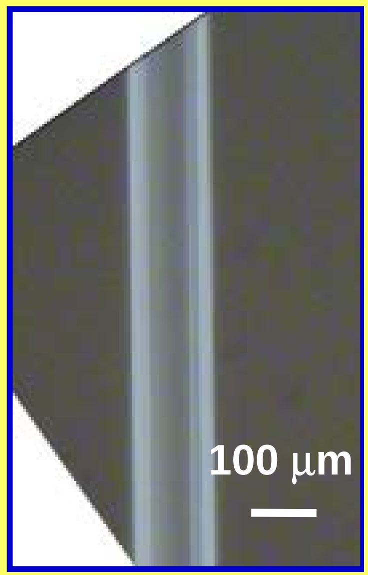
Jet speed : 30 ~ 50 m/s

Xe pressure : 1 ~ 2 MPa

Vacuum : ~ 0.5 Pa

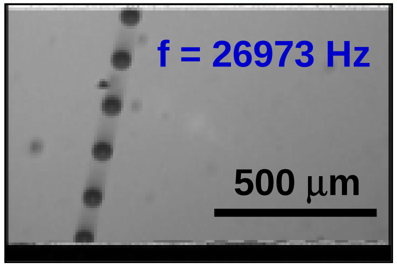
Xe capillary jet (Diameter : 150 / 110 μmφ)

Cryogenic Xe capillary jet was generated at,
Xe nominal pressure of **0.65 MPa**,
temperature range of **175 ~ 190 K**,
and vacuum level of **2 ~ 4 Pa**.
The jet velocity was estimated to be **0.2 ~ 0.4 m/s**.

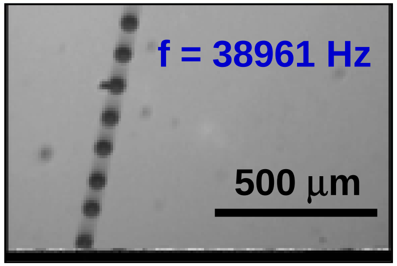


- At lower temperature of **< 175 K**, **Xe ejection was not observed**, *since high-viscose liquid Xe (or solid Xe) increased pressure loss at the annular nozzle*.
- At higher temperature of **> 190 K**, **liquid Xe jet was not ejected**, *since the Xe vapor pressure became close to the Xe back pressure*.
- The jet velocity will increase at higher Xe back pressure of >> 0.65 MPa.

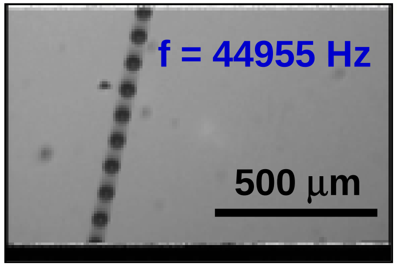
Formation of liquid droplets was studied.



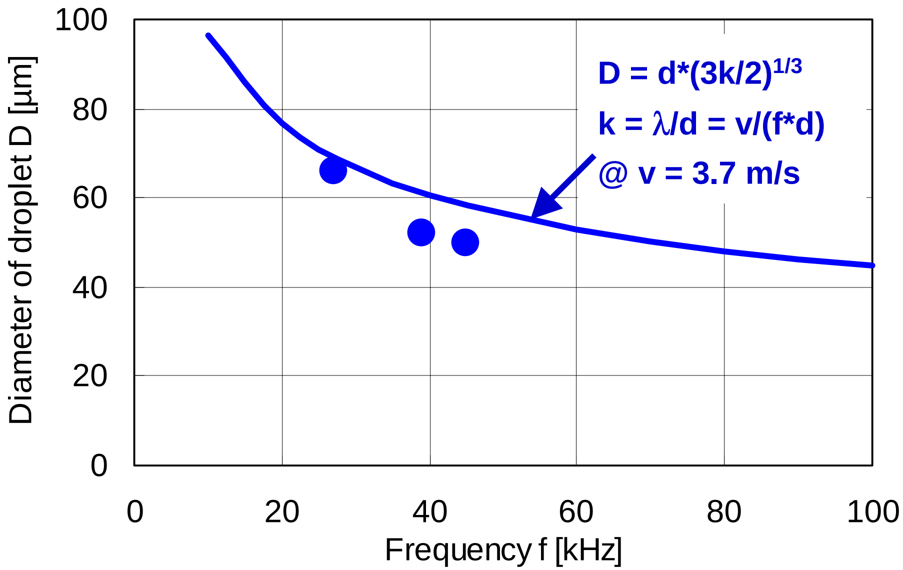
D= 66 μmϕ
v = 3.7 m/s
δ = 0.24 μm

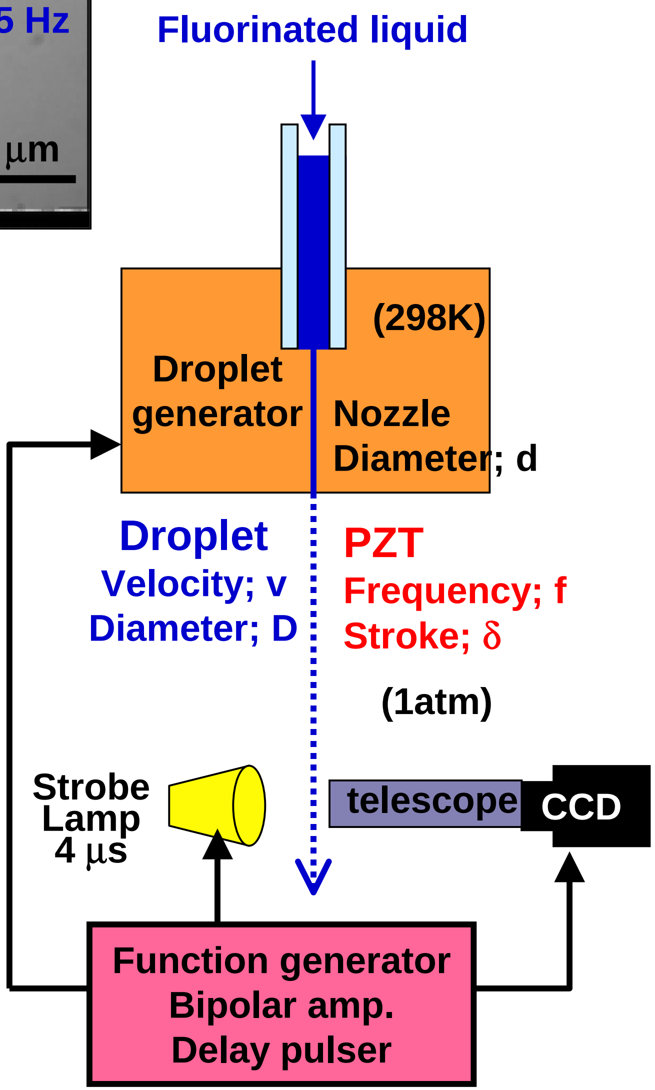


D= 52 μmϕ
v = 3.9 m/s
δ = 0.37 μm



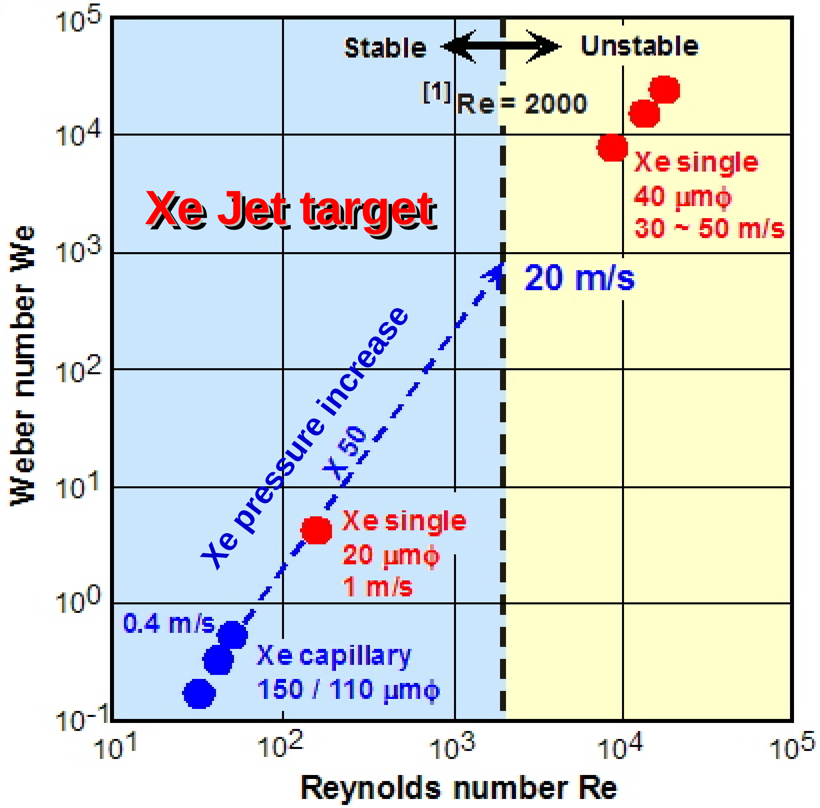
D= 50 μmϕ
v = 3.6 m/s
δ = 0.18 μm

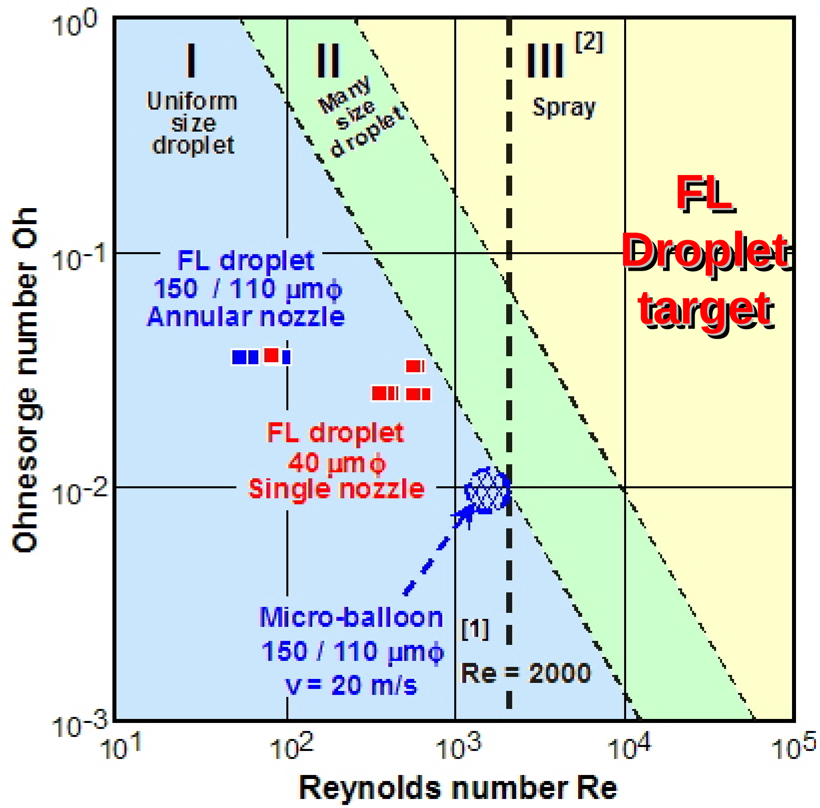




Scaling for droplet formation was obtained.

Stability conditions were compared for Xe jets and FL droplets





(1) Velocity of the Xe capillary jet can be increased to 20 m/s by increasing Xe pressure within Re = 2000.

(2) Stable FL droplets were obtained at area I.
(3) An expected micro-balloon with 20 m/s will be obtained at the cross- point of the boundary line (I - II) and the Re = 2000 line.

References

[1] T.C. Ho: “*Fluid Flow Handbook*”, ed. by J.M. Saleh, (New York, McGraw-Hill, 2002) p.8.2.
[2] M.J. McCarthy, and N.A. Molloy: Chem. Eng. J. **7** (1974) 1.

Acceleration of Xe droplet (micro-balloon) target is required to obtain a target distance of several mm.

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- **Stability condition (by Rayleigh [1])**

  $\lambda/d = \pi \sim 4.508 \equiv k,$

- **Multiplying f and λ produces v.**

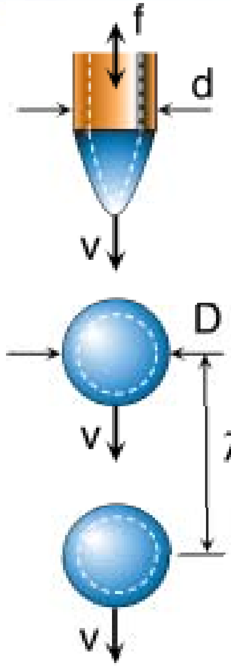
  $\lambda = v/f\ ,$

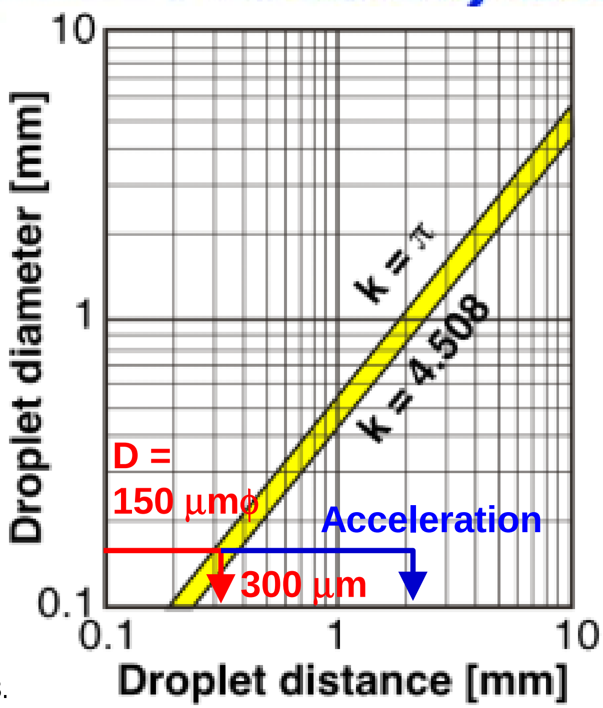
- **Mass conservation law of Xe**

  $D = d \cdot (1.68 \sim 1.89),$

- **Relationship between λ and D**

  $\lambda = D \cdot (1.87 \sim 2.38),$





[1] L. Rayleigh: "*On the instability of jets*", Proc. London Math. Soc. **10** (1878) p. 4-13.

Etendue of EUV source is limited under 3.3 mm²·sr.

Assuming : Correction angle of EUV radiation : **Ω = 2π**,

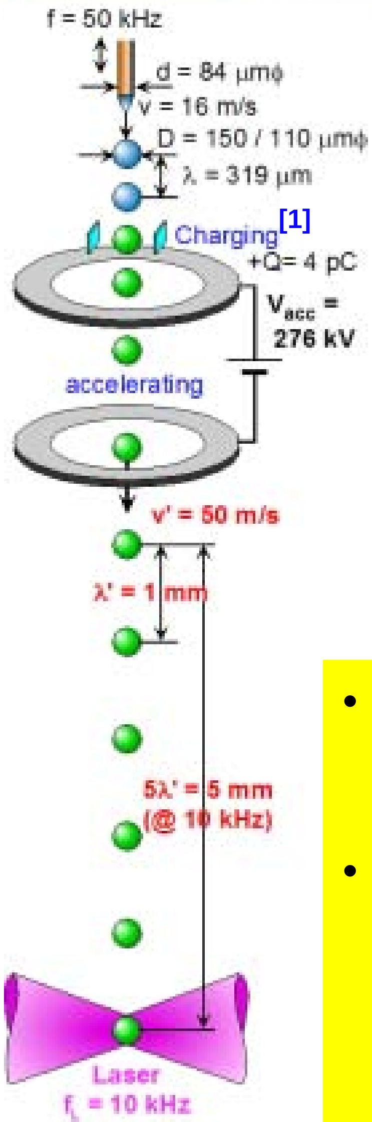
→ EUV source size (= spherical plasma) is calculated to be **D_p < 800 μm**φ.

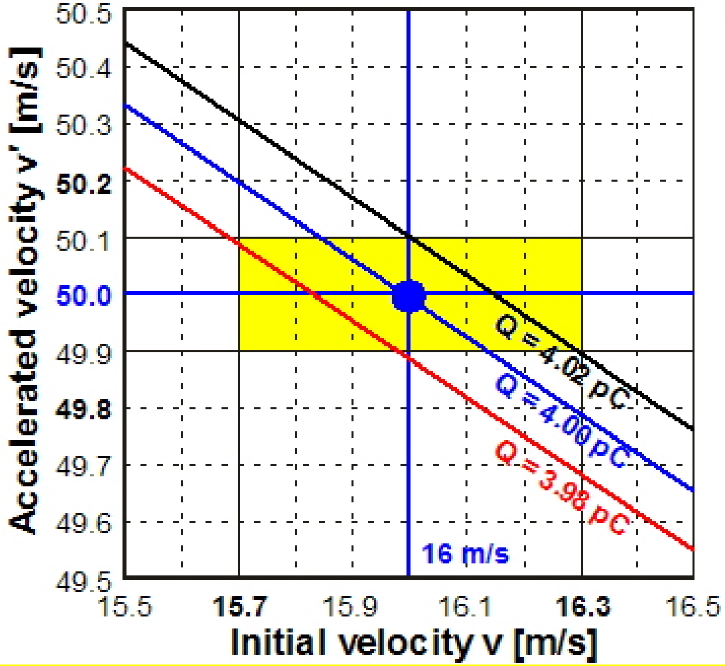
Optimum ion density of EUV radiation : **n_{ion} = 10^{18} ~ 10^{20} /cm³**.[2]

→ **Initial diameter of target material (spherical) is estimated to be D = 100 ~ 150 μmφ.**

[2] K. Nishihara: EUV03, Session 7, Source2, Antwerp, Belgium, Sep. 30 – Oct. 2, 2003

Electrostatic acceleration of Xe micro-balloon target was studied with numerical calculations.





The amount of charge that can be placed on a drop is limited, since the electric force generated by the charge on the surface of the drop counteract surface tension.

[1] J. Heinzl, and C.H. Hertz: "*Advances in Electronics and Electron physics*", ed. by P.W. Hawkes and B. Kazan, (Academic, Orlando, 1985), Vol. **65**, pp. 91-171.

- Acceleration voltage of **~ 280 kV** is required to obtain **a cryogenic Xe micro-balloon target (150 / 110 μmφ)** with **v' = 50 m/s** and **λ' = 1 mm**.
- Following accuracy is required to obtain **10 μm stability** of the micro-balloon target at a laser focus point.
  - **Acceleration voltage : ΔV_{acc} = ± 0.2 %,**
  - **Initial velocity : Δv = ± 1.9 %,**
  - **Charge : ΔQ = ± 0.5 %**

Summary

- ***Comparison of cryogenic Xe targets for 1 J / 10 kHz laser***
  - **Rotating cryogenic drum system**, **droplet target**, and **micro-balloon target** can fast-continuously supply cryogenic Xe targets for practical LPP-EUV sources.
- ***Rotating cryogenic drum system for solid Xe layer***
  - Rotating cryogenic drum system corresponded to 1J/10kHz laser irradiation in consideration of target stability, recovery speed of craters, exfoliation of target at a high rep-rate operation.
  - Stable EUV emission was obtained at 320 Hz.
- ***Cryogenic Xe capillary and micro-balloon targets were suggested.***
  - *Forming the plasma* ***in an optimum condition*** *is important to improve CE.* The optimum plasma may be obtained by irradiating uniformly a **micro-balloon target** by multi pre-pulse laser beams, and then by multi main-pulse laser beams. ***Plasma confinement effect*** *will elongate EUV radiation time, and improve CE.*
  - **Cryogenic Xe capillary jet** was successfully generated at **P_{Xe} = 0.65 MPa**, **T = 175 ~ 190 K**, and **Vac.= 2 ~ 4 Pa**.
  - **Forming of liquid droplets** was studied, and stability condition was obtained.
  - Electrostatic acceleration voltage of **~ 280 kV** is required to obtain **a cryogenic Xe micro-balloon target (150 / 110 μmϕ)** with v' = **50 m/s** and **λ' = 1 mm**.