Pulsed Power Plasma Experiment

- Generation of Photons in EUV Region -

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Outline of Presentation

- **Z-pinch Based Discharge**
  - **Capillary Discharge Ne-like Ar Soft X-ray Laser**
    - Background
    - Experimental Setup: Low Rep-Rate Operation
    - Characteristics of Ne-like Ar Soft X-ray Laser
  - **DPP EUV Light Source for Microlithography**

    (This work is supported by NEDO and MEXT Grant-in-aid)
    - Background: Why EUV? Requirements
    - Experimental Setup
    - Characteristics of DPP EUV Source
  - **Summary**

Application of Soft X-ray Laser

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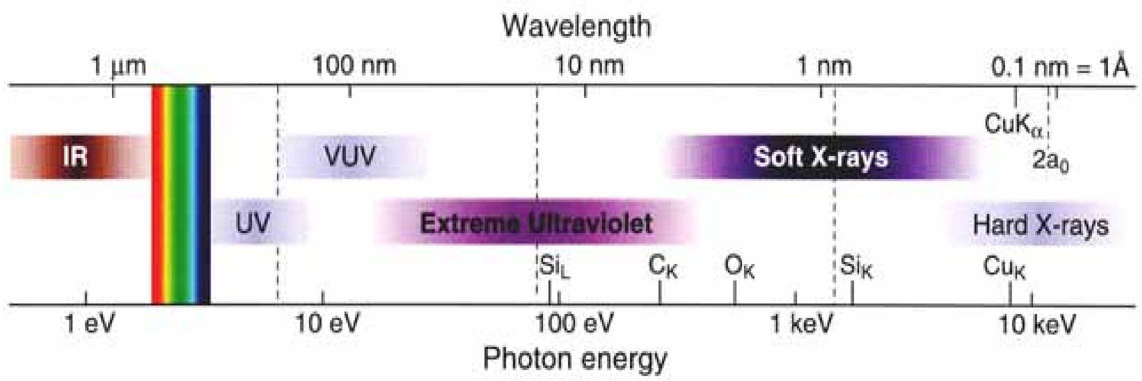
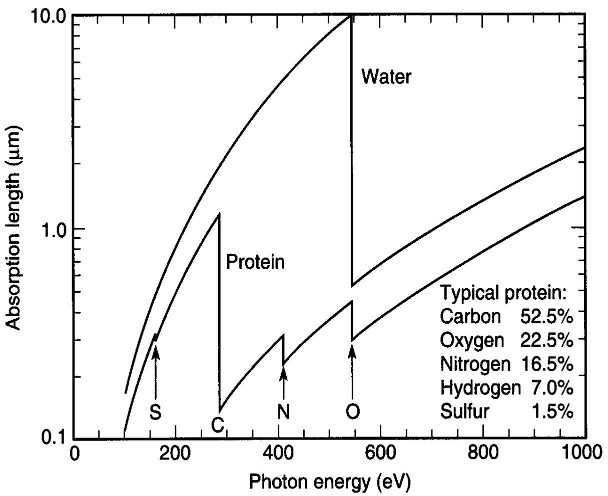
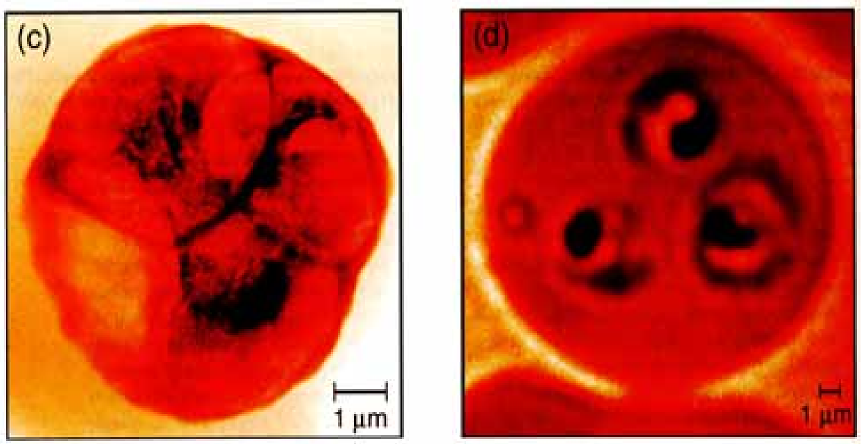
X-ray diagnostics
X-ray microscope
X-ray holography





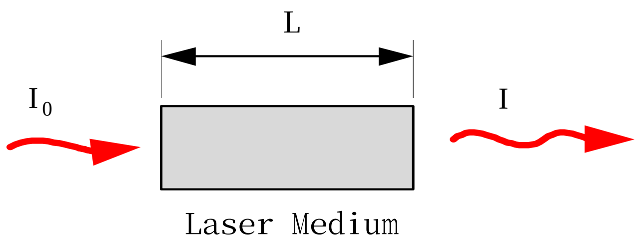
Water window (2.33-4.36nm)



Images of malaria infected red blood cells
(c) 2.4nm soft X-ray microscopy
(d) Visible light microscopy

Principles of soft X-ray laser

Schematic drawing of laser



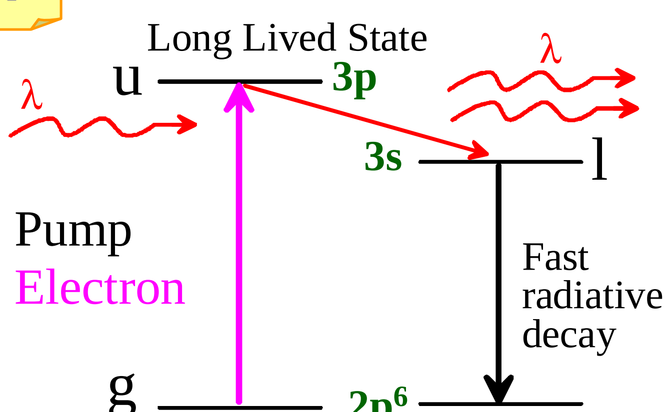
$$I = I_0 \exp(GL)$$

Characteristics of Soft X-ray Laser

- Monochromaticity
- Directivity
- High intensity
- Coherence

One of operational principle of plasma X-ray laser: Collisional excitation scheme

$\boldsymbol{P \propto 1/\lambda^4}$



Laser: Amplified Spontaneous Emission

$G \propto N_u - N_l$

Energy = $P_L \cdot \Delta t$

Soft X-ray Lasing by Fast Capillary Discharge

(V.N.Shlyaptsev, et al., SPIE Vol.2012, pp.99-110, 1993)

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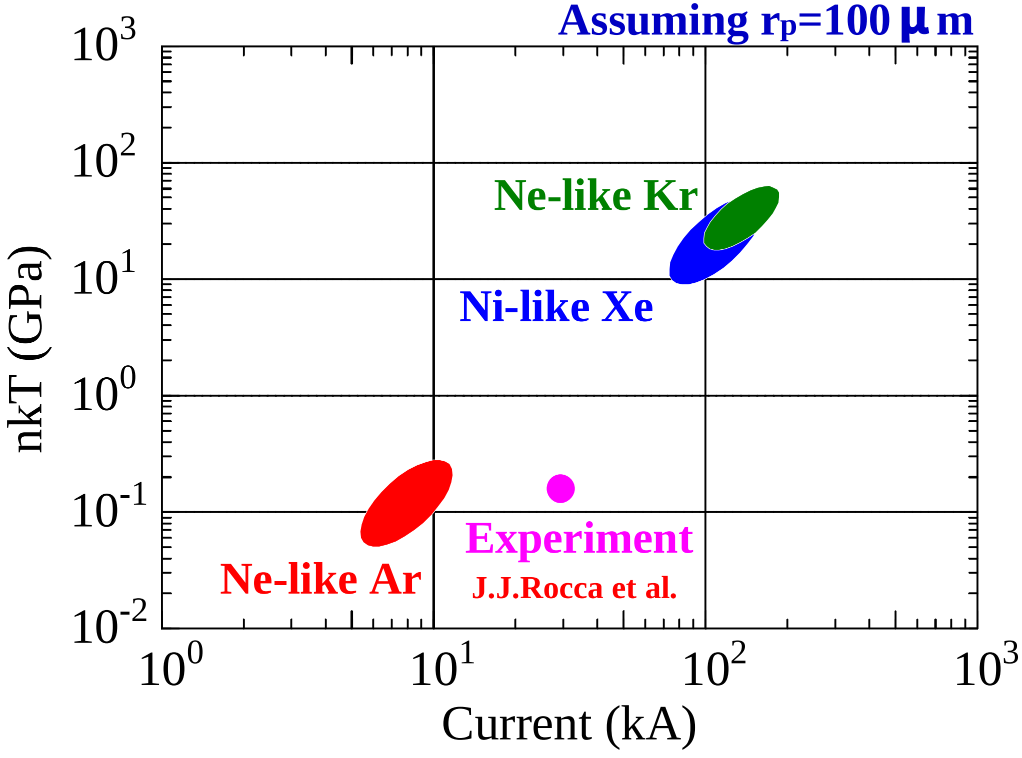
Radiative Collisional Model

- 3p-3s Ne-like ArIX (λ～40-70 nm)
  - r_p～150-250 μm, N_e～(0.5-2)×10^{19} cm^{-3}, T_e～60-90 eV
  - r_0～2 mm, p_0～0.1-0.2 Torr, I_p～10-12 kA, T/2～60-80 ns
- 3p-3s Ne-like KrXXVII (λ～17-30 nm)
  - r_p～50-100 μm, N_e～(2-5)×10^{20} cm^{-3}, T_e～500-700 eV
  - r_0～1 mm, p_0～2-4 Torr, I_p～150-180 kA, T/2～15-25 ns
- 4d-4p Ni-like XeXXVII (λ～9.1-9.5 nm)
  - r_p～75-150 μm, N_e～(2-5)×10^{20} cm^{-3}, T_e～300-600 eV
  - r_0～1 mm, p_0～2-4 Torr, I_p～200-270 kA, T/2～12-20 ns

Theoretically predicted lasing windows



Bennett's Relation

Experimental Setup

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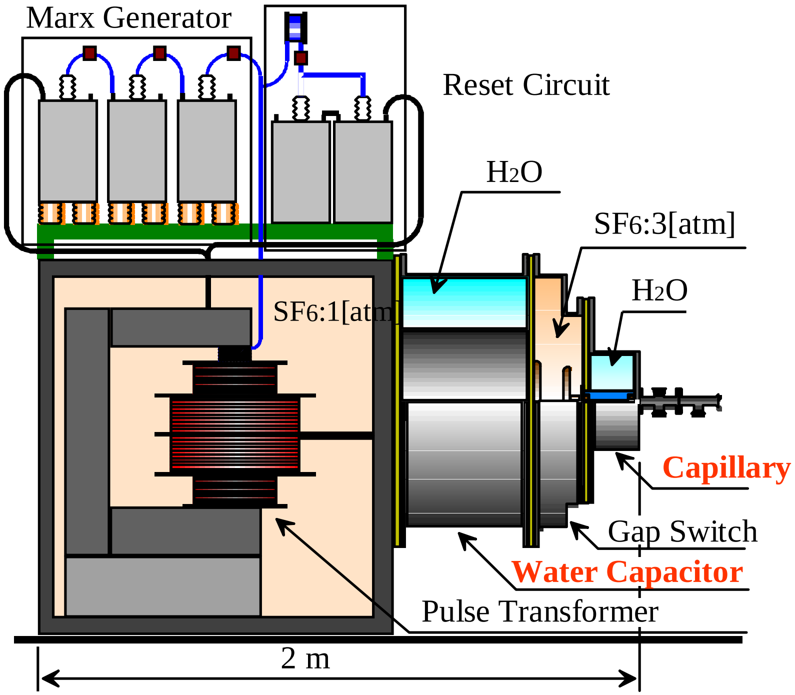
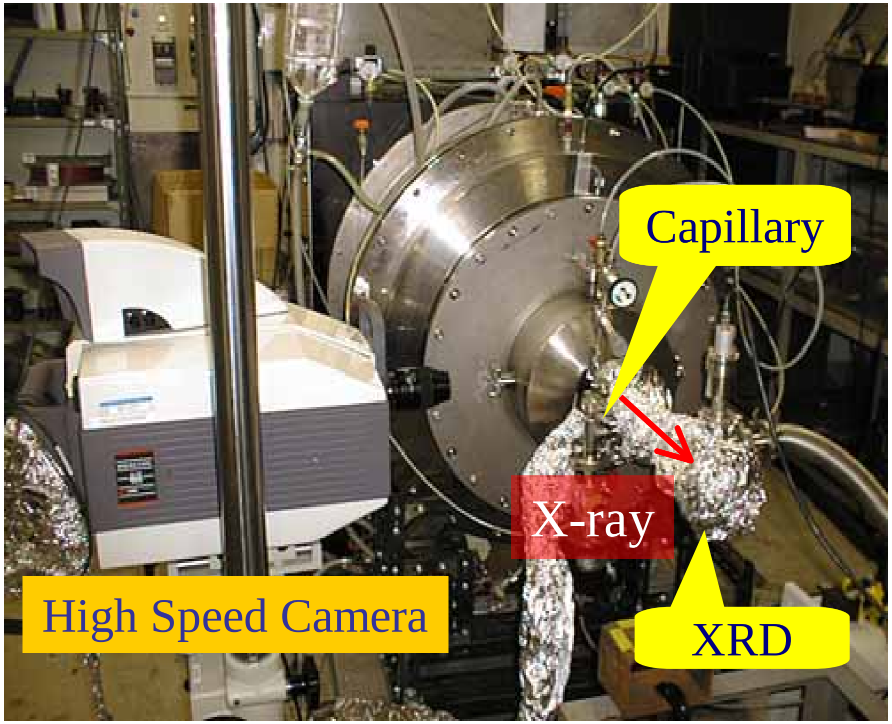
Schematic



Photograph



Specification

Water capacitor: 3nF, Max. 900 kV (1.2 kJ)

Current: T/2=110 ns, 9-32 kA, *dI/dt* = 2-8$\times 10^{11}$ A/s

Capillary: Polyacetal, Pyrex or Alumina Ceramics, ϕ3mm, 60-350 mm long

Filling gas: 100-1000 mTorr Ar

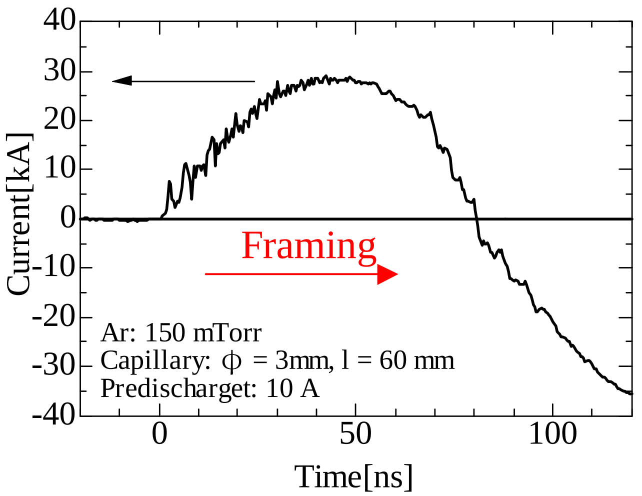
Streak photograph

In order to obtain a laser amplification, it is necessary to produce thin plasma that has a laser gain.
Side-on observations of plasma were made using Pyrex glass capillary.

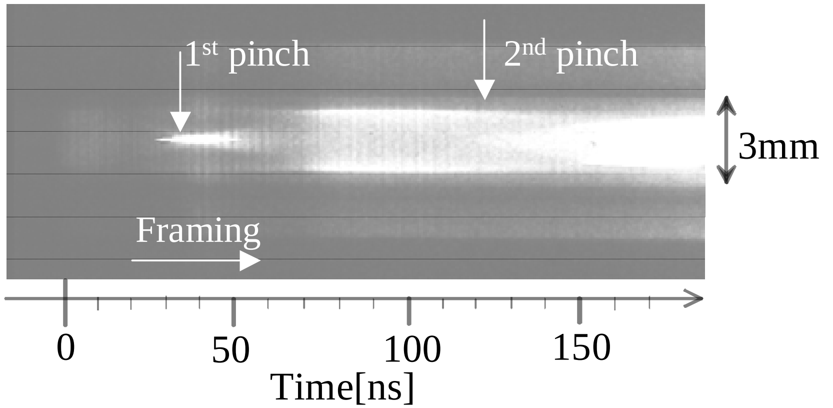
Discharge conditions

- Pyrex Capillary: l = 60 mm, d = 3mm
- Argon: 150 mTorr
- Predischarge: 10 A

Waveform of discharge current



Side-on Streak photograph



Effect of Pre-Ionization

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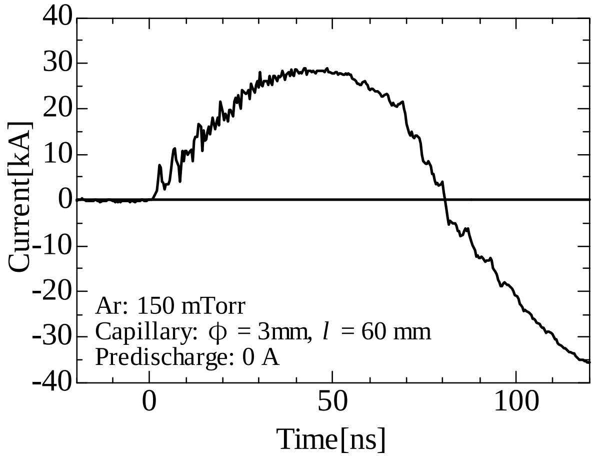
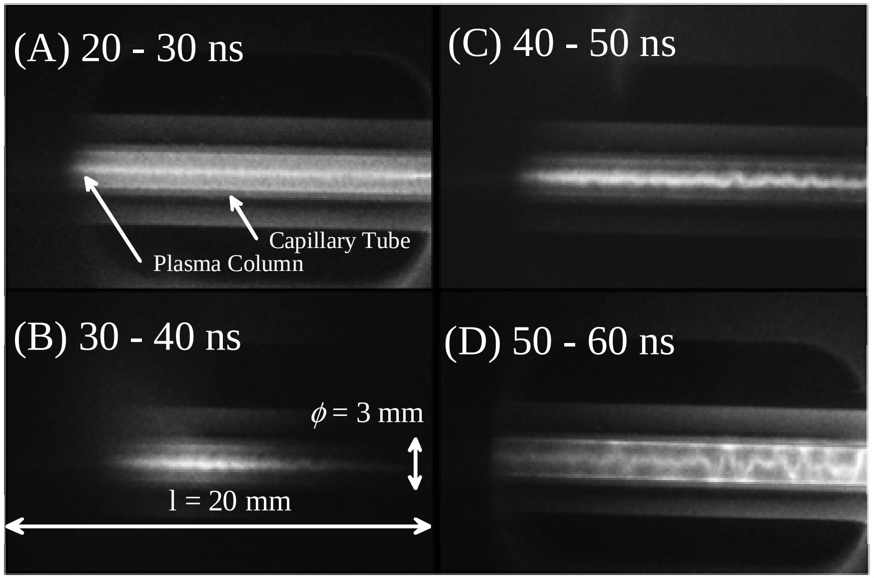


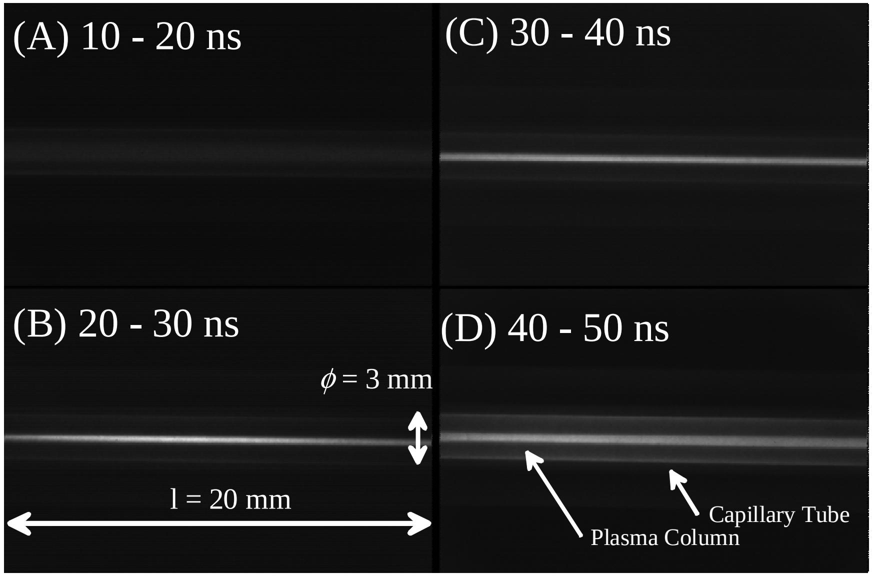
Without pre-ionization

- Helical instabilities are observed
- Poor reproducibility



With pre-ionization current of (10 A)

- Stable
- Highly reproducible
- Diameter of pinched plasma: 300μm

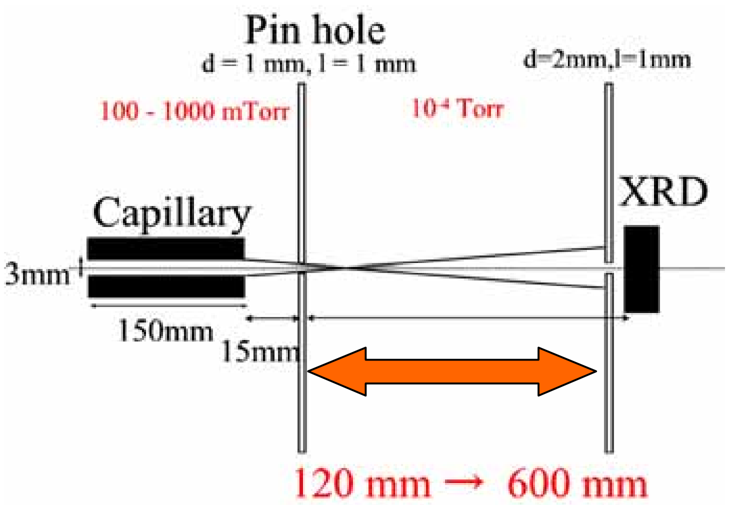


Pre-ionization is essential for production of stable plasma.

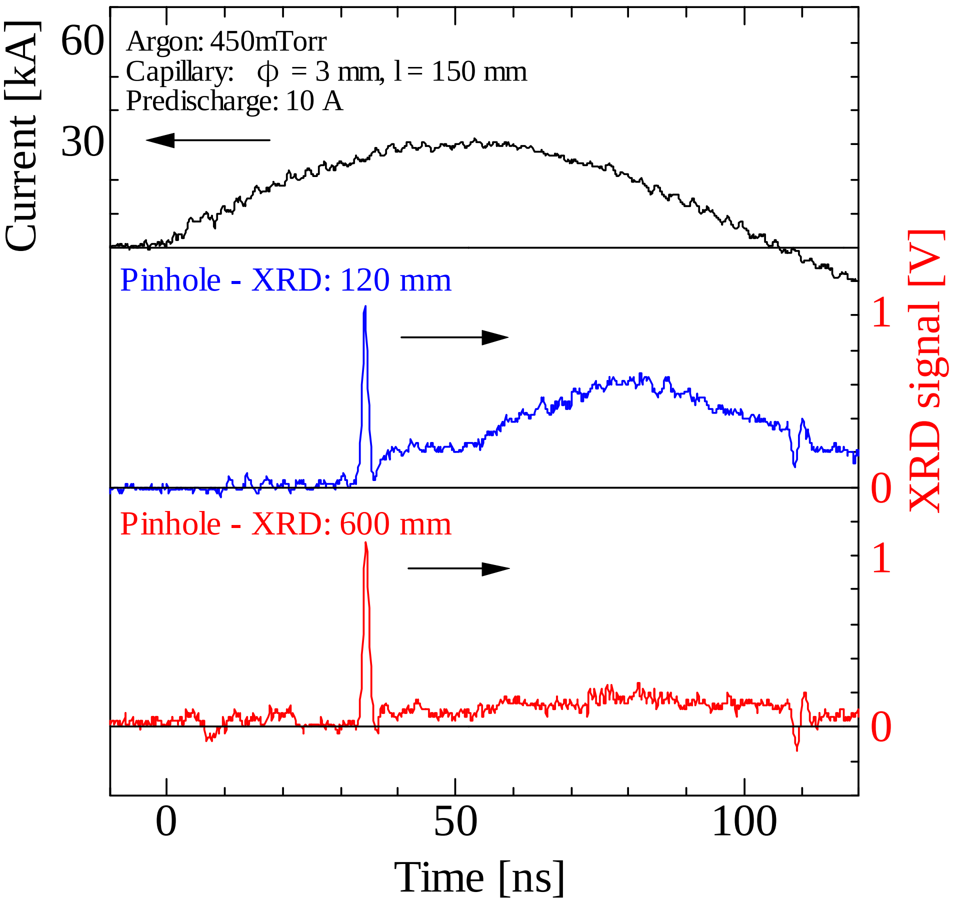
Directivity of Spike Output

Discharge condition

- **Capillary length : 150 mm, diameter : 3 mm**
- **Filling Ar pressure : 450 mTorr**
- **Preionization current : 10 A**



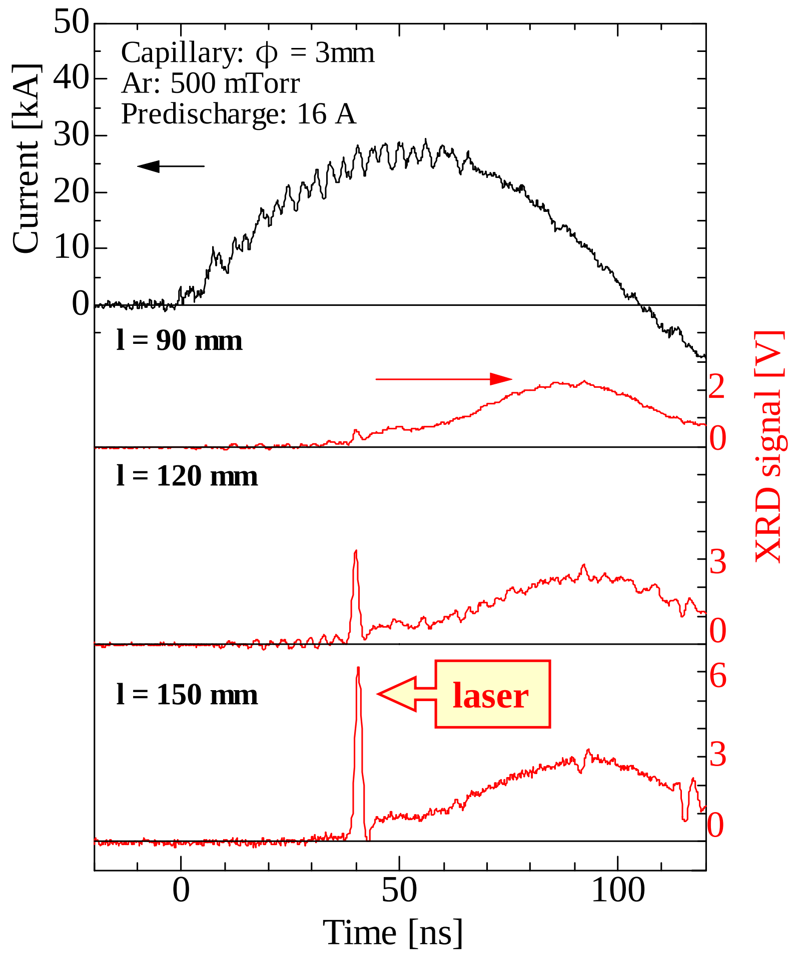
To confirm the directivity of laser, the distance from the capillary to the XRD is changed from 120mm to 600mm

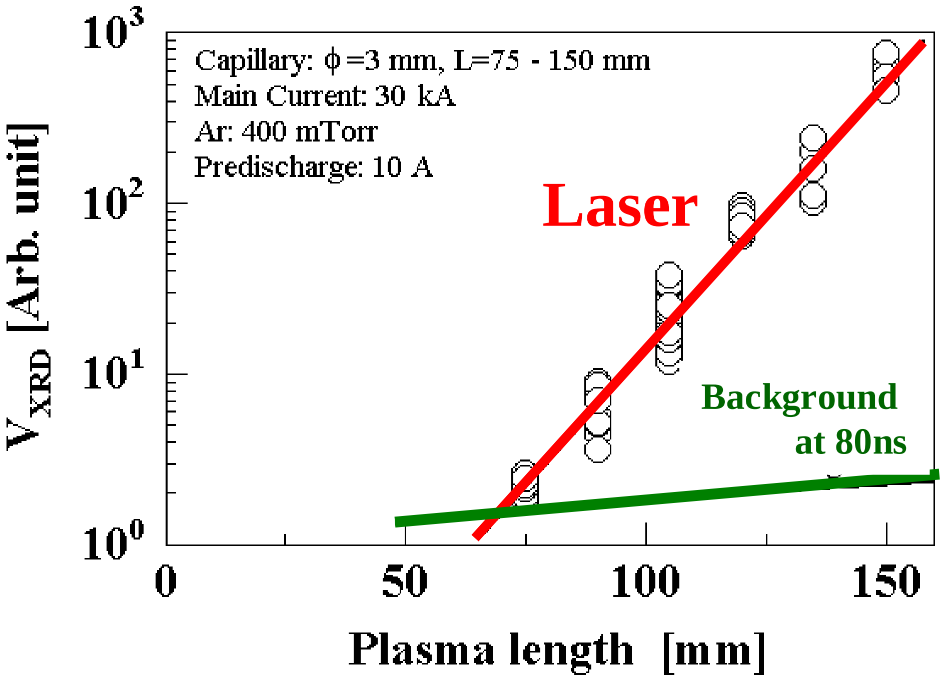


XRD output dependence on distance between capillary and detector

Sharp peaks have directivity.
It's a characteristics of laser.

Gain-Length Product





XRD output dependence on capillary length

Maximum gain-length product *gl* of 12 (g = 0.8 cm^{-1}) and Laser output energy of 5 - 6 μJ are obtained.

Spectroscopic Measurement

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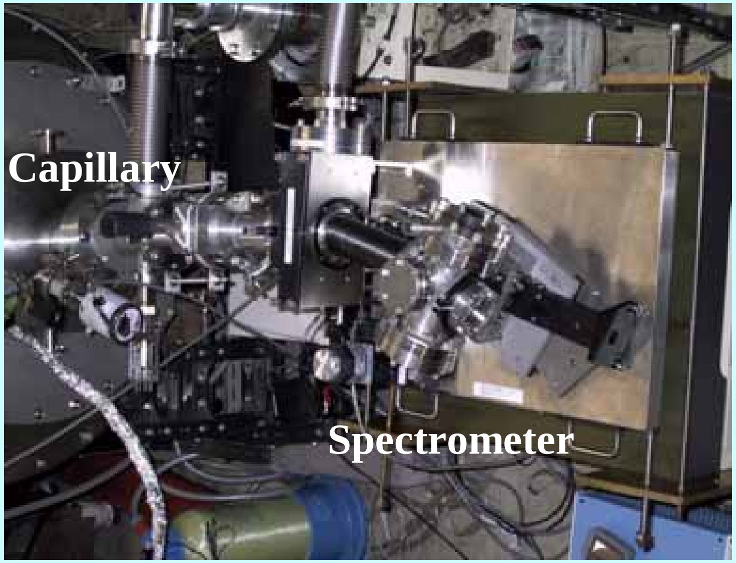
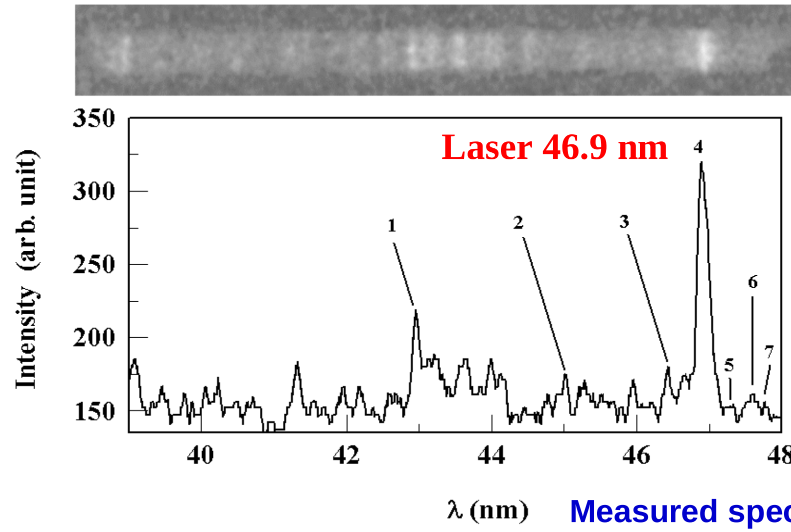


Grazing Incidence Spectrometer
(McPherson 248/310G)

Discharge condition
Capillary : ϕ3, *l* =150 mm
***I* = 22 kA**
***p* = 300 mTorr**



Measured spectrum

Label	Series	Transition	λ (Å)
1	*Ar IX*	$3s\ ^3P_1 - 3p\ ^1S_0$	431.123
2		$3p\ ^1P_1 - 3d\ ^1P_1$	450.660
3		$3p\ ^1P_1 - 3d\ ^1P_1$	465.118
4		$3s\ ^1P_1 - 3p\ ^1S_0$	468.793
5	*Ar VII*	3s3p – 3s3d (J = 0-1)	473.934
6		3s3p – 3s3d (J = 1-2)	475.654
7		3s3p – 3s3d (J = 2-3)	479.379

After P.S.Antsiferov et al.,
Physica Scripta, Vol.62, pp.127-131, 2000

Double-Slit Interference Fringes

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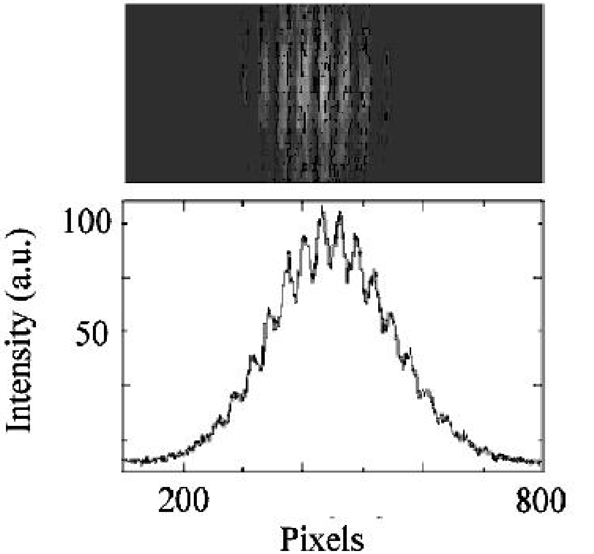
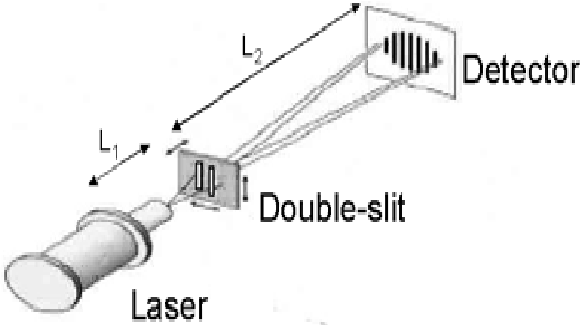
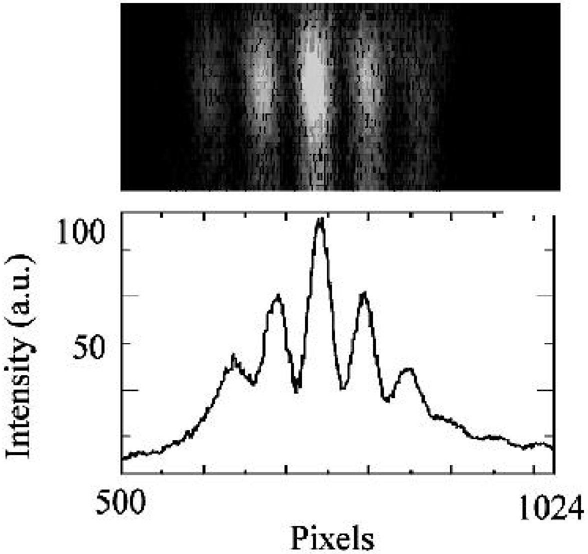
Discharge current pulse: ~23kA
Capillary length = 350 mm
L1 = 250 mm   L2 = 1070 mm

Ar pressure: ~340 mTorr
Capillary diameter = 3 mm
Detector: X-CCD







Slit separation b = 100 μm
Experimental λ = 45.9 ± 1.2 nm

Slit separation b = 50 μm
Experimental λ = 46.5 ± 0.9 nm

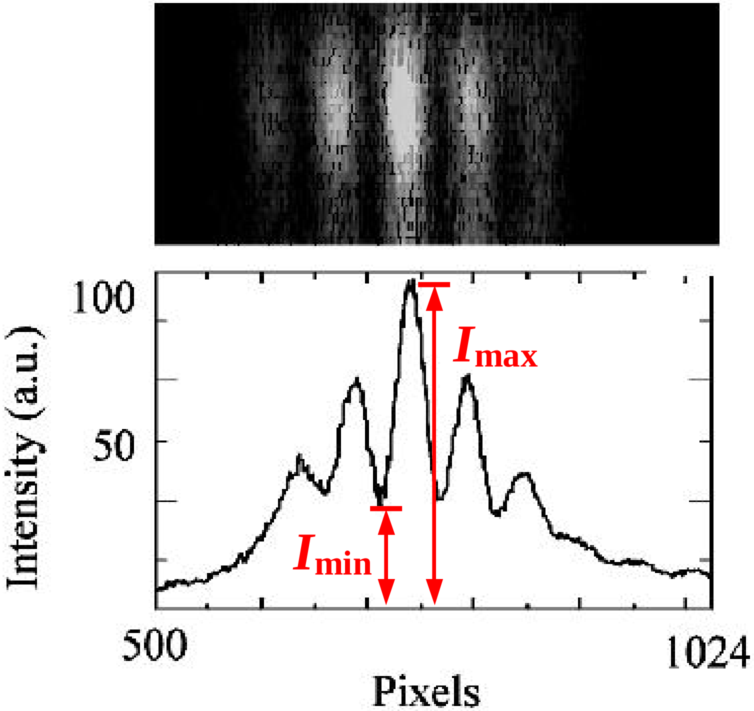
Ne-like Ar laser **λ** = 46.9 nm

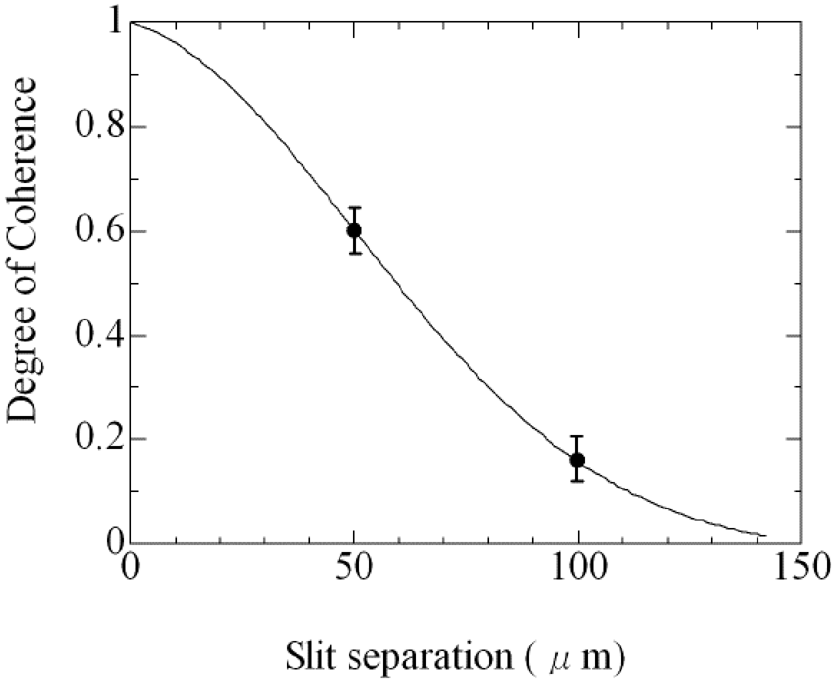
Measurement of the spatial coherence

Coherence degree:

$$\mu_{12}(\Delta d) = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \exp\left(-\frac{\Delta d^2}{2L_c^2}\right)$$

where L_c is coherence length



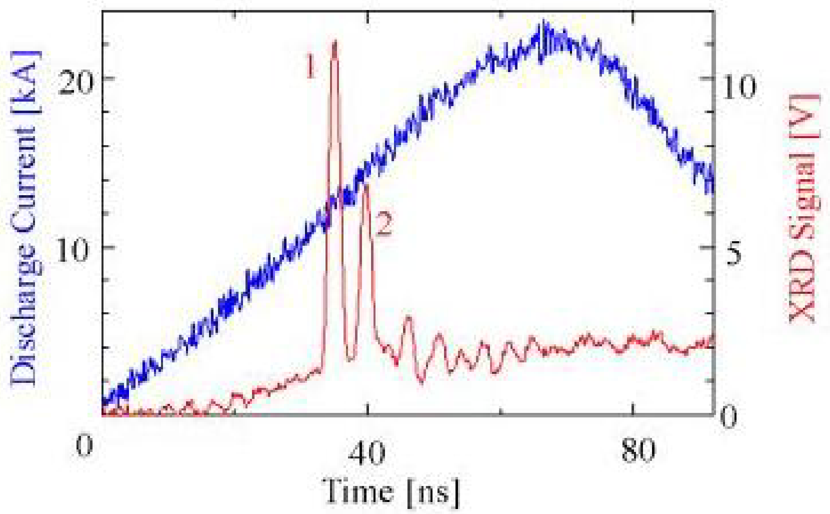


$\mu_{12}(50\ \mu m) = 0.60 \pm 0.05$

Measured coherence length is 50 μm

Coherence length reported by other group is L_c= 190μm for 450 mm capillary
PHYSICAL REVIEW A 70, 023818 (2004)

Another Lasing?



1

Experimental λ = 45.9 ± 1.2 nm

Ne-like Ar laser λ_1 = 46.9 nm
(Ar^{8+} *3s – 3p*)

2

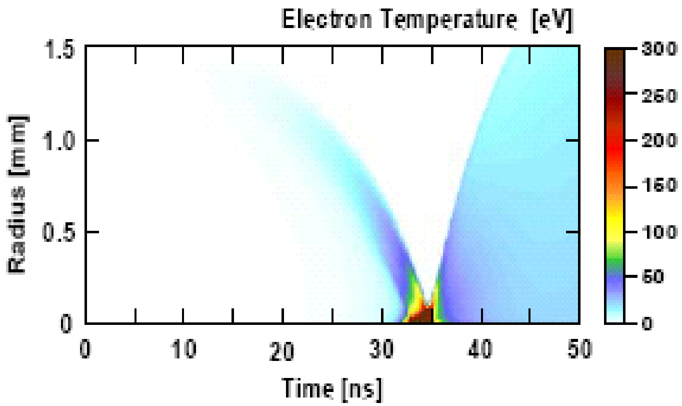
Experimental λ = 44.1 ± 3.0 nm

Be-like Ar laser λ_2 = 42.6 nm ?
(Ar^{14+} *2p – 2s*)

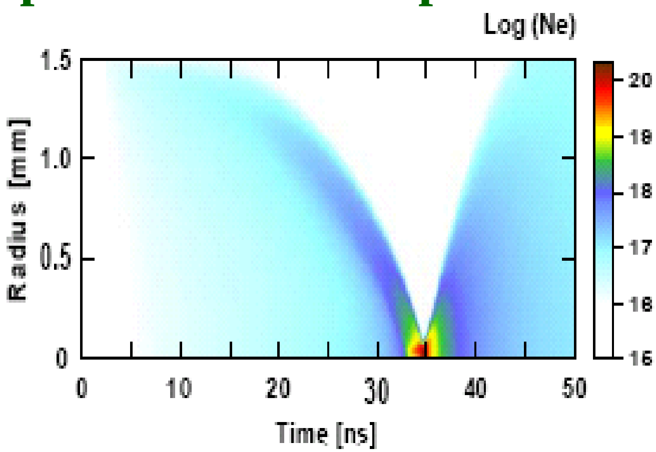
MHD Simulation 1

Plasma is compressed and heated → Highly ionized plasma expands to the capillary wall being cooled

34.8 ns

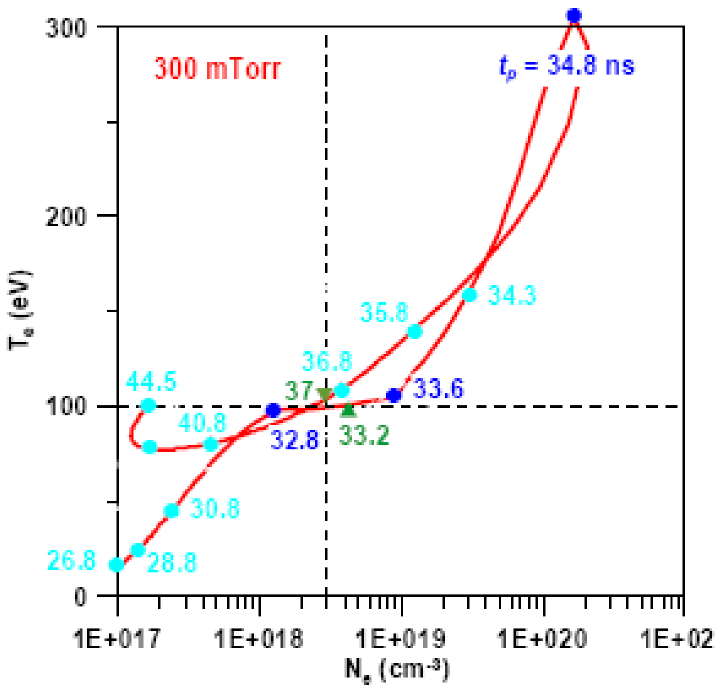


Space-Time development of T_e



Space-Time development of N_e

(P.Vrba, et al., CTU)



At 33.2 ns : Ne=4.3x10^{18} cm^{-3}, Te=100 eV

Ar^{8+} : Ne-like

At 37.0 ns : Ne= 3.14x10^{18} cm^{-3}, Te=105 eV

Ar^{14+} : Be-like

MHD Simulation 2

The evaluated spectrum predicts another strong lasing at the wavelength of λ= 42.6 nm at t = 37 ns,
when T_e = 105 eV, N_e = 3.14X10^{18} cm^{-3}
The lasing occurs by the transition
2p - 2s
Be-like argon (Ar^{14+}).

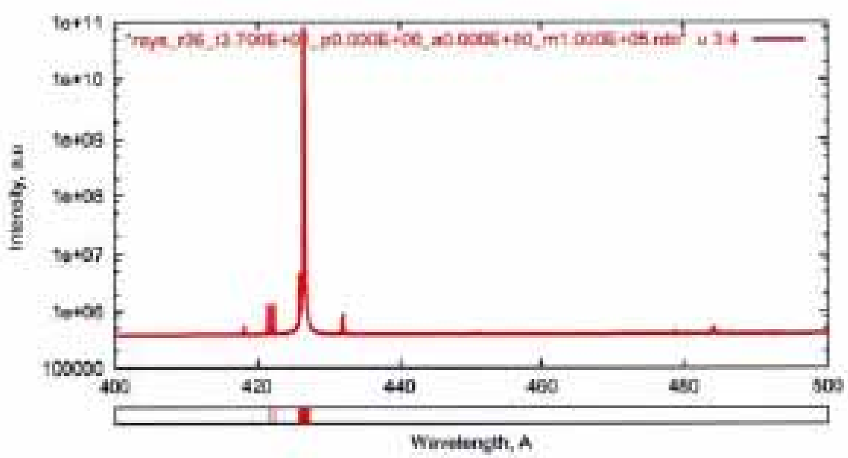
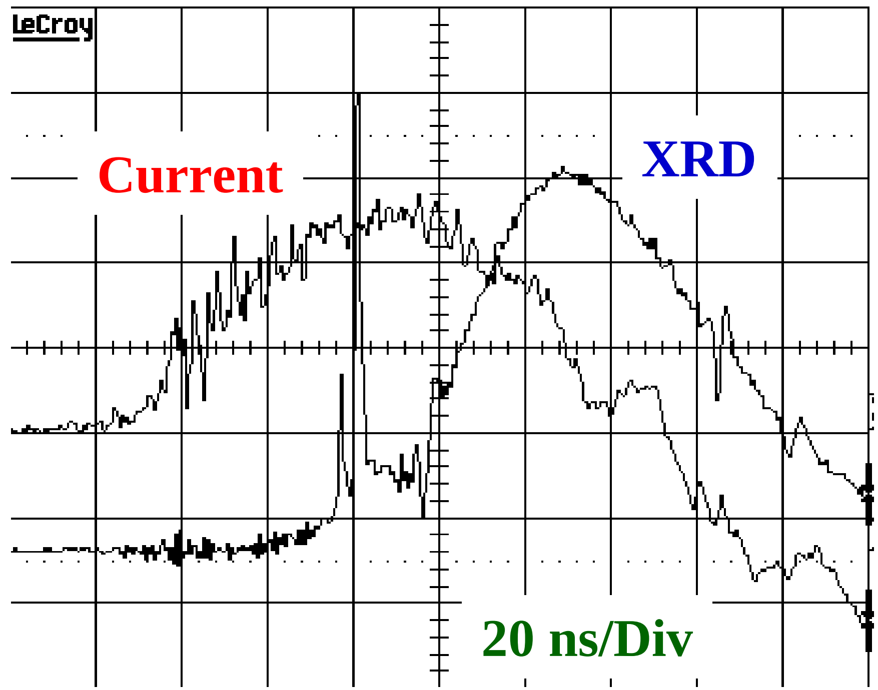
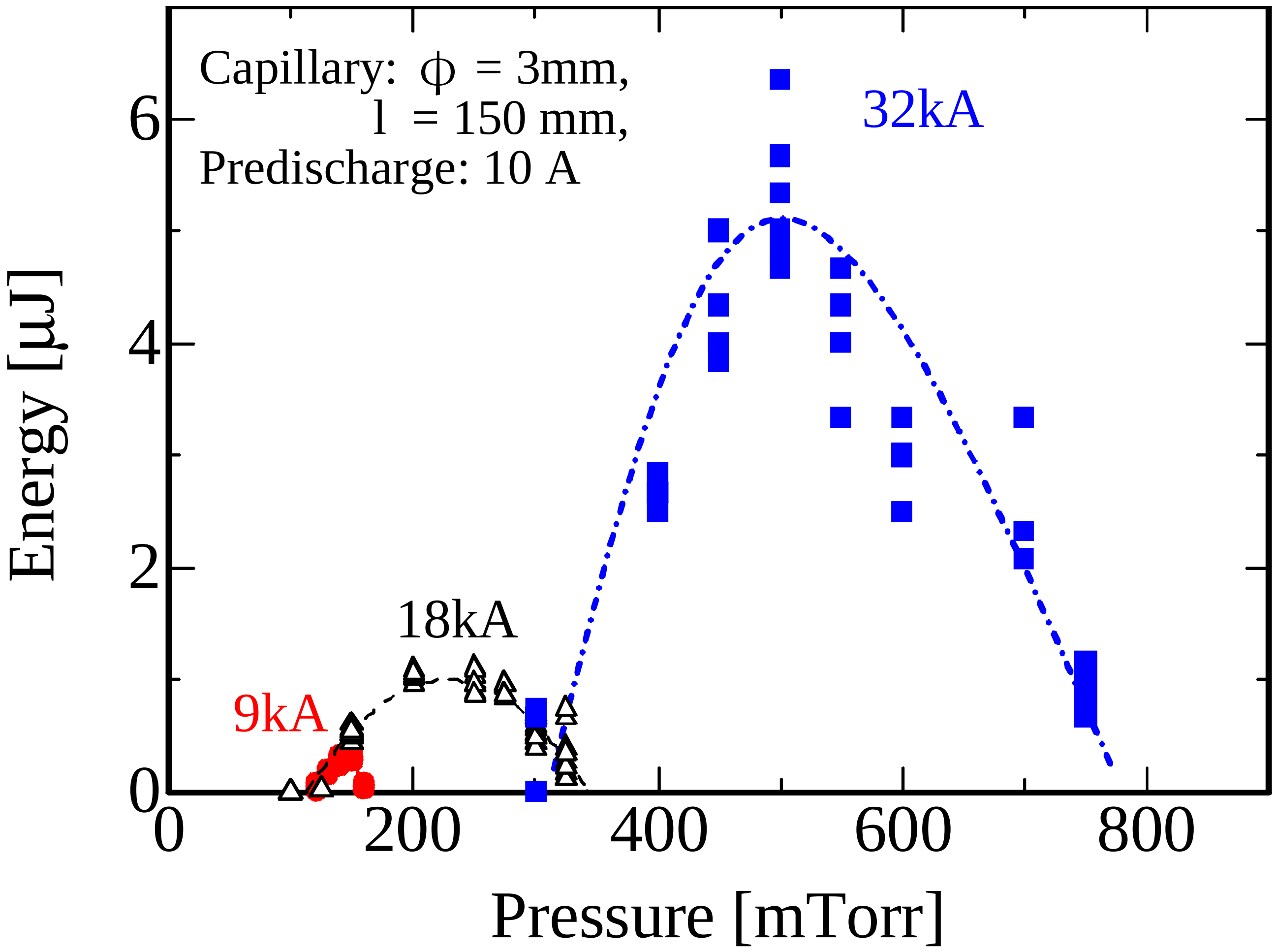


Figure 6: Instantaneous spectra emitted from pinching capillary discharge at t = 37.0 ns



Capillary length = 330 mm

Current and Pressure Range of Lasing



Lasing may be obtained with a current of below 9kA and over 32 kA, with adequate gas pressure.

Summary (soft X-ray laser)

- **Ne-like Ar (3p-3s) Soft X-ray Lasing was confirmed**
  - **Current of 9-32kA and half period of 110ns**
  - **Ceramic capillary : ϕ=3mm, l = 150 – 350 mm**
  - **Argon gas pressure: 150-800mTorr**
  - **Maximum gl =12 (g=0.8cm^{-1}) at 32kA, 500mTorr**
  - **Pre-discharge current: 5-15A**
- **Sufficient pre-discharge current is essential for**
  - **Production of uniform pre-ionized plasma**
  - **Suppression of instabilities of pinched plasma**
  - **Increase of laser output and improvement of reproducibility**
- **Possibility of another lasing transition was shown**
  - **Be-like Ar (2p-2s) ?**
- **Lasing at current of less than 10 kA may be possible**
  - **Lower laser output energy**
  - **Compact power supply**
  - **Higher rep-rate operation**

Outline of Presentation

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  - **Capillary Discharge Ne-like Ar Soft X-ray Laser**
    - **Background**
    - **Experimental Setup: Low Rep-Rate Operation**
    - **Characteristics of Ne-like Ar Soft X-ray Laser**
  - **DPP EUV Light Source for Microlithography**

    (This work is supported by NEDO and MEXT Grant-in-aid)
    - **Background: Why EUV? Requirements**
    - **Experimental Setup**
    - **Characteristics of DPP EUV Source**
  - **Summary**

ITRS Roadmap Potential Acceleration

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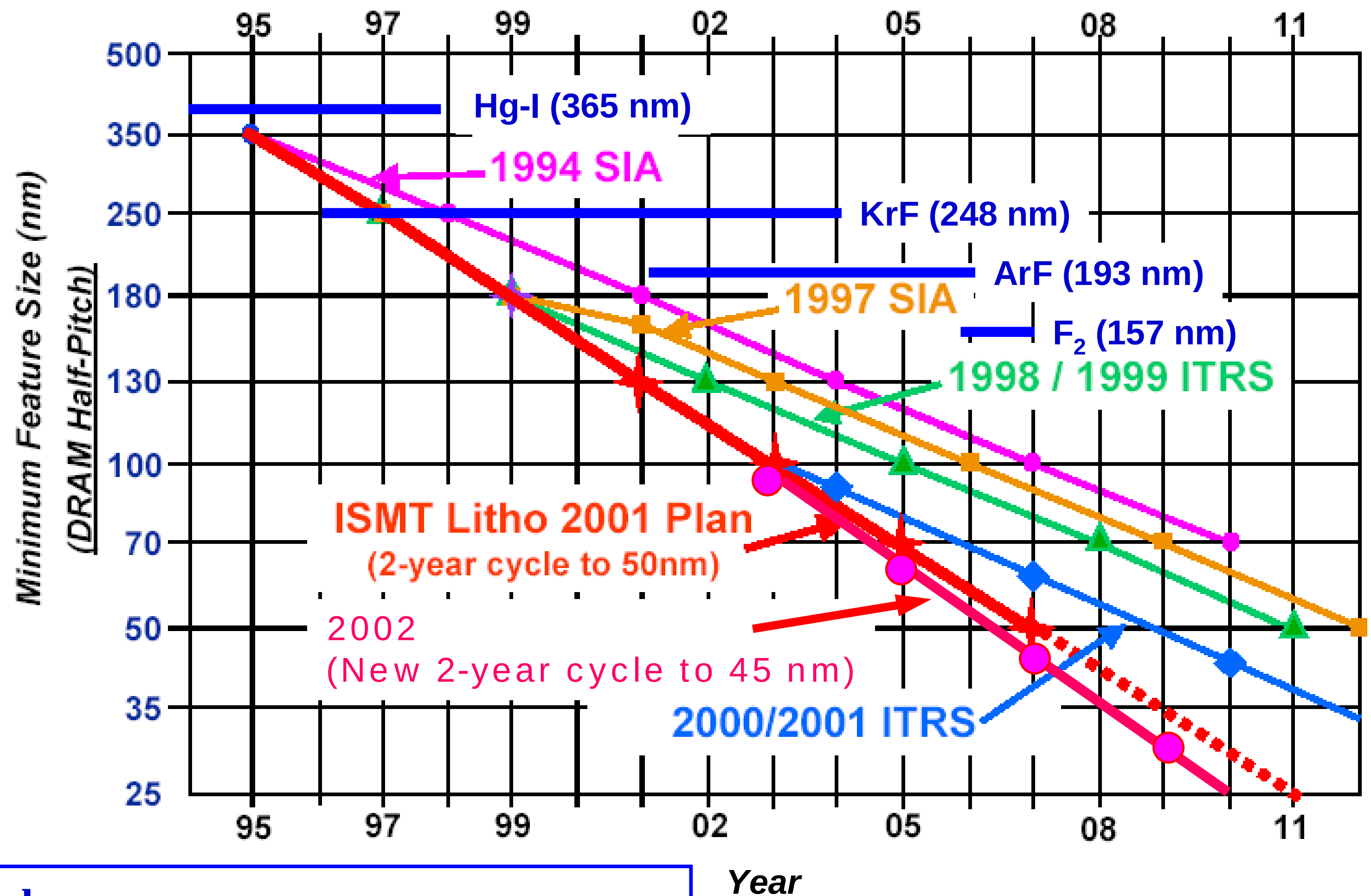
Why EUV (13.5 nm) ?



Moore's law
2-year cycle : 70 % reduction every 2 years

International Technology Roadmap for Semiconductor

Requirements for EUV Light Source

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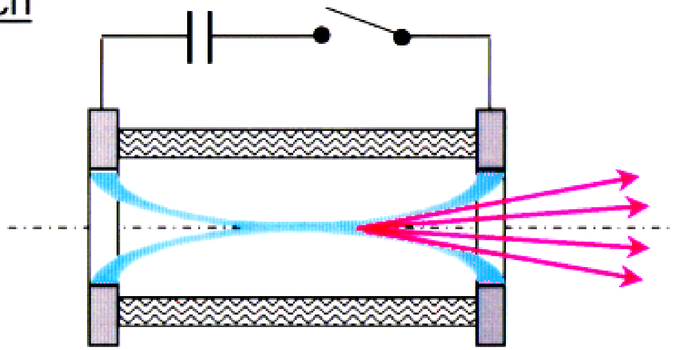
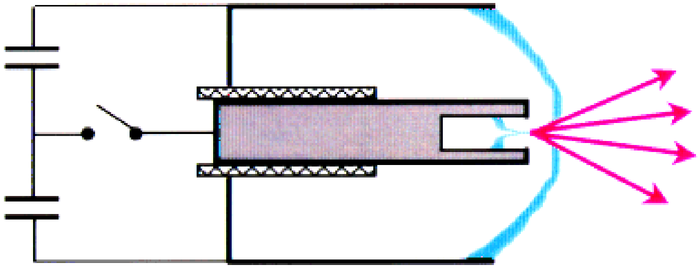
Item	Requirement
Wavelength	13.5 nm
EUV Power at IF (2% in-band @13.5 nm)	115 W (100 Wafers/hour)
Repetition Frequency	> 10-7 kHz
Integrated Energy Stability	±0.3 % (3σ over 50 pulses)
Etendue	1-3.3 mm^2sr
Source Cleanliness (lifetime of illuminator)	≧ 30,000 hours (after intermediate focus)

DPP Light Sources

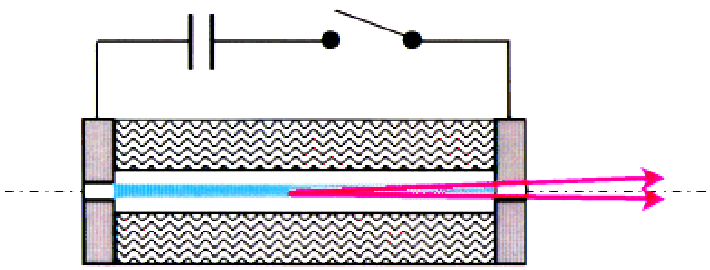
Z-Pinch



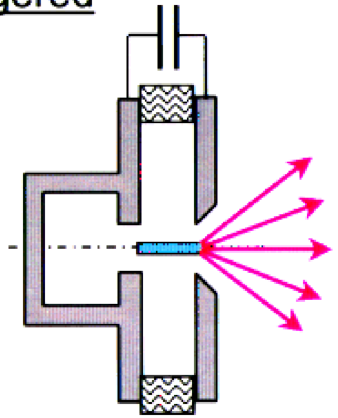
Plasma-Focus



Capillary-Discharge



Hollow-Cathode triggered (HCT) Z-Pinch



Shock wave heating, magnetic confinement, position stability

Xe or Sn Discharge

Dependence of Ion Fraction on T_e in Steady State

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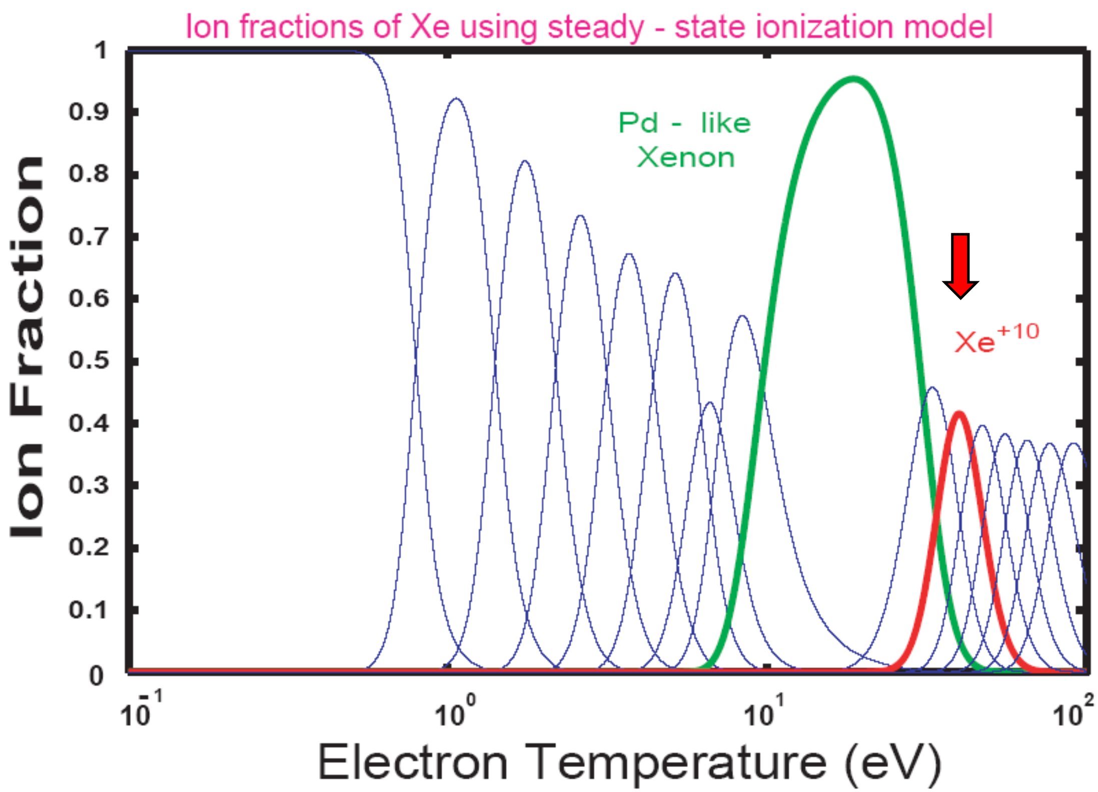


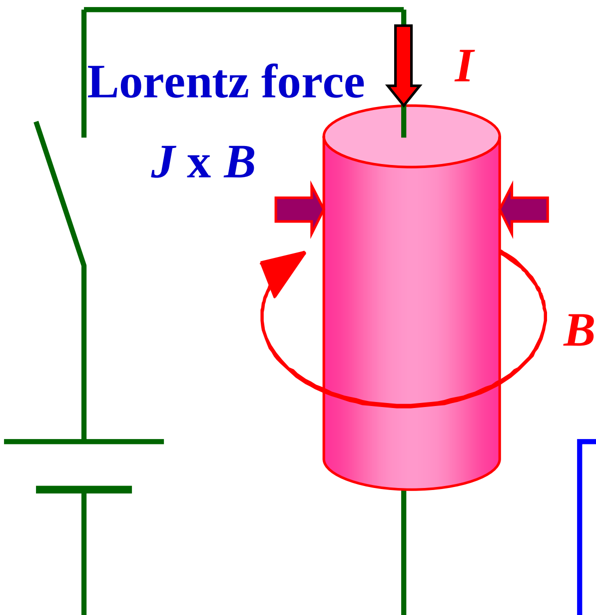
Optimum Xe plasma condition for EUV emission at 13.5 nm

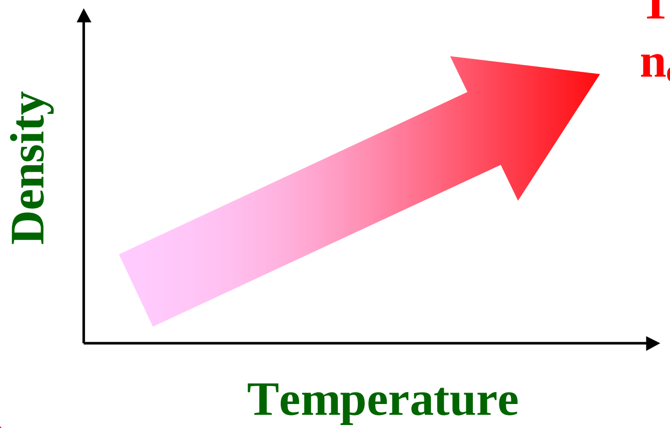
T_e = 20 – 40 eV

$n_e = 10^{18} – 10^{19}$ cm^{-3} (optically thin)

Pinch Dynamics

Pre-ionized Uniform Plasma

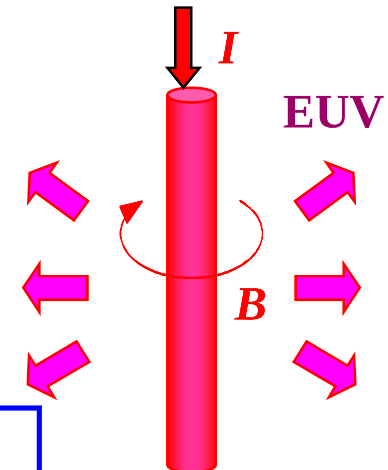




Thin, high-temperature and High-densty plasma

$T_e = 20 – 40$ eV

$n_e = 10^{18} – 10^{19}$ cm^{-3}



Implosion Phase

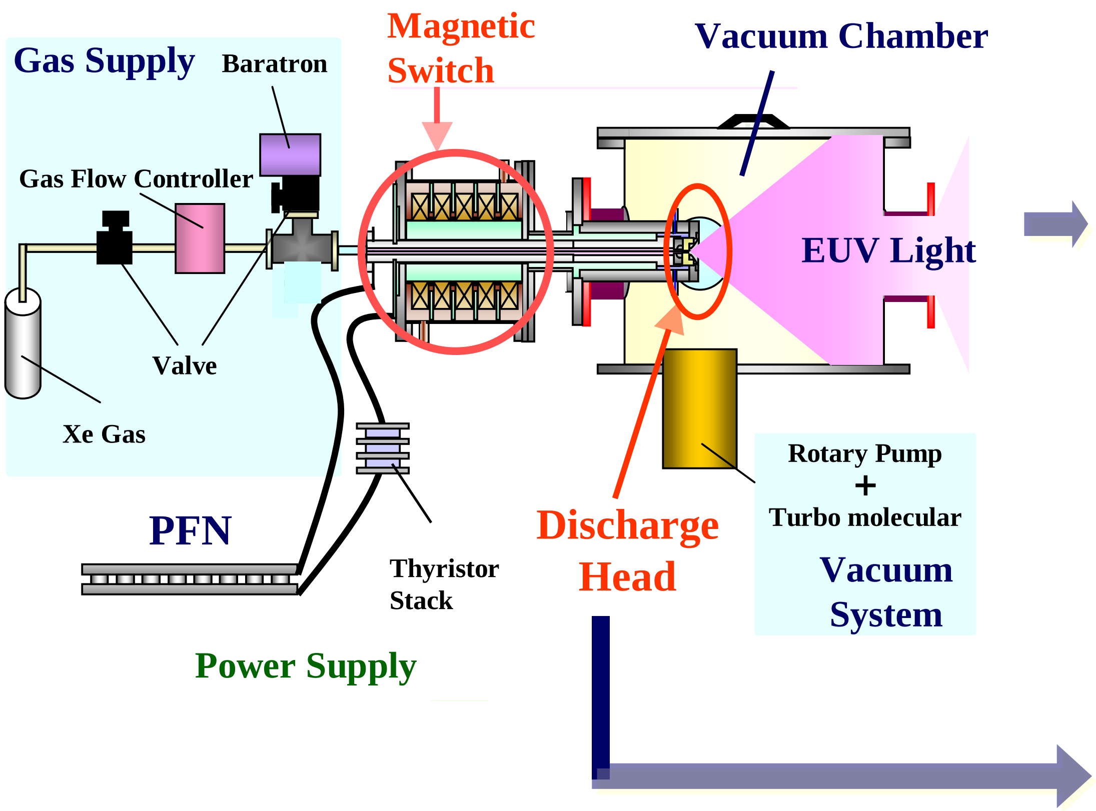
Joule (Resistive) Heating

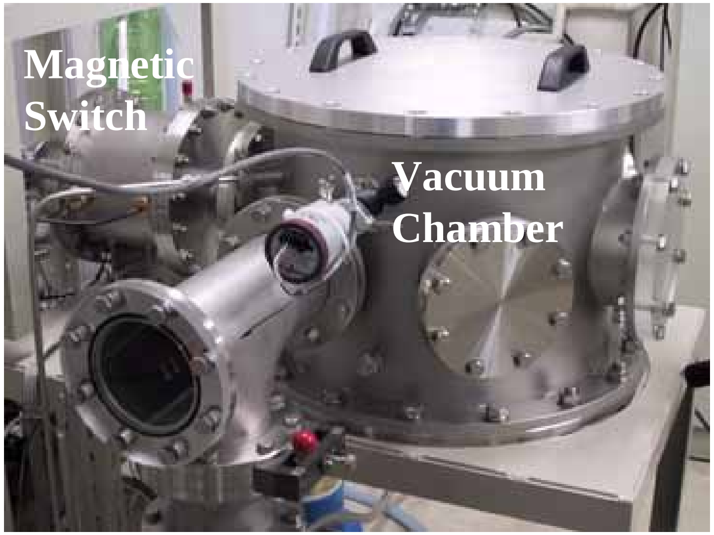
Compression : Adiabatic Heating

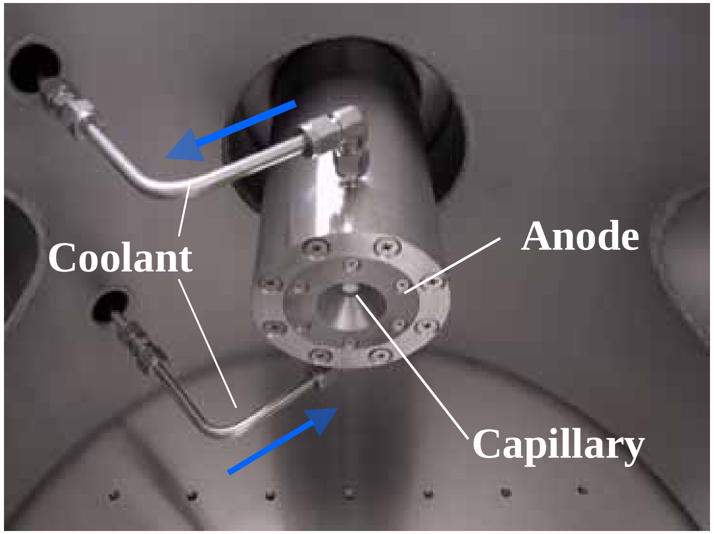
Shock Wave Heating

Kinetic Energy to Thermal Energy

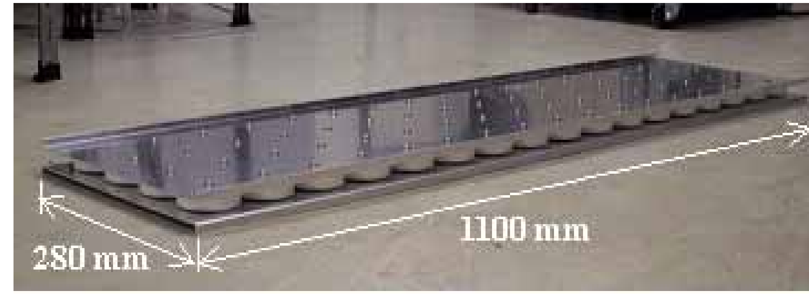
Experimental Setup

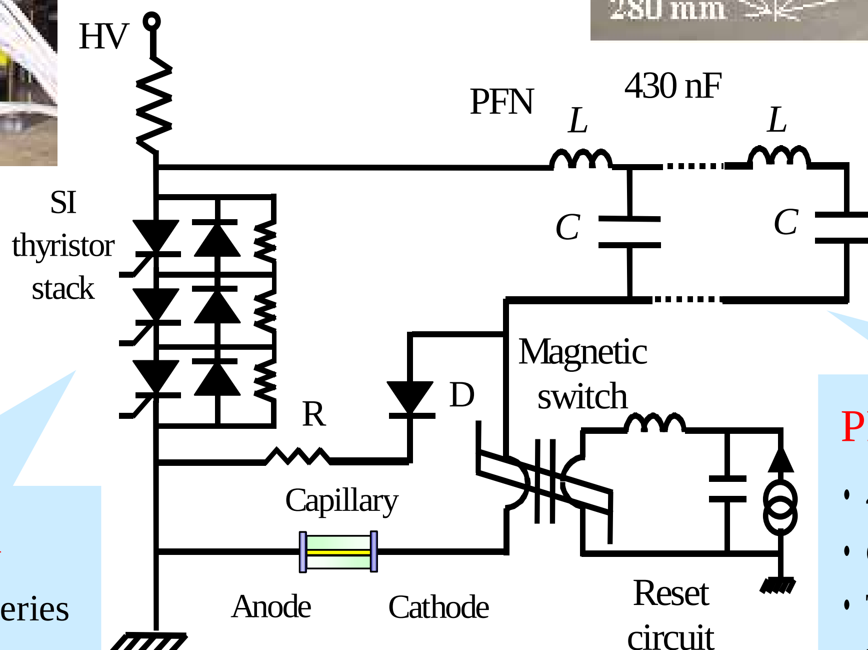






Pulse power supply system





Direct pulse method

SI Thyristor Stack

- 3 thyristors connected in series
- Blocking voltage : 12.0 kV
- Conducting current : 400A
- Surge On current : > 10 kA
- di/dt : > 100 A/ns

PFN (Pulse Forming Network)

- 4 nF, 20kV Ceramic capacitor
- Capacitors connected in parallel
- Total Capacitance : 403 nF
- Impedance : 0.44 Ω

Effect of dI/dt on Pinch Time and Plasma Radius

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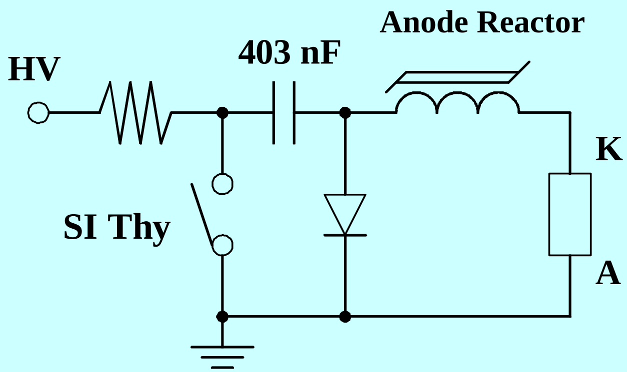
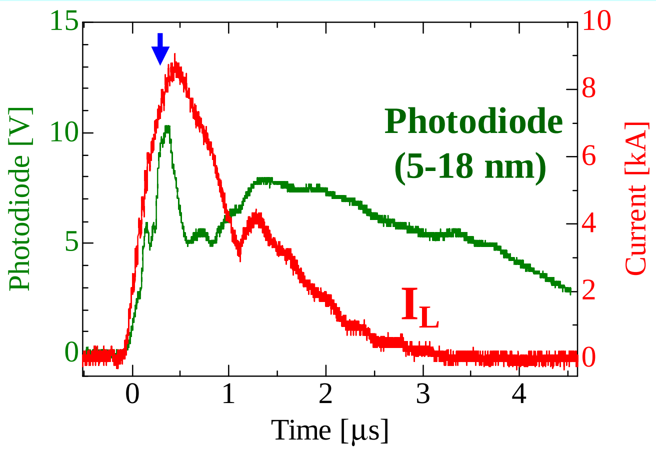
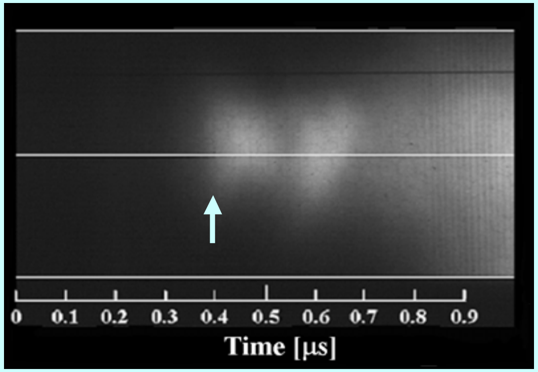


Output of Photodiode

5 Torr Xe

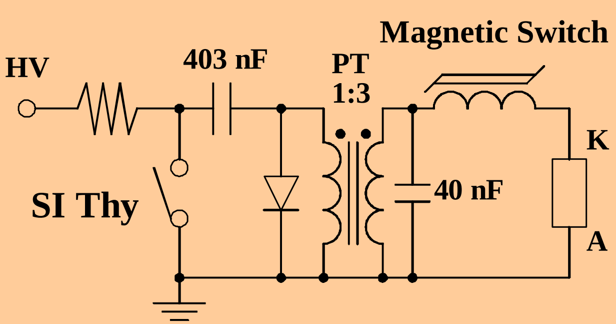


Streak Photograph

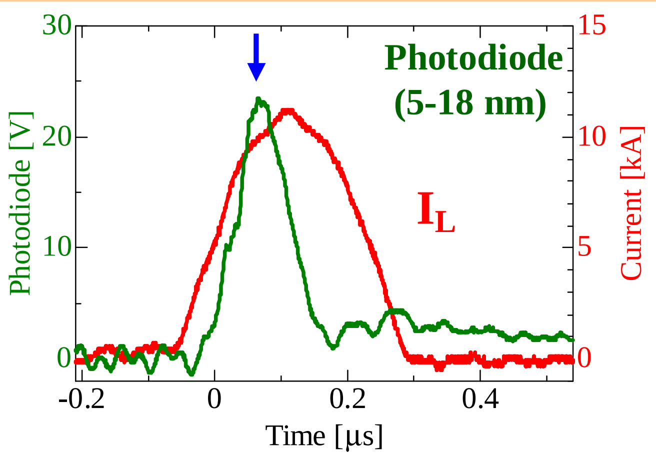


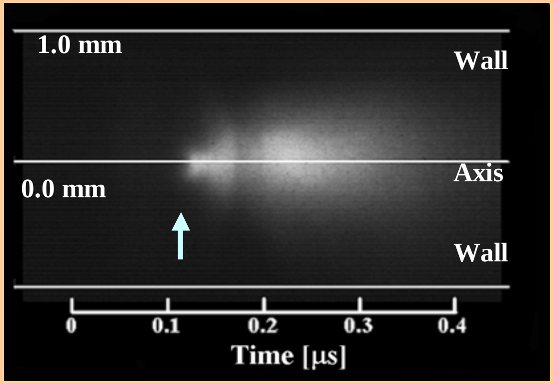
Current Pulse Width
~ 1µs ⇨ 300 ns

Magnetic Pulse Compression
(Reduction of Inductance)



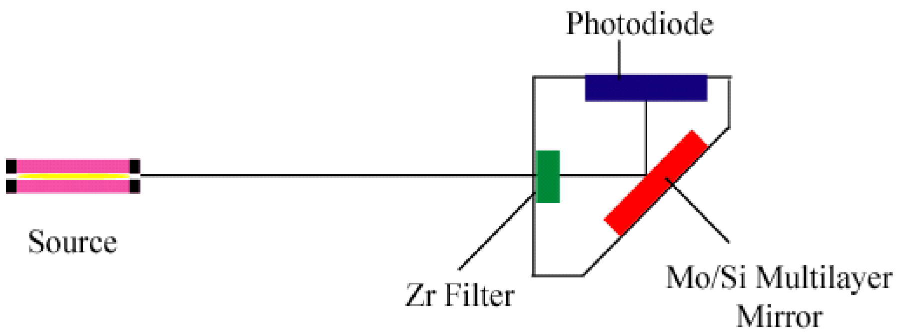
5 Torr Xe

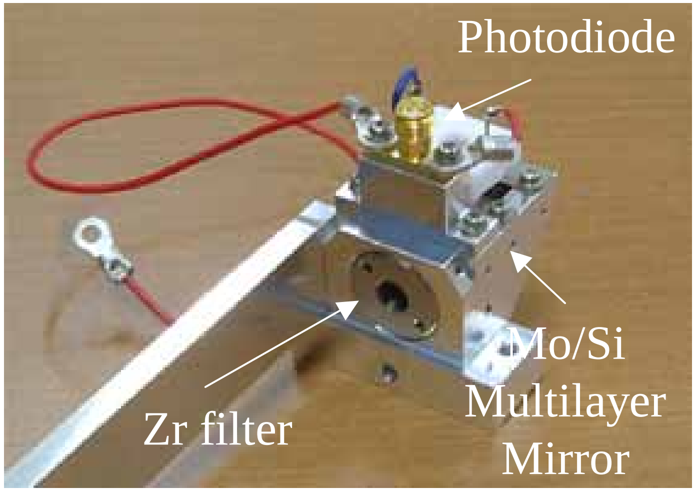




Absolute in-band EUV power

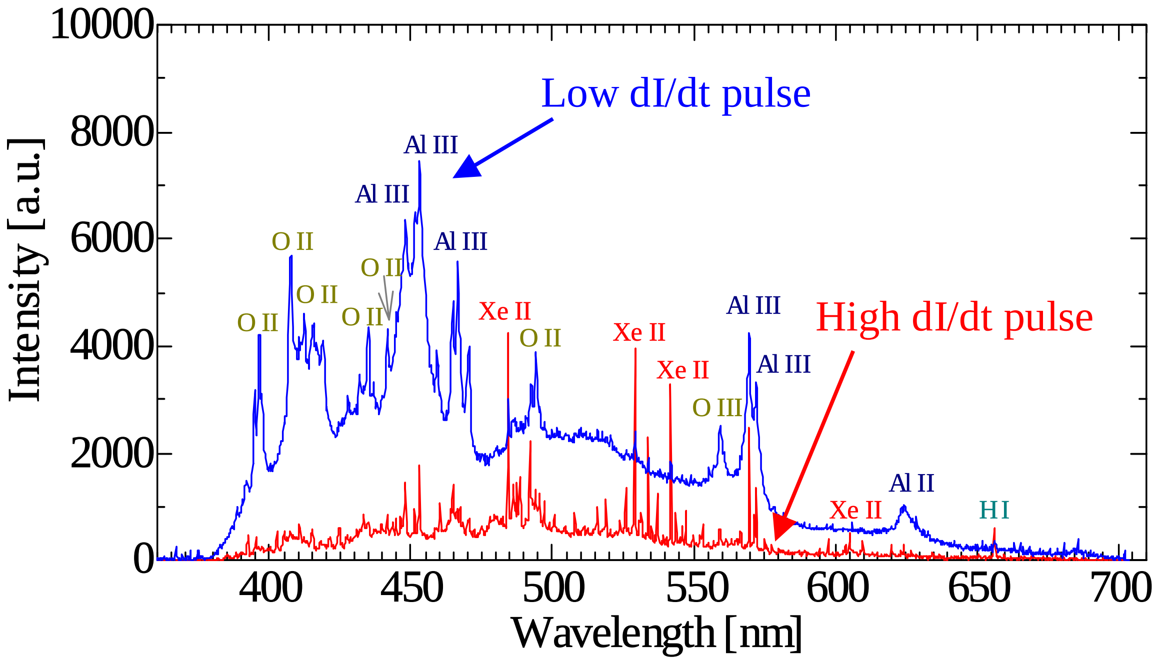
EUV mini calorimeter





	Low *dI/dt* pulse	High *dI/dt* pulse
EUV output energy [mJ/sr/2%BW/pulse]	2.5	3.3
Max. solid angle [sr]	2π	2π
EUV energy at the source [mJ/pulse]	15.7	20.7
Input energy [J/pulse]	5.6	4.7
Conversion efficiency [%]	0.28	0.44

Effect of *dI/dt* on the visible spectra



- Visible emission lines are identified in the each pulse system
- Impurities O and Al in low *dI/dt* pulse come mostly from the capillary : plasma - capillary wall interaction
- Contact time between plasma and capillary in high *dI/dt* pulse is short enough to prevent impurities from being ablated

Effect of *dI/dt* and pressure on EUV pinhole images

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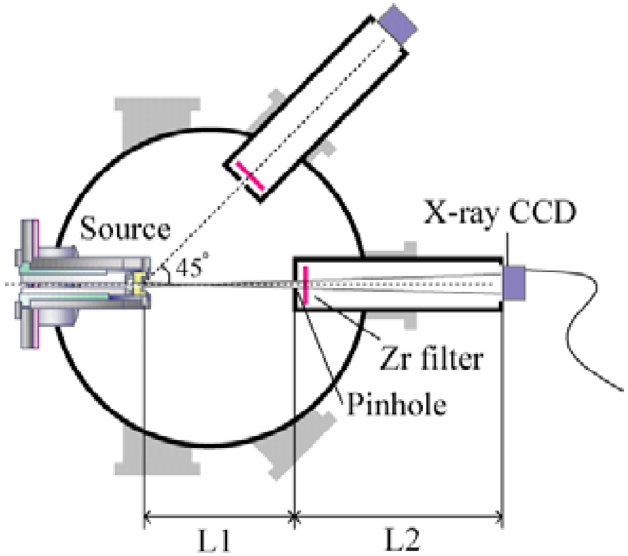
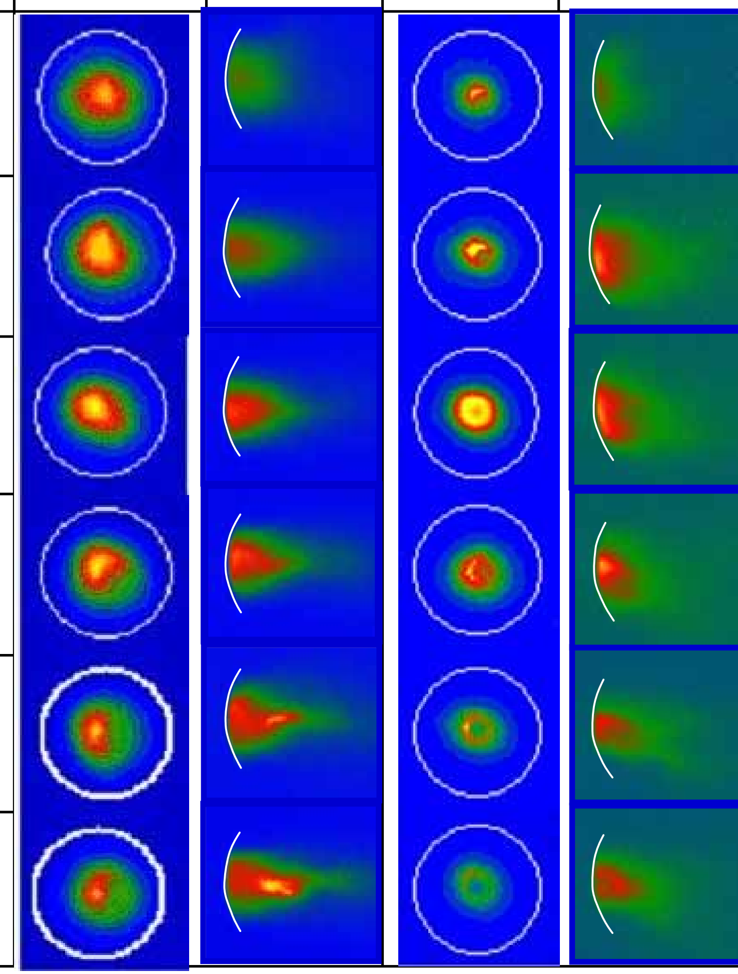


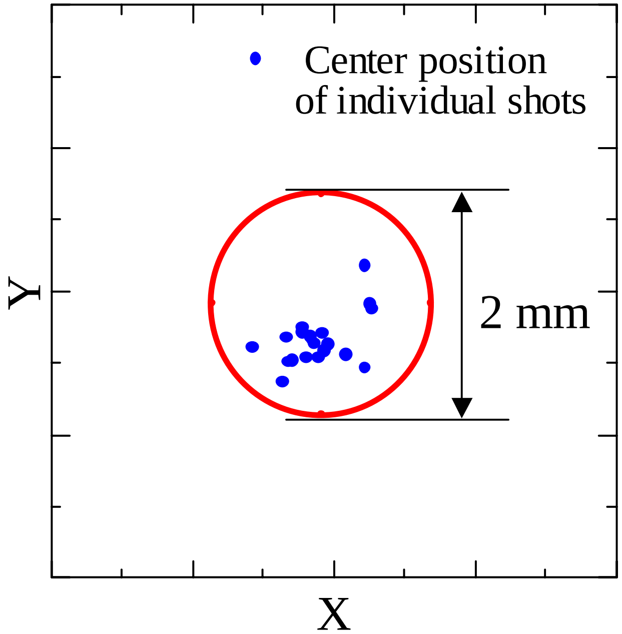
	Low *dI/dt* pulse		High *dI/dt* pulse	
Pressure	**0°**	**45°**	**0°**	**45°**
3 Torr				
4 Torr				
5 Torr				
6 Torr				
7 Torr				
8 Torr				



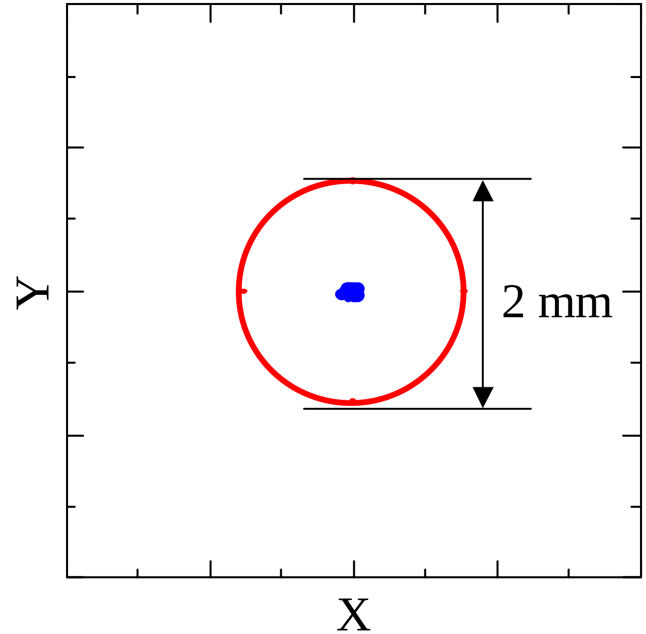
- **For higher *dI/dt***
  - **Source size is smaller**
  - **Position stability is better**

Effect of *dI/dt* on position stability

low *dI/dt* pulse



High *dI/dt* pulse



X : ±0.16 mm
Y : ±0.13 mm

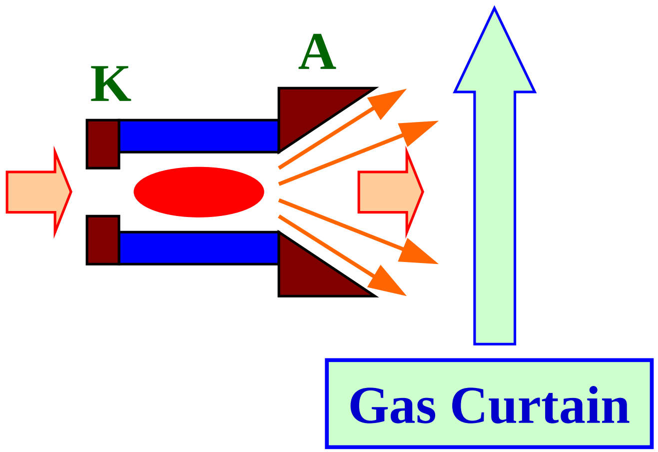
Standard deviation σ

X : ±0.018mm
Y : ±0.013mm

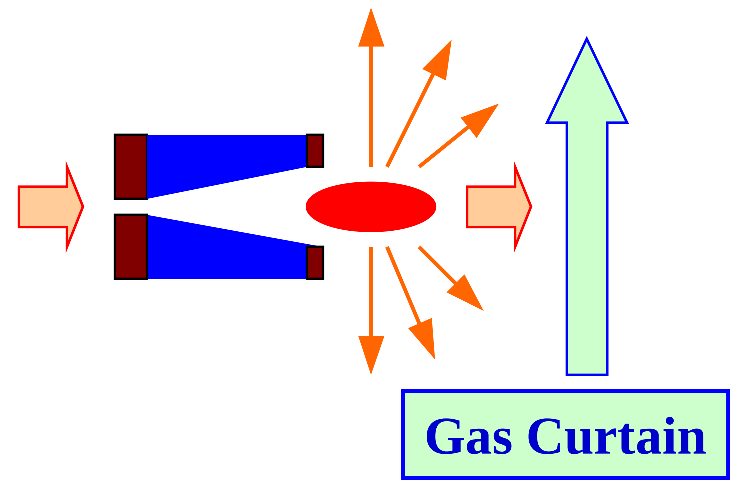
- Peak intensity positions of 20 pinhole image were recorded
- Position stability of fast pulse is better than that of slow one

For the higher power and steady state operation

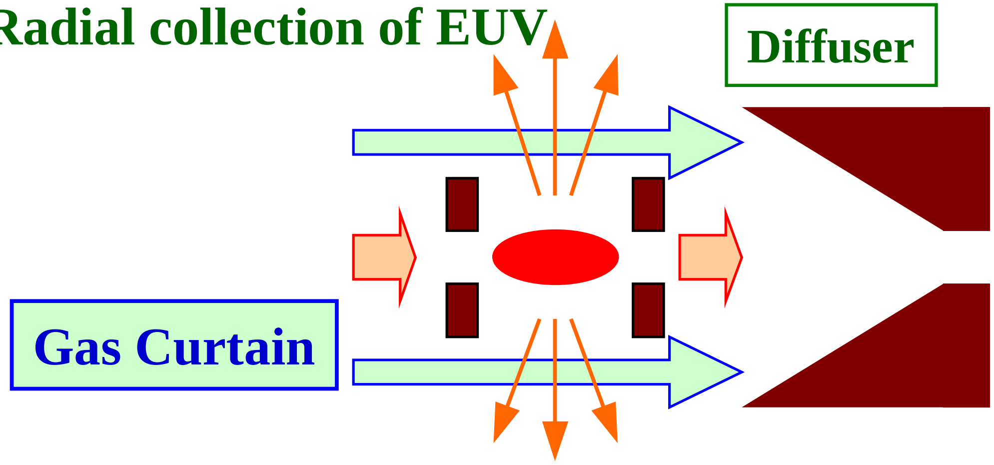
Ordinary Z-pinch and Gas Curtain



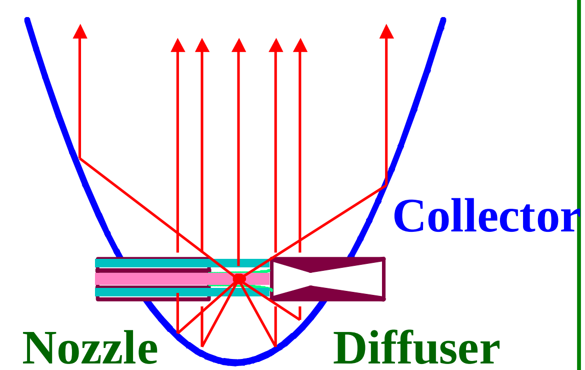
Tapered Pinch



Radial collection of EUV



Normal incidence



Gas jet type Z-pinch discharge system

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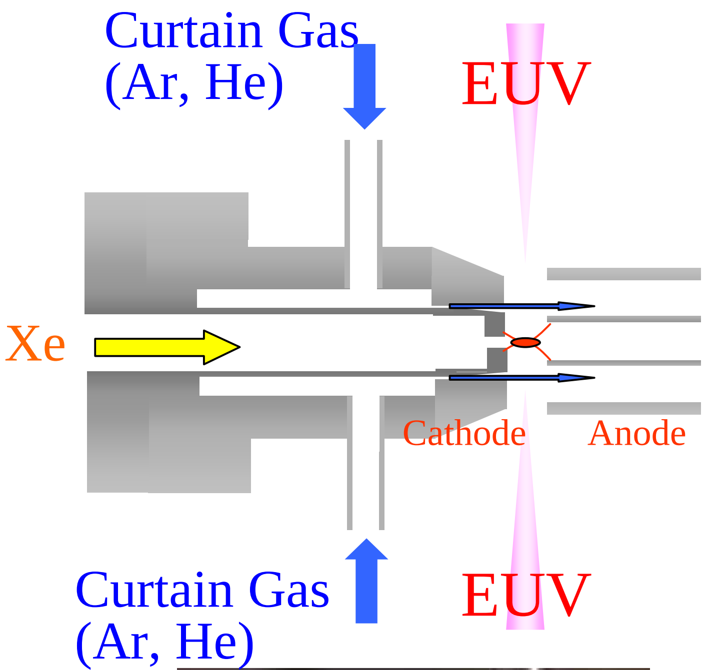
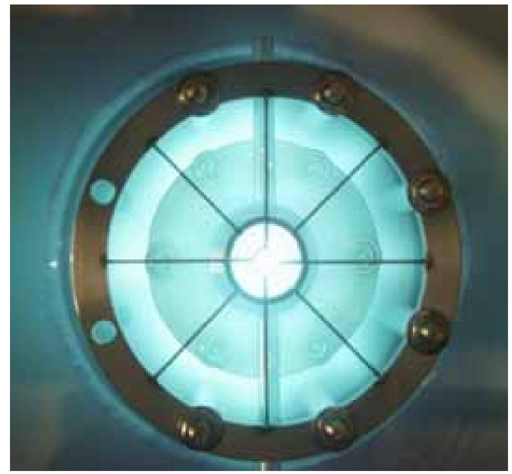
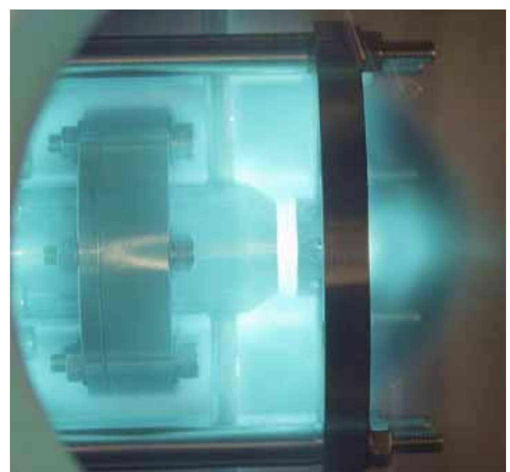




Front view



Side view

- ♦ Cathode (nozzle)
  - Xe nozzle diameter: 2 mm
  - He nozzle diameter
    Inner diameter: 11.6 mm
    Outer diameter: 12 mm
- ♦ Anode (diffuser)
  - Inner diameter: 6 mm
  - Outer diameter: 20 mm
- ♦ Conditions
  - V_{charge} = 9 kV
  - Xe gas supplying pressure = 10 Torr
  - Gap distance: d = 4 mm

Framing photographs (10 ns resolution)

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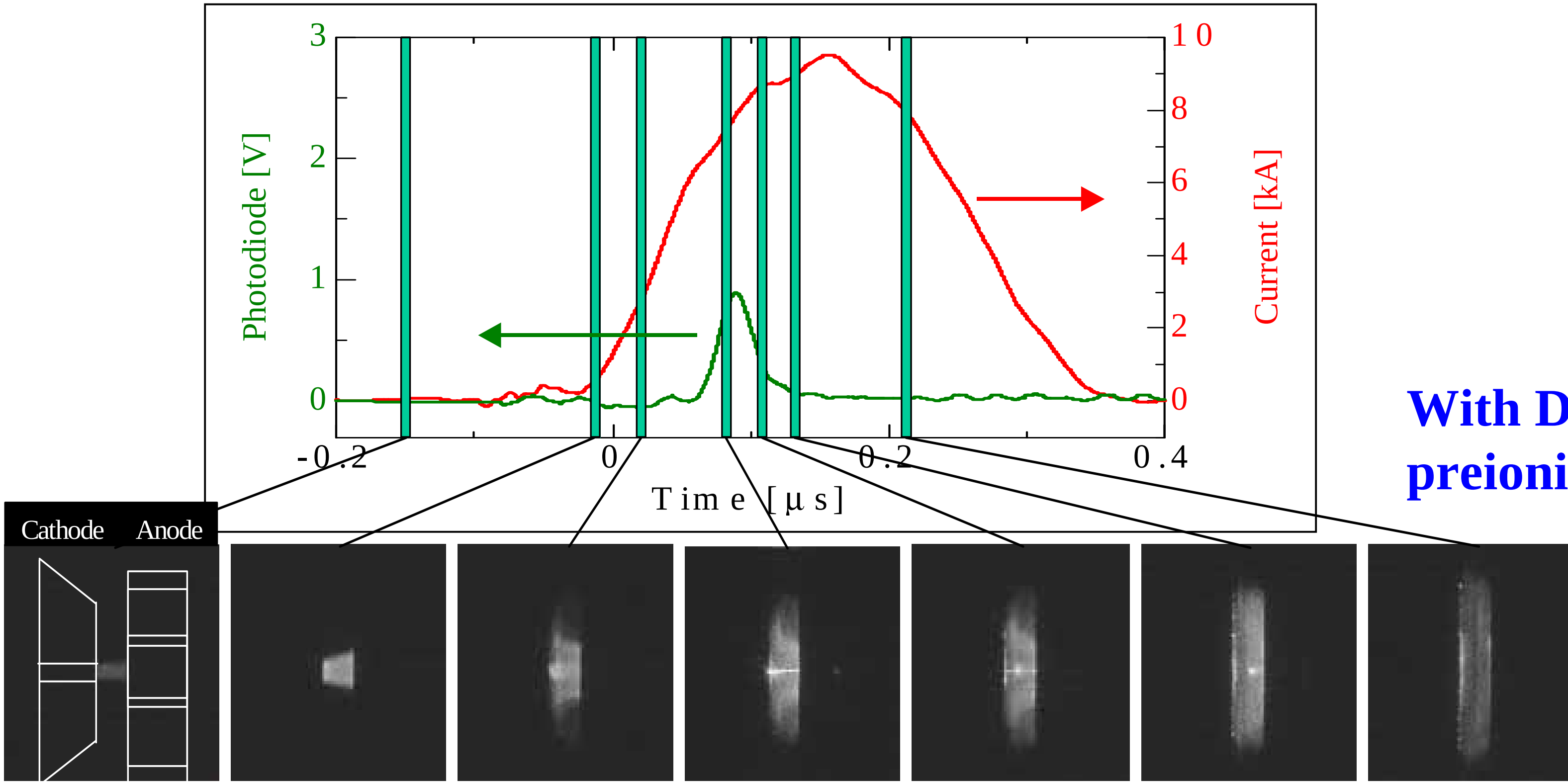


With DC preionization

-180 ns

-20 ns

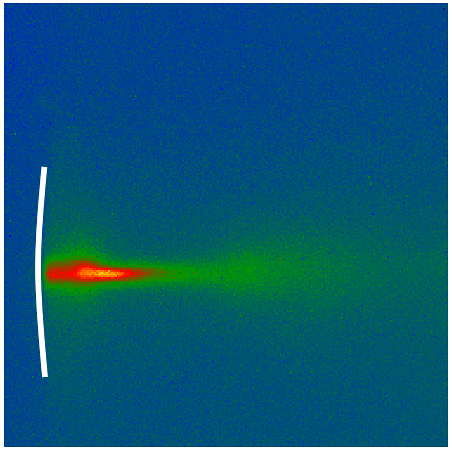
Without DC preionization

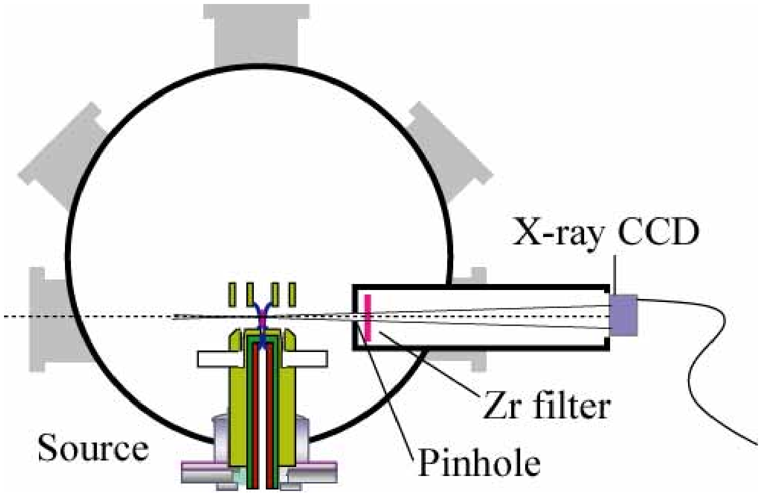
♦ Conditions

- V_{charge} = 9 kV
- Xe gas supplying pressure = 10 Torr
- Gap distance: d = 4 mm
- Without gas curtain

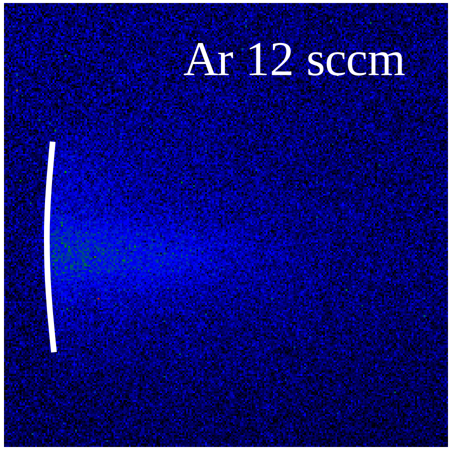
Effect of gas curtain (EUV pinhole image)

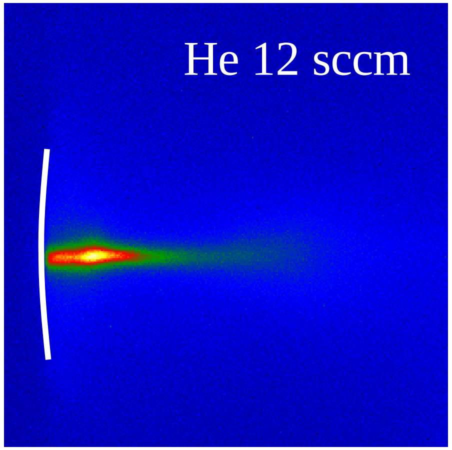
W/o Gas Curtain 10 kV, Xe 10 Torr





With Gas Curtain (w/o diffuser)





Pinch cannot be observed in case of Ar gas curtain

Confinement by curtain gas is observed

Absolute in-band EUV energy

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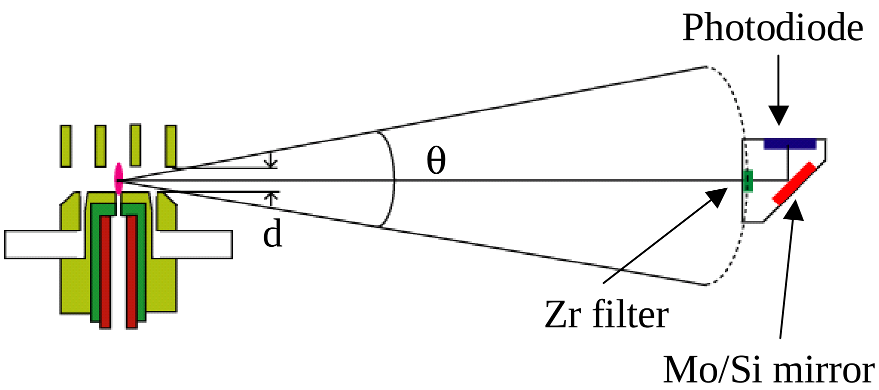
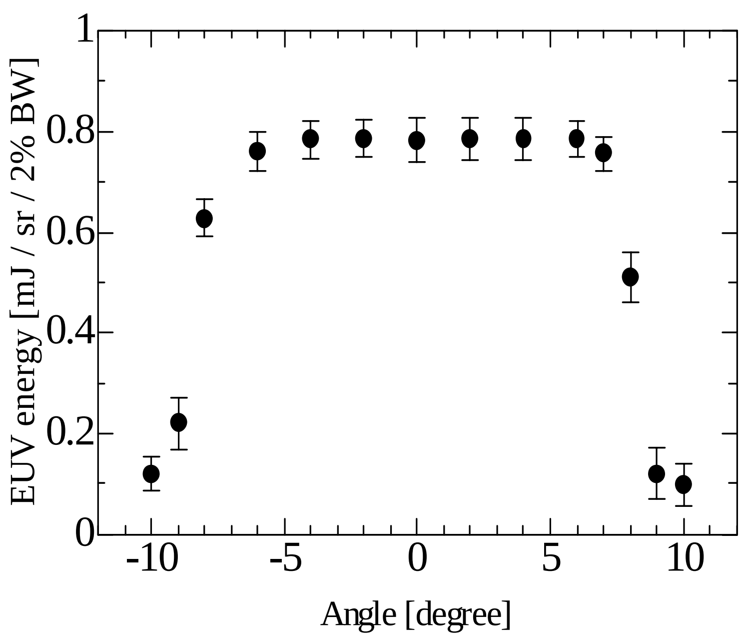
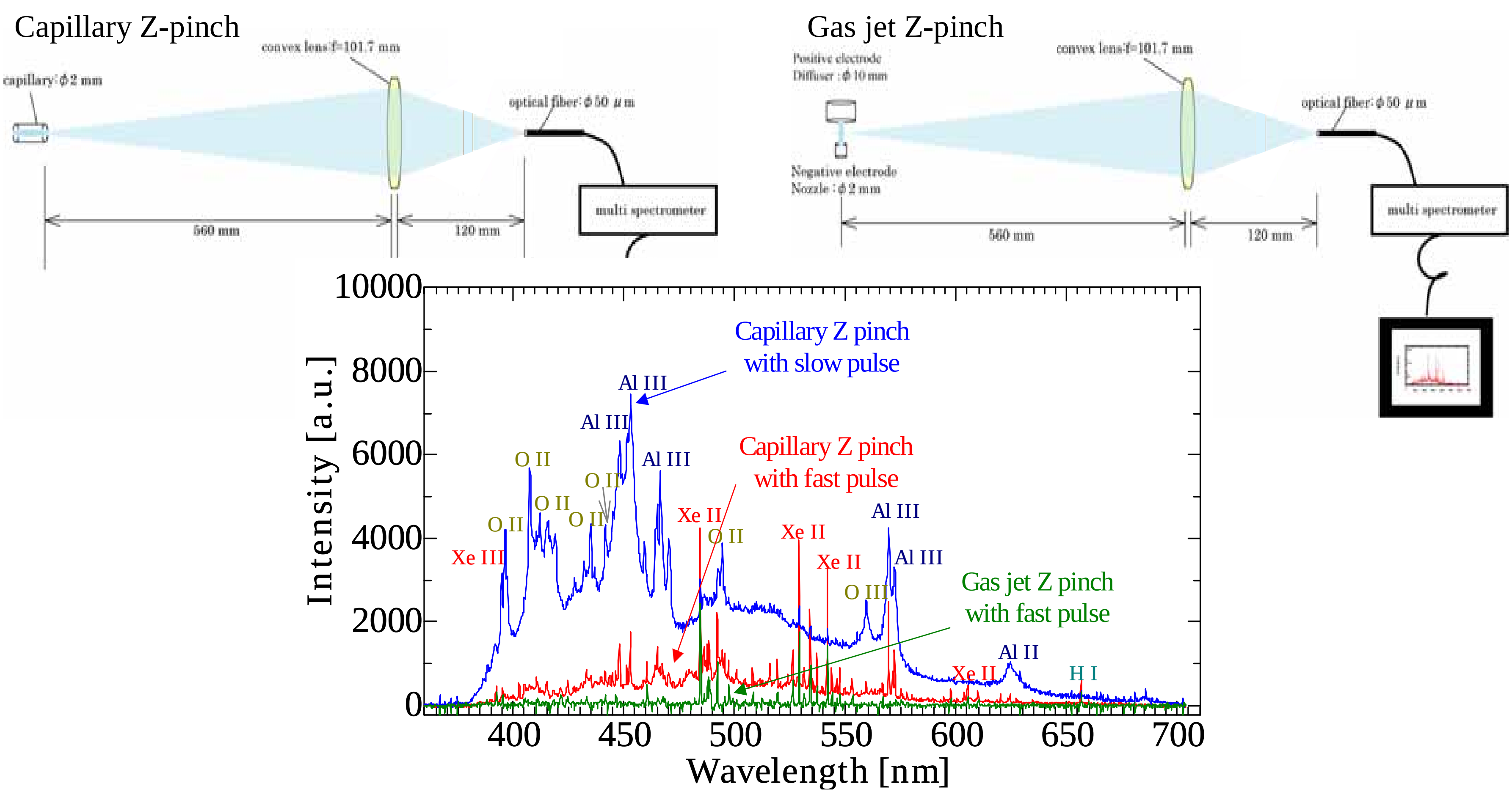




Angular distribution of EUV

- ♦ V_{charge} = 9 kV, Xe = 10 Torr, d = 4 mm, 100 Hz operation, without gas curtain
- ♦ **The EUV output in 2 % bandwidth at 13.5 nm is 5.1 mJ/pulse (at 2π sr)**
- ♦ The available observation angle (± 8 degree) may lead to partial obscuration of the source
- ♦ In spite of the low output energy, we believe that increasing the discharge current and improving the present nozzle design can achieve the high EUV yield

Visible spectra



♦ The observed impurity lines of different ionization states of O and Al in capillary discharge come mostly from the alumina capillary wall

♦ No significant impurity contribution from the electrode materials is marked in the gas jet type Z-pinch discharge

Summary (EUV light source)

- **Higher energy transfer efficiency**
  - **Lower stray inductance**
  - **Higher *dI/dt***
- **Debris mitigation**
  - **Tube less structure : radial collection**
  - **Gas curtain, Debris shield**
- **Future plan**
  - **Xenon ⇨ Tin (higher efficiency)**

Thank You for Your Attention