Optimization of Capillary Z-pinch Discharge Light Source for Lithography

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Objectives

♦ Development of high power EUV source

- Increase of EUV output power

?EUV power = $\eta_{generator} \cdot \eta_{coupling} \cdot \eta_{plasma} \cdot T \times$(Input energy/shot)×Rep-rate

?Improvement of energy conversion efficiency → Plasma physics

?High repetition rate → All solid-state power system and water cooling

♦ Development of high quality EUV source

- Stability

?Pre-ionization → Optimum condition

- Debris generation

?Minimum input energy → Improvement of energy conversion efficiency

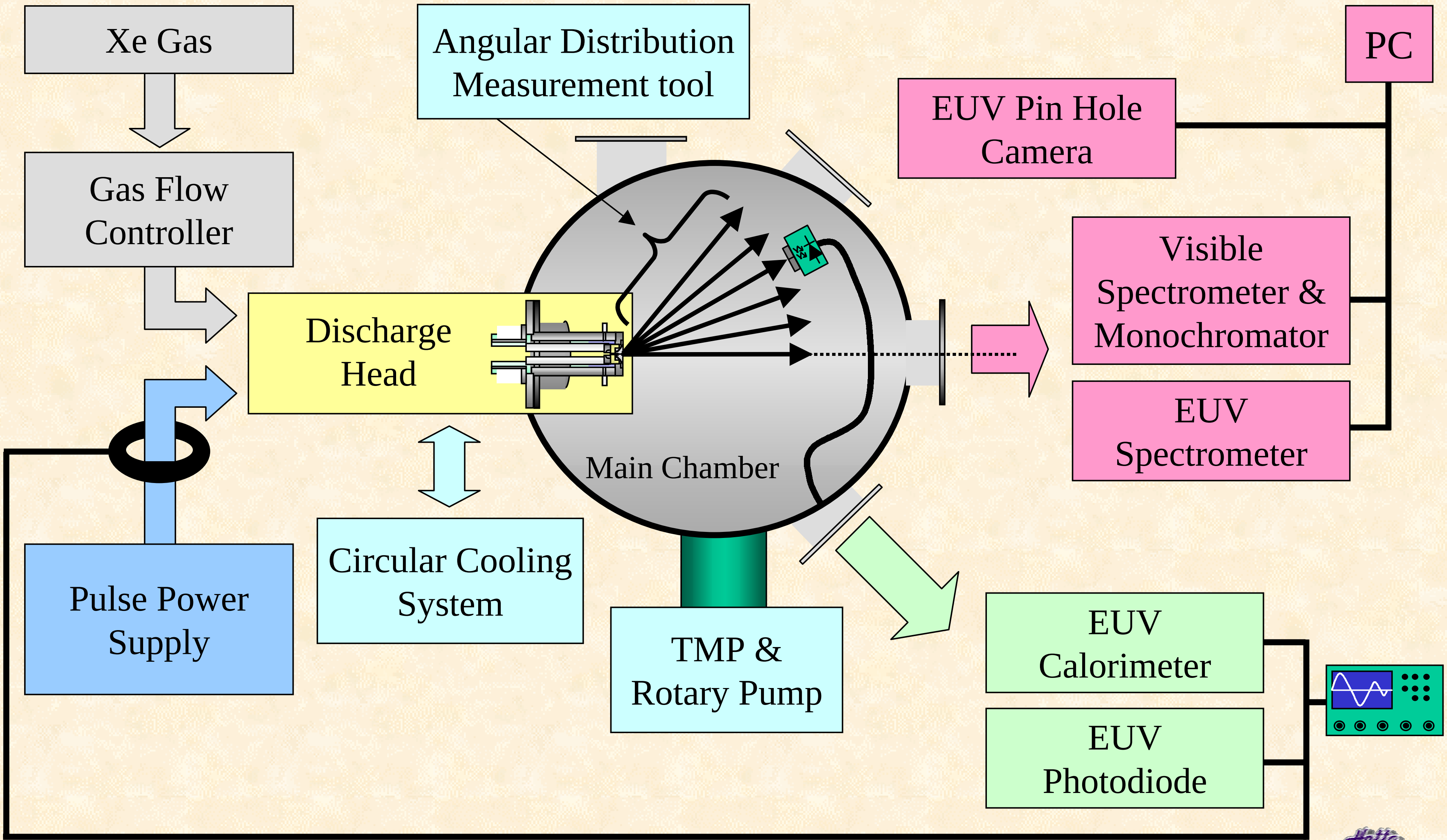
- Debris mitigation

?Gas curtain

Contents

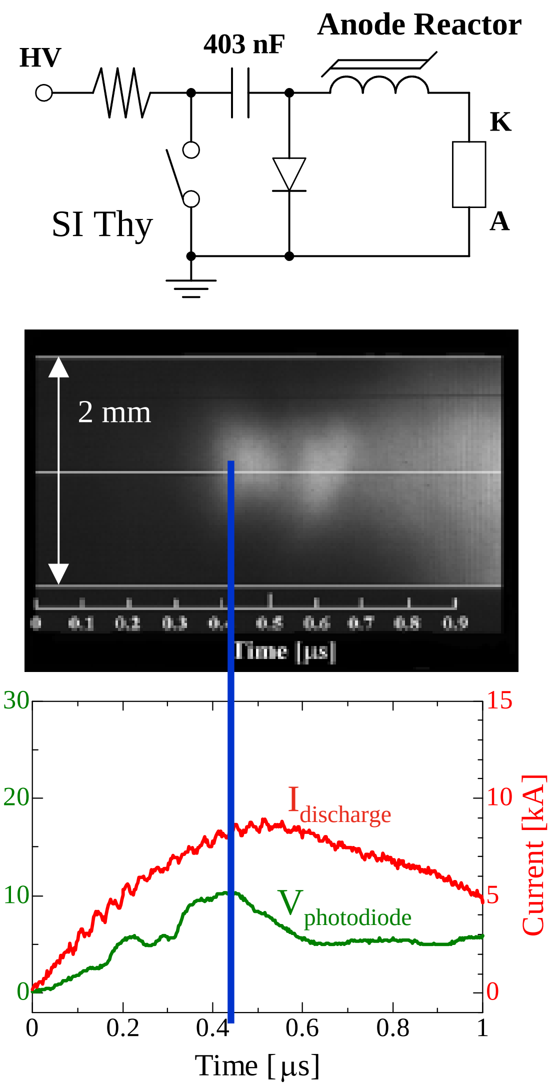
- ♦ Development of high power EUV source
  - Relation between current risetime and plasma property & $\eta_{coupling}$
  - Relation between input energy/shot and debris generation
  - Power measurements with EUV calorimeter
- ♦ New electrode
  - Z-pinch without surface discharge
  - Separated pre-ionization circuit design
    - → Optimum conditions such as plasma property, stability and EUV power
- ♦ Debris mitigation
  - Design and test setup of gas curtain

Block diagram of experimental system



Effect of dI/dt on plasma radius and peak EUV output

Direct pulse method



Current dI/dt

500 ns → 160 ns

Pulse width

2.3 us → 320 ns

Input energy (/shot)

5.6 J → 4.7 J

↓

Comp. ratio (r_0/r_{min})

2.8 → 9.1

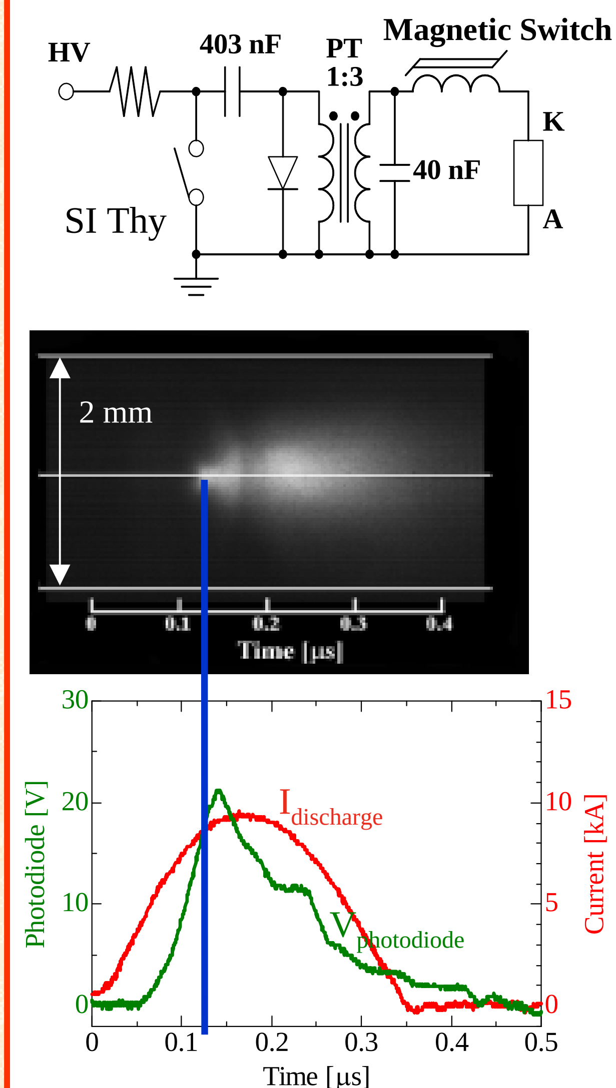
Peak of photodiode signal

10 V → 22 V

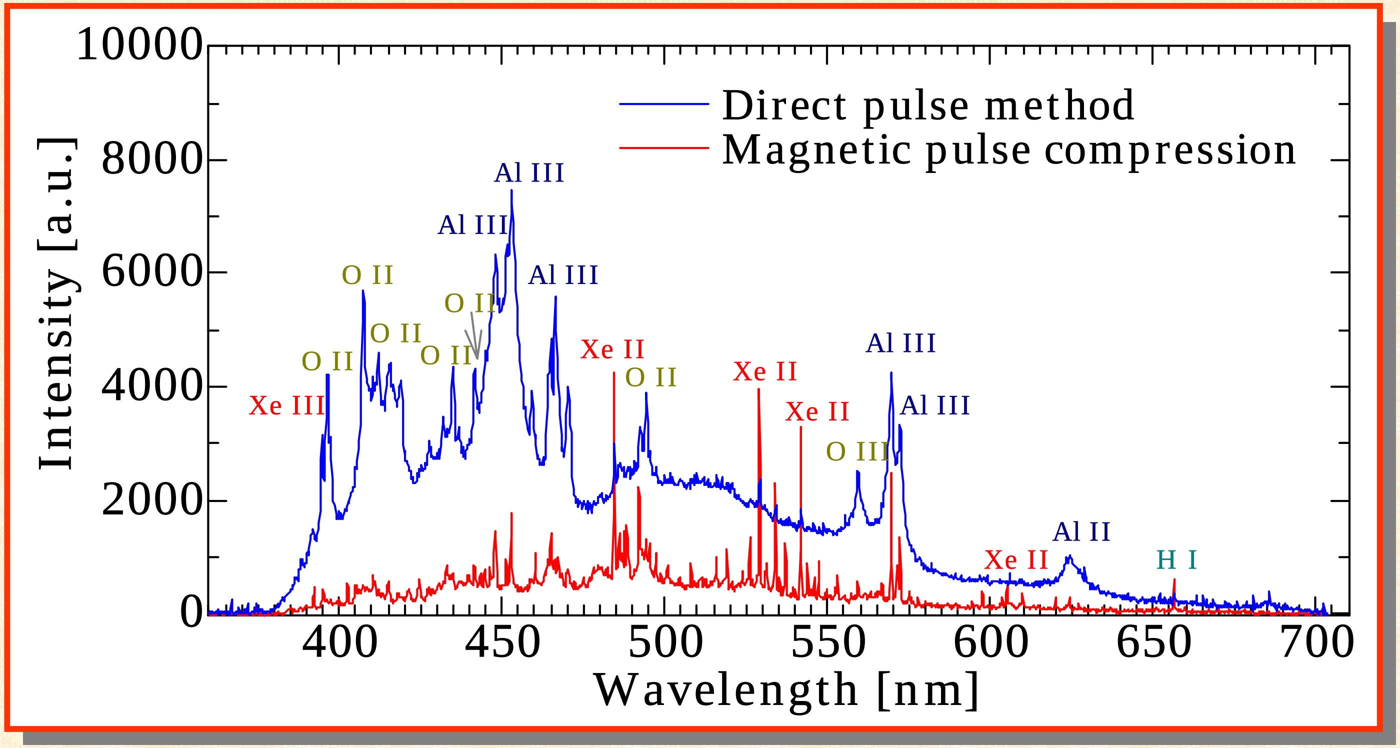
V•sec of photodiode signal

2.27×10^{-8} → 3.28×10^{-9}

Magnetic pulse compression

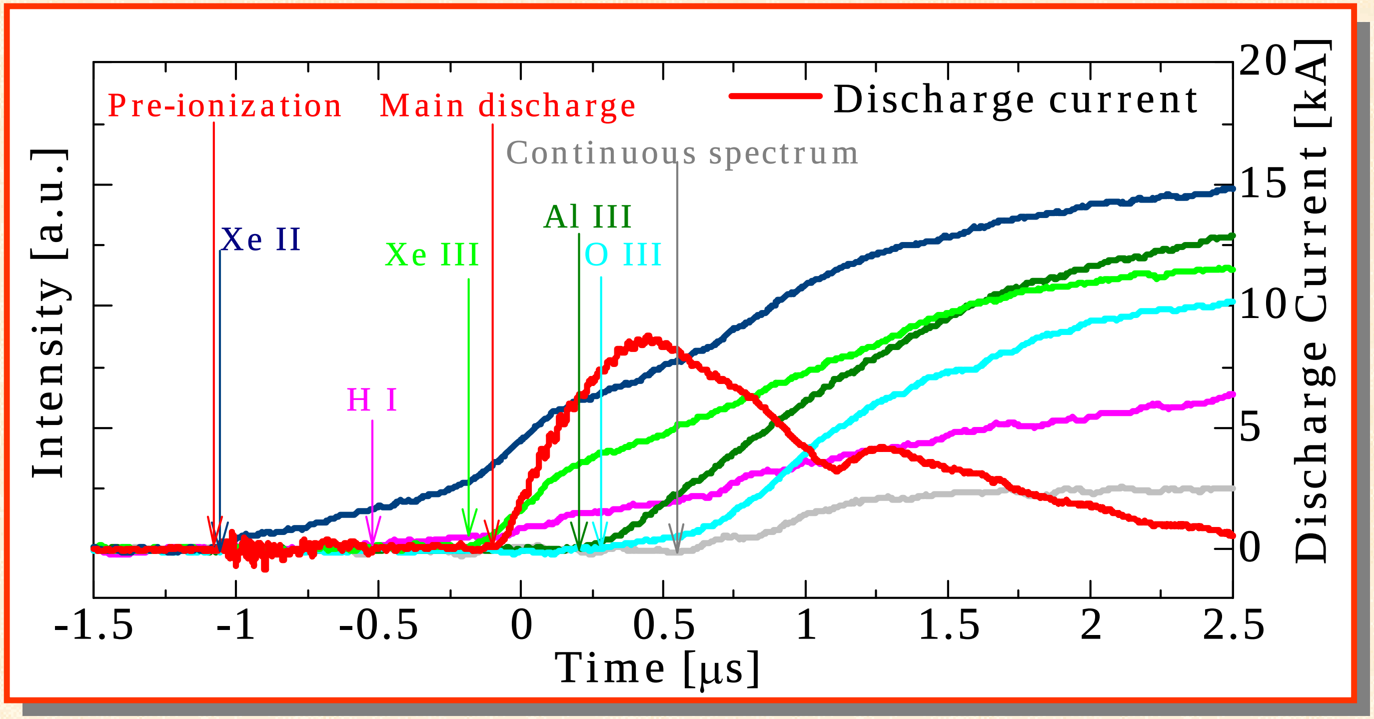


Effect of dI/dt on spectra in visible region



- Visible emission lines are identified in the each pulse system of plasma
- Impurities O and Al in direct pulse method come mostly from the capillary
- Contact time between plasma and capillary in magnetic pulse compression is short enough to prevent impurities from being ablated

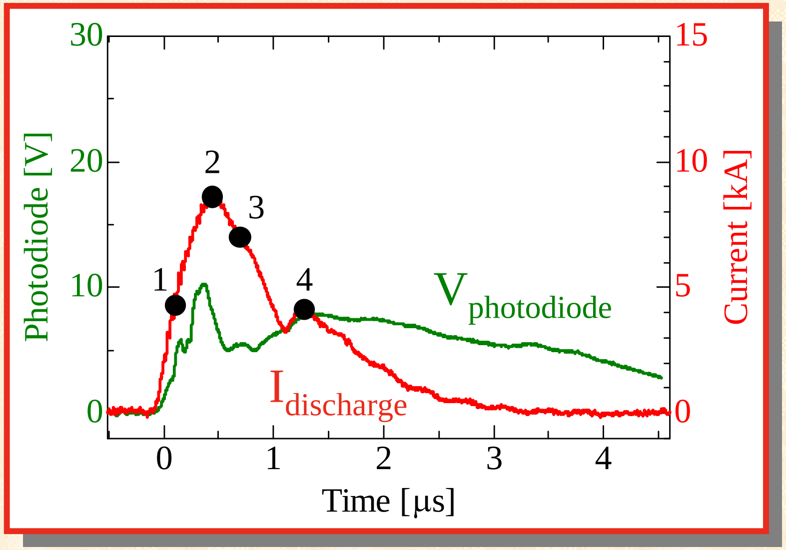
Spectral result of monochromator - direct pulse method

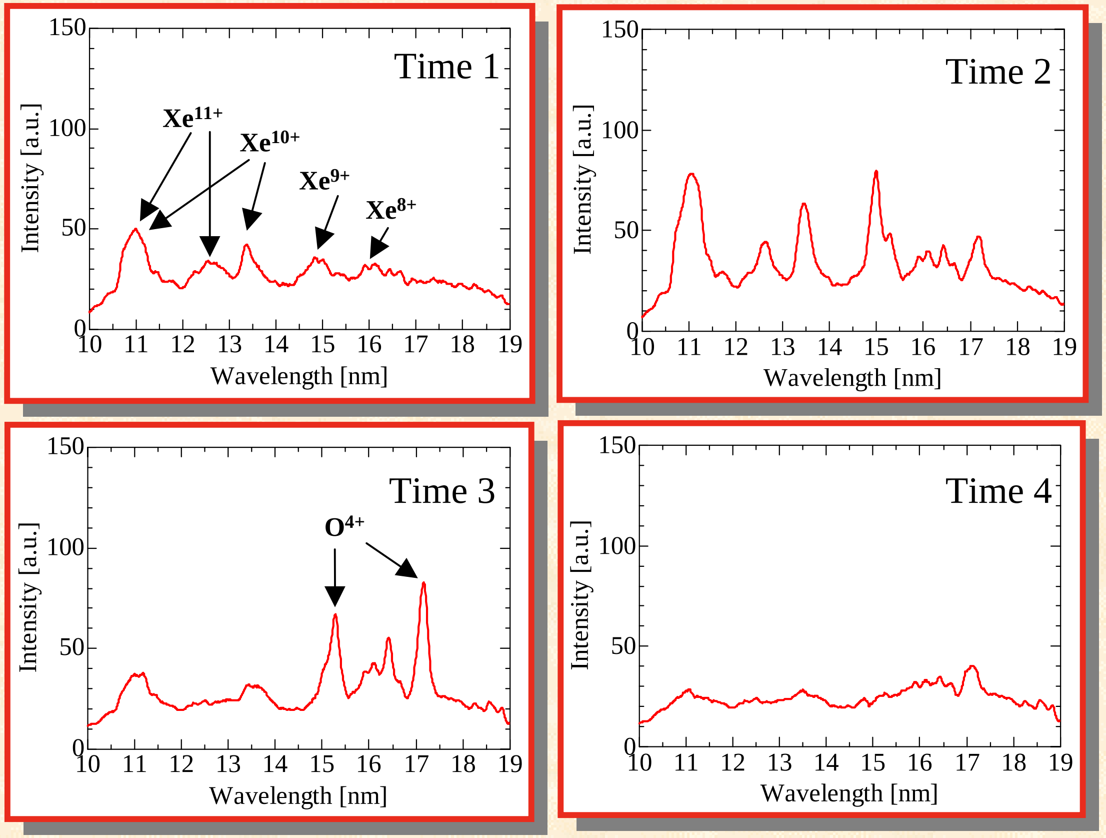


- Showing the beginning of emission of specific impurity lines
- Contact of plasma and capillary causes such impurities
- For magnetic pulse compression, the beginning point of impurity lines compared with discharge current and a kind of impurities are same, but the intensity of impurities is much lower

Time-resolved spectroscopic analysis - direct pulse method

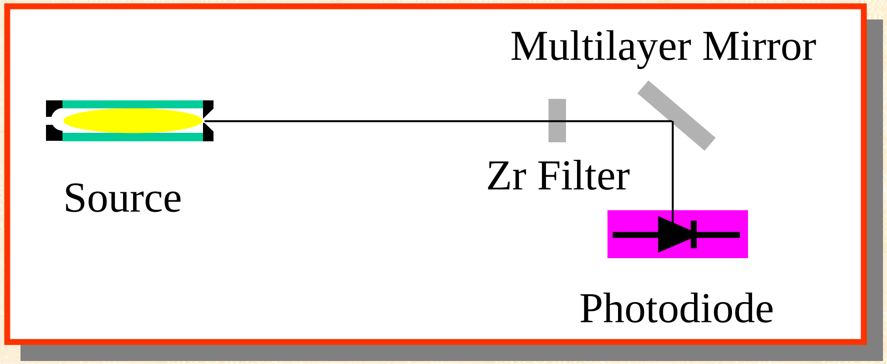
Gated images recorded at the times indicated on the current pulse

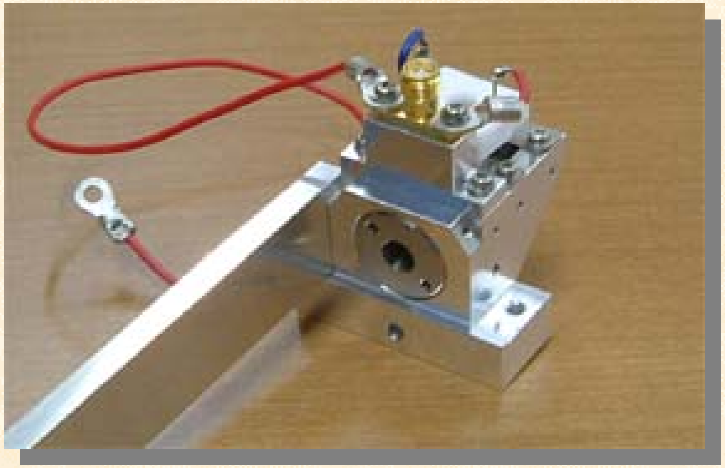


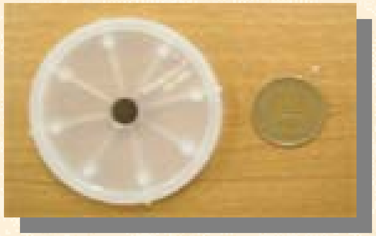


- ♦ Time-resolved analysis is conducted by using the grating incidence monochromator with 600 g/mm MCP, which is gated by an 130 ns, 600V high voltage pulse
- ♦ After the discharge current peak, O impurity lines dominate
- ♦ High dI/dt and short pulse width discharge current is preferable

EUV output measurements - magnetic pulse compression



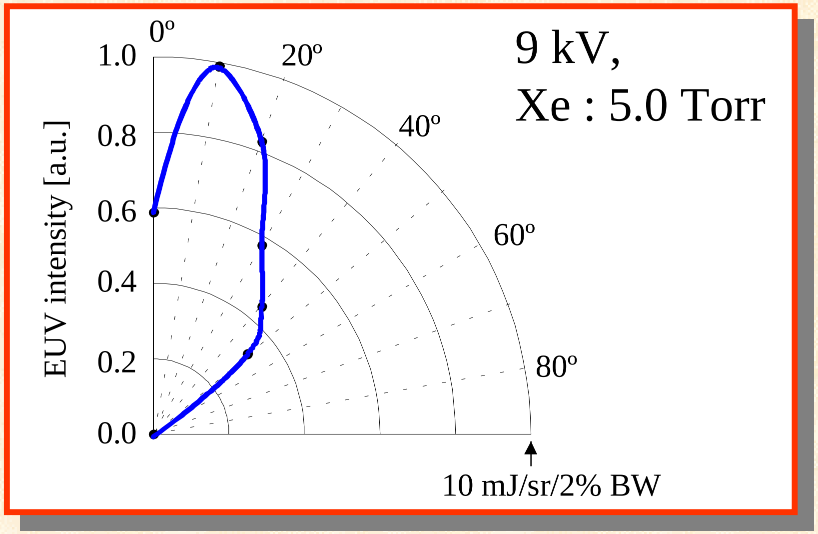




Multilayer Mirror

Filter

Parylene(0.1 μm)+Zr(0.2 μm)



- EUV output energy = 9.9 mJ/sr/2%BW/pulse
- Effective solid angle (Xe = 5.0 Torr) → Ω_{eff} = 1.74 sr
- EUV energy at the source (2 % BW) = 17.2 mJ/pulse
- EUV conversion efficiency = 0.24 %/pulse (Will be improved)

Erosion of capillary

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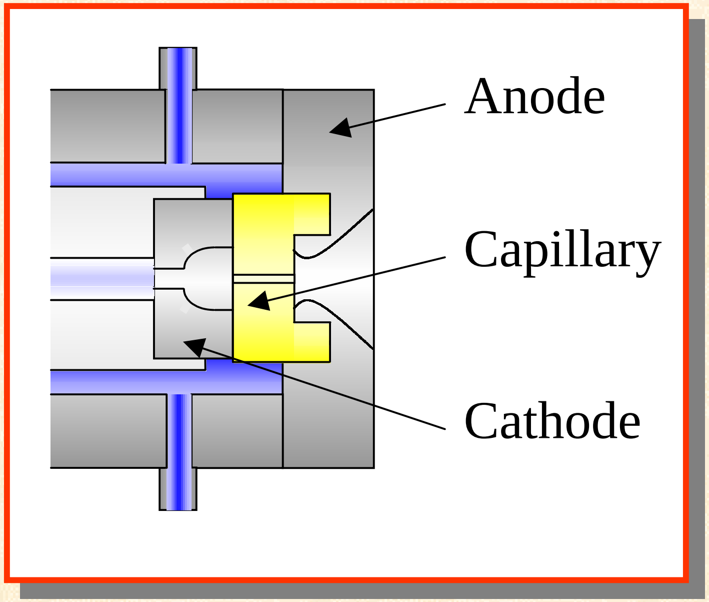
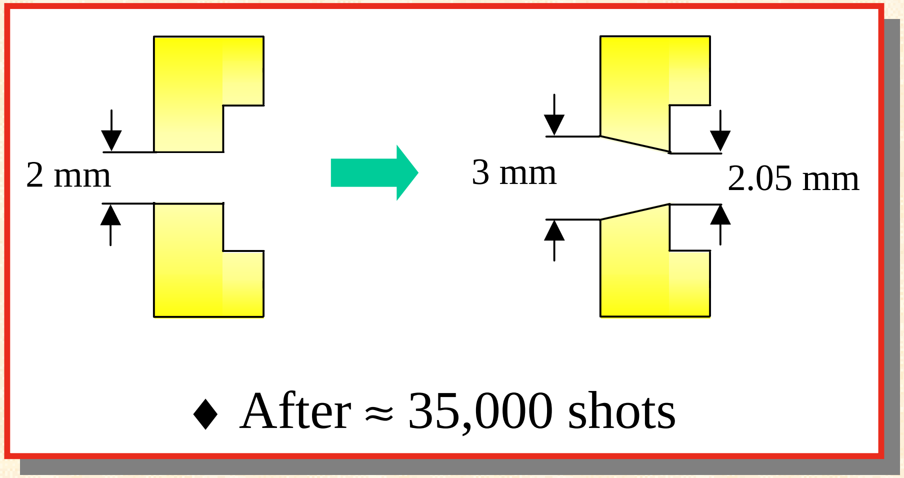
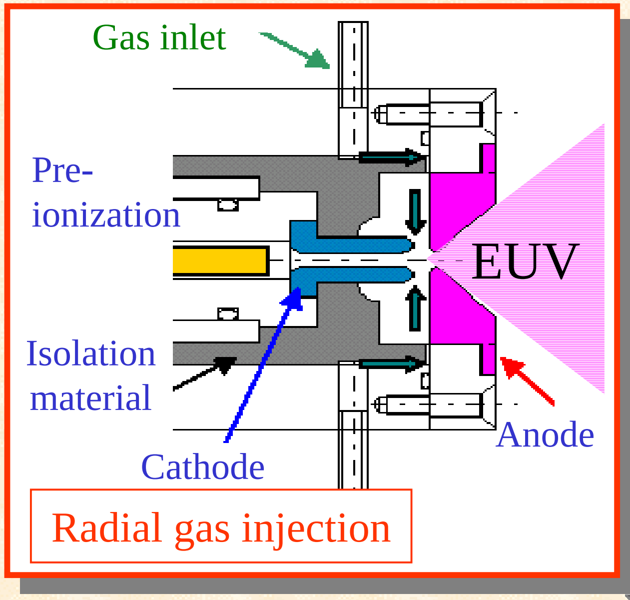




- Inner diameter of cathode side capillary was changed from ϕ2mm to ϕ3mm because of erosion
- Study of the capillary material
- Study of the structure of electrode and capillary
- New discharge concept

  → Designed new discharge head



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New electrode - Z-pinch without surface discharge

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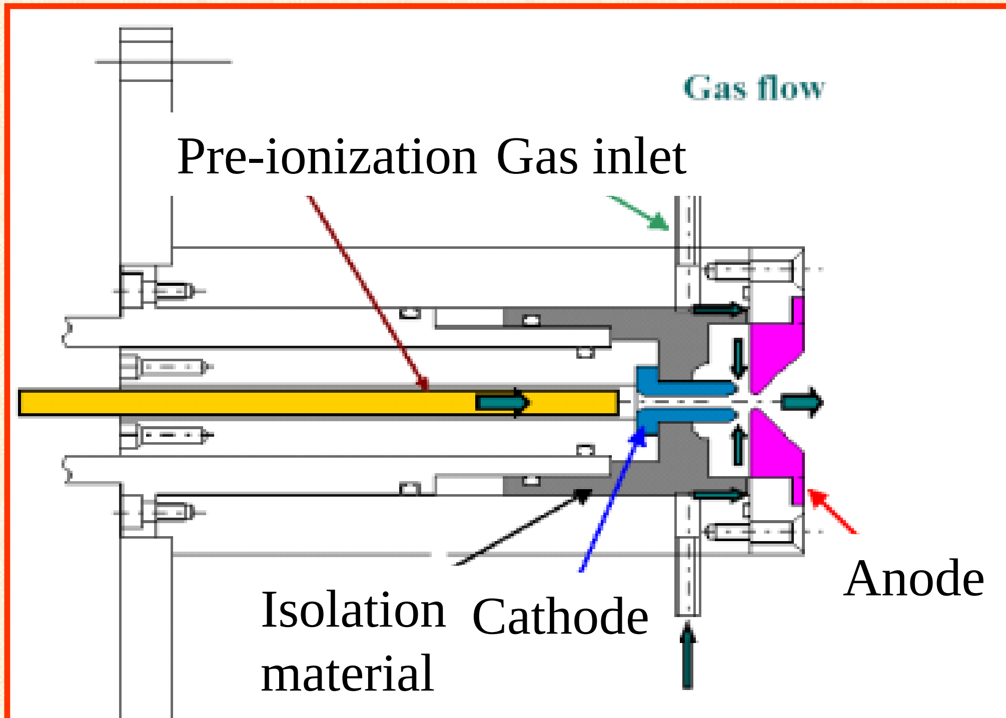
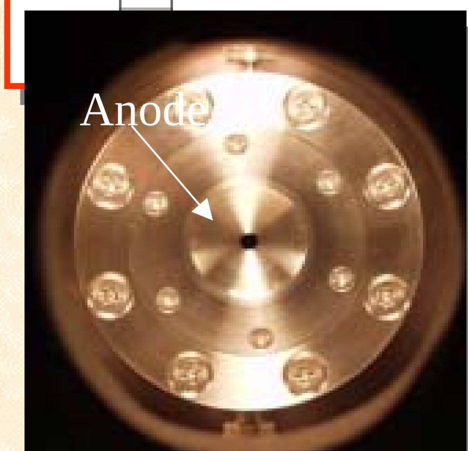
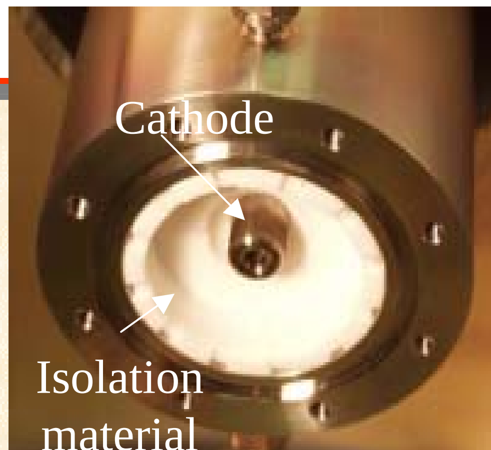






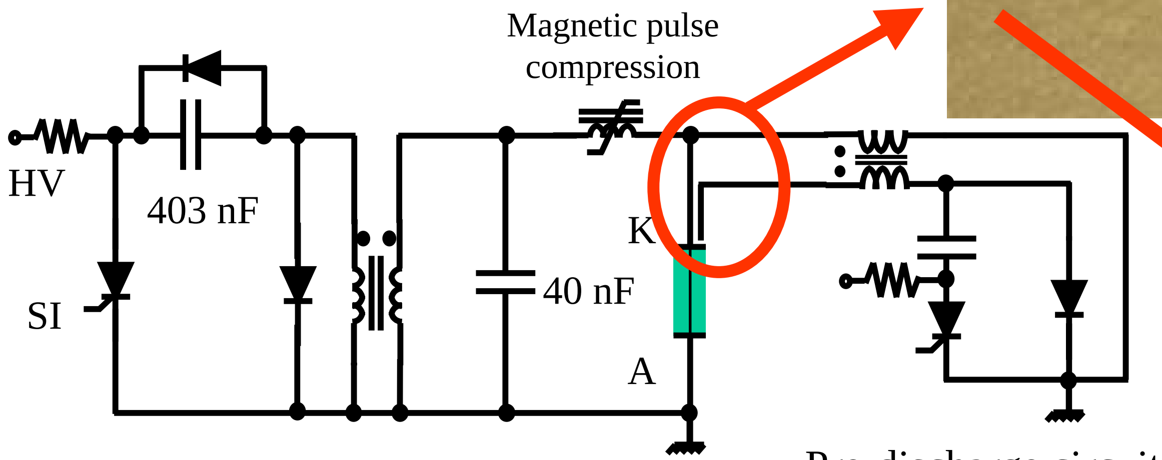
♦ Electrode

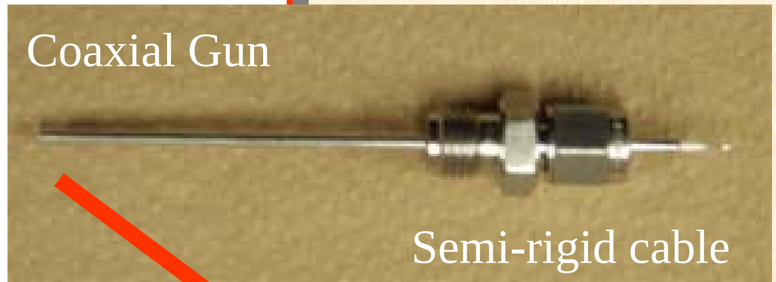
- Anode → Mo, inner radius : 4.2 mm
- Cathode → Mo, inner radius : 4 mm
- Insulation material → Teflon

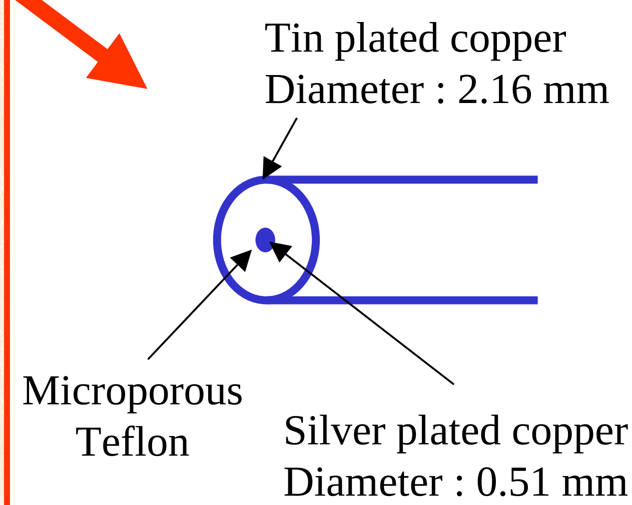
♦ Characteristics

- Z-pinch without surface discharge
- Plasma is isolated from insulation material
- Xe gas is supplied from axial and radial inlet
- Isolated pre-ionization circuit

Design of pre-ionization circuit







- Applying separated pre-ionization circuit
  → Confirm the plasma stability and EUV output
- Coaxial Gun
  → Use semi-rigid cable
  ; Microporous teflon, outer radius : 2.16 mm, inner conductor : 0.51 mm

Observation with high speed camera - Z-pinch without surface discharge

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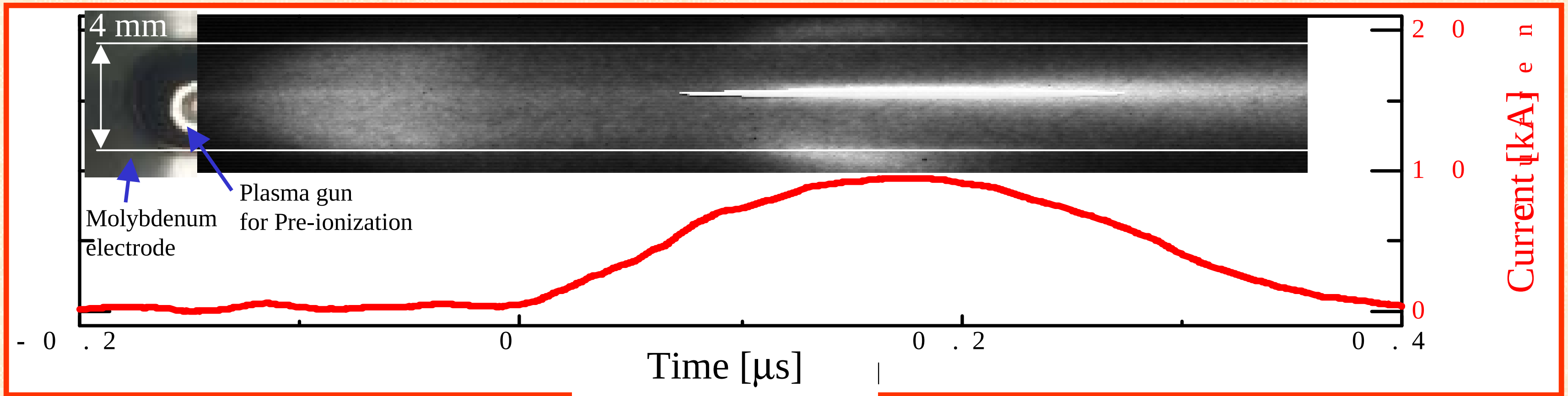
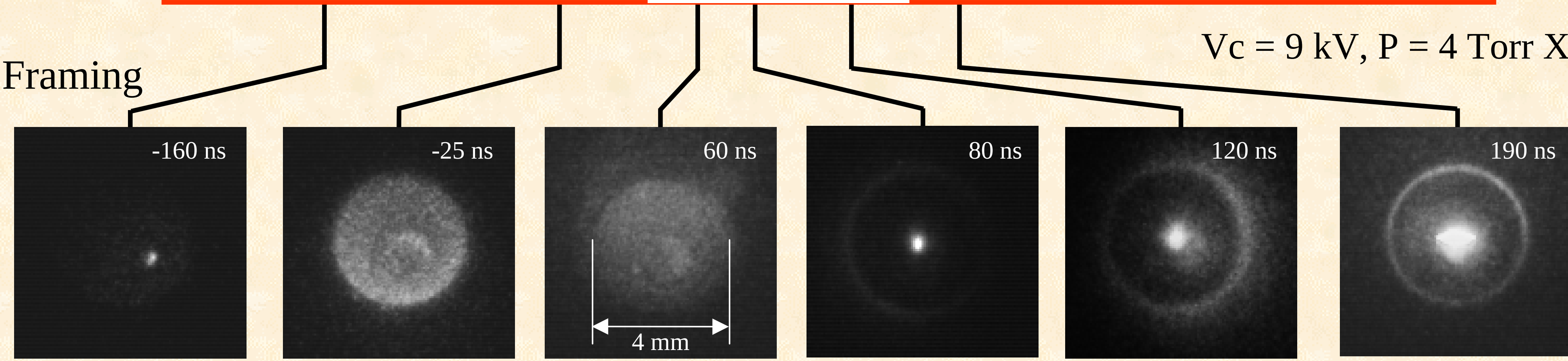
Streak



Vc = 9 kV, P = 4 Torr Xe

Framing



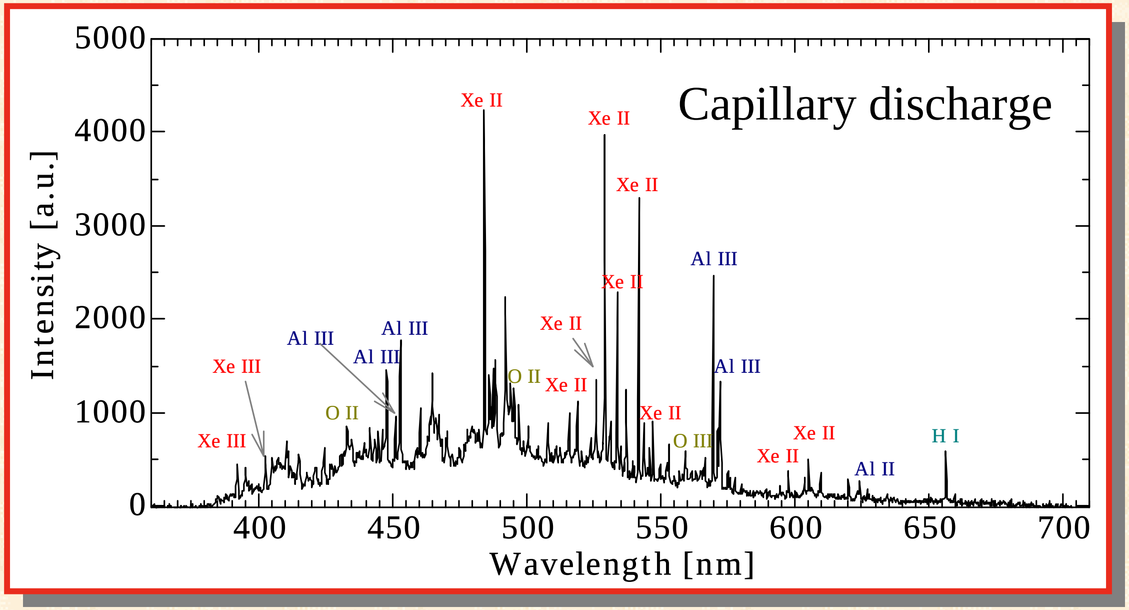
Pre-ionization by coaxial gun

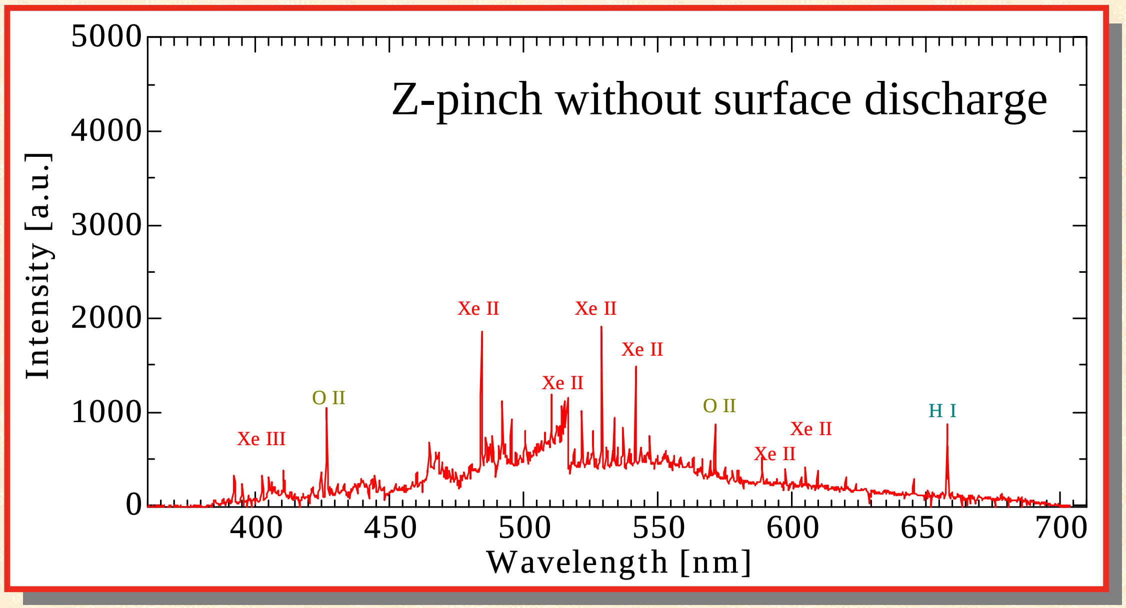
Pre-ionization by magnetic switch

Pinched

FWHM of pinch plasma = 330 μm

Spectra with and without surface discharge





- ♦ Charging voltage Vc = 9 kV, Xe gas pressure P = 4.5 Torr
- ♦ Z-pinch without surface discharge shows low spectrum intensity in entire band
- ♦ Al impurity lines are disappeared

Really pinched plasma ?

- ♦ Change the pre-ionization timing and value, discharge current

Angular distribution of EUV energy

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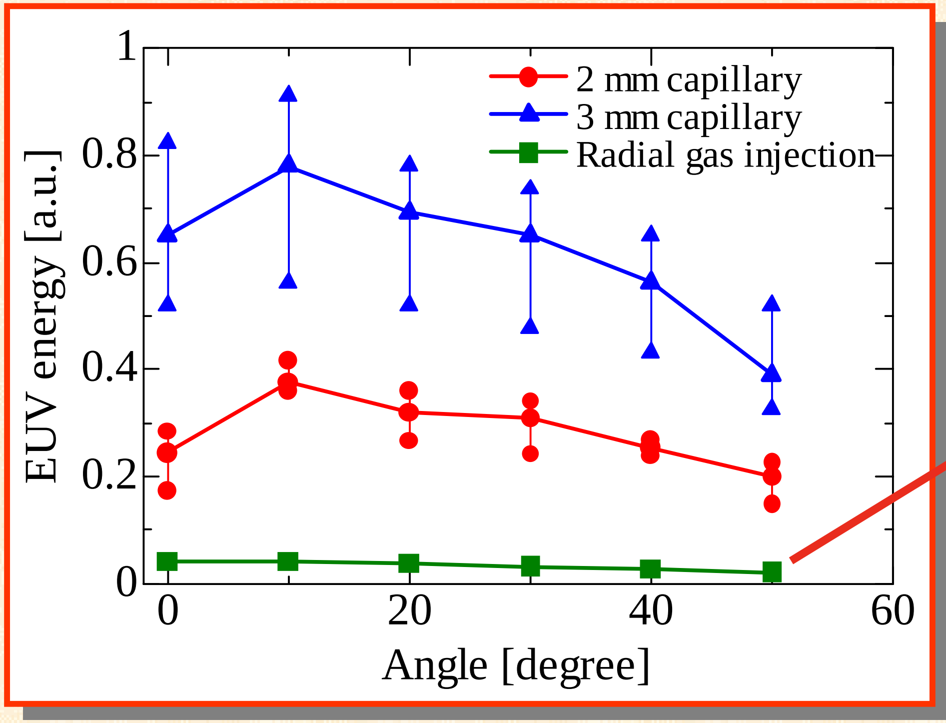

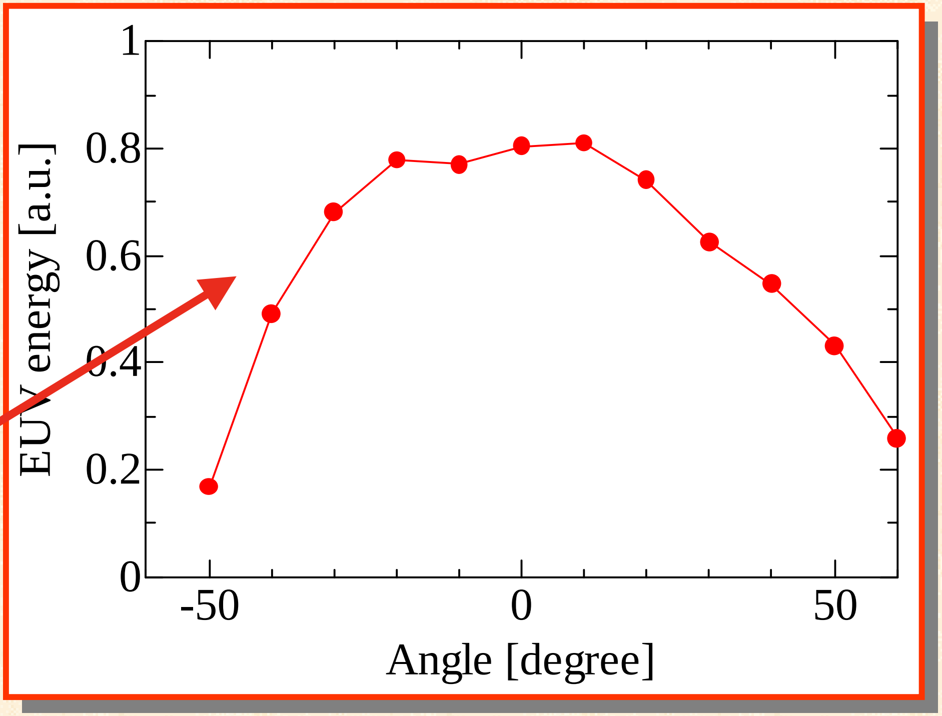

- EUV energy of 3 mm capillary is higher than the 2 mm capillary
- Stability of 2 mm capillary is better than 3 mm capillary
- EUV energy of radial gas injection is lower than that of capillary
- Need the study of the pre-ionization of Z-pinch without surface discharge

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Concepts of TITech type gas curtain

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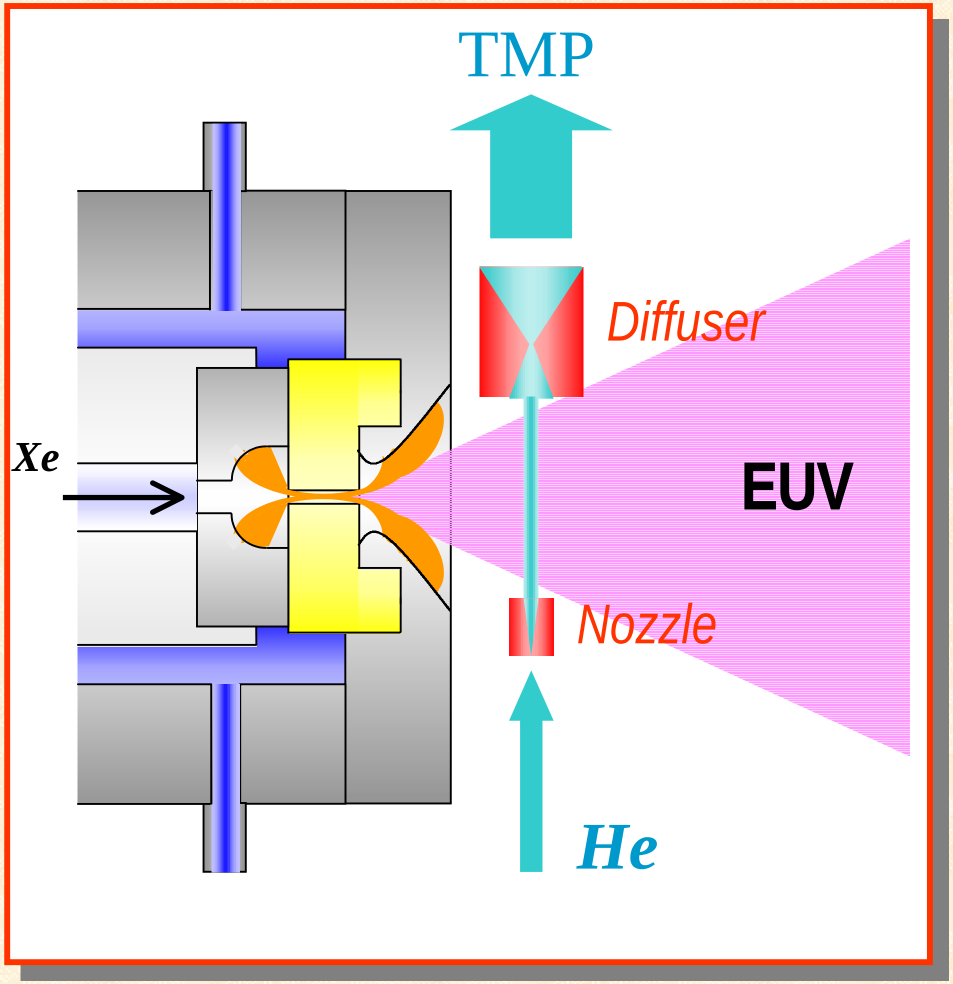

♦ Basic concept and characteristics

- Steady state operation
- Matching of pressure at outlet of nozzle
  - → Stable discharge
  - → Minimum caliber (smaller load)
- Slit type supersonic jet with high Mach number
- Nozzle with maximum expansion structure

→ Excellent optical performance

Schematic diagram of experiment

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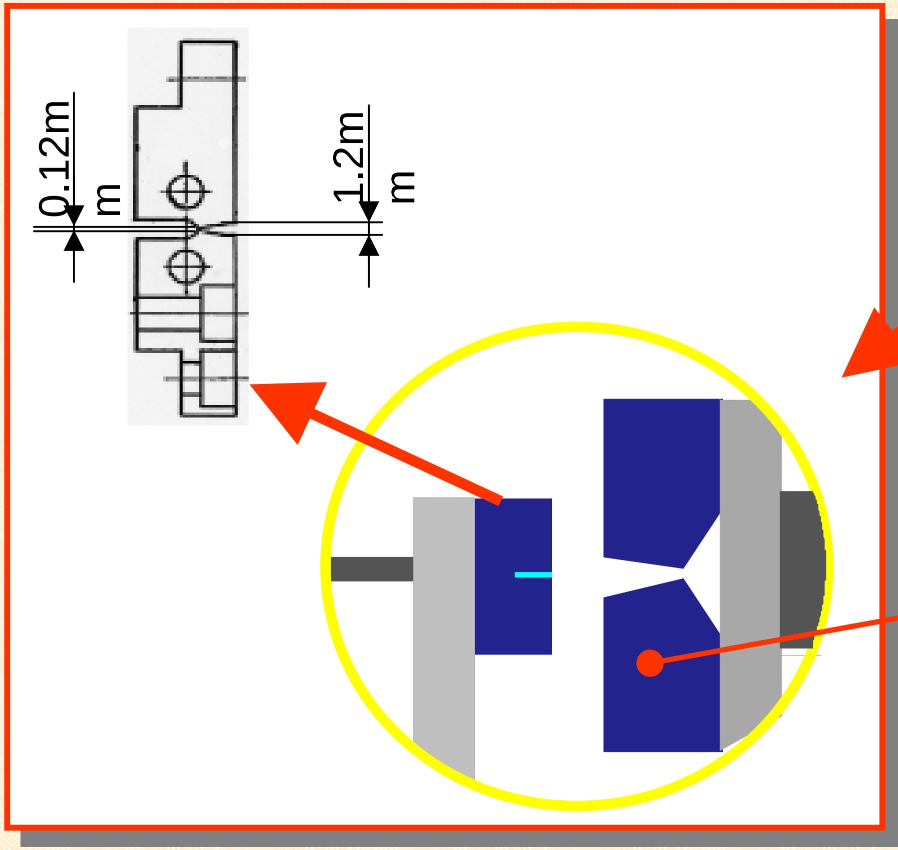
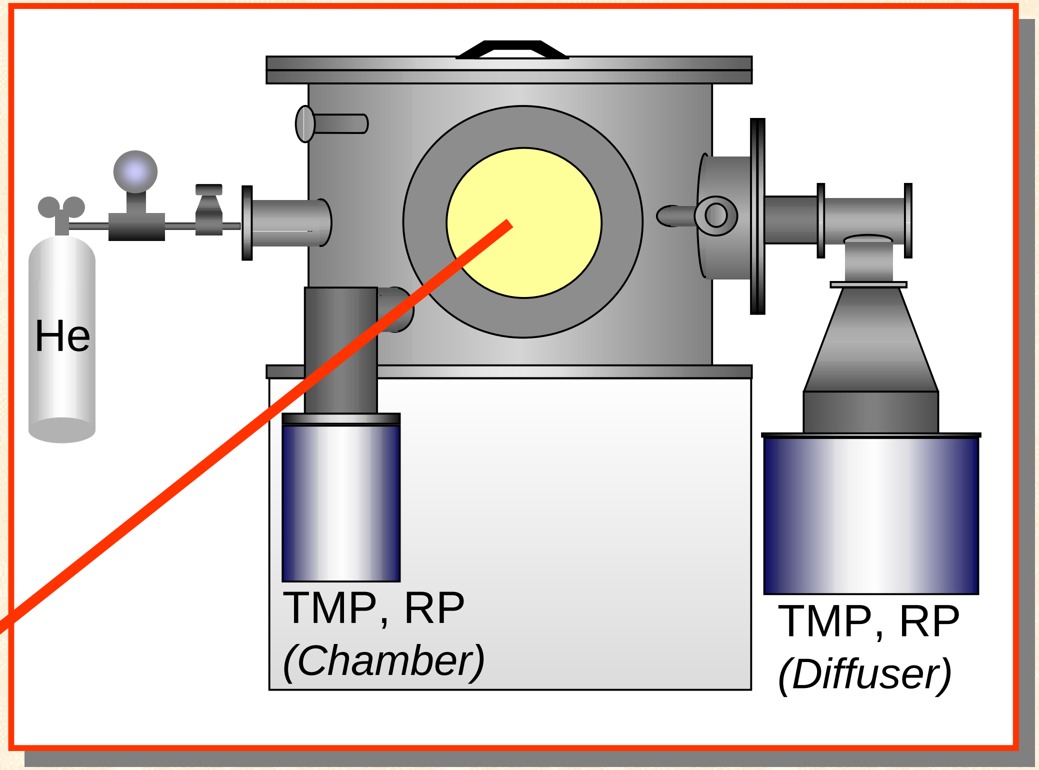
- Nozzle
  - Hypersonic type
  - Mach number ？5
  - Flow：width < 10 mm, thickness < 2 mm





- Diffuser
  - High efficient pressure recover
  - Minimum influence on the background gas pressure

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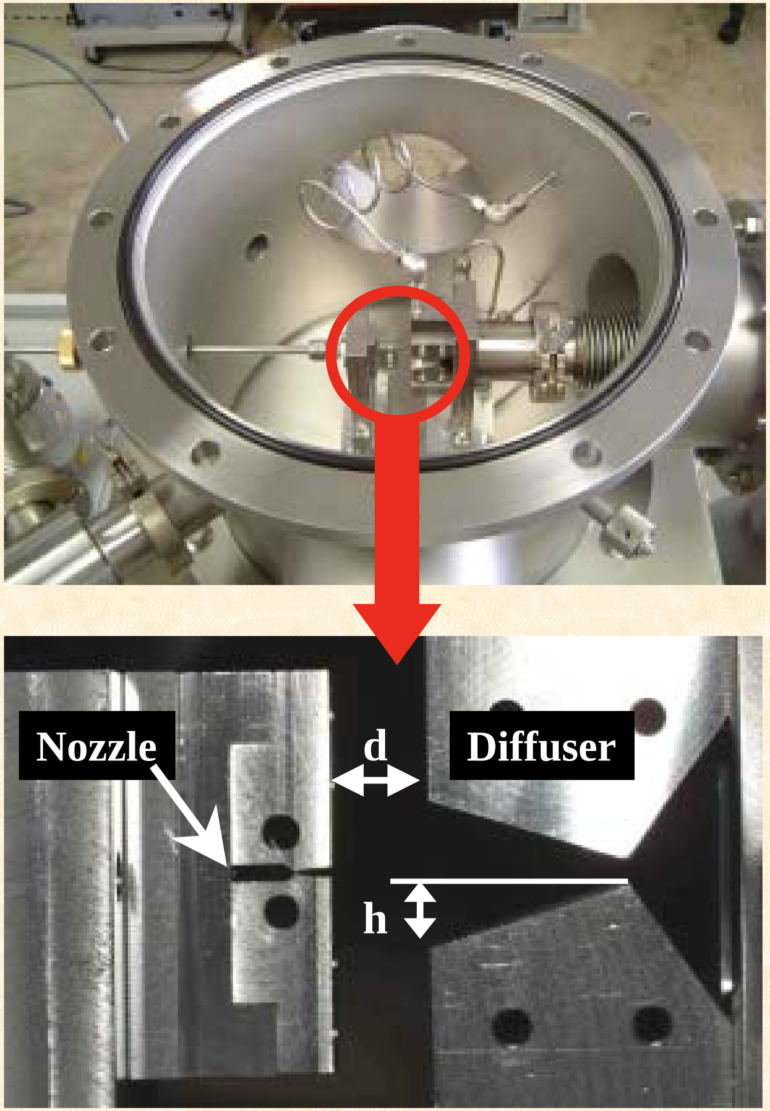
Gas curtain experiment



- ♦ Mach number ⁝5
- ♦ Nozzle and Diffuser
- - d = 5~15 mm
- ♦ Diffuser shapes
- - h = 4,6,8 & Throat width: 2-6 mm
- ♦ Now, Basic test is being conducted

Conclusions and acknowledgment

♦ Conclusions

- The effect of discharge current dI/dt on EUV power and debris generation is observed
- New electrode is tested and will be improved
- Test bed of gas curtain has been constructed and find optimum design value

♦ Acknowledgment

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