Development of high repetition rate and high power DPP EUV source

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This work has been supported by New Energy and Industrial Technology Development Organization (NEDO).

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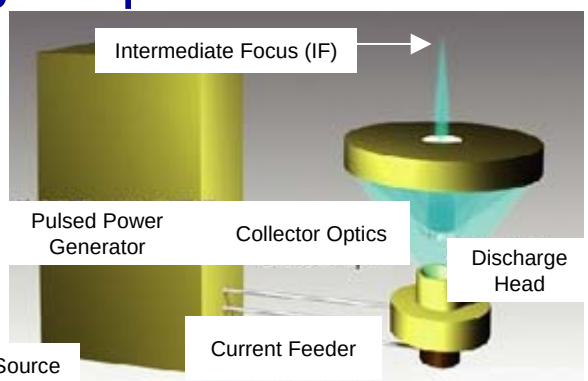
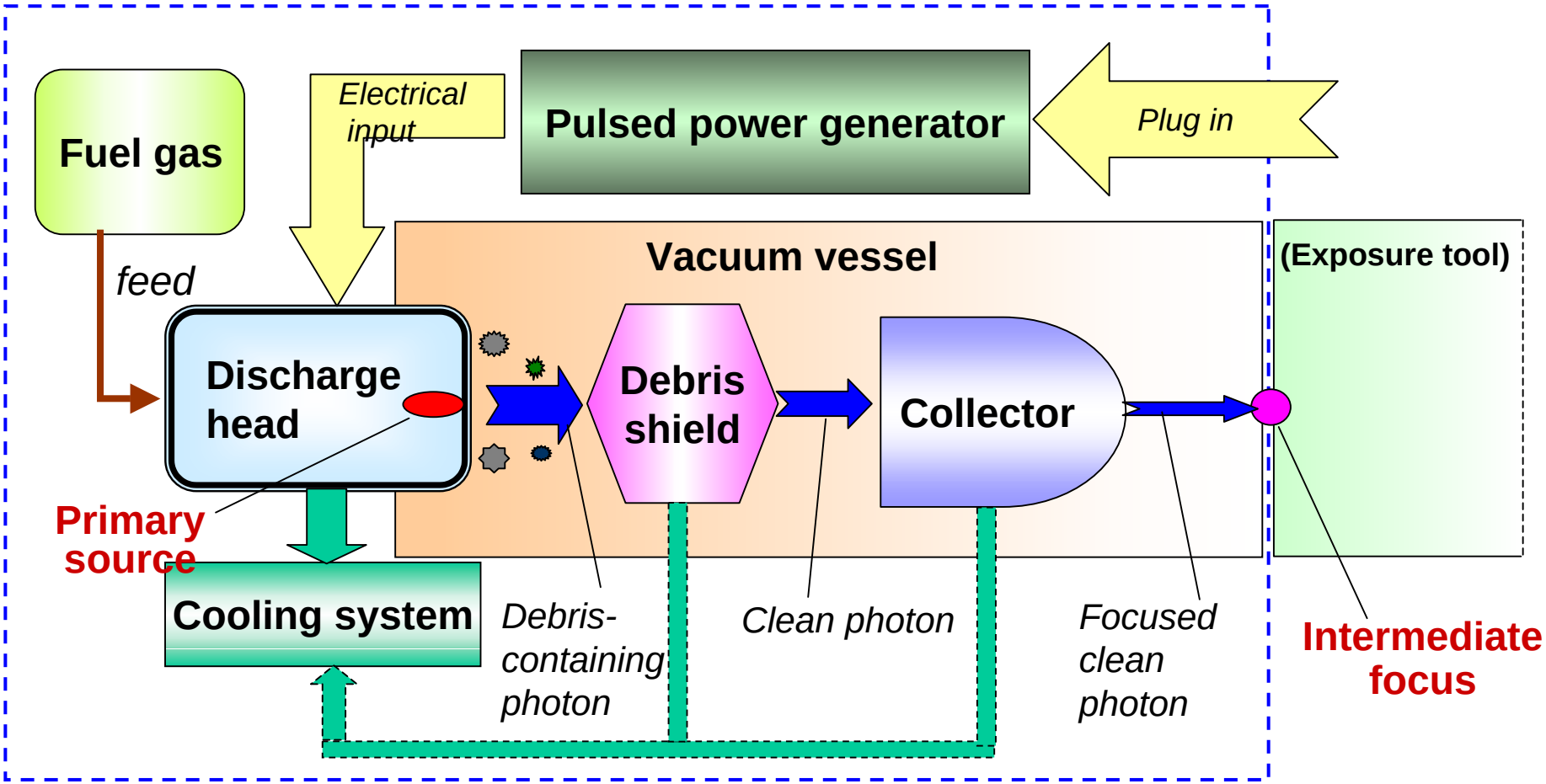
- Pinch plasma observation
- IF characterization
- debris mitigation
- **Summary**



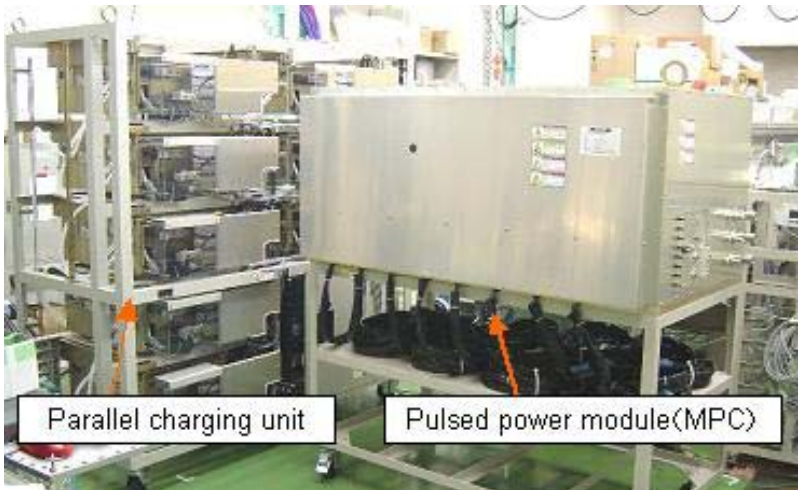
Discharge Produced Plasma (DPP) Source

Definition of EUV source

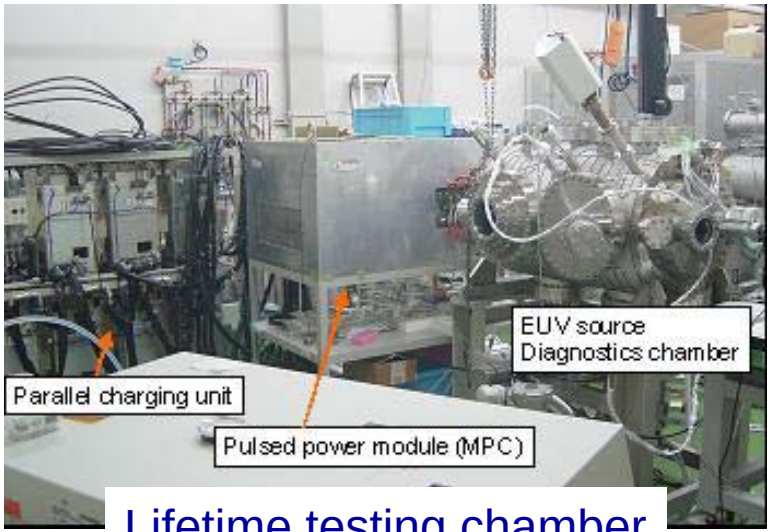
"EUV source"



Research facilities: power supplies and vacuum chambers



7-kHz pulsed power generator (G-4)



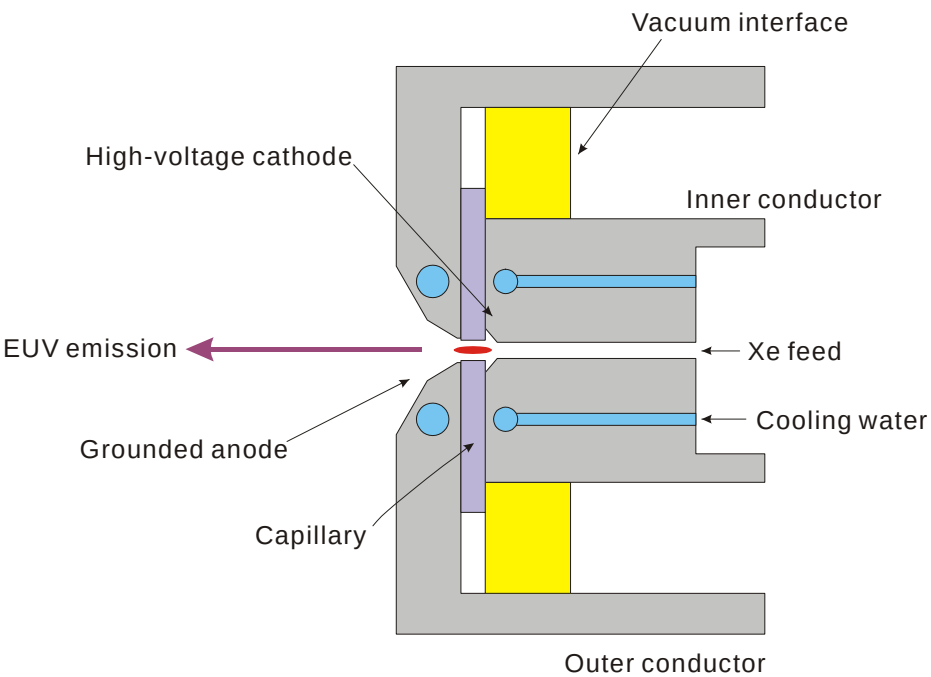
Lifetime testing chamber

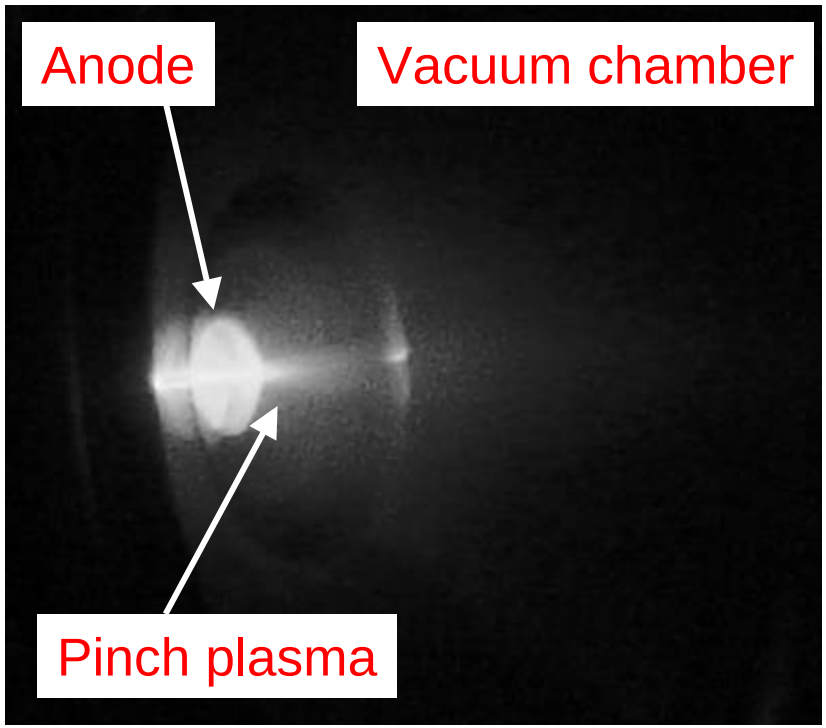
Source characterization chamber

Latest achievement: 19 W of EUV power obtained at IF with Xe-DPP

Terms	Achievement
Power supply	MPC generator (14.0 J x 7 kHz)
Fuel	Xe gas, Sn gas
Source EUV power @7 kHz	Xe: 189 W/2π sr, Sn:397W/2π sr
IF EUV power	Xe: 19 W, Sn:33 W [estimated value]
Plasma size	0.5 mm (D) × 1.56 mm (L)
Dose stability	Source: 1.3 % (1σ, 50 pulses) IF: 1.8 % (1σ, 50 pulses)
Collector	Nested grazing-incidence collector
CE	Xe: 0.5 %/2π sr, Sn: 1.27%/2π (radiated energy into 2π sr / total dissipated energy in final output circuit)
Lifetime	> 1.0x10^7 pulses (component, collector) (confirmed value, experiment still being carried out)

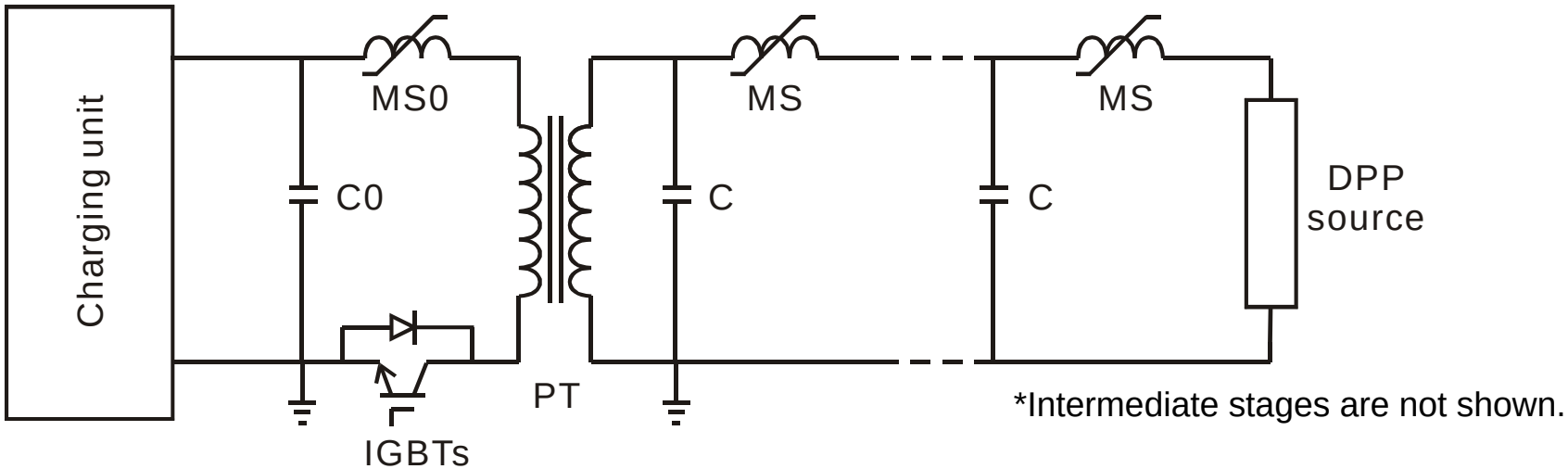
Capillary Z-pinch discharge head





- Installed in vacuum chamber
- Circulated water-cooling system
- Appropriate diameter and length
  : for increasing overall CE, lifetime, radiation stability
- Active pre-discharge

7-kHz MPC generator(G-5)



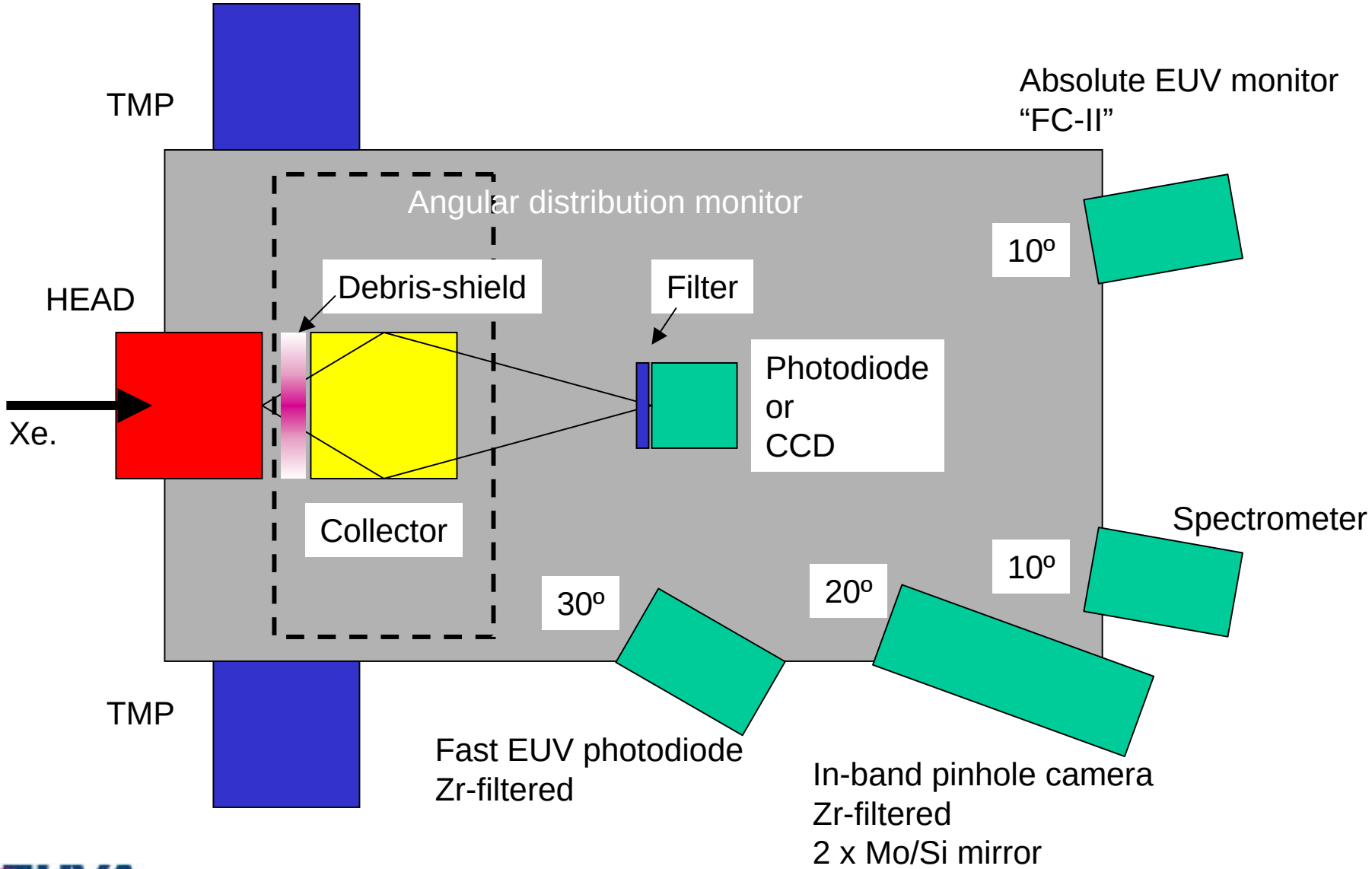
All-solid-state magnetic pulse compression generator ("G-5")

- Peak current: 52 kA (into short-circuit load)
- Pulse duration: 120 ns
- Stored energy: 14.0 J/pulse (rated output)
- Maximum repetition rate: 7 kHz (4kHz continuous)
- Energy recovery system employed: up to 41 % of stored energy recovered.

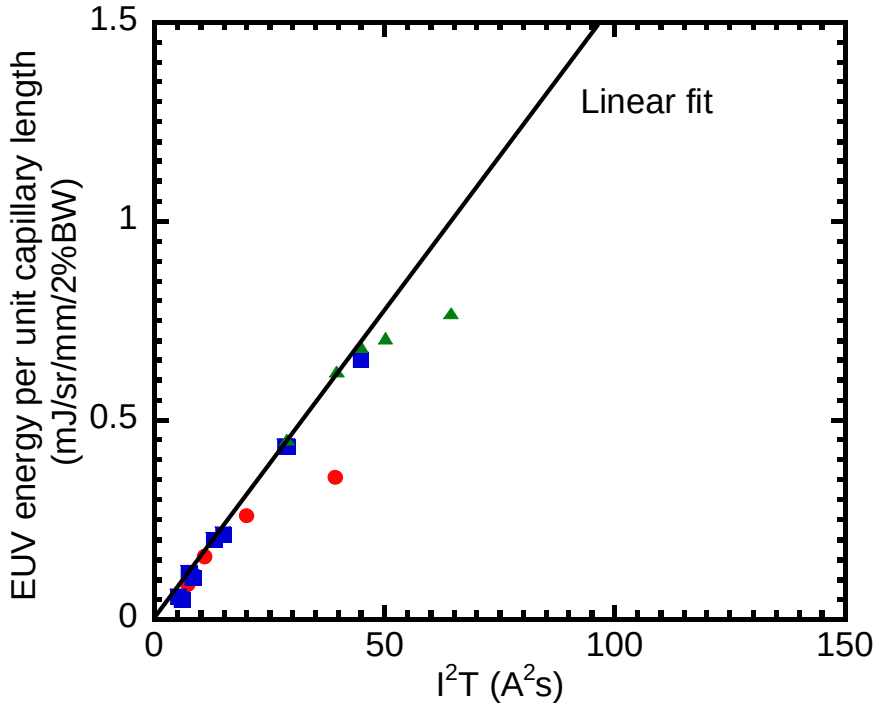
•Active pre-discharge unit placed upstream the source.

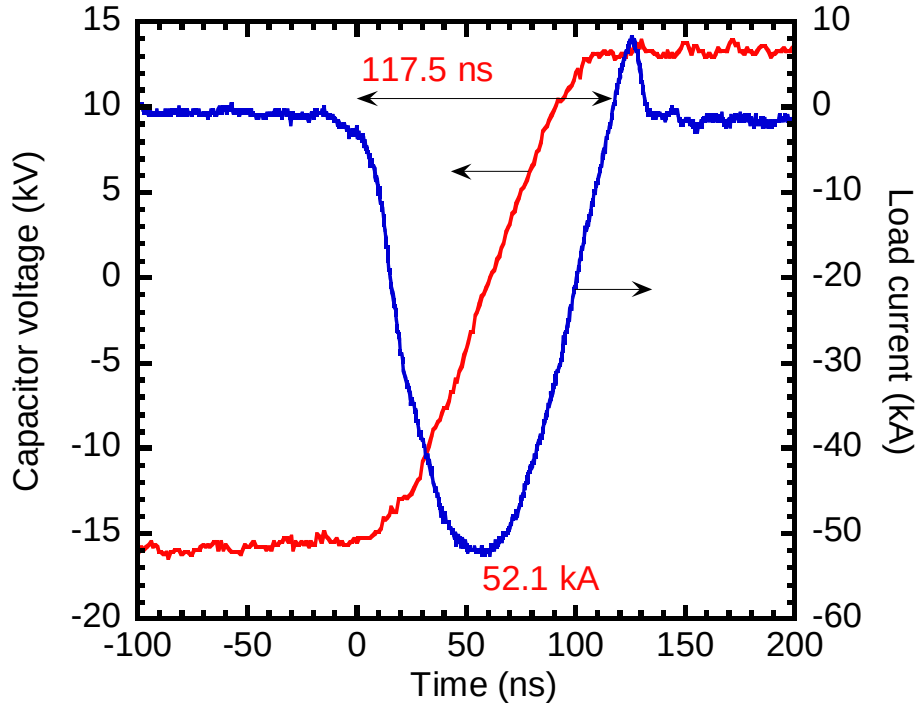
•Return energy is recovered in the generator and used for re-charge in subsequent pulse.

Experimental setup for source IF characterization



Modified pulsed power generator system for increasing EUV power



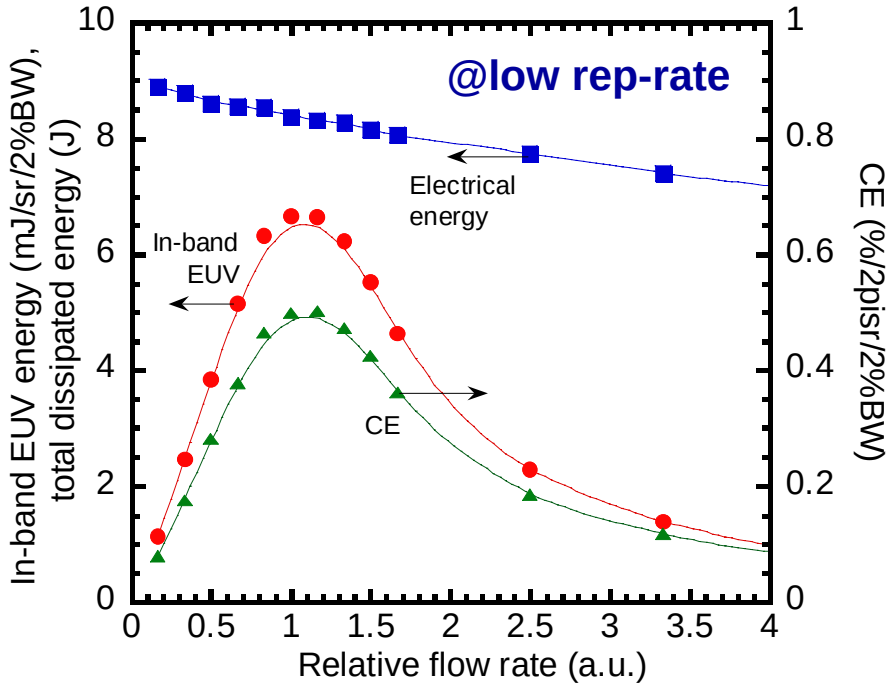


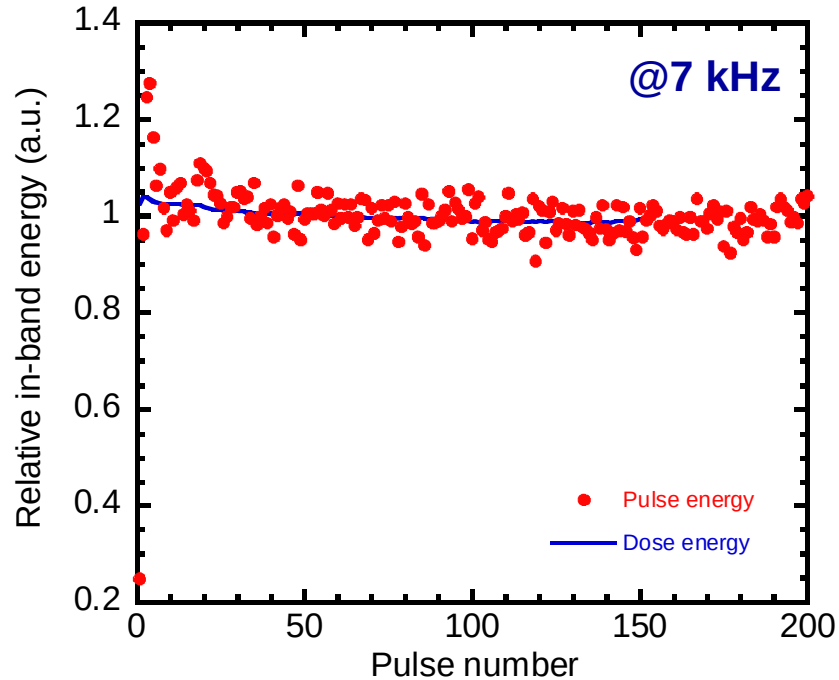
Decrease in output circuit inductance

Increase in electrical energy input to plasma → Increase in EUV power

Significant short duration of current pulse → Stability & CE improvement

Source power: basic and high rep-rate performance





Basic performance

- EUV energy: 6.7 mJ/sr
- CE*: ~0.5 %/2π sr

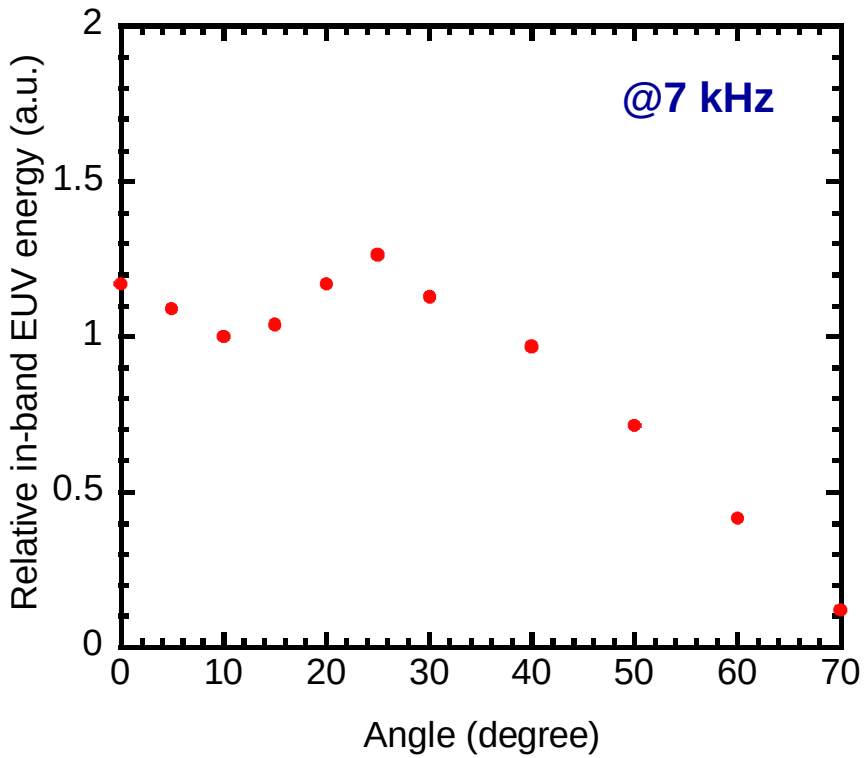
*including energy loss in the output circuit

High rep-rate performance (@7 kHz)

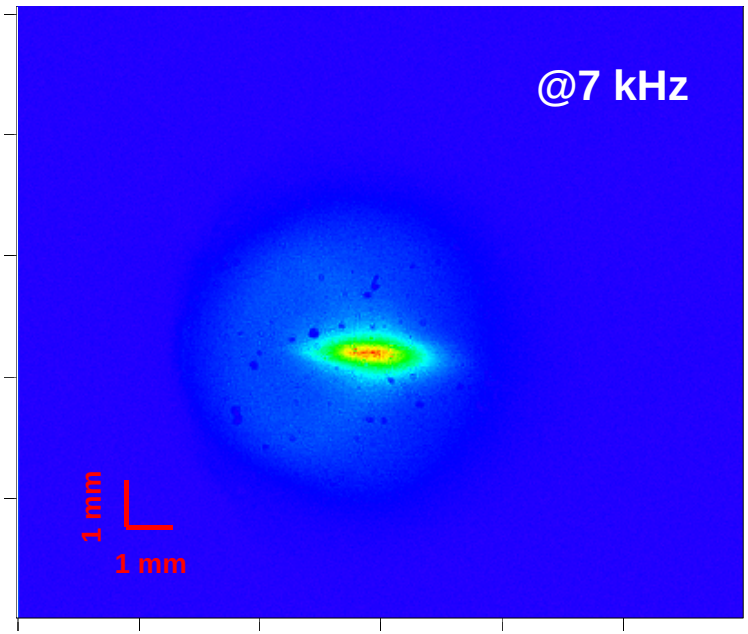
- 93 W (3.1 sr*) / 189 W (2π sr)
- Pulse stability: 6.9 % (σ)
- Dose stability: 1.3 % (σ, 50 pulses)

*see next page

Optical quality of the source: size and angular distribution



In-band distribution

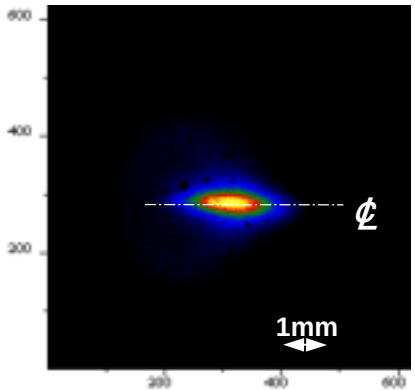


In-band image (20°)

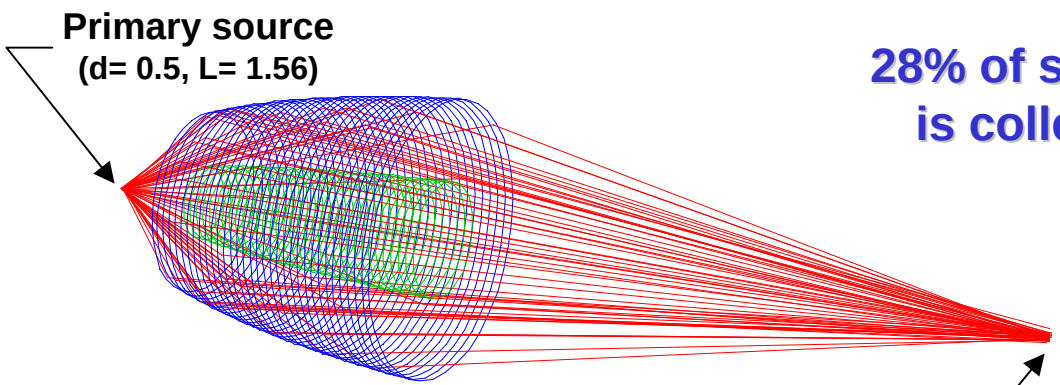
7-kHz result, flow rate optimized

- Effective solid angle: 3.1 sr
- Plasma size: ϕ0.5 x L1.56 mm (FWHM)

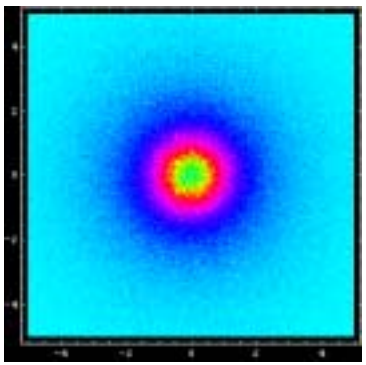
IF characterization: nested grazing-incidence collector



Source EUV image



28% of source power is collected to I.F.



Focus image

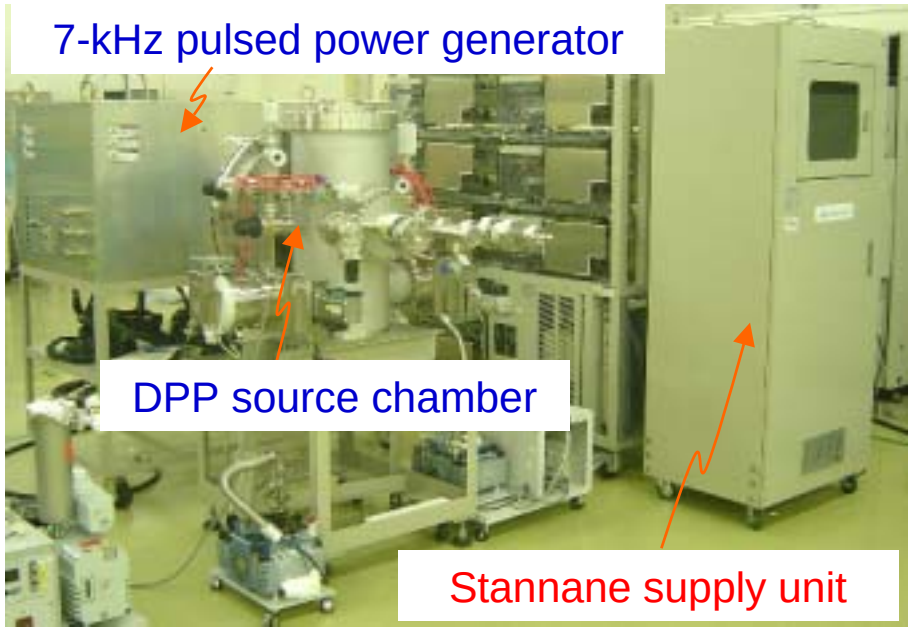
Primary source : 93W

Collection efficiency : 28%

Transmission (gas, shield) : 72%

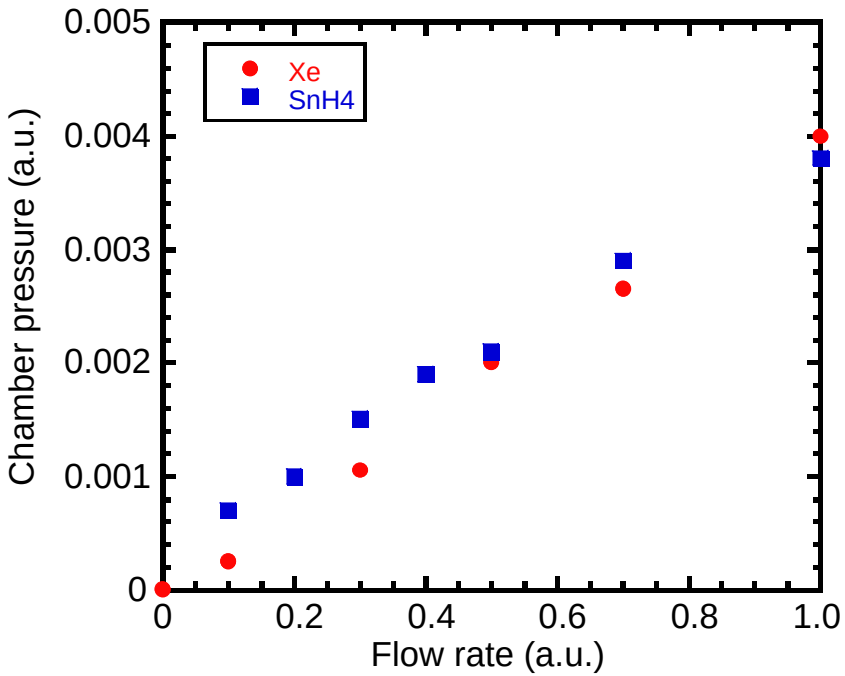
I.F. power = 19W

Tin-fueled Z-pinch: SnH_4 is now being tested as fuel gas.



$SnH_{4\ 122.742}$ (stannane, tin hydride)

- Melting point: -146 °C
- Boiling temperature: -52 °C

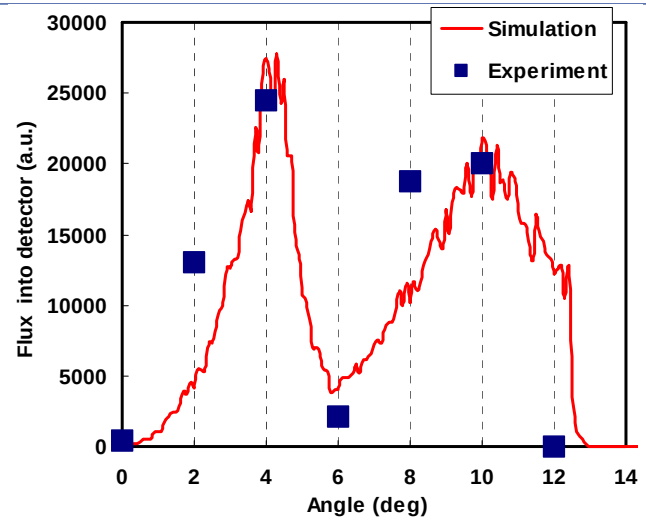


Molecular weight similar to $Xe^{54}_{131.293}$
Gaseous state at RT
Controllable by MFC

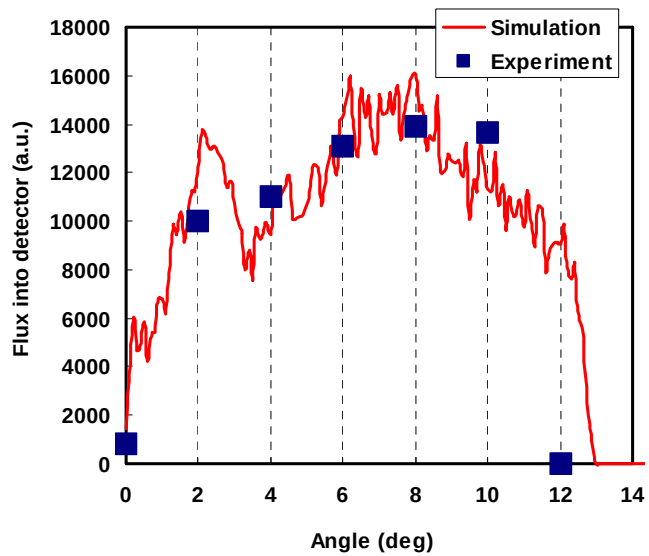
Pinch dynamics is similar to Xe source.
High CE as pure Sn is expected.

IF characterization: grazing-incidence collector

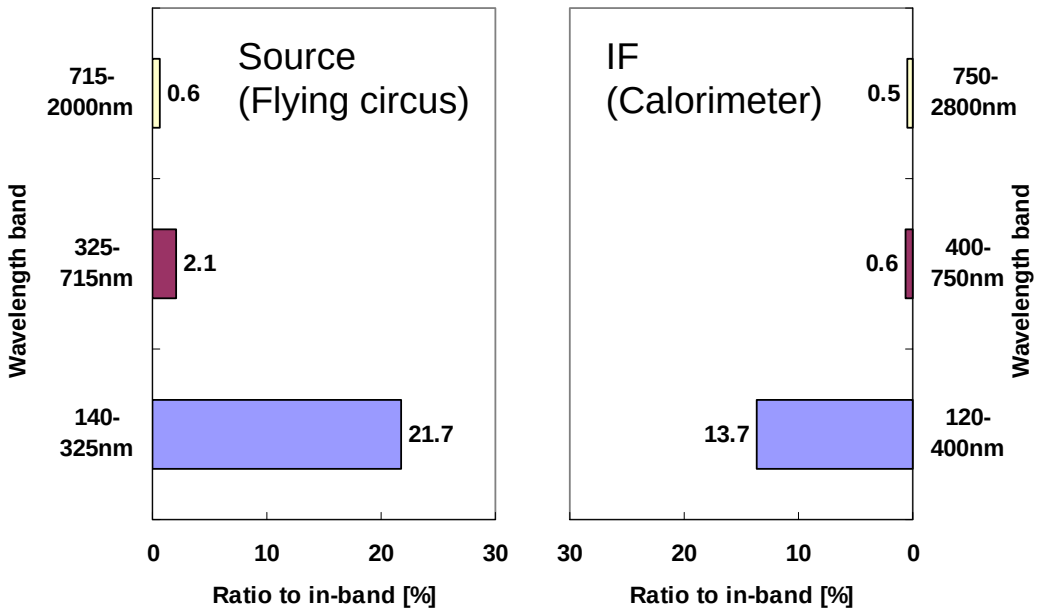
In-focus



Defocus



Emission profile at IF

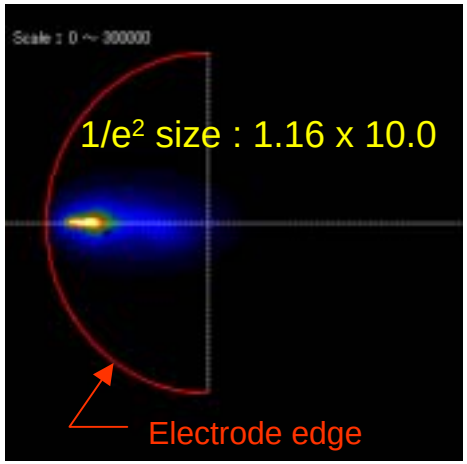


- Profile simulation results were in good agreement with the experiments.
- Spectral distribution at IF reflects that of the source plasma.

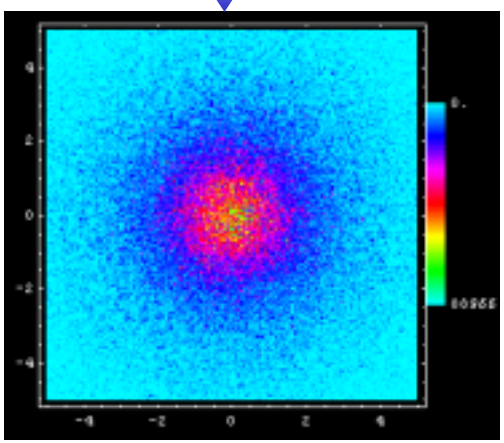
(OoB may not be a significant showstopper.)

Detailed presentation will be given on Thursday, in the source workshop.

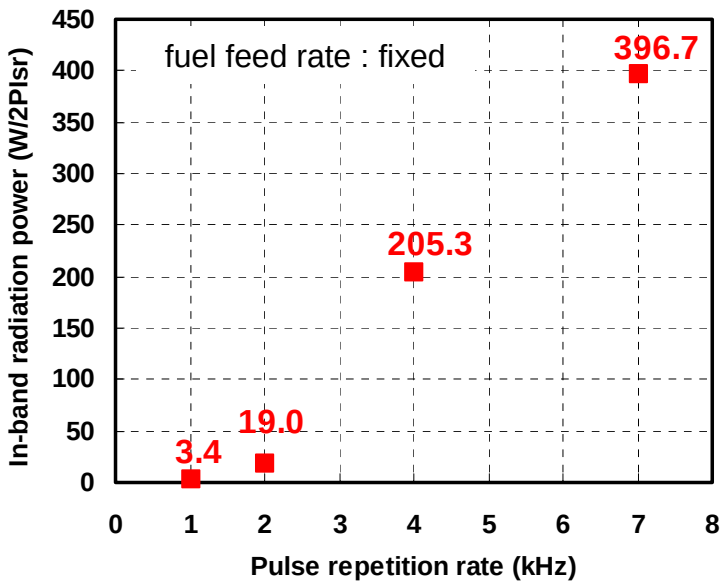
SnH_4-fueld Z-pinch source: IF power calculation



Plasma image (20 deg.)



Calculated focus image

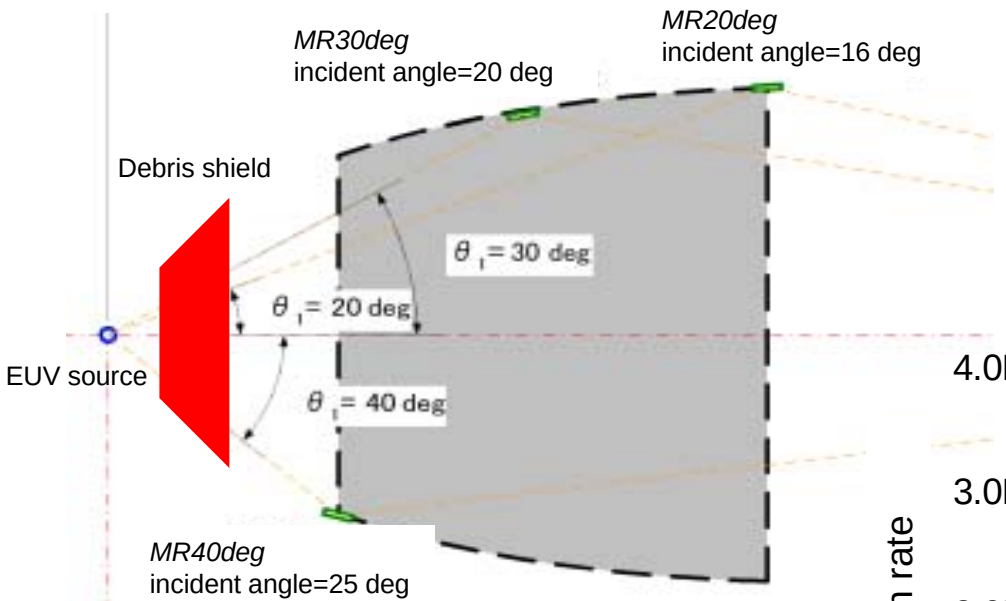


Primary source power

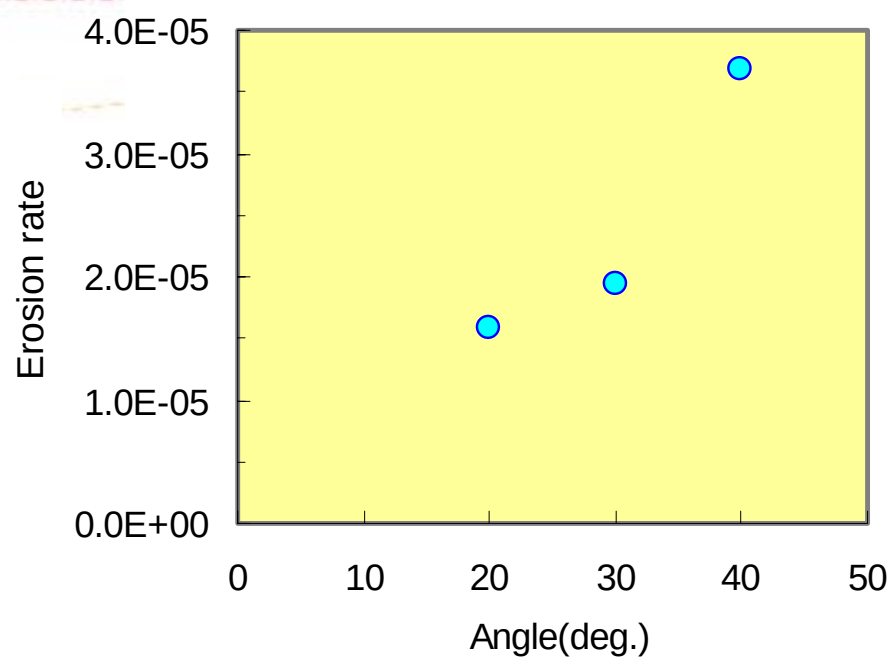
Stannane (SnH_4) fueled source:

- Demonstrated source power
  - ➪ 397 W /2πsr at 7kHz
- Estimated usable IF power
  - ➪ 33 W /3.3 mm^2sr
  - with πsr collector

Radiation Angle Dependence of Mirror Lifetime

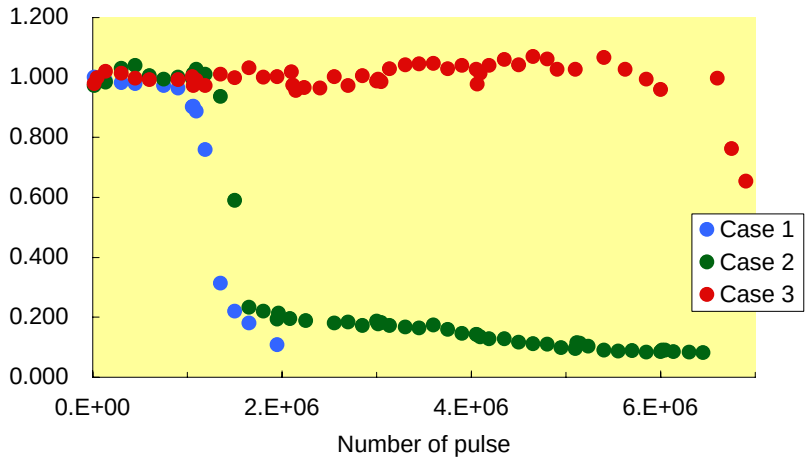


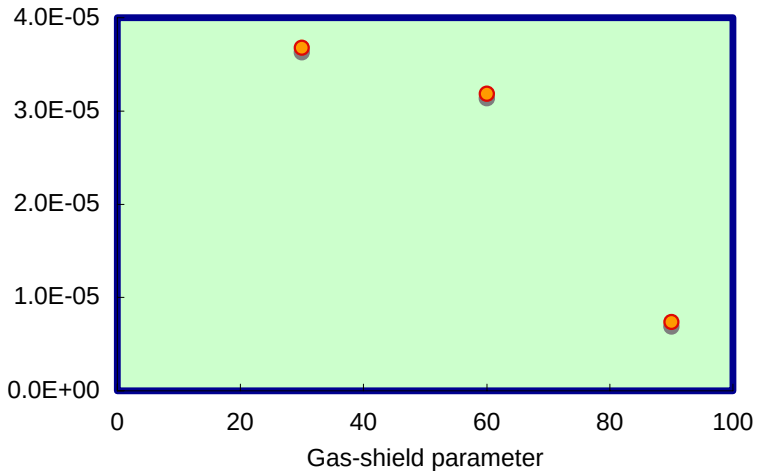
Radiation angle (deg.)	Mirror Lifetime (R = 90%)(Mshots)
20	3.2
30	2.5
40	1.3



Debris shield:
Gas curtain
Measuring instrument:
EUV photodiode

Gas-shield Dependence of Mirror Lifetime





Debris shield:

Gas curtain

Radiation angle:

20 deg.

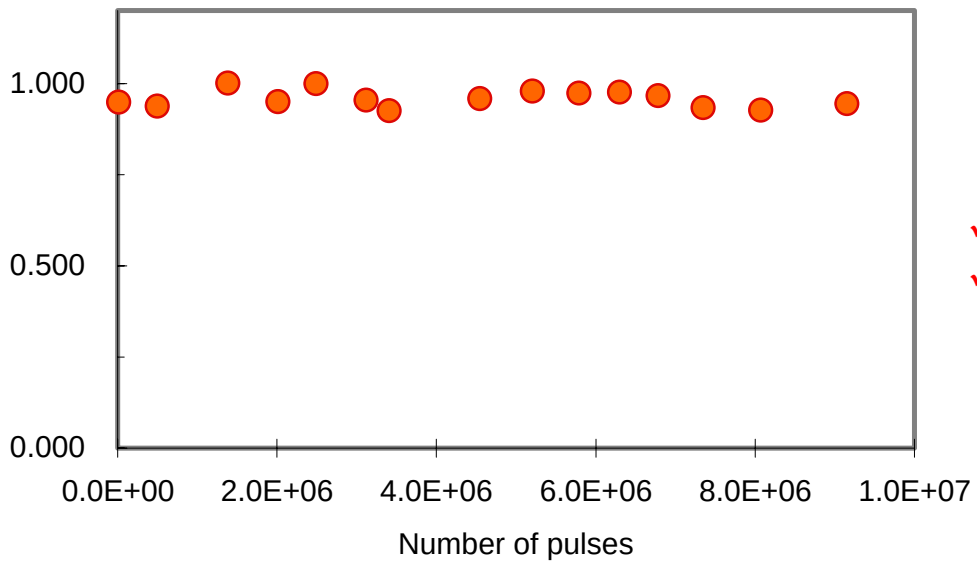
～Gas pressure ～

Case 1: Lifetime(R= 90%)= 1.3X10^6 shots

Case 2 Lifetime(R= 90%)= 1.5X10^6 shots

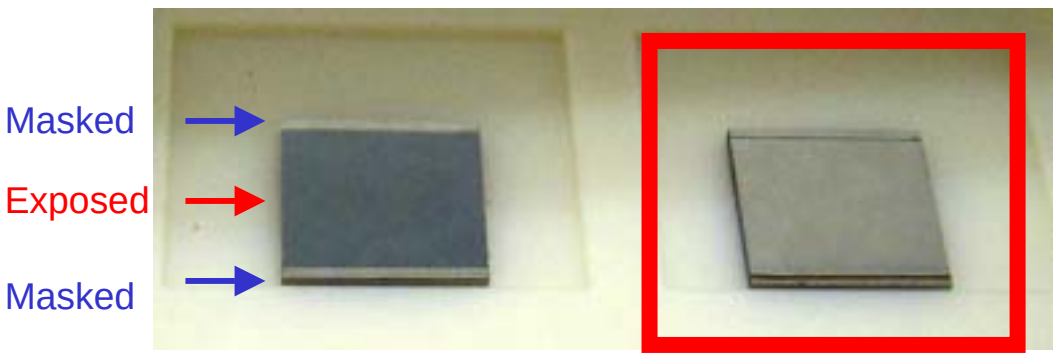
Case 3: Lifetime(R= 90%)= 6.5X10^6 shots

Mirror Lifetime with Debris Shields



Debris shields:
- Gas curtain
- Foil trap

- ✓ The normalized reflectance was kept 90%.
- ✓ Ru of a mirror material was left after the mirror was exposed.
  (using SEM and SIMS)



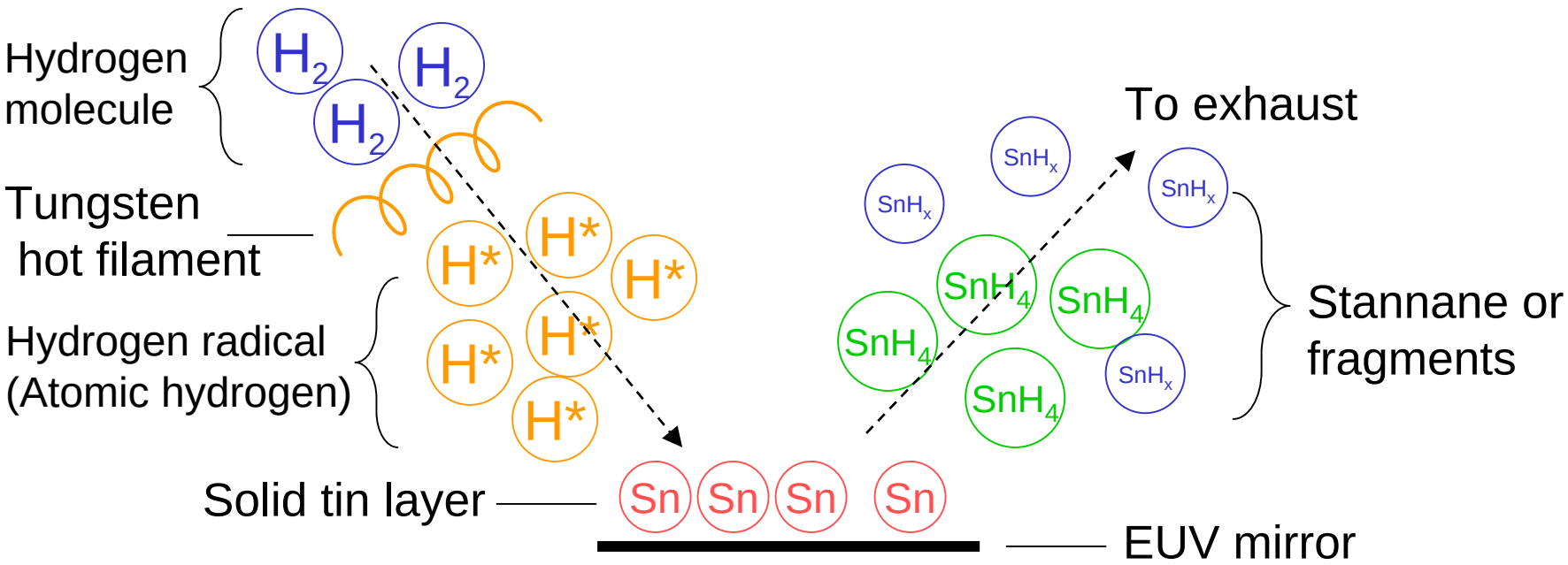
With gas curtain With gas curtain and foil trap

Radical Cleaning of Tin

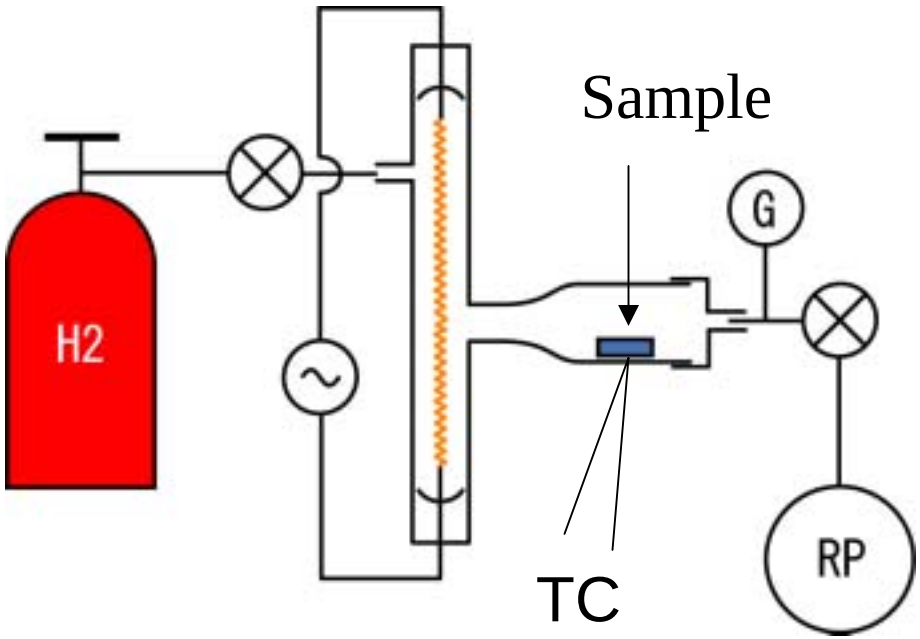
– Novel approach

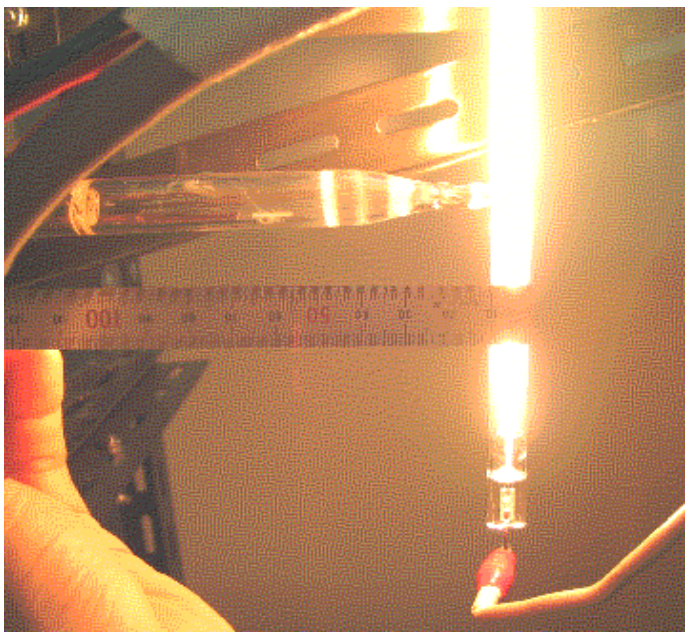
There are some reports for radical cleaning which is available for carbon contaminations.

We applied the tin removal with hydrogen radicals.

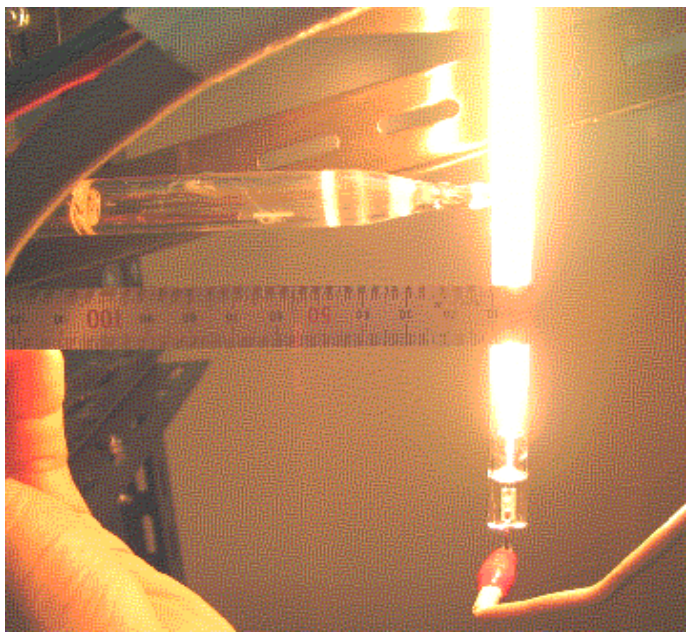


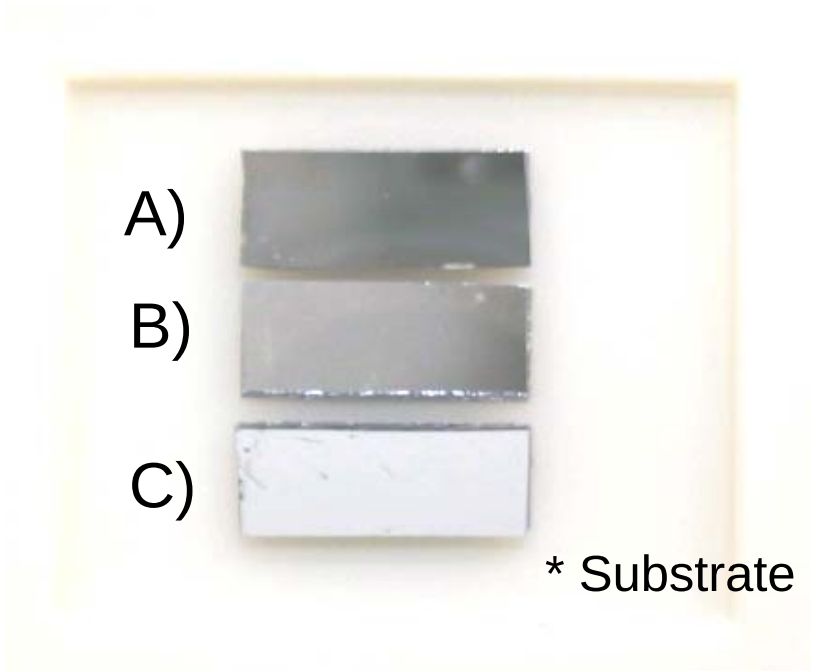
Experiments





Results 1 - Effect of distance from Radical source



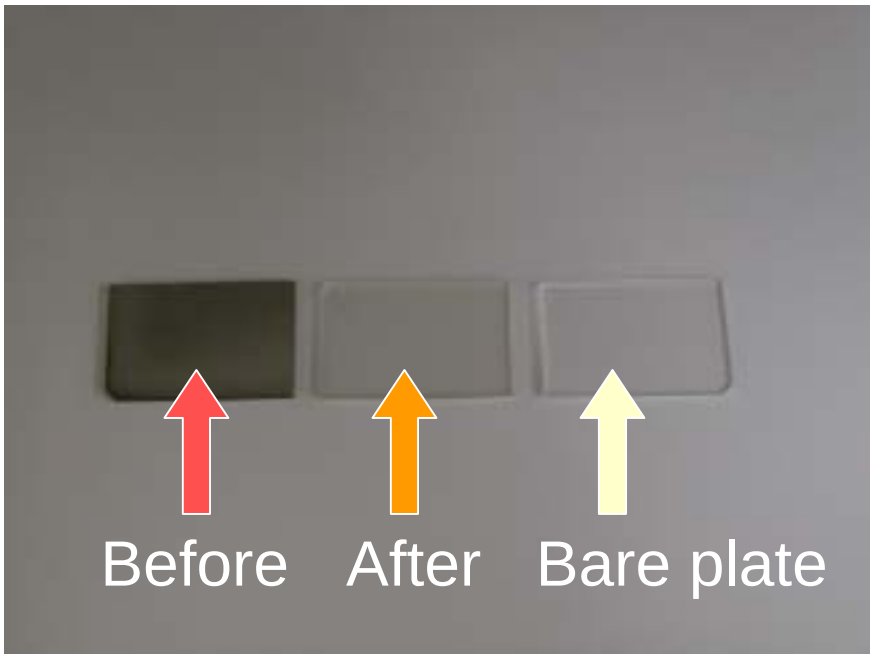


* Substrate : Si

A) 510 min. treatment at 40mm from W filament
B) 165 min. treatment at 50mm from W filament
C) Before treatment

Results 2 - Difference cleaning rate by substrates

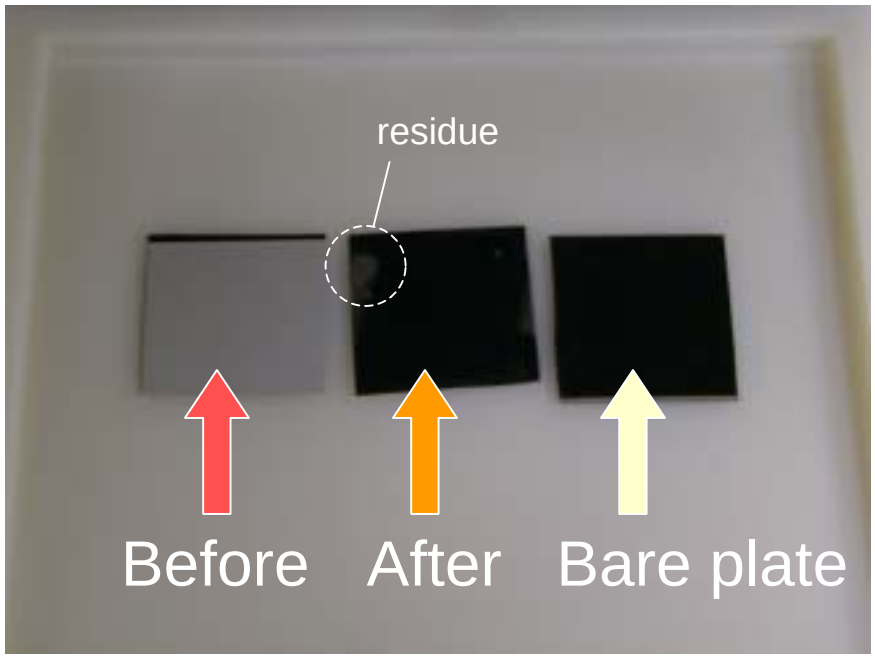
Glass plate (~13mm x 20mm)



Tin layer thickness: ~100 nm
Treatment time: 1 hour

➡ **Estimated removal rate: ~1 nm/min**

Silicon plate (~20 mm square)



Tin layer thickness: ~200 nm
Treatment time: 20 minutes

➡ **Estimated removal rate: ~10 nm/min**

Summary

<Latest achievement in EUV source development>

- 7-kHz pulsed power generator system modified.
- Xe-DPP EUV power reached ~189 W/2pi sr(19 W at IF).
- Sn-DPP EUV power reached ~397 W /2pi sr(33W at IF).
- Nested grazing-incidence collector installed.
- Study of radical cleaning started. The effect has confirmed.

<On-going/future plans>

- Experiment of Sn DPP source.
- Assessment of EUV power and quality at IF.
- Study on lifetime of DPP source components and optics.

Acknowledgements

Mr.Masaki Inoue and Dr. Taku Sumitomo, Ushio Inc., lamp company R&D center