Nanometer Scale Patterning and Processing

Spring 2016

Lecture 14

Extreme UV (EUV) Lithography – EUV Source (Hot and Dense Plasma)

Extreme UV (EUV) lithography

1. Overview, why EUV lithography?
2. EUV source (hot and dense plasma).
3. Optics (reflection mirrors).
4. Mask (absorber on mirrors).
5. Resist (sensitivity, LER, out-gassing).
6. Contamination control.

Source Power vs Throughput

Updated EUV power and wafer throughput:

250 W
~~120~~ W

Collectable EUV power
~~60~~ W

Collectable, in-band, "clean" (no debris, no out-of-band)

EUV Power @ reticle
3.5 W

Power @ wafer
140 mW

Illum. time per field
0.26 s

Illum. time per wafer
23 s

Raw wafer throughput
~~80~~ wafers/hr

120 wafers/hr

10
~~5~~ mj/cm² resist
300 mm wafers
89 fields/wafer

Original courtesy of Jos Benschop and Vadim Banine, ASML.

J. Benschop et al., SPIE *3997*, 34 (2000),
V. Banine and R. Moors, SPIE *4343*, 203 (2002).

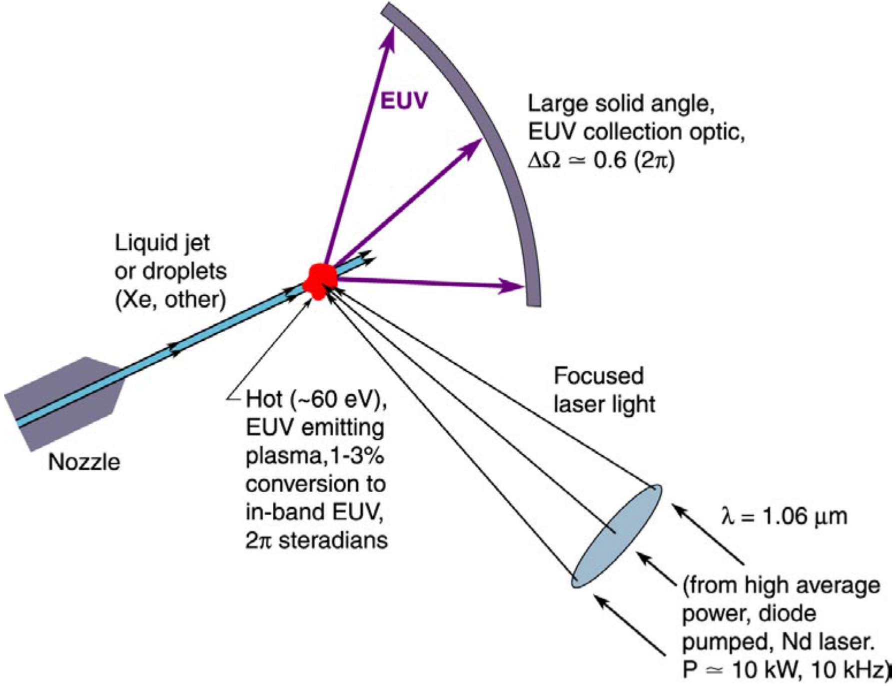
EUV Radiation Source from Plasma

Must match the wavelengths of 13.5 nm at which Mo/Si multi-layers have high reflectivity

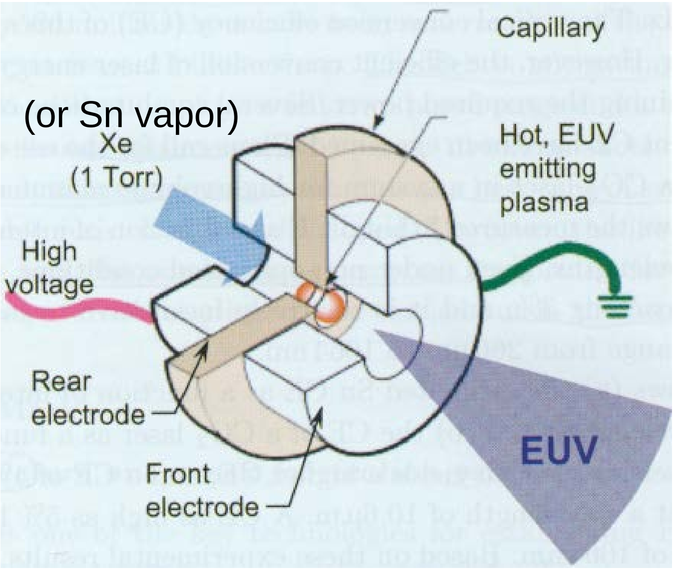
The only viable source for 13.5nm photons is a hot and dense plasma

- temperature of up to 200,000^{o}C, atoms ionized up to +20 state.
- Emit photons by (e - ion) recombination and de-excitation of the ions.
- Plasma must be pulsed: pulse length in pico- to nanosecond range
- produced by powerful pulsed laser or electric arc (discharge) of up to 60,000A peak current.

Laser Produced Plasma (LPP)



Discharge Produced Plasma (DPP)



Courtesy of Neil Fornaciari and Glenn Kubiak, Sandia.

Laser (LPP) and discharge (DPP) produced plasma

DPP: change electrical energy directly into EUV light, so high power, high efficiency; but ablation of electrode and more debris.

LPP: higher collection efficiency (larger collection angle), high repetition rate (more pulses/sec), more manageable thermal loads and debris, more scalable to HVM (high volume manufacturing).

EUV lithography tools using both DPP and LPP have been built.

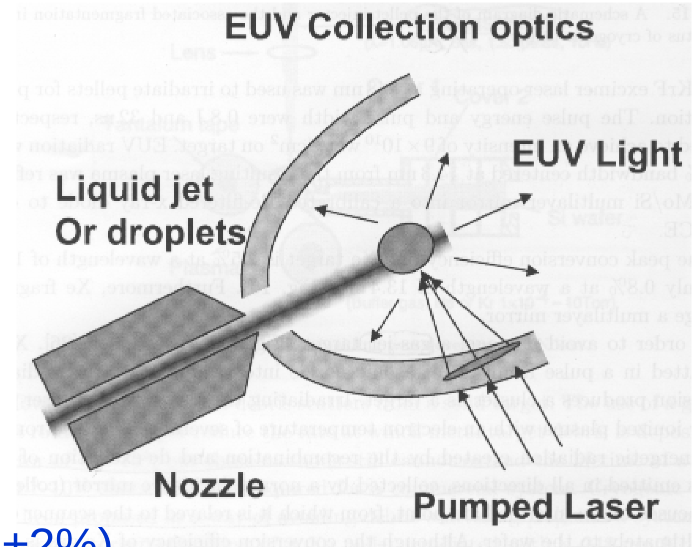


Figure 17. A gas-jet typed laser produced source.

Challenges:

- Radiate from IR to x-ray: need filter.
- Large source size into 4π spherical angles: need collector optics.
- Debris and thermal issues: may damage the optics.

For EUV lithography, ideally:

- Power > 110W
- Maximum in-band emission with narrow bandwidth (≤ ±2%).
- Forward directed, no collector

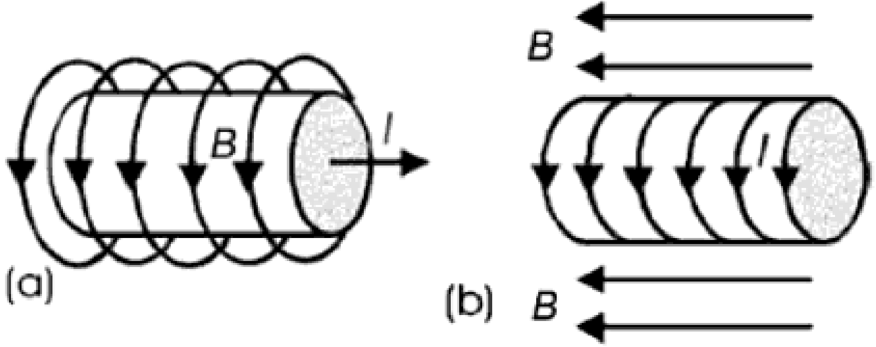
Low (μW) to mid-power (1W) has application in other fields:
Interference lithography, spectroscopy, microscopy, other metrology, testing EUV resist.

Discharge produced plasma (DPP)

- Hot plasma is created by magnetic compression of low-temperature plasma.
- Plasma is compressed with the magnetic field generated by the current used to heat the plasma, with two common geometries (see figure below).
- Because plasma is compressed by magnetic field B of current I, which generates the plasma, plasma is "self-heating".
- Two forces are present: the magnetic field pressure $B^2/2\mu_o$ and the plasma pressure.
- When these two forces are equal, the plasma achieves an equilibrium.

Equilibrium: $$\frac{\mu_o I^2}{4\pi} = \left(Z_{eff} + 1\right) N_i k T_e$$

I: total current ($B \propto I$), supplied by a capacitor in a pulsed mode;
T_e: electron temperature
$N_i = \pi r^2 n_i$, n_i=ion density; Z_{eff}: mean charge of the ions.



Two plasma compression geometries.

Laser produced plasma (LPP): overview

- Focusing a laser beam on a target material.
- Initial ionization occurs through photo-ionization, and the electric field of the laser accelerates these electrons (inverse Bremsstrahlung, see next slides).
- Non-elastic collision further ionize the plasma, whereas elastic collision transfers the electron's kinetic energy into ionic kinetic energy.
- As plasma expands, thermal energy is converted into kinetic energy and charge density decreases. (Expansion velocity of Sn plasma at ~30eV is about 2×10^6cm/s, so at the order of 100μm in front of target for 10 ns pulse.) This decreases both the further absorption of laser energy and energy conversion efficiency (CE).
- Therefore, the laser pulse length should not be very long: 10 ns is a good time scale.

- The corresponding optimum laser intensity for maximum CE is 1×10^{11} W/cm^2 for Nd:YAG laser (1.06 μm), and 1×10^{10} W/cm^2 for CO_2 laser (10.6μm).
- Longer wavelength preferred: Modeling shows that CE depends on laser wavelength -- CE (10.6 μm laser):CE (1.06 μm laser):CE(0.26 μm laser)=1.9:1.0:0.55.
- This is because: CE depends on a balance between emissivity and opacity; at longer wavelength laser absorption occurs at lower plasma (electron) density that is more transparent for EUV to escape.

Laser produced plasma: a clean, bright, narrow source

Plasma temperature:

$T_e \propto Z^{1/5} (\lambda^2 \phi)^{3/5}$. Longer wavelength is more efficient to heat up plasma, so higher CE.
λ: laser wavelength; ϕ: laser flux (Watt/cm^2); Z: target atomic number.

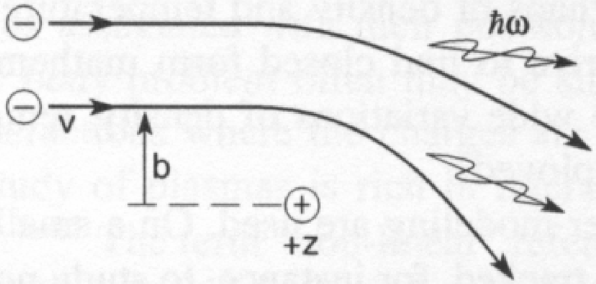
Energy levels:

Transitions and energy levels are calculated using Hartree-Fock methods. The UTA continuum spectra is due to $4p^6 4d^n - 4p^5 4d^{n+1} + 4d^{n-1} 4f$ line transitions.

Atomic processes (routes for radiation):

- Ionization and recombination between successive ion stages.
- UTA line radiation from bound-bound transitions (excitation and de-excitation).
- Continuous Bremsstrahlung occur as well (Bremsstrahlung: electron emits photon when it is accelerated by the positively charged ions).

Same idea as synchrotron radiation where electrons are accelerated radially by magnetic field.



From: Soft x-rays and extreme ultraviolet radiation, written by David Attwood

FIGURE 6.2. Bremsstrahlung occurs when a passing electron is accelerated by an ion, causing it to radiate. Because of the wide range of incident electron velocities and the range of distances of closest approach (*impact parameter b*) a broad continuum of radiation is generated in a plasma, with a spectrum closely related to the electron velocity distribution, or its characteristic temperature.

Energy conversion efficiency (CE) into 13.5nm radiation

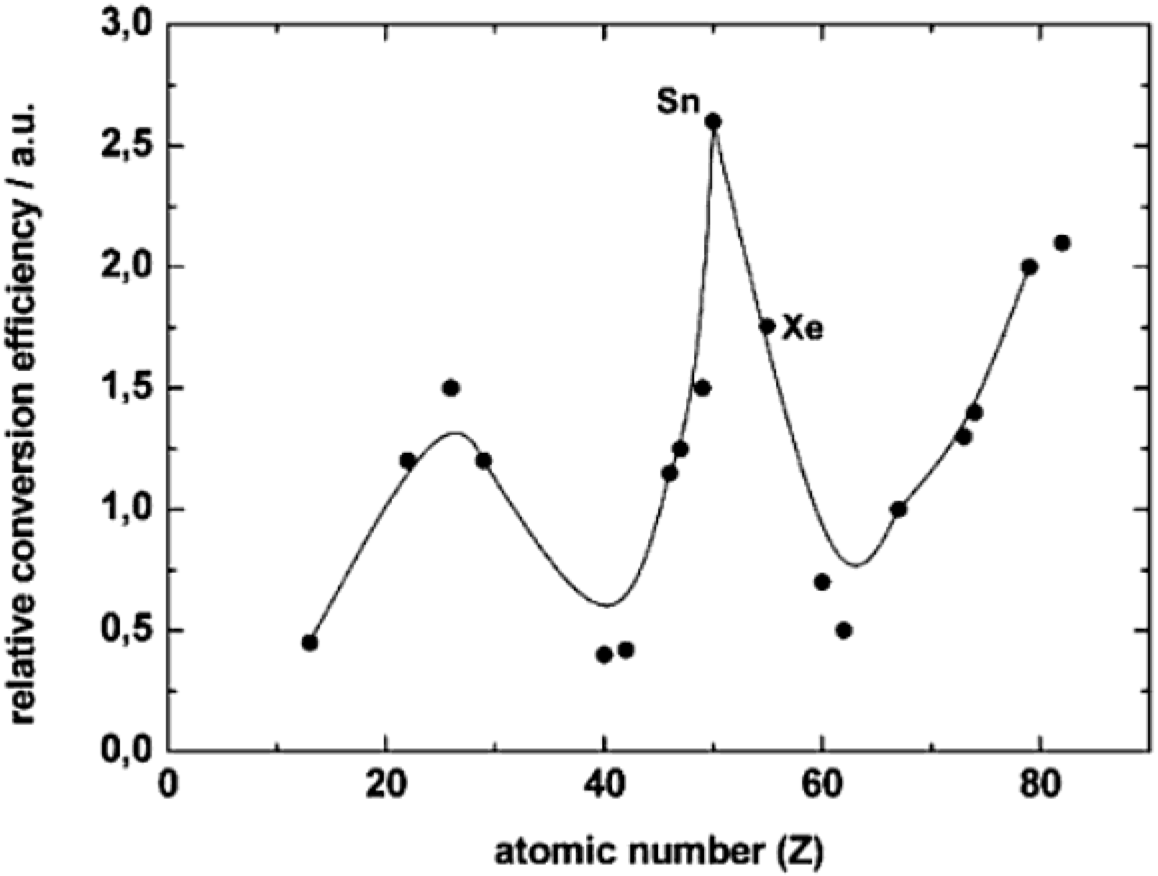
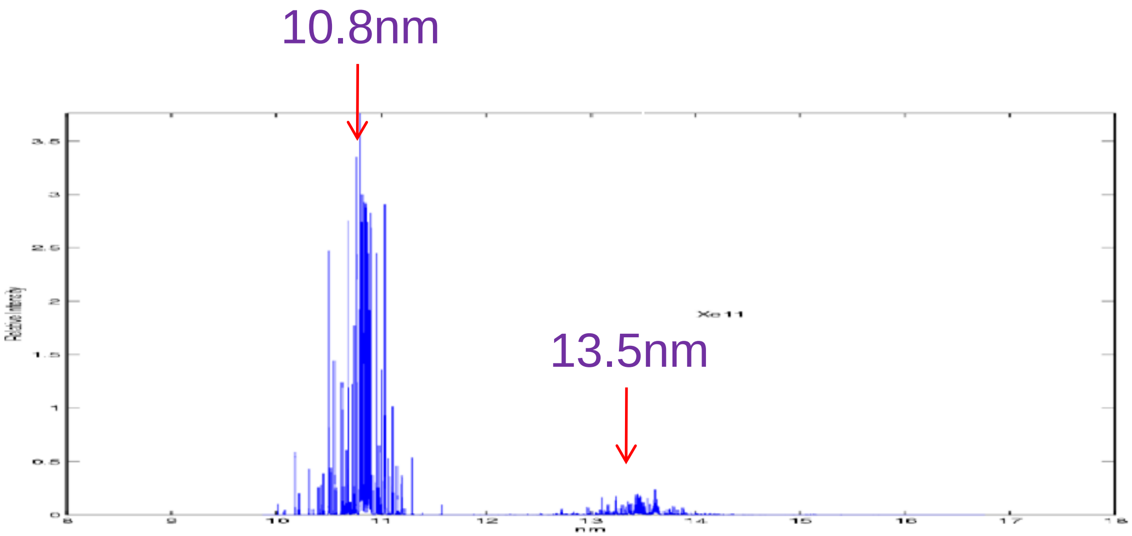


Figure 3.5 Relative CE into 13.5-nm radiation as a function of the atomic number of the emitter. The highly efficient Sn ($Z = 50$) and the frequently used Xe ($Z = 54$) are marked. (Reprinted from Ref. 14.)

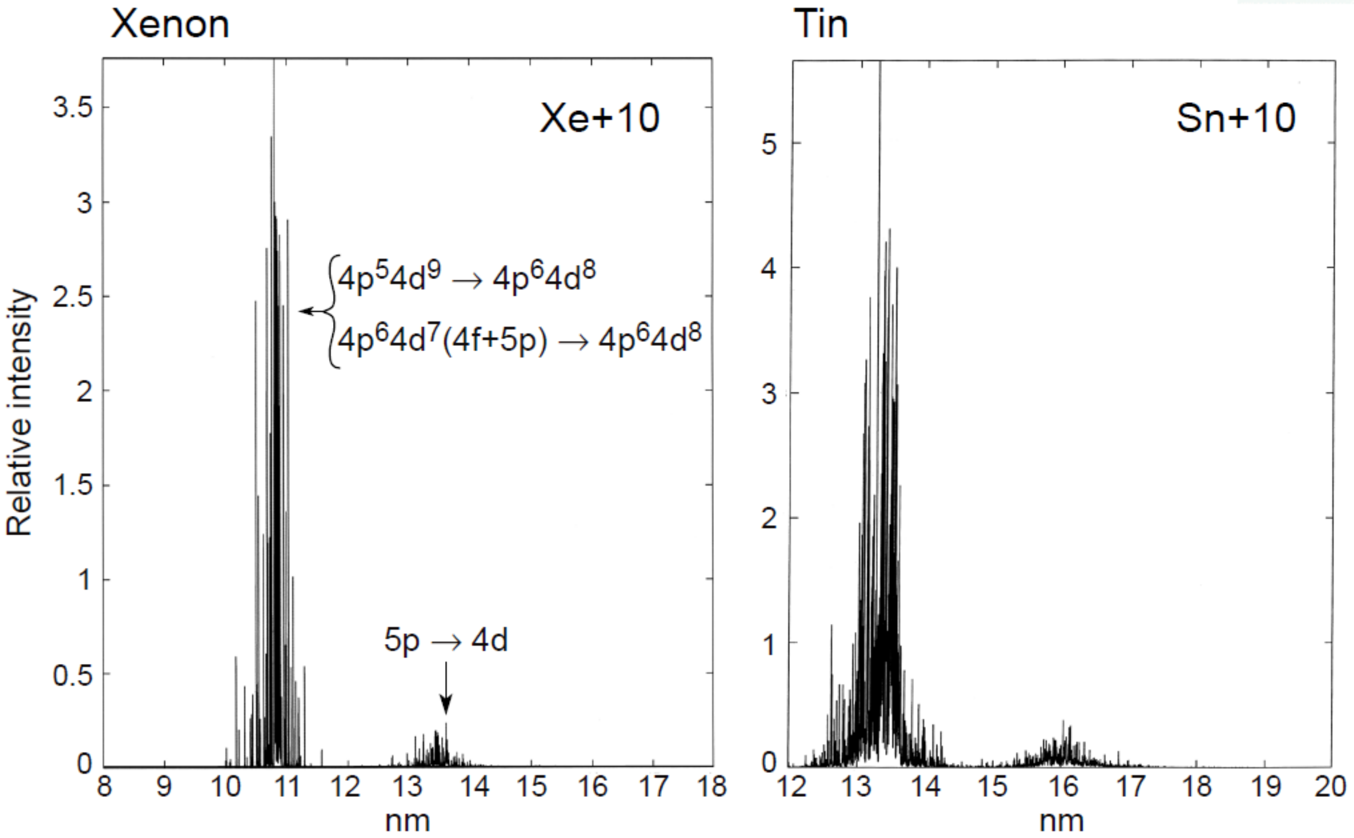
Sn is most efficient, followed by Li (?), then Xe.

Plasma radiation source for 13.5nm: Xe



- 13.5nm photons only generated by one ion state (Xe^{11+}).
- Maximum population of this state is 45%.
- Even this state emits 10 times more at 10.8nm than 13.5nm.
- That is, xenon is inefficient: to produce 100W at 13.5nm, kilowatts of other wavelengths would have to be removed.
- On the plus side, xenon is very clean and easy to work with (no debris).

Comparative Spectra: Xe and Sn

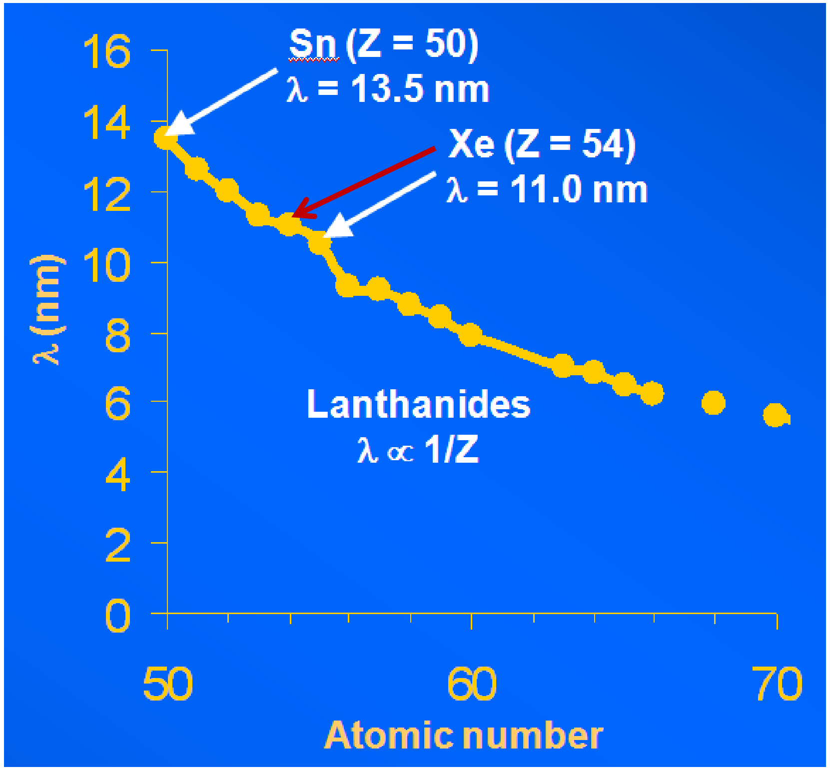


Courtesy of G. O'Sullivan (Univ. College Dublin)
R. Faulkner (UCD Ph.D, 1999)
A. Cummings (Nahond Univ. Ireland)

Plasma radiation source for 13.5nm: Sn

Peak wavelength emission decreased with increasing atomic number ($\lambda \propto 1/Z$).

UTA peak wavelength (nm) versus atomic number



Laser produced Sn plasma

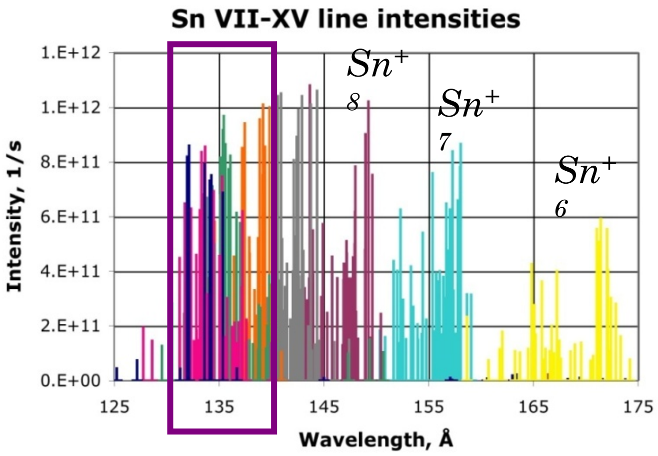
Target, Z=50 [Kr]$5s^2 4d^{10} 5p^2$	Sn
Laser wavelength, λ	1.064μm
Laser flux, ϕ	1×10^{11} W/cm^2
Electron temperature, T_e	48.8eV
Electron density, n_e	9.88×10^{20} cm^{-3}

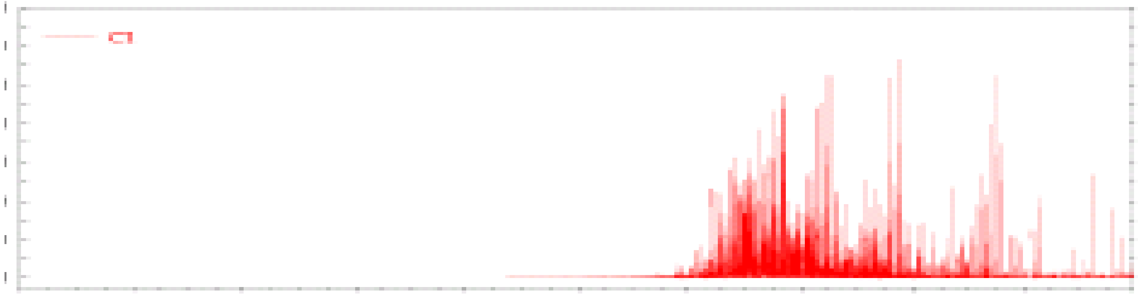
(300K is 26meV, 1eV is 1.15×10^4K)

Ion distribution	
Sn X	0.046
Sn XI	0.243
Sn XII	0.306
Sn XIII	0.330
Sn XIV	0.068

UTA: unresolved transition array, consisting of tens of thousands of lines (unresolved, overlapping 4d–4f transitions).

Plasma compositions for 13.5nm: Tin

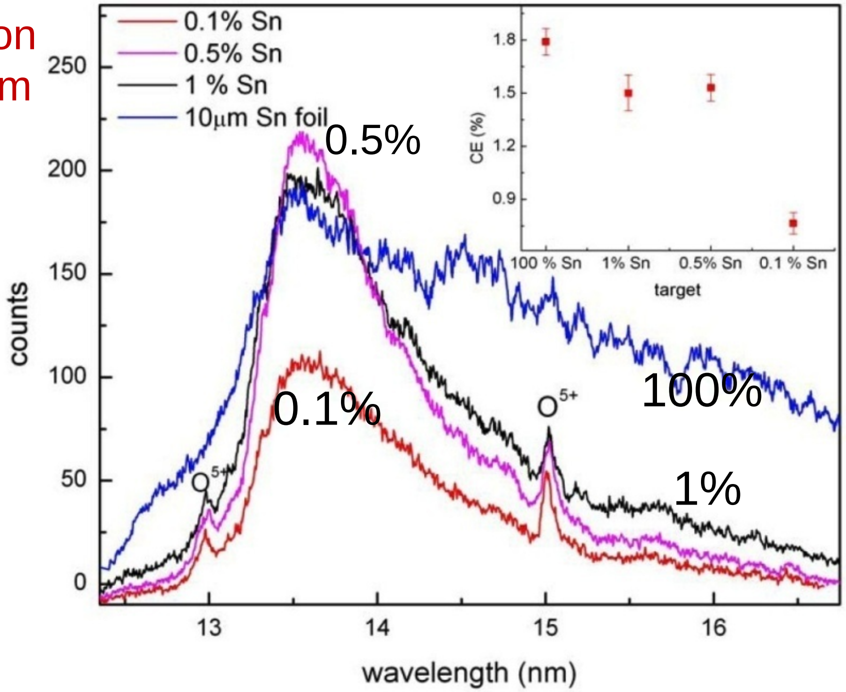


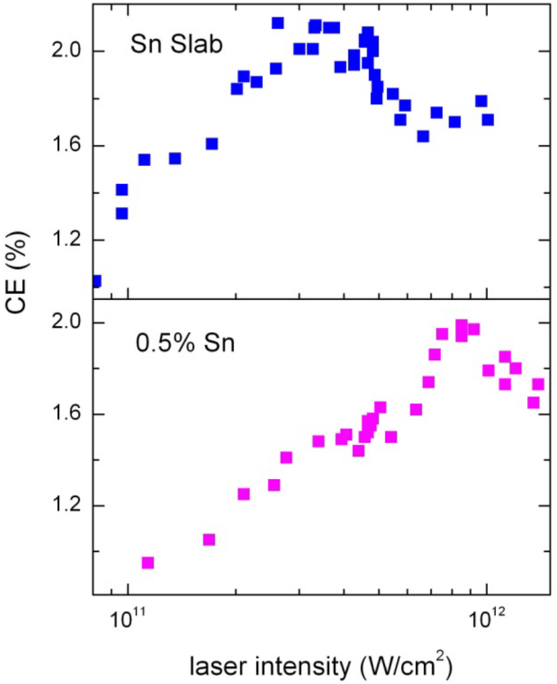


- Optimum emission when tin is a low-percentage impurity.
- Light comes from transitions between $4p^64d^n$ and $4p^54d^{n+1}$ or $4d^{n-1}(4f,5p)$.
- All ion states from Sn^{8+} to Sn^{13+} can contribute.
- Lighting up these transitions, and *only* these transitions requires exquisite control of laser plasma.
- But tin (debris) tends to condense on optics.
- In summary, tin is great as a 13.5nm source, if one can control the debris (yes).

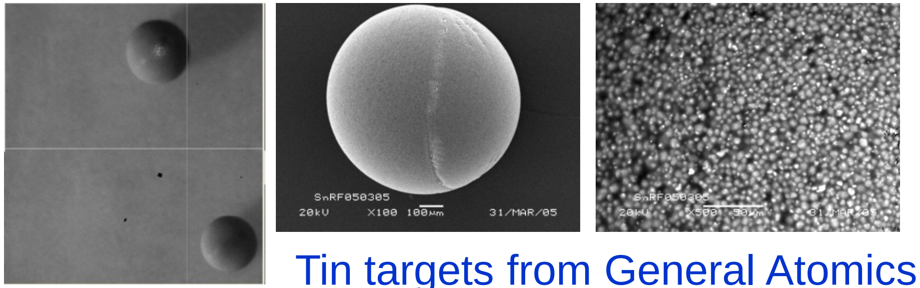
Low density (diluted) targets leads to narrow UTA

Radiation spectrum





CE: (energy) conversion efficiency

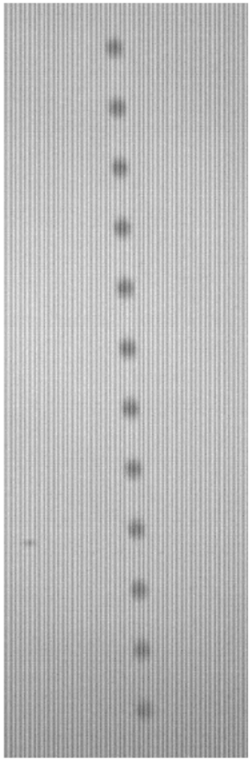


Tin targets from General Atomics

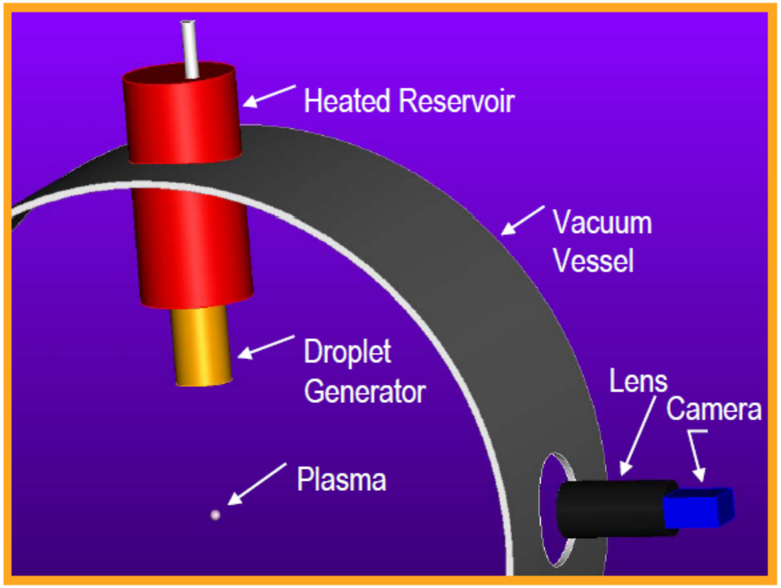
- 100 mg/cc RF foam
- 0.1-1% solid density Sn
- *e.g.*, $0.5\%Sn = Sn_{1.8}O_{17.2}C_{27}H_{54}$

- Low density tin also reduces debris contamination to optics.
- The optical depth at 13.5 nm is only ~7 nm of full density Sn. Beyond that, light is reabsorbed.
- CE (conversion efficiency) slightly reduced with low density Sn.

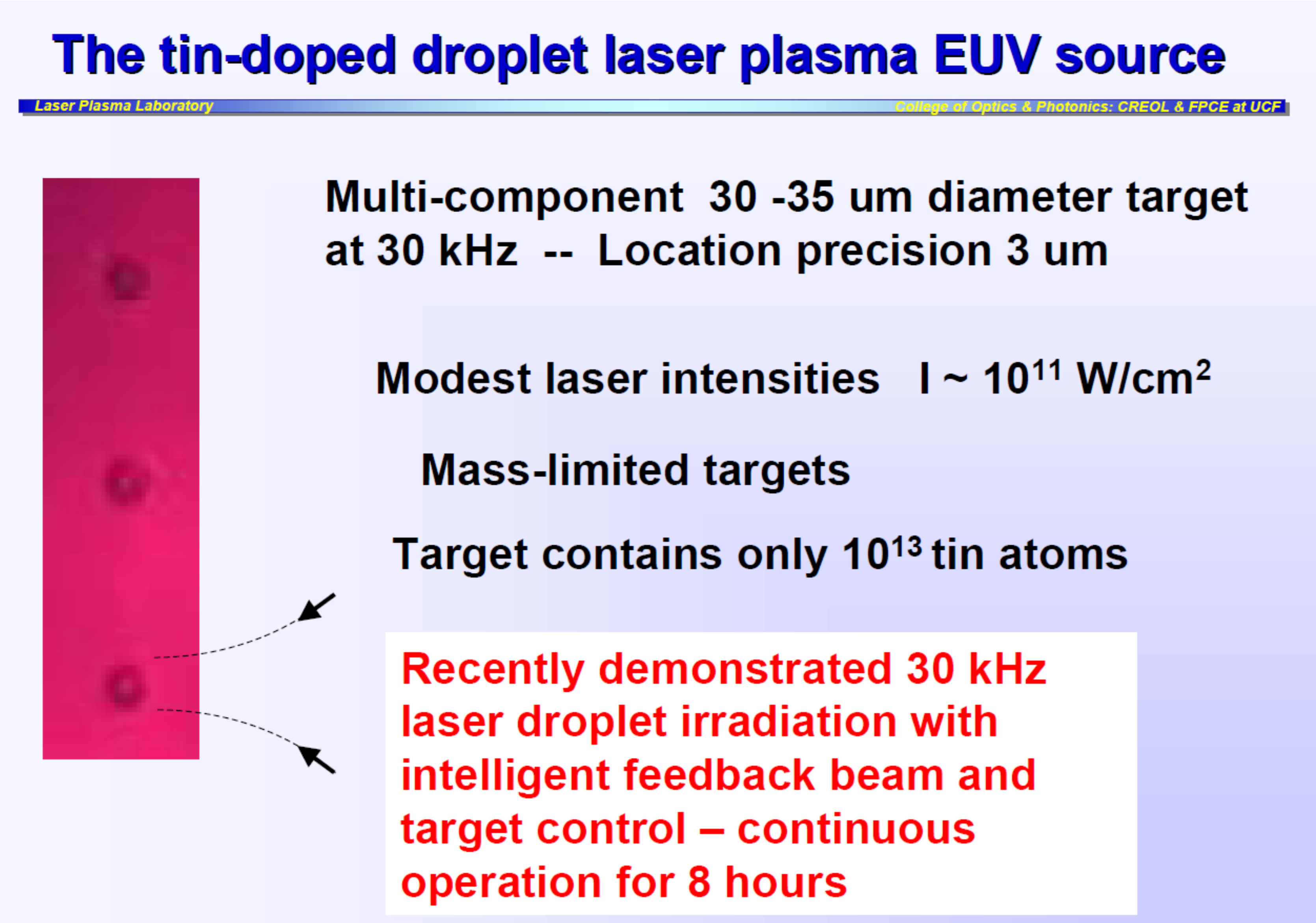
Liquid Metal Droplet Generator Developed



100 μm Sn droplets at 36 kHz, captured using strobe lighting



- Continuous stimulated droplet generation of liquid metals (Li and Sn) at temperatures up to 250°C
- Droplets diameter $\leq 100\ \mu$m
- Droplet rates up to 48 kHz
- Working distance of 50mm



The tin-doped droplet laser plasma EUV source

Laser Plasma Laboratory — College of Optics & Photonics: CREOL & FPCE at UCF

Multi-component 30 -35 um diameter target at 30 kHz -- Location precision 3 um

Modest laser intensities I ~ 10^{11} W/cm^2

Mass-limited targets

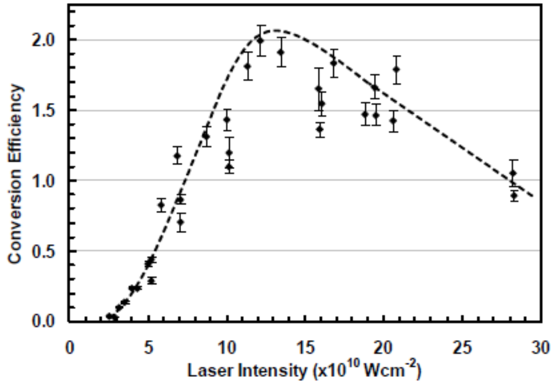
Target contains only 10^{13} tin atoms

Recently demonstrated 30 kHz laser droplet irradiation with intelligent feedback beam and target control – continuous operation for 8 hours

High CE demonstrated with Droplet Target

Laser Plasma Laboratory *College of Optics & Photonics: CREOL & FPCE at UCF*

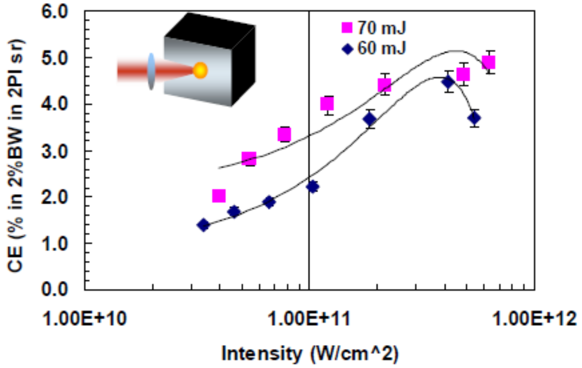
CE = 2% at 13.5 nm for tin-doped droplet target source



<u>FOM FC2 team</u>

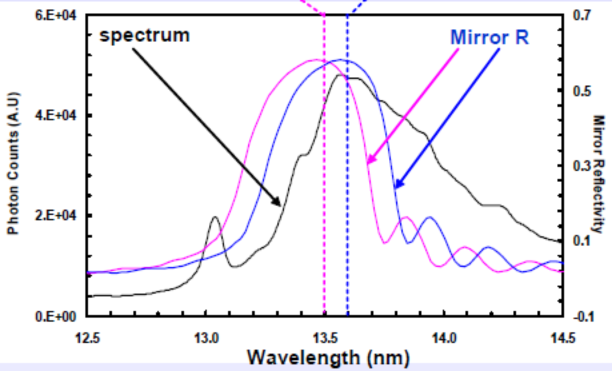
F. Bijkerk S.A. vd Westen C. Bruineman

CE = 5.5 % with solid tin!



at 13.5nm, **CE = 2%**

at 13.6nm, **CE = 2.25%**

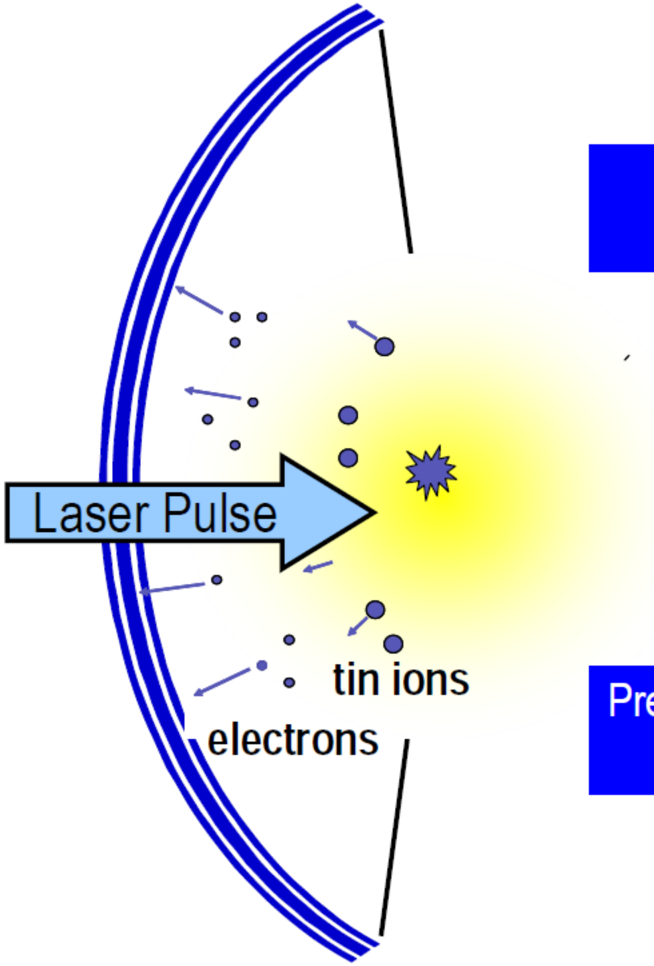


CE = 3% achievable with droplet source

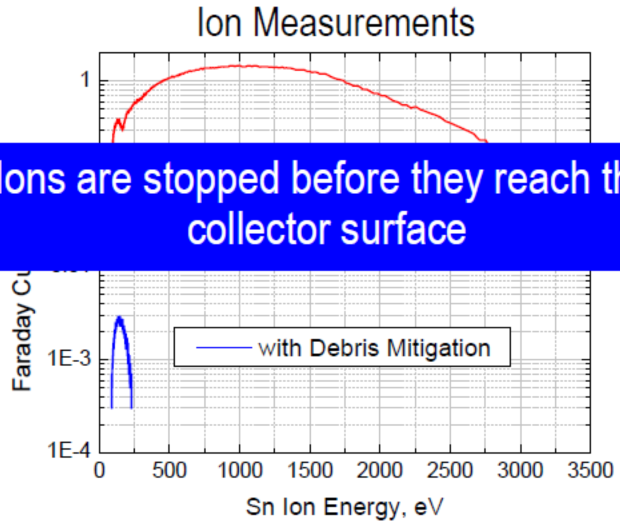
--- for 30 kHz, 140 mJ laser

→ 120 W / 2π

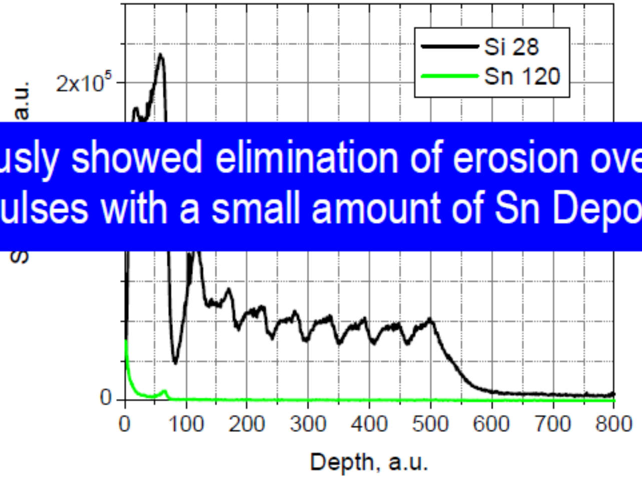
Debris Mitigation Stops Erosion from Ions



All measurements taken at collector surface



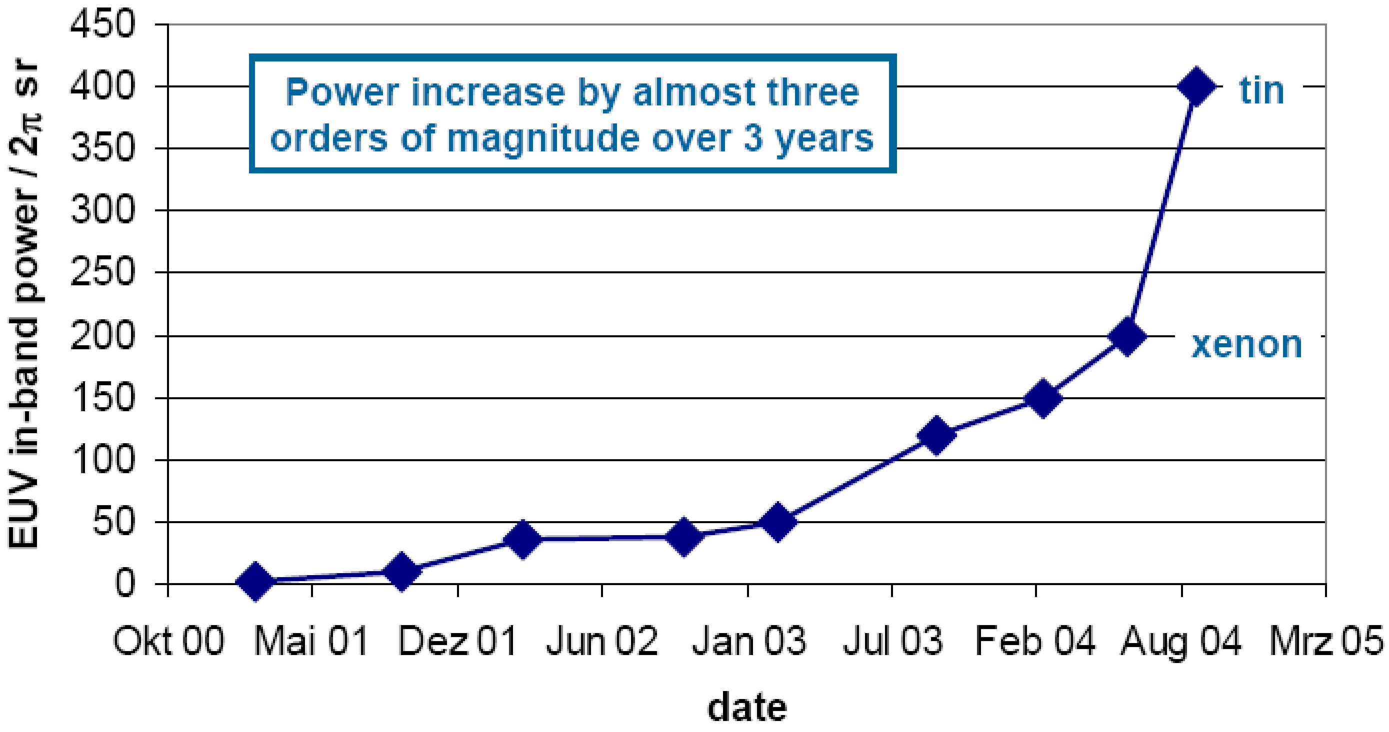
Sn Ions are stopped before they reach the collector surface



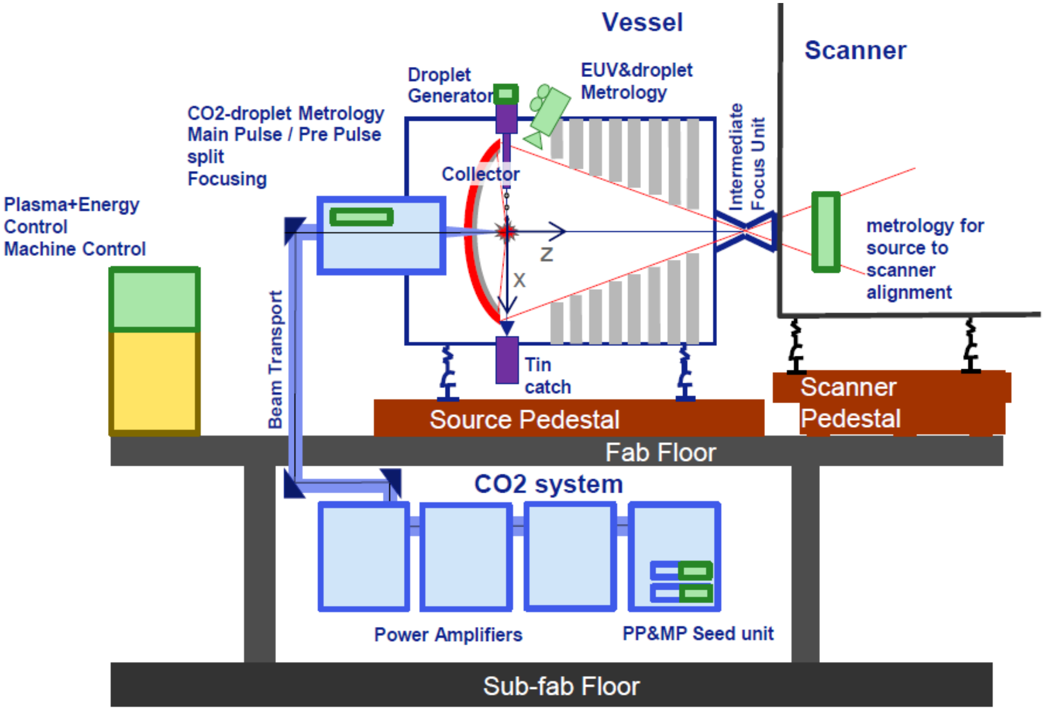
Previously showed elimination of erosion over 3 Mpulses with a small amount of Sn Deposition

Gas discharge produced plasmas source scaling

two orders


Power increase by almost three orders of magnitude over 3 years

LPP EUV Source System Cross-Section



x=droplet stream direction, z=CO2 light direction, y=orthogonal

Key components:

- **Drive Laser**
- **Collector**

Power

- **Droplet generator**
- **Vessel**

Availability

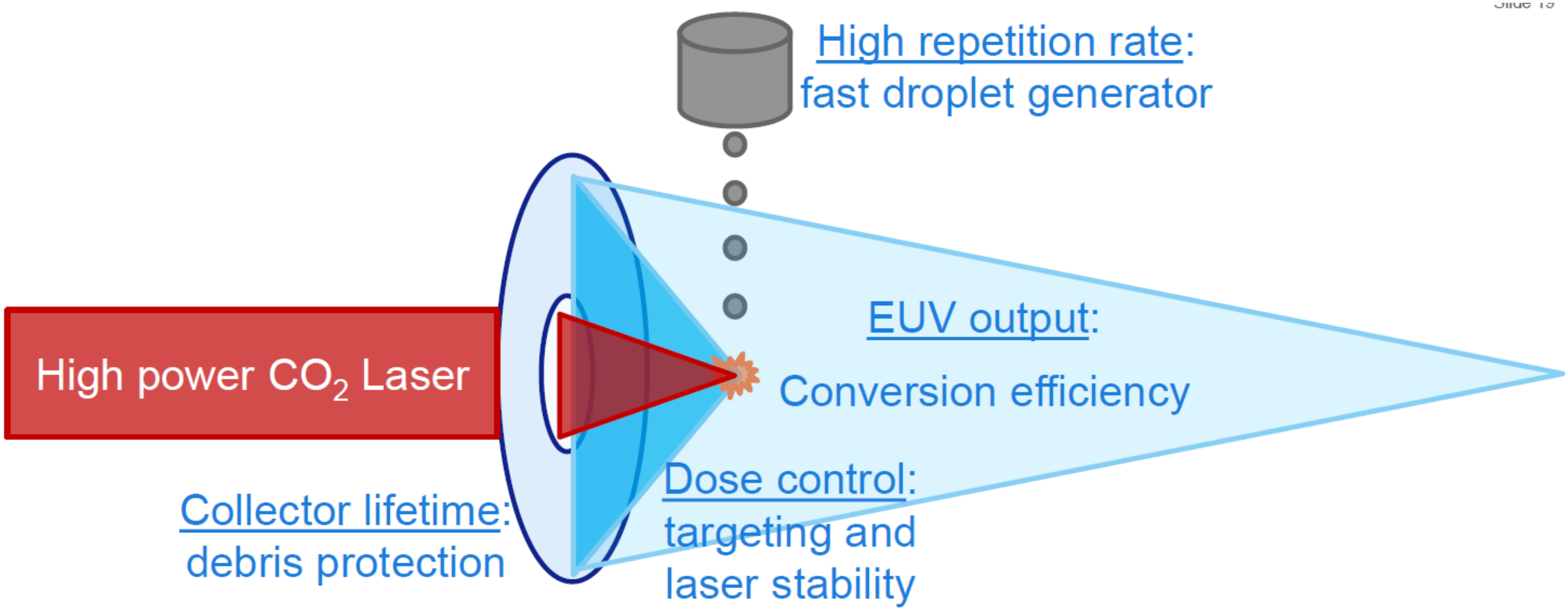
- **Controls (E,x,y,z,t)**
- **Final Focus Assembly**

Dose control

http://vestige.lmsal.com/TRACE

Source: Cymer ASML company

EUV Power Scaling



High repetition rate:
fast droplet generator

High power CO_2 Laser

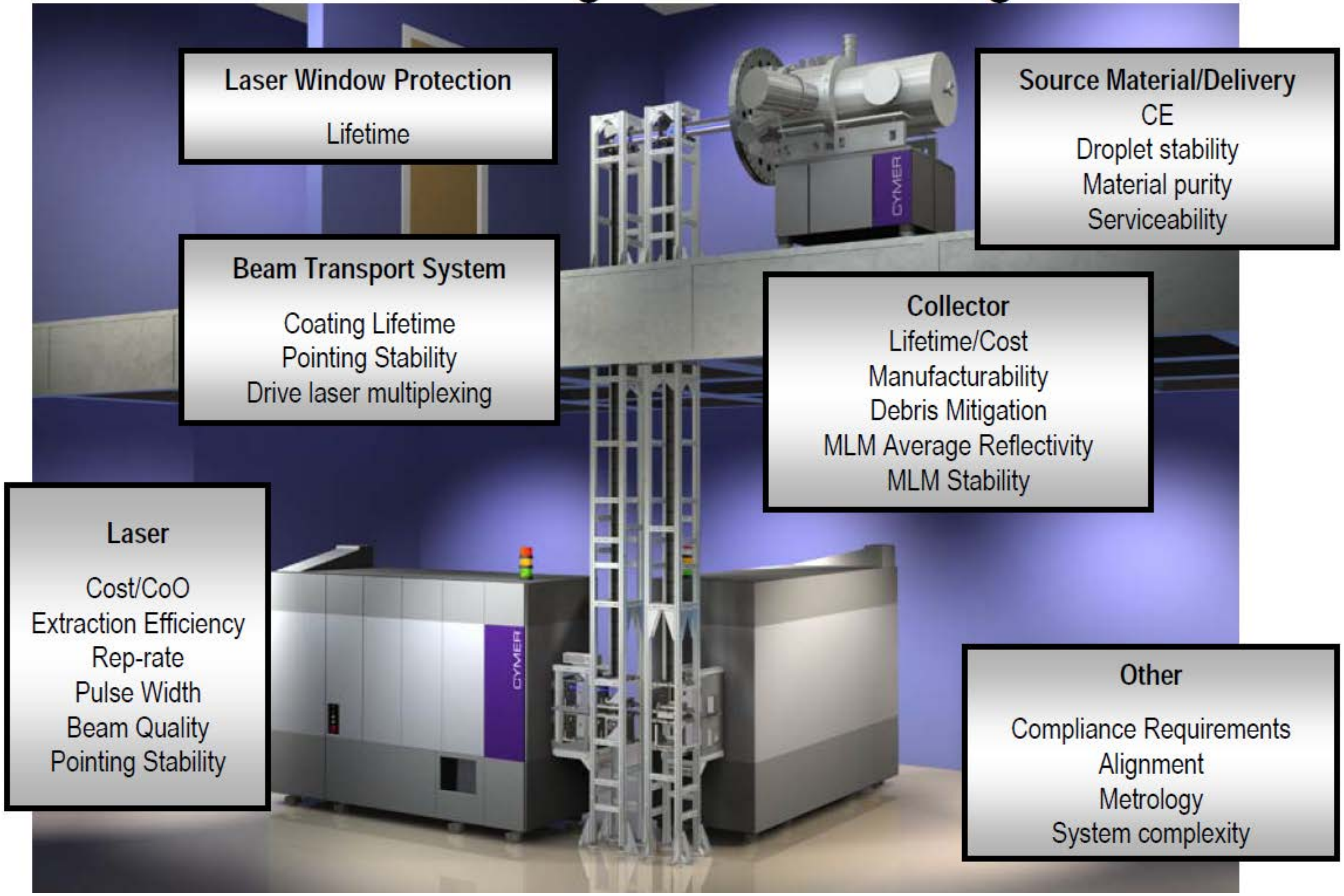
EUV output:
Conversion efficiency

Collector lifetime:
debris protection

Dose control:
targeting and
laser stability

- CO_2 laser power: 47 kW
- Conversion efficiency: 3.3%

Development of a Laser Produce Plasma EUV Source has Significant Challenges



Laser Window Protection

Lifetime

Source Material/Delivery

CE
Droplet stability
Material purity
Serviceability

Beam Transport System

Coating Lifetime
Pointing Stability
Drive laser multiplexing

Collector

Lifetime/Cost
Manufacturability
Debris Mitigation
MLM Average Reflectivity
MLM Stability

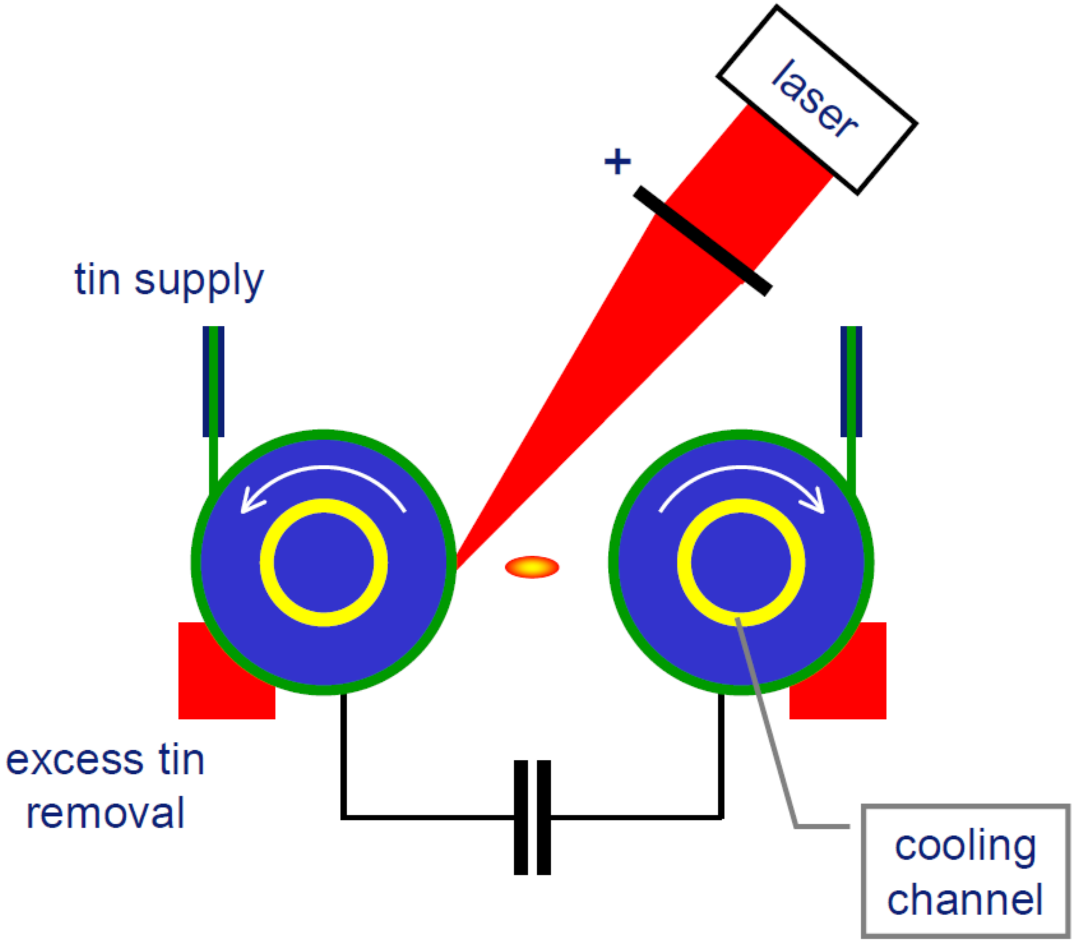
Laser

Cost/CoO
Extraction Efficiency
Rep-rate
Pulse Width
Beam Quality
Pointing Stability

Other

Compliance Requirements
Alignment
Metrology
System complexity

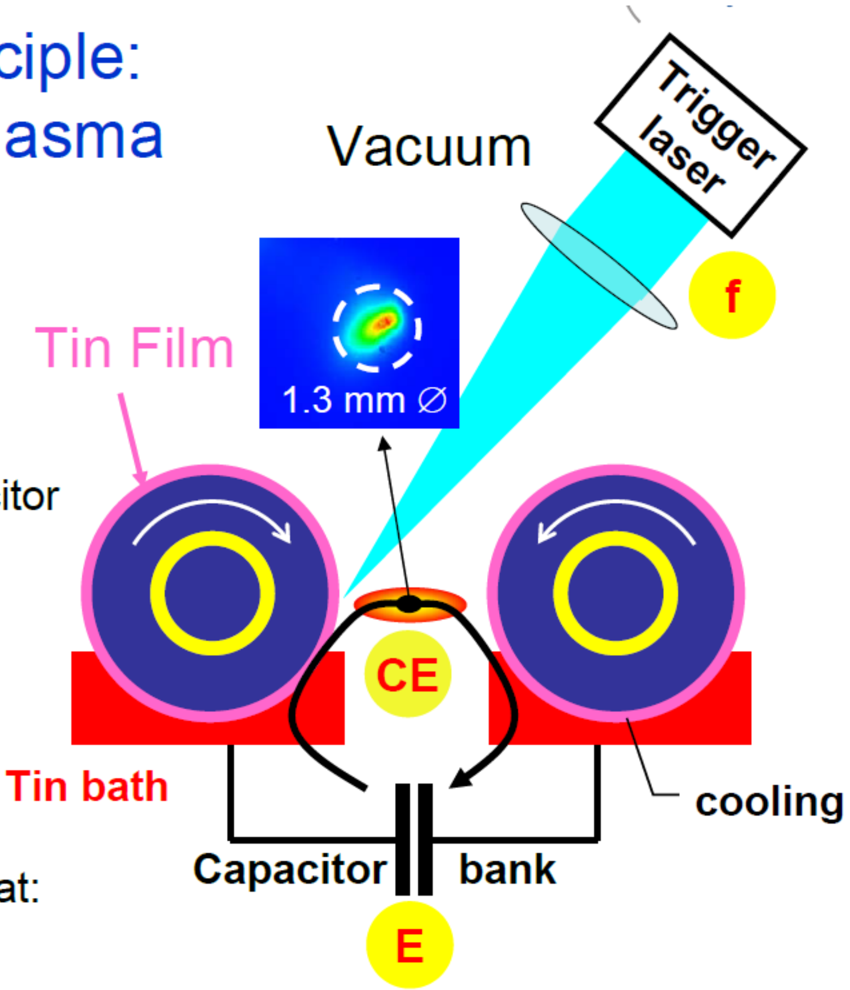
Philips EUV source



- CE 2%
- 5 kHz
- 120W continuous operation, 260 W short term

Basic light generation principle: Sn *Discharge* Produced Plasma using rotating electrodes

- Laser Triggered Vacuum Spark
- Electrical contact through tin
  - Simple power supply to load capacitor bank
- Regenerating liquid tin surface
  - Electrode erosion problem fundamentally solved !
- Liquid metal cooling with tin
  - Very efficient to remove excess heat: >>100kW input power



Power scaling parameters