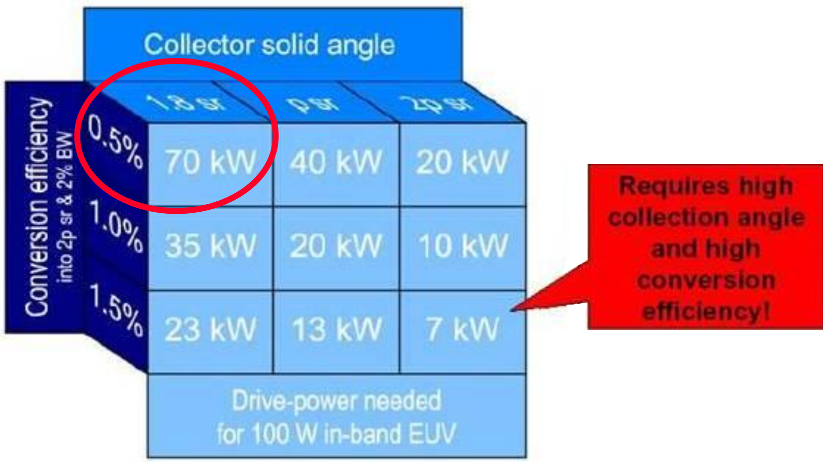
EUV sources



Radiating power of a pulsed EUV source

Laser produced plasmas (LPP)

Discharge produced plasmas (DPP)

Sources for EUV technology

- Hollow cathode triggered (HCT) pinch plasma
- Laser-assisted DPP

Challenges of source development

Different source concepts and providers

Radiating power of a pulsed EUV source

$$P_{\Delta\lambda} = f \cdot E_{\Delta\lambda} = f \cdot \eta_{CE} \cdot E_C$$

$P_{\Delta\lambda}$ *average in-band radiating power (in 2 % bandwidth at λ_0),*
f *repetition rate,* η_{CE} *conversion efficiency,*
$E_{\Delta\lambda}$ *radiation energy in 2 % bandwidth at λ_0,* E_C *input energy*

An increase of the EUV radiating power can therefore be reached on one hand by increasing the repetition rate f, and, on the other hand, by maximizing the usable radiation energy $E_{\Delta\lambda}$ emitted per pulse.

With spatially extended sources, not the entire radiation emitted by the source can be used by the optical system. Therefore a term "usable radiation energy" or "usable radiation power" is introduced. In order to keep the power input $f{\cdot}E_C$ manageable the conversion efficiency is crucial, i.e. the transformation of the provided input energy into the usable radiation energy.

Both aspects, the maximization of the repetition rate and the optimization of the conversion efficiency are intensively investigated during the EUV light source development.

LPP and DPP

From a technological point of view, there are two most attractive ways to feed the energy necessary for the pulsed heating into the plasma:

• Laser produced plasmas (LPP)

The energy for the production of the plasma is applied here in form of pulsed laser radiation to a target.

• Discharge produced plasmas (DPP)

The energy necessary for the production of the plasma is delivered by a high-current discharge within a working gas.

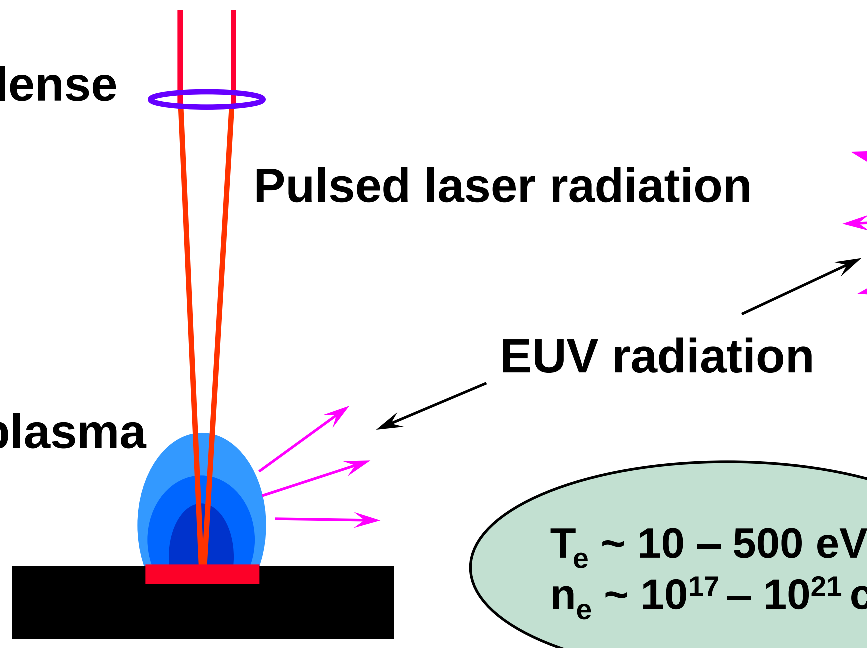
An overview of the typical parameters for the two different EUV source concepts:

Parameter	LPP	DPP
Pulse duration [ns]	0.2-10	10-100
Energy [J/pulse]	0.25–1.5	2-10
Diameter [μm]	50-100	100-500

Main further difference is the much lower number density in discharge plasmas.

Schemas of LPP und DPP

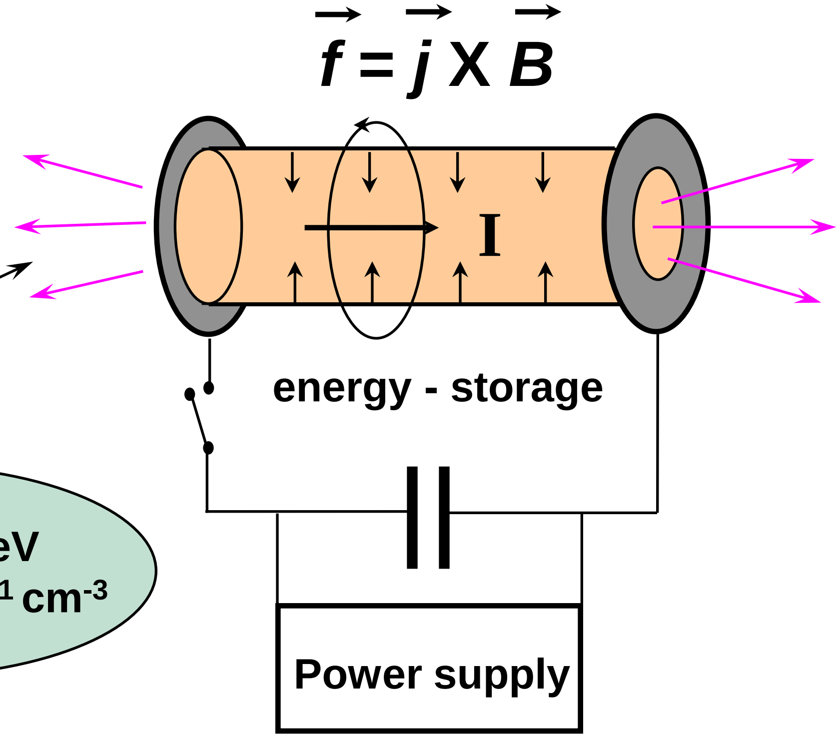
Laser produced plasma (LPP)



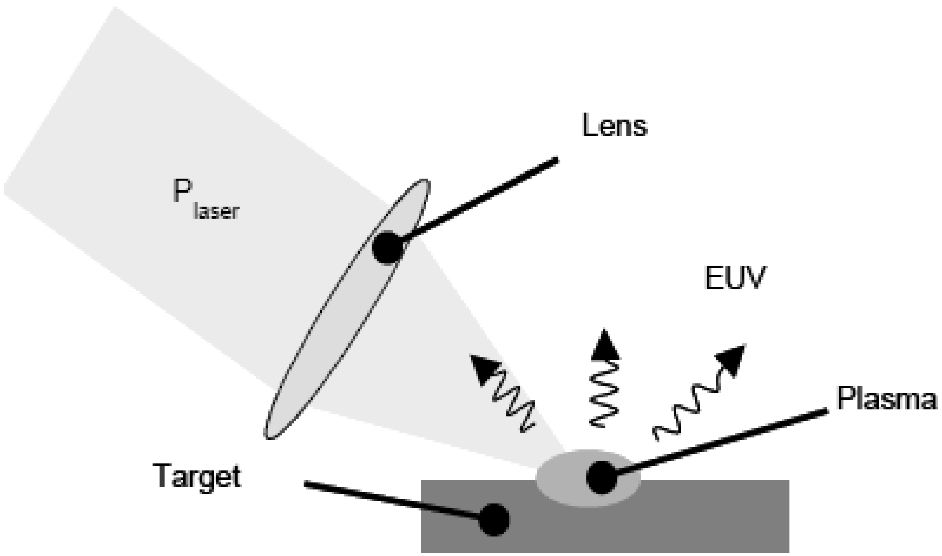
Target (solid, liquid, cluster)

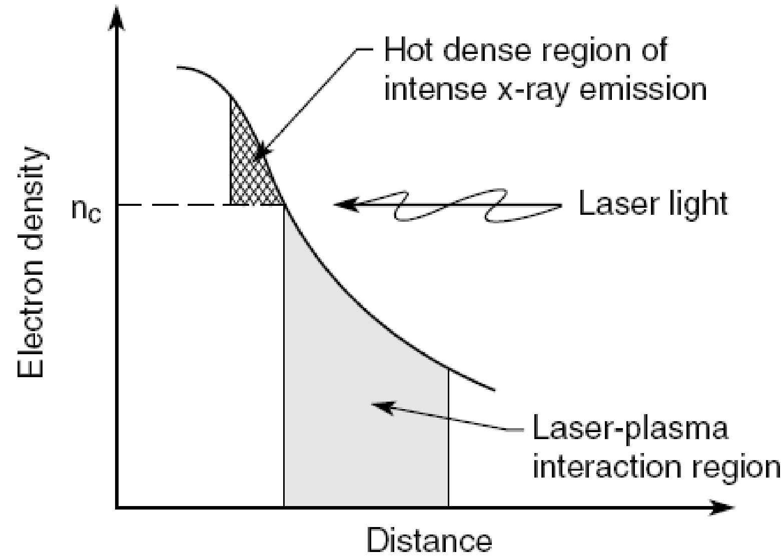
$T_e \sim 10 – 500$ eV
$n_e \sim 10^{17} – 10^{21}$ cm^{-3}

Gas discharge plasma (DPP)



Laser produced plasmas for EUV radiation





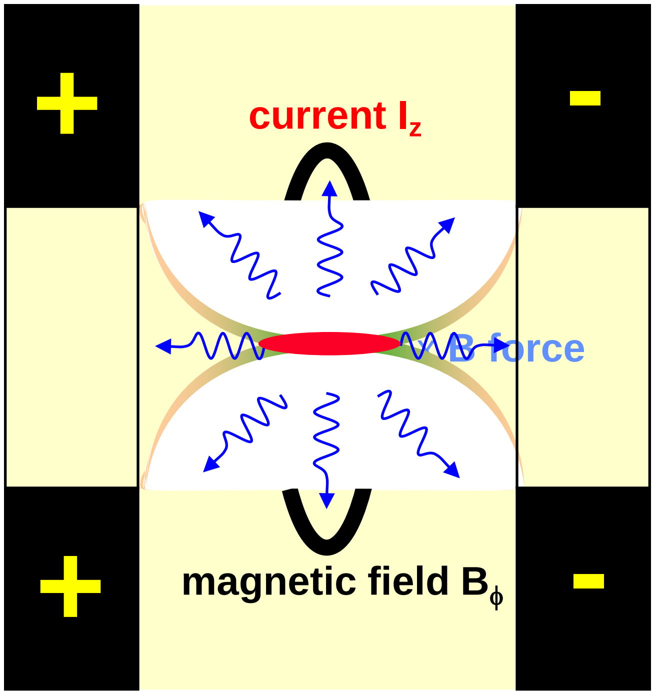
A laser beam is focused onto a target with intensities around 10^{11} W/cm^2. The laser light converts neutral target material into a hot and dense plasma (by e.g. photoionization, high-field breakdown etc.). Dominant mechanism for the subsequent plasma heating is the inverse bremsstahlung. The emitted EUV light depends on the chemical and physical composition of the target (elements, phase, size) and the laser parameters (pulse duration, wavelength, intensity).

- $\kappa T_e \sim 50$ eV to 1 keV
- $n_e \sim 10^{20}$ to 10^{22} e/cm^3

$$n_{crit} = \frac{\epsilon_0 m_e \omega_L^2}{e^2} = \frac{1.11 \times 10^{21}}{(\lambda_L/[\mu\mathrm{m}])^2} \quad [\mathrm{cm}^{-3}]$$

$$T_e = 2.85 \times 10^{-4} \times \left(I_L/[\mathrm{W/cm^2}]\right)^{4/9} \quad [\mathrm{eV}]$$

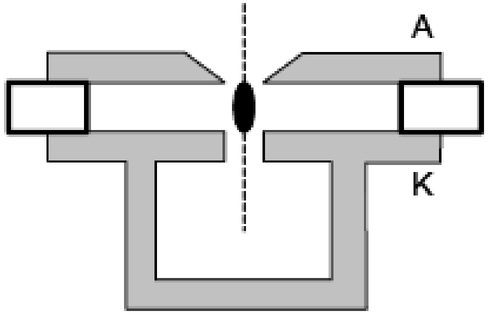
Discharge plasmas for EUV radiation



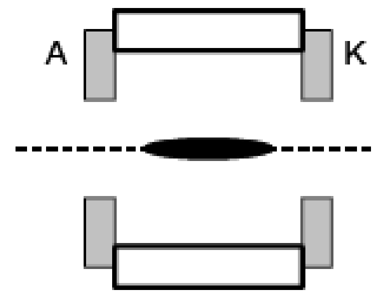
- Plasma temperature (T_e) > 20 eV
- Plasma density (n_e) > 10^{18} cm^{-3}
- Initial gas pressure (p) 10 - 100 Pa
- Peak current (I_{max}) 10 - 20 kA
- Pulse duration (t_p) few 100 ns
- Current density (j) 10^4 - 10^5 A/cm^2
- Pulse energy (E) 1 - 10 J
- Dimensions (d) mm - cm

Different electrode geometries of DPP EUV sources

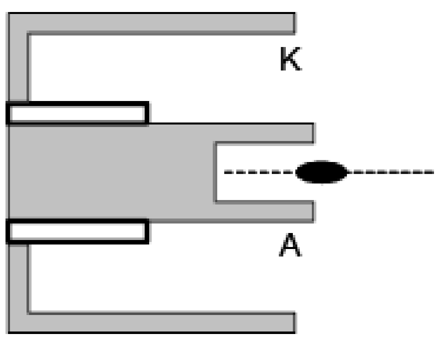
Hollow cathode triggered (HCT) pinch plasma



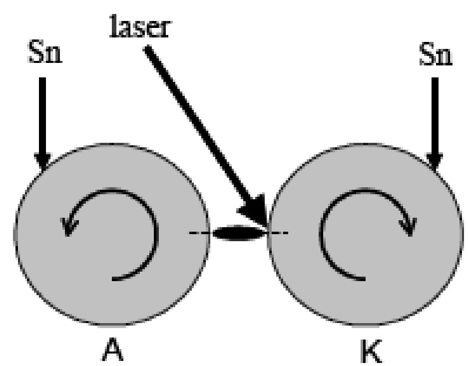
Z-pinch configuration



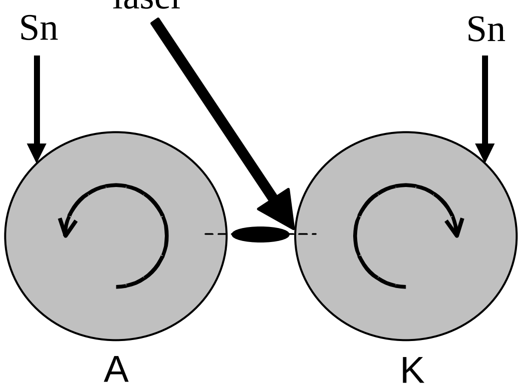
Plasma focus



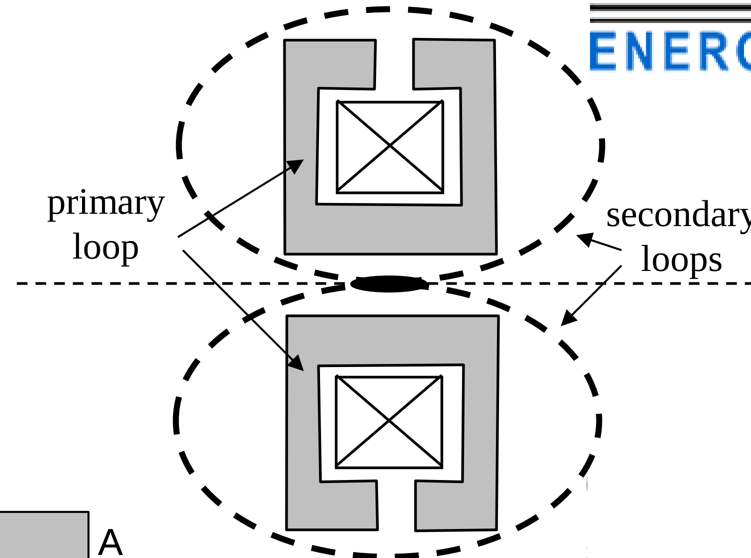
Laser triggered vacuum arc with rotating electrodes



Commercial EUV sources



ENERGETIQ



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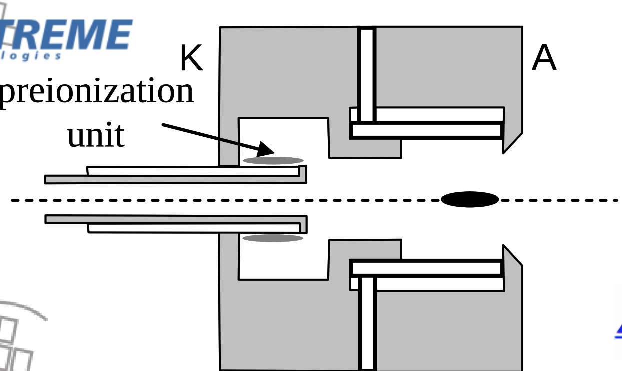
XTREME technologies

ILT Fraunhofer Institut Lasertechnik



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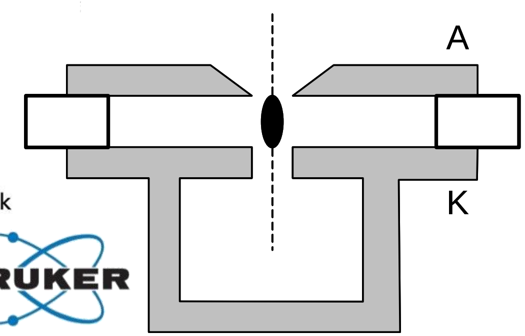
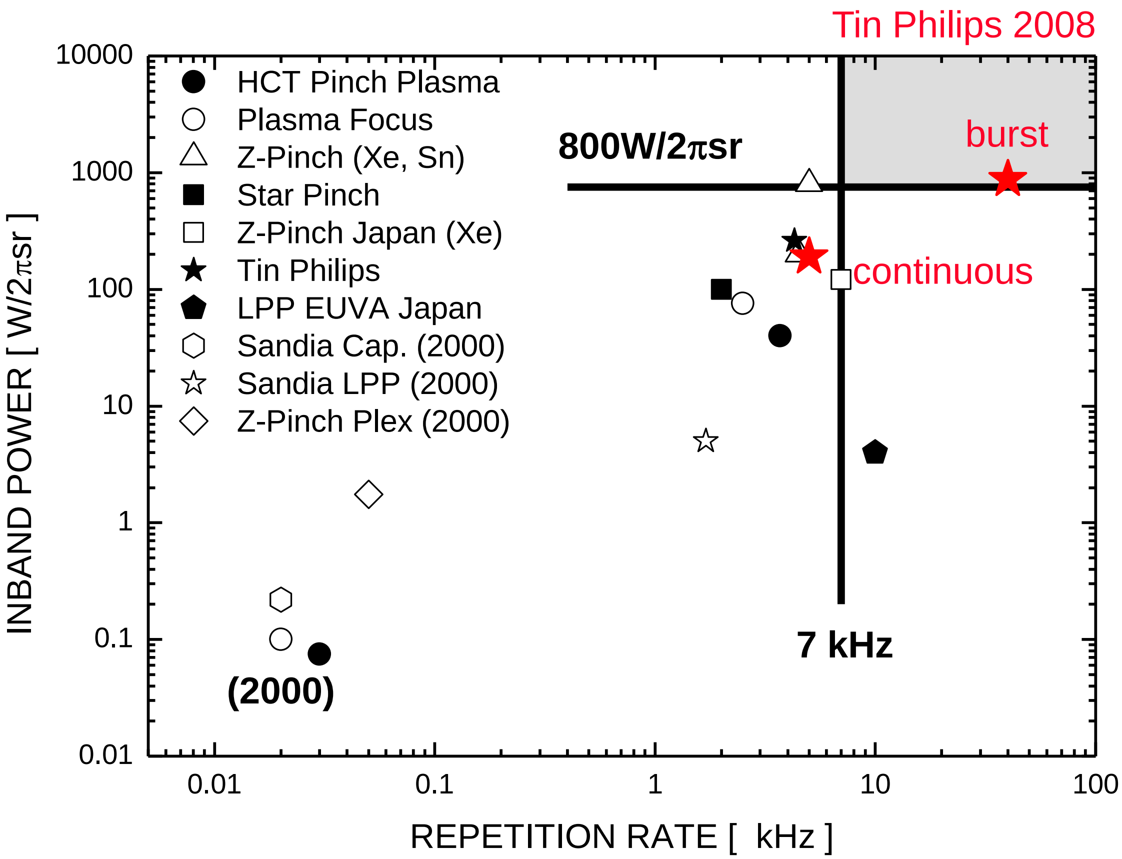
AIXUV EUV-Technology

BRUKER Bruker ASC



Sources for EUV technology



Today's achieved radiating power (λ_0 = 13.5 nm) and repetition rates for different source concepts

EUV sources in Aachen

N_2

Wavelength λ= 2.88 nm (430 eV)
Repetition Rate: 1 – 2 kHz
Photon Flux: $1*10^{14}$ Ph/2πsr

Fraunhofer ILT

Repetition rate up to 4 kHz

EUV (10 – 20 nm): > 400 W/2πsr

EUV (13.5 nm, 2% bw): 65 W/2πsr

Xe

Xe

AIXUV EUV-Technology

BRUKER Bruker ASC

Sn

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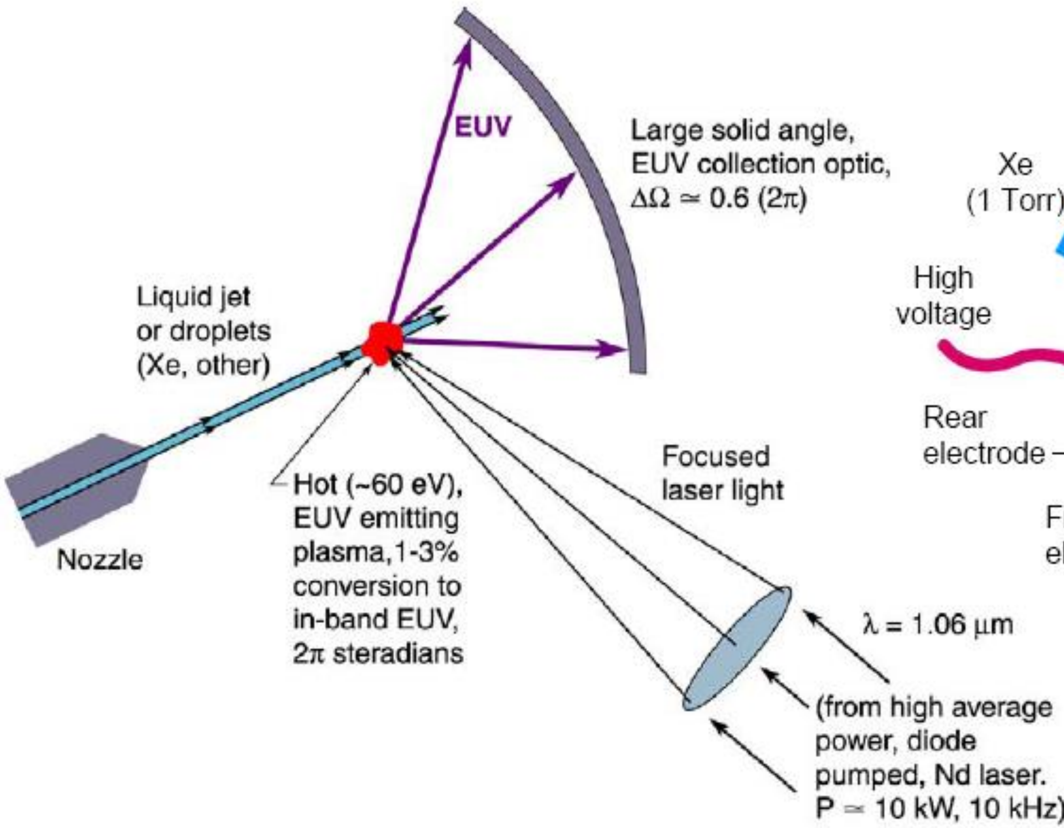
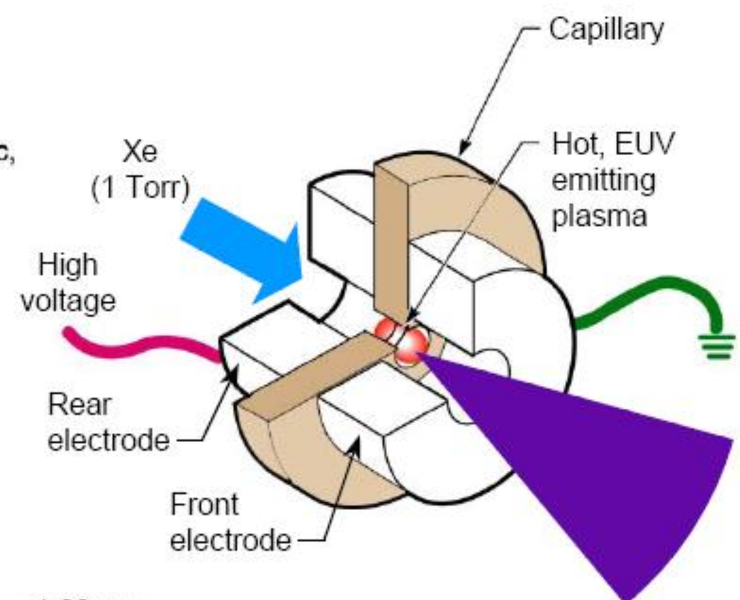
EUV Source Candidates for Clean, Collectable 13-14 nm Wavelength Radiation

Laser Produced Plasma Source

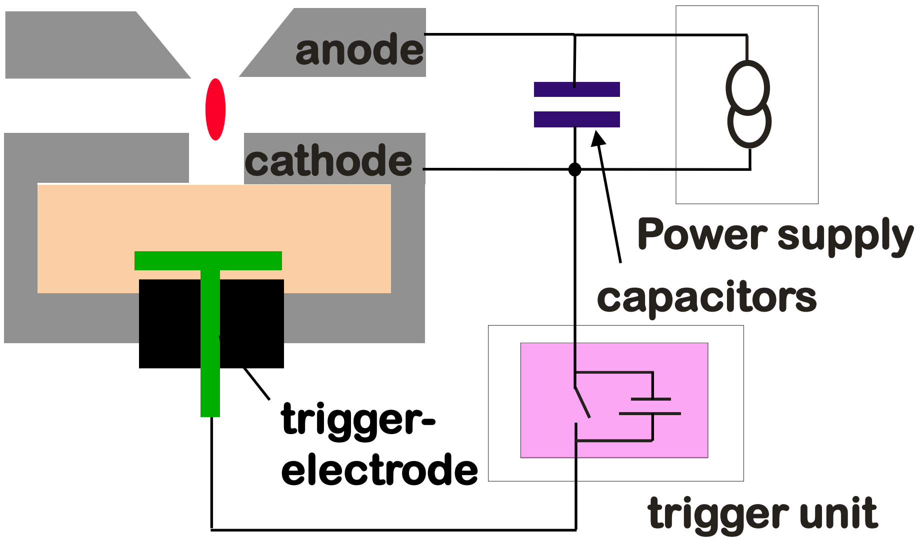


Electrical Discharge Plasma Source

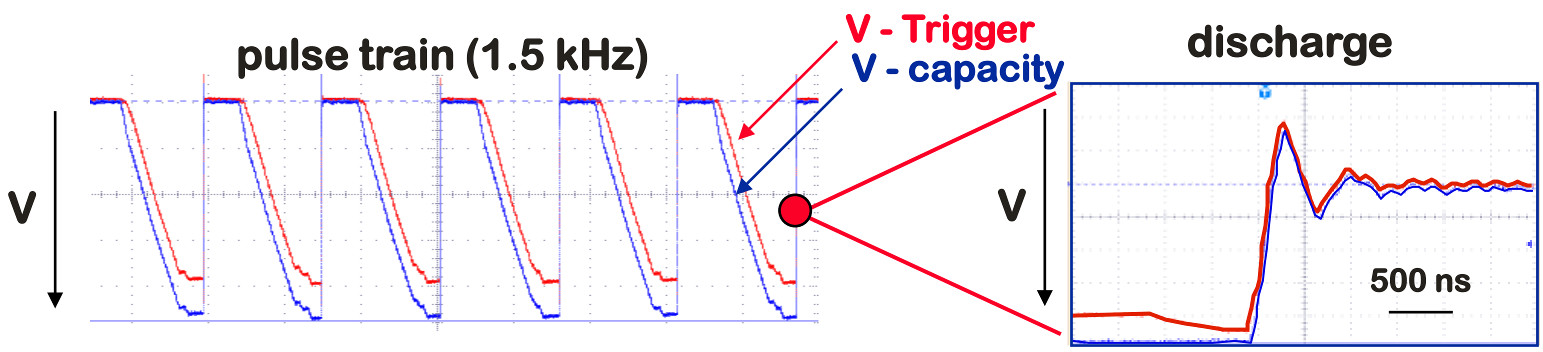


Courtesy of Neil Fornaciari and Glenn Kubiak, Sandia.

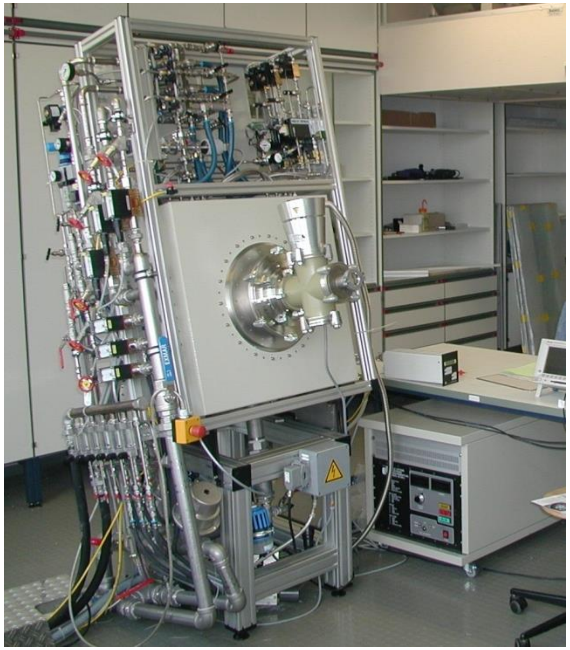
Hollow Cathode Triggered (HCT) pinch plasma

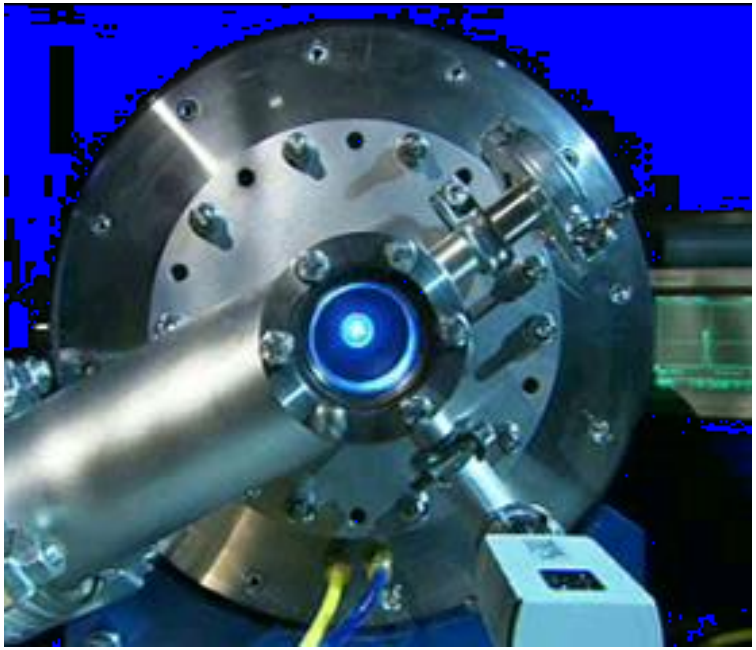


"Simple" operation due to combination of high current switchers and pinch plasma generation!



EUV lithography - driving force of source development





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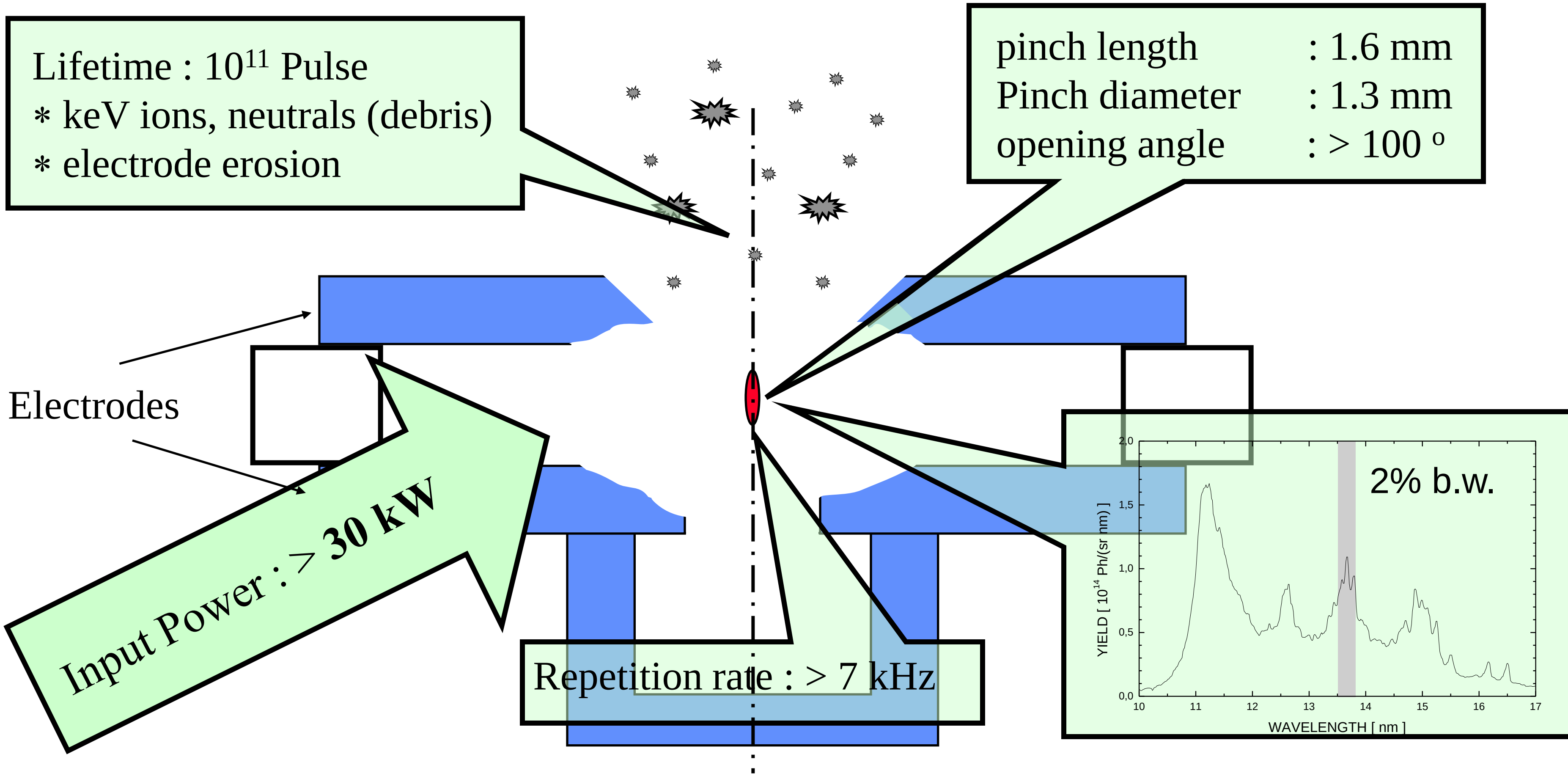
USHIO GROUP

AIXUV EUV-Technology

Bruker ASC

Challenges due to EUV lithography

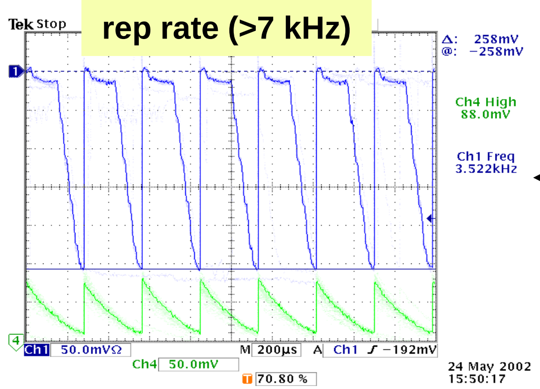


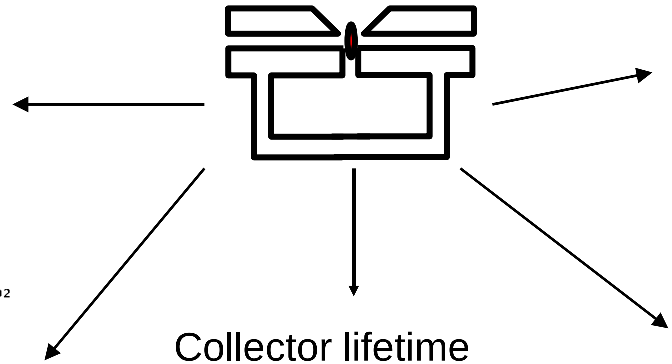
References : Sematech Symposia, Antwerp 2003, Dallas 2002

Challenges of source development

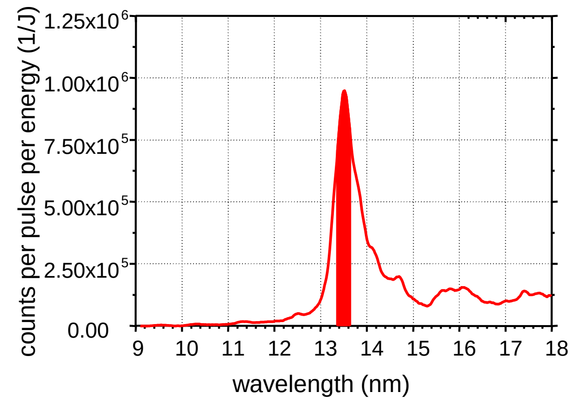
High power (30 kW)

rep rate (>7 kHz)



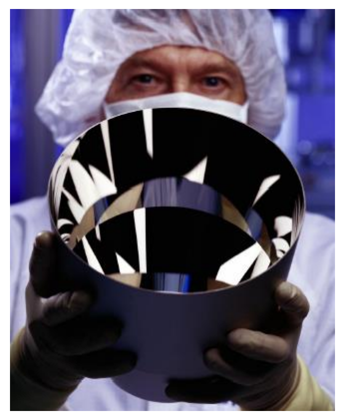


Conversion efficiency

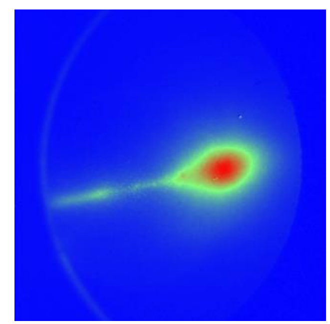


Electrode erosion

Collector lifetime

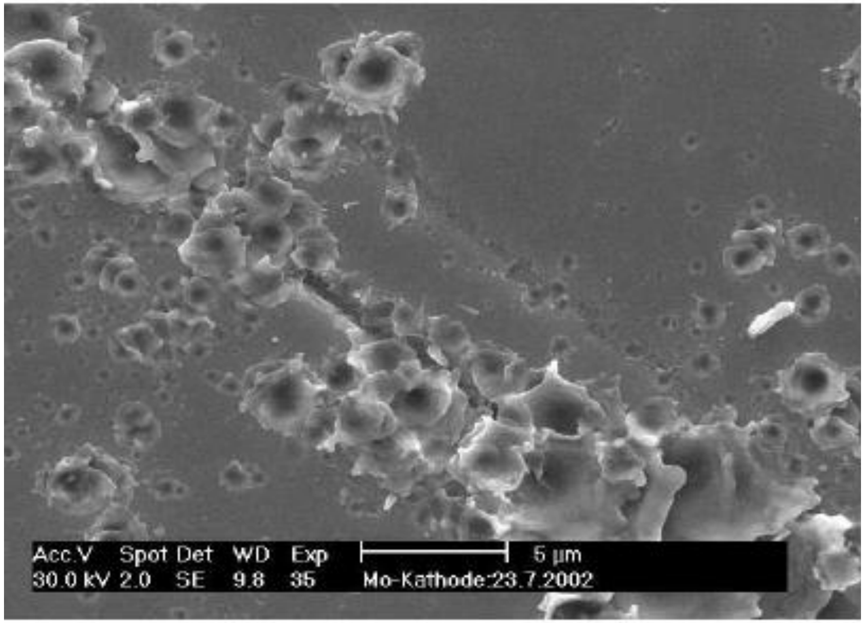


Etendue
(1.3 x 1.6 mm²)



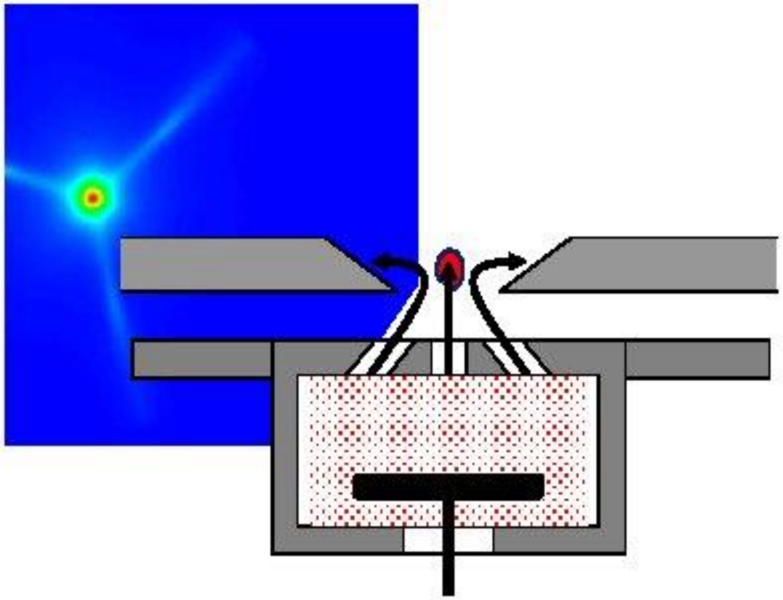
Electrode lifetime: multiple cathodes

Cathode spots



Electrode surface after one shot in a HCT discharge

End-on image in EUV



Film: pinch images in the visible spectral range in a time window of 500 ns

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TOS RWTH RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN LEHRSTUHL FÜR TECHNOLOGIE OPTISCHER SYSTEME

Dr. Larissa Juschkin

PHILIPS

Scalable power concept: rotating electrodes

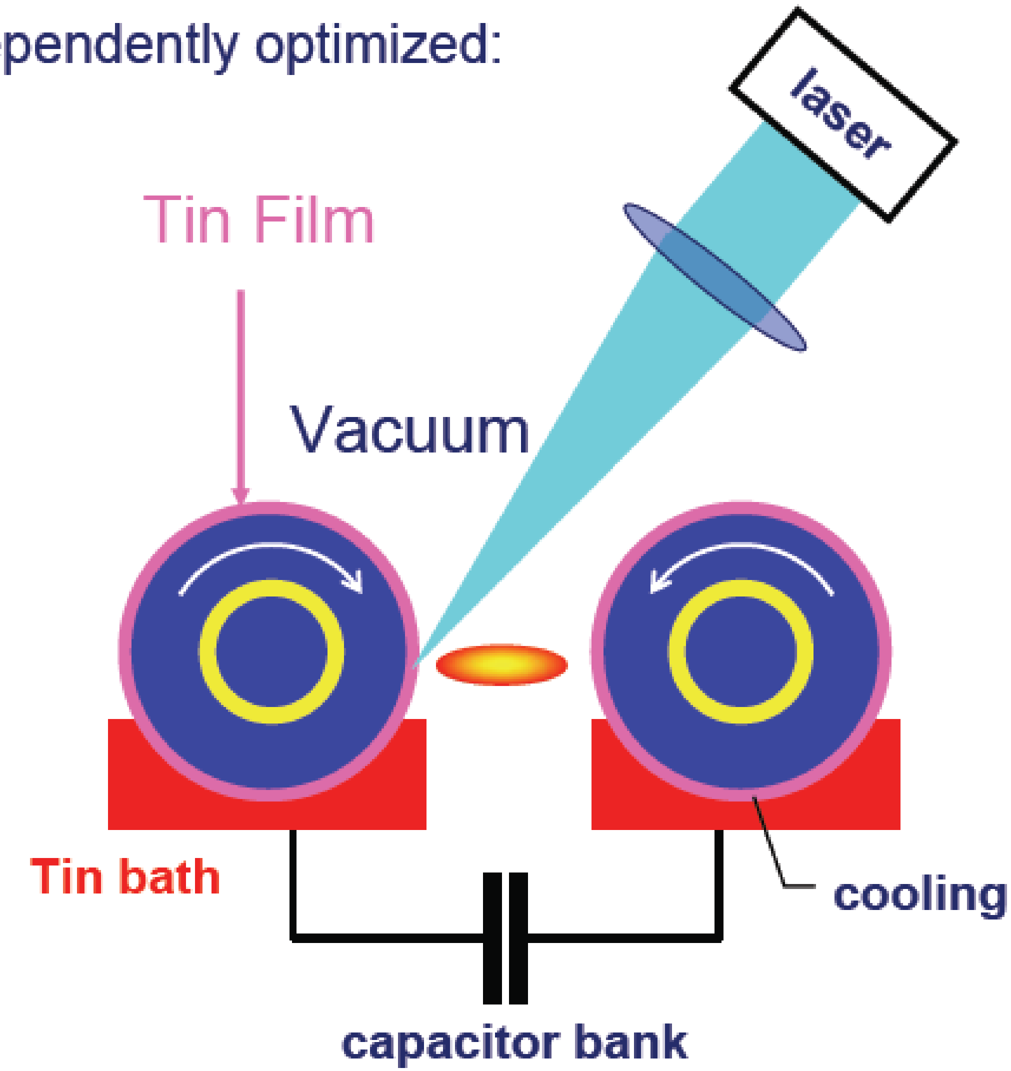
Three parameters that can be independently optimized:

- Conversion Efficiency
- Pulse energy
- Rep rate

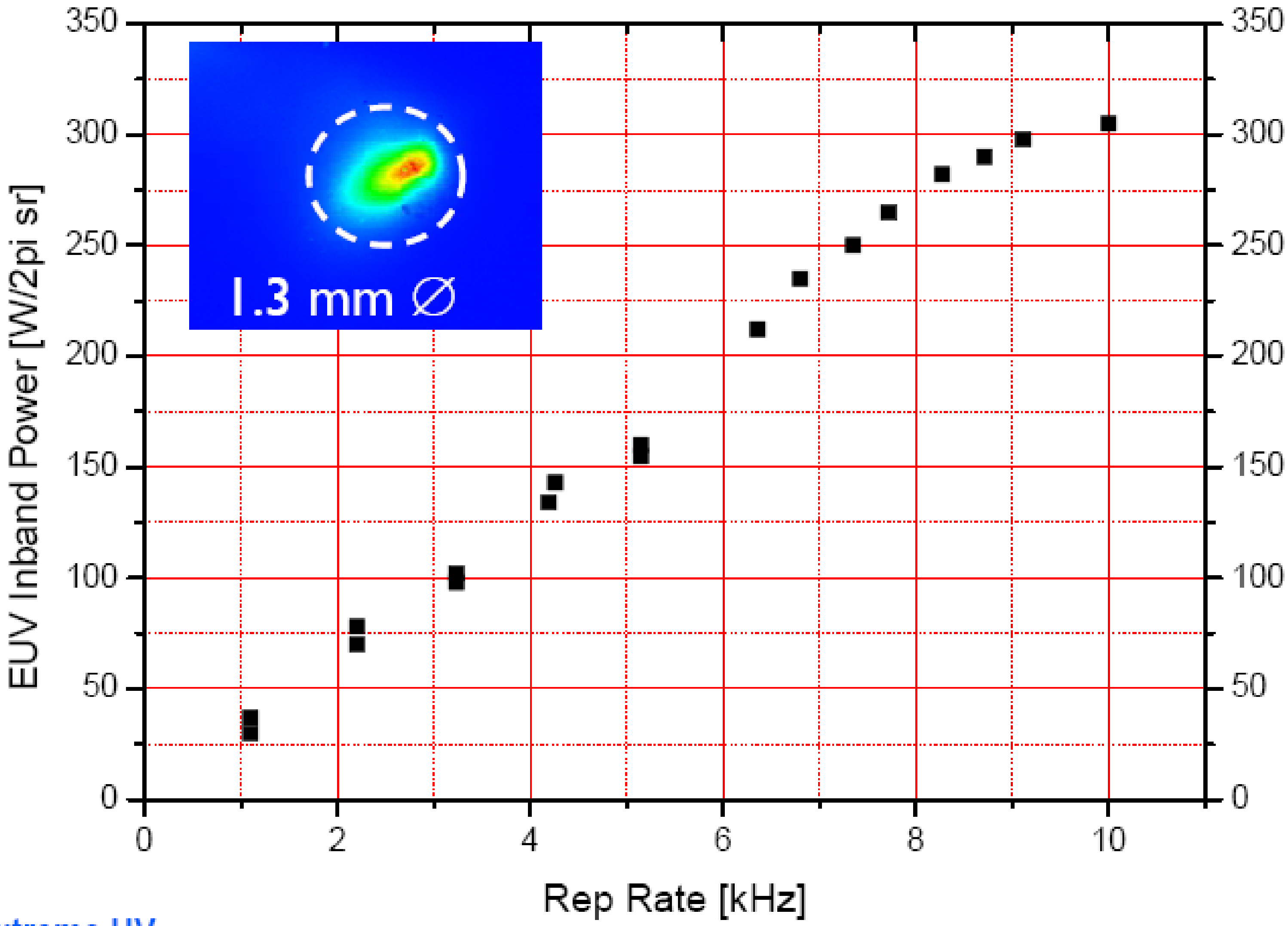
Keeping the source cool…

… and the scanner clean

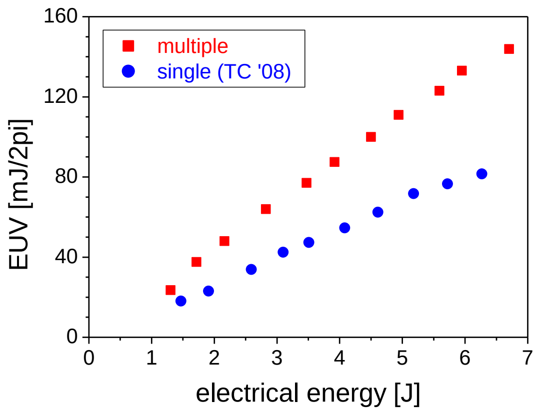
are the bigger challenges



Turning the rep rate scalability "button"

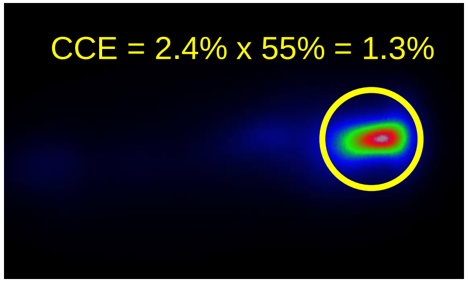


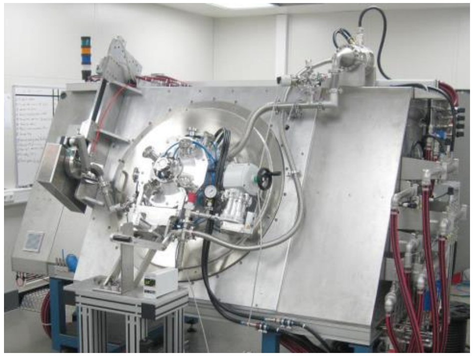
Tin vacuum arc - power scaling

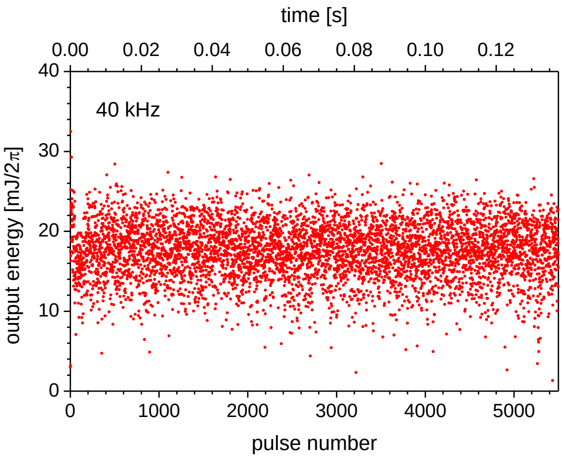


Increase of conversion efficiency by factor >2

Improvemnet of collection efficiency smaller source size

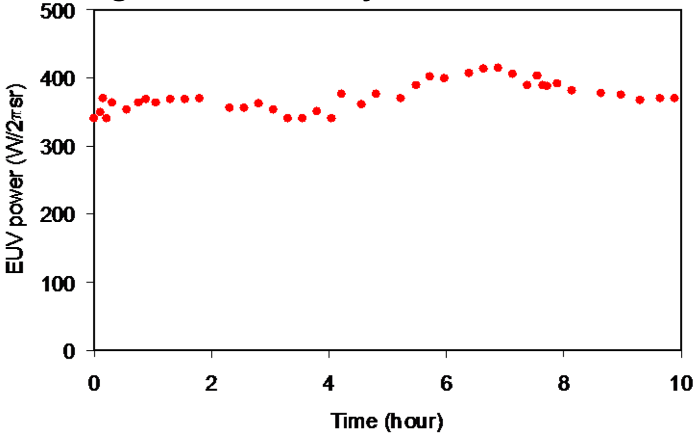




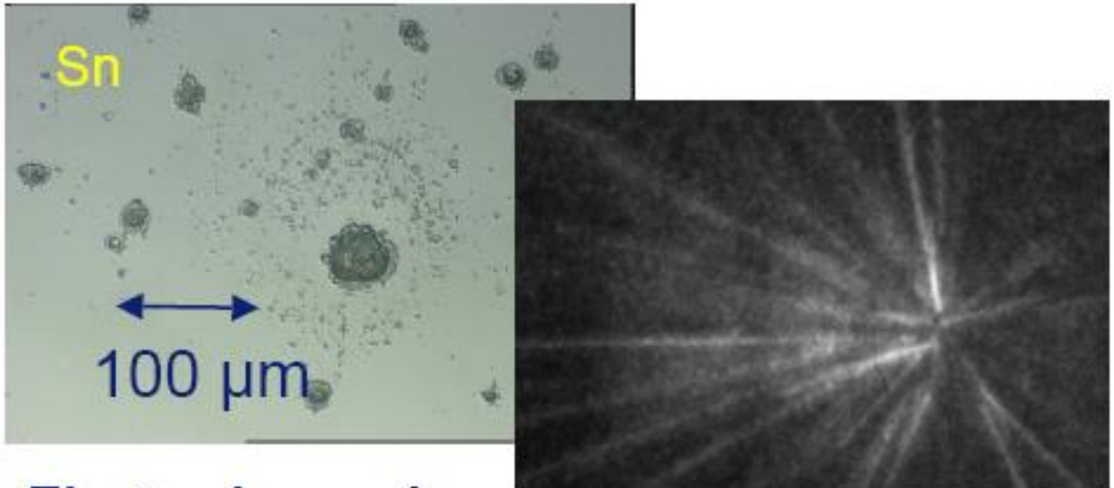


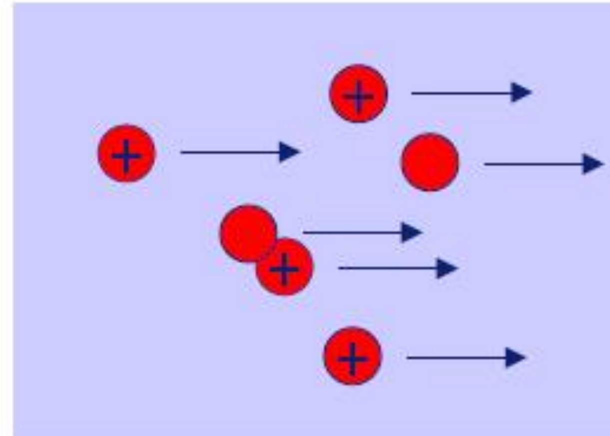
Power-frequency scaling

Long term stability



Debris from Light Source: Major challenge

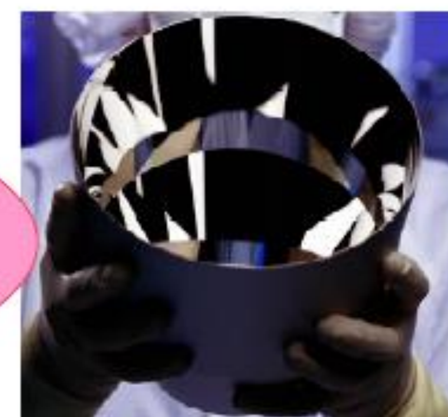




Electrode erosion
(proportional to current)

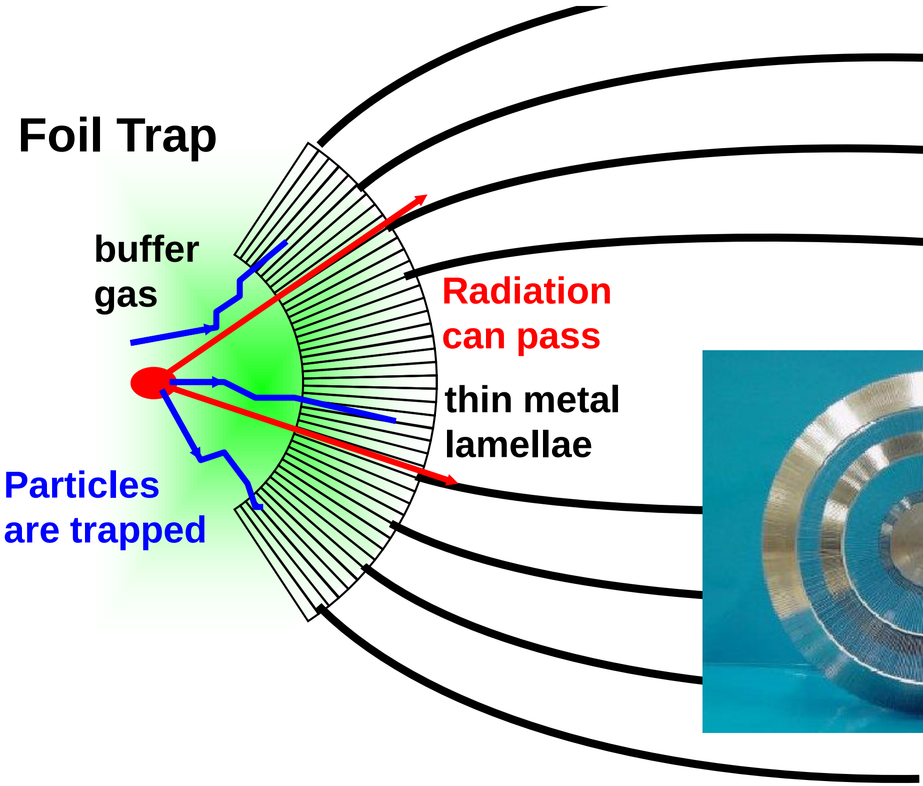
Fast ions & atoms from pinch

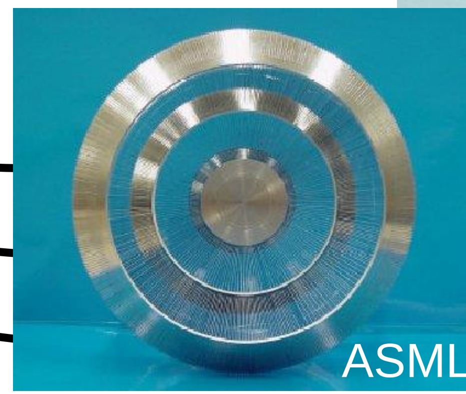
Sn deposition on the high precision collector surfaces
0.6 nm Sn -10% reflectivity



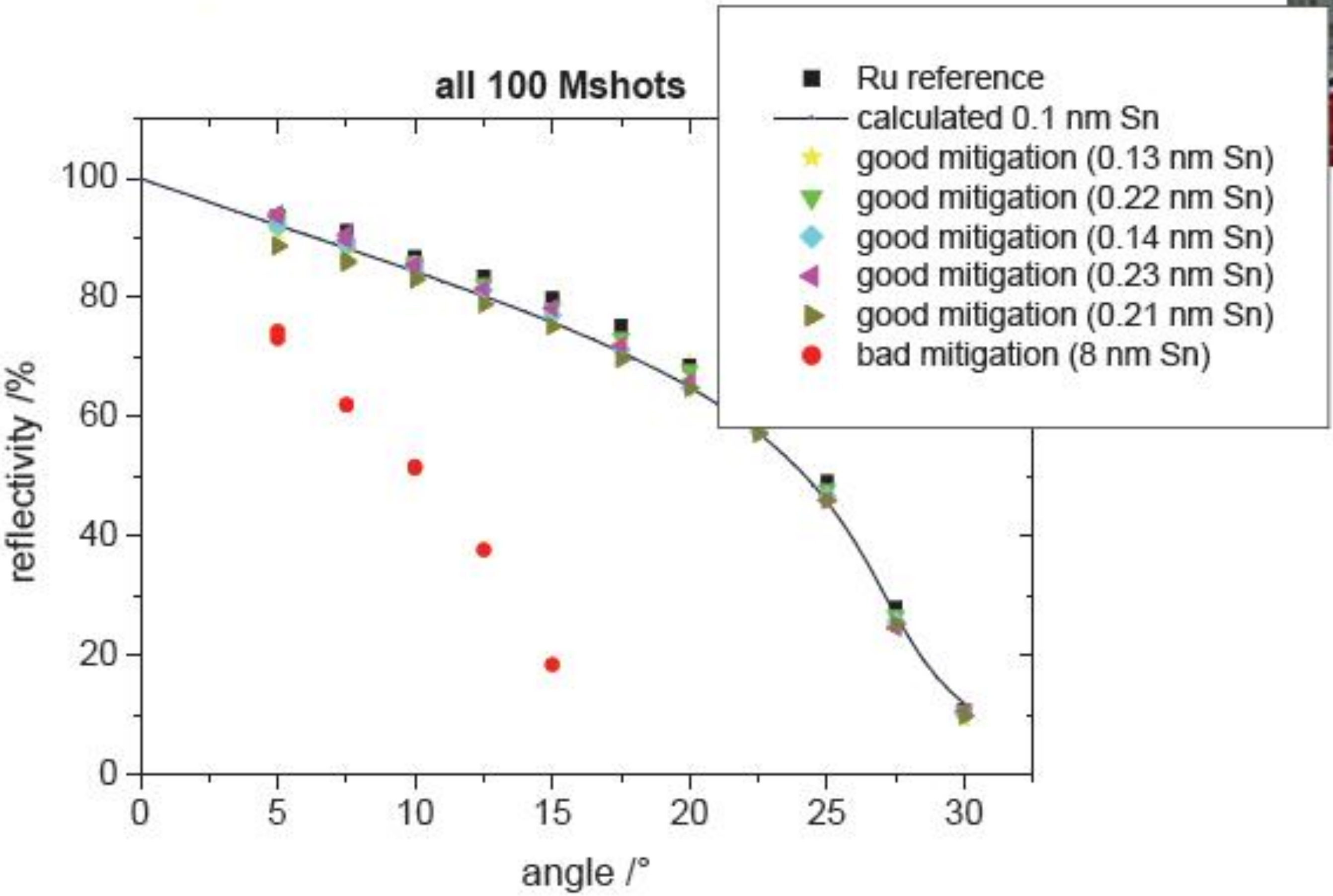
Debris - particles emitted from the source

- Fast particles from pinch plasma itself (charged)
- Sputtered particles from electrodes (charged and neutral)
- Sn from discharge



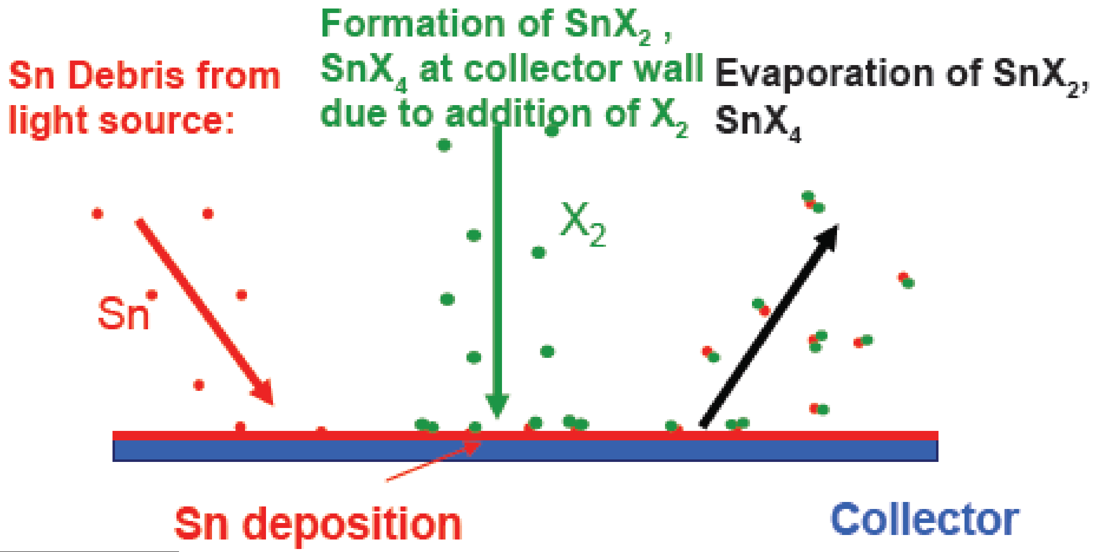


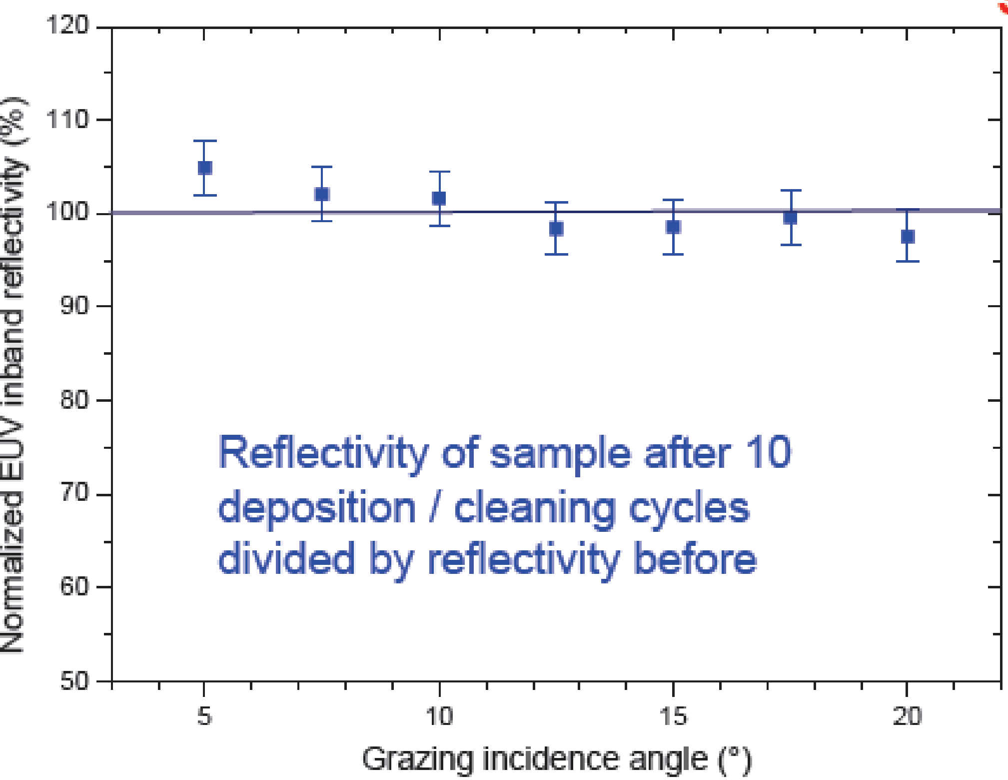
Sn Debris mitigation at test stand: study of process window



No significant reflectivity loss with good mitigation after 100M shots
→ >1Gshot lifetime before cleaning

Cleaning of collectors: additional to suppression



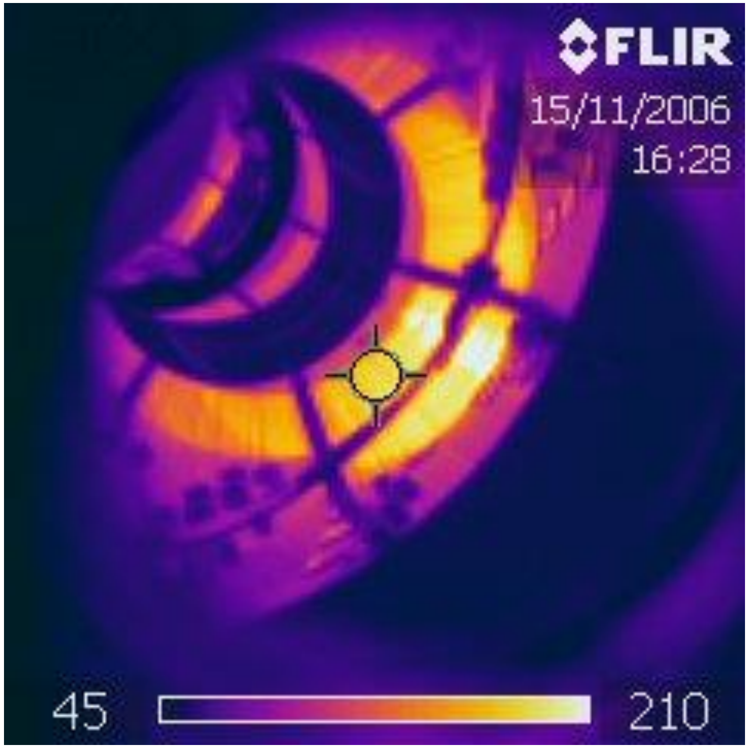


Enables >> 10^{10} Shots collector lifetime

Photos

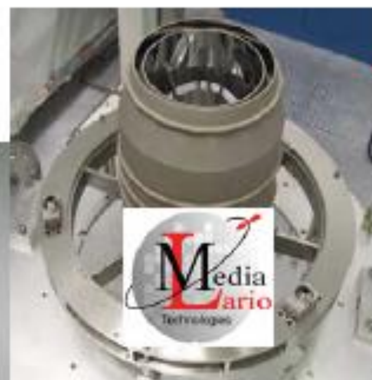
Philips Extreme UV Sn Source

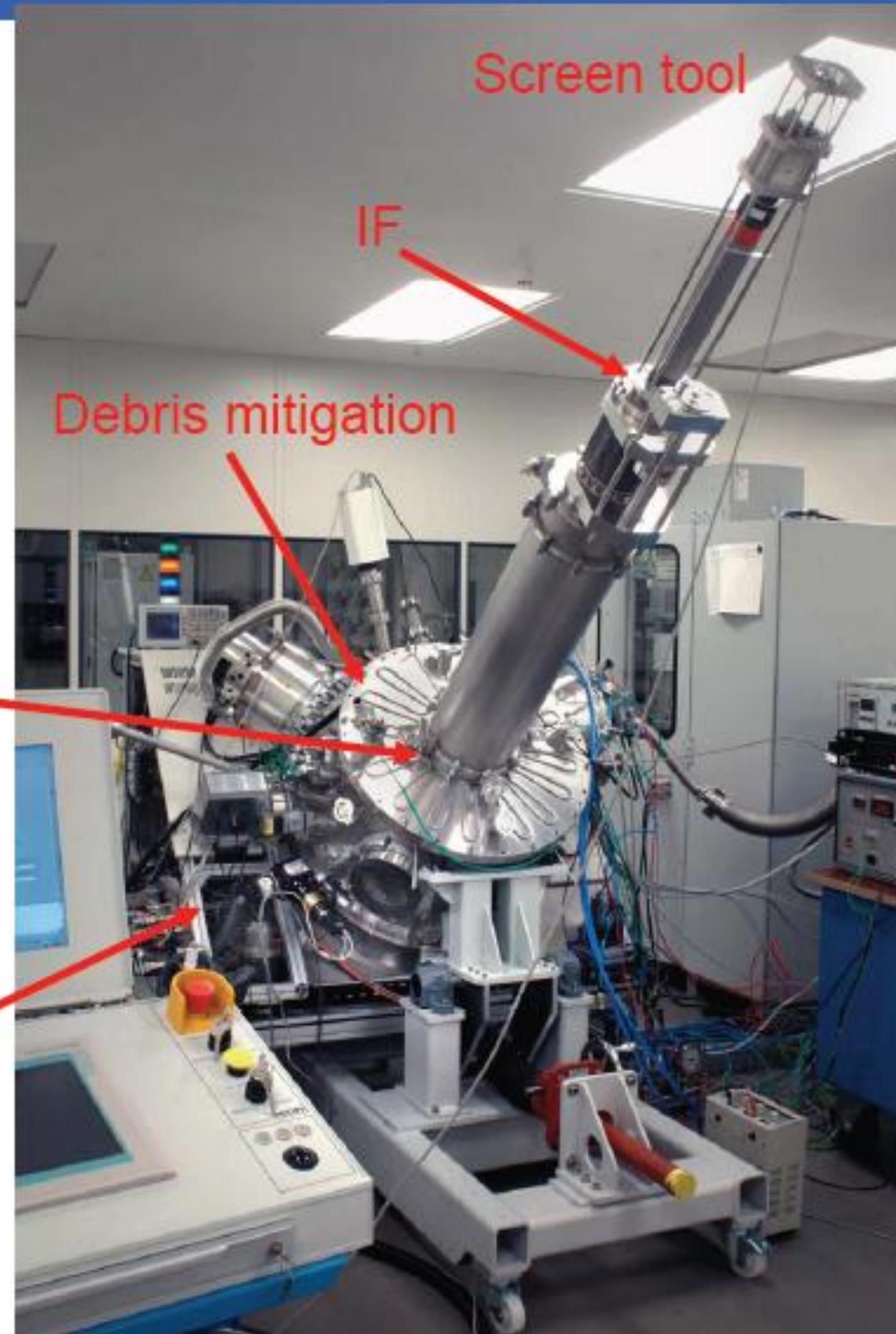
Debris mitigation: IR camera image



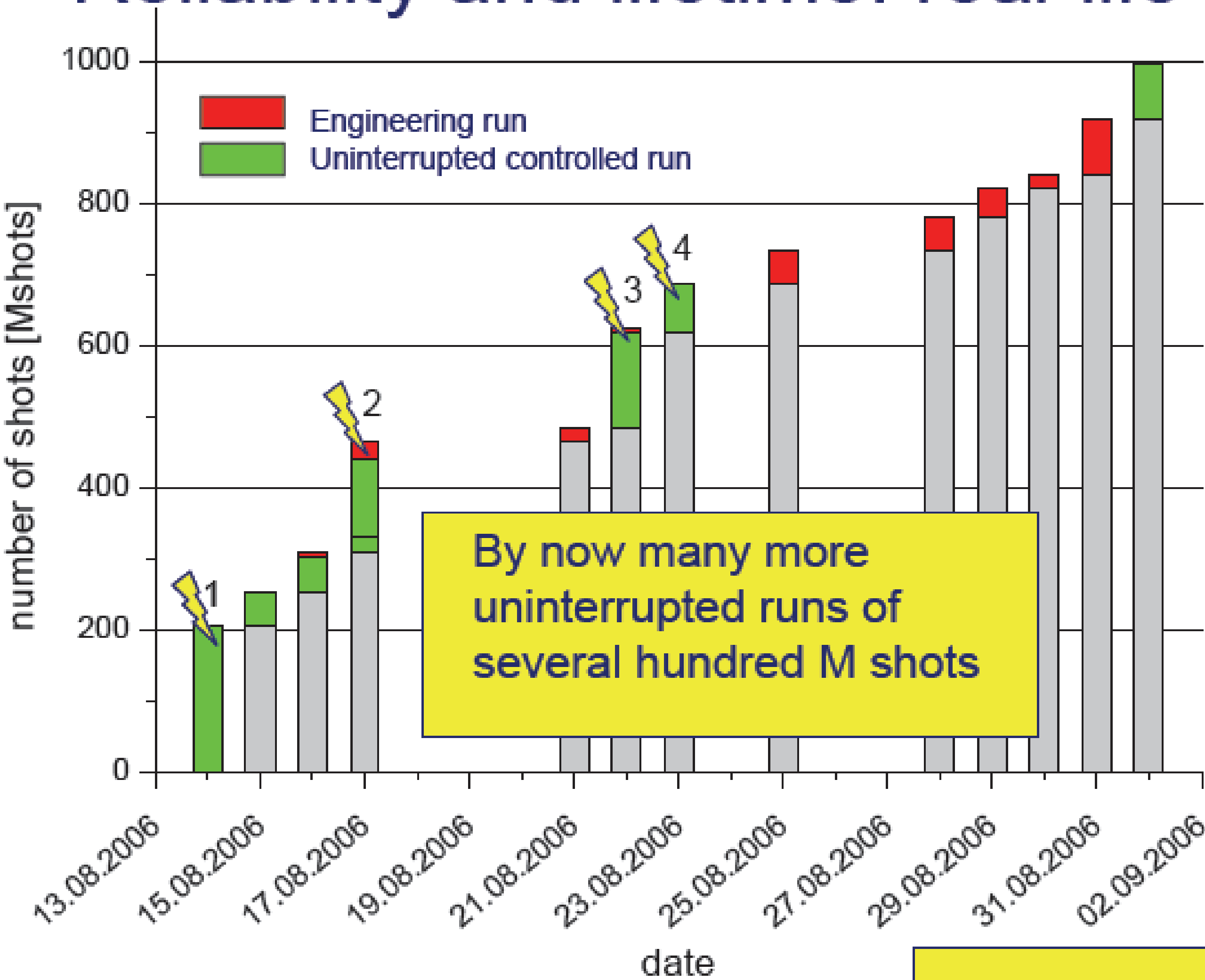
Putting our Sn SoCoMo prototype together:

- EUV source
- 2-shell collector
- mitigation and
- IF and far field analysis





Reliability and lifetime: real-life data



By now many more uninterrupted runs of several hundred M shots

Failures:

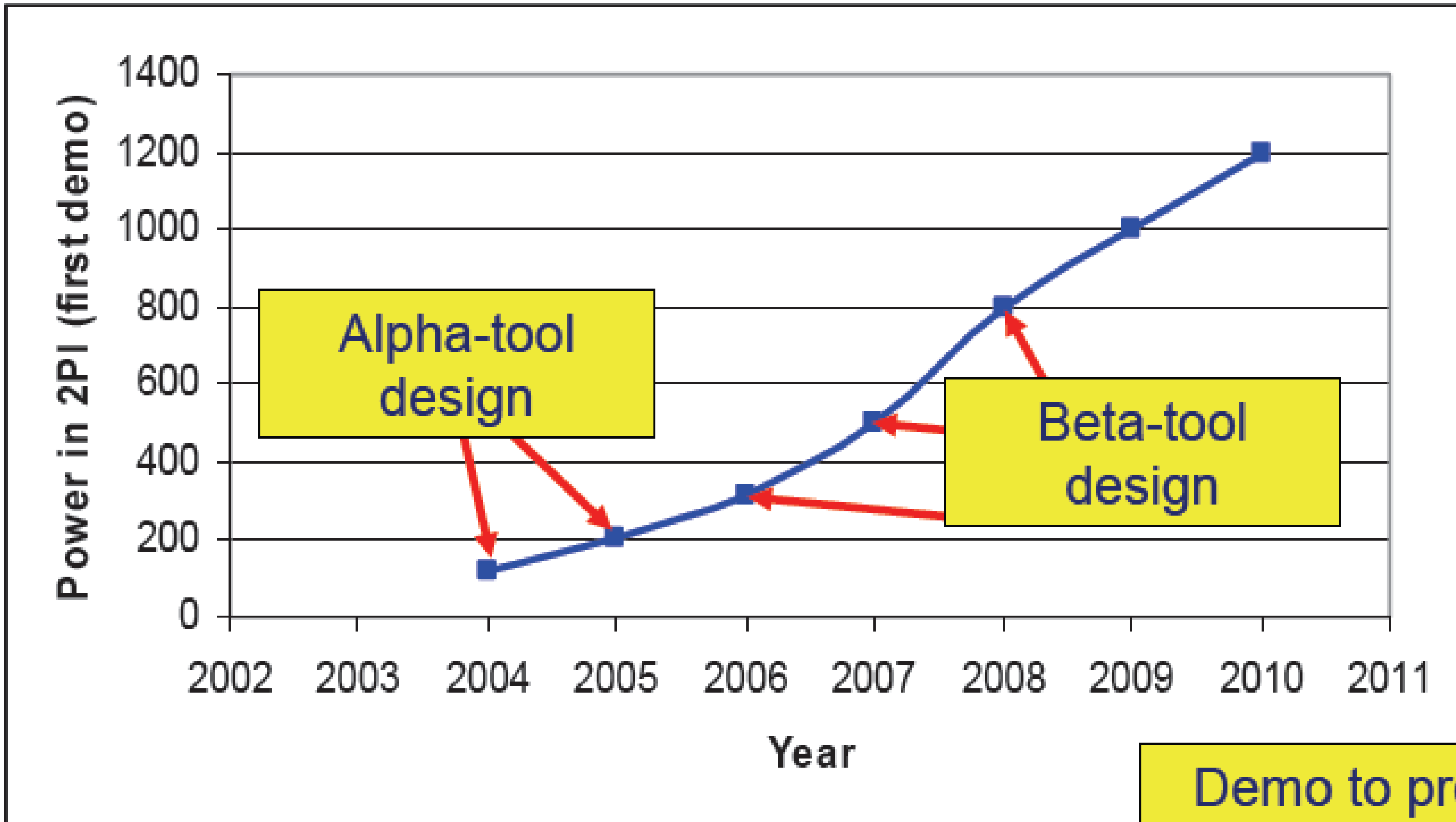
1. failure in control electronics
2. failure in tin handling
3. failure in tin handling
4. failure in control electronics

Rotating electrodes remained intact

2 failures in tin handling
2 failures in control electronics
4 failures in 1 Gshots **MTBF = 250 Mshots**

Continuous step-by-step improvement
Expected to increase alpha-tool MTBF
By more than an order of magnitude!

Philips Extreme UV roadmap for HVM



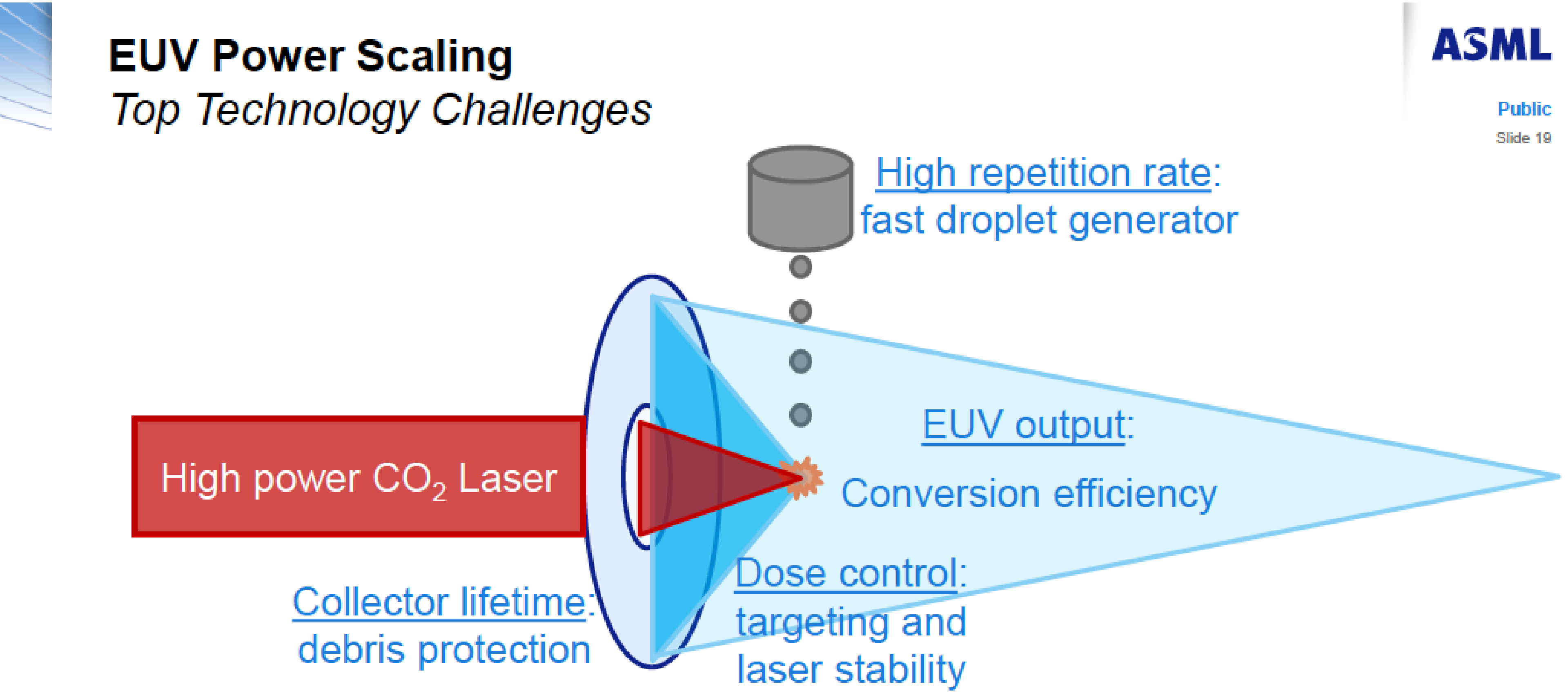
Demo to product

1-2 years

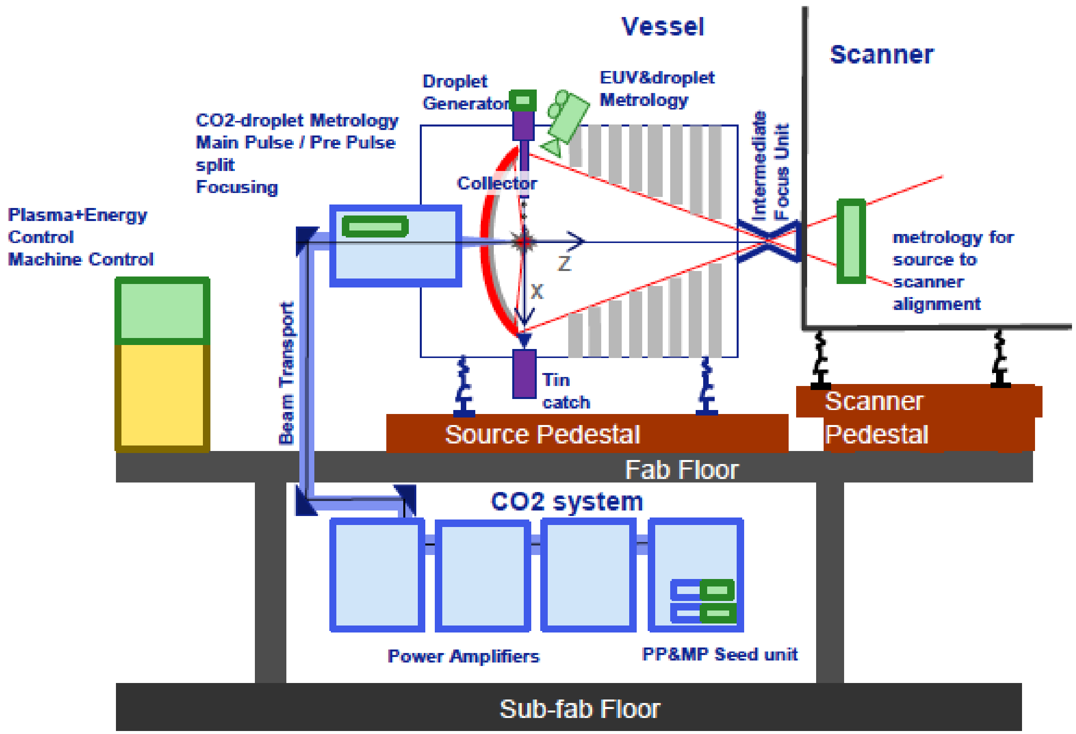
EUV source technology limits

	DPP				LPP			
	Xe		Sn		Xe		Sn	
	Today	Ultimate	Today	Ultimate	Today	Ultimate	Today	Ultimate
Input power (kW)	20	30	20	30	2.5	15	1	15
Conversion efficiency (%)	1.00	1.00	2.00	3.00	0.8	1.2	2.5	3
Power at the source (W)	200	300	400	900	20	180	25	450
Collection (sr, out of 2πsr)	1.8	3.14	1.8	3.14	3.14	5	3.14	5
Collection ability (% of 2πsr)	29	50	29	50	50	80	50	80
Collectior transmission (%)	65	70	65	70	65	70	65	70
Debris mitigation transmission (%)	80	80	80	80	100	100	100	100
Gas transmission (%)	85	85	85	85	85	85	85	85
SPF transmission (%)	40	70	40	70	40	70	40	70
Etendue match (%)	75	100	75	100	100	100	100	100
Effective collection capability (%)	4	17	4	17	11	33	11	33
Power at intermediate focus (W)	8	50	15	150	2	60	3	149

ASML LPP source concept



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

Source Cymer ASML company

Figure Nr. 30

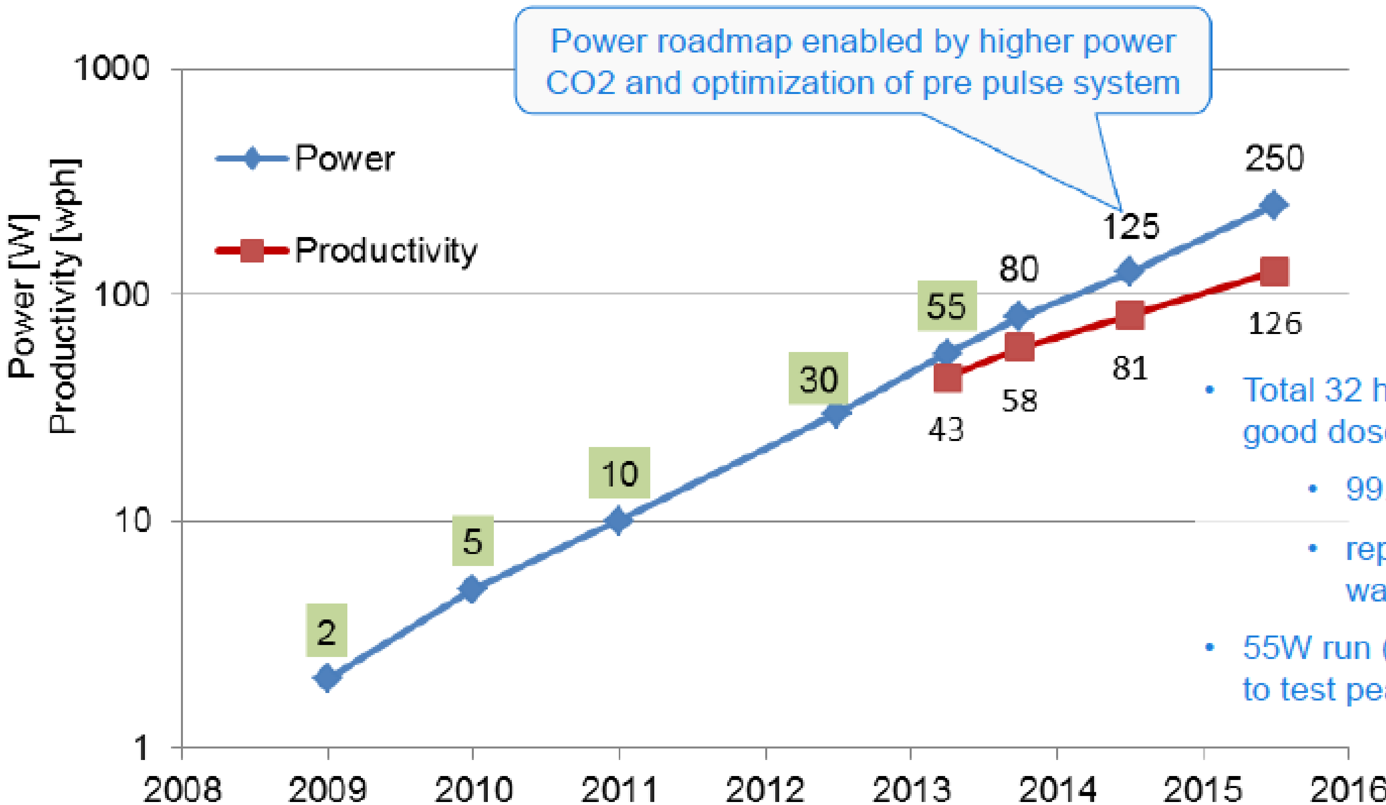
ASML source yield and projected scanner productivity

MOPA PrePulse sources demonstrated repeatable, stable performance & dose controlled

ASML

Public

Slide 32



- Total 32 hours 40W & 50W runs with good dose reproducibility:
  - 99.7% of the dies < 0.5% dose
  - representing ~ 1330 exposed wafers @ 15 mJ/cm^2
- 55W run (97.5% of dies in spec) to test peak performance

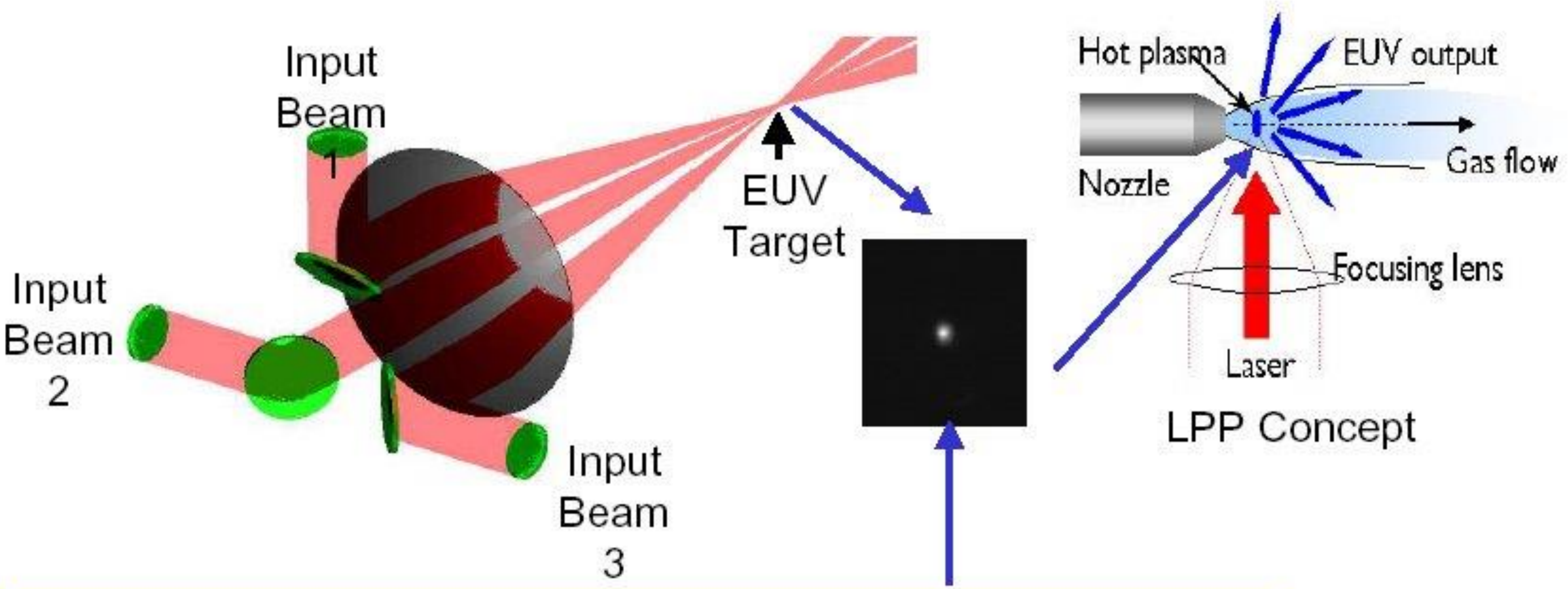
EUV source power roadmap with dose control

Power scaling is achieved with increased CO_2 laser power and conversion efficiency

	NXE:3300B	NXE:3300B	NXE:3300B
EUV dose controlled power (in-burst)	80W	125W	250W
Drive Laser	26kW	33kW	47kW
CE	3.0%	3.0%	3.3%

Spatial multiplexing

- Beams spatially combined using specially designed optics
- Using a single lens for focussing



- Far-field imaging camera permits spatial overlap of multiple beams to be monitored in real time during EUV generation

Source: 2nd international EUVL Symposium 2003; Antwerp; Belgium

Players with papers in the conferences

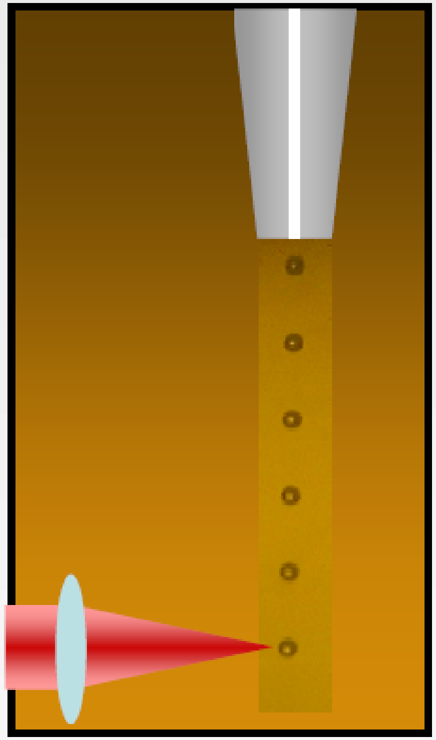
Laser-produced plasma (LPP):

- TRW
- Innolite
- JMAR
- Xtreme technologies
- Powerlase
- Alcatel / Thales
- Gigaphoton / Komatsu
- Cymer

Gasdischarge plasma (GDP):

- Cymer (historically, untill ~2004)
- Plex
- Xtreme technologies
- Gigaphoton / Ushio
- Philips Extreme UV

The UCF tin-doped droplet source



Martin Richardson

K. Takenoshita, C-S Koay, S. George, T. Schmid, S. Teerawattansook R. Bernath, C. Brown

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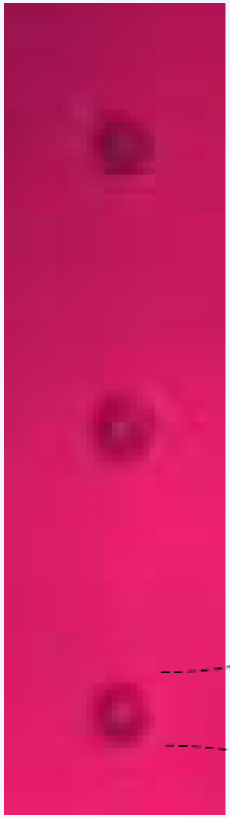
Vivek Bakshi
SEMATECH

Funded by SEMATECH, SRC Intel and the State of Florida

The tin-doped droplet laser plasma EUV source



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

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

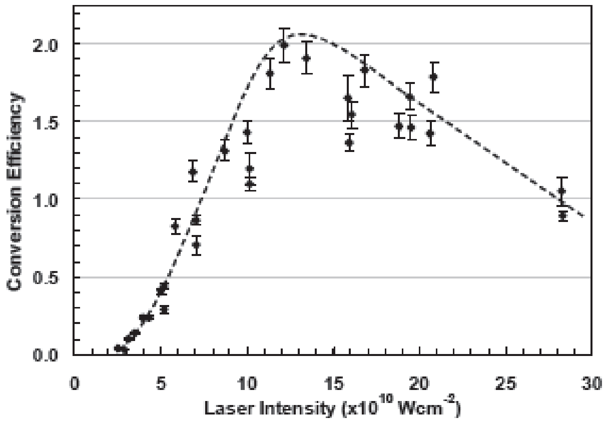
Mass-limited targets

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

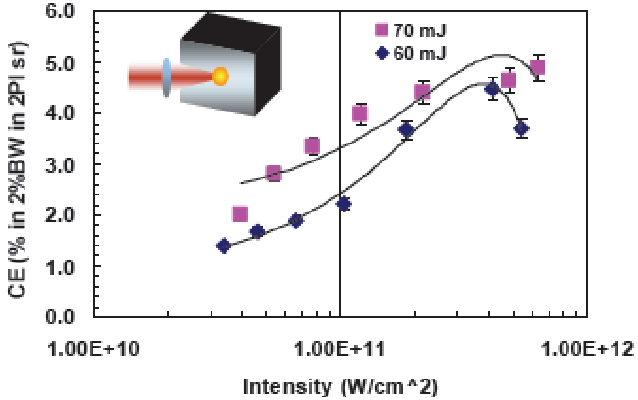
High CE demonstrated with Droplet Target

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

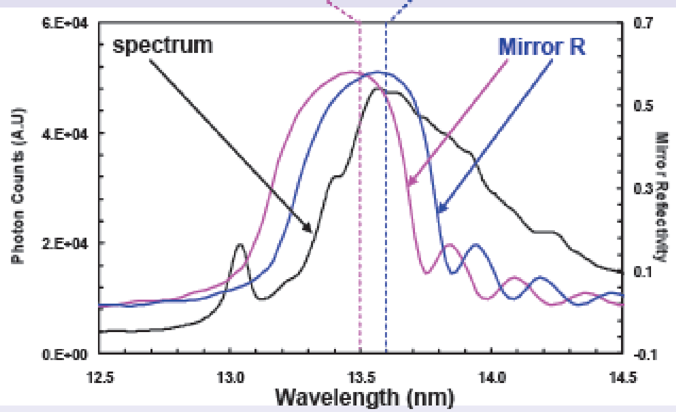


FOM FC2 team
F. Bijkerk S.A. vd Westen C. Bruineman

CE = 5.5 % with solid tin!



at 13.5nm, CE = 2%   at 13.6nm, CE = 2.25%

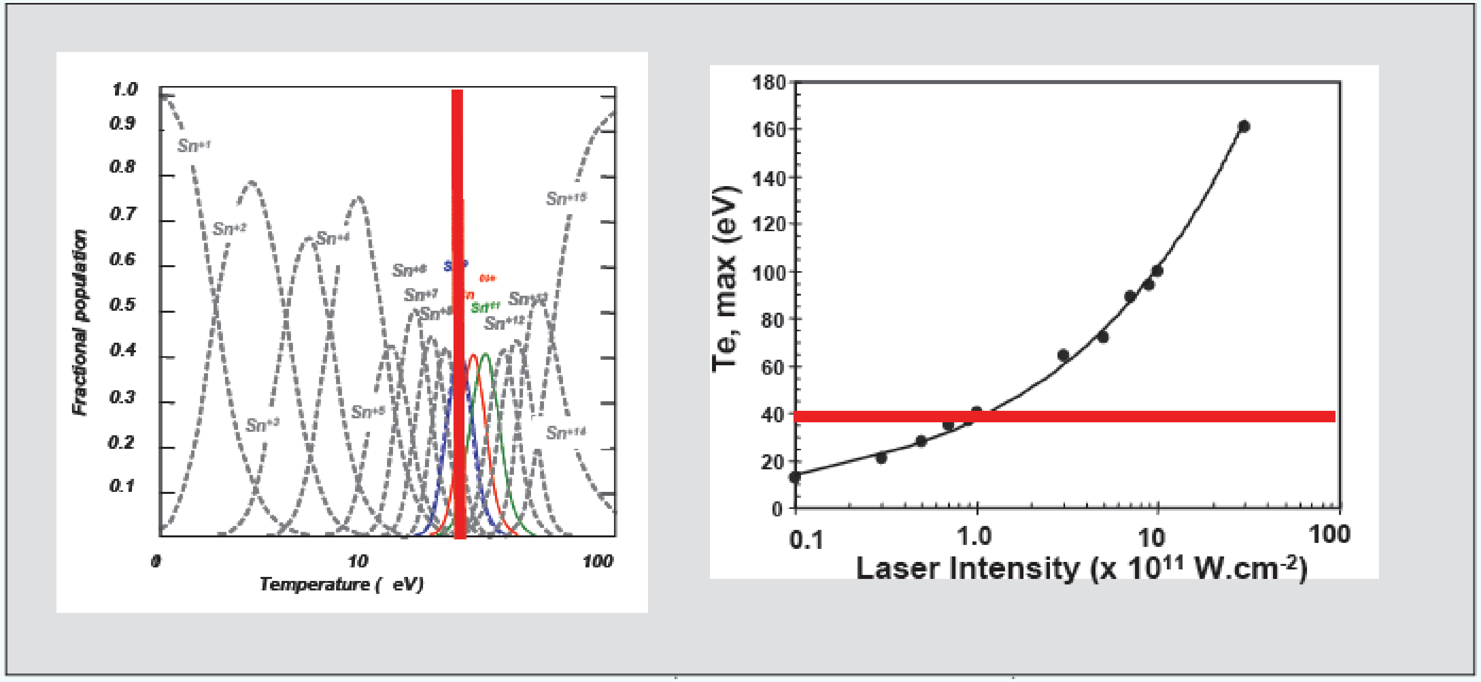


CE = 3% achievable with droplet source

--- for 30 kHz, 140 mJ laser

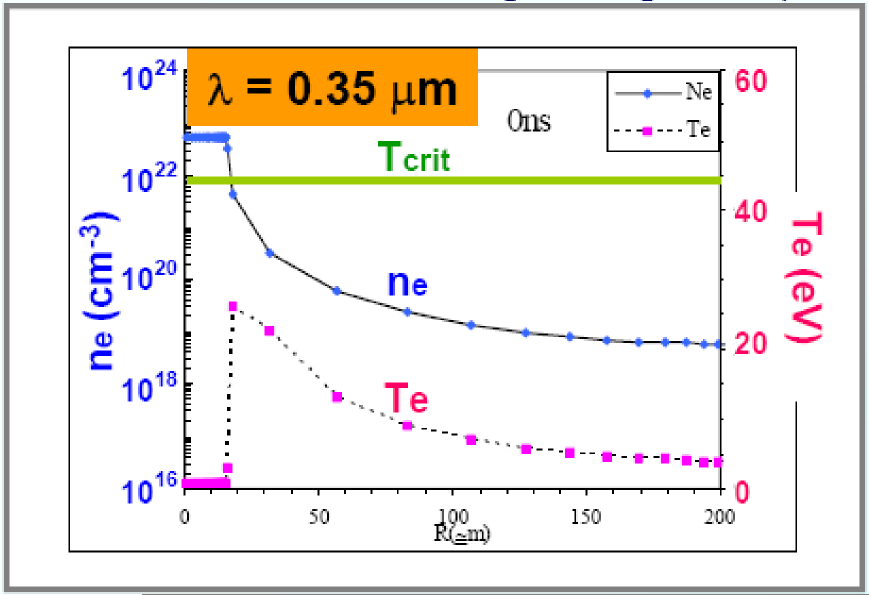
→ 120 W / 2π

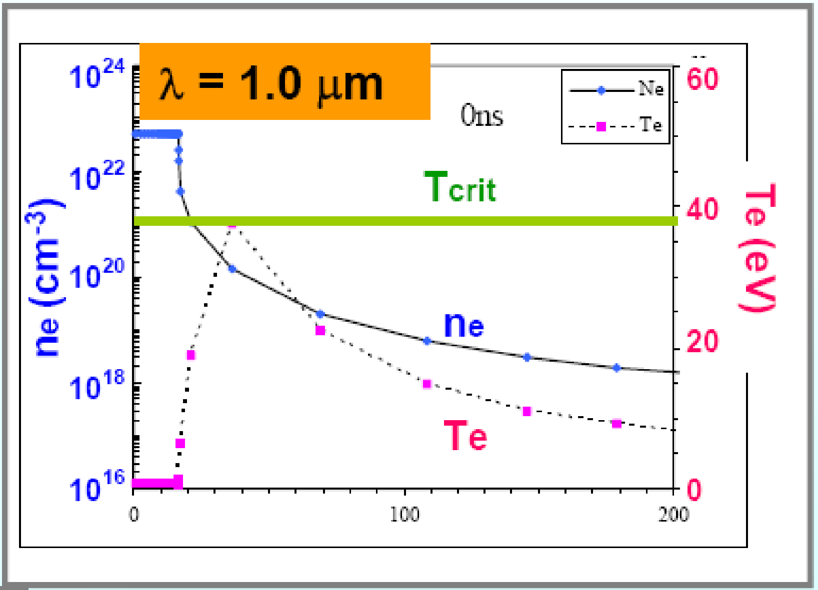
We can now manipulate the UTA emission spectrum

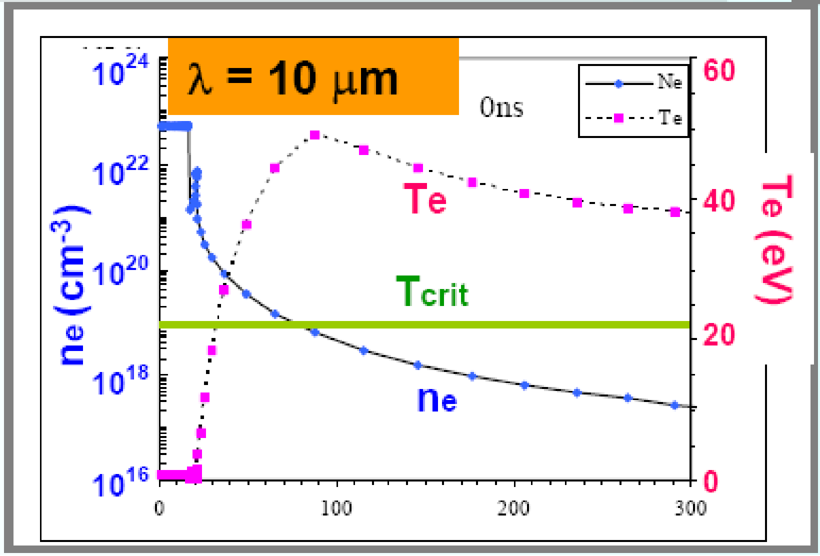


Conversion efficiency - Tin with other laser wavelengths

Condition: Tin-doped droplet, 35 μm dia, 10ns pulse, I = 1.0 x 10^{11} W/cm^2



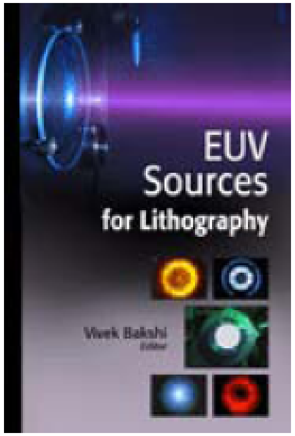




0.35μm: Te - Higher laser intensities required

10μm: -Emission comes from lower n_e region

EUV Sources for Lithography (SPIE, November 2005)
Vivek Bakshi, Editor



This comprehensive volume, edited by a senior technical staff member at SEMATECH, is the authoritative reference book on EUV source technology. The volume contains 38 chapters contributed by leading researchers and suppliers in the EUV source field. Topics range from a state-of-the-art overview and in-depth explanation of EUV source requirements, to fundamental atomic data and theoretical models of EUV sources based on discharge-produced plasmas (DPPs) and laser-produced plasmas (LPPs), to a description of prominent DPP and LPP designs and other technologies for producing EUV radiation. Additional topics include EUV source metrology and components (collectors, electrodes), debris mitigation, and mechanisms of component erosion in EUV sources. The volume is intended to meet the needs of both practitioners of the technology and readers seeking an introduction to the subject.

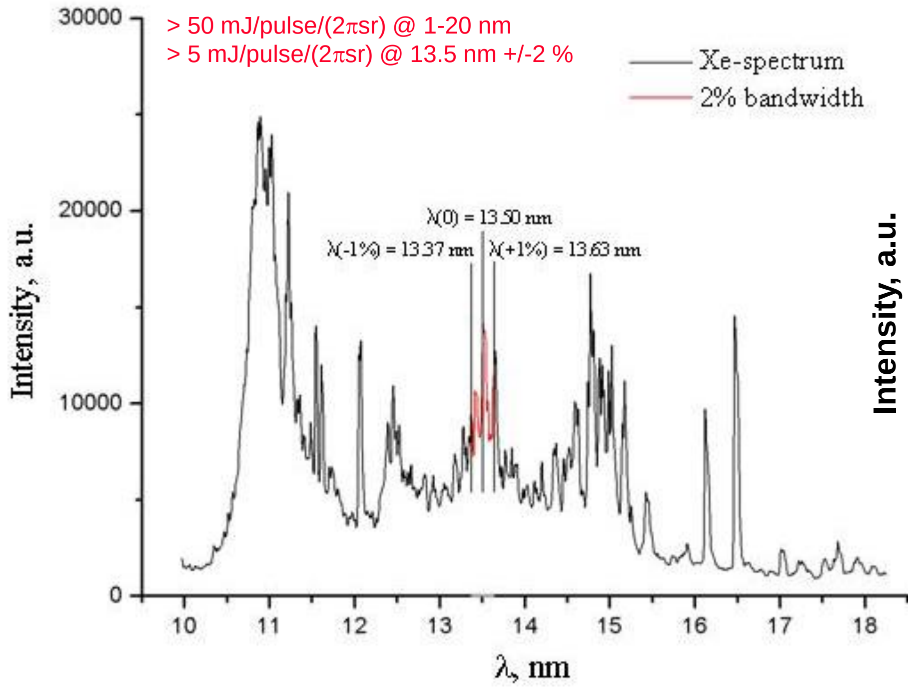
Prices: $127 / $150 (SPIE Member/List)
(Available November 2005)

Radiation from hot plasmas

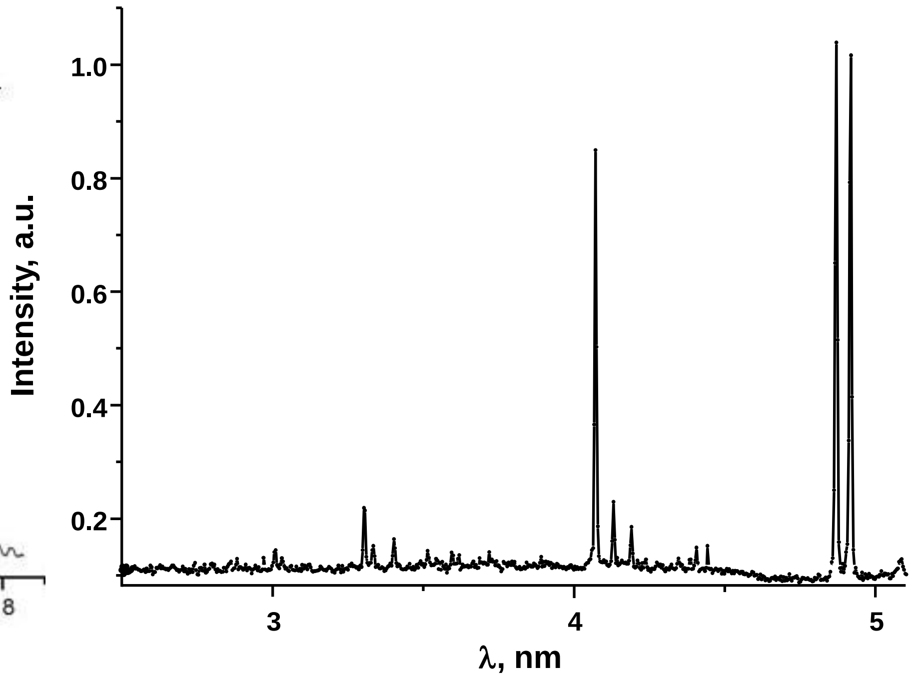
T_e ~ 10 – 500 eV, n_e ~ 10^{17} – 10^{21} cm^{-3}
E_{input} ~ 0.25 – 10 J/Puls, t_{puls} ~ 0.2 – 100 ns
$\varnothing_{plasma}$ ~ 50 – 500 μm

$$P_{rad} = P_{line} + P_{rec} + P_{br}$$

Xenon emission spectrum in the EUV region



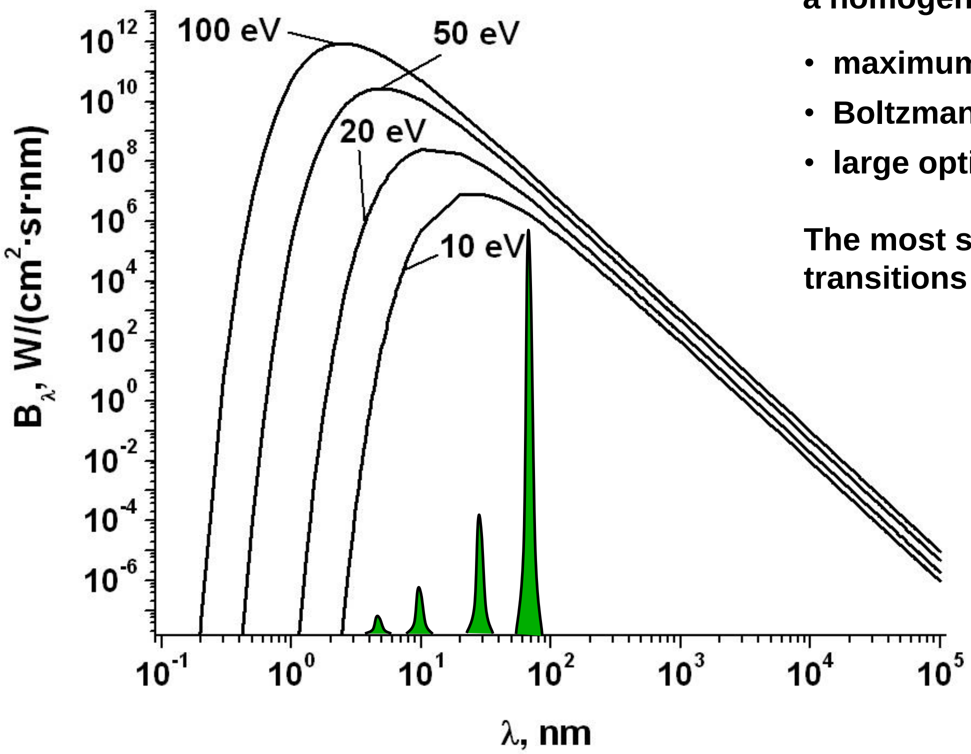
Argon emission spectrum in the soft x-ray region



Pseudo-Planck emitter

Pseudo-Planck emitter: radiation source, whose emission in a spectrally limited interval reaches the Planck curve, not however necessarily for the entire and/or a broader range

Planck function



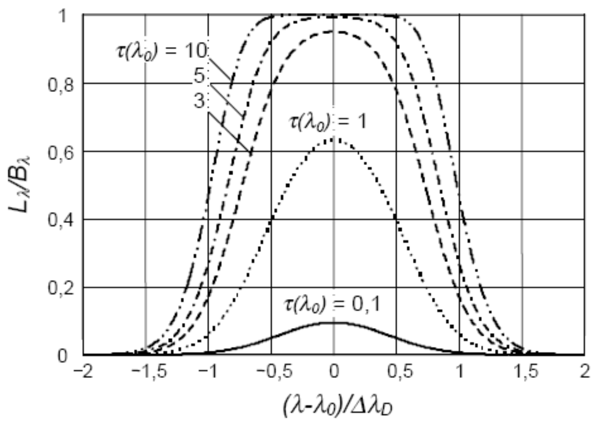
Spectral radiance L_λ at the surface of a homogeneous radiating plasma:

$$L_\lambda = S_\lambda \cdot \left(1 - e^{-\tau(\lambda)}\right)$$

- **maximum possible radiance for T_{plasma} in steady state**
- **Boltzmann distribution of population densities required**
- **large optical thickness over the line of sight required**

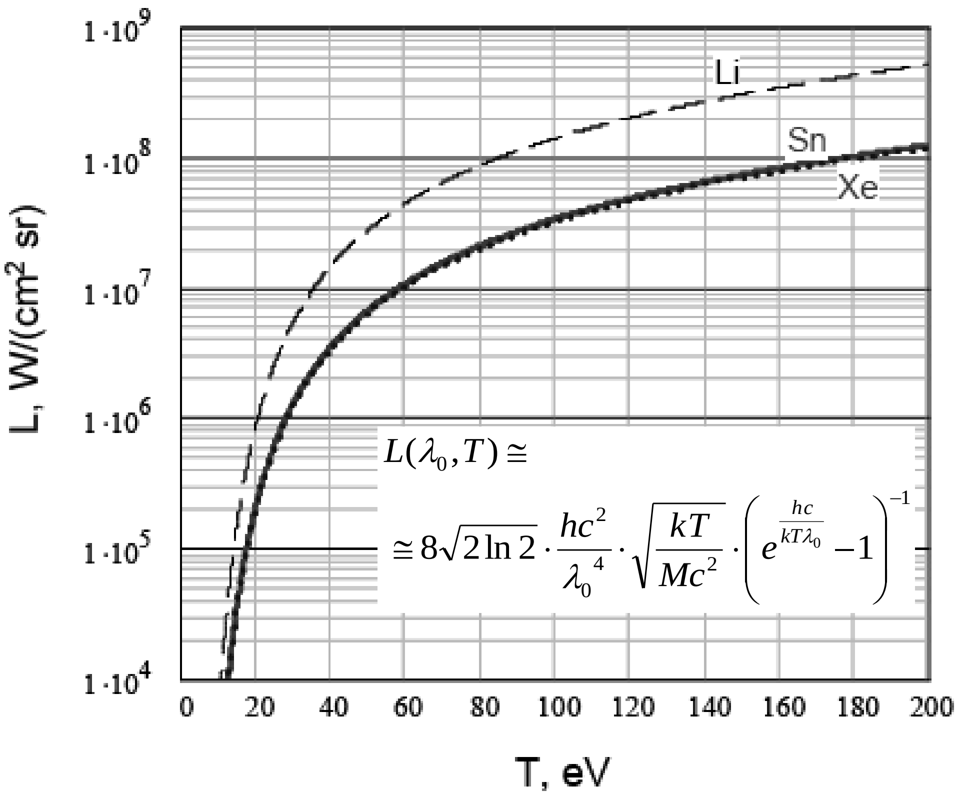
The most suitable candidates in XUV: Resonance transitions

Opacity influence on line profile



Possible line intensities

Radiance of one optically thick line ($\Delta\lambda_{1/2} \sim 2\Delta\lambda_{Doppler}$) at 13.5 nm for Li (6.94 u), Sn (118.7 u) and Xe (131.3 u)

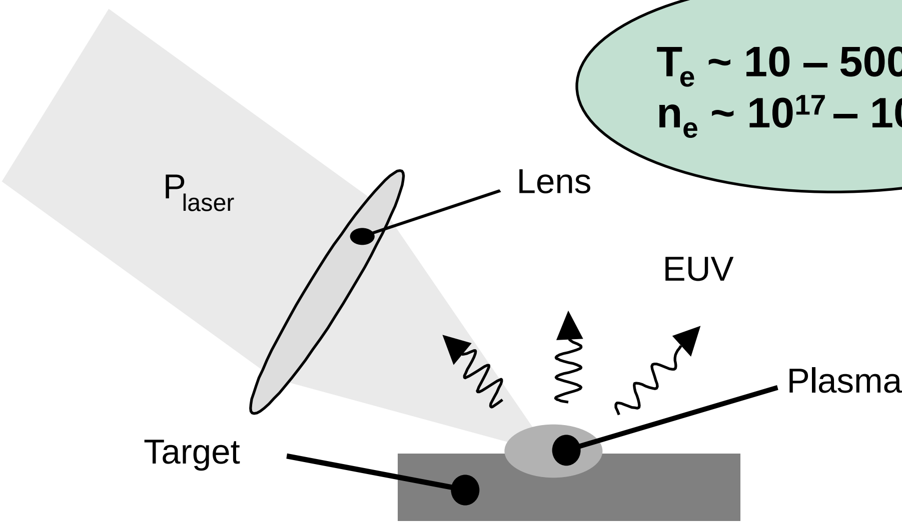


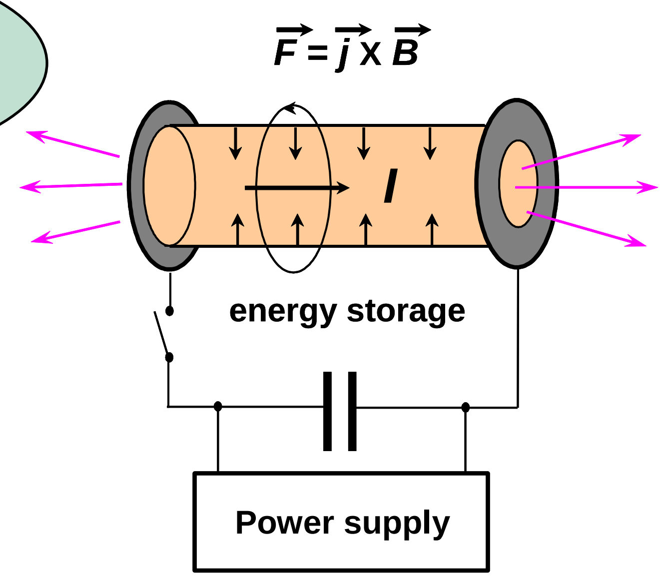
- **useful for rough estimate of maximum power**
- **electron temperature has to match ionization level balance (avoid over-ionization)**
- **electron density ensuring Boltzmann distribution and opacity**
- **optimizing by increasing T_e possible in transient plasmas, especially for lower densities**
- **resonance UTA with broader spectral range and corresponding higher radiation power**
- **increasing of lifetime for higher radiation energy**

LPP und DPP

Laser produced plasma | **Discharge produced plasma**

$T_e \sim 10 - 500$ eV
$n_e \sim 10^{17} - 10^{21}$ cm^{-3}



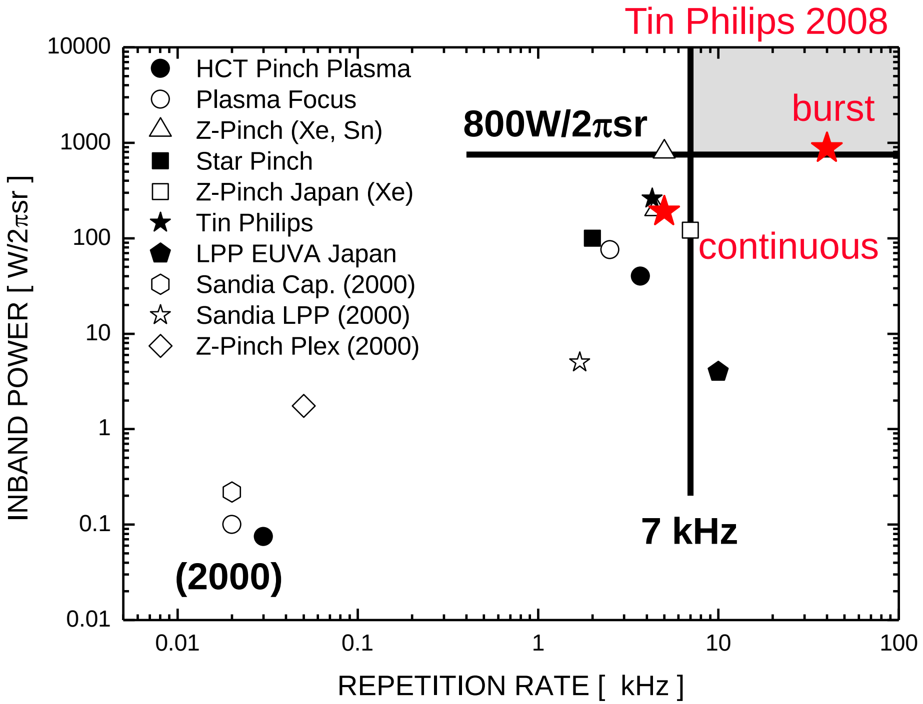


Typical parameters for laser and discharge produced plasmas ➡

Parameter		LPP	DPP
Pulse duration	ns	0.2 – 10	10 – 100
Energy	J/Puls	0.25 – 1.5	2 – 10
Diameter	μm	50 – 100	100 – 500

Summary on XUV sources

Today's achieved radiating power (λ_0 = 13.5 nm) and repetition rates for different source concepts



Source: L. Juschkin, G. Derra, K. Bergmann, EUV Light Sources, Contr. to „Low Temperature Plasmas. Fundamentals, Technologies, and Techniques", ed. by R. Hippler, H. Kersten, M. Schmidt, K.H. Schoenbach, 619-654, (2007)

basic physics:

- single lines or bunch of lines (UTA) are most intense contributors
- Planck limit better achieved in LPP because of higher density
- XUV lasers exist - more sophisticated to achieve plasma parameters
- emission always pulsed, max. few 100 ns

technological aspects

- LPP and DPP with main differences in diameter and pulse duration
- large technological progress within the last decade due to EUV lithography
- commercial sources already available
- impact on laboratory scale applications