# EUV Lithography and EUVL sources: from the beginning to NXE and beyond.

V. Banine

# Content

- EUV lithography: History and status
- EUV sources- historical perspective:
    - Age of choice
    - Age of Xe
    - Age of Sn
    - Age of industrialization
    - … and beyond
- Conclusions

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# EUV has come a long way in last 25 years

1st papers soft X-ray for lithography (LLNL, Bell Labs)

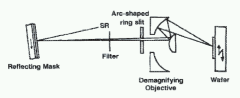
ASML start EUVL research program

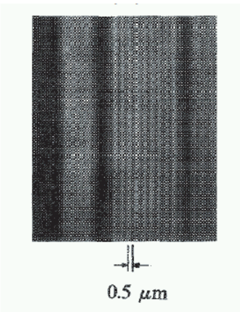
ASML ships 2 alpha tools to IMEC (Belgium) and CNSE (USA)

ASML ships pre-production tools

'85 '86 '87 '88 '89 '90 '91 '92 '93 '94 '95 '96 '97 '98 '99 '00 '01 '02 '03 '04 '05 '06 '07 '08 '09 '10 11

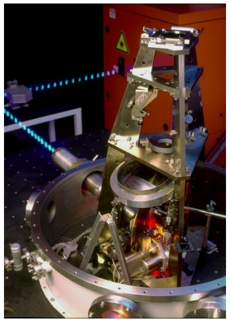
**Japan:**

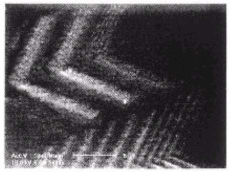




Kinoshita et al

**NL:**





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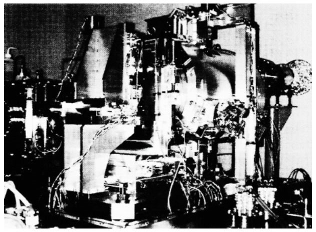

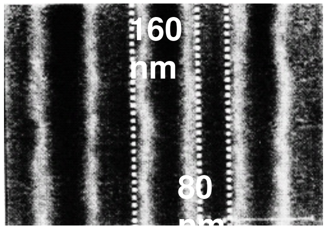

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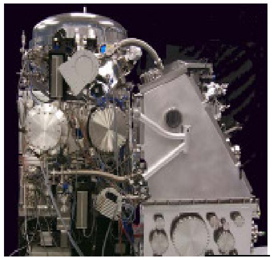

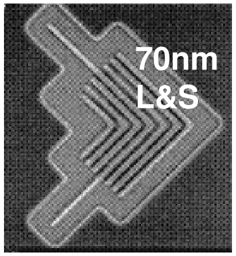

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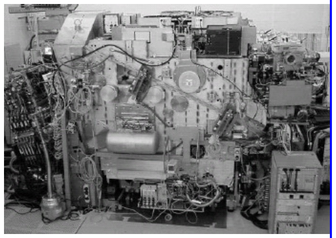

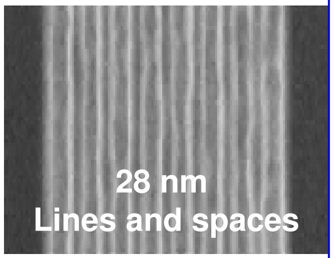

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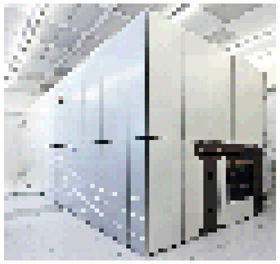
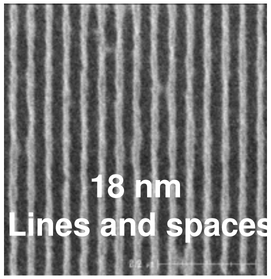




- ASML has active program since 1997.
- Currently >1000 people work on pre-production systems are shipped 2010-11.

# EUV and BEUV product roadmap spans >10 years

|  |  |  |  |  | *Under study* |  |
|---|---|---|---|---|---|---|
|  | **0.25 NA** |  | **0.33 NA** |  | **>0.40 NA** |  |
| **Lens mirrors** | 6M | 6M | 6M | 6M | 6/8M | 6/8M |
| **Wavelength** | 13.5 nm | 13.5 nm | 13.5 nm | 13.5 nm | 13.5 nm | New $\lambda$ |
| **Product** | **ADT** | **3100** | **3300B** | **3300C** | **3500** | **>3500** |
| **Introduction year** | **2006** | **2010** | **2012** | **2013** | **2016** | **>2018** |
| **Resolution (hp)** | 32 nm | 27 nm | 22 nm | 18 nm | 11 nm | <8 nm |
| **Sigma** | 0.5 | 0.8 | 0.2-0.9 | OAI | flex OAI | flex OAI |
| **Overlay (SMO)** | 7.0 nm | 4.5 nm | 3.5 nm | 3.0 nm |  |  |
| **Throughput (wph)** | 4 wph | 60 wph | 125 wph | 150 wph |  |  |
| **Dose (mJ/cm$^2$)** | 5 | 10 | 15 | 15 |  |  |
| **Source (W)** | 3 | 105 | 250 | 350 |  |  |

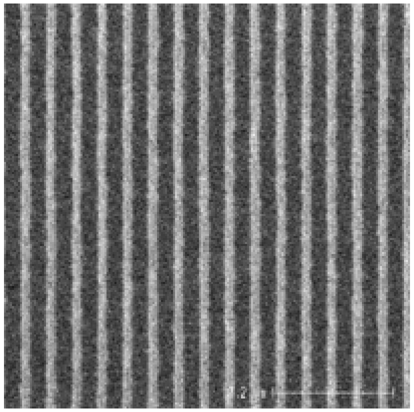
# Next step in EUV Manufacturing integration: 4 NXE:3100 shipped, 1st operational at customer site

- Imaging
    - Resolution 27nm
    - NA=0.25
    - σ=0.8
- Overlay
    - DCO=4.0 nm
    - MMO=7.0 nm
- Productivity
    - 60wph
    - 10mJ/cm$^2$ resist

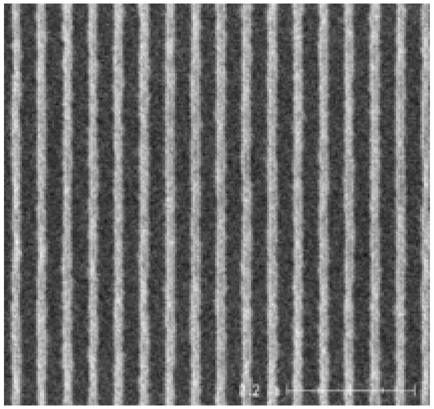
# Further Resolution extension with 0.25NA

## supports resist and process development for NXE:3300

- dipole-60, inorganic negative tone resist
- further reduction of resolution with smaller poles possible



21p42



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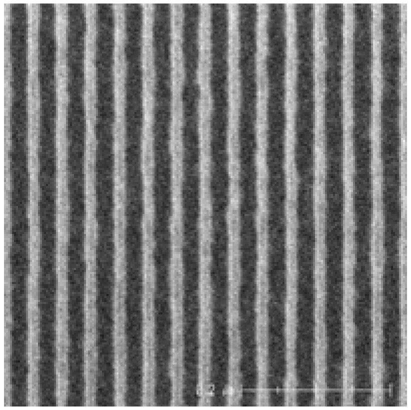

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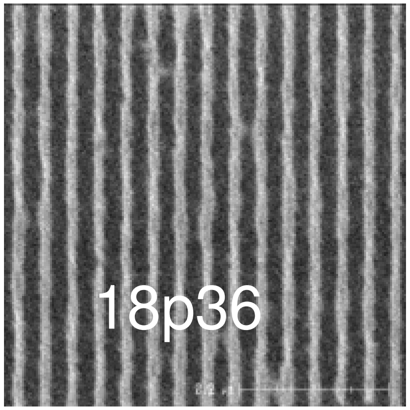

18p36

*in collaboration with IMEC, resist Inpria*

# NXE:3100 and source challenges

Challenges:

- To produce enough power (Plasma source)
- To protect collection optics from the debris produced by the source (Plasma sputtering and deposition)

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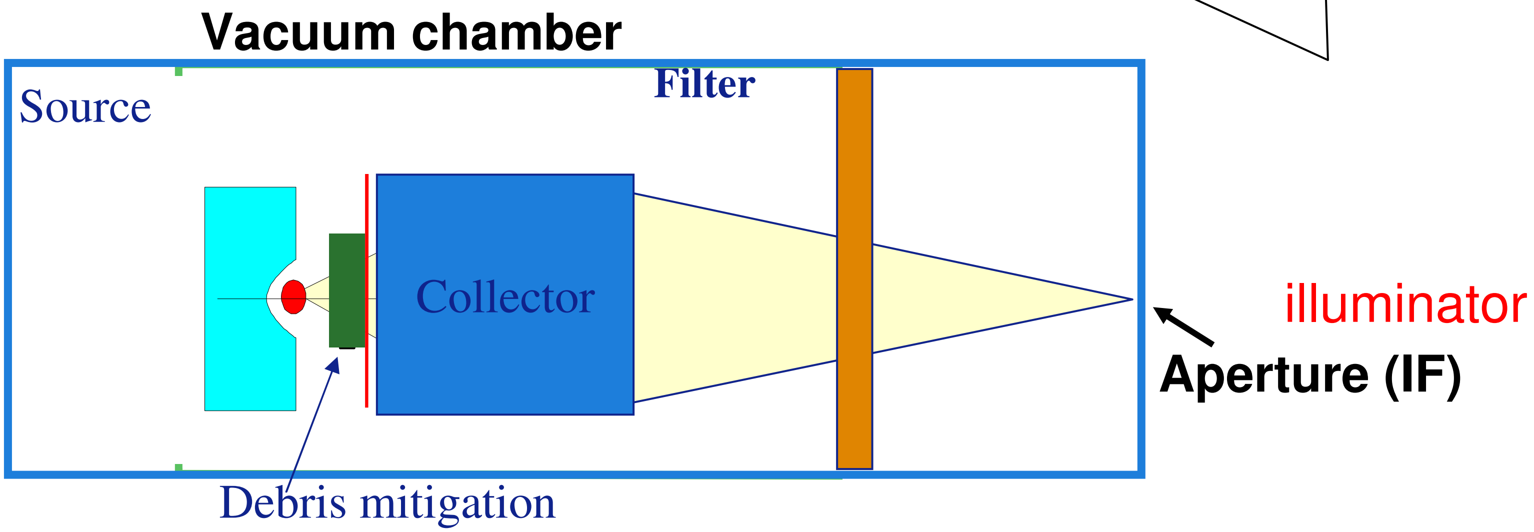
# Definition of clean photon spot at intermediate focus (IF)

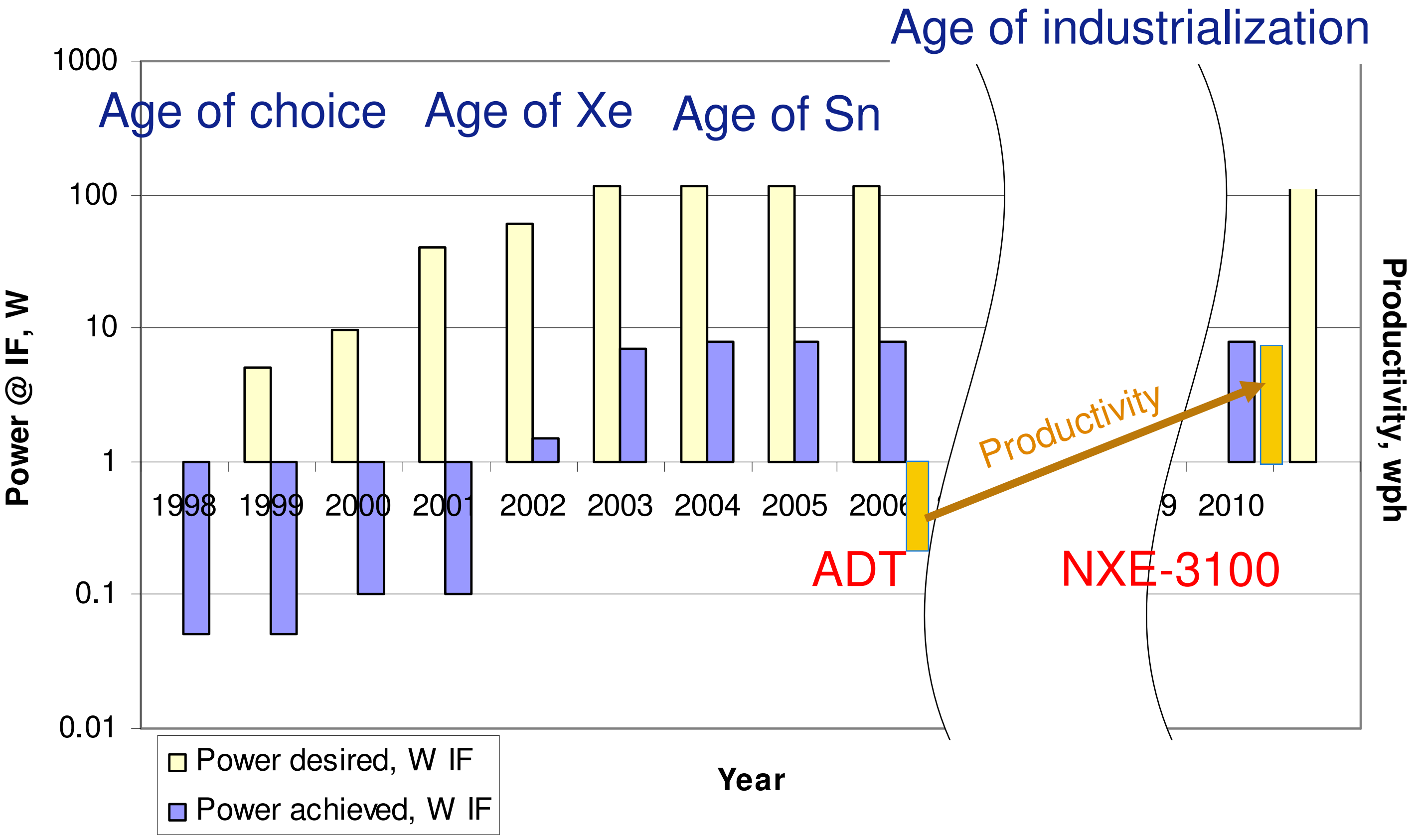
Source specifications are defined at intermediate focus (IF) which is illuminator entrance



# Joint Requirements for EUV Source till not long ago (2008)

| SOURCE CHARACTERISTIC | REQUIREMENT |
|---|---|
| •Wavelength | 13.5 [nm] |
| •EUV Power (in-band) | 115 [W] |
| •Etendue of Source Output | max 1 - 3.3 mm$^2$sr |
| •Collector lifetime (to 10% loss) | > 15000 hours |
| •Source Cleanliness at IF | ≥ 30,000 hours |
| •Max. solid angle input to illuminator | 0.03 - 0.2 [sr] |
| •Repetition Frequency | > 6000 Hz |
| •Integrated Energy Stability | ±0.3%, $3\sigma$ over 50 pulses |
| •Spectral purity: | |
| 130-400 [nm] (DUV/UV) | ≤ 3 - 7% |
| ≥ 400 [nm] (IRVis) at Wafer | TBD |

# Historical perspective: Production power requirement, achieved power, productivity



Averaged and independent on supplier

Gap in productivity is being bridged, in reliable power is still 10x to go.

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# Synchrotron wiggler, undulator , FEL

Never made it

Principle:

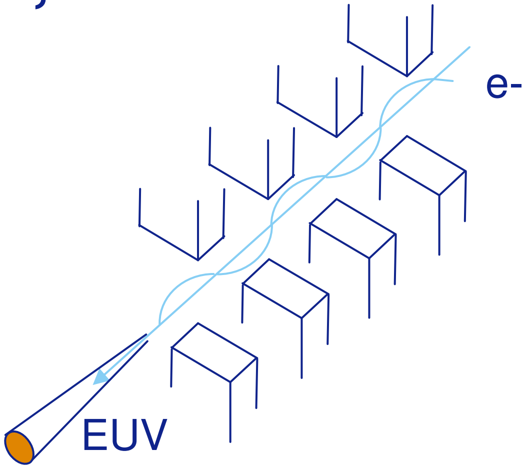
1. Relativistic electrons traversing a periodic magnetic structure are being bent;
2. Being bent, electrons emit EUV.

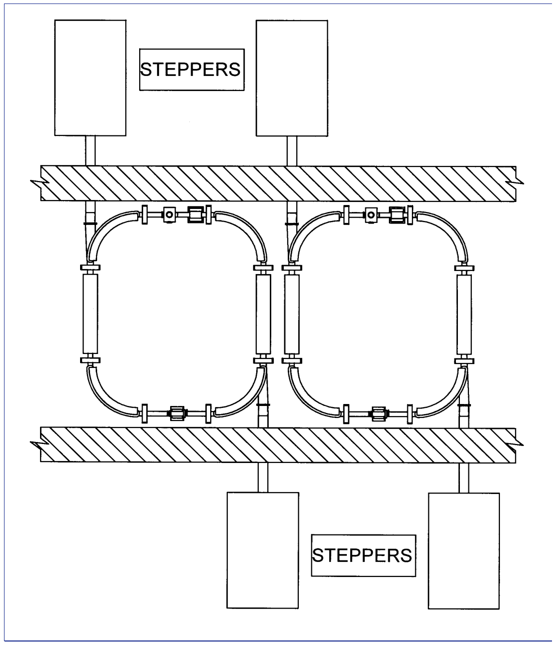
Prospects before 2000:

1. No debris;
2. Good dose repeatability;
3. High maturity (1999!);
4. High uptime

Issues:

1. High CoO;
2. Non-flexible configuration.
3. Not enough power (2005!)
4. Current update: 0.2 W with FLASH (250 m installation)

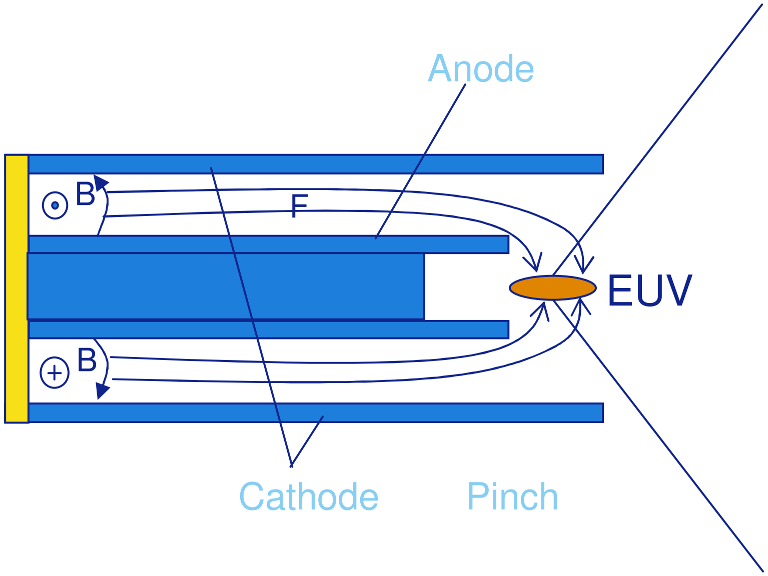




See for further reference eg: DC Ockwell et al J. Vac. Sci. Technol. B **17**, 3043 (1999)

RIP 2004

# Plasma focus (Cymer)



Principle:

1. Voltage is applied between anode and cathode;
2. Interaction of magnetic field with current pushes the current to the anode top;
3. Very hot Xe plasma cluster (PF) is formed;
4. EUV is emitted

Prospects before 2000 :

1. Low CoO.

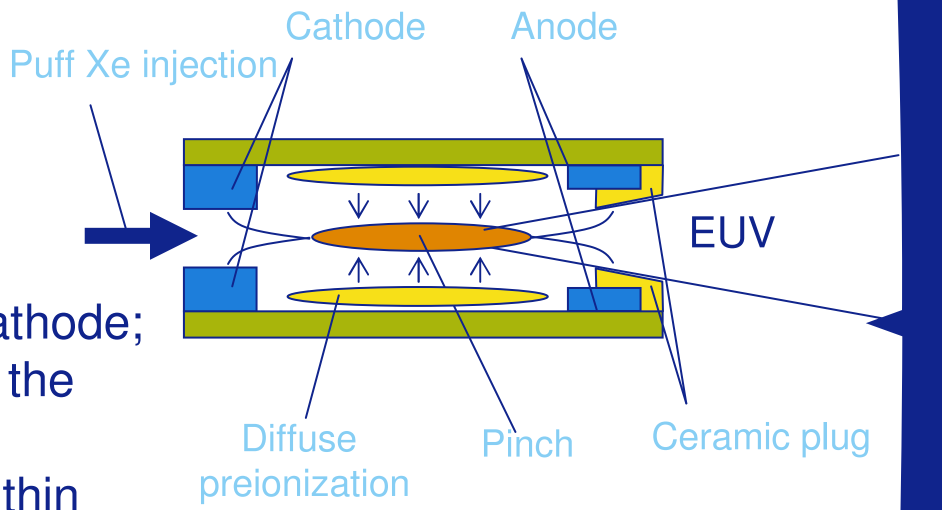
Issues:

1. Debris (solution is forseen);
2. Heat load;
3. Component erosion;
4. Pulse to pulse repeatability.

See for further reference eg: Fomenkov et al, Sematech International workshop on EUVL, 1999

# Z-pinch

Changed but still alive



Principle:

1. Xe is puffed into the system;
2. Diffused preionization is applied;
3. Voltage is applied between anode and cathode;
4. Azimuthal magnetic field is generated by the current;
5. Magnetic field contracts discharge into a thin thread,
   which is called Z-pinch;
6. This produces high temperature and thus EUV.

Early prospects:

1. Low CoO;

Issues:

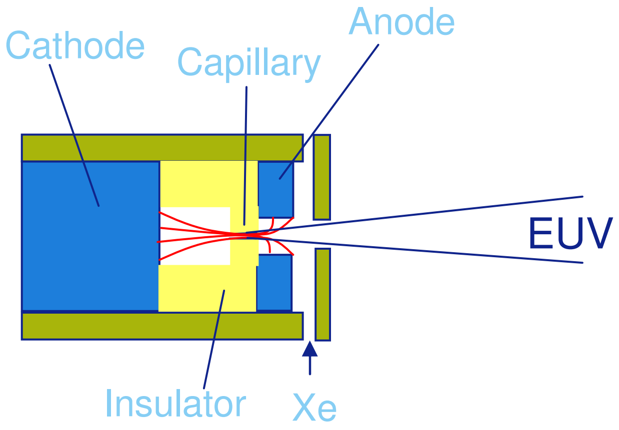
1. Debris (solution is foreseen);
2. Heat load;
3. Component erosion;
4. High rep. rate.

See for further reference eg:Bakshi V, EUV Sources for Lithography, SPIE Press, Bellingham, Washington, USA, 2006

Never made it

# Capillary discharge

Principle:



1. Xe is being pumped through the system;
2. Voltage is applied between anode and cathode;
3. Geometrically current is driven to flow through a narrow capillary;
4. Due to Joule dissipation Xe is being heated and emits EUV;

Prospects before 2000 :

1. Low CoO.

Issues:

1. Debris;
2. Heat load;
3. Component erosion;
4. High rep. rate. ( >1000 Hz)

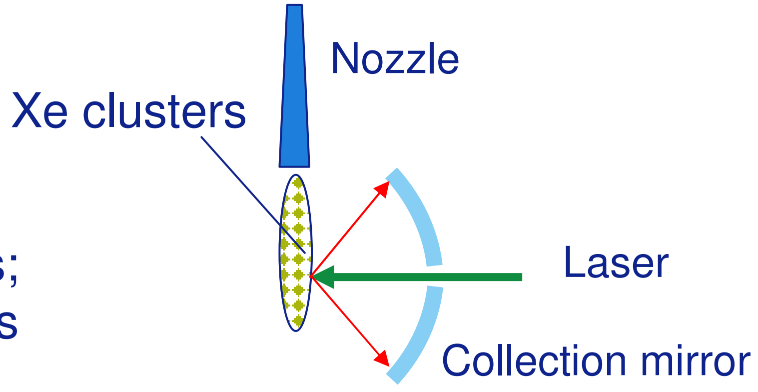
See for further reference eg: F. Jin. and M. Richardson., *Applied Optics* **34**, p.5750, 1995

Changed but still alive

# LPP plasma

Principle:

1. An intense pulsed laser is focused on targets, which are jet produced Xe clusters;
2. Xe is highly ionized by heating and emits EUV.



Prospects before 2000 :

1. High maturity;
2. Good dose repeatability.

Issues:

1. CoO;
2. Debris;
3. MoBe optics (11 nm) (1999!)

See for further reference eg:Bakshi V, EUV Sources for Lithography, SPIE Press, Bellingham, Washington, USA, 2006

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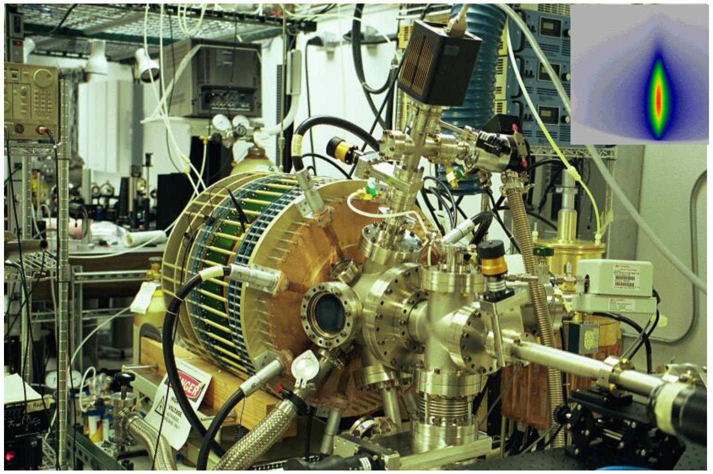
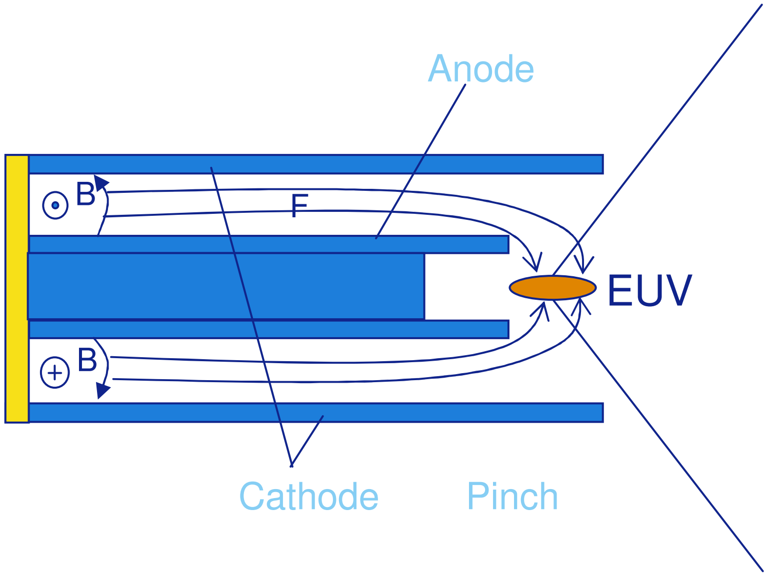
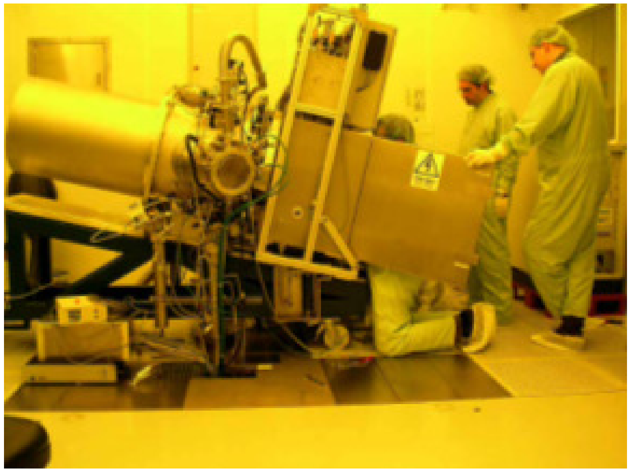
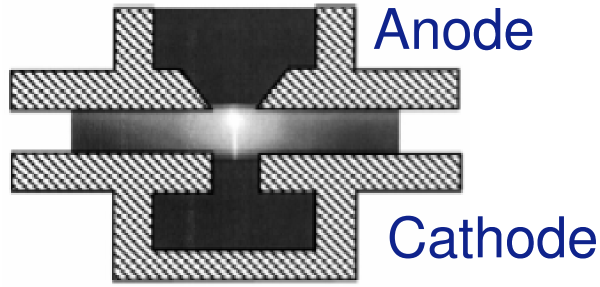
## Plasma Focus of Cymer





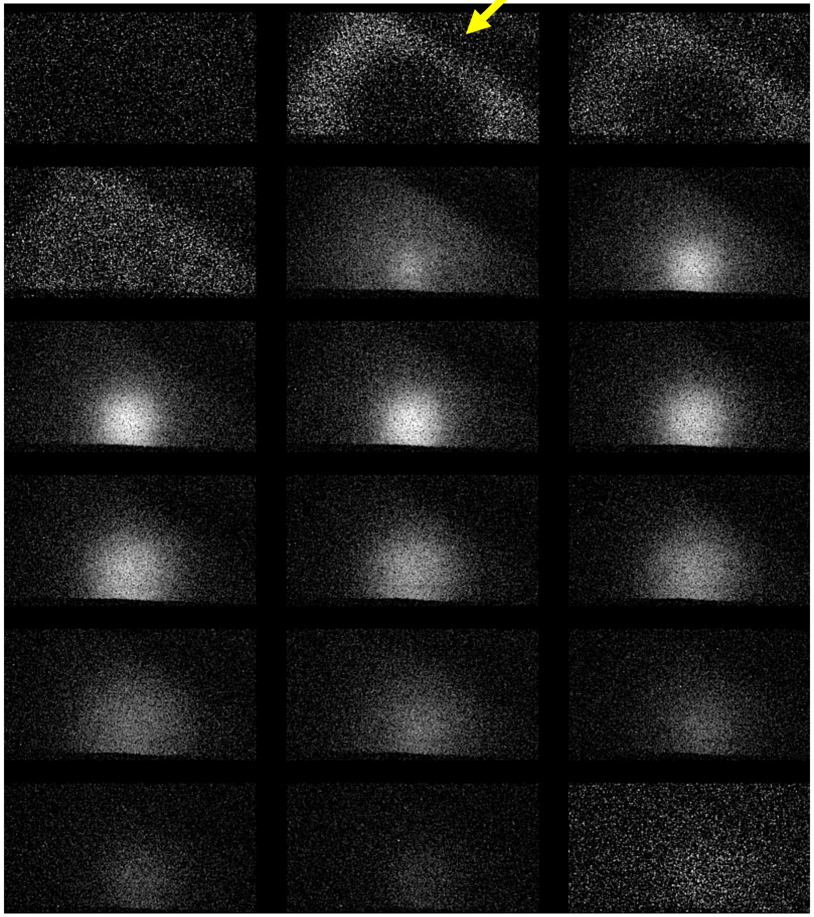
## HCT of Philips





Bergmann *et al.*, Microel .eng. 57-58, 2000, pp. 71-77

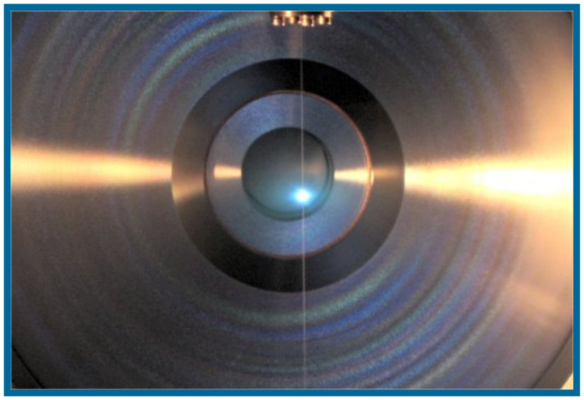
# EUV pictures of plasma pinching for Philips source (5ns frame)

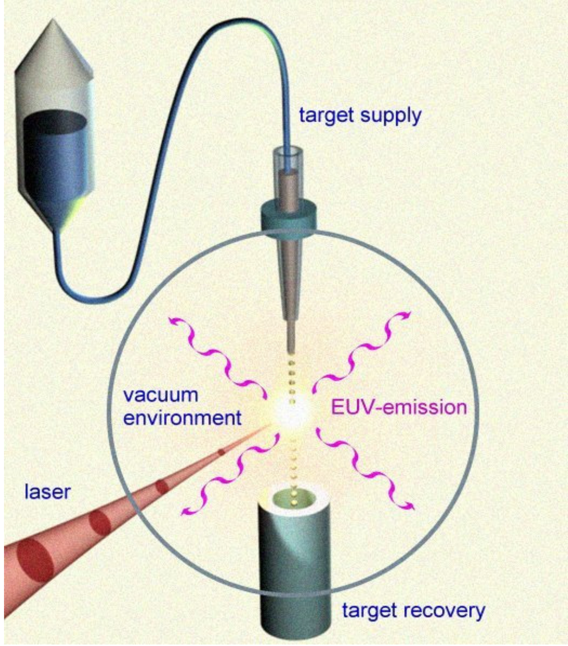


Measured:

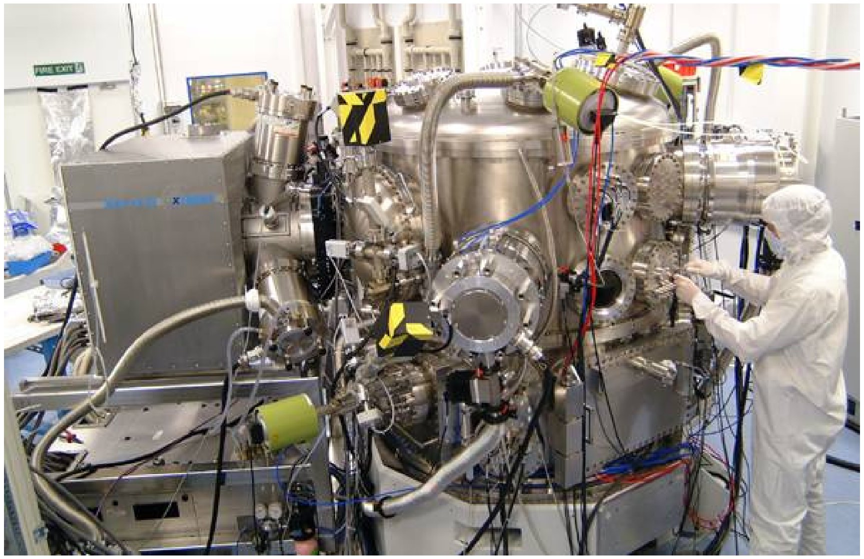
CE = 0.4%

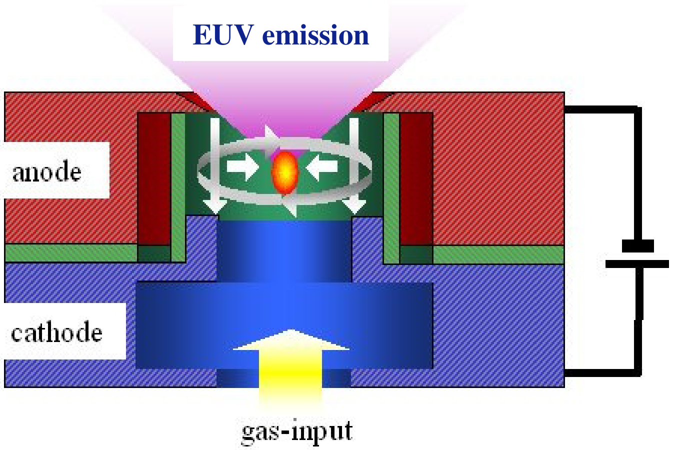
## Xtreem (Lambda) LPP





## Z-pinch

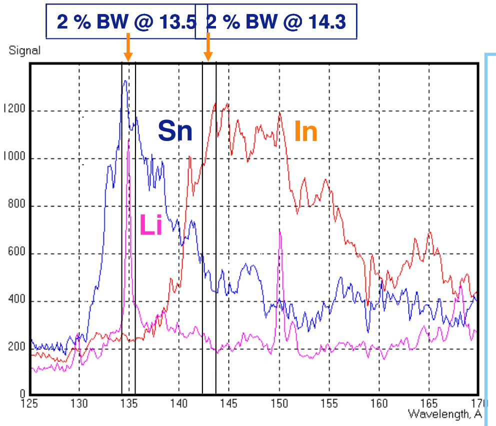




# End of Xe age

- Too low conversion efficiency 0.5-1.1% (in-band in 2π)
- Not high enough projected maximum power (30-40 W @IF)
- Short lifetime of electrodes (DPP) (several hours of operation)
- Too high CoO for LPP at such CE
- Emerging alternative: Sn and Li (up to 3.5-5 % CE) and potential multiplexing (early trials at ASML-ISAN, Cymer et al)

# Emerging alternative



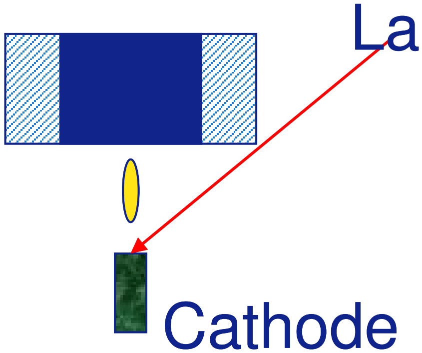
$E_{in}$= 3 J

CE (2% BW, 2π):

in 13.5nm:
Li = 0.5%
Sn = 2 - 3.5 %
(best ever)
in 14.3 nm:
In = 1 %

Concern: Potentially increased debris production with respect to gaseous materials

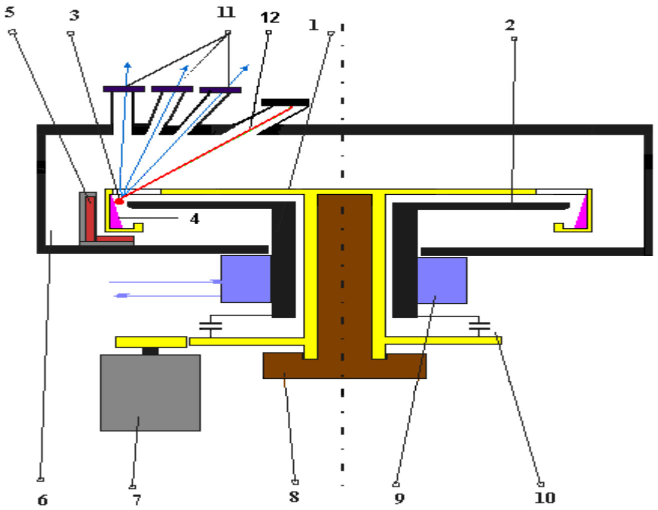
## Pseudo spark (ASML-Troitsk) 2000



Anode

Laser

Cathode



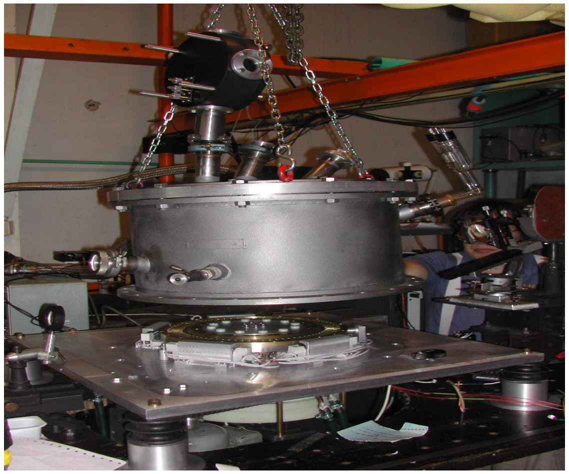
Multiplexing

Achieved:
- 2 % CE
- 100 Hz (ignition laser limited)

10 W in 2π in-band (1-2 W in IF)

Prospect:
- 2-3%
- 1000 Hz

>100 W in IF



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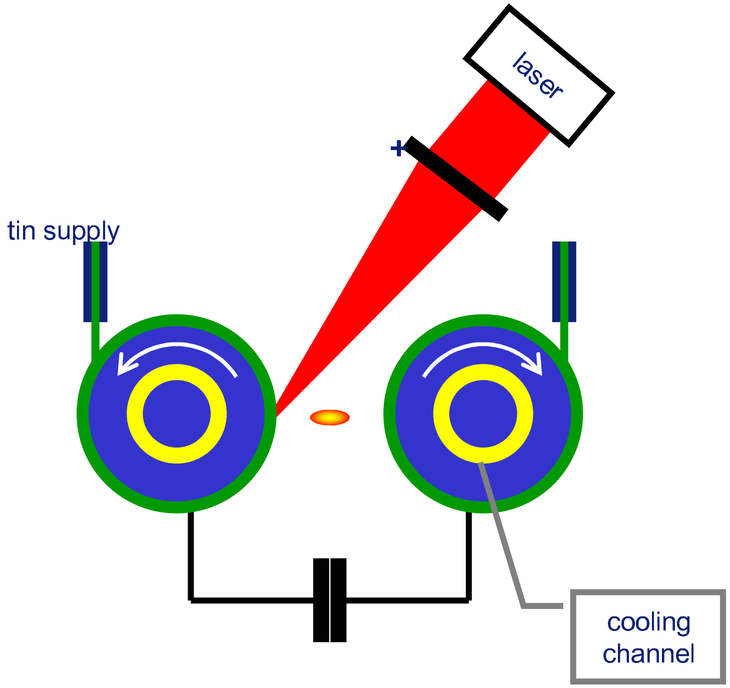
# Philips‘ EUV Lamp: Sn-based rotating electrodes



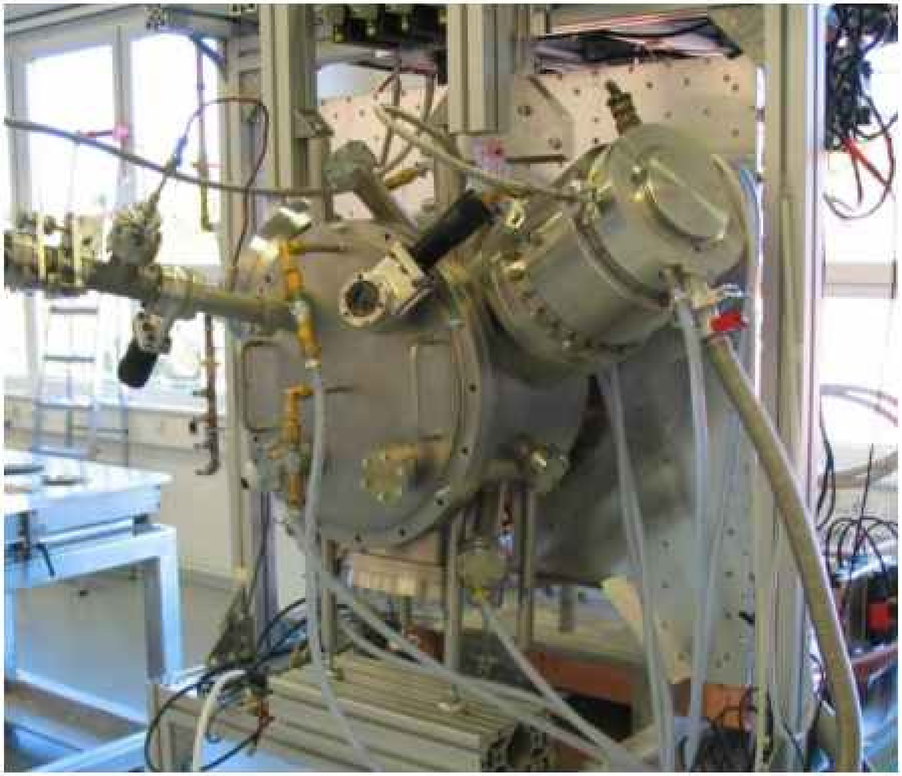
- 200W/2π continuous operation (scalable to >600W /2π)
- very small pinch (<1mm)
- >>1 bln shots electrode life
- commercial product

# GDPP EUV Sources for HVM approach: Tin based

Maximum demonstrated EUV power:
800 W / 2π sr at 5000 Hz

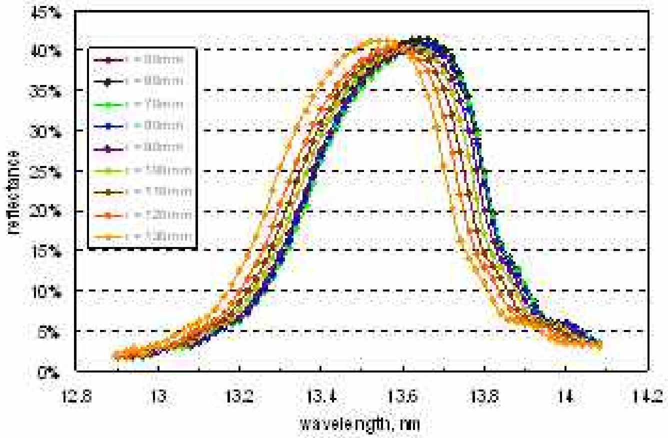
Usable IF power:
up to 115 W (depends on etendue)
not longer an issue

Main challenges to overcome:
- Electrode lifetime improvement
  - => Rotating disk electrodes
- Collector optics lifetime improvement
  - => Optics protection
  - => Optics cleaning
- Collector power handling
  - => New optical design
  - => Collector cooling

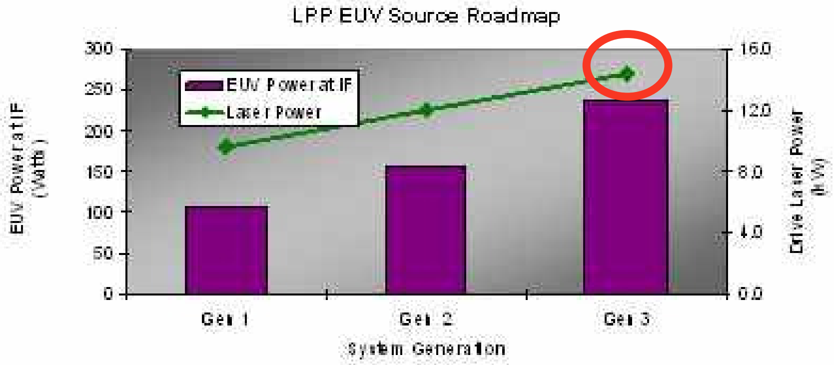


# Development of one of the first LPP with Sn was started

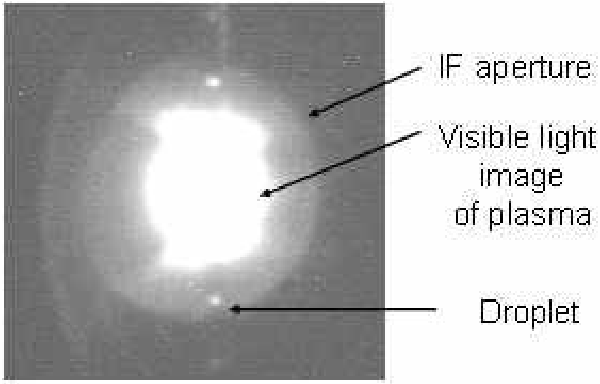
- 320mm diameter 1.6 sr collector



- First article collector, ~41% peak reflectivity



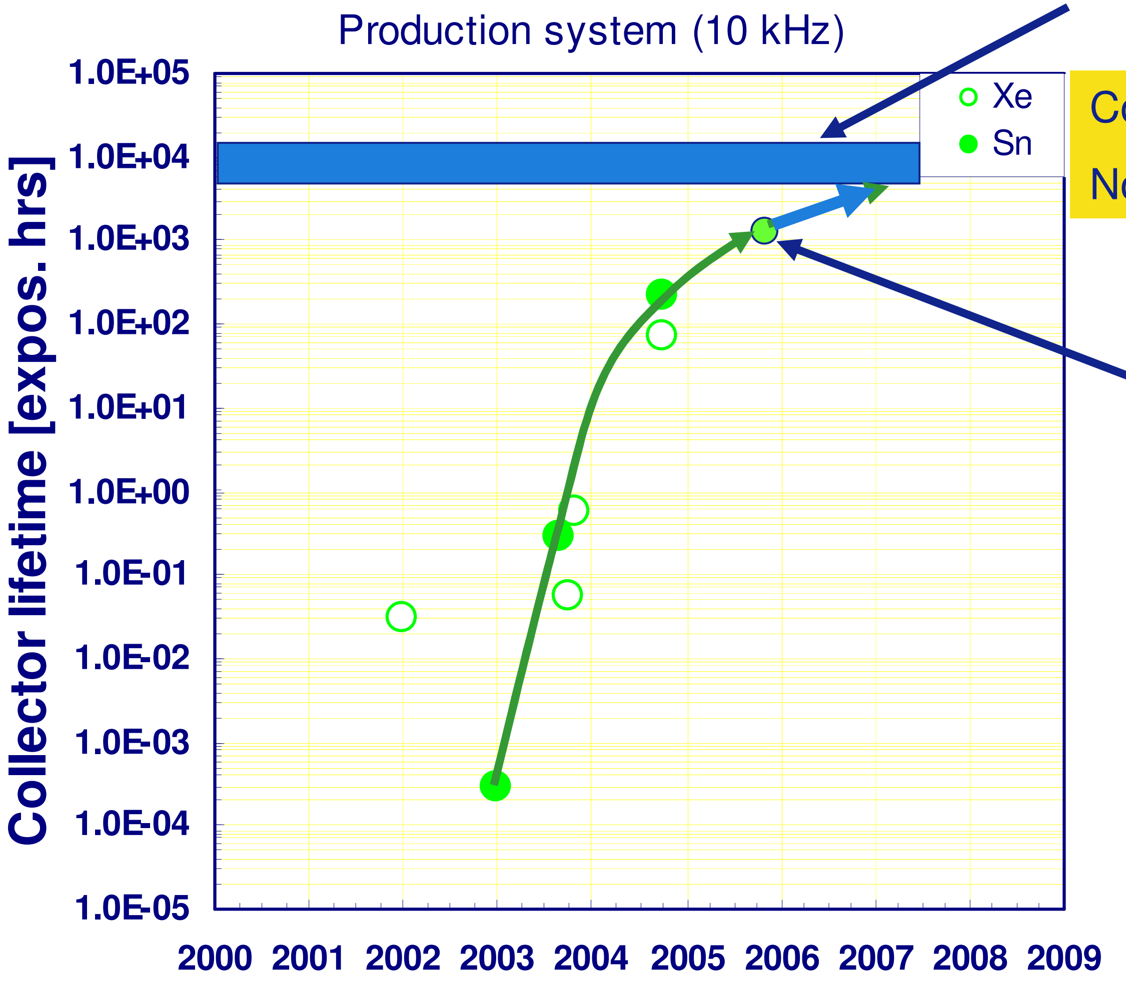
- LPP EUV Source Power at IF Roadmap



- Image of the plasma aligned with the IF aperture as seen through the collector

# Price to pay:

## Collector lifetime (DPP) combining a number of methods



Consumable 3000 hr

Non-consumable 15000 hr

**Combination of methods**

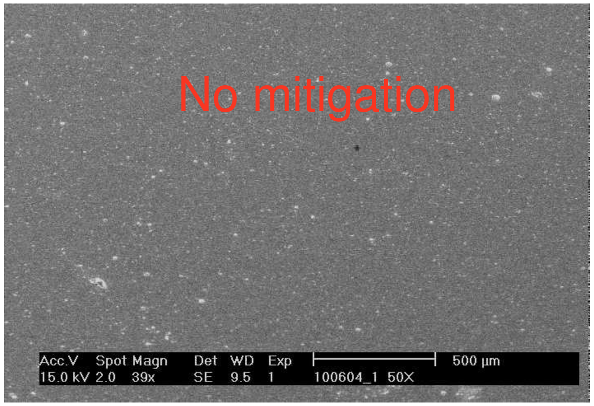
**Combination of methods demonstrate lifetime of ~0.5 year**

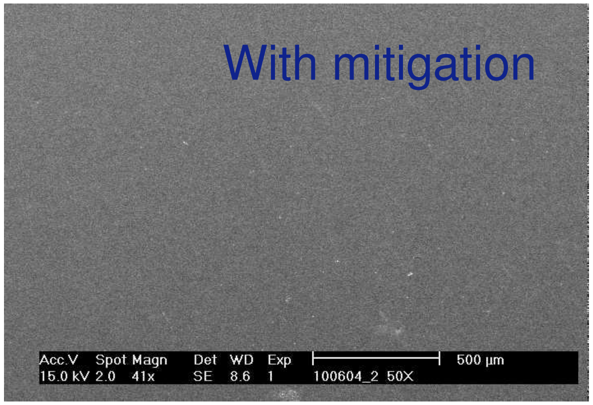
# Debris characterization

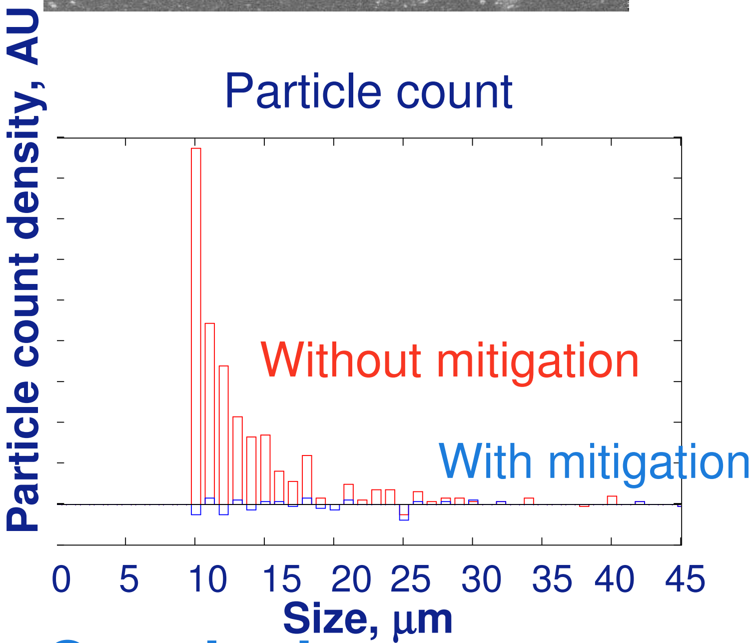
- Total amount produced debris
    - Micro particles -> non-uniform collector surface coverage
    - Fast ions -> surface sputtering
    - Atomic/ ionic debris -> uniform collector surface coverage

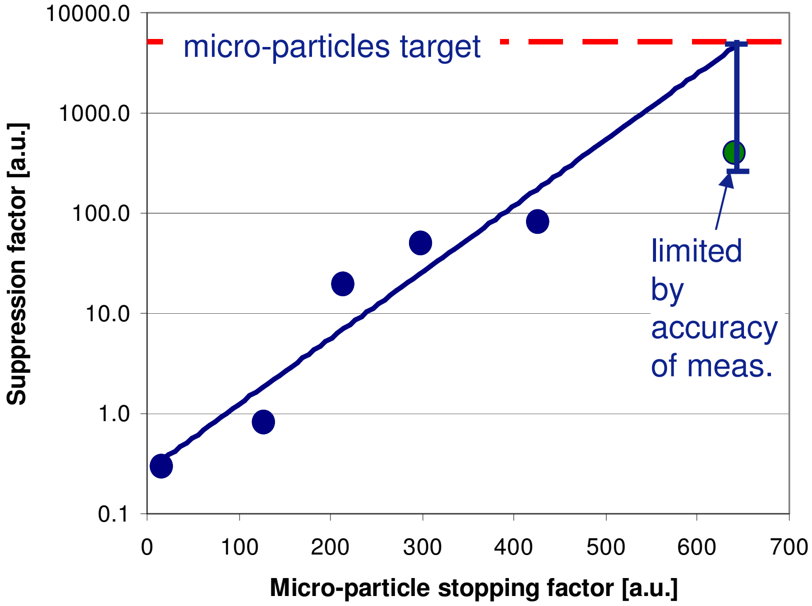
# Suppression of Sn micro-particles

~ 2005









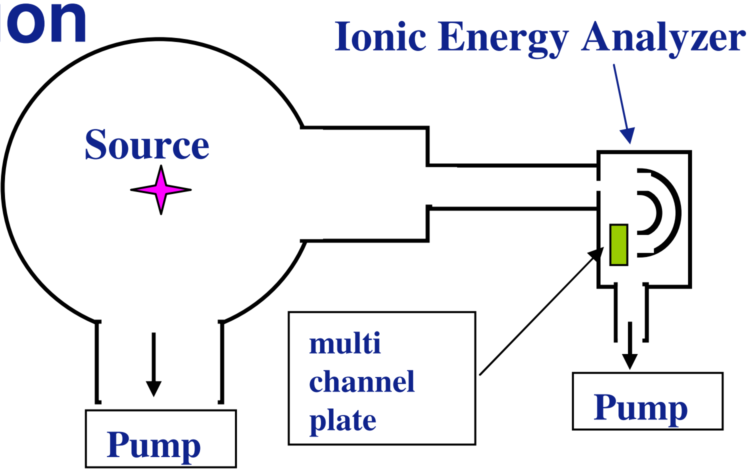
## Conclusion

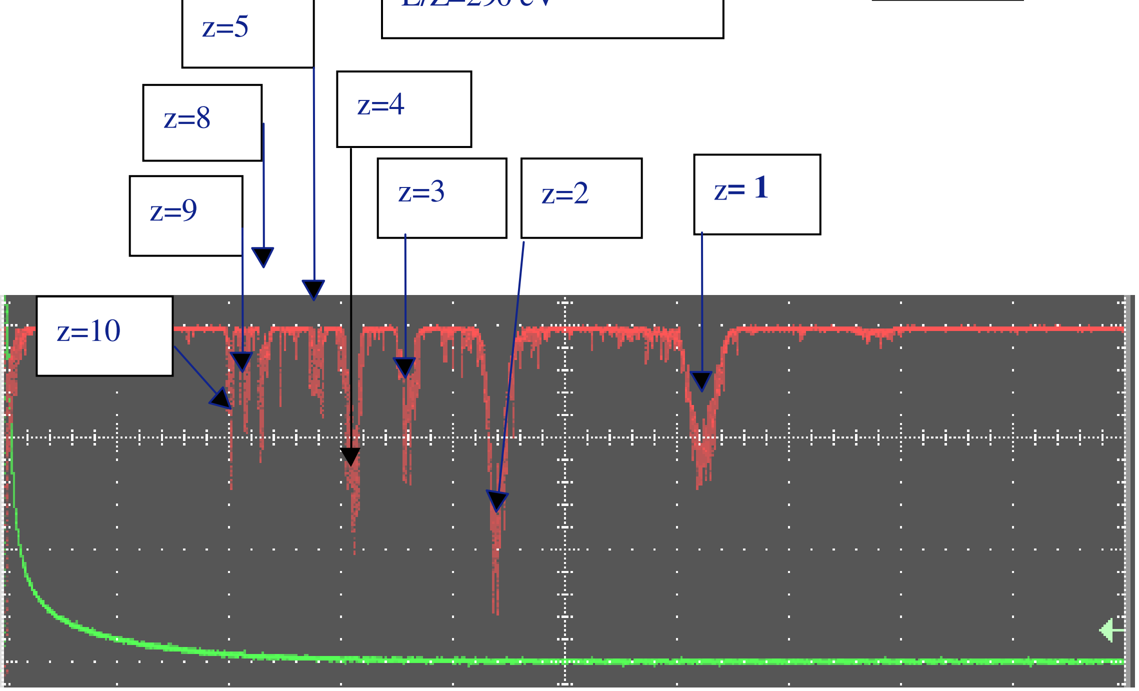
- ***Sn particulates (>100nm) can be suppressed to desired values from reaching the collector***

~ 2005

# Ionic debris characterization

**Ions form z=1 to z=10 are present in the ionic debris**

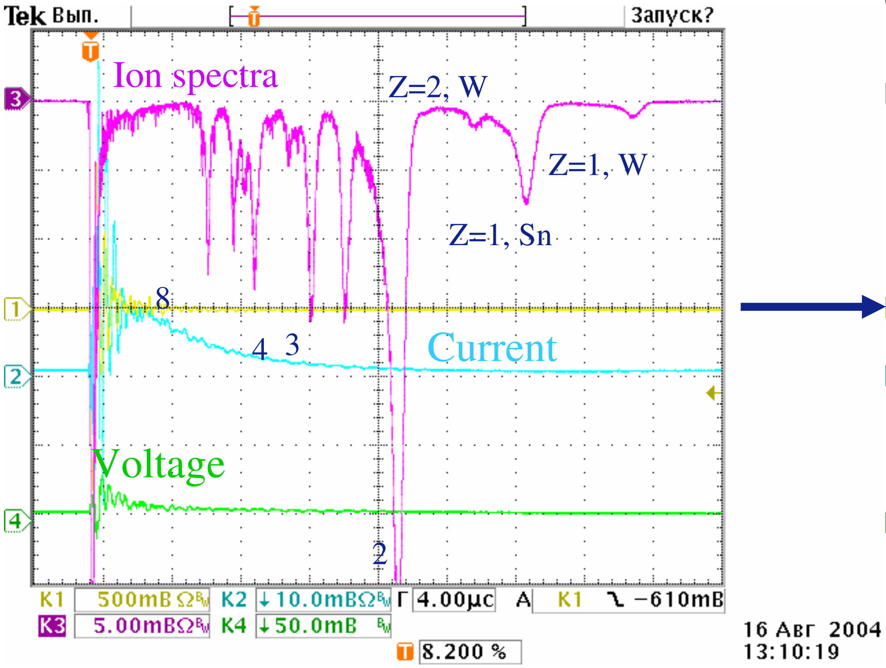




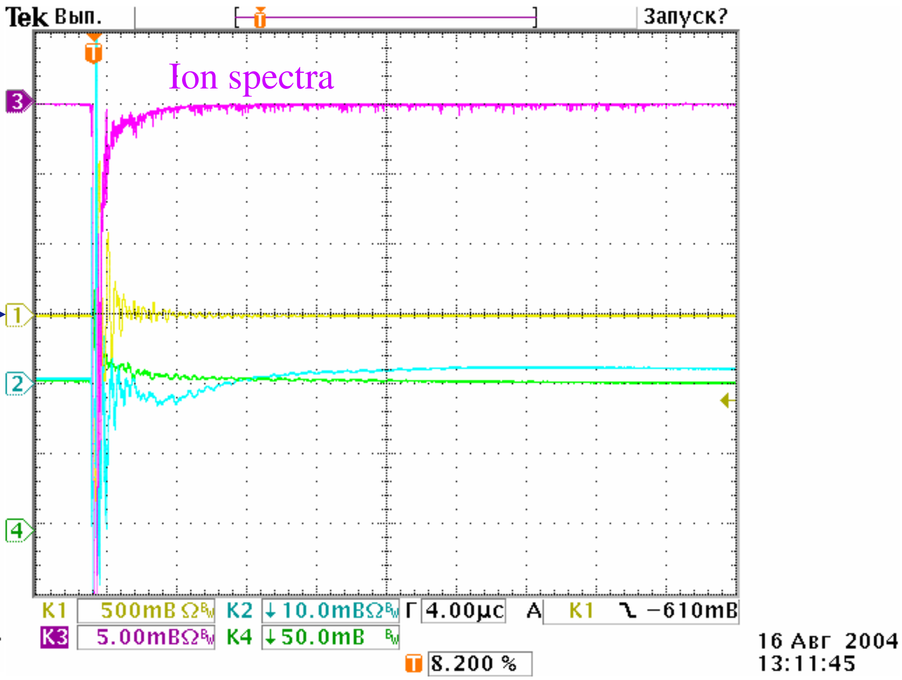
~ 2005

# Ionic debris mitigation

No mitigation applied



Mitigation applied

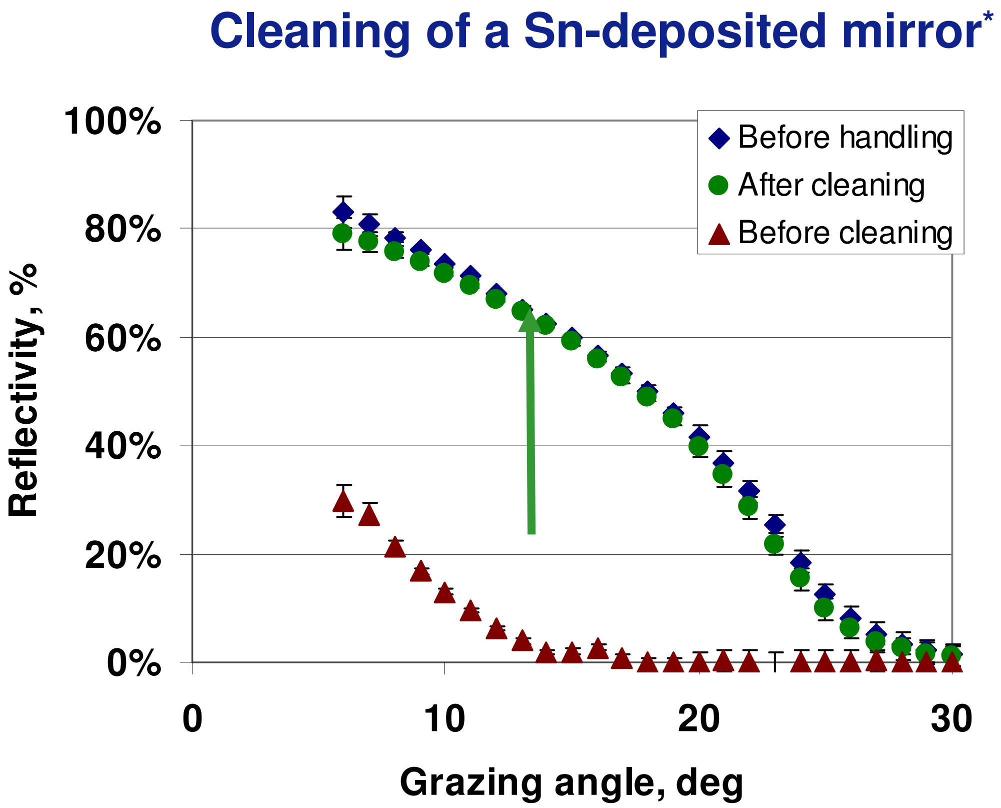


**As measured with witness samples no fast ion induced damage has occurred with an equivalent $10^7$-$10^8$ pulses of lifetime (determined by the detection limit)**

Ionic debris can be successfully stopped by applied mitigation

# Sn deposition and cleaning

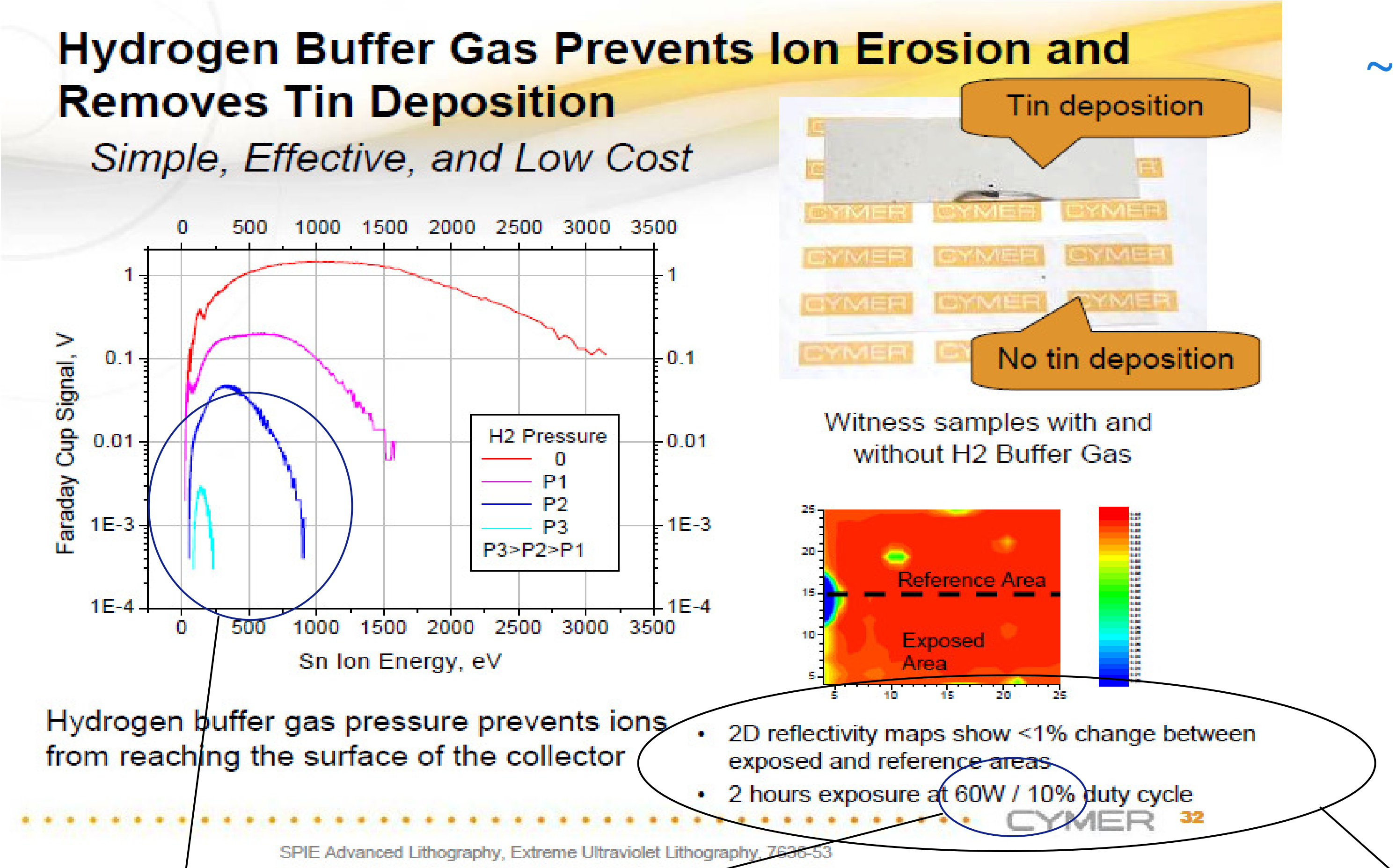
~ 2005



If Sn deposition  would limit the collector lifetime it is proven to be cleanable

# Collector lifetime must be ensured also at higher power levels

~ 2008



## Hydrogen Buffer Gas Prevents Ion Erosion and Removes Tin Deposition

*Simple, Effective, and Low Cost*

Witness samples with and without H2 Buffer Gas

Hydrogen buffer gas pressure prevents ions from reaching the surface of the collector

- 2D reflectivity maps show <1% change between exposed and reference areas
- 2 hours exposure at 60W / 10% duty cycle

SPIE Advanced Lithography, Extreme Ultraviolet Lithography, 7636-53

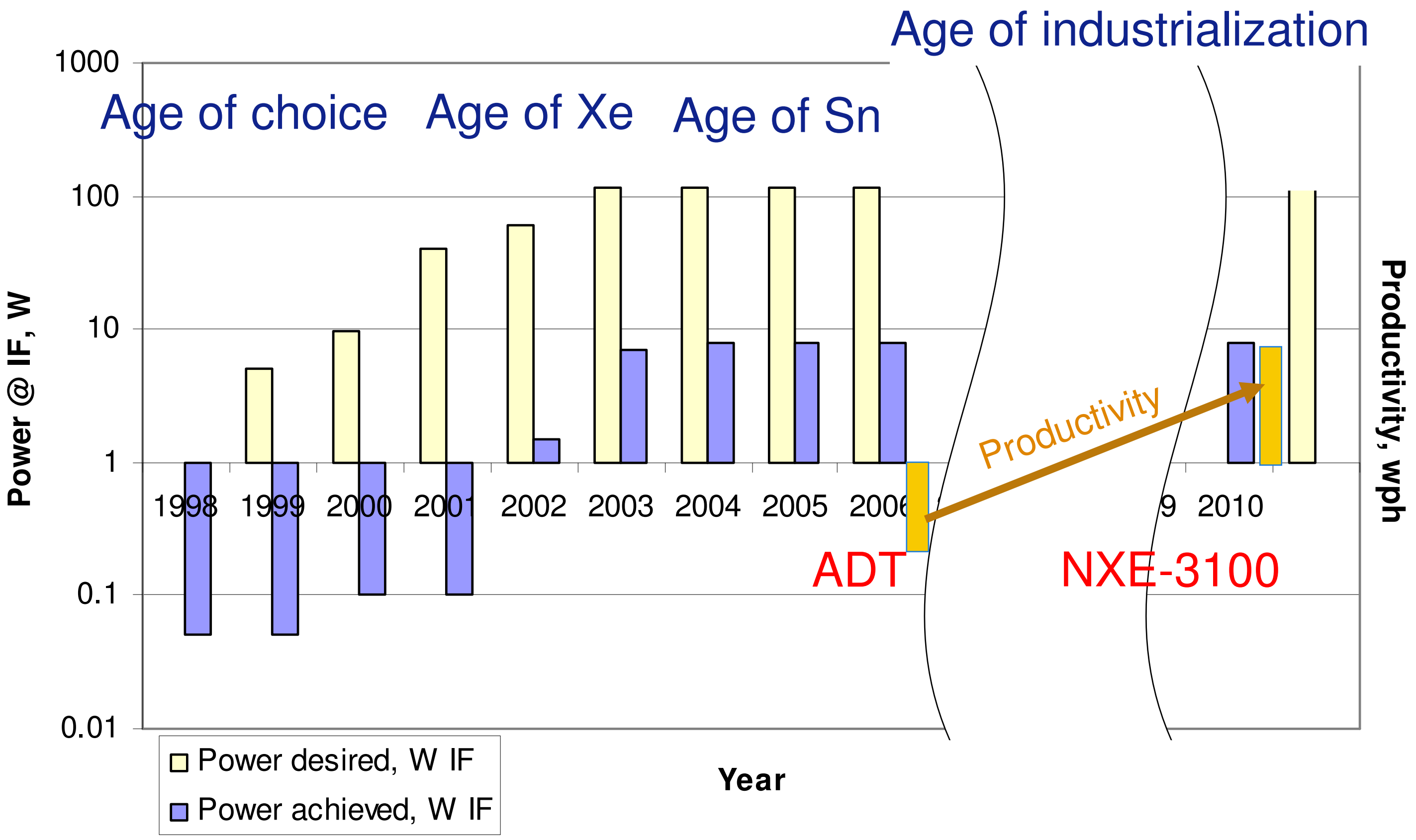
**Lifetime demonstration of 1000x is needed**

**Maintaining debris suppression with power scaling of up to 100x is necessary**

# Content

- EUV lithography: History and status
- EUV sources- historical perspective:
  - Age of choice
  - Age of Xe
  - Age of Sn
  - Age of industrialization
  - … and beyond
- Conclusions

# Historical perspective: Production power requirement, achieved power, productivity

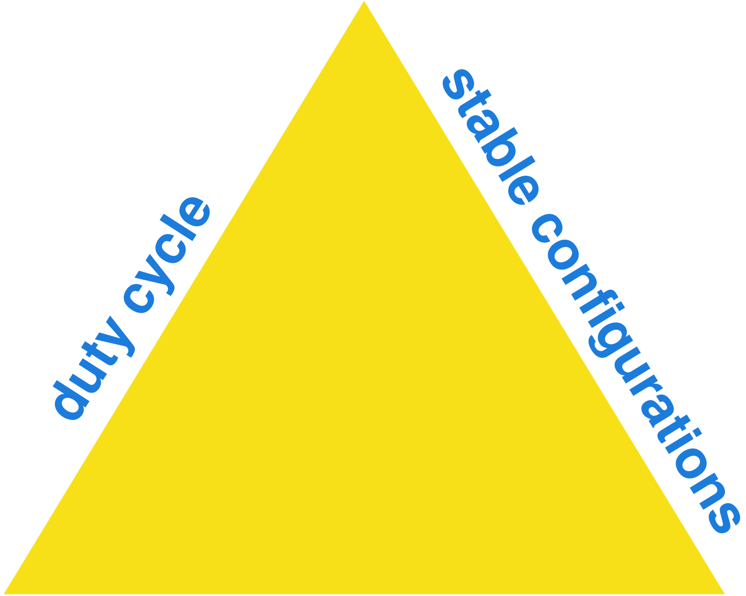


Averaged and independent on supplier

Gap in productivity is being bridged, in reliable power is still 10x to go.

# Source roadmap activities driven by 3 items

## power scaling, debris and stability



**power scaling**

2-3x more power needed for volume production (250W)

**duty cycle**

**stable configurations**

**test time**

**Lifetime/debris**

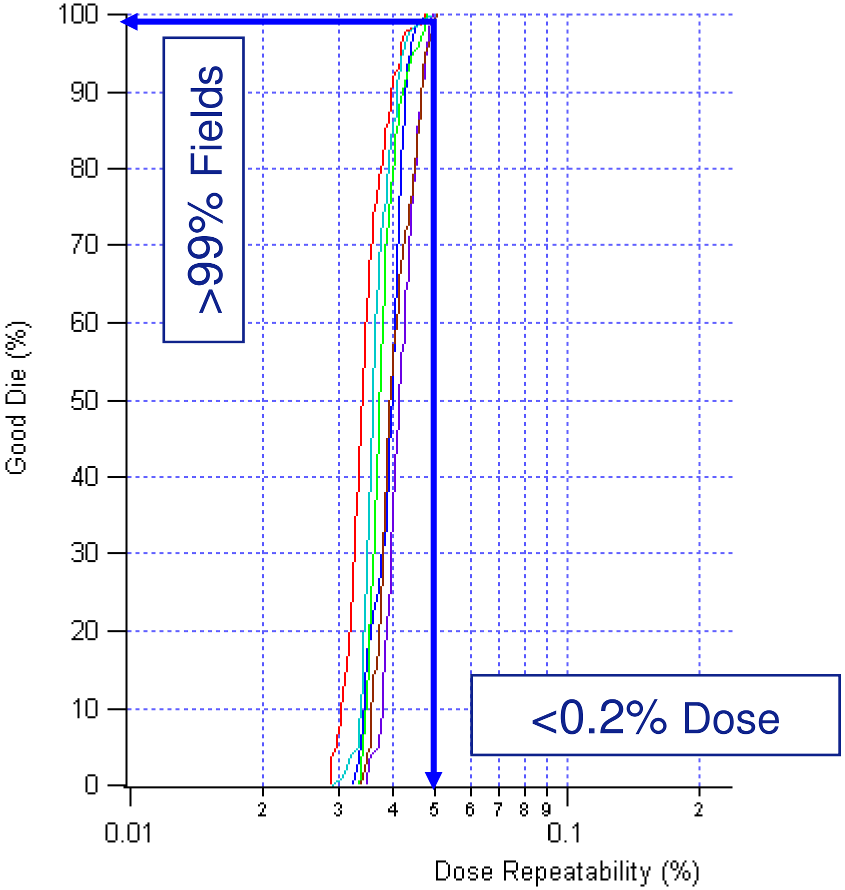
Degradation and thermal load
of parts close to plasma

**Stability**

tin management
start up issues of new H/W

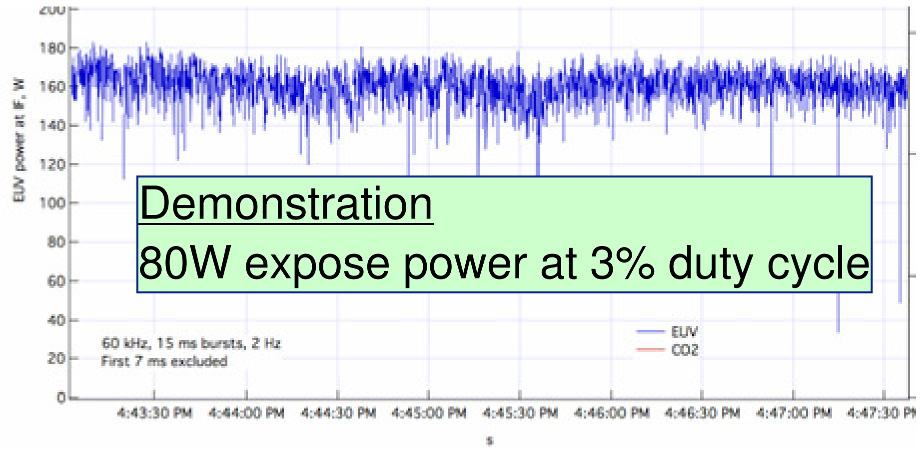
# 4 Cymer LPP sources integrated to NXE:3100

## 11W expose power being implemented at scanner



>99% Fields

<0.2% Dose

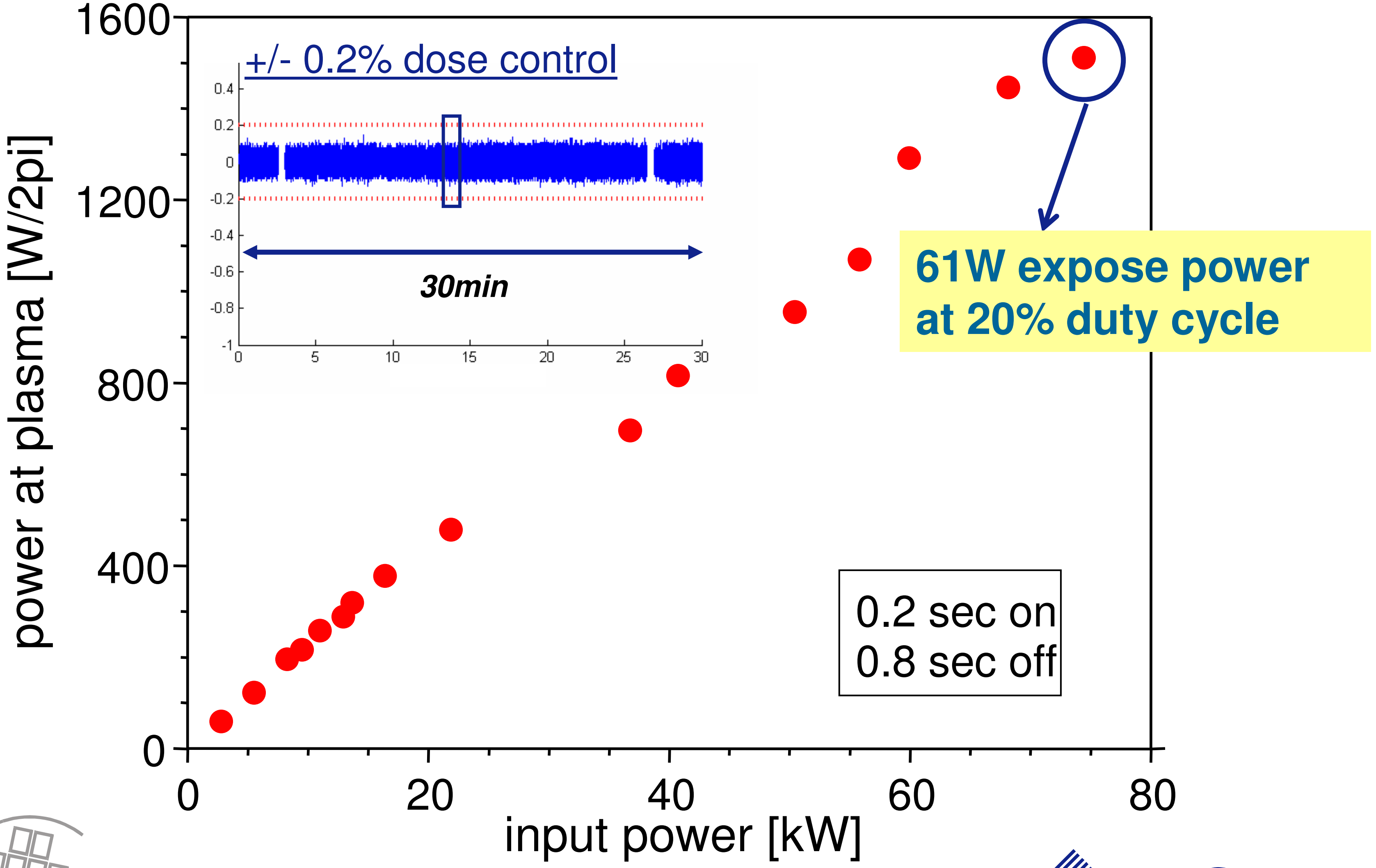


Demonstration

80W expose power at 3% duty cycle

# 1st Ushio source integrated and exposing wafers

## 9 shell collector, 7W integrated, 12W (61W, 20%) demonstrated

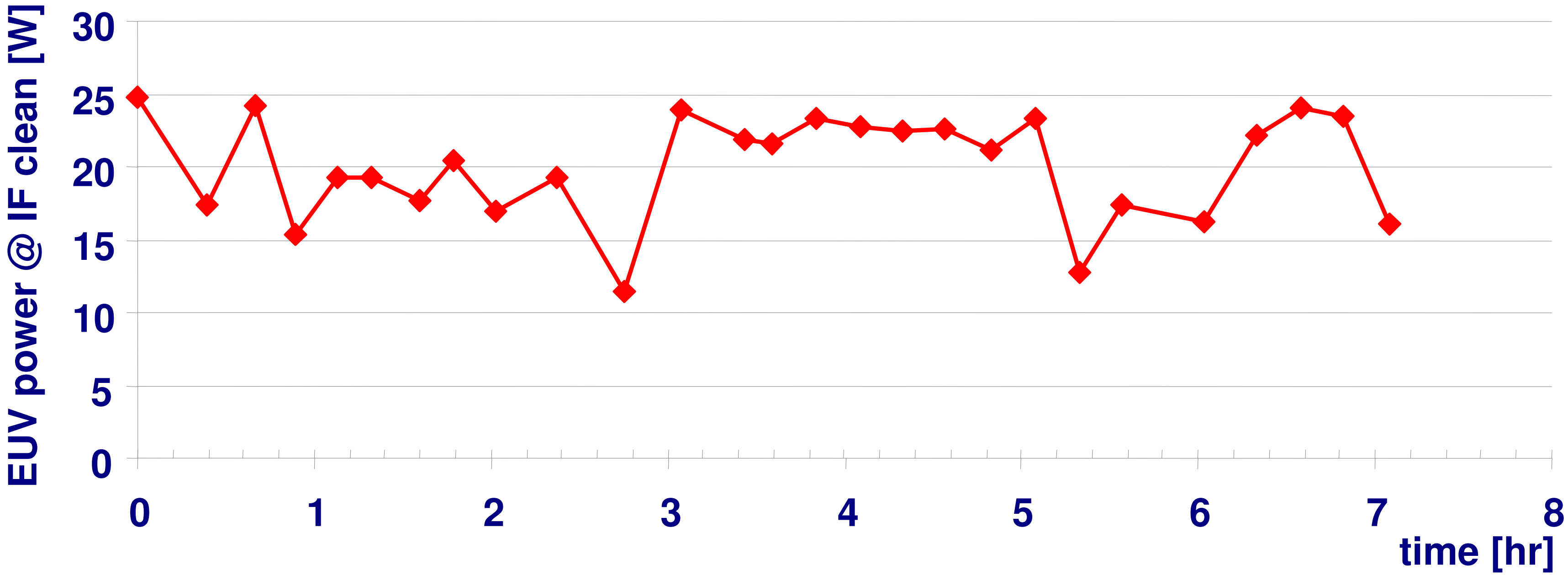


61W expose power at 20% duty cycle

0.2 sec on
0.8 sec off

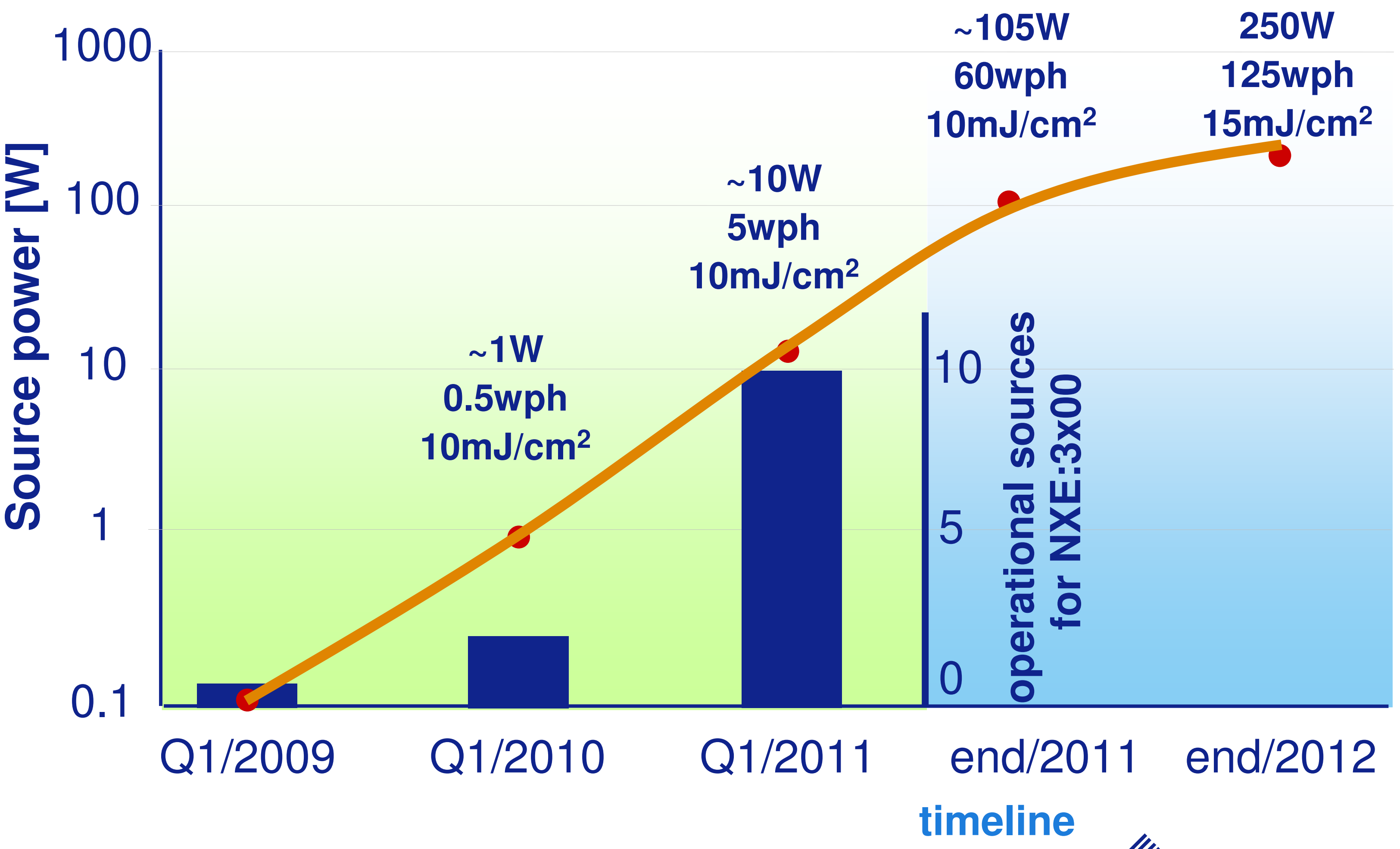
# GPI demonstration source assembly completed

## 20 W expose power at 5% duty cycle and 3.6 kW CO2



# Source industrialization is progressing

## 3 suppliers committed for volume manufacturing with NXE:3300B



# Content

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- EUV sources- historical perspective:
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    - Age of Xe
    - Age of Sn
    - Age of industrialization
    - … and beyond
- Conclusions

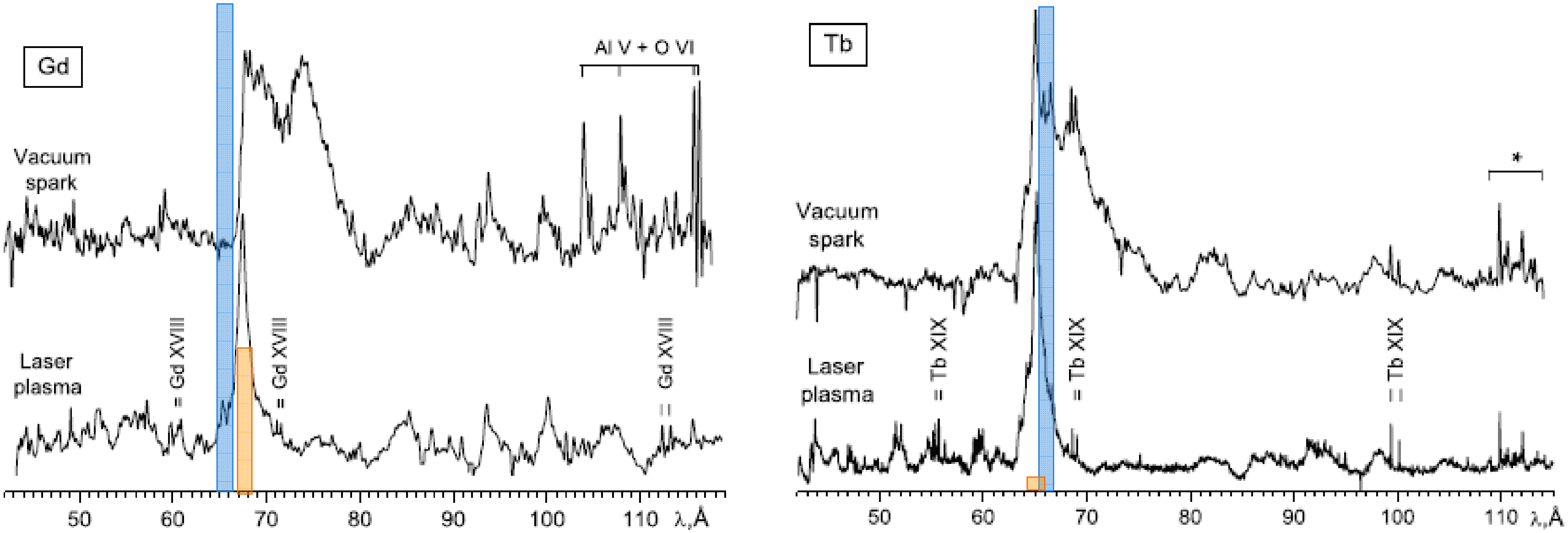
# EUV and BEUV product roadmap spans >10 years

| | | | | | *Under study* | |
|---|---|---|---|---|---|---|
| | 0.25 NA | | 0.32 NA | | >0.40 NA | |
| **Lens mirrors** | 6M | 6M | 6M | 6M | 6/8M | 6/8M |
| **Wavelength** | 13.5 nm | 13.5 nm | 13.5 nm | 13.5 nm | 13.5 nm | New $\lambda$ |
| **Product** | **ADT** | **3100** | **3300B** | **3300C** | **3500** | **>3500** |
| **Introduction year** | **2006** | **2010** | **2012** | **2013** | **2016** | **>2018** |
| **Resolution (hp)** | 32 nm | 27 nm | 22 nm | 18 nm | 11 nm | <8 nm |
| **Sigma** | 0.5 | 0.8 | 0.2-0.9 | OAI | flex OAI | flex OAI |
| **Overlay (SMO)** | 7.0 nm | 4.5 nm | 3.5 nm | 3.0 nm | | |
| **Throughput (wph)** | 4 wph | 60 wph | 125 wph | 150 wph | | |
| **Dose (mJ/cm$^2$)** | 5 | 10 | 15 | 15 | | |
| **Source (W)** | 3 | 105 | 250 | 350 | | |

Possible new wavelength = 6.x nm

# Source: materials and spectra

Source: Churilov etc Phys. Scr. 80 (2009)

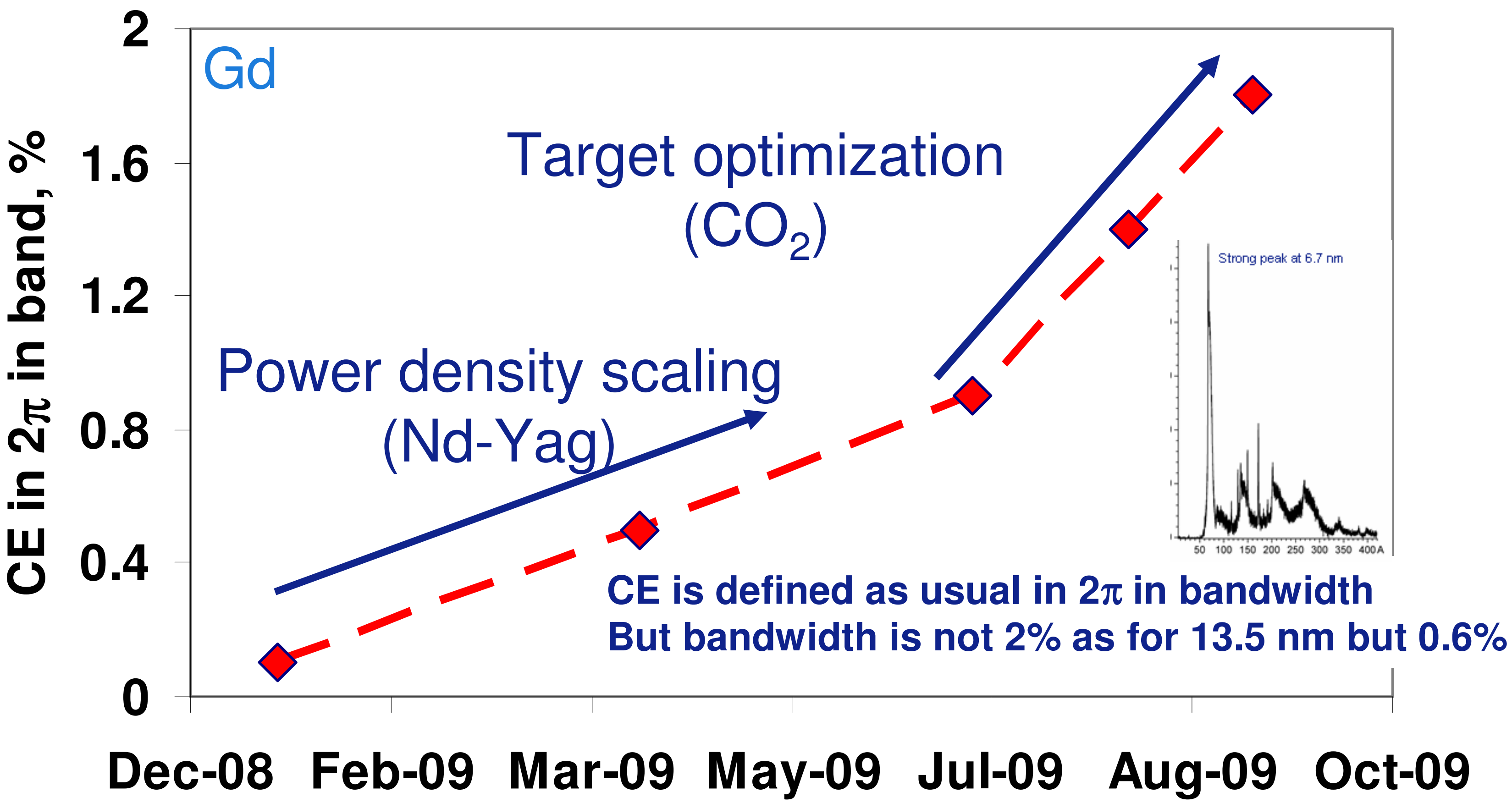


🟦 Optical throughput optimized for the coating (10 mirrors)

🟧 Optical throughput optimized for the maximum emission spectrum

- Gd and Tb are the main potential materials of choice for 6.x lithography
- Simultaneous optimization of ML band and emission spectral power is required

# Investigating Conversion efficiency (CE) for 6.77 nm with LPP



Target optimization ($CO_2$)

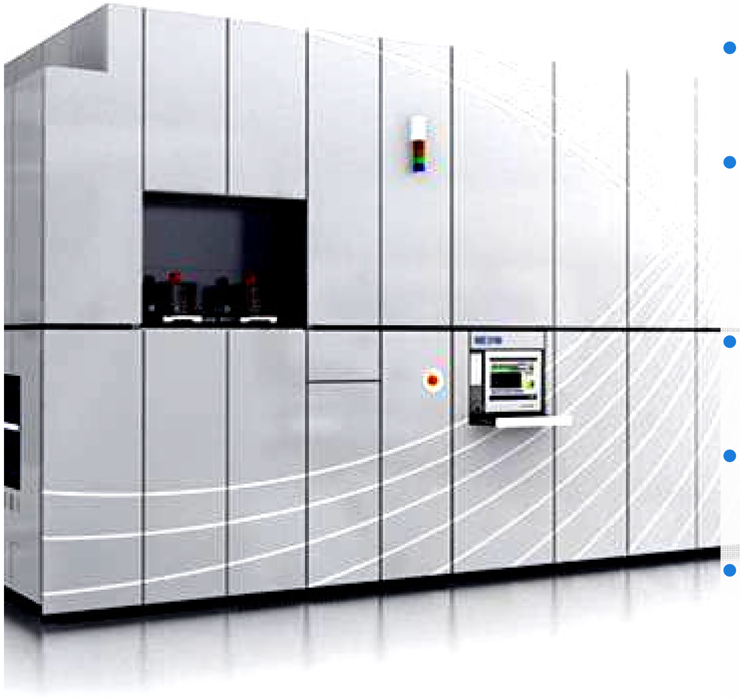
Power density scaling (Nd-Yag)

**CE is defined as usual in $2\pi$ in bandwidth**
**But bandwidth is not 2% as for 13.5 nm but 0.6%**

In-band CE for 6.x nm (1.8% vs theoretical 3-5%) is already comparable with that of 13.5 nm Sn

# Summary: First 4 NXE:3100 systems shipped

## 1st system operational in the field



- Full wafer imaging of 27nm L/S demonstrated
- Resolution down to 18nm demonstrated
- 7nm Matched Machine Overlay demonstrated
- Platform roadmap in place for cost effective EUV production

- Significant source power scaling > 100x is achieved In last 10 years
- Source showed a significant progress in reliability (10x)
- Source suppliers are committed to support volume manufacturing needs

# Acknowledgements

The work presented today, is the result of hard work and dedication of teams at ASML and many technology partners worldwide including our customers

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