EUV Source for High Volume Manufacturing: Performance at 250 W and Key Technologies for Power Scaling

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Outline

- Background and History
- EUV Imaging
- Principles of EUV Generation
- EUV Source: Architecture
- EUV Sources in the Field
- Source Power Outlook
- Summary

Background and History

Why EUV? - Resolution in Optical Lithography

Critical Dimension:

$$CD = k_1 \times \frac{\lambda}{NA}$$

Depth of focus:

$$DOF = k_2 \times \frac{\lambda}{NA^2}$$

k: process parameter
NA: numerical aperture
λ: wavelength of light

KrF-Laser:	248nm
ArF-Laser:	193 nm
ArF-Laser (immersion):	193 nm
EUV sources:	**13.5 nm**

theoretical limit (air): NA=1
practical limit: NA=0.9
theoretical limit (immersion):NA ≈ n (~1.7)

k_1 is process parameter

traditionally:	>0.75
typically:	0.3 – 0.4
theoretical limit:	0.25

EUV development has progressed over 30 years

from NGL to HVM insertion

1st lithography (LLNL, Bell Labs, Japan)

ASML starts EUVL research program

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

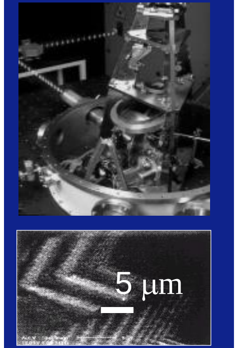
ASML ships 1st pre-production NA 0.25 system NXE:3100

ASML ships 1st NA 0.33 system NXE:3300B

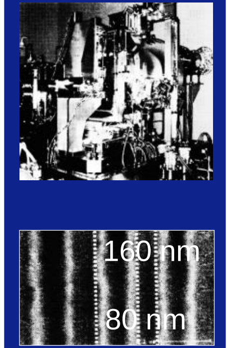
ASML ships 1st HVM NA0.33 system NXE:3400B

’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 ’12 ‘13 ’14 ’15 ’16 ’17 ’18

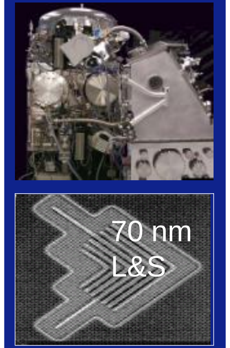
NL



Japan



USA



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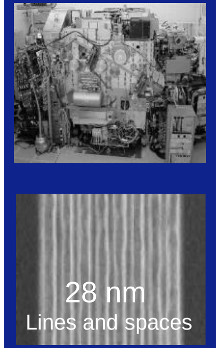

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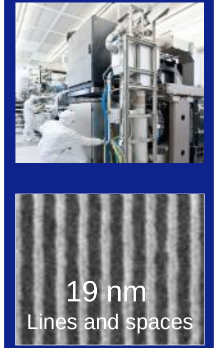

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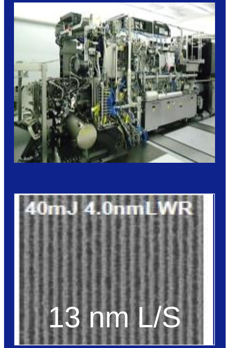

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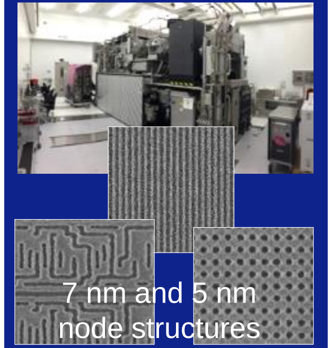
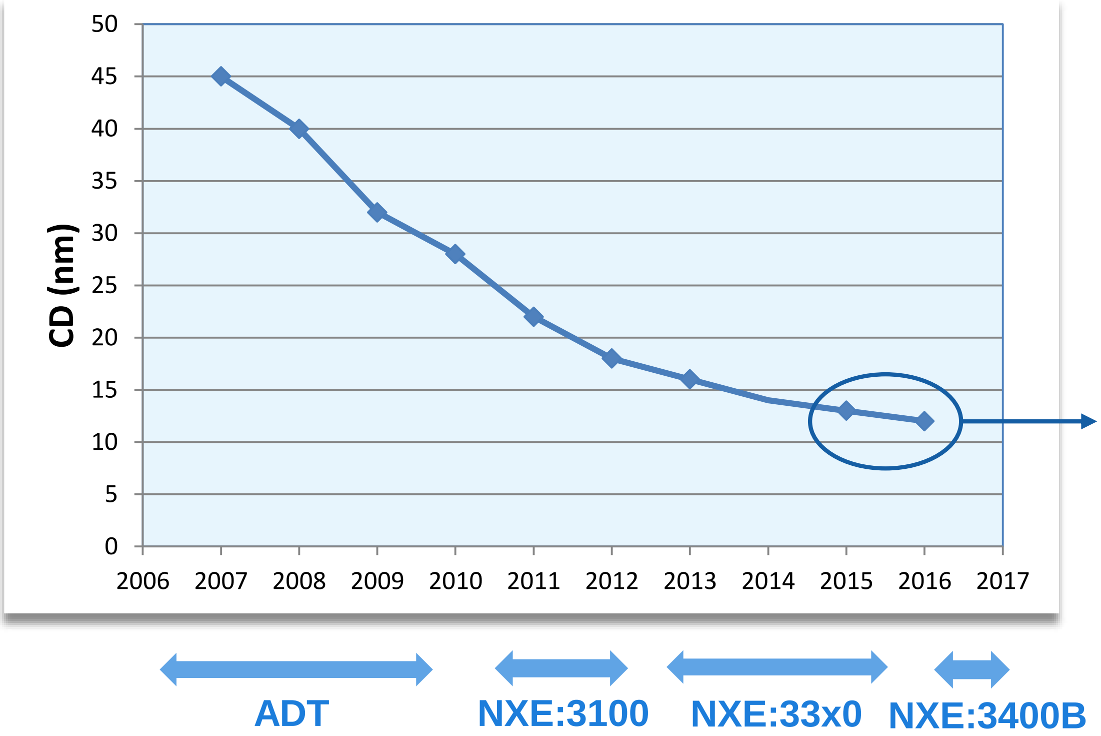


EUV resist: 4x resolution improvement in ten years

12nm half pitch resolved with non-CAR resist on 0.33 NA EUV



inpria

Non-CAR resist

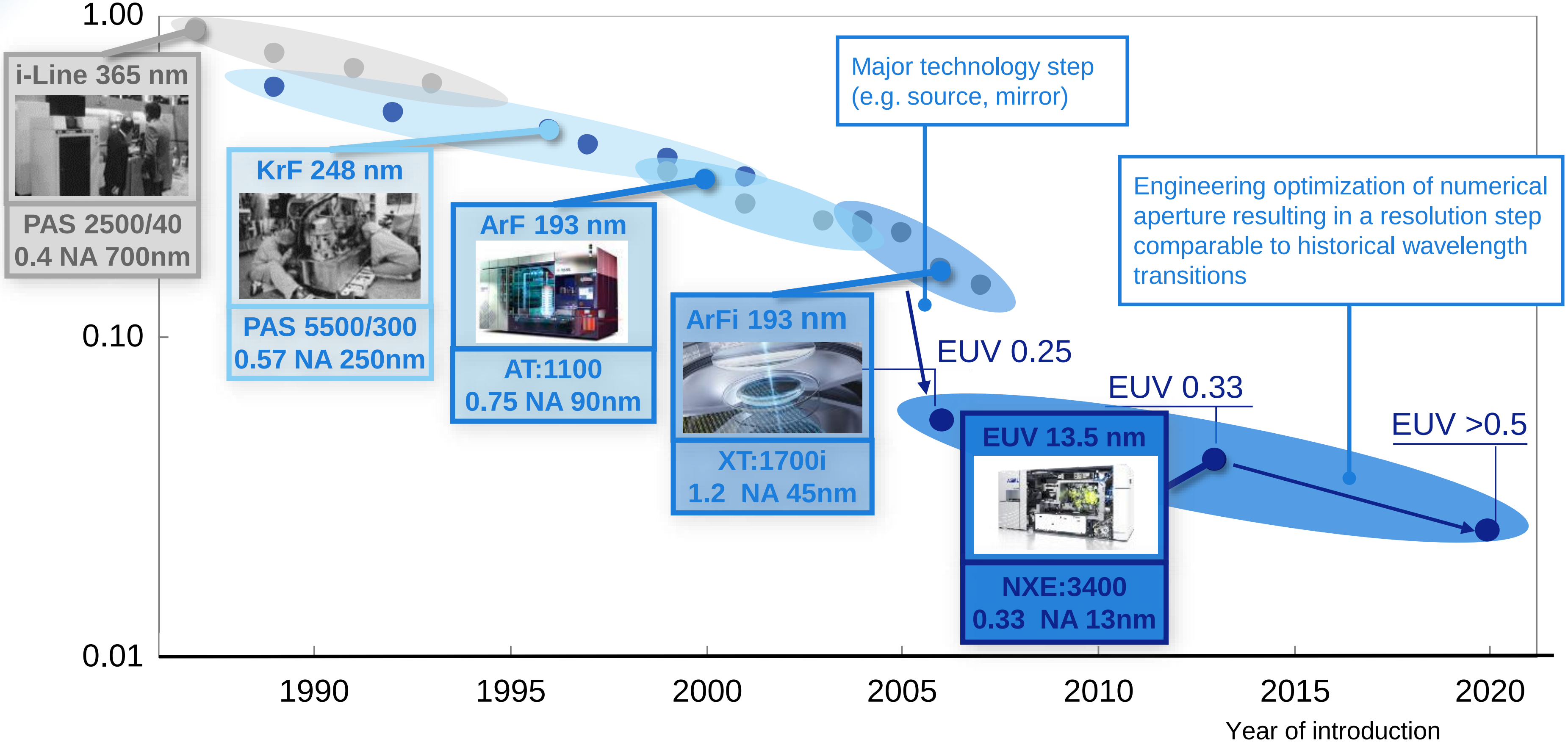
Half Pitch: 12nm

ADT, NXE:3100, NXE:33x0, NXE:3400B as measured by ASML/ IMEC,

Exposure Latitude > 10% and / or Line Width Roughness < 20%, Dose ≤ 35mJ/cm2

High-NA EUV targets ≤8nm resolution

Relative improvement:5X over ArFi, 40% over 0.33 NA EUV



Major technology step (e.g. source, mirror)

Engineering optimization of numerical aperture resulting in a resolution step comparable to historical wavelength transitions

EUV roadmap

Supporting customer roadmaps well into the next decade

Introduction	55 WPH	125 WPH	145 WPH	185 WPH	Overlay [nm]
2013	NXE:3300B				7
2015		NXE:3350B			3.5
2017		NXE:3400B			3
			NXE:next		<3
				High NA	<2

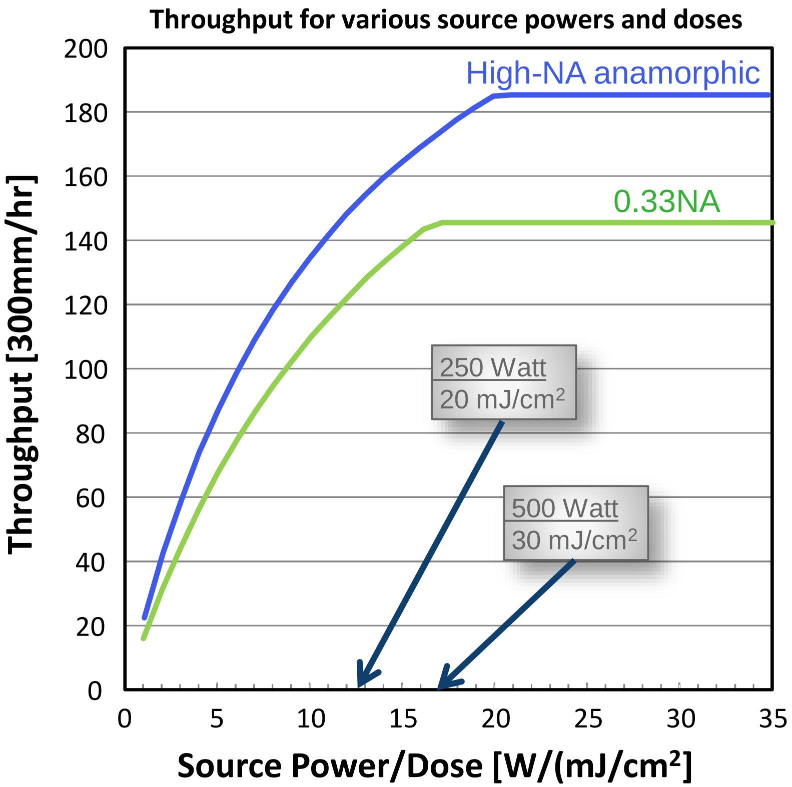
At customer upgradable

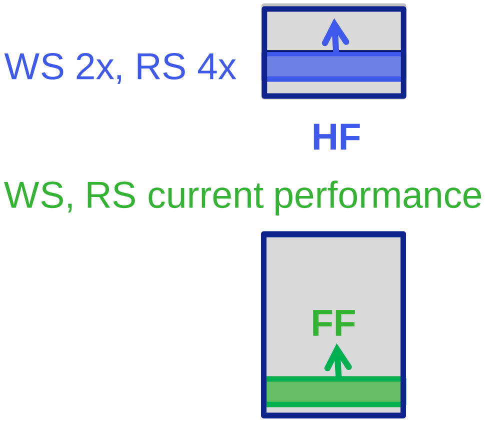
products under study

New platform

High-NA Field and Mask Size productivity

Throughput >185wph with anamorphic Half Fields



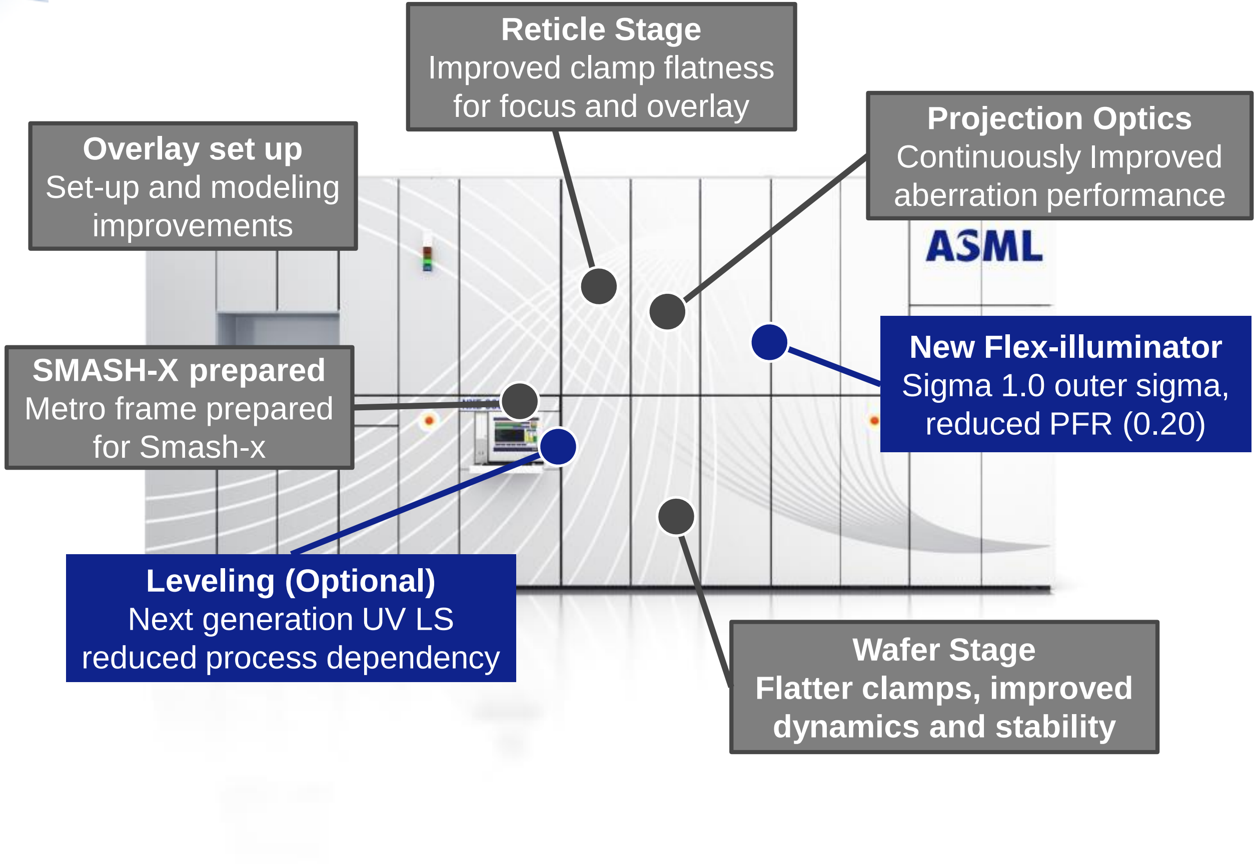


Fast stages enable high throughput despite half fields

EUV Imaging – NXE:3400B

NXE:3400B: 13 nm resolution at full productivity

Supporting 5 nm logic, <15nm DRAM requirements



Reticle Stage
Improved clamp flatness for focus and overlay

Overlay set up
Set-up and modeling improvements

Projection Optics
Continuously Improved aberration performance

New Flex-illuminator
Sigma 1.0 outer sigma, reduced PFR (0.20)

SMASH-X prepared
Metro frame prepared for Smash-x

Leveling (Optional)
Next generation UV LS reduced process dependency

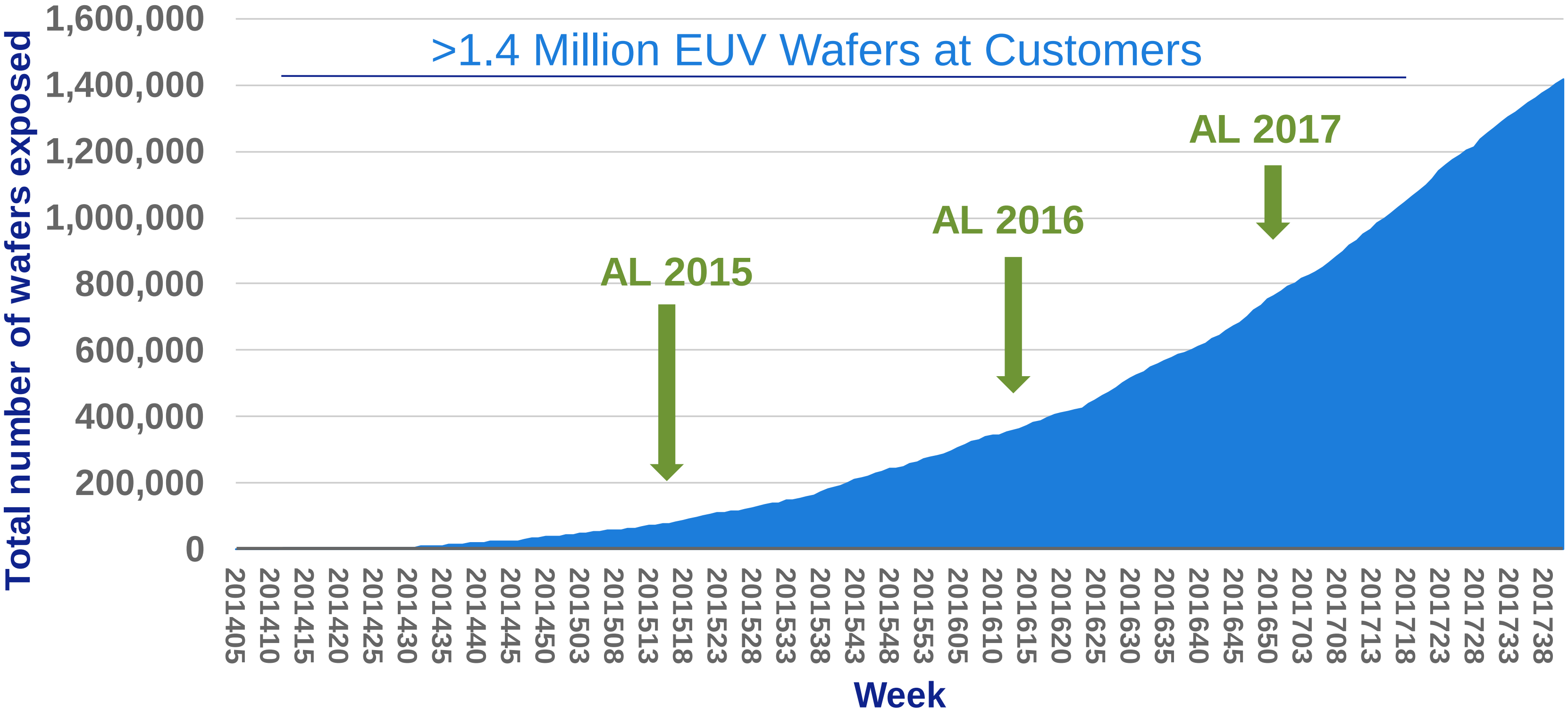
Wafer Stage
Flatter clamps, improved dynamics and stability

Resolution	13 nm
Full wafer CDU	≤ 1.1 nm
DCO	≤ 1.4 nm
MMO	≤ 2.0 nm
Focus control	≤ 60 nm
Productivity	≥ 125 WPH

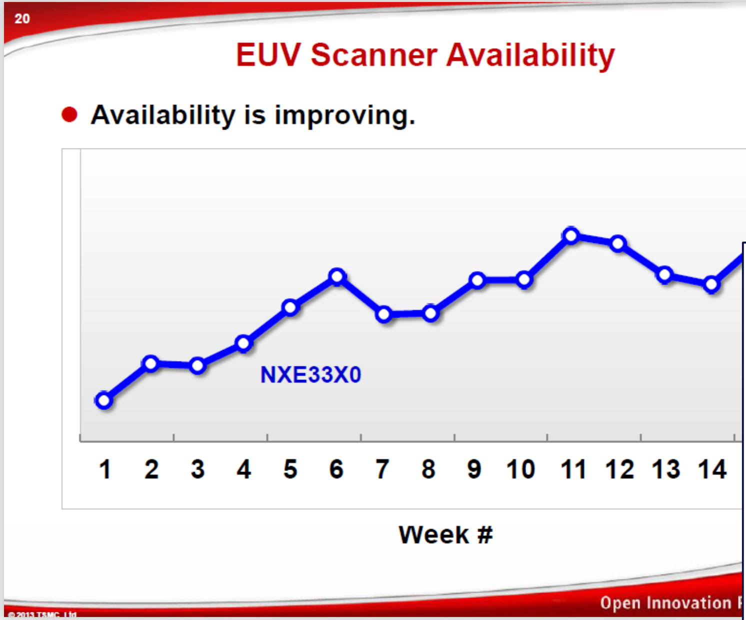
- ▨ Overlay
- 🟦 Imaging/Focus
- 🟩 Productivity

>1.4M wafers exposed on NXE:3xx0B at customer sites

Currently 15 systems running in the field. First system was shipped Q1 2013



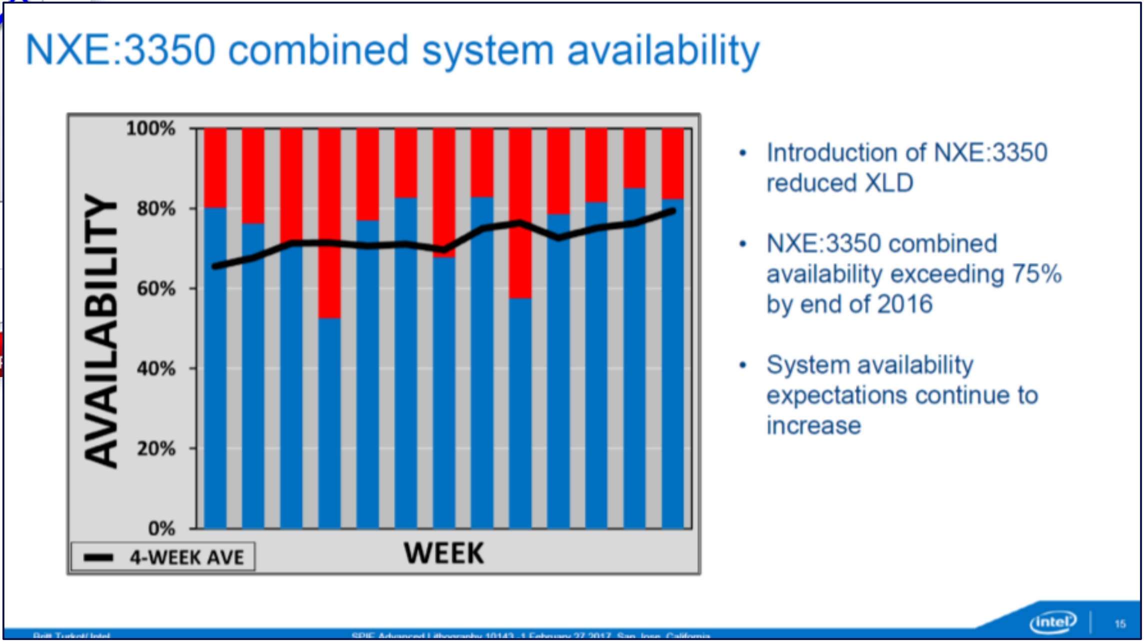
Significant progress in system availability is recognized by our customers



EUV Scanner Availability

TSMC Property

- Availability is improving.



NXE:3350 combined system availability

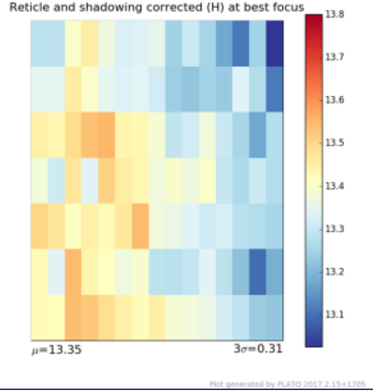
- Introduction of NXE:3350 reduced XLD
- NXE:3350 combined availability exceeding 75% by end of 2016
- System availability expectations continue to increase

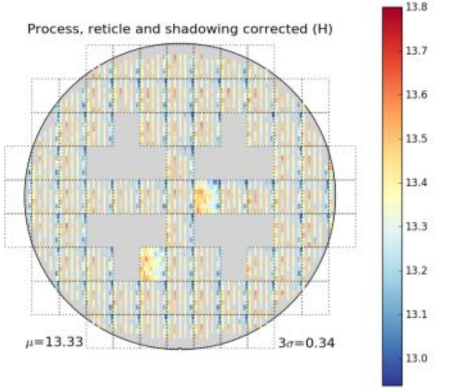
Source: Intel and TSMC presentations
 at EUVL Symposium 2016, and SPIE 2017.

13nm LS and 16nm IS: full-wafer CDU 0.3 nm

meets 5 nm logic requirements, with excellent process windows

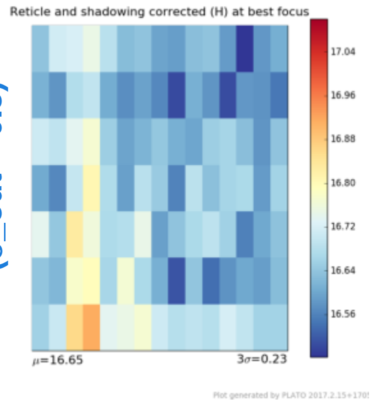
13 nm LS
leafshape dipole

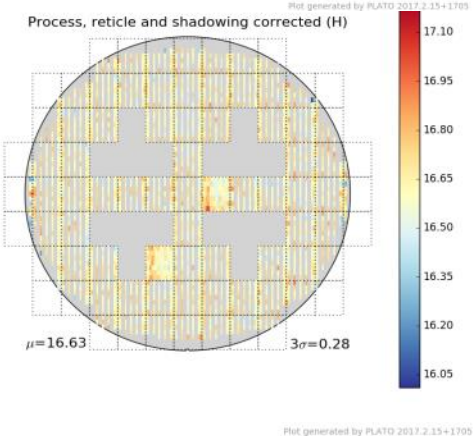


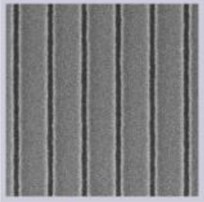


	non-CAR resist
	
Dose to size	34mJ
EL	20.7%
DoF	160nm
LWR	3.8nm

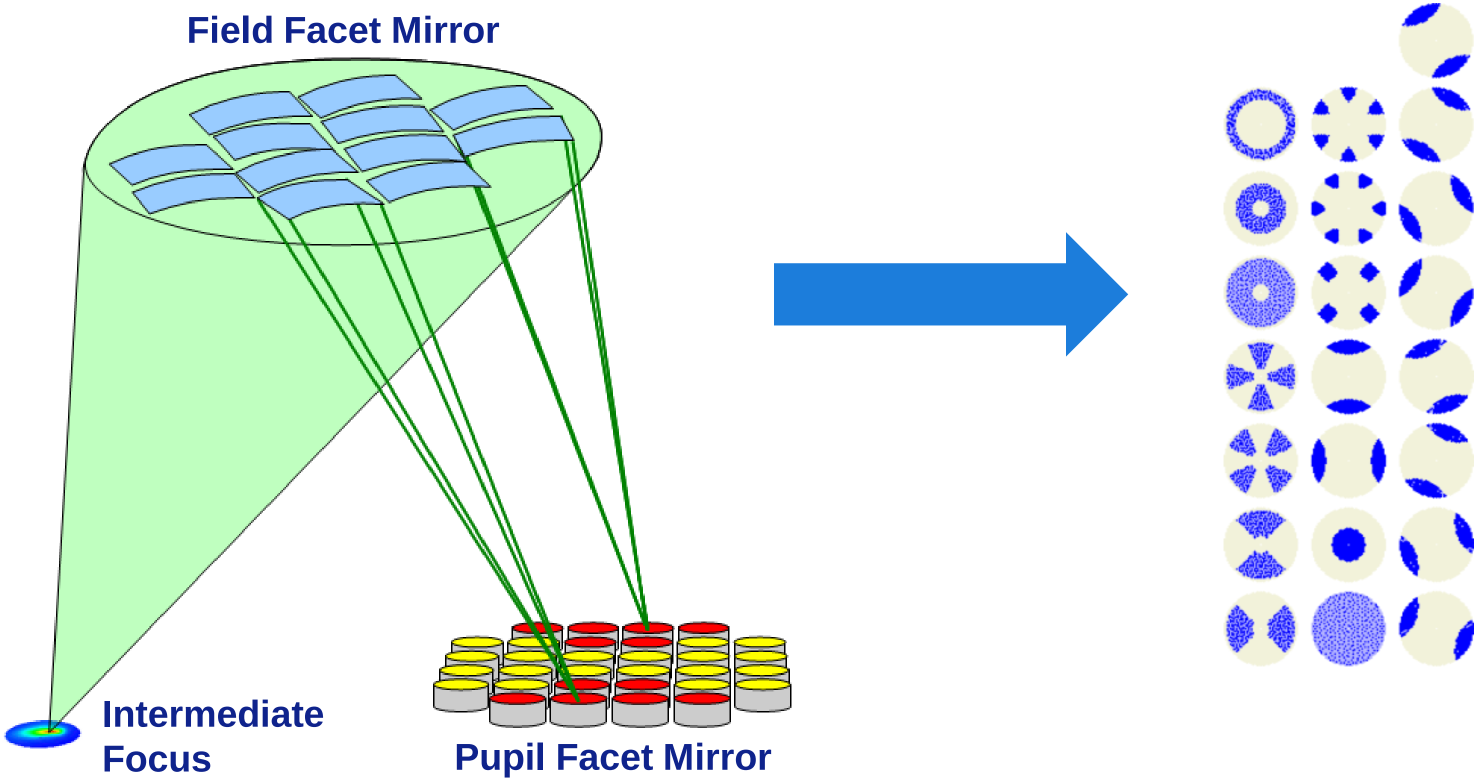
16 nm IS
small-conventional
(σ_out = 0.5)





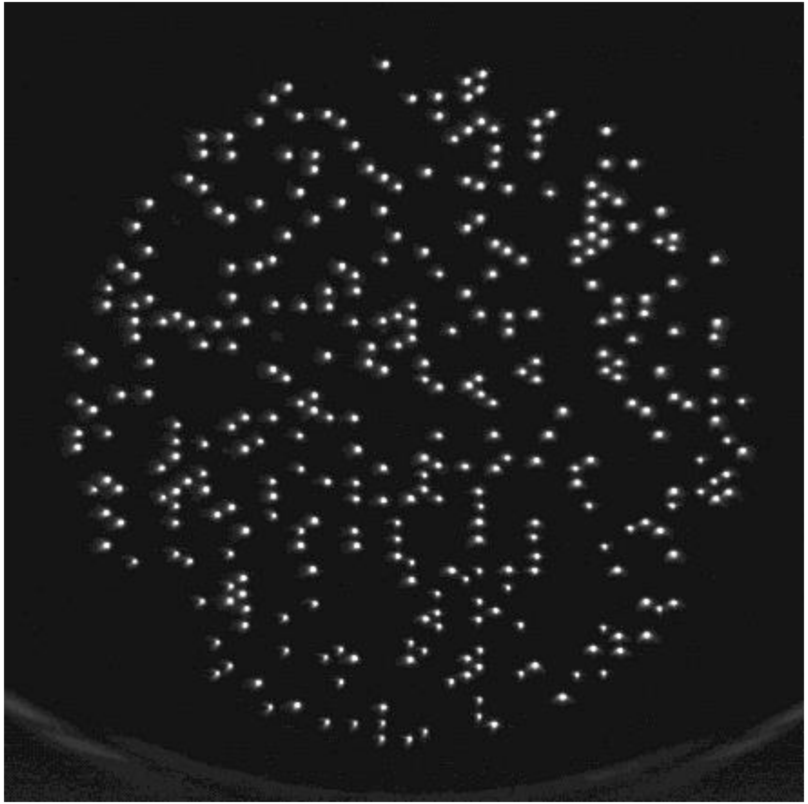
	CAR resist
	
Dose to size	58mJ
EL	18.7%
DoF	140nm
LWR	3.2nm

NXE:3400B illuminator: increased pupil flexibility at full throughput



New flex illuminator on NXE:3400B

13nm resolution without light loss at 20% pupil fill ratio

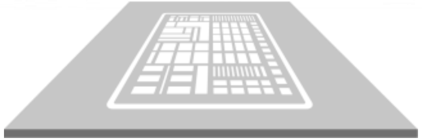


First illuminators qualified and currently being integrated in a system

The animation shows the 22 standard illumination settings. They are measured in the illuminator work center, using visible light and a camera on top of the illuminator

Two-fold approach to eliminate reticle front-side defects

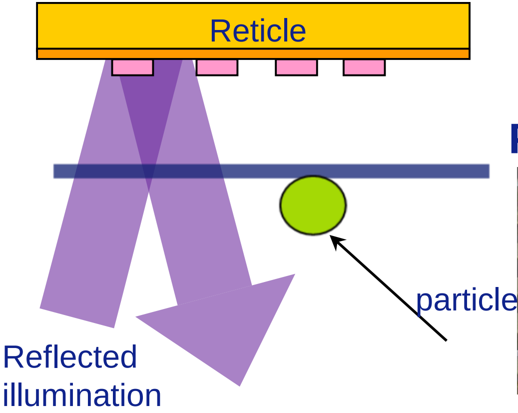
1. Clean scanner



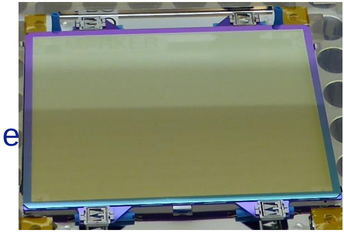
Without Pellicle

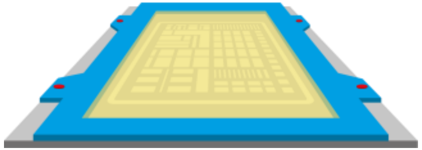
2. EUV pellicle

EUV Reticle (13.5nm)



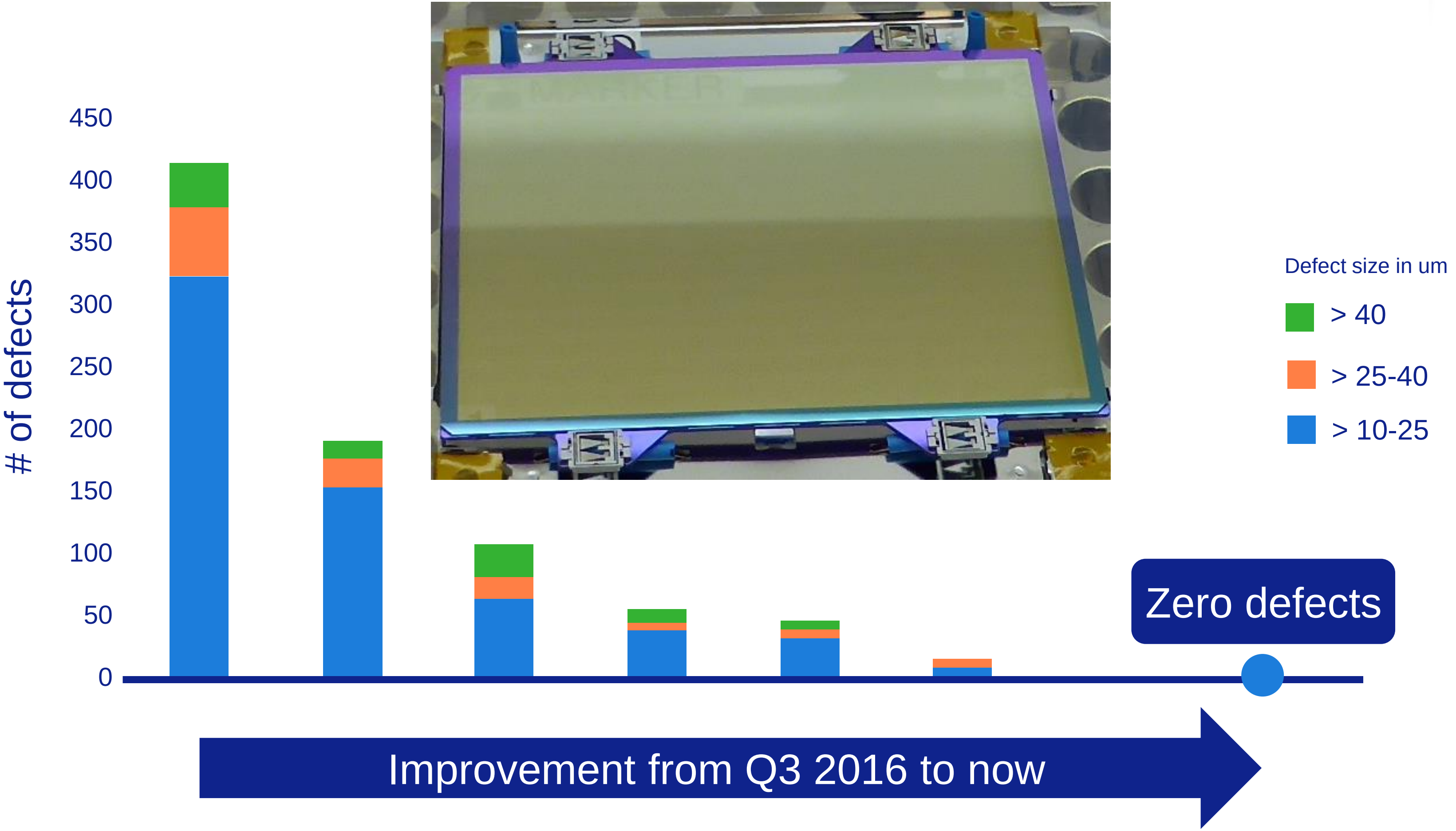
Pellicle





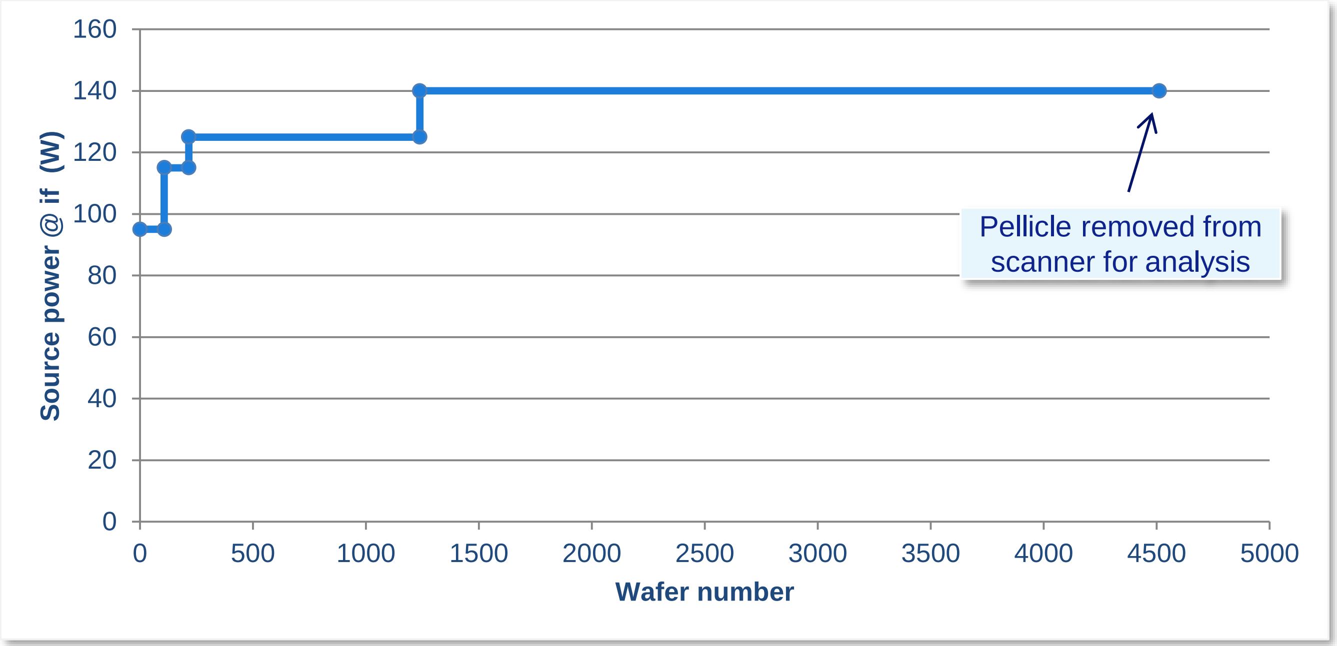
With Pellicle

Pellicle film produced without defects that print



ASML pellicle confirmed for use in NXE:3400B to at least 140W

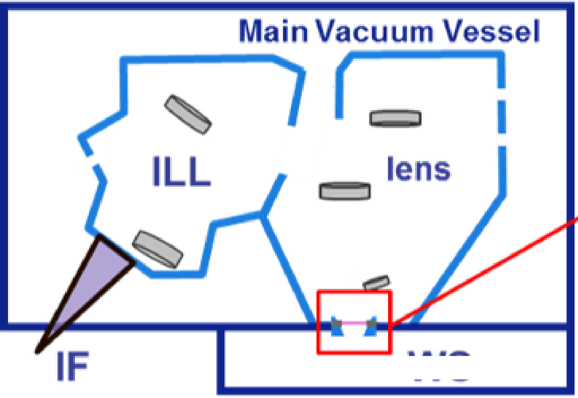
Y-nozzle cooling can extend pellicle to >205W

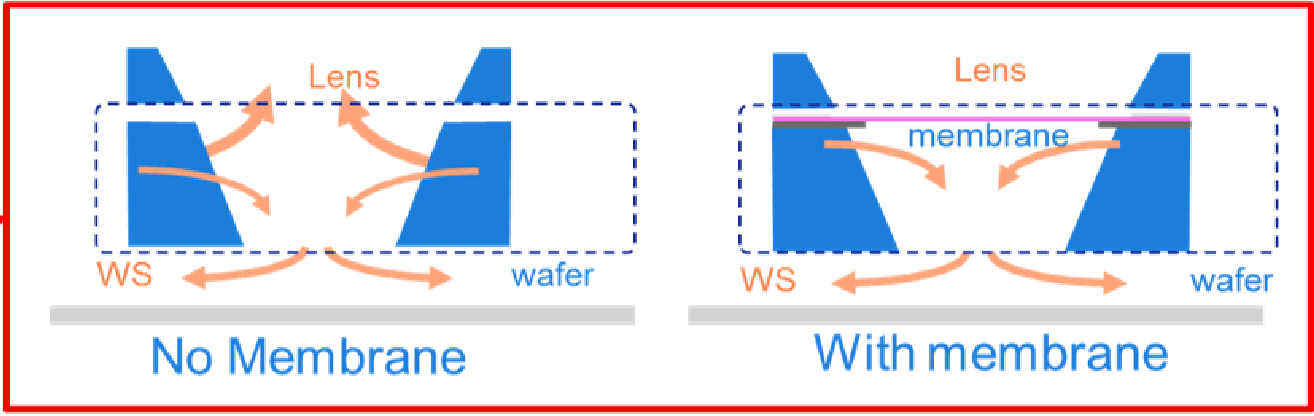


NXE:3400B @ 140W
Power ramp in 4 steps: 95W, 115W, 125W, 140W
22nm PRP-i reticle with pellicle

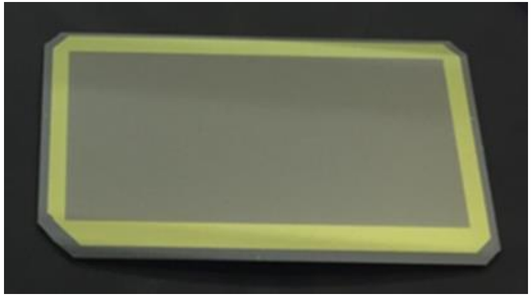
DGL membrane as spectral filter

located at Dynamic Gas Lock (DGL)
suppresses DUV and IR, plus removes outgassing risk to POB

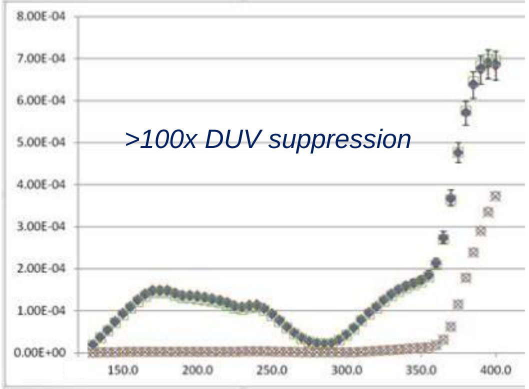


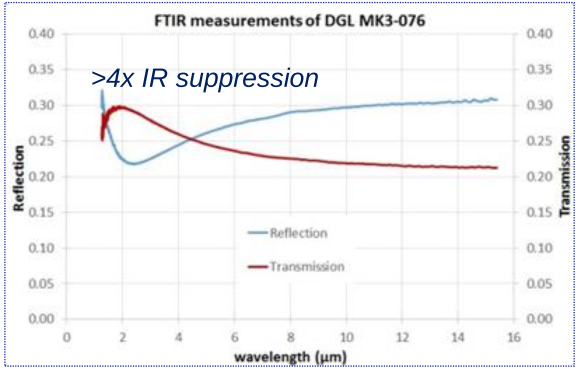


DGL membrane (~ 50 x 25 mm)



Effective DUV and IR suppression


>100x DUV suppression


FTIR measurements of DGL MK3-076

>4x IR suppression

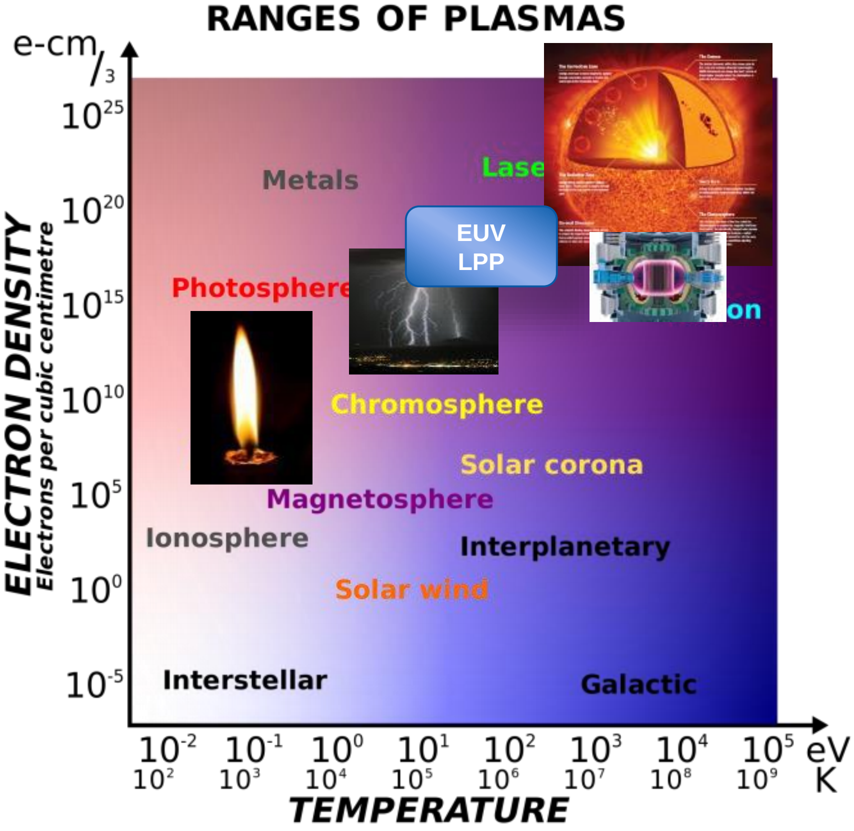
EUV: Principles of Generation

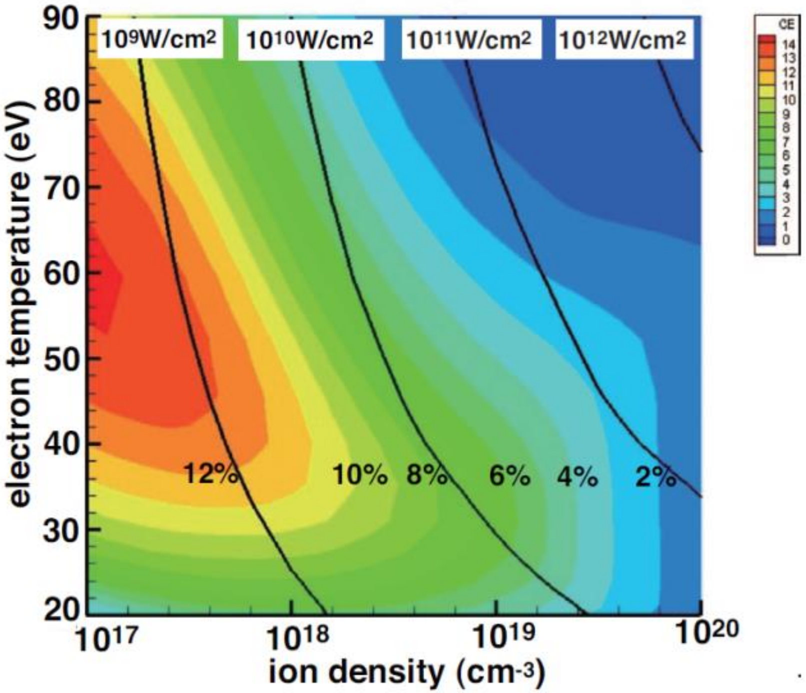
Laser Produced Plasma Density and Temperature

Nishihara et al. (2008)

Ion density ~ $10^{17} – 10^{18}$ #/cm^3

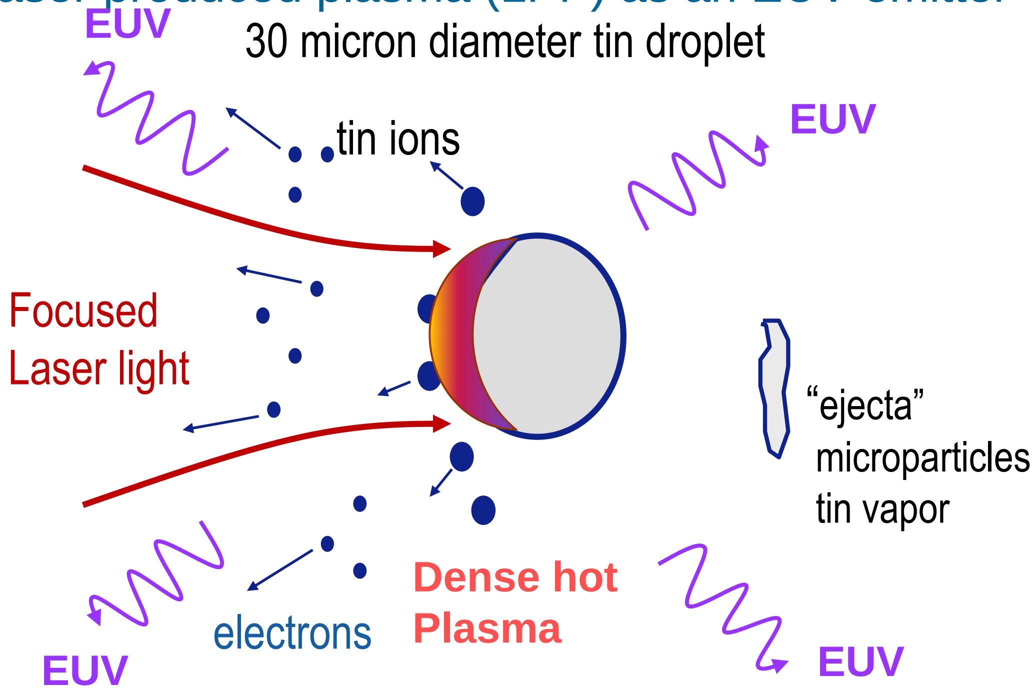
Temperature ~ 30 -100 eV





Fundamentals: EUV Generation in LPP

Laser produced plasma (LPP) as an EUV emitter



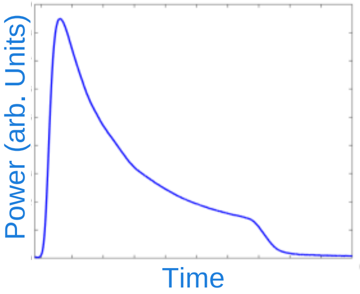
Tin Laser Produced Plasma Image

1. High power laser interacts with liquid tin producing a plasma.
2. Plasma is heated to high temperatures creating EUV radiation.
3. Radiation is collected and used to pattern wafers.

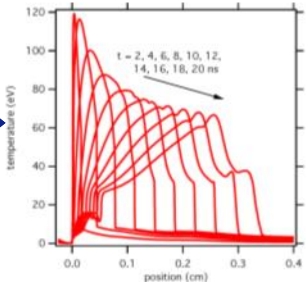
Plasma simulation capabilities

Main-pulse modeling using HYDRA

Main-pulse shape

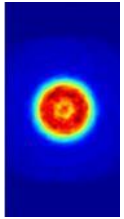


1D:
real pulse shape

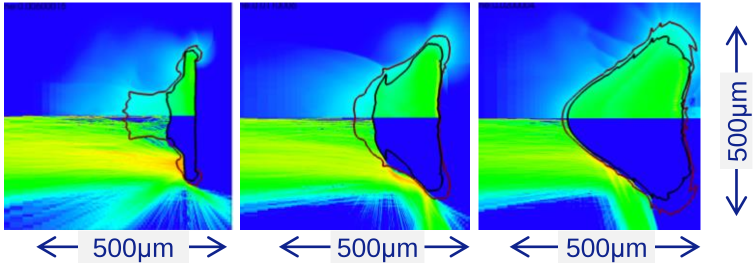


1D simulations are fast and useful for problems that require rapid feedback and less accuracy

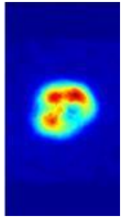
2D:
+ symmeterized beam profile

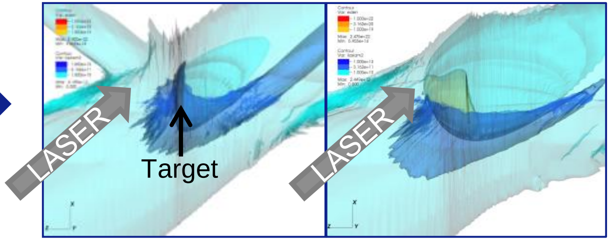


Electron density (top half) with laser light (bottom half)



3D:
+ real asymmetric profile





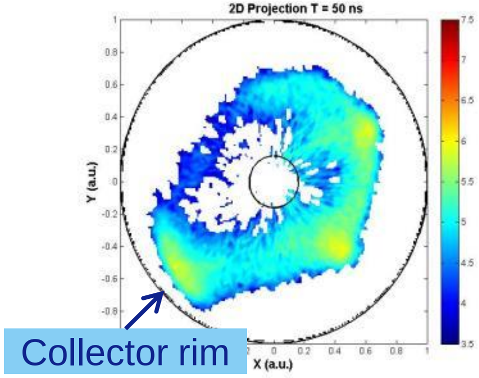
2D and 3D simulations are run for the full duration of the Main pulse. Results include temperature, electron density, spectral emission, etc.

Sn target using a real irradiance distribution

Simulation of the EUV source

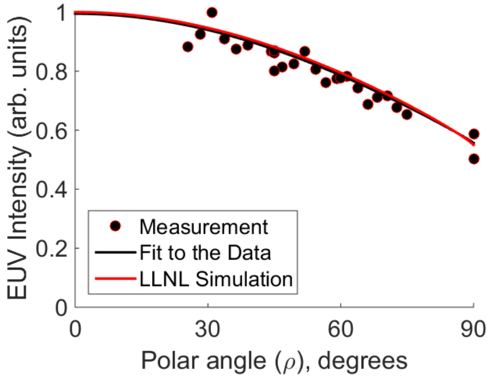
The plasma code’s outputs were processed to produce synthetic source data. The comparison to experiments helps to validate the code and understand it’s accuracy.

Reflected laser modeling

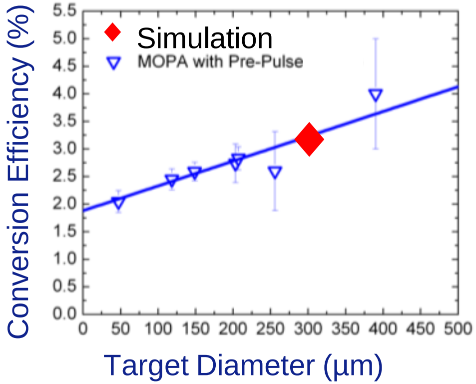


Collector rim

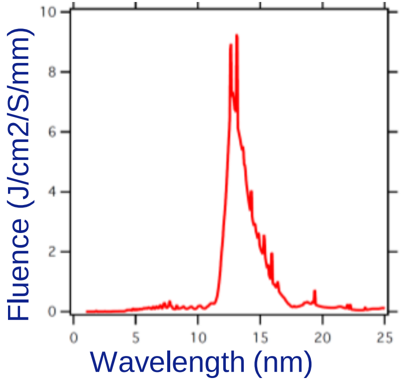
Emission anisotropy



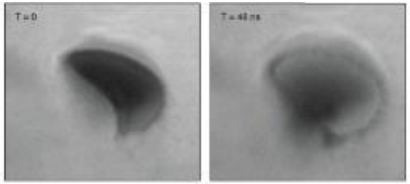
Conversion Efficiency



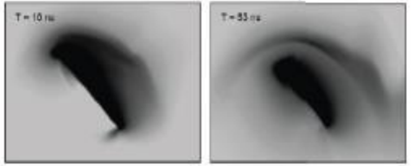
Simulated EUV spectra



Measured Shadowgrams



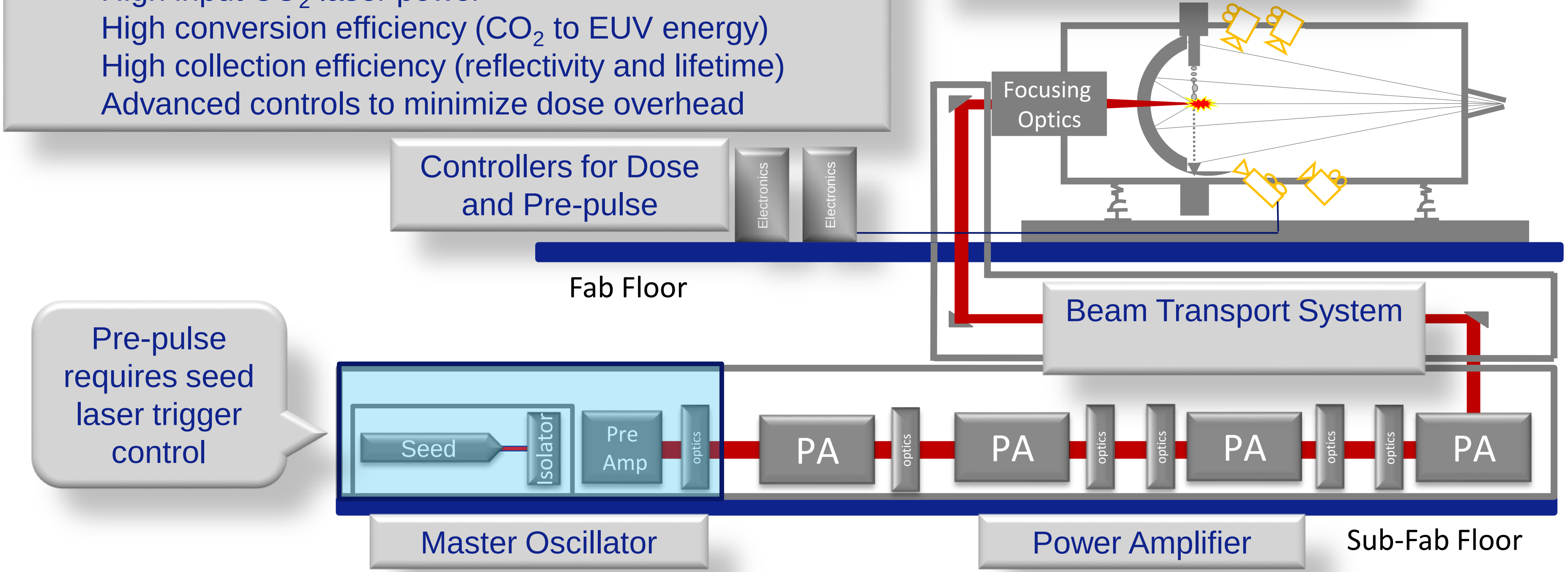
Simulated Shadowgrams



EUV Source: Architecture and Operation Principles

LPP: Master Oscillator Power Amplifier (MOPA) Pre-Pulse Source Architecture

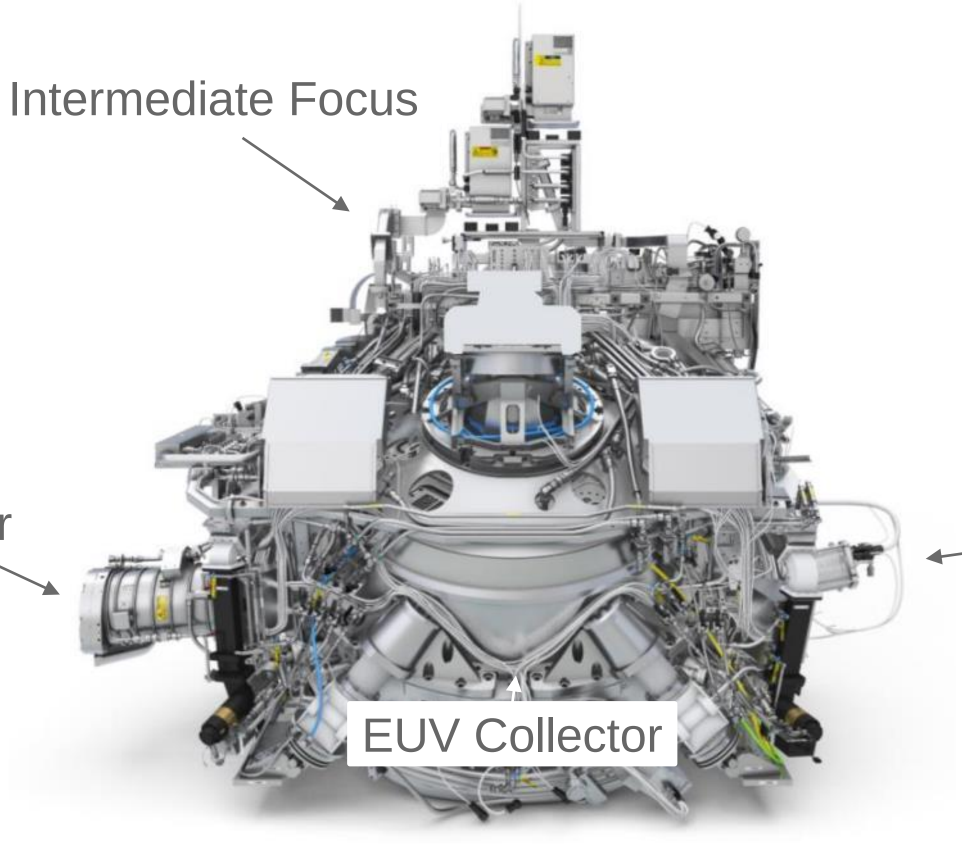
- Key factors for high source power are:
  - High input CO_2 laser power
  - High conversion efficiency (CO_2 to EUV energy)
  - High collection efficiency (reflectivity and lifetime)
  - Advanced controls to minimize dose overhead



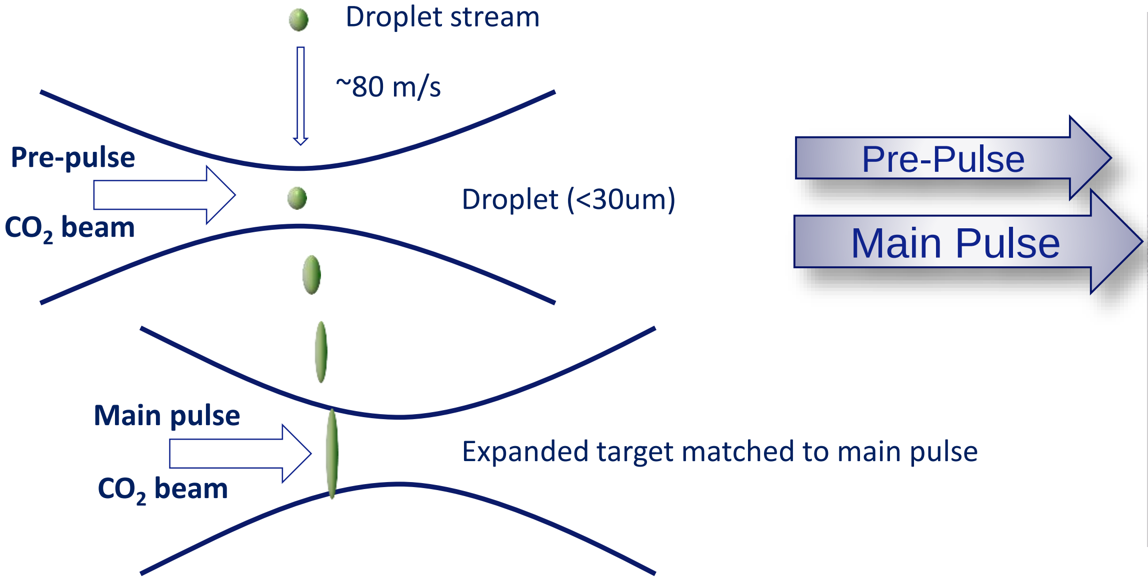
EUV power (source/scanner interface, [W]) ∝ **CO_2 power [W]** * **Conversion Efficiency [%]** * **1 – Dose Overhead [%]**

NXE:3XY0 EUV Source: Main modules

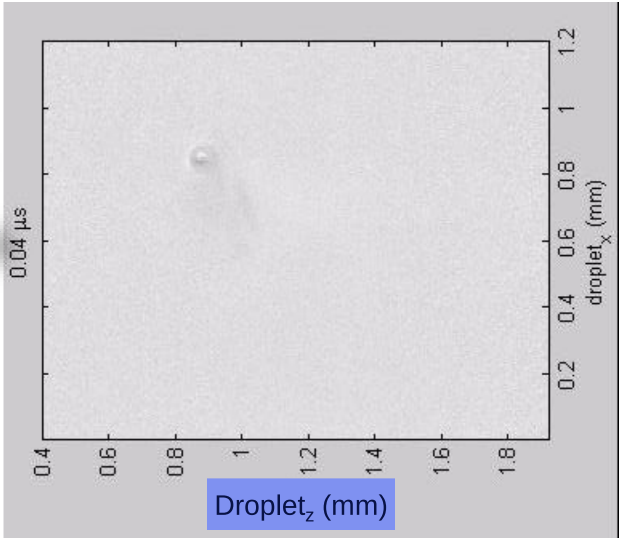
Populated vacuum vessel with tin droplet generator and collector



EUV Source: MOPA + Pre-Pulse



Movie: Backlight shadowgrams from a 3300 MOPA+PP source



Pre-pulse transforms tin droplet into
“pancake/mist” that matches
CO_2 main pulse beam profile

>5% conversion efficiency achieved

Pre-pulse laser

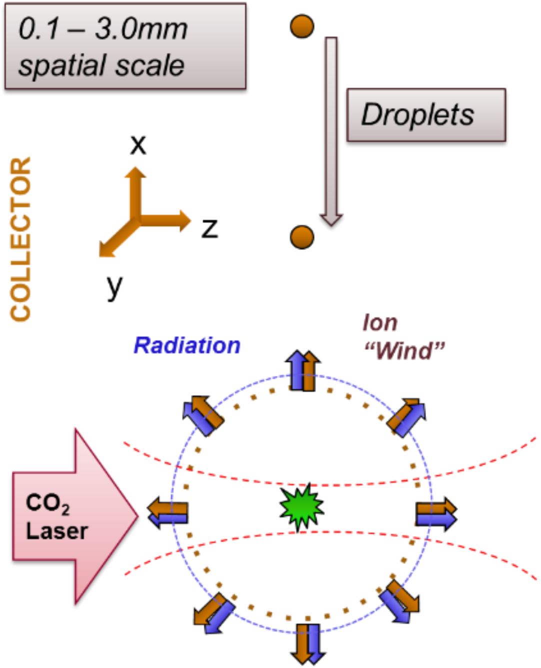
→Expands the droplet and prepares the Sn target

Main-pulse laser

→Heats and ionizes the Sn target to produce EUV light

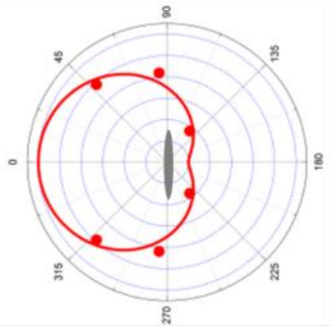
MOPA = Master Oscillator Power Amplifier
PP = Pre-Pulse
MP = Main Pulse

Forces on Droplets during EUV Generation



Measured
Angular dependence of
Forces on the droplets

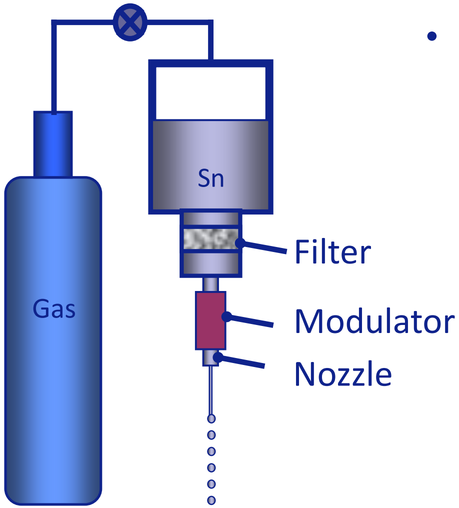
Function fit: Force ~
EUVen *A*(1+cosθ+B) / R^2

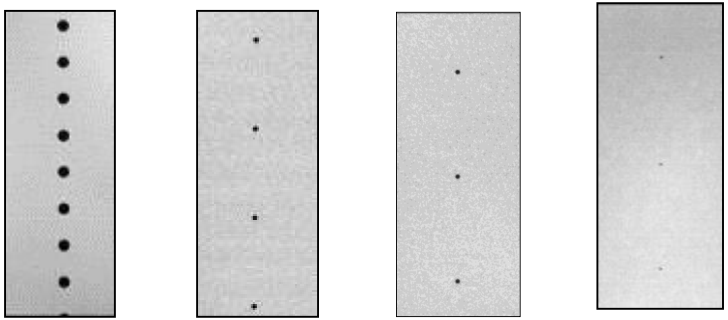


High EUV power at high repetition rates drives requirements for higher speed droplets with large space between droplets

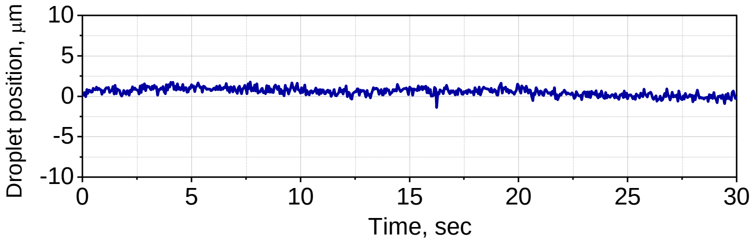
Droplet Generator: Principle of Operation

- Tin is loaded in a vessel & heated above melting point
- Pressure applied by an inert gas
- Tin flows through a filter prior to the nozzle
- Tin jet is modulated by mechanical vibrations





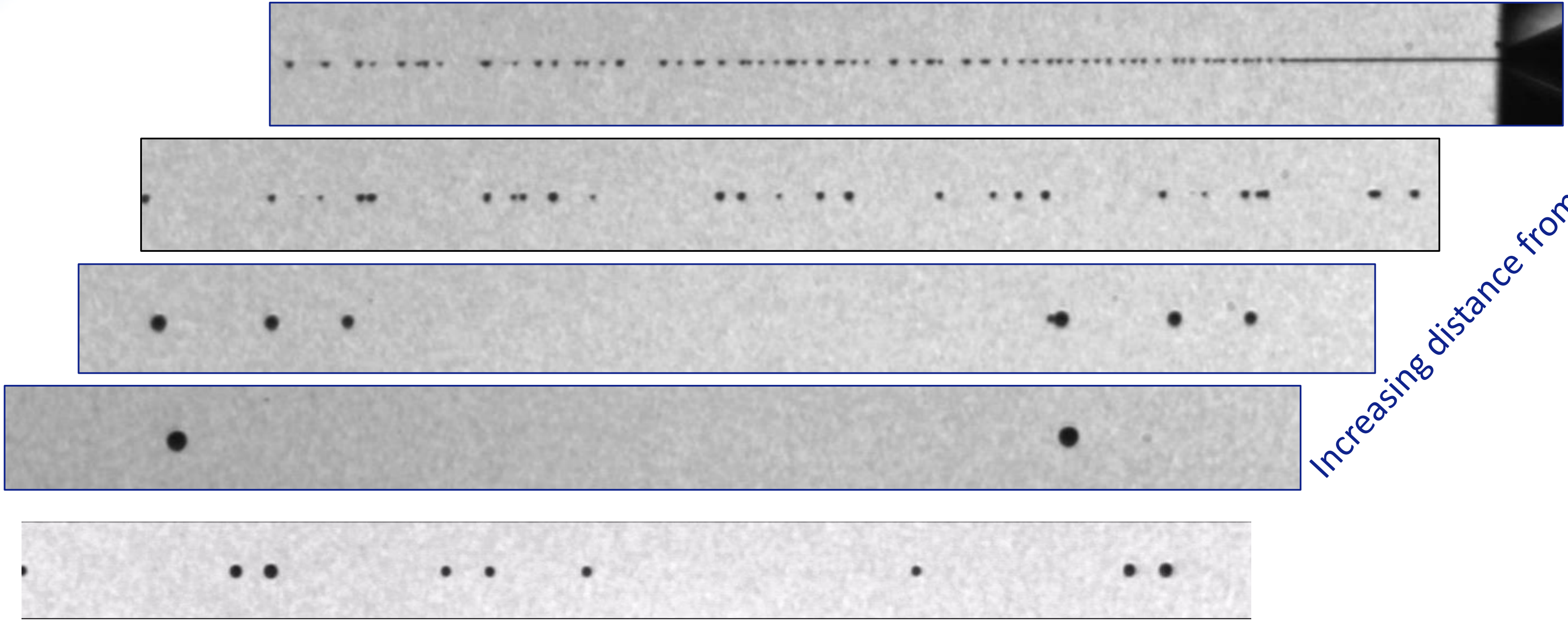
140 μm 50 μm 30 μm 16 μm



Short term droplet position stability σ~1μm

Droplet Generator: Principle of Operation

Large separation between the droplets by special modulation

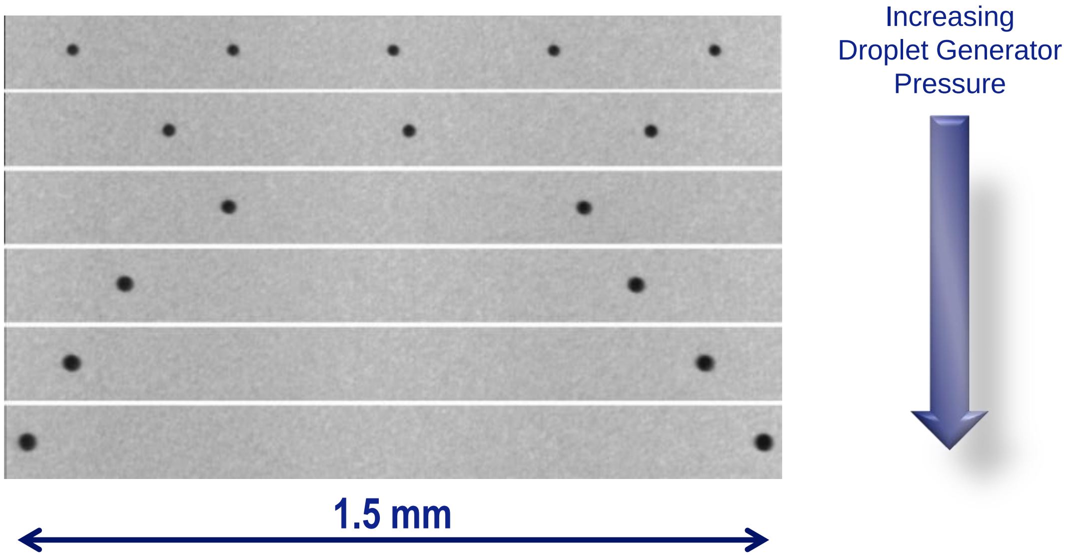


Increasing distance from nozzle

Multiple small droplets coalesce together to form larger droplets at larger separation distance

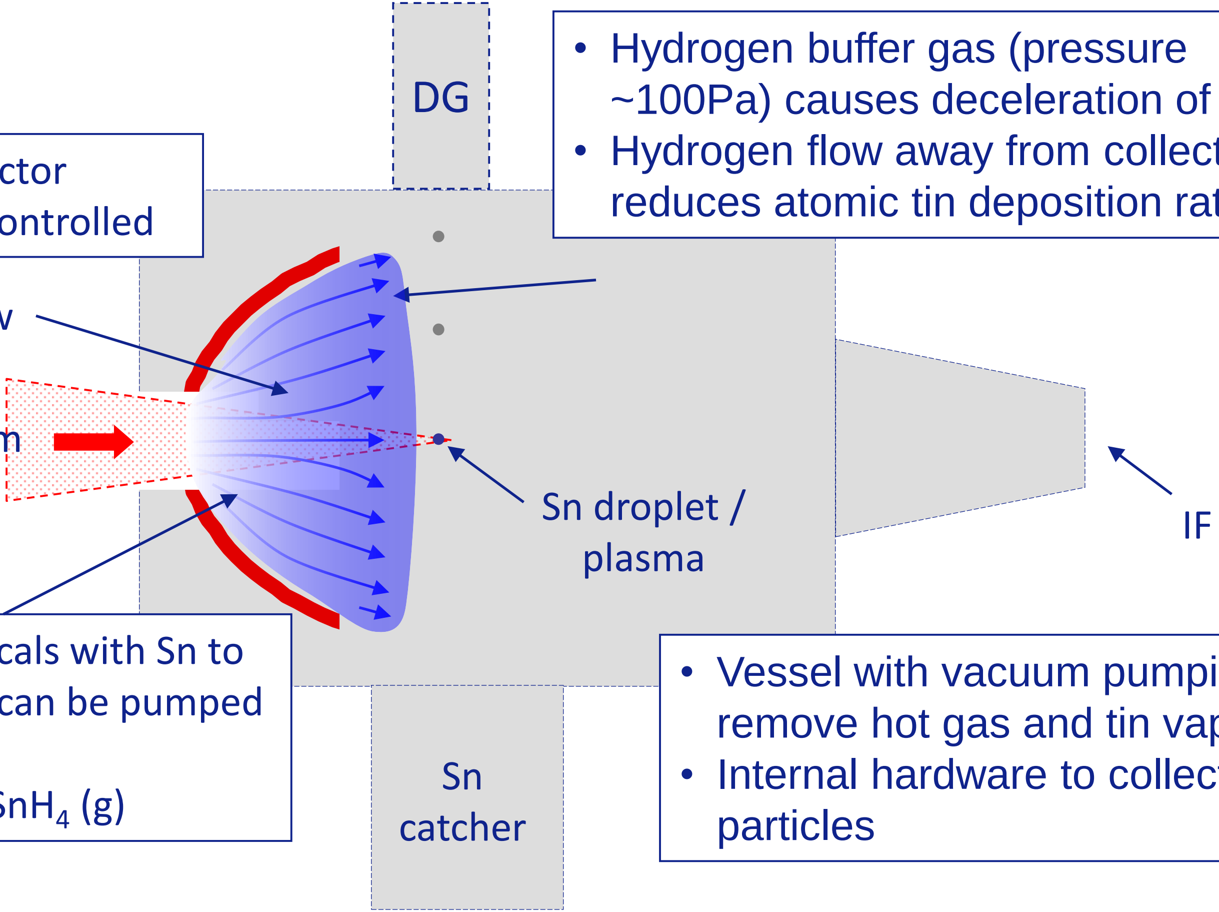
Droplet Generator: Principle of Operation

Large separation between the droplets by special modulation



Tin droplets at 80 kHz and at different applied pressures.
Images taken at a distance of 200 mm from the nozzle

Collector Protection by Hydrogen Flow



EUV collector
Temperature controlled

- Hydrogen buffer gas (pressure ~100Pa) causes deceleration of ions
- Hydrogen flow away from collector reduces atomic tin deposition rate

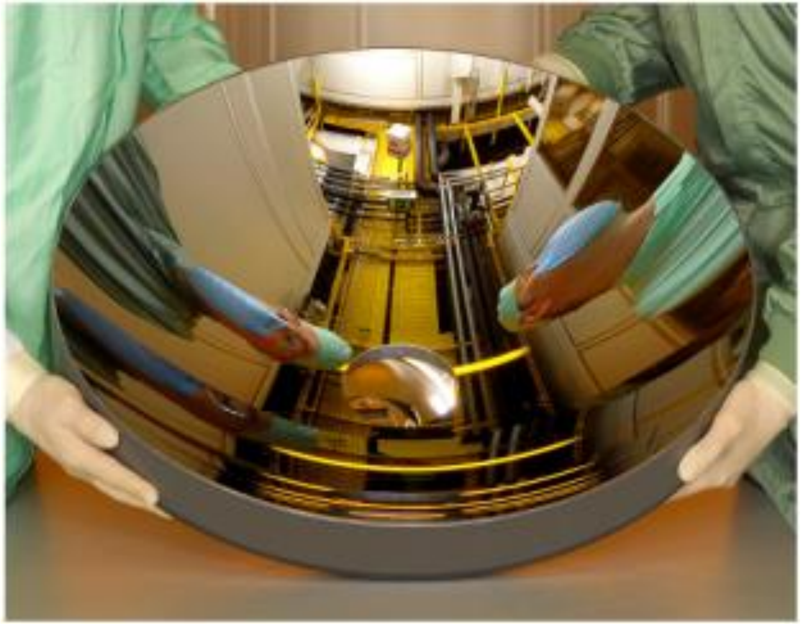
Reaction of H radicals with Sn to form SnH_4, which can be pumped away.

$Sn\ (s) + 4H\ (g) \rightarrow SnH_4\ (g)$

- Vessel with vacuum pumping to remove hot gas and tin vapor
- Internal hardware to collect micro particles

EUV Collector: Normal Incidence

- Ellipsoidal design
  - Plasma at first focus
  - Power delivered to exposure tool at second focus (intermediate focus)
- Wavelength matching across the entire collection area



Normal Incidence Graded Multilayer Coated Collector

Productivity increases via source availability

Secured EUV power is matched with increasing availability

$$\boxed{\text{Productivity} = \text{Throughput}(\propto \text{EUV Power}) \times \text{Availability}}$$

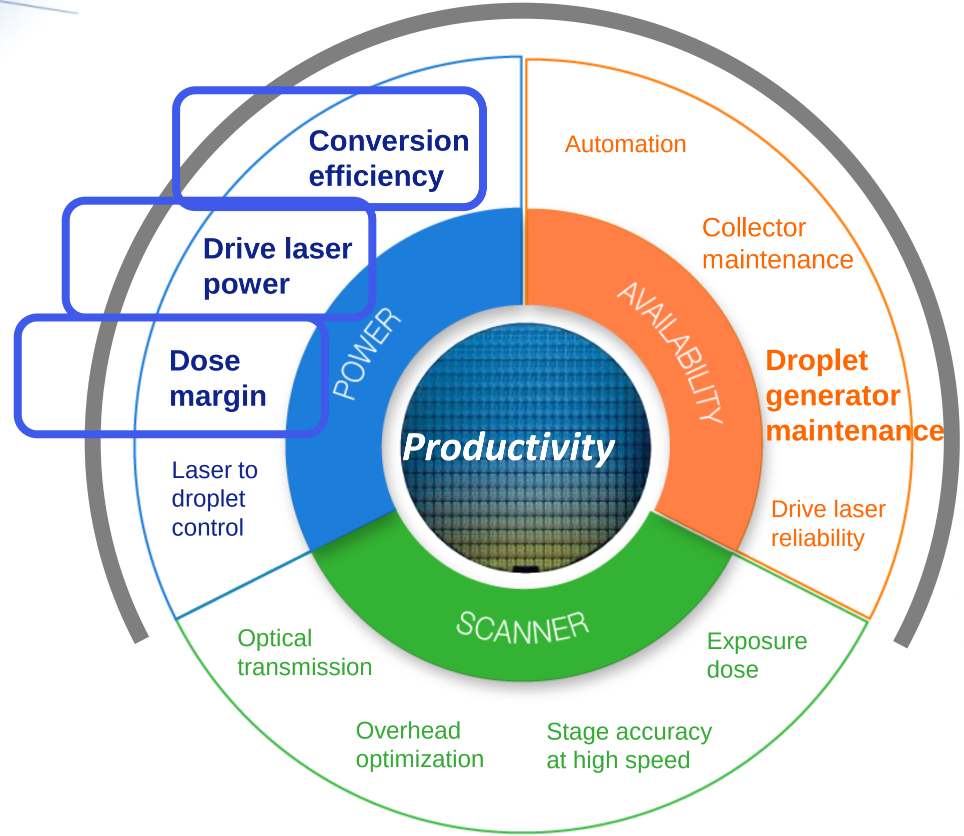
$$\text{EUV Power} = (CO_2\ \underbrace{\text{laser power} \times CE \times \text{transmission}}_{\text{Raw EUV power}})*(1\text{-dose overhead})$$

Source power **from 10 W to > 250 W**	Drive laser power	from 20 to 40 kW
	Conversion efficiency (CE)	from 2 to 6% (Sn droplet)
	Dose overhead	from 50 to 10%
	Optical transmission	
Source availability	Automation	
	Collector protection	
	Droplet generator reliability & lifetime	
	Drive laser reliability	

EUV Sources in the Field

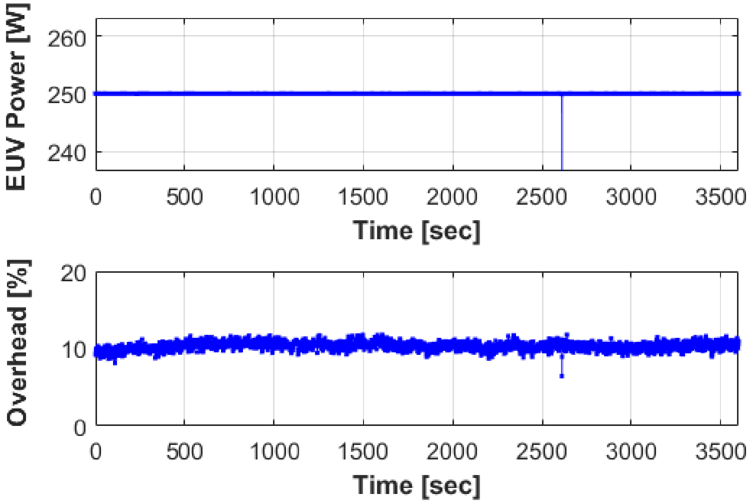
Productivity targets for HVM

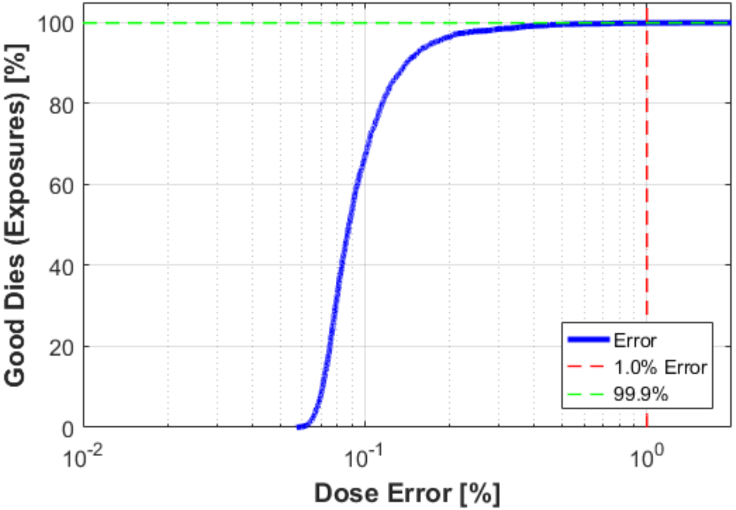
Source contribution to productivity



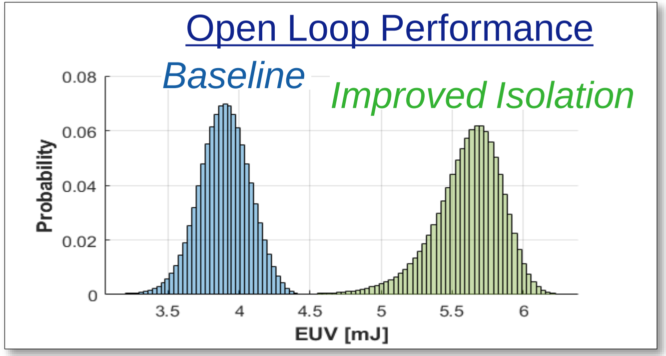
EUV Source operation at 250W

with 99.90% fields meeting dose spec



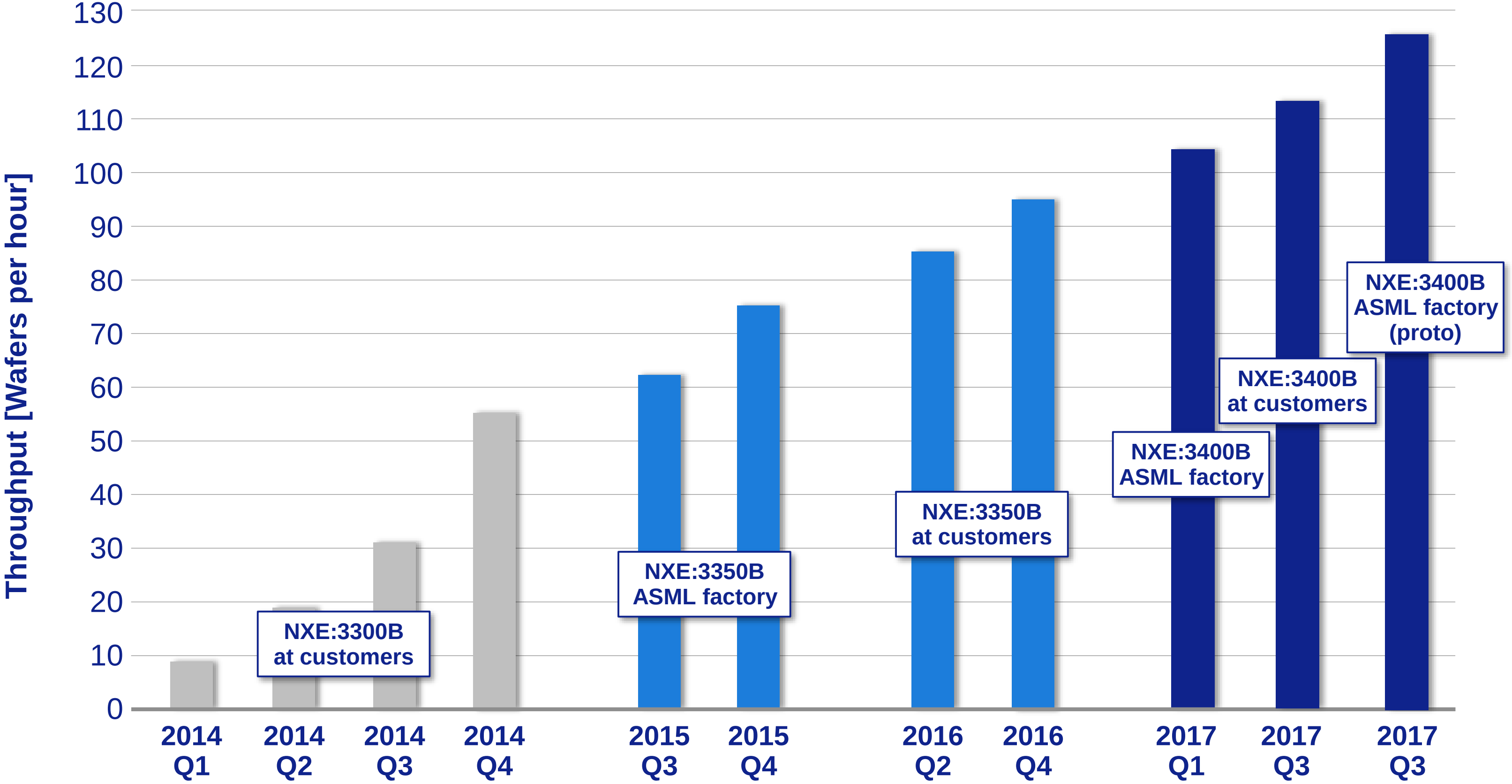


Operation Parameters	
Repetition Rate	50kHz
MP power on droplet	21.5kW
Conversion Efficiency	6.0%
Collector Reflectivity	41%
Dose Margin	10%
EUV Power	**250 W**


Open Loop Performance

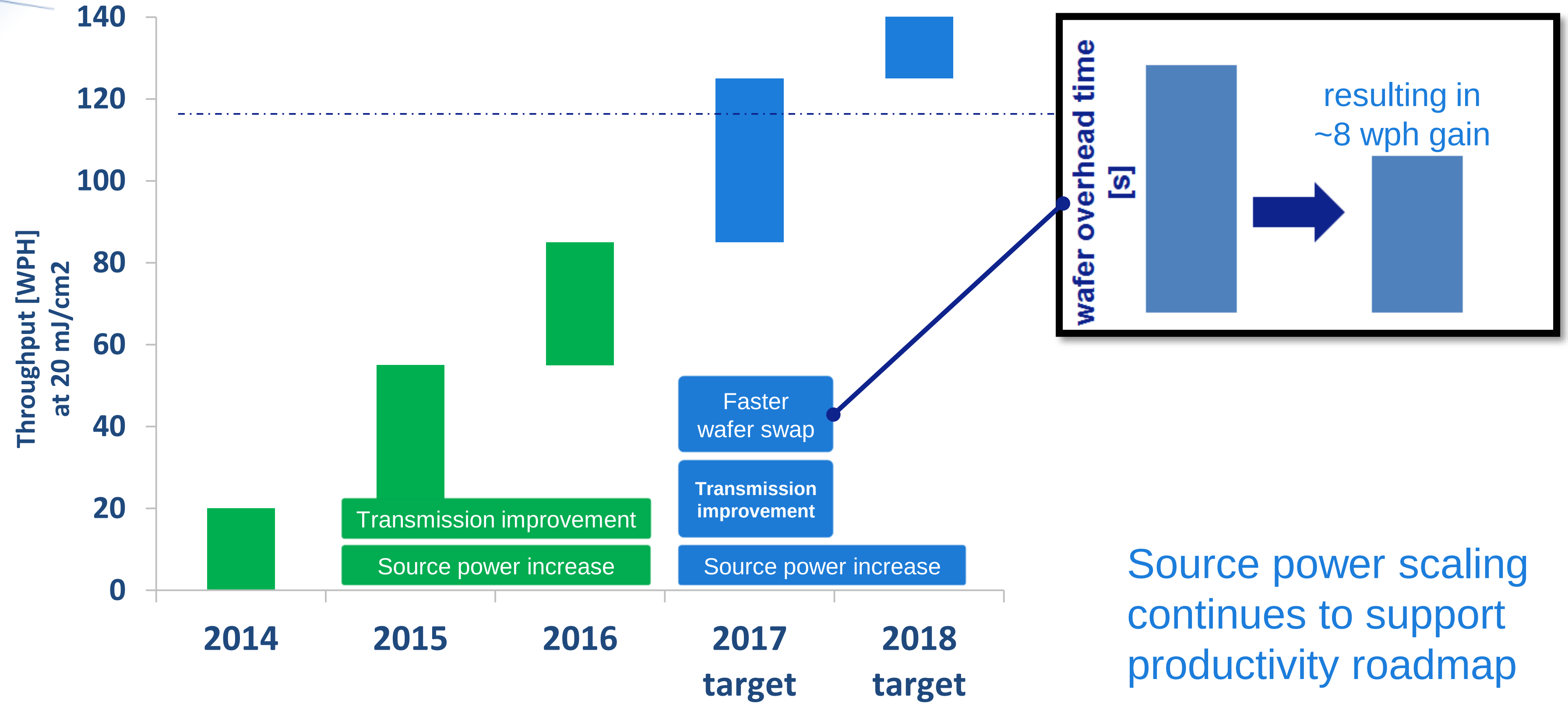
NXE scanner productivity above **125** wafers per hour

NXE:3400B at 207W, **126 WPH**



NXE:3400B ATP test: 26x33mm^2, 96 fields, 20mJ/cm^2

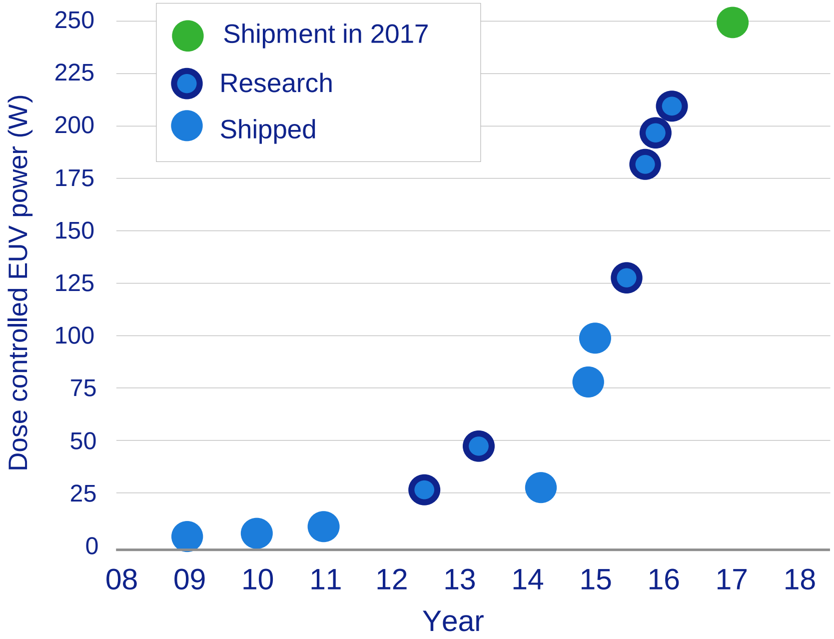
Productivity roadmap towards >125 WPH in place



Source power scaling continues to support productivity roadmap

Progress for 2017: 250W demonstrated

EUV power (source/scanner interface, [W]) $\propto$ **CO_2 power [W]** * **Conversion Efficiency [%]** * **1 – Dose Overhead [%]**



>250W is now demonstrated, shipping planned end of 2017

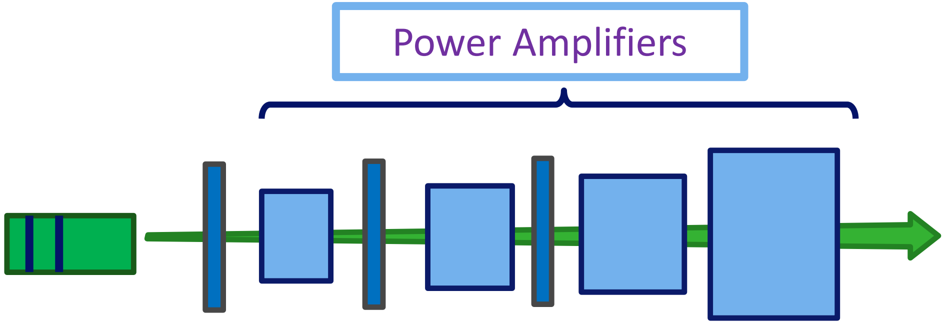
Increase average and peak laser power
Enhanced isolation technology

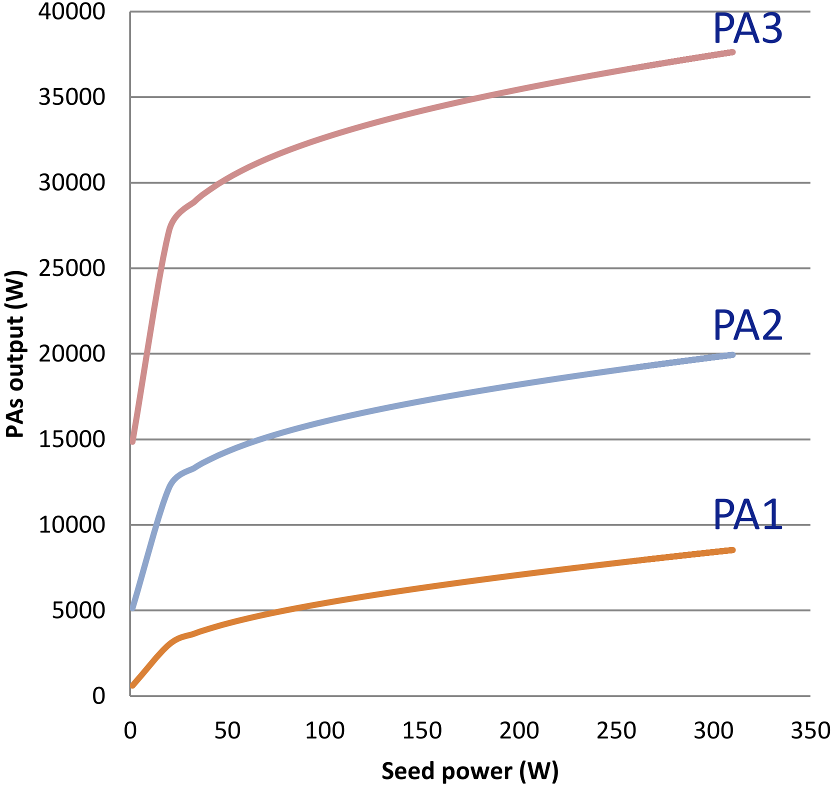
Advanced target formation technology

Improved dose-control technique

Power Amplifier Chain Increases CO_2 Power

Good beam quality for gain extraction and EUV generation

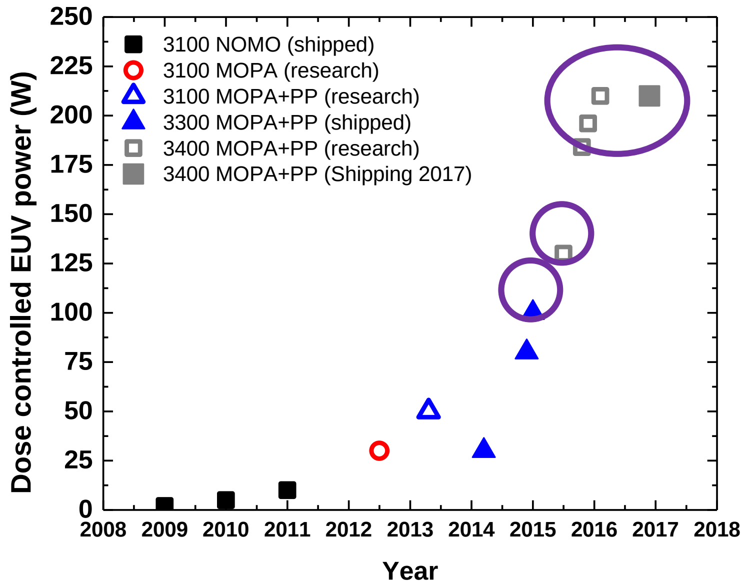


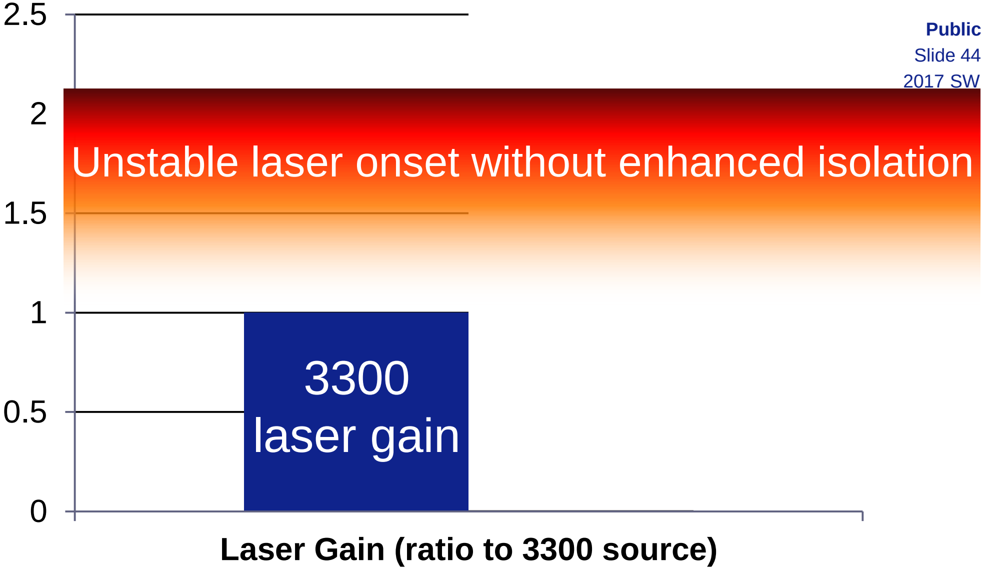


Key technologies:

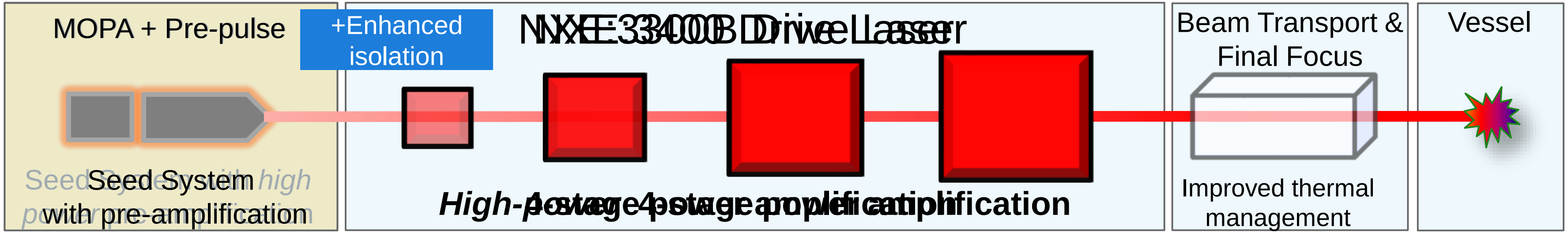
1. Drive laser with higher power capacity
2. Gain distribution inside amplification chain
3. Mode-matching during beam propagation
4. Isolation between amplifiers
5. Metrology, control, and automation

Scaling laser power requires laser isolation advances



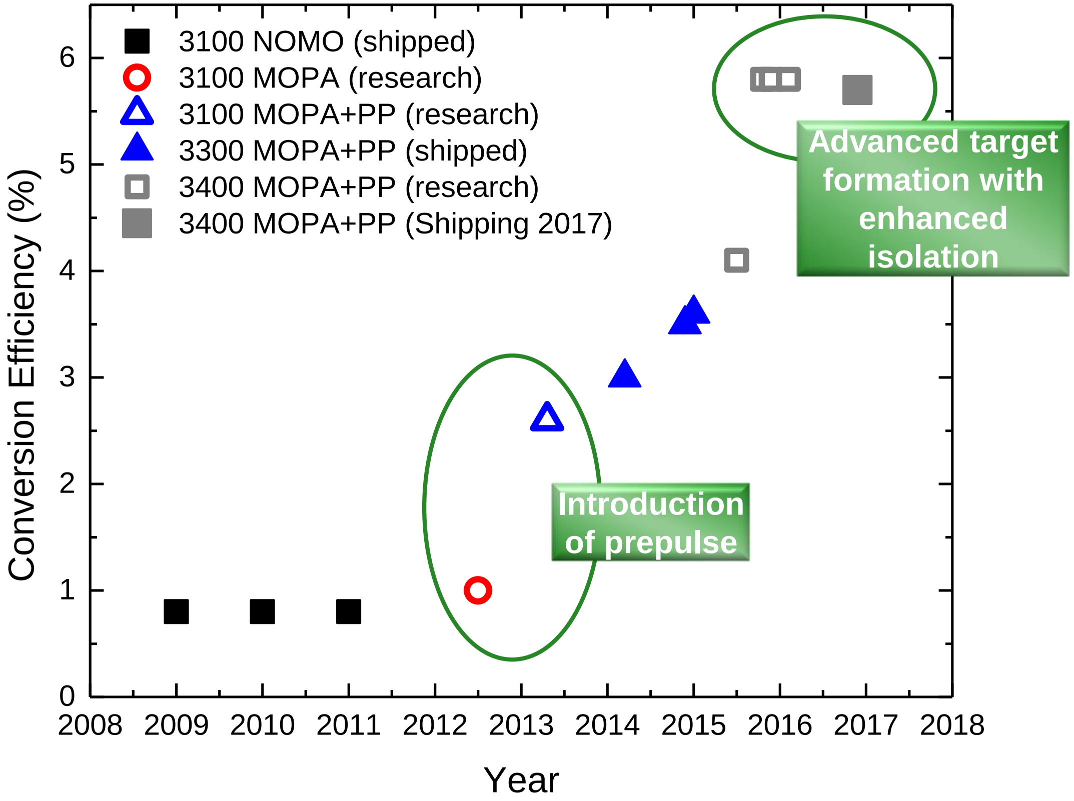


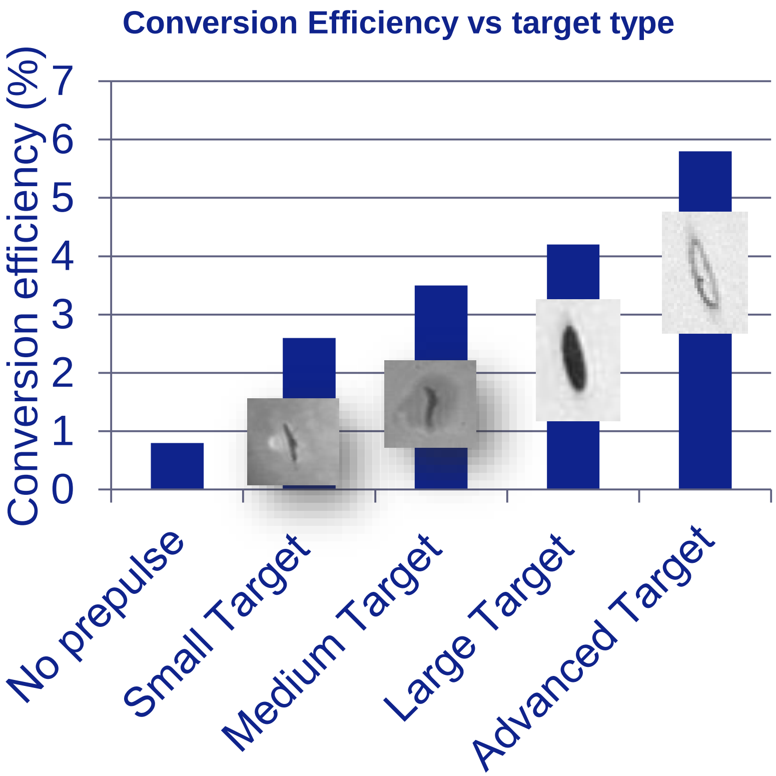
From NXE:3300 to NXE:3400, enhanced isolation gives stable >2x increase laser gain



Enhanced isolation leads to >205W EUV power

via advanced target formation for high CE

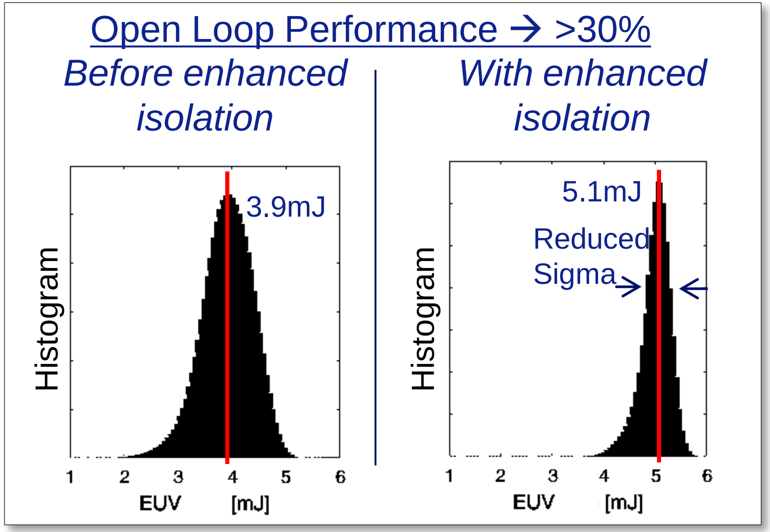




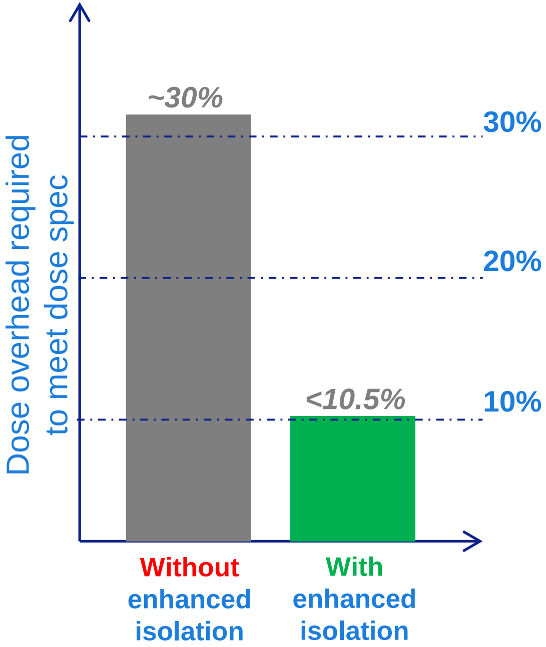
Enhanced isolation improves EUV performance

Benefits of enhanced isolation:

- **Higher, stable CO_2 laser power → lower dose overhead**
- **High conversion efficiency operation → higher pulse energy**

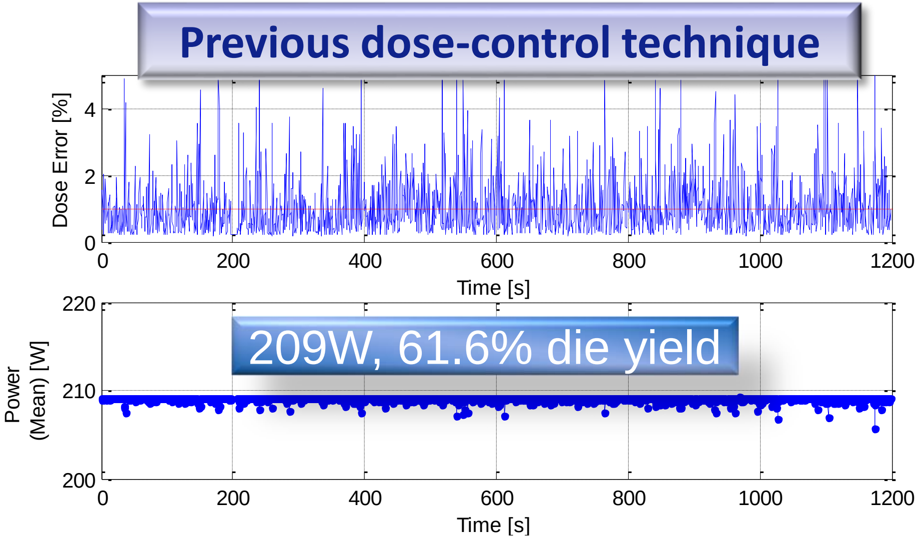


Open Loop Performance → >30%



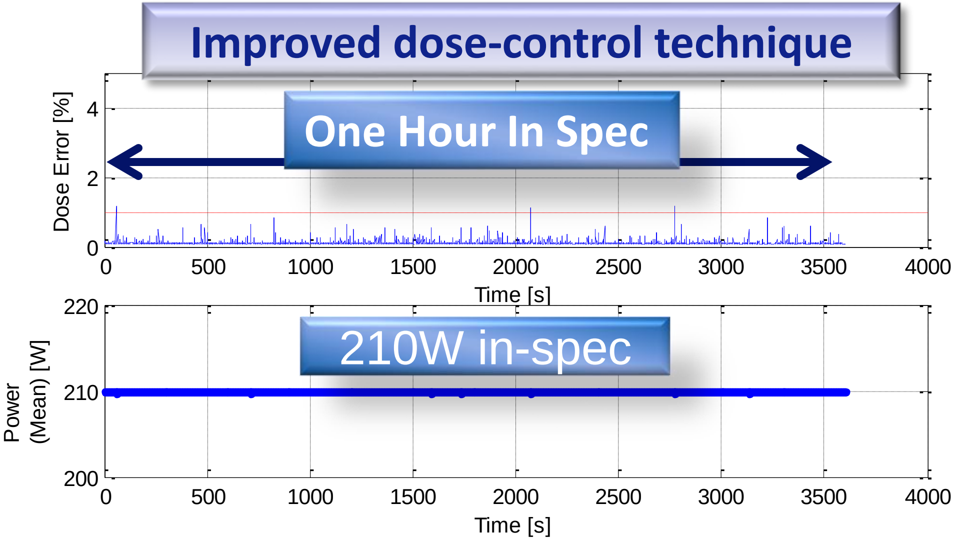
Comparing two dose-control techniques **at 210W**:

higher in-spec power with improved dose-control technique



Previous dose-control technique

209W, 61.6% die yield



Improved dose-control technique

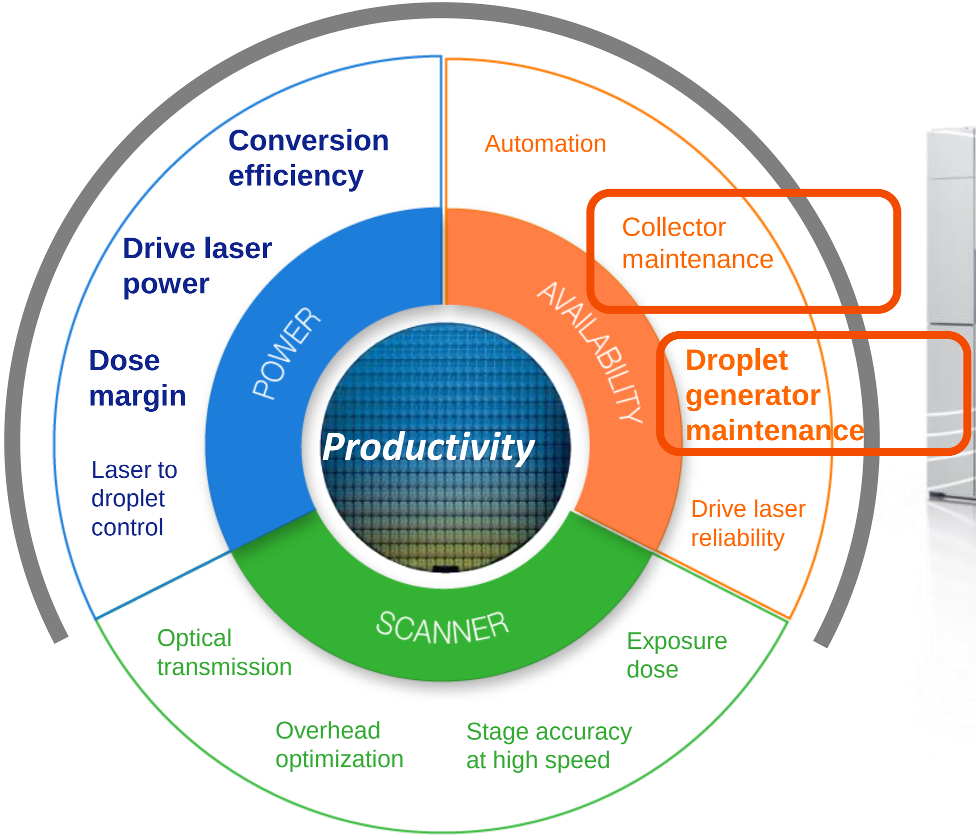
One Hour In Spec

210W in-spec

On the same EUV source, back-to-back performance comparing previous and improved dose-control techniques demonstrates higher in-spec power can be delivered with reduced overhead

Productivity targets for HVM

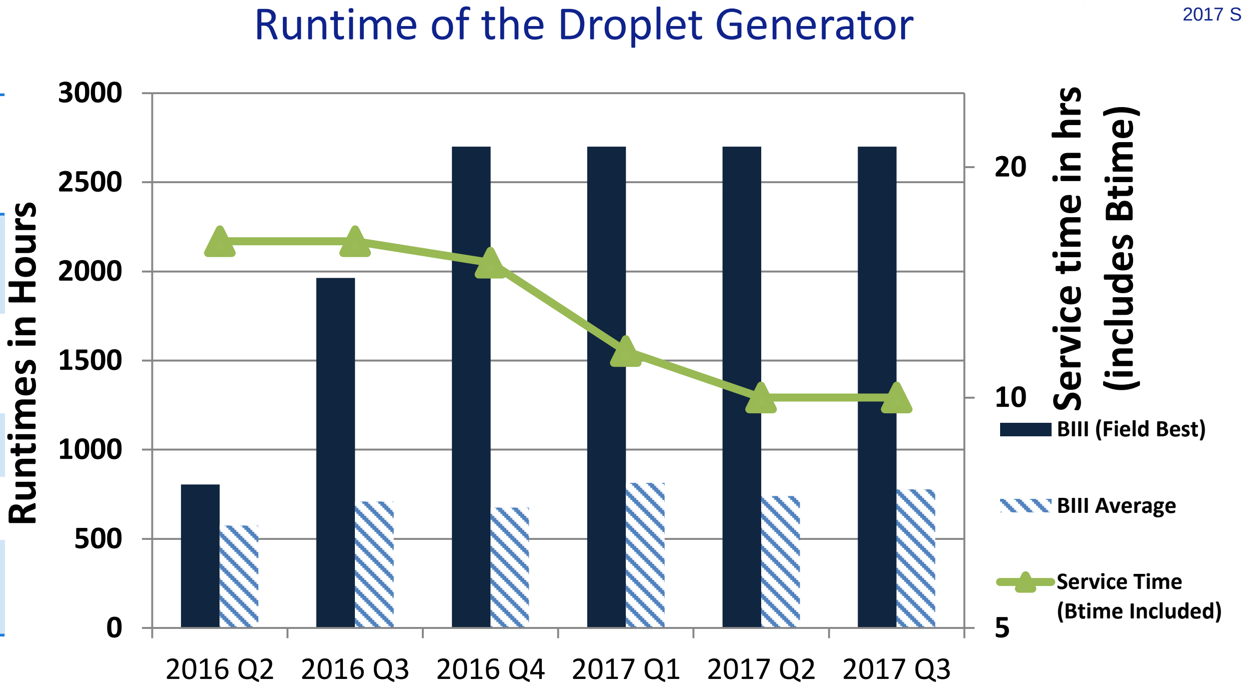
Source contribution to productivity



Third generation Droplet Generators: average lifetime increased

Run time ~ 2700 hours

Performance parameter	**Gen III**
Key Features	Restart & Refill capable
Run-time	~780 hrs (Ave) (2700 hrs max)
Start-up yield	>95%
Availability	95%
Droplet diameter	27 µm


Runtime of the Droplet Generator

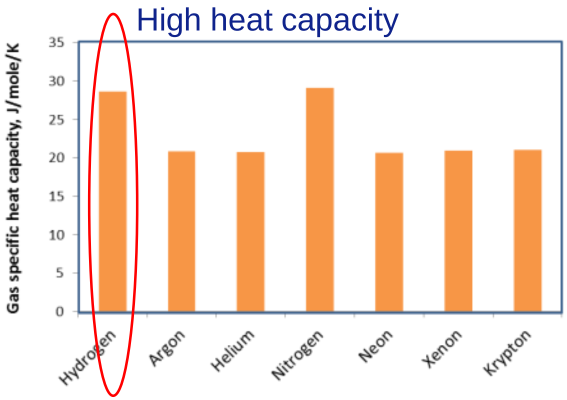
Long runtime and high reliability

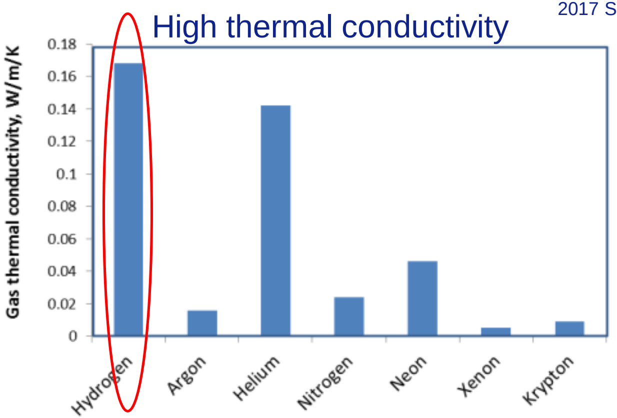
70% reduction in average maintenance time

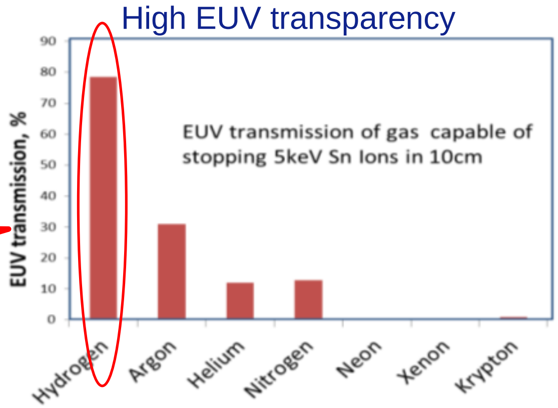
Hydrogen gas central to tin management strategy

Requirements for buffer gas:

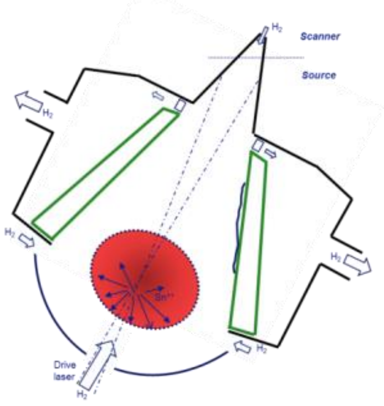
- **Stopping fast ions (with high EUV transparency)**
- **Heat transport**
- **Sn etching capability**


High heat capacity


High thermal conductivity


High EUV transparency

EUV transmission of gas capable of stopping 5keV Sn Ions in 10cm

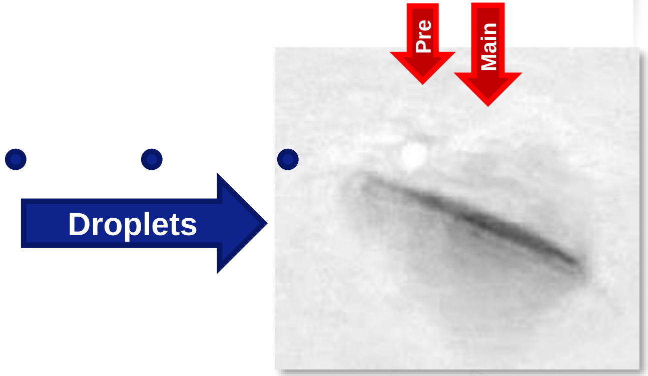


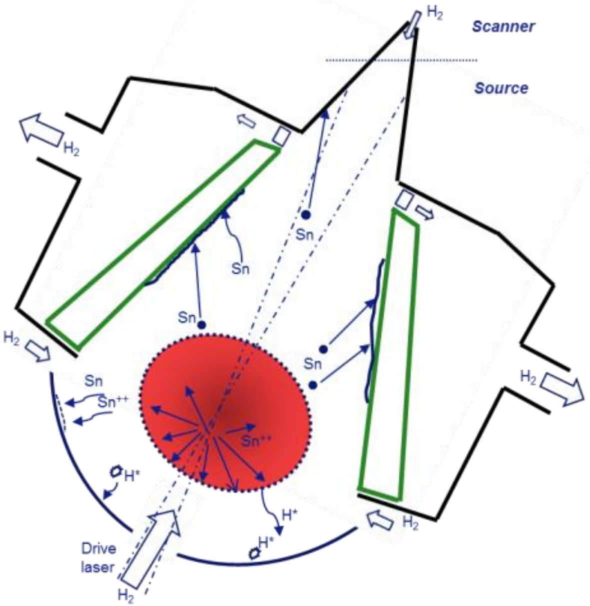
Hydrogen performs well for all these tasks!

Primary debris

Primary debris – directly from plasma and before collision with any surface:

- Heat and momentum transfer into surrounding gas
    - Kinetic energy and momentum of stopped ions
    - Absorbed plasma radiation
- Sn flux onto collector
    - Diffusion of stopped ions
    - Sn vapor
    - Sn micro-particles





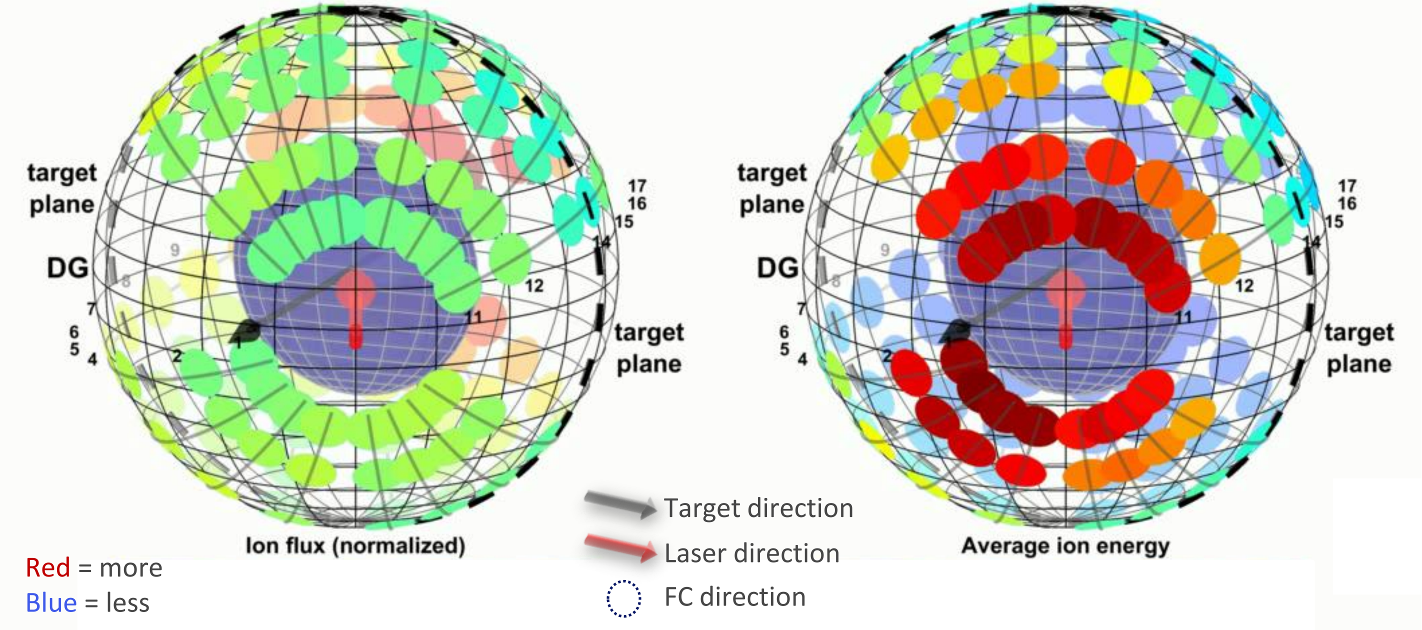
Sn → Sn vapor (diffusion debris)

Sn^+ → Fast Sn ions (line of sight debris)

Sn● → Sn particles

3D measurement of fast tin ion distributions

Faraday cups measure tin ion distributions

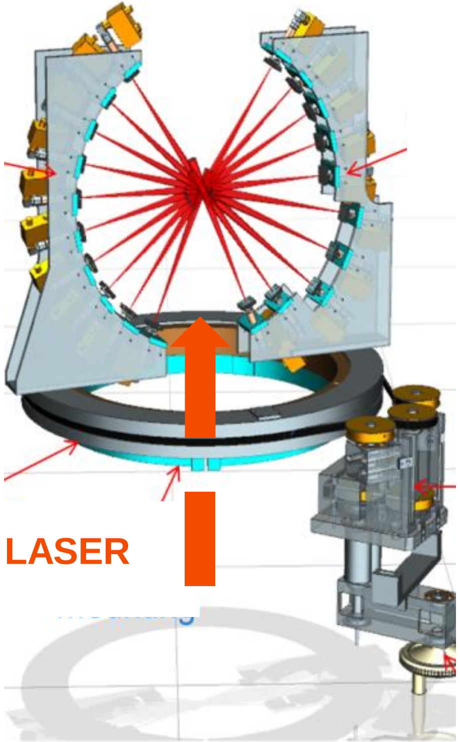


Ion flux (normalized)

Average ion energy

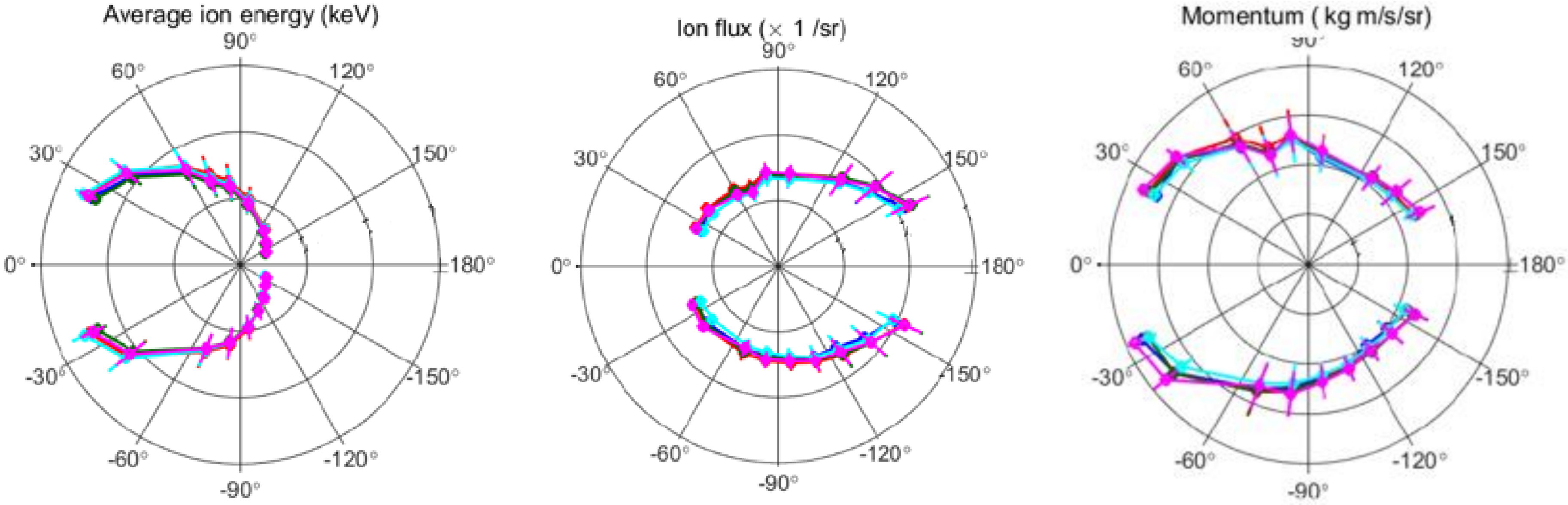
Red = more
Blue = less

Faraday cup



Ion measurements inform H_2 flow requirements for source

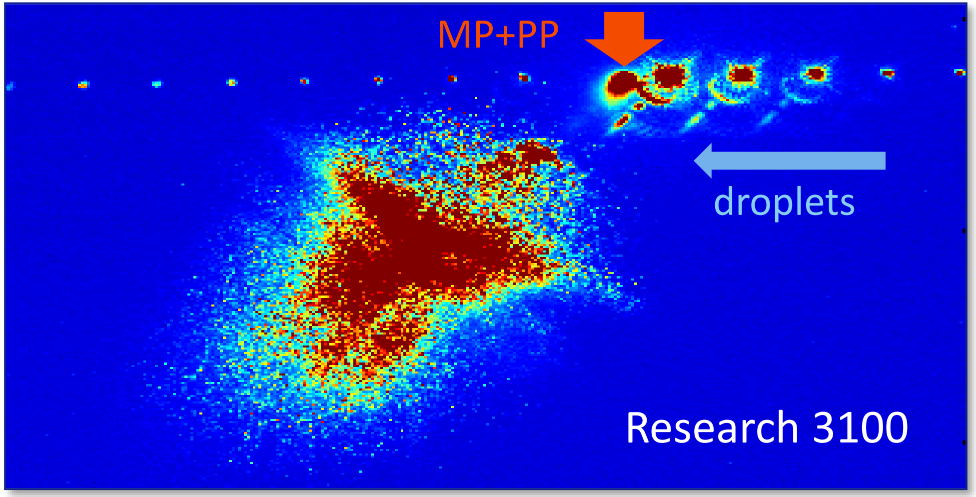
Tin ion distributions



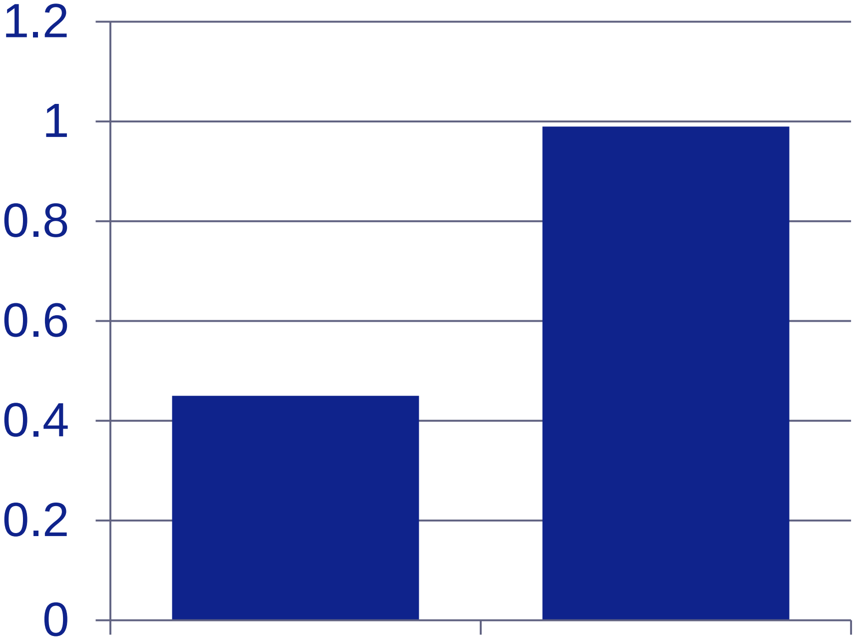
Data are used for optimization of H_2 flow in the source

Microparticle debris from plasma

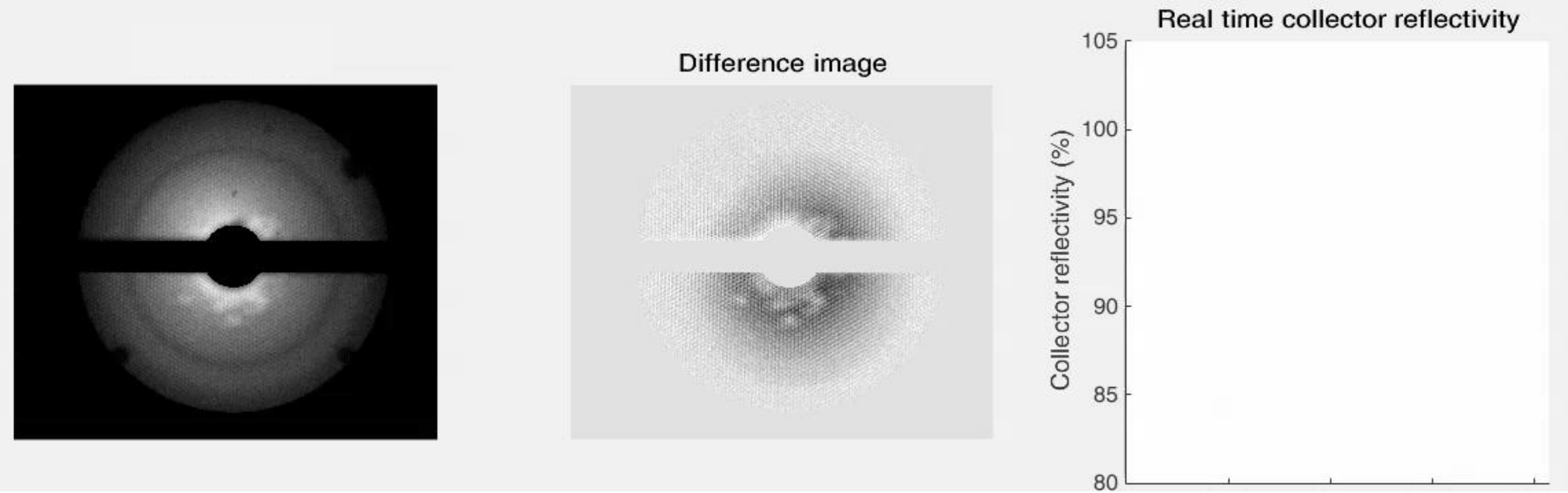
Dark-field scattergraph imaging



Fraction of pulses without microparticle debris



Plasma-generated self-cleaning

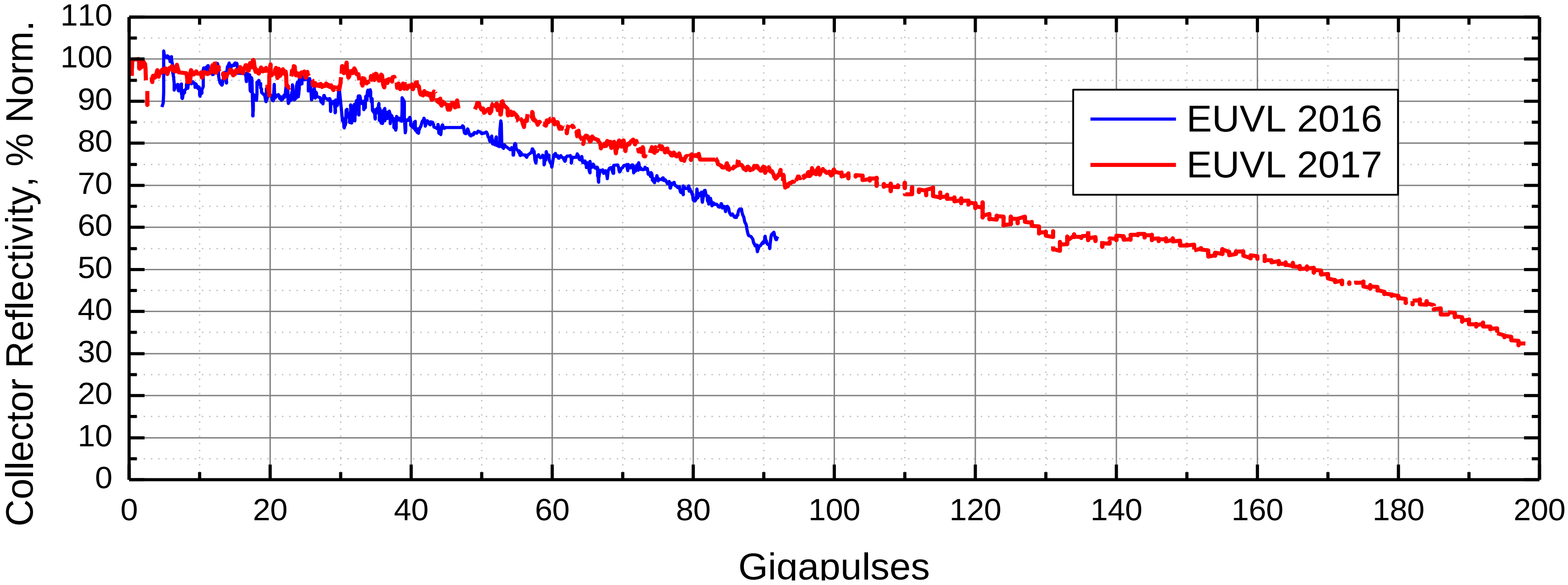


Elemental hydrogen (H*) reacts with tin (Sn) to form Stannane (SnH_4) which is gaseous and is pumped out of the vessel.

$Sn\ (s) + 4H\ (g) \rightarrow SnH_4\ (g)$

Collector Lifetime Continues to Improve

>100 Gpulse to 50% EUVR

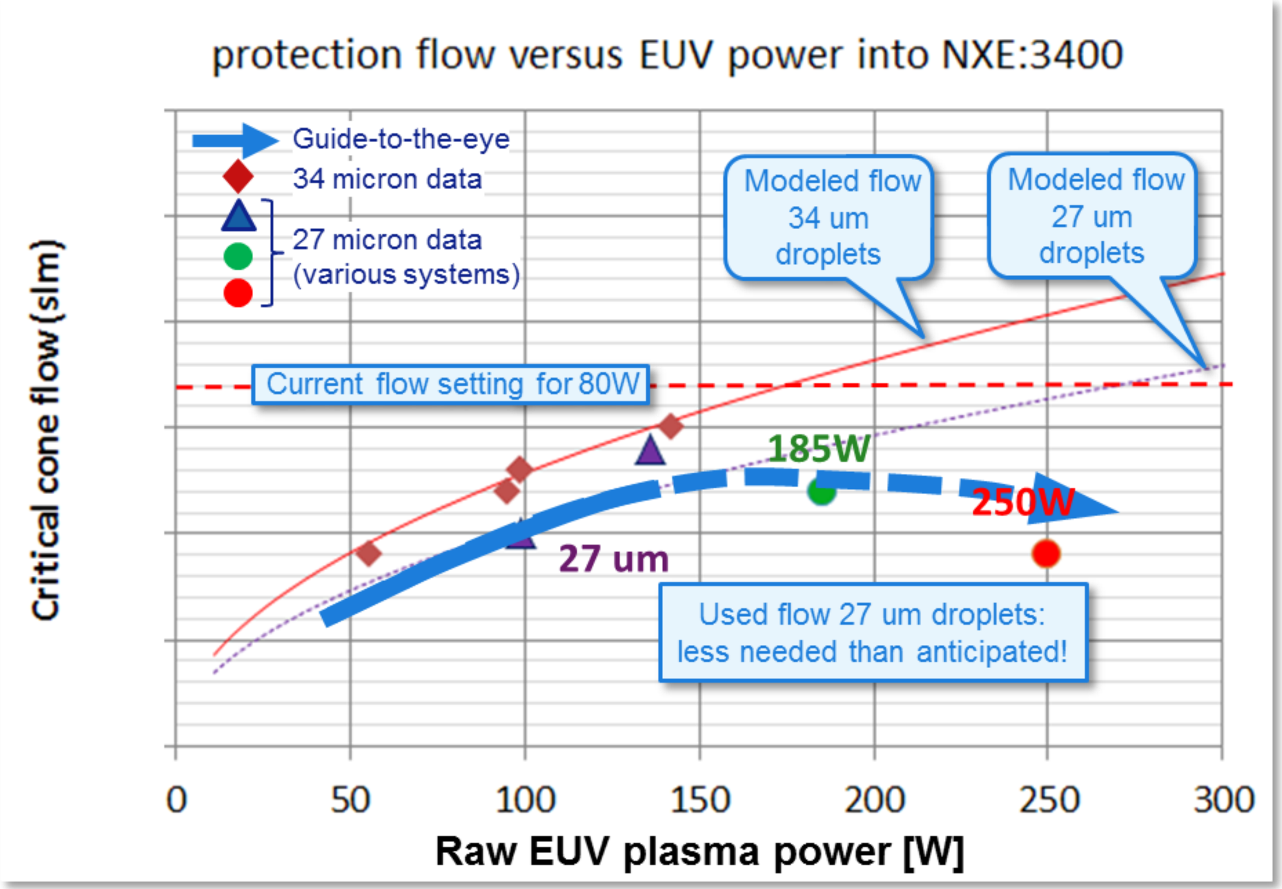


Collector reflectivity loss over time reduced to <0.4%/Gp

EUV Source Power Outlook

Collector protection secured up to 250 W

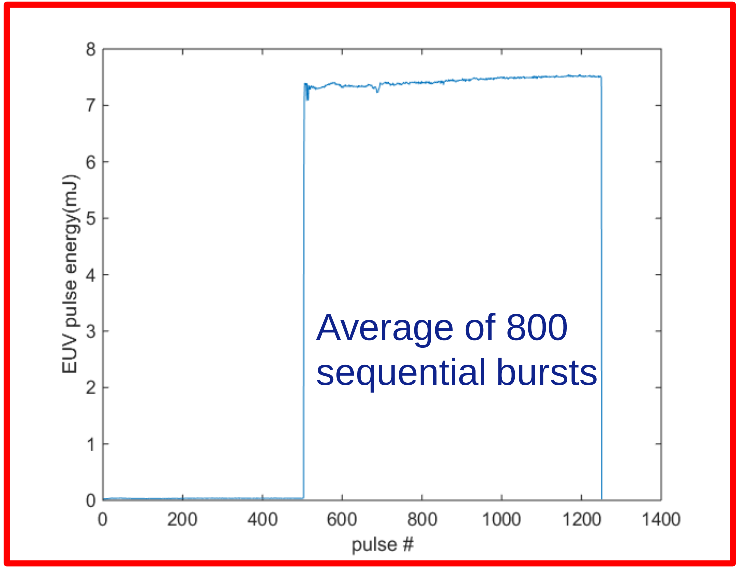
Collector protection demonstrated on research tool



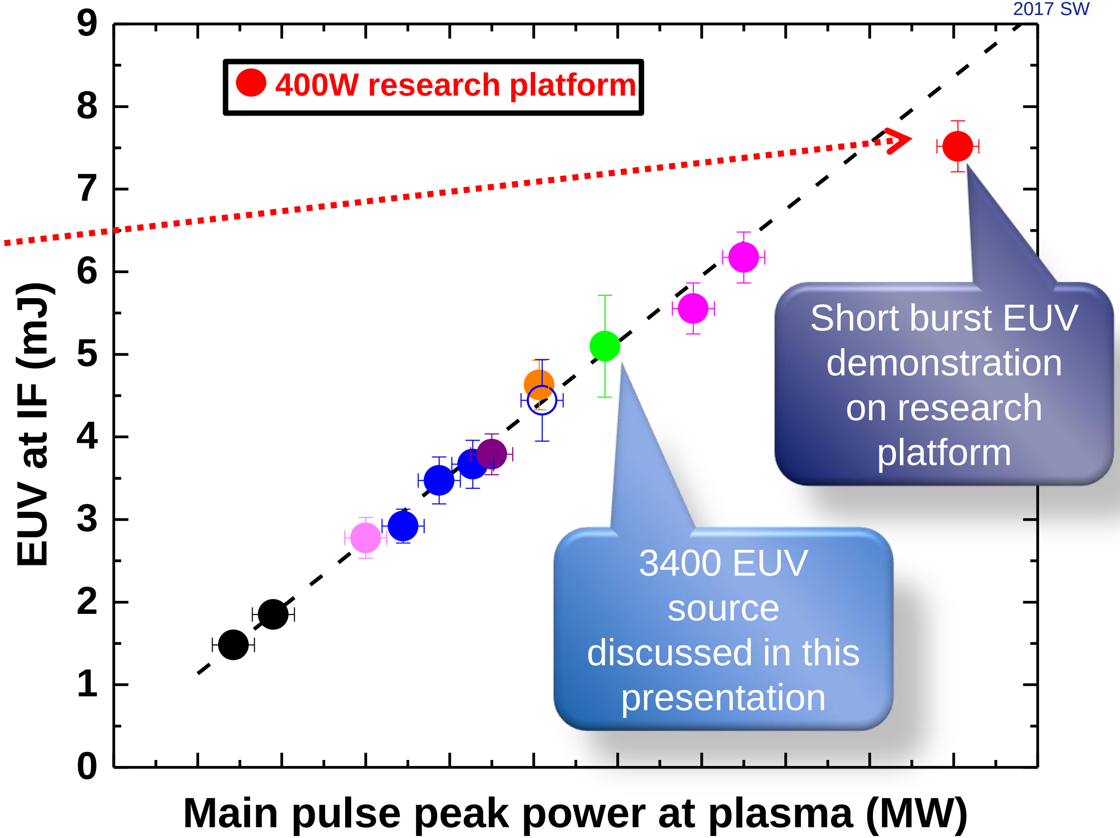
Research progress in EUV source

Demonstrated EUV pulse energy of 7.5mJ

375W in-burst at 50kHz



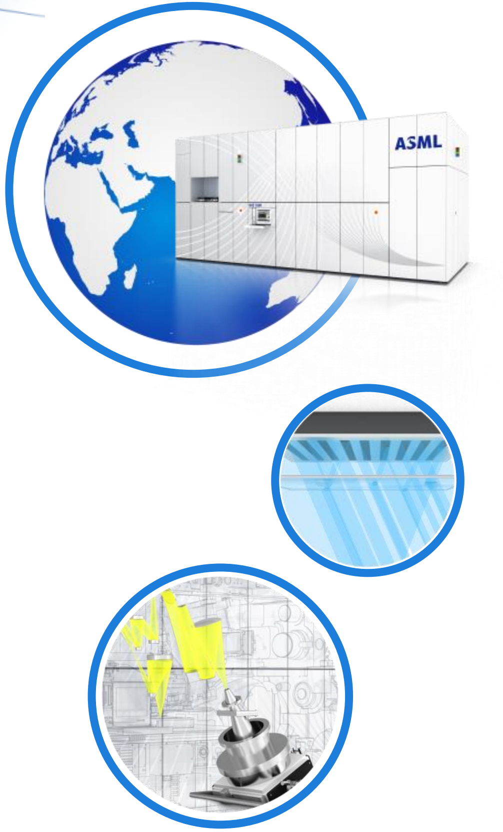
Average of 800 sequential bursts



Short burst EUV demonstration on research platform

3400 EUV source discussed in this presentation

Summary: EUV readiness for volume manufacturing



15 NXE:3XY0B systems operational at customers

Significant progress in EUV power scaling for HVM
- Dose-controlled power of 250W
- EUV CE of 6%

CO_2 development supports EUV power scaling
- Clean (spatial and temporal) amplification of short CO_2 laser pulse
- High power seed system enables CO_2 laser power scaling

Droplet Generator with improved lifetime and reliability
- >700 hour average runtime in the field
- >3X reduction of maintenance time

Path towards 400W EUV demonstrated in research
- CE is up to 6 %
- In-burst EUV power is up to 375W

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