ASML

EUV Source for Lithography:

Readiness for HVM and Outlook for Increase in Power and Availability

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ASML Fellow

Source Workshop, Prague, November 7th 2018

Outline

- Background and History
- EUV Lithography with NXE:3400B
- Principles of EUV Generation
- EUV Source: Architecture
- EUV Sources in the Field
- Source Power Outlook
- Summary

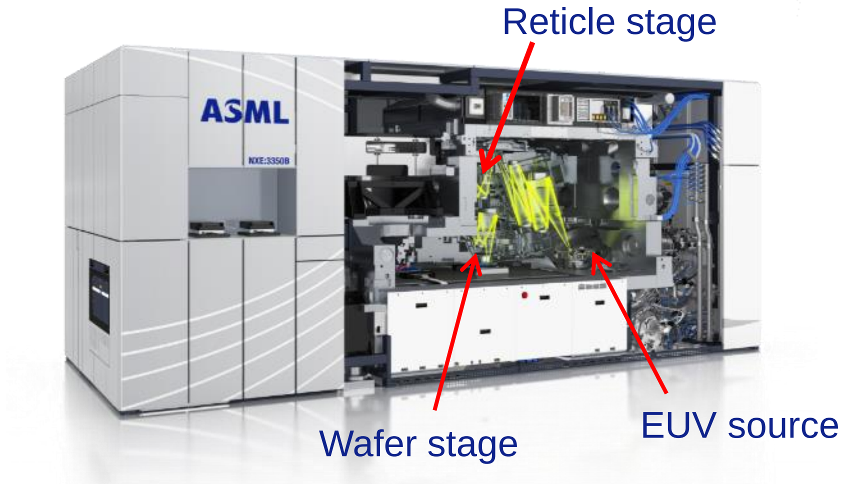
Why EUV? - Resolution in Optical Lithography

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

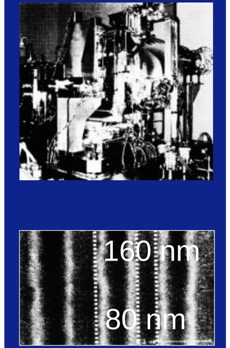
ASML ships 1st NA 0.33 system NXE:3300B

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

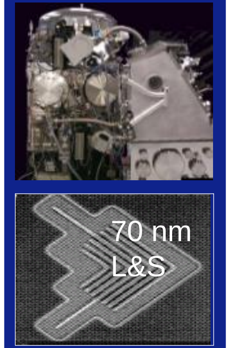
'85 '86 '87 '88 '89 '90 '91 '92 '93 '94 '95 '96 '97 '98 '99 '00 '01 '02 '03 '04 '05 '06 '07 '08 '09 '10 '11 '12 '13 '14 '15 '16 '17 '18

NL

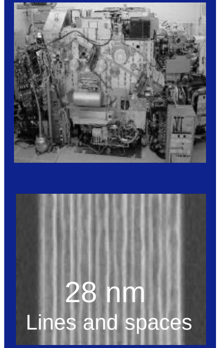
Japan



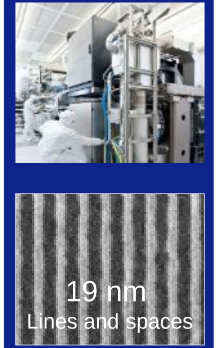
USA



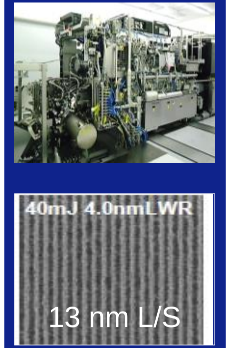
NL



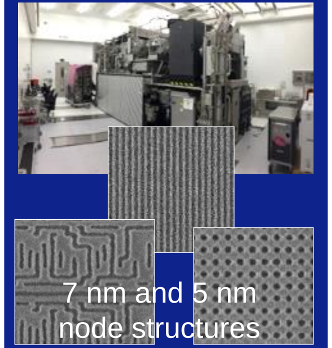
NL



NL

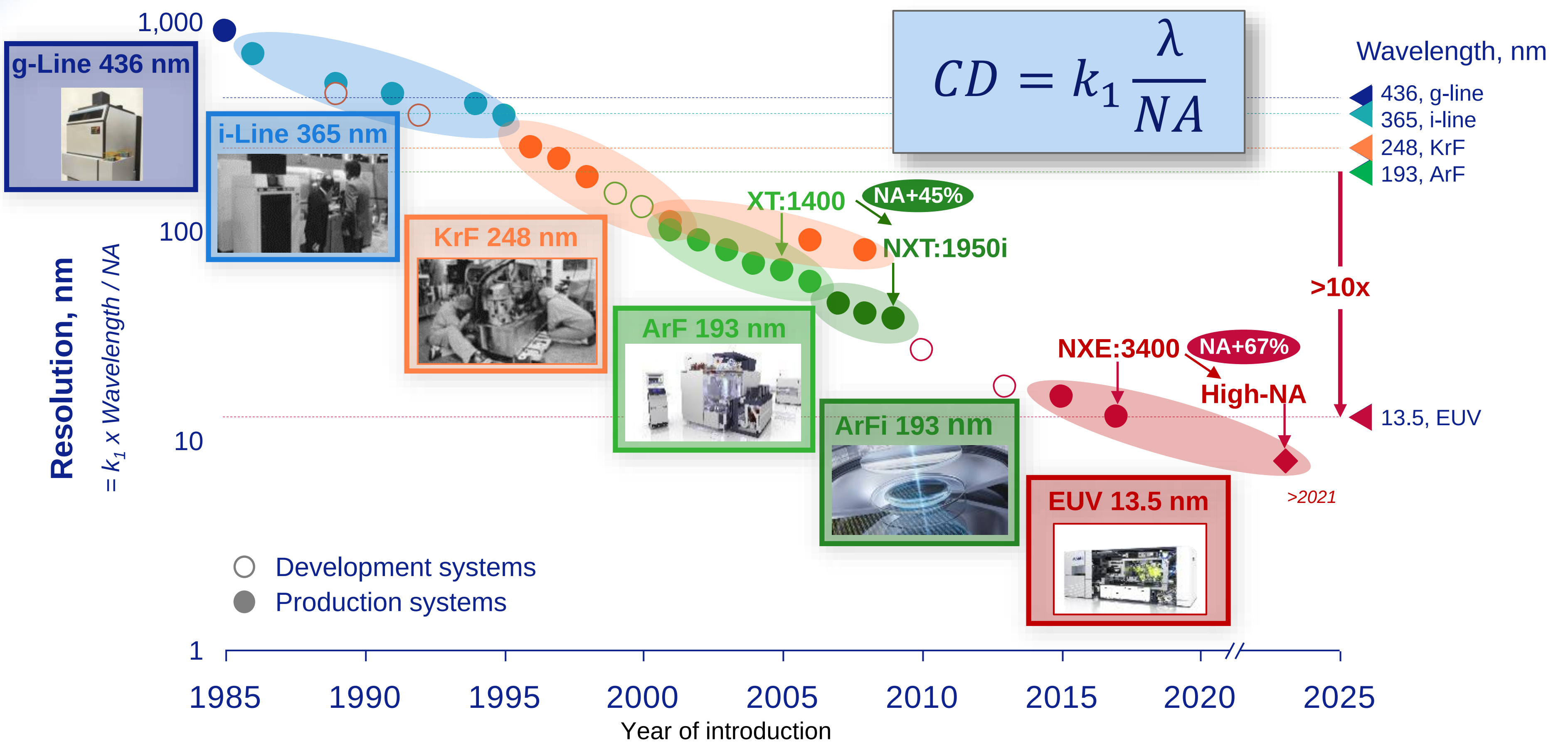


NL



High-NA EUV targets <7nm resolution

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



TWINSCAN EUV Product Roadmap

Supporting customer roadmaps well into the next decade

	2016	2017	2018	2019	2020	2021	2022	2023	2024
EUV 0.55 NA 8nm	**Product** Matched Overlay, Throughput								**High NA** 1.1nm|185wph
0.33 NA 13nm[1]	**NXE:3350B** 2.5|125wph	**NXE:3400B** 2.0nm|125wph	**+OFP[2]** 1.7nm	**+PEP[3]** 145	**NXE:3400C** 1.7nm|155wph		**Next** 1.1nm|≥ 170 wph		

3400B uptime improving to >90% for 2018/2019 HVM, extending productivity to >150 W/hr @ 20 mJ/cm²

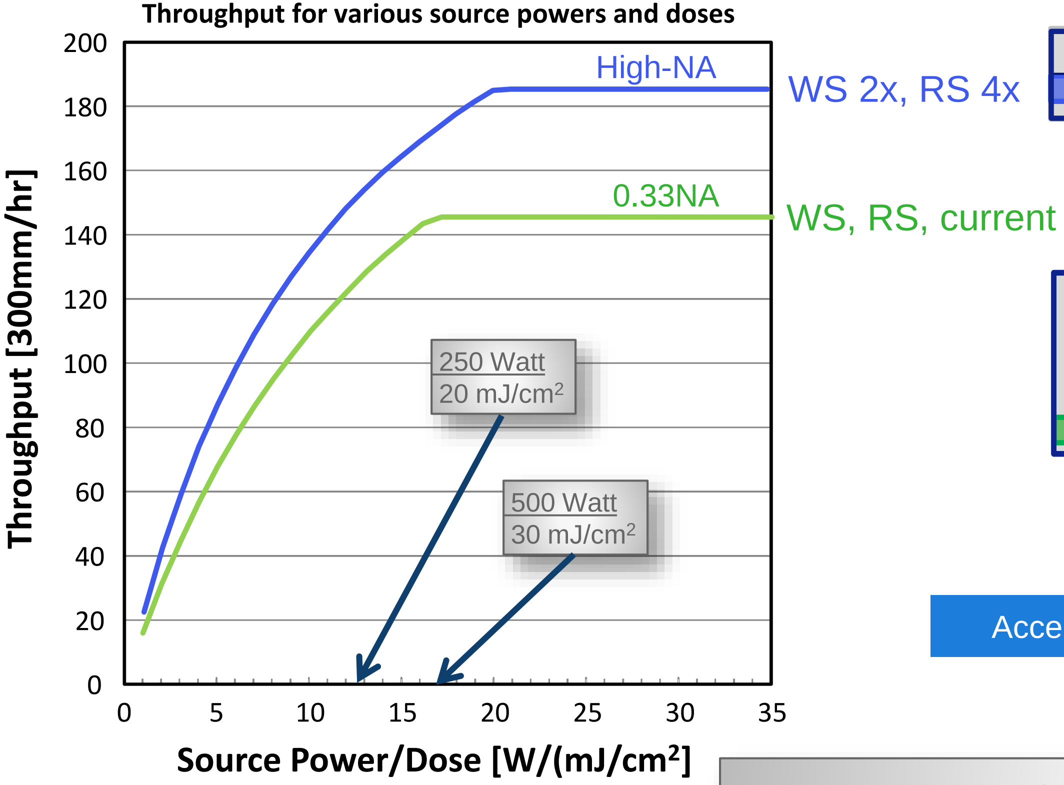
High-NA platform designs learning from our 20-year EUV journey

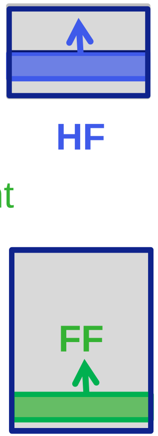
Current Product status

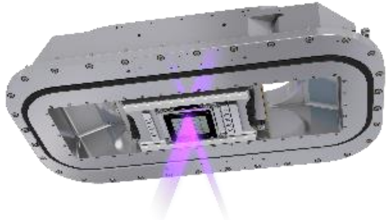
- **Released**
- **Development**
- **Definition**
- **Study**

High-NA Field and Mask Size productivity

Throughput >185wph with Half Fields







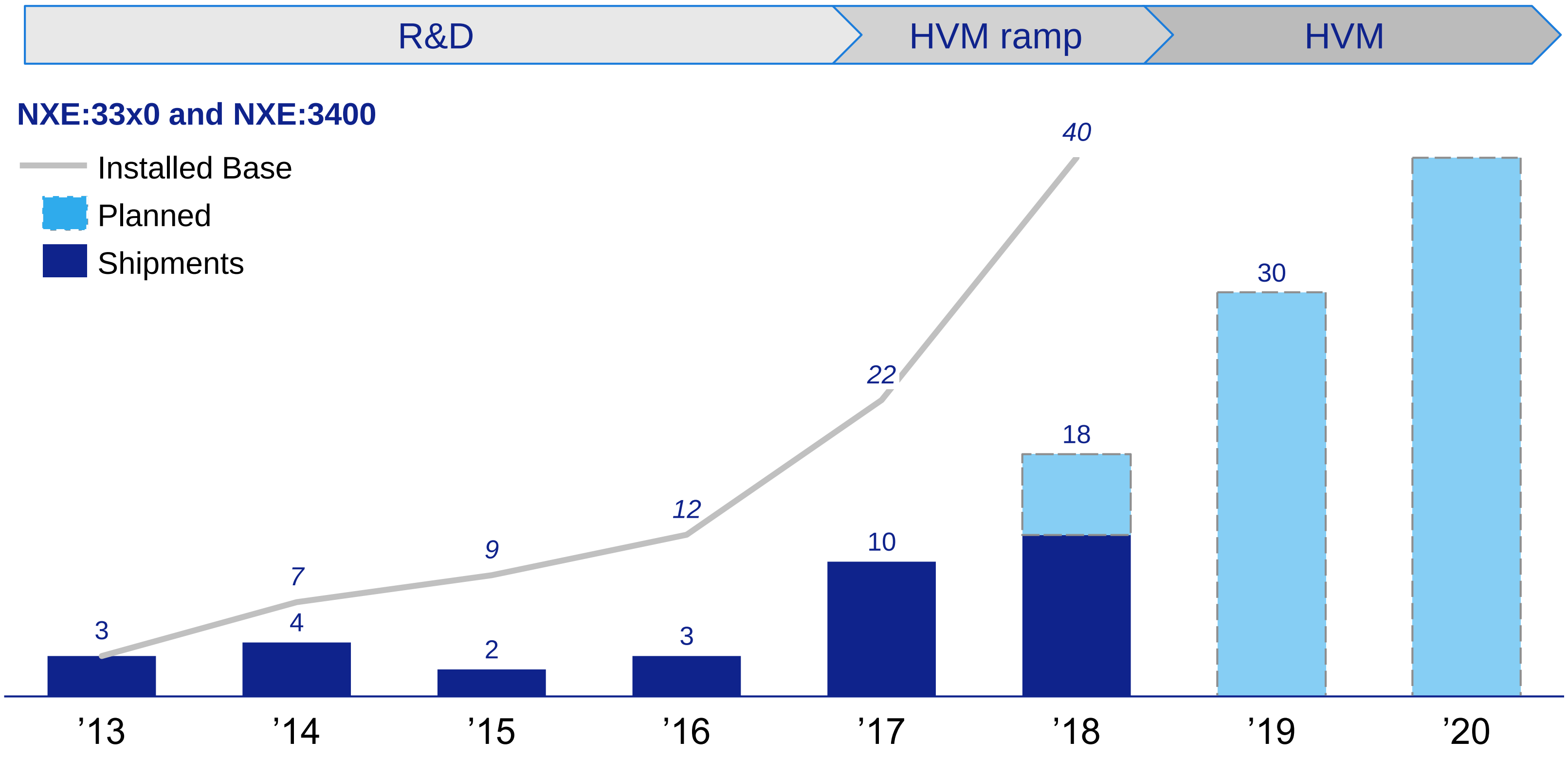
Acceleration of mask stage ~4x

Acceleration of wafer stage ~2x

Fast stages enable high throughput despite half fields

EUV HVM introduction targeted at 7nm

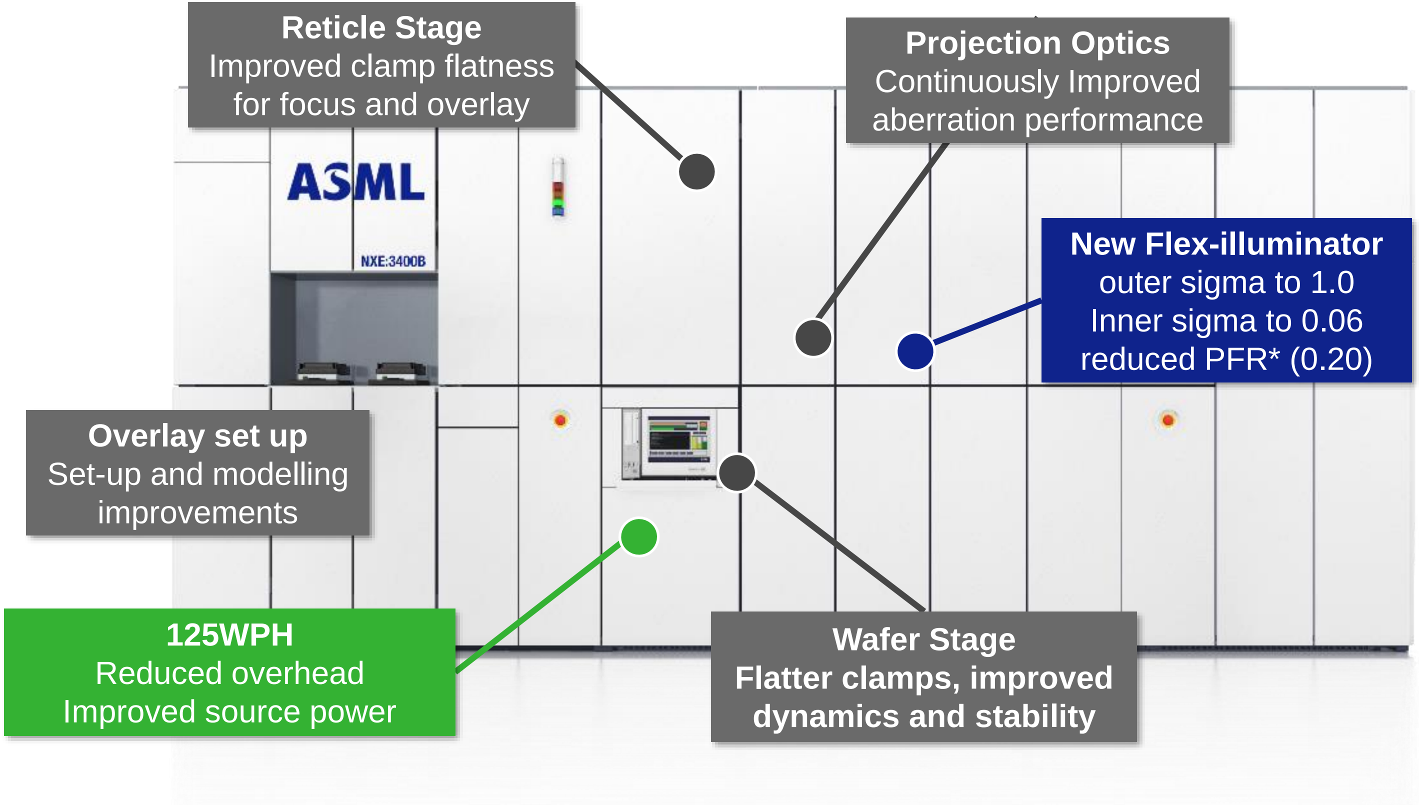
Installed base of EUV systems expected to ~double in 2018



EUV Lithography, NXE:3400B

NXE:3400B: 13 nm resolution at full productivity

Supporting 5 nm logic, <15nm DRAM requirements



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

*PFR = pupil fill ratio

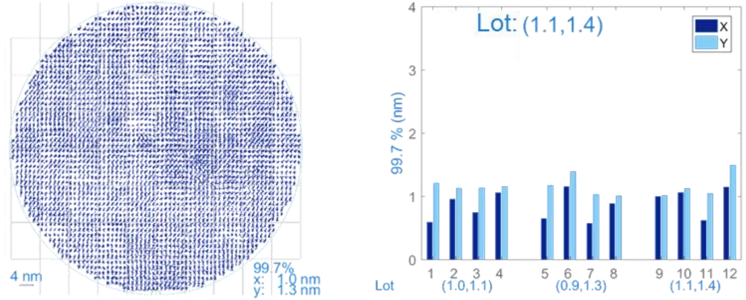
NXE productivity above 140 wafers per hour

NXE:3400B, 140 WPH at 246W

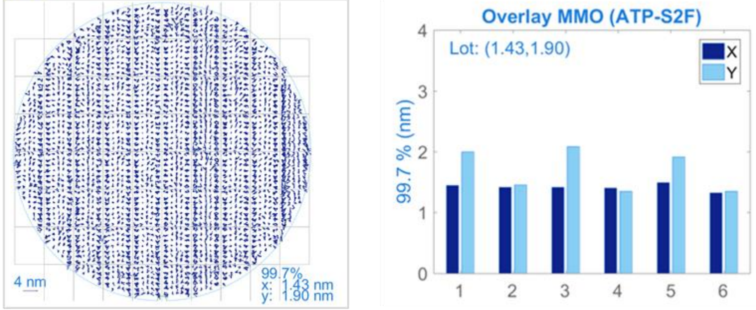
Overlay in spec at 125 WPH throughput

~200W power at IF with proto version SIM

DCO



MMO



Throughput of 140 WPH achieved at 246W

Actual: 195W Target: 205W

Throughput without pellicle — **125 WPH**

Full field, 96 fields at 20 mJ/cm²

Actual: 246W Target: 250W

Throughput without pellicle — **140 WPH**

Road-map — **>150 WPH**

Full field, 96 fields at 20 mJ/cm²

Actual: 246W Target: 250W

Throughput with pellicle+DGLm — **>100* WPH**

Target — **125** WPH**

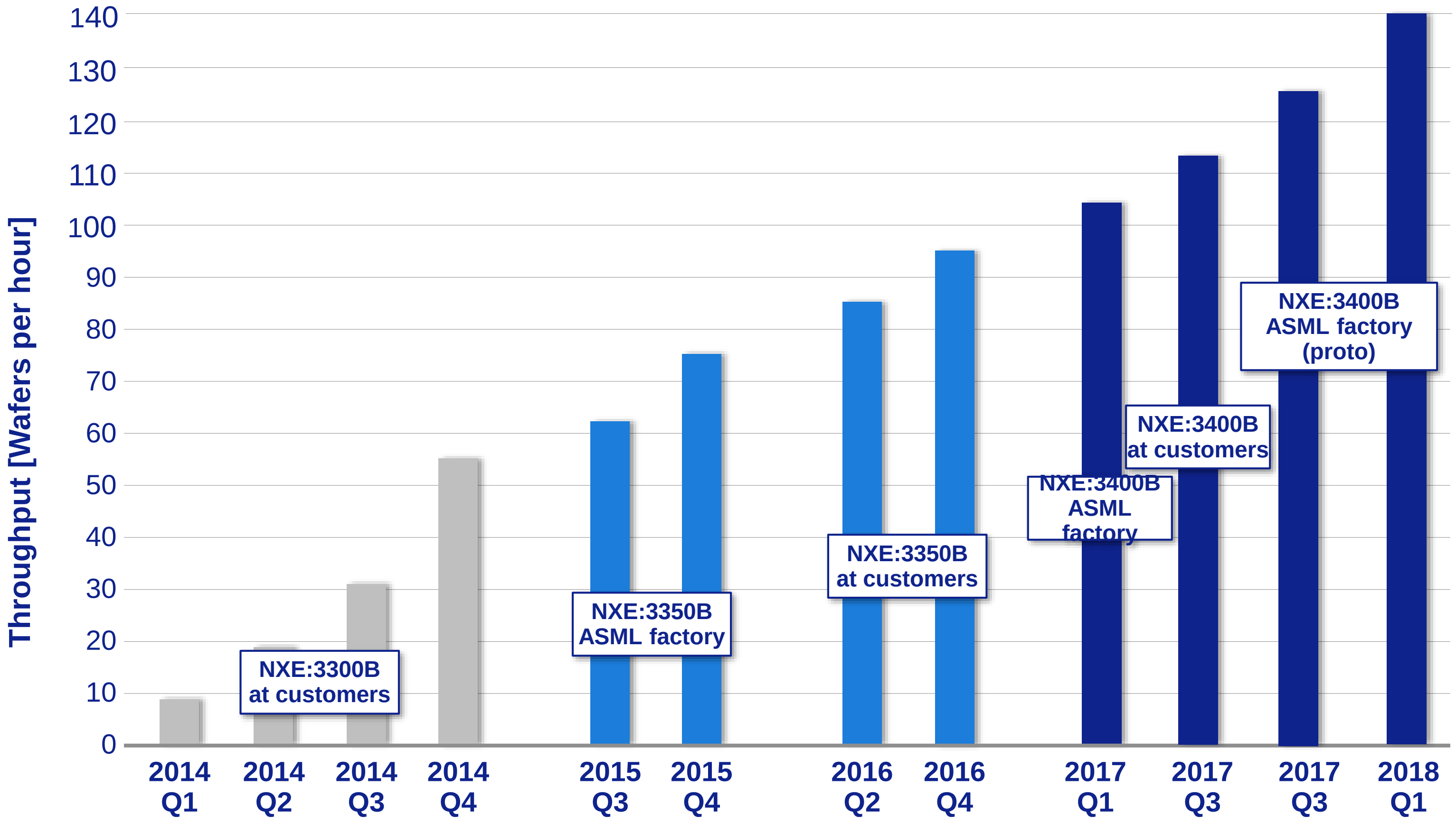
Full field, 96 fields at 20 mJ/cm²

*Measured 116 WPH using pellicle with >83% transmission without DGL membrane. Throughput with membrane is calculated.

**Improvement plan for pellicle transmission to 88% and DGL membrane transmission to 90% included

NXE productivity above **125** wafers per hour

NXE:3400B, 140 WPH at 246W

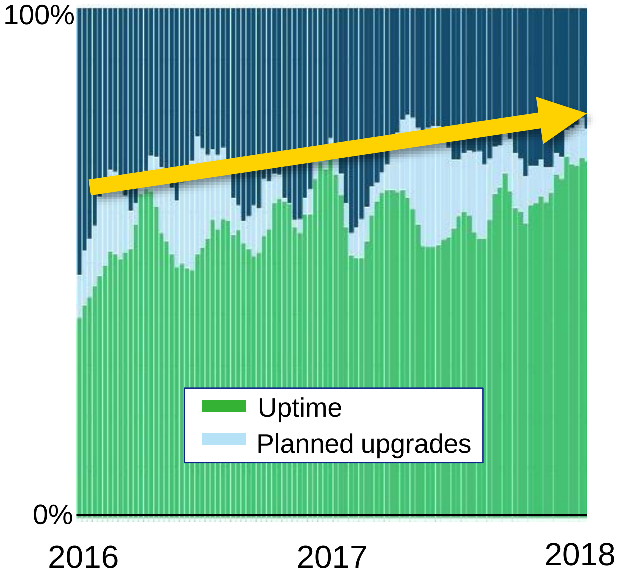


NXE:3400B ATP test: 26x33mm2, 96 fields, 20mJ/cm2

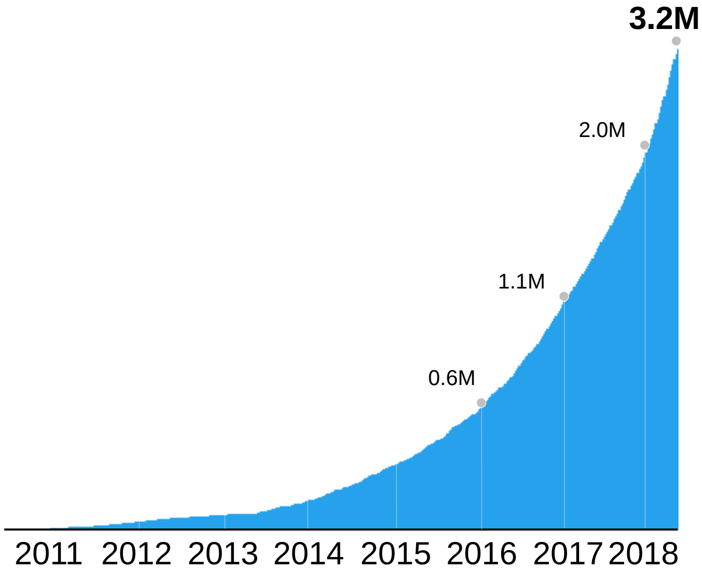
>3.2M wafers exposed on NXE:3xx0B at customer sites

Currently 34 systems running in the field. First system was shipped Q1 2013

EUV Availability
Uptime %



Cumulative EUV wafer exposures
NXE:3xxx, Wafers



Productivity increases via source availability

Secured EUV power is matched with increasing availability

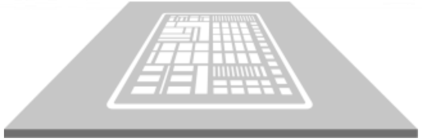
$$\text{Productivity} = \text{Throughput}(\propto \text{EUV Power}) \times \text{Availability}$$

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

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	

Two-fold approach to eliminate reticle front-side defects

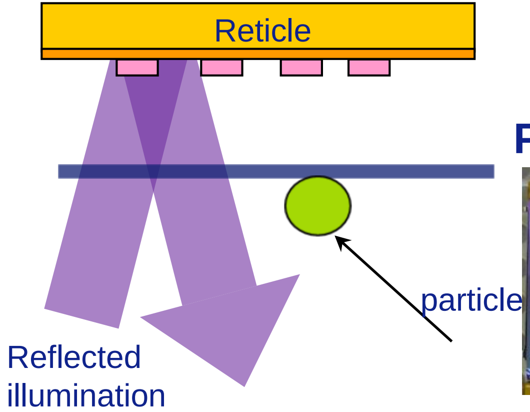
1. Clean scanner



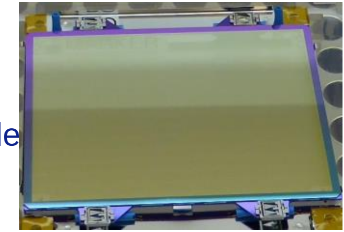
Without Pellicle

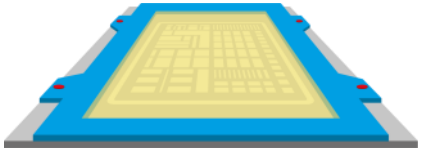
2. EUV pellicle

EUV Reticle (13.5nm)



Pellicle

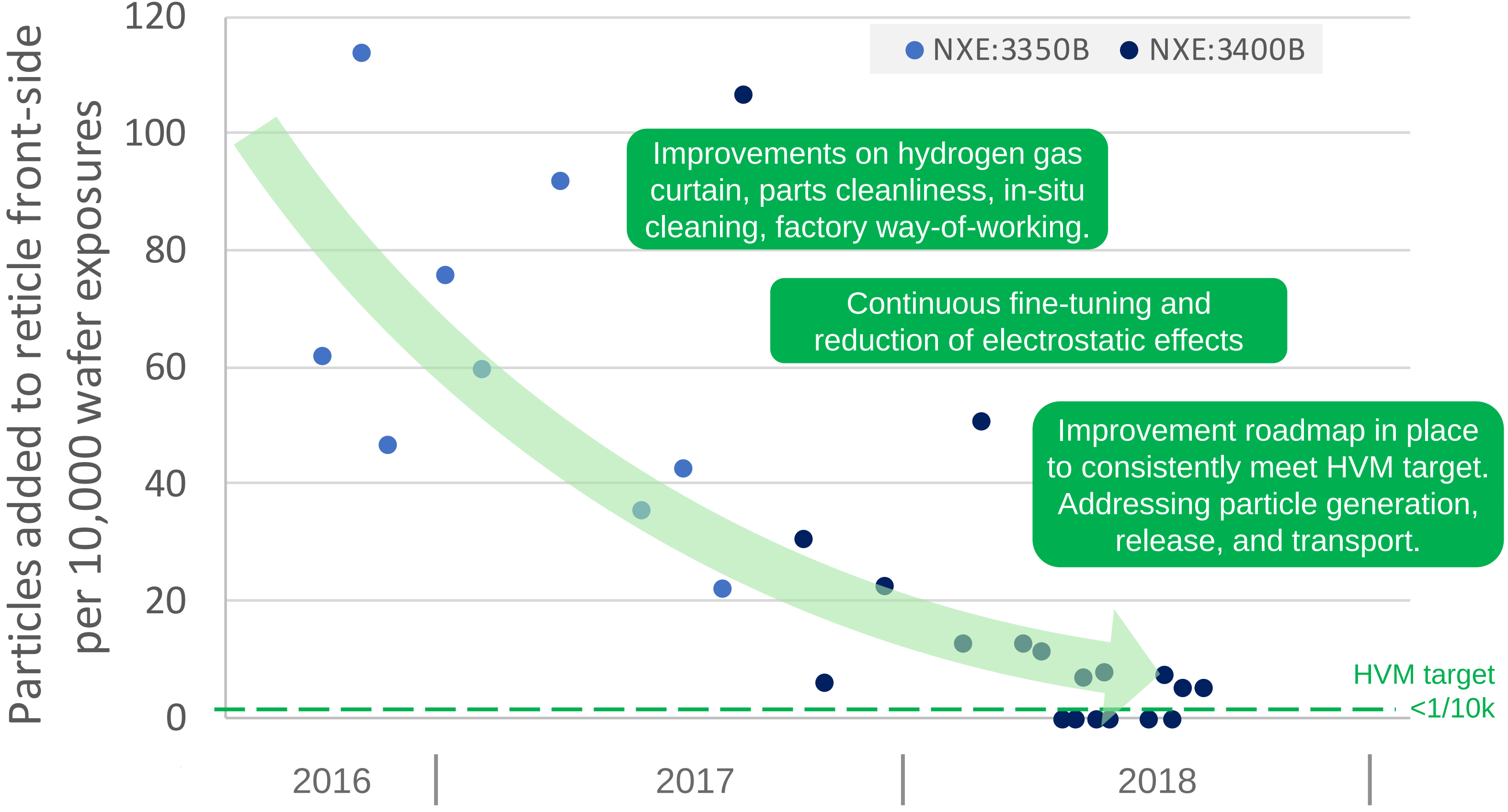




With Pellicle

Clean Scanner

Reticle front-side defectivity ~1/10k

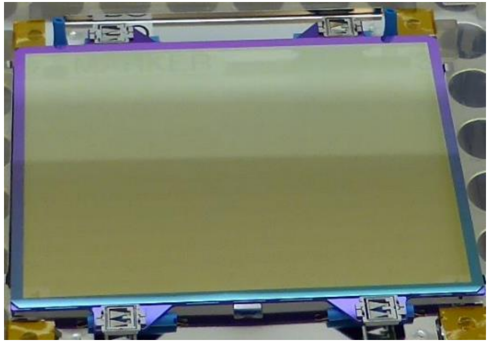


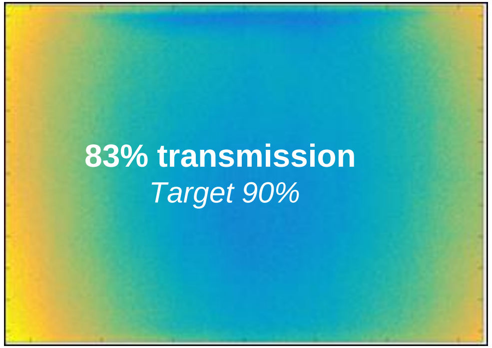
Each data point represents between 1,000 and 10,000 wafer exposures in ASML factory or at a customer

EUV pellicle industrialization

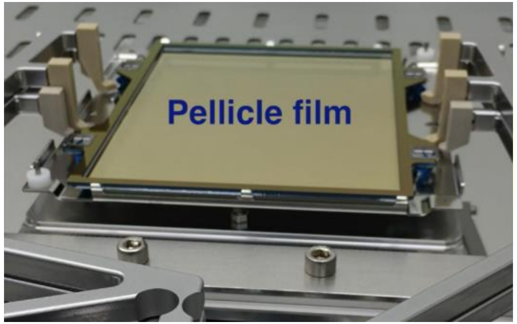
Pellicle infrastructure in place and 100 WPH throughput achieved

Pellicle Film
EUV Transmission

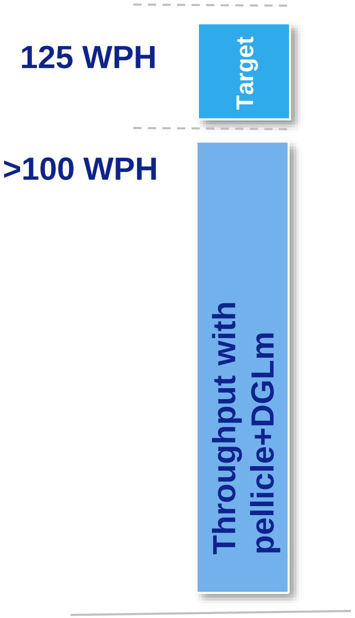




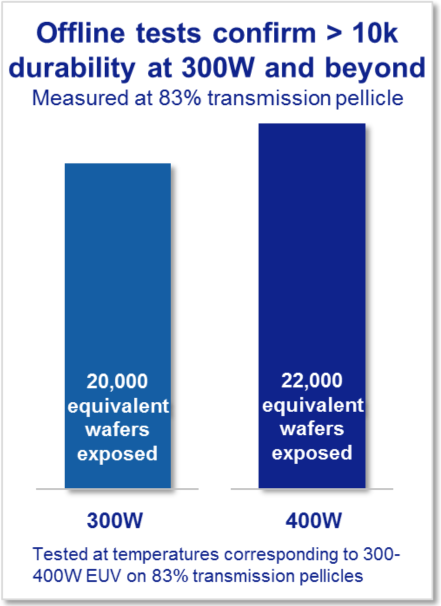
Pellicle Mounting
Automated Equipment



Pellicle Performance
\# defects, Max Power

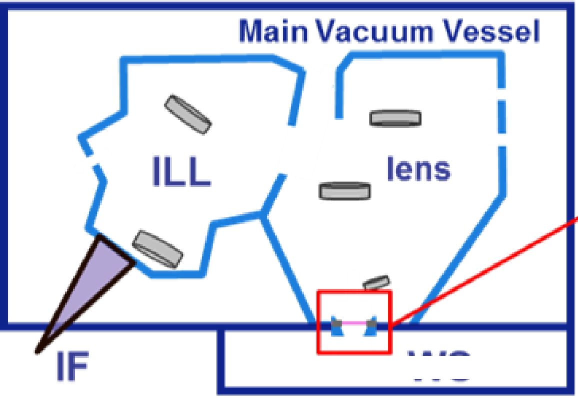


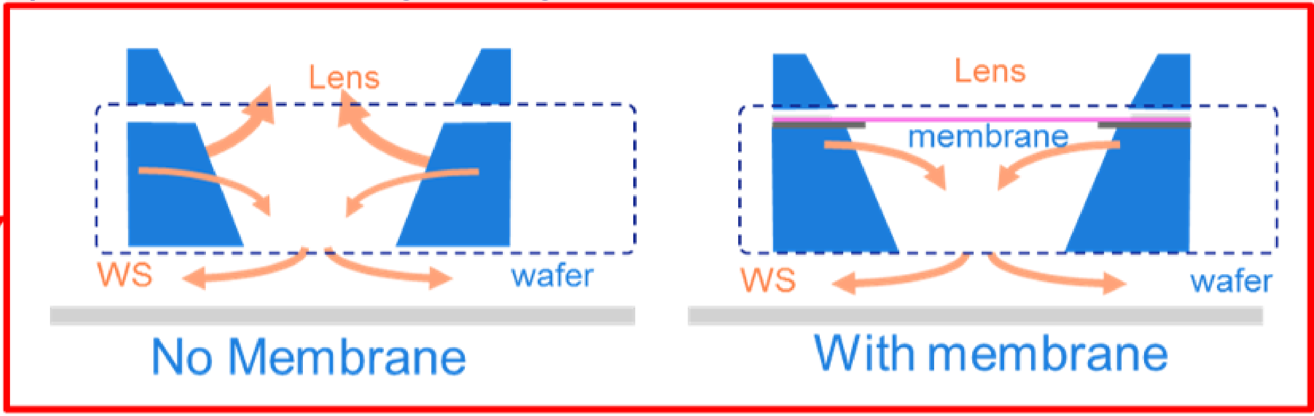
Actual: 246W
Target: 250W



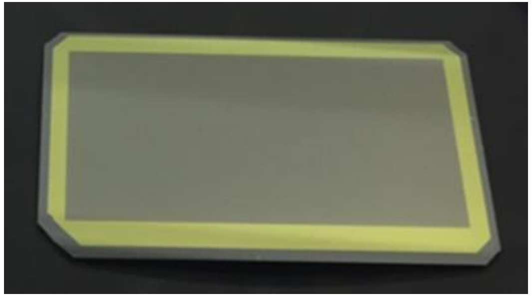
DGL membrane as spectral filter

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

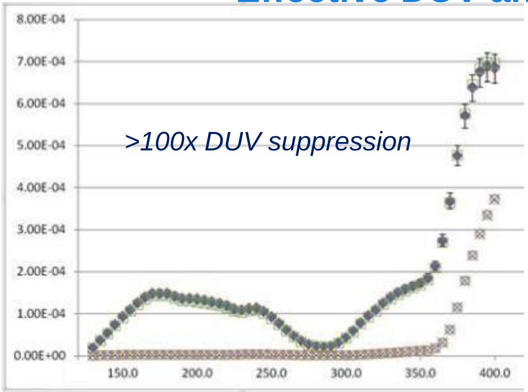


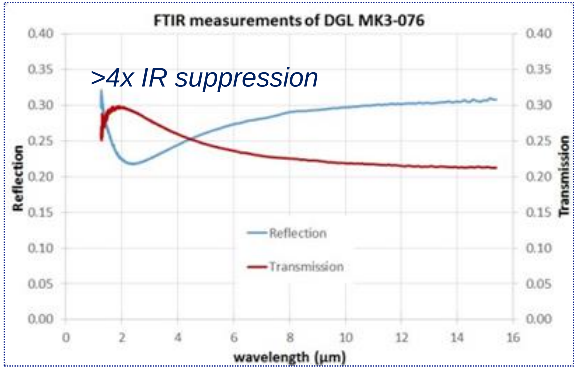


DGL membrane (~ 50 x 25 mm)



Effective DUV and IR suppression



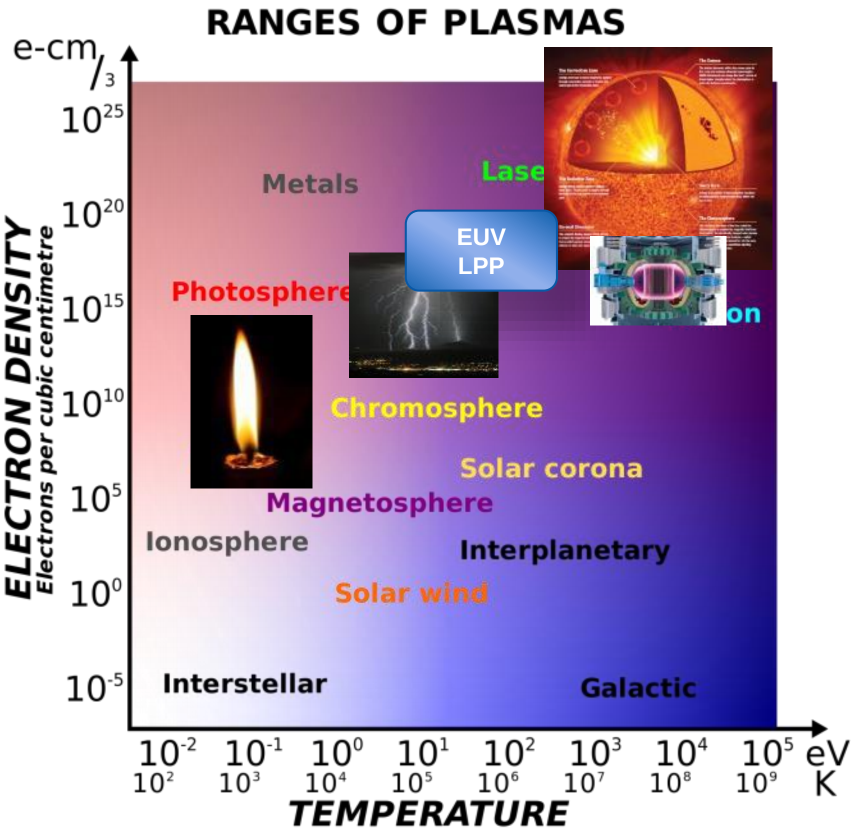


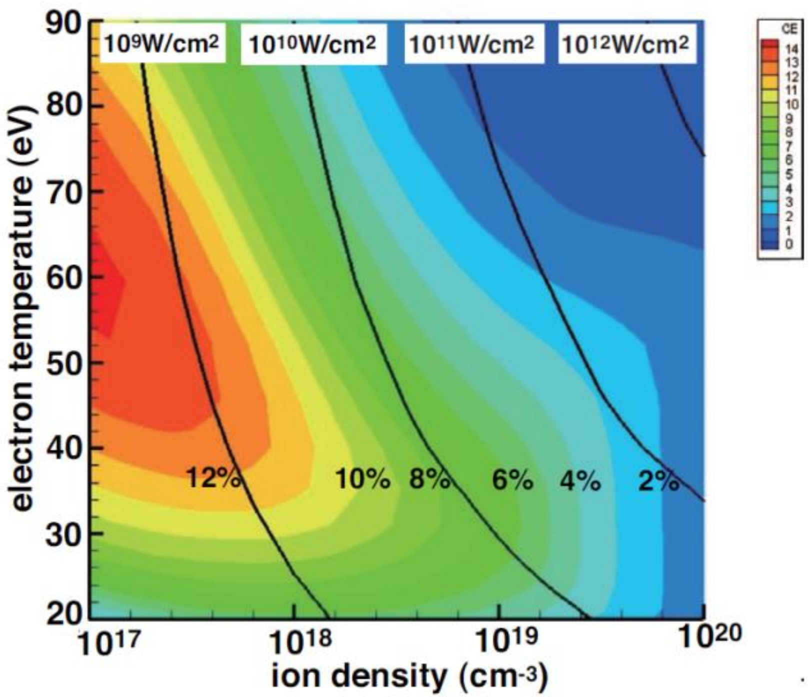
EUV: Principles of Generation

Laser Produced Plasma Density and Temperature

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

Temperature ~ 30 -100 eV

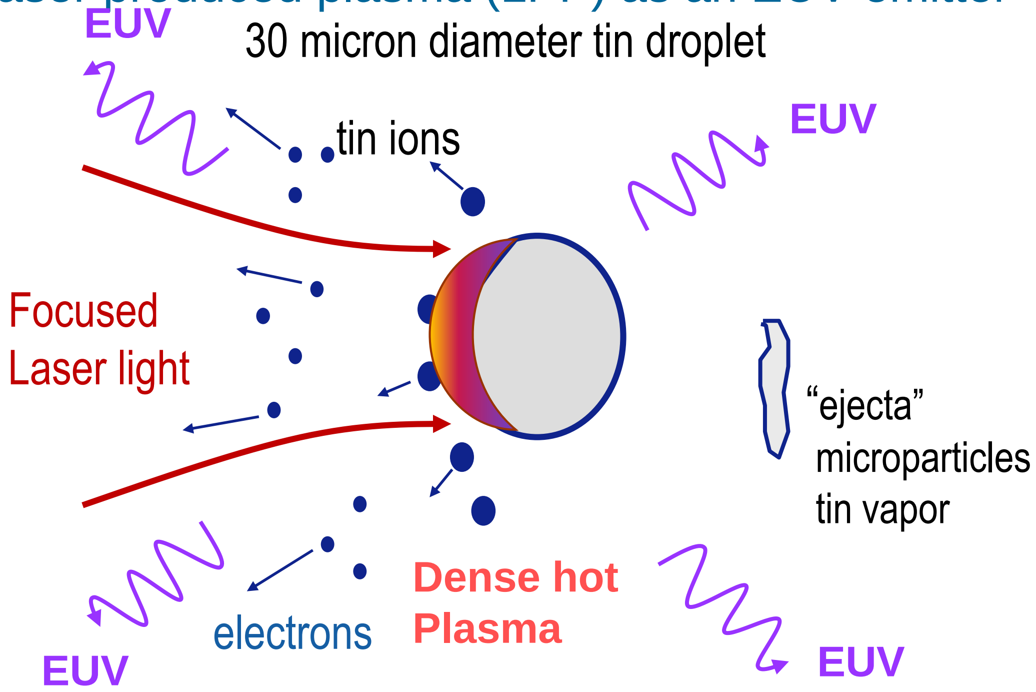




Nishihara et al. (2008)

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.

Modelled EUV CE of LPP Sn Plasma vs. Wavelength

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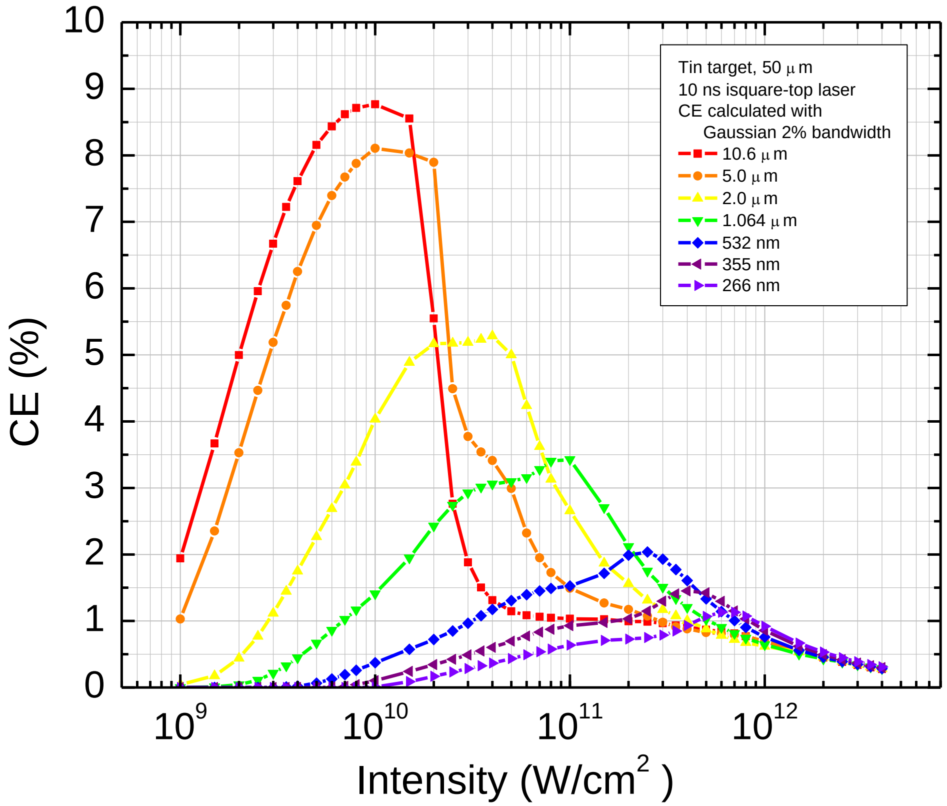
Public



Simulation Assumptions:

- 1D modeling
- Sn flat target (50um thickness)
- Laser Pulse: 10ns duration (rectangular)
- Uniform radial distribution of intensity in beam spot
- Prizm Computational Sciences, Inc., 2005

EUV CE defined into 2% bandwidth, 2π sr solid angle

EUV Spectra of Laser Produced Sn Plasma

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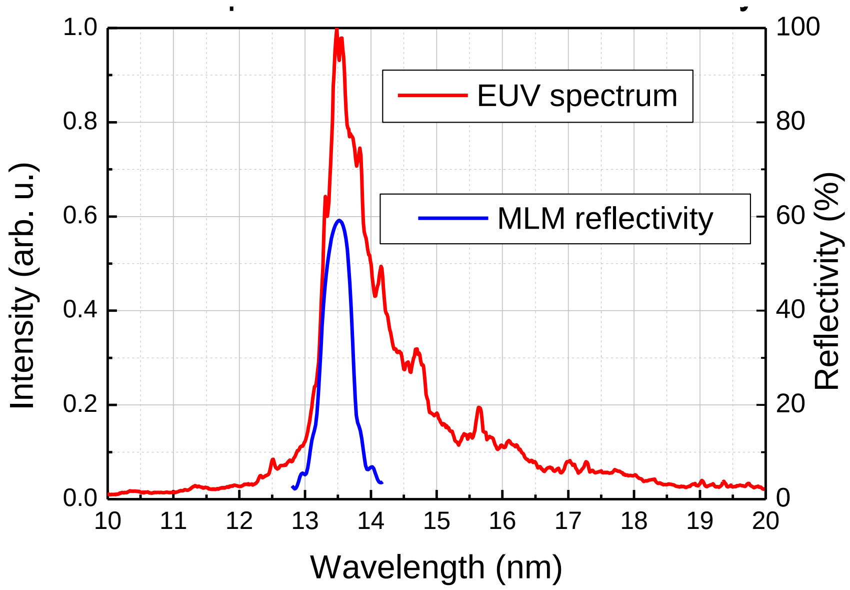
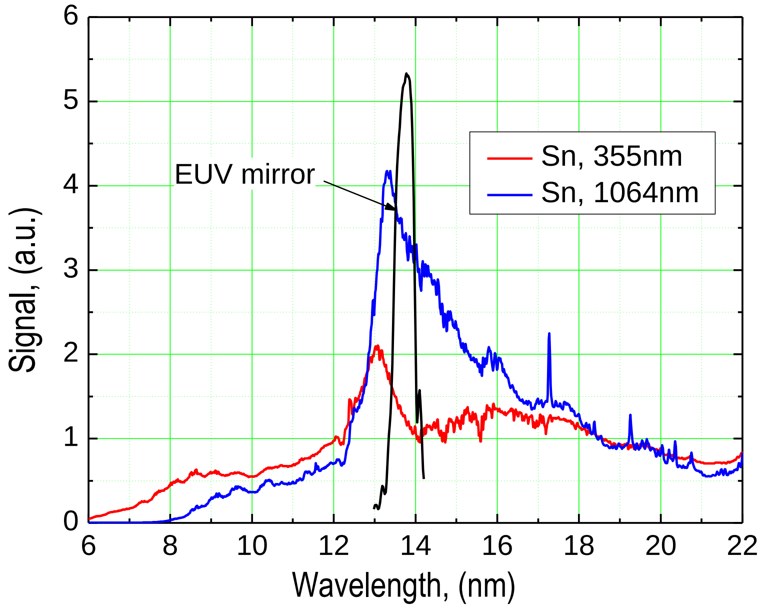
EUV spectrum with CO_2 Laser at 10.6 µm



EUV spectrum with Nd:YAG Laser at 1064 nm and 355 nm



Peak of EUV spectrum matches the MoSi multilayer reflectivity band at 13.5 nm

LPP Target Material and Laser Wavelength Options

High Efficiency is the Key to a Low Cost Architecture

	Xe	Sn	Li
Excimer (351nm)	-	0.5-1.0%	2.0-2.5%
Solid State (1064nm)	0.5-1.0%	2.0-2.5%	2.0-2.5%
CO_2 (10.6µm)	0.5-1.0%	4.0-5.0%+ (+ Updated)	1.0-1.5%* (* Modeled Data)

CYMER

- Best high efficiency options of laser/target combinations for future HVM sources

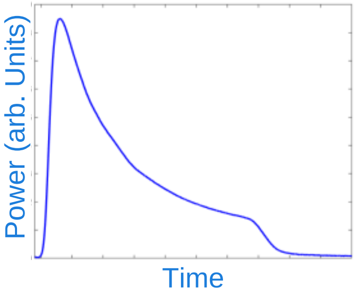
October 21, 2006 SEMATECH EUV Source Workshop, October 2006, Barcelona Spain 9

CO_2 Laser with Sn target was selected for industrialization in 2006

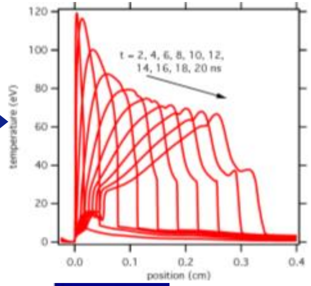
Plasma simulation capabilities

Main-pulse modeling using HYDRA

Main-pulse shape

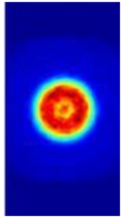


1D:
real pulse shape

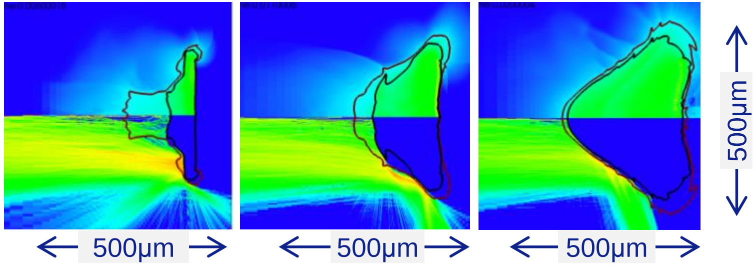


1D simulations are fast and useful for problems that require rapid feedback and less accuracy

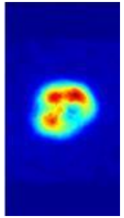
2D:
+ symmeterized beam profile

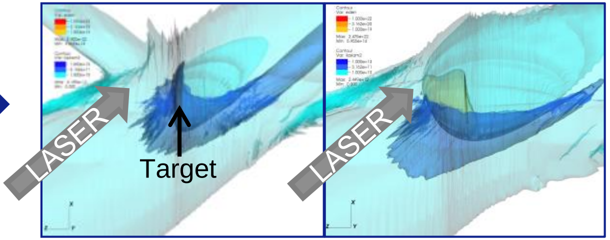


Electron density (top half) with laser light (bottom half)



3D:
+ real asymmetric profile





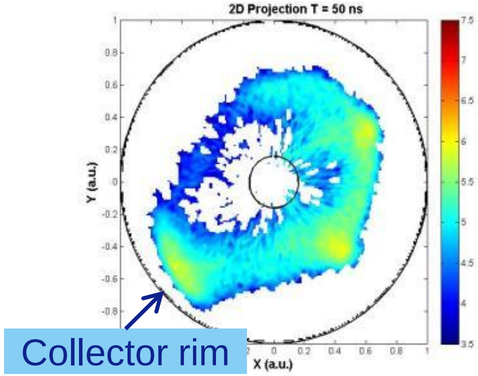
2D and 3D simulations are run for the full duration of the Main pulse. Results include temperature, electron density, spectral emission, etc.

Sn target using a real irradiance distribution

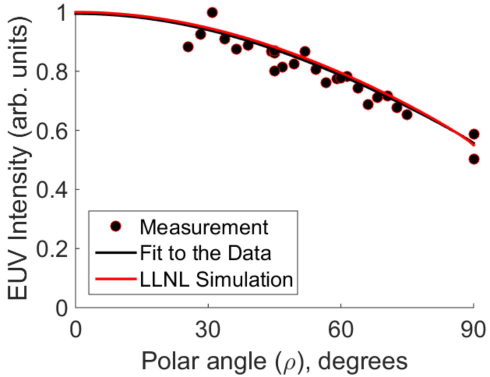
Simulation of the EUV source

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.

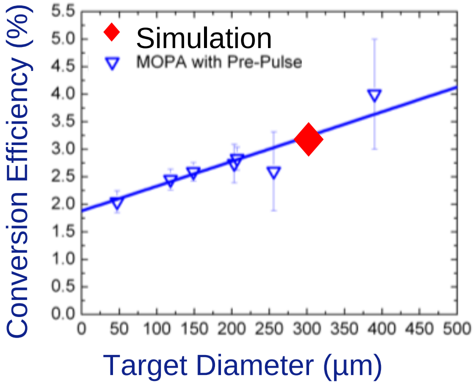
Reflected laser modeling



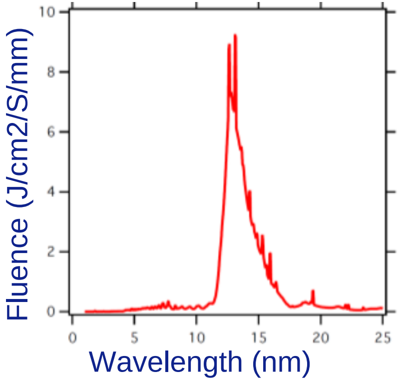
Emission anisotropy



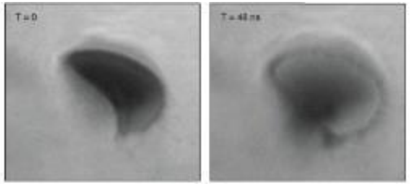
Conversion Efficiency



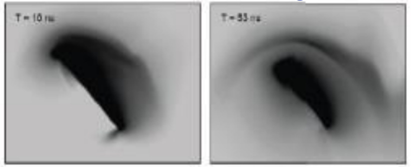
Simulated EUV spectra



Measured Shadowgrams

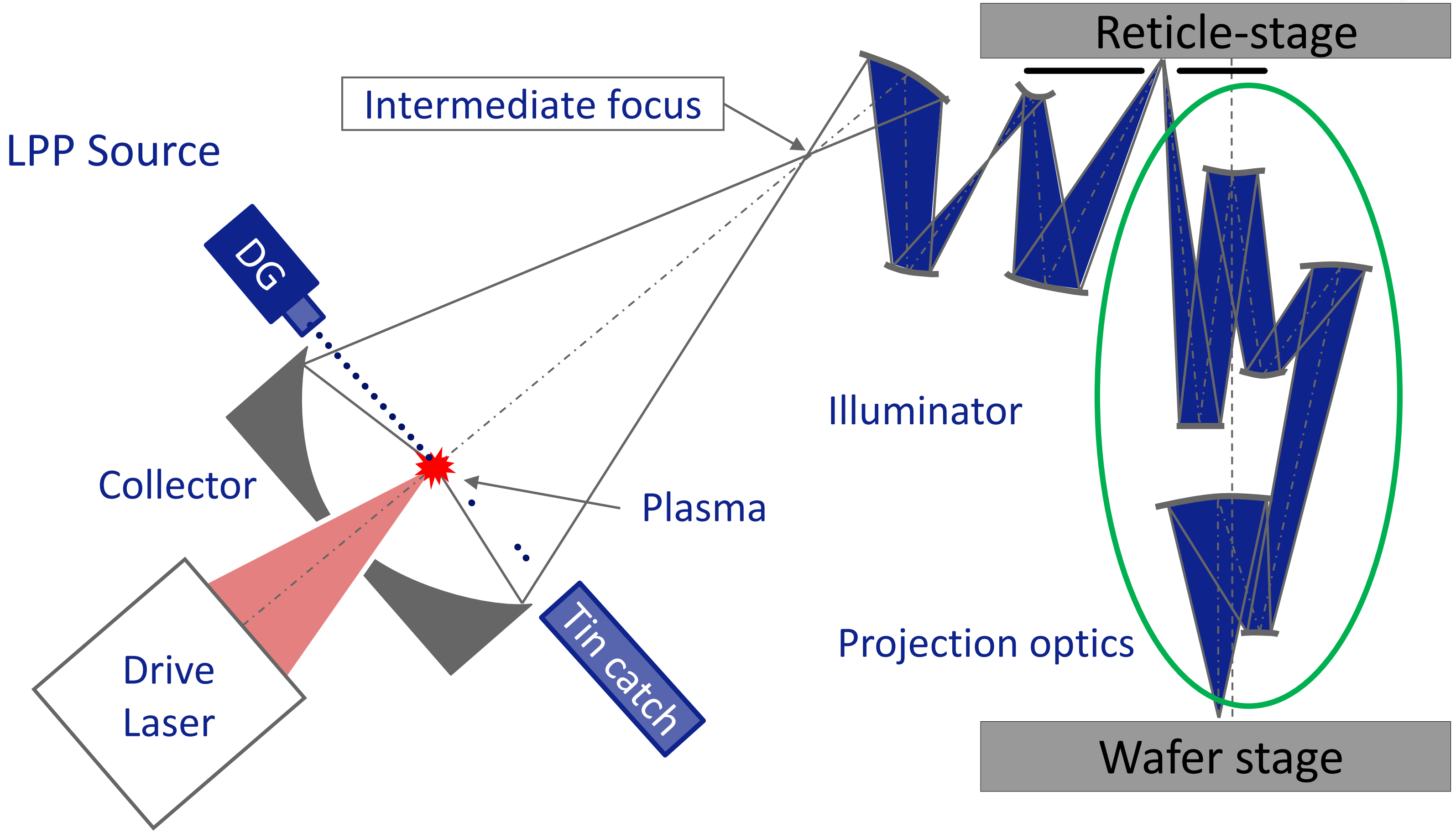


Simulated Shadowgrams



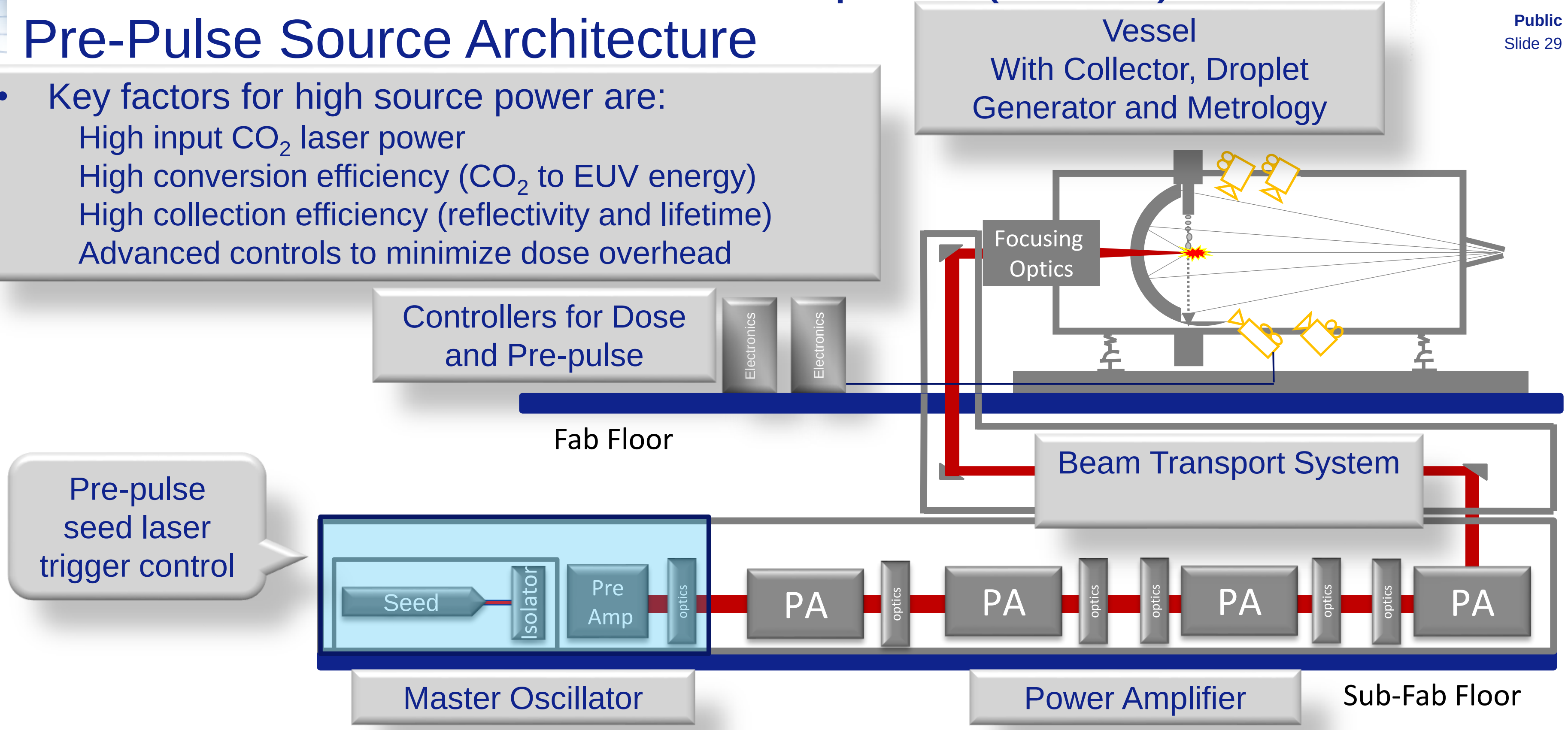
EUV Source: Architecture and Operation Principles

EUV Lithography System Schematic



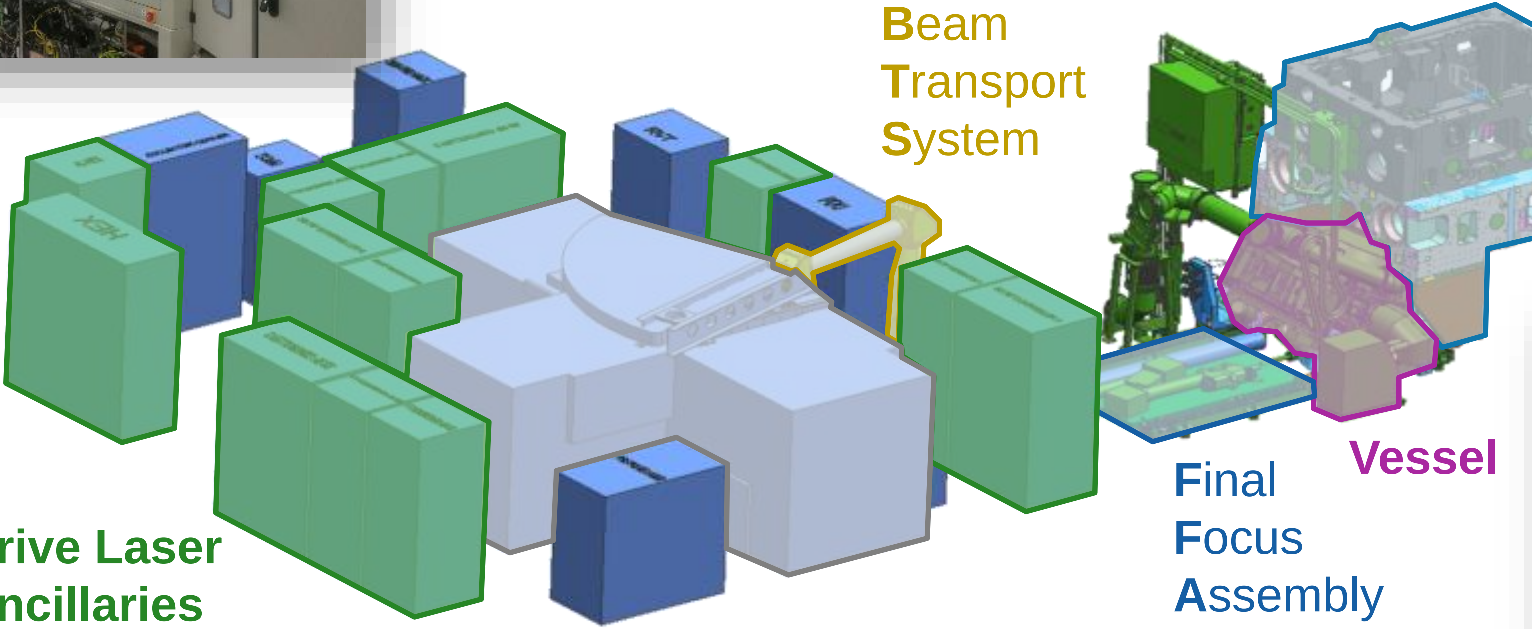
LPP: Master Oscillator Power Amplifier (MOPA) Pre-Pulse Source Architecture

- 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



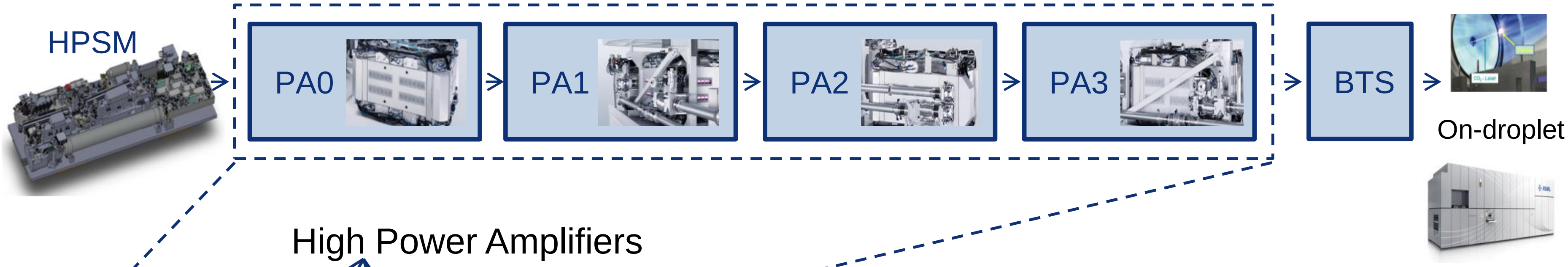
EUV power (source/scanner interface, [W]) ∝ **CO_2 power [W]** * **Conversion Efficiency** * **1 – Dose Overhead**

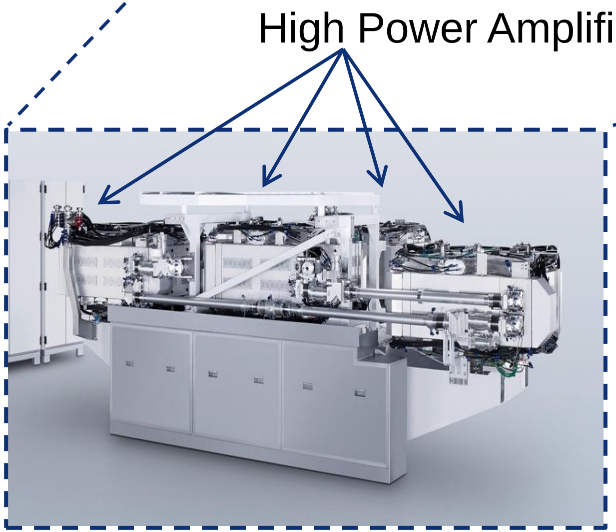
EUV System overview



Industrial high power CO_2 laser

High beam quality for gain extraction and EUV generation

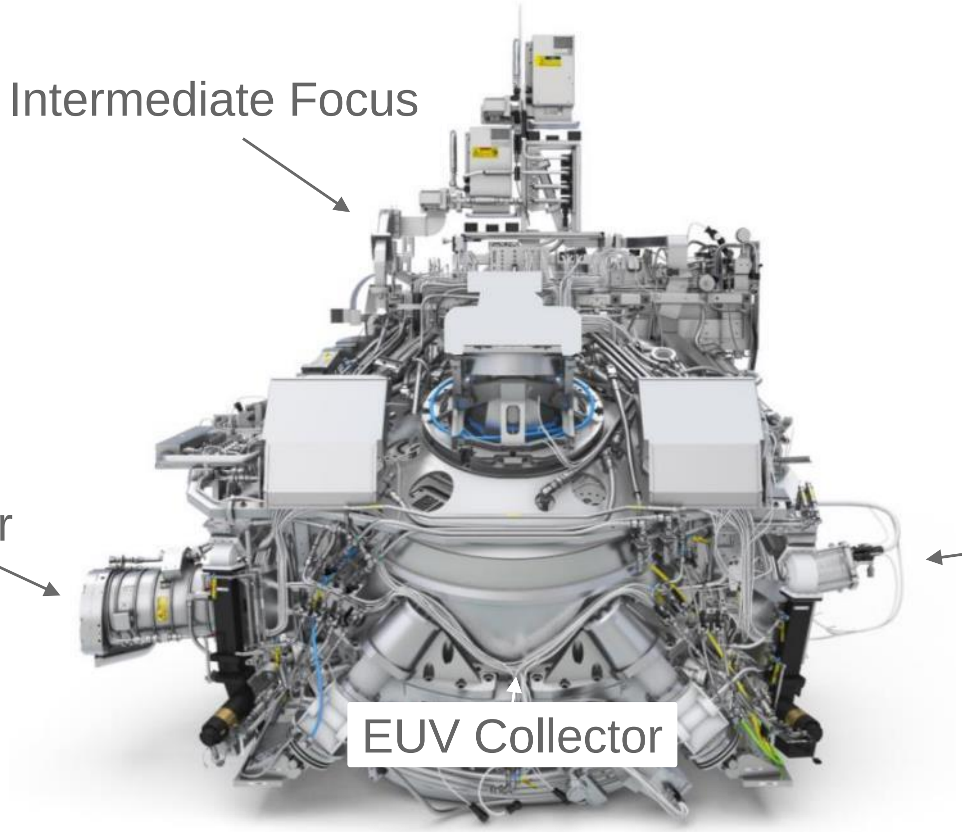




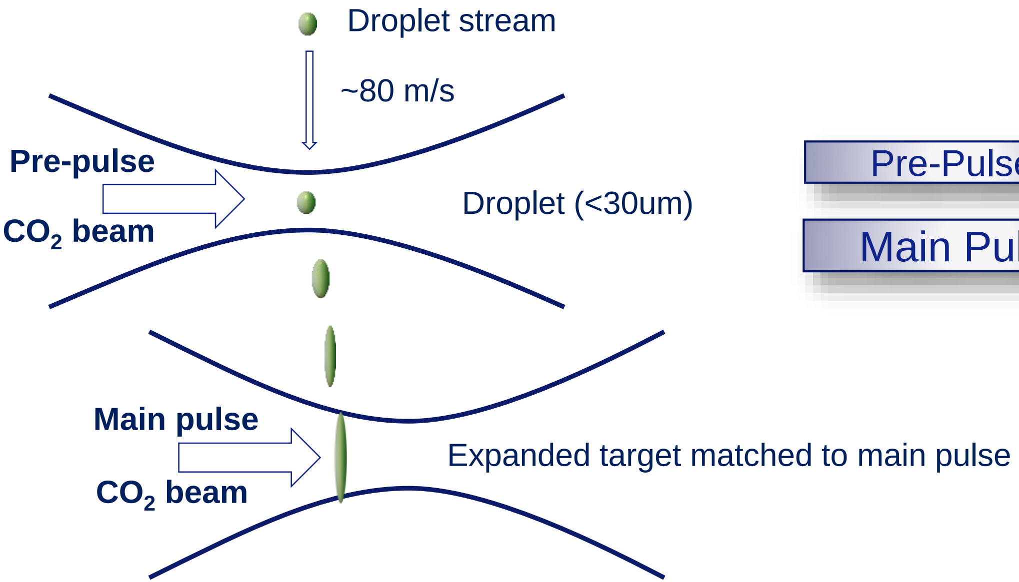
- 4 cascaded power amplifiers (PAs) in HPAC
- Individually optimized geometry and settings
- Connected by relay optics
- Extensive metrology between amplifiers & at DL exit

NXE:3XY0 EUV Source: Main modules

Populated vacuum vessel with tin droplet generator and collector



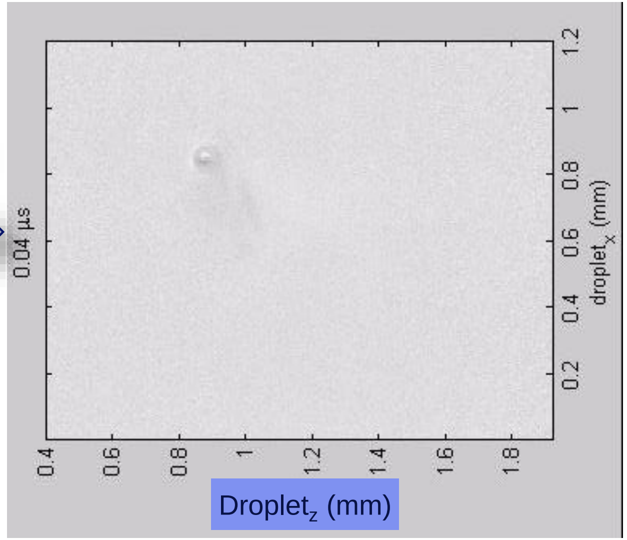
EUV Source: MOPA + Pre-Pulse



Pre-Pulse

Main 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

6% conversion efficiency achieved

Pre-pulse laser

→Expands the droplet and prepares the Sn target

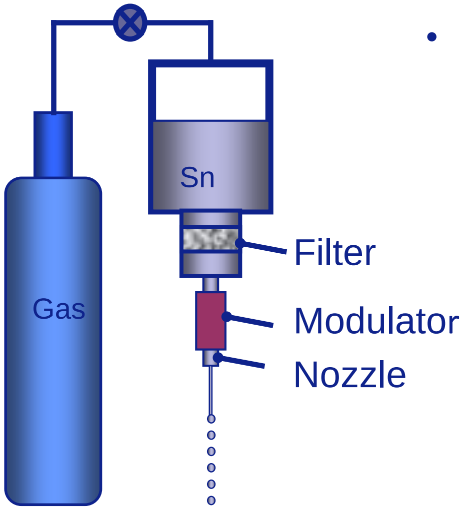
Main-pulse laser

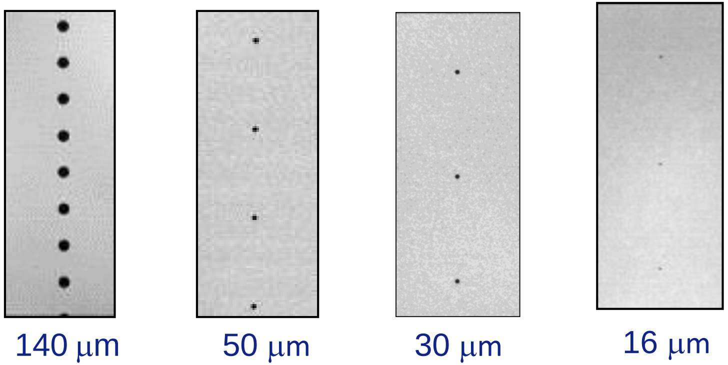
→Heats and ionizes the Sn target to produce EUV light

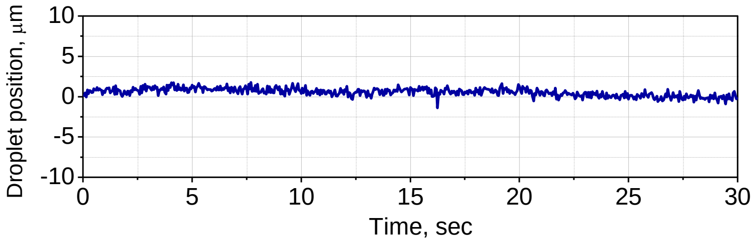
MOPA = Master Oscillator Power Amplifier
PP = Pre-Pulse
MP = Main Pulse

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



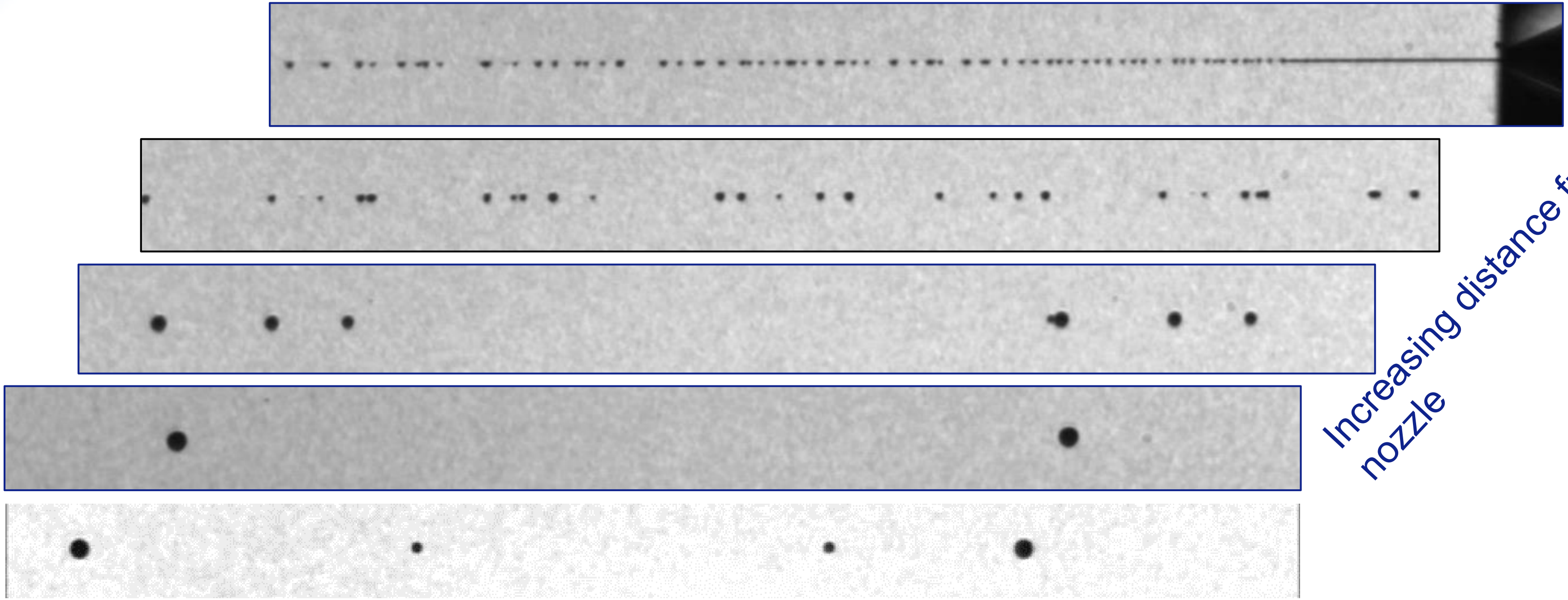




Short term droplet position stability σ~1μm

Droplet Generator: Principle of Operation

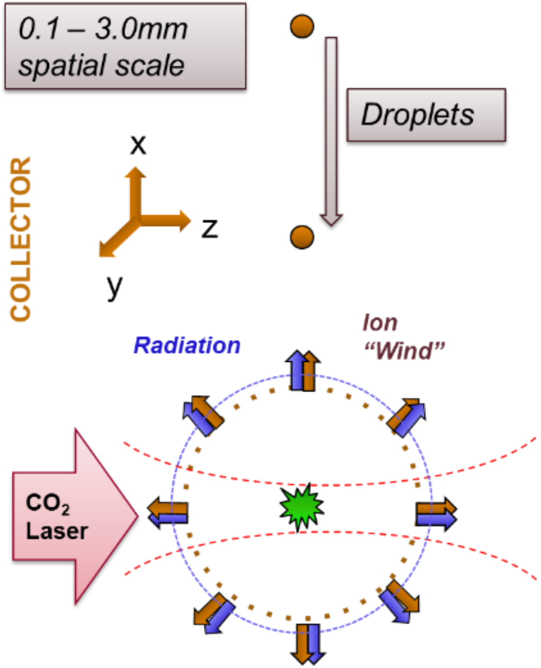
Large separation between the droplets by special modulation

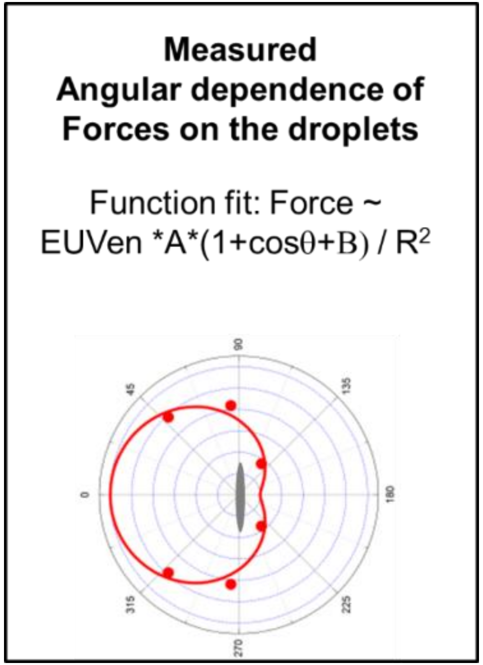


Increasing distance from nozzle

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

Forces on Droplets during EUV Generation

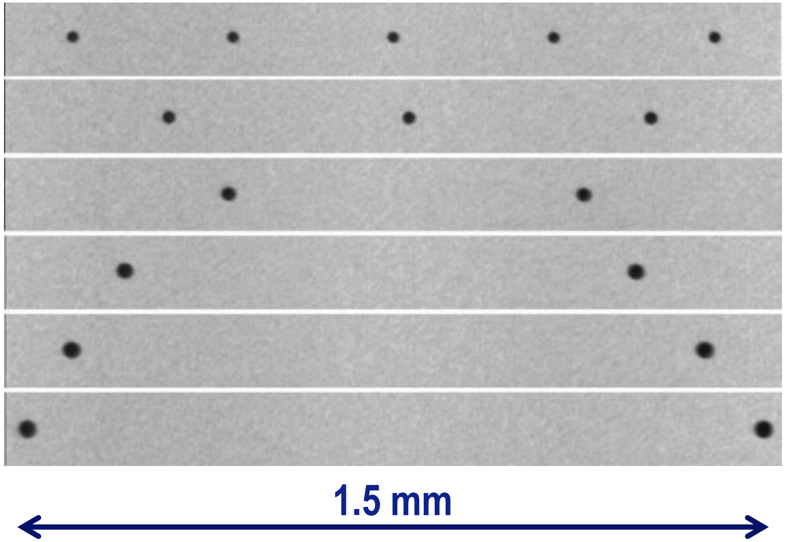




High EUV power at high repetition rates drives requirements for higher speed droplets with large space between droplets

Droplet Generator: Principle of Operation

Large separation between the droplets by special modulation

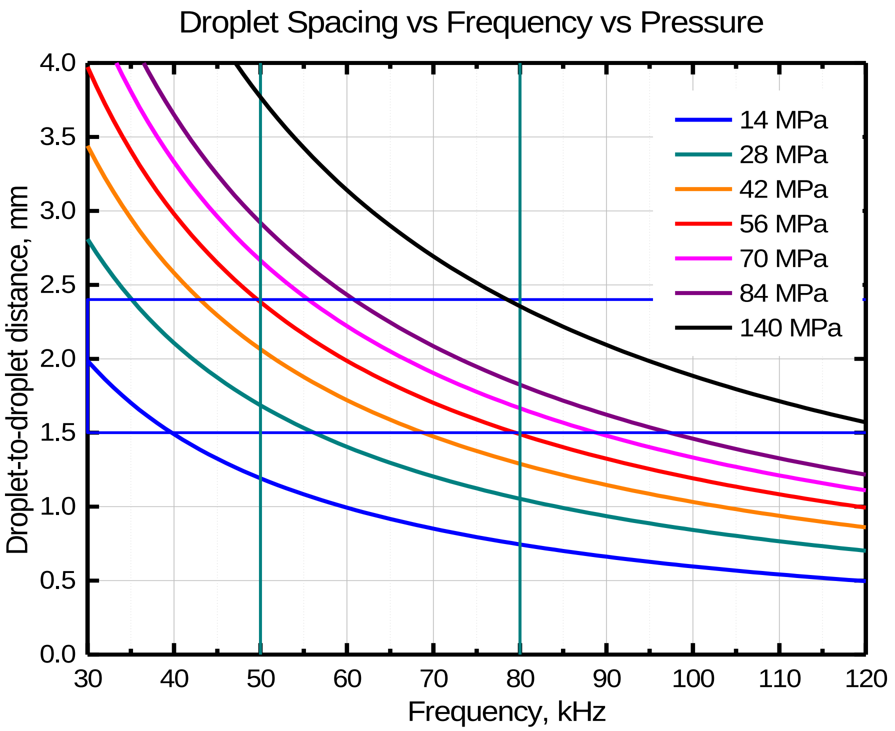


Increasing Droplet Generator Pressure

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

Increase of droplet spacing

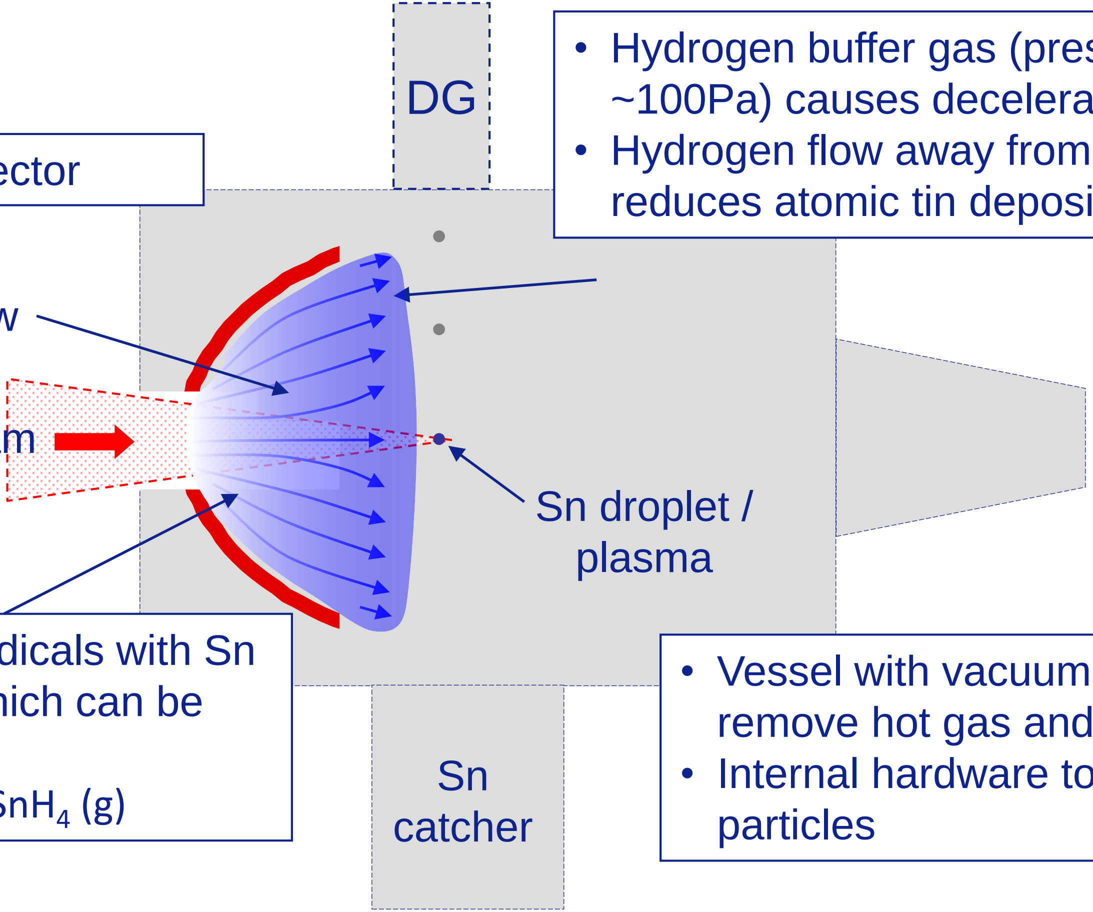
Larger separation between the droplets needed for higher pulse energies



Droplet spacing of 1.5 mm demonstrated at 80 Khz

Collector Protection by Hydrogen Flow

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



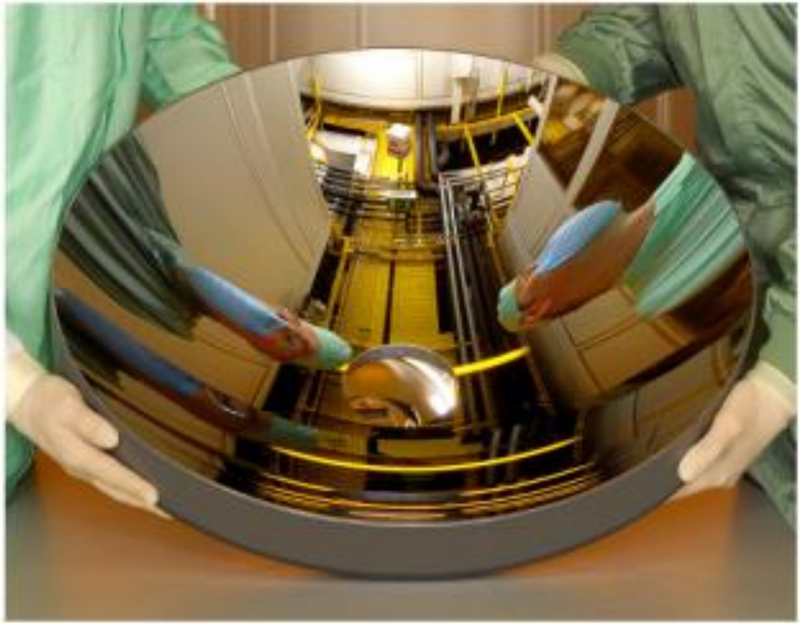
Reaction of H radicals with Sn to form SnH_4, which can be pumped away.

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

- 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



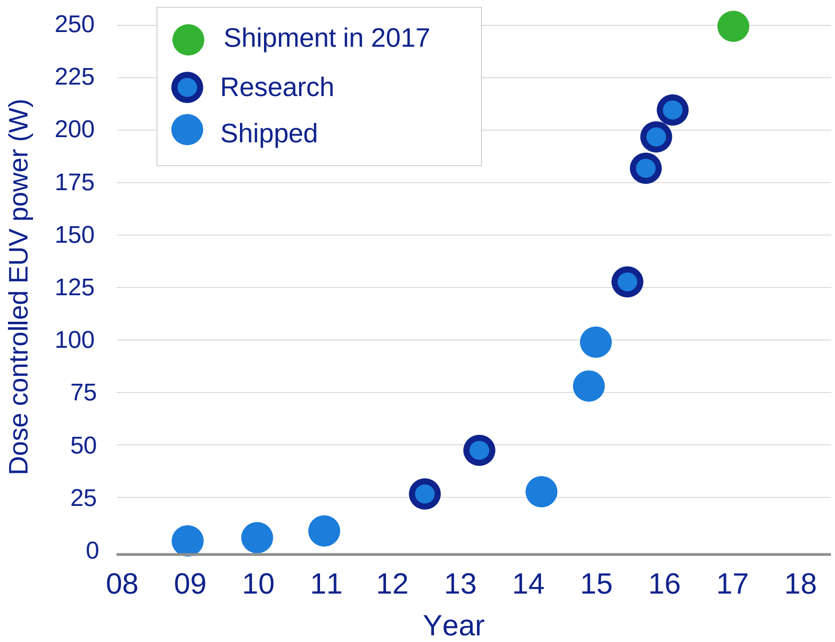
Normal Incidence Graded Multilayer Coated Collector

EUV Sources in the Field

Progress for in EUV power: 250W

ASML

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



Increase average and peak laser power
Enhanced isolation technology

Advanced target formation technology

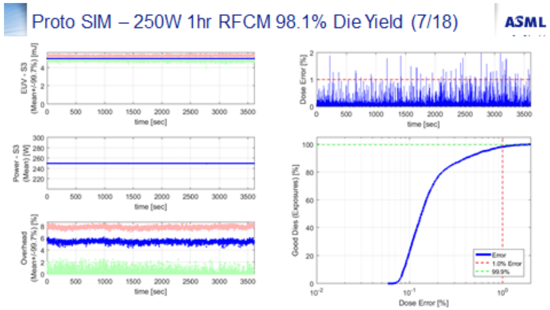
Improved dose-control technique

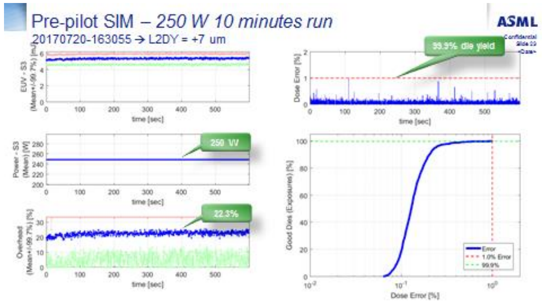
>250W is now demonstrated,
Shipping started in the end of 2017

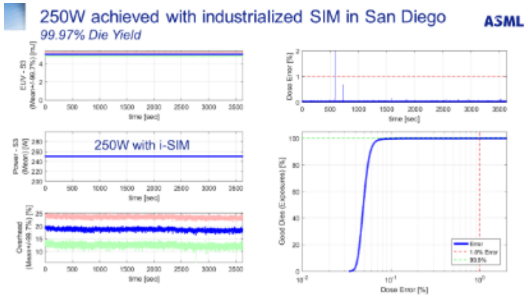
250W demonstrated multiple times in 2017

Including industrialized version of SIM, field upgrades in progress

Proto 1	Pre-Pilot	Industrialized module
May 2017 @ 250W	July 2017 @ 250W / 125wph	December 2017 @ 250W



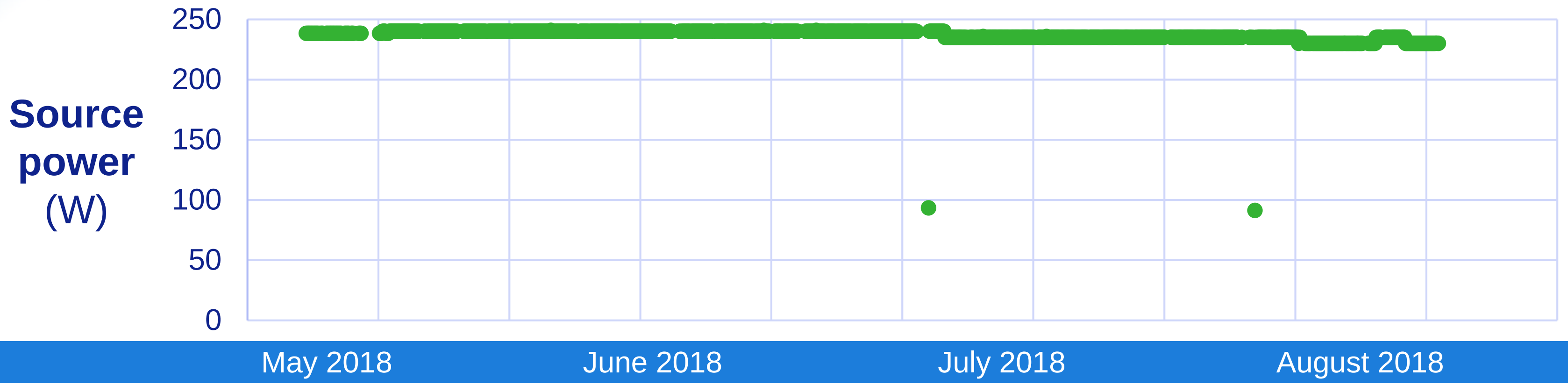


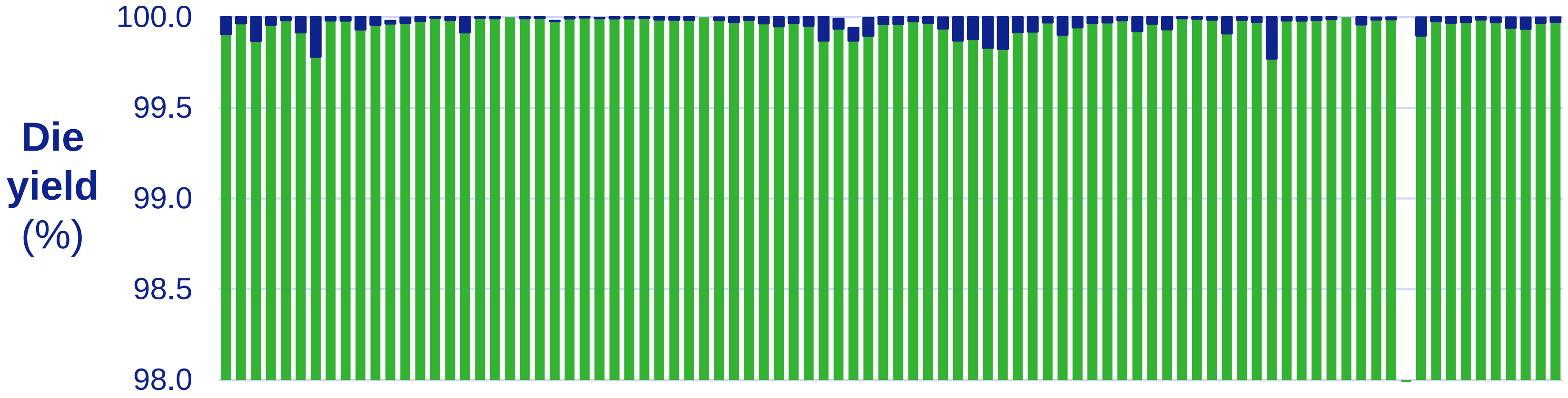


SIM – Seed Isolation Module

EUV Source operation at 250W

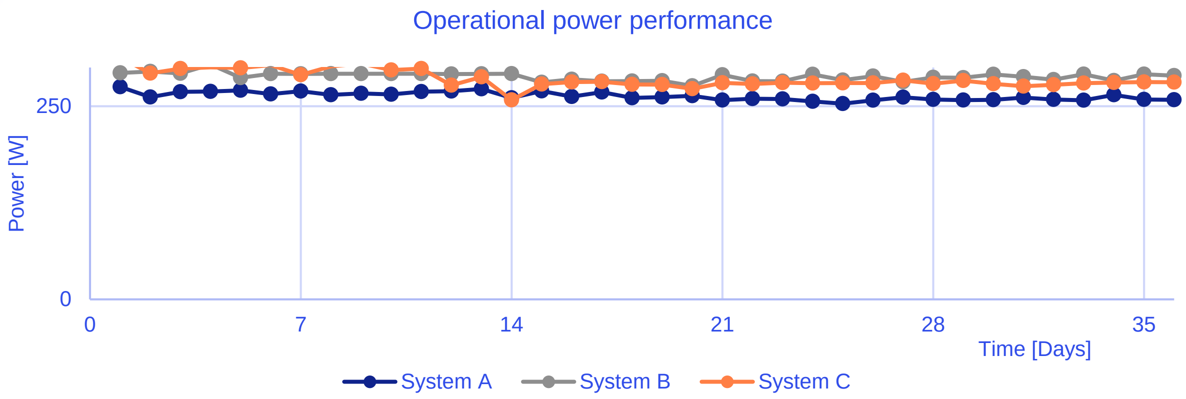
with 99.90% fields meeting dose spec

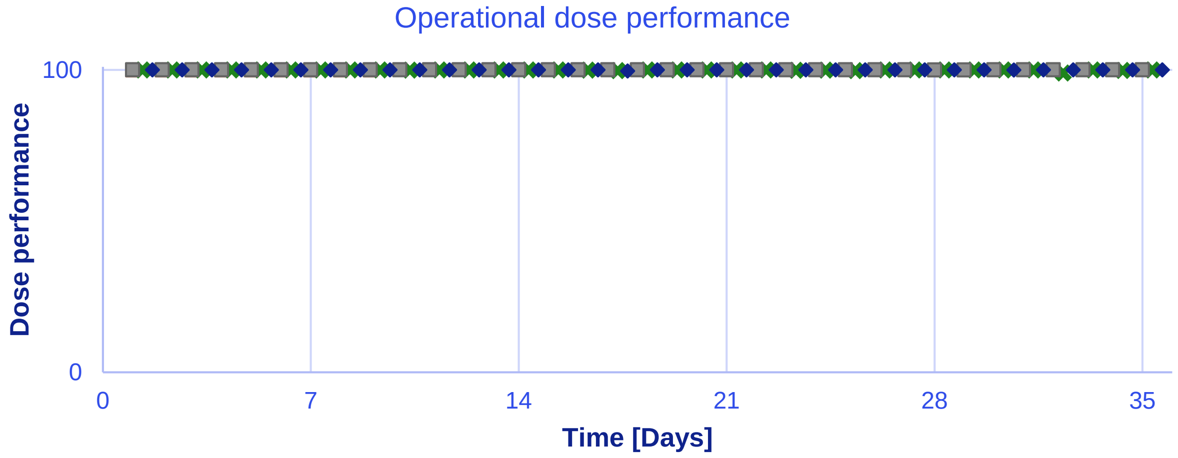




Performance at customers sites at 250W

On multiple systems





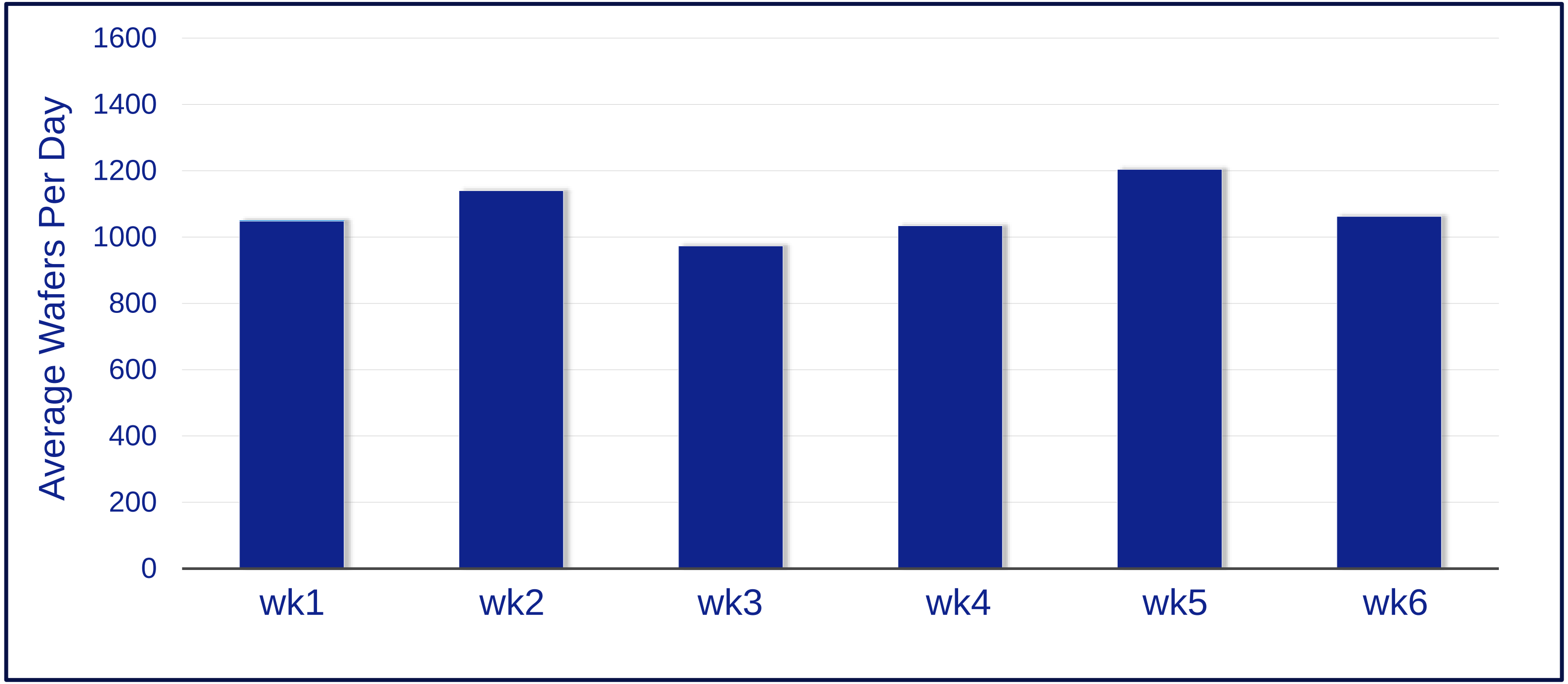
- Source Power >250W
- Power fluctuations corrected by scanner dose control

- At 250W, Average dose performance well above >99.99%

Clean collector power

NXE:3400B productivity of average >1000 WPD

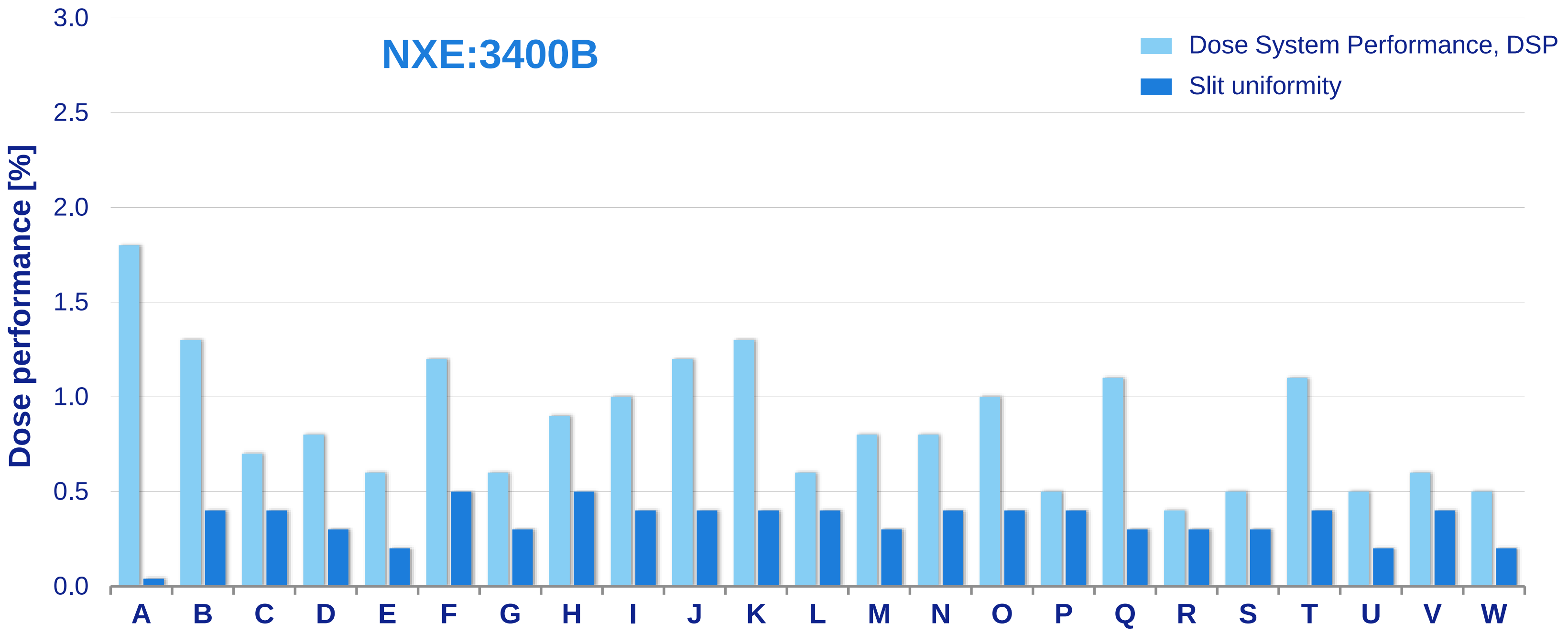
Wafers per day for 6 consecutive weeks



At a customer site

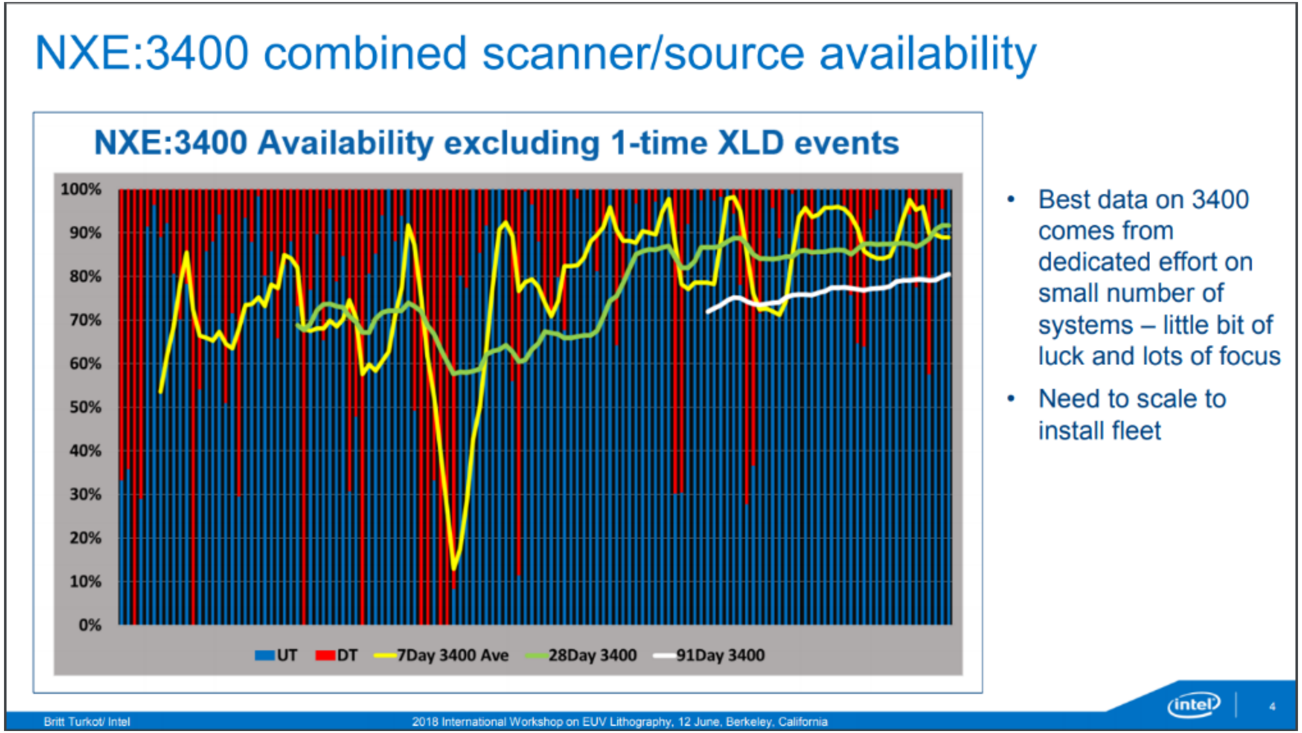
Dose Performance and Slit uniformity show stable results

Supporting requirements for 5 nm node CD control



NXE:3400B availability plan to 88% availability EoY ‘18

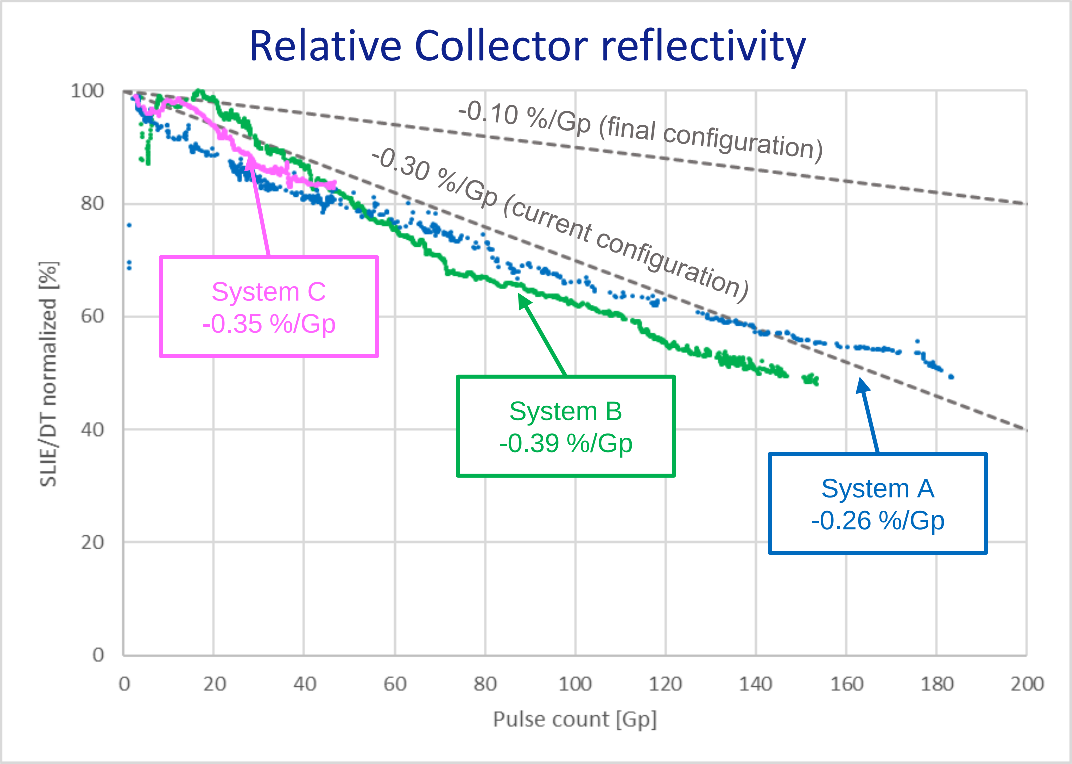
Roadmap in place to 95% availability for 95% of fleet

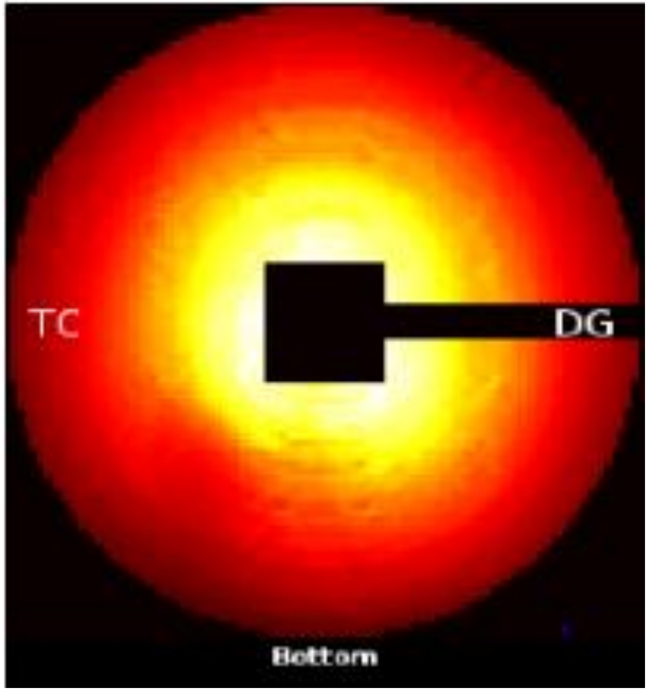


NXE:3400B availability, in final configuration, climbing steadily from 40% end of Q1 to 70-80% worldwide (4 weeks average), variation reduction is key

Collector lifetime improvement at 250 W

Longer collector lifetime confirmed at full power





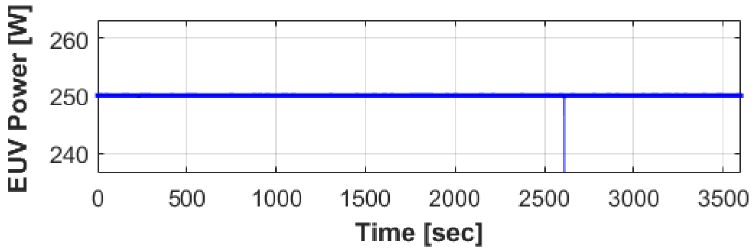
Far Field EUV intensity
(image of the collector)

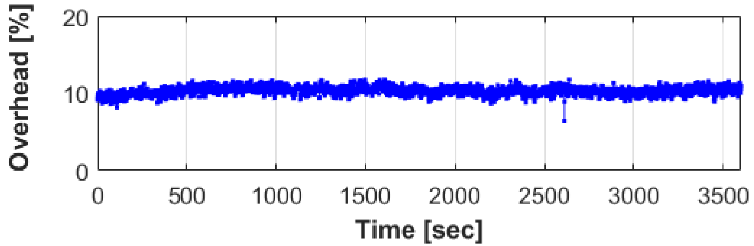
Collector reflectivity loss over time reduced to <0.3%/Gp

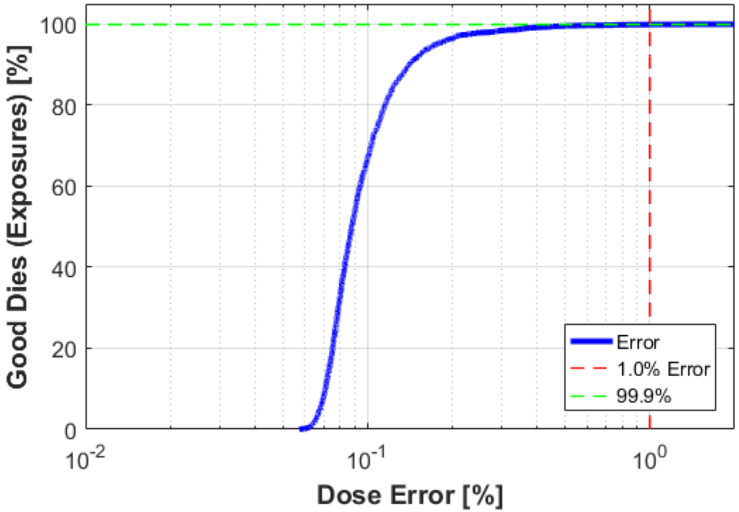
EUV Source Power Outlook

EUV Source operation at 250W

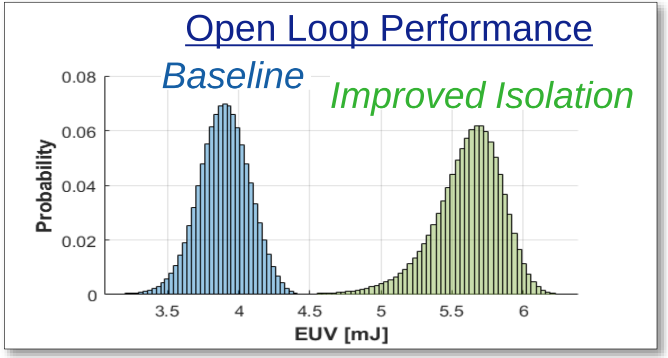
with 99.90% fields meeting dose spec







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**



Hydrogen gas central to tin management strategy

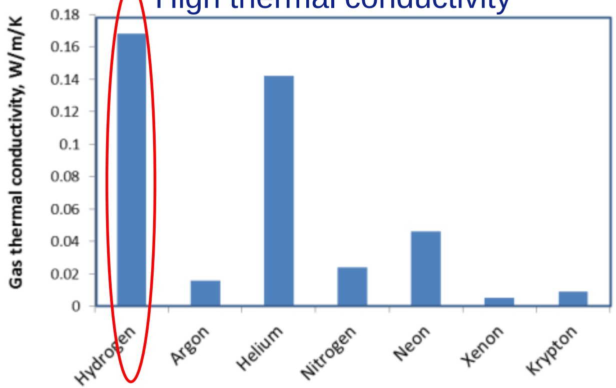
Requirements for buffer gas:

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

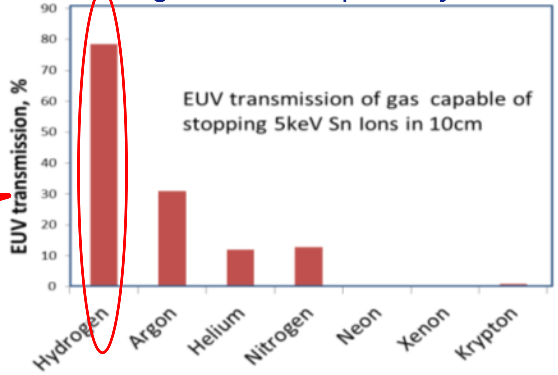
Hydrogen performs well for all these tasks!

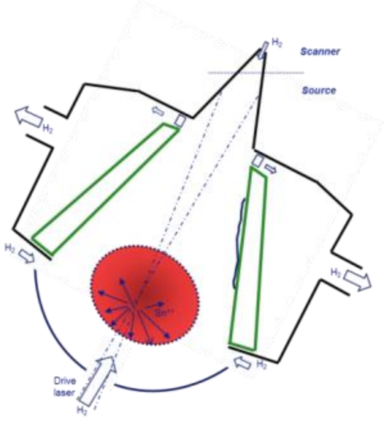
High heat capacity

High thermal conductivity



High EUV transparency



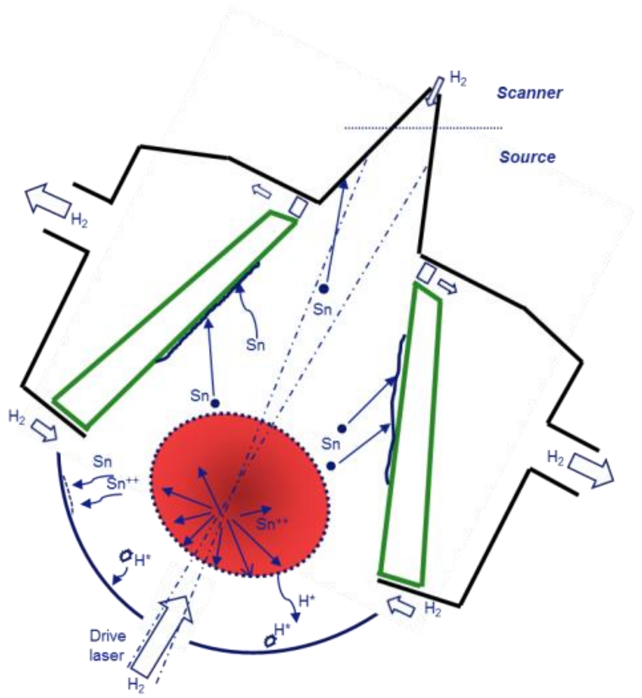


Debris in the tin LPP EUV source

Sn → Sn vapor (diffusion debris)

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

Sn● → Sn particles

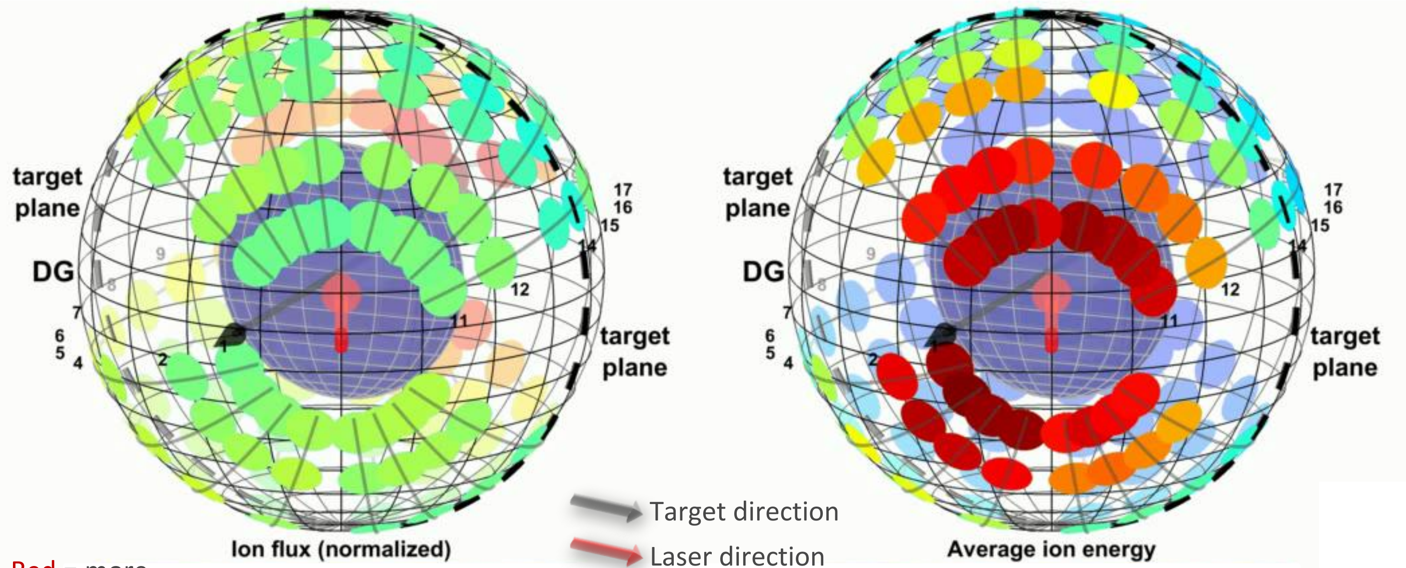


Primary debris – directly from plasma and before collision with any surface:

- 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

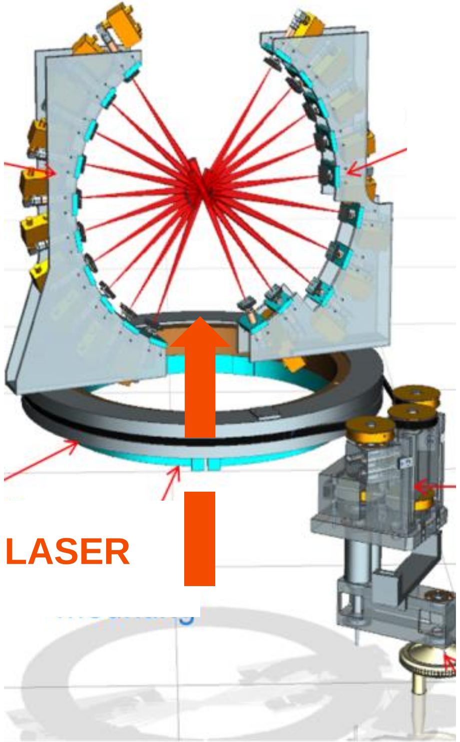
3D measurement of fast tin ion distributions

Faraday cups measure tin ion distributions



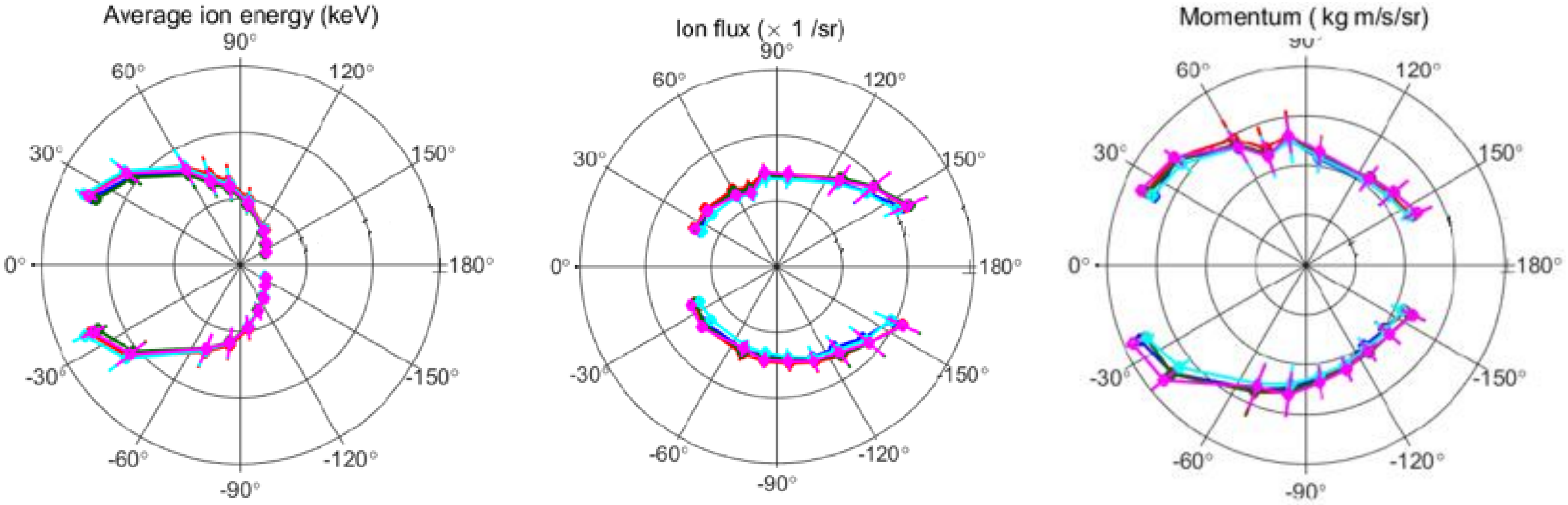
Red = more
Blue = less

Target direction
Laser direction
FC direction



Ion measurements inform H_2 flow requirements for source

Tin ion distributions



Data are used for optimization of H_2 flow in the source

Measurement of fast tin ion and radiation distributions

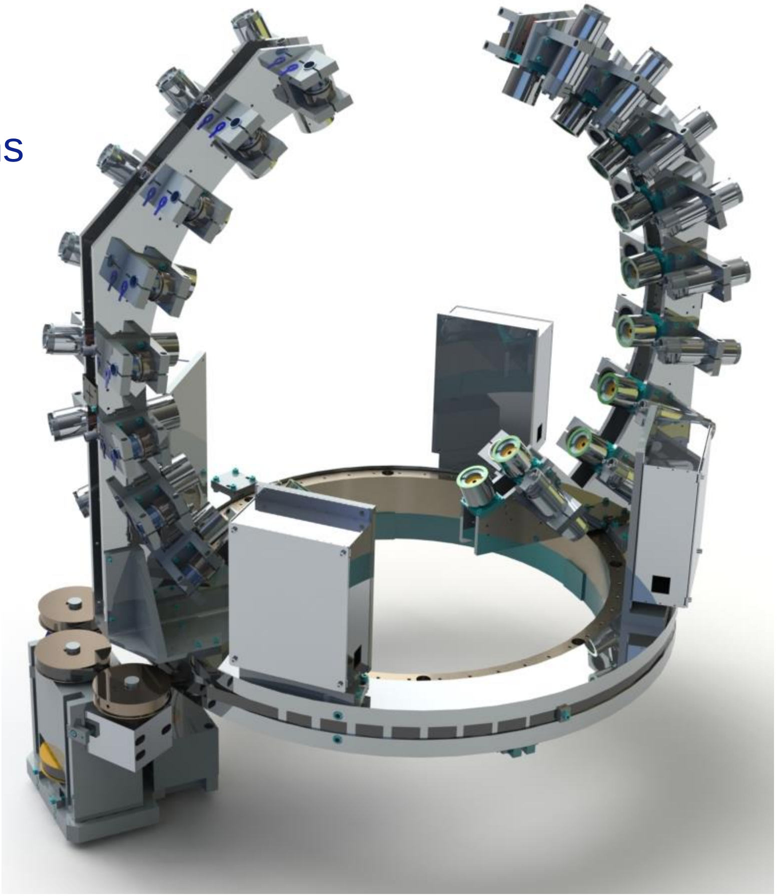
Multiple sensors on a rotating frame

Sensors

- Faraday Cups: ion energy and charge distributions
- CO_2 PEMs: scattered infrared radiation
- EUV PDs: EUV emission and anisotropy

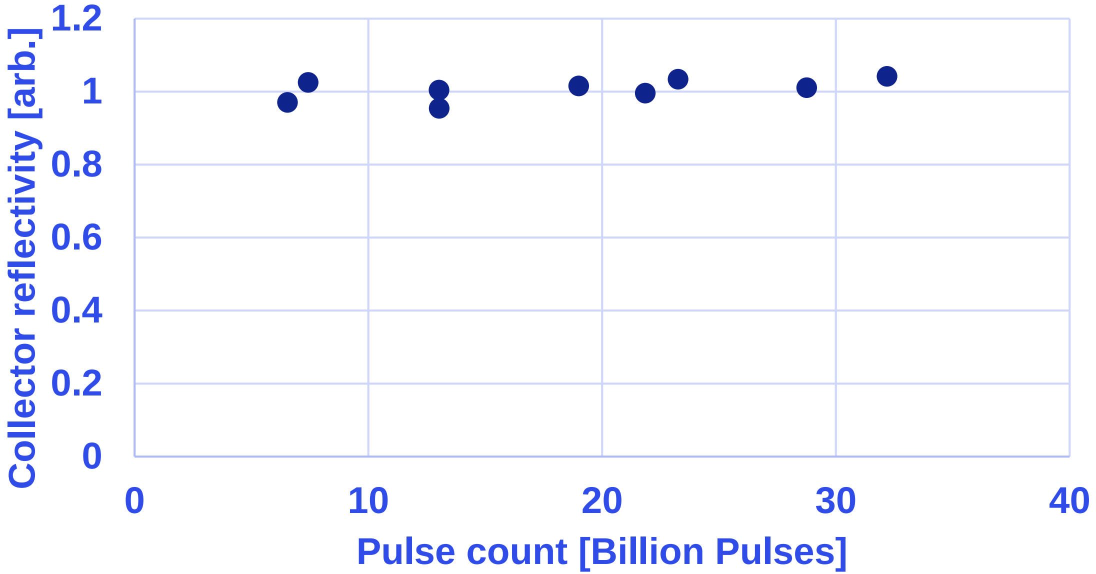
Applications

- Input to Plasma-Gas Interaction / Computational Fluid Dynamics model
- Evaluation of collector protection capability
- Improvement of Conversion Efficiency



Improved debris mitigation

At 250 watt of EUV power

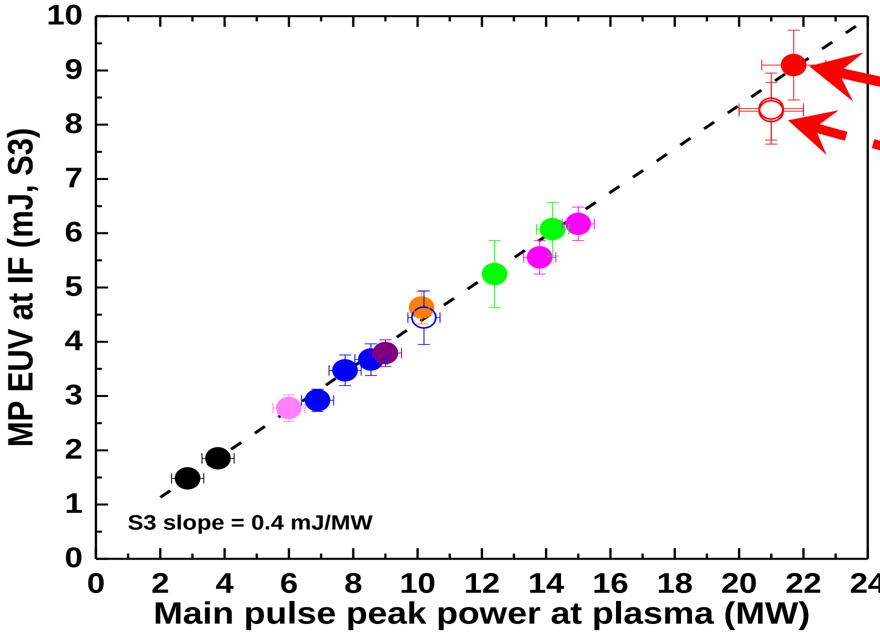


Data from the EUV source development system

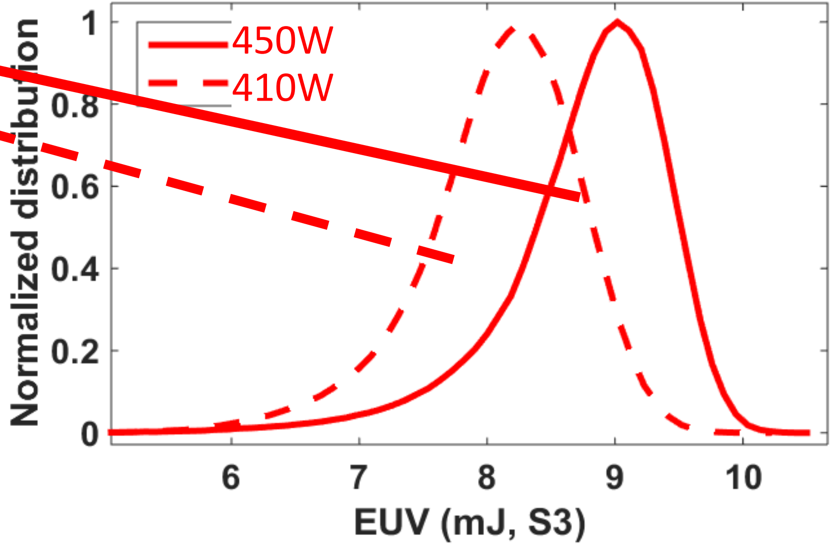
450W in-burst EUV power demonstration

Demonstrated IF EUV pulse energy of 9 mJ at 50 kHz

EUV data over 8 EUV LPP source architectures



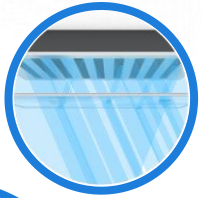
Open loop, EUV pulse energy histograms

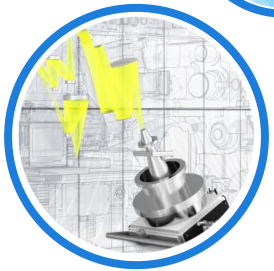


Open loop, 15 ms Bursts, 3% duty cycle

On the development system

Summary: EUV readiness for volume manufacturing





34 NXE:3XY0B systems operational at customers

- Dose-controlled power of 250W on multiple tools at customers

Progress in EUV power scaling for HVM

- Dose-controlled power of 250W on multiple tools at customers
- Collector lifetime ~ 150 Billion Pulses in the field

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 500W EUV demonstrated in research

- CE is up to ~ 6 %
- In-burst EUV power is up to 450W

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