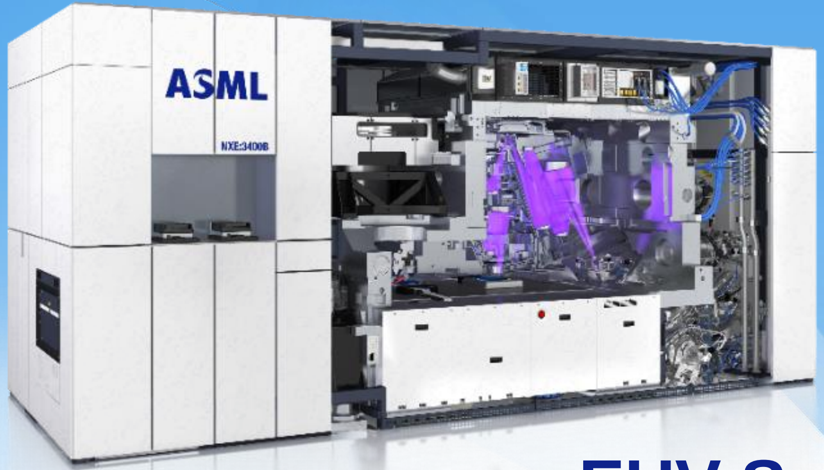


EUV Source for Lithography in HVM: performance and prospects

Igor Fomenkov
ASML Fellow

Source Workshop, Amsterdam, November 5th 2019

Outline

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

And it’s here: we see EUV - enabled chips in 2019

EUV up and running in High Volume Manufacturing

TSMC's 5nm EUV Making Progress: PDK, DRM, EDA Tools, 3rd Party IP Ready

TSMC this week has said that it has completed development of tools required for design of SoCs that are made using its 5 nm (CLN5FF, N5) fabrication technology. The company indicated that some of its alpha customers (which use pre-production tools and custom designs) had already started risk production...

TSMC: First 7nm EUV Chips Taped Out, 5nm Risk Production in Q2 2019

Last week, TSMC made two important announcements concerning its progress with extreme ultraviolet lithography (EUVL). First up, the company has successfully taped out its first customer chip using its second generation 7 nm process technology, which incorporates limited EUVL usage. Secondly, TSMC disclosed plans to start risk production of 5...

Samsung Completes Development of 5nm EUV Process Technology

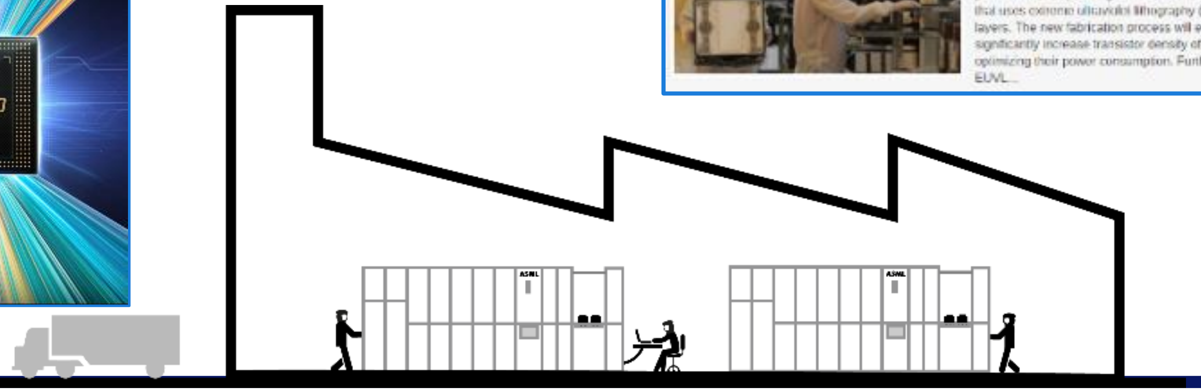
Samsung Foundry this week announced that it has completed development of its first-generation 5 nm fabrication process (previously dubbed 5LPE). The manufacturing technology uses extreme ultraviolet lithography (EUVL) and is set to provide significant performance, power, and area advantages when compared to Samsung's 7 nm process (known as 7LPP)...

TSMC Reveals 6 nm Process Technology: 7 nm with Higher Transistor Density

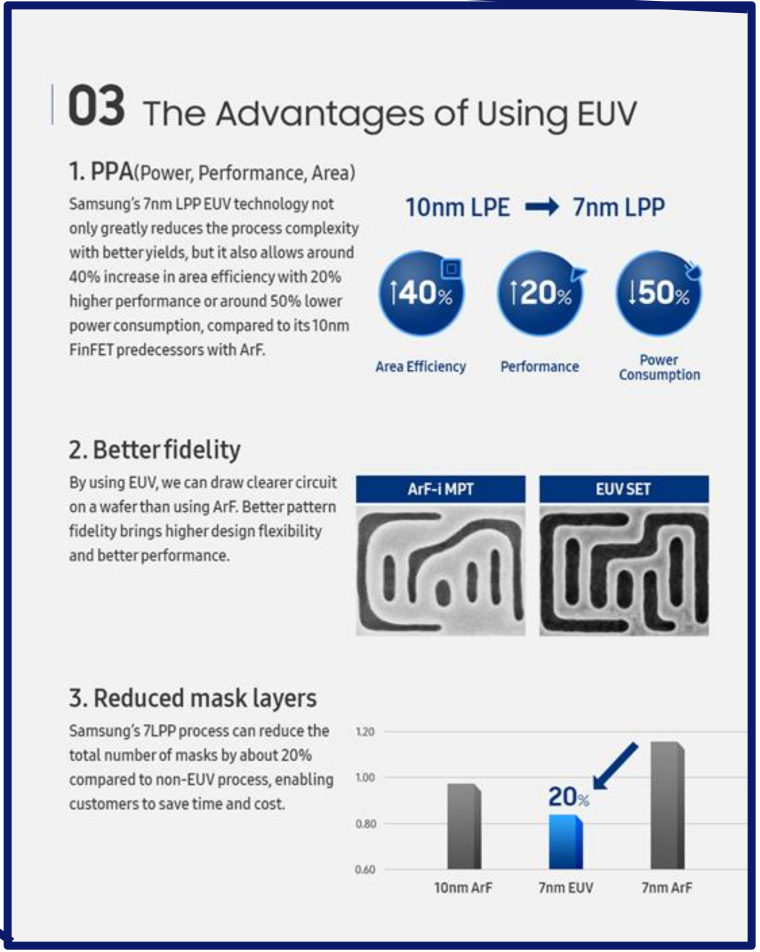
TSMC this week unveiled its new 6 nm (CLN6FF, N6) manufacturing technology, which is set to deliver a considerably higher transistor density when compared to the company's 7 nm (CLN7FF, N7) fabrication process. An evolution of TSMC's 7nm node, N6 will continue to use the same design rules, making...

Samsung Starts Mass Production of Chips Using Its 7nm EUV Process Tech

Samsung Foundry on Wednesday said that it had started production of chips using its 7LPP manufacturing technology that uses extreme ultraviolet lithography (EUVL) for select layers. The new fabrication process will enable Samsung to significantly increase transistor density of chips while optimizing their power consumption. Furthermore, usage of EUVL...



Advantages of EUVL : Samsung Infographic



https://news.samsung.com/global/infographic-euv-samsungs-latest-investment-on-developing-next-generation-semiconductor-products

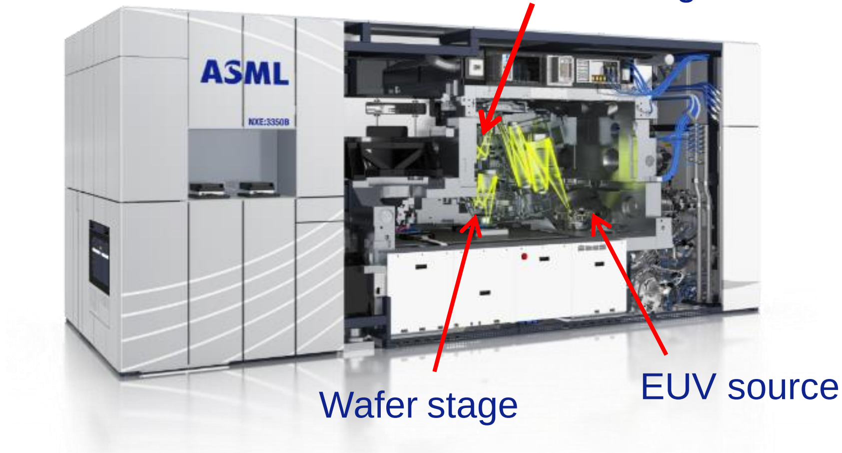
Why EUV? - Resolution in Optical Lithography

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

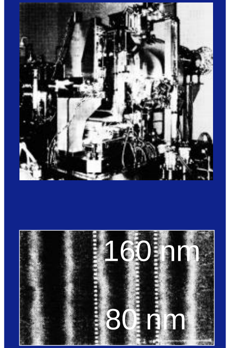
ASML ships 1st NA 0.33 system NXE:3300B

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

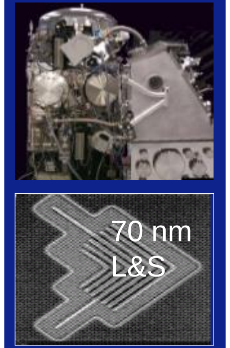
’85 ’86 ’87 ’88 ’89 ’90 ’91 ’92 ’93 ’94 ’95 ’96 ’97 ’98 ’99 ’00 ’01 ’02 ’03 ’04 ’05 ’06 ’07 ’08 ’09 ’10 ’11 ’12 ‘13 ’14 ’15 ’16 ’17 ’18

NL

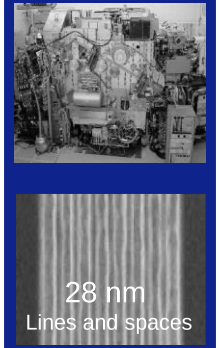
Japan



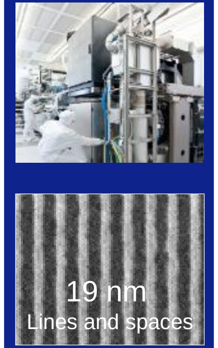
USA



NL



NL



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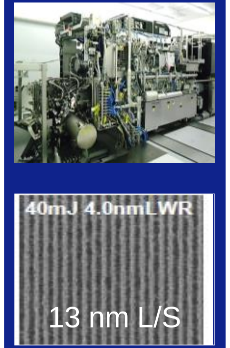
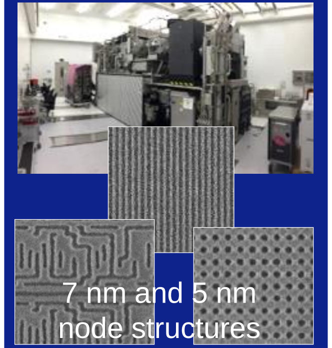
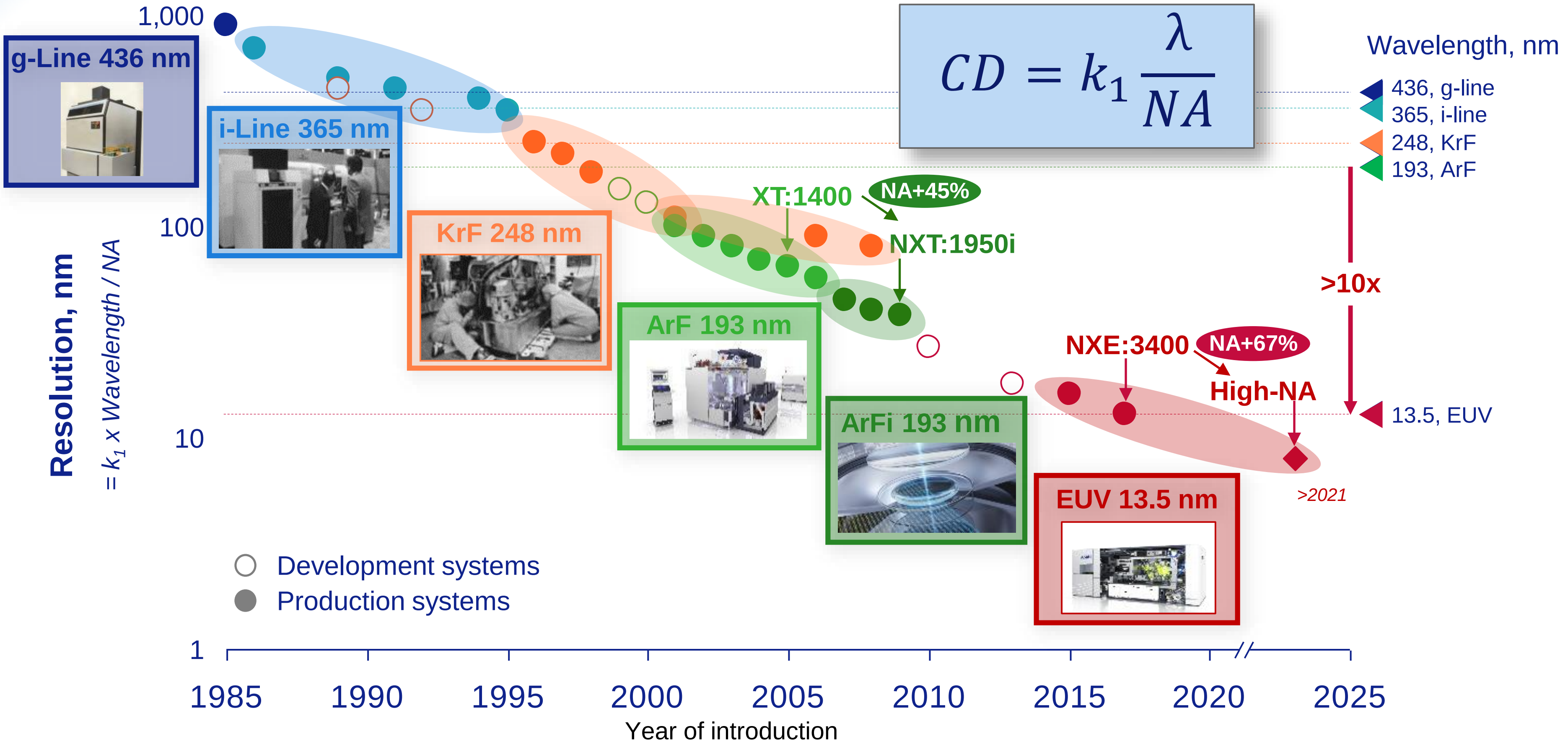


NL



High-NA EUV targets <7nm resolution

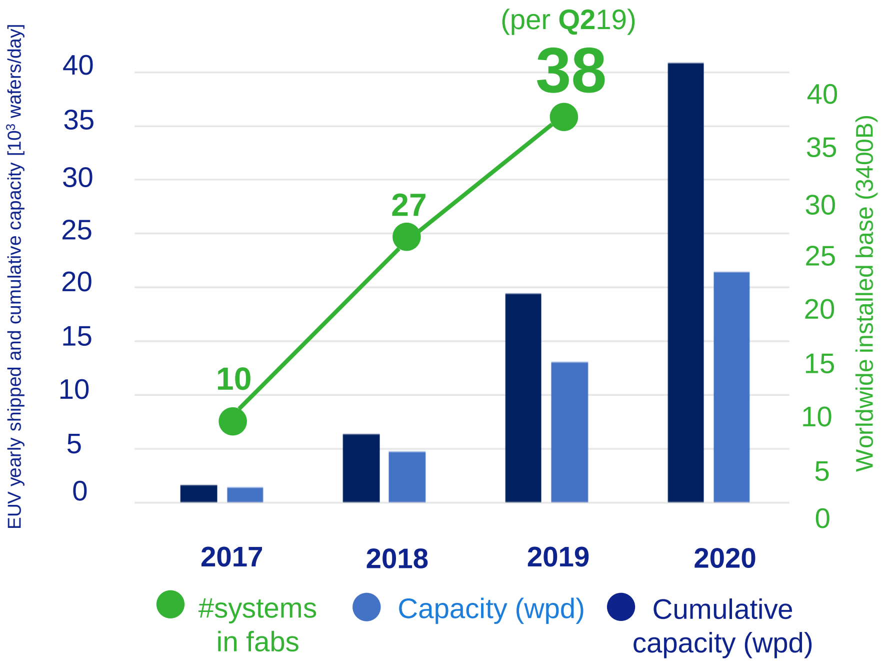
Relative improvement:5X over ArFi, 40% over 0.33 NA EUV



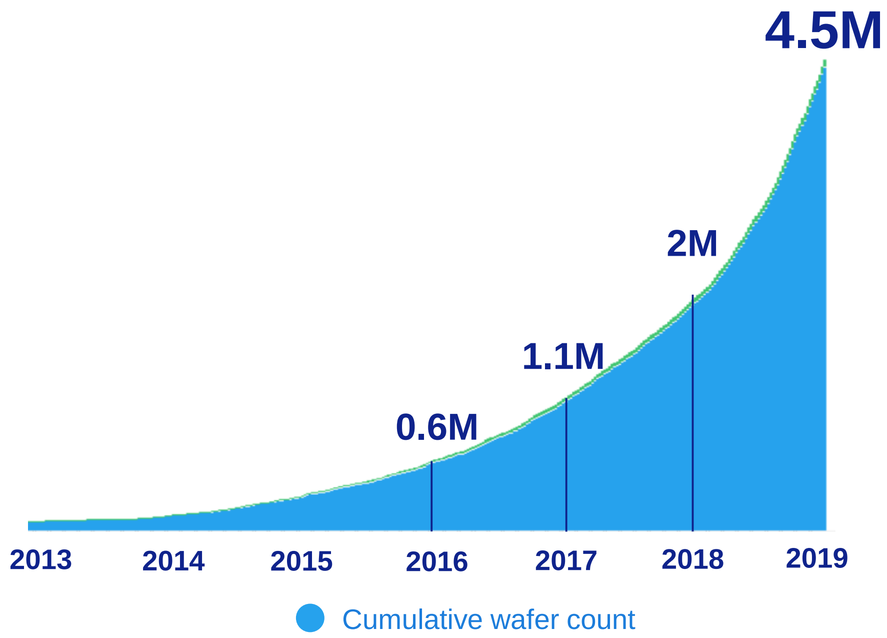
EUV is being ramped up quickly now

ASML

Installed base NXE:3400B



Cumulative EUV wafer count

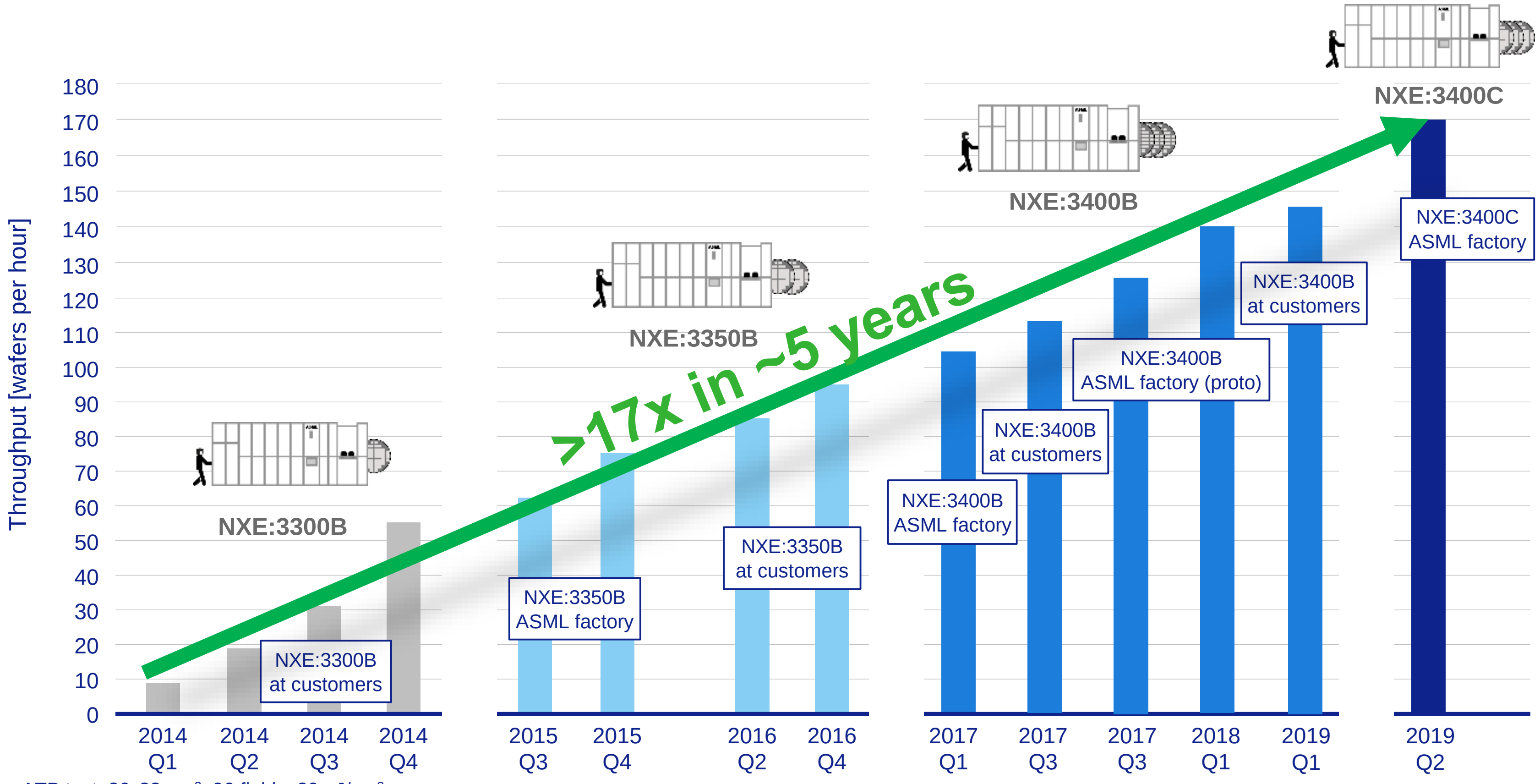


NXE:3400B installed base stands at 38 (per Q2 2019), cumulative EUV wafer capacity will approach 10^8 wafers per year by 2020

Since Jan 2018, EUV systems have run more wafers (2.5M) than 2011-2017 combined

NXE productivity reached **170** wafers per hour

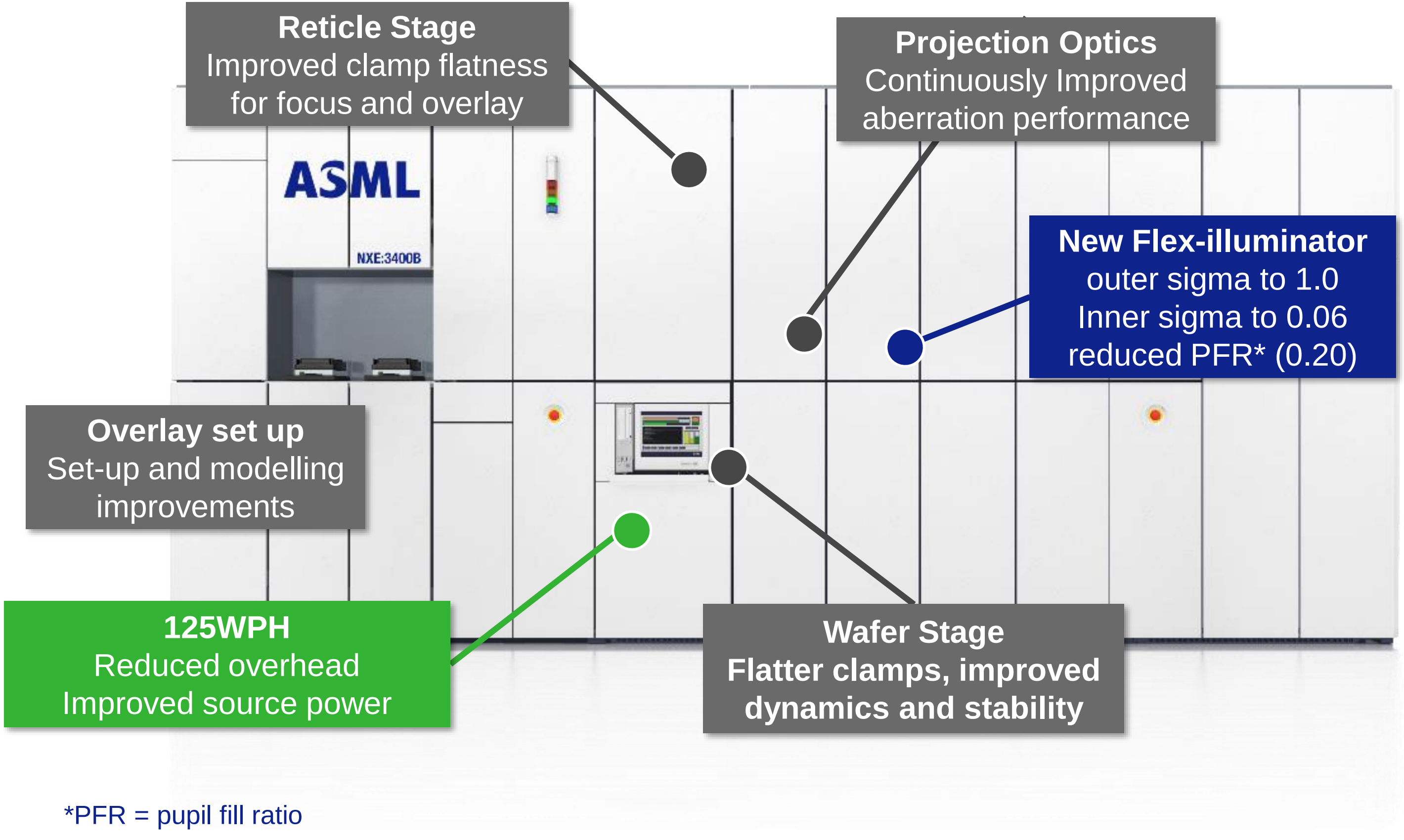
On NXE:3400C in ASML factory



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

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: 3400C improvements with higher productivity

Demonstrated in ASML factory, shipping to the customers

OFP:3400B (standard)
ORION
UV-LS 2nd Gen

Optics
Transmission improvement

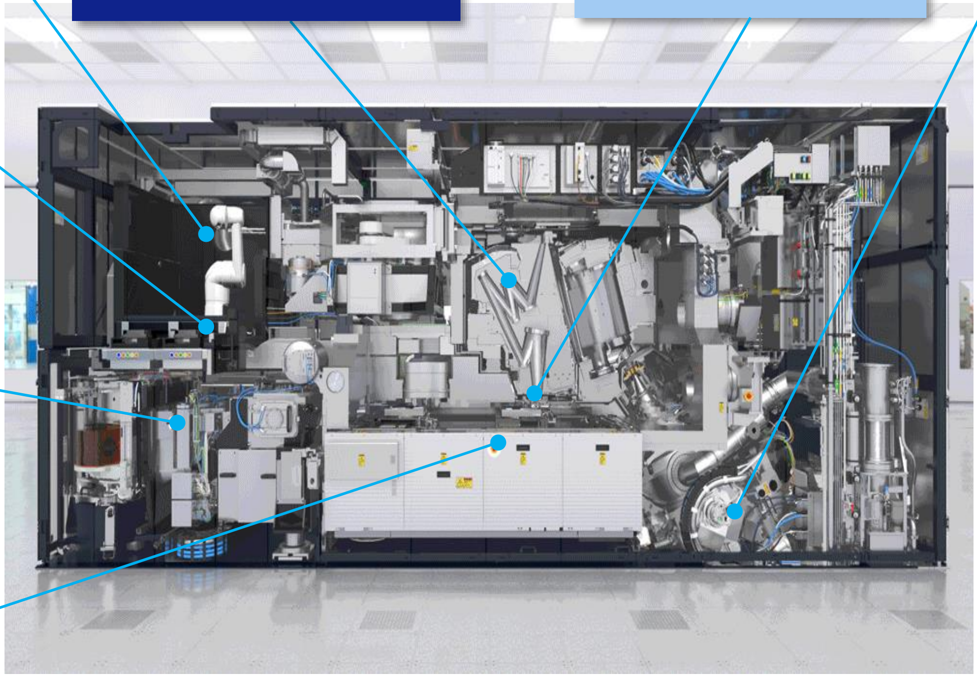
DGL Membrane
(optional)

Source with Modular Vessel
collector swap <8hrs
Inline tin refill

Reticle Handler
Improved productivity

Wafer Handler
@ ≥170WPH

Faster Reticle Align /
reduced wafer
overhead



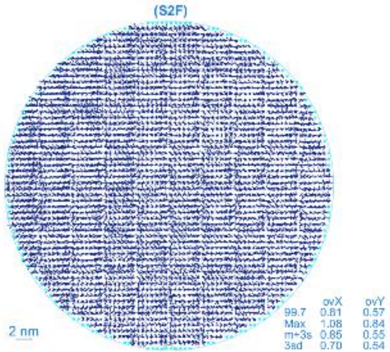
	NXE:3400B +OFP:3400	NXE:3400C
Resolution	13 nm	13 nm
Full wafer CDU	≤ 1.3 nm	≤ 1.1 nm
DCO	≤ 1.4 nm	≤ 1.4 nm
MMO	≤ 1.5 nm	≤ 1.5 nm
XMMO	≤ 1.9nm	≤ 1.9 nm
Matched to	NXT:2000i	NXT:2000i
Productivity*	≥ 125 WPH	≥ 170 WPH
OPO (M+3S)**	≤ 2.4 nm	≤ 2.4 nm
Focus control**	≤ 60 nm	≤ 60 nm

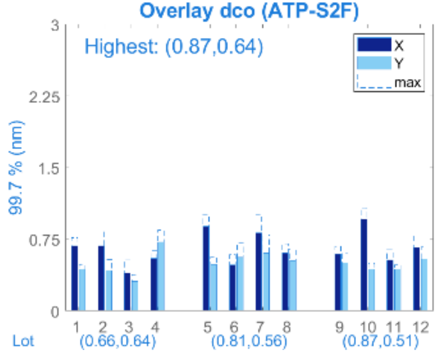
ATP test: 26x33mm², 96 fields, 20mJ/cm²

World class overlay performance now at 170wph on NXE:3400C systems

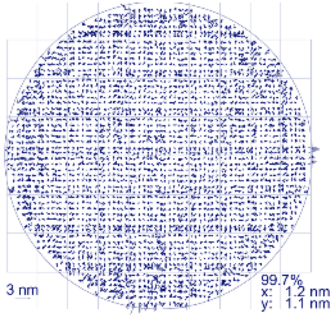
Overlay well in spec at 170 WPH throughput

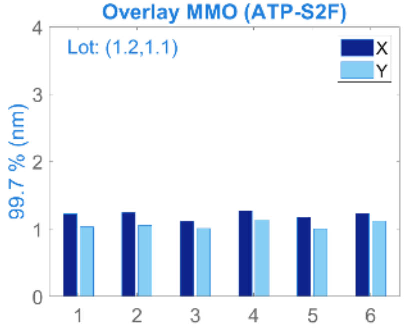
DCO





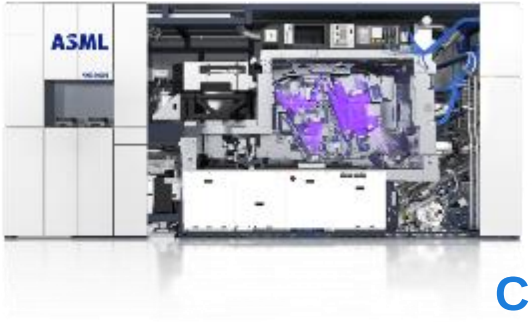
MMO





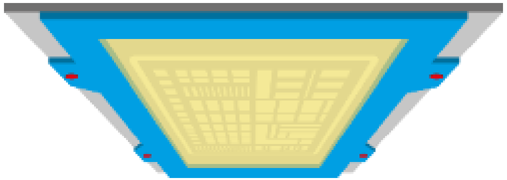
EUV Reticle frontside protection options

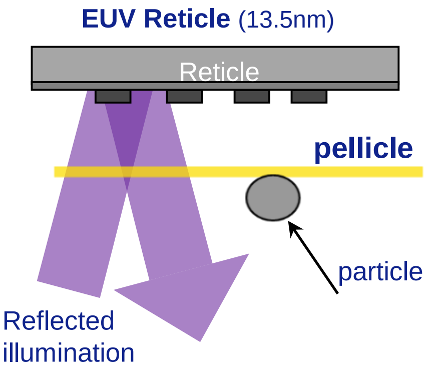
Reticle



Clean system
(without pellicle)

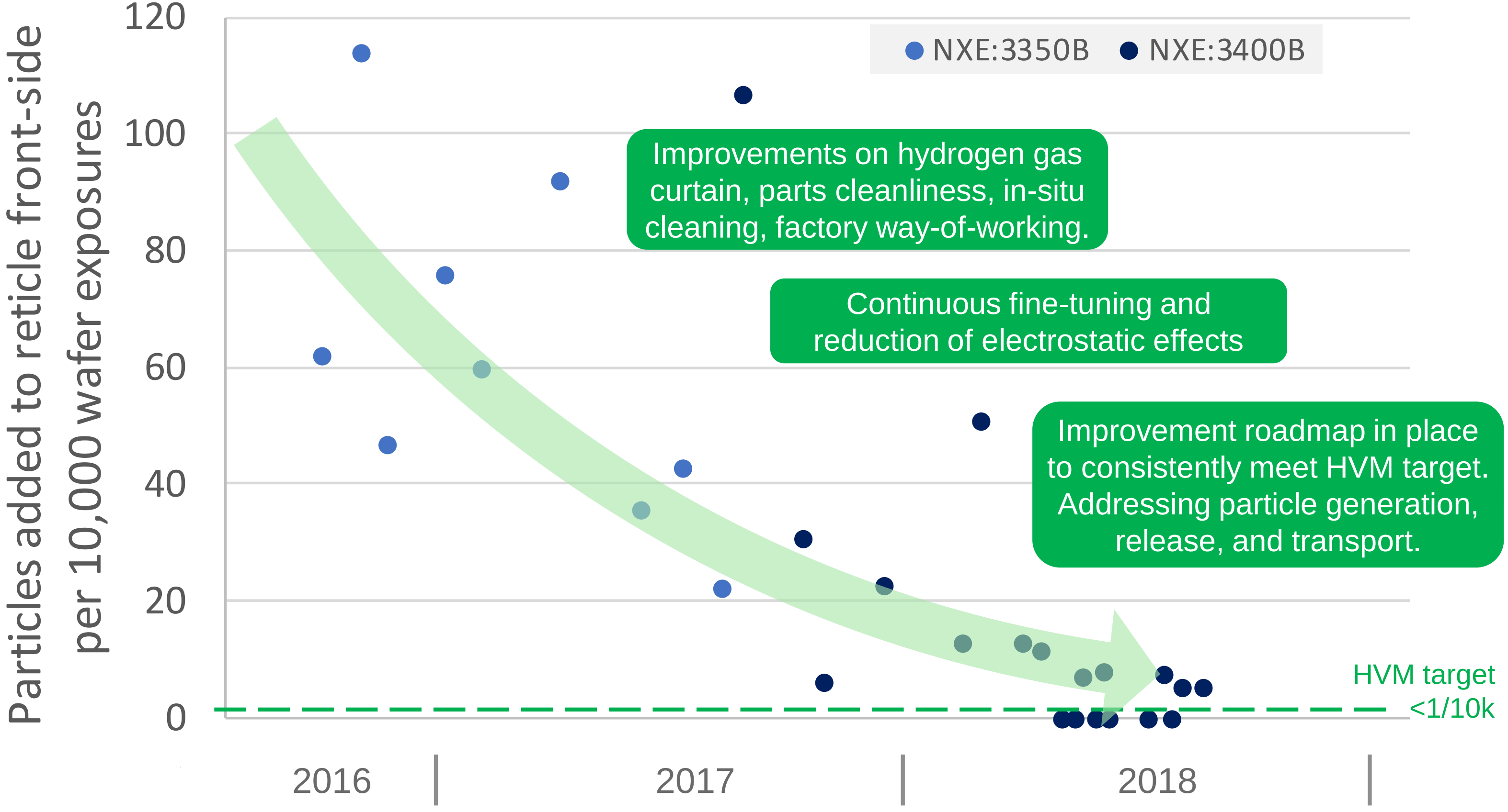
Reticle with pellicle





Clean Scanner

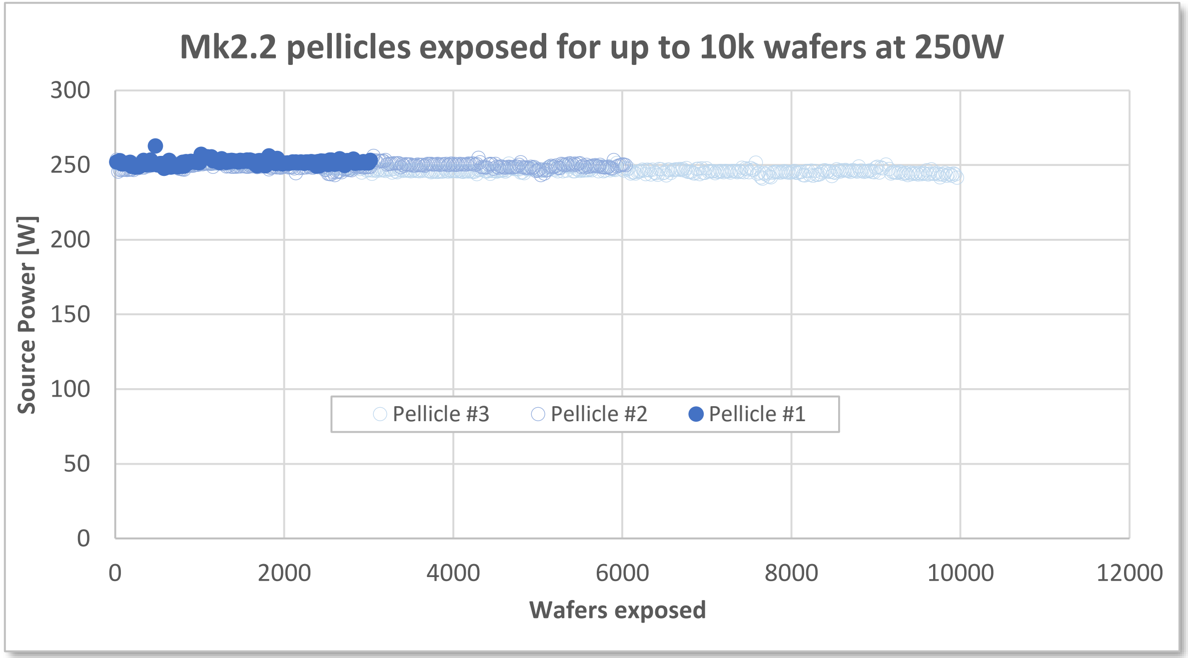
Reticle front-side defectivity ~1/10k

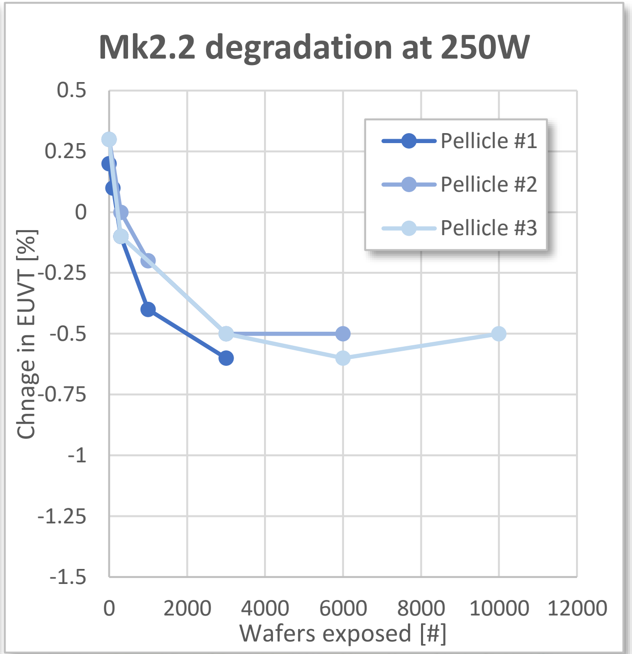


Each data point represents between 1,000 and 10,000 wafer exposures in ASML factory or at a customer

Pellicles robust to at least 10k wafers at 250W

No measurable degradation after 3k





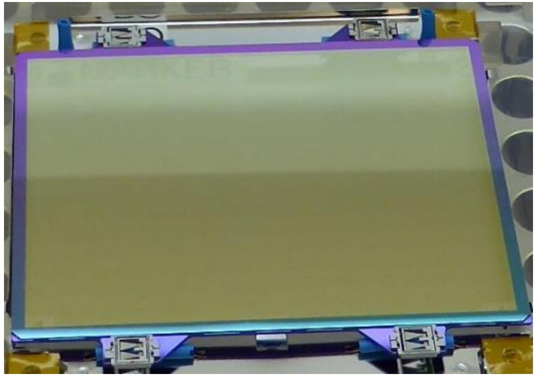
NXE:3400B @ 250W, 96 fields per wafer, 50mJ/cm2 sensor based, 35mJ/cm2 in resist
Pellicle #1 0-3k wafers, Pellicle #2 0-6k wafers, Pellicle #3 0-10k wafers, all latest version Mk2.2.

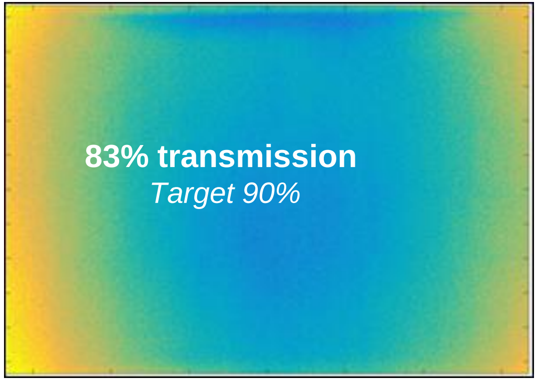
Pellicle #3 pre/post EUVT delta at 300, 3k, 6k and 10k wafers

EUV pellicle industrialization

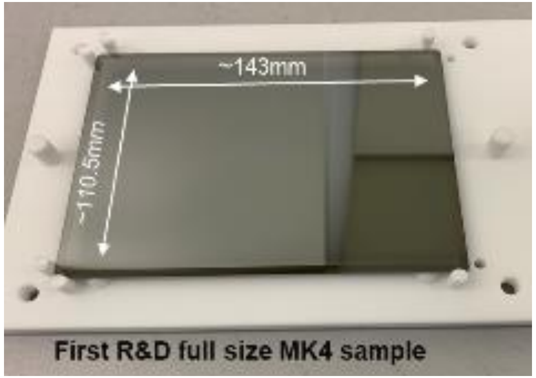
first 88% transmissive pellicle film available mid 2020

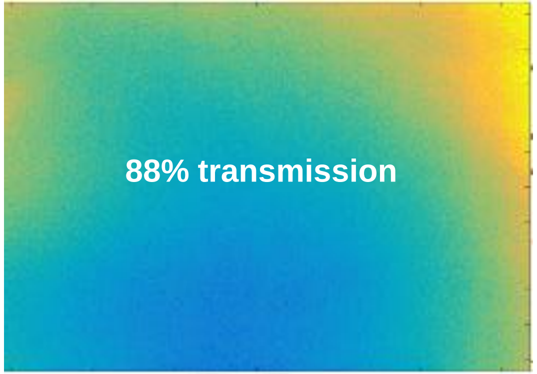
Pellicle Film as of 2018
EUV Transmission at 83%





Next generation Pellicle
EUV Transmission at 88%

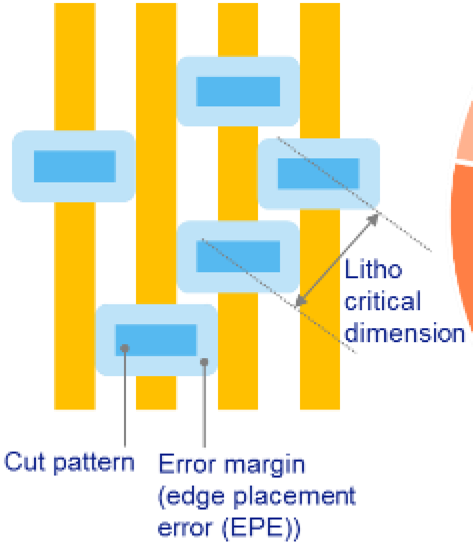




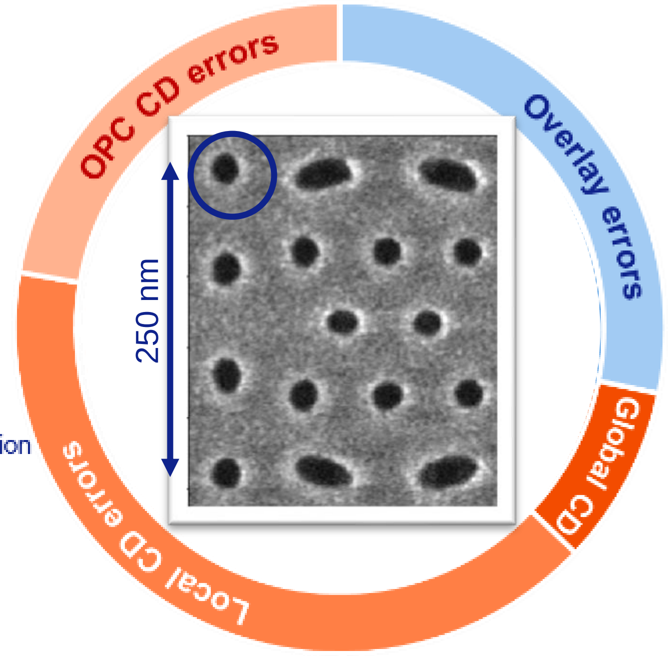
Scaling drives multiple patterning performance

Driven by Edge Placement Error and increasing local CD and placement

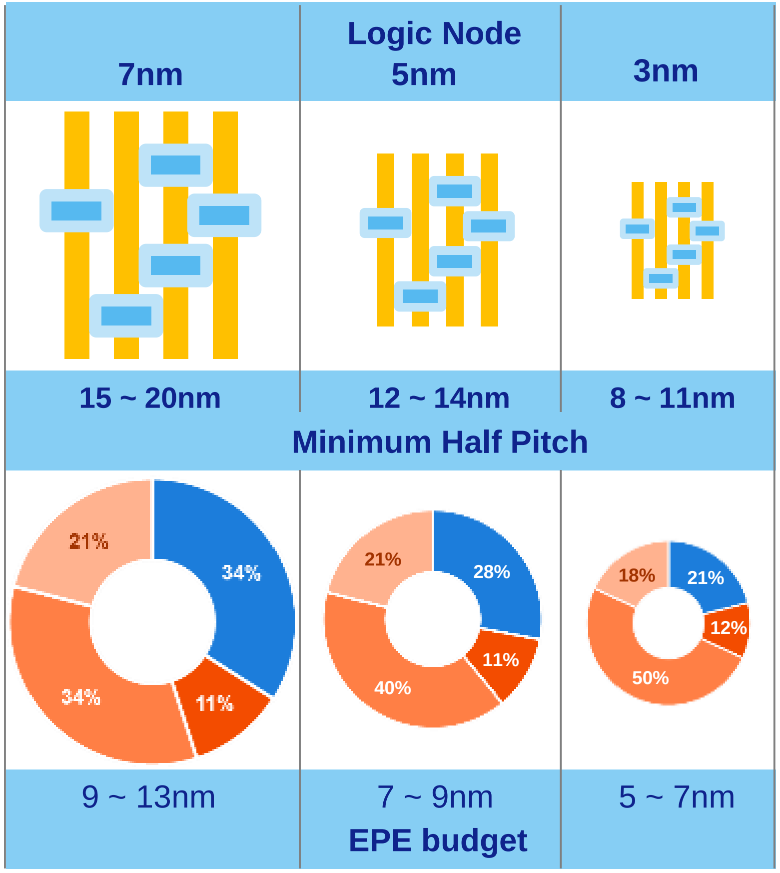
Typical Logic Pattern



Typical Logic EPE budget



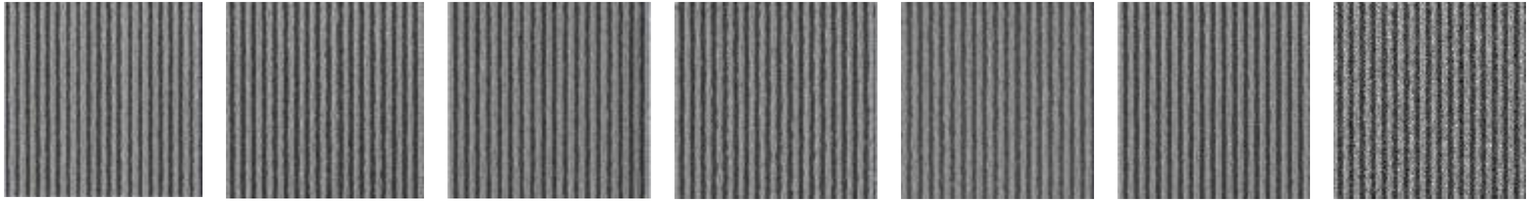
Edge placement error (EPE): combined error of overlay and CD uniformity (global CDU, local stochastic and OPC error)



CD: Critical Dimension, OPC: Mask Optical Proximity Correction

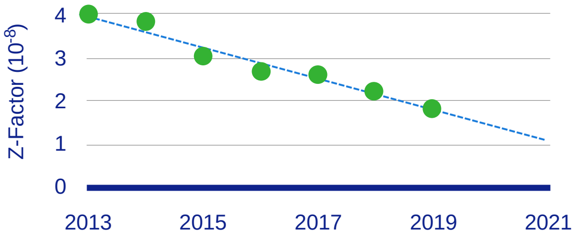
Resist improved more than 2x in the last 6 years

Improved Line Width Roughness (LWR) and dose as measured by Z-factor*



	2013	2014	2015	2016	2017	2018	2019
Dose	50mJ	58mJ	42mJ	23mJ	21mJ	38 mJ	37mJ
LWR	4.4nm	4.0nm	4.2nm	5.3nm	5.5nm	3.8	3.5
Z-factor	4.0	3.8	3.0	2.6	2.6	2.2	1.9

16nm DL horizontal; Dipole90Y



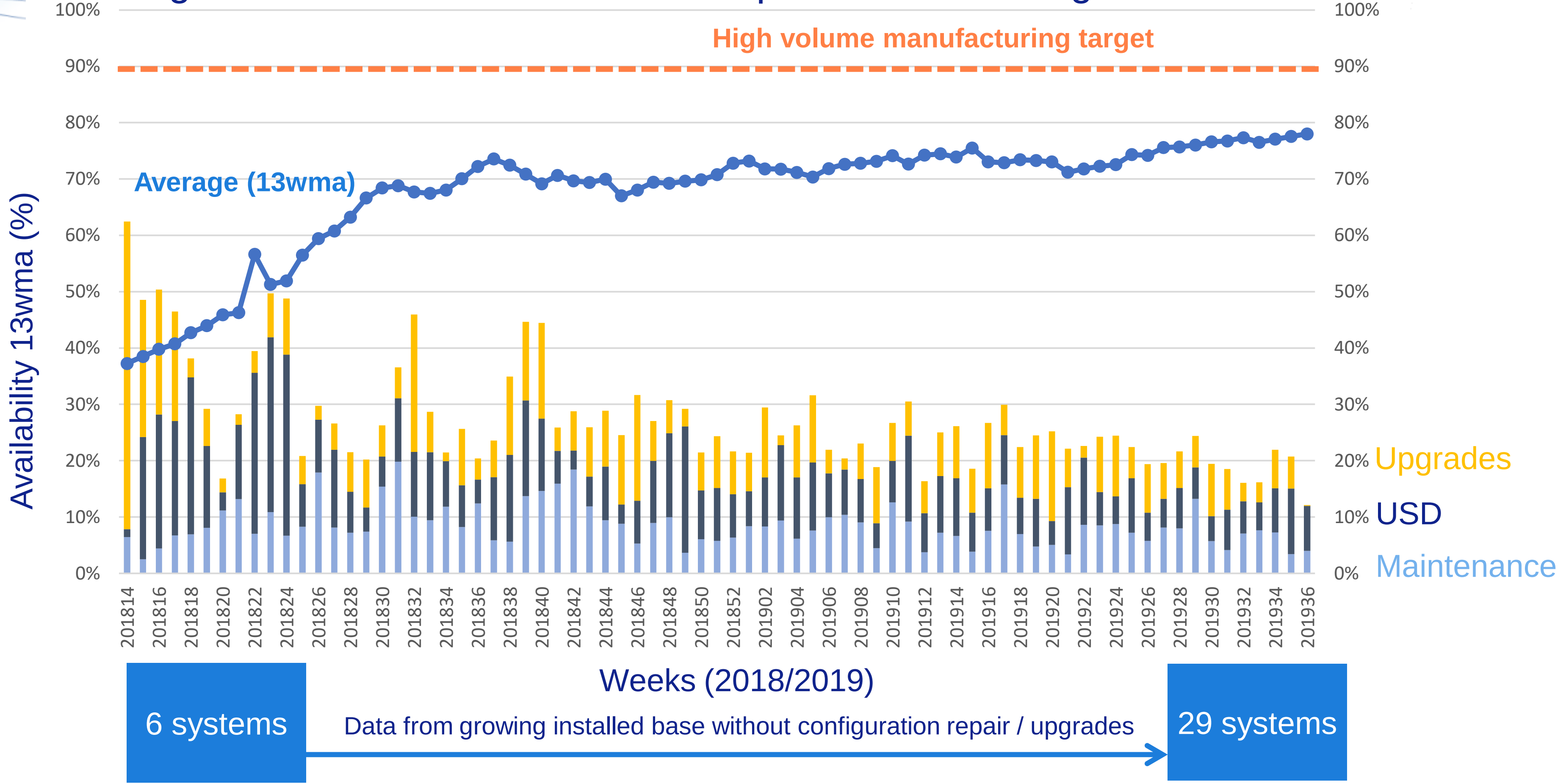
***Z-factor** = Res^3 x LWR^2 x Dose

Source: ‘Progress in EUV resists towards high-NA EUV lithography’, Xiaolong Wang et al. (PSI), SPIE 2019

Performance of NXE:3400B in the Field

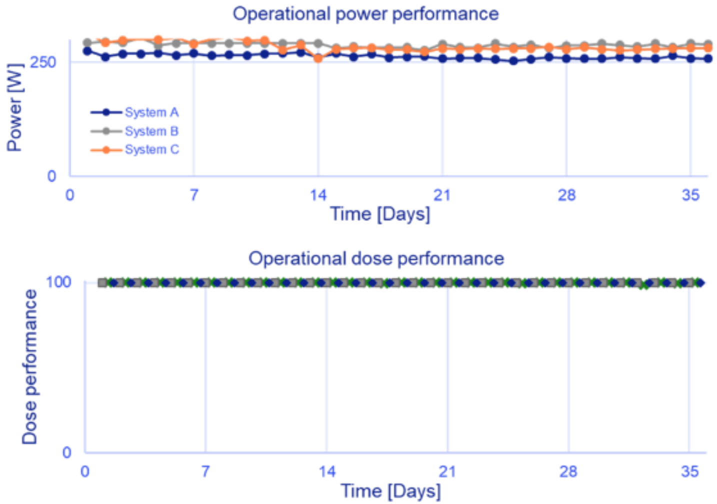
NXE:3400B's availability substantially improved in 2018

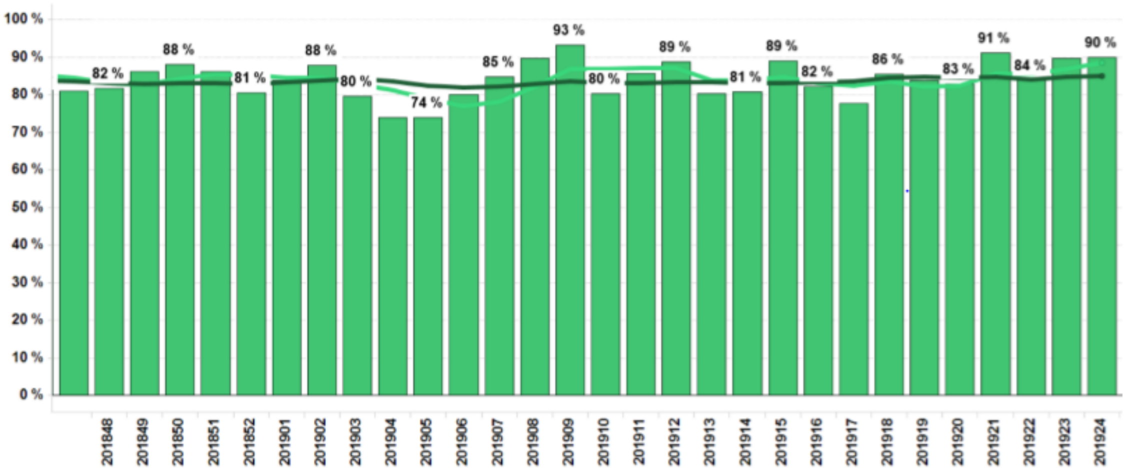
Growing installed base needs further improvements for high volume



250W EUV power, Source availability >85%

Customers have started HVM





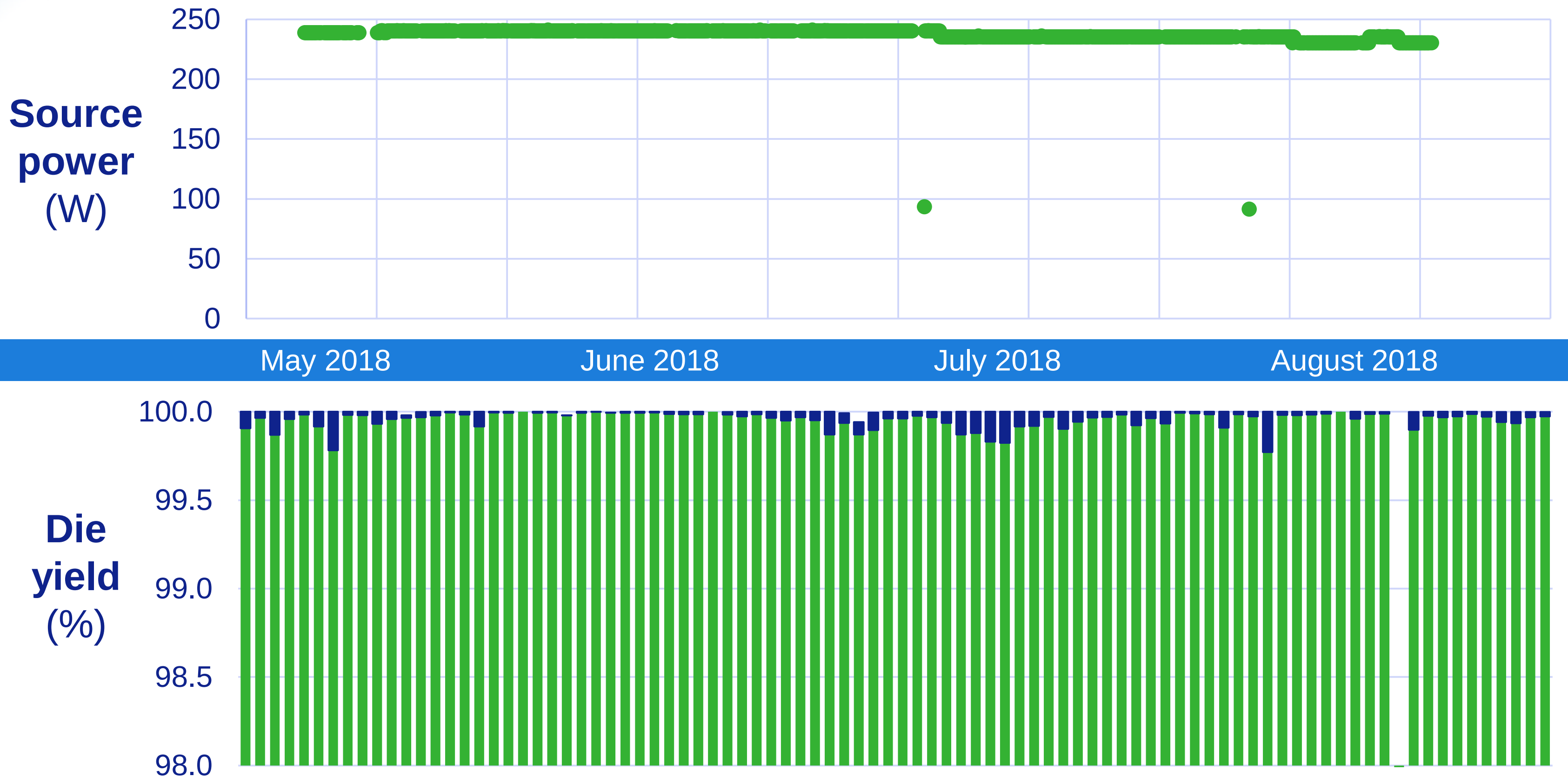
- (left) 250W EUV power meeting dose stability requirements
- (right) >85% Source Availability over 13 weeks at customers, without configuration repair / upgrades

EUV Source operation at 250W

with 99.90% fields meeting dose spec

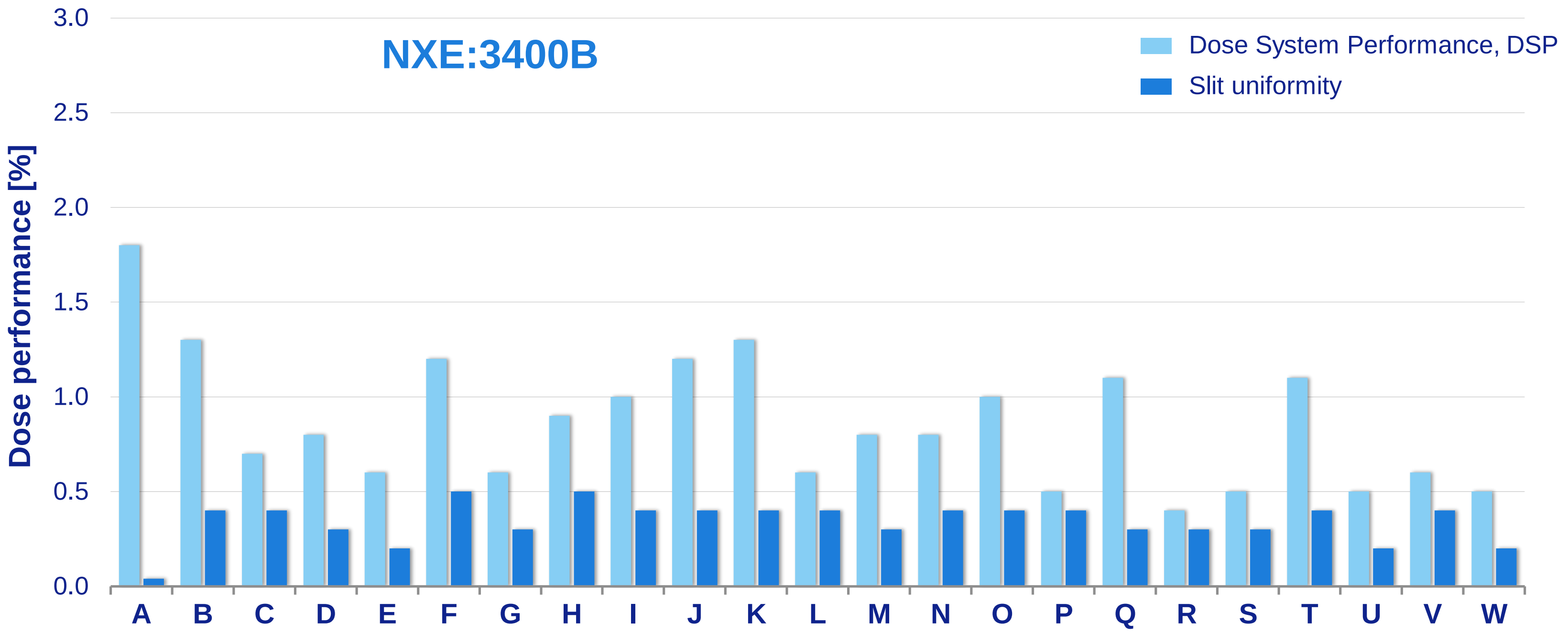
ASML

Public



Dose Performance and Slit uniformity show stable results

Supporting requirements for 5 nm node CD control



NXE and EXE to drive scaling beyond the next decade

Cost-effective scaling through accelerated innovation and lithography simplification

ASML

Public
Slide 24




EUV

0.33 NA | 13nm
Matched Machine Overlay
Throughput

NXE:3350B	NXE:3400B	Overlay	TPut[1]	NXE:3400C	NXE:Next
4.0nm	3.0nm	2.5nm		2.5nm	<1.5nm
125wph	125wph		155wph	170wph	≥185wph

NXE will be extended to provide state-of-the-art overlay and node-to-node productivity improvements

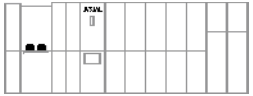
2016 2017 2018 2019 2020 2021 2022 2023 …2025

EUV

0.55 NA | 8nm
Matched Machine Overlay
Throughput

EXE:5000
1.7nm
185wph

EXE to be introduced at the 3 nm node for affordable scaling beyond the next decade



[1] Tput: Throughput upgrade (wph)

TWINSCAN EUV Product Roadmap

Supporting customer roadmaps well into the next decade

EUV scanner

EUV 0.33 NA

EUV 0.33 platform will be extended to provide state of the art overlay and node to node productivity improvements

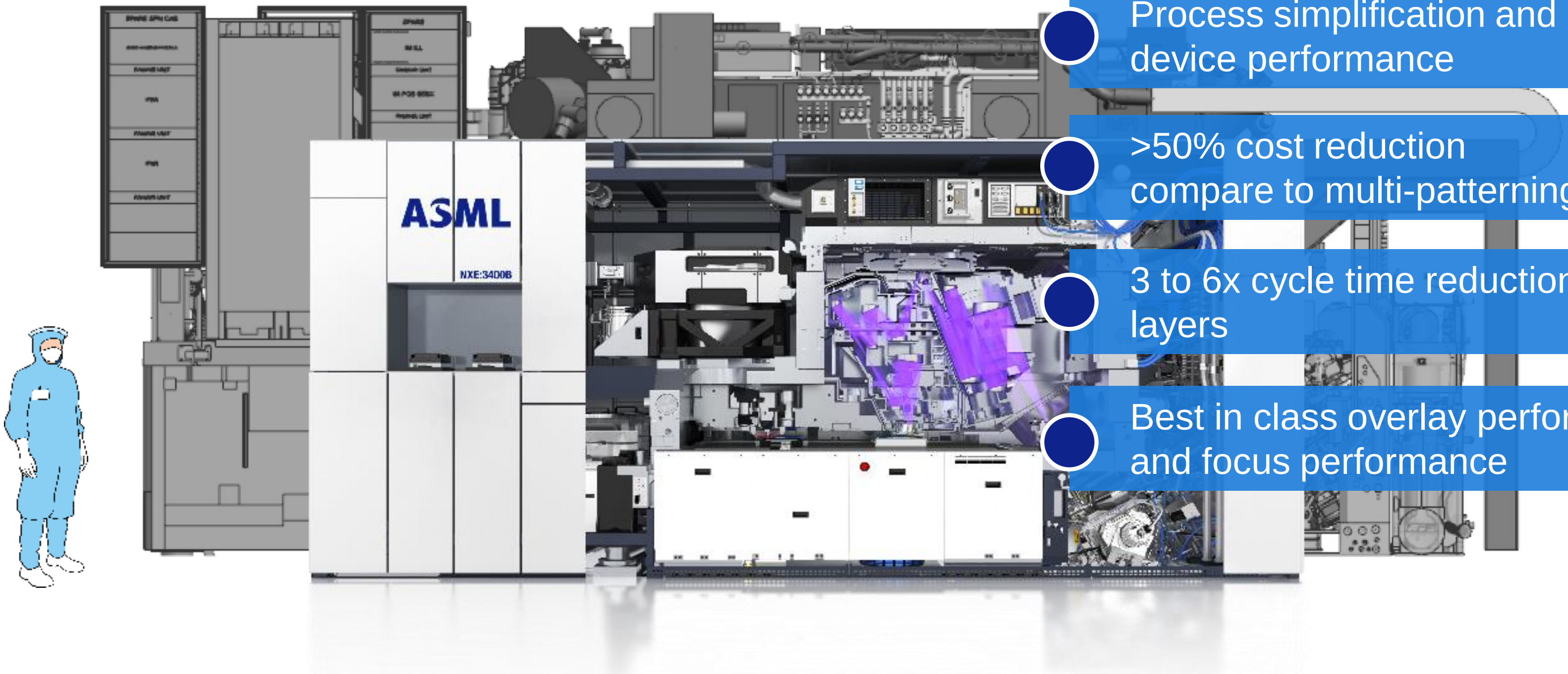
	2016	2017	2018	2019	2020	2021	2022	2023	…2025
EUV 0.33 NA 13nm	**NXE:3350B** 4.0 | 125wph	**NXE:3400B** 3.0nm | 125wph	**OVL** 2.5nm	**TPut** 155	**NXE:3400C** 2.5nm | 170wph		**NXE Next** <1.5nm | ≥ 185wph		
0.55 NA 8nm									**EXE:5000** 1.7nm | 185wph

EUV source

- **S2:** source power to 125W
- **S3 Intro:** source power to 200W
- **S3 (Now)** Up to 250 W (at 155 wph) + gas, water, electrical simplification
- **S3 for NXE:3400C** >250 W, Modular vessel, availability to ~95%
- **EUV Source Next** Power scaling for throughput, dose and stability improvements, further step in availability. Source horizontal to support EXE5000.

Deliver continuation of shrink roadmap: **EXE platform**

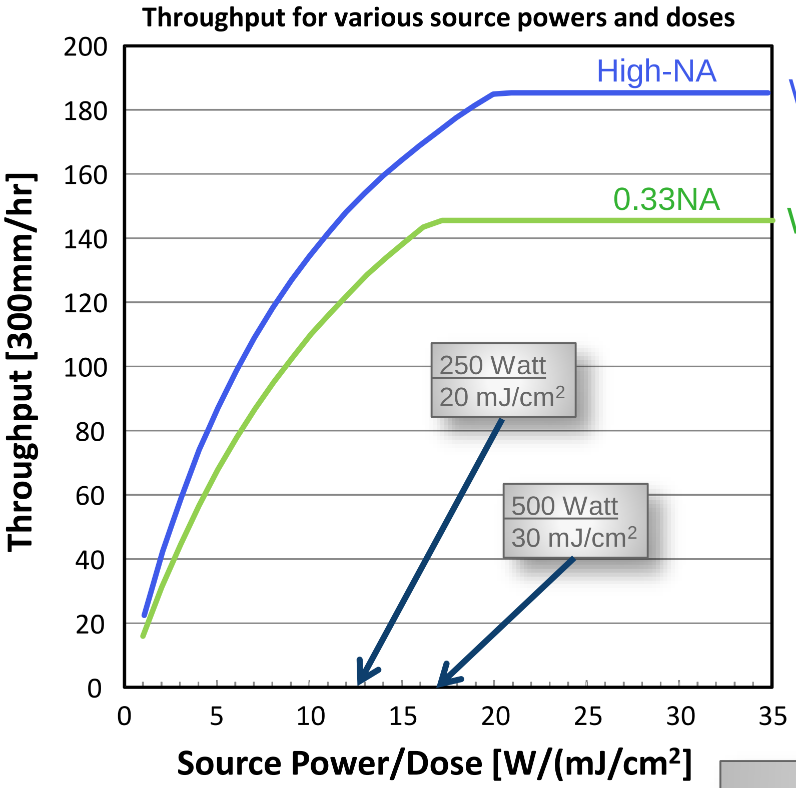
In the same way that 0.33NA enables 7nm and 5nm Logic, **0.55NA** EUV will be needed to enable 3nm Logic

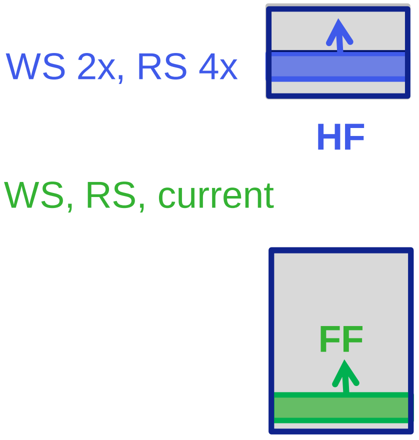


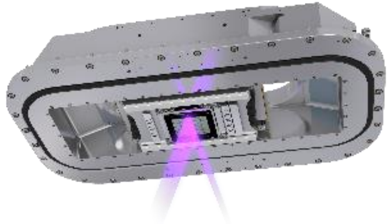
- Process simplification and improved device performance
- >50% cost reduction compare to multi-patterning schemes
- 3 to 6x cycle time reduction for critical layers
- Best in class overlay performance and focus performance

High-NA Field and Mask Size productivity

Throughput >185wph with Half Fields







Acceleration of mask stage ~4x

Acceleration of wafer stage ~2x

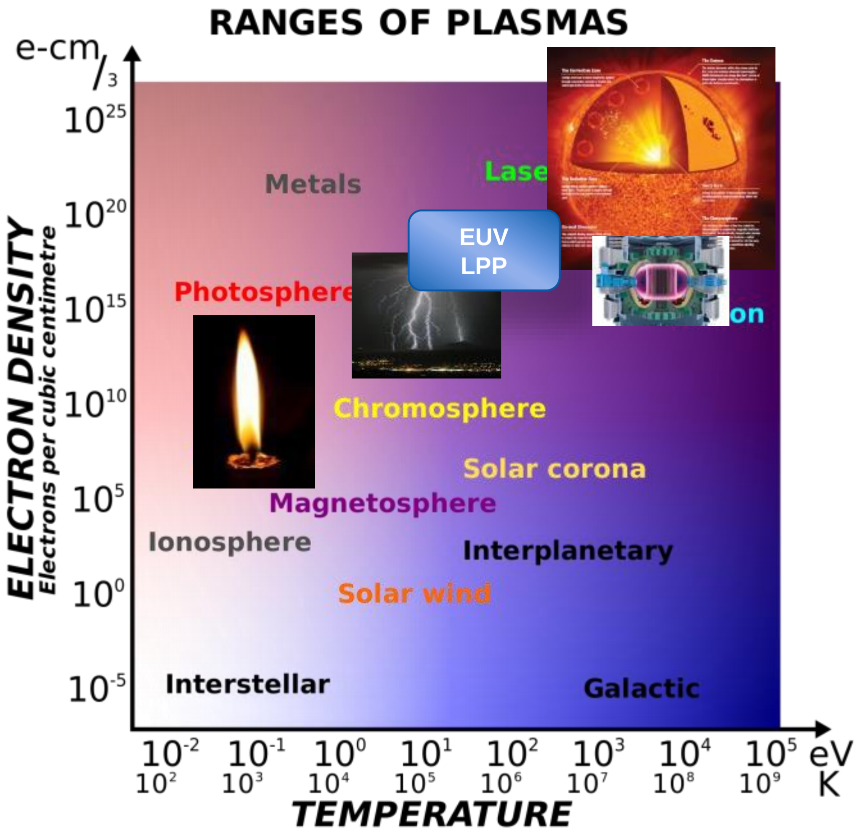
Fast stages enable high throughput despite half fields

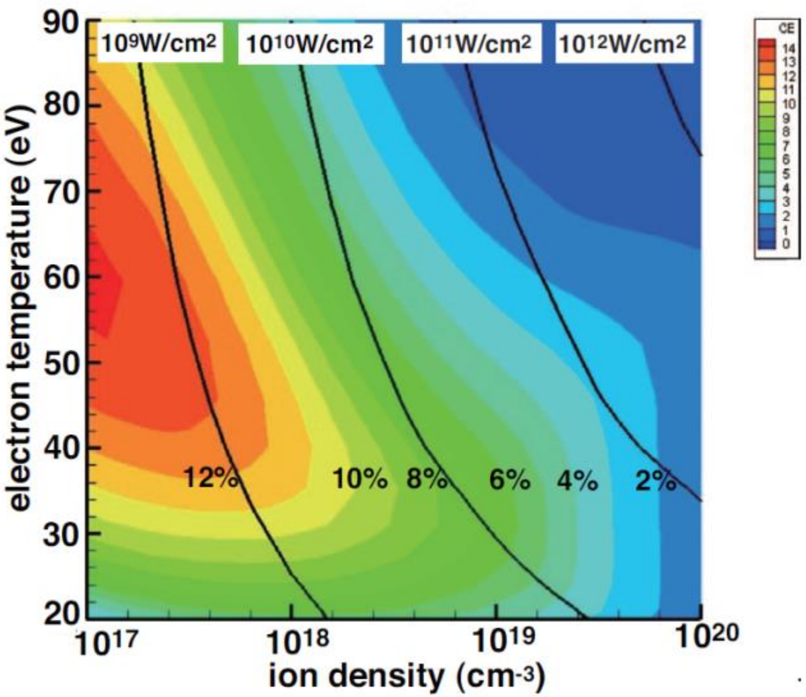
EUV: Principles of Generation

Laser Produced Plasma Density and Temperature

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

Temperature ~ 30 -100 eV

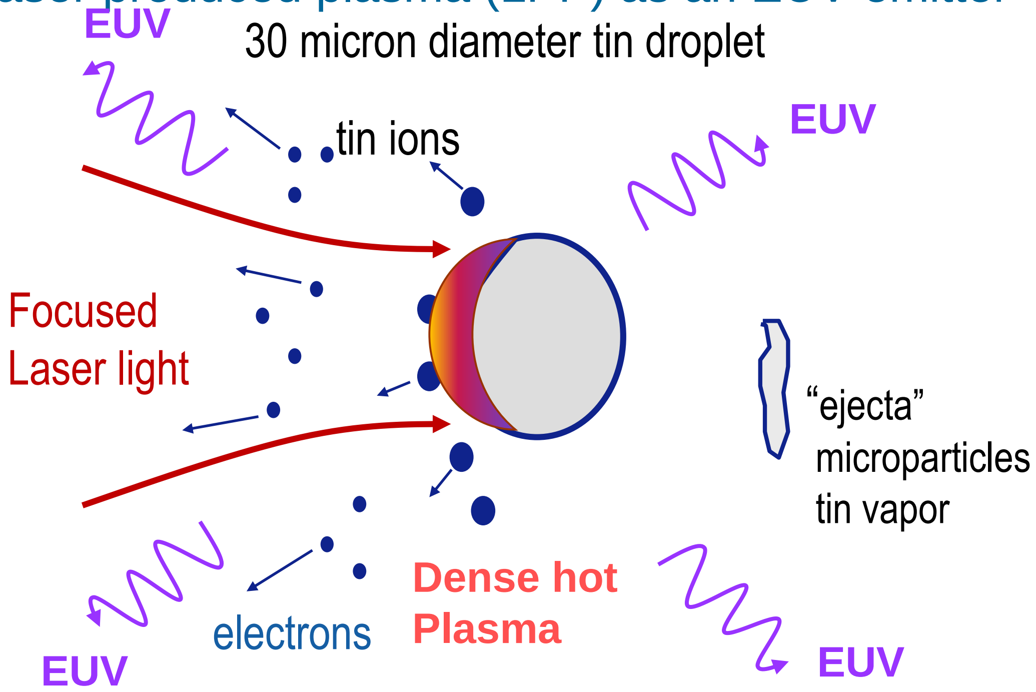




Nishihara et al. (2008)

Fundamentals: EUV Generation in LPP

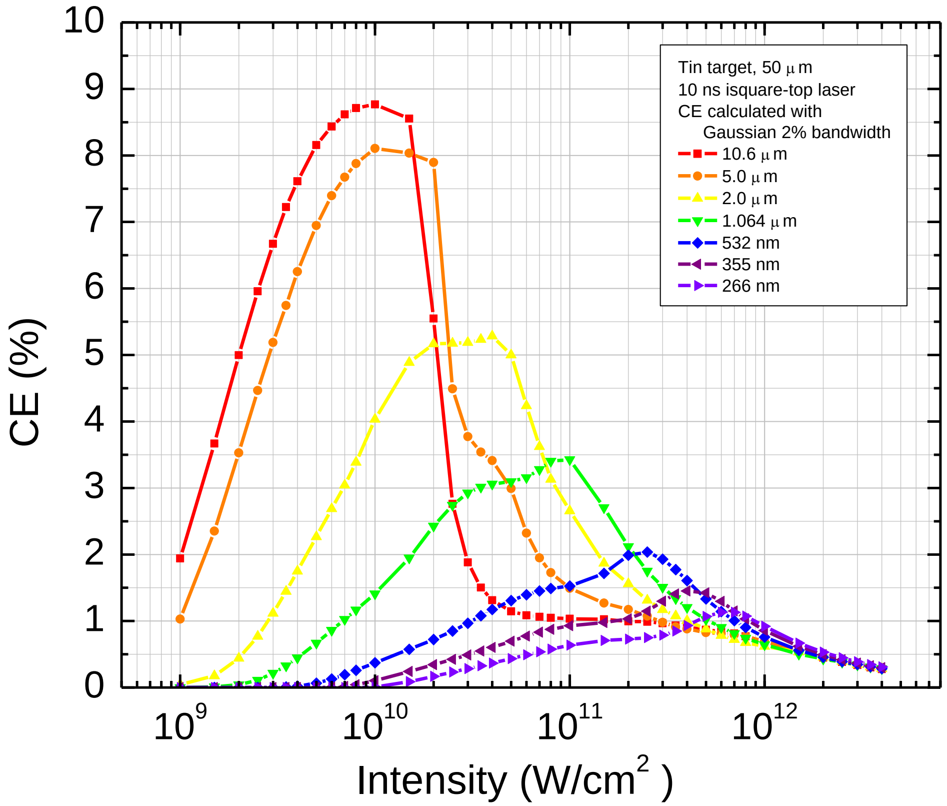
Laser produced plasma (LPP) as an EUV emitter



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



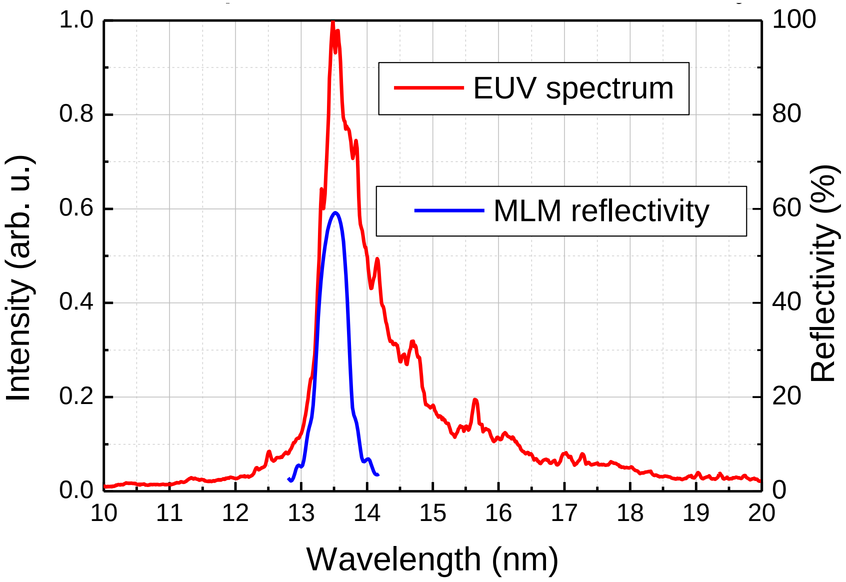
Simulation Assumptions:

- 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

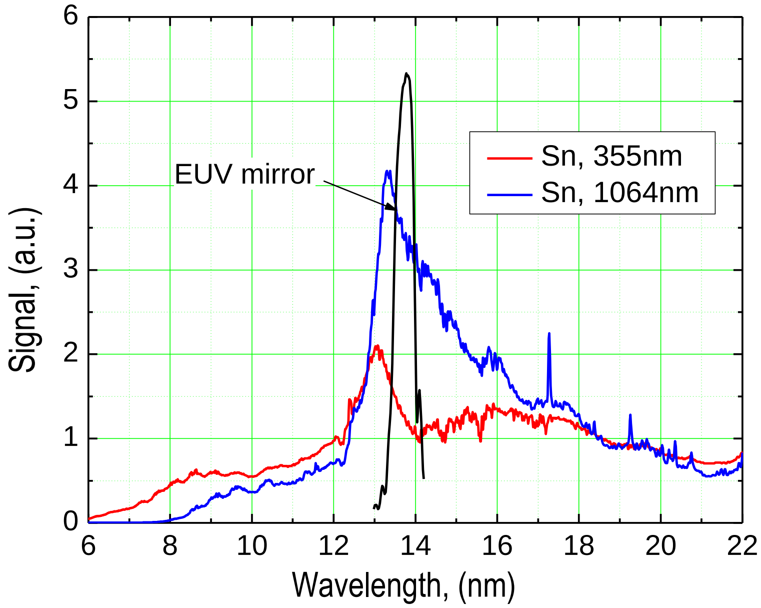
EUV CE defined into 2% bandwidth, 2π sr solid angle

EUV Spectra of Laser Produced Sn Plasma

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

CYMER

	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

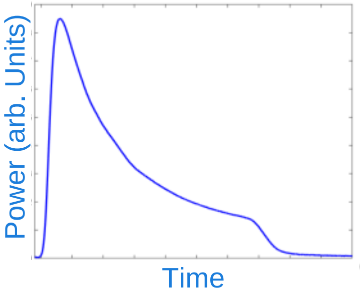
- Best high efficiency options of laser/target combinations for future HVM sources

CO_2 Laser with Sn target was selected for industrialization in 2006

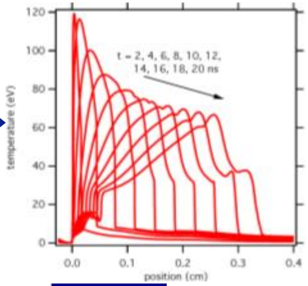
Plasma simulation capabilities

Main-pulse modeling using HYDRA

Main-pulse shape

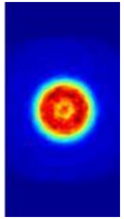


1D: real pulse shape

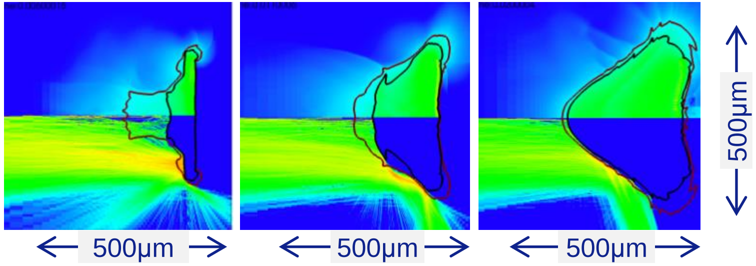


1D simulations are fast and useful for problems that require rapid feedback and less accuracy

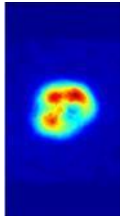
2D: + symmeterized beam profile

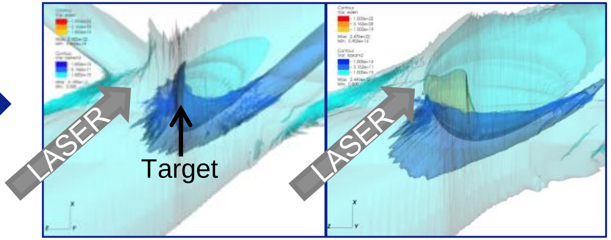


Electron density (top half) with laser light (bottom half)



3D: + real asymmetric profile





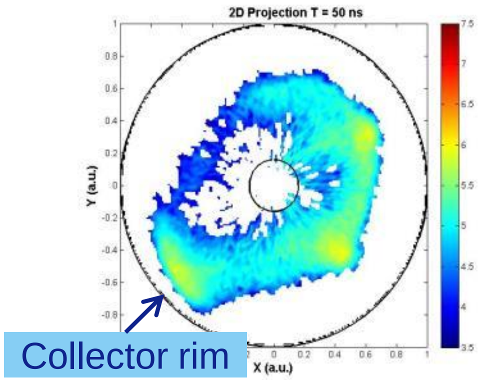
2D and 3D simulations are run for the full duration of the Main pulse. Results include temperature, electron density, spectral emission, etc.

Sn target using a real irradiance distribution

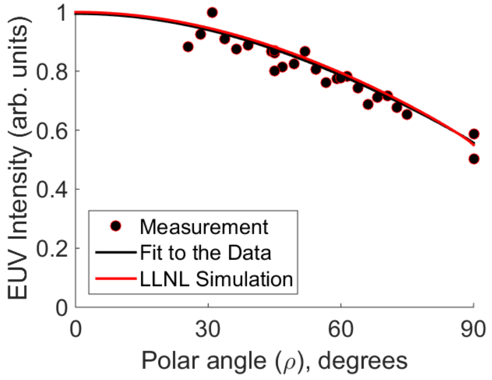
Simulation of the EUV source

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.

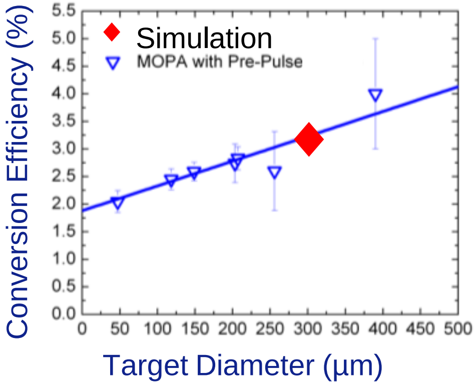
Reflected laser modeling



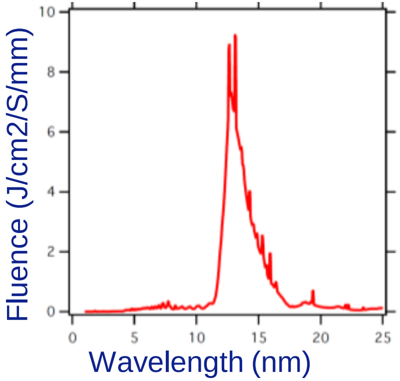
Emission anisotropy



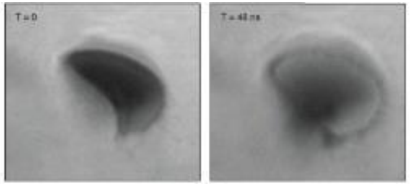
Conversion Efficiency



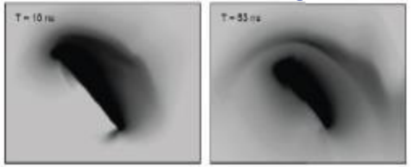
Simulated EUV spectra



Measured Shadowgrams

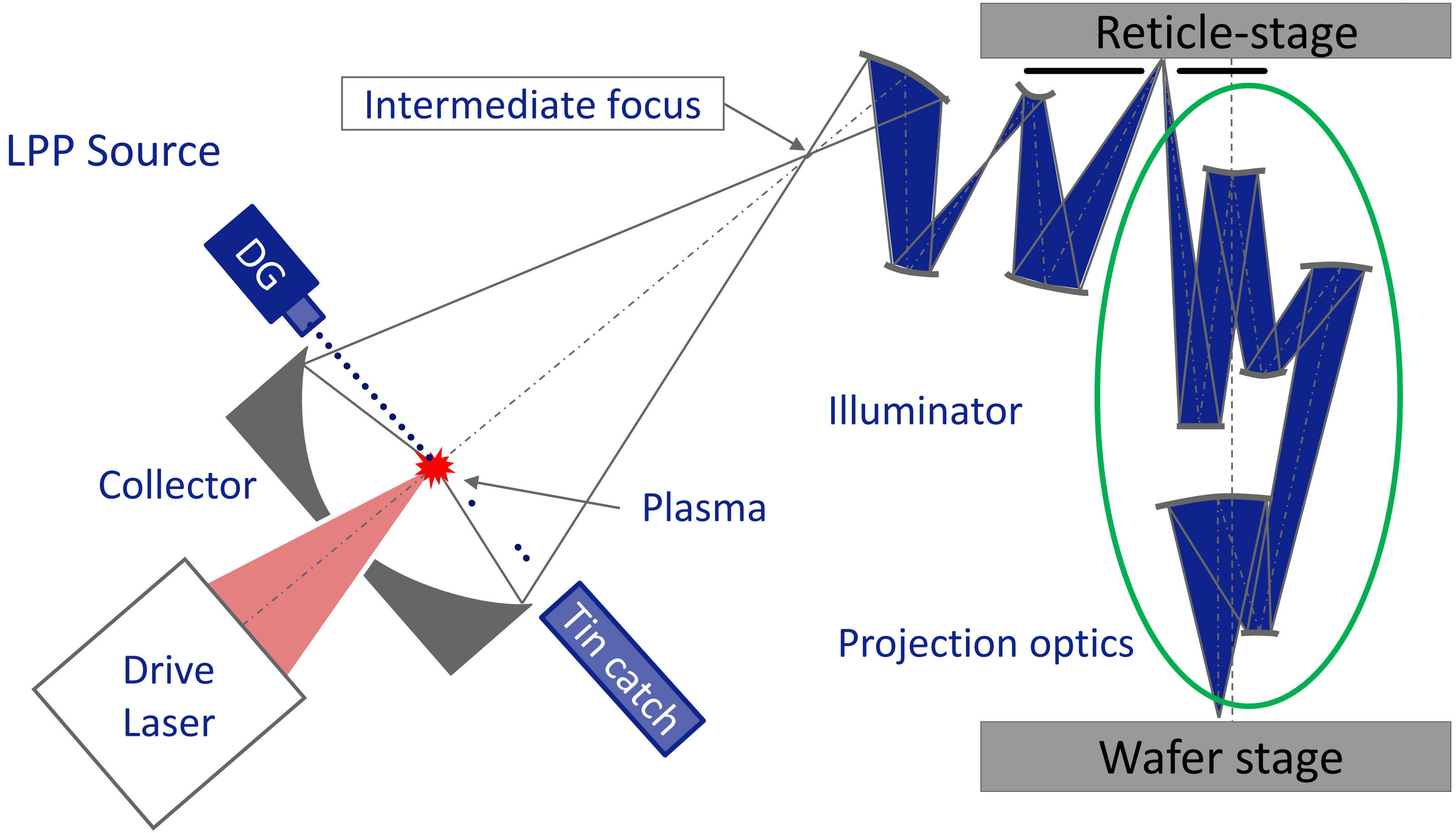


Simulated Shadowgrams



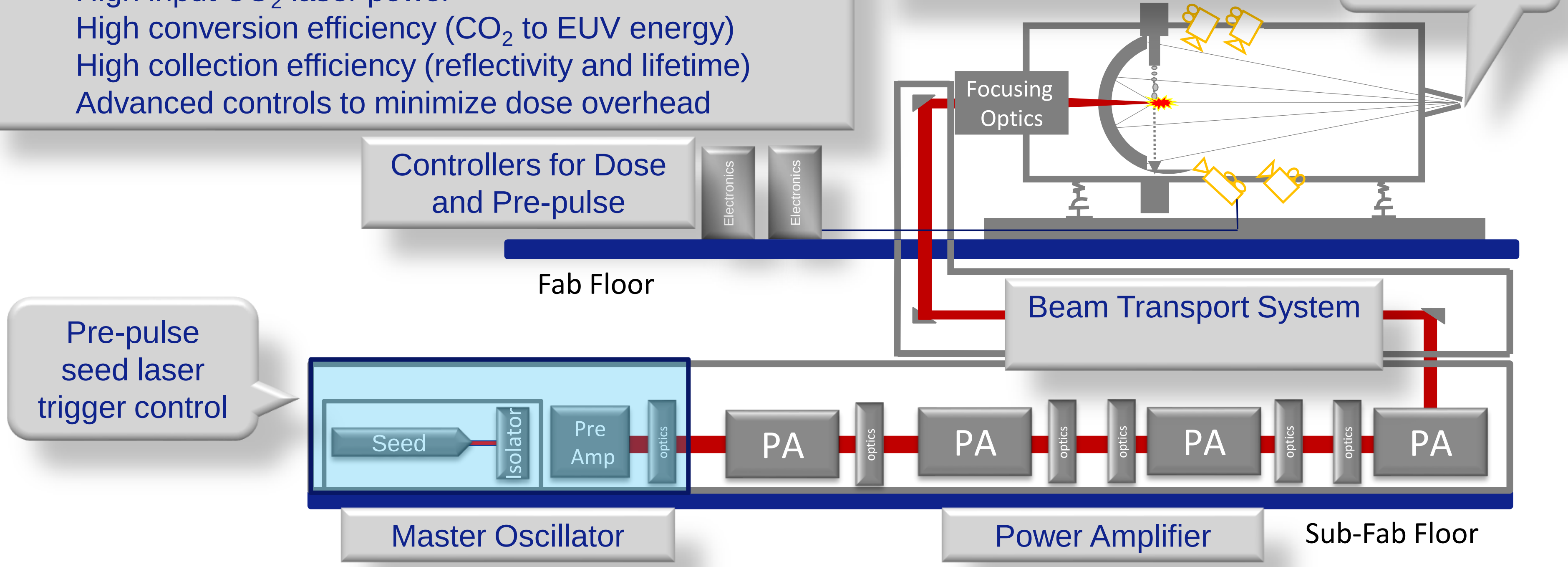
EUV Source: Architecture and Operation Principles

EUV Lithography System Schematic



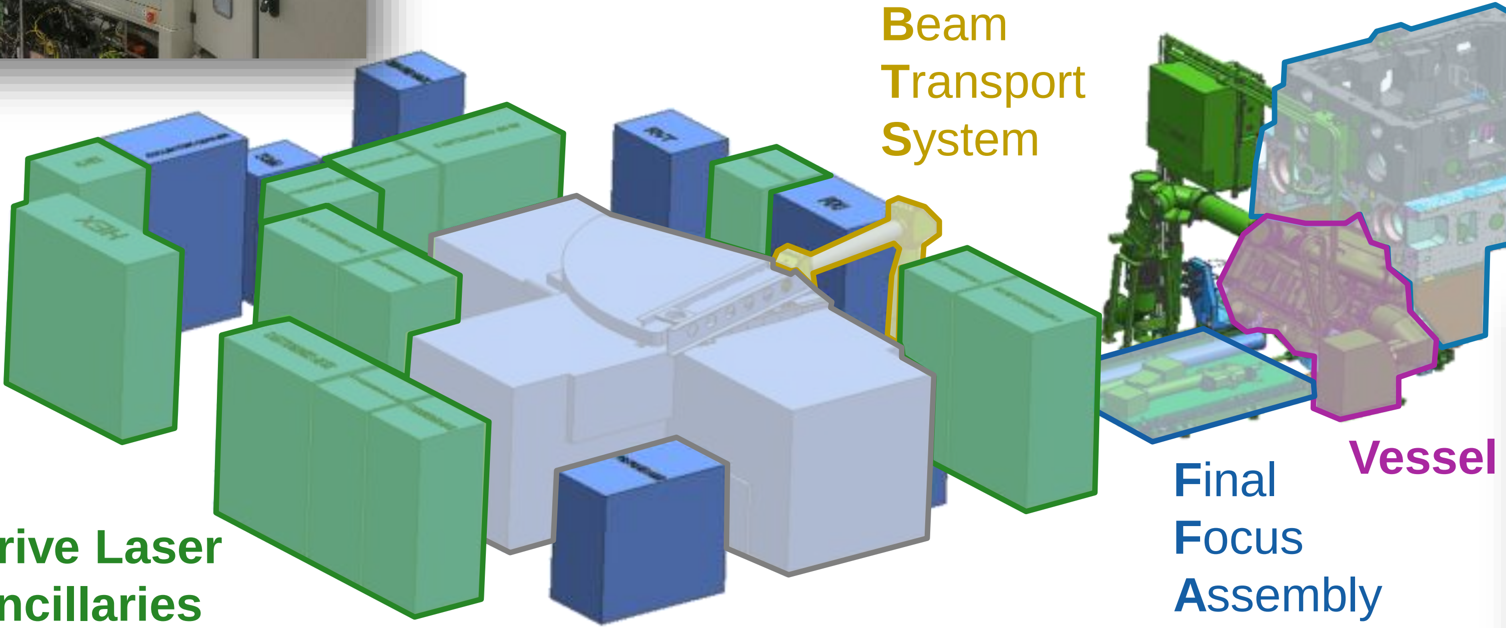
LPP: Master Oscillator Power Amplifier (MOPA) Pre-Pulse Source Architecture

- 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



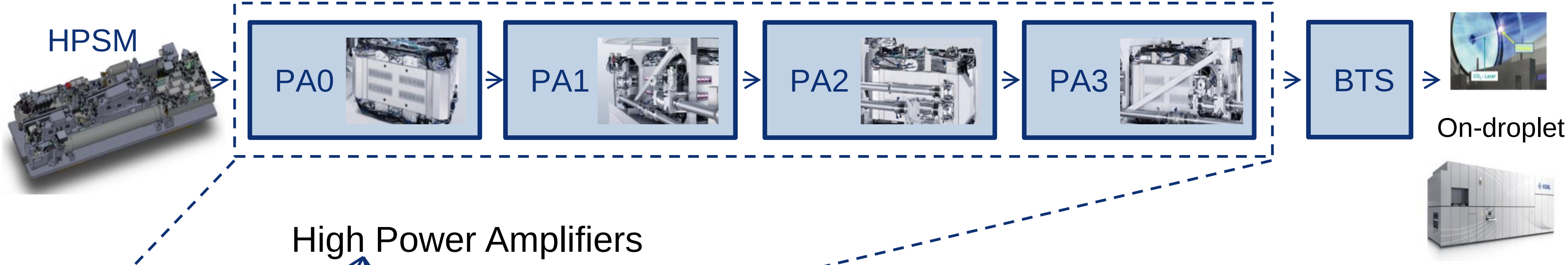
EUV power (source/scanner interface, [W]) ∝ **CO_2 power [W]** * **Conversion Efficiency** * **1 – Dose Overhead**

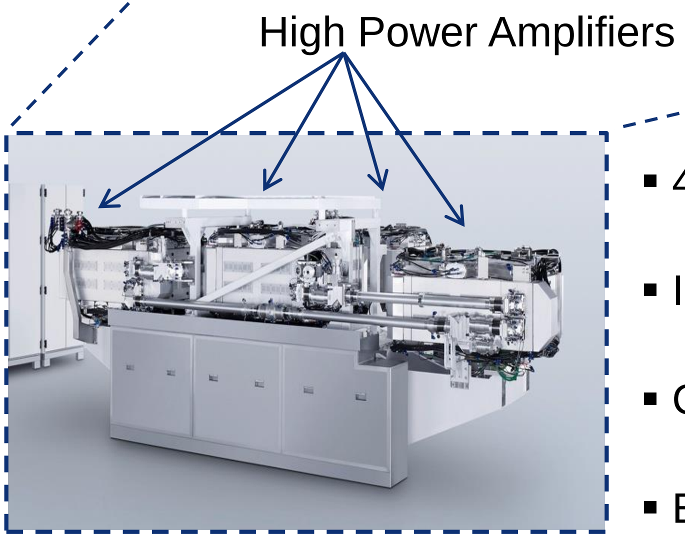
EUV System overview



Industrial high power CO_2 laser

High beam quality for gain extraction and EUV generation



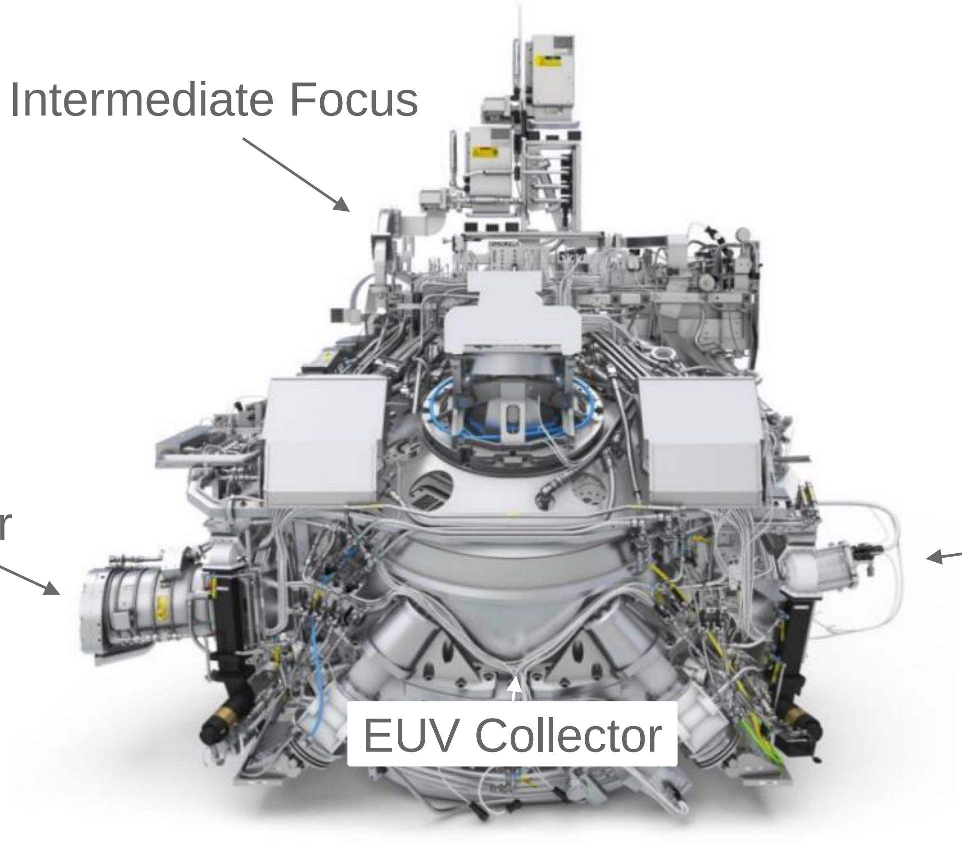


- 4 cascaded power amplifiers (PAs) in HPAC
- Individually optimized geometry and settings
- Connected by relay optics
- Extensive metrology between amplifiers & at DL exit

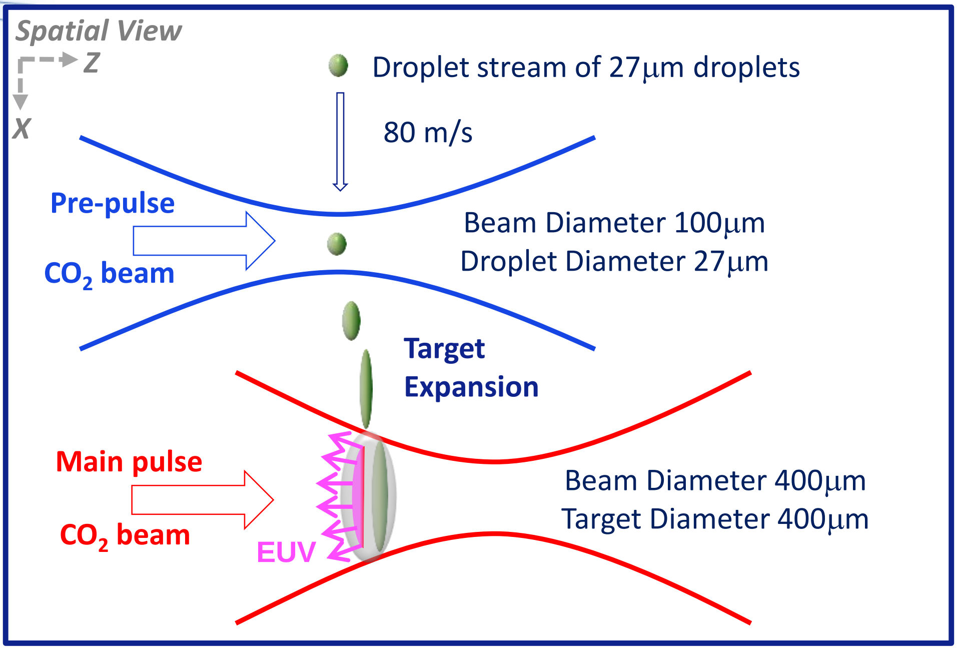
TRUMPF

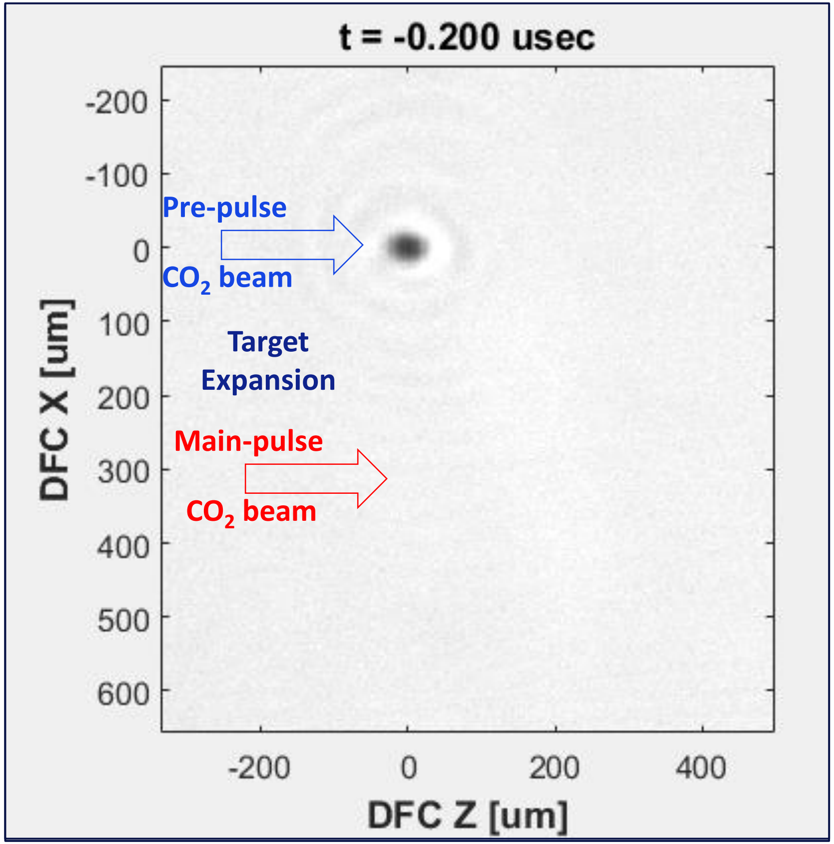
NXE:3XY0 EUV Source: Main modules

Populated vacuum vessel with tin droplet generator and collector



EUV Source: MOPA + Pre-Pulse Operation

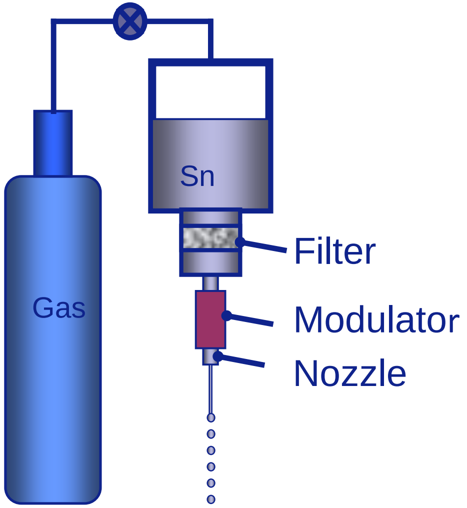




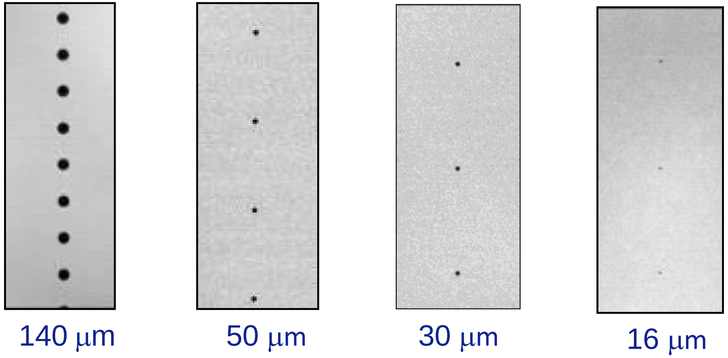
Droplet generation

Droplet Generator: principle of operation

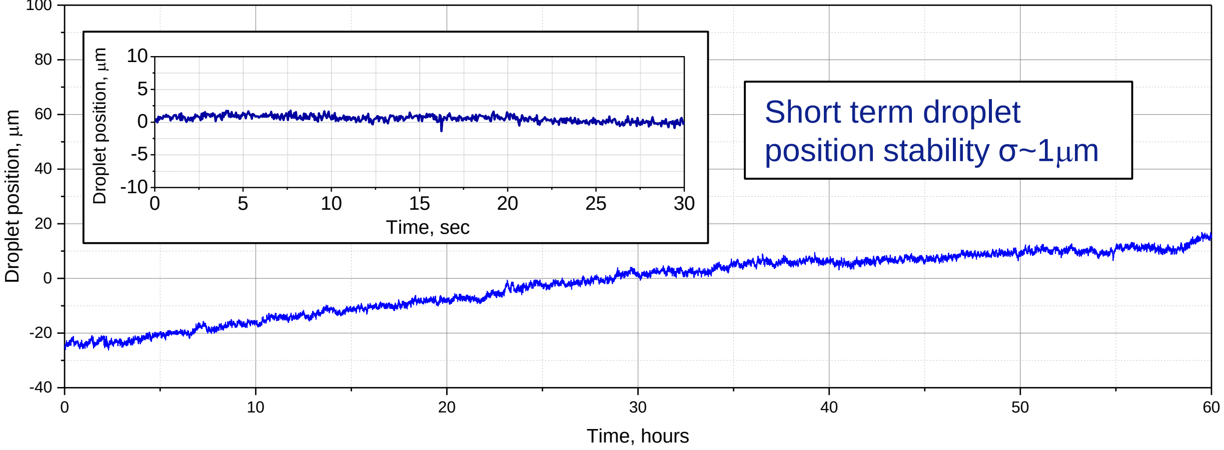
- Tin is loaded in a vessel & heated above melting point
- Pressure applied by an inert gas
- Tin flows through a filter prior to the nozzle
- Tin jet is modulated by mechanical vibrations



Droplets of different sizes can be generated

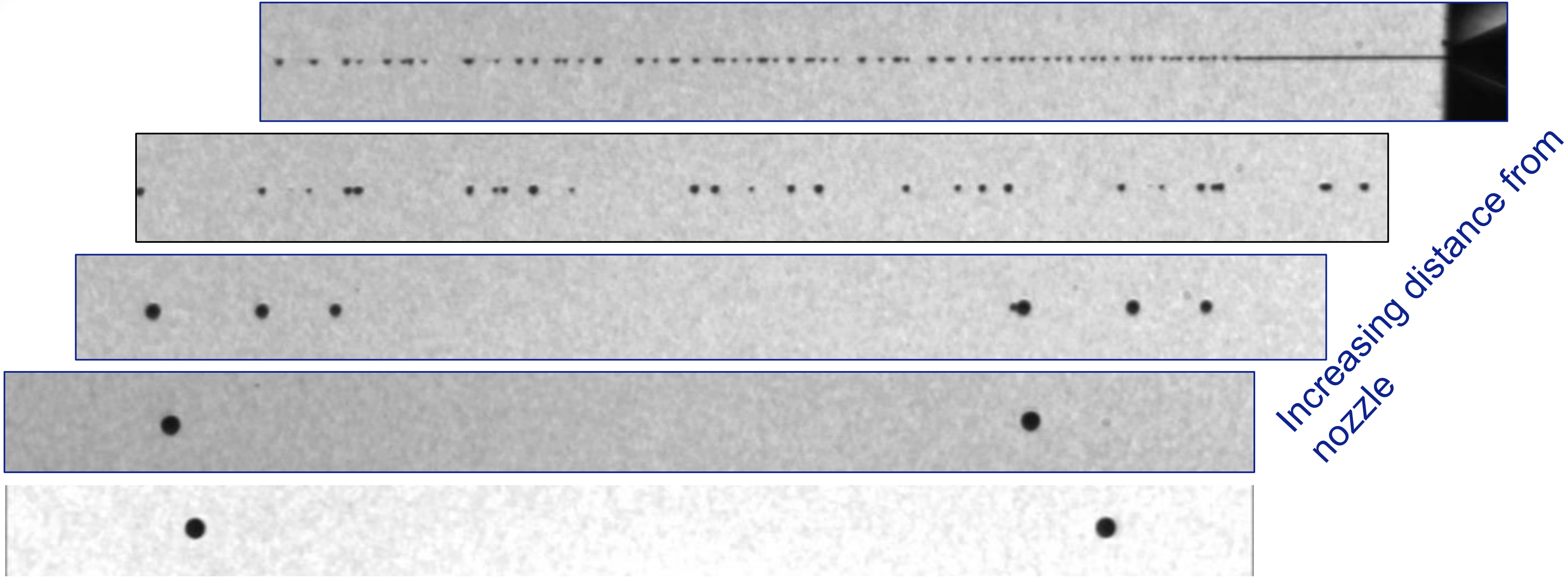


Droplet position stability, long and short term



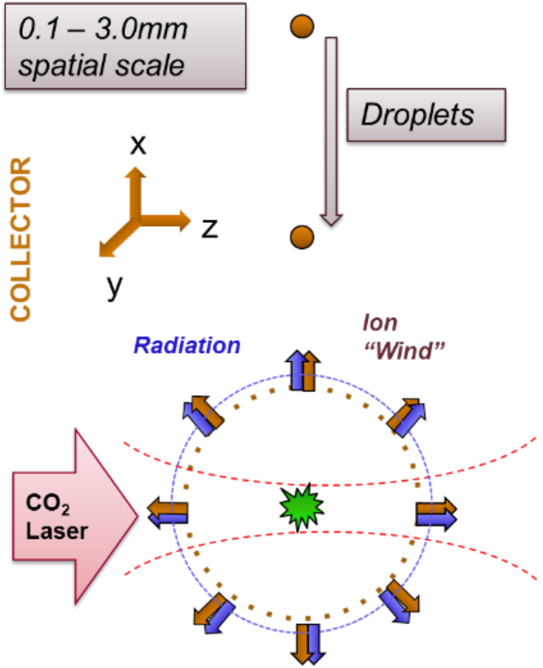
Droplet Generator: Principle of Operation

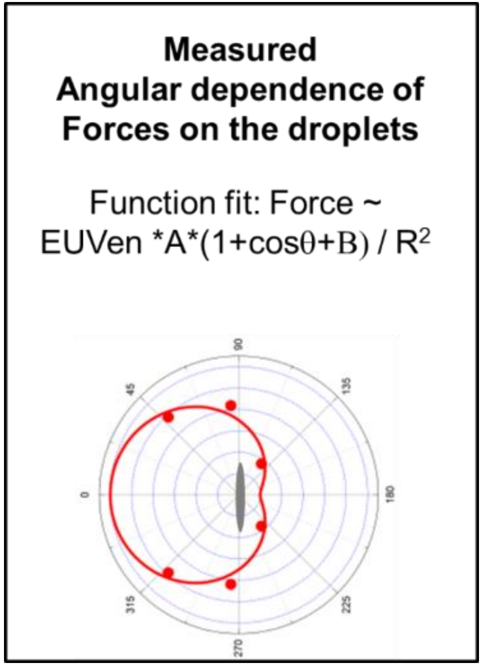
Large separation between the droplets by special modulation



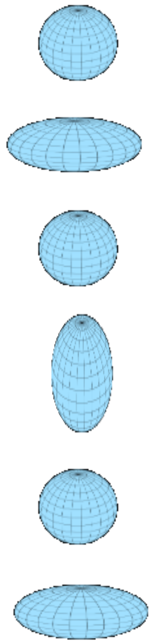
Multiple small droplets coalesce together to form larger droplets at larger separation distance

Forces on Droplets during EUV Generation





Droplet deformations induced by LPP of previous pulses

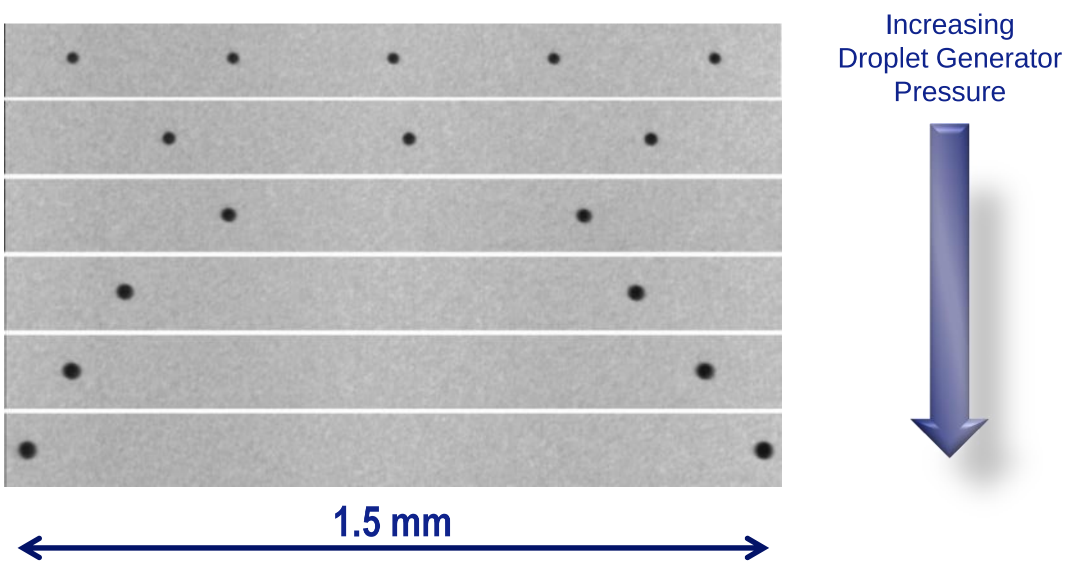


Lowest vibrational mode n=2

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

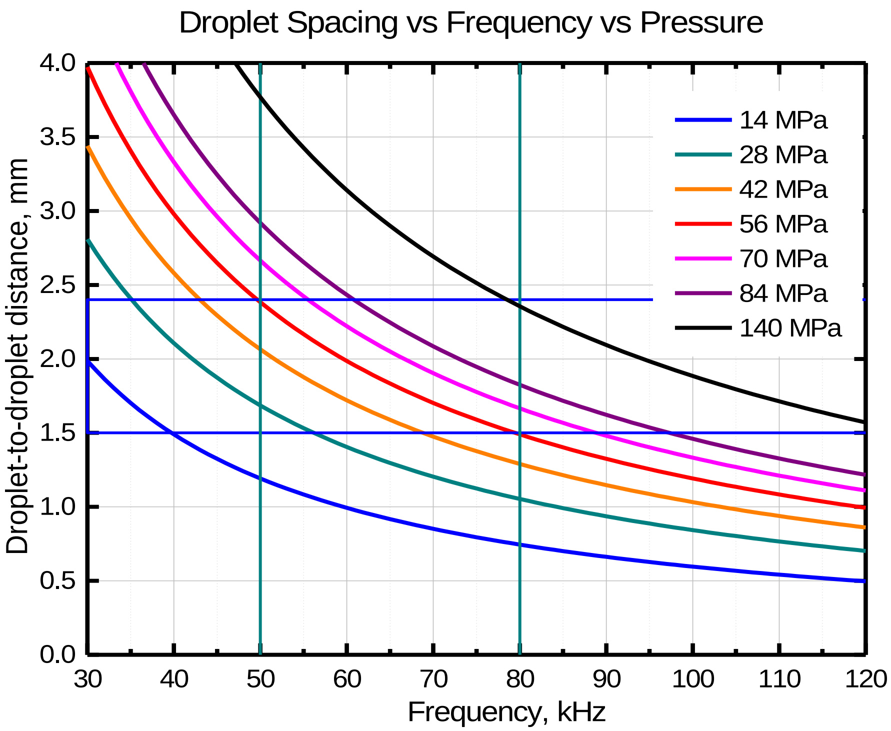


Tin droplets at 80 kHz and at different applied pressures.

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

Droplet generator history

Improvements in performance and availability

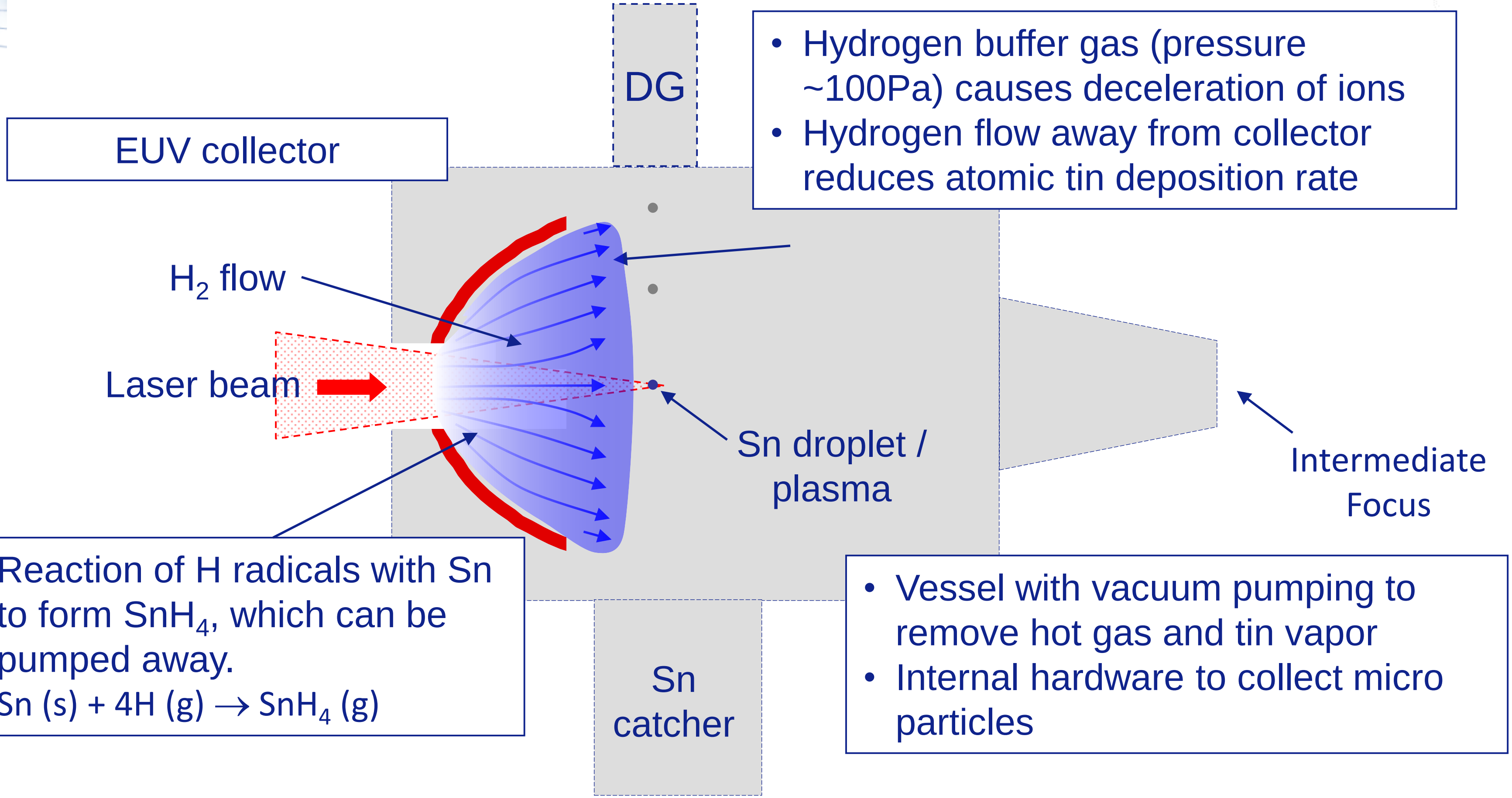
	2013	2014	2015	2016	2017	2018	2019	2020
Above timeline		**Engineering improvements**		**Inert material eliminates particle formation**			**Continuous droplets**	**Next…**
Below timeline	**First Generation NXE3300 Droplet Generators**		Droplet reduced from 34µm to 27µm			Pressure increased to 4ksi for larger droplet spacing		

	2013	2014	2015	2016	2017	2018	2019	2020
Droplet Generator Availability	**64%**	**77%**	**81%**	**87%**	**94.7%**	**96%**	**99%**	**>99.5%**
Nozzle Runtime Capability (hours)	**80**	**100**	**180**	**675**	**750**	**1000**	**1500**	**4000**

EUV Collection
Debris management

Collector Protection by Hydrogen Flow

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

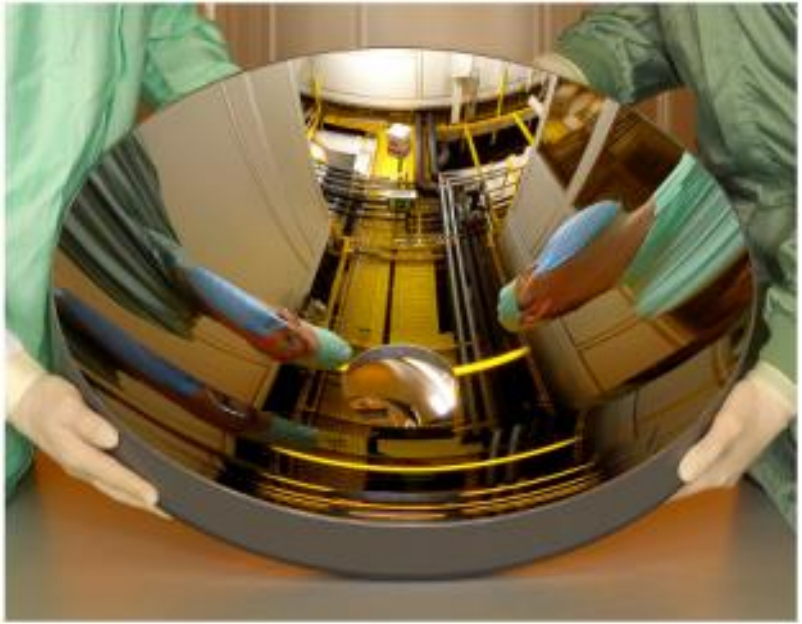


Reaction of H radicals with Sn to form SnH_4, which can be pumped away.
$Sn\ (s) + 4H\ (g) \rightarrow SnH_4\ (g)$

- 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

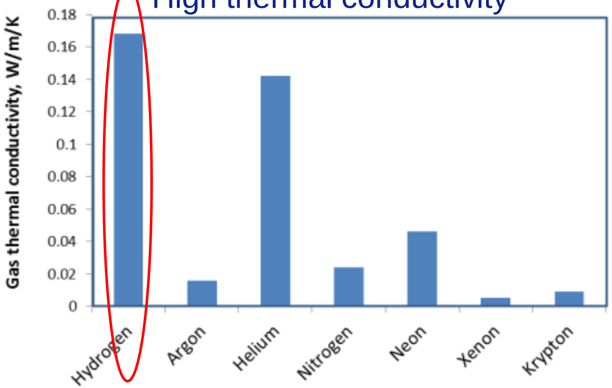
Hydrogen gas central to tin management strategy

Requirements for buffer gas:

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

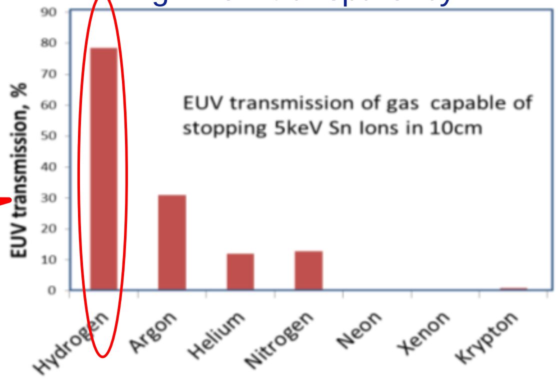
High heat capacity

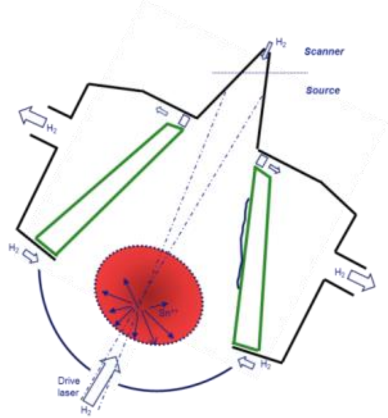
High thermal conductivity



Hydrogen performs well for all these tasks!

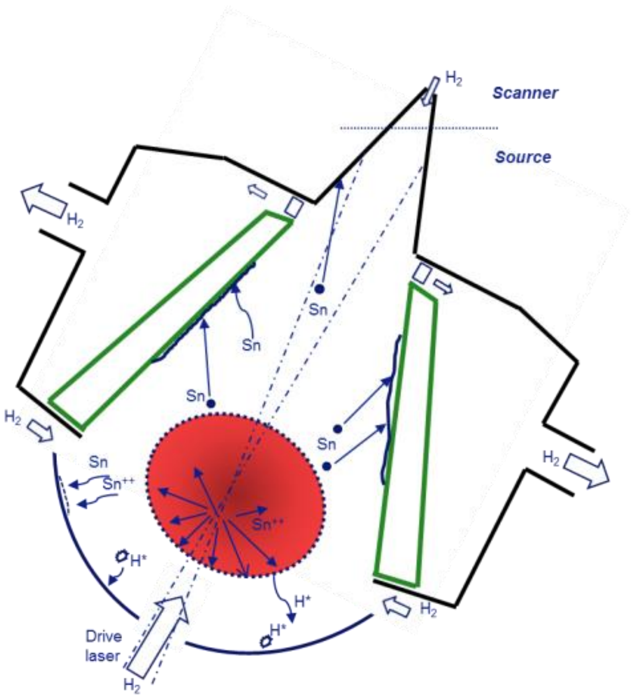
High EUV transparency





Debris in the tin LPP EUV source

- Sn → Sn vapor (diffusion debris)
- Sn^+ → Fast Sn ions (line of sight debris)
- Sn● → Sn particles

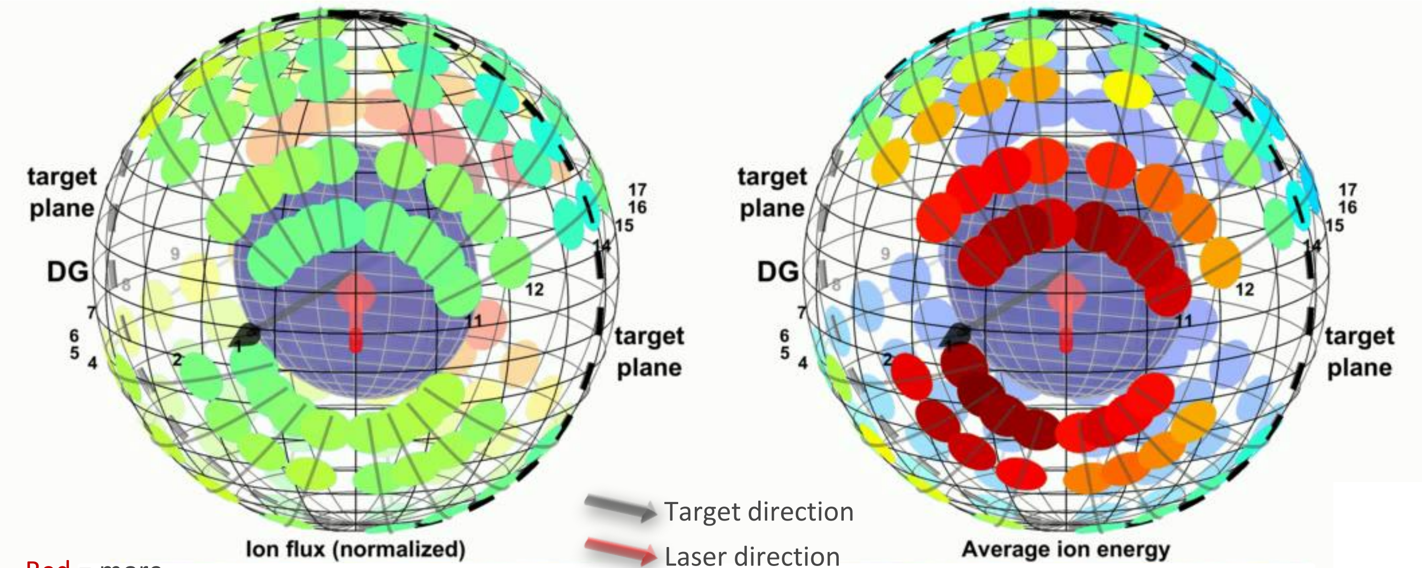


Primary debris – directly from plasma and before collision with any surface:

- 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

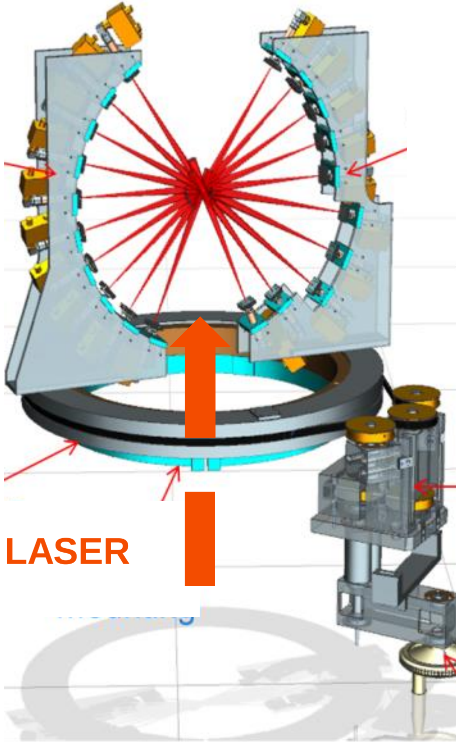
Faraday cups measure tin ion distributions



Red = more
Blue = less

Target direction
Laser direction
FC direction

Faraday cup



Ion measurements inform H_2 flow requirements for source

Measurement of fast tin ion and radiation distributions

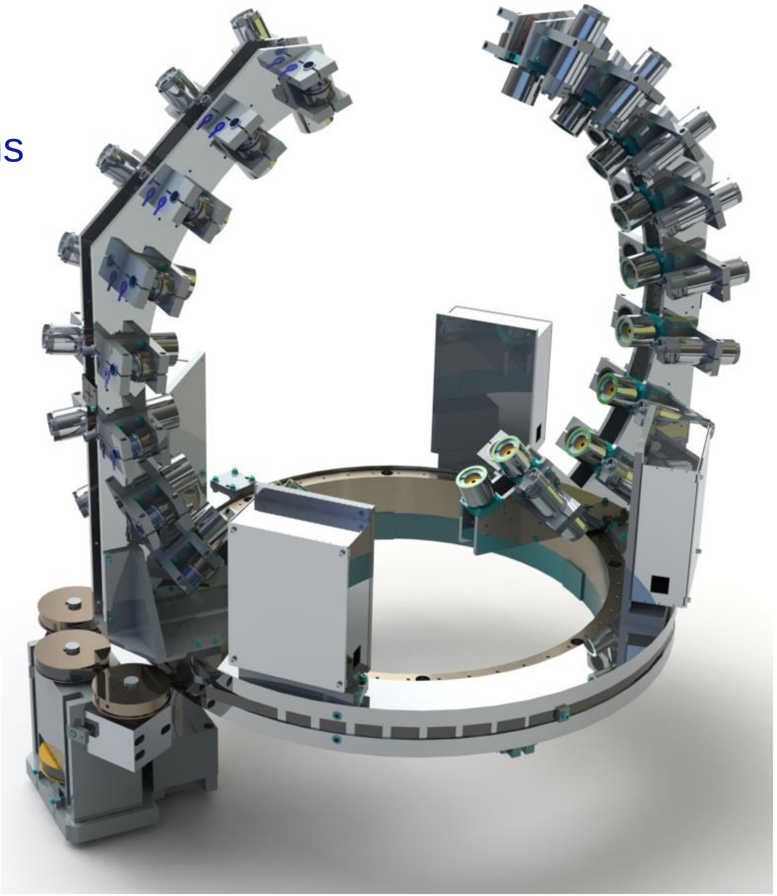
Multiple sensors on a rotating frame

Sensors

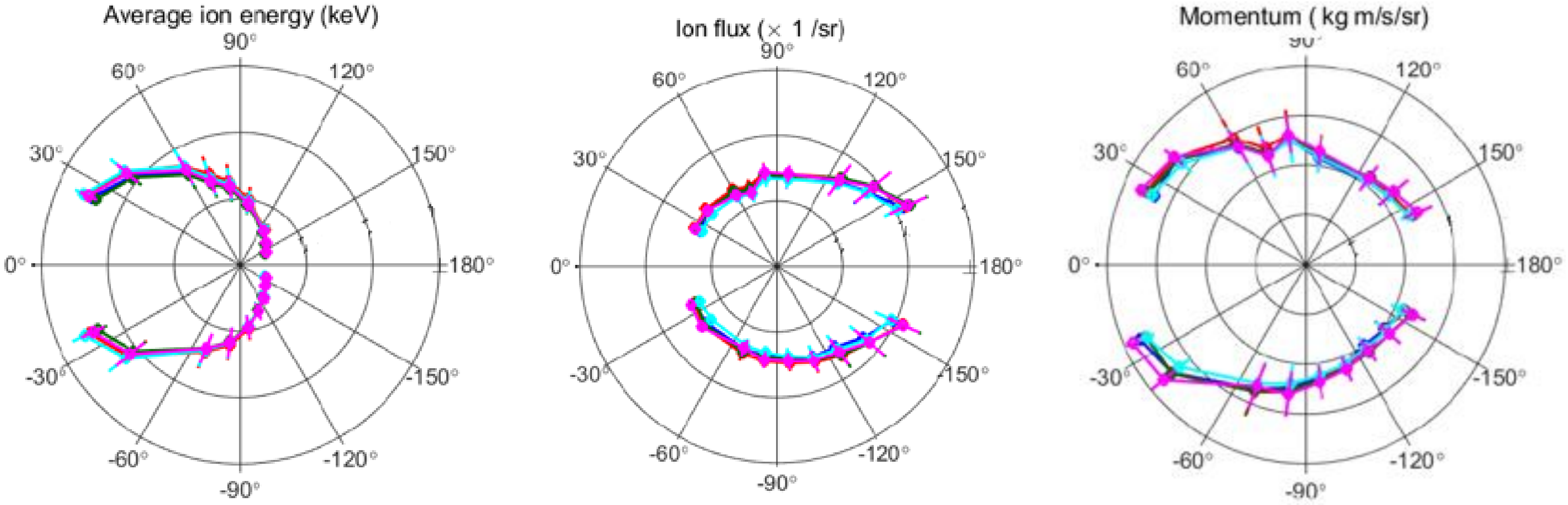
- Faraday Cups: ion energy and charge distributions
- CO_2 PEMs: scattered infrared radiation
- EUV PDs: EUV emission and anisotropy

Applications

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



Tin ion distributions



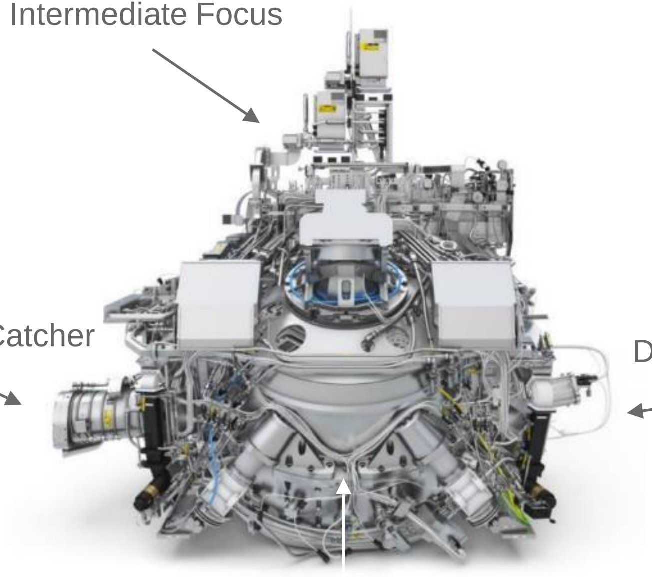
Data are used for optimization of H_2 flow in the source

EUV Source improvements

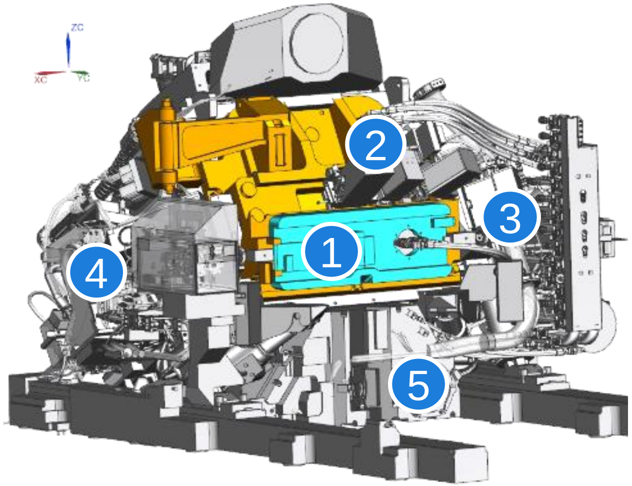
EUV Source: Changes to Vessel in 2019

Introduction of modularity enables faster service and lower downtime

Current vessel

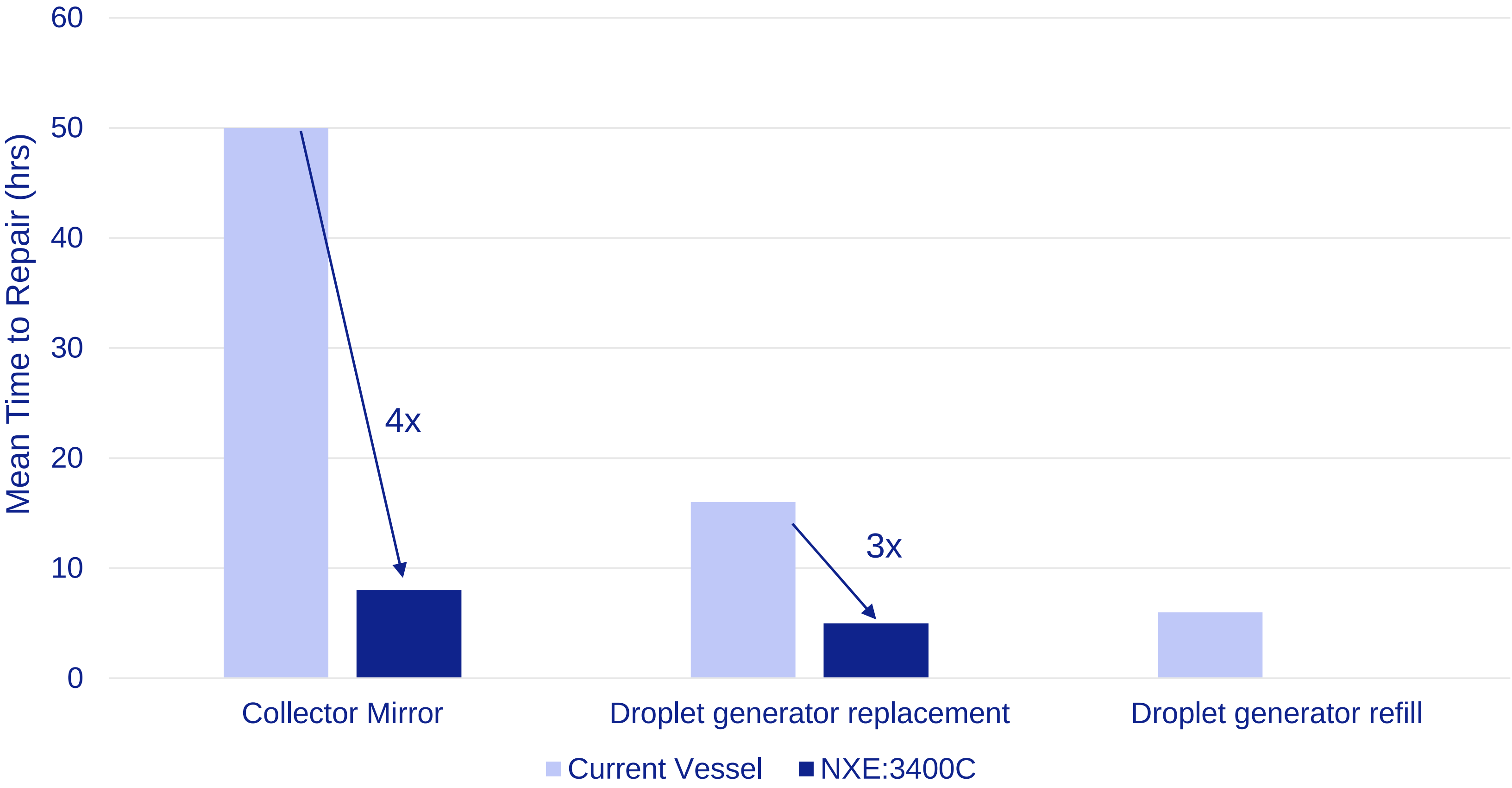


Modular vessel (EUV source for 3400C)



1: Collector swap door
2: Vessel service door
3: Metrology directly on vessel, fast EUV recovery
4. Continuous tin supply droplet generator
5. Eliminate manual laser beam adjustment

NXE:3400C improves serviceability and reduces maintenance time with new vessel

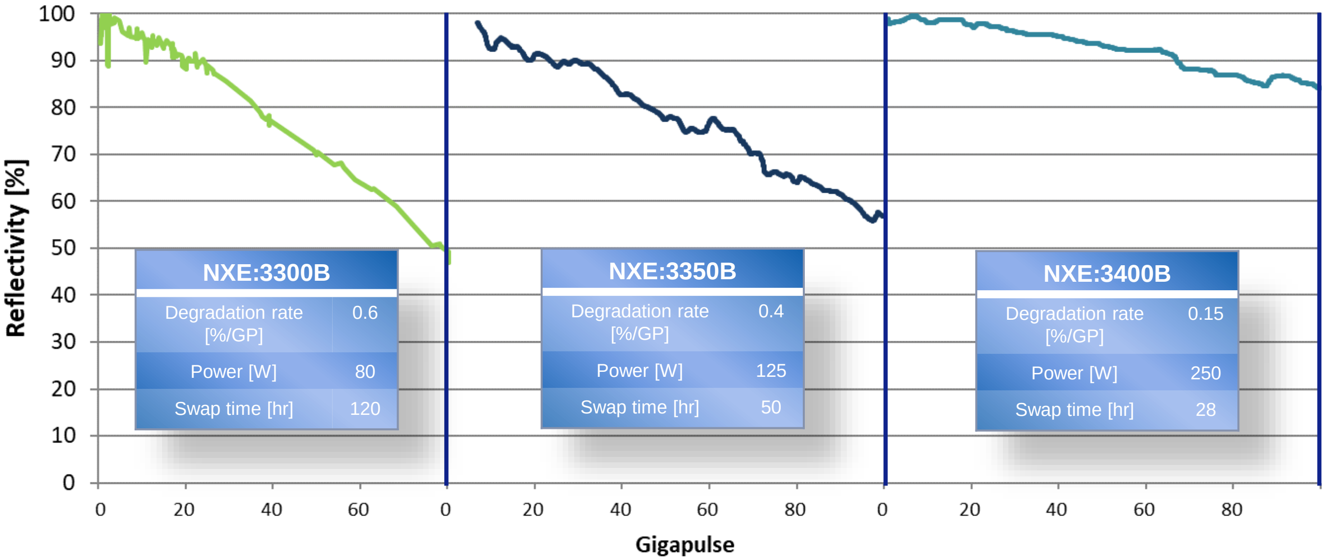


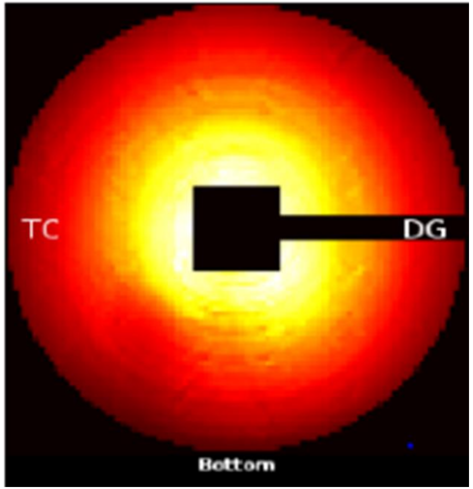
MTTR includes total time for diagnostics, access, part replacement and system recovery (green to green)

Collector lifetime improvements

4x reduction in collector degradation at 3x higher power

Normalized average collector reflectivity



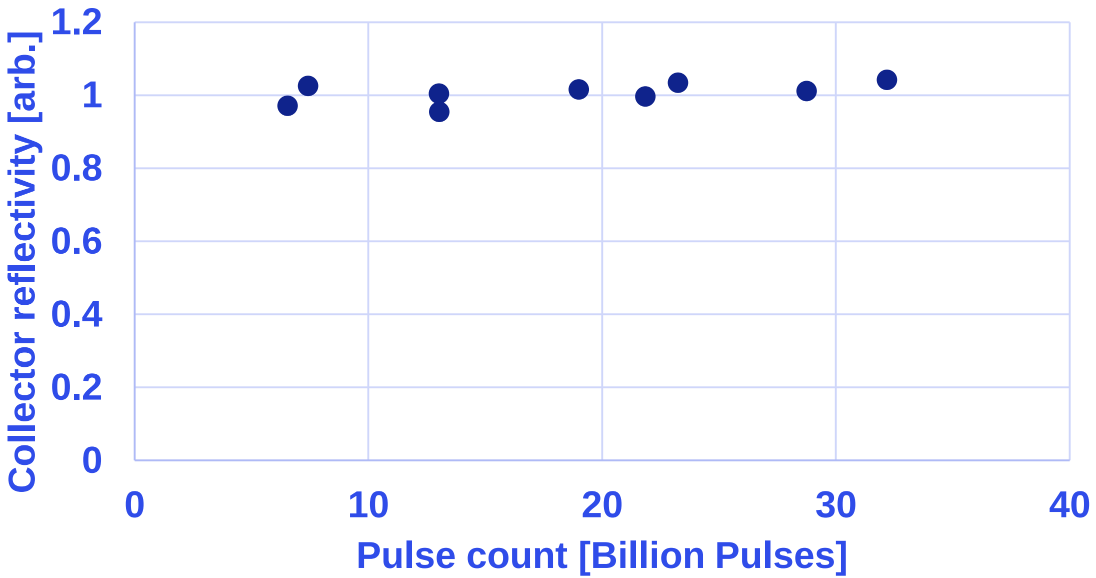


Far Field EUV intensity (image of the collector)

Reduced EUV collector degradation and swap times leading to higher productivity and availability

Improved debris mitigation

At 250 watt of EUV power



Data from the EUV source development system

EUV Source Power Outlook

Progress for in EUV power: 250W

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

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**

Increase average and peak laser power
Enhanced isolation technology

Advanced target formation technology

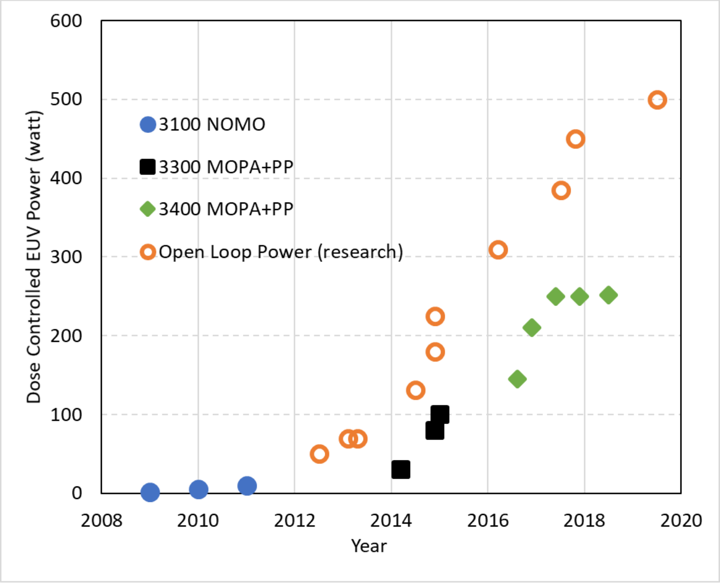
Improved dose-control technique

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

500W in-burst EUV power demonstration

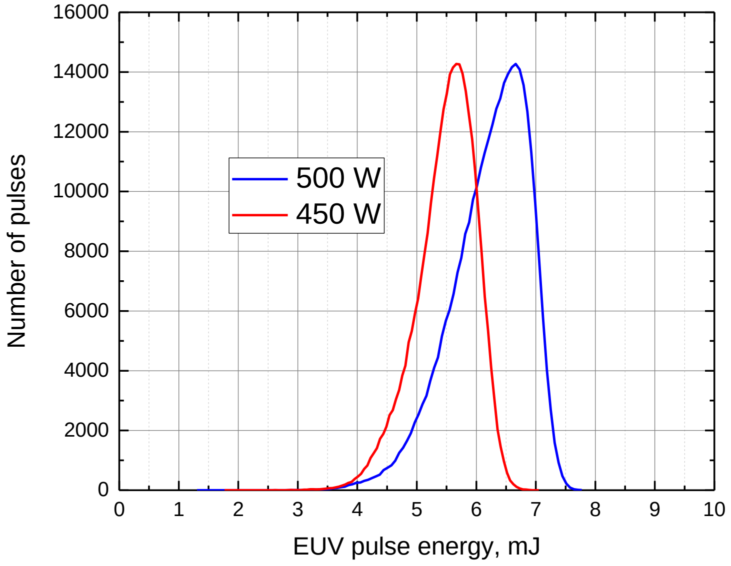
Demonstrated on the development system at 80 kHz

EUV source power and key technology steps



Historical trend: ~ two years from demonstration in research to a product

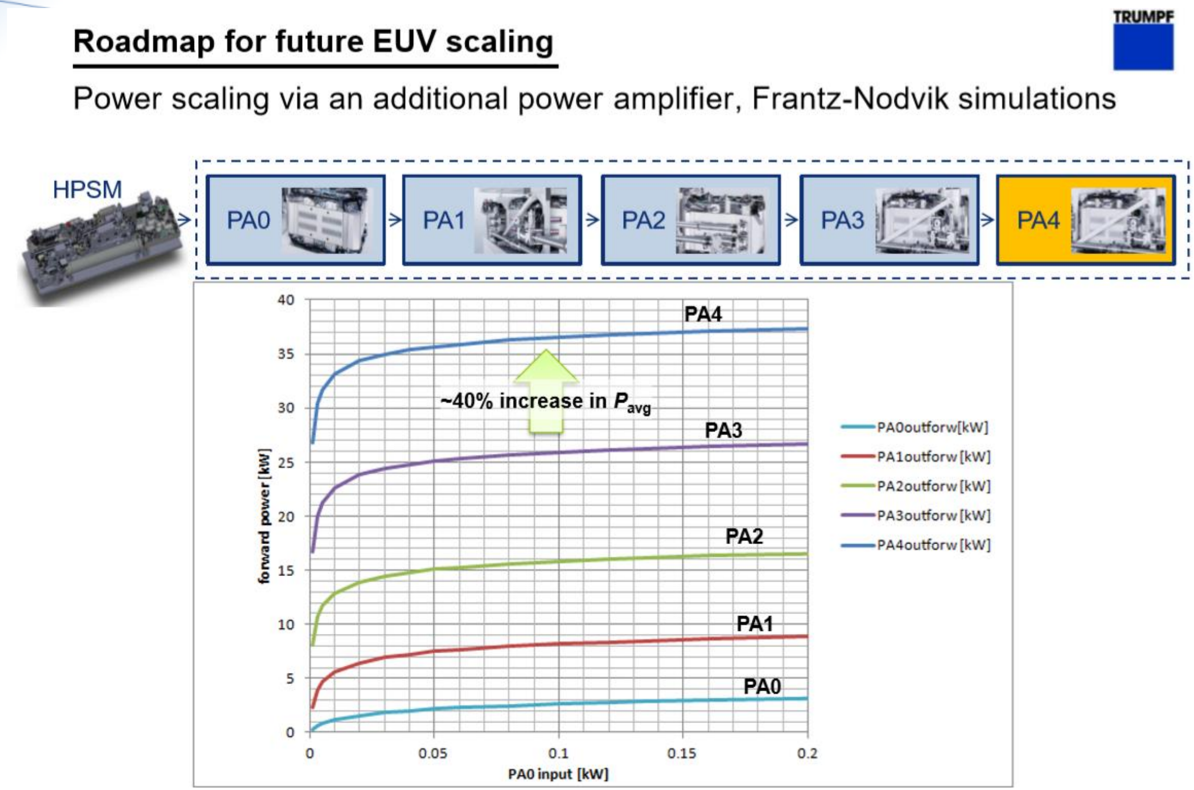
EUV pulse energy histograms



Open loop, 15 ms Bursts, 80 kHz,
3% duty cycle
On the development system

Increase of CO_2 laser power

High beam quality for gain extraction and EUV generation

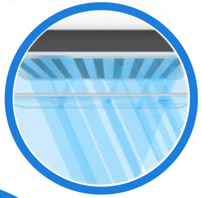


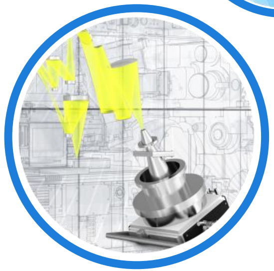
Key technologies:

1. Pulsed drive laser with high average power capability
2. Gain distribution inside amplification chain
3. Isolation between amplifiers
4. Metrology, control, and automation

Source: Beam Quality of Higher Power Lasers- EUVL 2018 Trumpf

Summary





EUV chips have made it to the end market!

Our customers are ramping up EUV for the 7nm Logic node and preparing for the 16nm DRAM node with systems deliveries and qualification on-going. EUV layers adoption continues to grow to reduce patterning complexity and cost

ASML EUV lithography systems continue to improve on productivity and availability supporting our Logic and DRAM customers roadmap while maintaining, state of the art overlay performance and year on year cost reduction

- Dose-controlled power of 250W on multiple tools at customers
- Droplet Generator with improved lifetime and reliability >700 hour average runtime in the field>3X reduction of maintenance time
- Collector lifetime improved to > 100Gp (4X at 3X higher power)

Availability improvements are well underway to meet our customers requirements, with the NXE:3400C supporting >90% availability

Path towards 500W EUV demonstrated in research

- EUV CE is up to ~ 6 %
- In burst EUV power demonstration up to 500W
- CO_2 Laser development supports EUV power scaling

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