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EUVL Exposure Tools for HVM: Status and Outlook

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Outline

- NXE3300 and NXE3350B progress and status
  - Roadmap, Layout, Performance
  - Imaging, Overlay, Defectivity
  - EUV pellicle status
- EUV source architecture and performance
- EUV source power scaling
  - EUV LPP technologies
  - Pre-pulse technology
  - EUV source drive laser
  - Droplet generator: performance, availability
  - Collector: protection, lifetime
- Summary

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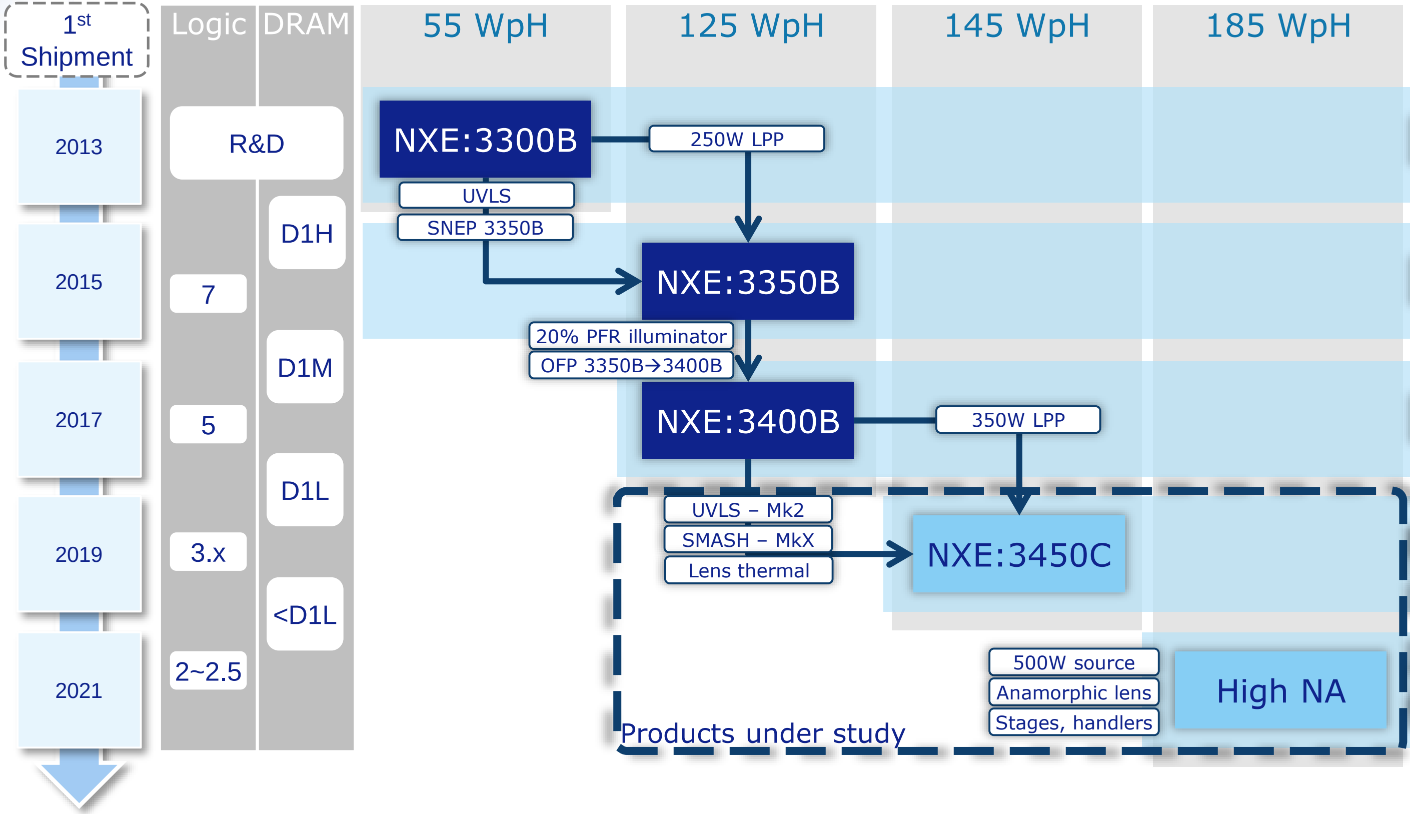
EUV technology roadmap, source architecture and performance

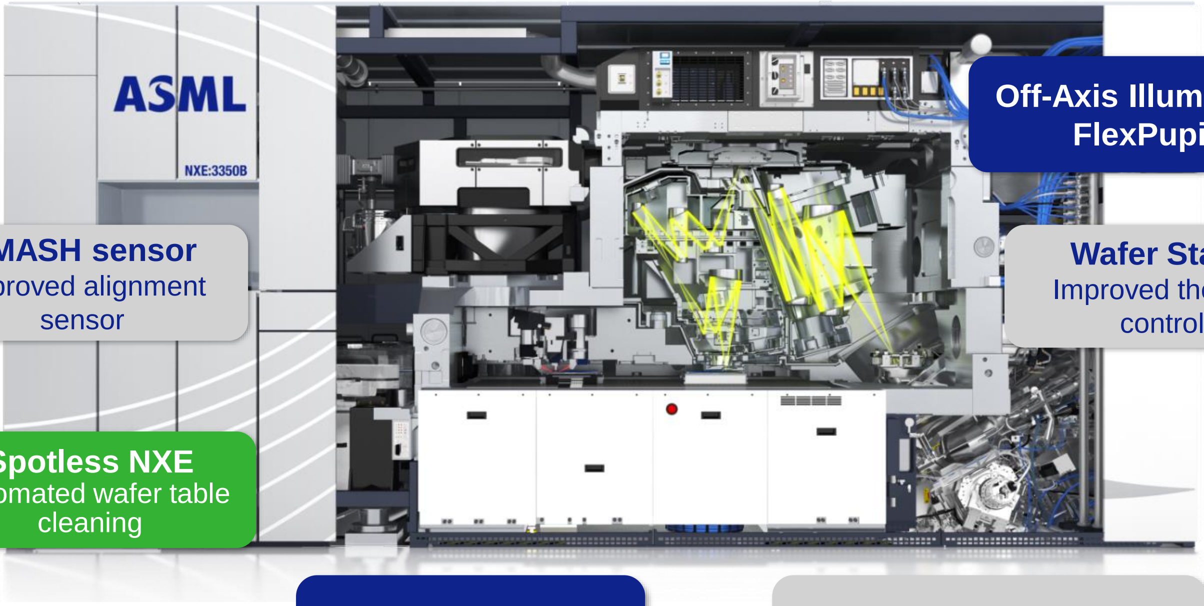
NXE extension roadmap to optimize capital efficiency



1st Shipment	Half pitch	Focus	DCO/MMO	OPO
2013	22 nm	110 nm	3.0/5.0 nm	7.0 nm
2015	16 nm	70 nm	1.5/2.5 nm	3.5 nm
2017	13 nm	60 nm	1.4/<2.0 nm	2.5 nm
2019	13 nm	50 nm	1.2/<1.7 nm	2.0 nm
2021	<8 nm	<40 nm	1.0/<1.4 nm	1.5 nm

NXE:3350B: 2x overlay improvement at 16nm resolution

Supporting 7nm logic, ~15nm DRAM requirements



Overlay set up
Set-up and modeling improvements

Reticle Stage
Better thermal control increased servo bandwidth

Projection Optics
Higher lens transmission improved aberrations and distortion

Off-Axis Illuminator FlexPupil

SMASH sensor
Improved alignment sensor

Wafer Stage
Improved thermal control

Spotless NXE
Automated wafer table cleaning

New UV level sensor

Improved air mounts

Resolution	16nm
Full wafer CDU	≤ 1.3nm
DCO	≤ 1.5nm
MMO	≤ 2.5nm
Focus control	≤ 70nm
Productivity	≥ 125 WPH

- ⬜ Overlay
- 🟦 Imaging/Focus
- 🟩 Productivity

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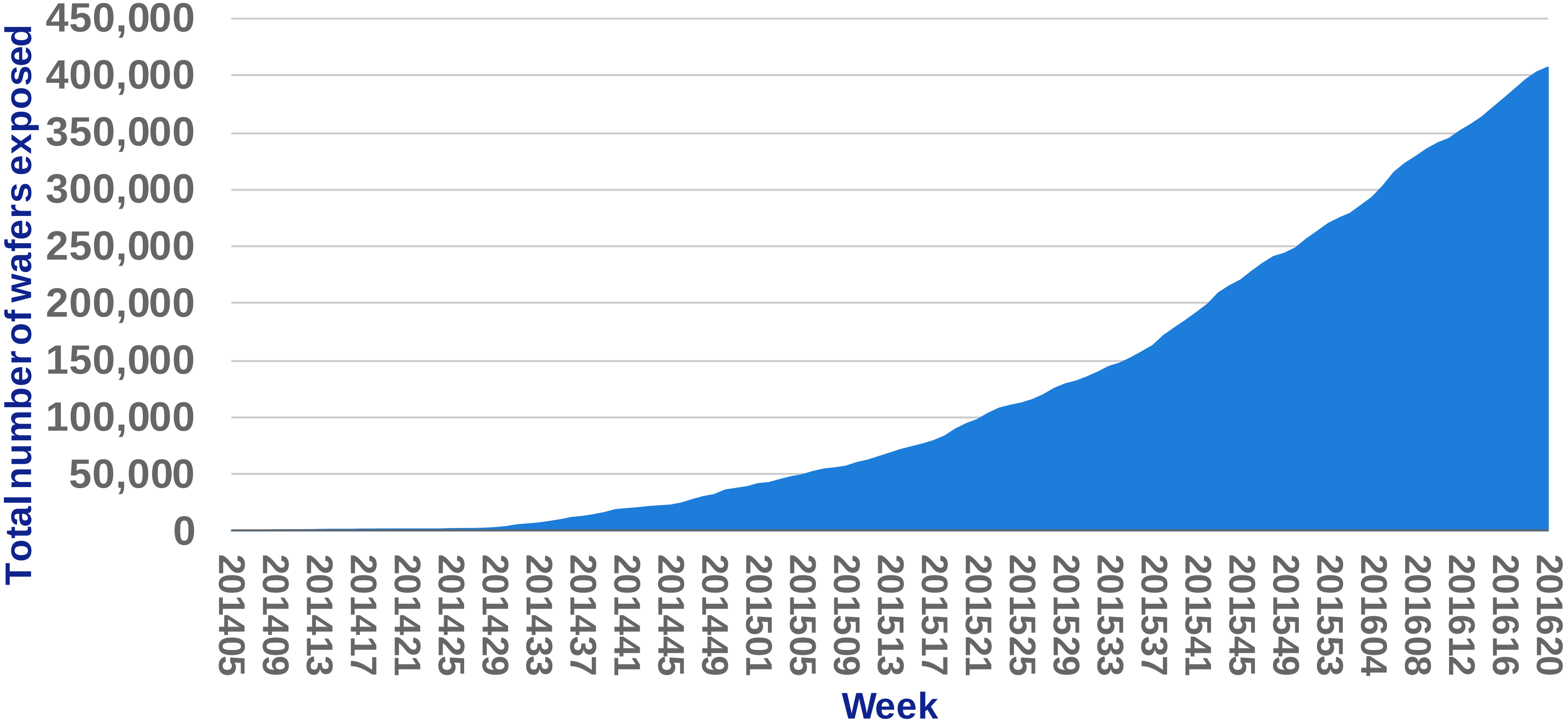
Productivity, Availability, Source Power

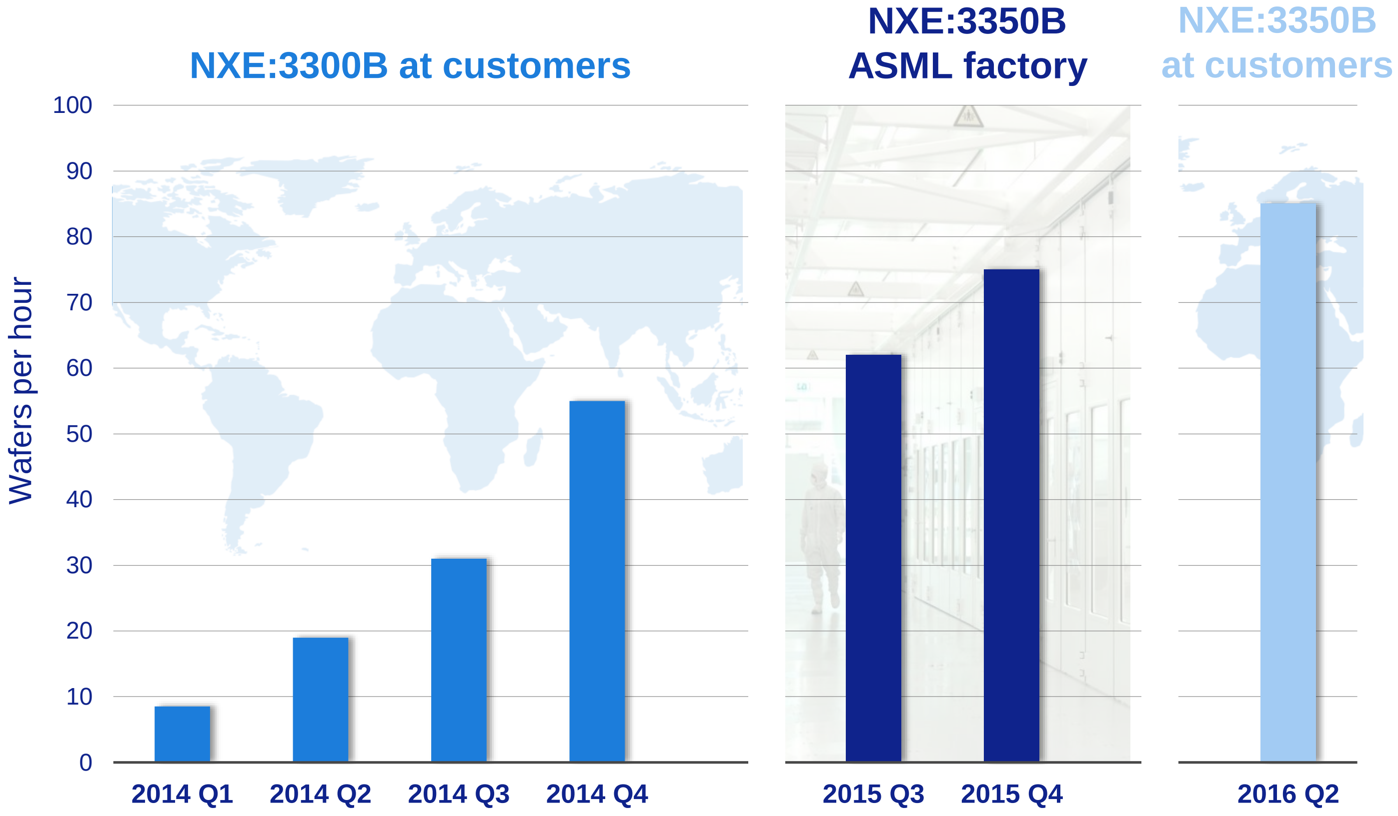
>405k wafers exposed on NXE:3300B at customer sites

Currently 8 systems running in the field



Demonstrated 85 WPH on NXE:3350B

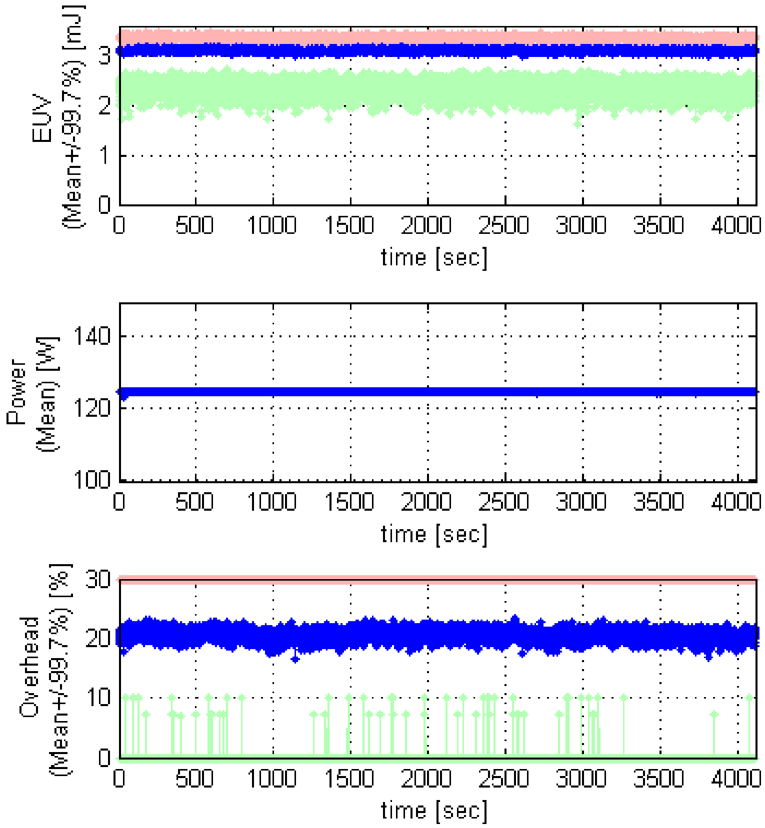
Achieved with 125W configuration



NXE:3350B ATP test: 26x33mm^2, 96 fields, 20mJ/cm^2

NXE:3350B: 125W settings qualified

being implemented at the customer

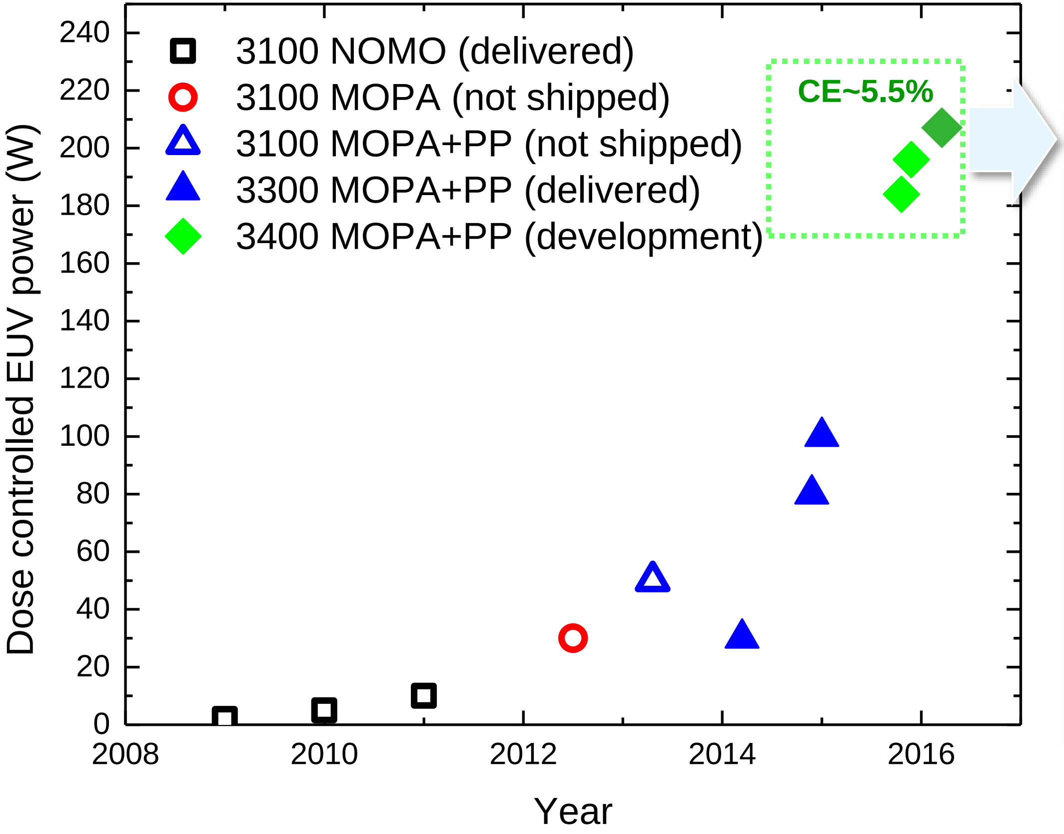


Mean pulse energy at Intermediate Focus ~3mJ

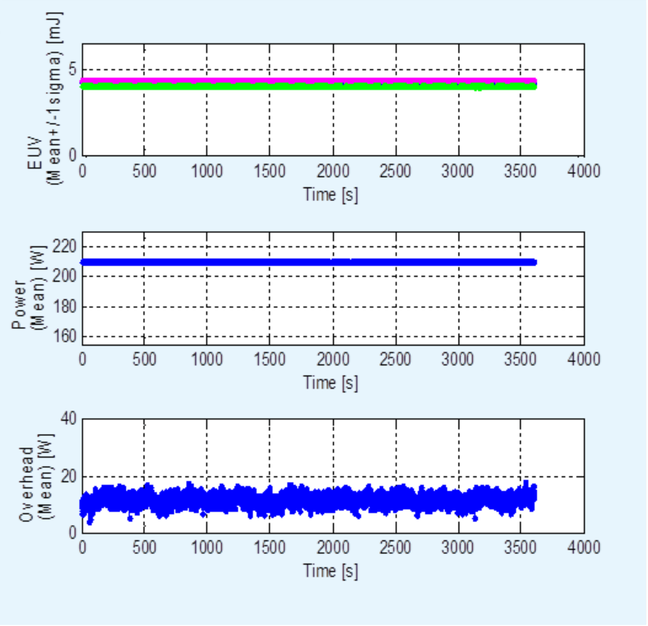
EUV power at Intermediate Focus 125W

Energy control Overhead ~20%

Progress in source power supporting productivity roadmap to >125 WPH

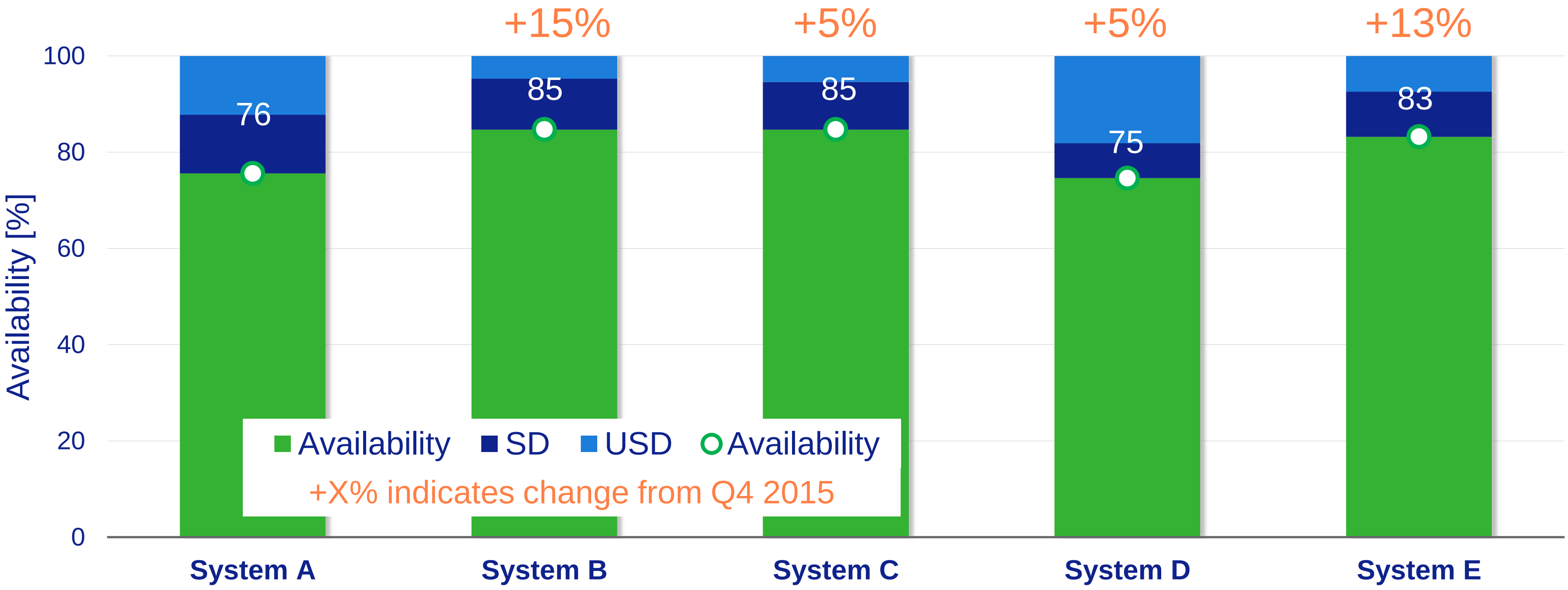


210W with dose in specifications obtained on development source



Three customer systems have achieved 80% availability

Best four-week average on systems in 80W configuration

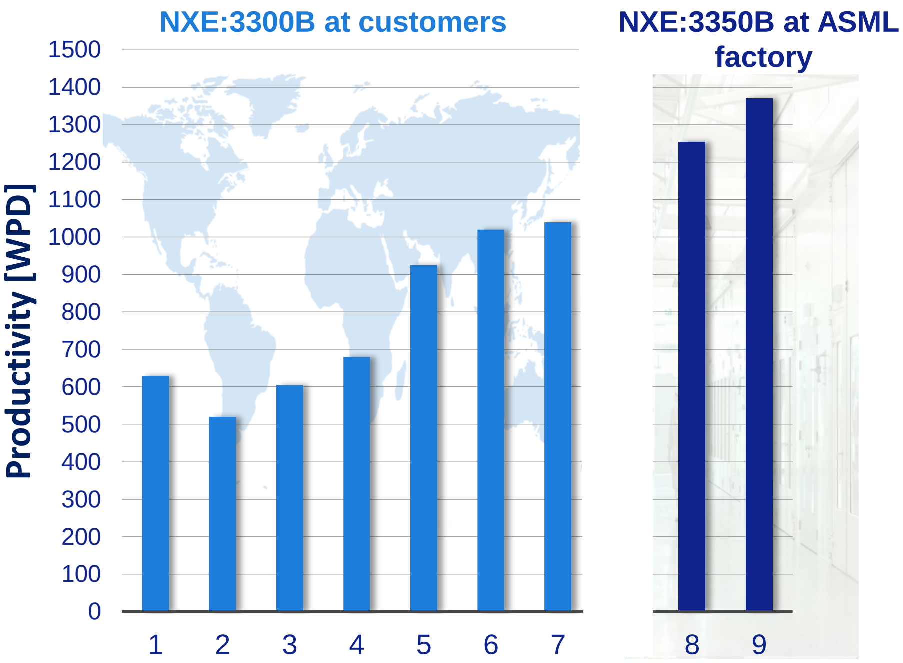


Uptime = productive time + standby time + engineering time
SD: Scheduled down • USD: Unscheduled down

NXE:3300B multiple customers exposed >1,000 WPD;

NXE:3350B exposed 1,368 WPD at ASML factory

Best single day results



- WPD: maximum number of wafers exposed in a 24 hour period
- Each bar represents an individual system

Best full week result

- NXE:3350B with S2 source config. at ~80W EUV power.
- TPT job: 26x33mm field @ 20 mJ/cm^2, full wafer coverage (96 fields)

Source power, availability, productivity summary

Status April 2016

Source power

- 80W configuration rolled out to customer sites, 125W configuration qualified
- 210W of dose-controlled EUV power demonstrated at ASML

Availability

- Three customer systems achieved more than 80% average availability over four weeks
- While overall average availability has increased, consistency still needs to be further improved

Productivity

- More than 1000 wafers per day exposed on NXE:3300B at customer sites, further improved to more than 1,350 wafers per day on NXE:3350B at ASML
- In a manufacturing readiness tests at a customer site an average of 800 wafers per day over two weeks was achieved

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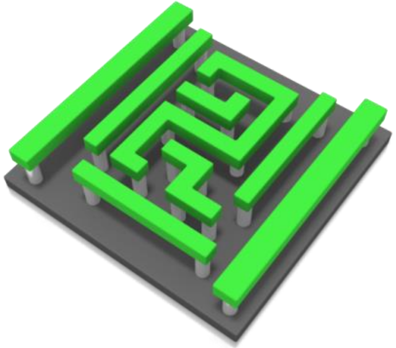
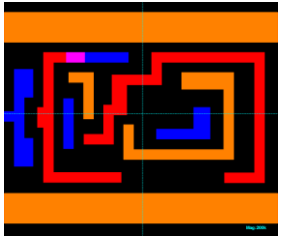
Imaging, Overlay, Defectivity

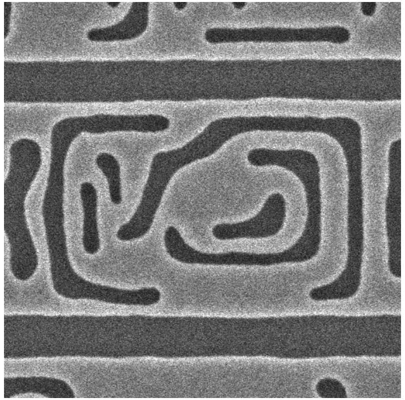
EUV single exposure replaces immersion multiple patterning

*2D-Metal at **32nm pitch** achieved with Quasar illumination*

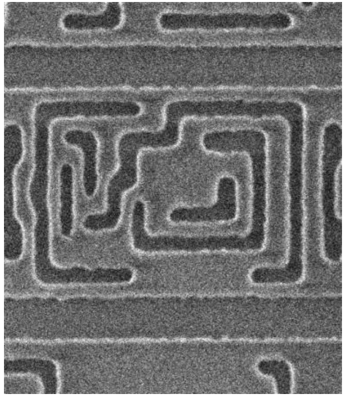




ArFi LE^3
(triple patterning)



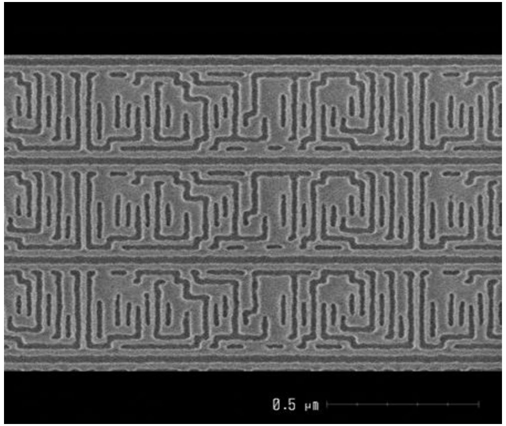
EUV Single Exposure

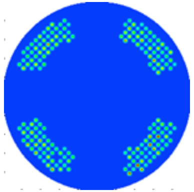


Dose: 20 mJ/cm^2

48nm pitch / 24nm CD

32nm pitch / 16nm CD



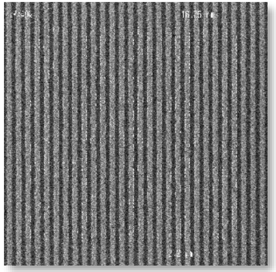


Quasar,
Pupil Fill ratio 20%

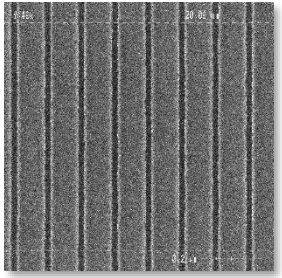
In cooperation with IMEC

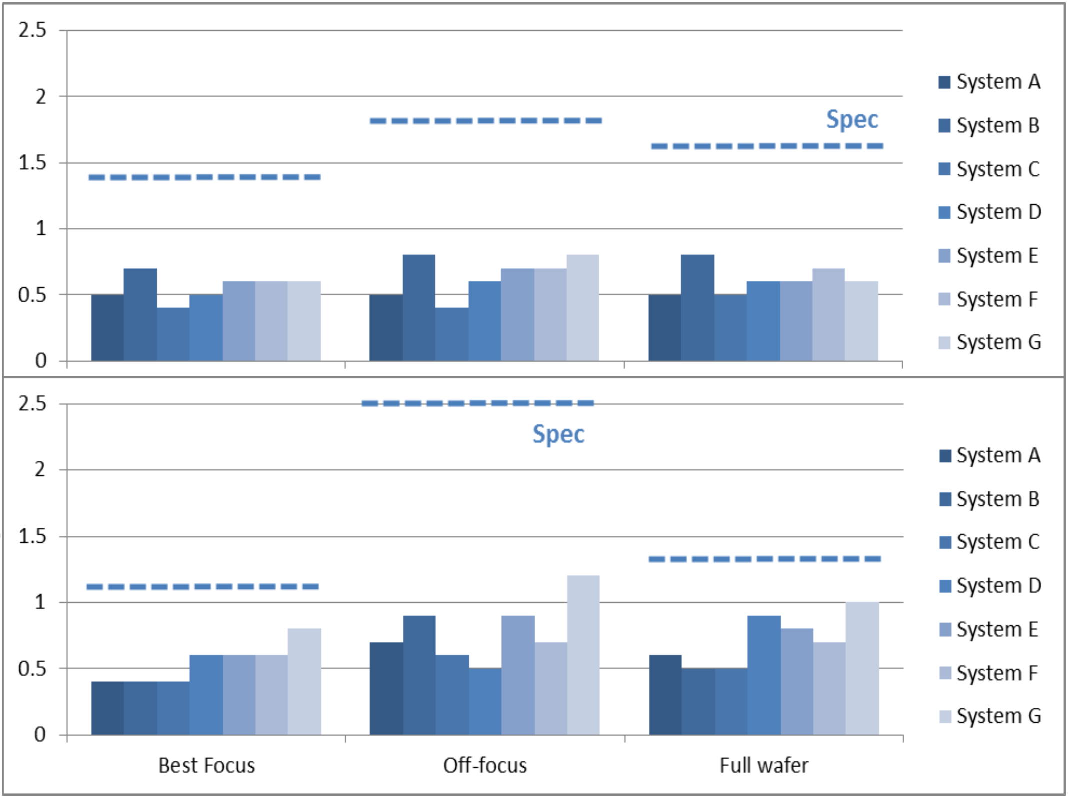
NXE:3350B **imaging**: 16nm dense lines and 20nm iso space consistently achieve <1.0nm Full Wafer CDU

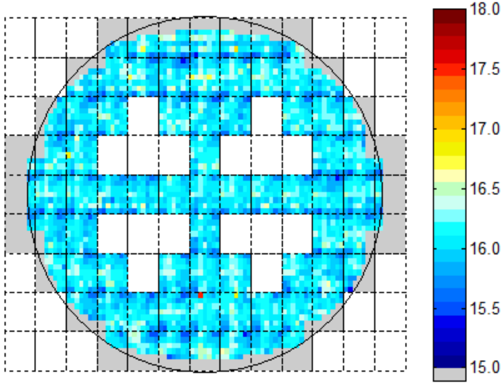
16nm dense lines

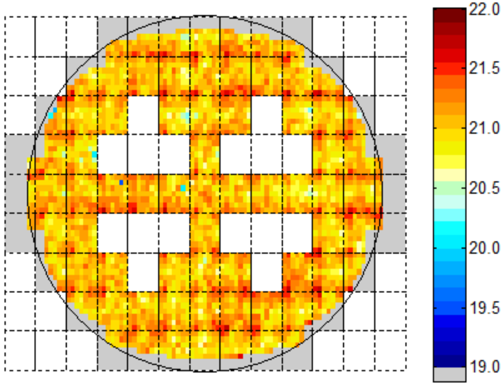


20nm iso space





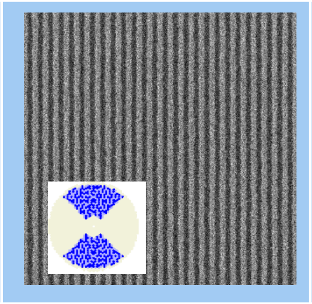
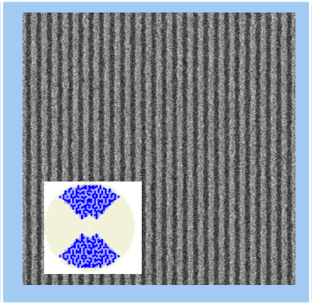
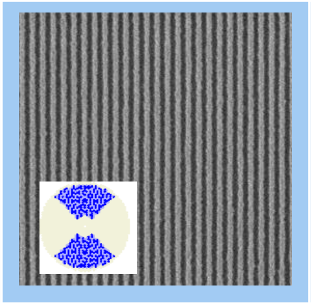
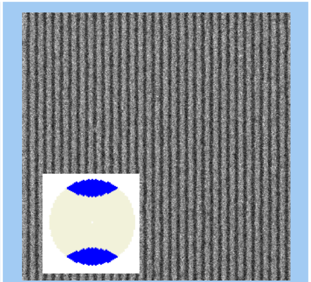
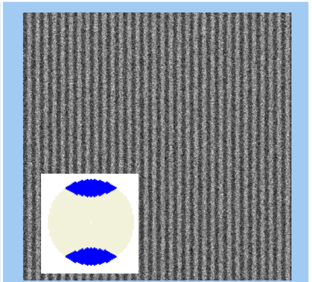




Tested with new ATP – 0mm field spacing and 15x9 grid

Progress resist materials: towards 16nm resolution at 125 WPH

19% EL, 4.4nm LWR @18.5mJ/cm^2. Also 13nm resolved with 17% EL and 4.2nm LWR @31mJ/cm^2

NXE:3350B	**16nm Horizontal Dense lines/spaces**			**13nm Horizontal Dense lines/spaces**	
	Reference CAR	New formulation CAR	New Inpria resist (NTI non-CAR)	CAR	New Inpria resist (NTI non-CAR)
SEM image @BE/BF					
Dose	40 mJ/cm^2	25 mJ/cm^2	**18.5 mJ/cm^2**	~40 mJ/cm^2	31 mJ/cm^2
Exposure Latitude	16 %	16 %	19 %	-	17 %
DoF	145 nm	100 nm	125 nm	-	150 nm
LWR	4.6 nm	5.2 nm	4.4 nm	4.5 nm	4.2 nm

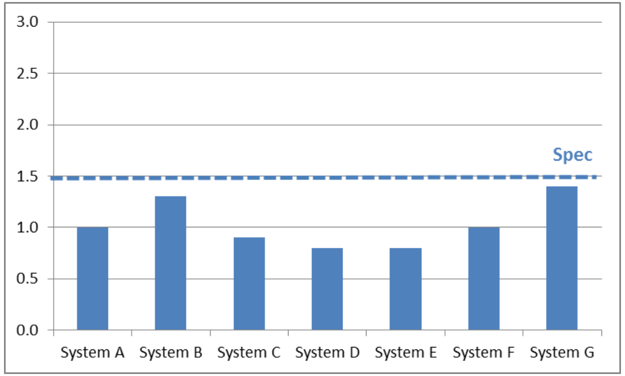
LWR = Line Width Roughness
DoF = Depth of Focus
EL = Exposure Latitude

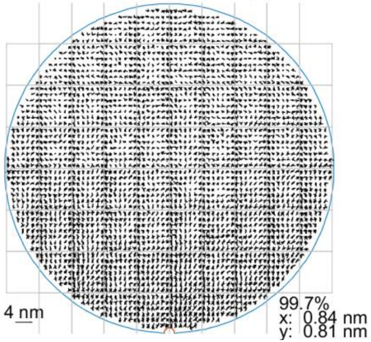
BE/BF = Best Energy/Best Focus
CAR = Chemically Amplified Resist

NXE:3350B **overlay** and **focus** performance

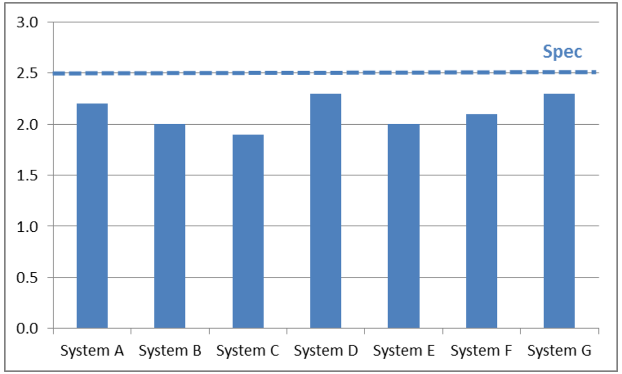
Well in specification due to HW improvement and new calibrations

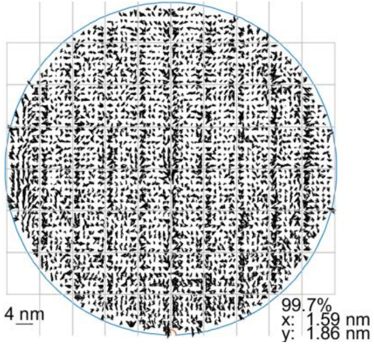
Dedicated chuck overlay [nm]



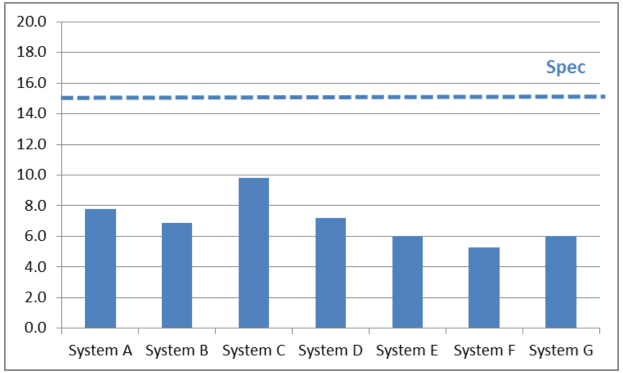


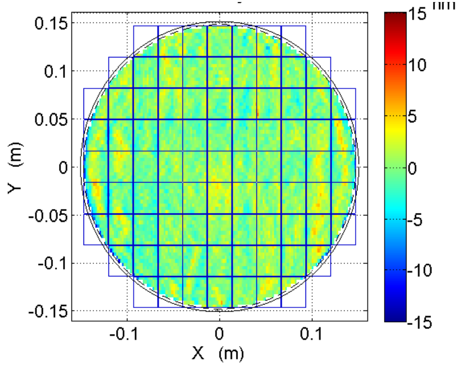
Matched machine overlay [nm]



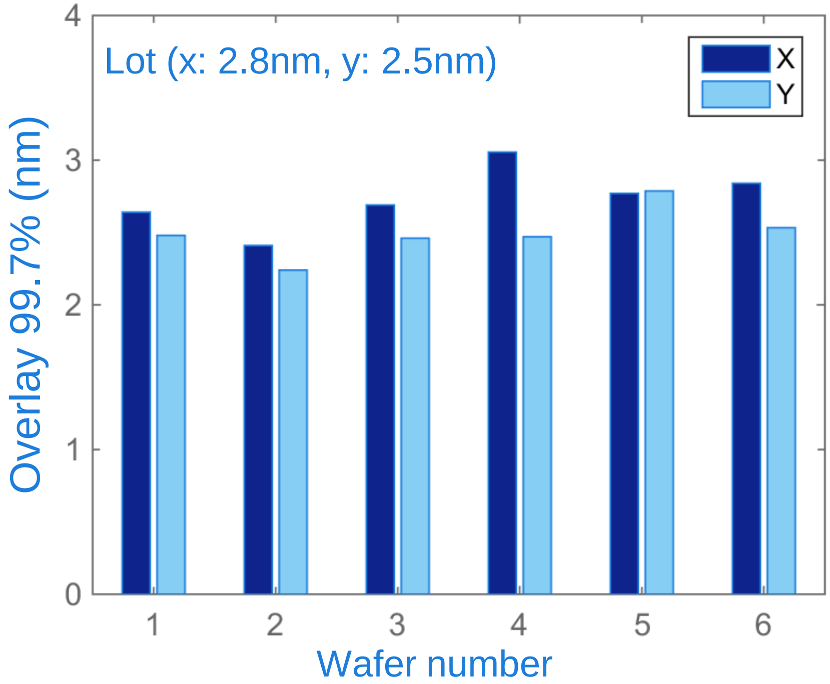


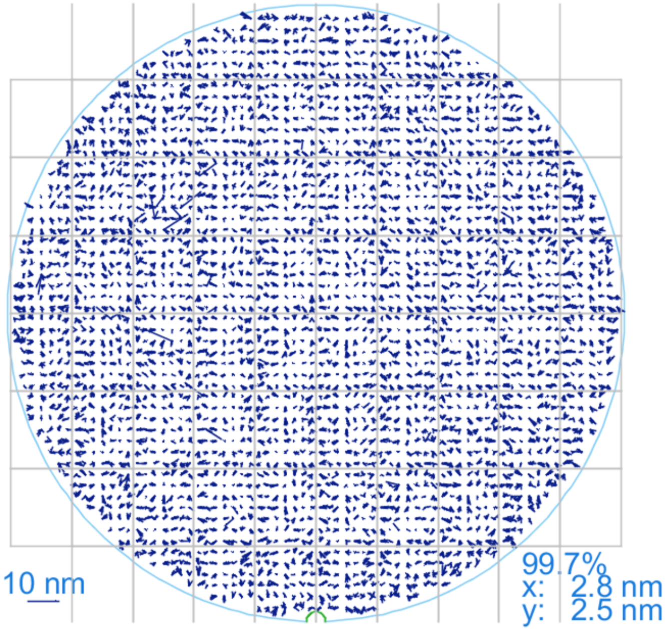
Focus uniformity [nm]



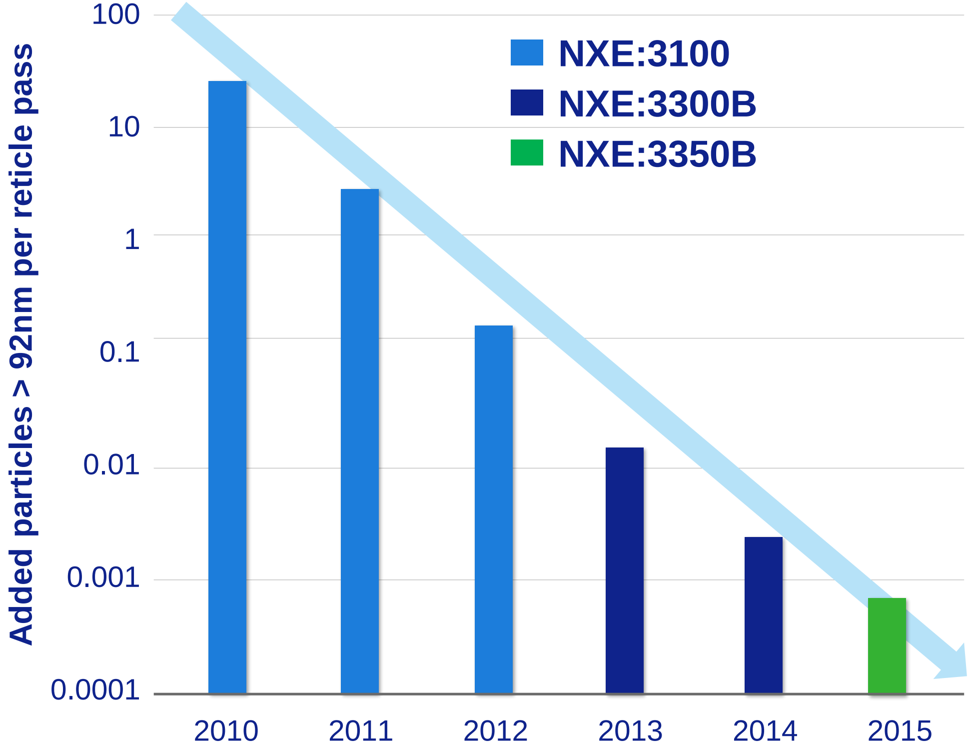


NXE:3350B **matched machine overlay** with NXT:1980Di <2.8nm





Front-side reticle defectivity: 10x reduction/year realized



Key improvements

Optimization of flow around reticle stage using new hardware

Optimized maintenance sequence to flush out particles

Imaging, overlay, focus, defectivity summary

Status April 2016

Imaging

- NXE:3350B imaging and overlay results for 7nm Logic are good
- 16 nm dense lines and 20 nm iso space consistently achieve full-wafer CDU below 1 nm

Overlay and focus

- NXE:3350B: 2x overlay improvement over NXE:3300B
- Matched-machine overlay below 2.5 nm, focus uniformity below 10 nm

Defectivity

- Front-side reticle defectivity: 10x reduction/year realized

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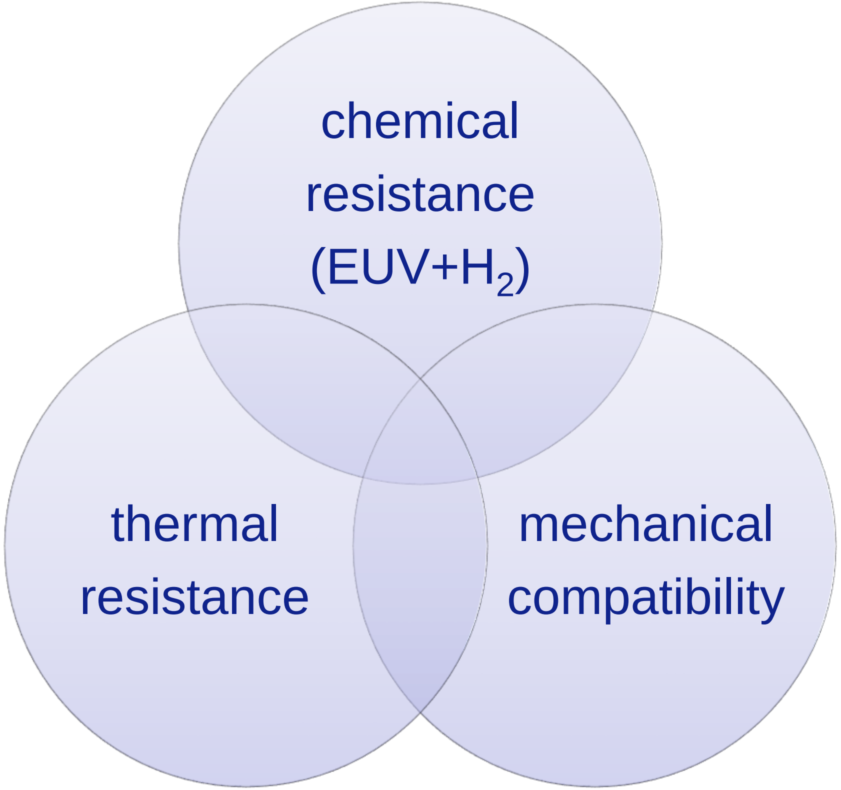
EUV Pellicle

Pellicle film must simultaneously fulfill all key requirements

Polycrystalline silicon based films meet the key requirements

Pellicle robustness

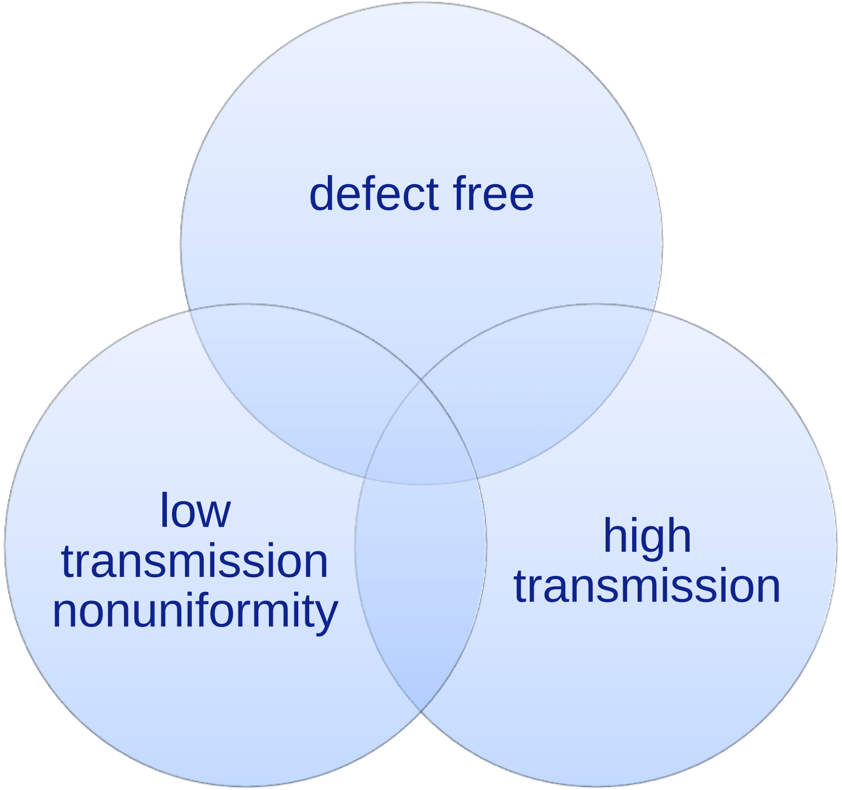


chemical resistance ($EUV+H_2$)

thermal resistance

mechanical compatibility

Scanner (imaging) performance

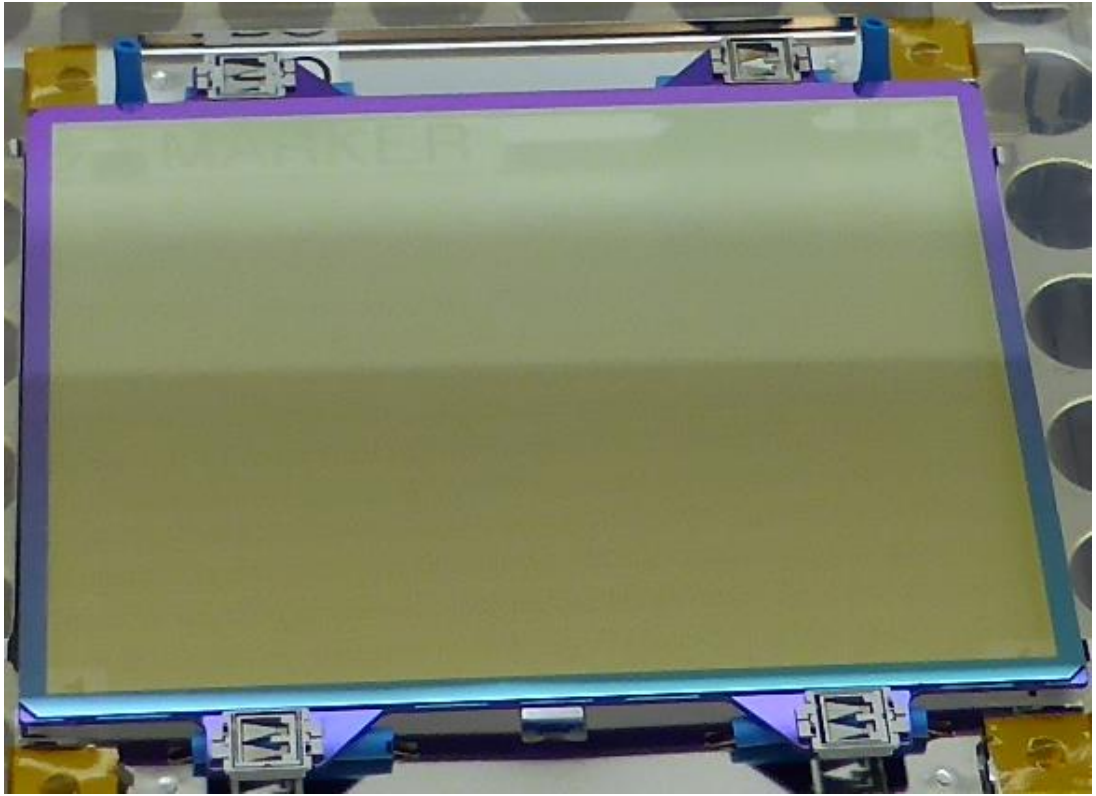


defect free

low transmission nonuniformity

high transmission

NXE Pellicles are being mounted and used in scanners



Prototype pellicle on early integration mounting tooling

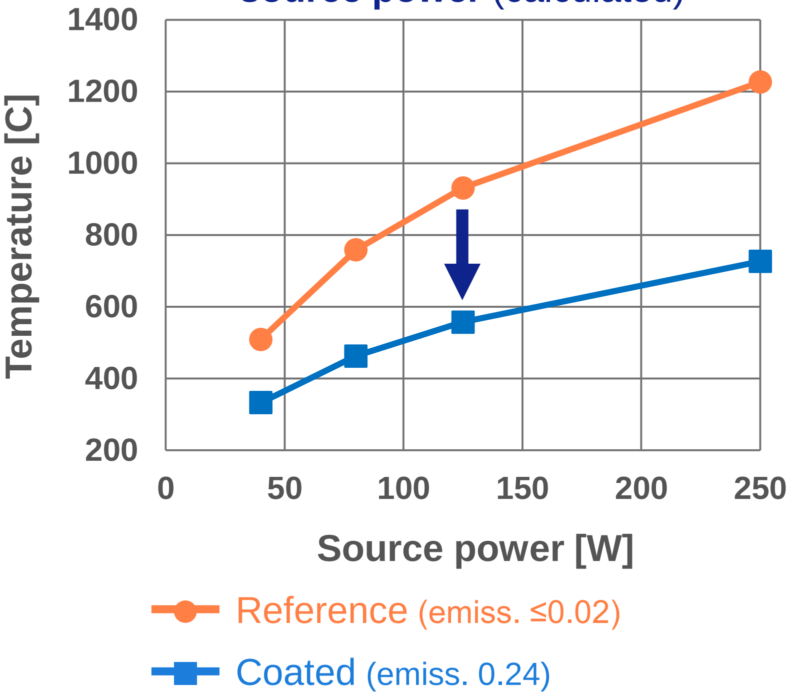
Pellicle technology: durability proven to at least 125 W

Heat load test results

Film stack	Equivalent source power	Sample survivability
Uncoated	40 W	9/9
Uncoated	125 W	3/5
Coated	125 W	33/33

ASML pellicle integration Work Center at our Veldhoven production facilities

Maximum pellicle temperature vs source power (calculated)



* Duration of tests: equivalent with exposure of 1000 wafers

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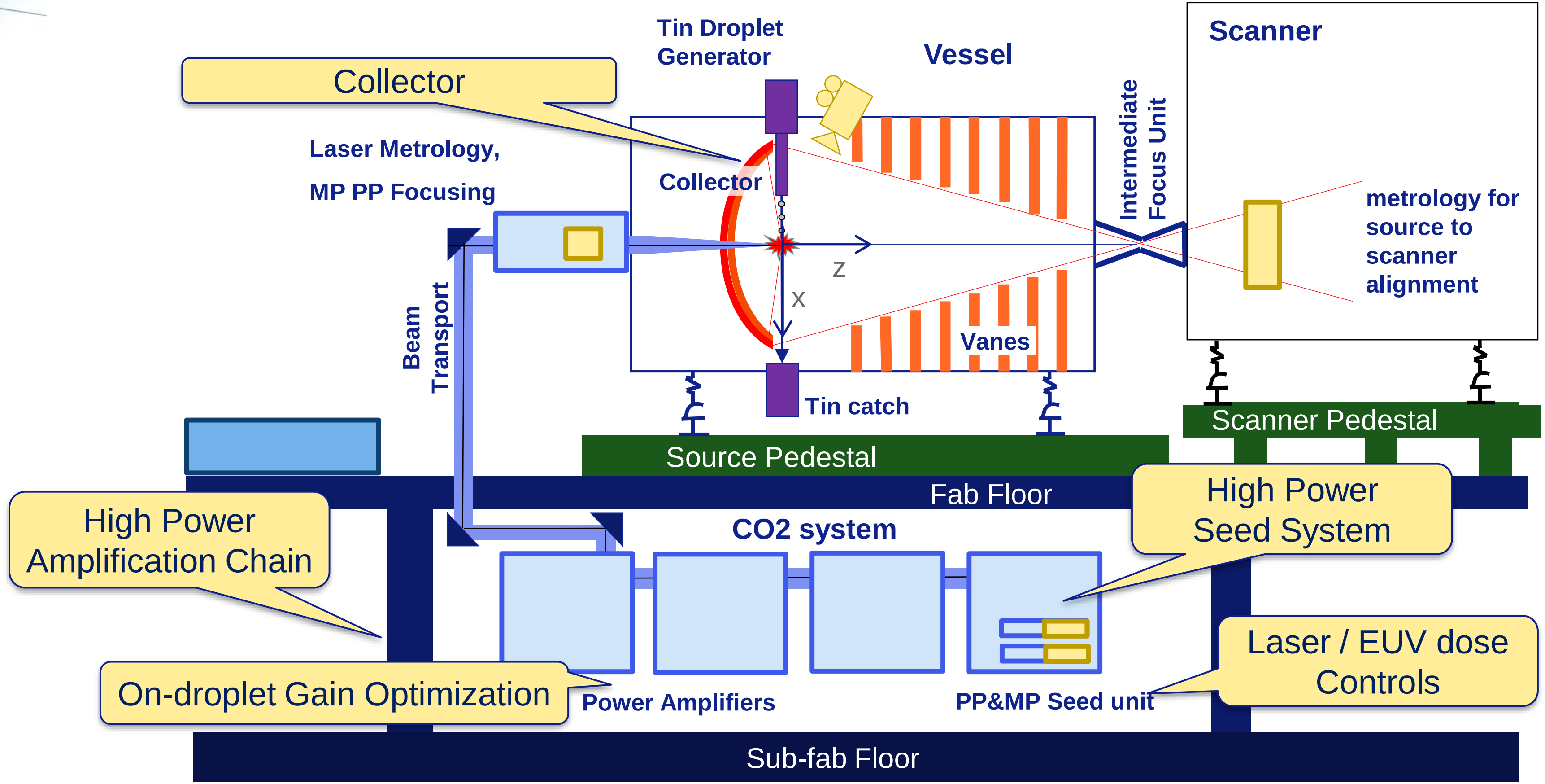
EUV source power scaling

EUV Source Architecture, Sn LPP MOPA with Pre-pulse



Collector

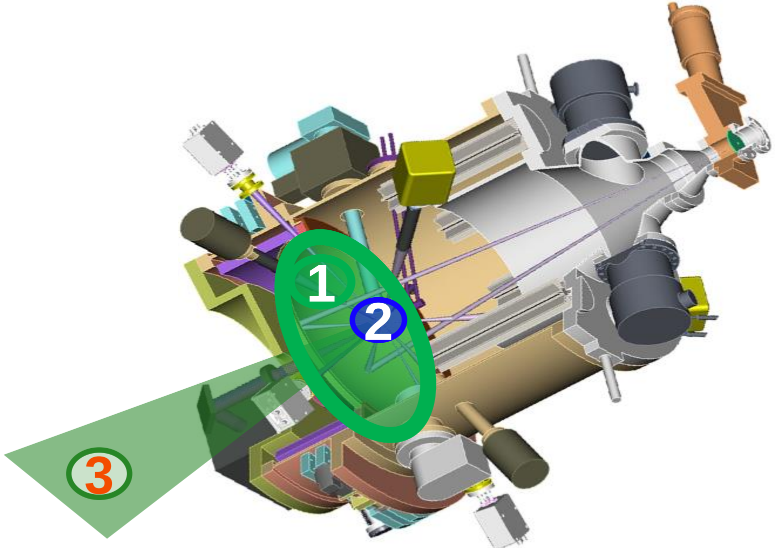
High Power Amplification Chain

On-droplet Gain Optimization

High Power Seed System

Laser / EUV dose Controls

EUV LPP Source Key Technologies



Optics Protection ①
(Debris Management)
- Collector protection by gas flow
- In-situ collector cleaning
- Collector capping layers

Availability / CoO

Targeting Dynamics ②
- Target conditioning
- Focus Control
- x,y,z, E & t control

Dose Control / Yield

CO_2 Laser Power ③
- High power drive laser

Conversion Efficiency
- Prepulse

EUV Power / Throughput

Source power and availability drive productivity

Technology development work is ongoing to improve all aspects

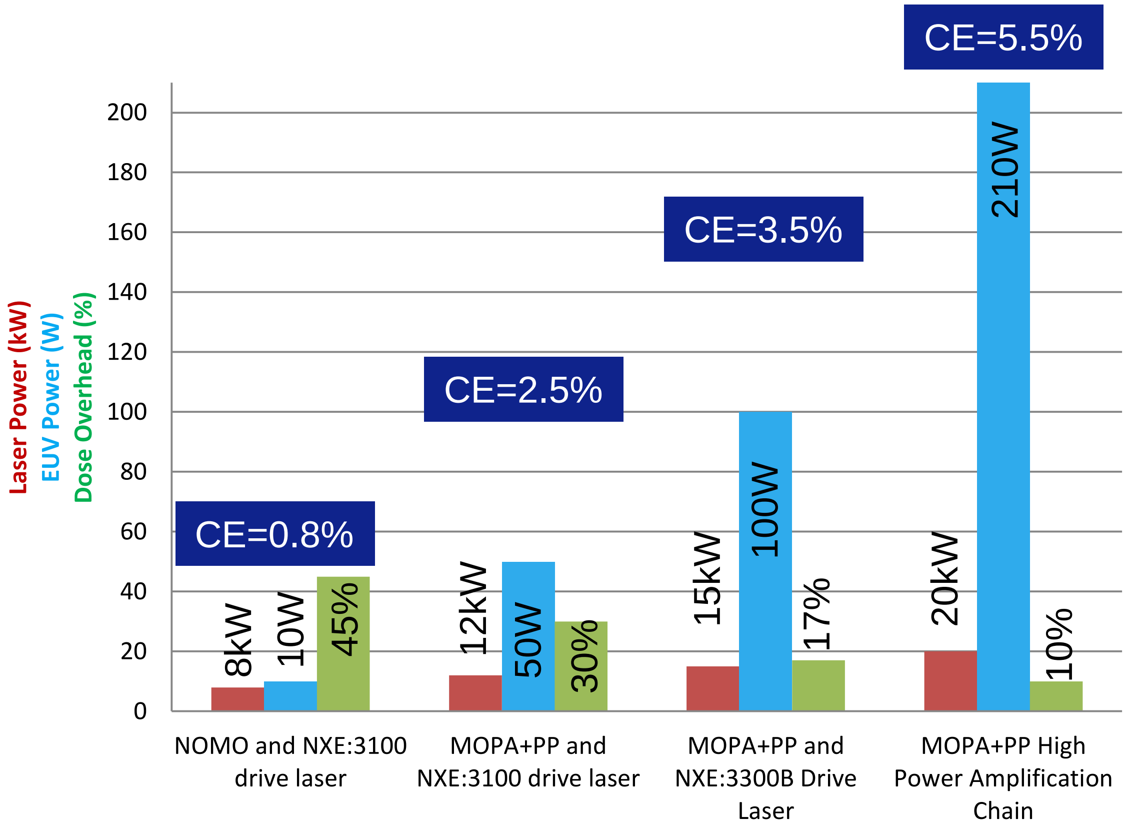
$$\boxed{\text{Productivity} = \text{Throughput}(\propto \text{EUV Power}) \times \text{Availability}}$$

$$\boxed{\text{EUV Power}= (\underbrace{\text{CO}_2\ \text{laser power} \times \text{CE} \times \text{transmission})}_{\text{Raw EUV power}}*(1\text{-dose overhead})}$$

Source power **from 10 W to > 250 W**	Drive laser power	from 20 to 40 kW
	Conversion efficiency (CE)	from 1 to 6%
	Dose margin	from 50 to 10%
	Optical transmission	
Source availability	Automation	
	Collector protection	
	Droplet generator reliability & lifetime	
	Drive laser reliability	

EUV power scaling through 2016

$$\text{EUV power} \sim \text{CO}_2\ \text{power} * \text{Conversion Efficiency} * (1\text{-Dose Overhead})$$



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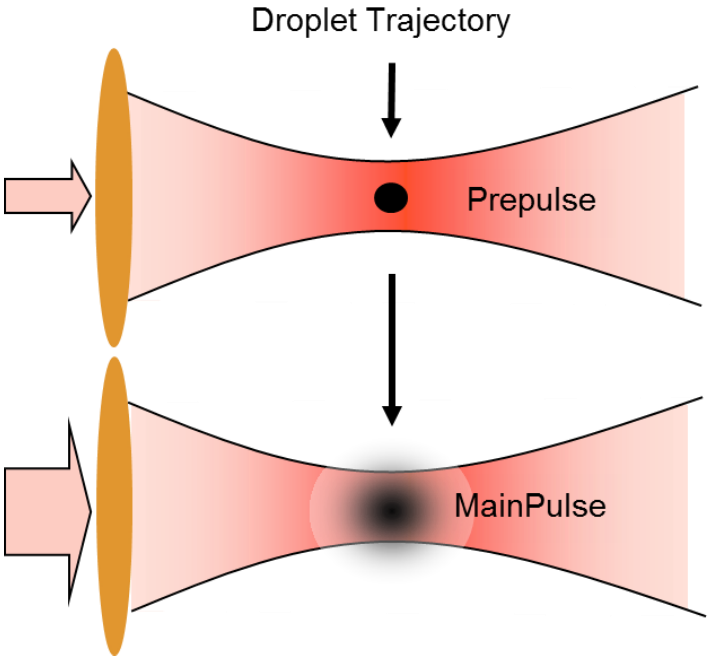
Pre-pulse technology

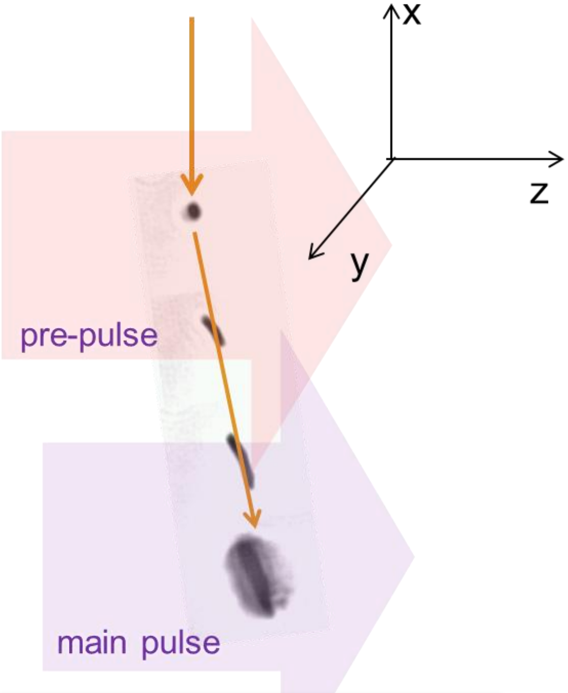
Conversion efficiency: Optimizing pre-pulse to create a

Target expansion fills main pulse beam waist

Prepulse
(low energy)

Mainpulse
(high energy)

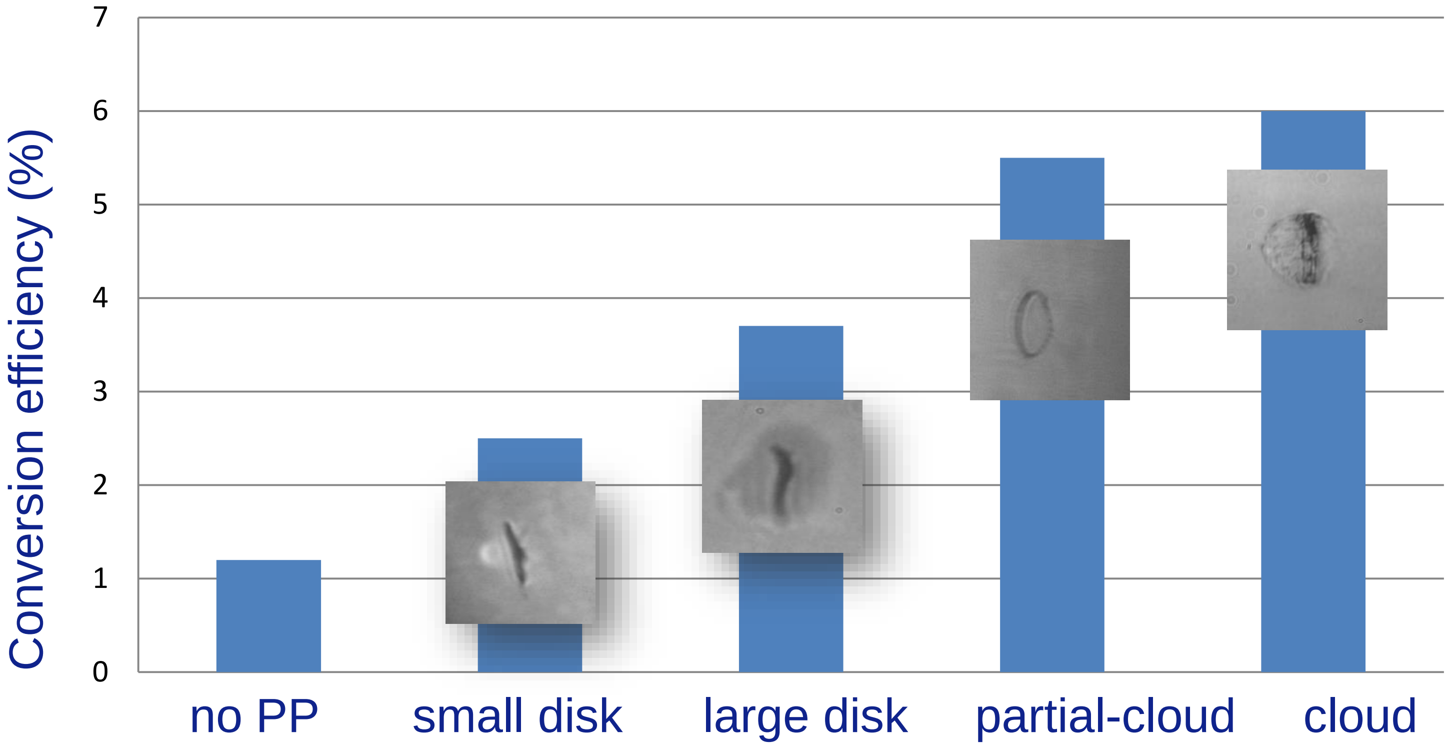




Target shape changes
from droplet to disk

Increased conversion efficiency with Pre-pulse

by optimization of target size, shape and density

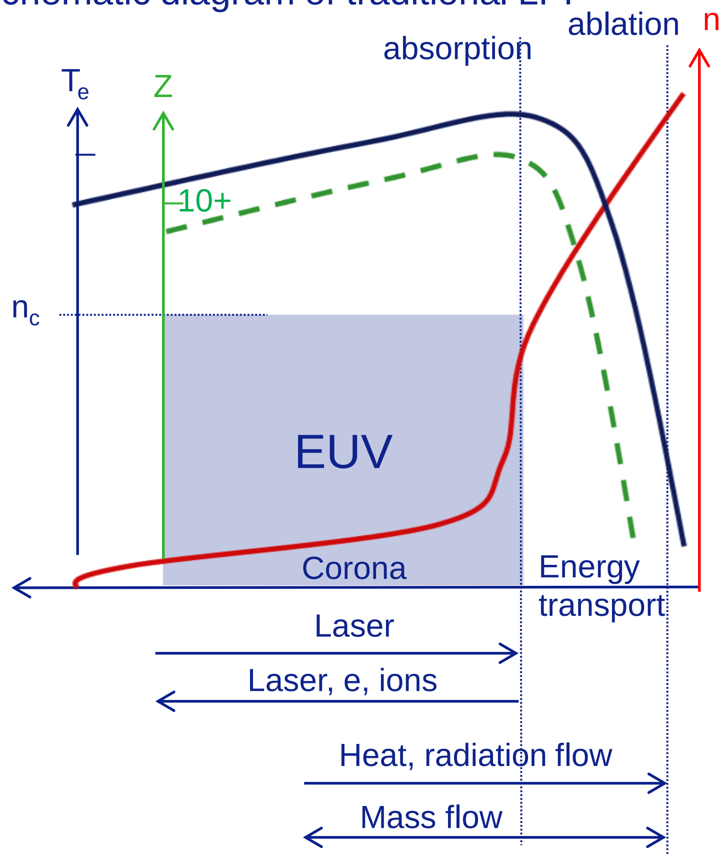


EUV CE ~6% demonstrated on development platforms

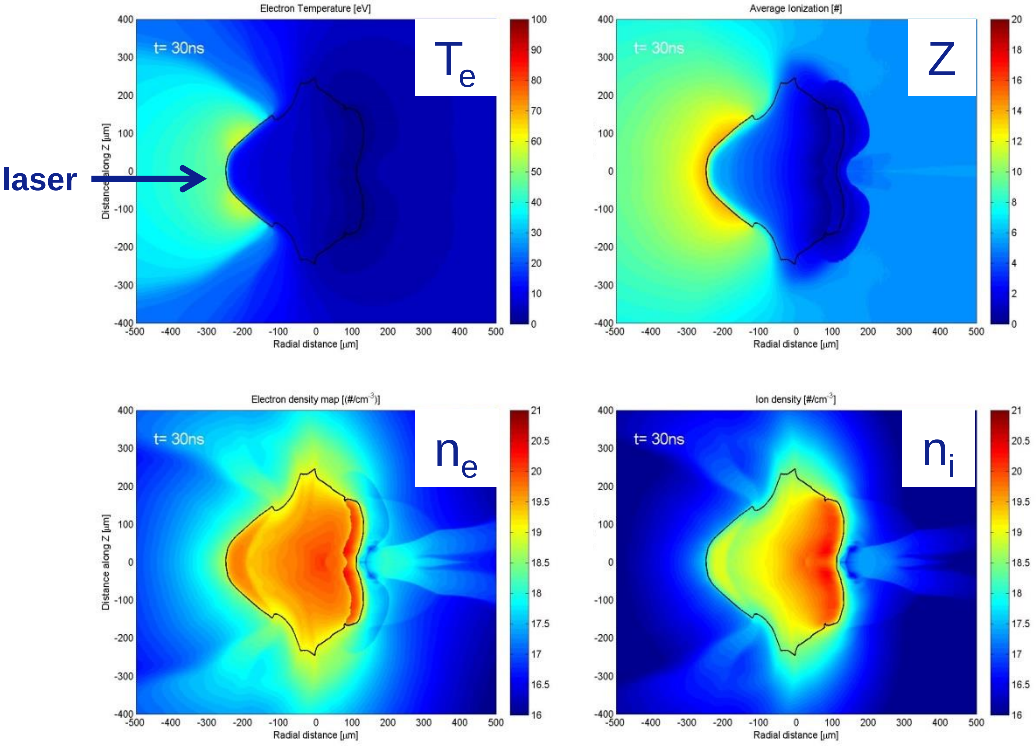
Plasma scale length (Z) is the key to increase its volume

Volume-distributed laser absorption enhances CO_2 laser deposition in plasma

Schematic diagram of traditional LPP



Hydrodynamic simulation of CO_2 Sn LPP



SPIE 2016, 97760K-1, Michael Purvis
“Advances in predictive plasma formation modelling”

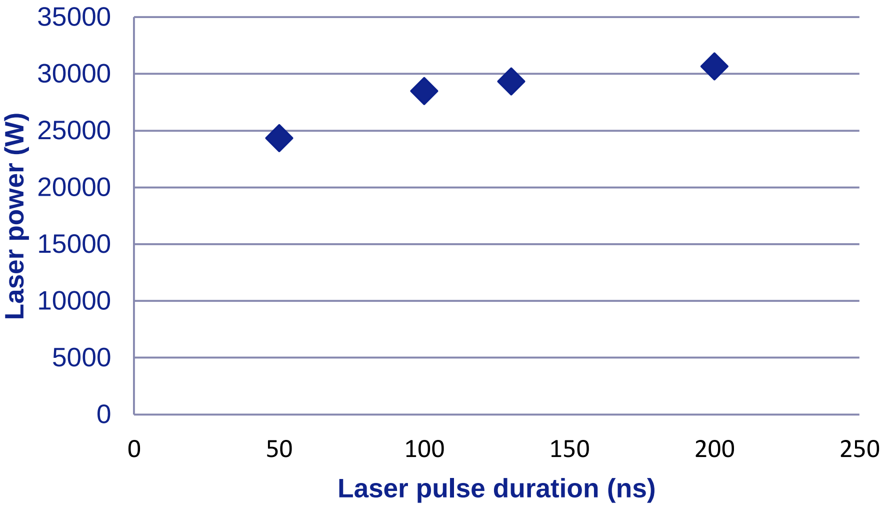
EUV Source, Drive Laser Development Progress

CO_2 laser power scaling to scale EUV power

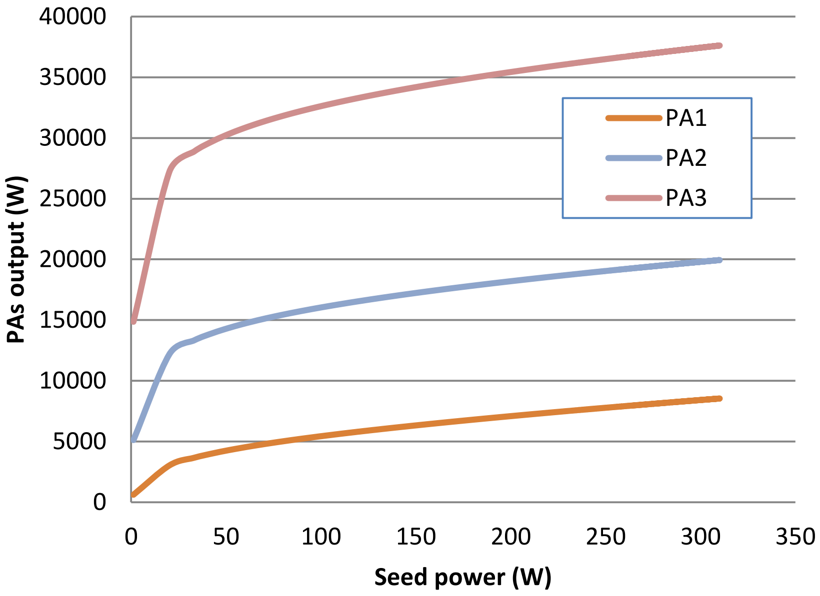
Efficient CO_2 laser pulse amplification

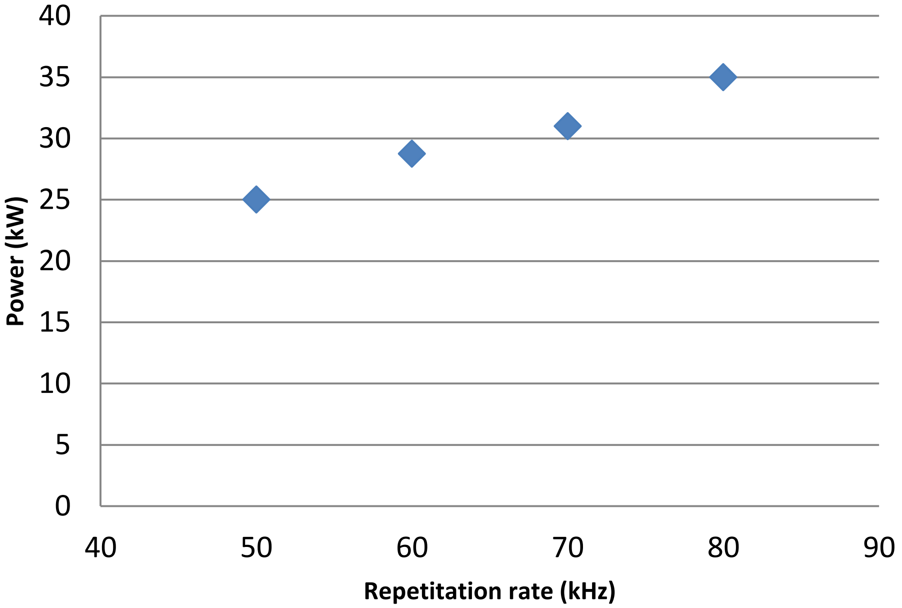
Throughput, WPH	**125**	**145**	**185**
EUV power (W)	250	350	500
CO_2 lase power (kW)	27	30	40

3300 CO_2 drive laser



CO_2 drive laser power scaling





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 and automation

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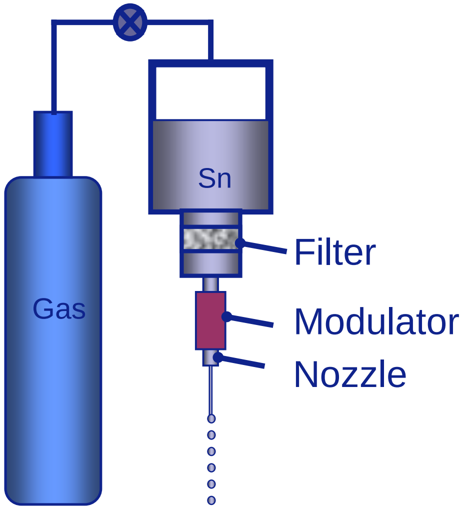
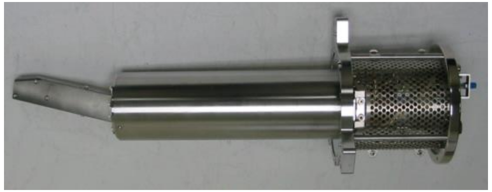
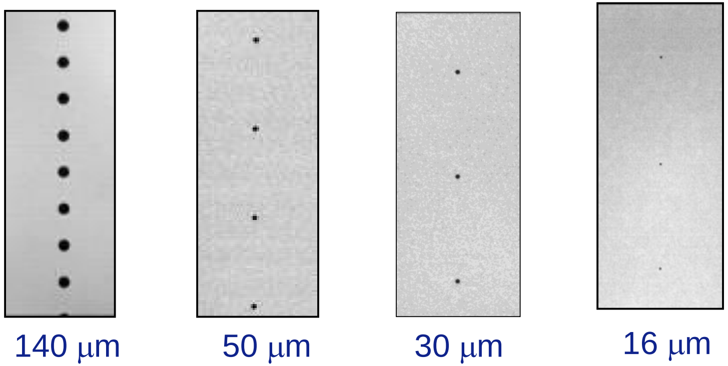
Droplet Generator

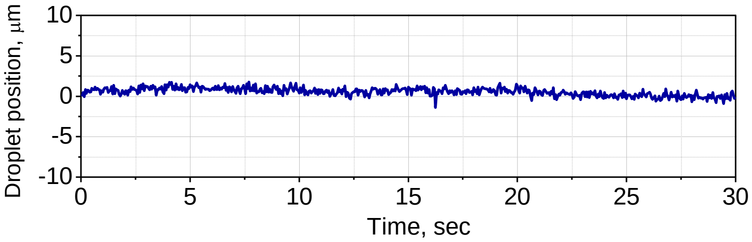
Droplet Generator, Principle of Operation

- 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



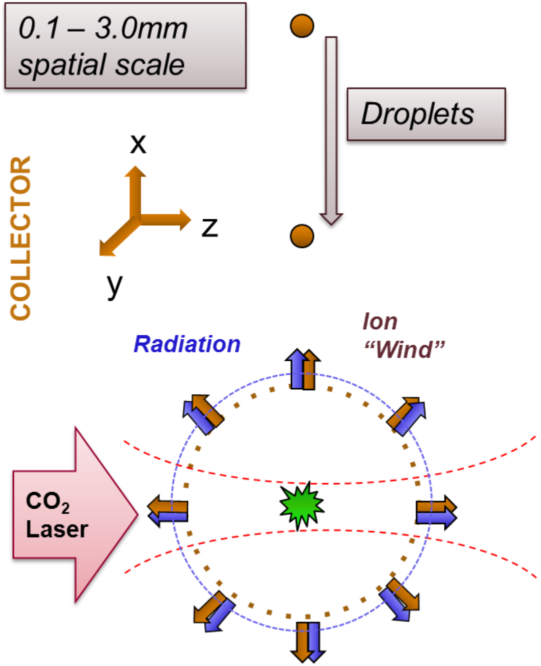






Short term droplet position stability σ~1μm

Forces on Droplets during EUV Generation

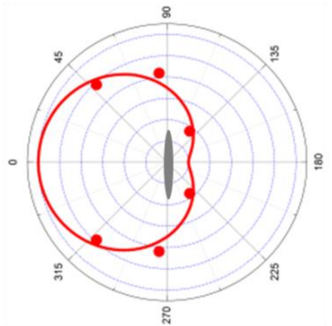


0.1 – 3.0mm spatial scale

Droplets

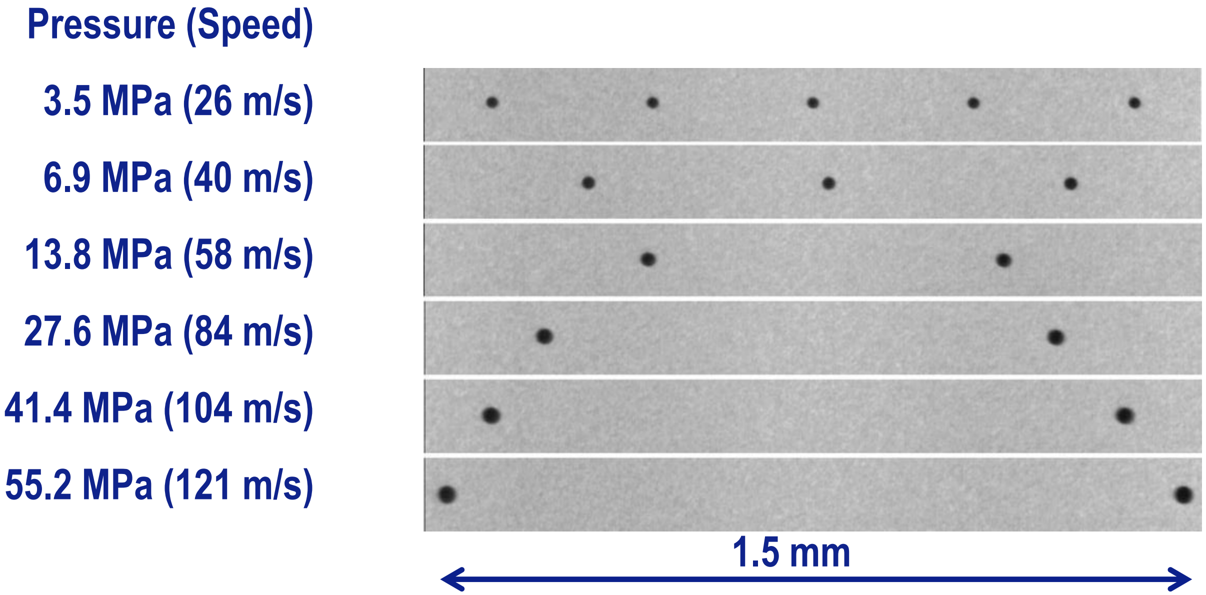
Measured Angular dependence of Forces on the droplets

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

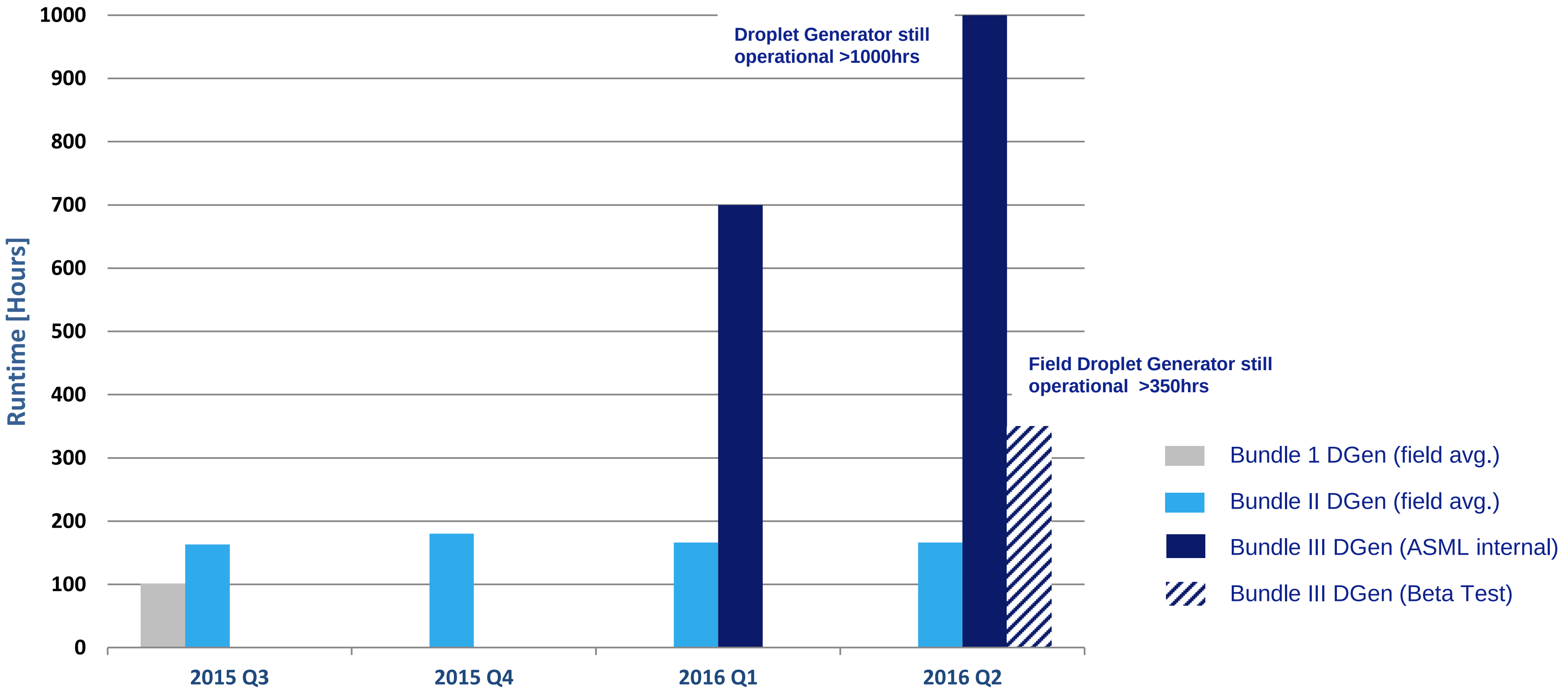
High Speed Droplet Generation



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

5x improvement in Droplet Generator run time demonstrated

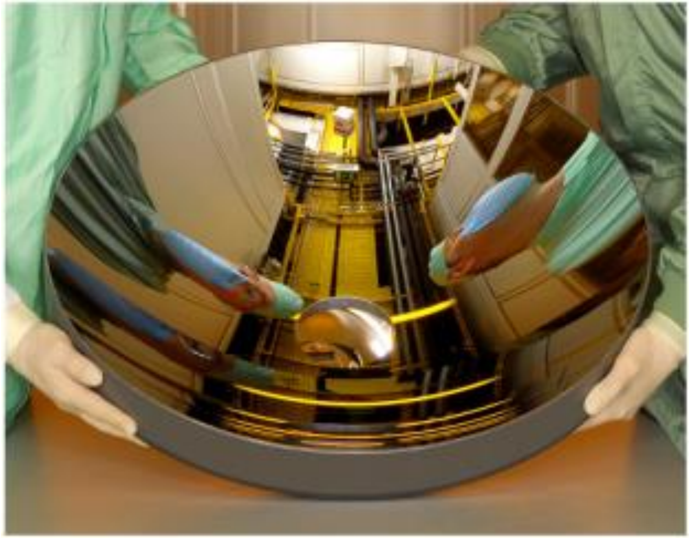
Data based on ASML internal testing; Field qualification started



EUV Collector, Lifetime

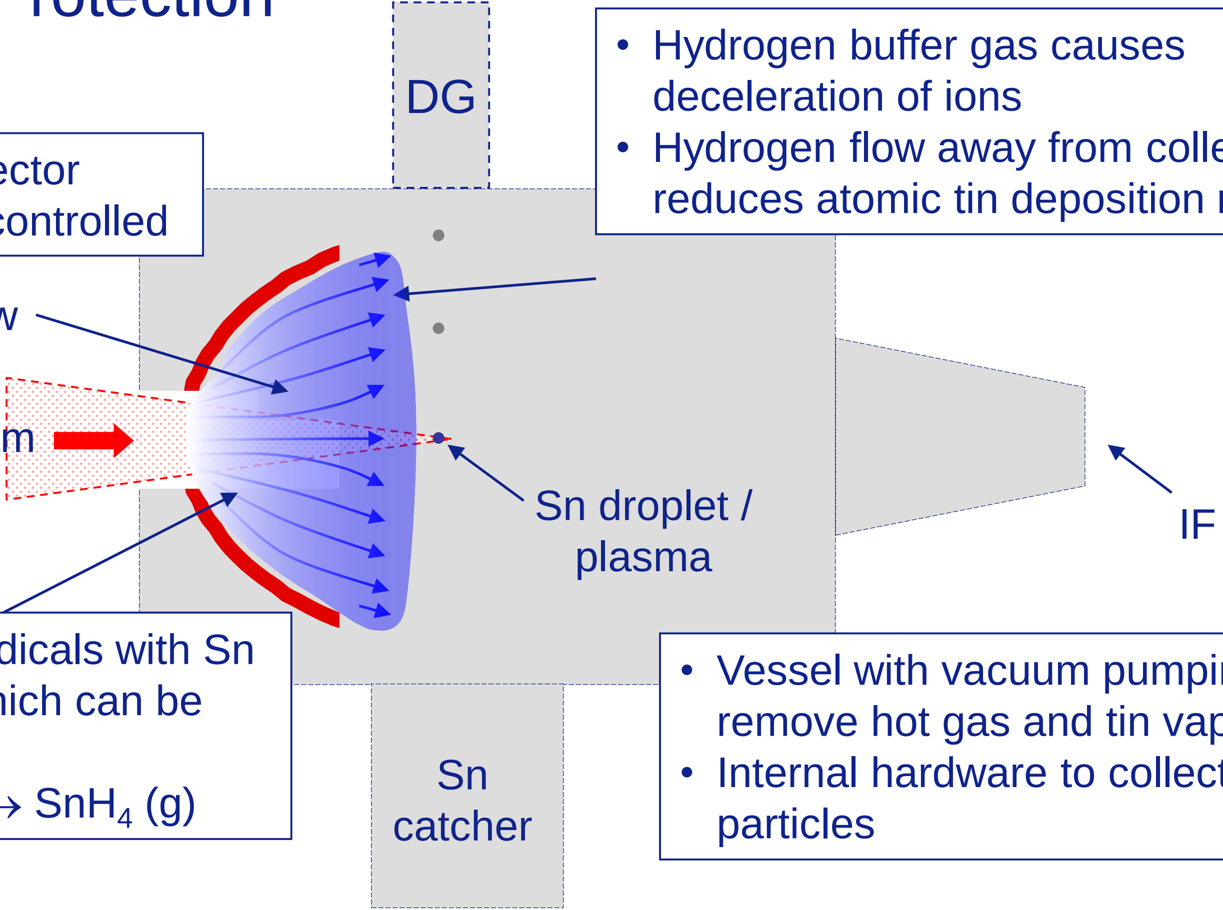
EUV Collector: Normal Incidence

- Ellipsoidal design
  - Plasma at first focus
  - Power delivered to exposure tool at second focus (intermediate focus)
- 650 mm diameter
- Collection solid angle: 5 sr
- Average reflectivity: > 40%
- Wavelength matching across the entire collection area



5sr Normal Incidence Graded Multilayer Coated Collector

Collector Protection



EUV collector
Temperature controlled

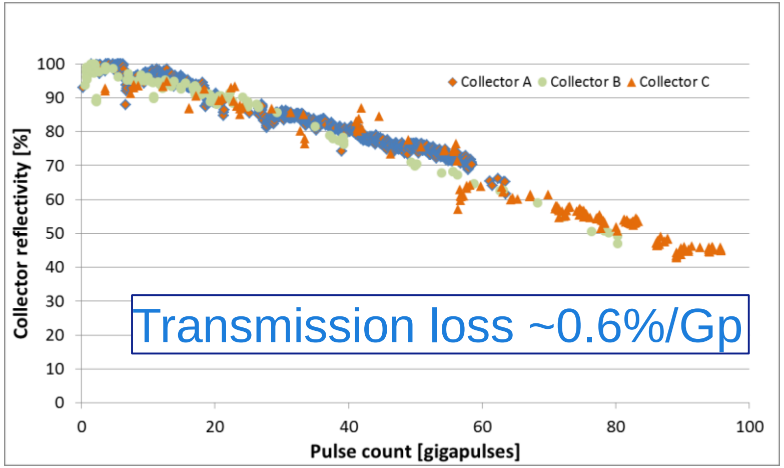
- Hydrogen buffer gas causes deceleration of ions
- Hydrogen flow away from collector reduces atomic tin deposition rate

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

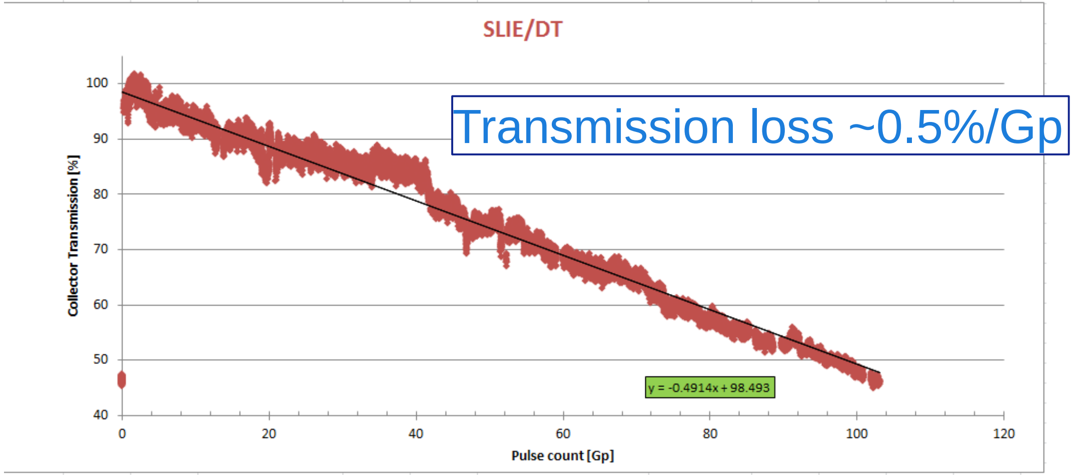
- Vessel with vacuum pumping to remove hot gas and tin vapor
- Internal hardware to collect micro particles

Collector Lifetime on NXE:3300 Sources

UP2 configuration operating at 60-80W



Transmission loss ~0.6%/Gp

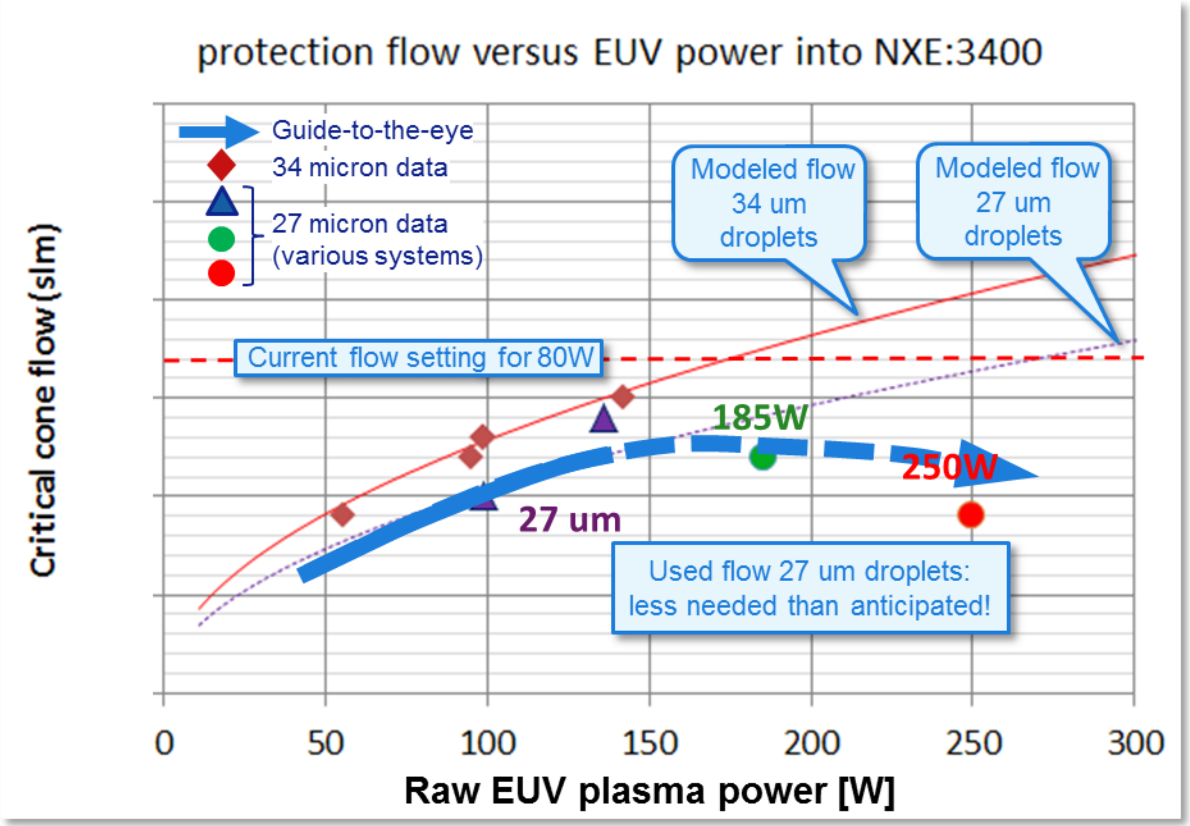


Transmission loss ~0.5%/Gp

- Collector lifetime ~3 months (~80Gp) on sources in the field
- Customer Demo (Q1'16): >100 Gpulse

250W feasibility proven without increase in protective Hydrogen flow

No rapid collector contamination, allowing stable droplets and >125 w/hr@20 mJ/cm²


protection flow versus EUV power into NXE:3400

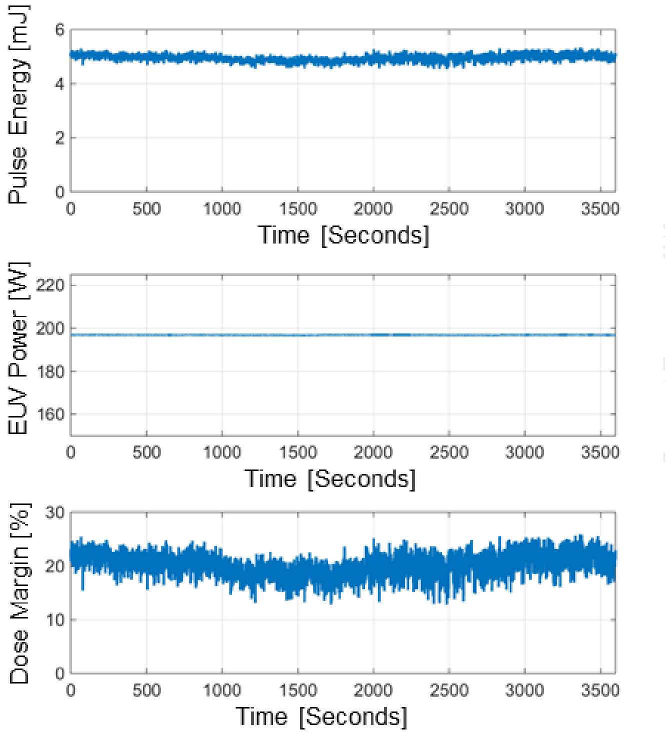
Modeled flow 34 um droplets

Modeled flow 27 um droplets

Current flow setting for 80W

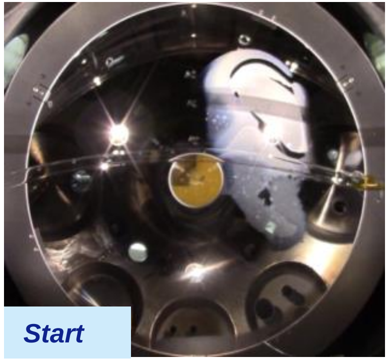
Used flow 27 um droplets: less needed than anticipated!

~200W dose controlled power

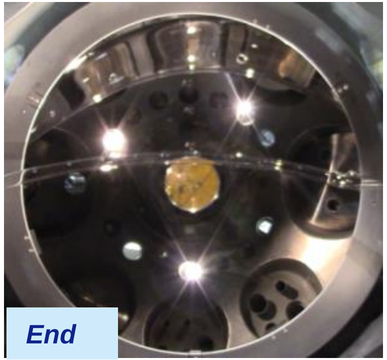


In-situ collector cleaning

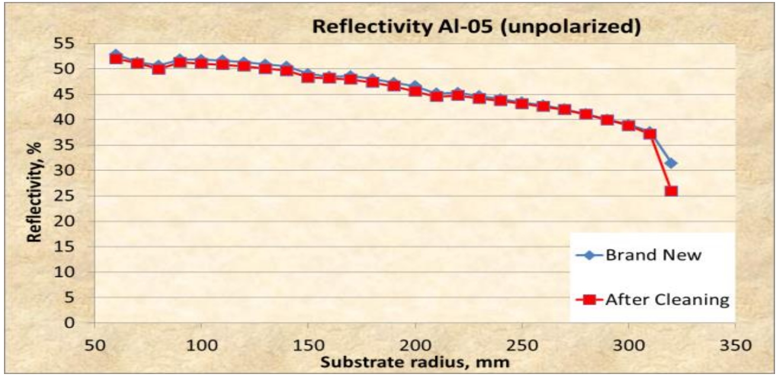
Effectiveness of product configuration confirmed



Start



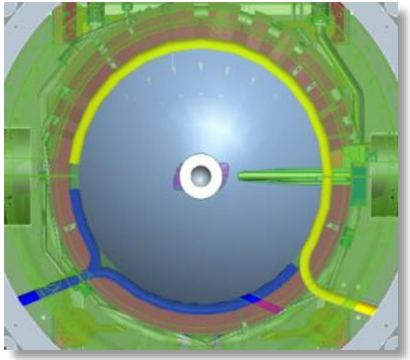
End



Reflectivity restored within 0.8% of original

Cleaning in off-line MOPA Prepulse development vessel

Field collector cleaned in NXE:3300 source vessel test rig



Start

End

Off-line cleaning using NXE:3300B source vessel with product configuration hardware

Summary: EUV readyness for volume manufacturing

- 8 NXE:3300B systems operational at customers
  - Completed qualification of five NXE:3350B, the 4th generation EUV exposure tool, one system qualified at 75 wph
  - Multiple systems demonstrated >1,000 wafers per day capability, with one system exceeding 1,350 wpd
  - 80W configuration operational in the field, 125W configuration qualification completed
  - 80% source availability capability demonstrated
  - Excellent NXE:3350B imaging and overlay performance at> 80W power
- Continuous progress in resist formulation promising towards enabling 13nm half pitch at high throughput

Summary

Significant progress in EUV power scaling,

- CE is up to 6 %
- Dose-controlled power is up to 210 W

CO_2 developments support EUV power scaling,

- Clean (spatial and temporal) amplification of short CO_2 laser pulse
- High power seed-table enables CO_2 laser power scaling

Significant progress made in Source Availability

- >80% source availability in the field
- >1000 hrs droplet generator runtime
- >100 Gp collector lifetime

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