EUV lithography: status, future requirements and challenges

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with the help of Rudy Peters, David Brandt, Igor Fomenkov, Maarten van Kampen, Andrei Yakunin, Vladimir Ivanov and many other people of ASML and Cymer

EUVL
Dublin

November 2013

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EUV is a cost effective solution

ASML

Public

EUV single exposure reduces Cost and Cycle Time vs. Multiple Patterning

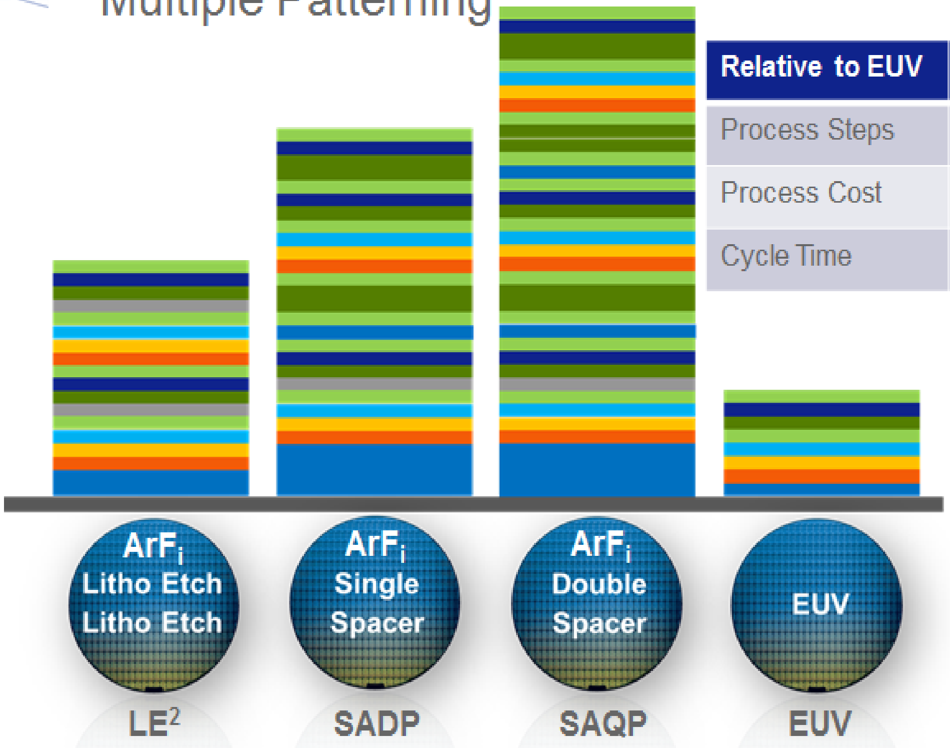
ASML

Relative to EUV	LE^2	SADP	SAQP
Process Steps	x2	x4	x5
Process Cost	+10%	+30~50%	+>50%
Cycle Time	x2	x4	x5

LE = Litho-Etch, n = number of iterations

SADP = Self Aligned Double Patterning

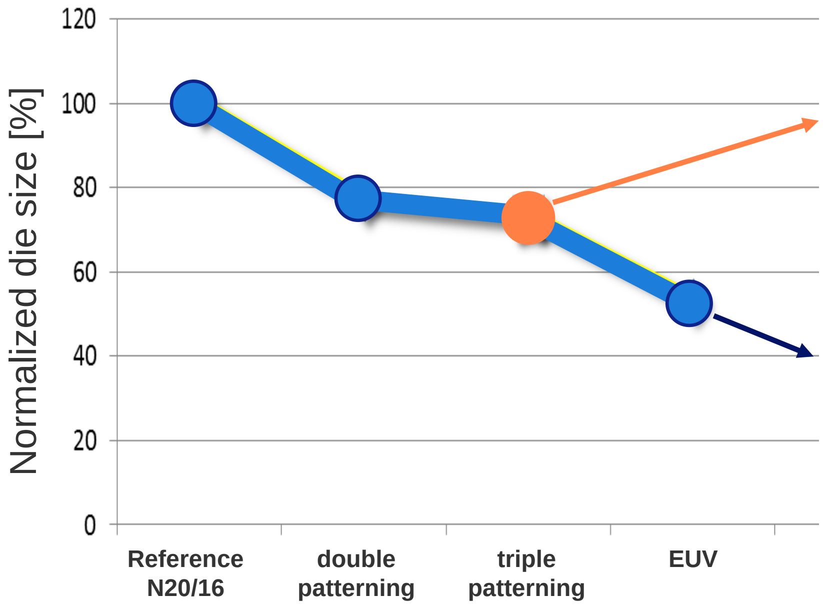
SAQP = Self Aligned Quadruple Patterning

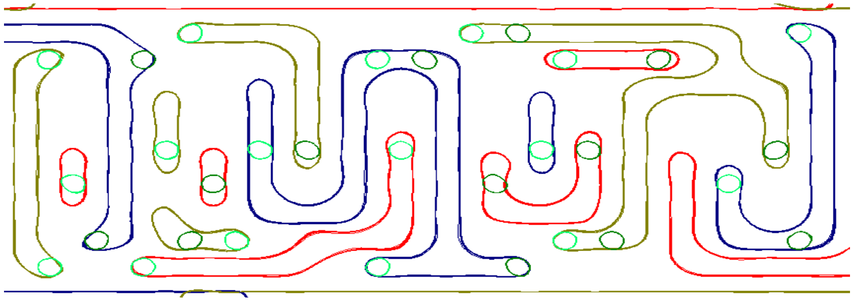


- Strip/clean
- Etch
- Defect inspection
- Metrology
- Develop
- Expose
- Coat
- CVD

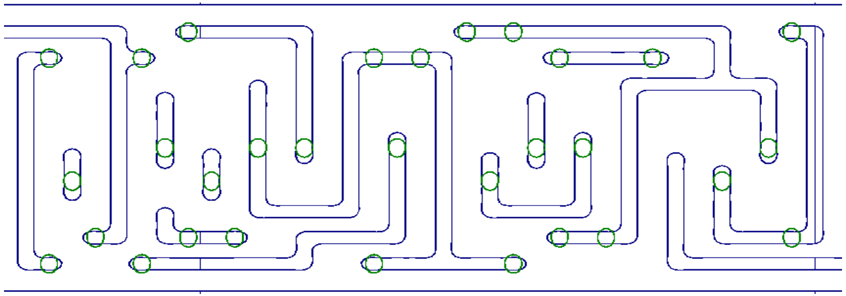
EUV enables 50% Scaling for the 10 nm logic node

Layout restrictions and litho performance limit shrink to ~25% using immersion





Triple patterning does not show a process window



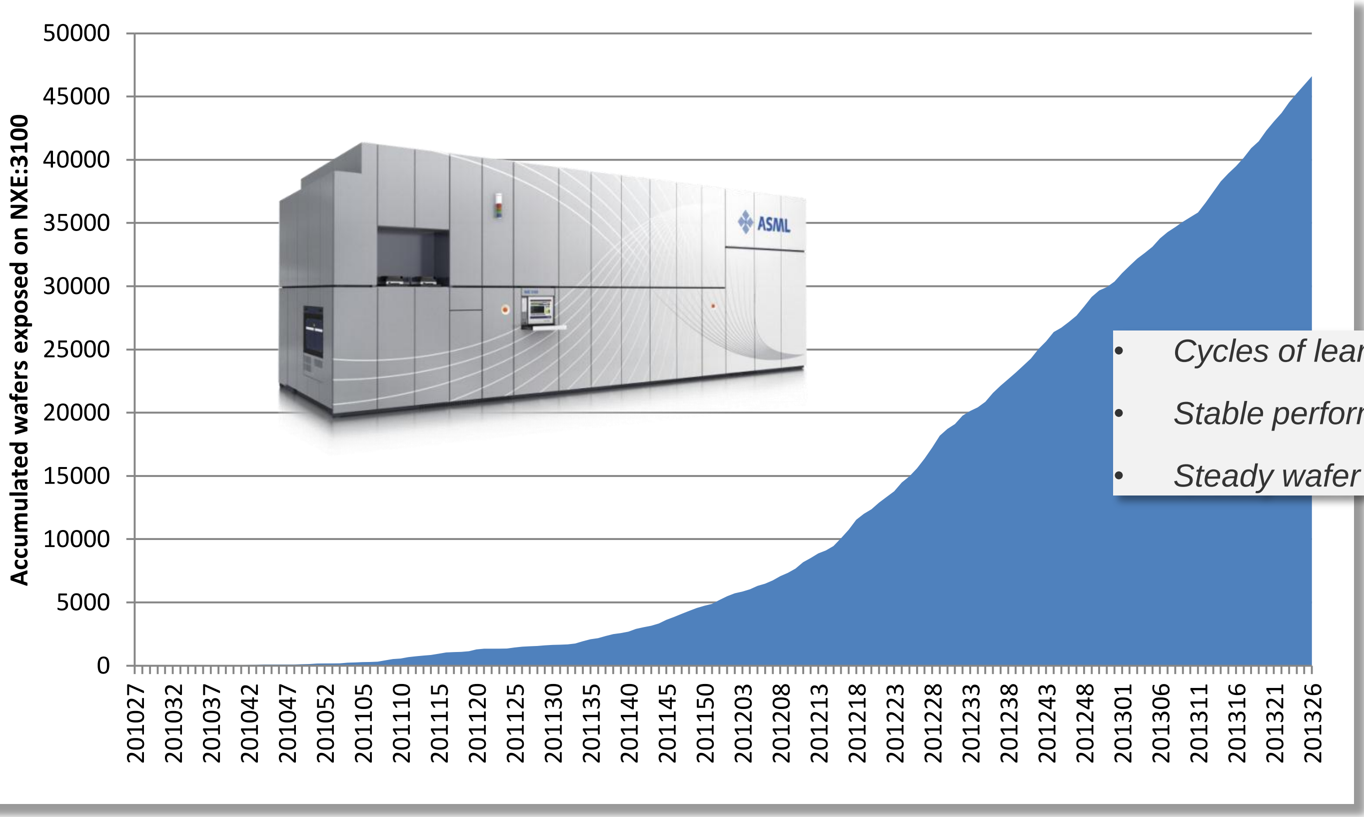
EUV meets all litho requirements

Source: ARM

ASML's NXE:3100 and NXE:3300B

	NXE:3100	NXE:3300B
NA	0.25	0.33
Illumination	Conventional 0.8 σ	Conventional 0.9 σ Off-axis illumination
Resolution	27 nm	22 nm
Dedicated Chuck Overlay / Matched Machine Overlay	4.0 nm / 7.0 nm	3.0 nm / 5.0 nm
Productivity	6 - 60 Wafers / hour	50 - 125 Wafers / hour
Resist Dose	10 mJ / cm2	15 mJ / cm2

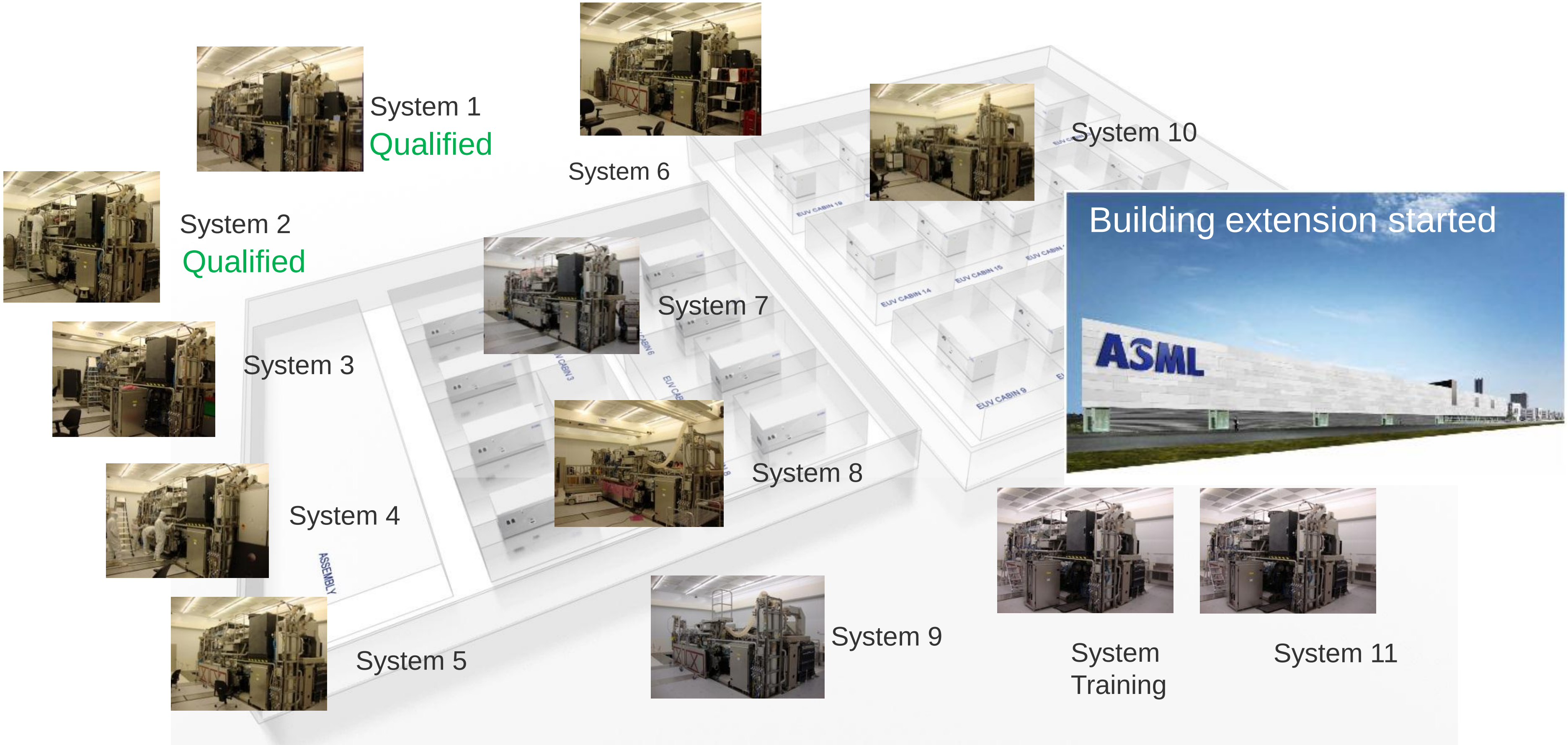
The NXE:3100 has exposed >46,000 wafers



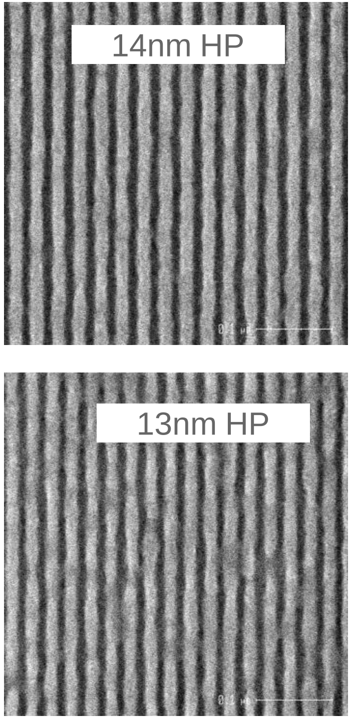
- *Cycles of learning*
- *Stable performance*
- *Steady wafer output*

Contents

Eleven NXE:3300B systems in various states of integration

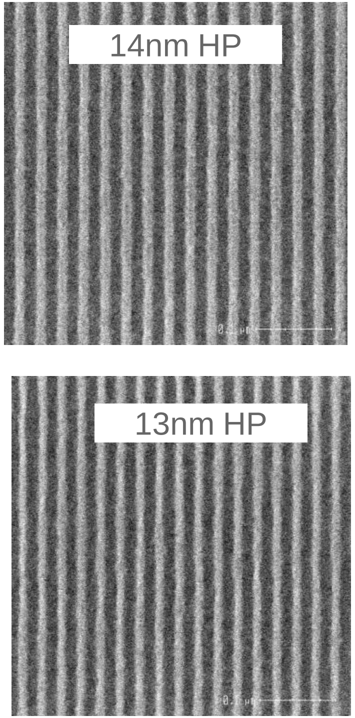


Resolution shown on NXE:3300B for dense line spaces, regular and staggered contact holes; all single exposures



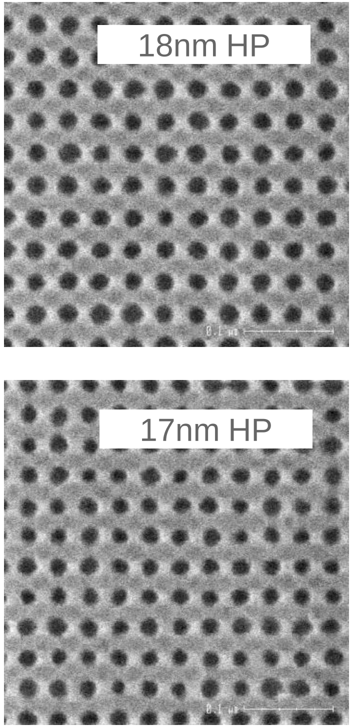
Dipole30,

Chemically Amplified Resist (CAR)

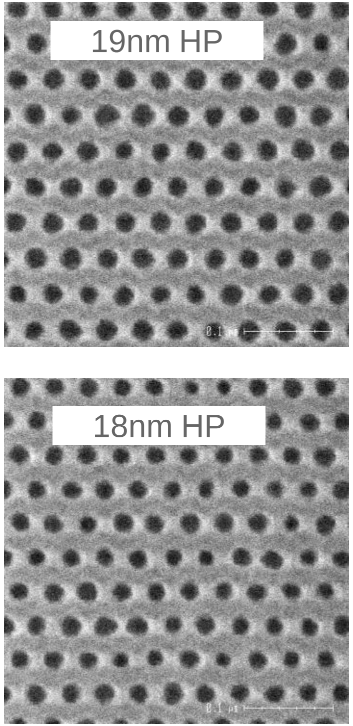


Dipole45,

Inpria Resist



Quasar 30 (CAR)



Large Annular (CAR)

NXE:3300B enables single exposure random logic metal layer with large DoF *minimum HP 23 nm (N10 logic cell)*

focus

-80nm
-60nm
-40nm
-20nm
0nm
20nm
40nm
60nm
80nm

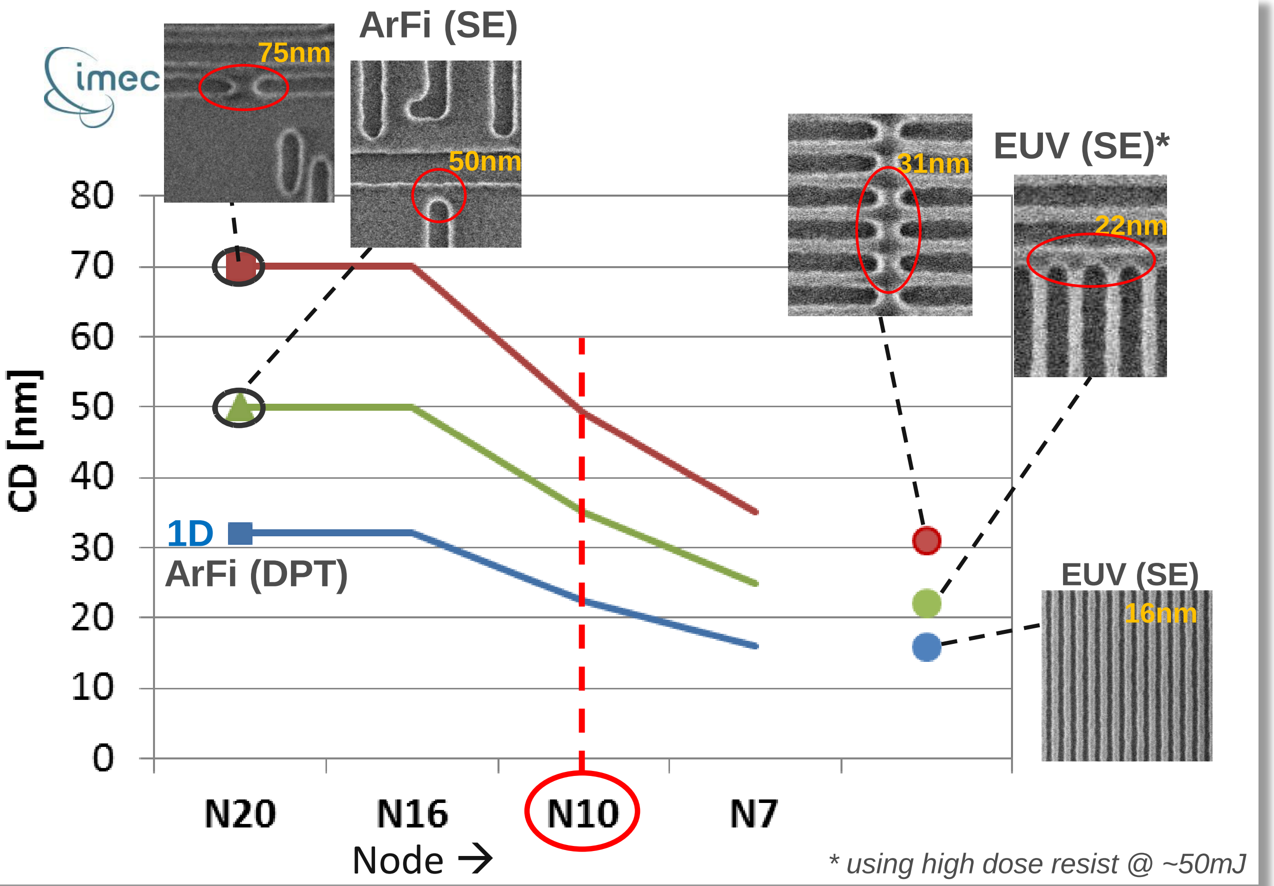
EUV	ArF immersion
▪ Node: N10 (23nm HP) ▪ **Target insertion point for EUV**	▪ Node: N20 (32nm HP)
▪ Single Exposure ▪ Conventional illumination	▪ Double Patterning (design split)
▪ Best focus difference ~10nm	▪ Best focus difference up to 40-60nm
▪ Overlapping DoF current 100..120nm *(expected to improve after further optimization (e.g. OPC))*	▪ Overlapping DoF typical ≈ 60nm

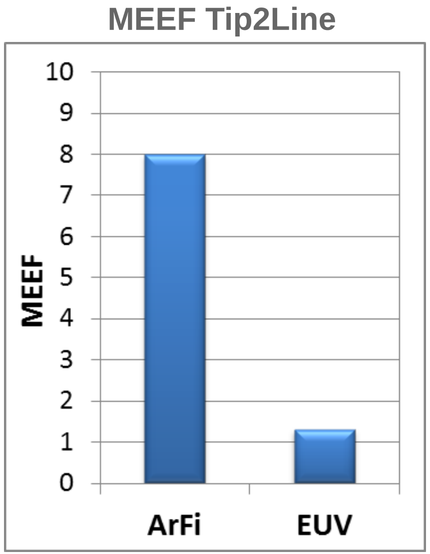
-12mm *0mm* *+12mm*

Excellent print performance over the full exposure slit

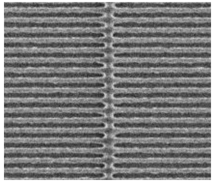
EUV enables aggressive shrink on 2D logic

shrink possible beyond N10 node requirement

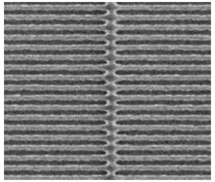




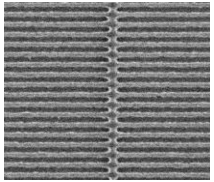
NXE3300B: Line ends imaging - tip2tip and tip2line - supports 10nm logic node with Quasar illumination



15 mJ/cm²

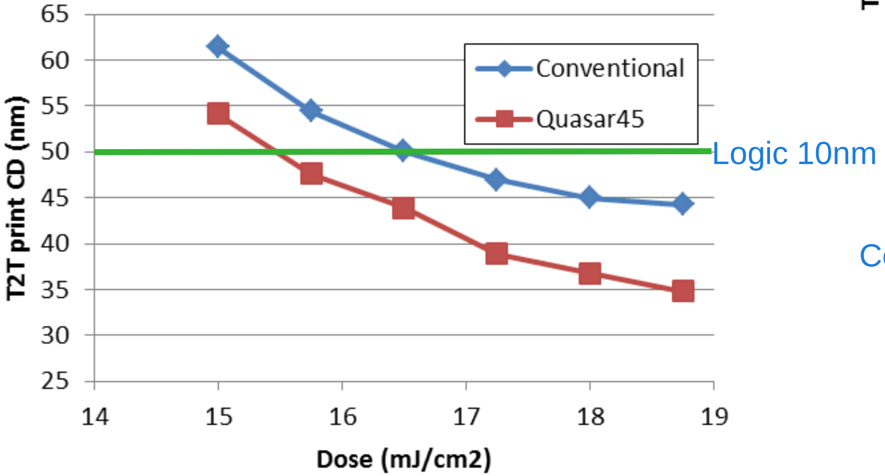


16.5 mJ/cm²

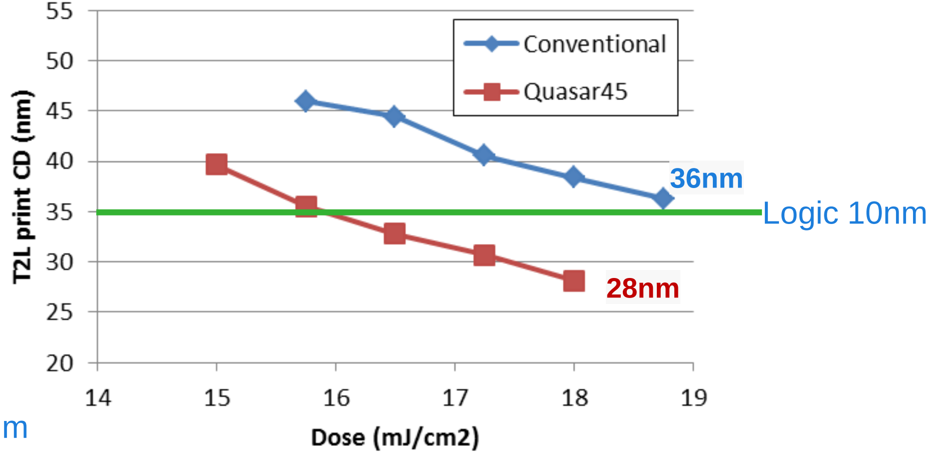


18 mJ/cm²

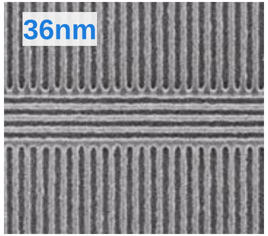
20nm mask gap 22nm L/S grating

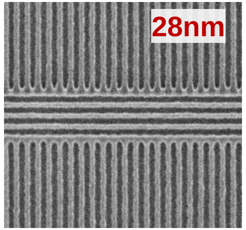


22nm mask gap



Conv.



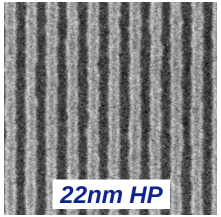


Quasar

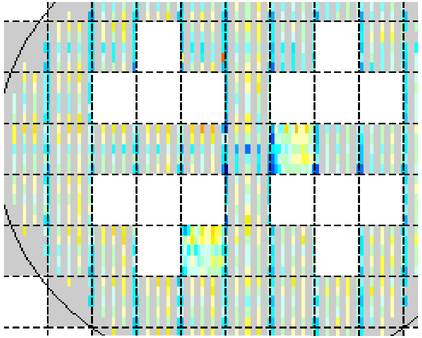
NXE:3300B imaging and overlay beyond expectations

matched overlay to immersion ~3.5nm

Scanner qualification

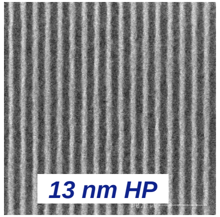


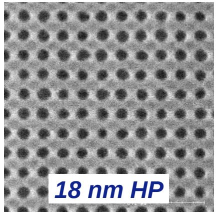
BE = 15.9 mJ/cm^2
EL = 13%
DoF = 160 nm

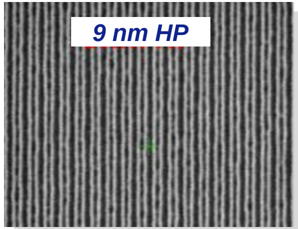


Full wafer CDU = 1.5nm

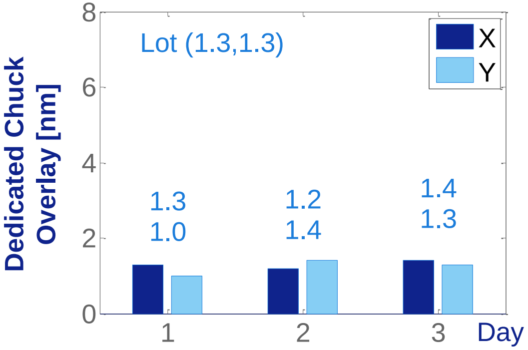
Scanner capability

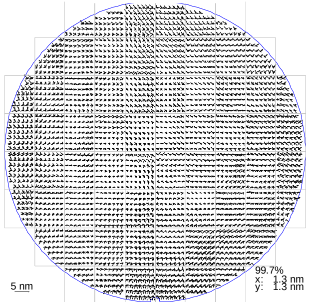


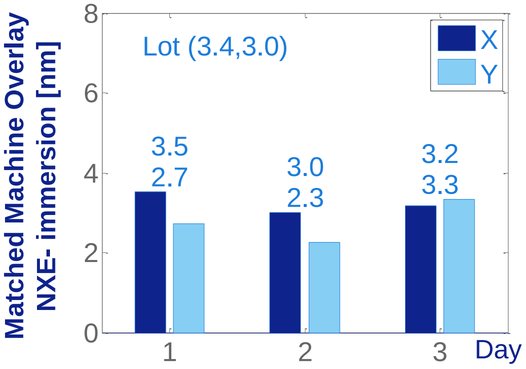


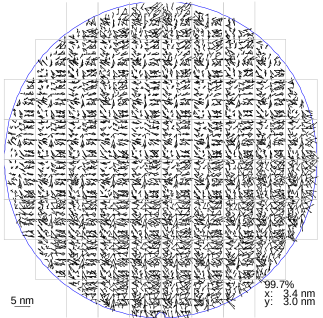


Single exposure EUV Spacer



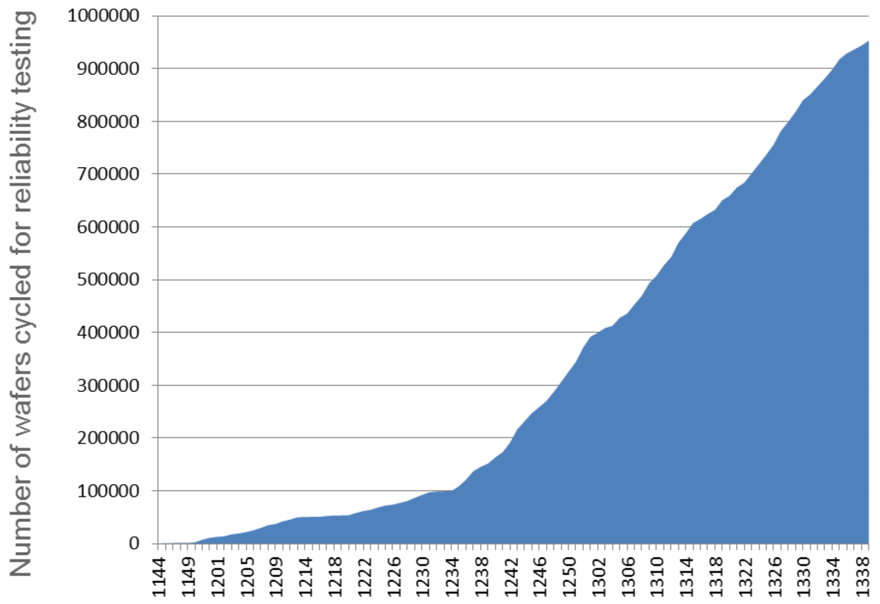






XT:1950i reference wafers
EEXY sub-recipes
18par (avg. field) +
CPE (6 par per field)

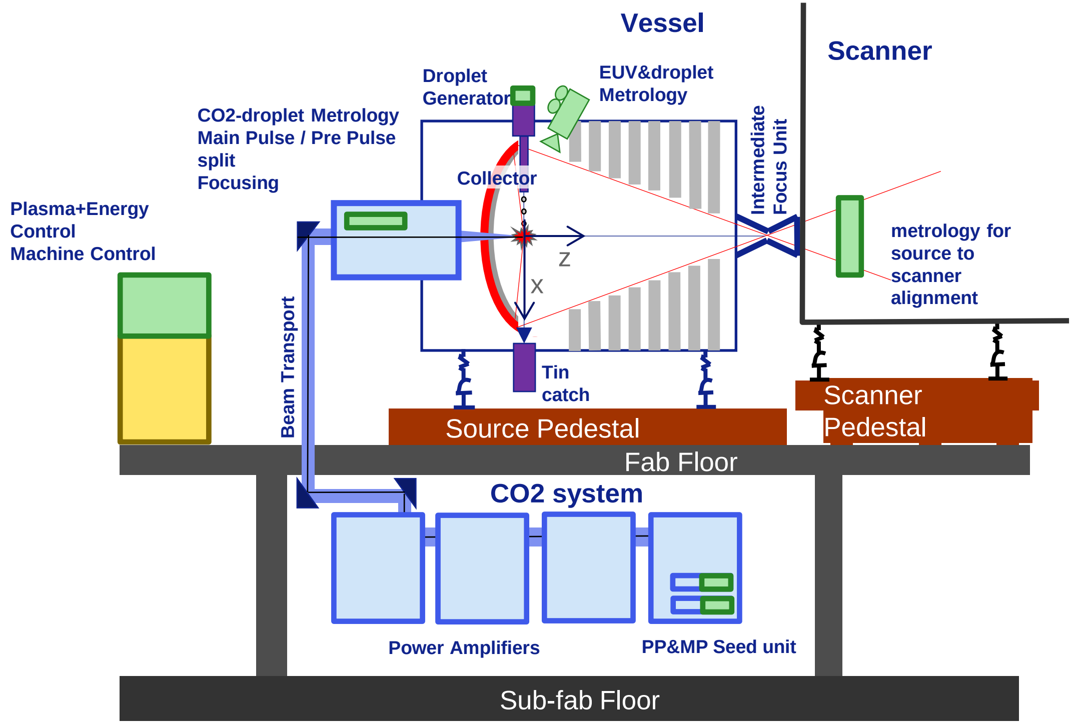
>900,000 wafer cycled on NXE:3300B for integration and reliability testing



		100 wafers per Hour	
	unit	Required	NXE 3300B results
Move parameters			
Step velocity	[m/s]	1	1
Scan velocity expose	[m/s]	0.25	0.25
Scan acceleration expose x/y	[m/s²]	35/25	35/25
Scan velocity measure	[m/s]	1	1
Jerk x/y	[m/s³]	3500/2500	3500/2500
WS accuracy at expose			
MA-xy	[nm]	1	1
MA-z	[nm]	6	4.2
MSD-xy	[nm]	2.2	2.1
MSD-z	[nm]	21	9.1
Total (WS-RS/4) accuracy at expose			
MA-xy	[nm]	0.6	0.4
MA-z	[nm]	6	4.2
MSD-xy	[nm]	2.5	1.9
MSD-z	[nm]	21	9.1

Contents

EUV source system cross-section



x=droplet stream direction, z=CO2 light direction, y=orthogonal

Key components:

- **Drive Laser**
- **Collector**

Power

- **Droplet generator**
- **Vessel**

Availability

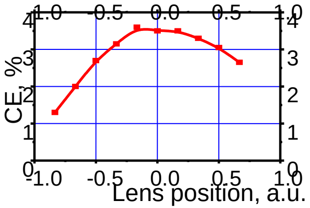
- **Controls (E,x,y,z,t)**
- **Final Focus Assembly**

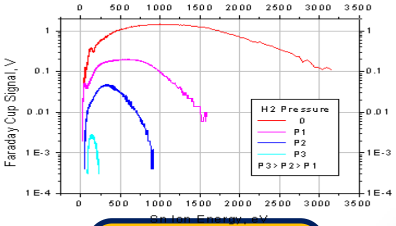
Dose control

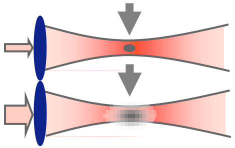
Source Cymer ASML company

Cymer/ASML LPP Source Development History

ASML







2006 2007 2008 2009 2010 2011 2012 2013

CO_2/Sn for high CE

1st source Development

Active gas debris mitigation

30μm droplets with wide spacing

First 5sr collector

Proto source integrated with scanner

MOPA + PP Development

3100 source shipment

Collector protection to 60W

Coatings for collector lifetime

SPF collector

CO_2 PP

Cymer/ASML cooperation established

Automated 50W MOPA+PP

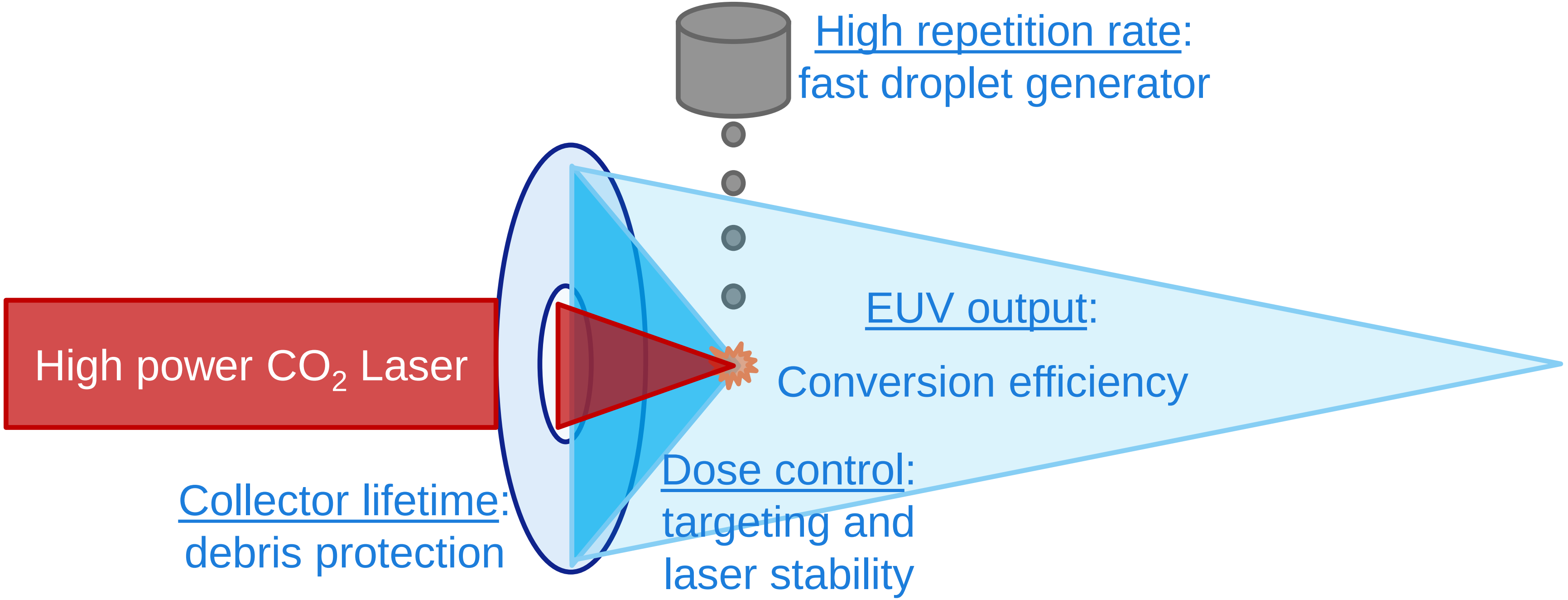
40W stable MOPA+PP

3300 Vessel shipment

3300 Source Shipment

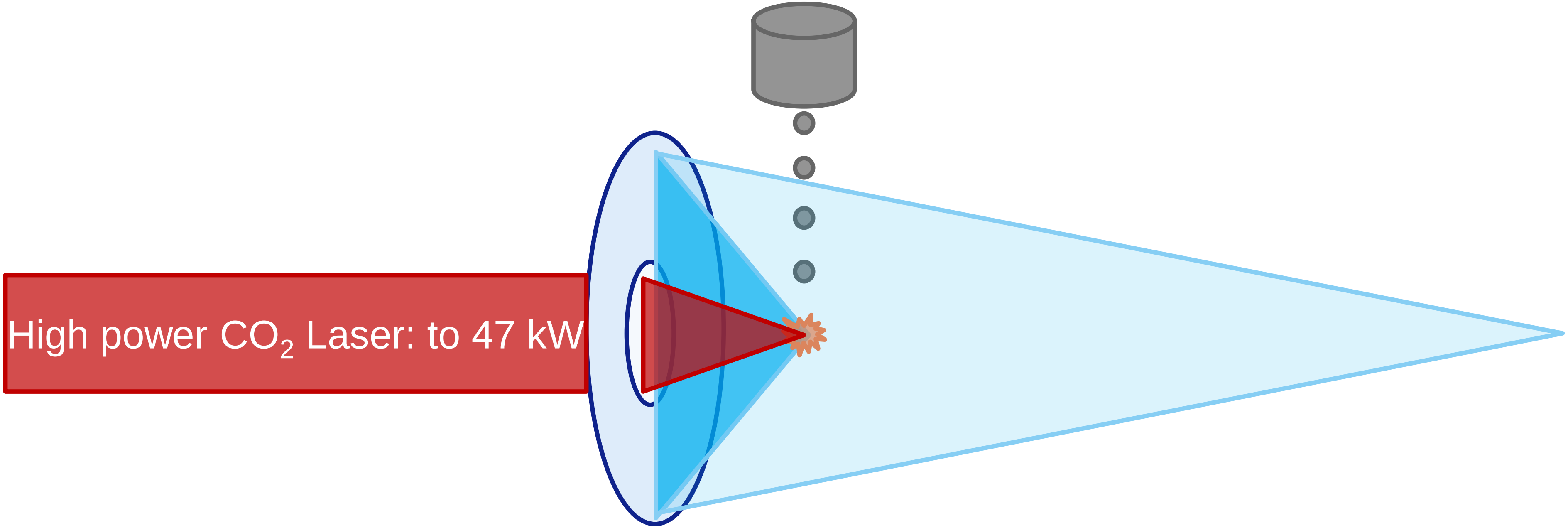
EUV Power Scaling

Top Technology Challenges



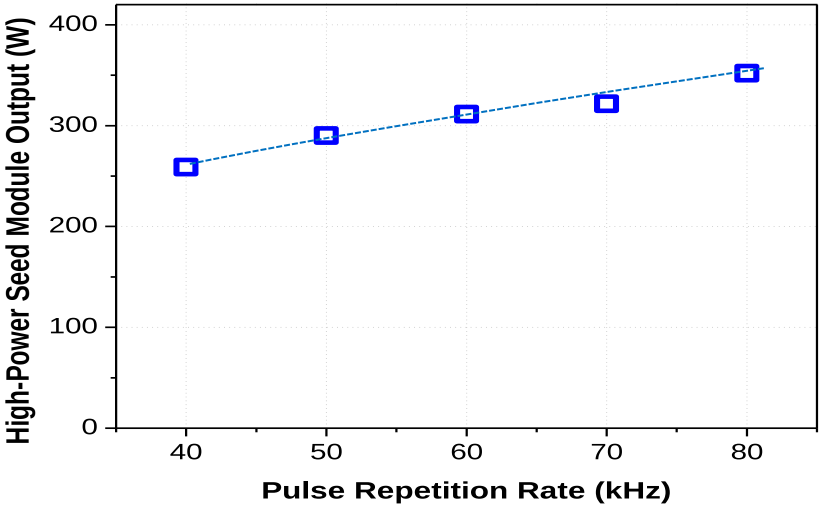
EUV Power Scaling

Top Technology Challenges



High Power Seed Laser is Key to the Drive Laser
350W at 80kHz Demonstrated

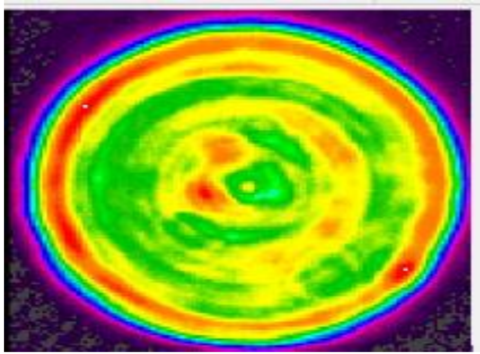
- Seed Laser power delivery to the amplifiers is critical to achieving saturation and maximum power extraction from the amplifiers
- 350W target design power at 80 kHz repetition rate
  - Already achieved in system-level bench testing

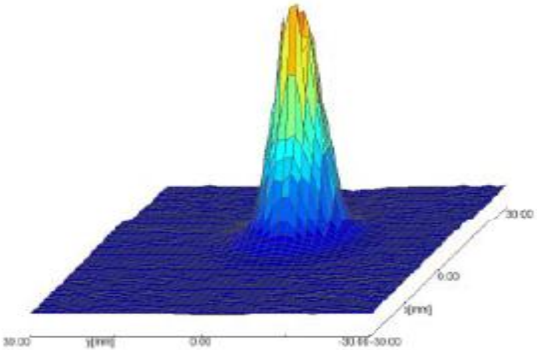


Source Cymer ASML company

New Amplifier for Increase Power is Operational
Reached maximum of 35kW with good laser mode profile

- Higher power amplifier development completed at supplier
- Repeatable, stable operation at ~35kW (increased from 20kW)
  - Single amplifier continuous (cw) output power
  - Pulsed mode operation is ~30% of cw
- Good beam quality measured → good focusability

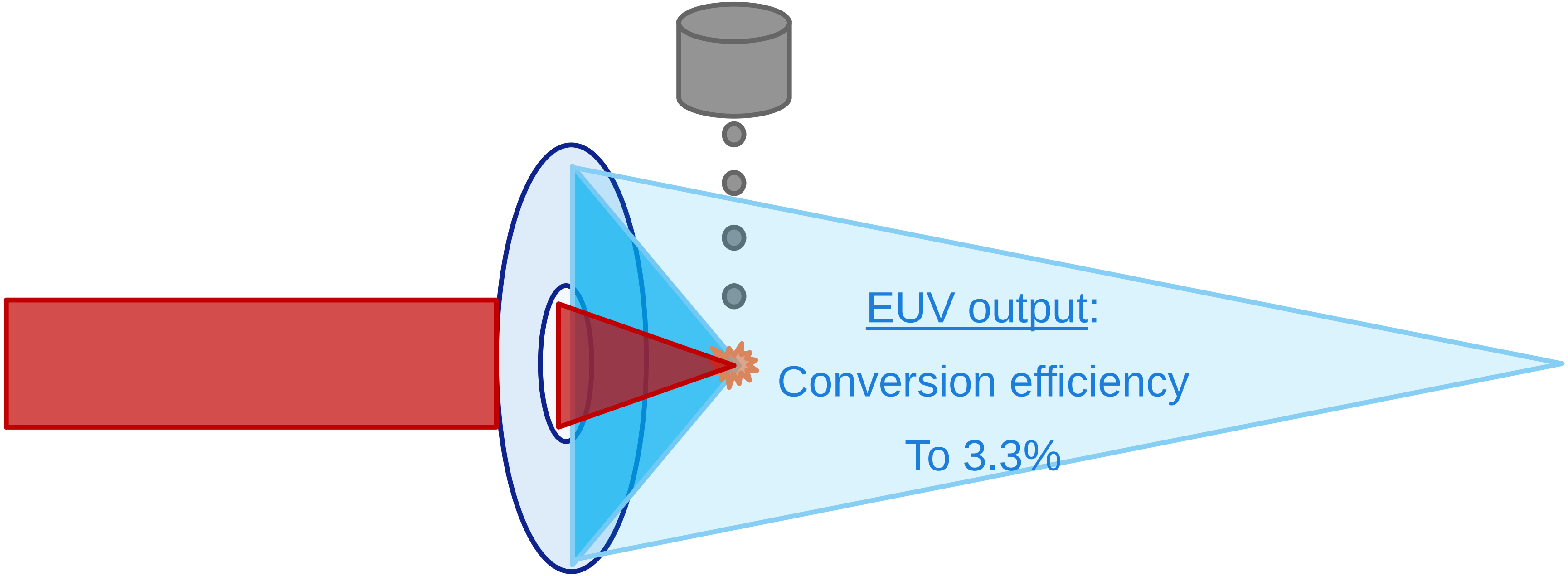




Source Cymer ASML company

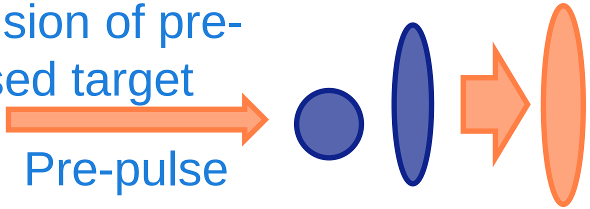
EUV Power Scaling

Top Technology Challenges



MOPA pre-pulse explained

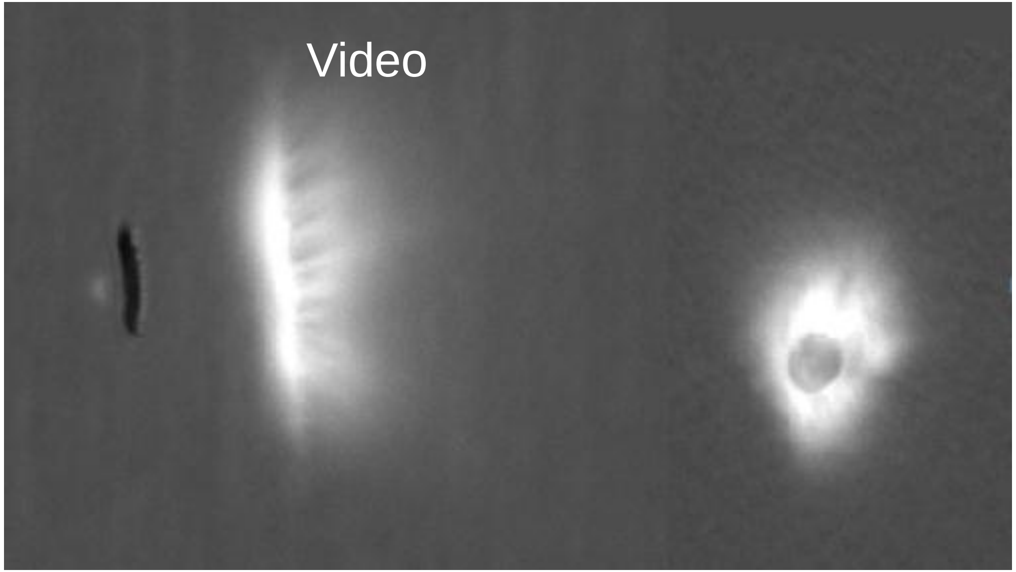
Expansion of pre-pulsed target



Pre-pulse

Shooting with the main pulse

Shadow-gram from the front

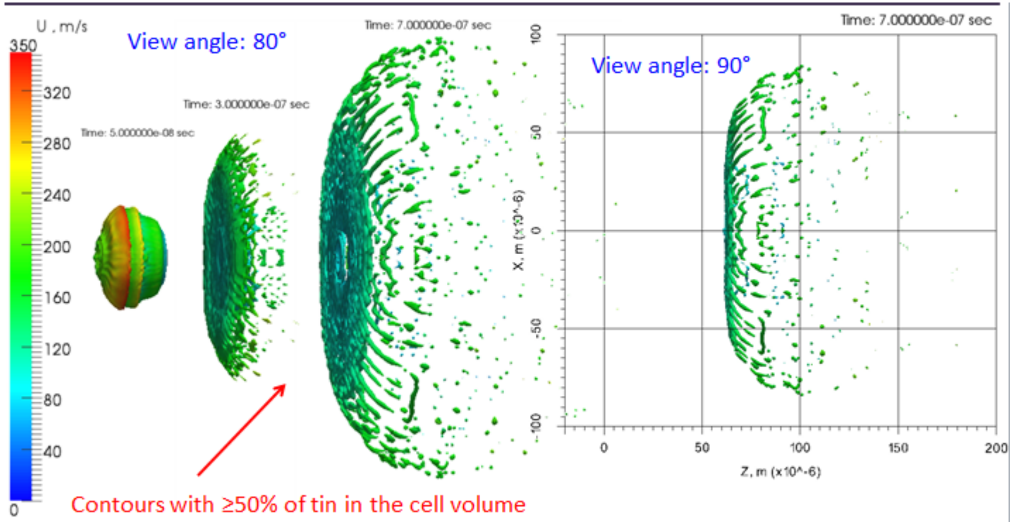


Shadow-gram from a side

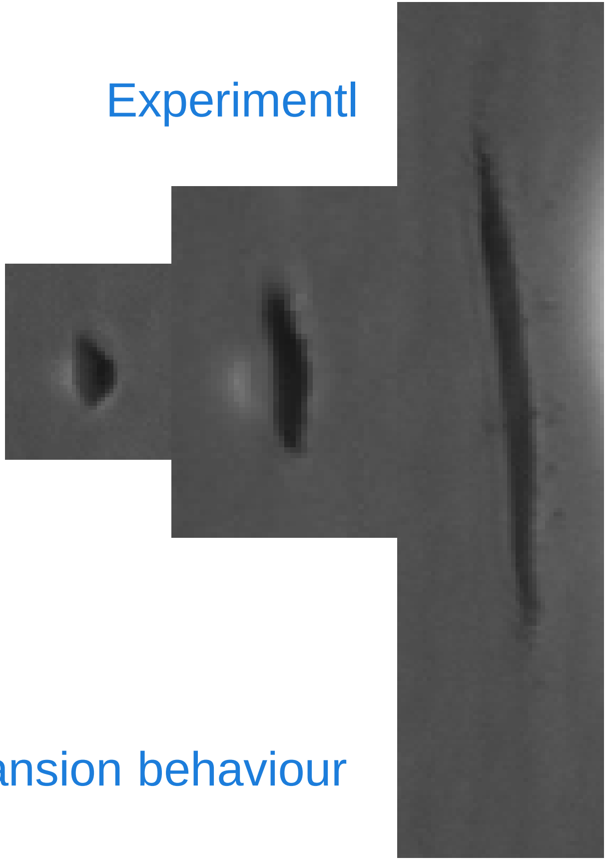
Diagnostics is at place to understand and tune the MOPA pre-pulse process

Modeling of the particle break down

Model



Experimentl

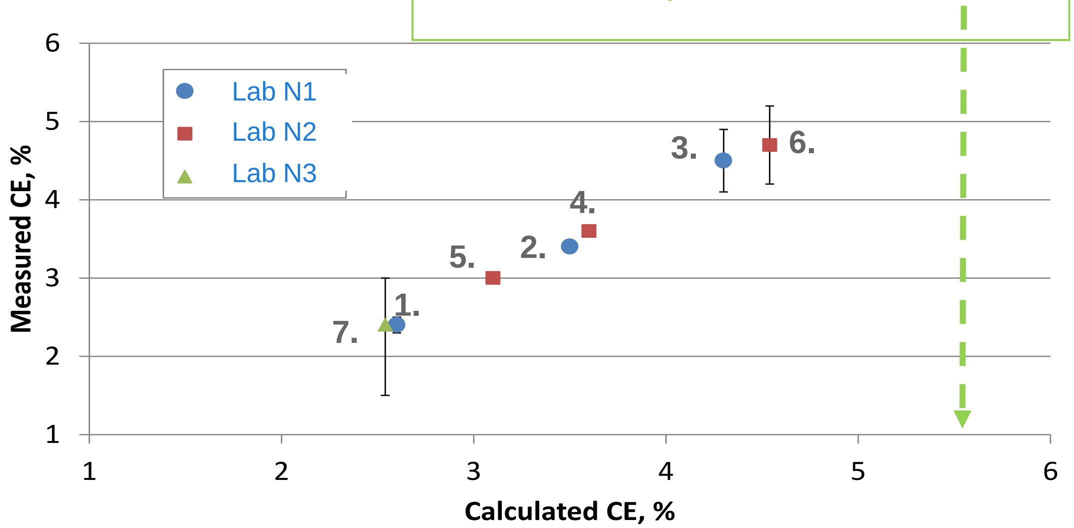


Model is being created to predict the droplet expansion behaviour

More on this in the presentation of V. Ivanov at this conference

CE: RZLINE vs measured for various target and laser configurations

Maximum predicted for optimal pulse shape CE=5.5%



Data points:

Lab N1

1. MOPA+PP; Type A
2. MOPA+PP; Type B
3. TEA; Plane target (E=0.3 J)

Lab N2:

4. MOPA+PP Type C
5. MOPA+ PP Type D
6. MOPA+ PP Type E

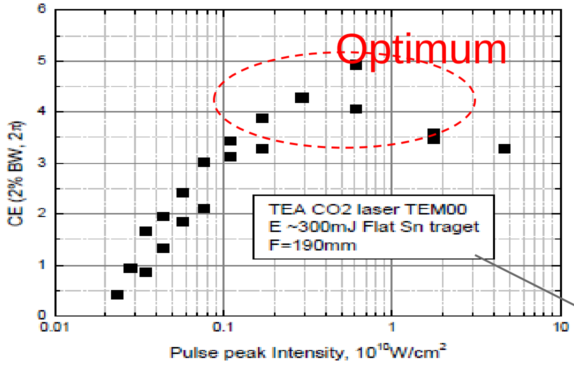
Lab N3:

7. Other wavelength

- No fitting parameters are used in the model
- RZLINE predicts well CE trend for various target geometries
- Maximum predicted CE=5.5% (for λ=10.6 um)

RZLINE vs experimental CE data on plane target (variation of laser spot size)

Cymer experiment (SPIE data)



Laser-Produced Plasma Light Source for EUVL

Igor V. Fomenkov*, David C. Brandt, Alexander N. Bykanov, Alex I. Ershov, William N. Partlo, David W. Myers, Norbert R. Böwering, Nigel R. Farrar, Georgiy O. Vaschenko, Oleh V. Khodykin, Jerzy R. Hoffman, Christopher P. Chrobak, Shailendra N. Srivastava, Daniel J. Golich, David A. Vidusek, Silvia De Dea, Richard R. Hou

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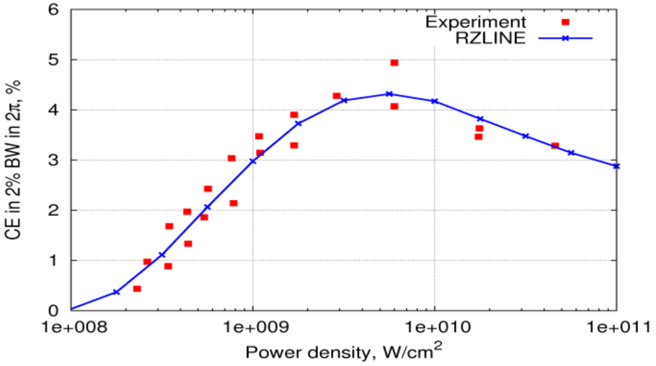
Cymer experiment vs RZLINE



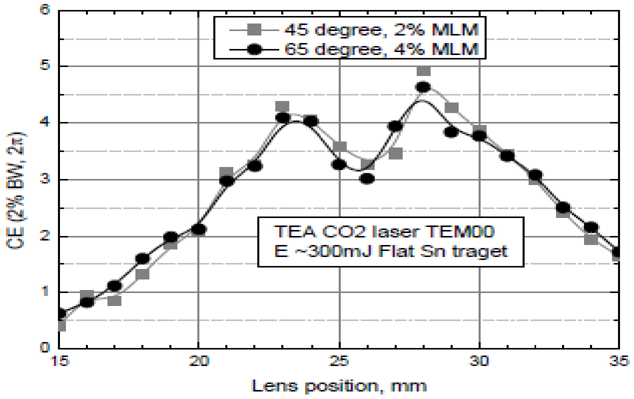
RZLINE parameters

- Sn flat target
- E=300 mJ
- F=190 mm
- CO2 laser

RZLINE predicts well optimal power density and general CE trend on plane target

RZLINE vs Cymer CE data on plane target (Z-variation)

Cymer experiment (SPIE data)



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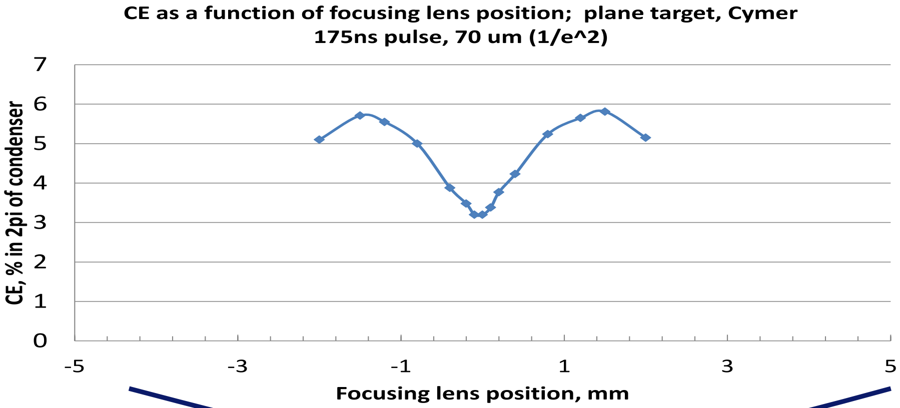
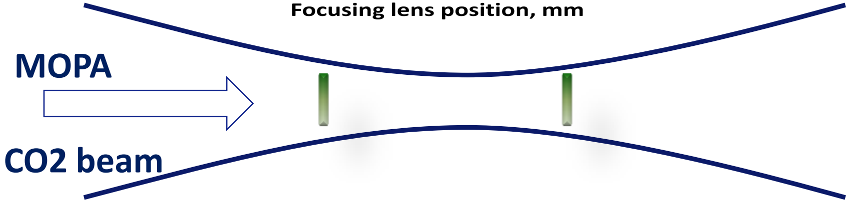
RZLINE with laser caustics



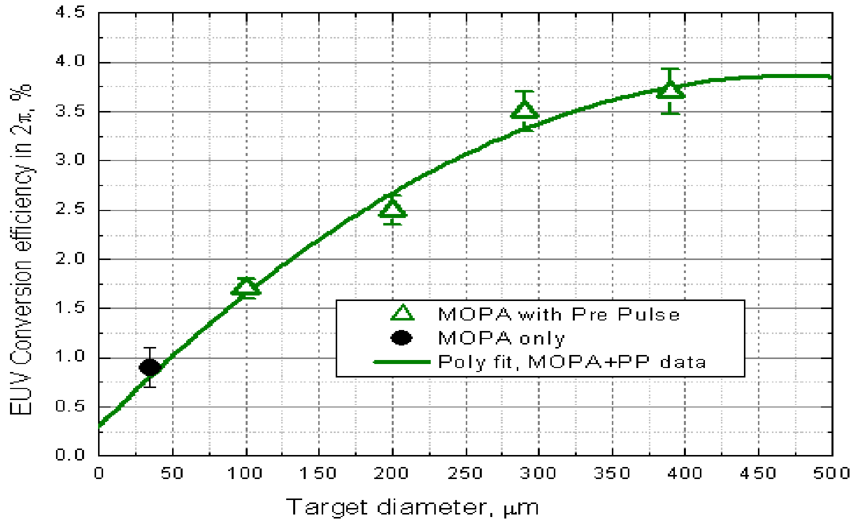


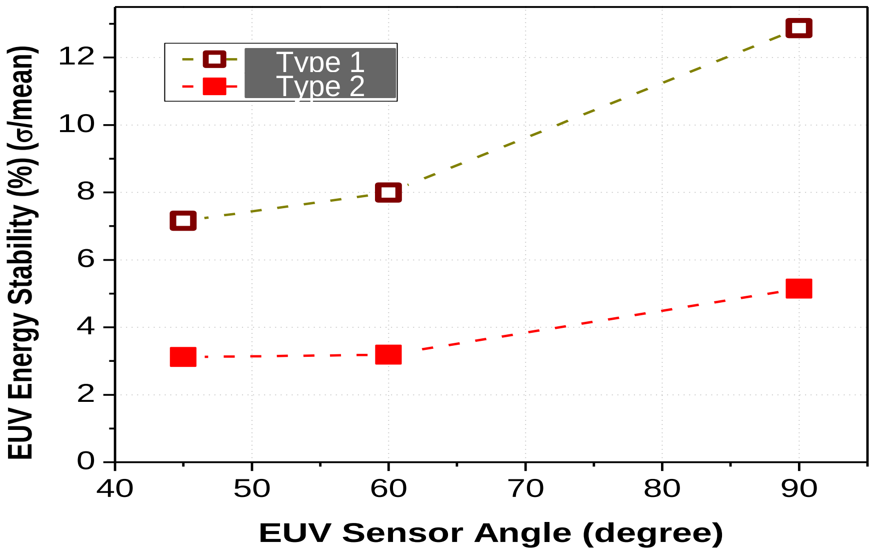
RZLINE reproduces "double hump" behavior of CE

This module is developed to account for back reflection of laser

MOPA Prepulse Technology for High Power Sources

Improved Prepulse shows 3.7% CE, driven by target size and stability (droplet and expanded target)





LT1 EUV power at low DC

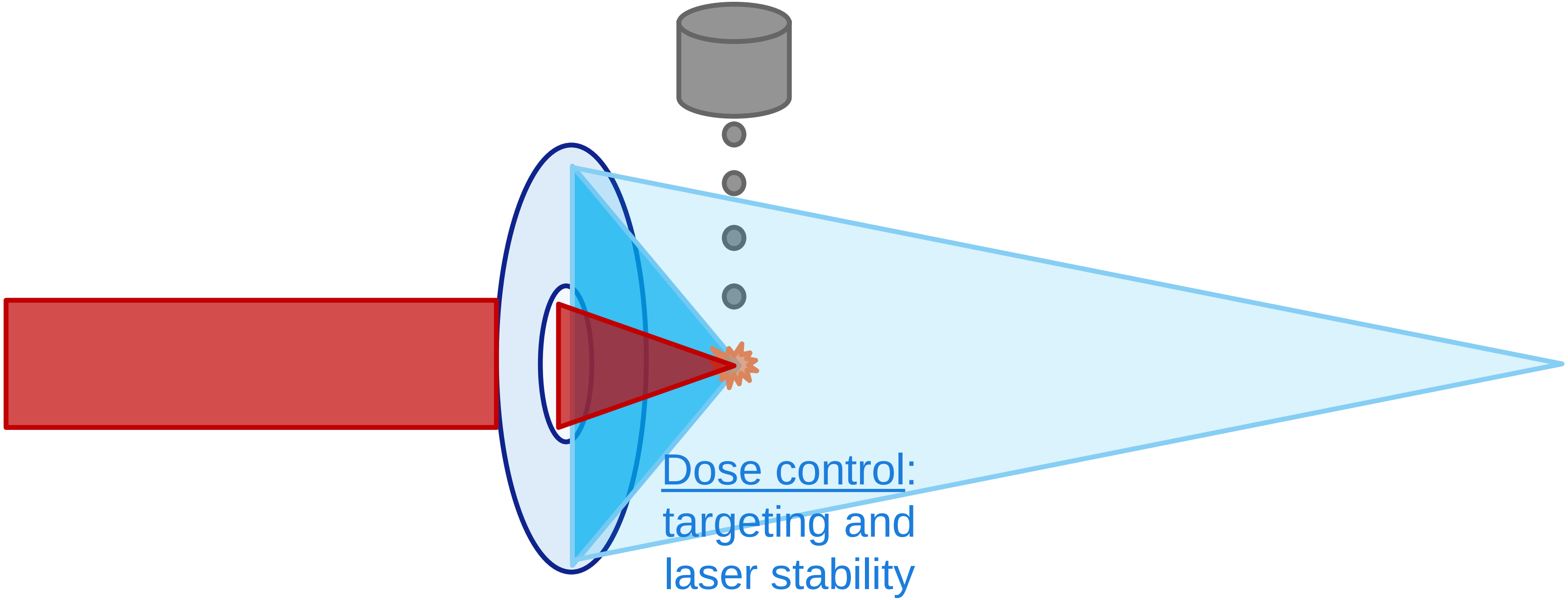
720W in 2π → 176W raw at IF → 140W at IF

(calc dose controlled)

Source Cymer ASML company

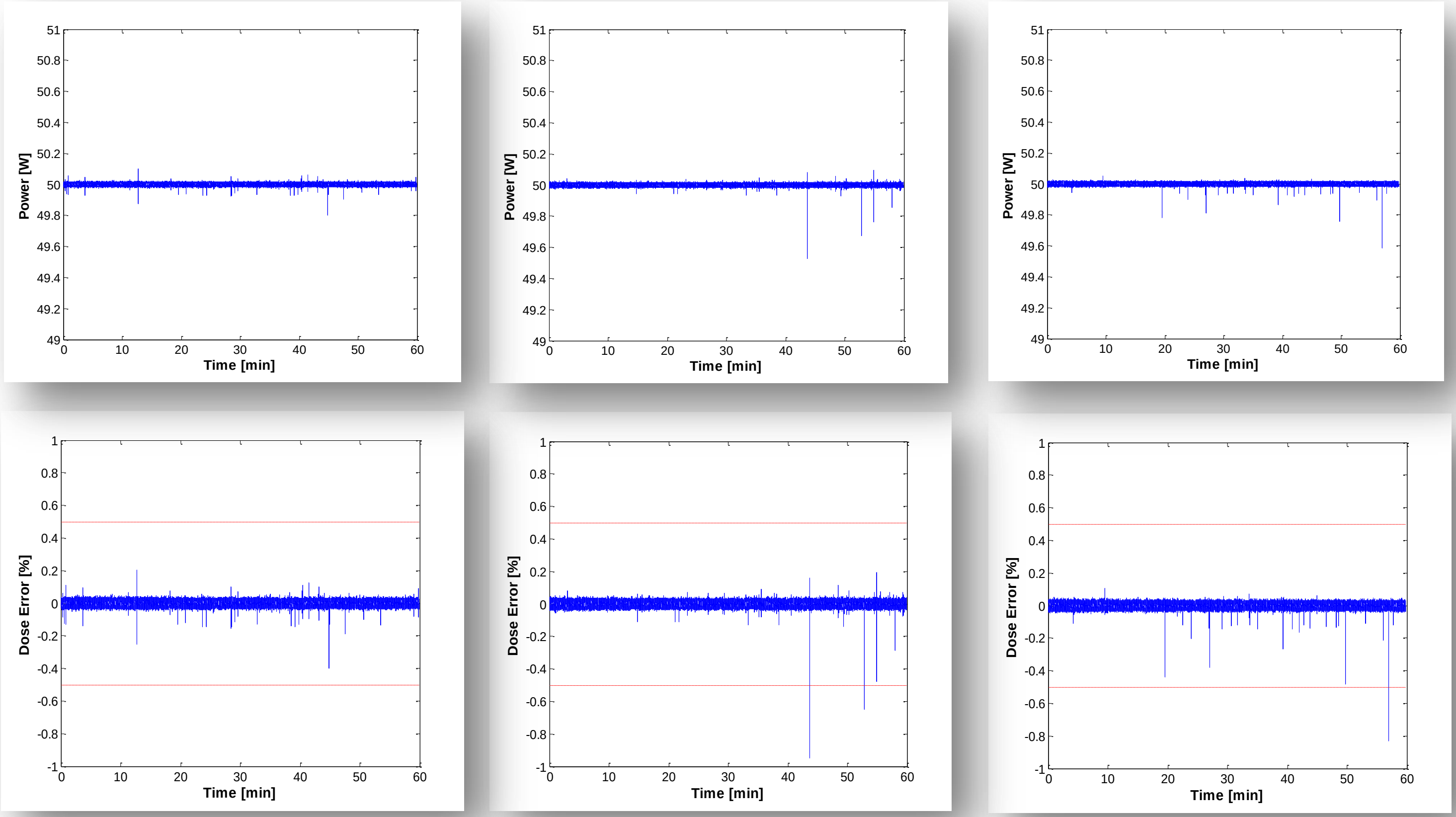
EUV Power Scaling

Top Technology Challenges

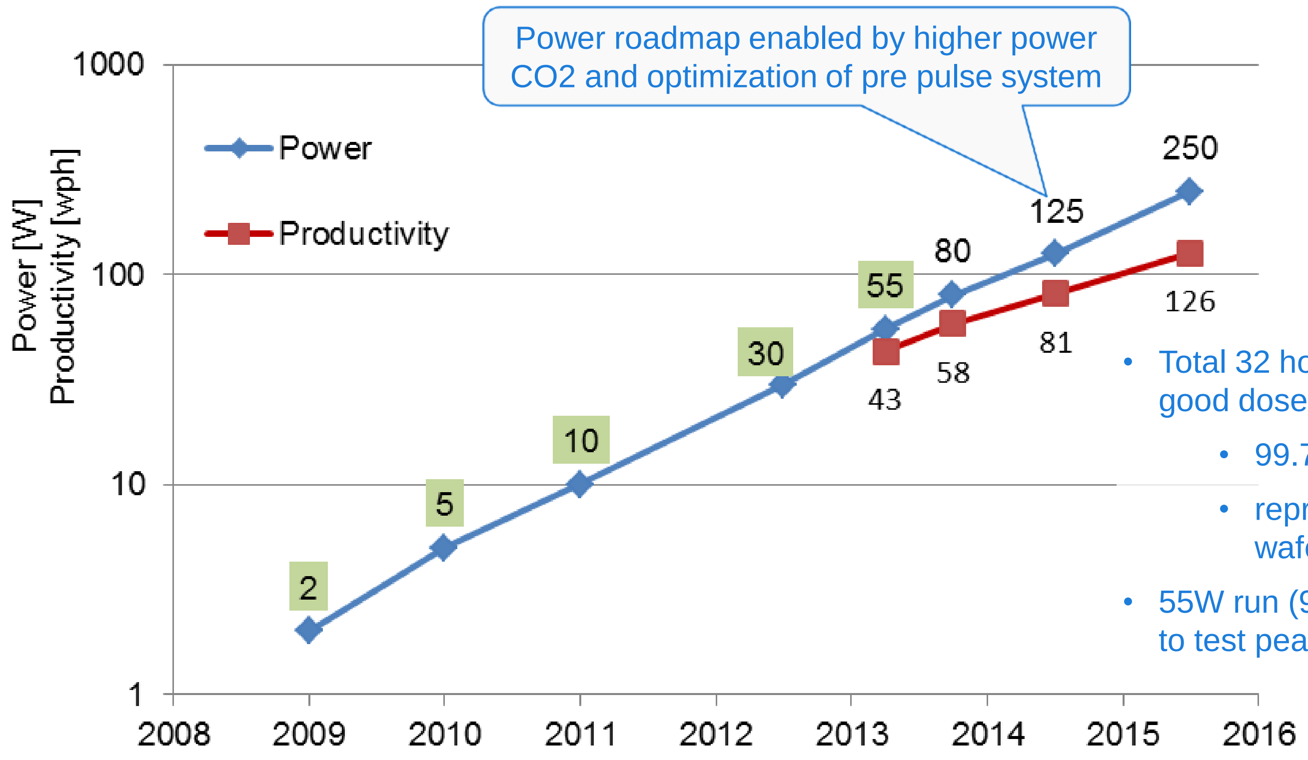


Repeatable 50W MOPA PrePulse EUV Power and Dose Stability

Dose Stability <±0.5%, Die Yield >99.7%



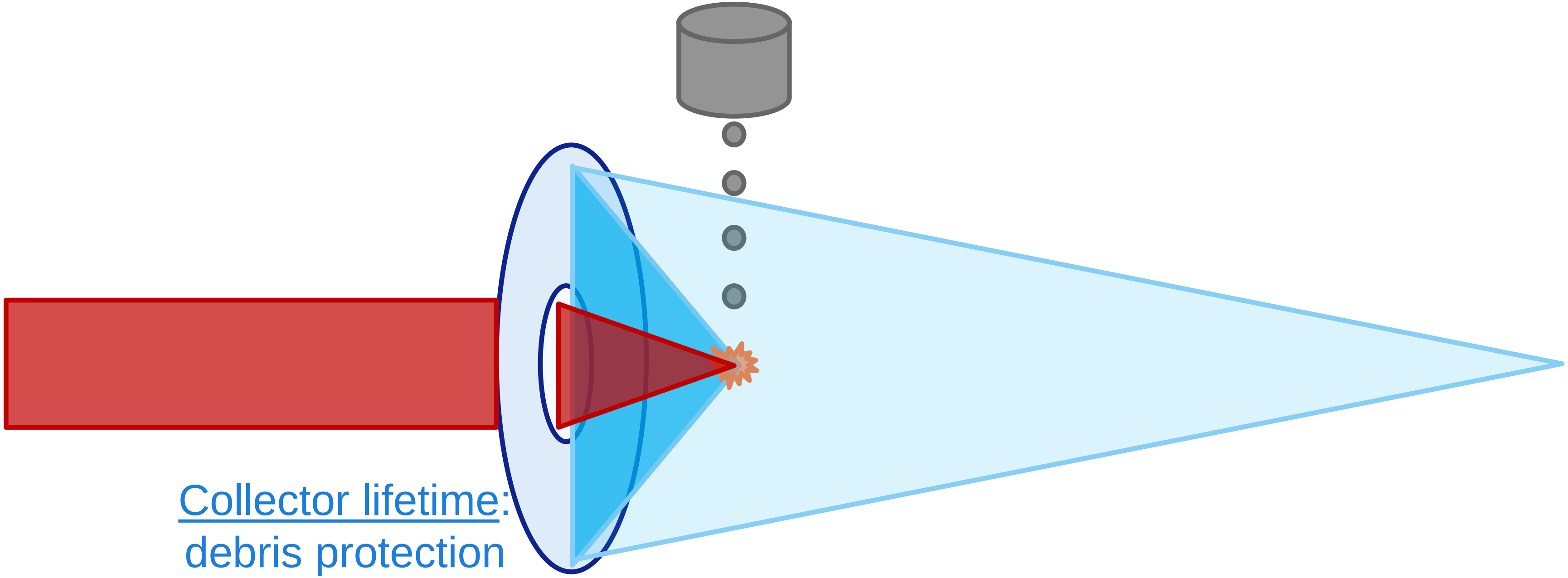
MOPA PrePulse sources demonstrated repeatable, stable performance & dose controlled



- Total 32 hours 40W & 50W runs with good dose reproducibility:
  - 99.7% of the dies < 0.5% dose
  - representing ~ 1330 exposed wafers @ 15 mJ/cm^2
- 55W run (97.5% of dies in spec) to test peak performance

EUV Power Scaling

Top Technology Challenges

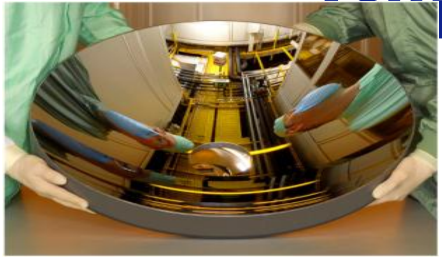


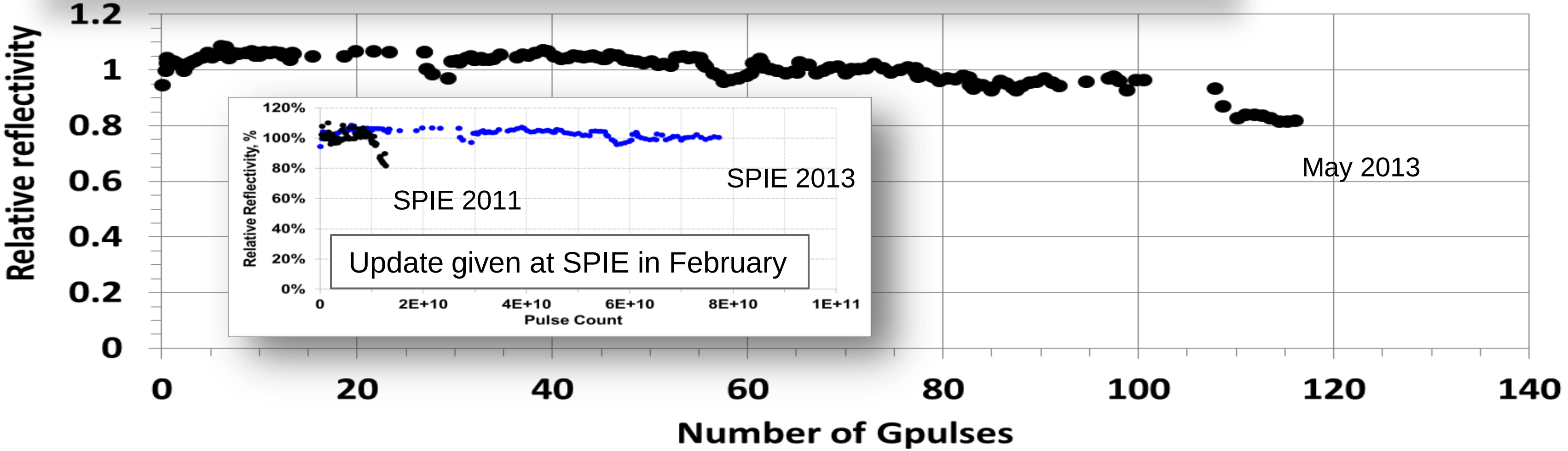
Collector lifetime:
debris protection

3100 Collector Lifetime in the

Champion lifetime in the field ~11 months
(~120 billion pulses)

Six collectors with >6 months lifetime





Type	Average Lifetime (sample size)	Best lifetime
Uncapped	7 Gp (8)	15 Gp (1)
Current Cap Layer	**42 Gp (19, 5 still going)**	**120 Gp (1)**

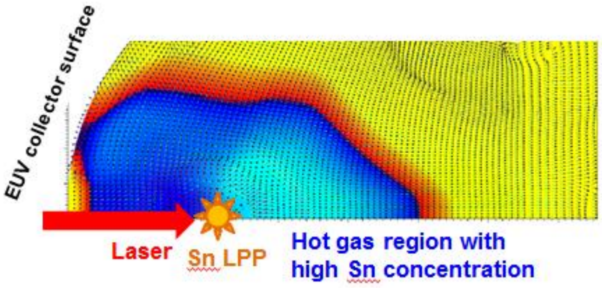
Cap layer development has increased average collector lifetime by >5X since initial installations

Source Cymer ASML company

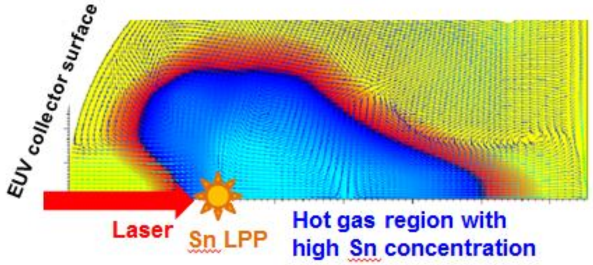
Modeling of flow and collector contamination

Model example

Example of model calculations for different source operation regimes



Background pressure $P_1 = P$
Sn ion flux reaches collector



Background pressure $P_2 = 2P$
Sn ion flux to collector suppressed

Model assists in determination of EUV source operation regime with low collector contamination rate

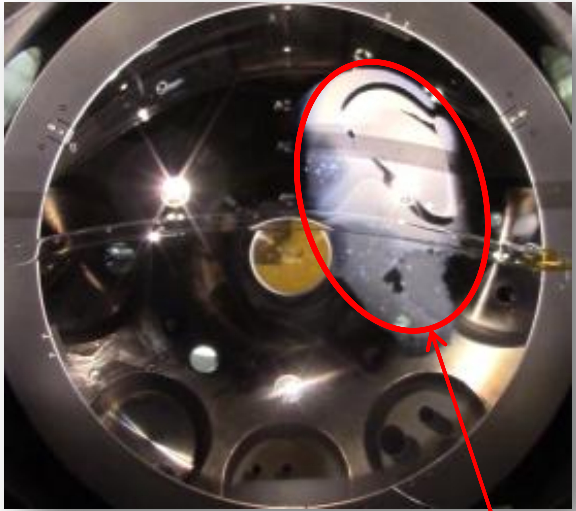
Target:

Minimization of collector contamination

More on this in the presentation of V. Ivanov at this conference

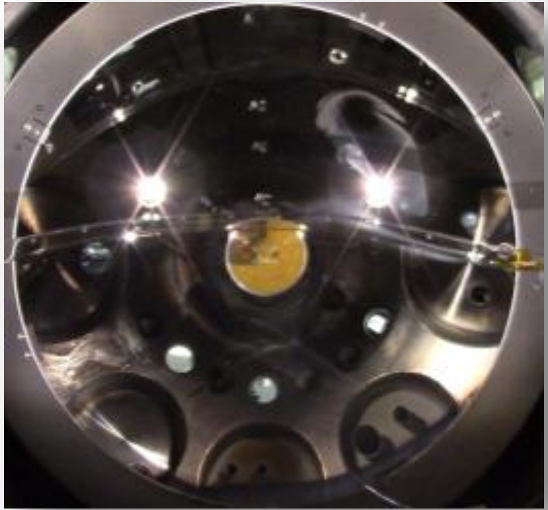
In-situ collector cleaning has been demonstrated and is a key enabler for availability and CoO

- Cleaning on standard MLM capped NXE:3100 Collector
  - Tin deposited during normal EUV operation was removed with reactive gas



- Start of test

Area to be cleaned

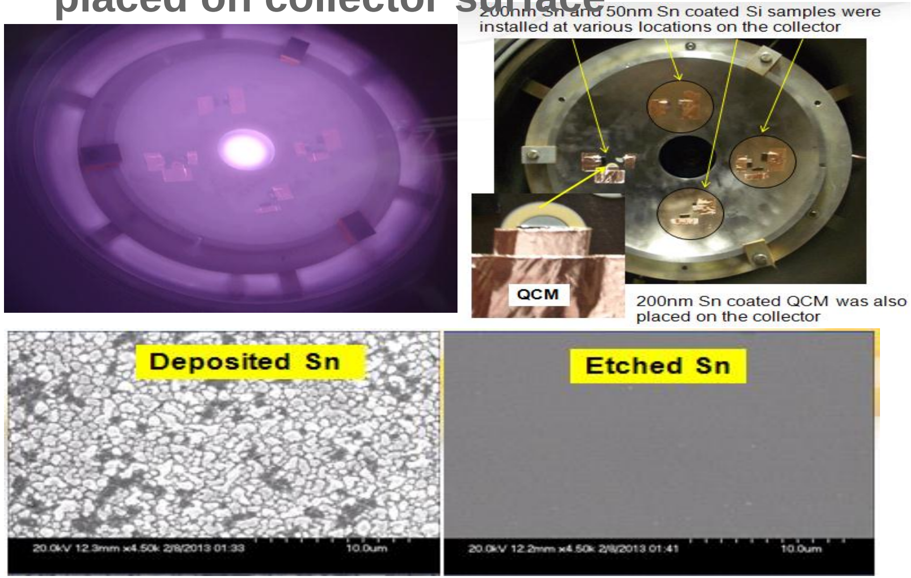


- Collector after cleaning in-situ (in the vessel) → reflectivity fully recovered

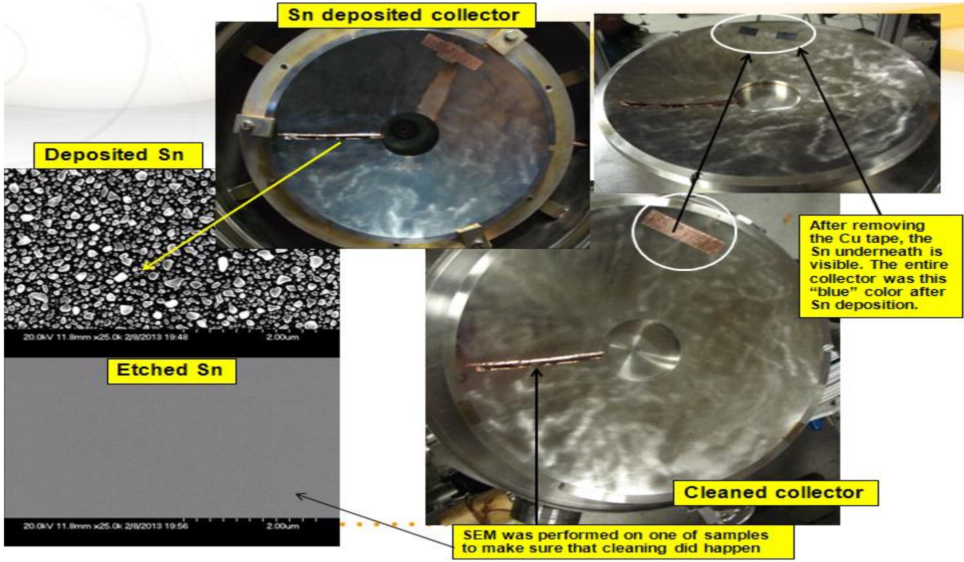
Collector Cleaning using RF Plasma

- Cymer funded project with University of Illinois at Urbana – Champaign
- Demonstrated 200nm Sn cleaning from Si sample placed on collector surface
- Demonstrated 25nm Sn cleaning from the entire 300mm dummy LT-1 collector

200nm Sn cleaning from Si samples placed on collector surface



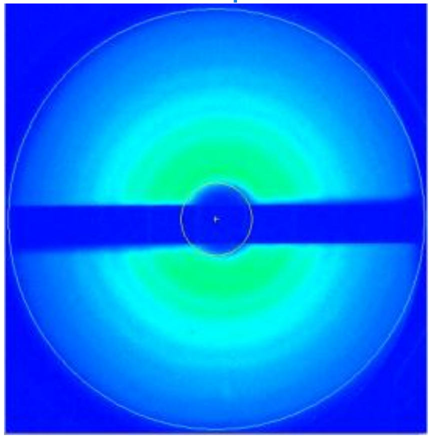
25nm Sn cleaning from 300mm dummy collector



Source Cymer ASML company

MOPA +PP collector protection demonstrated on NXE:3100 source with full reflectivity recovery

Top

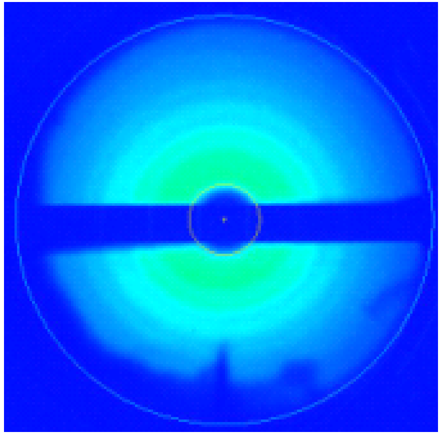


Bottom

1.2 Mpulses

$R/R_0 = 100\%$

Top

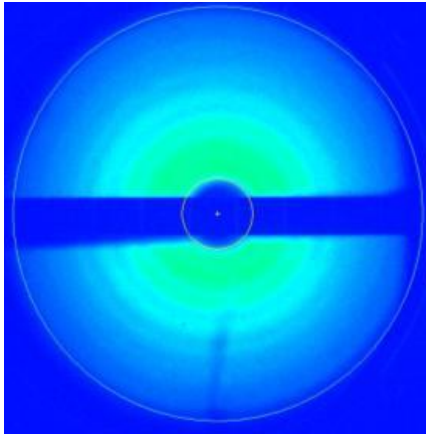


Bottom

15 Gpulses

$R/R_0 \sim 95\%$

Top



Bottom

After cleaning (15 Gp)

$R/R_0 \sim 100\%$

- Source operated at 40W and all loops closed

EUV source power roadmap with dose control

Power scaling is achieved with increased CO_2 laser power and conversion efficiency

	NXE:3300B	NXE:3300B	NXE:3300B
EUV dose controlled power (in-burst)	80W	125W	250W
Drive Laser	26kW	33kW	47kW
CE	3.0%	3.0%	3.3%

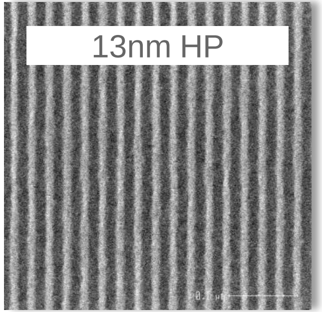
NXE:3300B D ser

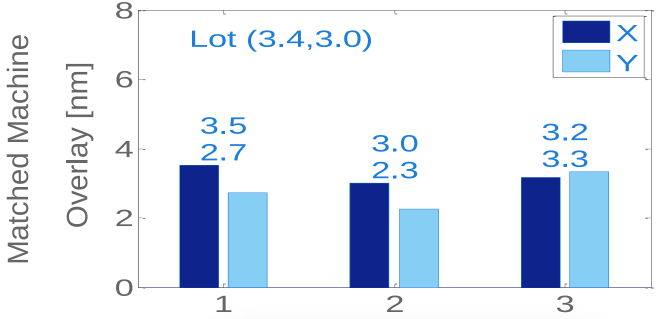
NXE:3300B Vessel

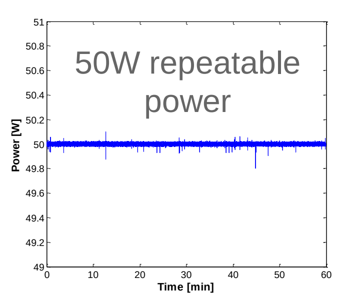
Contents

Summary

- **NXE:3100** in use for process and device development at customers
- **NXE:3300B** performance fit for customer development 10nm Logic and sub-20nm DRAM
  - Overlay performance of DCO<2nm and MMO<4nm demonstrated
  - Resolution of 13nm LS and 18nm Contact Holes demonstrated. Further process optimization to be done
  - Good imaging performance for 1D (Line Space), 2D (Contact Holes and Metal 1), and Tip-to-Tip / Tip-to-Line have been shown
  - Dose reduction achieved by utilizing contrast enhancement with off-axis illumination
  - 50W repeatable source power demonstrated with good dose control







Acknowledgements

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

Special thanks to our partners and customers for allowing us to use some of their data in this presentation