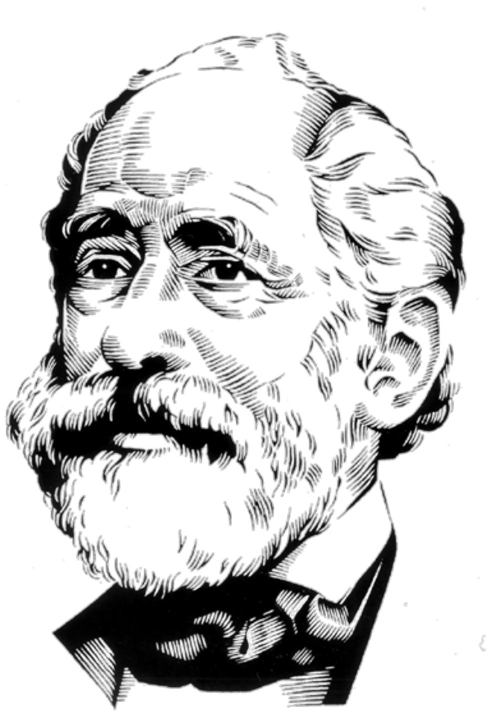
Optics for EUV Lithography

Dr. Sascha Migura
Carl Zeiss SMT GmbH, Germany

June 12th, 2019, Berkeley, CA, USA

The company founders

Ernst Abbe
(1840–1905)



Carl Zeiss
(1816–1888)

Their mission

- Offering customers extreme precision and maximum quality
- Enabling cutting-edge applications
- Social responsibility

Resolution

Abbe’s insight (1873) enabled the production of microscopes by optical designs.

Ernst Abbe

(1840–1905)

$$\text{Resolution} = k_1 \frac{\lambda}{NA}$$

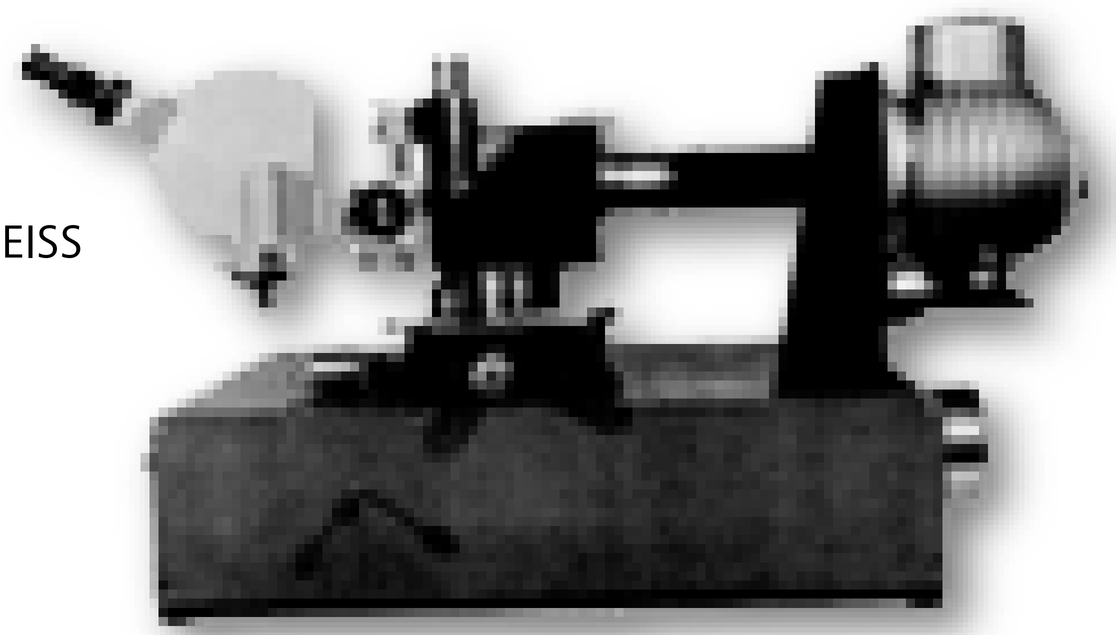
k_1 is process factor
λ is wavelength
NA is numerical aperture

Moore’s Law drives the requirements on the optical system.

The early years
Telefunken

1968

IC Printer Setup from ZEISS
for Telefunken
Resolution ~15µm



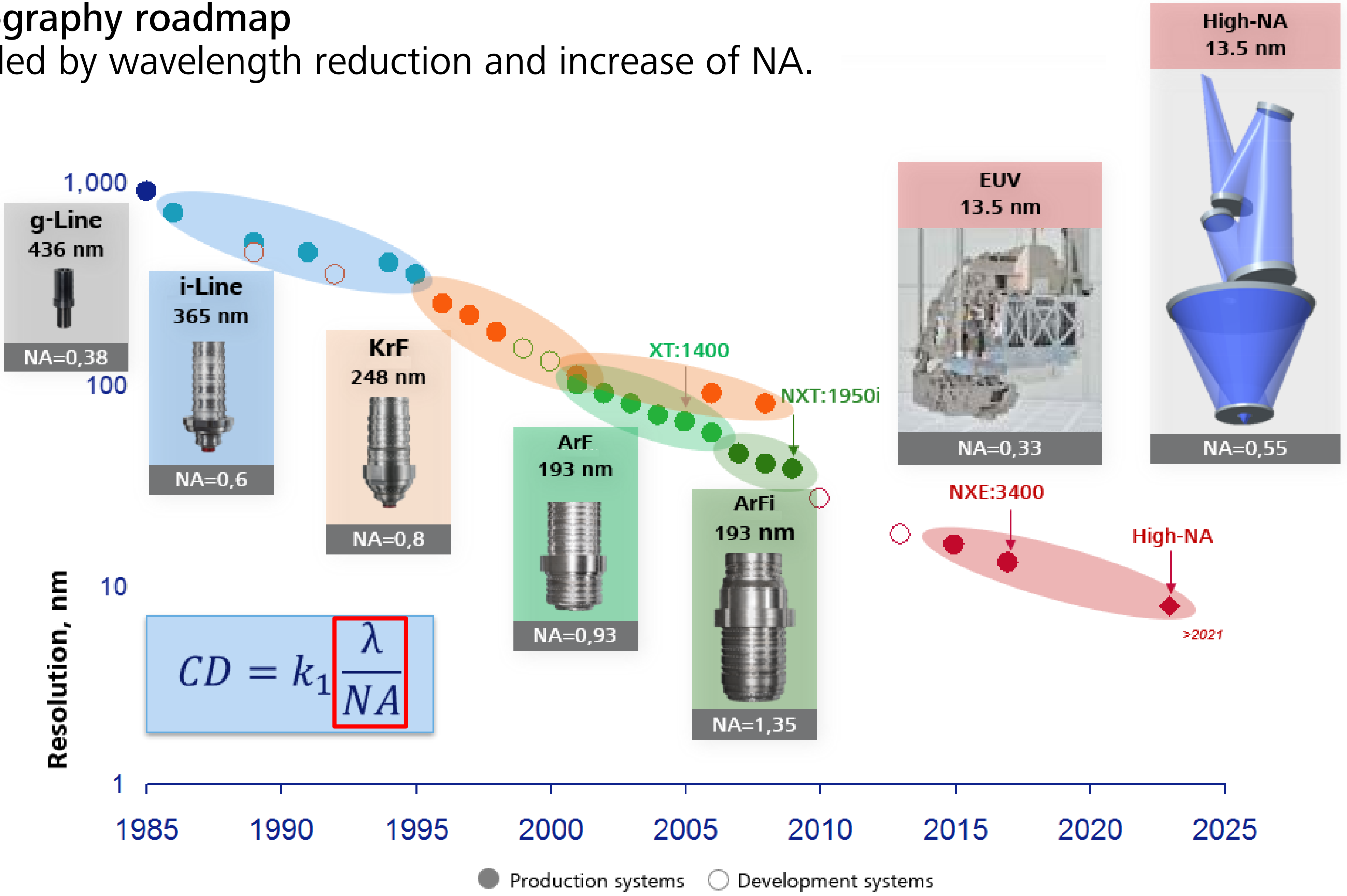
The early years
David Mann / GCA

1975

Mann 4800 with optics from ZEISS
Resolution: 1.4µm

Lithography roadmap

Enabled by wavelength reduction and increase of NA.



Beginning: Collaborations and funding in Europe
First EUV Workshop at ZEISS held on November 13th/14th, 1995.

In search of the Next Generation Lithography (NGL)

Optics seen as issue #1 for EUV.

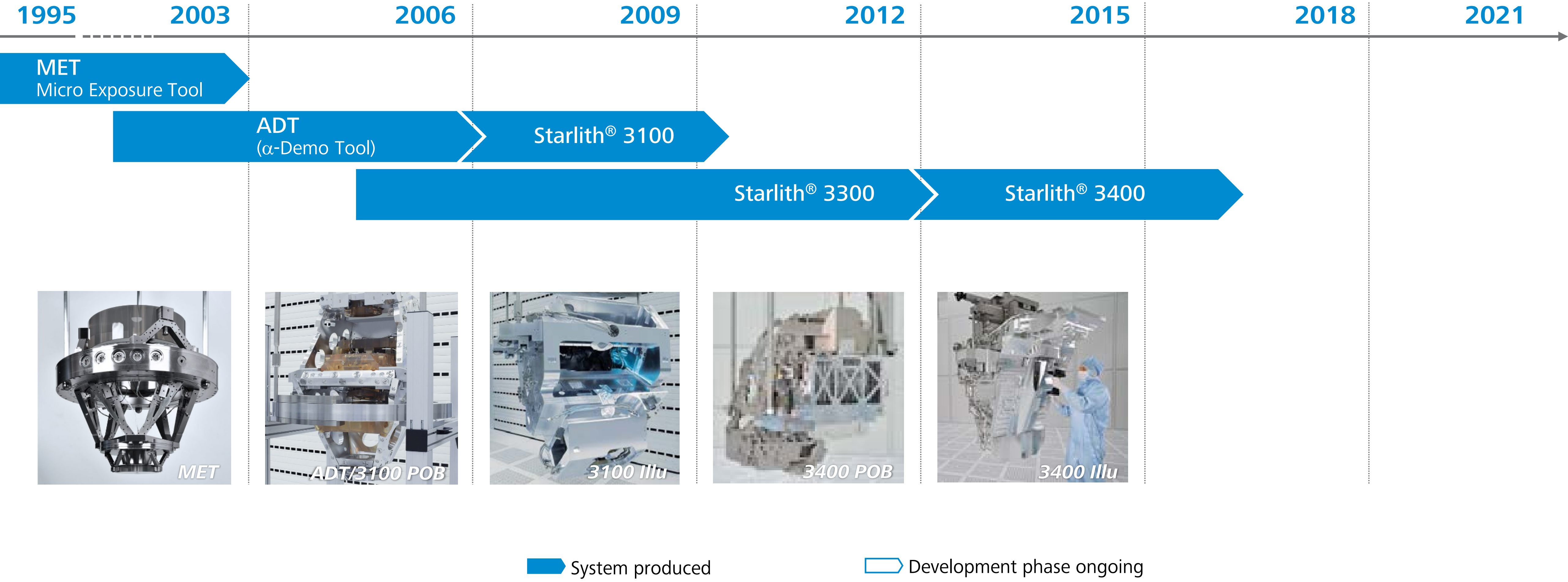
Critical Issues of Advanced Lithography Technologies
(EPL and EUV Issues from Dec '98 NGL Task Force)

Alternative	193nm + O.E.	157nm	EUV	EPL
Critical Issue #1	Progress on exposure tools to support 100nm node	Feasibility of a pellicle solution	Full Field Optical Design	Beam blur relation to CD, TPT, and IP vs. feature size
Critical Issue #2	Progress on masks to support the 100nm node	Incorporation of purging into exposure tool design	Defect free mask mfg. at 65nm	Wafer heating
Critical Issue #3	Progress on resists to support the 100nm node	Timing / Risk of production tools for the 100nm node	Defectivity and thermal mgmt. of ULE masks	Dynamic stitching vs. throughput
Critical Issue #4	Assessment of 193nm Lithography to do 100nm node	Feasibility of 157nm resists	Specifications & CoO for debris free source	Defect free mask mfg. at 65nm
Critical Issue #5	------	Quality and scale-up of modified fused silica supply	Defect density scaling vs. size to 55nm	Electron proximity correction
Critical Issue #6	------	CoO of 157nm vs. 193nm with optical extensions	Defectivity of thin layer imaging (TLI)	Alignment capability

Advanced Lithography Critical Review Task Force Assessment of

From November 1997 to August 2001, Optics matured from "Potential Showstopper" to "Solution Anticipated" in SEMATECH's NGL workshop survey.

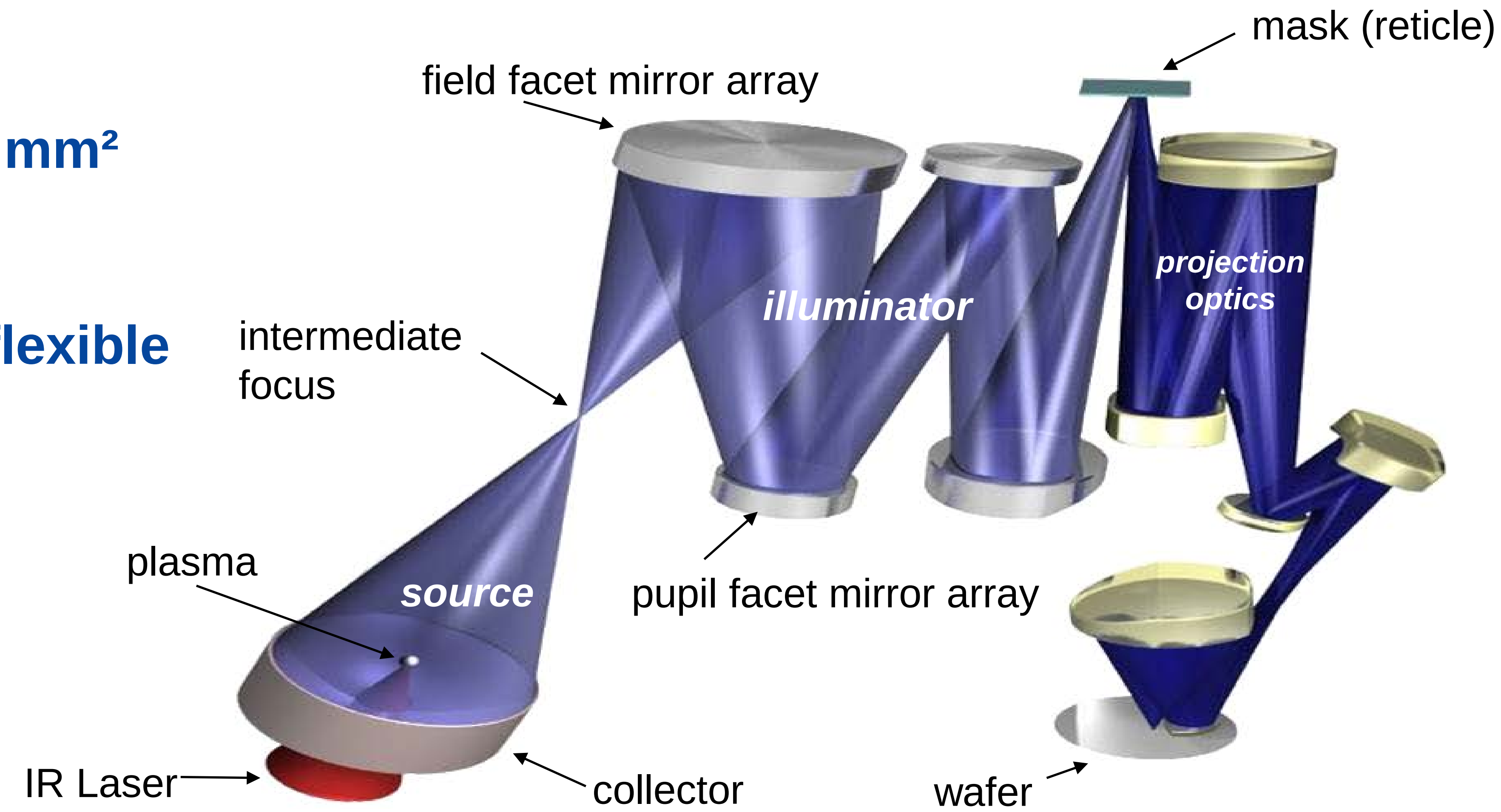
Starlith® 3400
The solution for volume production with EUV.



Starlith® 3400

Optical Column: Low-k1 EUV Optics enabling 13nm single-shot resolution.

λ	**13.5 nm**
NA	**0.33**
Field	**26 x 33 mm²**
MAG	**4x**
Res	**13 nm**
Illum	**highly flexible**



design scheme

Starlith® 3400
The solution for volume production: Optical column.

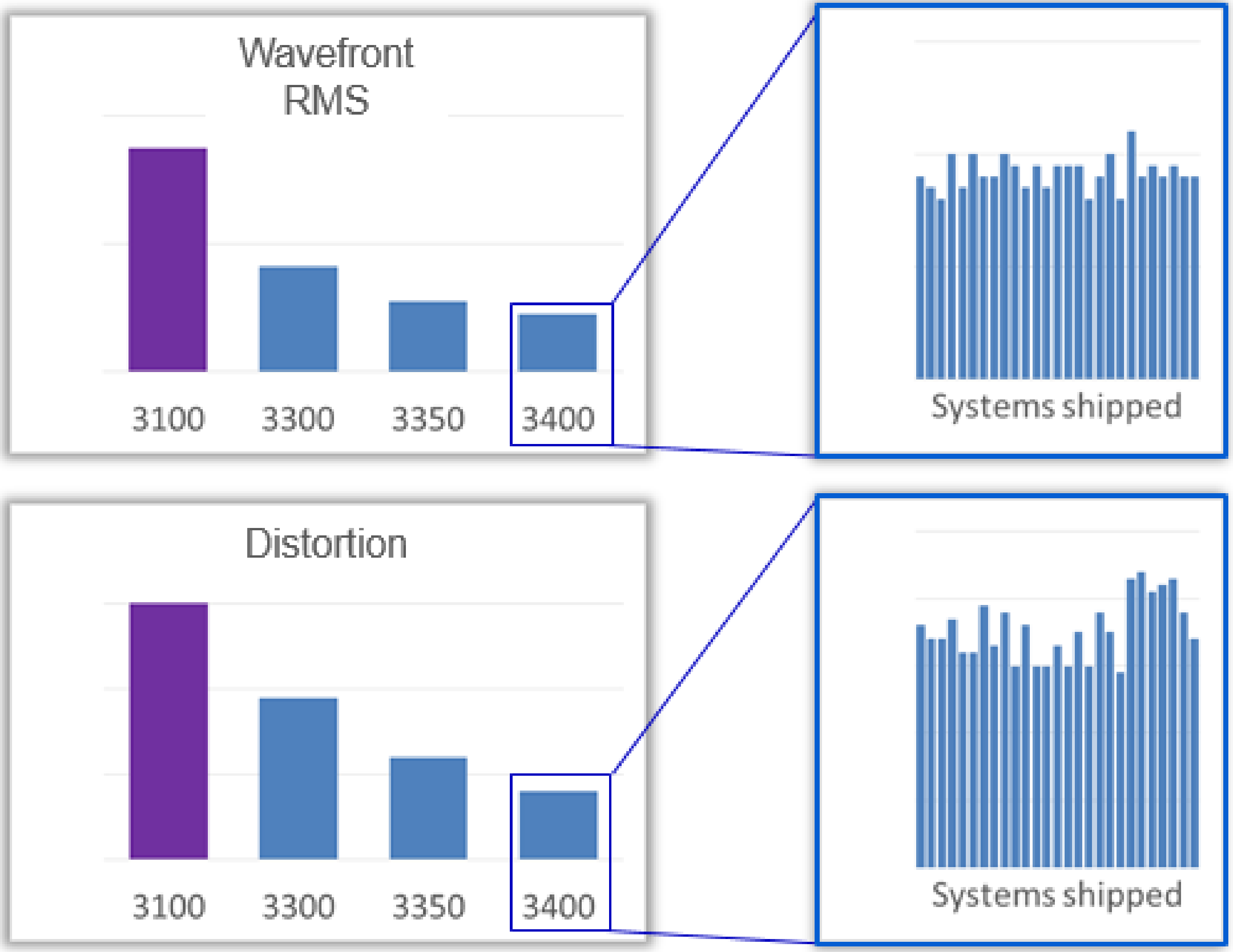
3400 Projection Optics

Proven 3400 Optics Design
- Improved Overlay Performance
- Improved Wavefront Performance

3400 Illuminator

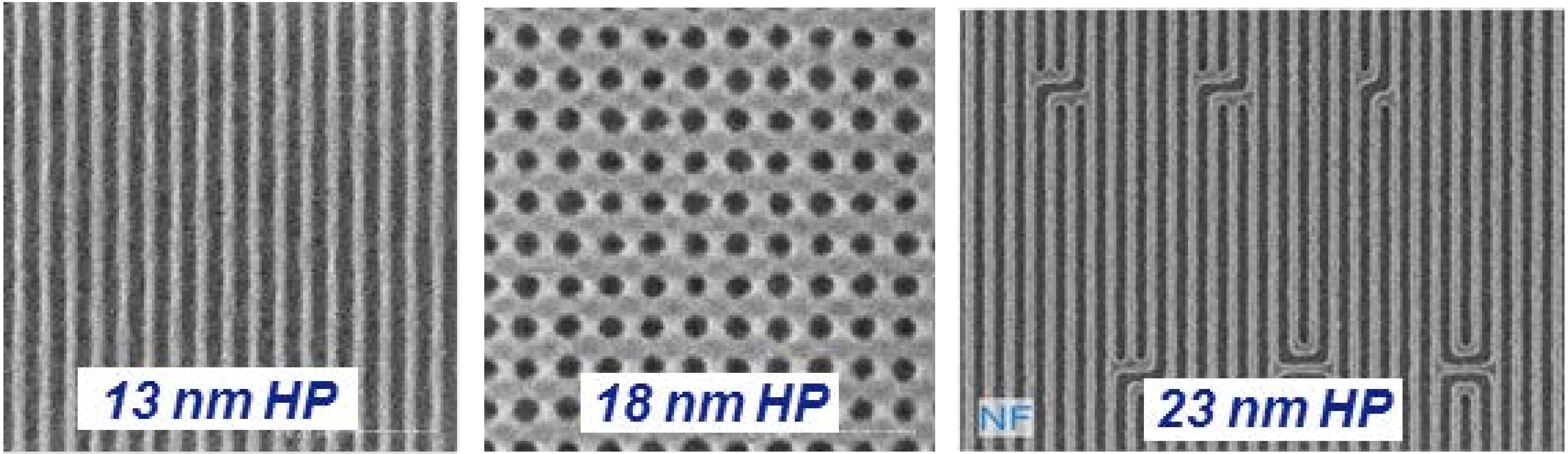
Reduced Pupil Fill Ratio from 40% to 20%
- Enhanced Sigma up to 1.0
- Maximized Setting Flexibility at full Throughput

Starlith® 3400: Projection Optics
Improved aberrations consistently achieved in serial production.



ZEISS inhouse EUV qualification

Starlith® 3400: Projection Optics
The optics delivers excellent imaging.

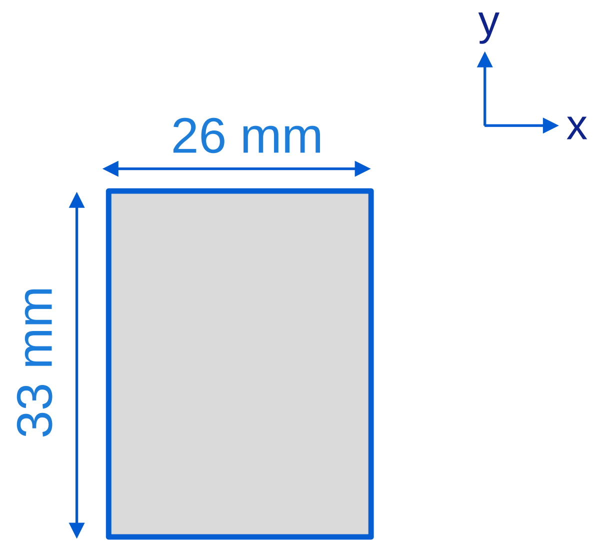


Source: ASML

Starlith® 3400: Projection Optics

The optics transports a Terapixel of information in every shot.

field @ wafer



Assuming a pixel size of 13nm x 13nm…

 # pixel in x = 26mm / 13nm = $2.0 \cdot 10^6$

 # pixel in y = 33mm / 13nm = $2.5 \cdot 10^6$

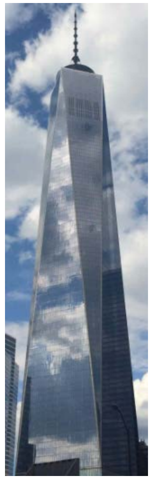
…results in $5.0 \cdot 10^{12}$ pixels per field.

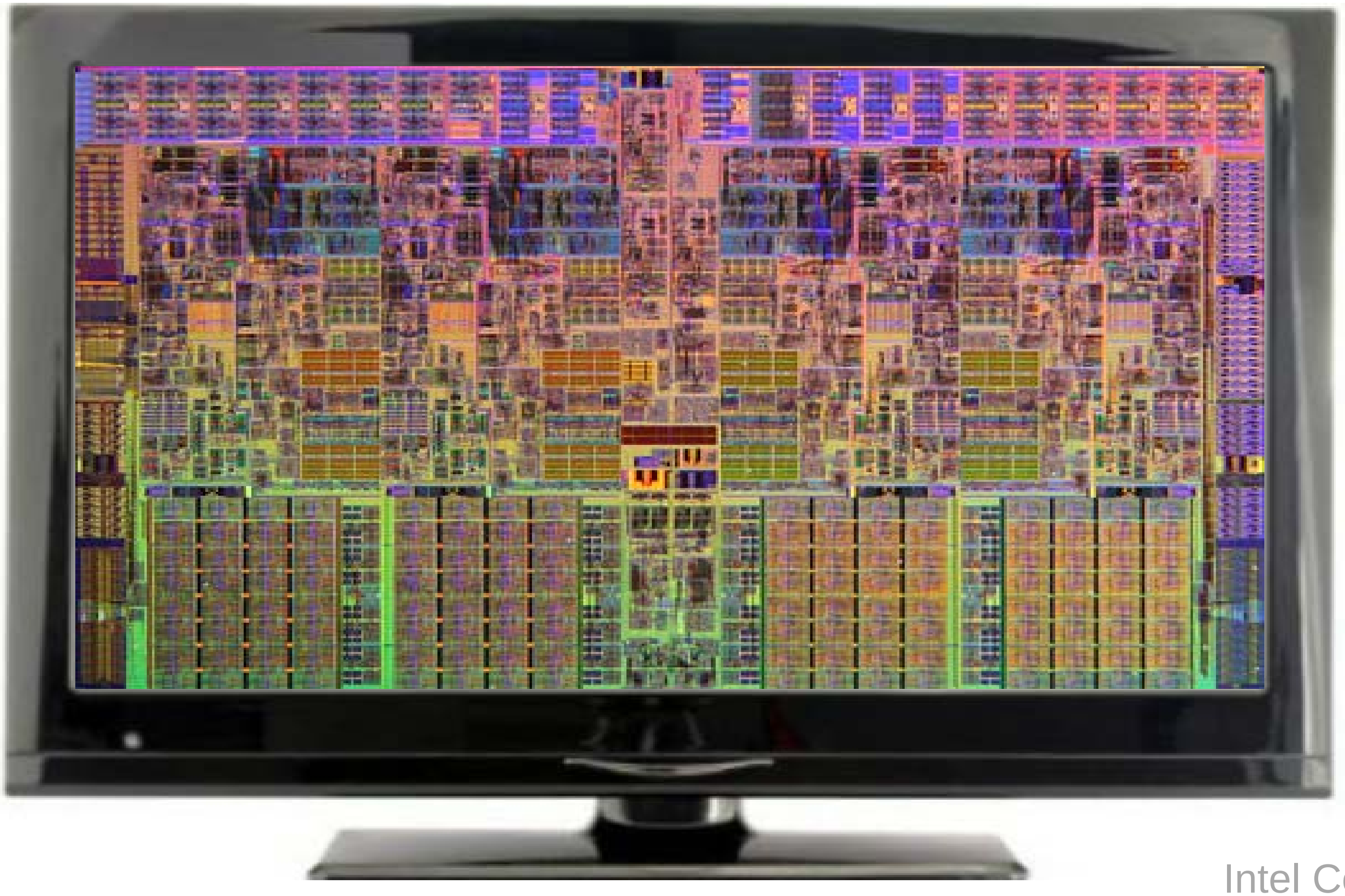
That is 2.4 million times more pixels compared to Full HDTV.

Starlith® 3400: Projection Optics

Displaying the information, a TV screen of 780m x 1370m is required.

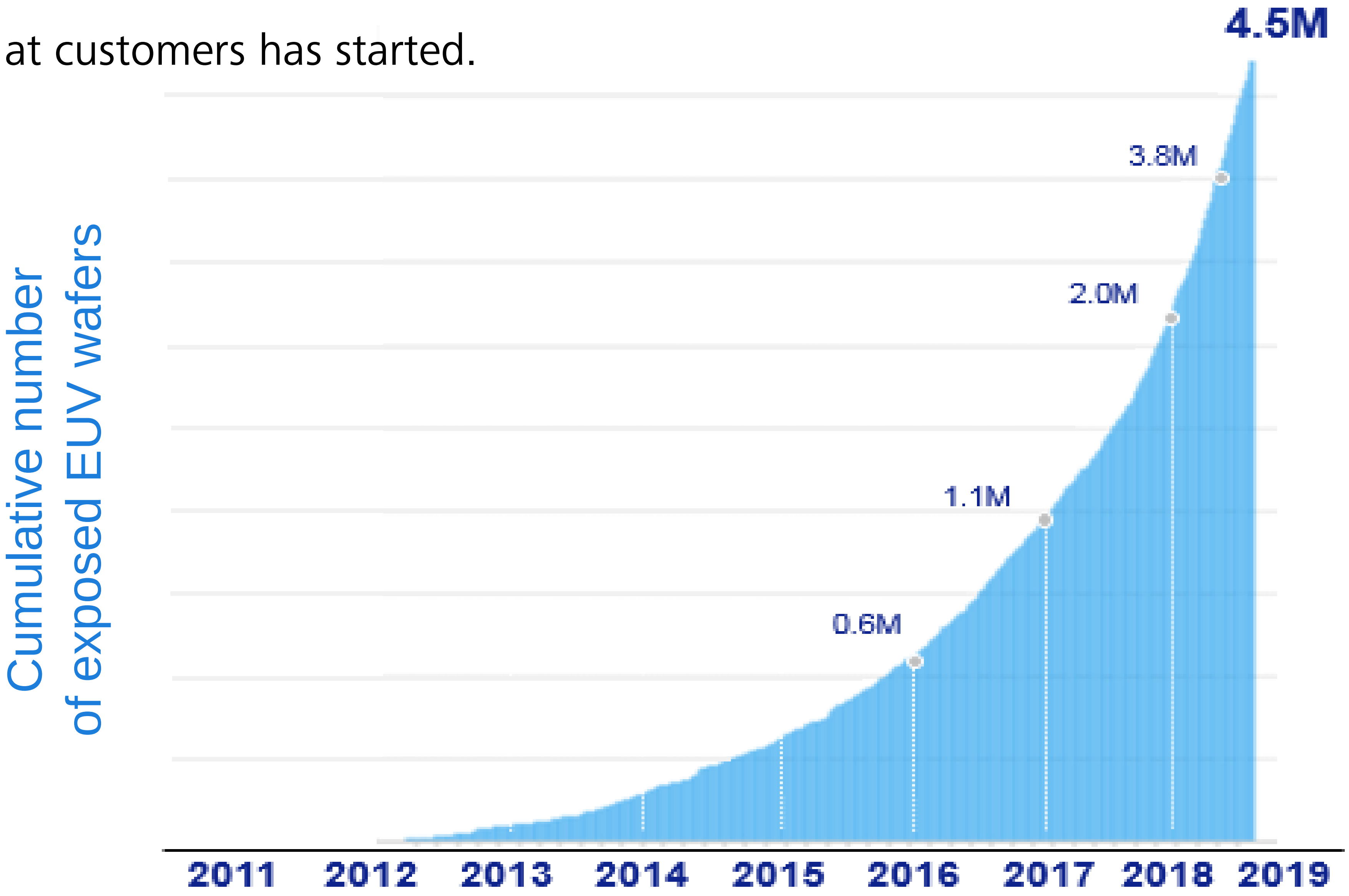
One World Trade Center
541 m
From Wikipedia





Intel Core i7 layout

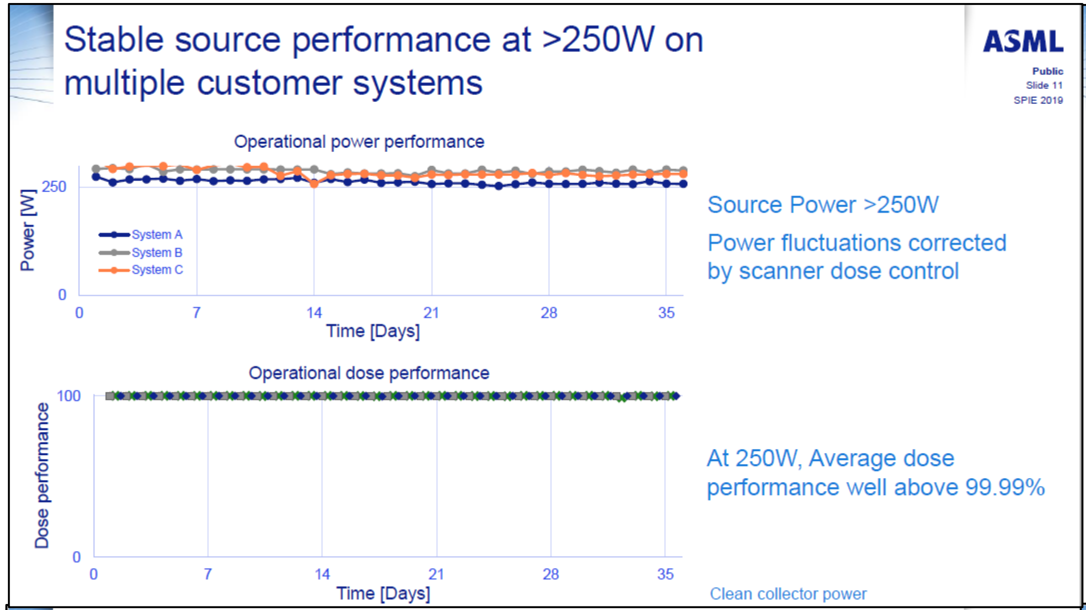
NXE:3400
EUV ramp at customers has started.

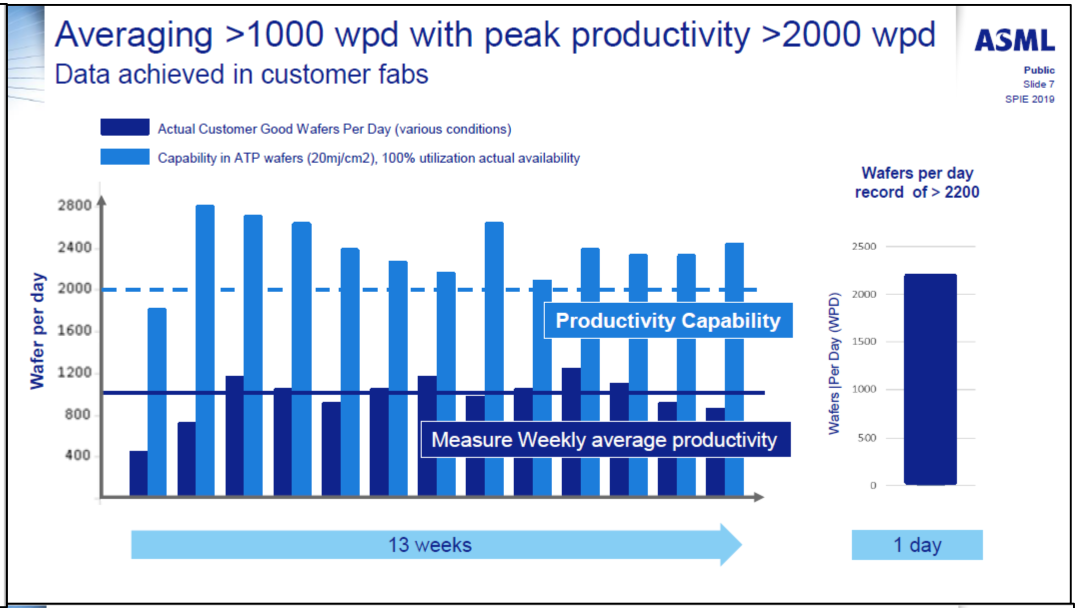


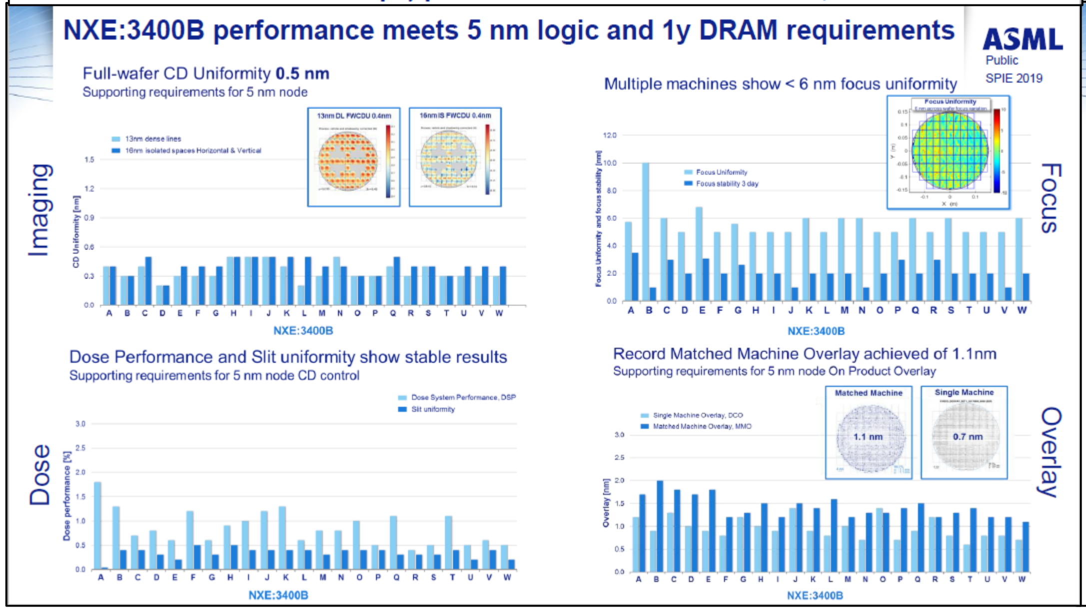
Source: ASML

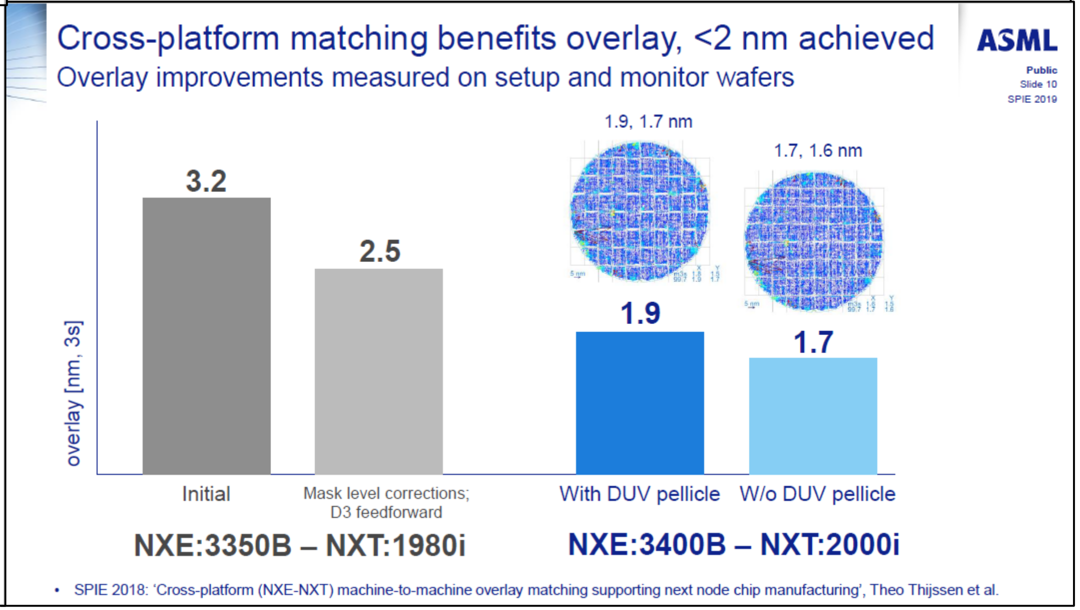
More than 4.5 Million wafers run since 2011.

NXE:3400
40 systems now in the field.









Source: ASML

Starlith® 3400: Projection Optics
Mirror manufacturing

Starlith® 3400: Projection Optics
Figure control on atomic level

Computer Controlled Polishing

Ion Beam Figuring

Figuring process

multiple
iterative
loops

Highly accurate
metrology

Interferometric Surface
Metrology

Polishing technologies and metrology closing the loop

Starlith® 3400: Projection Optics
Critical quality parameters for polishing of optical surfaces

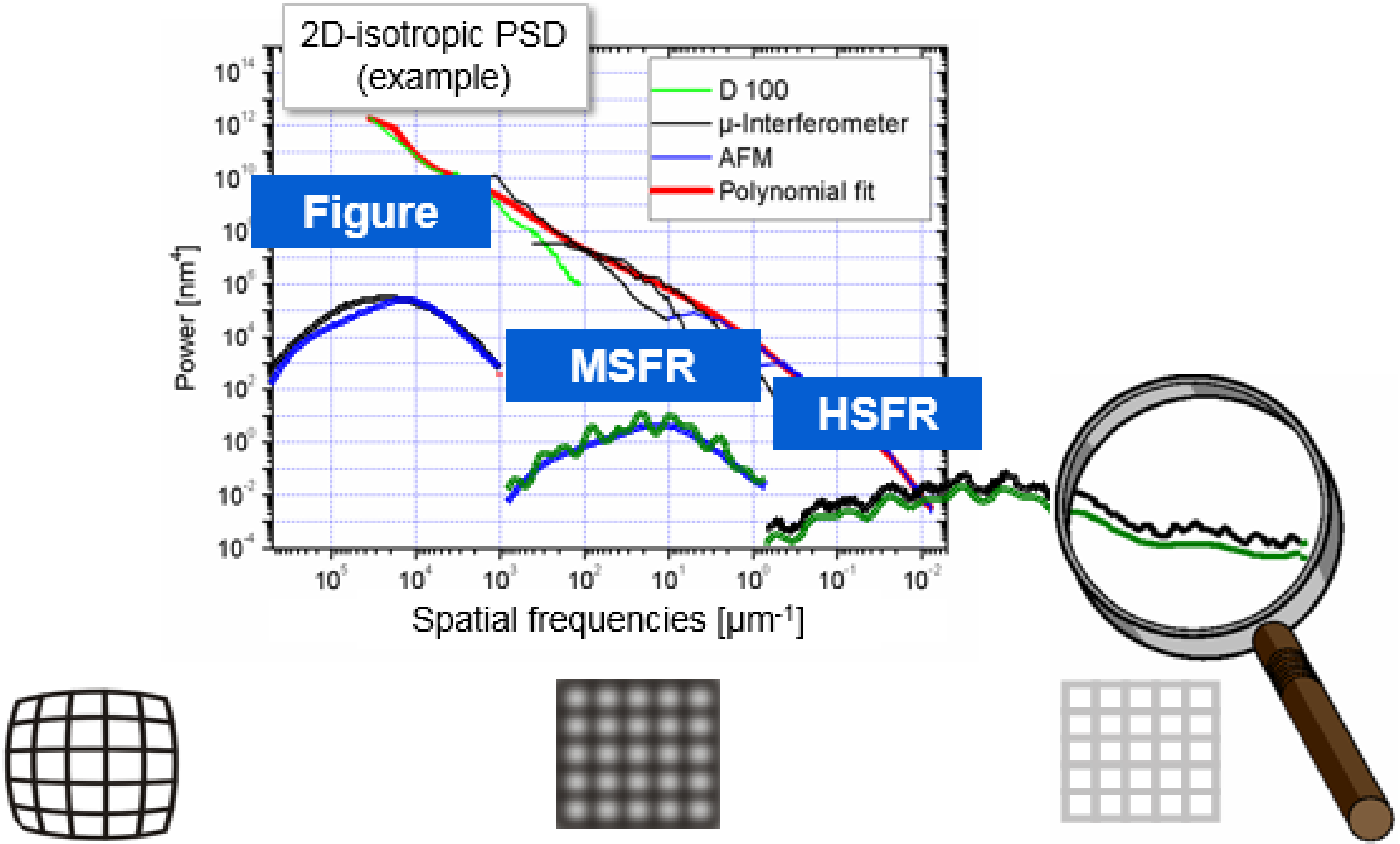


Figure	MSFR	HSFR
aberrations	Scattering light in the illuminated field	Reduced reflectivity
CD Uniformity, Overlay	**Uniformity, Contrast**	**Transmission**

Starlith® 3400: Projection Optics
Mirror fabrication: The sizes and challenges get bigger with each generation.

Photos show relative mirror size

	MET	ADT	3100	3300/3400	
					
Figure [pm rms]	350	250	140	<50	**aberrations**
MSFR [pm rms]	250	200	130	<80	**flare**
HSFR [pm rms]	300	250	150	<100	**light loss**

Starlith® 3400: Projection Optics
What does 50pm surface deviation mean?

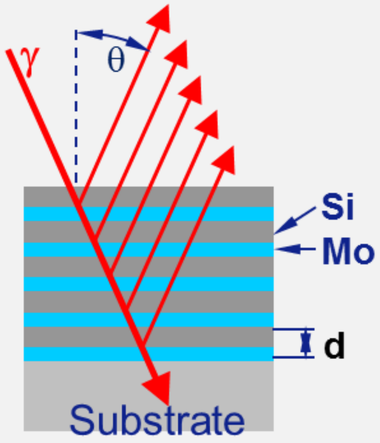
Zugspitze
2962m

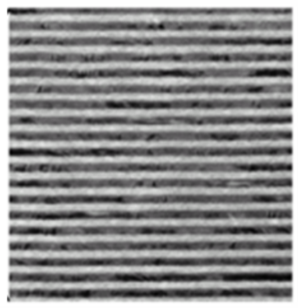
450mm

Correspond to heights of
100µm
in Germany.

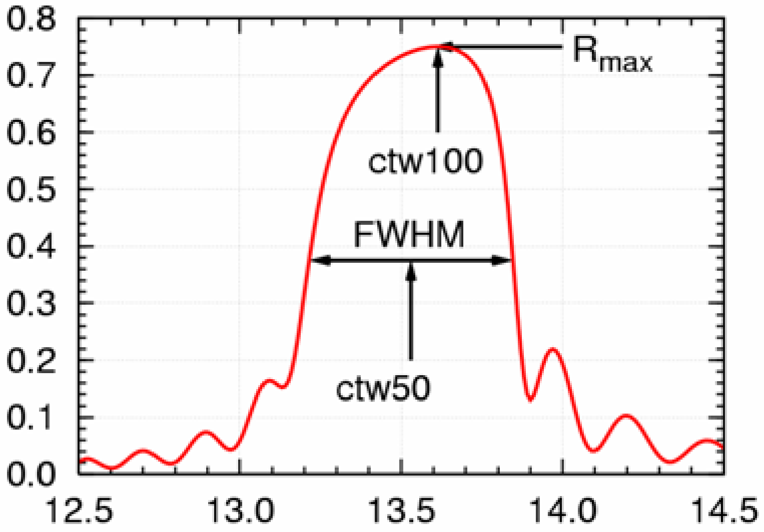
Starlith® 3400: Projection Optics
Coating technology: The multilayer coating defines EUV.

EUV Coating:
Mo/Si
Bragg Reflectors





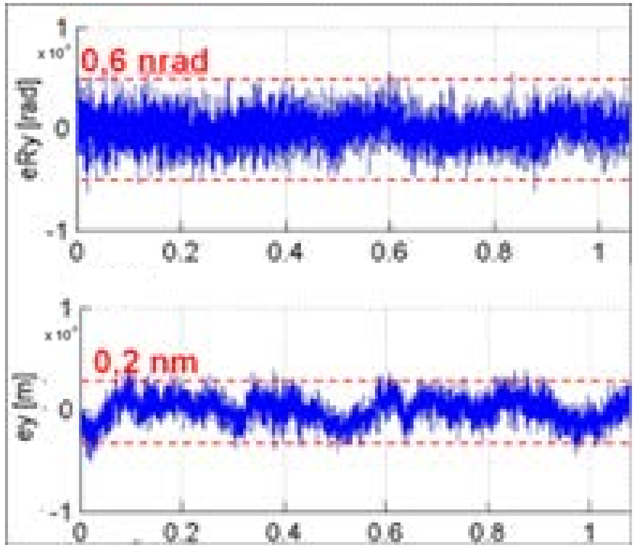
> 50 Bi Layers

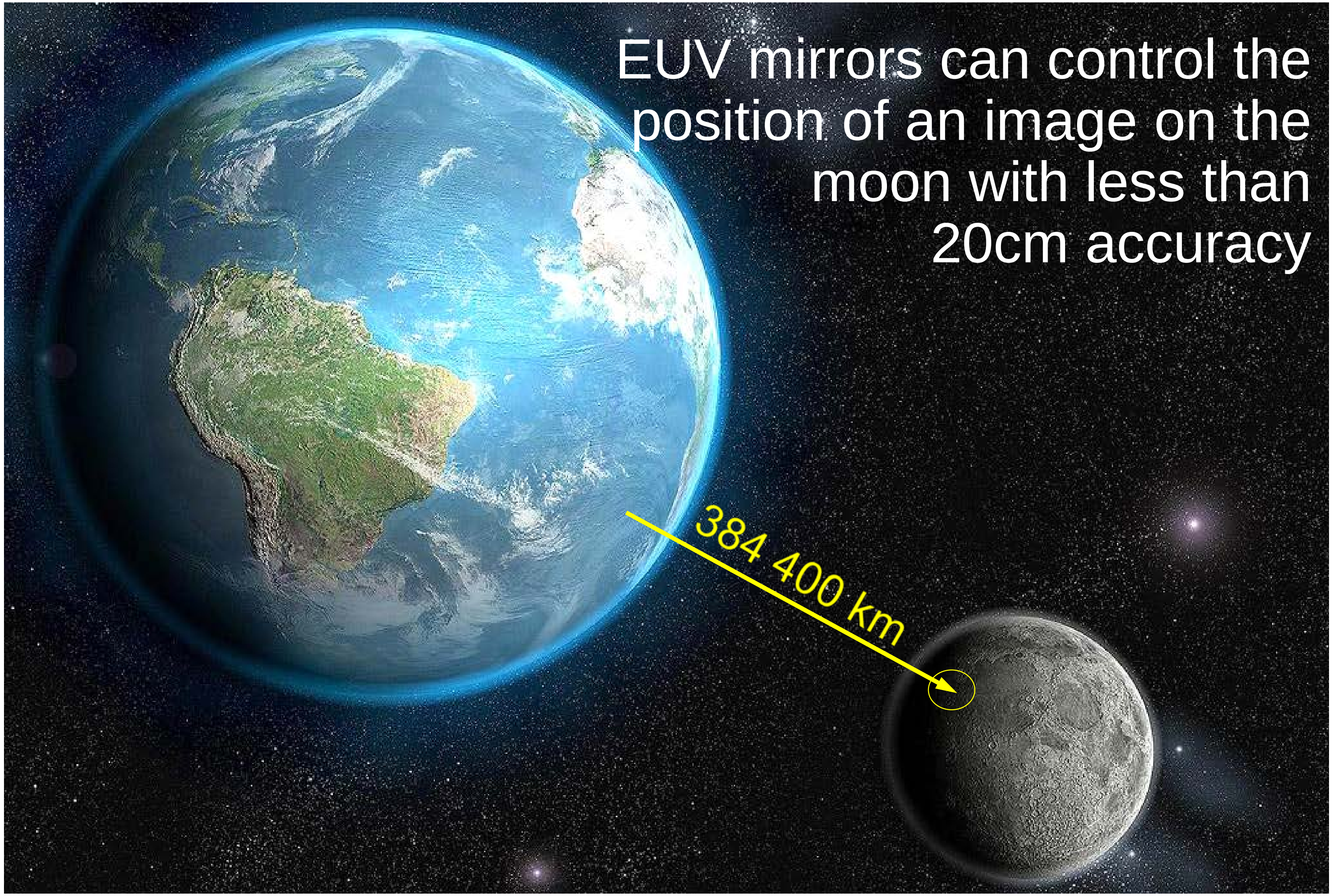


Reflectivity	**>67%, high bandwidth**
Layer thickness control	**<0.2%**
Lateral uniformity	**<0.2%**
Coating stress	**100 MPa**
Thermal Stability	**200°C**

Starlith® 3400: Projection Optics
Mirror tilts controlled with sub nrad accuracy to enable sub nm image placement.

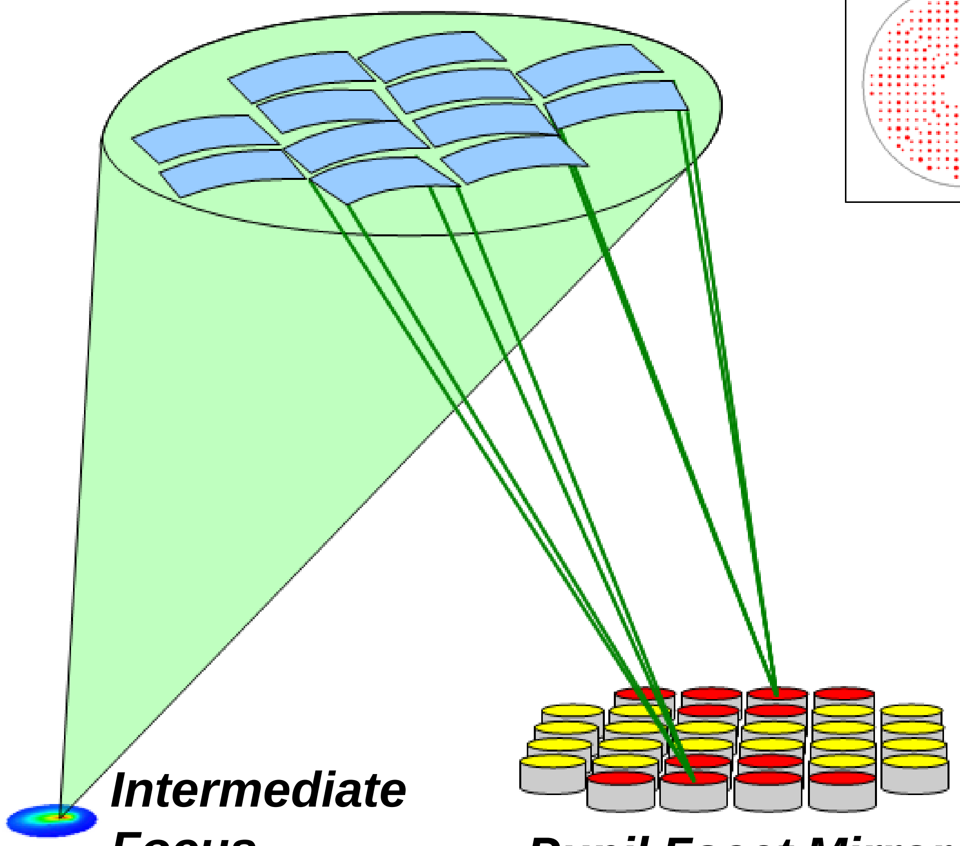
Test module for EUV mirror positioning

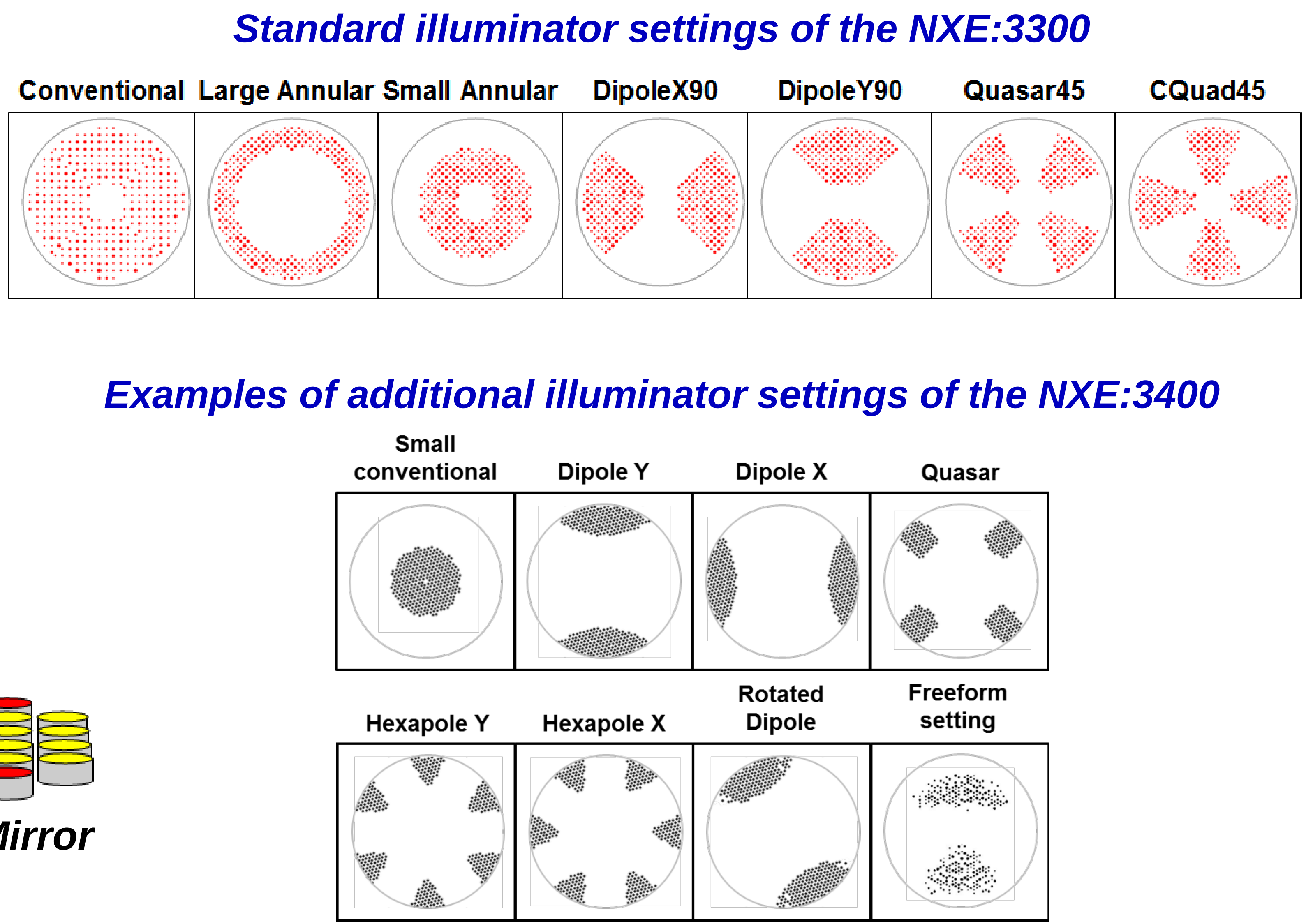




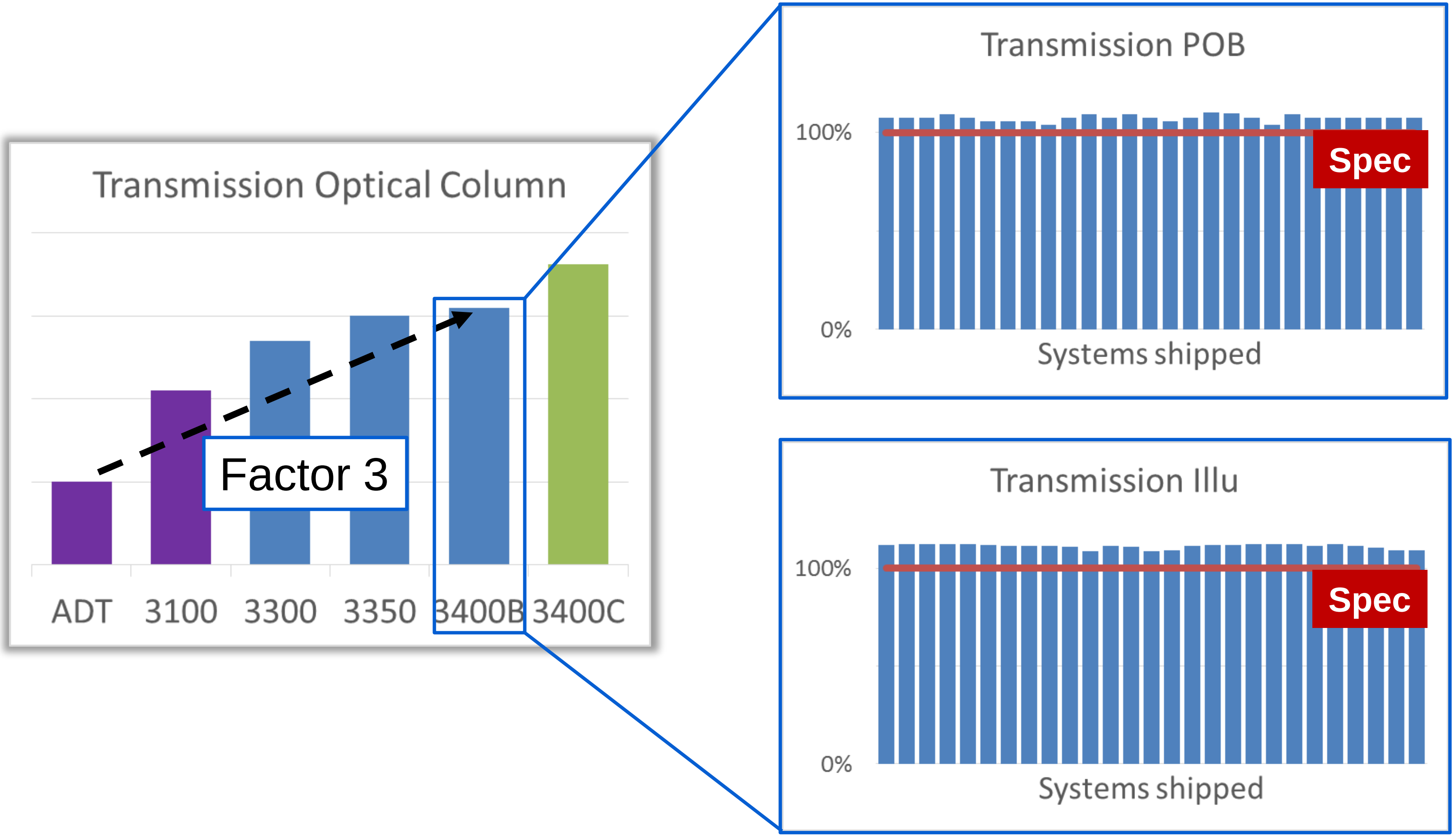
Starlith® 3400: Highly flexible illuminator

Allows lossless changes of settings and the optimization of image contrast.





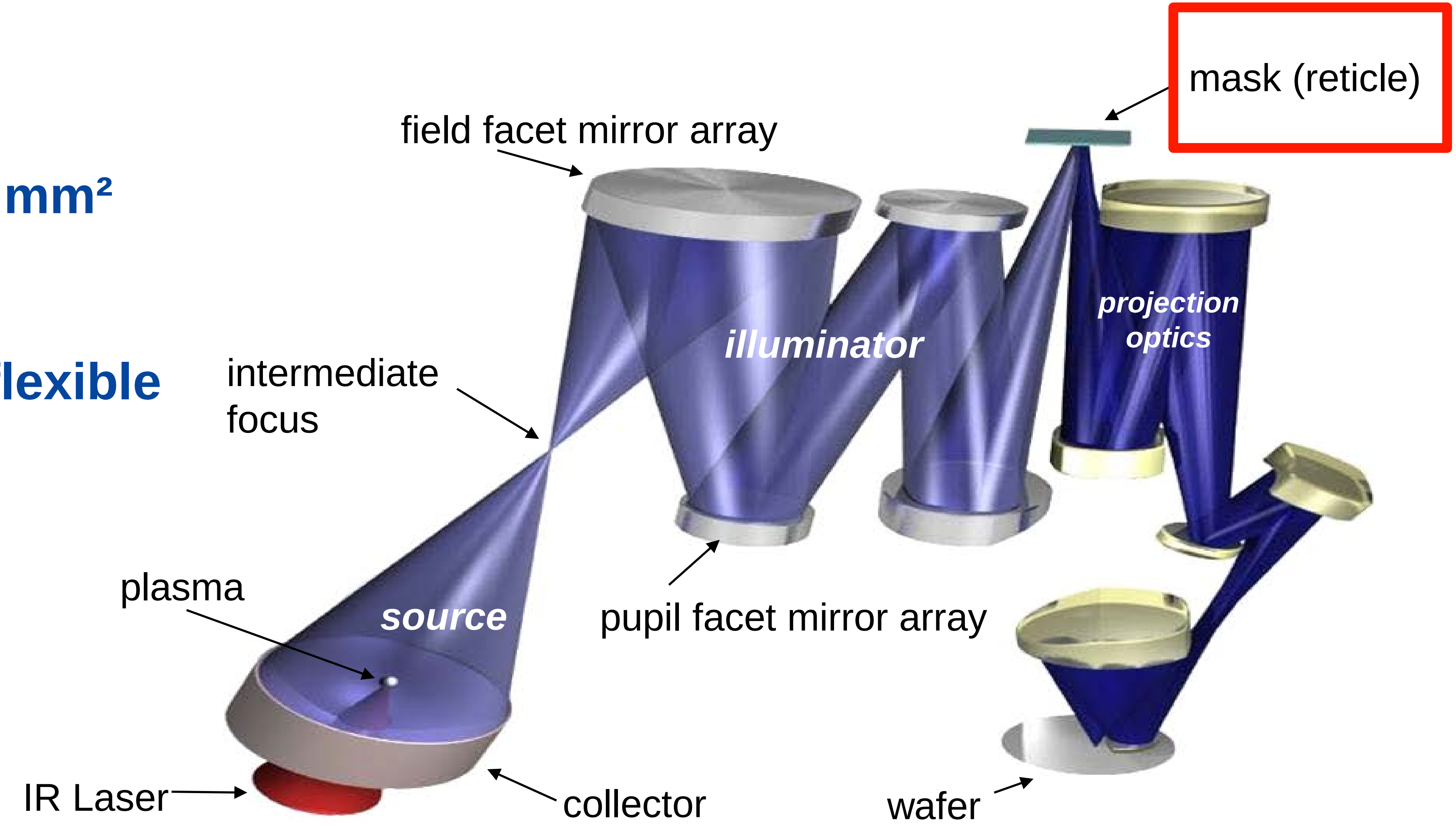
Starlith® 3400 productivity
Robust transmission trend supports increased throughput.



ZEISS inhouse EUV qualification

AIMS™ EUV
The EUV mask is a special mirror in the optical column.

λ	**13.5 nm**
NA	**0.33**
Field	**26 x 33 mm²**
MAG	**4x**
Res	**13 nm**
Illum	**highly flexible**



design scheme

AIMS™ EUV

Challenges for EUV mask making addressed by ZEISS.

Simplified Mask Making Process

Patterning → Metrology → Tuning → Inspection → Repair → Verification → Cleaning

Products

PROVE®

ForTune

MeRiT®

AIMS™ EUV

Challenges

Registration Metrology

- High resolution metrology
- High measurement repeatability required

Mask Tuning

- Tuning of EUV mask to improve registration / wafer on-product -overlay

Mask Repair

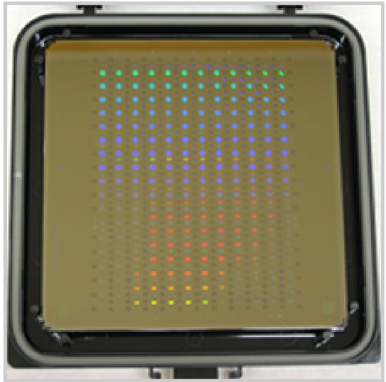
- High lateral resolution
- Accurate height control
- No destruction of multilayers
- Extendable to new materials

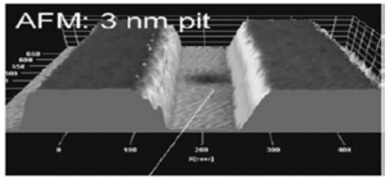
Mask Verification

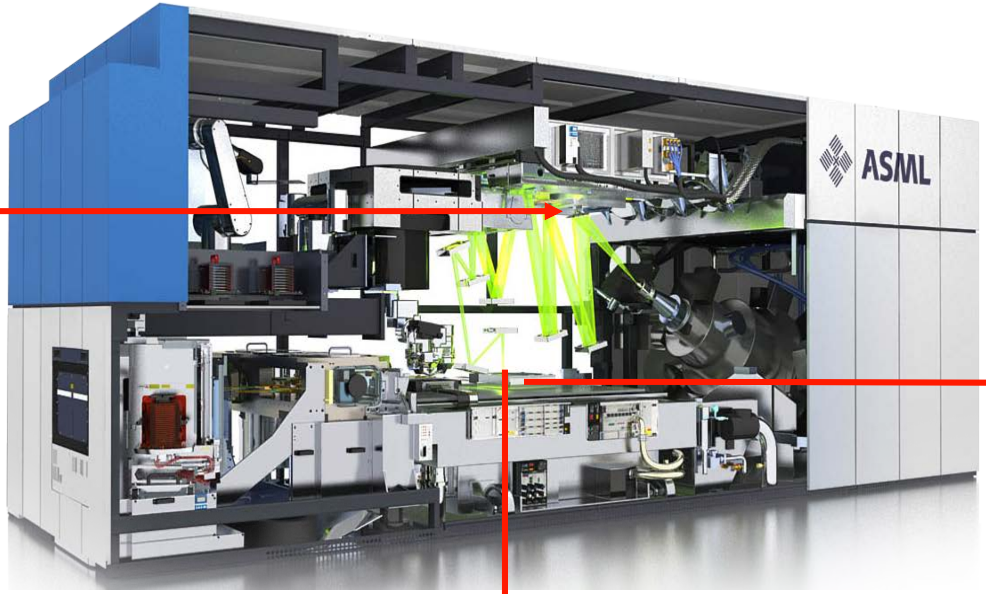
- Actinic Repair verification
- Cleanliness

AIMS™ EUV
Sees already in the mask shop what the wafer will see.

Mask

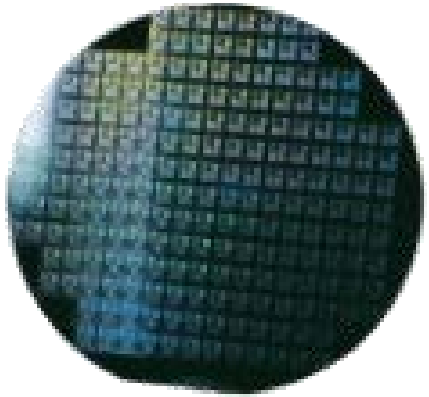


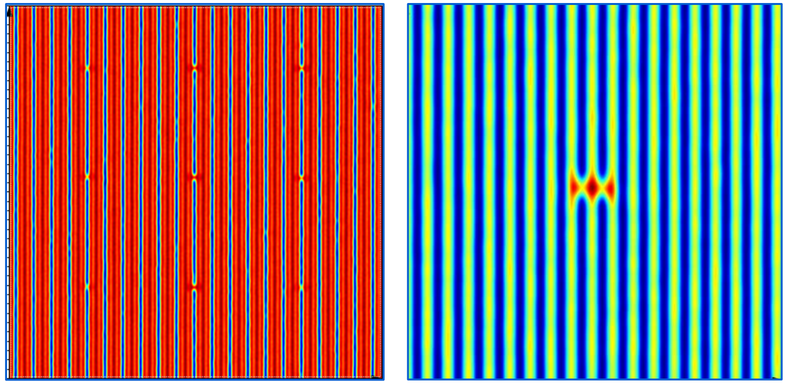




Source: ASML

Exposed wafer



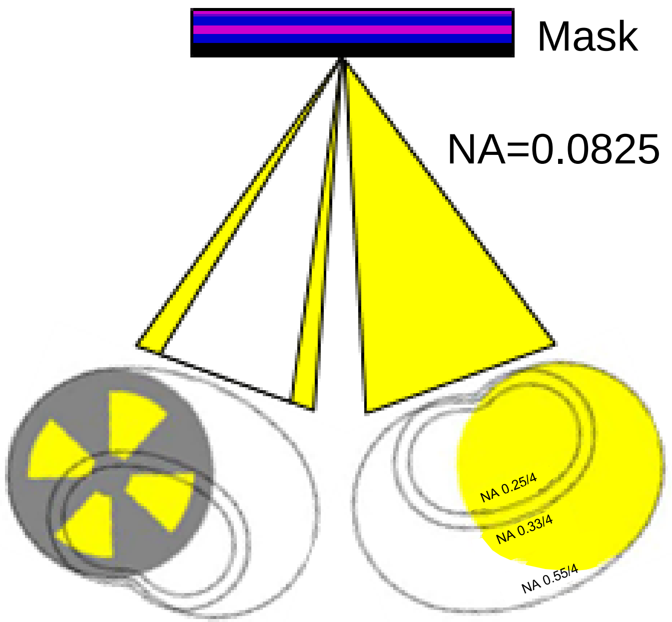


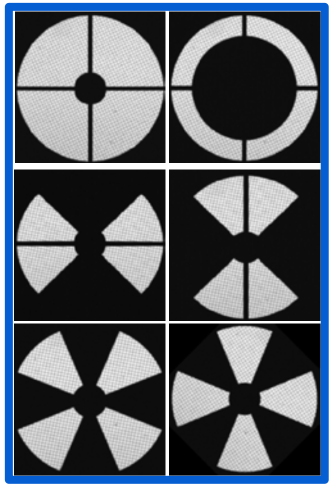
Mask aerial image

- Mask shop tool which measures the mask image
- Mask qualification free of resist effects and photon noise (stochastics)

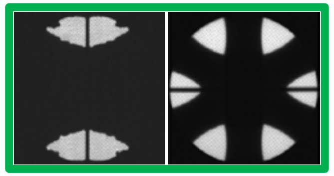
AIMS™ EUV
Core functionality at a glance

Equivalent image generation as on scanner





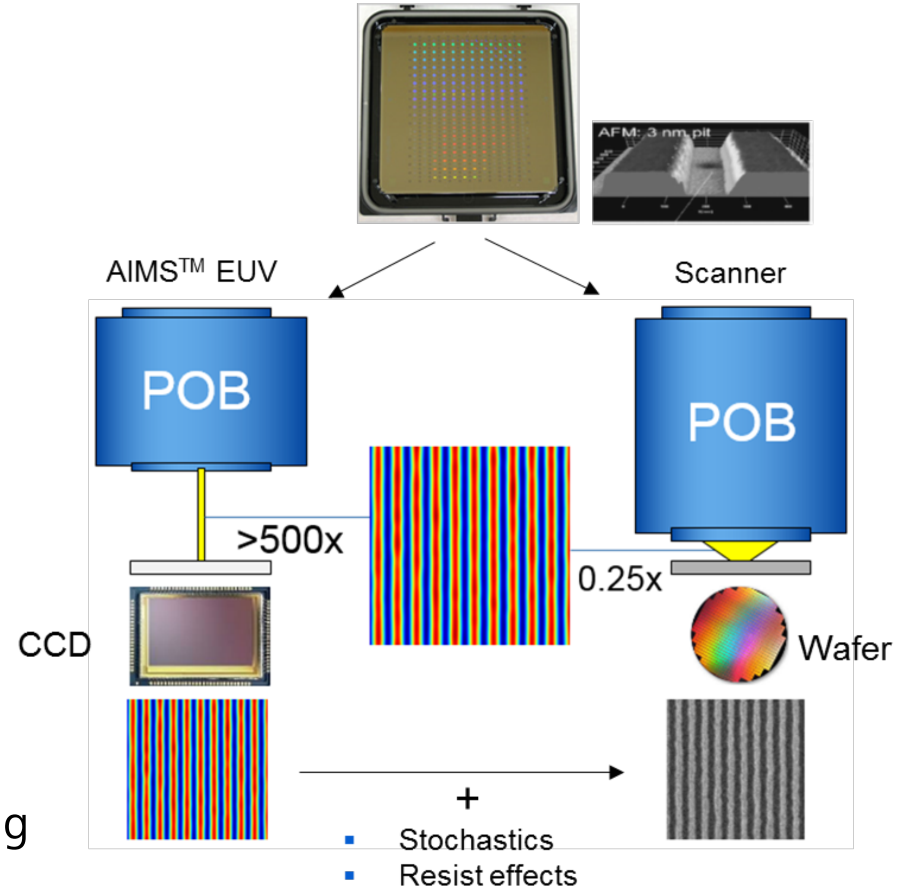
33X0 (PFR≥38%)



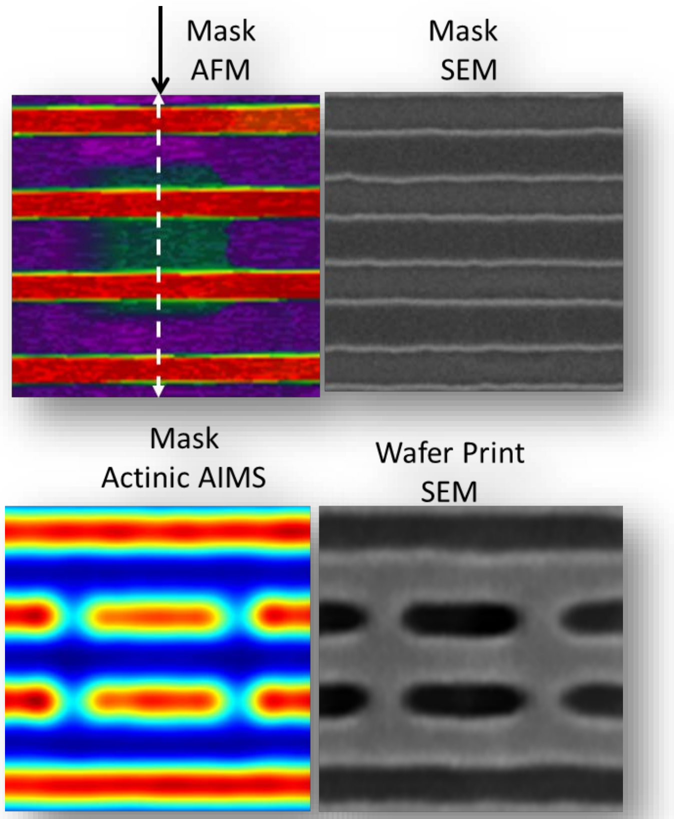
34X0 (PFR≥20%)

- Illumination setting available for optimized scanner matching
- Equivalent angular space selection (CRAO)

Same information collected from the mask to create aerial image

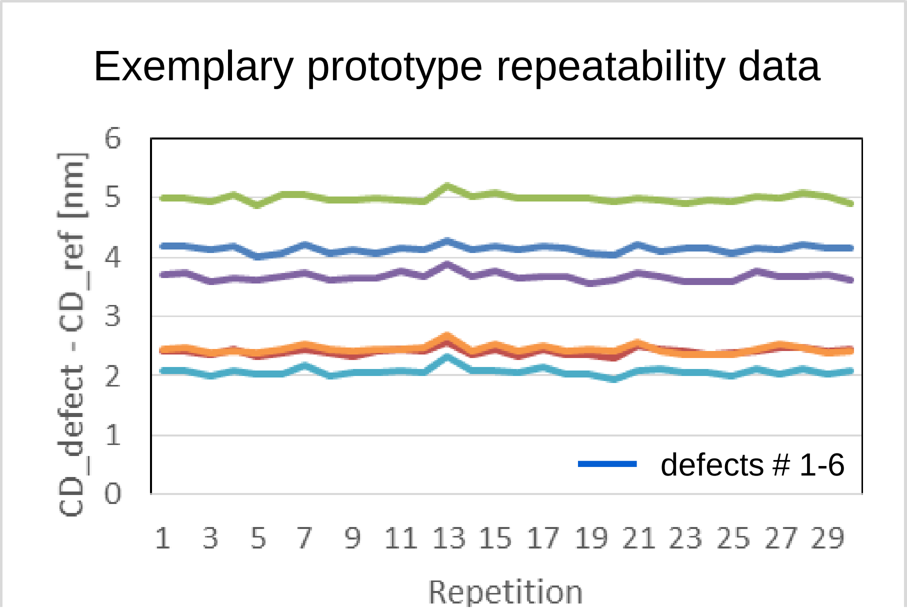


AIMS™ EUV
Precise quantification of aerial image impact for all kinds of defects.



E. Verduijn et al. 2017, 'Printability and actinic AIMS review of programmed mask blank defects'

- Suitable also for phase defects
- Scanner matching: λ, NA, sigma, CRA,..

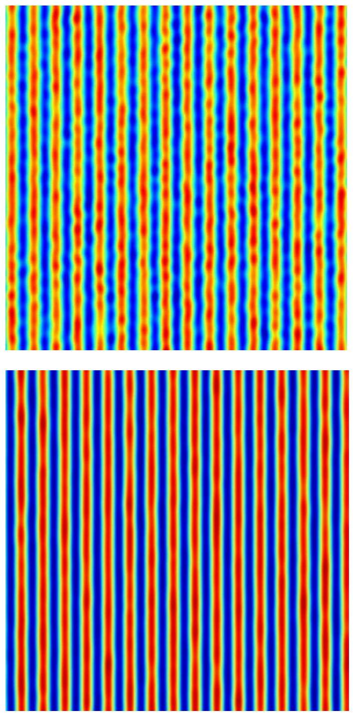


Structure	FAT	ATP	Spec (a.u.)
64nm L/S 1:1	0.4	0.4	1.0
80nm CH 1:1	0.5	0.6	1.0

Capelli R. et al. 2018, "AIMS™ EUV first insertion into the back end of the line of a mask shop: a crucial step enabling EUV production"

- Precise quantification
- Reliable OK/NOK decision

Photon stochastics mode



8 mJ/cm²*

* Equivalent of **40mJ/cm²** with 20% resist absorption

AIMS™ mode

Capelli R. et al. 2018, "Aerial image based metrology of EUV masks: recent achievements, status and outlook for the AIMS™ EUV platform"

- „Clean" image of mask contribution

High-NA EUV: Starlith® 5000
The optical system for the ultimate printing machine with NA = 0.55

Ernst Abbe
(1840–1905)

$$\text{Resolution} = k_1 \frac{\lambda}{NA}$$

High-NA

NA	**0.25**	**0.33**	**…**	**0.45**	**0.50**	**0.55**
Resolution @ k_1=0.3 single exposure / nm	**16.2**	**12.3**	**…**	**9.0**	**8.1**	**7.4**

High-NA EUV: Starlith® 5000

The optical system for the ultimate printing machine with NA = 0.55

1995 2003 2006 2009 2012 2015 2018 2021

MET
Micro Exposure Tool

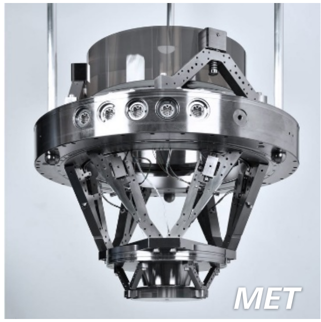
ADT
(α-Demo Tool)

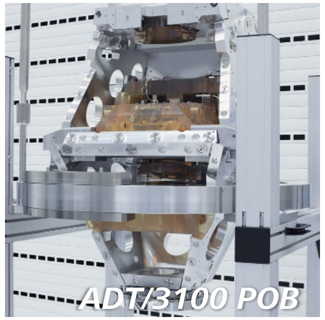
Starlith® 3100

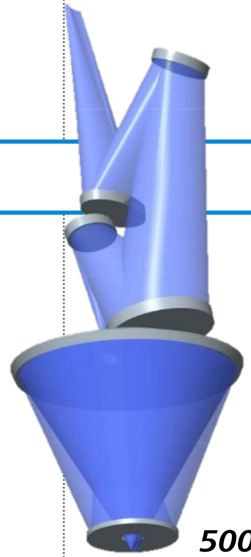
Starlith® 3300

Starlith® 3400

High-NA EUV: Starlith® 5000







5000 POB

System produced

Development phase ongoing

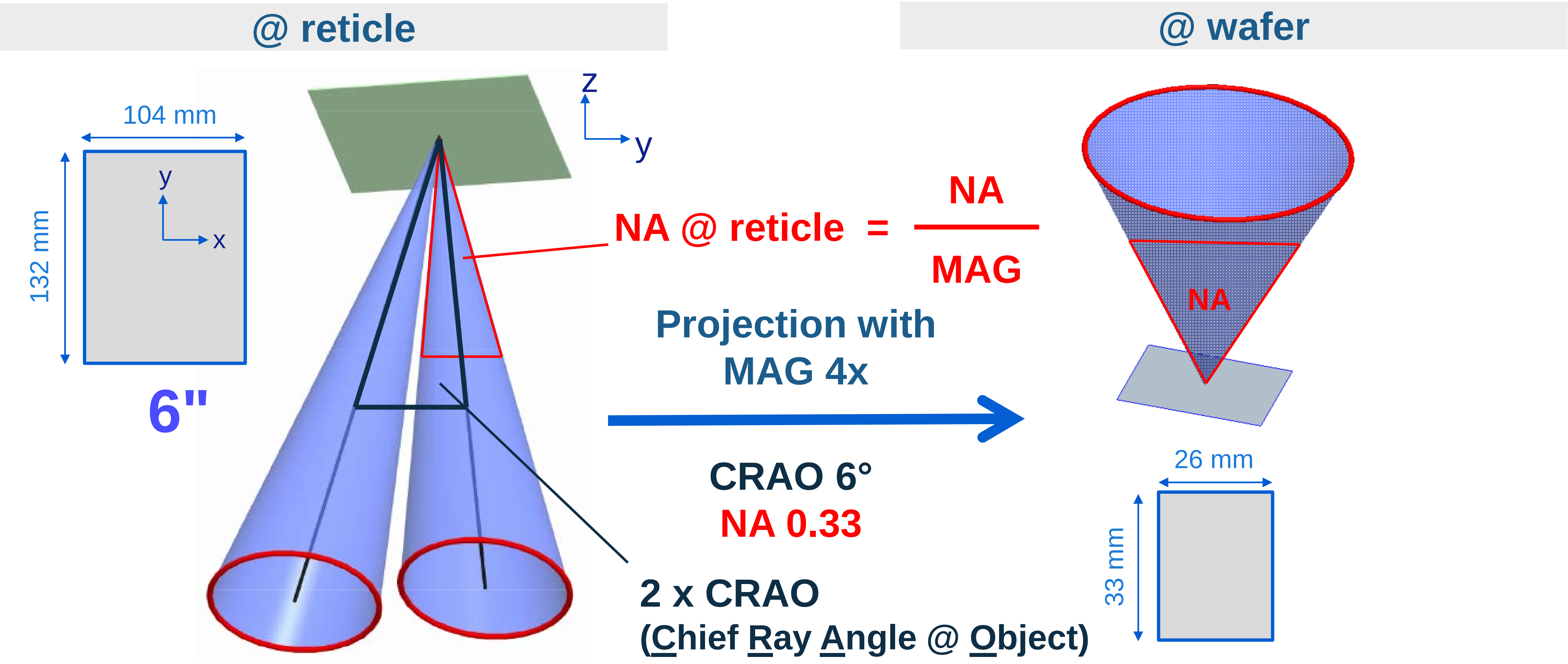
High-NA EUV: Starlith® 5000

The optical system for the ultimate printing machine with NA = 0.55

design scheme

High-NA EUV: Starlith® 5000

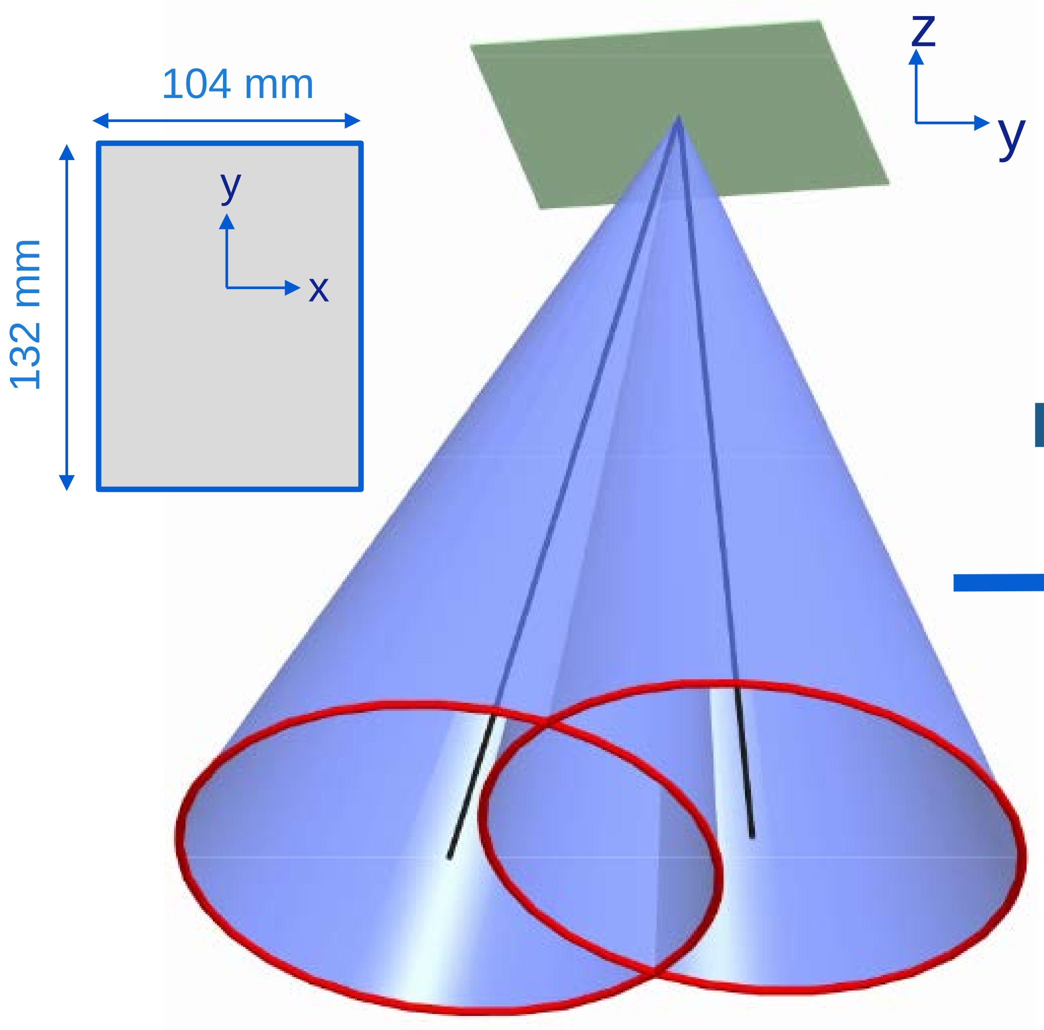
Fields and light cones at reticle and wafer are connected via MAG (magnification).



High-NA EUV: Starlith® 5000

Increasing NA, light cones @ reticle start to overlap.

@ reticle

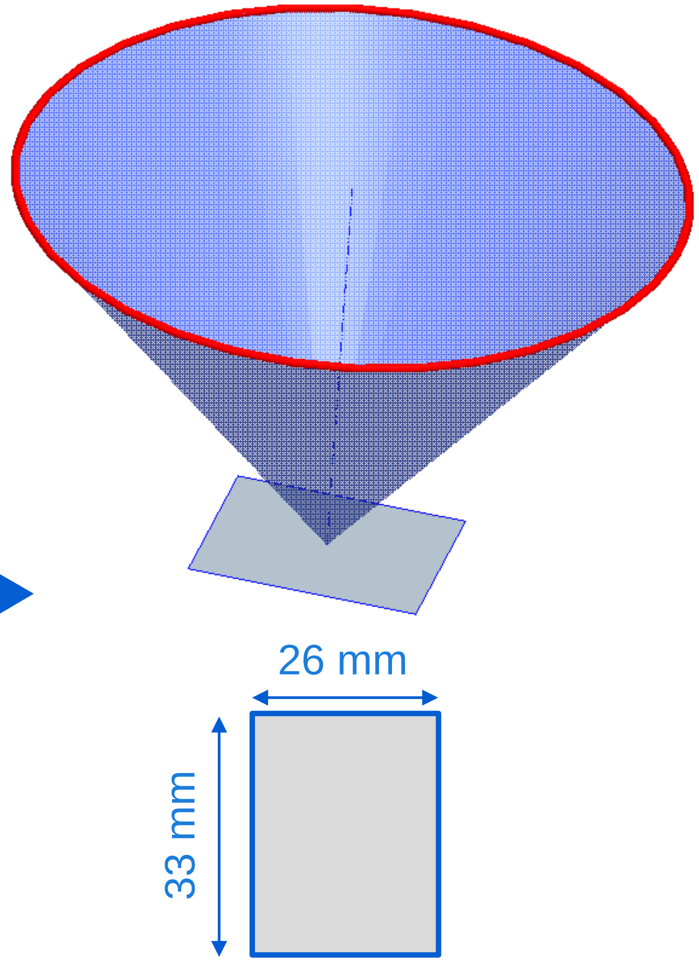


Projection with MAG 4x

CRAO 6°

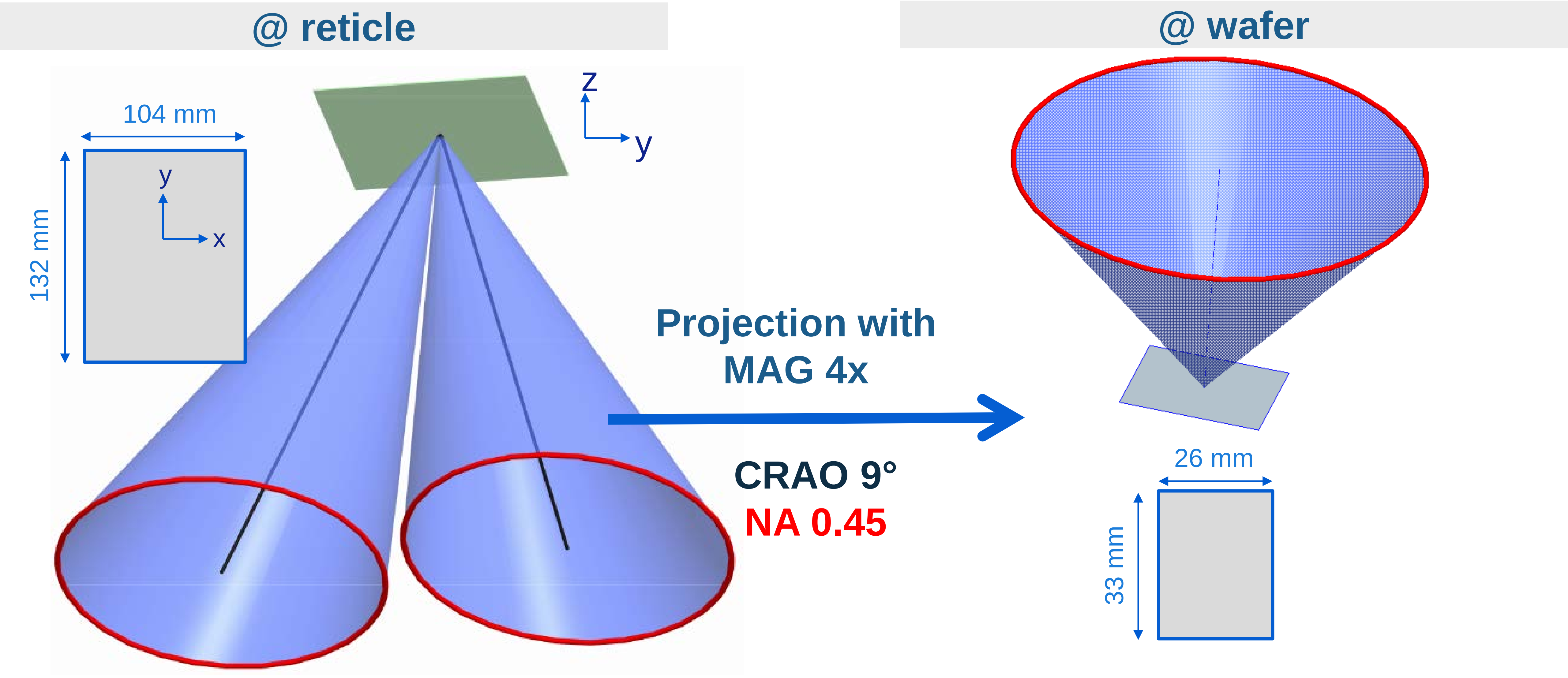
NA 0.45

@ wafer



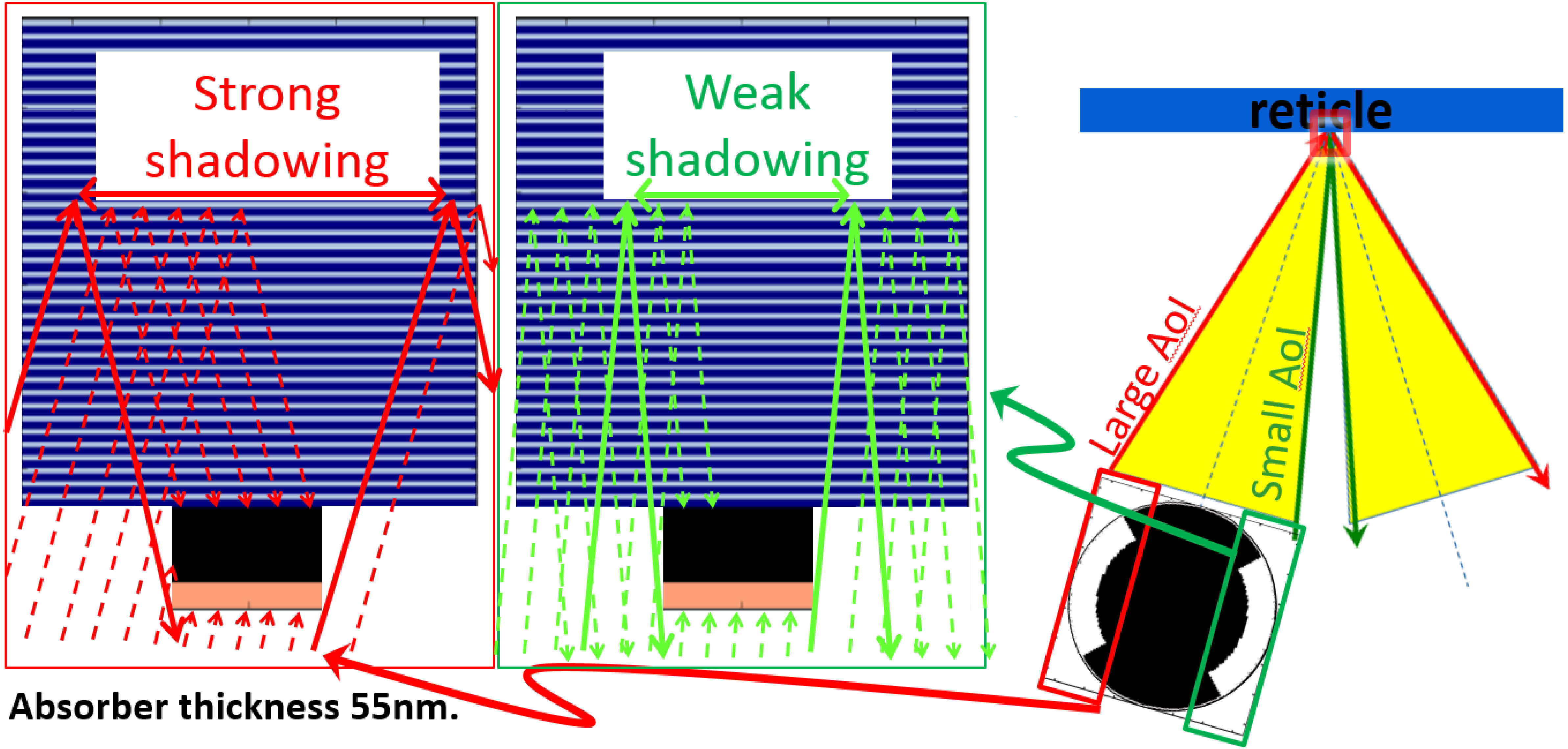
High-NA EUV: Starlith® 5000

To separate light cones again, CRAO must be increased.



High-NA EUV: Starlith® 5000

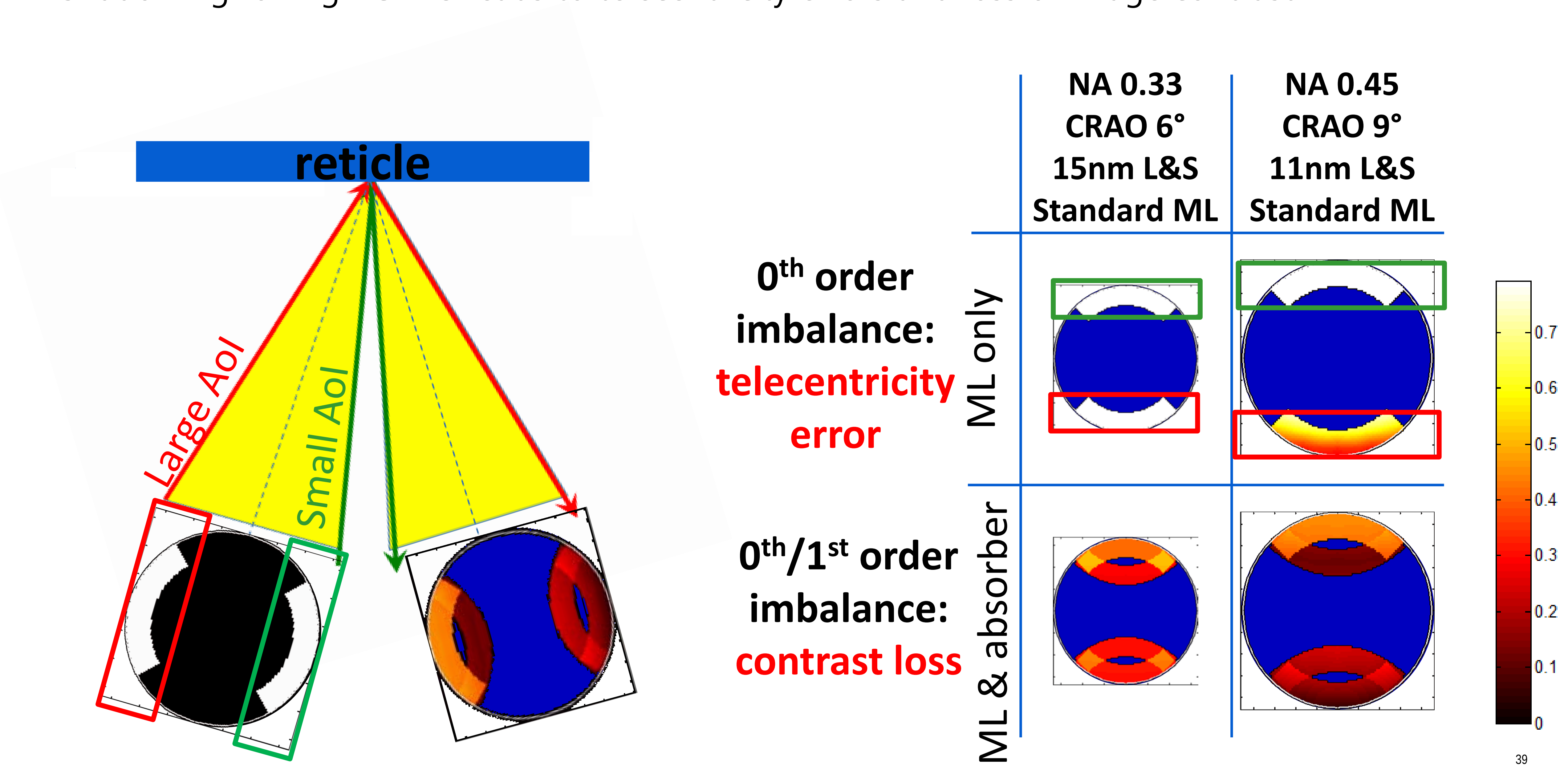
Absorber shadowing @reticle is angular dependent.



Absorber thickness 55nm.

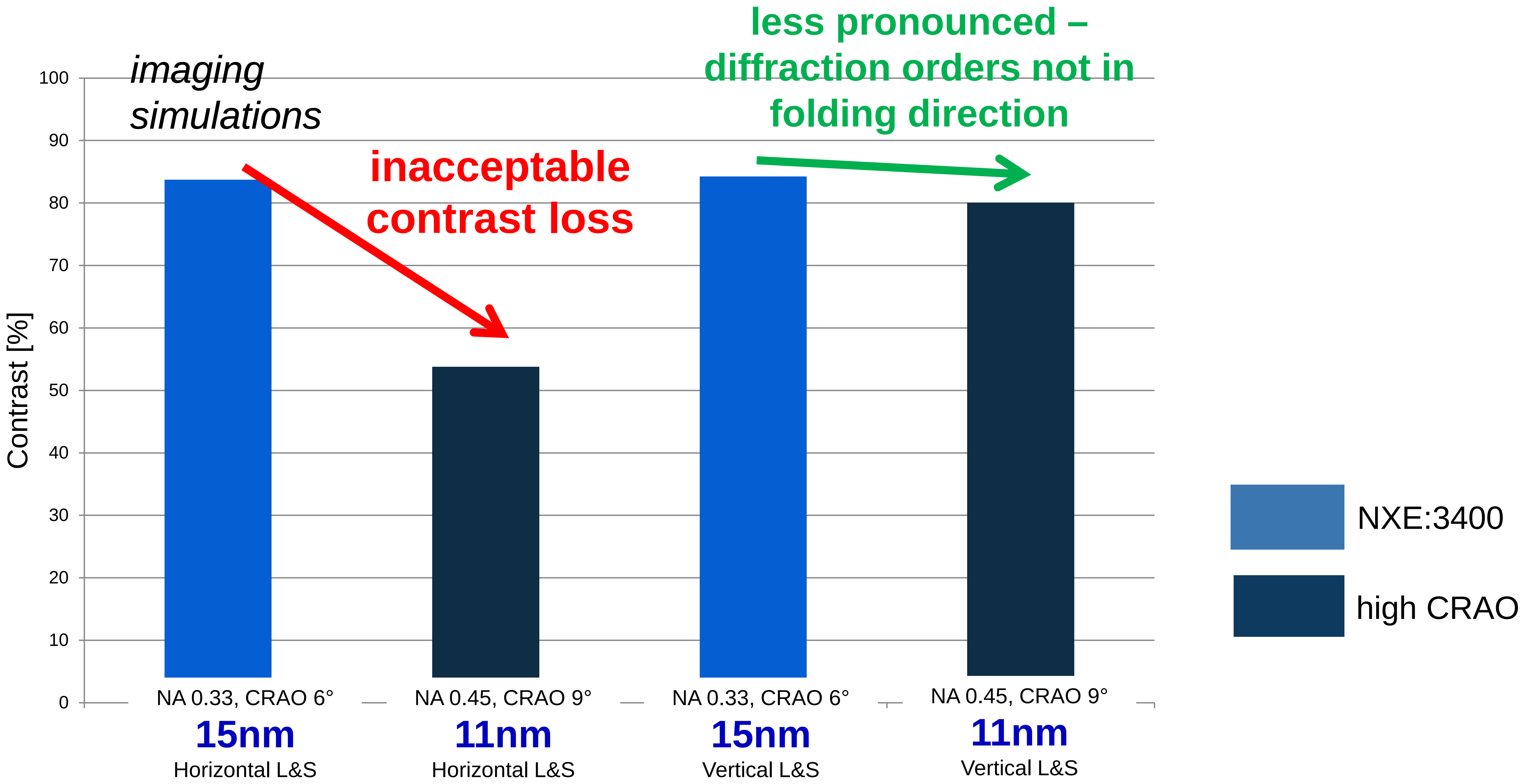
High-NA EUV: Starlith® 5000

Shadowing for high CRAO leads to telecentricity errors and loss of image contrast.



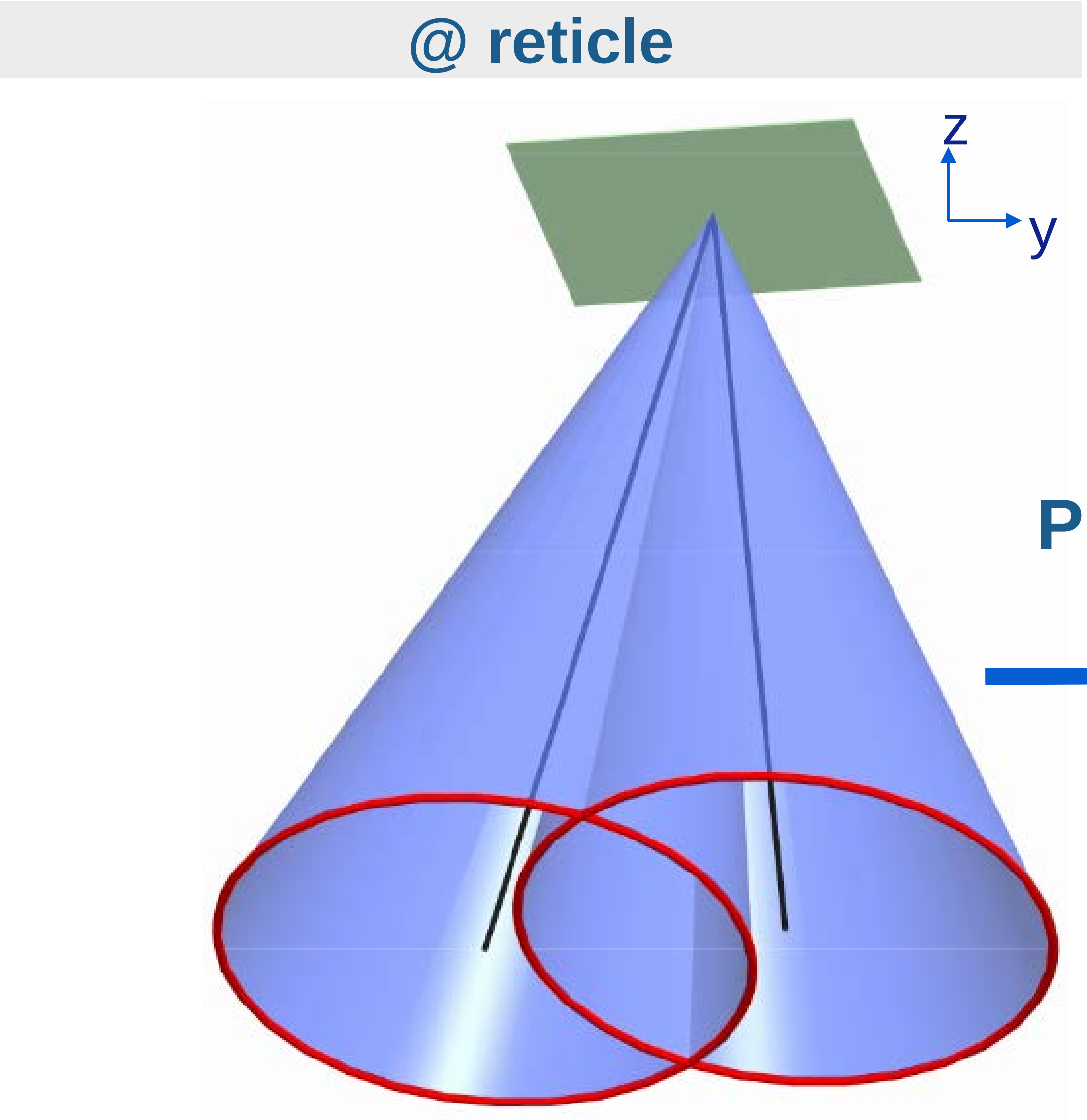
High-NA EUV: Starlith® 5000

Due to shadowing, a system with high CRAO does not resolve even 11 nm hp.



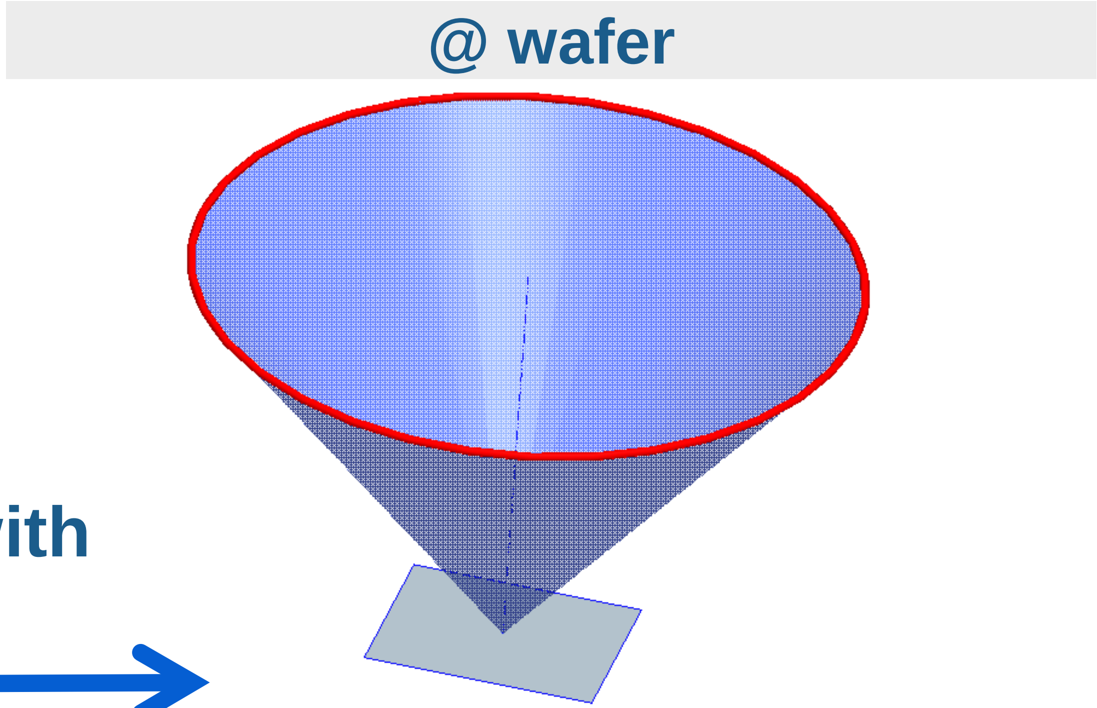
High-NA EUV: Starlith® 5000

The only way to decrease angular spread @reticle is to increase MAG.



Projection with MAG 4x

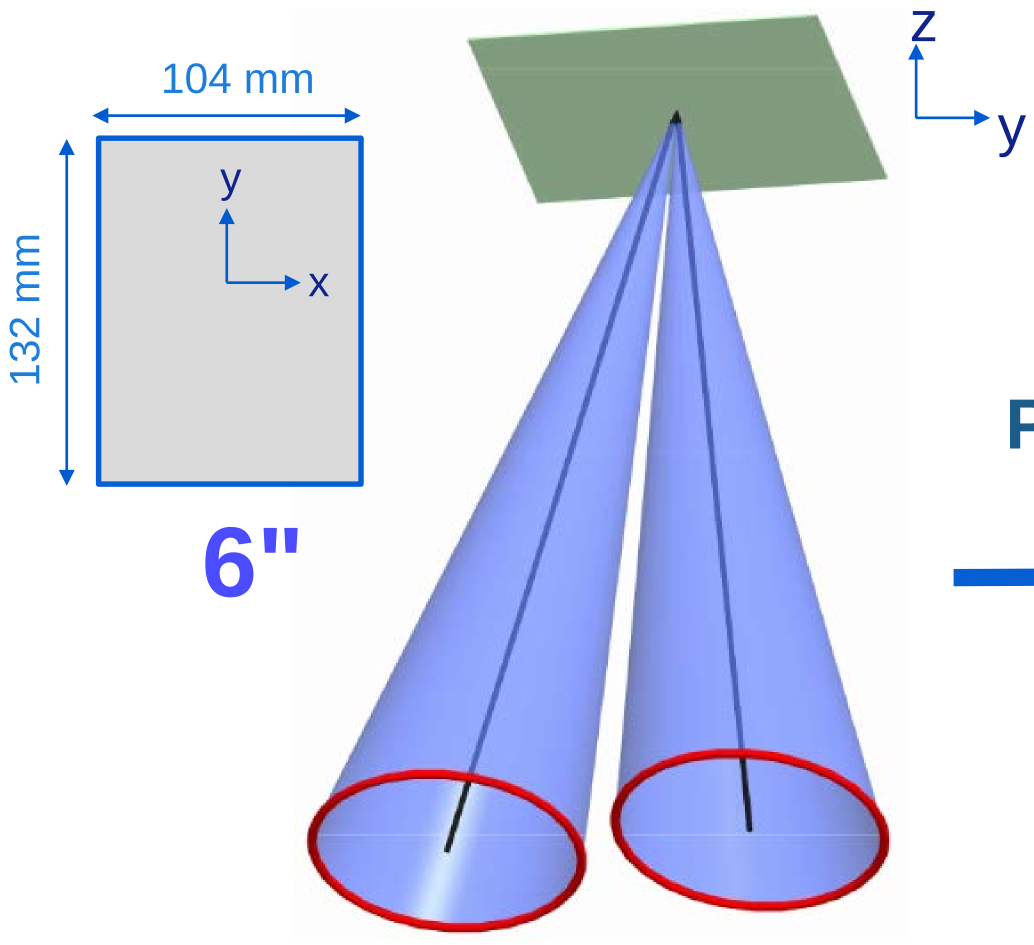
CRAO 6°



High-NA EUV: Starlith® 5000

Changing MAG is changing field sizes: Same mask leads to Quarter Field…

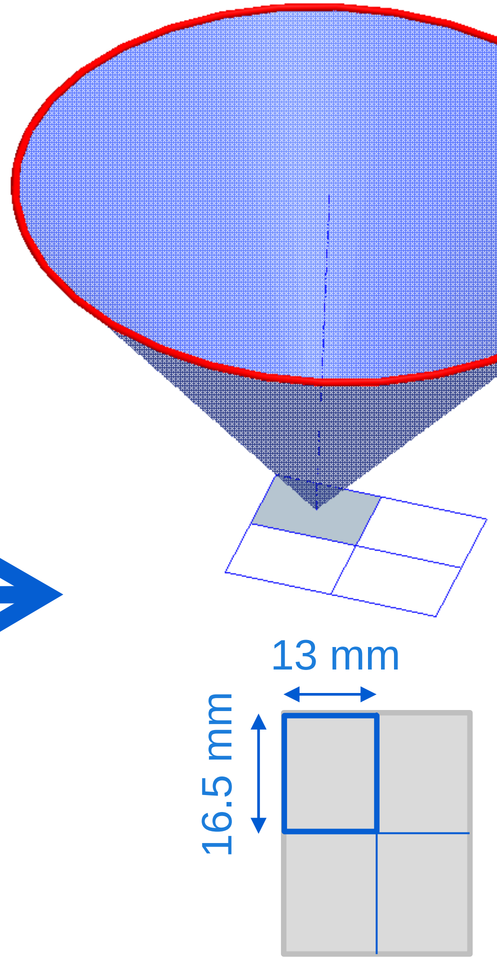
@ reticle



Projection with MAG 8x

CRAO 6°

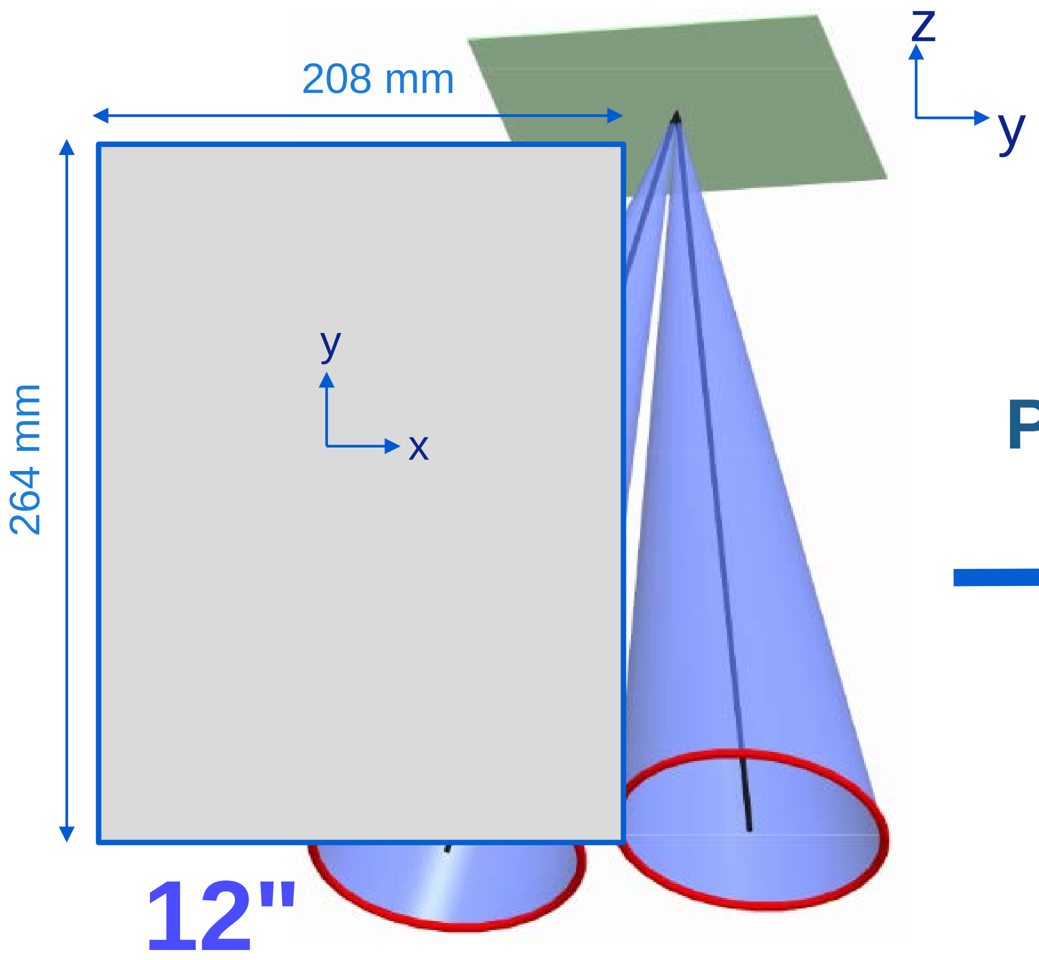
@ wafer



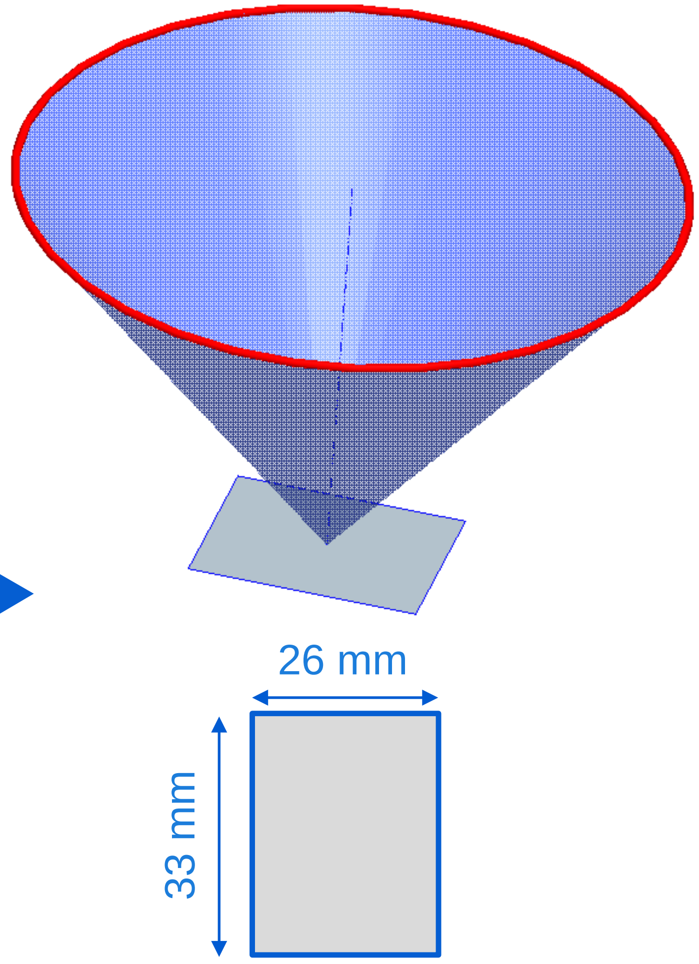
High-NA EUV: Starlith® 5000

…or keeping Full Field requires a large mask.

@ reticle



@ wafer



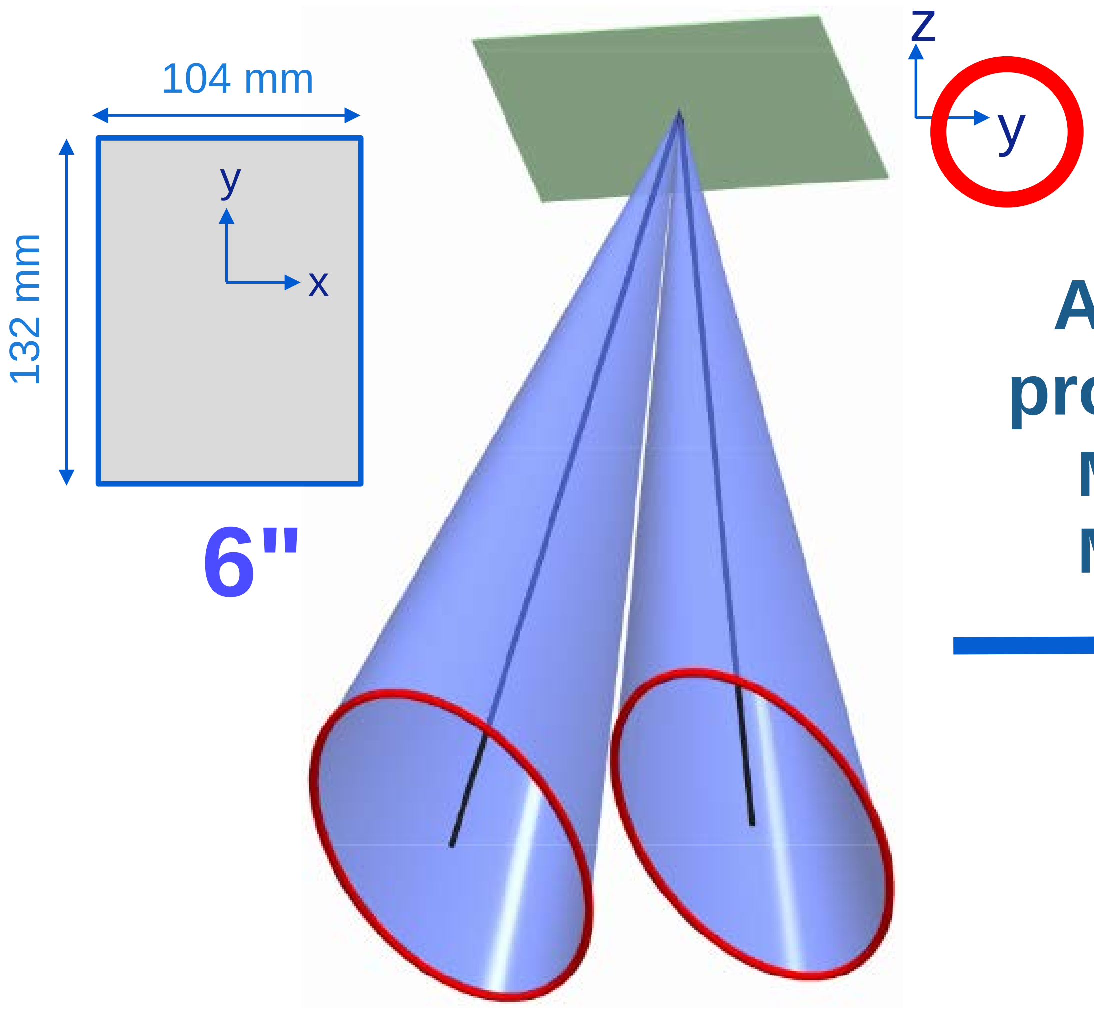
Projection with MAG 8x

CRAO 6°

High-NA EUV: Starlith® 5000

Reducing angles by increasing MAG only in the direction that matters.

@ reticle



Anamorphic projection with

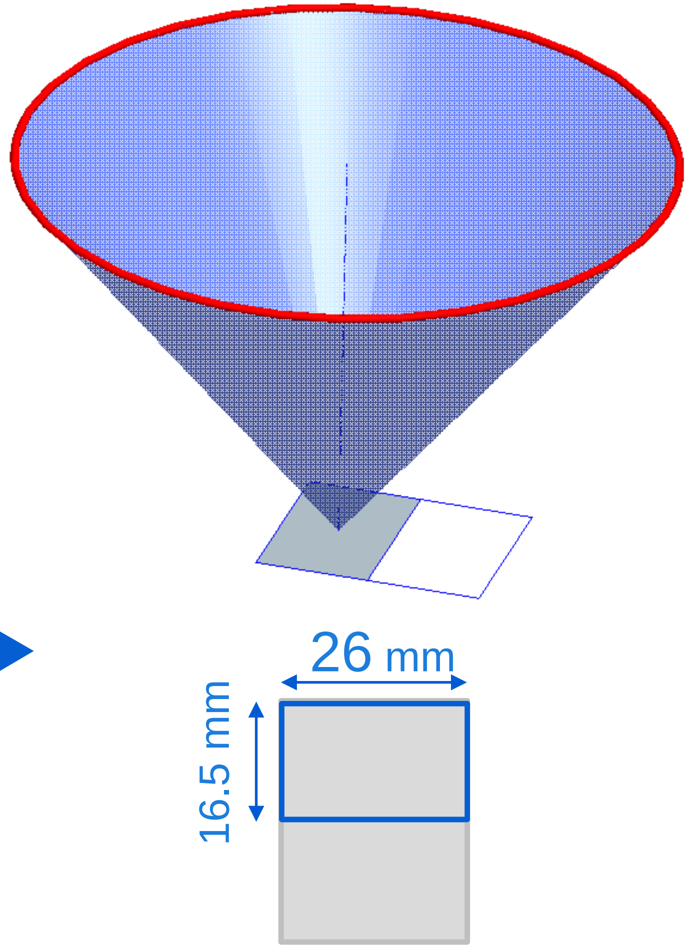
MAG 4x in x

MAG 8x in y

CRAO 6°

NA = 0.55

@ wafer



High-NA EUV: Starlith® 5000

Design enables sub 8 nm resolution imaging using standard multilayer @ reticle.

High-NA EUV: Starlith® 5000

Looking at the movies…

Reality

Film

Cinema Widescreen

Image by Bernd Geh

Record with a conventional lens

Project with a conventional lens

Same aspect ratio, same angles.

BUT: Bad usage of space, lower resolution

High-NA EUV: Starlith® 5000

…where anamorphic cinematographic lenses are used…

Reality

Film

Cinema Widescreen

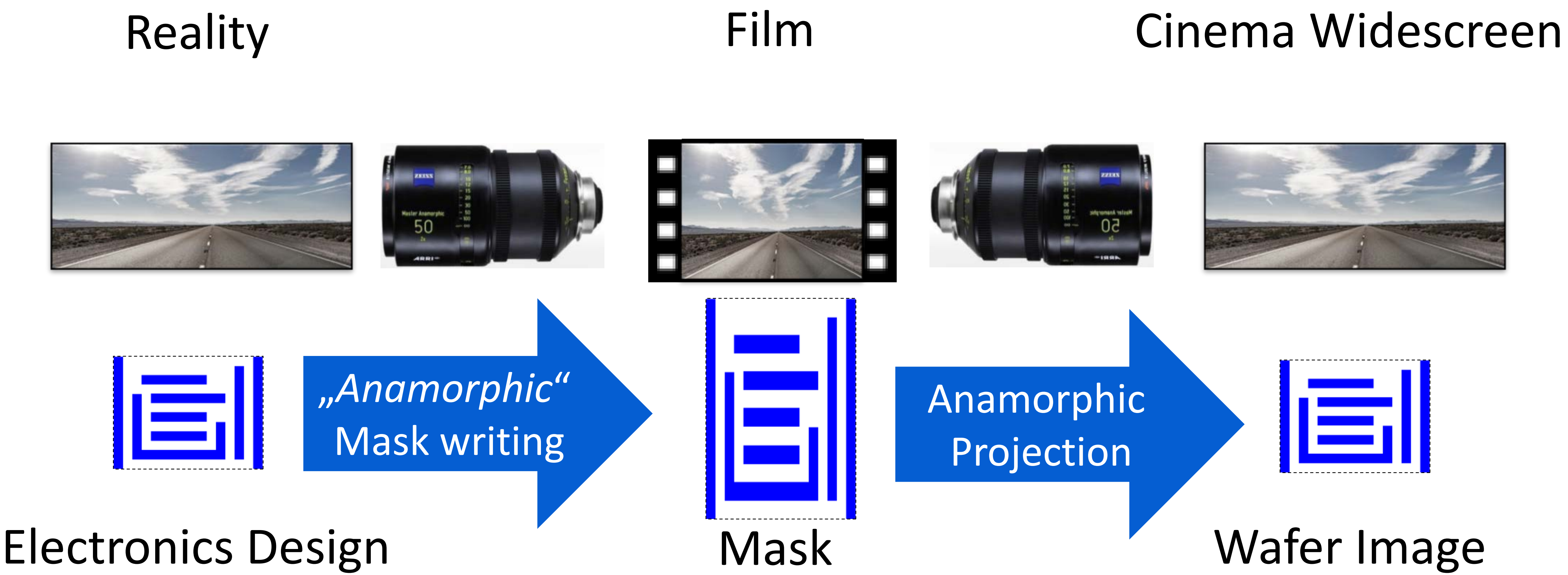
Record with an **Anamorphic** lens*

Project with an **Anamorphic** lens

Anamorphic MAG vertically „stretches“ image
for good usage of space, lower angles, better resolution

**e.g. a ZEISS Master Anamorphic Lens*

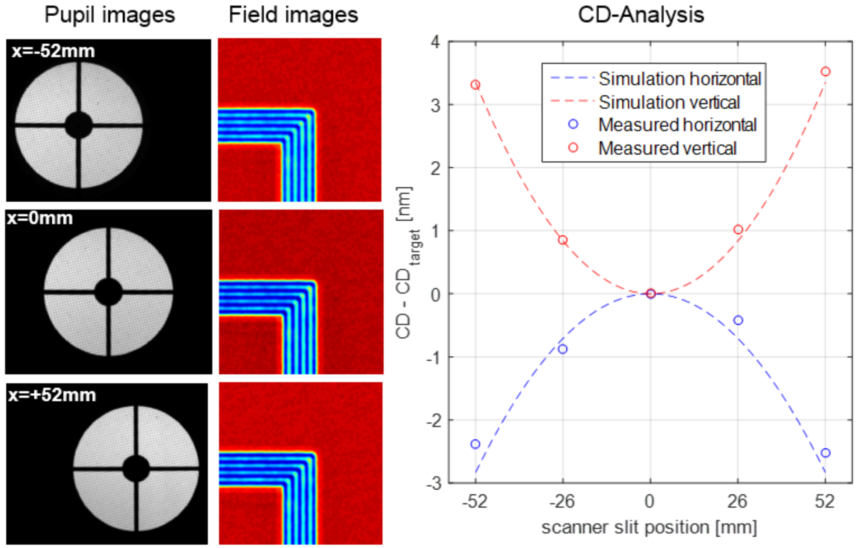
High-NA EUV: Starlith® 5000
…to reduce angles at the mask and increase resolution in lithography.



Same image on wafer, but much lower angles in stretching direction.

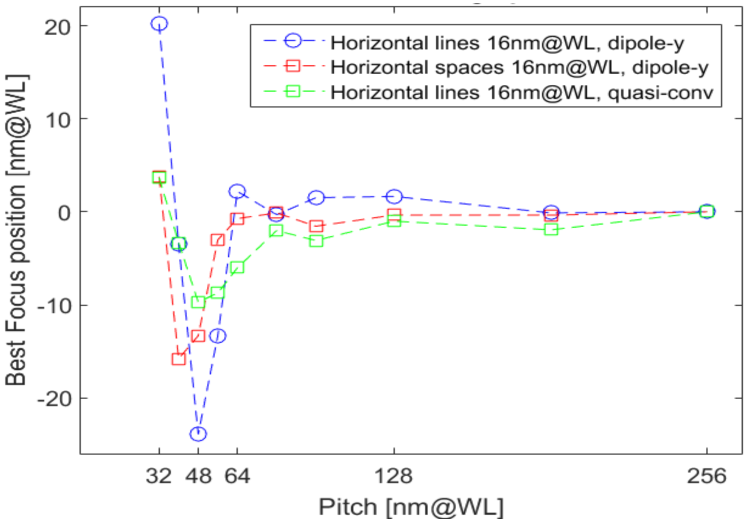
High-NA EUV: Starlith® 5000
AIMSTM EUV for mask 3D effects qualification

Impact of shadowing effects and full mask bias qualification



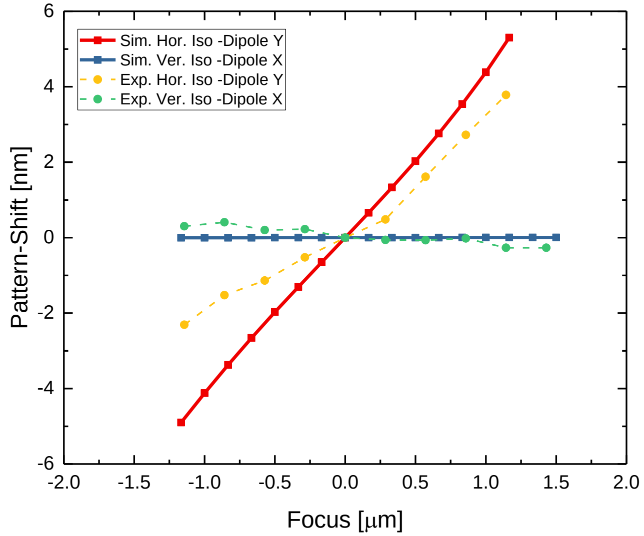
Hellweg et al. 2016, "Actinic Review of EUV Masks: Performance Data and Status of the AIMSTM EUV System

Best focus shift through structure pitch



Hellweg at al. 2017, "Actinic Review of EUV masks: Challenges and achievements in delivering the perfect mask for EUV production"

Pattern placement shift through focus



Capelli R. et al. 2018, "AIMSTM EUV tool Platform: Aerial image based qualification of EUV masks"

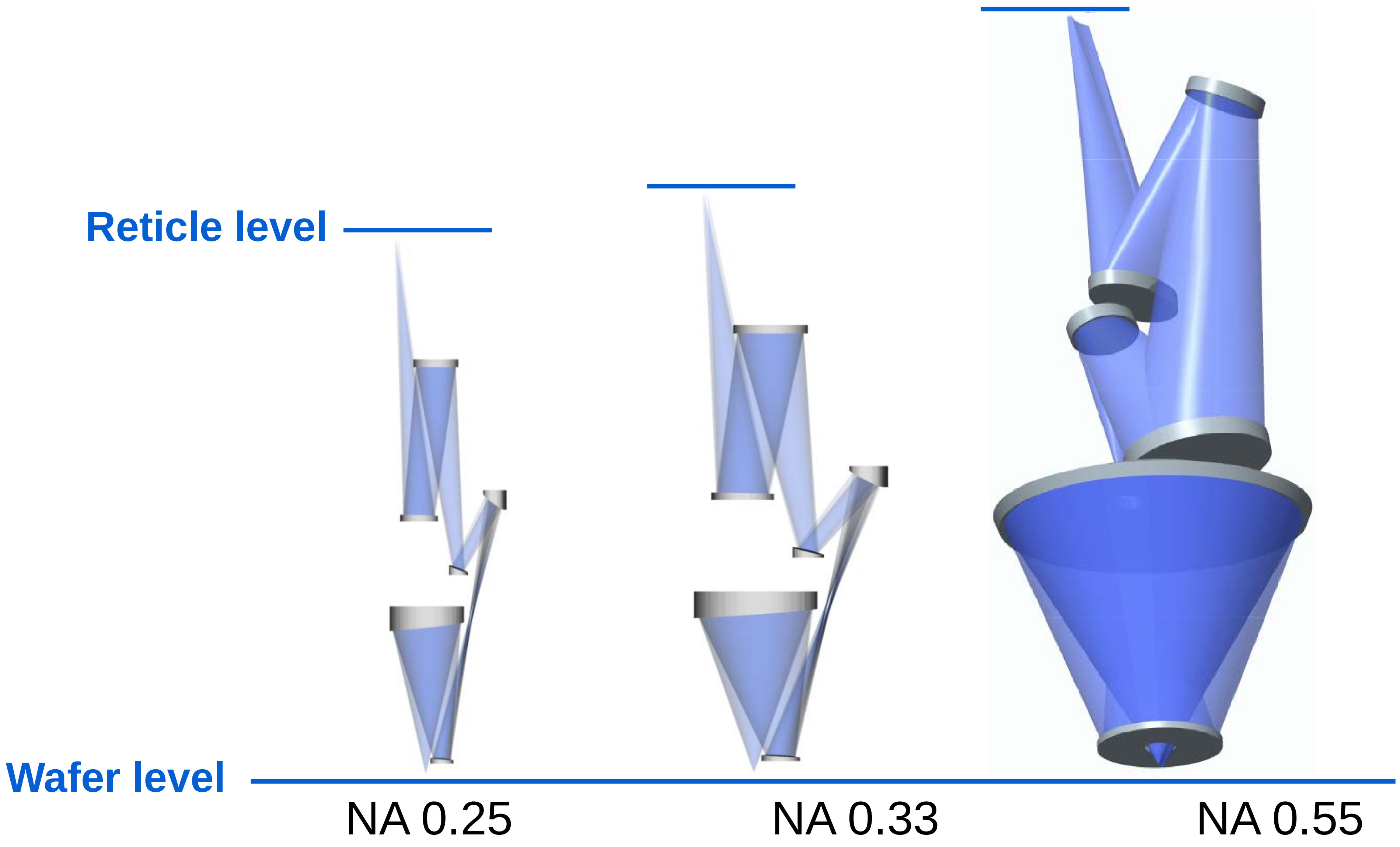
Mask shop benefits

- equivalent image generation as on scanner NXE:33X0-34X0 (illumination, NA)
- same diffraction orders collected by POB → **relevant information only**

Provides the means for a full qualification of mask 3D effects, and their dependence on process parameters.

High-NA EUV: Starlith® 5000

The design has been finalized.

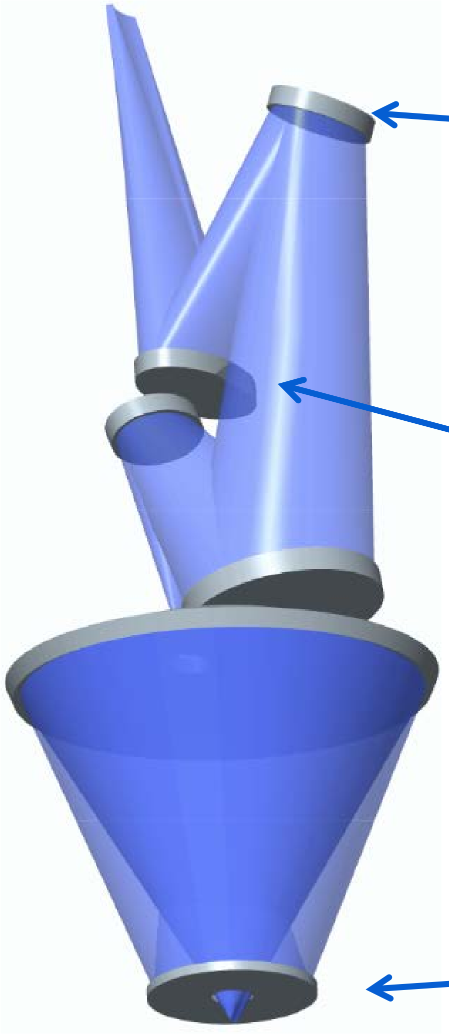


Design examples

High-NA EUV: Starlith® 5000

Big optical system with very large mirrors and extreme aspheres.

Large overall size of optical system



Extreme aspheres enabling **further improved wavefront / imaging performance**

Tight surface specifications enabling **low straylight / high contrast imaging**

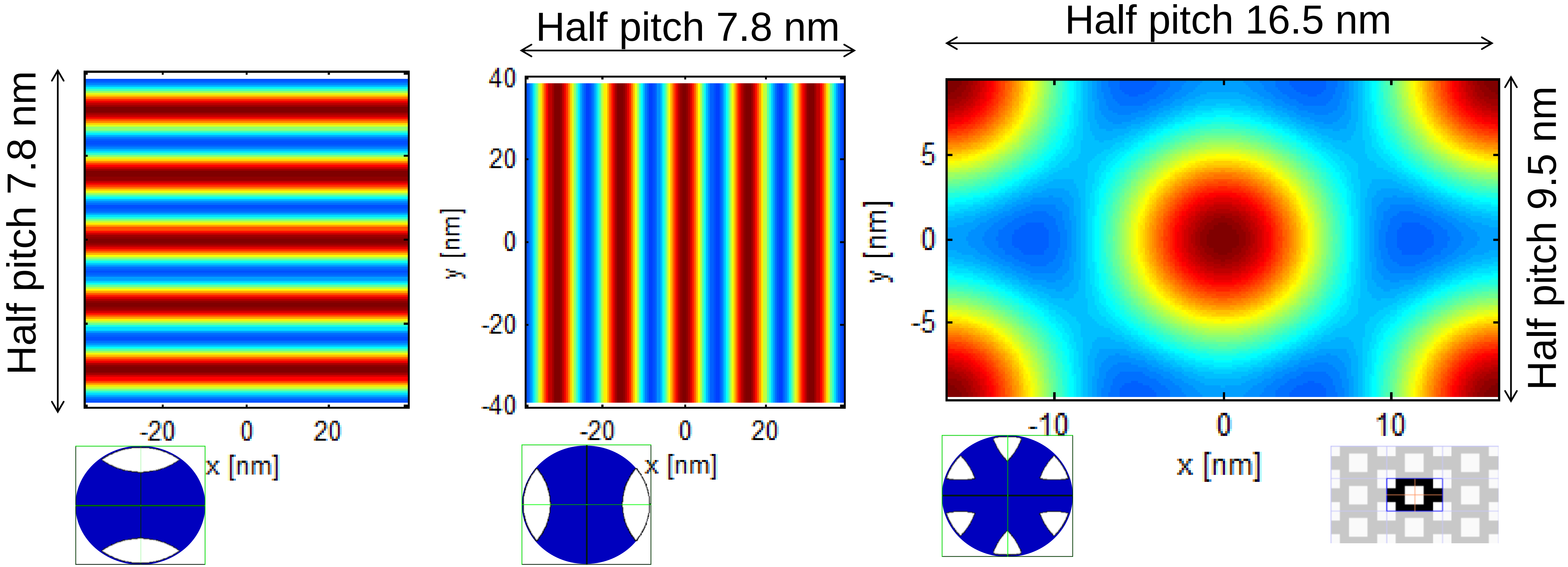
Big last mirror driven by **High NA**

Obscuration enables **high transmission**

→ Challenge to optics technology and manufacturing

High-NA EUV: Starlith® 5000

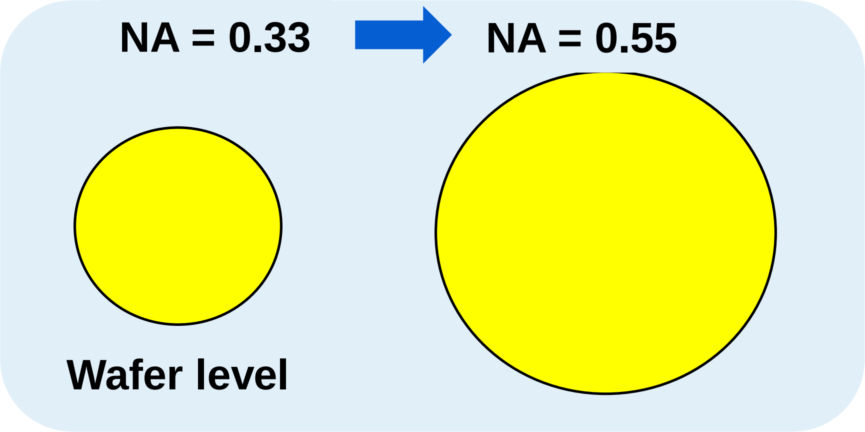
Single exposure resolution power optics for the EXE:5000 scanner.

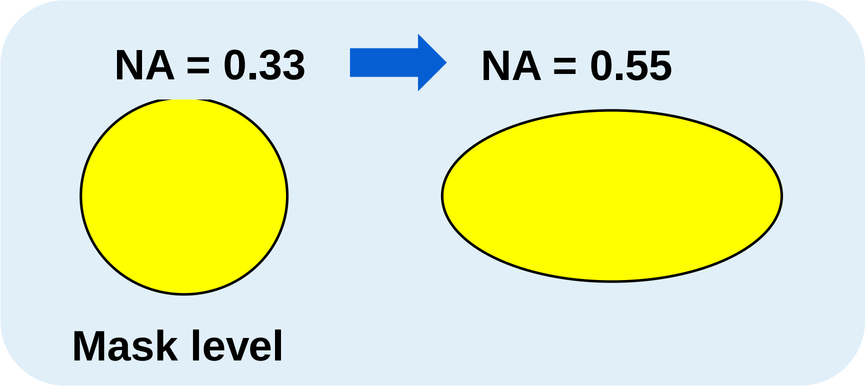


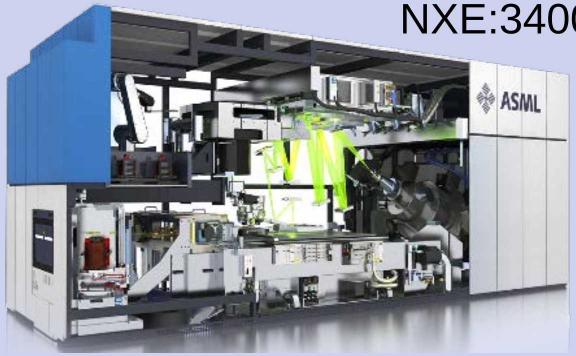
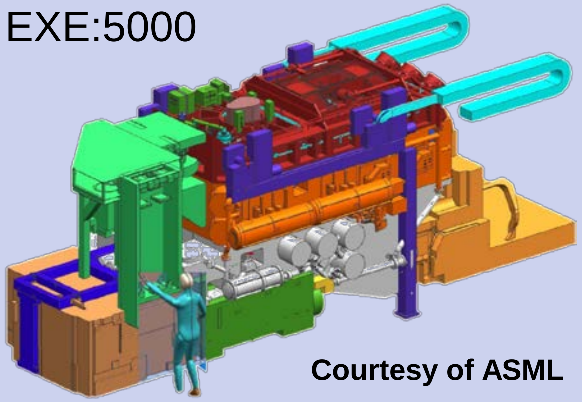
The EXE:5000 scanner will be the ultimate lowest cost/pixel printing machine.

High-NA EUV: Starlith® 5000

AIMS™ EUV solution for EXE:5000 High-NA emulation.



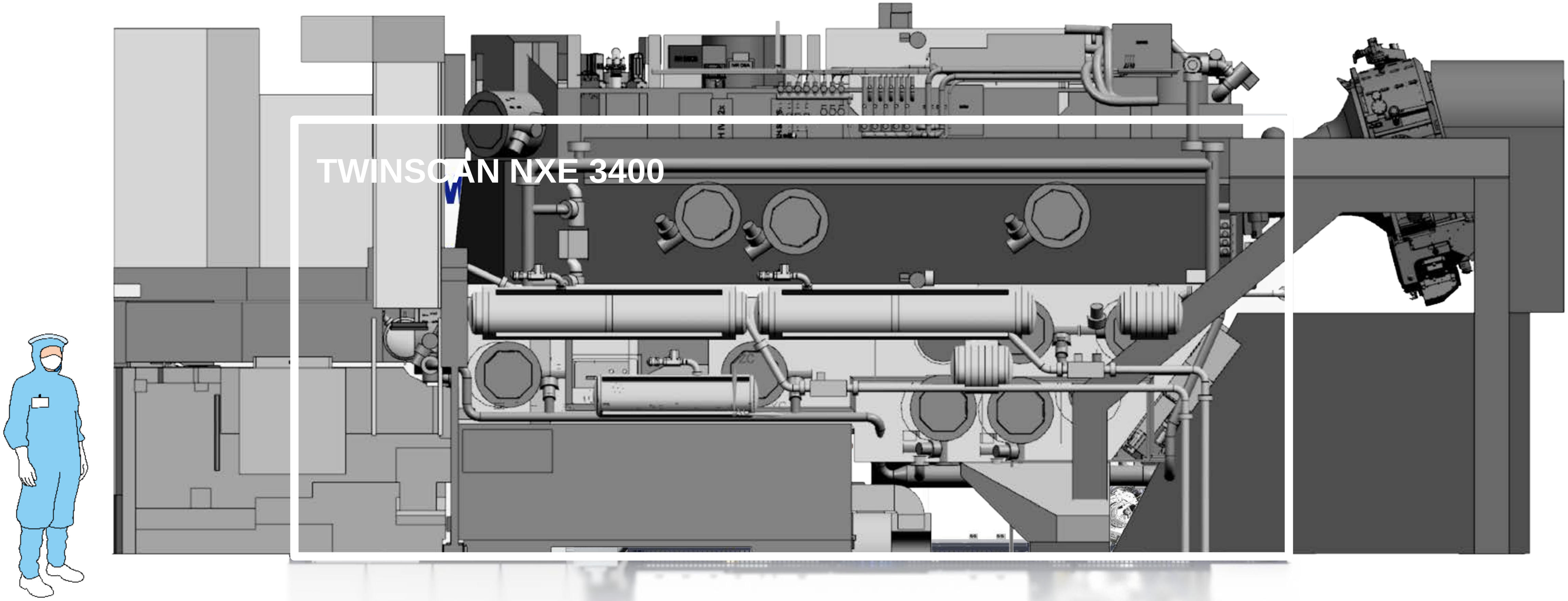


	NA 0.33	NA 0.55
Scanner	NXE:3400 	EXE:5000  **Courtesy of ASML**
AIMS™ EUV	 Current platform	 Same platform changes to component level

Pre-development started

AIMS™ EUV for High-NA will be based on existing platform to guarantee forward and backward compatibility.

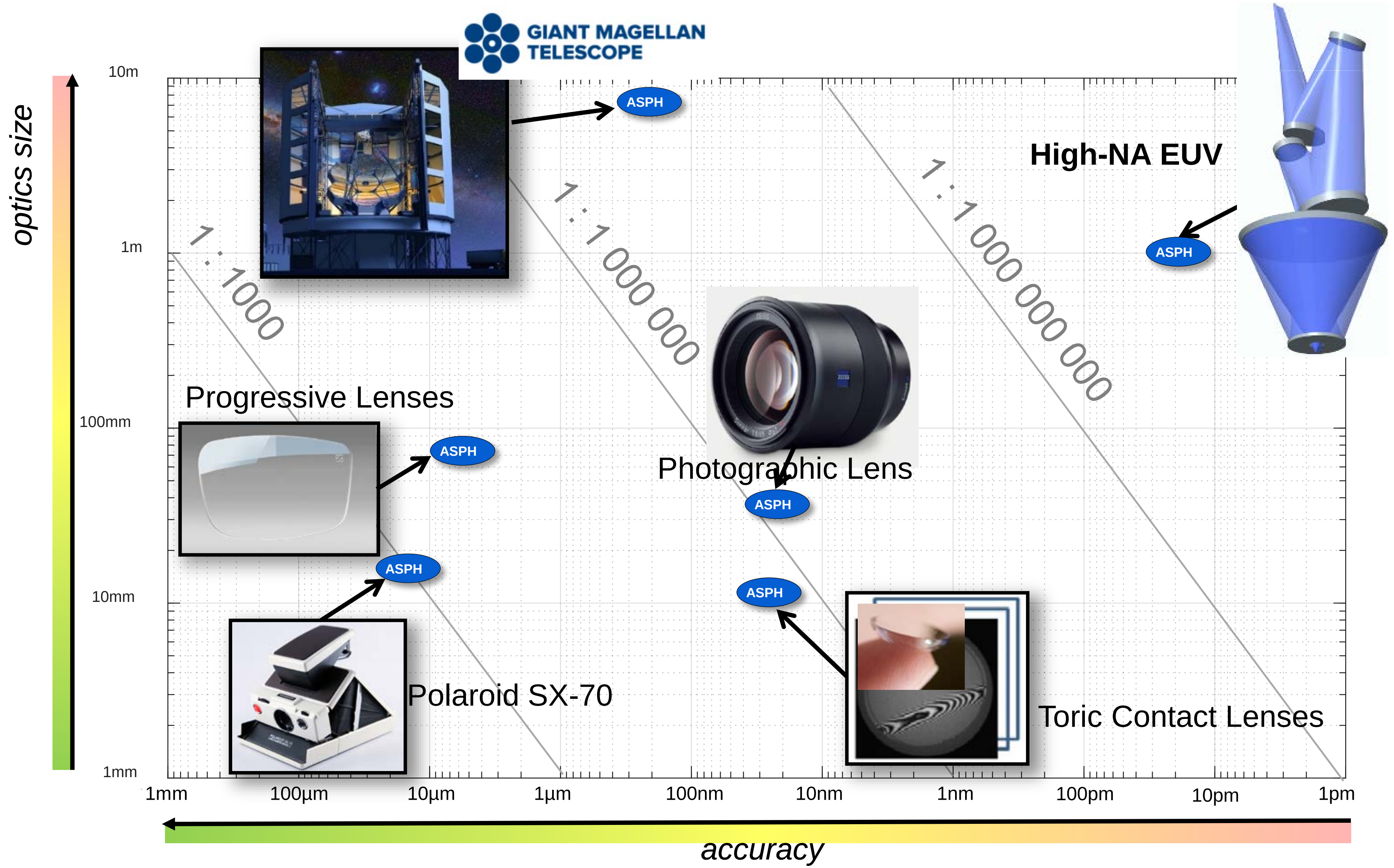
High-NA EUV: Starlith® 5000
Scanner layout for EXE:5000 compared to NXE:3400.



Source: ASML

High-NA EUV: Starlith® 5000

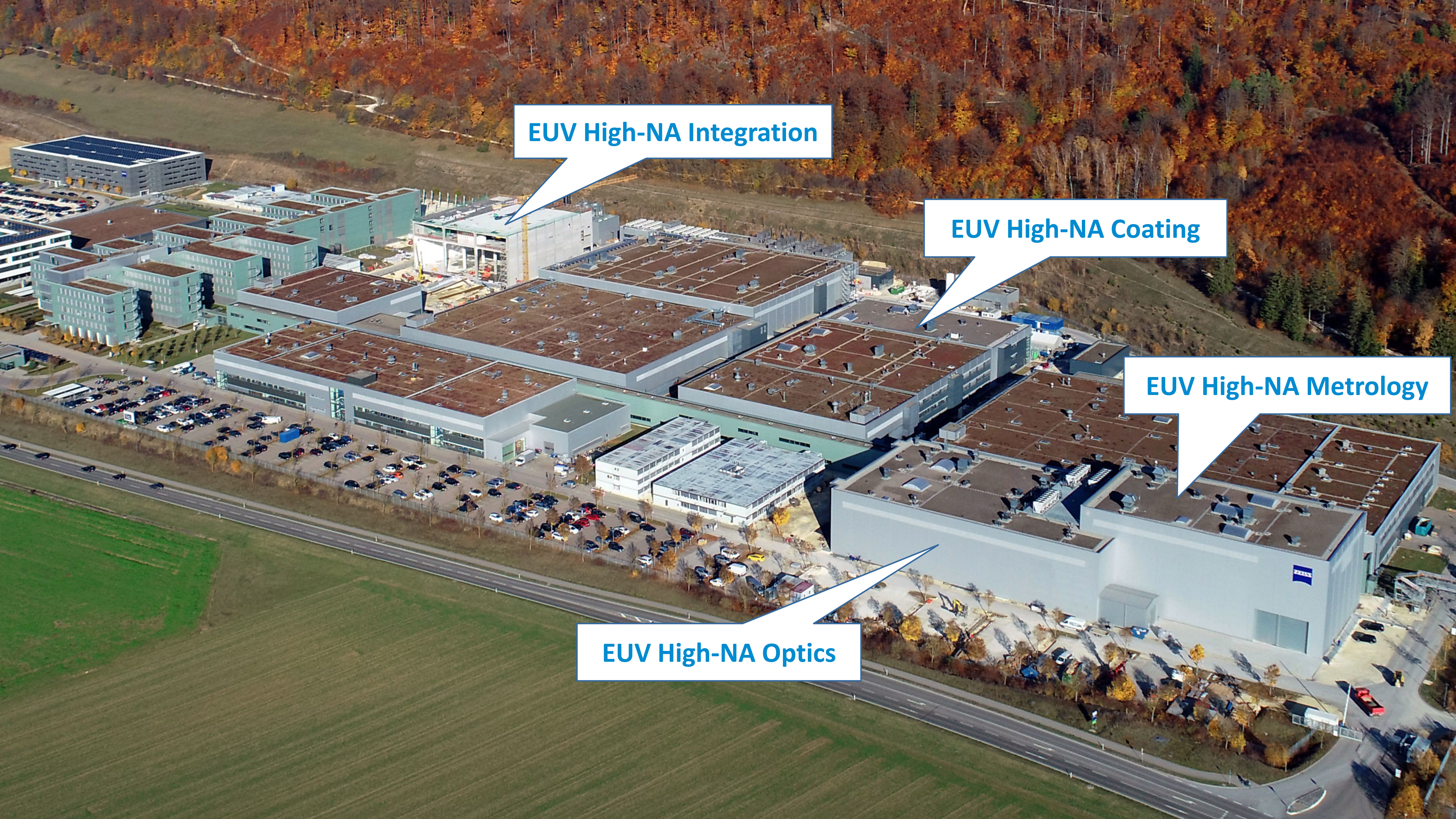
Comparison of aspherical surfaces in different optical instruments.



High-NA EUV: Starlith® 5000
Metrology vessel transport and integration at ZEISS in Oberkochen, Germany.

High-NA EUV: Starlith® 5000

Accuracy of mirror metrology is key for imaging quality.


EUV High-NA Integration
EUV High-NA Coating
EUV High-NA Metrology
EUV High-NA Optics

Conclusions

- TODAY - The Starlith® 3400 for the NXE:3400B
  - ✓ Multiple systems shipped.
  - ✓ ZEISS is fully committed and ready for high volume ramp-up.

- TOMORROW - High-NA with the Starlith® 5000 for the EXE:5000
  - ✓ Enables further shrink for the semiconductor industry to continue Moore’s Law.
  - ✓ Design has been finalized; mirror production has started.
  - ✓ Fast infrastructure and equipment build-up at ZEISS.

Acknowledgements

EUVL Teams at ASML & ZEISS and at our partners

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ZEISS