Transient Thermoelastic Structure Analysis to quantify the Thermal Stability of Extreme-Ultraviolet (EUV) Projection Systems

Timo Laufer

Carl Zeiss SMT GmbH

Oberkochen, Germany

Agenda

- Speaker's Bio
- CARL ZEISS AG
- Sequence of Producing Micro Chips, History of Lithography
- The EUVL-System (**E**xtreme **U**ltra**v**iolet **L**ight)
- Thermal Architecture of the EUV-**P**rojection **O**ptics **B**ox (POB)
- Simulation FEM-Model of a simplified POB
- Transient Thermal Response of a simplified POB
- Transient Thermoelastic Response of a simplified POB

  → comparison with the stability requirement of the image drift on wafer level
- Summary

Speaker's Bio

Dipl.-Ing. Timo Laufer

- He has studied mechanical engineering, focussing on precision engineering, micro techniques, heat- and mass transfer and optics.
- For the last 20 years he has been working within research and development for optics for the semiconductor industry at Carl Zeiss SMT GmbH.
- Main focus is the thermal architecture of EUV- and DUV-systems.
- Contact: timo.laufer@zeiss.com

Four ZEISS Future-Shaping Segments

ZEISS

6,428 billion revenue

nearly **31.000** employees

SMT
Semiconductor Manufacturing Technology

EUR **1.634 billion** revenue

3,979 employees

IQR
Industrial Quality & Research

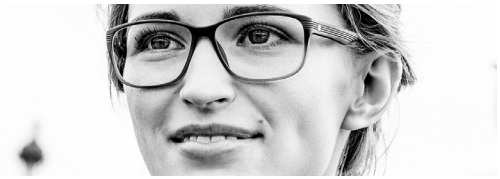
EUR **1.742 billion** revenue

7,417 employees

MED
Medical Technology

EUR **1.760 billion** revenue*

5,254 employees



COM
Consumer Markets

EUR **1.211 billion** revenue

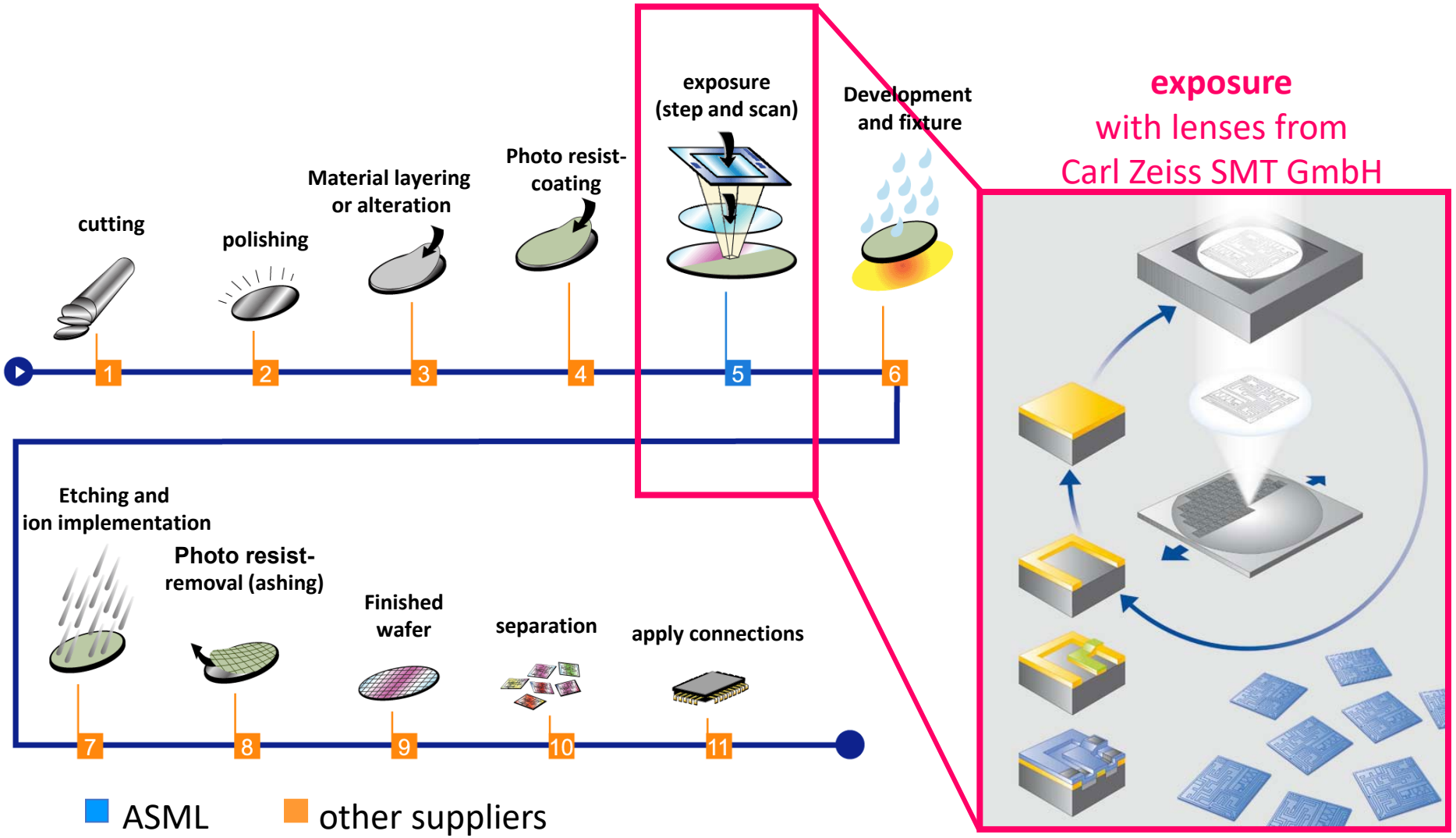
10,760 employees

As of 30 September 2019

*Not identical to Carl Zeiss Meditec AG

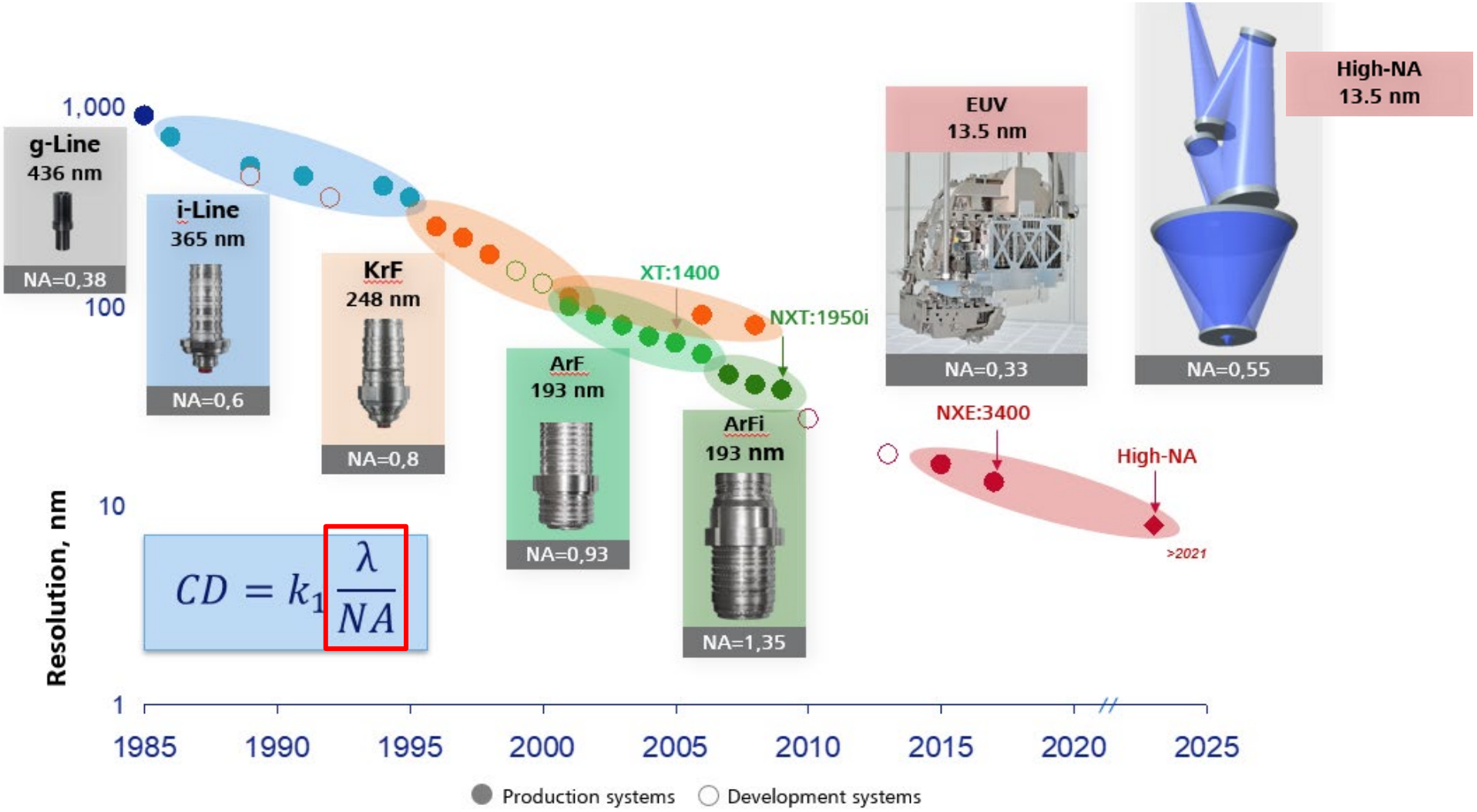
ZEISS

Sequence of Producing Micro Chips



Wavelength Reduction and Increase of NA enables the Roadmap

more than 100x gain of resolution within the last ~35 Years



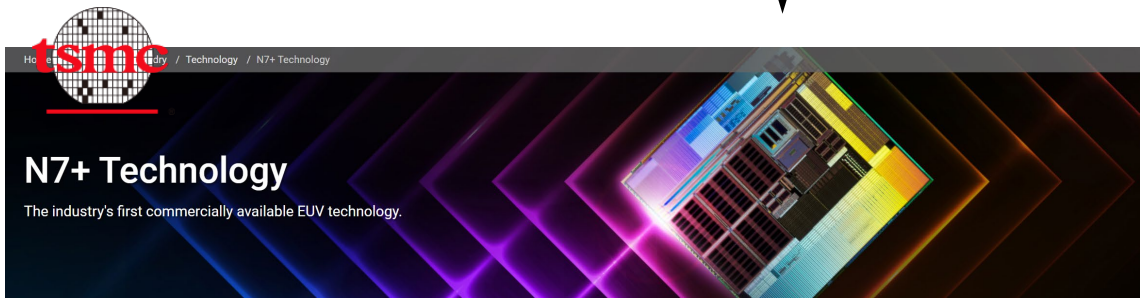
Powerful EUV-Chips

ZEISS EUV-Optics → successful 7nm node

ZEISS EUV-Optics

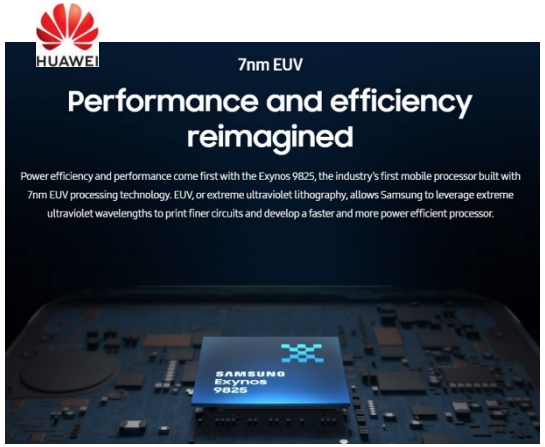
First EUV Process Delivering Customer Products to Market in High Volume

Customers flagship products are powered with 7nm EUV



TSMC's N7+ Technology is First EUV Process Delivering Customer Products to Market in High Volume. The N7+ process with EUV technology is built on TSMC's successful 7nm node and paves the way for 6nm and more advanced technologies.

source: https://www.tsmc.com/english/campaign/N7plus/index.htm



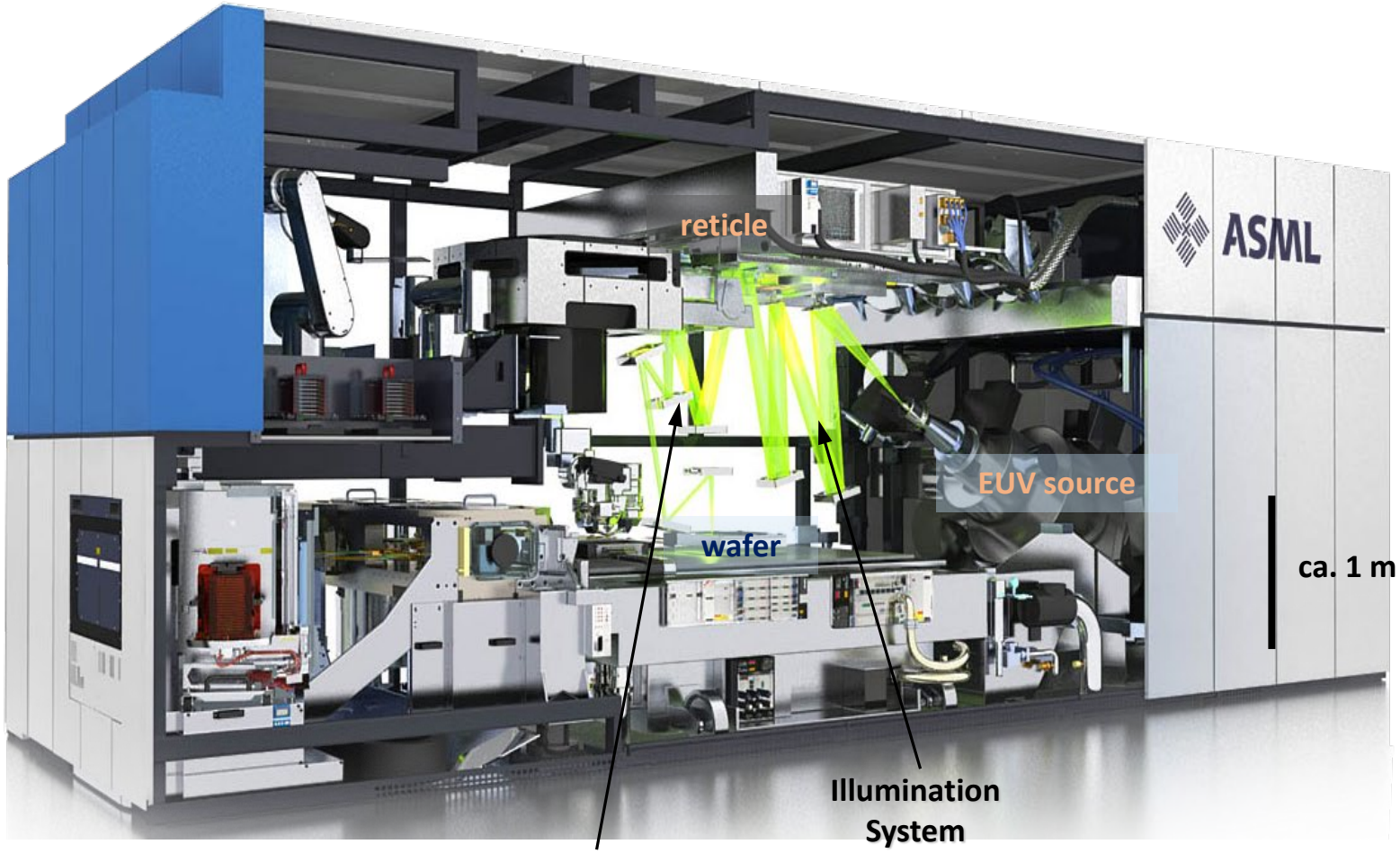
source:https://consumer.huawei.com/en/campaign/kirin-990-series/

source: https://www.samsung.com/semiconductor/minisite/exynos/products/mobileprocessor/exynos-9825/

The 7 nm node is a very big challenge to the thermal stability of the EUV-optics.

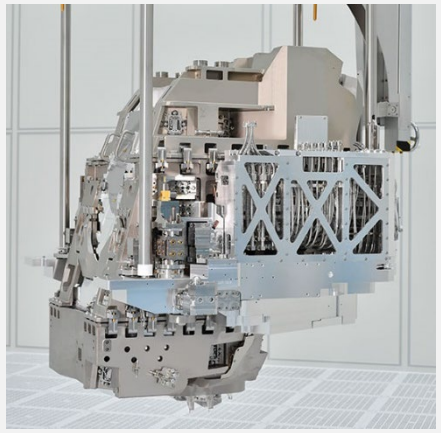
EUV-System

EUV wafer scanner (ASML)



POB
= **P**rojection
Optics **B**ox

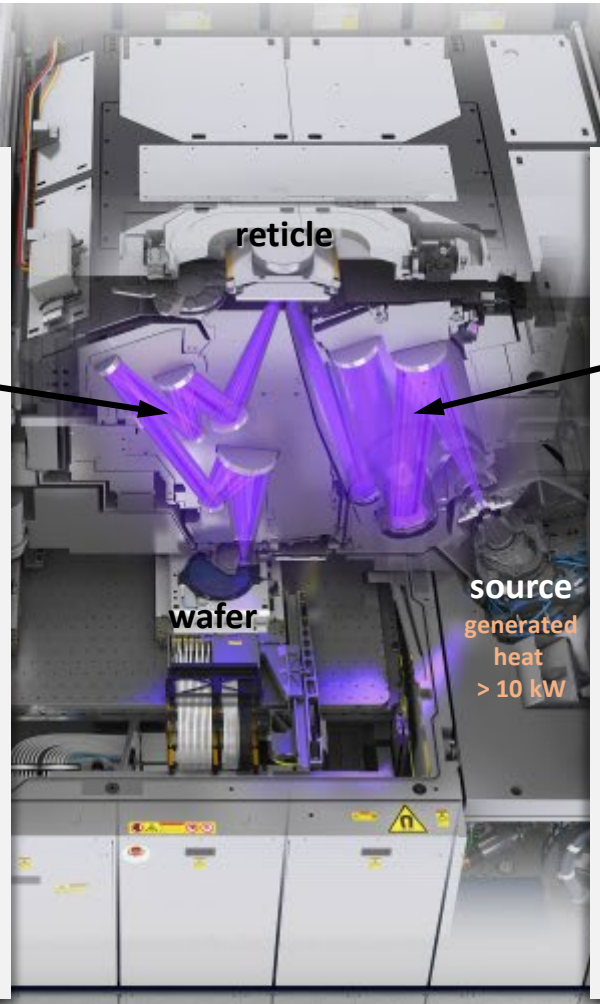
EUV-System
ZEISS EUV-Optics

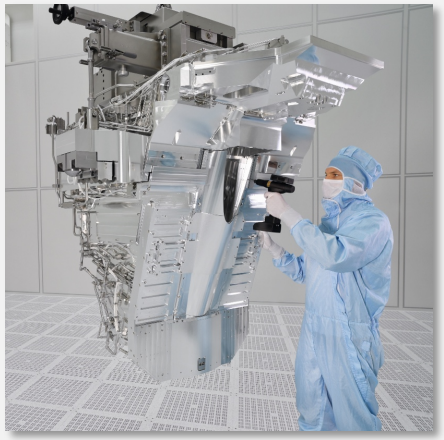


Projection Optics Box (POB)

Absorbed EUV-light and
generated heat (e.g. electronics) **> 50 W**

Pressure of atmosphere < **10 Pa**



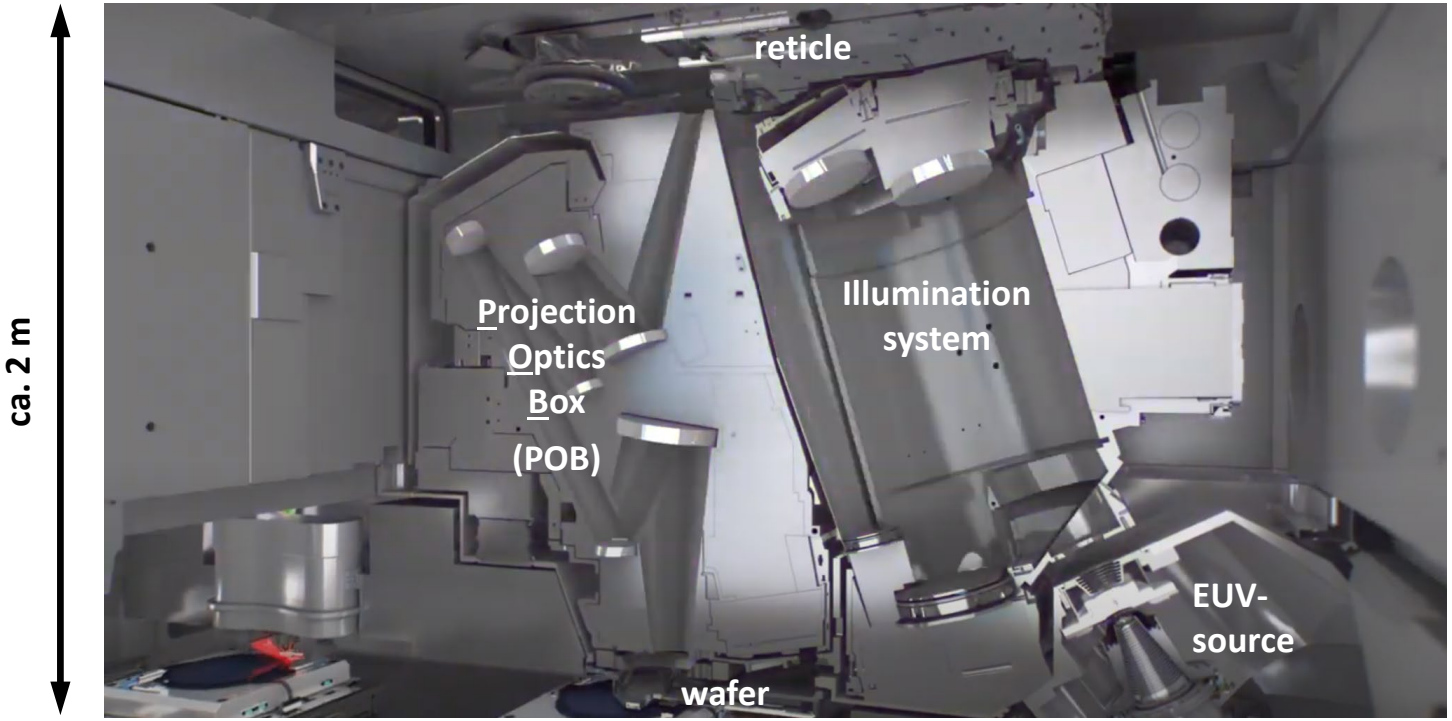


Illumination System

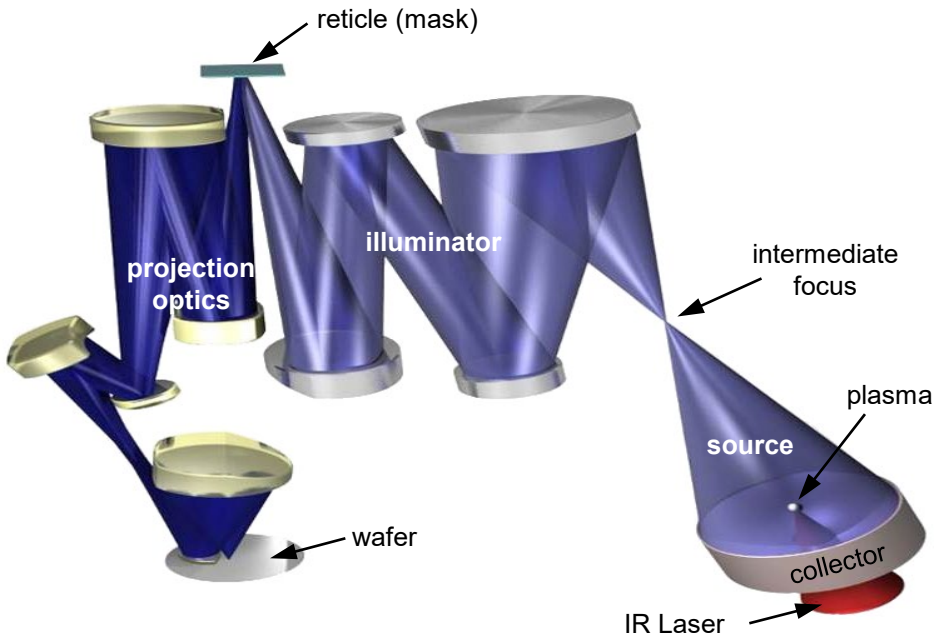
Absorbed EUV-light and
generated heat (e.g. electronics) **> 1 kW**

Pressure of atmosphere < **10 Pa**

EUV-System
ZEISS EUV-Optics

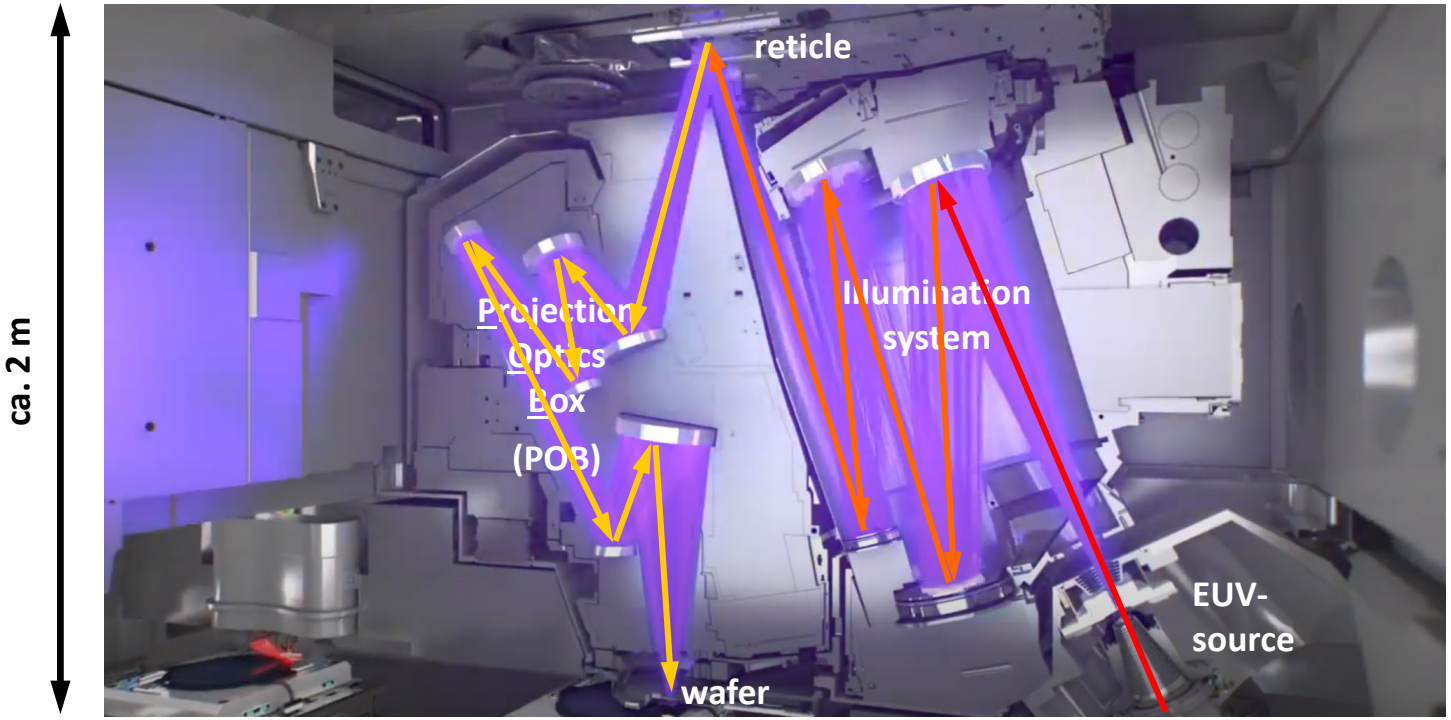


λ	13.5 nm
NA	0.33
Field	26 x 33 mm²
MAG	4x
Printing	“7nm-node”



EUV-System

ZEISS EUV-Optics – the light path



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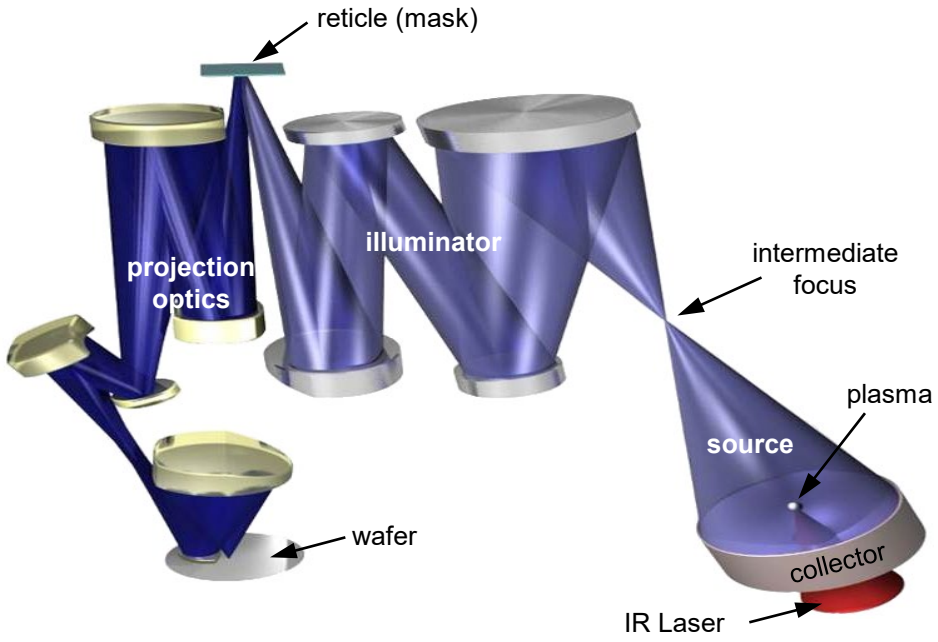
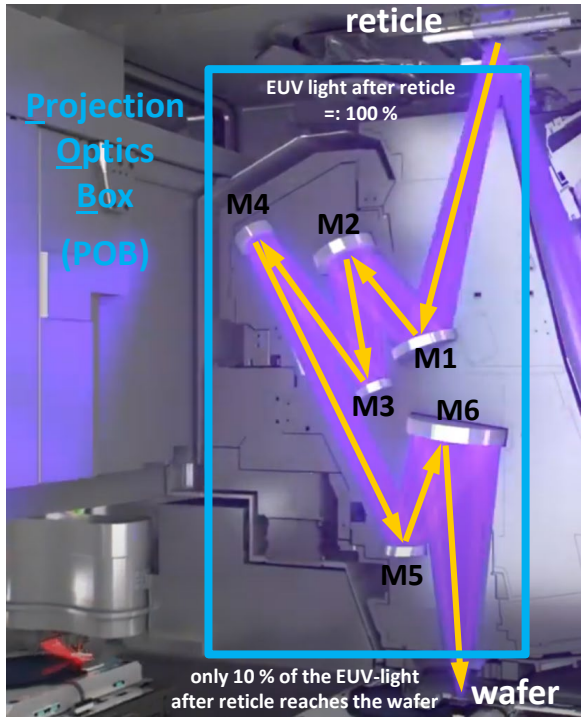


EUV-System

ZEISS EUV-Optics – the Projection Optics Box POB

ca. 2 m



The Projection

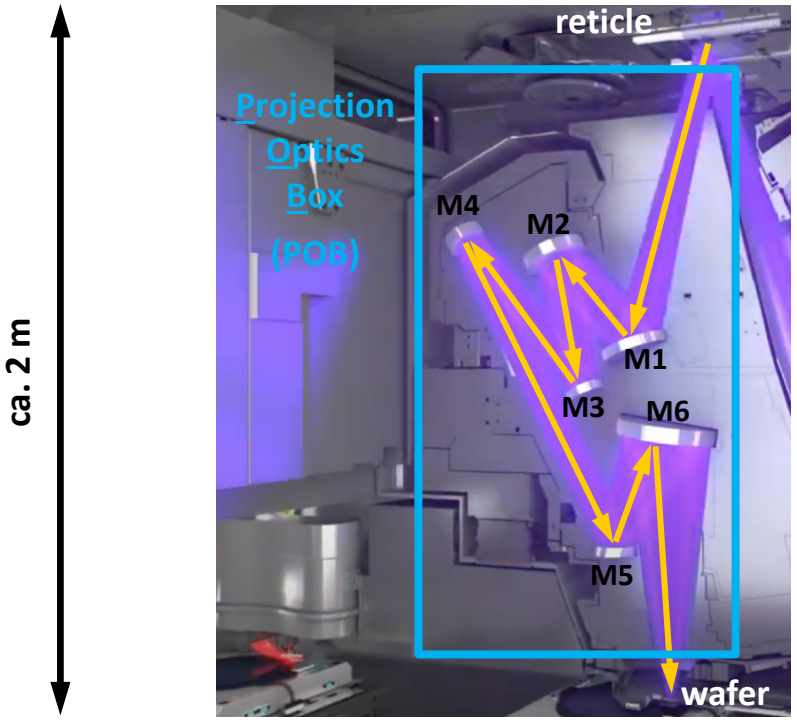
- The POB-mirrors projects the reticle pattern onto the wafer.
- Each POB-mirror reflects only about 2/3 of the incoming EUV-light.
- In case of six POB-mirrors (M1 to M6), only 10 % of the EUV-light after reticle reaches the wafer; 90 % of the EUV-light is absorbed by the six POB-mirrors.

The **P**rojection **O**ptics **B**ox (**POB**)

- The POB-mirrors are mounted on the POB-structure (mirror support structure).
- Heat loads within the POB heats up the POB-structure
  - → The POB-structure (mirror support structure) expands, the mirrors follow the thermal expansion of the POB-structure, and the mirrors leave their ideal position.
  - → The image, projected onto the wafer, shifts (drifts).
  - → **This image drift on wafer level must be avoided or must at least be limited.**

The Thermal Architecture

boundary conditions and image stability requirements



Mechanical Boundary Conditions

- The optical design → Dimensions of the POB
- The design space → Is there enough room for thermal measures like cooling?
- Maximum weight → Choice of material for the POB-structure.

Thermal Boundary Conditions

- Heat loads: Location, amplitude and switching cycles.
- Heat sinks: Is water cooling possible everywhere?
- Pressure of atmosphere within the EUV-system < 10 Pa.

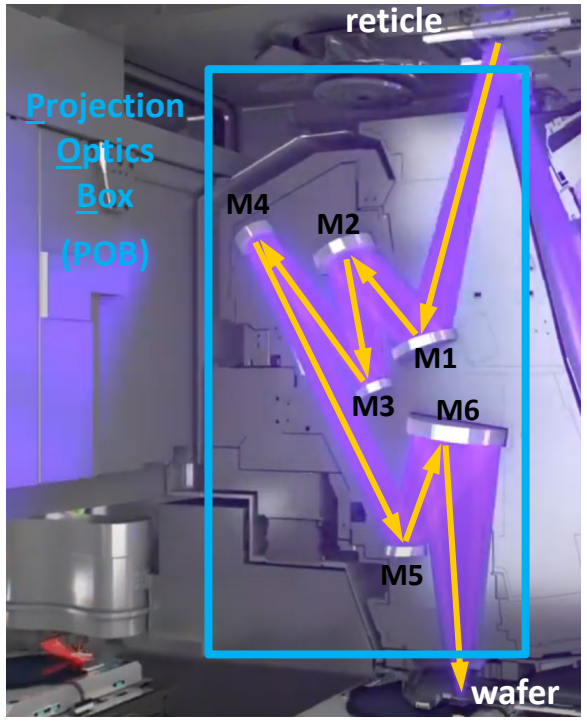
Optical Boundary Conditions and Requirements

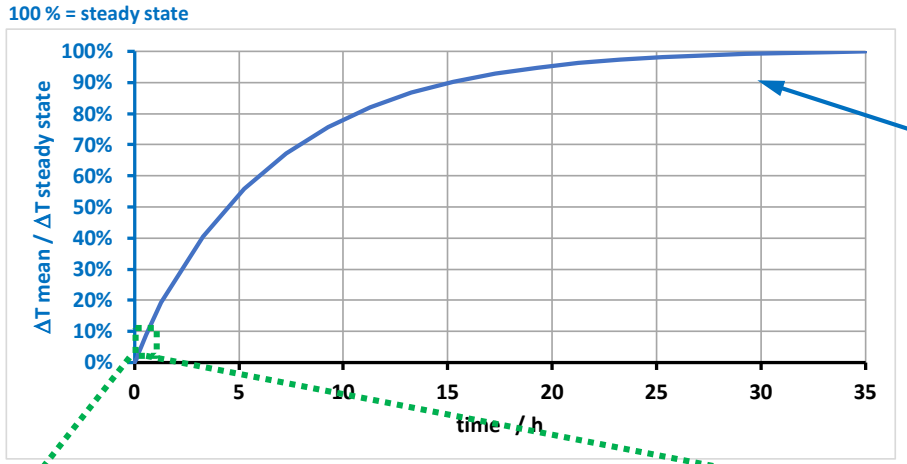
- The image drift on wafer level can't be measured during wafer exposure.
- The image position on wafer level is measured during wafer change.
- The POB-mirrors can be actuated and are repositioned during wafer change.
- **The maximum allowed image drift on wafer level during wafer exposure is < 1 nm.**

The Thermal Architecture

boundary conditions and image stability requirements

ca. 2 m

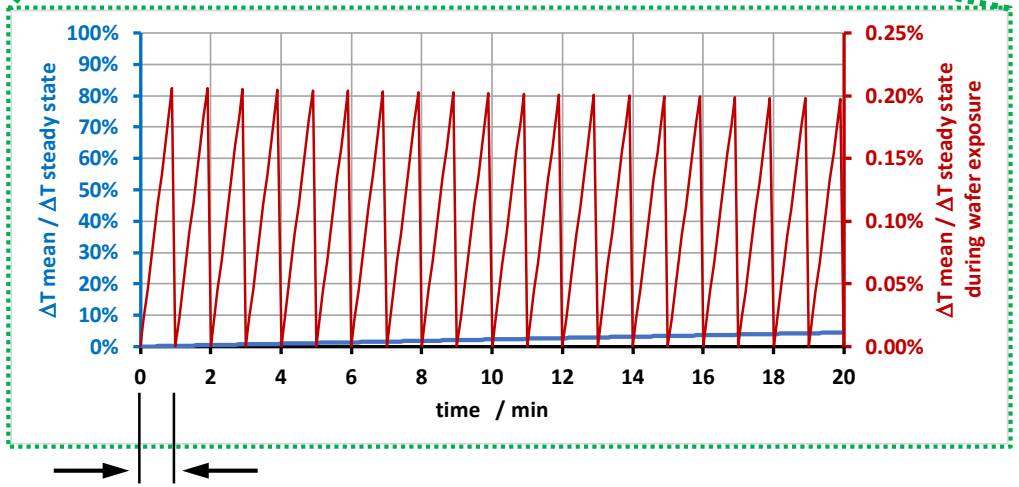




Typical thermal drift (thermal response) of a simplified POB-structure.

The exposure of the first wafer starts with a cold POB.

The time constant τ (63 % of steady state) of the simplified POB-structure is about **7 h**.



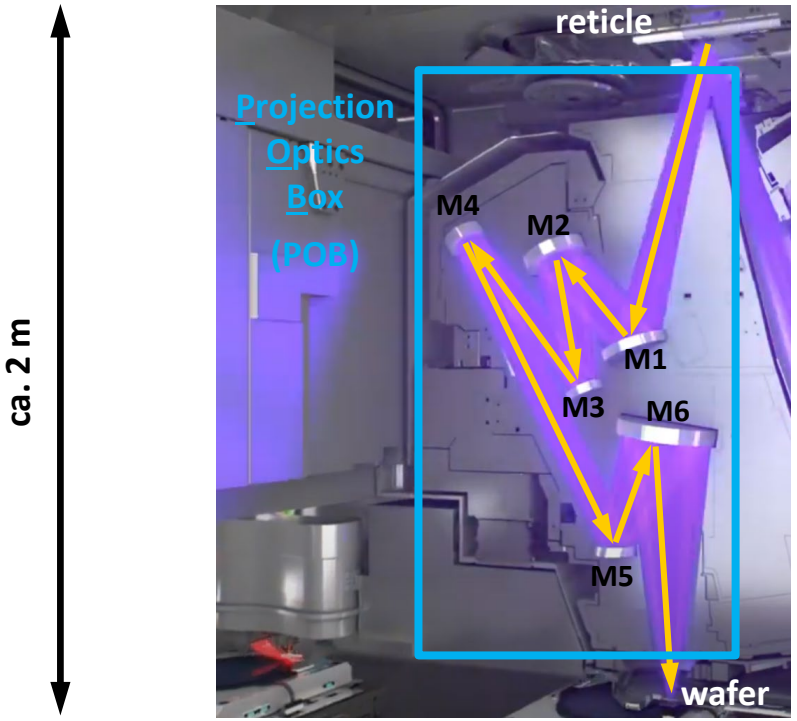
The image position on wafer level is measured during wafer change and the mirror actuators reposition the POB-mirrors.

→ The image drift on wafer level always starts at zero after wafer change.

The exposure of <u>one</u> wafer takes about 1 min

The Thermal Architecture

estimation of the temperature stability requirement of the POB-structure



Boundary conditions

Dimension of POB-structure (mirror support structure) about **2 m**.

The exposure of one wafer takes about **1 min**.

Max. allowed image drift during wafer exposure less than **1 nm**.

Thermal Architecture

How to limit the image drift on wafer level to **< 1 nm within wafer exposure of 1 min** ?

Thermal Requirements (rough estimation → back-of-the-envelope calculation)

$\Delta L = L \times CTE \times \Delta T$

ΔL = 1 nm	max. image drift on wafer level during wafer exposure
L = 2 m	dimension of POB-structure (mirror support structure)
CTE = 15 ppm/K	let's simply start with steel

Necessary temperature stability of the POB-structure:

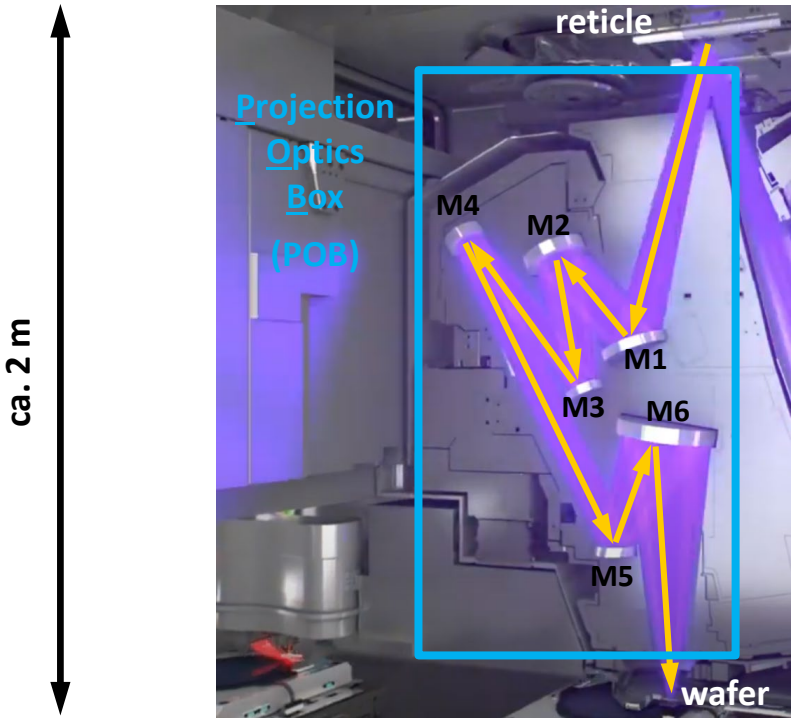
max. $\Delta T = \Delta L / (L \times CTE)$ = 1 nm / (2 m x 12 ppm/K) = **42 µK within 1 min**

- *if 1 nm POB-structure expansion causes 1 nm image drift on wafer level*
- *normally, mirror rotations are much worse than mirror shifts.*

Keep in mind: After starting up the whole EUV-system, the exposure of the first wafer always starts with a cold POB-structure !!!

The Thermal Architecture

How to reduce the image drift on wafer level?



Choice of the Material for the POB-structure

- Take a material with low thermal expansion
  → low CTE
- Take a big thermal mass to make the thermal drift as slow as possible
  → high density and high specific heat capacity

Further Thermal Measures

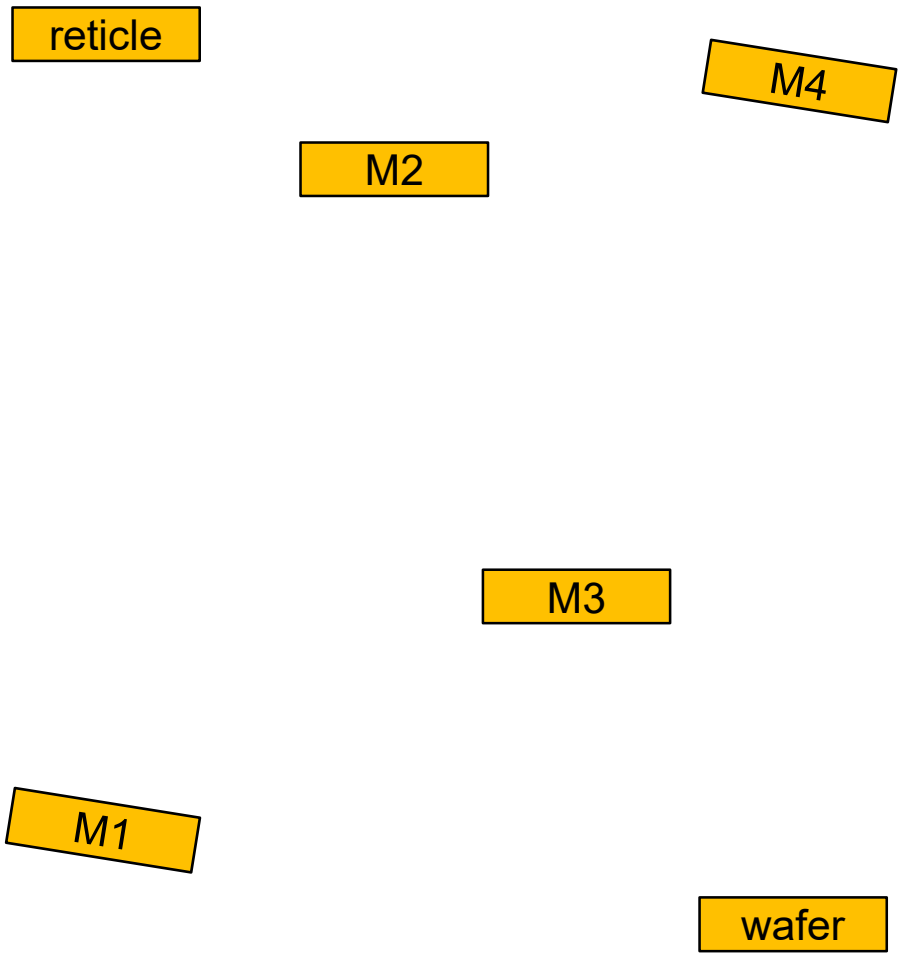
- Apply water cooling if possible, to transport the heat out of the system.
- Best to apply the water cooling where the heat is generated or absorbed.
  → Is there enough design space?
- What is the best routing of the cooling pipes?
- Where to put the water inlet and outlet? The heating of the cooling water is taken into account.
- How stable is the cooling water temperature at the cooling water inlet of the POB?
- Can you apply temperature sensors at the POB-structure and predict the image shift on wafer level?
  → Is the simulation model good enough to predict the image shift on wafer level?
  → How accurate do you have to measure the temperature of the POB-structure?
  → Where are the best places to put the temperature sensors?

Heat Transfer Mechanisms

- Heat conduction in solids.
- Heat transfer in rarefied gases.
- Radiation.
- Heat transfer at clamped / bolted contacts.
- Heating of the cooling water in cooling water flow direction.

How to Calculate the Image Drift on Wafer Lever?

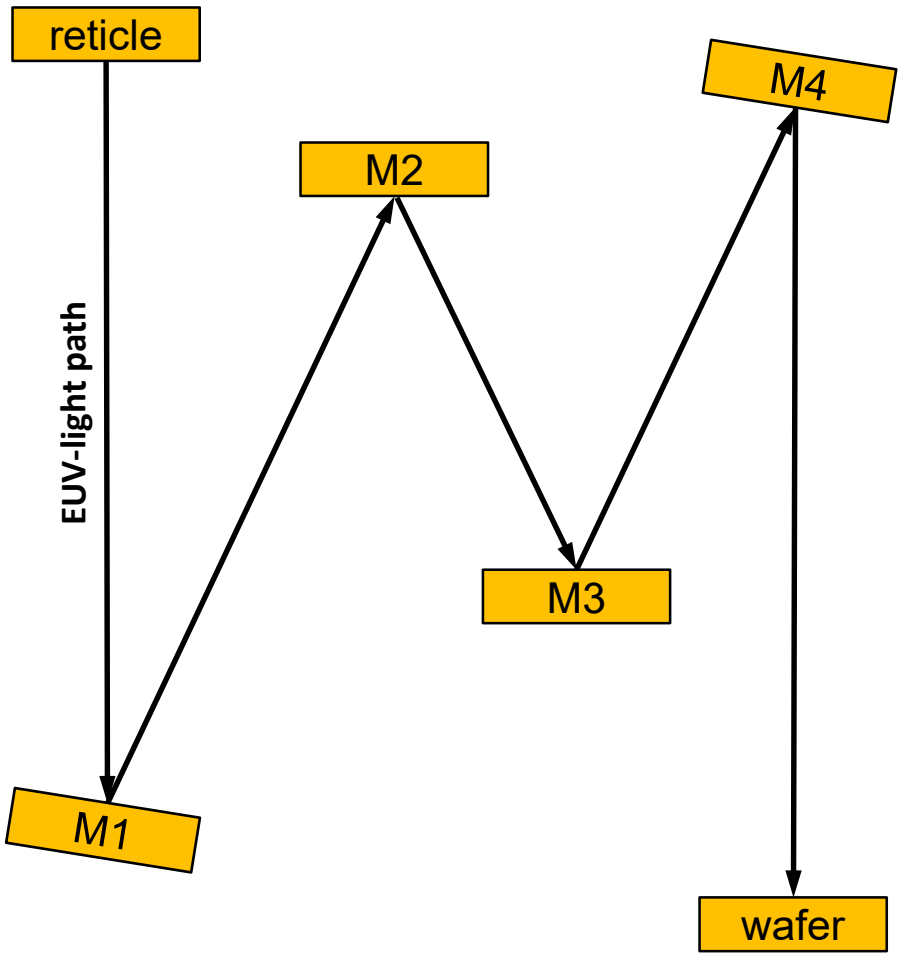
simplified POB-model with four POB-mirrors



Four POB-mirrors, reticle and wafer

How to Calculate the Image Drift on Wafer Lever?

simplified POB-model with four POB-mirrors

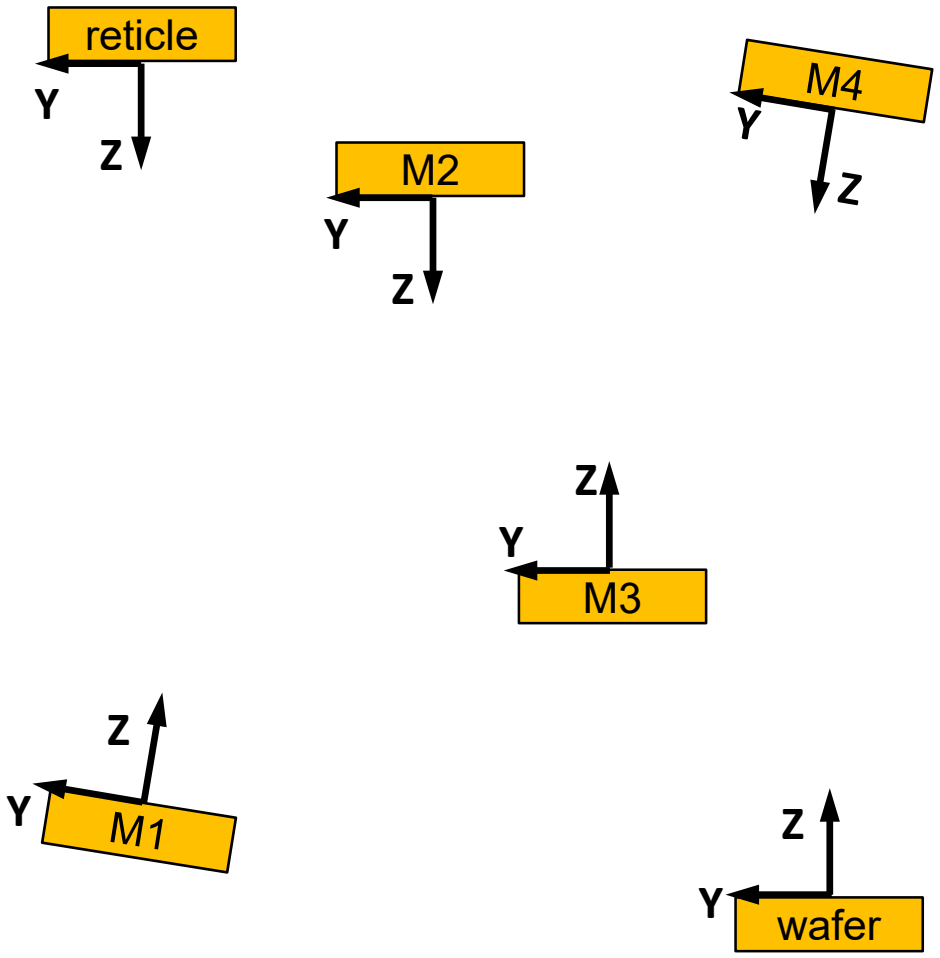


Four POB-mirrors, reticle and wafer

Light path

How to Calculate the Image Drift on Wafer Lever?

simplified POB-model with four POB-mirrors



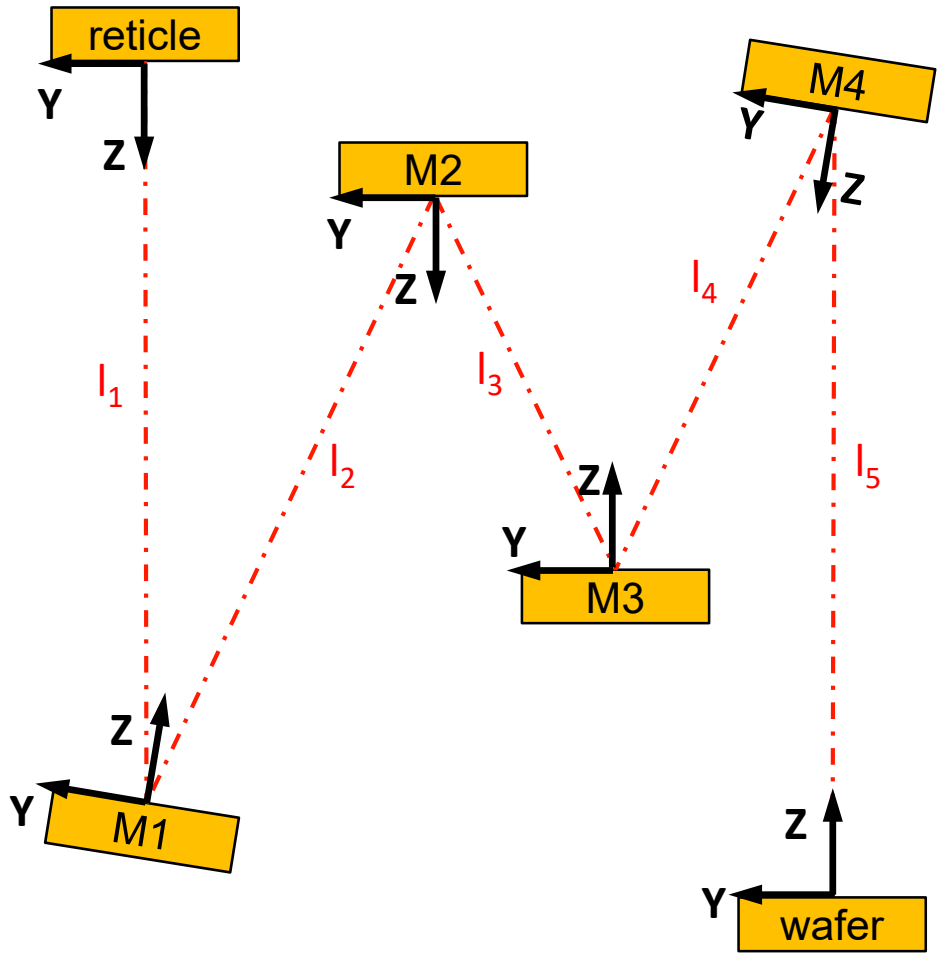
Four POB-mirrors, reticle and wafer

Optics co-ordinate systems and optics position

→ Mirror distances and orientations

How to Calculate the Image Drift on Wafer Lever?

simplified POB-model with four POB-mirrors



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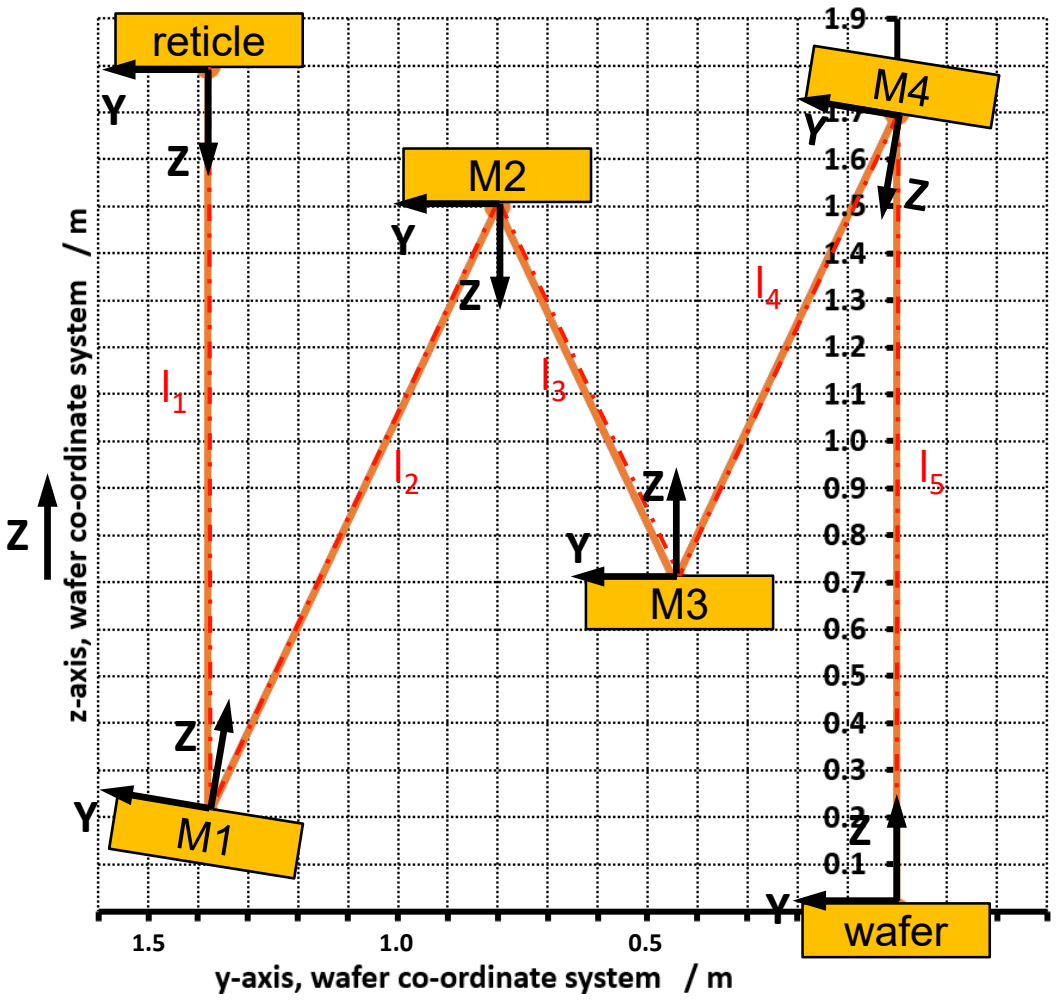


Four POB-mirrors, reticle and wafer

Optics co-ordinate systems and optics position

→ Mirror distances and orientations

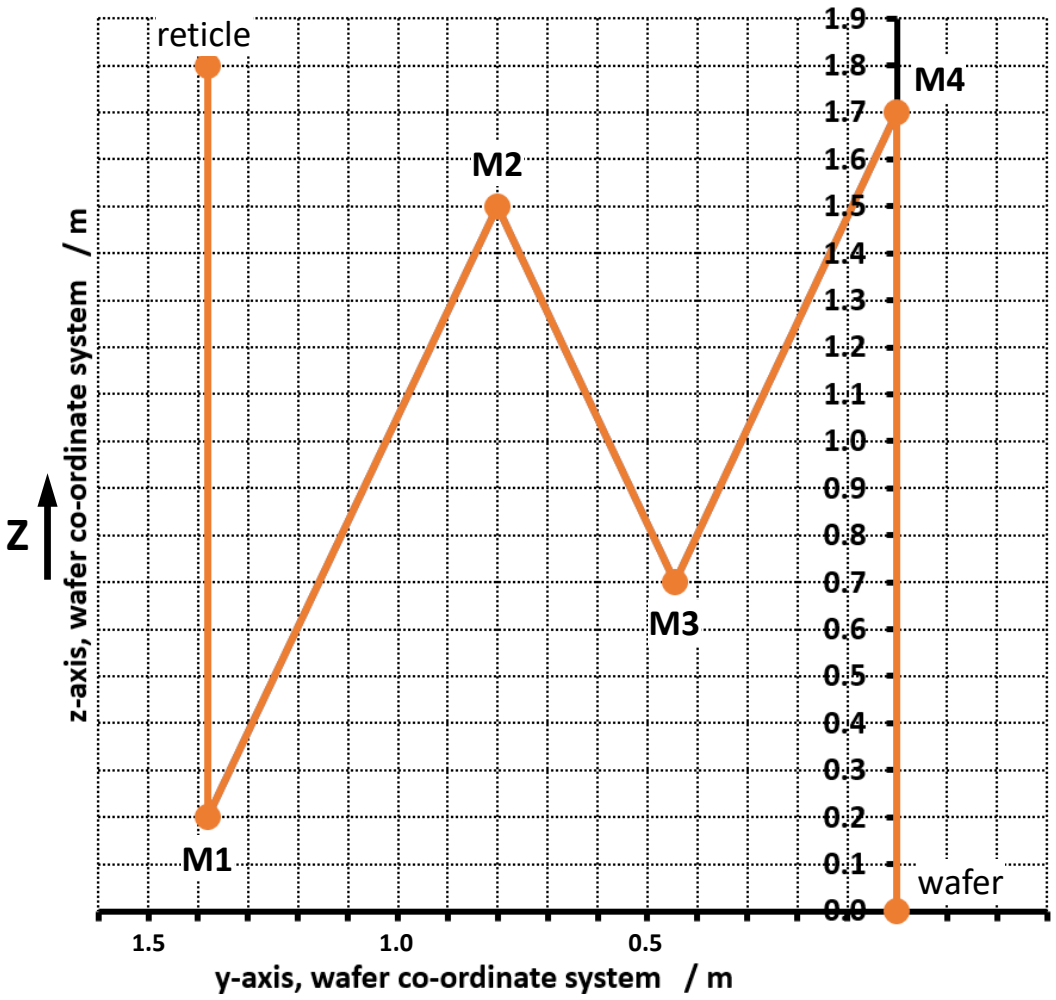
Example

Calculation of image drift in y-direction on wafer level.

The wafer co-ordinate system is the reference co-ordinate system.

How to Calculate the Image Drift on Wafer Lever?

simplified POB-model with four POB-mirrors

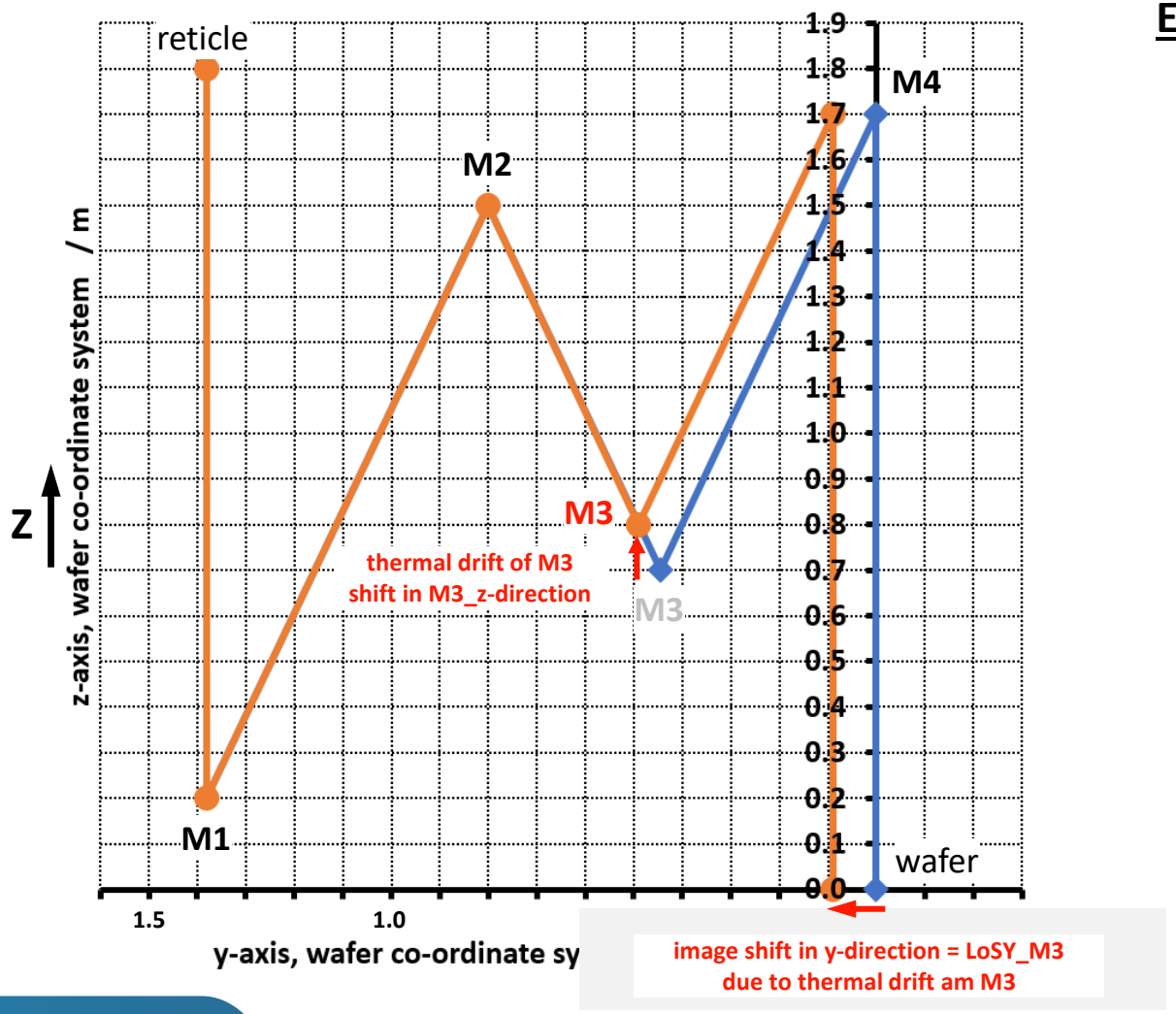


Example

Calculation of image drift in y-direction on wafer level

How to Calculate the Image Drift on Wafer Lever?

simplified POB-model with four POB-mirrors



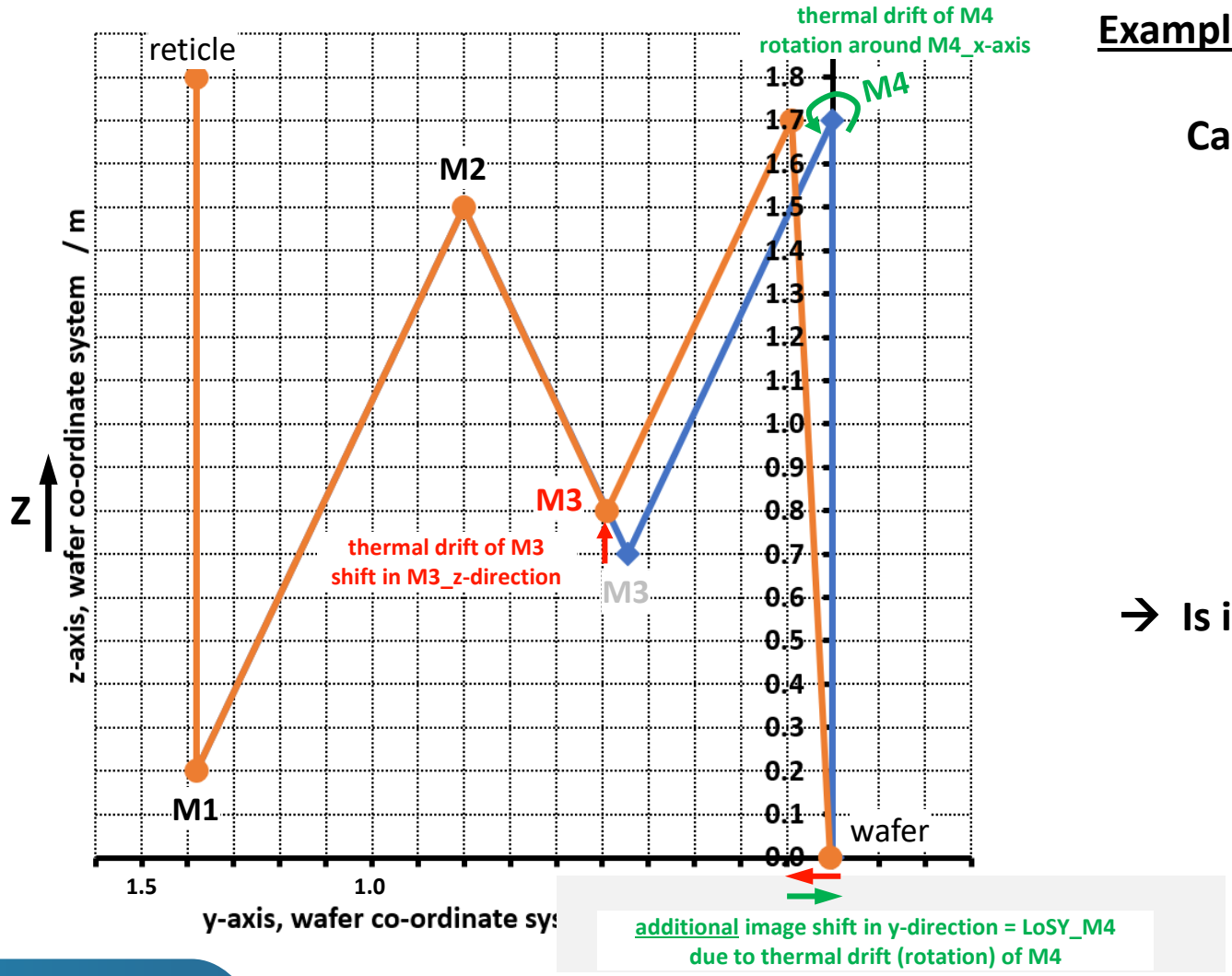
Example

Calculation of image drift in y-direction on wafer level

Thermal drift (shift) of M3 in M3_z-direction
causes image shift_M3 in **plus** y-direction.

How to Calculate the Image Drift on Wafer Lever?

simplified POB-model with four POB-mirrors



Example

Calculation of image drift in y-direction on wafer level

Thermal drift (shift) of M3 in M3_z-direction causes image shift_M3 in **plus** y-direction.

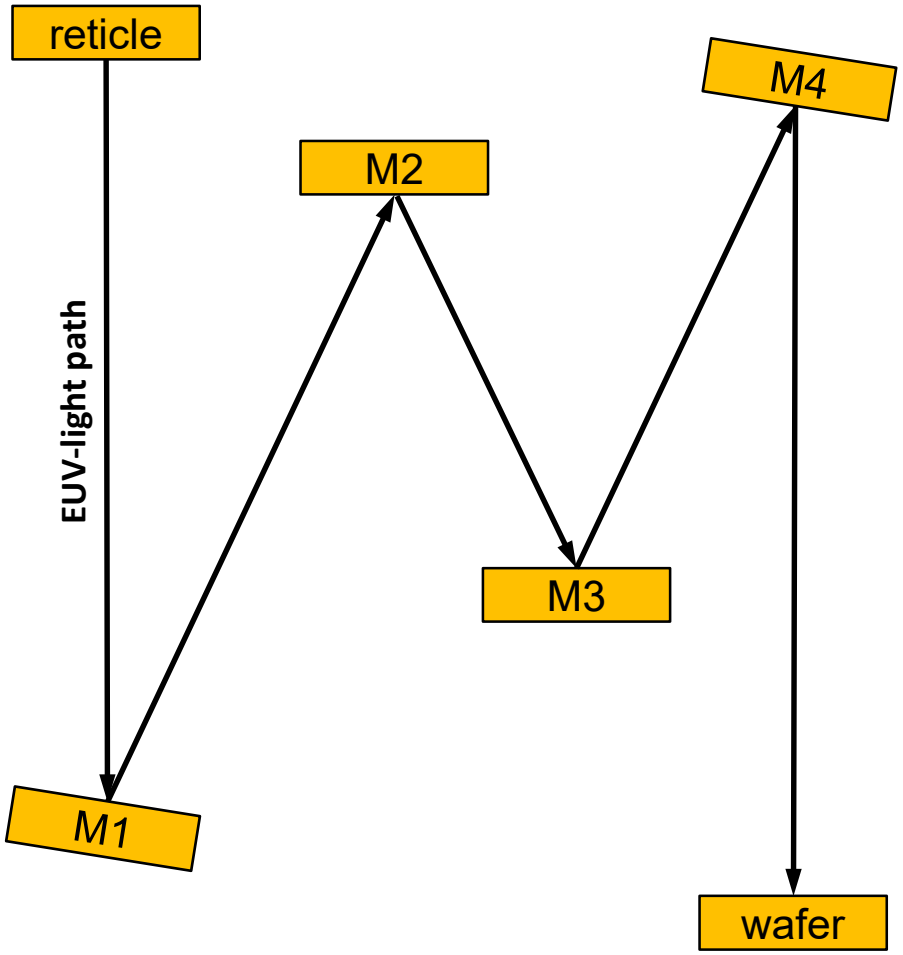
Additional thermal drift (rotation) of M4 around the M4_x-axis causes image shift_M4 in **minus** y-direction.

→ The biggest parts of the image drift caused by M3_movement is compensated by M4_rotation !!!

→ Is it wise to rely on self-compensation of image drift ???

Simulation FEM-Model

simplified POB-model with four POB-mirrors

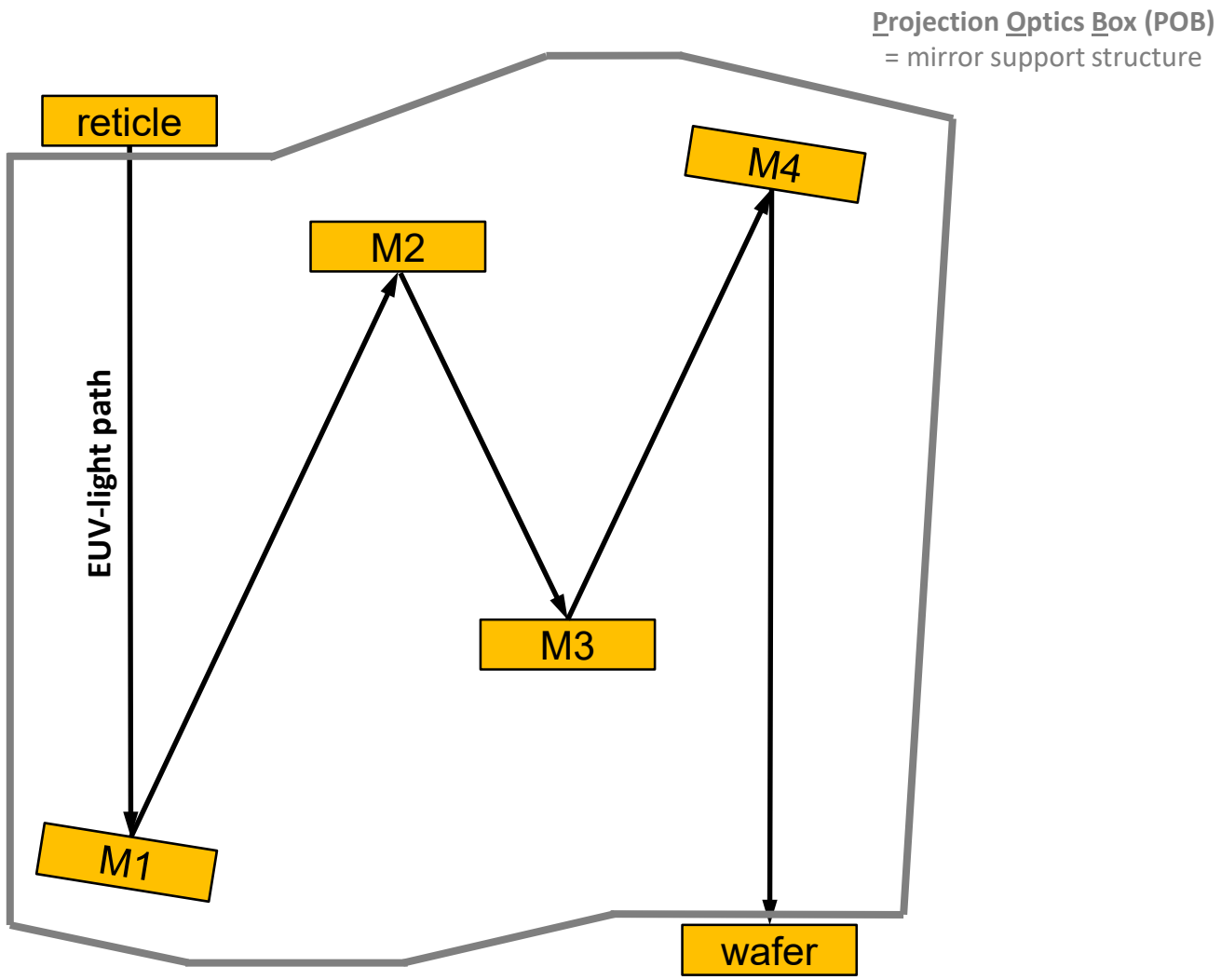


POB-mirrors, reticle and wafer

EUV-light path

Simulation FEM-Model

simplified POB-model with four POB-mirrors



POB-mirrors, reticle and wafer

EUV-light path

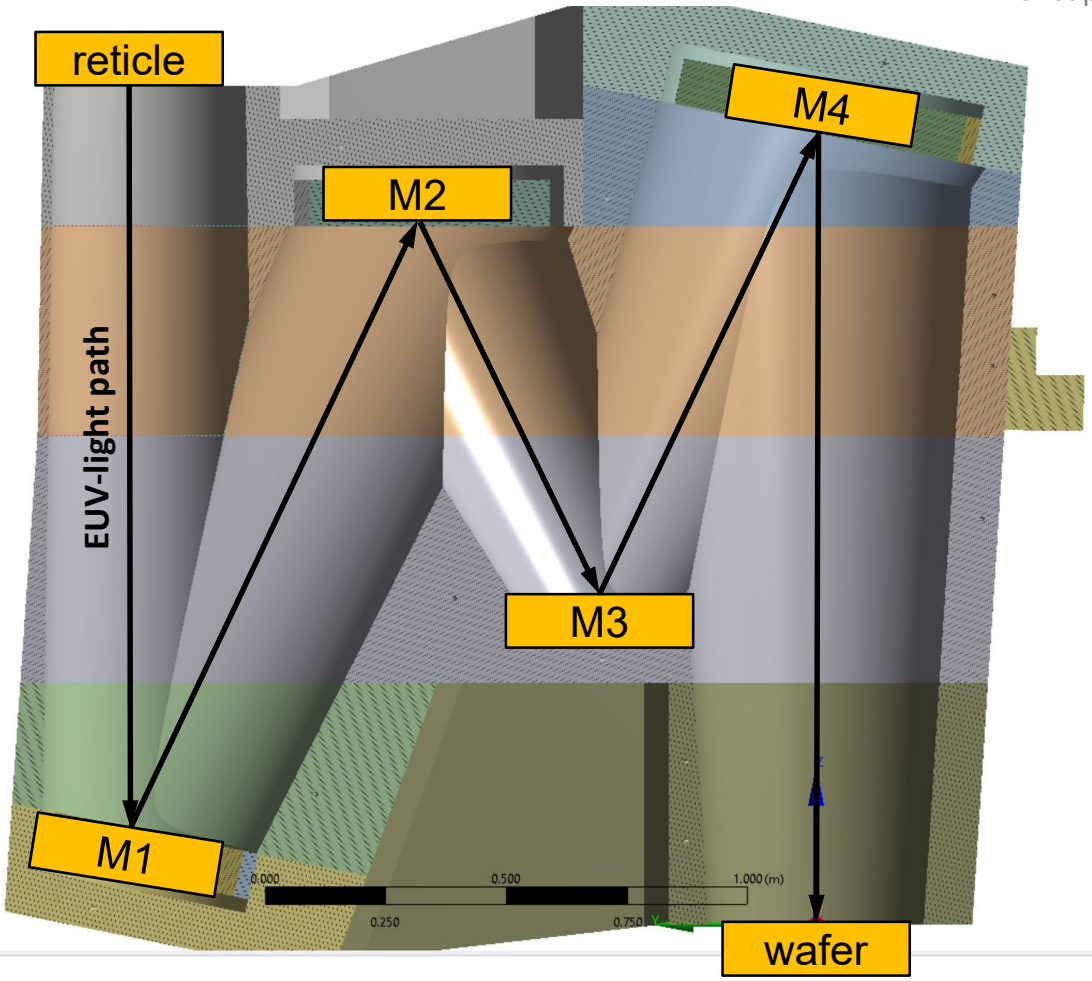
Projection Optics Box (POB)

Simulation FEM-Model

simplified POB-model with four POB-mirrors

Projection Optics Box (POB)
= mirror support structure

cross-section



POB-mirrors, reticle and wafer

EUV-light path

Projection Optics Box (POB)

FEM simulation model

Simulation FEM-Model

simplified POB-model with four POB-mirrors

Projection Optics Box (POB)
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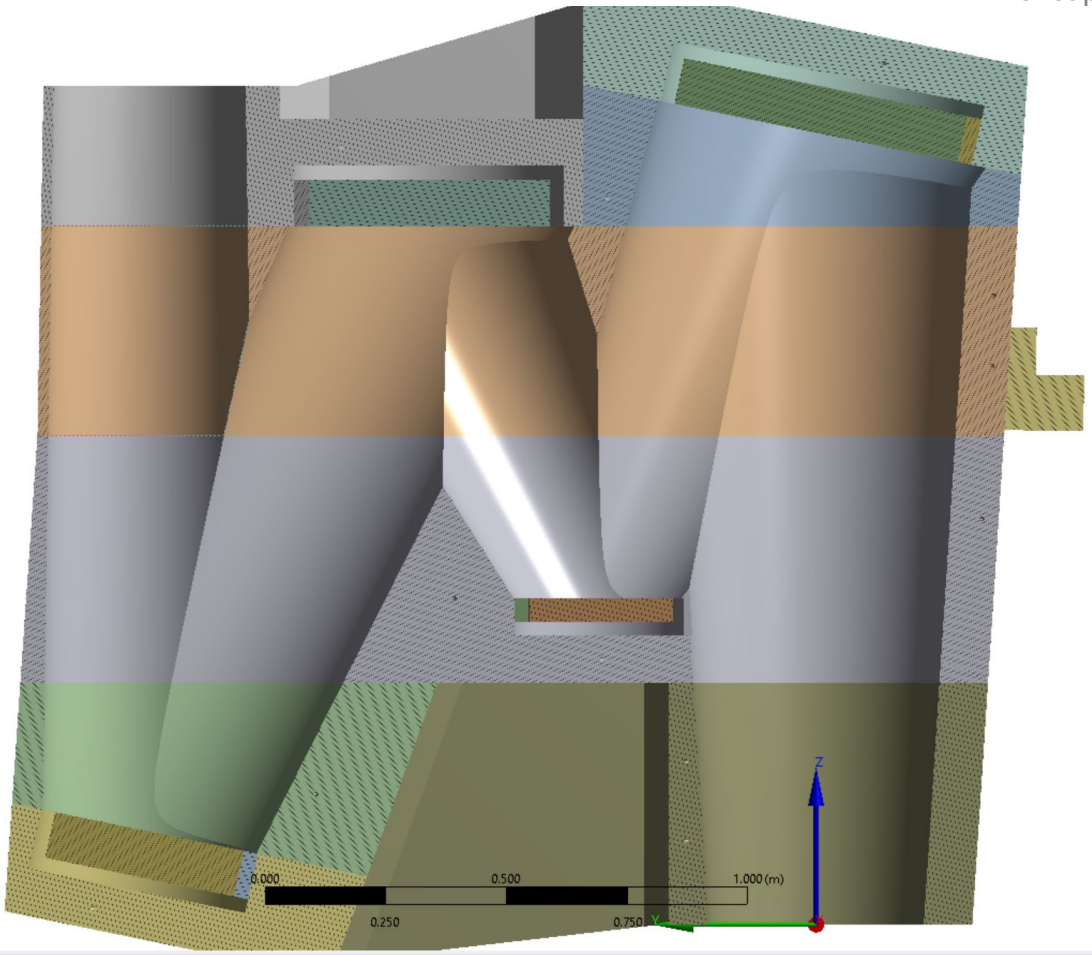
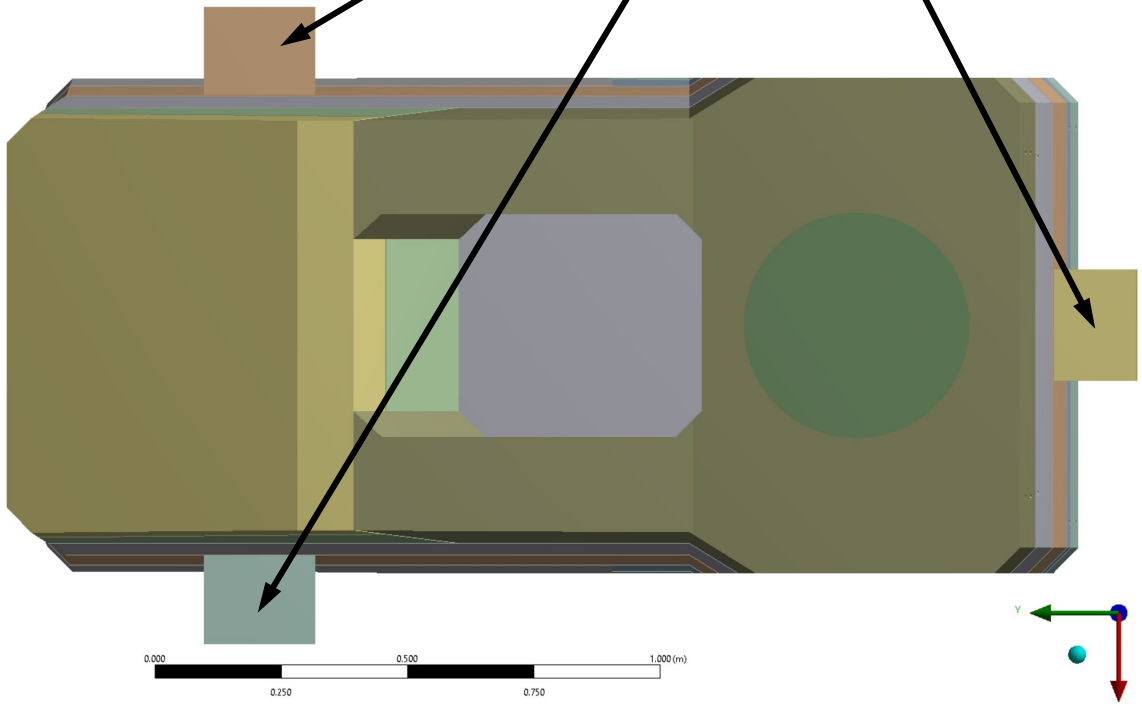


Mechanical Suspension

The POB-structure can expand freely without any constraints.



Simulation FEM-Model

simplified POB-model with four POB-mirrors

Projection Optics Box (POB)
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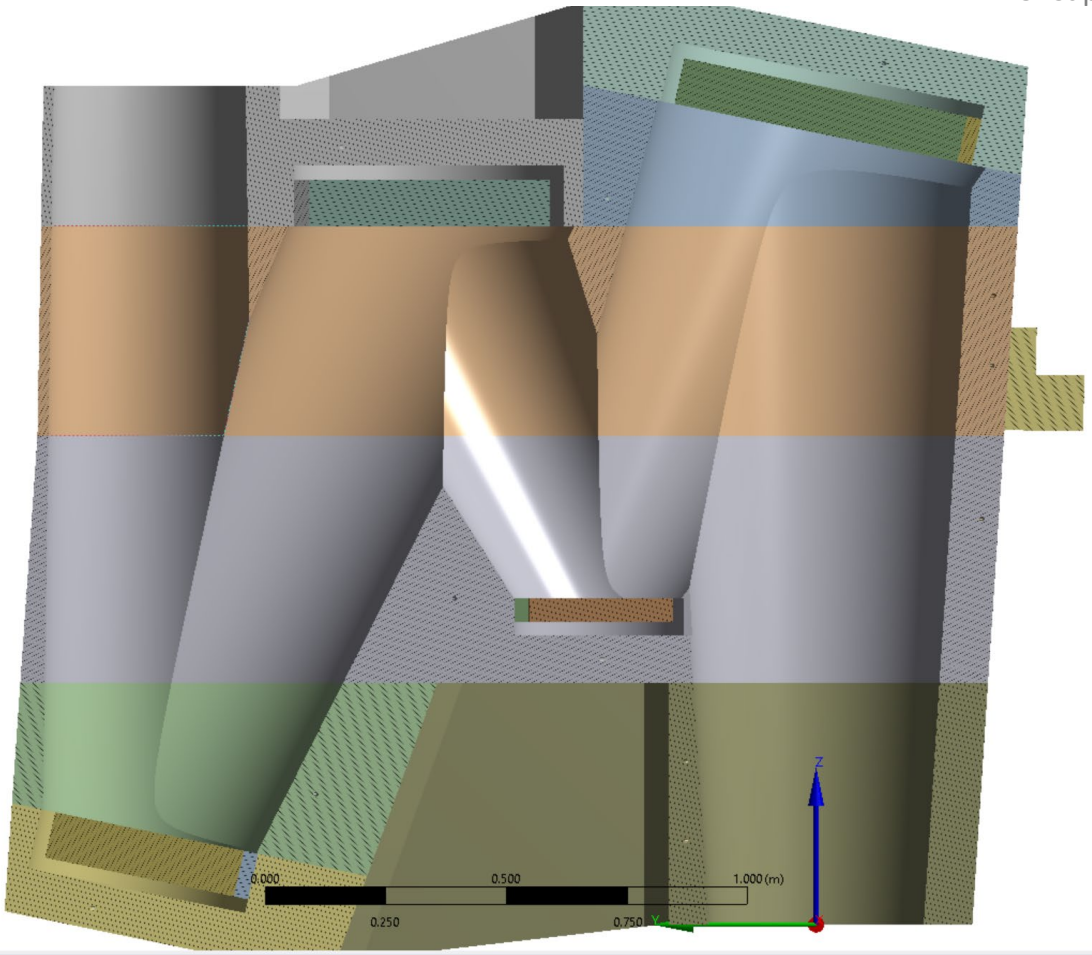
cross-section



Heat Loads

- 1 W absorbed by each mirror.
- Generated average actuator heat load about 7.4 W each.
- **Σ = 93 W**

Heat Sinks

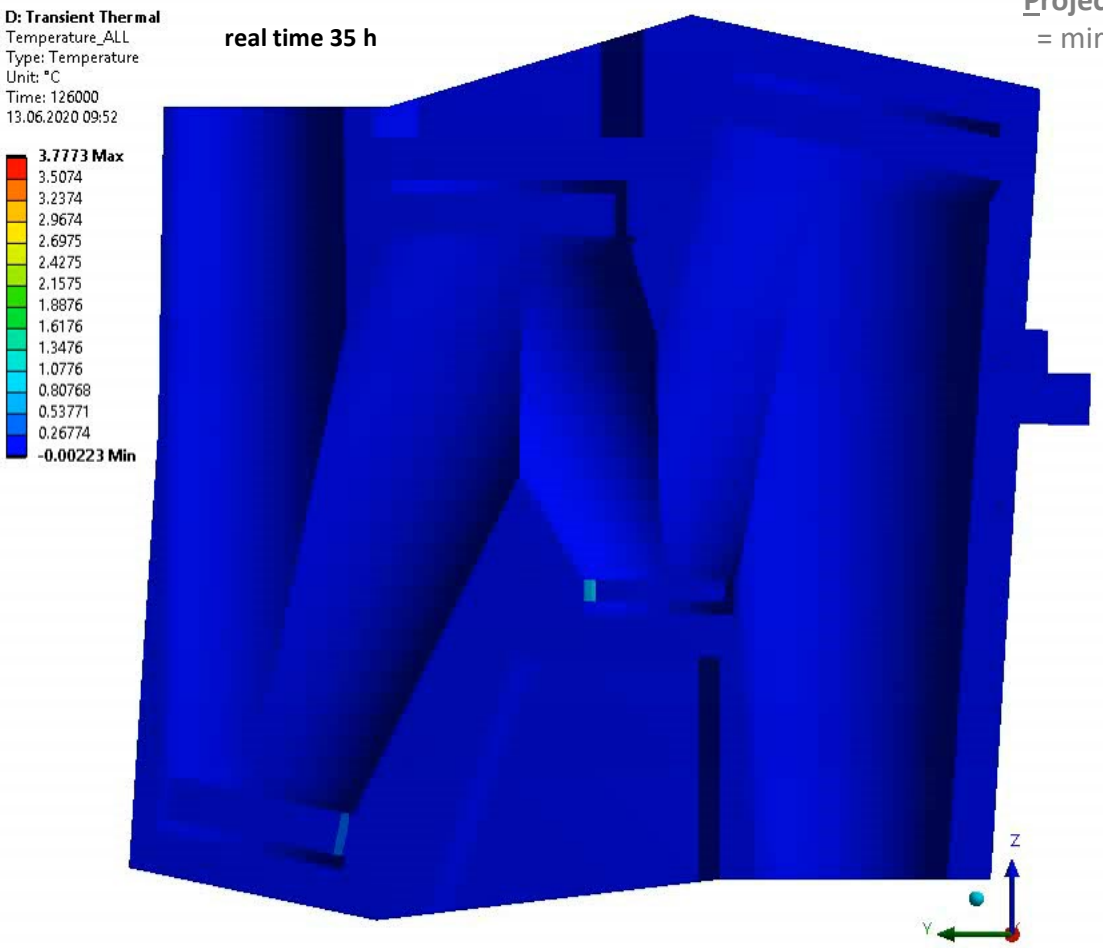
- 8 water cooling channels within the POB-structure.
- Volume flow about 0.5 l/min at each cooling line.
- Heating of cooling water in cooling water flow direction is taken into account.

Materials

- POB-structure and mirror actuators are out of steel.
- POB-mirrors are out of glass.

Simulation Results

transient thermal response of the whole simplified POB (structure, mirrors and actuators)



Projection Optics Box (POB)
= mirror support structure

cross-section

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Materials

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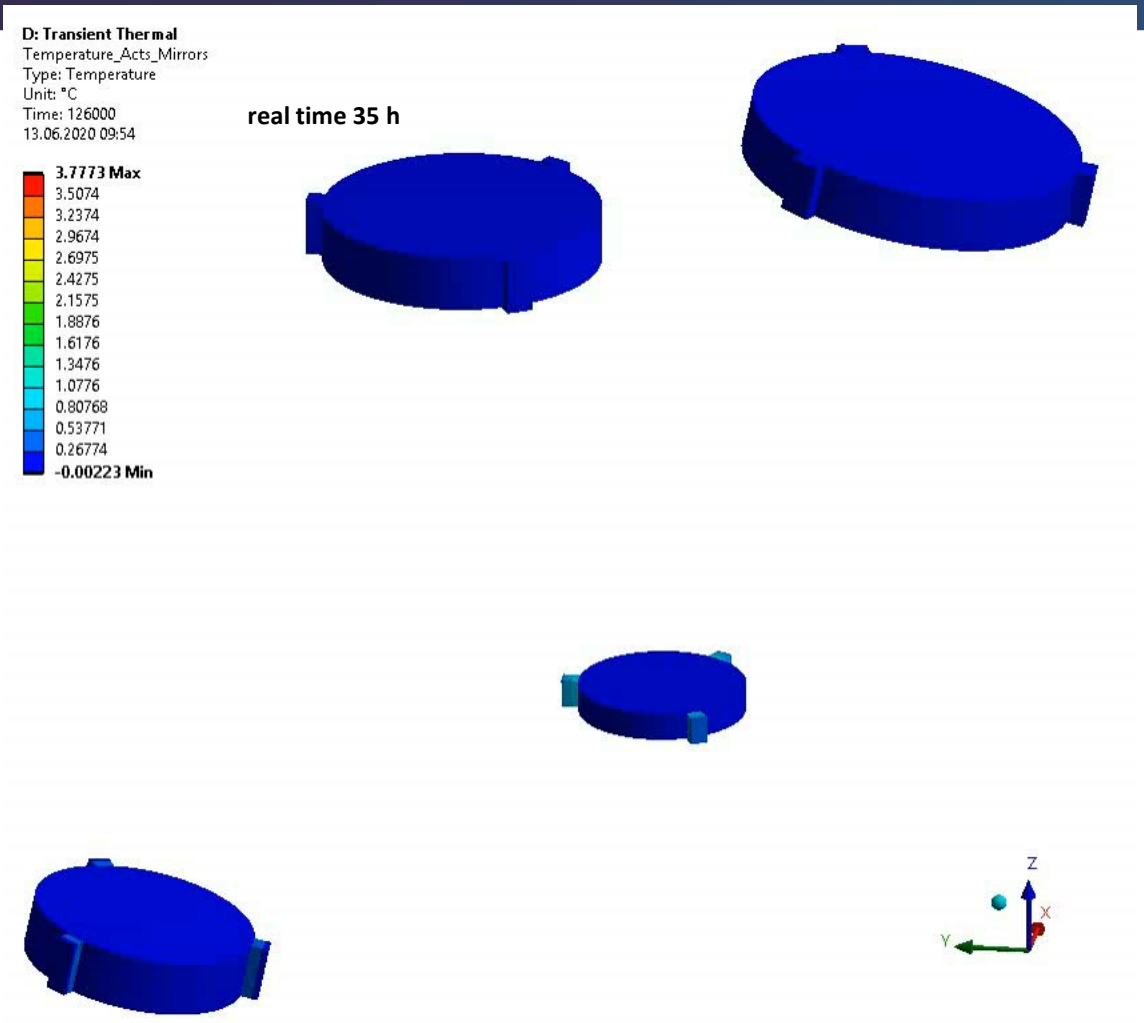
Simulation Results

transient thermal response of the simplified POB-mirrors and actuators only



The mirror actuators heat up very fast,
in contrast to the POB-mirrors, they heat up very slowly.

Heat Loads

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- **Σ = 93 W**

Heat Sinks

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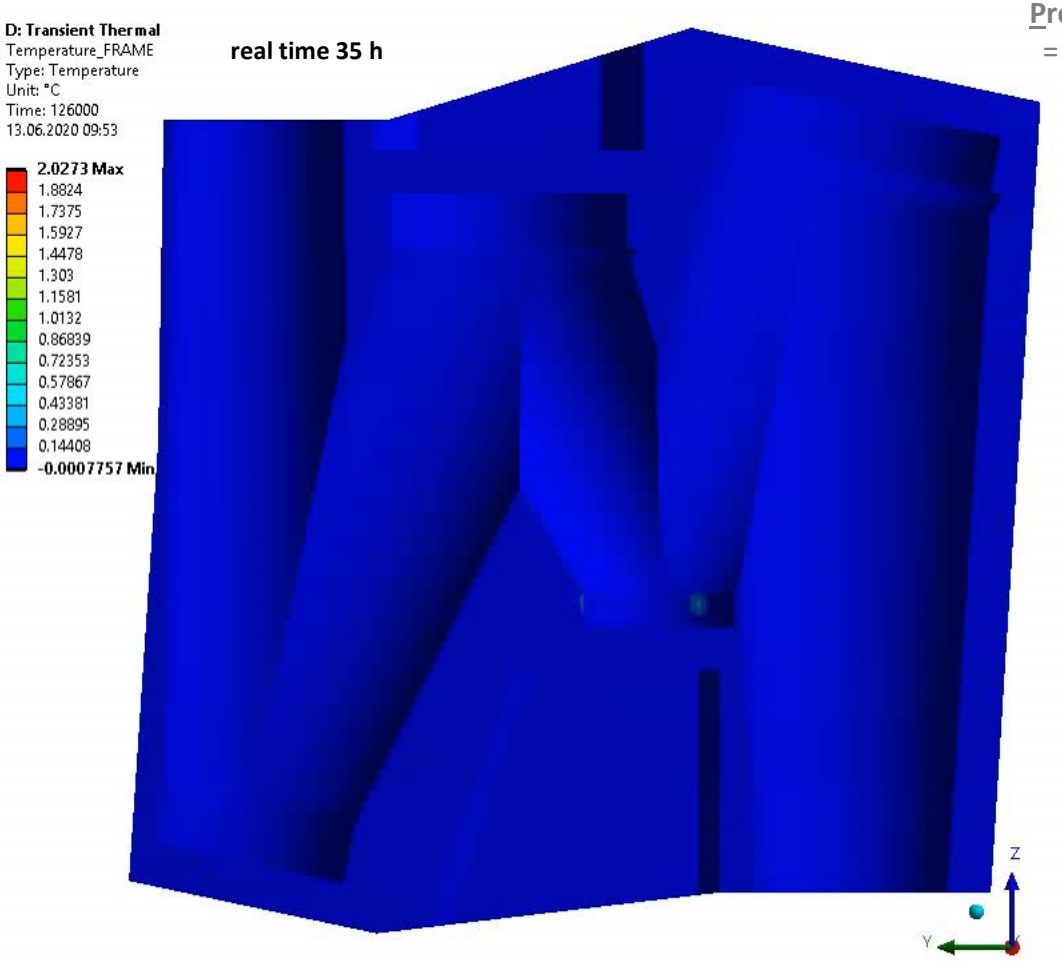
Materials

- POB-structure and mirror actuators are out of steel.
- POB-mirrors are out of glass.

Simulation Results

transient thermal response of the simplified POB-structure only

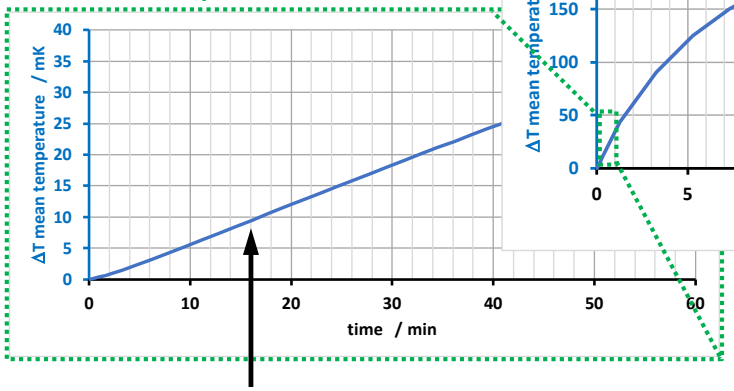


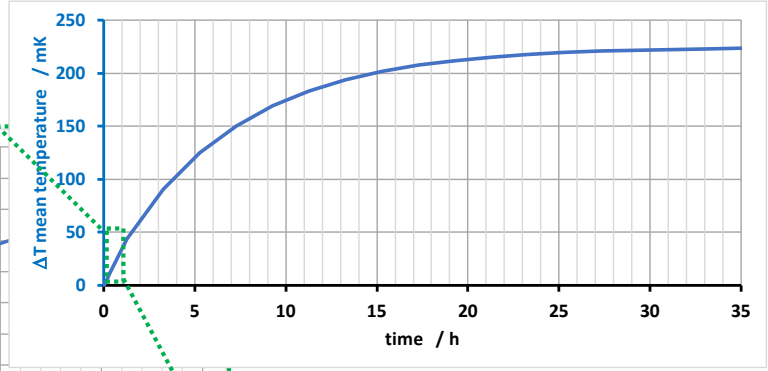
Projection Optics Box (POB)
= mirror support structure

cross-section

Most important to calculate the image drift on wafer level is the transient heating of the POB-structure.

the first hour only



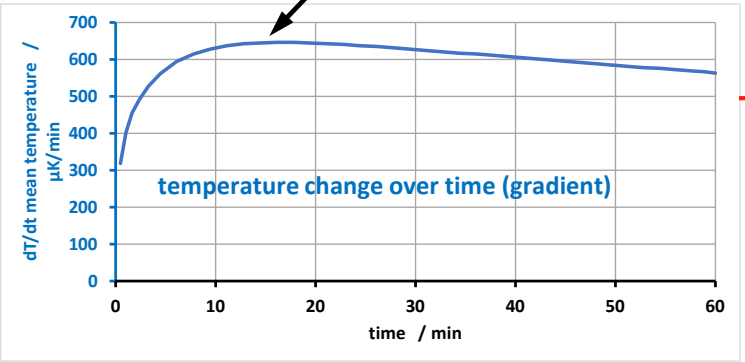


max. temperature gradient
= **646 µK/min** at t = 16 min

requirement of temperature stability < **42 µK/min**

mean ΔT of POB-structure (simulation)
= **646 µK/min**

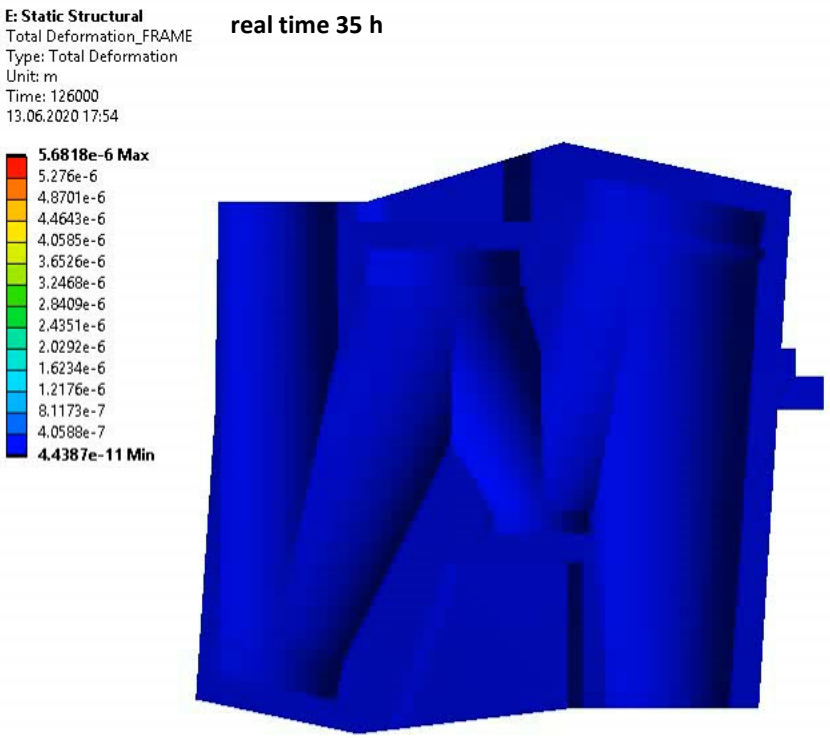
the first hour only



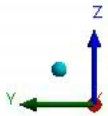
→ **The required temperature stability is about a factor 10 out of spec !!!**

Simulation Results

transient thermoelastic response of the simplified POB-structure only



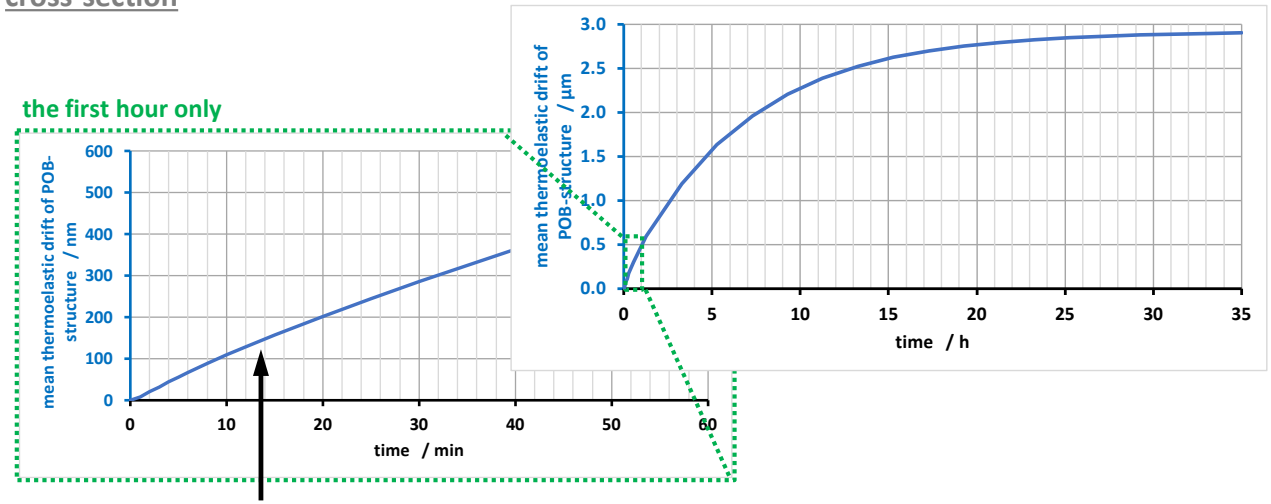
real time 35 h



Projection Optics Box (POB)
= mirror support structure

cross-section

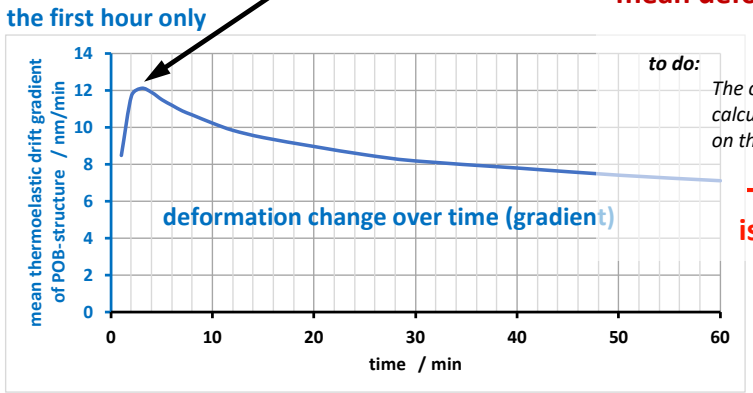
Based on the temperature field of the POB-structure, its transient thermoelastic deformation can be simulated.



max. thermoelastic drift gradient
= **12 nm/min** at t = 3 min

requirement image drift on wafer level < **1 nm/min**

mean deformation of POB-structure (simulation)
= **12 nm/min**



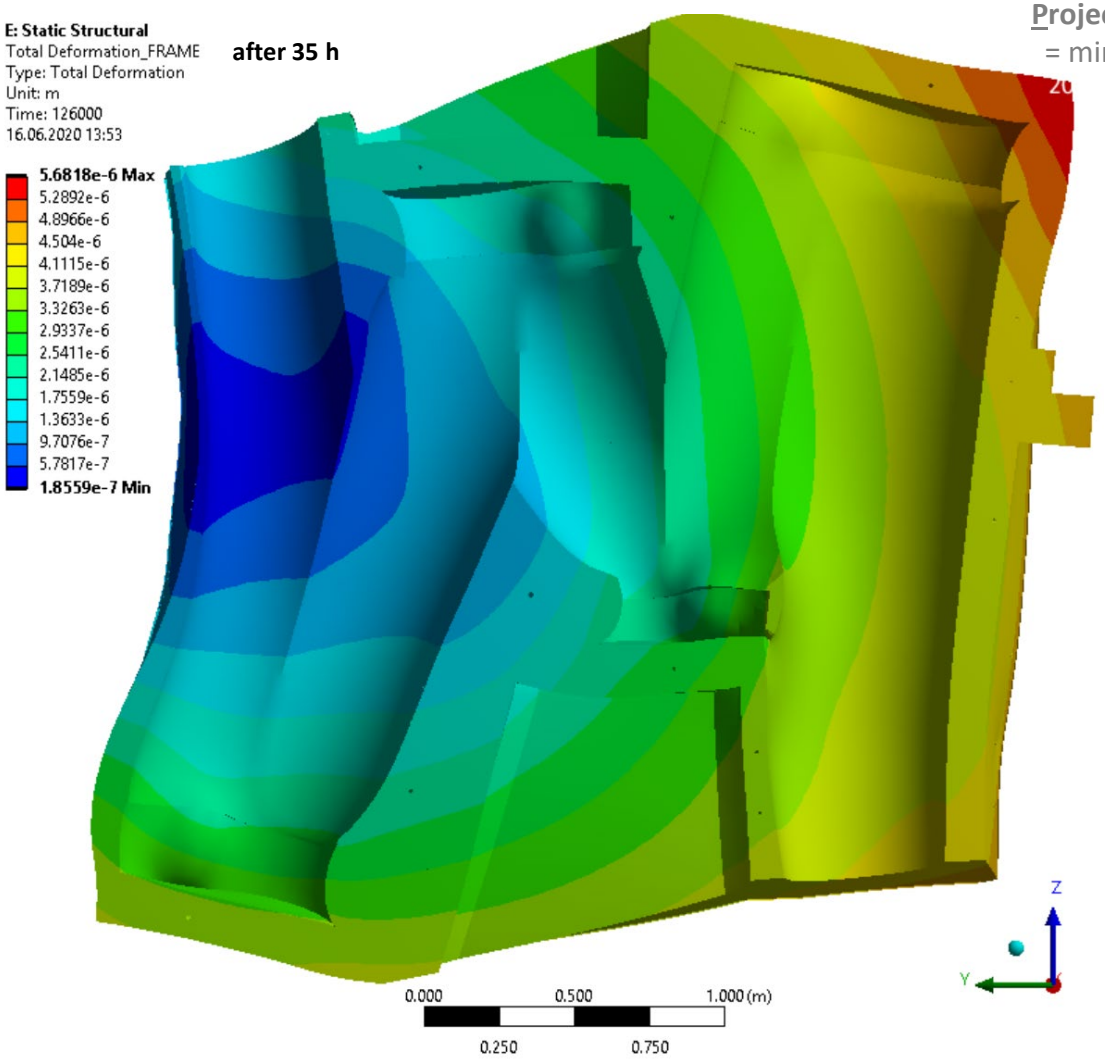
to do:

The optical sensitivities must also be taken into account to calculate the resulting (total) image shift on wafer level based on the POB-structure deformation.

→ The image drift on wafer level is about a factor 10 out of spec !!!

Simulation Results

max image drift on wafer level (simplified POB-structure)



Projection Optics Box (POB)
= mirror support structure

cross-section

Based on the transient deformation of the POB-structure, the max. image drift during wafer exposure (1 min) can be calculated.

The transient shifts and tilts of all 4 POB-mirrors are simulated.
→ **Result**: 4 mirrors x 6 **d**egree **o**f **f**reedom (DOF) = **24 transient DOFs**

Each DOF can be translated into an image shift on wafer level.
The result are **24 optical sensitivities**.
The optical sensitivities can be positive or negative!

24 transient DOFs are multiplied with **24 optical sensitivities.**
The sum represents the total (resulting) image drift on wafer level.
Self-compensation occurs!

Summary
simplified POB

Optical Boundary Conditions and Requirements

- The image position on wafer level is measured during v
- The POB-mirrors can be actuated and are repositioned
- The maximum allowed image drift on wafer level durin

Mechanical Boundary Conditions

- The optical design, limited design space, limited max. v

Thermal Boundary Conditions

- About 90 W within the POB
- Water cooling of th ture.
- Pressure of atmos the EUV-system < 10 P
- Heat transfer mec

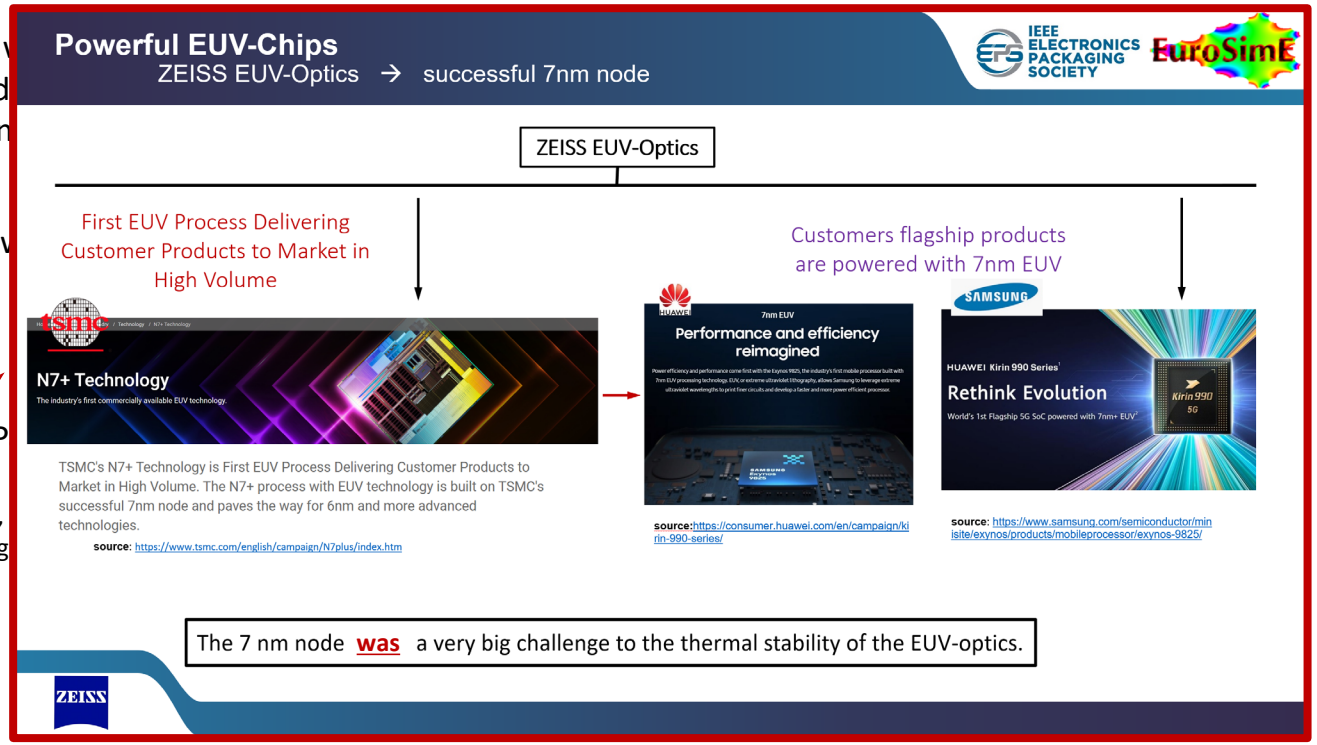
  Heat conduction in so fer in rarefied gases, radiation,
  heating of the cooling w ling water flow direction, cooling

Simplified POB Simulation FEM-Model

- POB-structure and mirror actuators out of steel.
- POB-mirrors out of glass.
- Heat loads: Two different kind of heat loads only (mirrors and actuators).
- Heat sinks: 8 cooling channels within the POB-structure (mirror support structure).

→ **A water cooled simplified steel POB-structure is about a factor 10 out of spec.**

→ **Many more ideas are needed to achieve the stability requirement "image drift on wafer level" of less than 1 nm/min.**



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Acknowledgement

This work has been funded by the German **Federal Ministry for Economic Affairs and Energy** (BMWi) in the frame of the "**Important Project of Common European Interest on Microelectronics"** (IPCEI-ME).

Supported by:

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End

Thanks for your attention !!!

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