Advancing Precision:

Mechatronic Principles from Semiconductor Manufacturing to Next-Generation Beamline Equipment

Icaleps 2025, Chicago
Mocraf Workshop

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Content

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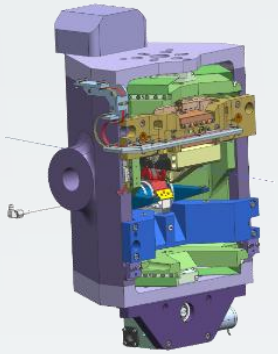
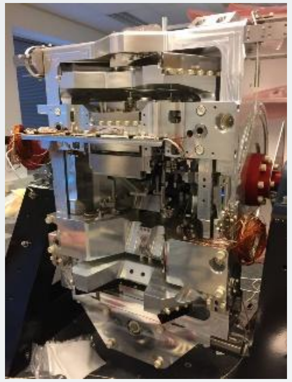
- Mechatronics in semiconductor manufacturing: an overview of mechatronics principles
- Principles applied in a synchrotron applications: High Dynamic DCM

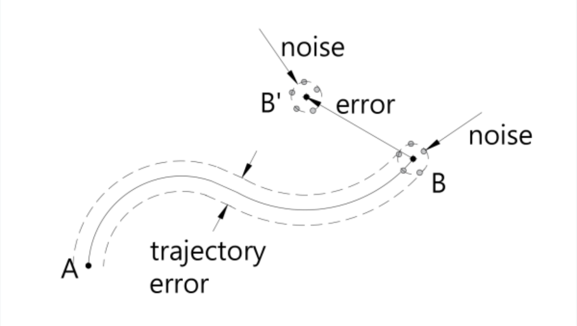
Beam line challenges

Trent in beamline equipment: experiments need fast and high dynamic scanning with nm precision

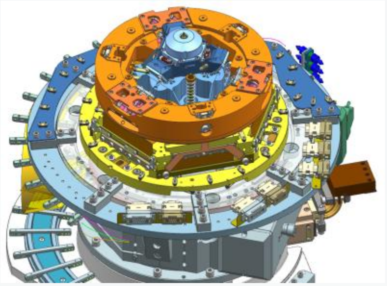
Scanning DCM of LLNS (nrad level)





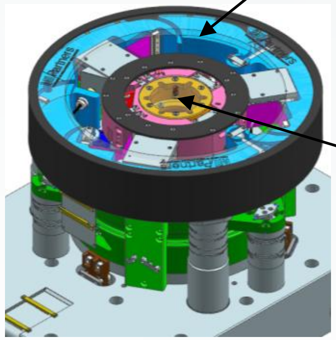


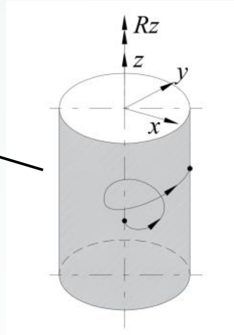
Sample manipulator fast xy-scanning
at fixed Rz (nm level)



Scanning tomography stage (nm level)

Metrology system 6 DoF
nm level





Scanning [x,y,z,Rz]
simultaneously

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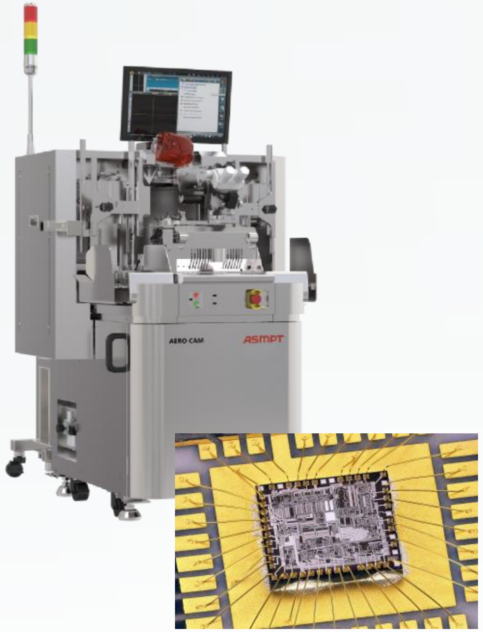
Mechatronics in semi-conductor manufacturing

High-end (mechatronic) systems since mid-80



Semiconductor manufacturing: Front- and Back-end

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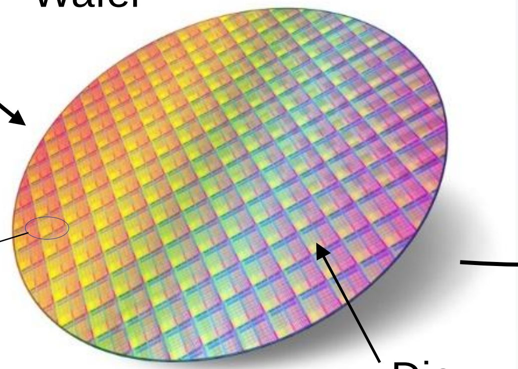
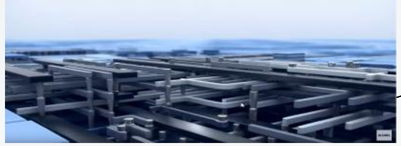
Front-end | Back-end

Source: ASML

Optical Lithography

Wafer

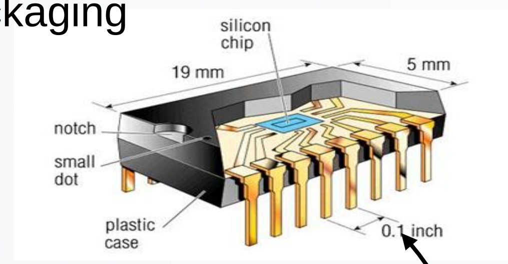


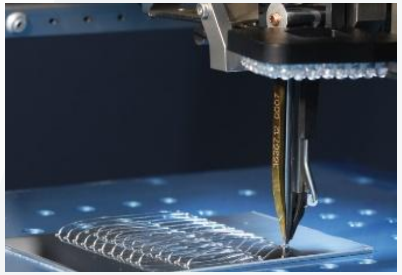


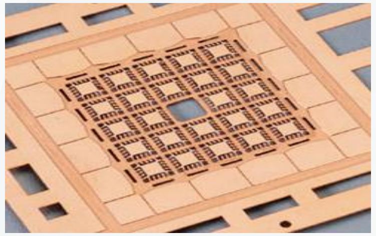
Die

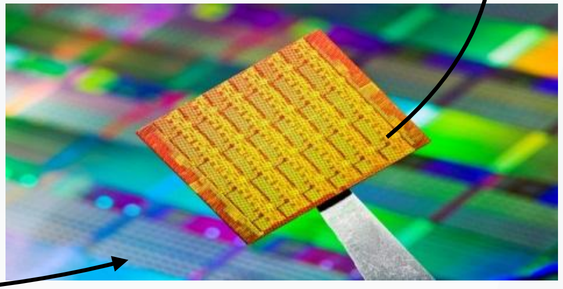
- Integrated circuits: multi layer devices with nm precision
- 200 wafer/hours
- Stage at x m/s with sub nm positioning requirements

Electrical contacting and packaging









Dicing

Die bonding:

- Low cost
- extreme fast 72.000 Dies/hour (= 0.050 s/Die or 20 Hz)
- Stage accelerations x00 m/s^2
- Sub-micron to 50 nm positioning requirements

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Semi-conductor manufacturing

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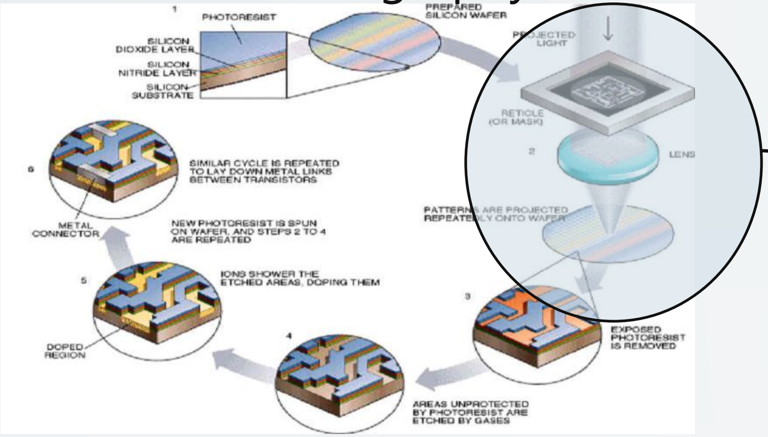
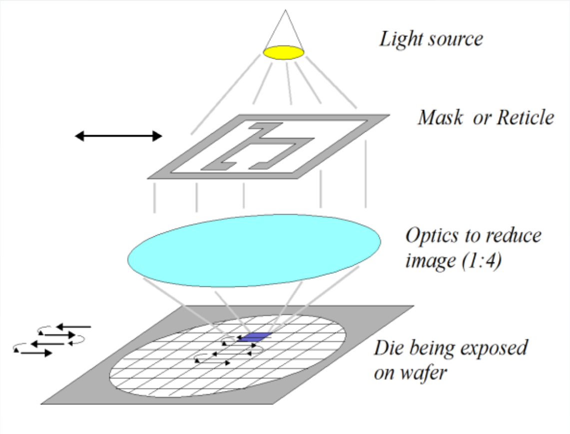
Semiconductor Lithography Process



Illumination in Litho-tool is scanning process:

(object)



(image)

ASML Lithography system (Wafer Scanner)

Overall system

Installed EUV system (info Intel)

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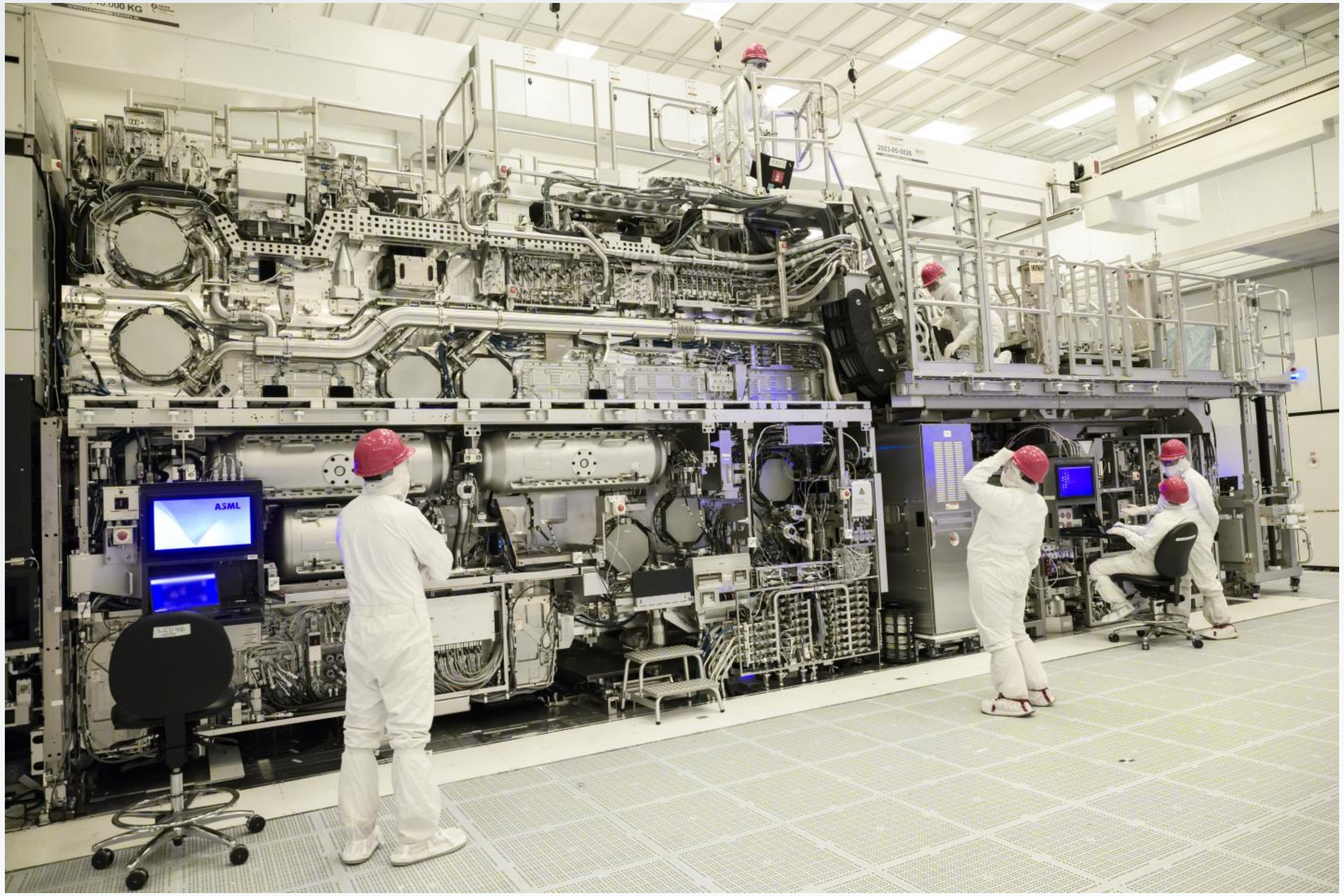

Intel completes assembly of EUV lithography system

Semiconductor Lithography: Wafer Scanner

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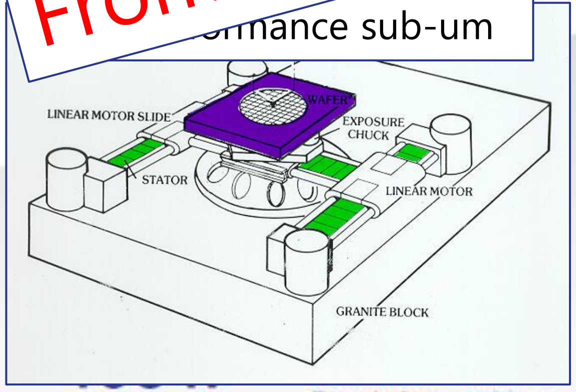
Complexity / technology

Costs

From <0.5M€ …… … to …… ……. >200M€

H-drive configuration:
- Stepping
- Linear mo...
- ...
- ...rformance sub-um



PAS 2000
Resolution: >1 μm
overlay: 250 nm

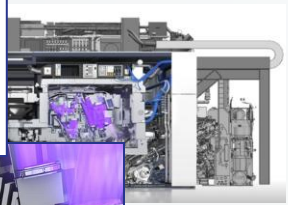
Resolution: <500 nm
overlay: 100 nm

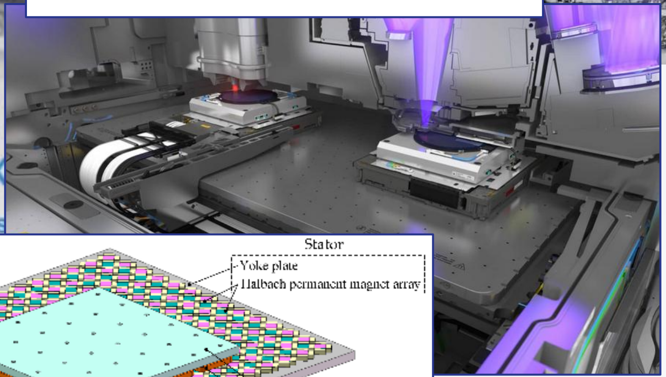
1990's:
PAS 5500 steppers/scanners
Resolution: 400 to 90 nm
overlay: 100 to 12 nm

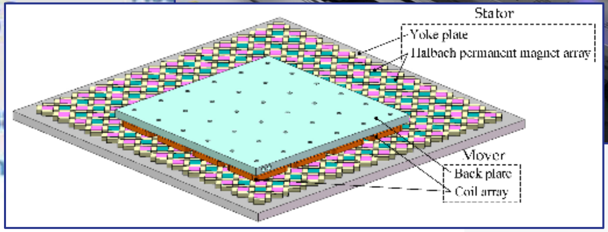
2000's
Twinscan
Resolution: 100 to 3...
overlay: 20 to 4 n...

NX...
Res...

...tion:
- ...ontinues scanning
- Planer 6 DoF actuator
- Magnetic levitation
- Long/short stroke
- Performance sub-nm







Info from www.ASML.com

ASML
For engineers who think ahead

Accuracy

250nm 100nm 10nm 1nm

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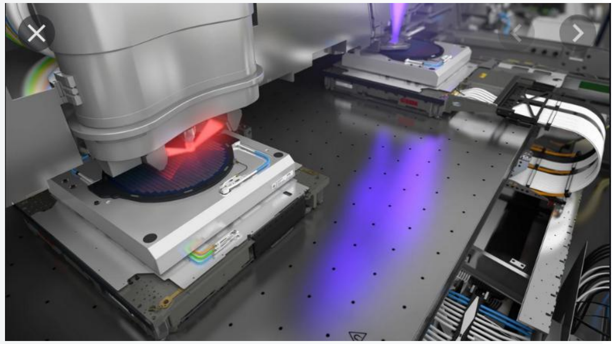
Motion system: Wafer and Reticle stage

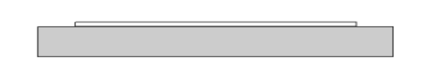
Increasing throughput (200 Wafer/hour)

Stage velocity: ~x m/s
Stage acceleration: ~x00 m/s^2



Magnetic levitated stages in vacuum

ASML: EUV system



Stage x00 m/s^2

F) m/s^2

F) m/s^2

M 0 m/s^2

This all while maintaining:

- stage positioning error < 1 nm
- metrology error < 0.5 nm
- extreme reliability & uptime

High-end Lithography stages

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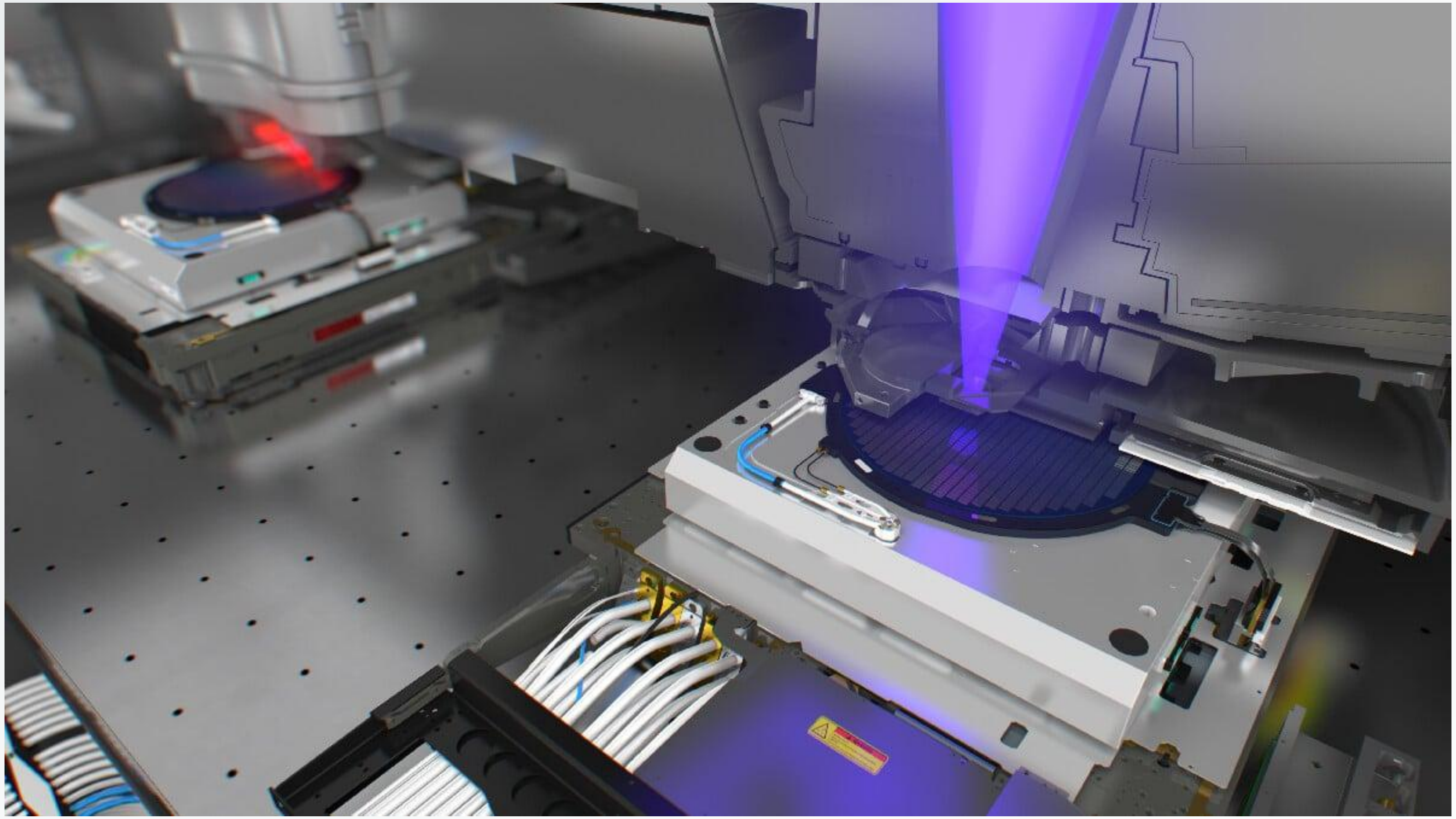

Stage architecture

- Long/short stroke principle
- Dual stage configuration
- “Compliant”actuation
- Planer magnetic levitation
    - Cleanliness (particles)
    - Low CxHy outgassing

Planner stage

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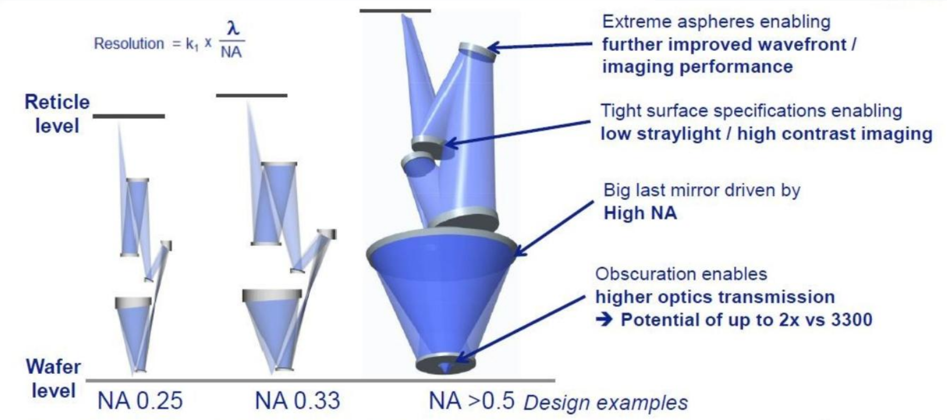
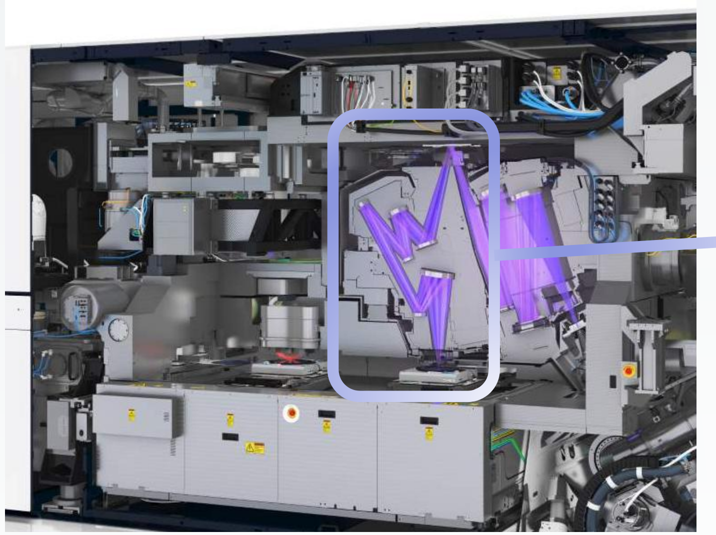
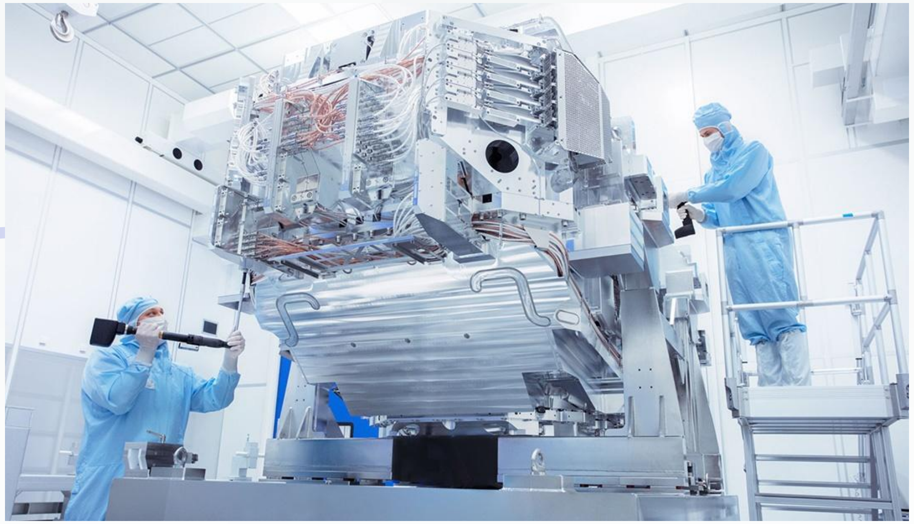
Projection Optics: EUV mirrors

- Projection Optics Box:
- 6 EUV mirrors, all 6 DoF position controlled
- Servo bandwidth ~x00 Hz
- Mirror mass x0…x00 kg
- Position stability << 1 nrad / 1 nm
- **Position stability reached from active feedback**



Source: Zeiss, "EUV lithography optics for sub-9nm resolution," Proc. SPIE 9422, (2015).





Mechatronic Architecture and some Principles

System level mechatronisch design approach

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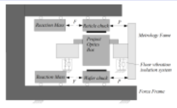
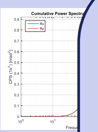
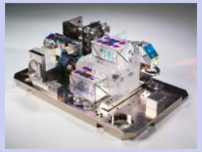
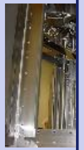
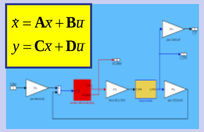
System Architecture
Balancing the design, error budgeting

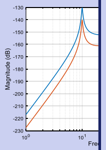



Metrology
System level metrology, sensors and calibration

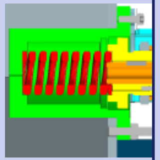



Dynamics and Control
Servo control, vibration isolation and damping

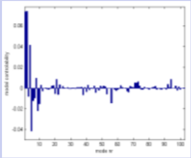




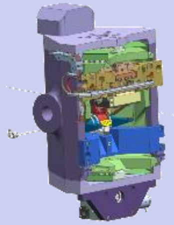
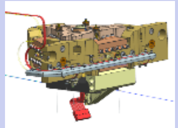
Precision Design principles
Design roles for ultra-precision systems

Thermal
Stability, temperature control, error compensation

Reliability, robustness, …
Design for manufacturing, assembly, …

Design Approach on System Level →
Understanding of the entire system to be able to balance performance.

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Mechatronic System Architectures

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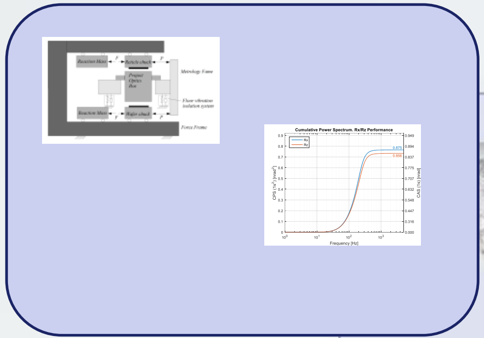
System Architecture
Balancing the design, error budgeting



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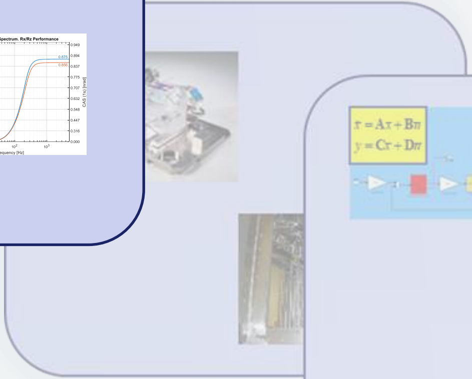
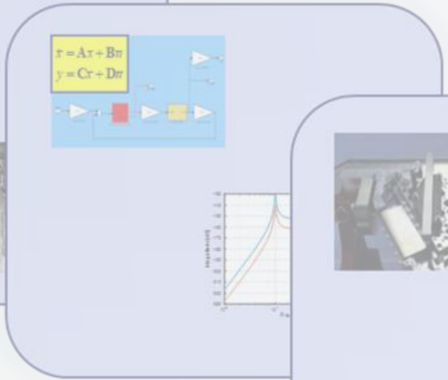
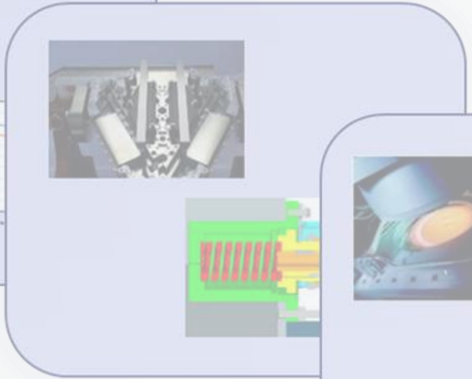
System level metrology, sensors and calibration



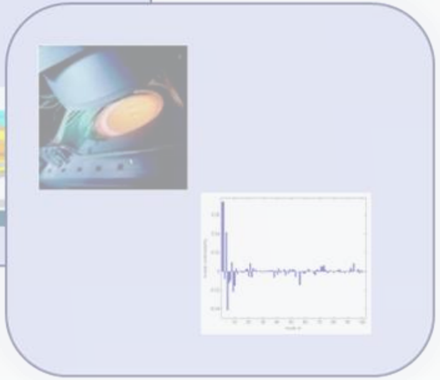
Dynamics and Control
Servo contro, vibration isolation and damping



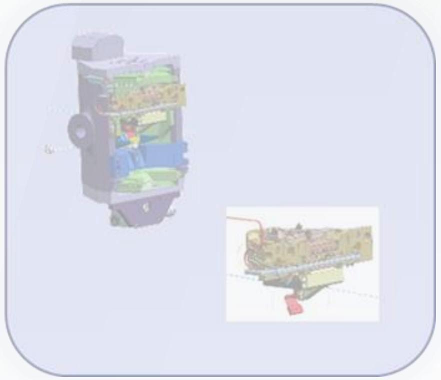
Precision Design principles
Design roles for ultra-precision systems



Thermal
Stability, temperature control, error compensation



Reliability, robustness, …
Design for manufacturing, assembly, …



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Mechatronic System Architecture

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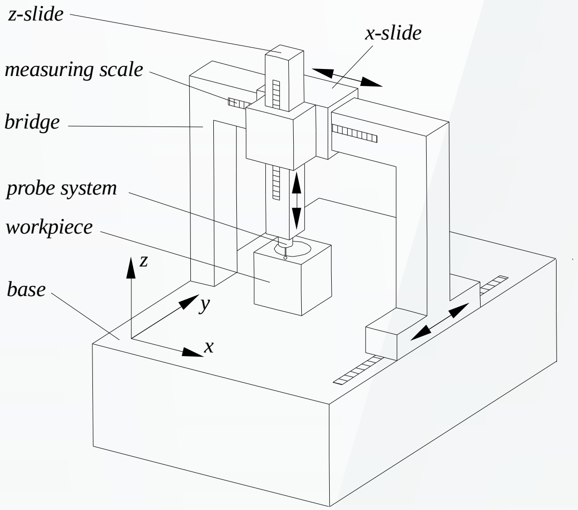
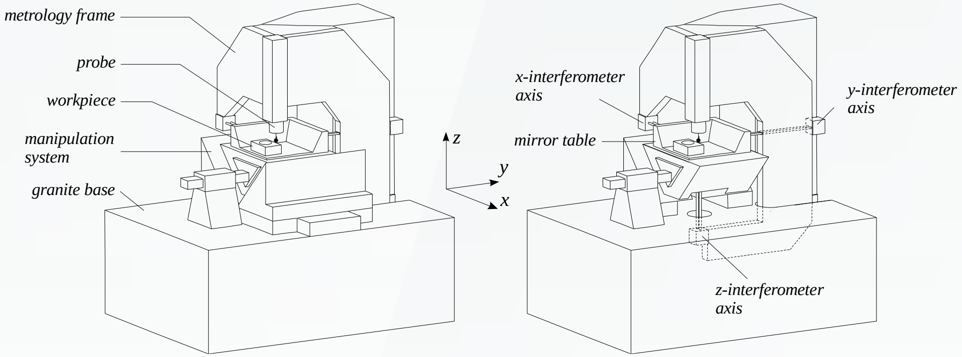
Ultra-precision and high-dynamic systems:

- Multiple frame architecture
  - Force and metrology frame separation
- Dynamic decoupling
- Isolation of reaction forces
- Long-stroke/ short stroke stage concept
- Actuator choice: inherent compliant versus stiff





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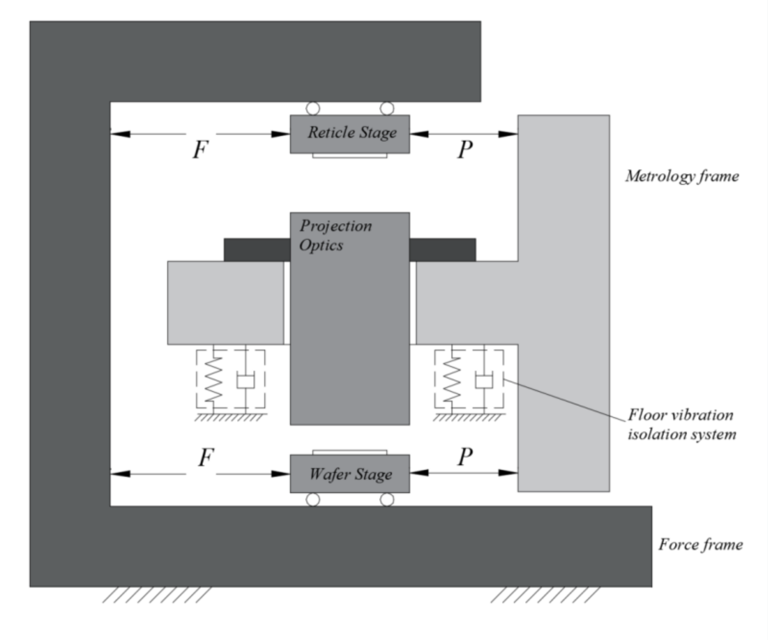
Mechatronic System Architecture

Ultra-precision and high-dynamic systems:

- Multiple frame architecture
- Dynamic decoupling
  - Dynamic separation between fast moving stages and sensitive projection optics on metrology frame
  - Position fully based on active feed back (servo position based on position metrology signal P)
- Isolation of reaction forces
- Long-stroke/ short stroke stage concept
- Actuator choice: inherent compliant versus stiff



Mechatronic System Architecture

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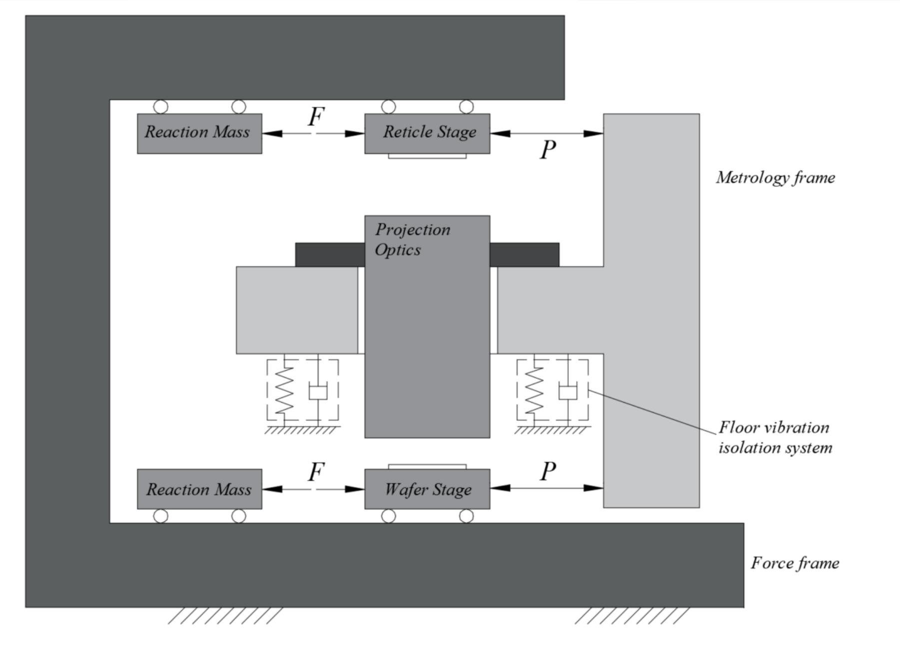
Ultra-precision and high-dynamic systems:

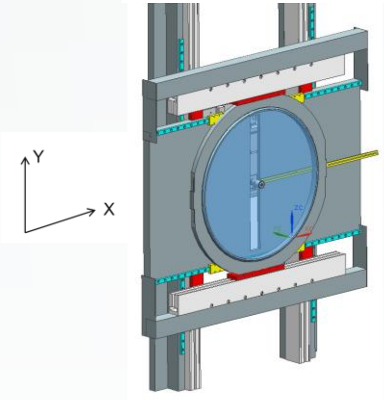
- Multiple frame architecture
- Dynamic decoupling
- Isolation of reactions forces

For high dynamic systems, extreme acceleration forces are needed:

- Reaction forces will excide metrology frame via force-frame and floor
- Servo stability issues due to dynamics in force frame

- Long-stroke/ short stroke stage concept
- Actuator choice: inherent compliant versus stiff

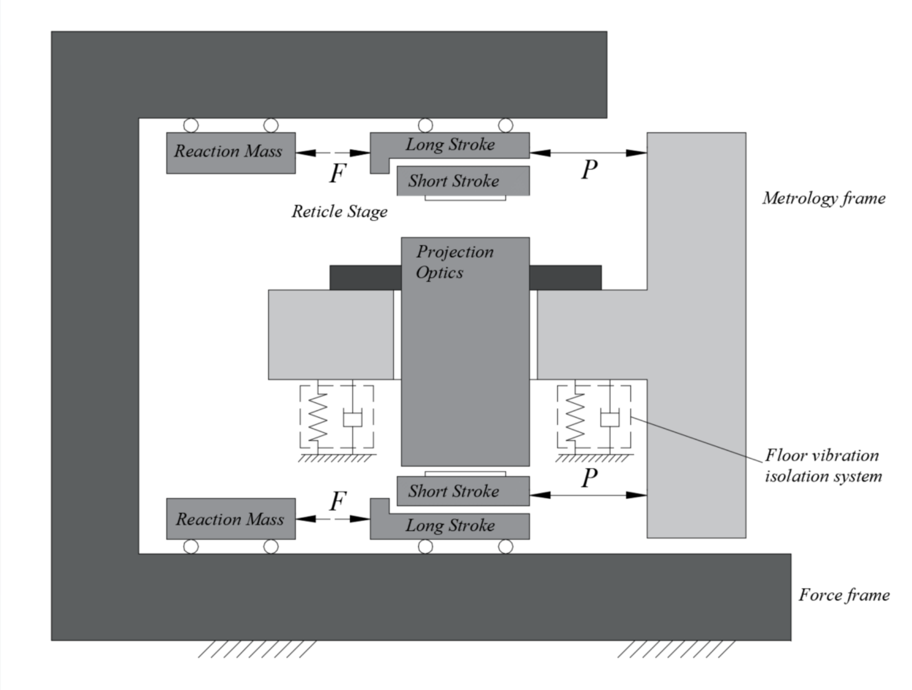


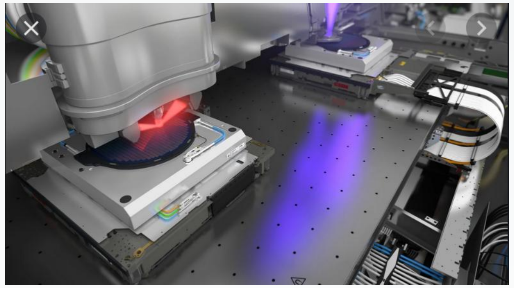


Mechatronic System Architecture

Ultra-precision and high-dynamic systems:

- Multiple frame architecture
  - Force and metrology frame separation
- Dynamic decoupling
- Isolation of reaction forces
- Long-stroke/ short stroke stage concept
  - Long-stroke reaching um level positioning
  - Short stroke reaching nm level positioning
- Actuator choice: inherent compliant versus stiff





Optical pickup unit

Long-stroke/ short stroke: Dynamic decoupling

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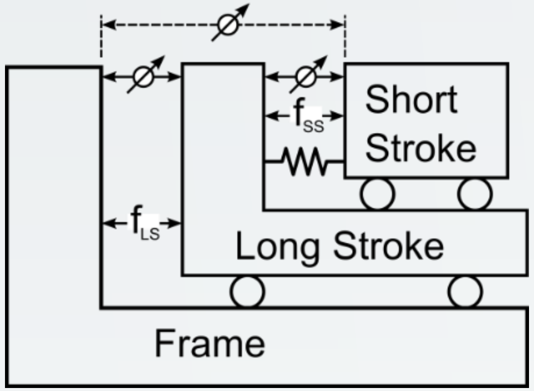
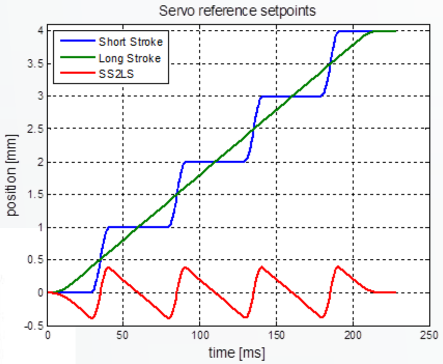
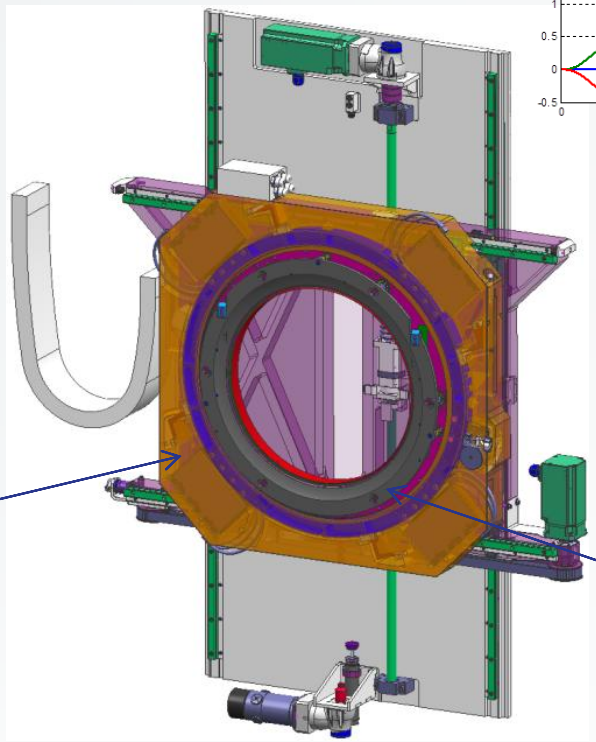
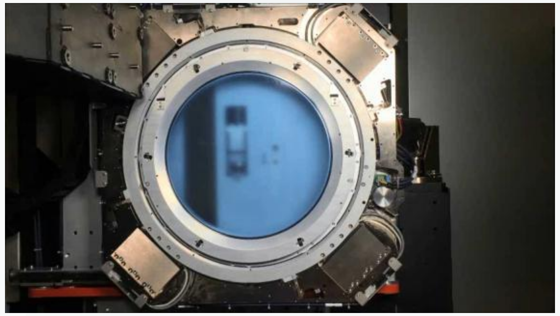
Long stroke acts as balance mass
for high-dynamic short stroke









Long Stroke XY

- X: driven by belt
- Y: drive by spindles
- Ball bearings

Short Stroke X-Y-Rz

- Linear motor
- Linear encoders
- Leaf springs

Wafer table

Detail table

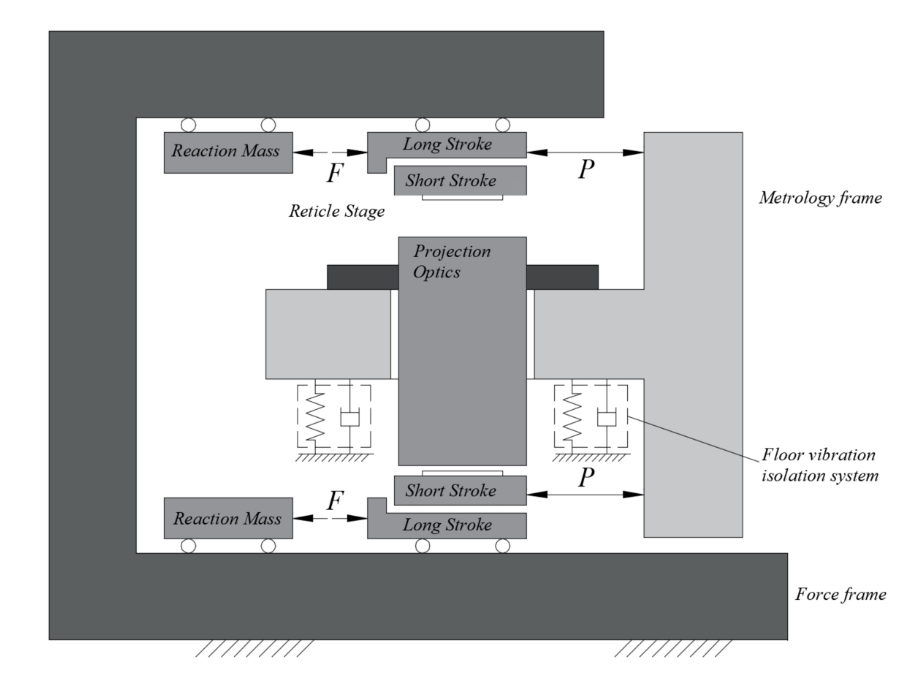
Mechatronic System Architecture

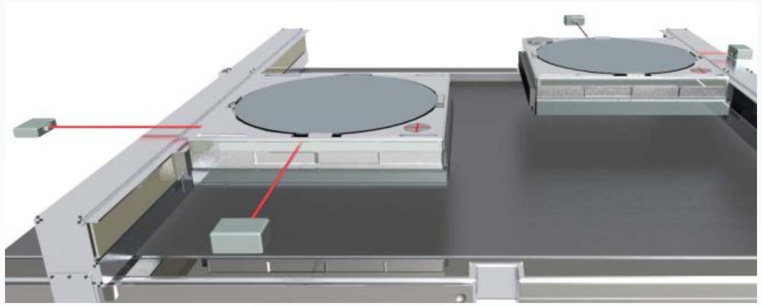
Ultra-precision and high-dynamic systems:

- Multiple frame architecture
    - Force and metrology frame separation
- Dynamic decoupling
- Isolation of reaction forces
- Long-stroke/ short stroke stage concept
- Actuator choice: inherent compliant versus stiff

Behavior of actuator should enable dynamic architecture (6 DoF):

- Long stroke to short stroke configuration
- Reaction mass decoupling





Actuator Dynamics: Piezo versus Lorentz

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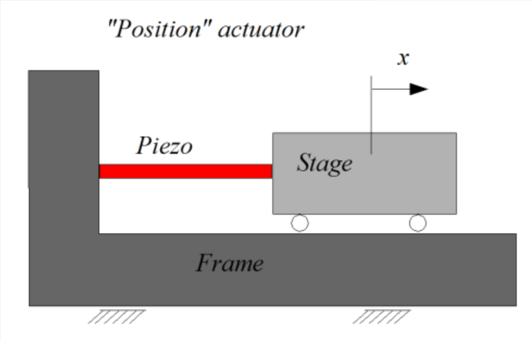
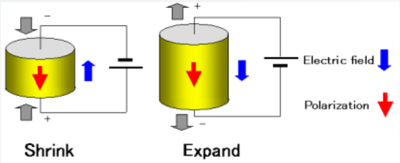
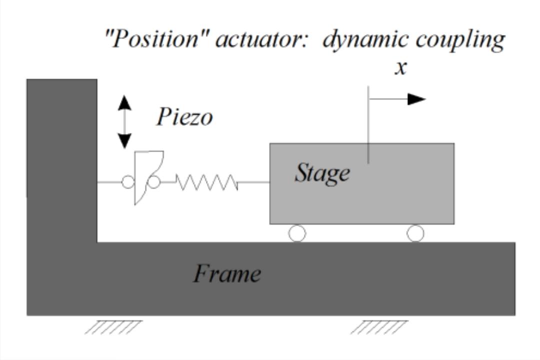
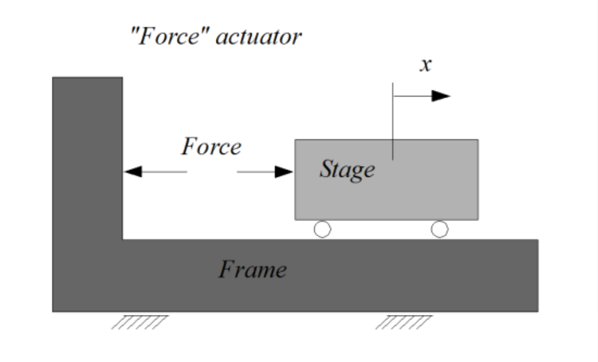


$$\Delta x = f(Q) - \frac{F}{k}$$

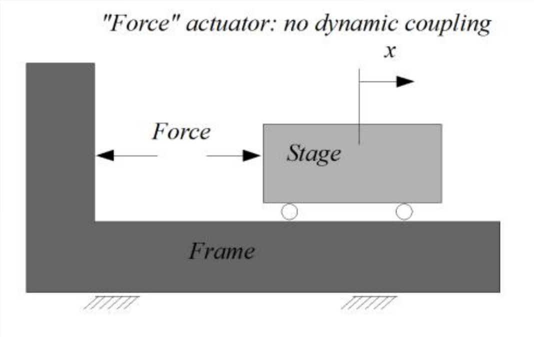




Dynamic coupling between stage and frame due inherent stiffness of piezo actuator.



$$Force = f(I)$$



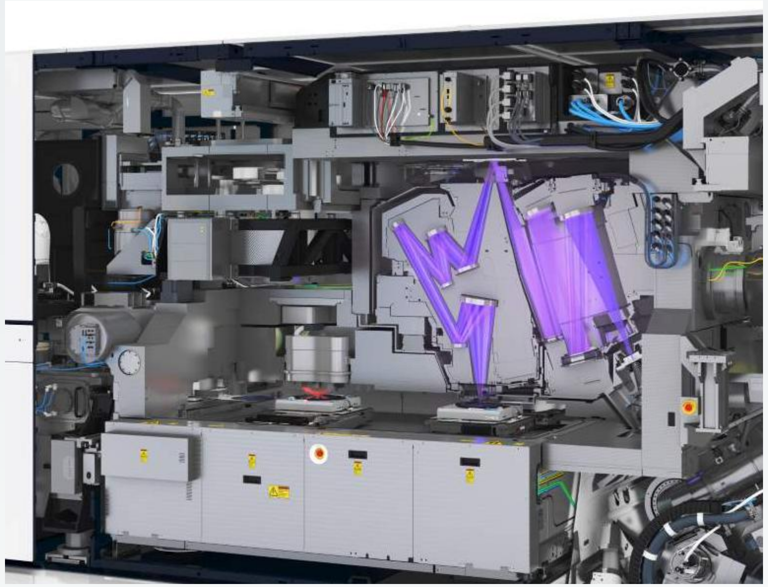
Force is only result of current I, no inherent stiffness.
Hence, stage and frame are decoupled.

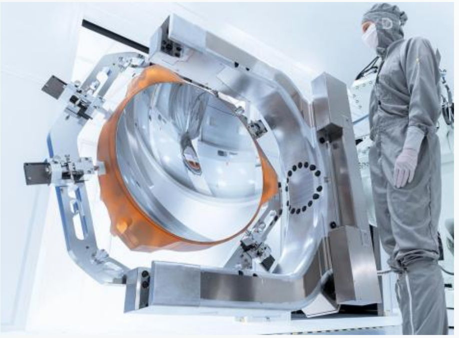
Inherent compliant actuator (e.g. Lorentz)
→ Decoupled dynamic architecture
→ Enables multiple frame and stage concepts

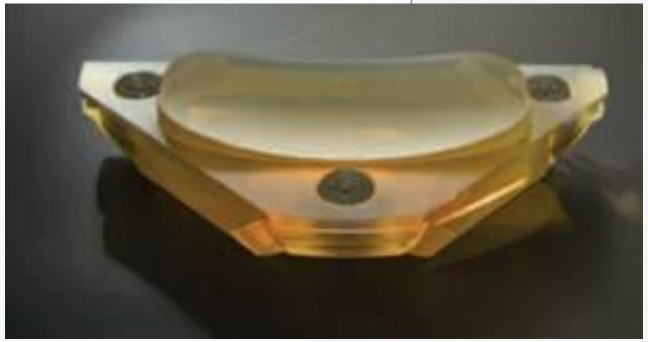
Example: Mirror Positioning (quasi-static)

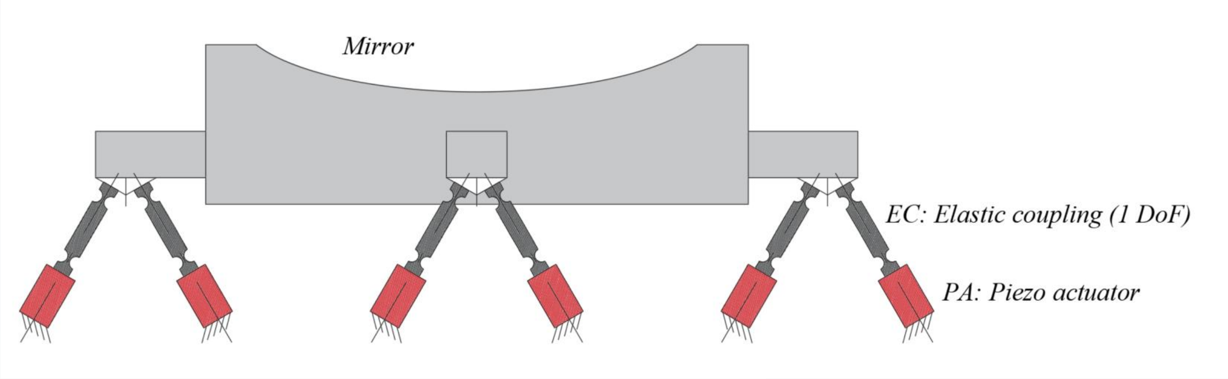
Active mirror positioning:

- Active 6 DoF based on positioning feedback
- Stroke mm range
- Positioning stability << 1 nm









Support hexapod configuration:
Very compliant elastic coupling (elastic element: strut - 1 DoF) is needed to avoid deformation of mirror itself.

Example: Mirror positioning (quasi-static)

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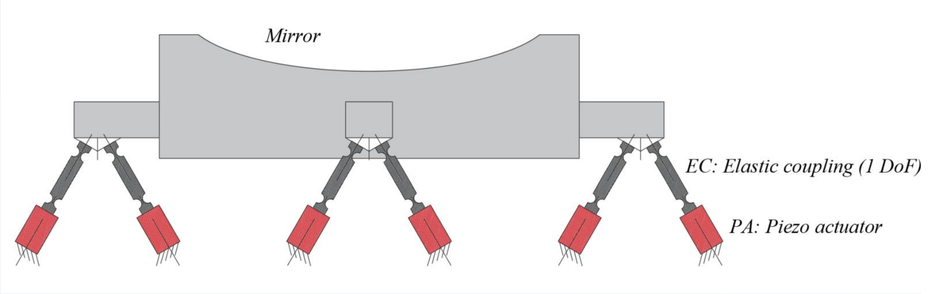
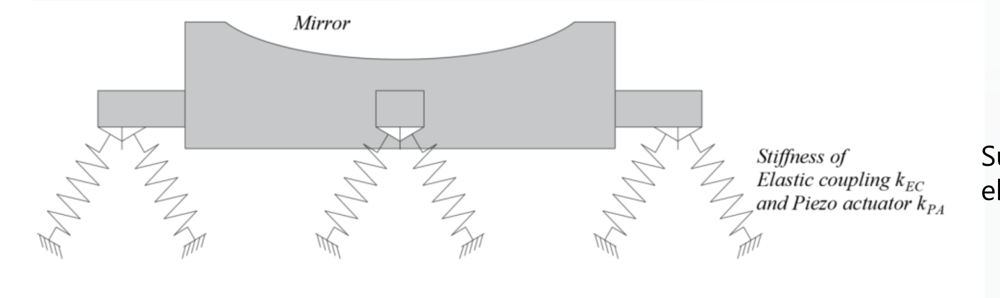


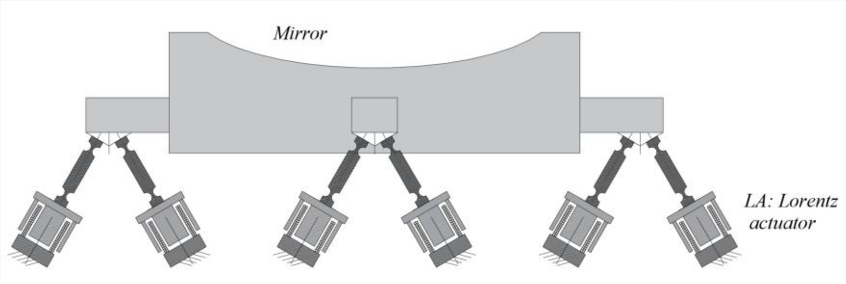


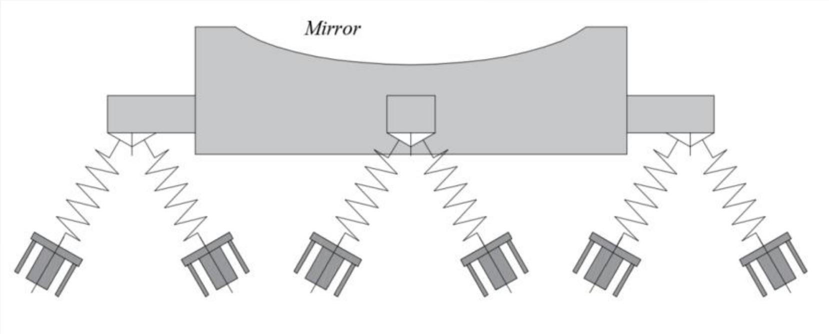
Eigenfrequency limiting dynamic performance

$$f_{PE} = \frac{1}{2\pi}\sqrt{\frac{k_{support}}{M_{mirror}}}$$

Support stiffness (compliance) due to piezo and elastic element (strut)

$$k_{support} = (1/k_{EC} + 1/k_{PA})^{-1}$$





Eigenfrequency limiting dynamic performance is now dominated by mass of actuator body LA, not by mass of mirror

$$f_{LA} = \frac{1}{2\pi}\sqrt{\frac{k_{support}}{M_{LA}}} \gg f_{PE}$$

Active position control by inherent compliant actuator:
→ higher servo bandwidth
→ higher disturbance rejection and better tracking performance

Dynamics and Control: Error Budgeting

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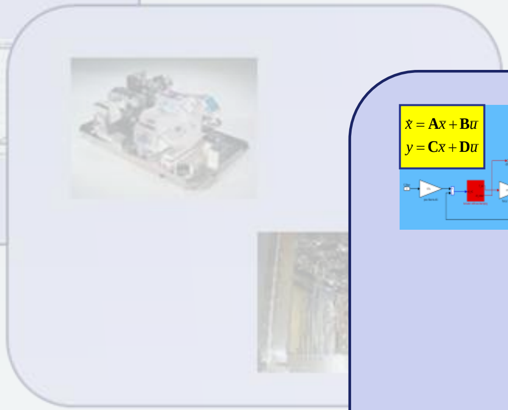
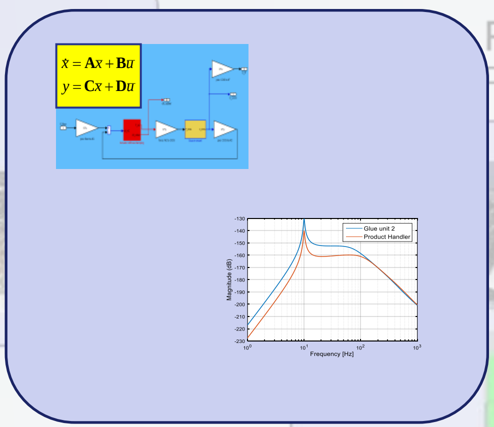
System Architecture
Balancing the design, error budgeting

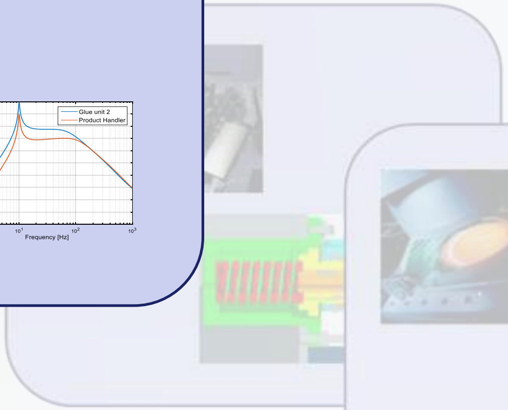
Metrology
System level metrology, sensors and calibration



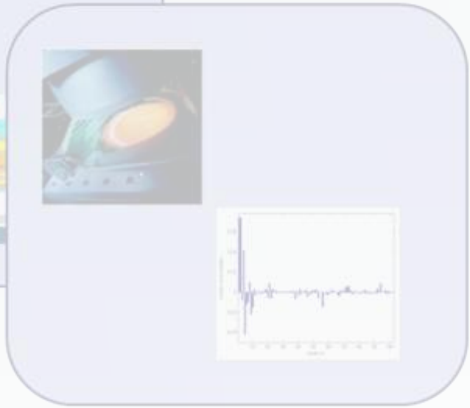
Dynamics and Control
Servo control, vibration isolation and damping



Precision Design principles
Design roles for ultra-precision systems



Thermal
Stability, temperature control, error compensation



Reliability, robustness, …
Design for manufacturing, assembly, …

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Dynamic Error Budgeting as design tool

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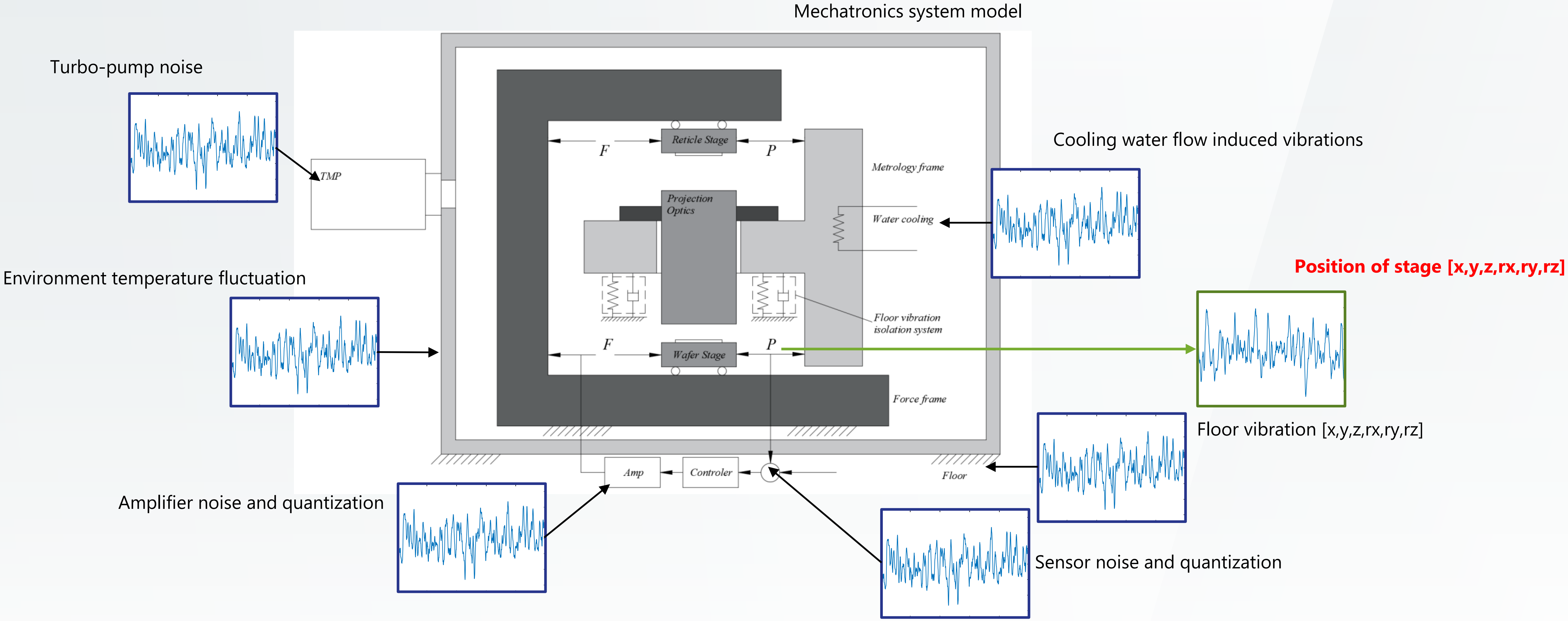
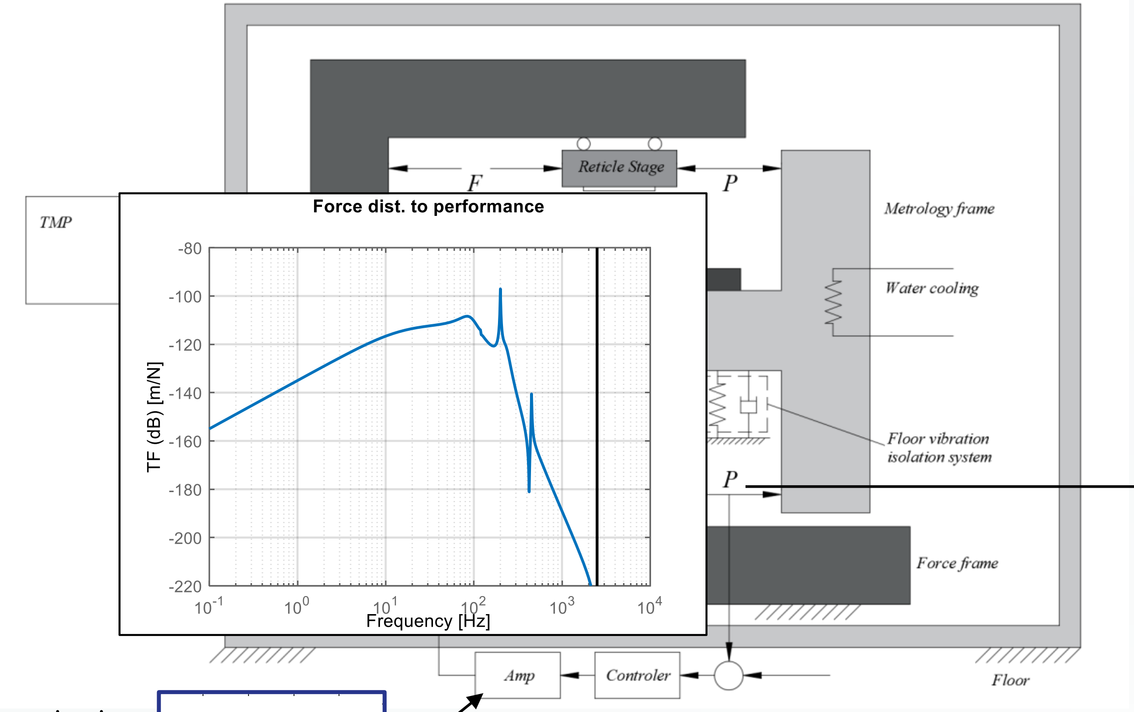
Dynamic Error Budgeting (DEB): way to predict performance of Mechatronic systems.
An objective method to make design choices.

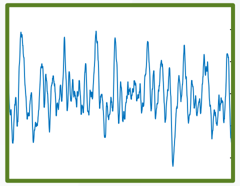


Dynamic Error Budgeting as design tool

Mechatronic system model links the inputs (e.g. noise sources) to the output (stage position x,y,z,rx,ry,rz)
Error propagation via Transfer Functions:

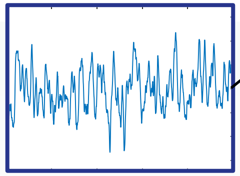
Mechatronics system model





Position of stage [x,y,z,rx,ry,rz]

Amplifier noise and quantization



Dynamic Error Budgeting as design tool

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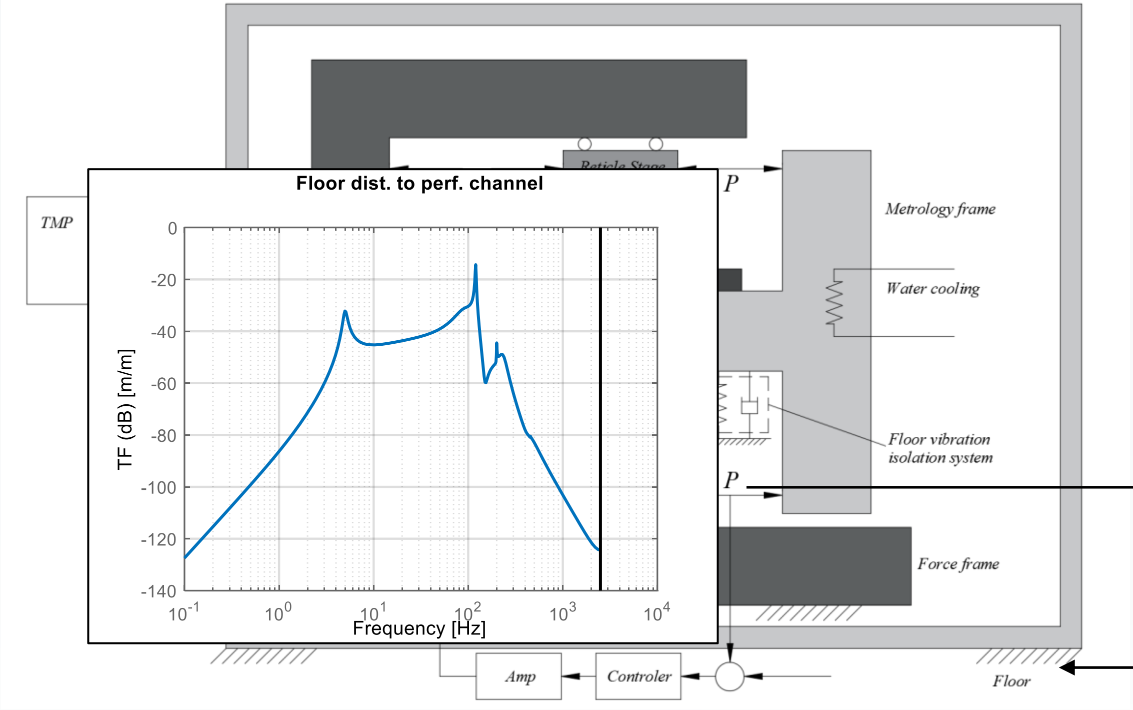
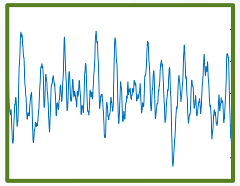
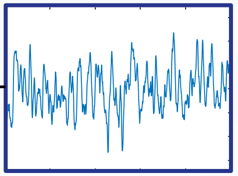
Mechatronic system model links the inputs (e.g. noise sources) to the output (stage position [x,y,z,rx,ry,rz])

Mechatronics system model





Position of stage [x,y,z,rx,ry,rz]



Floor vibration [x,y,z,rx,ry,rz]

Dynamic Error Budgeting as design tool

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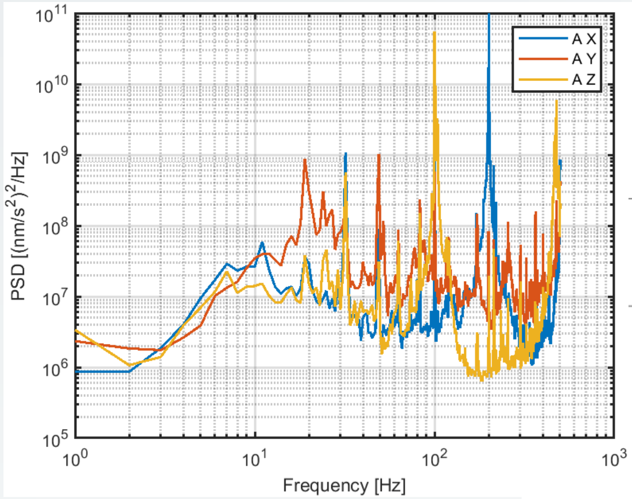
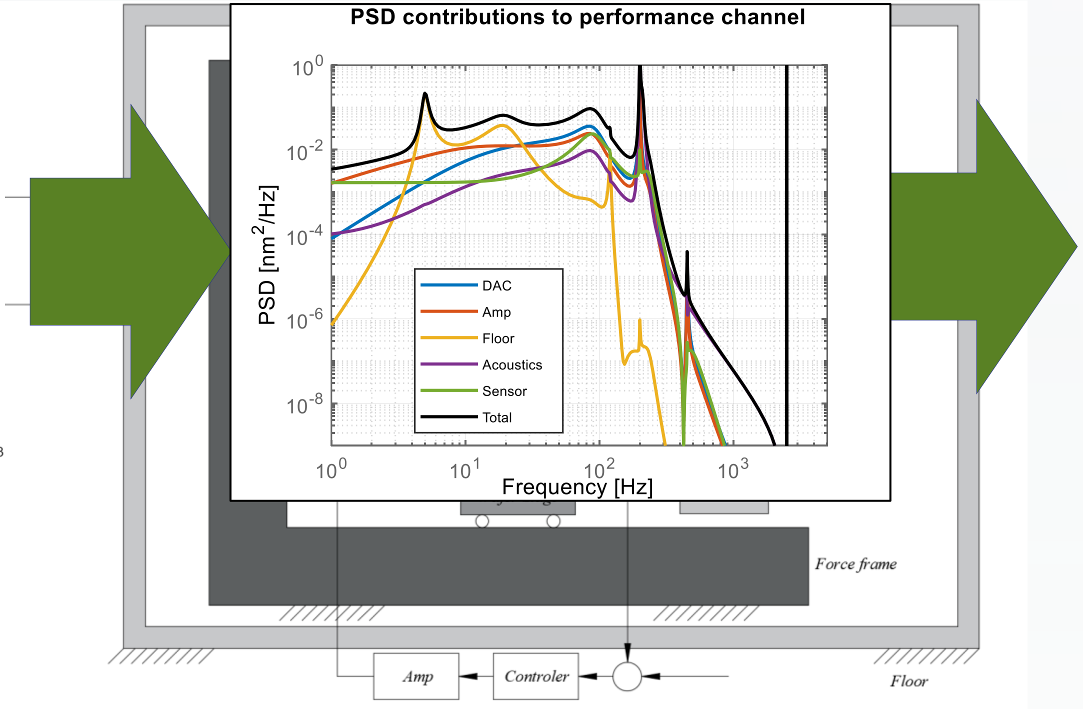
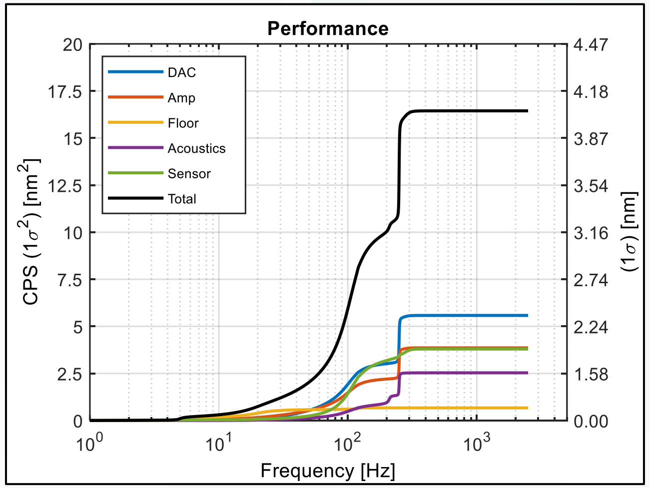
Input: Data in frequency domain, PSD

Output: CPS or CAS

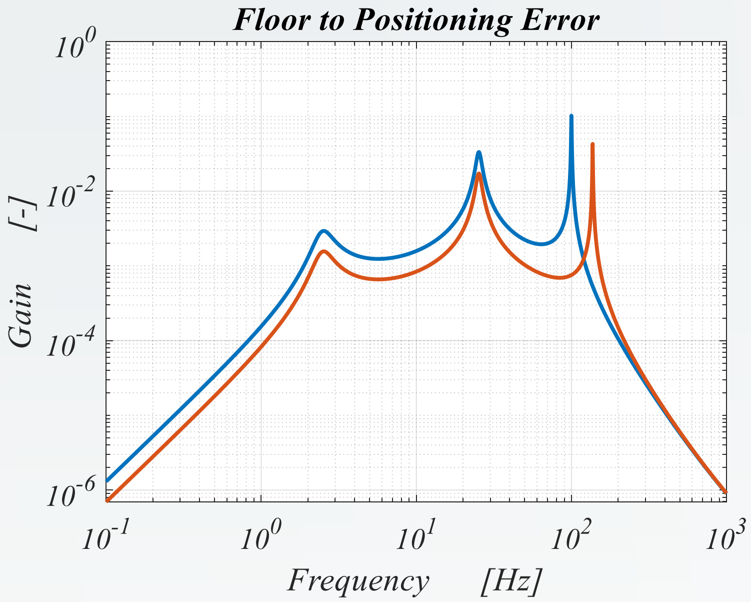


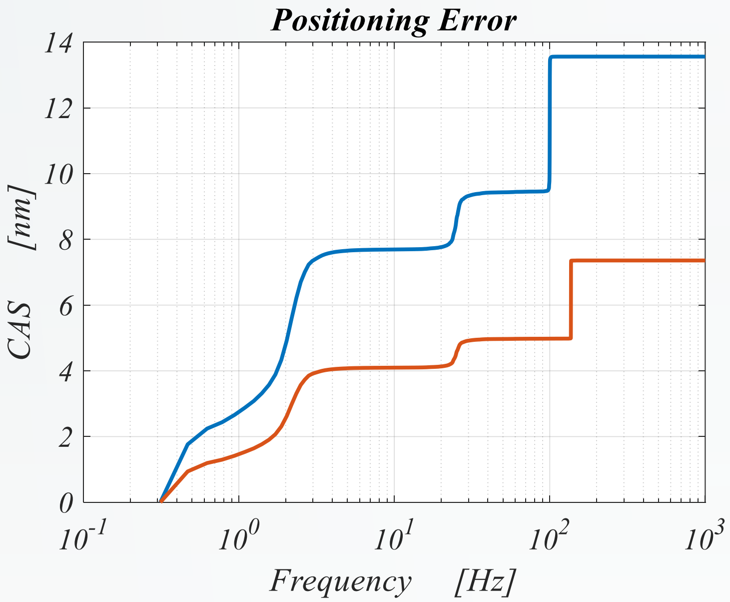




Dynamic Error Budgeting as design tool

Optimizing performance in an object manner



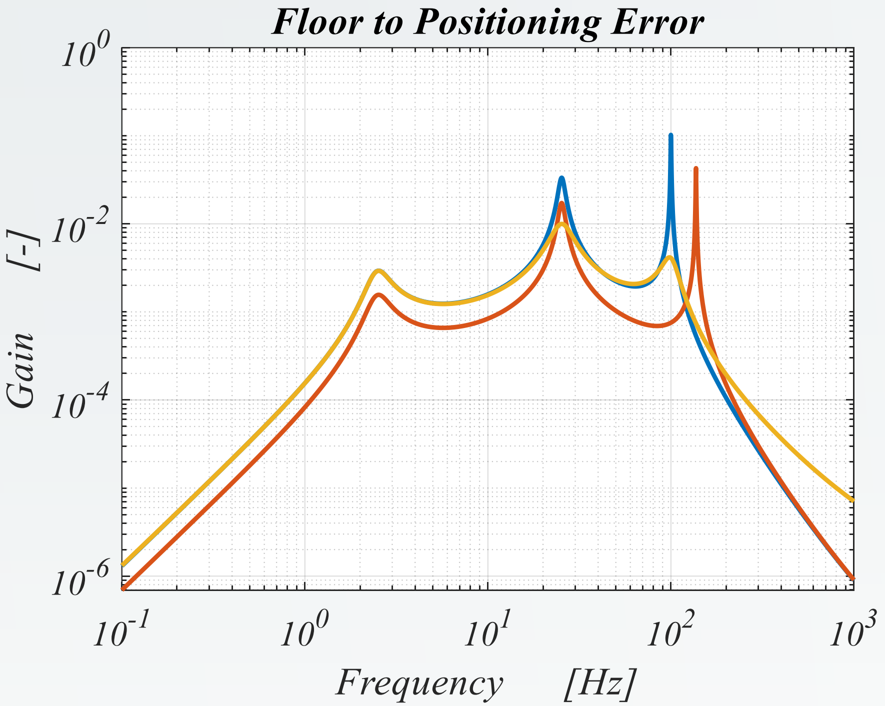


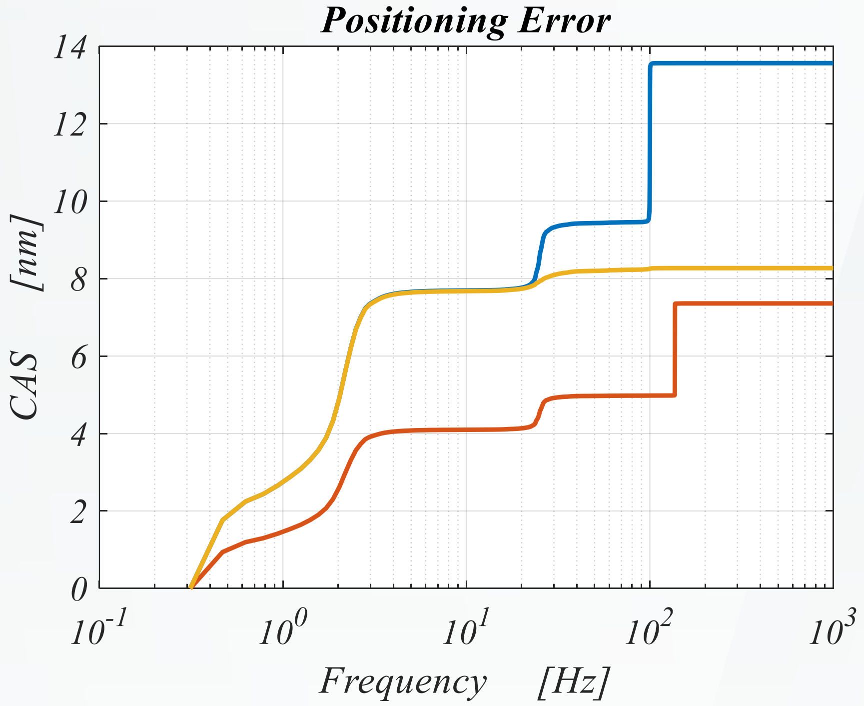
Cuck optimized for dynamic performance:

- Topography Optimization and AM

Increasing damping

Increasing damping, e.g. by means of polymer



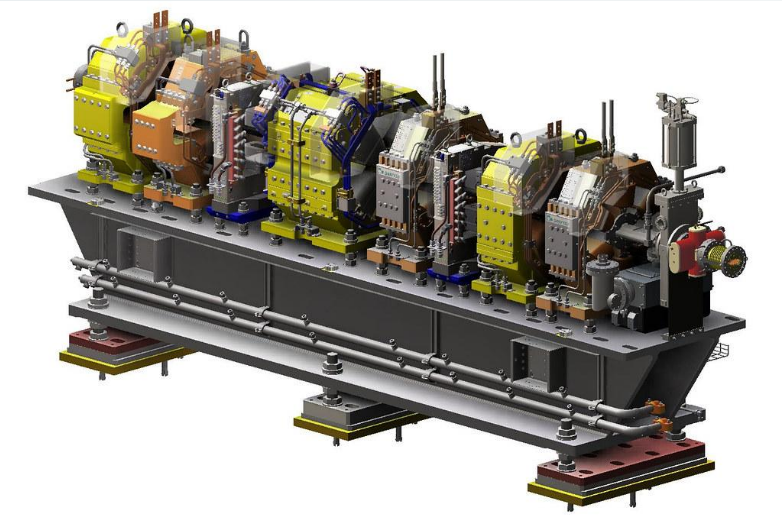


Damping video

Higher damping

Higher stiffness

Girder, why 120 Hz?

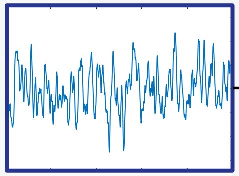


Aiming to reach a first eigenfrequency above 120 Hz (example)

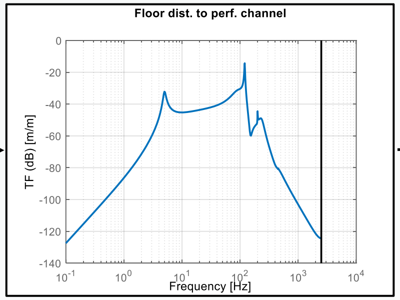
But why 120 Hz?

How to judge the performance without considering the input spectrum and transfer function!

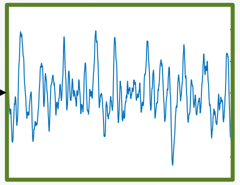
Floor input



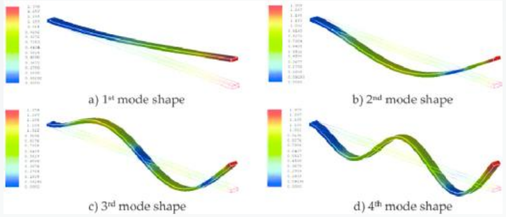
Girder TF



Magnet motion



1. Mode shapes
2. Damping
3. Input/output positions



Synchrotron application

- high-dynamic double-crystal monochromator (DCM)

Main Specifications and drivers

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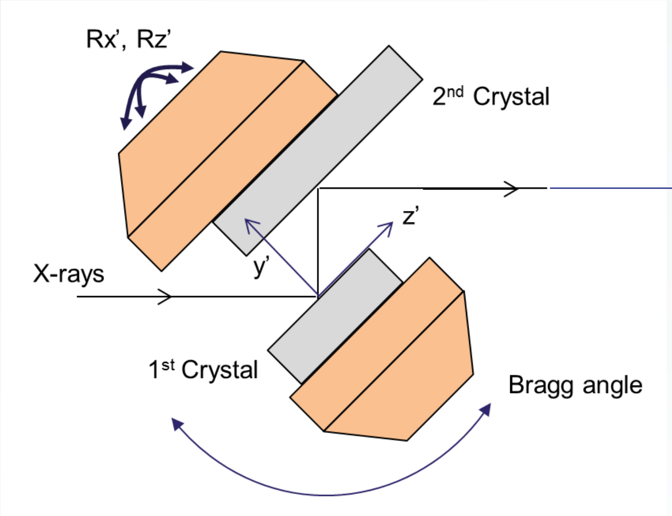
	Uncertainty (3σ)	Remark
Rx', Rz' parallelism between crystals	10 nrad	Over the full y' stroke 9 …18 mm and Bragg angle range 3…60° during fly-scan
y' gap distance between crystals	0.1 um	
Bragg angle Rx absolute to beam (floor as reference)	1 urad	

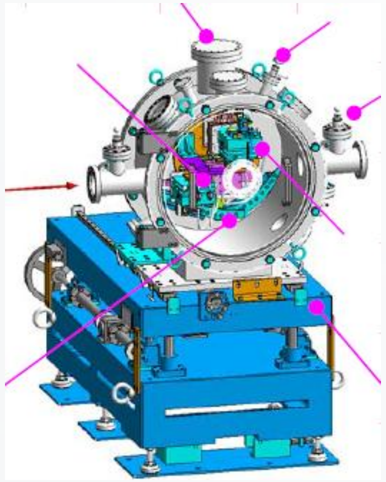


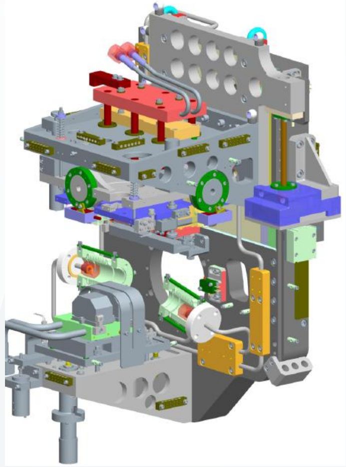
Design Approach

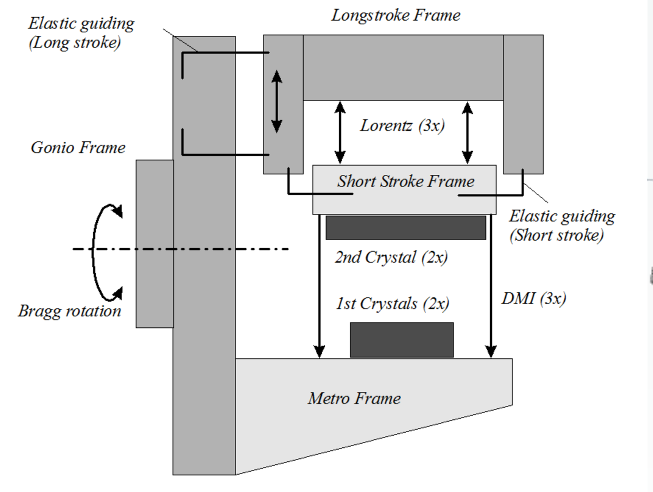
Common approach:
- Stacking mechanical elements (slide)
- No metrology from crystal to crystal

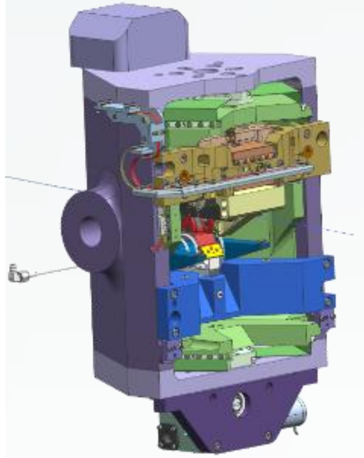
To achieve nrad instead of urad performance

Our solution:
Fully actively controlled 2nd crystal towards 1st cystal based on interferometer (DMI) feedback









Layout: Gonio Frame, Long-Stroke and Short-Storke

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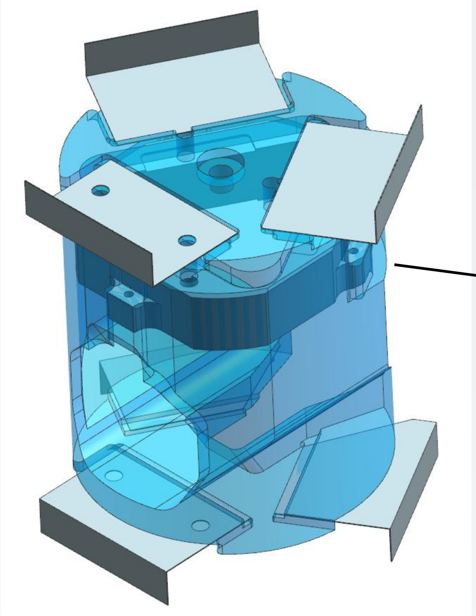
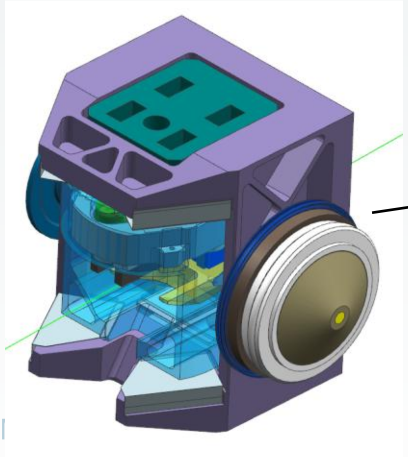
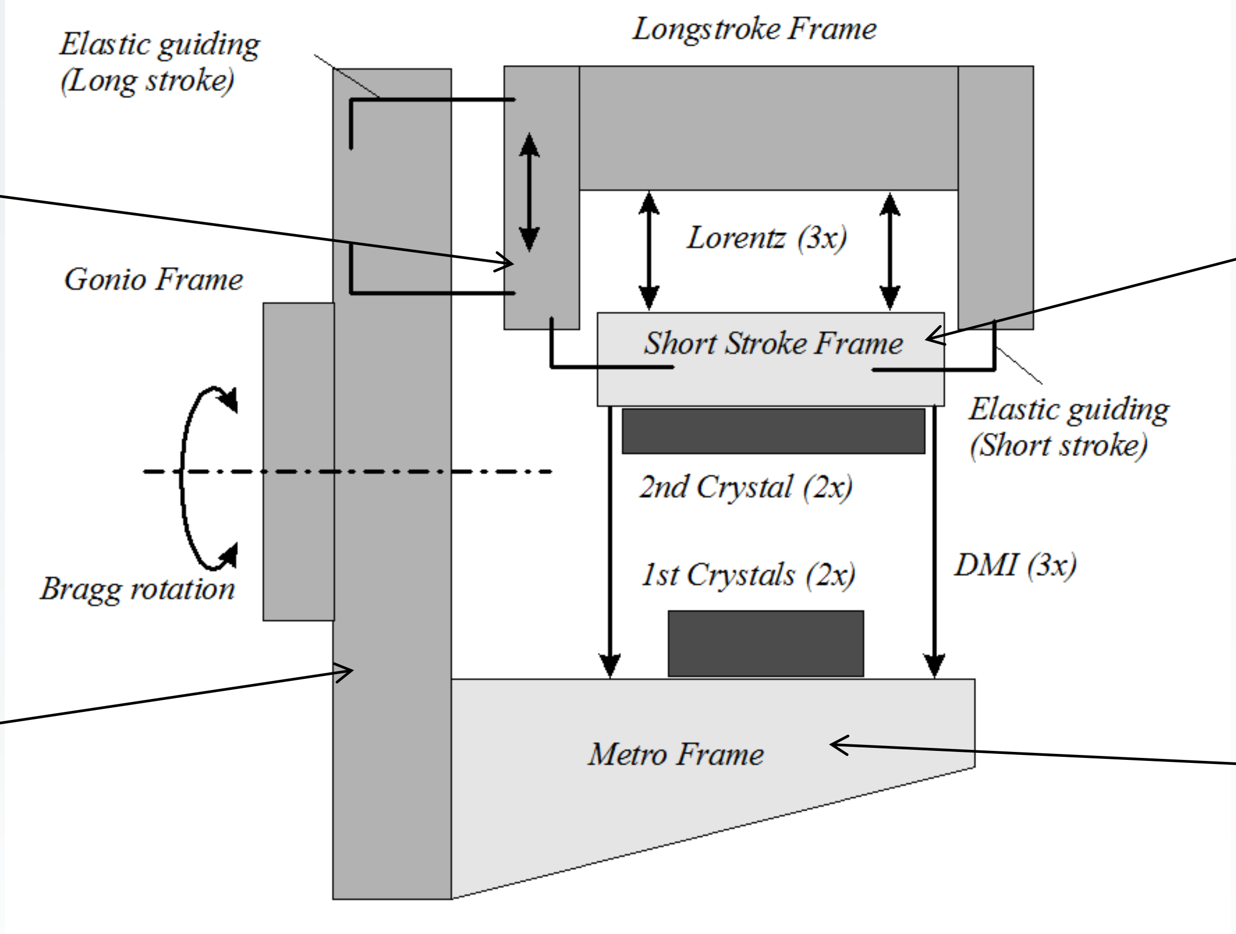
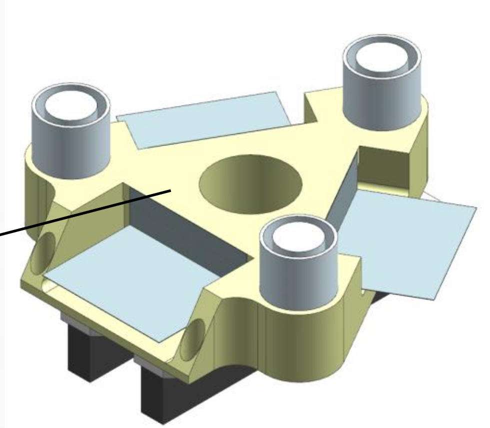
Active position control of 2^{nd} to 1^{st} crystal based on 3xDMI feedback

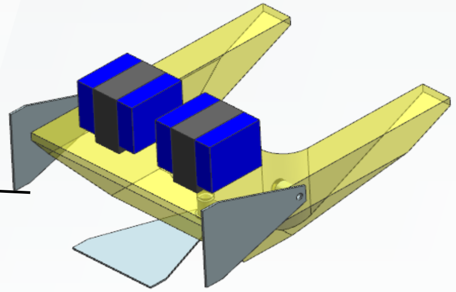






Lorentz actuation





Metrology loop, Long-Stroke and Short-Storke

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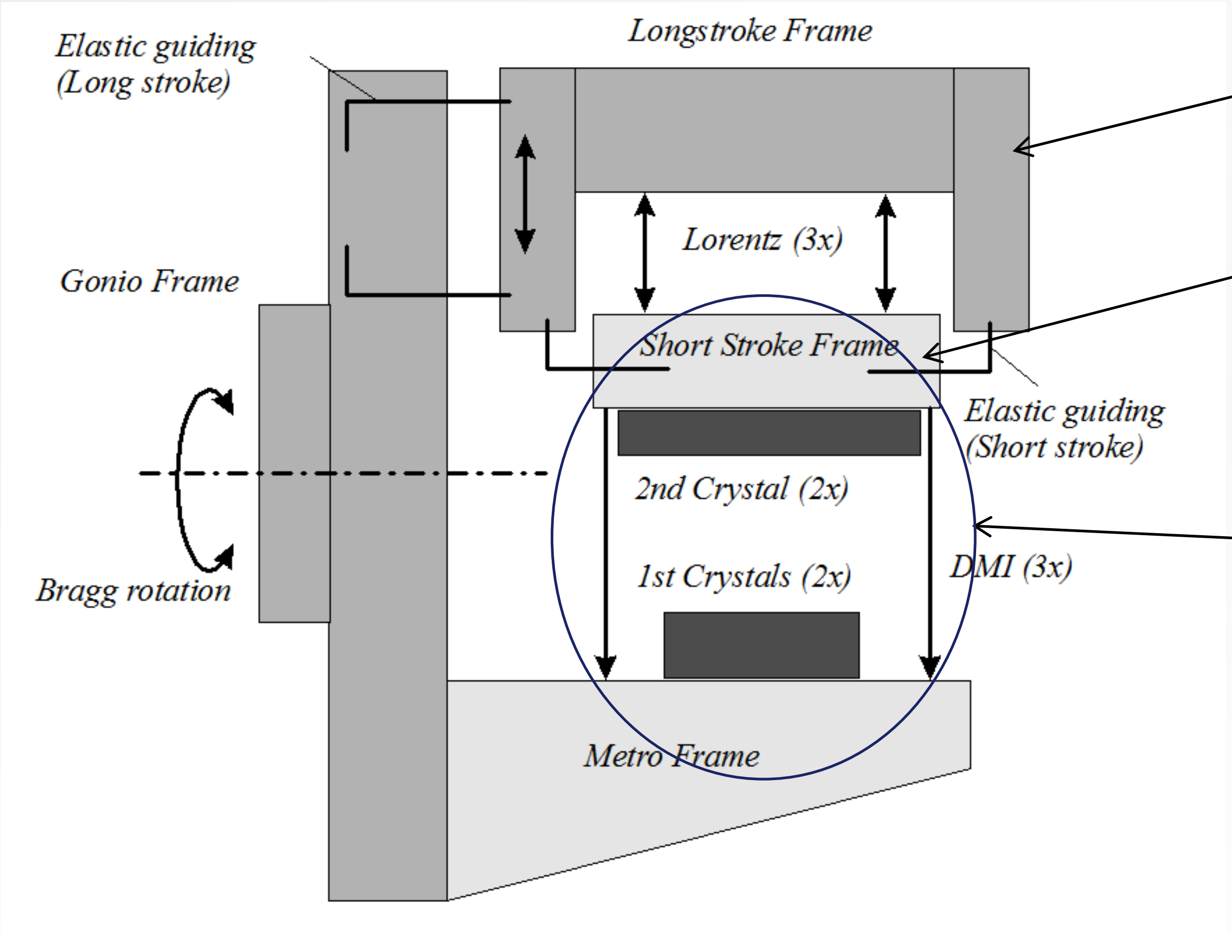

Long stroke (um level)

Short stroke (nm level)

Short metrology loop enabling high stability

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Dynamic Architecture

Issues in backward path dynamics

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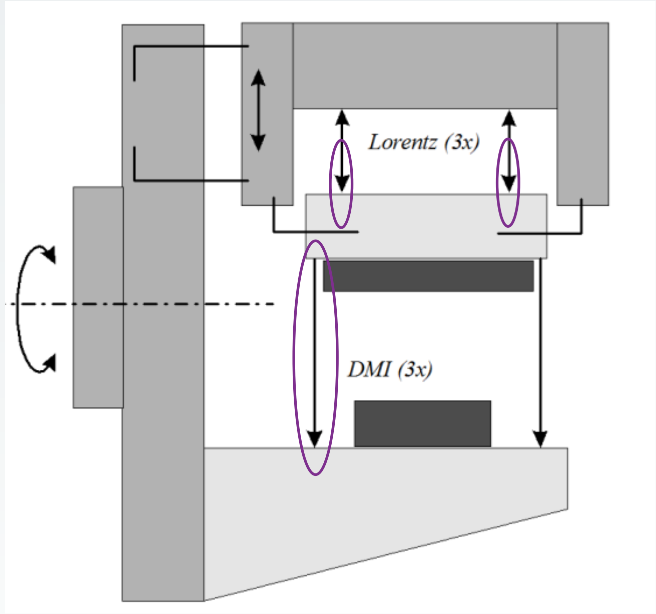
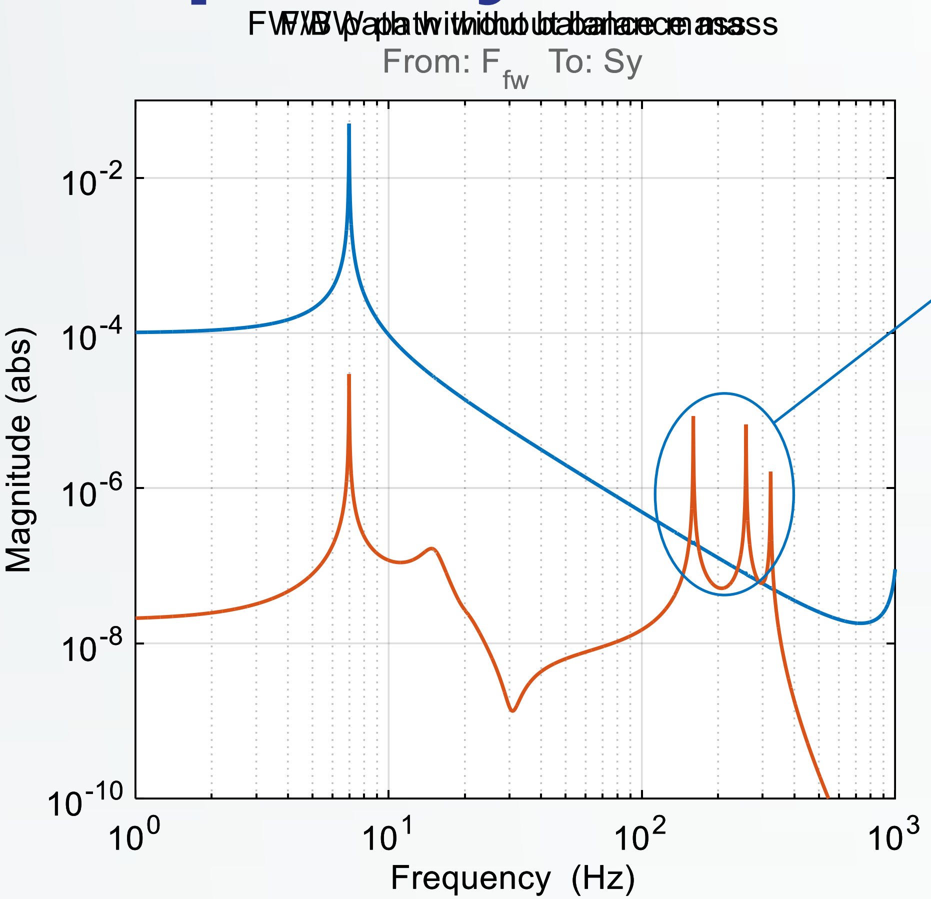
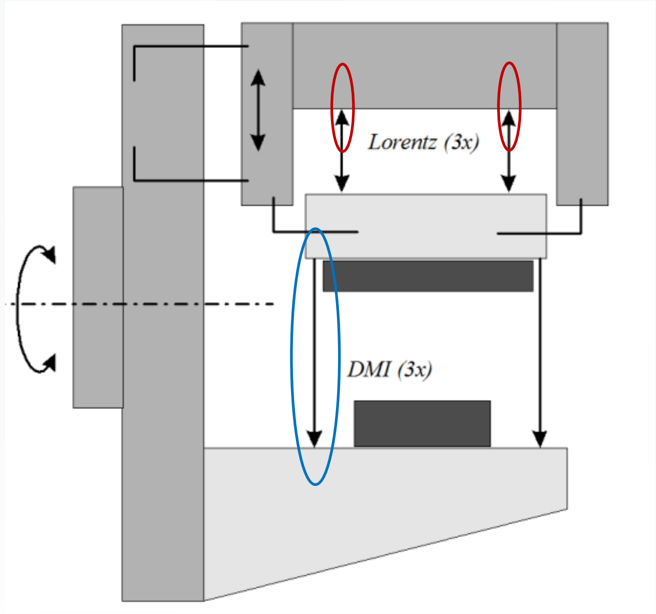
Forward path





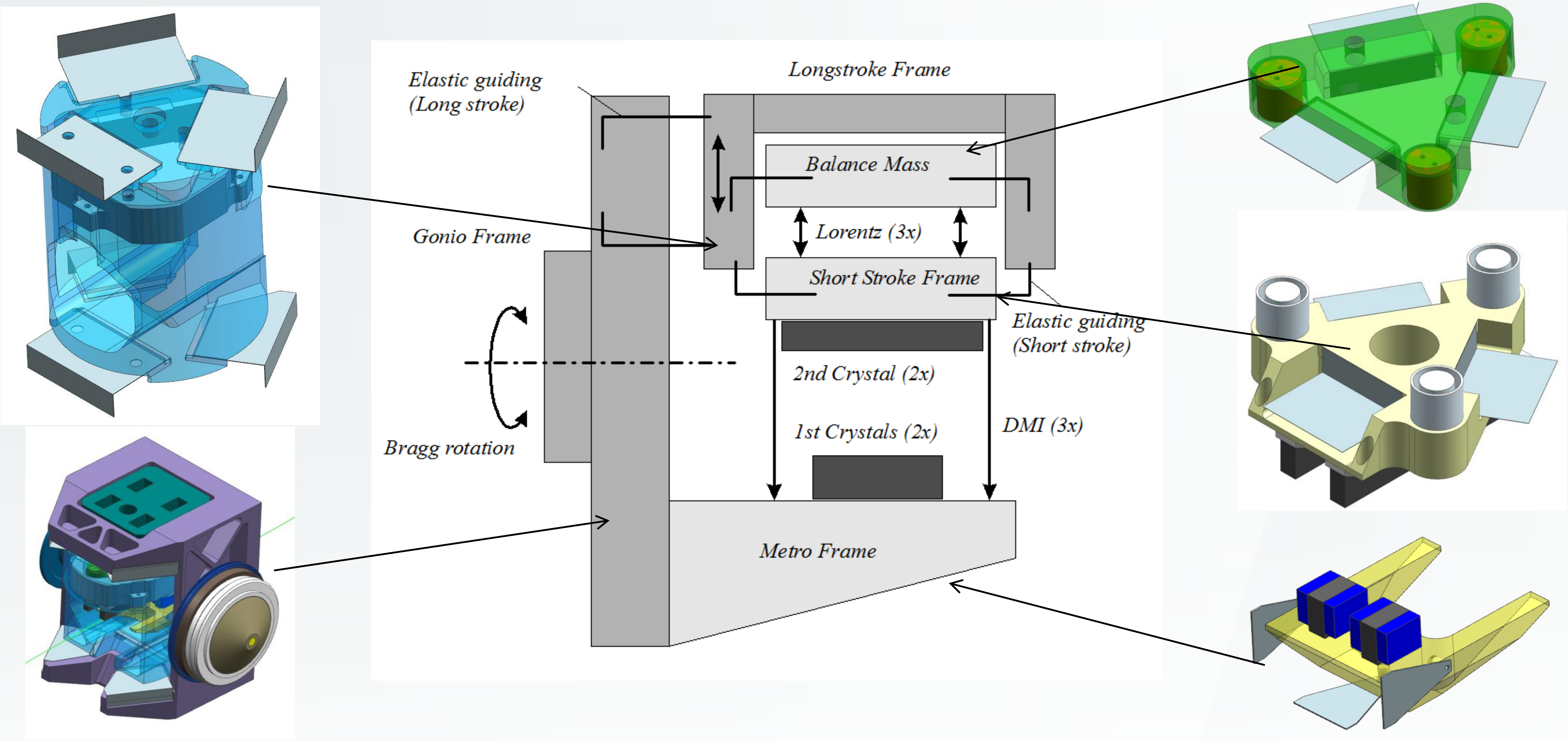
Frame dynamics excited in backward-path

Backward path

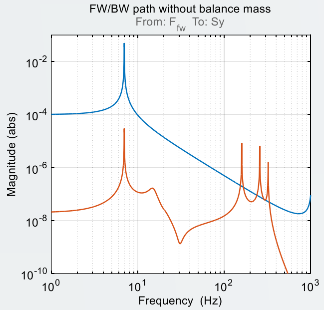


System dynamics: combination of forward- and backward-path

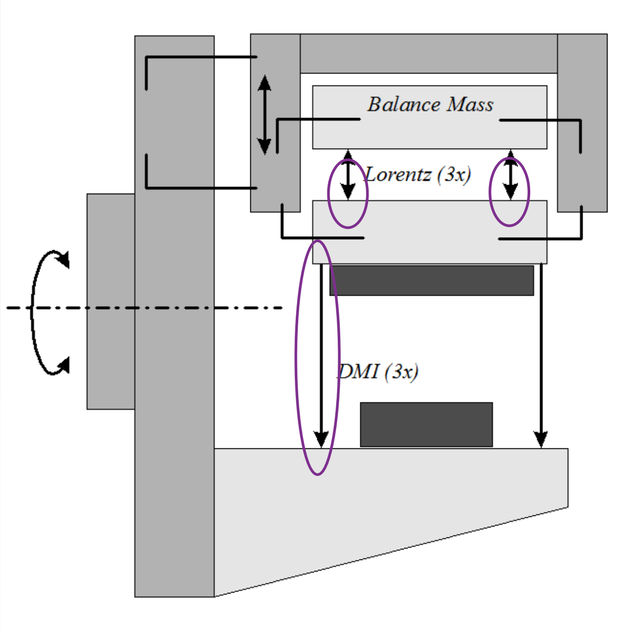
Issues in backward path dynamics: Balance Mass

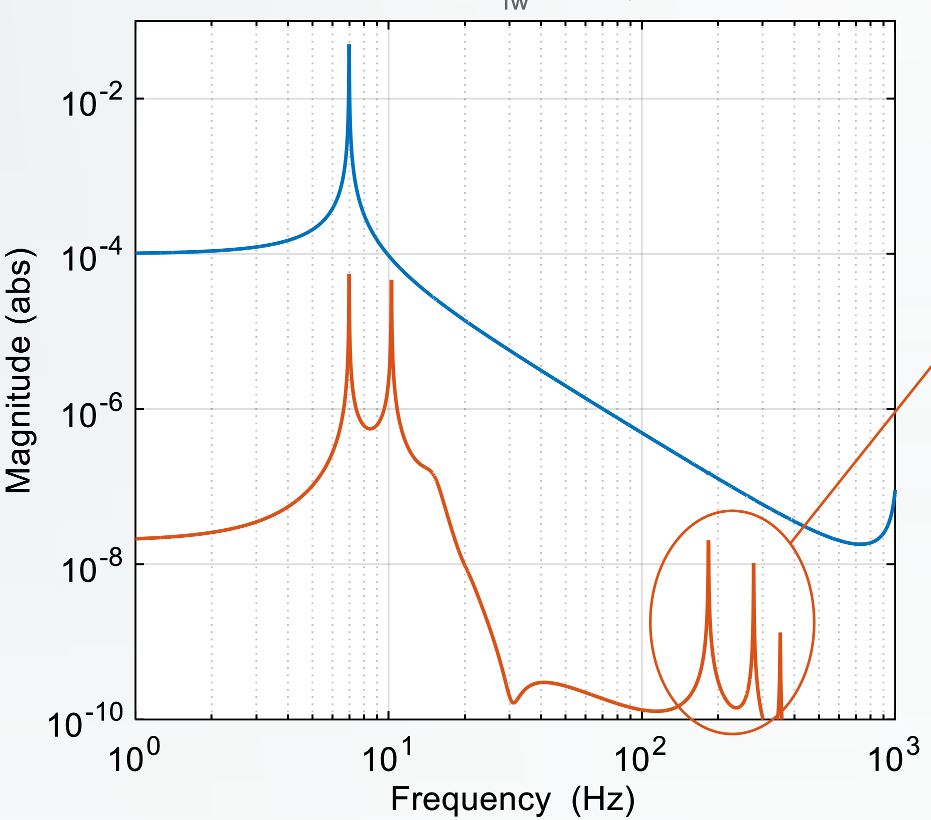


Balance mass: decoupling at 10 Hz



Forward path

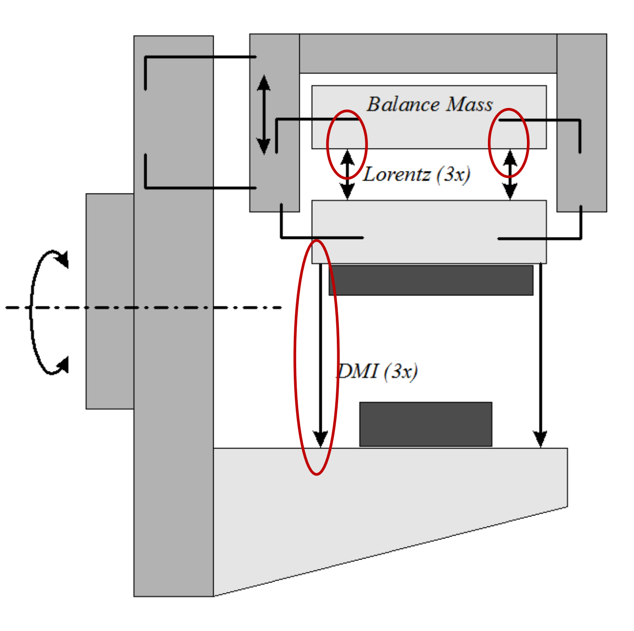




System dynamics: combination of forward- and backward-path

Frame dynamics excitation reduced by balance mass.

Backward path



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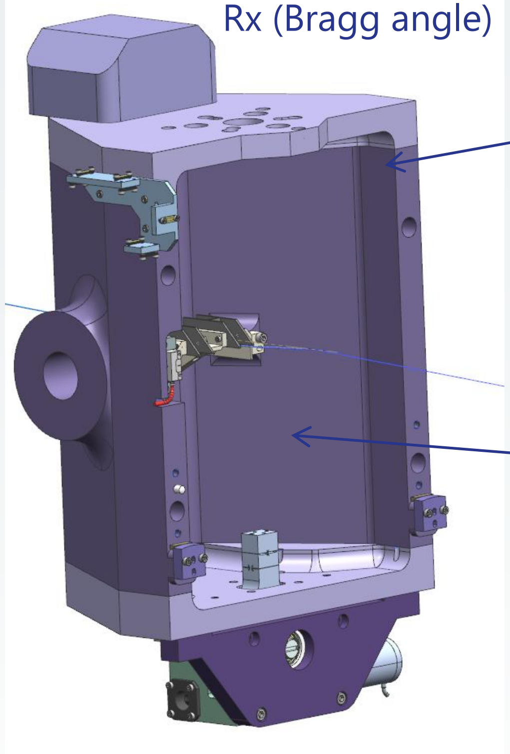
Mechanical layout

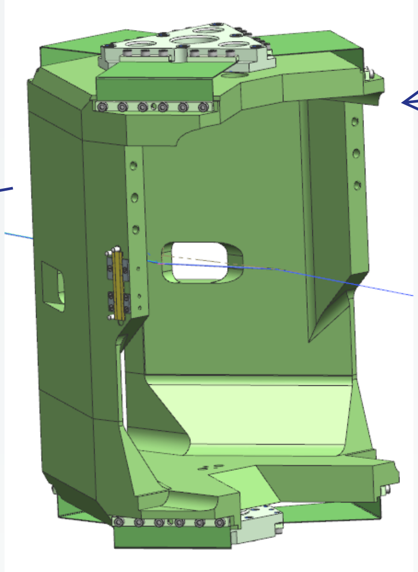
Design for assembly and manufacturability:

- Modular assembly
- Alignement of submodules
- Robustness/cable routing

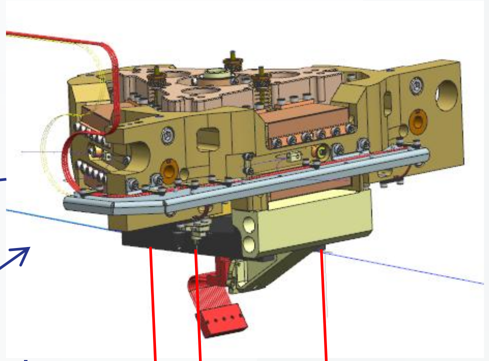
Gonio Frame
Rx (Bragg angle)



LOS Frame
Y (Large Crystal to Crystal gap)



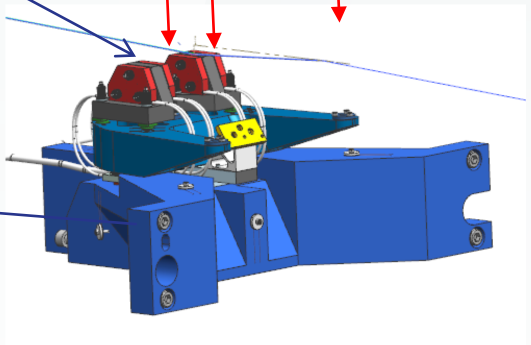
SHS module
Y,Rx,Ry
(fine Crystal to Crystal adjustment)



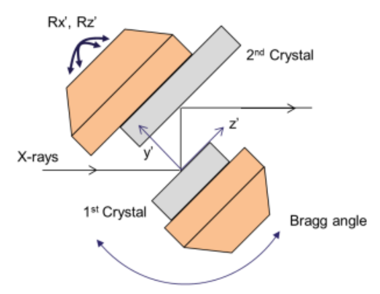
2nd Crystal

DMI beams (3x)

1st Crystal

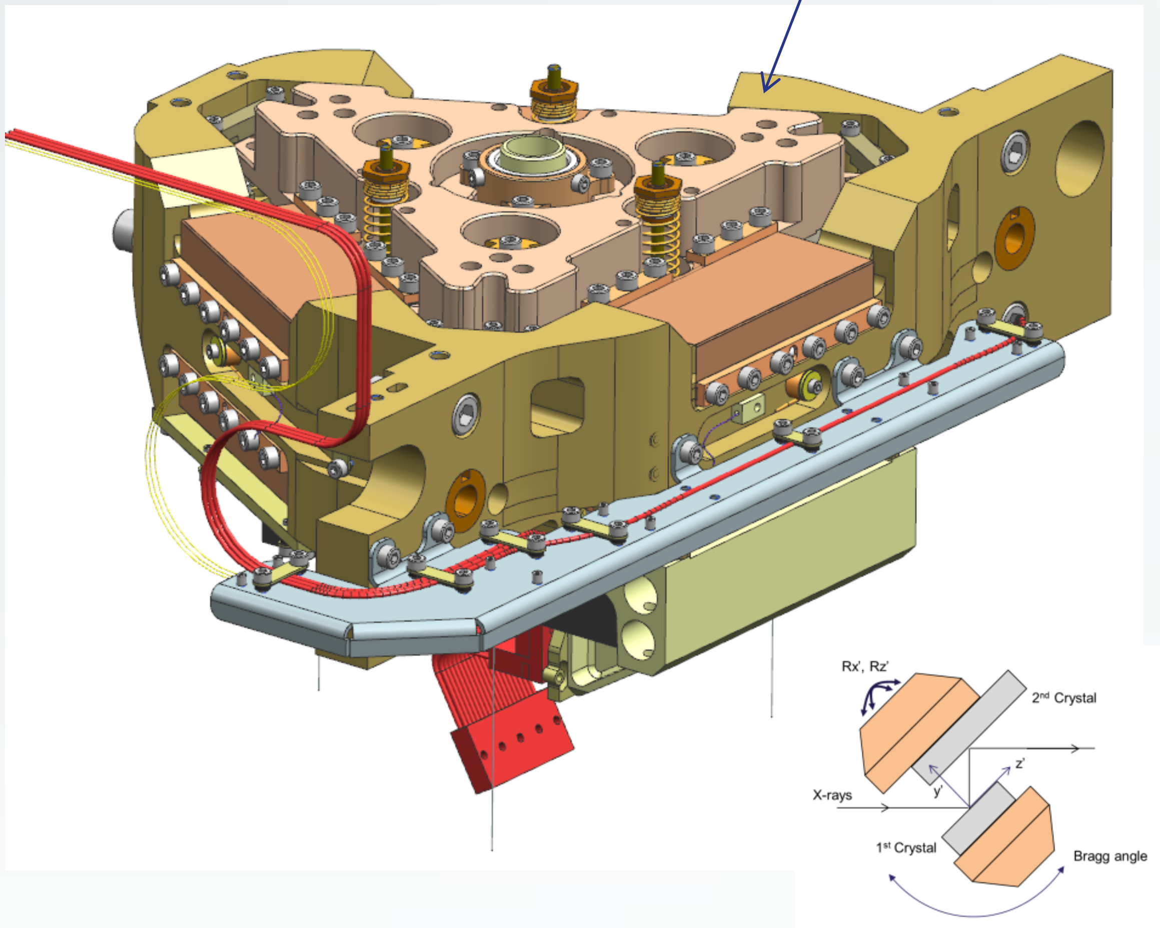


MEF1 Module
Fixed to Gonio frame, Rx rotation



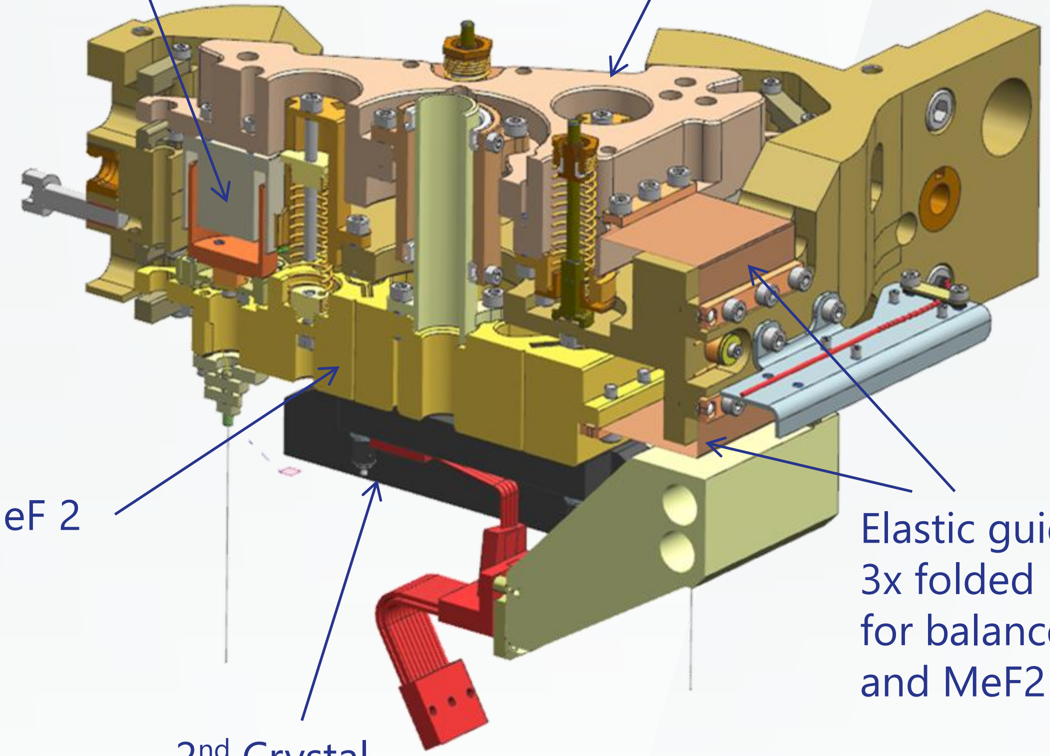
Short Stroke Module

Short Stroke support frame



Lorentz actuators (3x)

Balance mass

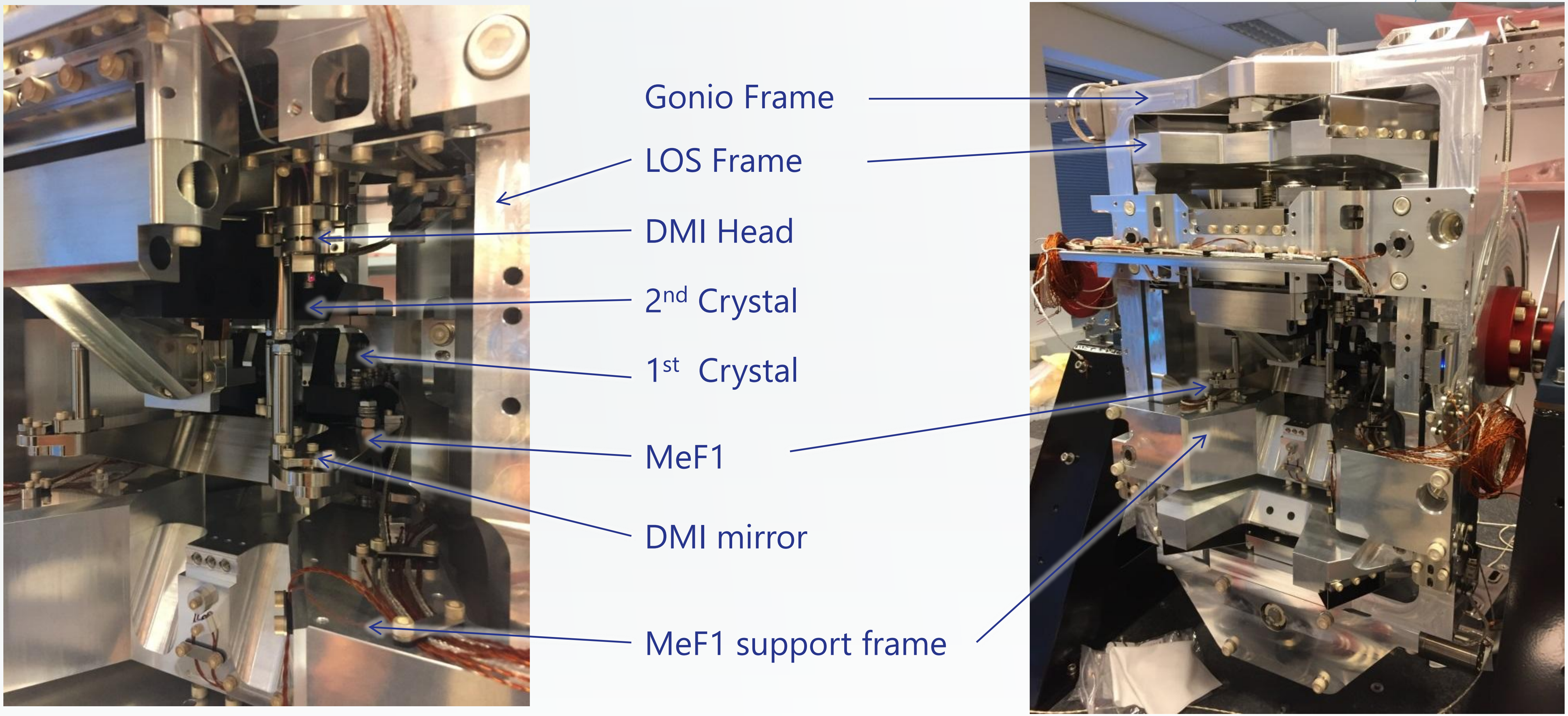


MeF 2

2nd Crystal

Elastic guiding X,Z,Ry:
3x folded leaf springs
for balance mass
and MeF2

System at MI-P under servo control



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Thank you for your attention

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