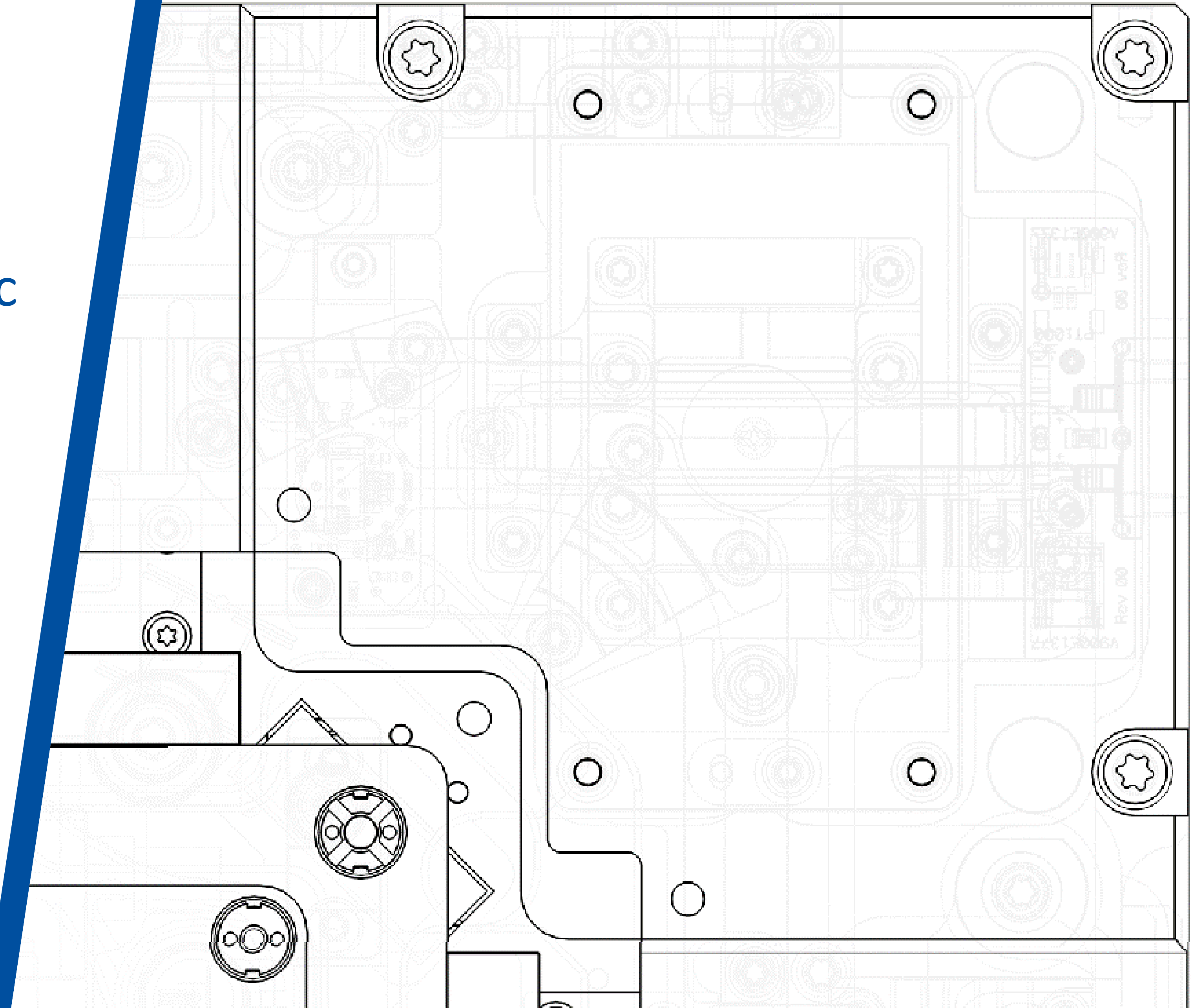
PHYSIK INSTRUMENTE

Electromagnetic levitation for atomic resolution positioning



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16.11.2023

Motivation

Looking back at 2022…

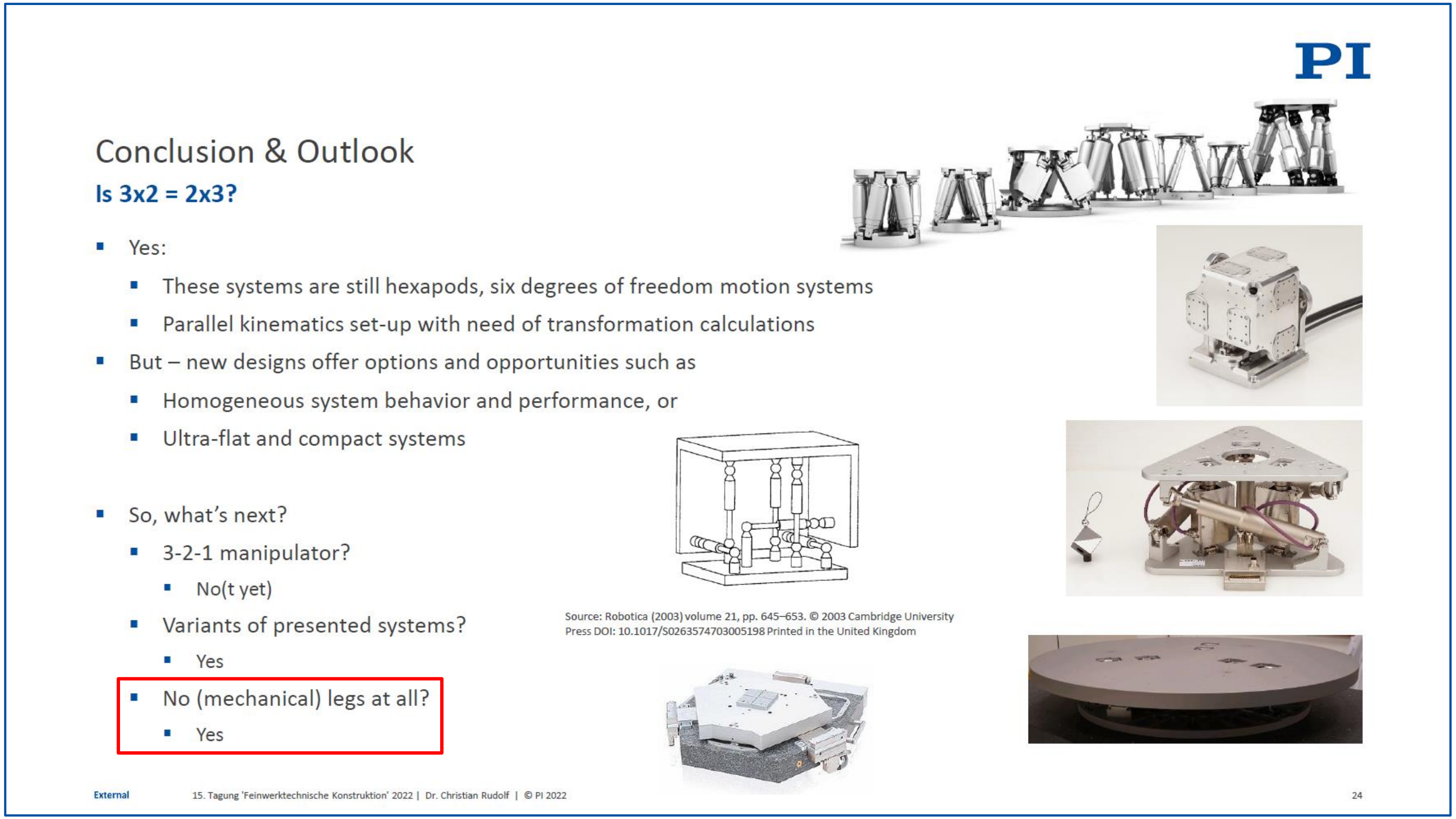


Image reference: [1]

Why magnetic levitation (MagLev)?

Eliminating the restrictions of mechanical guiding elements and couplings

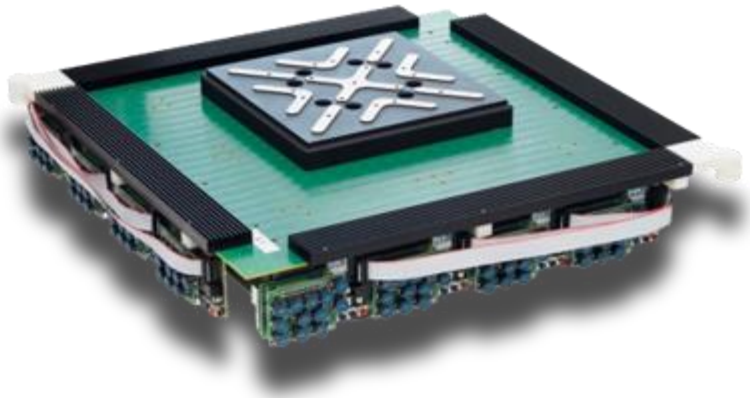
- Full control in six degrees of freedom
- Completely frictionless guiding – no rolling elements, no lubrication, no air flow
- No stick-slip effects
- No abrasion or wear, no particle generation
- Vacuum compatibility

MagLev technology has the potential to achieve ultra-high precision in dynamic and continuous (maintenance free) operation!

Magnetic levitation at PI

PIMag6D

- Planar stage with six actuation coils
- 100 mm x 100 mm x 0,1 mm
- Up to 100 mm/s
- Resolution < 10 nm



Mag6D

- Planar stage with 144 PCB-integrated coils
- Decentralized drive and sensor modules
- 120 mm x 120 mm x 1.6 mm

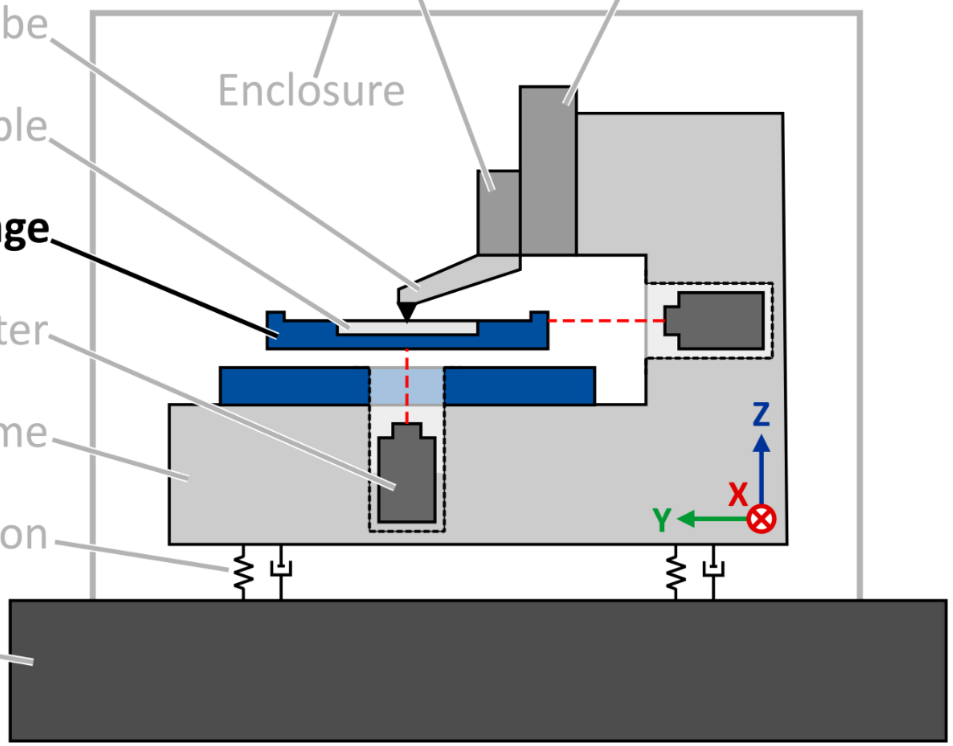
MagLin 6D

- Linear stage with 6 DoF micro-positioning capability
- Integrated electronics
- Powerless levitation
- 45 mm x 0.5 mm x 0.5 mm
- Resolution < 5 nm

Background and motivation for the new development

Project overview for MetExSPM

Metrological **Ex**press **S**canning **P**robe **M**icroscope



The task at hand…

… and specification requirements

Planar motion stage for sample positioning and scanning

<u>Motion range</u>

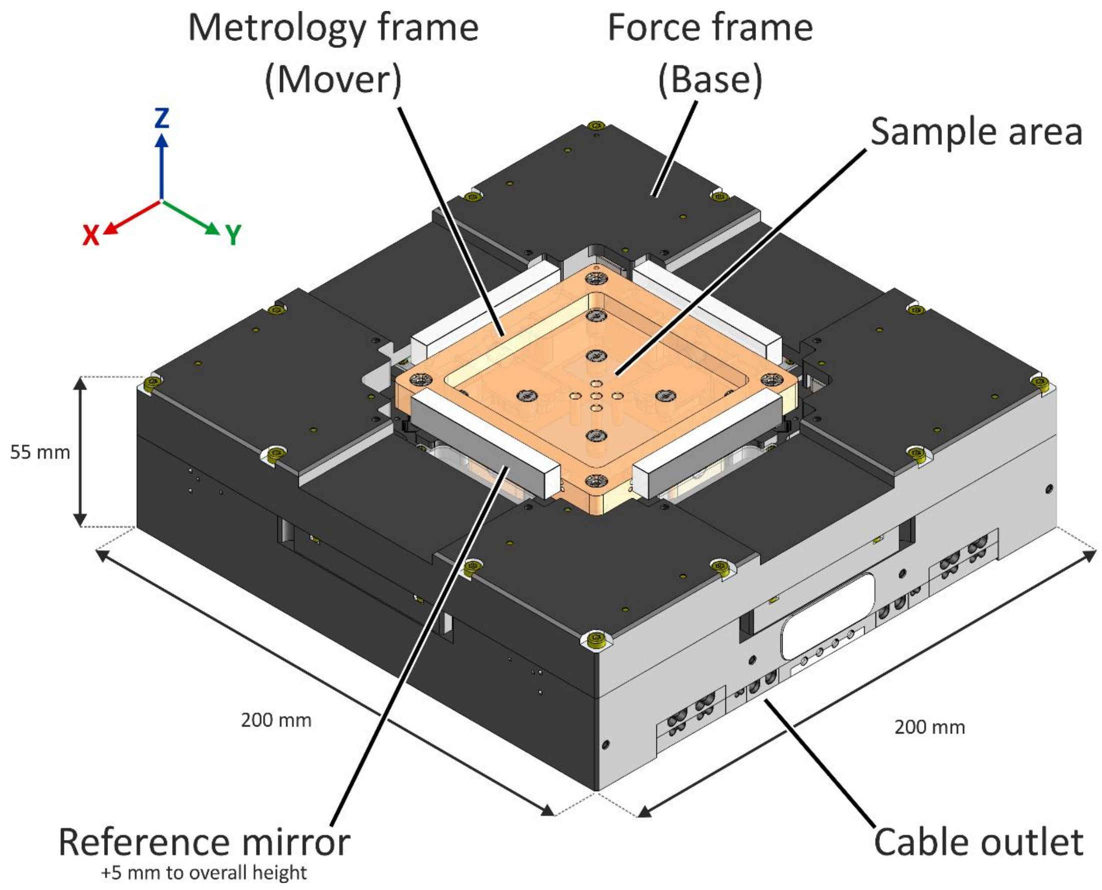
- Motion range in XY plane = 12.7 mm x 12.7 mm
- Motion in Z = ±0.25 mm
- Rotary motion (roll, pitch and yaw) = ±0.25°

<u>Dynamics</u>

- Motion velocity (XY plane) = 10 mm/s
- Acceleration (XY plane) = 1 m/s²
- Bandwidth (1 µm amplitude) ≈ 100 Hz

<u>Precision</u>

- Position resolution < 0.1 nm



The task at hand…

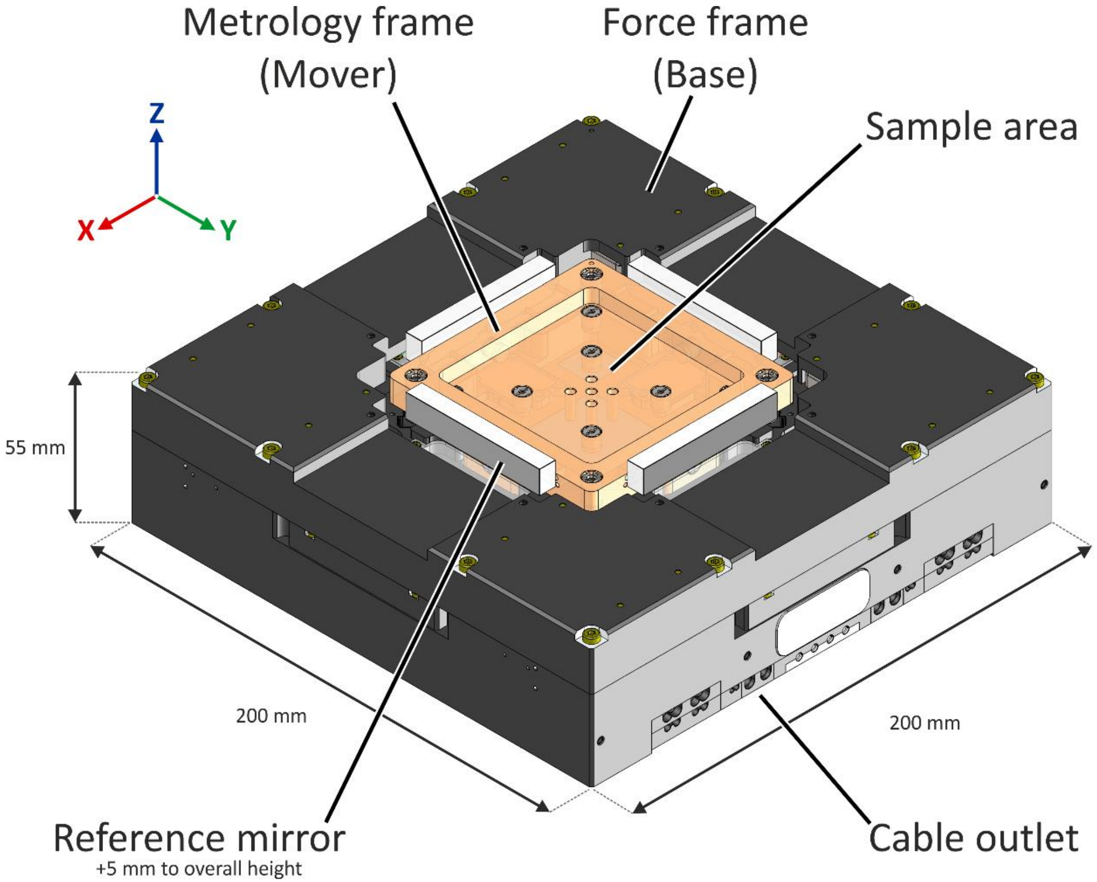
… and key challenges

Sensor system

- Sub-nanometer resolution sensors for 6 DoF measurements
- Precision and accuracy with respect to planar travel range
- Robustness against distance changes and rotation

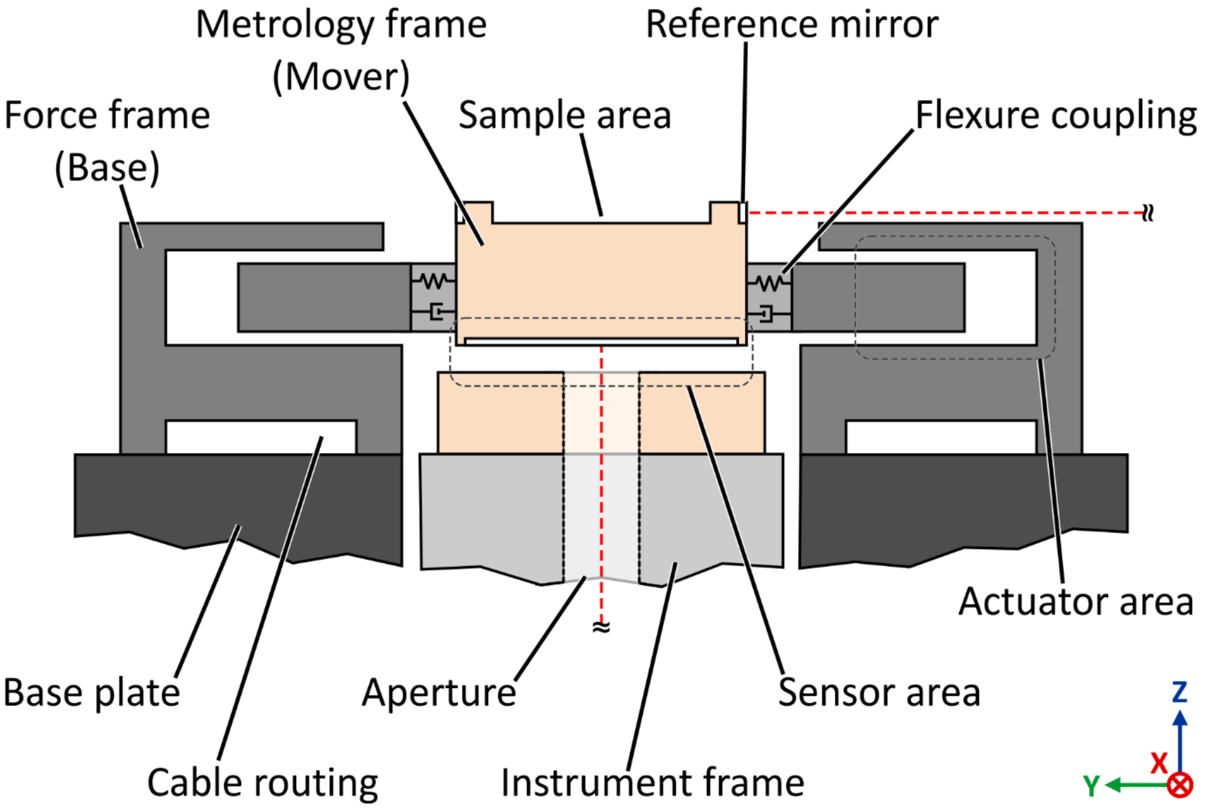
Thermal effects and long-term stability

- Management of losses from active components (actuators and sensors)
- Powerless levitation
- Separation of force and metrology loops
- Ultra-low expansion materials (integration and interface design)



Architecture of the MagLev stage

- Decoupled force and metrology loops
- Metrology frame made from ultra-low expansion material
- Integrated mirrors for reference metrology
- Thermo-mechanical decoupling for mover frames



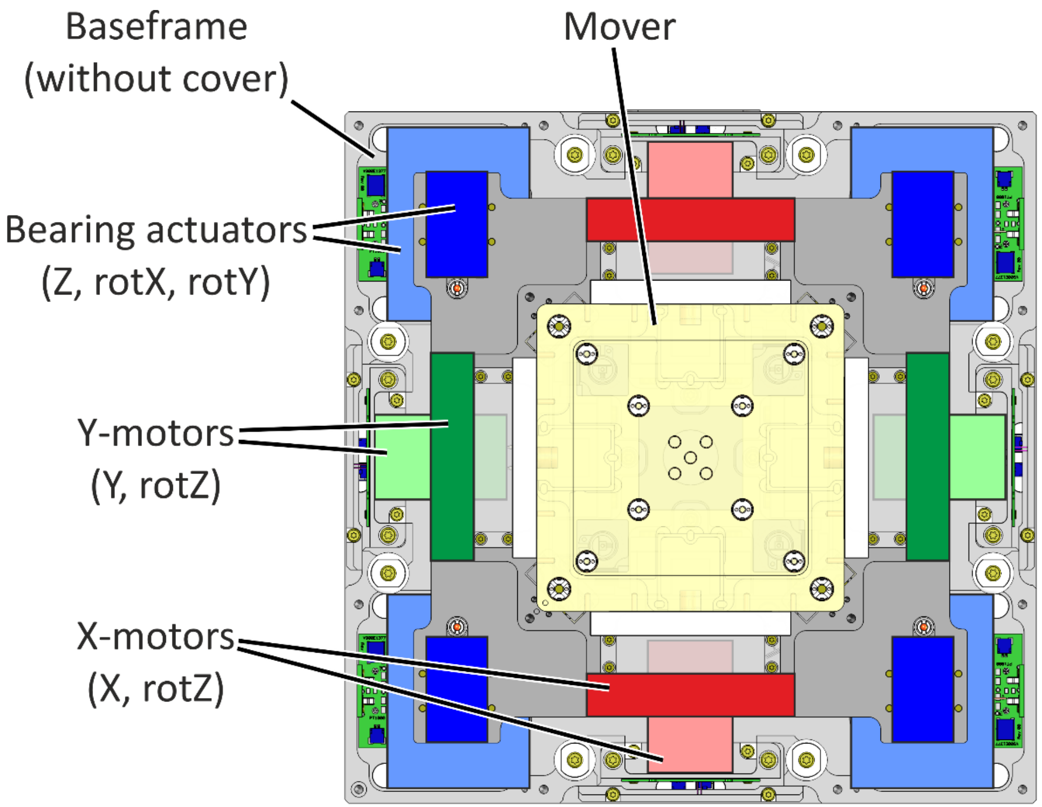
Actuator configuration

4x Bearing actuators for (near) powerless levitation (Z, rotX, rotY)

- Reluctance force actuators with integrated gravity compensation (for a mover mass of 1 kg plus a load of 100 g)
- Consistent points of force actuation on the mover
- Force constant k_i = 2.45 N/A
- Motor constant k_M = 2.21 N/√W

4x Linear motors for long-stroke planar motion (X, Y, rotZ)

- Over-sized Lorentz force actuators for minimized losses
- Optimized for minimum cross-talk with Z-actuators
- Force constant k_i = 1.11 N/A
- Motor constant k_M = 1.52 N/√W



*Lighter components (active) fixed to frame, darker components (passive) fixed to mover!

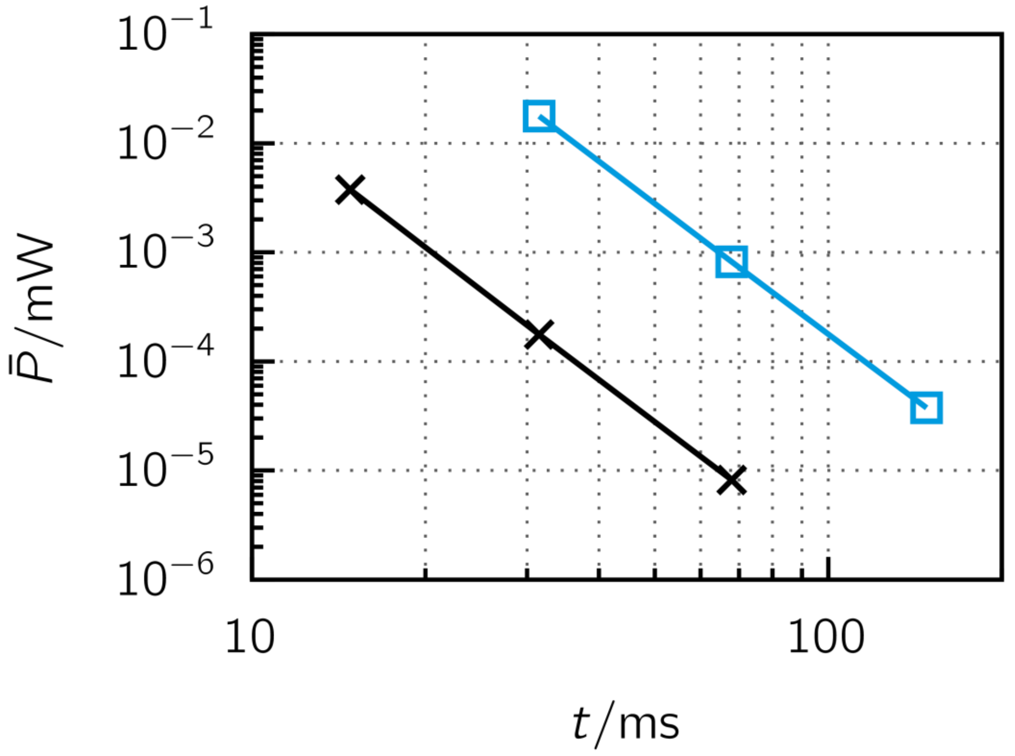
Thermal performance of XY-motors

Simulation of exemplary step-settle-motion for raster scanning application

- Maximum jerk determines step time for equal step size
- Step size: **1 µm** and **100 nm**
- Three different jerk values: 0.1 m/s³, 1 m/s³ and 10 m/s³

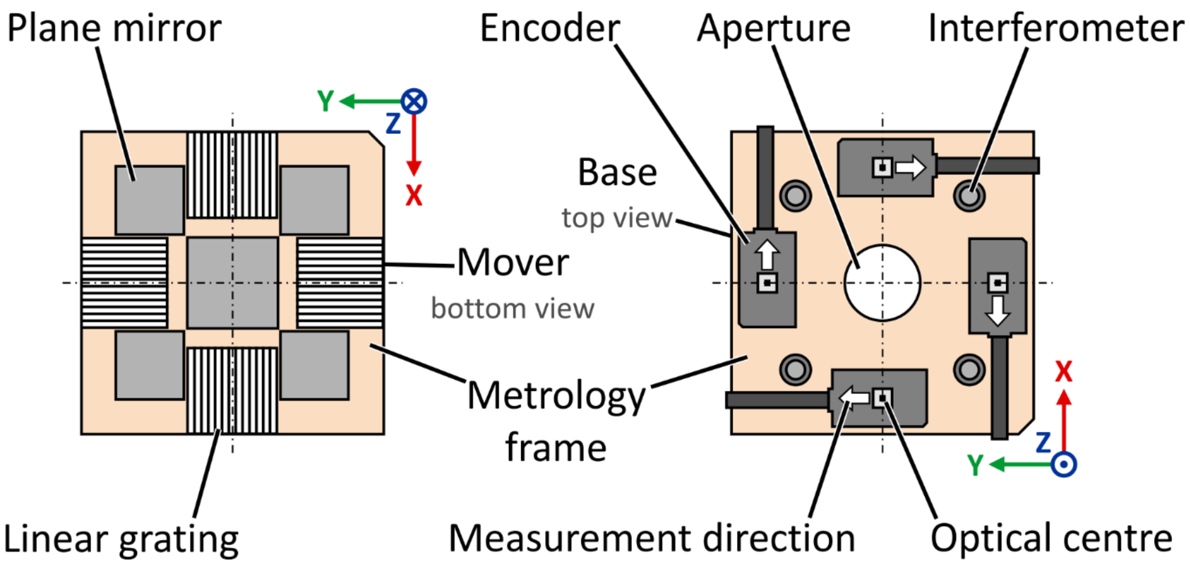
Findings

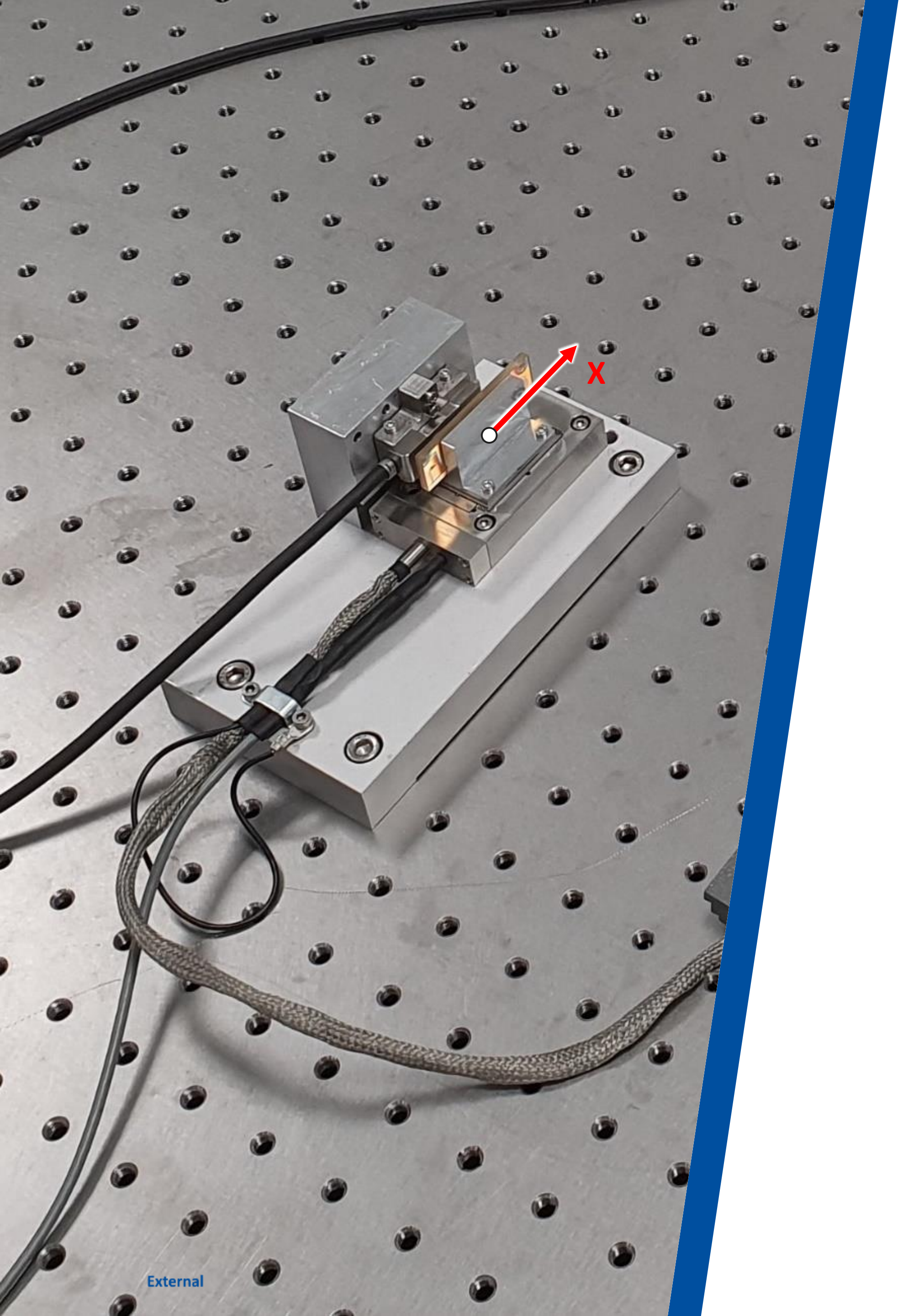
- The average power demand during a step is < 20 µW
- Considering the settling and measurement times, average power during a scan motion is even smaller
- Note that time values on the right only include step times and not the respective settling times



Metrology concept

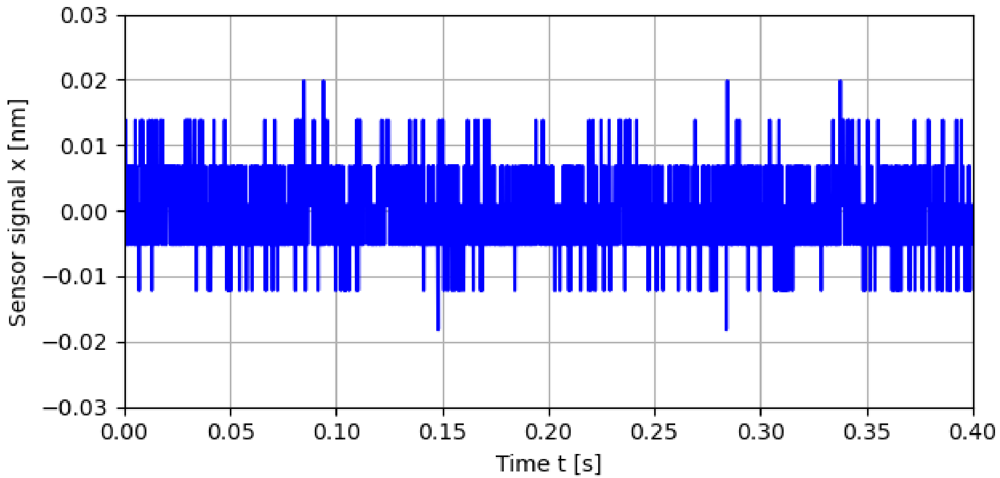
- **Optical encoders** for XY-motion and rotation about Z
- **Interferometers** for Z-motion and tip-tilt (rotation about X and Y)
- Sensor redundancy for improved signal-to-noise ratio per DoF
- Completely passive mover with integrated mirror surfaces and custom linear gratings for planar motion

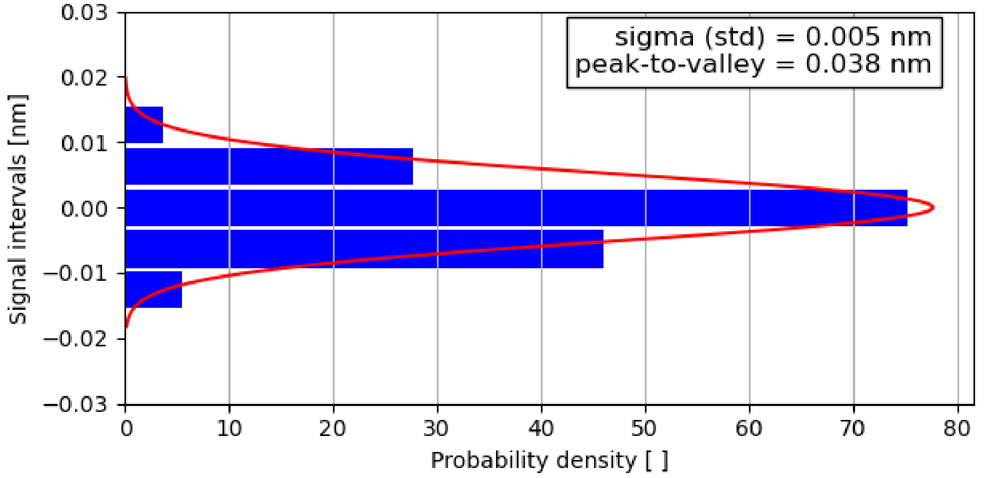


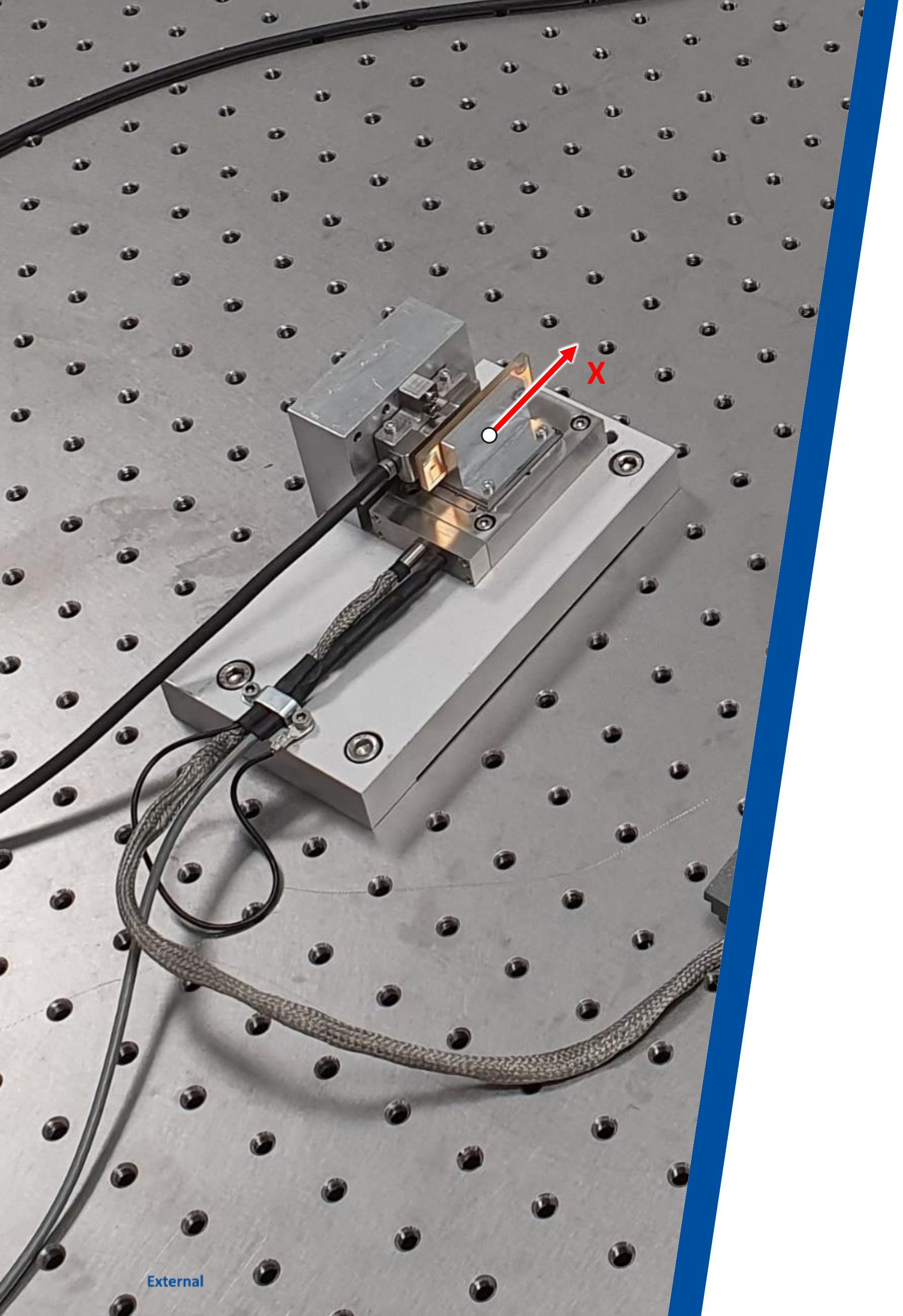


Encoder for X, Y and yaw (rotZ)

Resolution and noise (at 64,000 interpolation and f_s = 10 kHz)



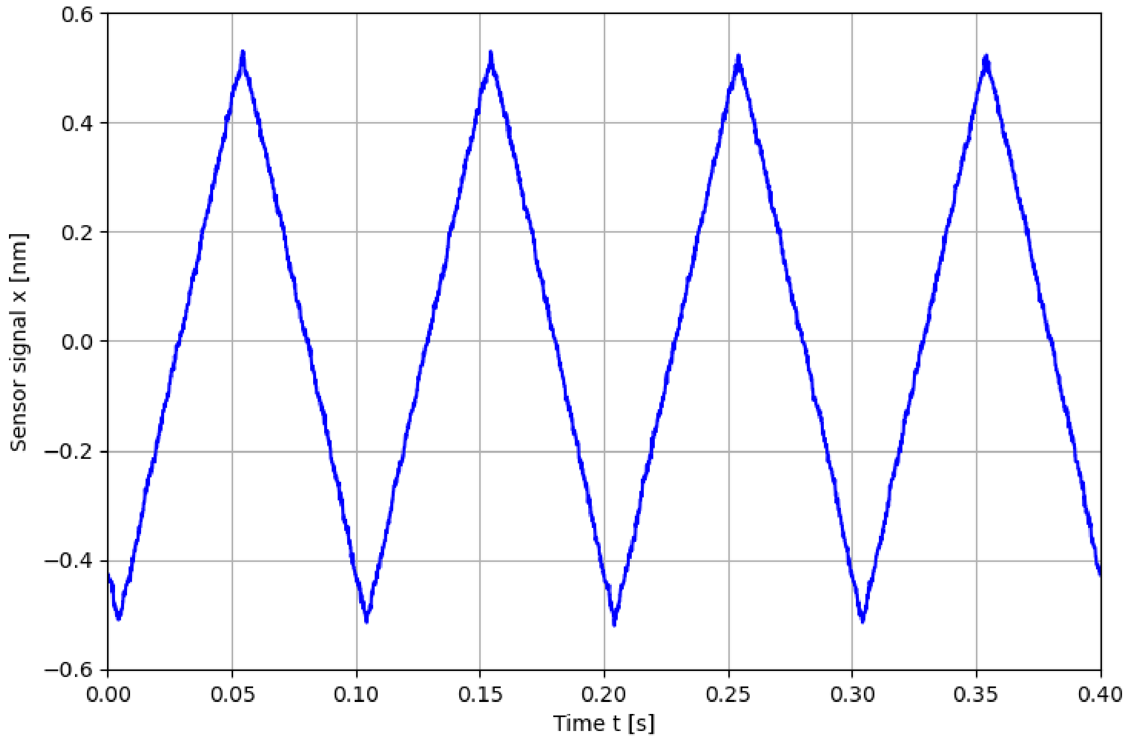


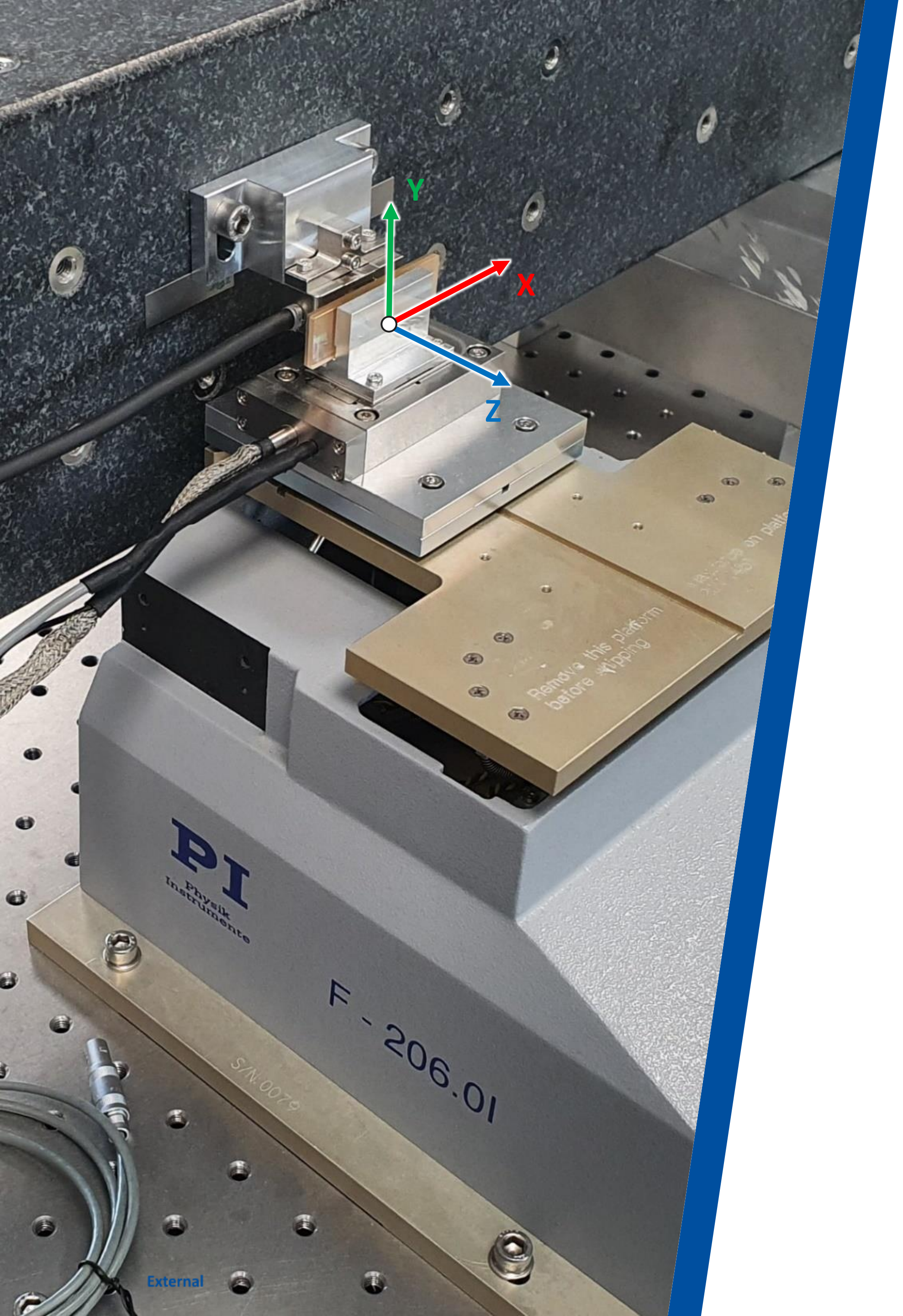


Encoder for X, Y and yaw (rotZ)

Exemplary position measurement

- Raw sine-cosine-signals into interpolator, counts per SPI into C-702 controller (sample rate f_s = 10 kHz, no additional filters or data processing)
- P-752 piezo stage in open-loop mode (voltage ramp with 7 mV at 10 Hz)

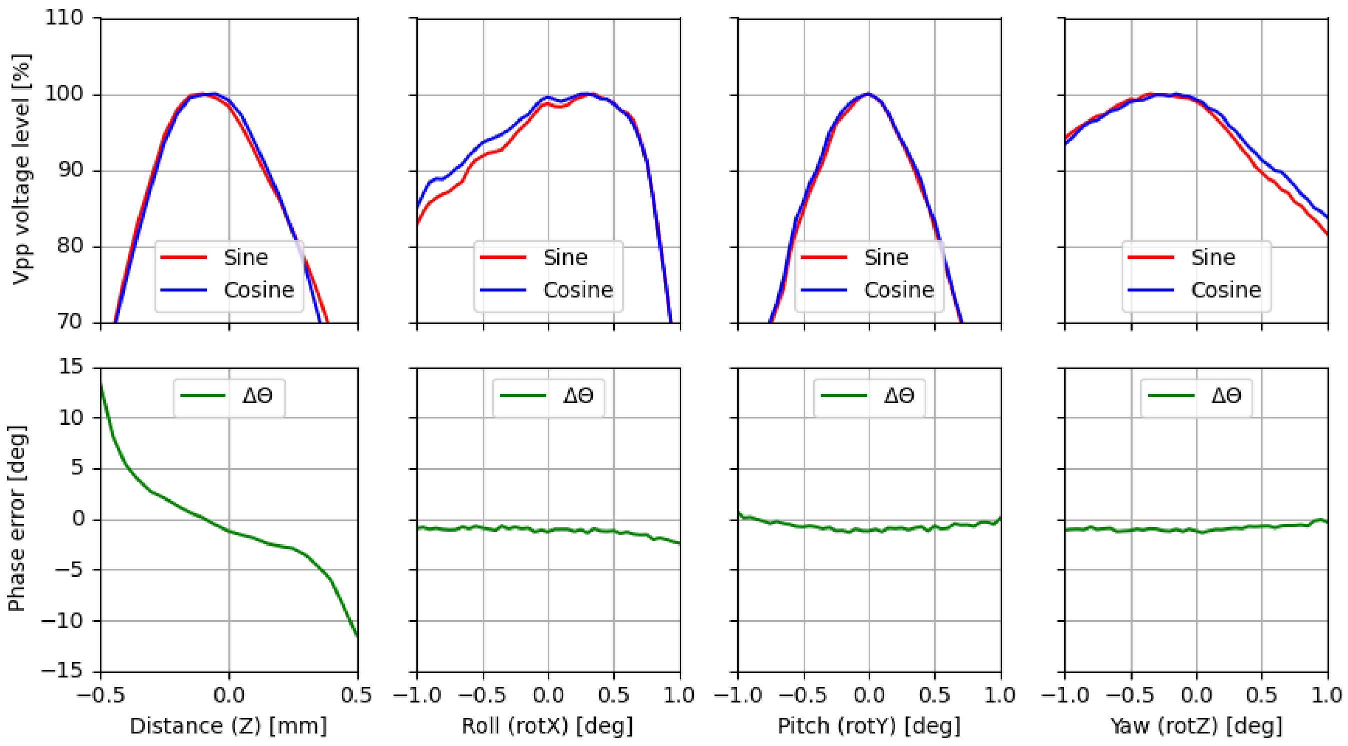




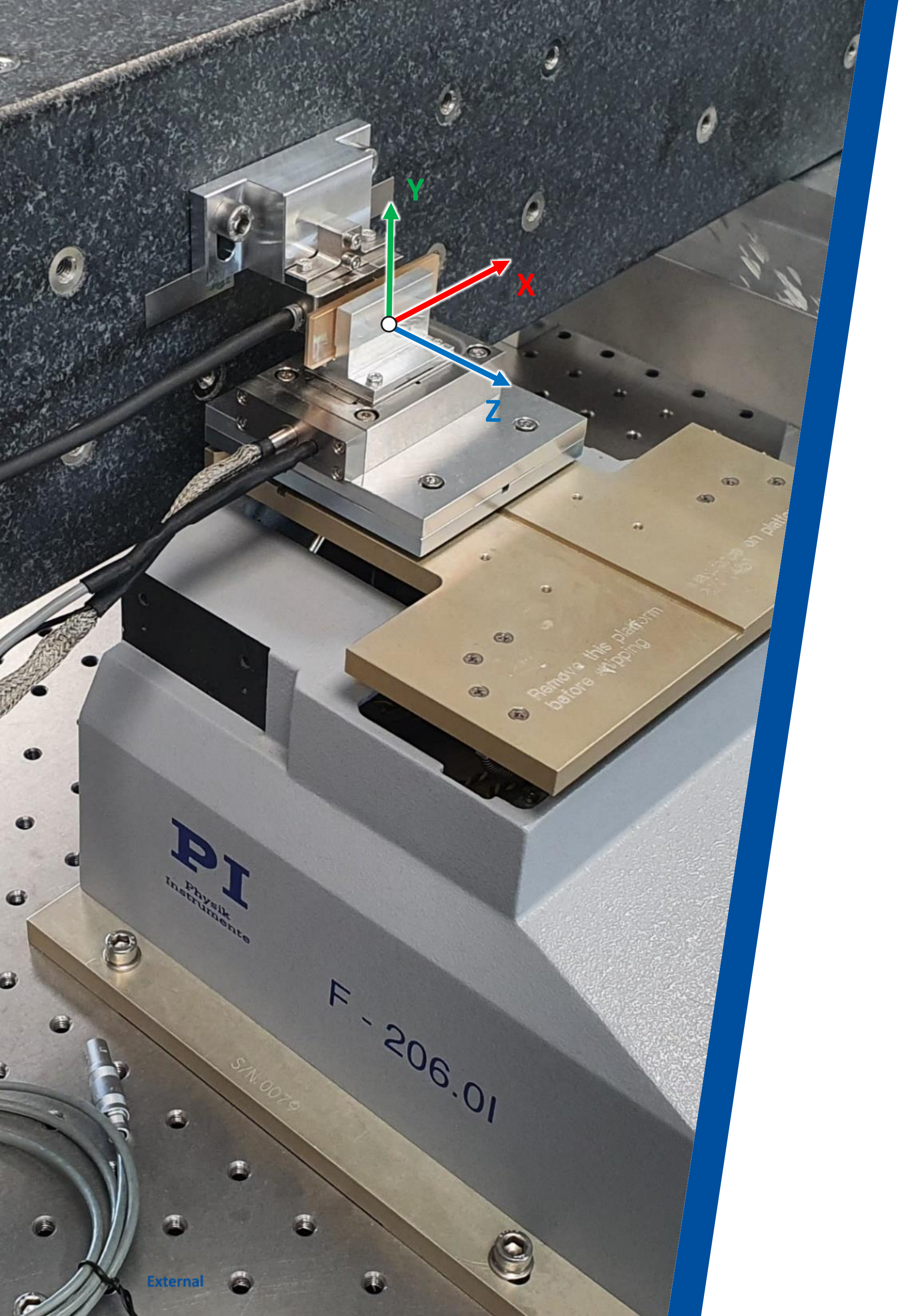
Encoder for X, Y and yaw (rotZ)

Robustness against distance changes and angular misalignment

Sine and cosine levels of the 1 V_{pp} signal for single axis misalignment



External

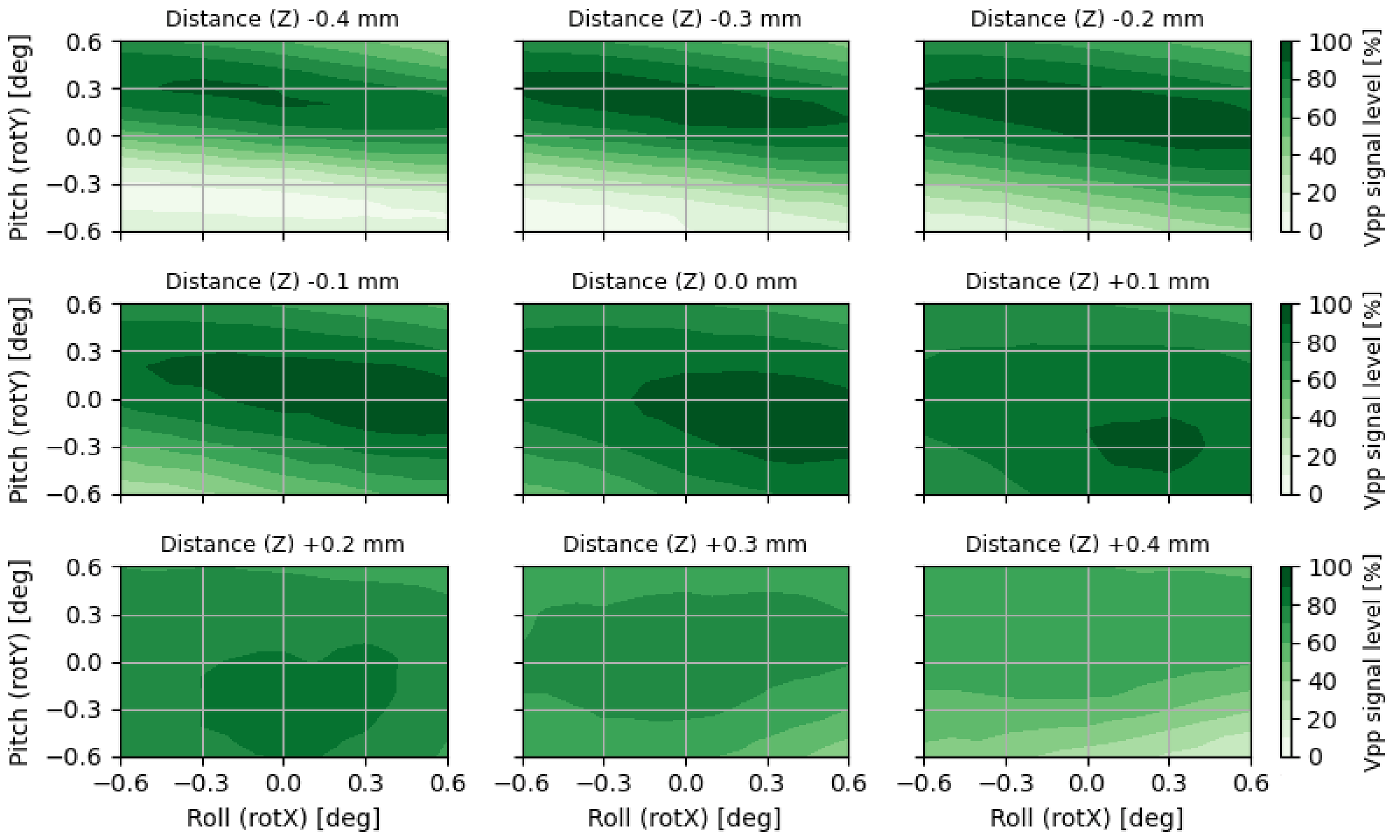


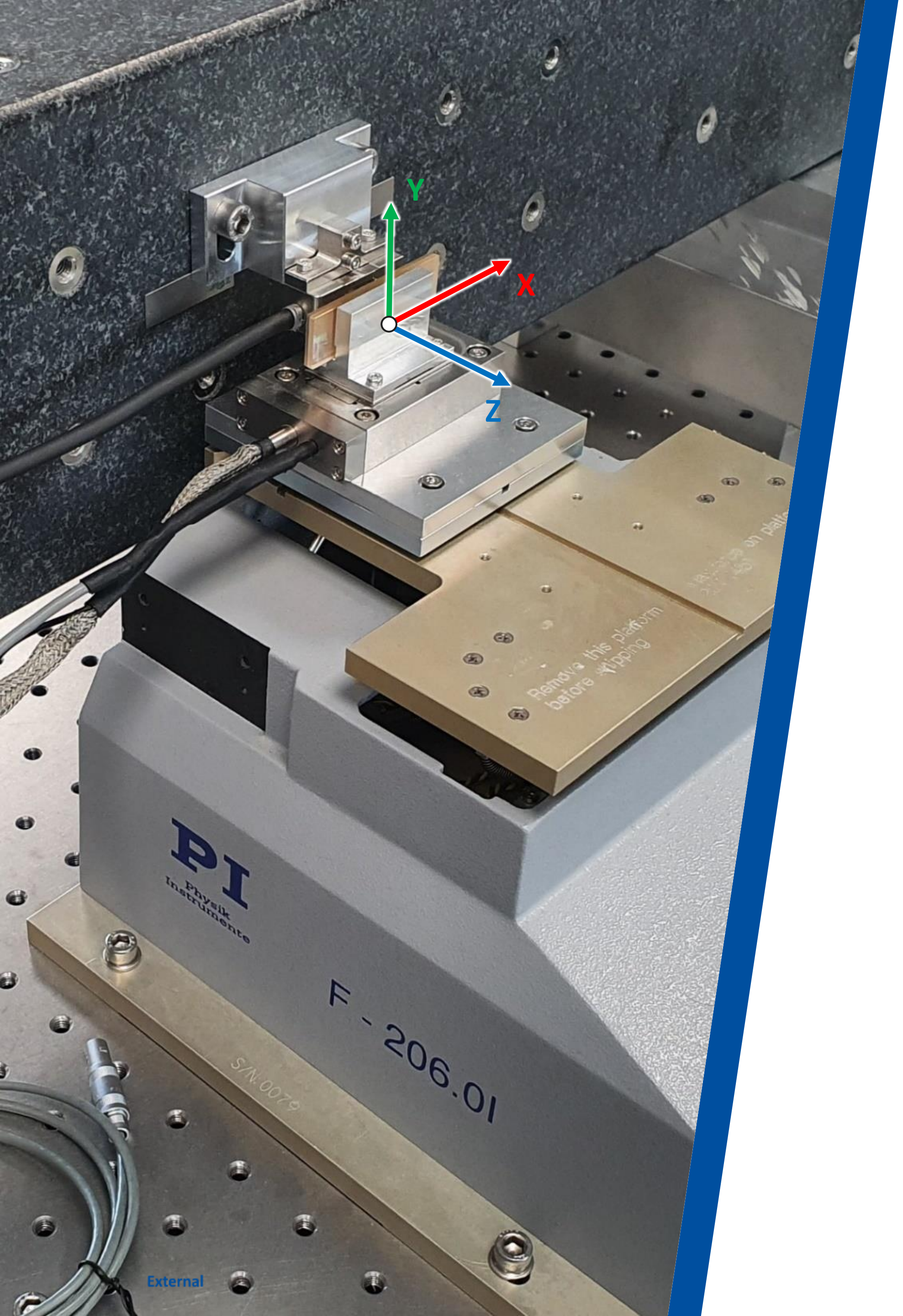
External

Encoder for X, Y and yaw (rotZ)

Robustness against distance changes and angular misalignment

Sine levels of the 1 V_{pp} signal for multi-axis misalignment

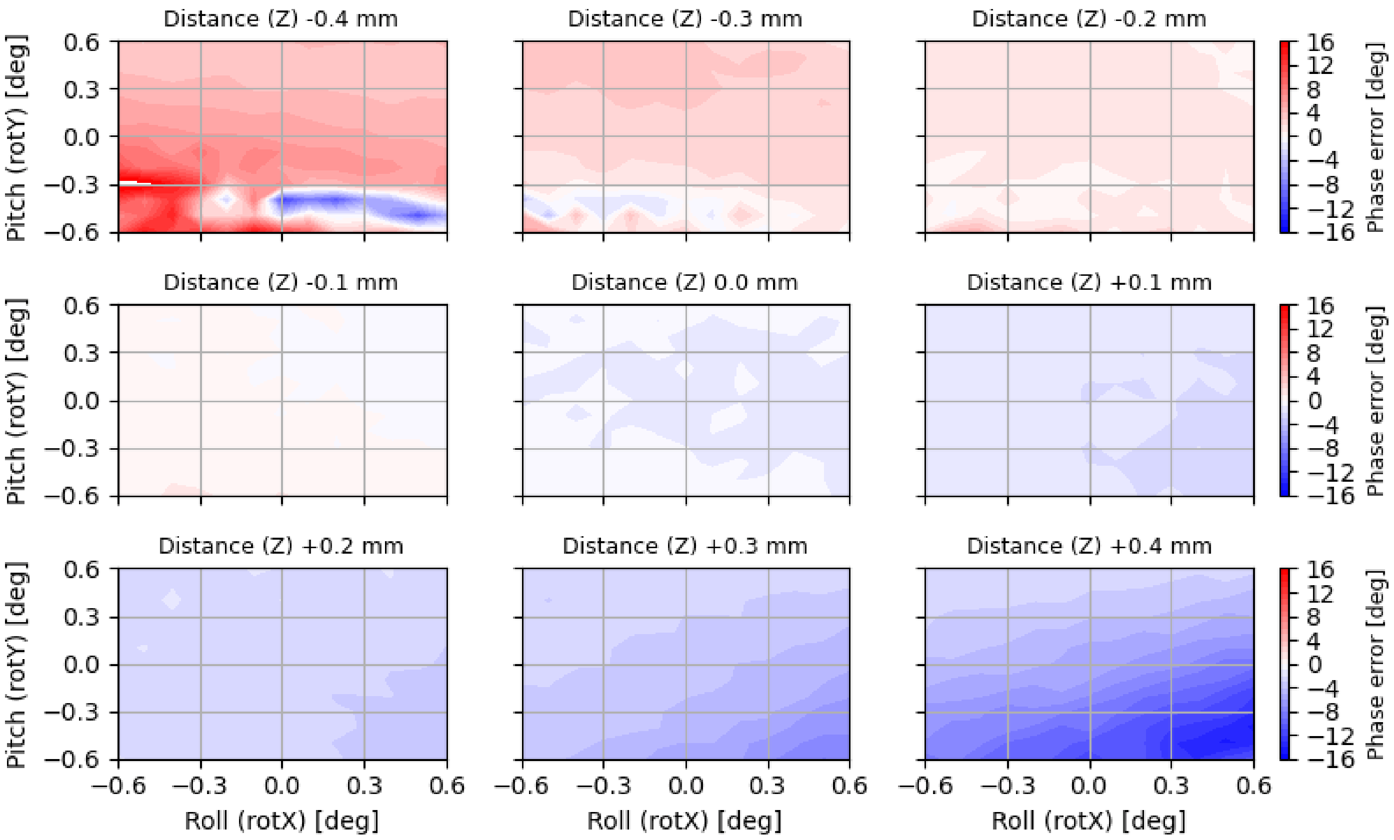




Encoder for X, Y and yaw (rotZ)

Robustness against distance changes and angular misalignment

Resulting phase errors for multi-axis misalignment



External

Integration aspects of ultra-low expansion materials

General issues

Different CTEs of glass and metal components

… in combination with brittle properties of glass and glass-ceramics

Why is this relevant?

- Thermal effects cannot be neglected! Sensors and actuators will generate a certain amount of heat!
- Active cooling would introduce additional disturbances (vibrations)

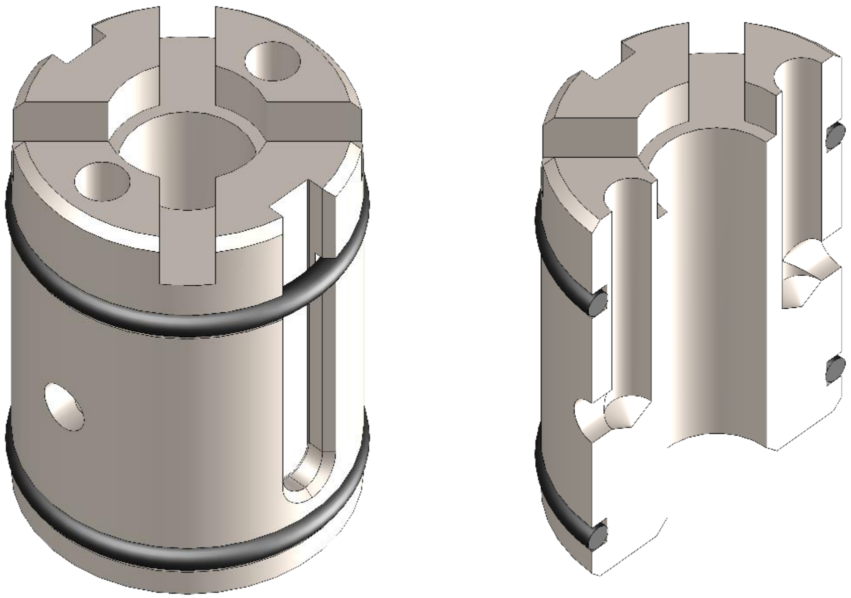
Critical mechanisms for equivalent stress in glass-ceramic components

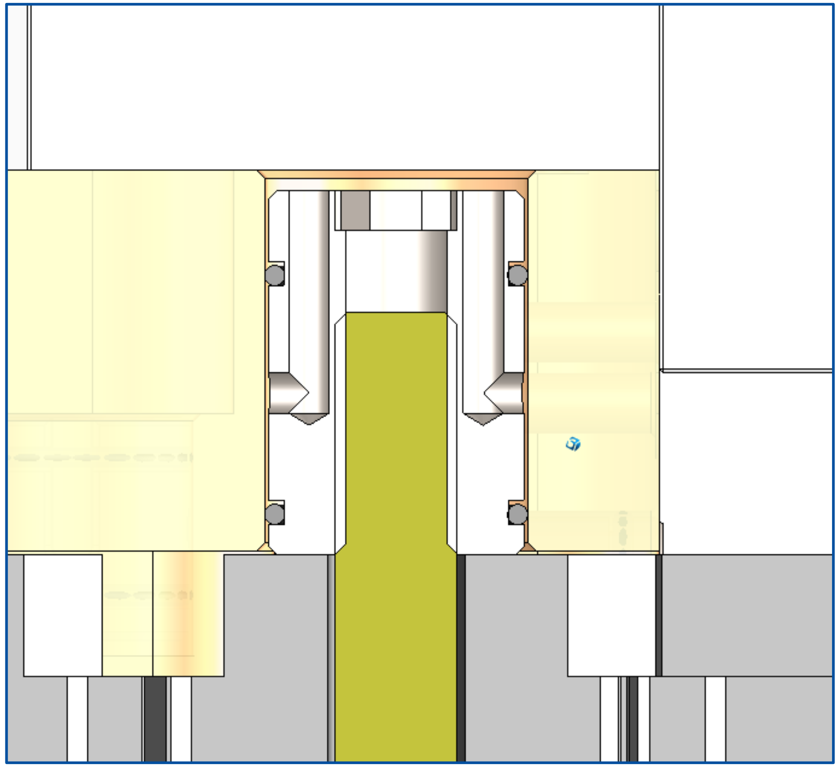
- Expansion of metal inserts (and adhesives)
- Bolt pretension
- Expansion of the actuator frame

Metal inserts in ultra-low expansion glass-ceramic

Insert and interface design for actuator frame interface

- Insert made from Invar (D = 6.3 mm with M3 thread)
- Epoxy-based adhesive (curing at room temperature with minimal shrinkage)
- Radial alignment via seal rings (acting as additional adhesive barriers)
- Protruding installation in glass-ceramic to allow bolt pretension





Thermo-mechanical decoupling of actuator and metrology frames

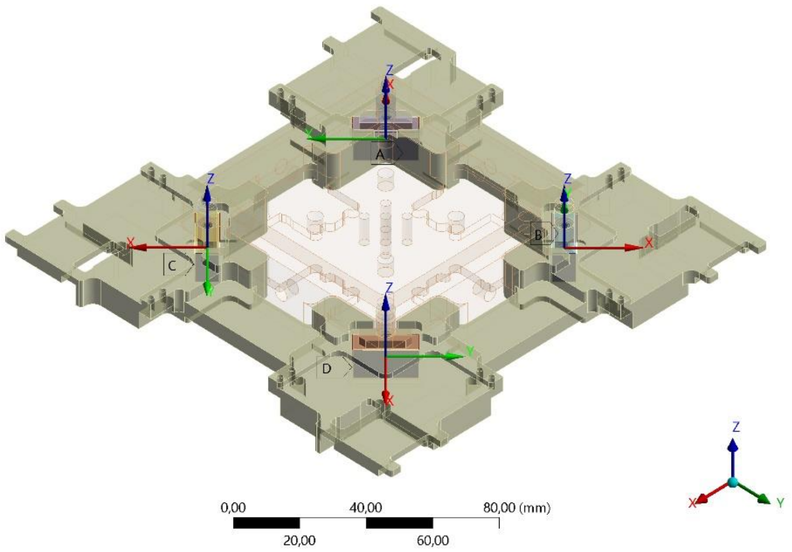
General issues and solution approach for integration of brittle ultra-low expansion materials

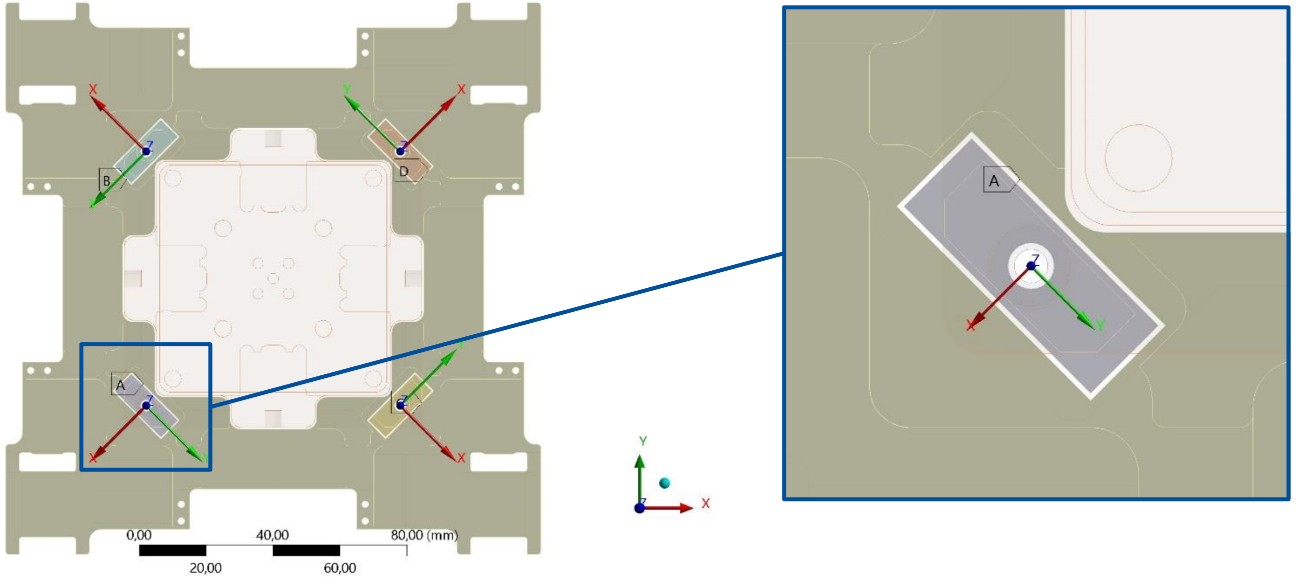
Conflicting objectives result in compromise

- Minimal amount of thermally induced stress in glass-ceramic → compliant coupling between actuator and metrology frames
- Dynamically precise actuation of the mover → stiff coupling between actuator and metrology frames

Solution approach

- Flexure-based decoupling mechanism allowing for deformation of the actuator frame (in the XY-plane) while maintaining a sufficiently stiff connection between actuator and metrology frame



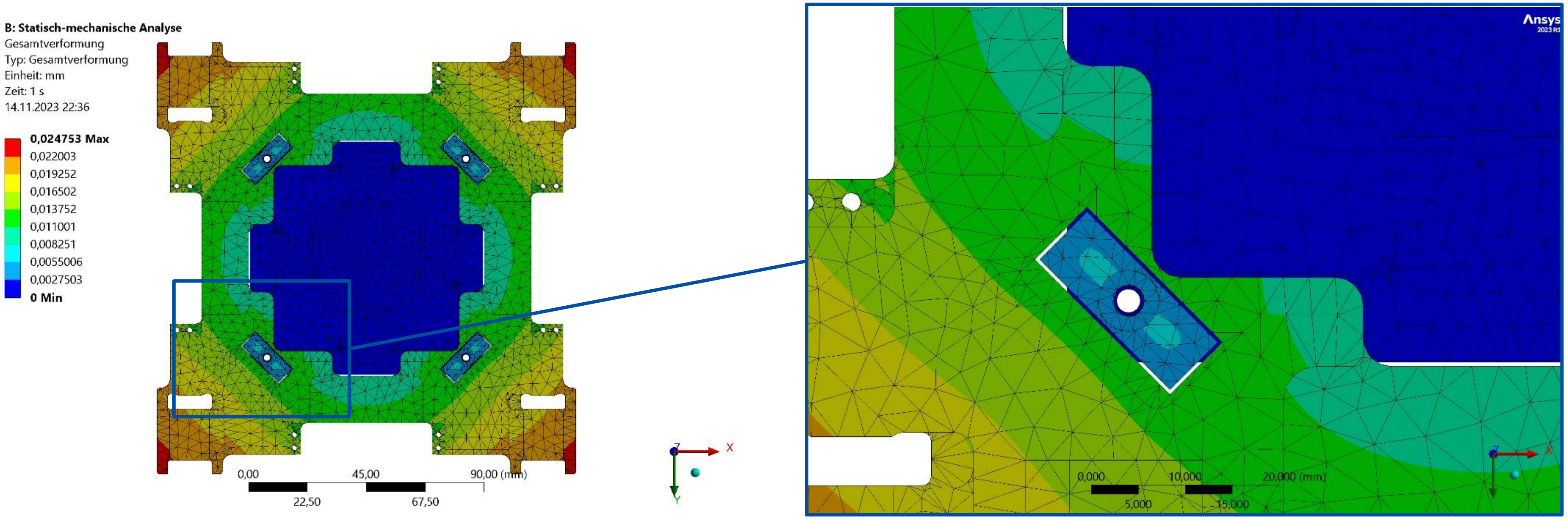


Thermo-mechanical decoupling of actuator and metrology frames

Simulation-based proof of concept

Simulation setup

- Flexures modelled via 6-DoF bushings with stiffness matrix
- Inserts and adhesives fully modelled
- Bolt pretension included in initial load step
- Evaluation of deformation and equivalent stress in glass-ceramic component for extended temperature range (±10 K)

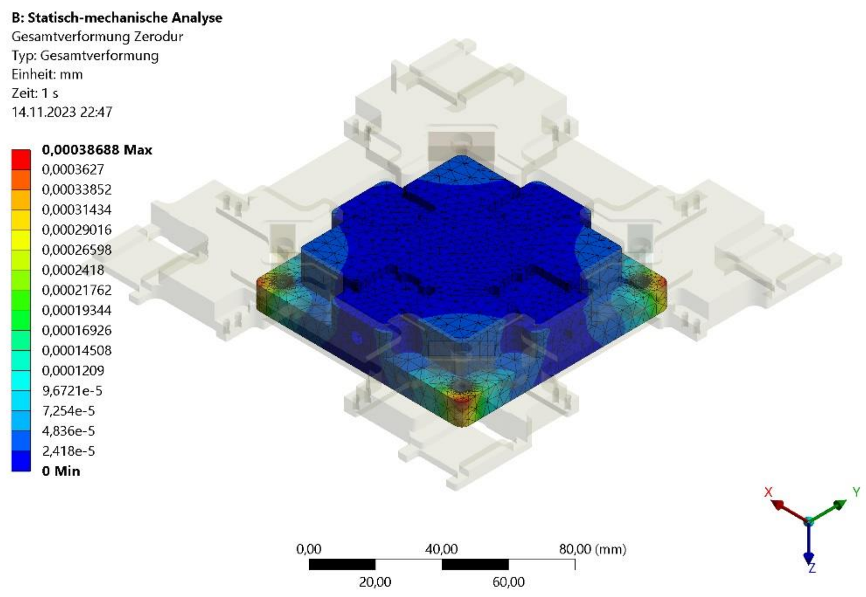


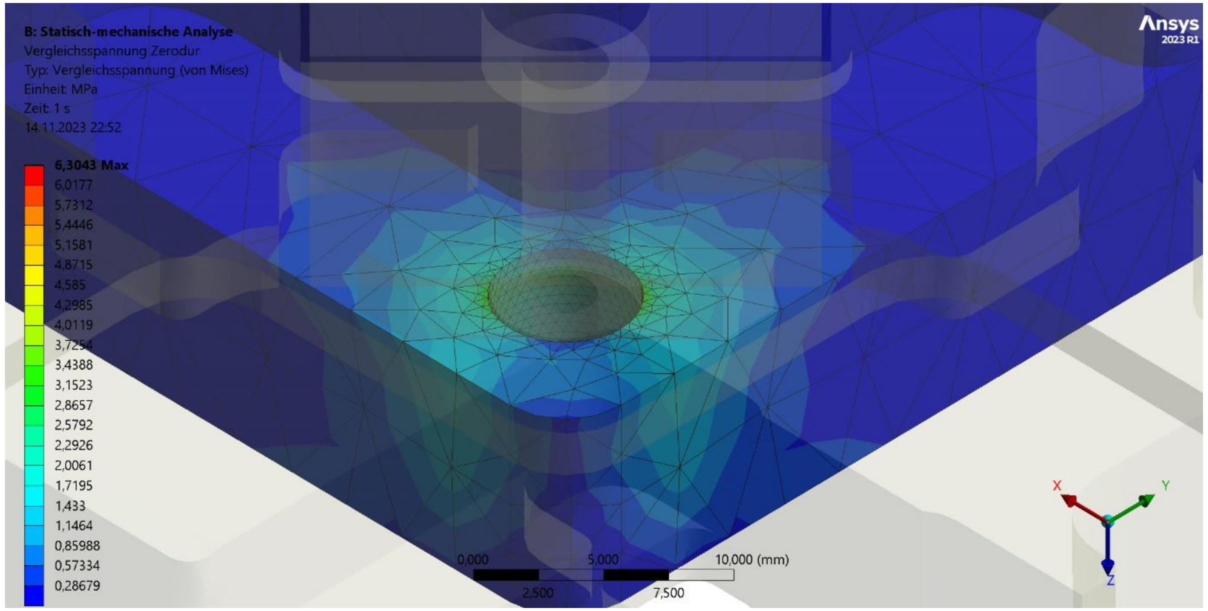
Thermo-mechanical decoupling of actuator and metrology frames

Simulation-based proof of concept

Findings (exemplary data for temperature +10 K)

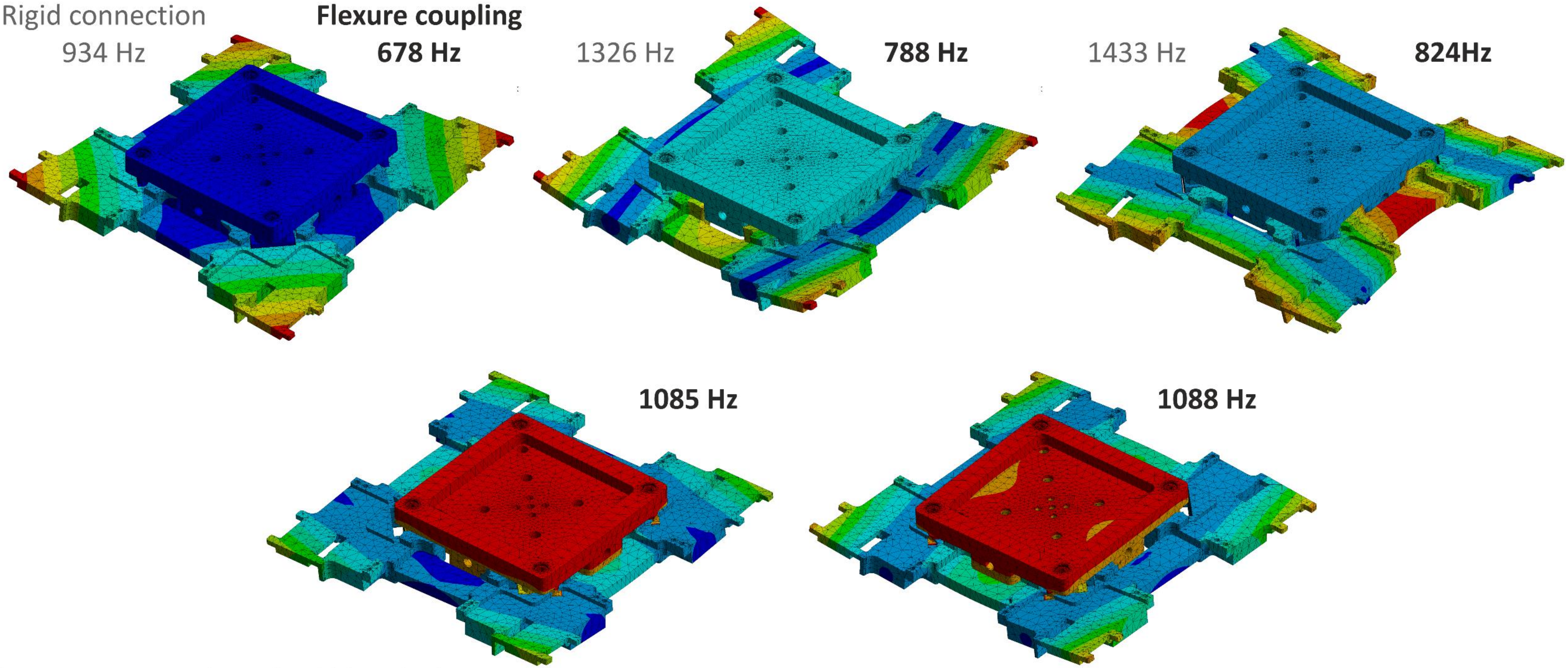
- Force reaction significantly reduced from 130 N to < 4 N per insert
- Deformation of glass-ceramic reduced from 2 µm to < 40 nm
- Stress in glass-ceramic component reduced from 11 MPa to < 7 MPa – note that this value corresponds to a base level due to expansion of insert, contribution of actuator frame deformation account to less than 1 MPa





Thermo-mechanical decoupling of actuator and metrology frames

Impact on eigenmodes and frequencies of the mover



*Actuator components suppressed in images but included in simulation!

Acknowledgement and references

Acknowledgement

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- Funder ID: 10.13039/100014132
- Grant number: 20IND08 MetExSPM

References

[1] **Christian Rudolf**: Ist 2x3=3x2? Oder: Sind das noch Hexapoden? *15. Tagung Feinwerktechnische Konstruktion*, 13.10.-14.10.2022, Dresden.

[2] **Rudolf Krueger, Rainer Gloess**: Magnetically levitated planar motion stage with atomic resolution for metrological high-speed scanning probe microscopy. *Proceedings of the euspen’s 23rd International Conference and Exhibition*, 12.06.-16.06.2023, Copenhagen.

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