MEDSI 2023 Beijing
Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation

# Nanopositioning at Sirius/LNLS beamlines

***a review and future opportunities***

November 9th, 2023


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LNLS Brazilian Synchrotron Light Laboratory · CNPEM Brazilian Center for Research in Energy and Materials · Ministry of Science Technology and Innovation · Brazilian Government Brasil Uniting and Rebuilding

# Outline

- Introduction
- Motivation
- Commercial Scenario
- Development Framework
- Examples
- Conclusions & Perspectives

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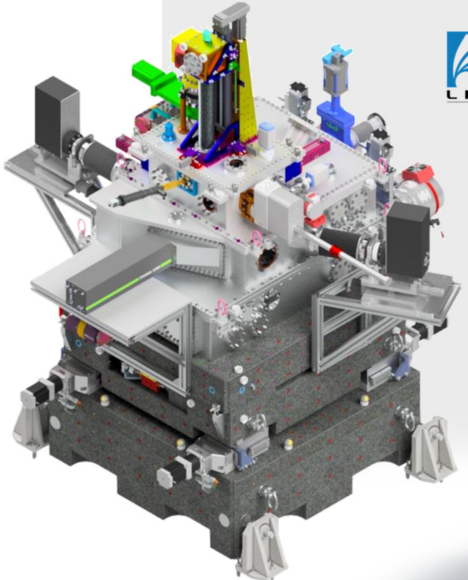
- Introduction
- Motivation
- Commercial Scenario
- Development Framework
- Examples
- Conclusions & Perspectives

1. Short Biography
2. The CNPEM, the LNLS and Sirius

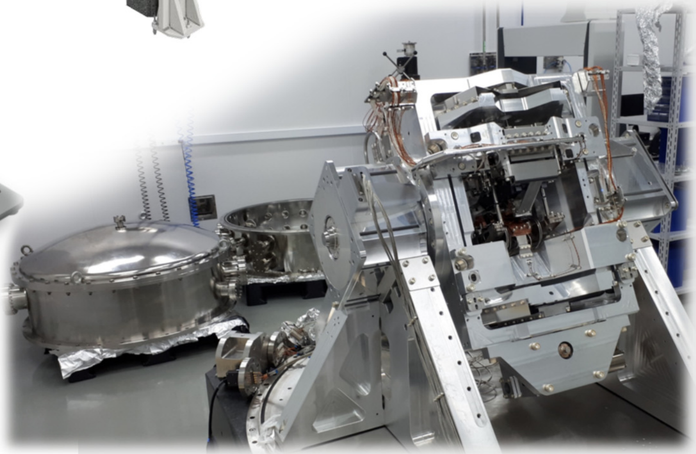
# 1. Short Biography

- Bachelor in Engineering Physics (UFSCar, Brazil)
- Master in Physics w/ emphasis in Scientific Instrumentation (CBPF, Brazil)
- PhD in Mechatronics (TU/e, The Netherlands)
- 14 years at the LNLS (UVX and Sirius)
    - Head of the Precision Engineering and Mechatronics group (MEP)

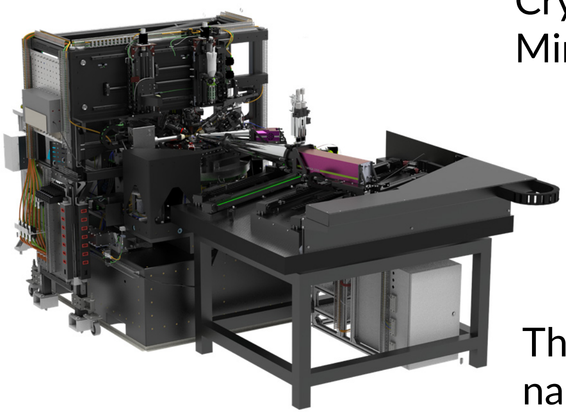


The SAPOTI nanoprobe

The HD-DCM

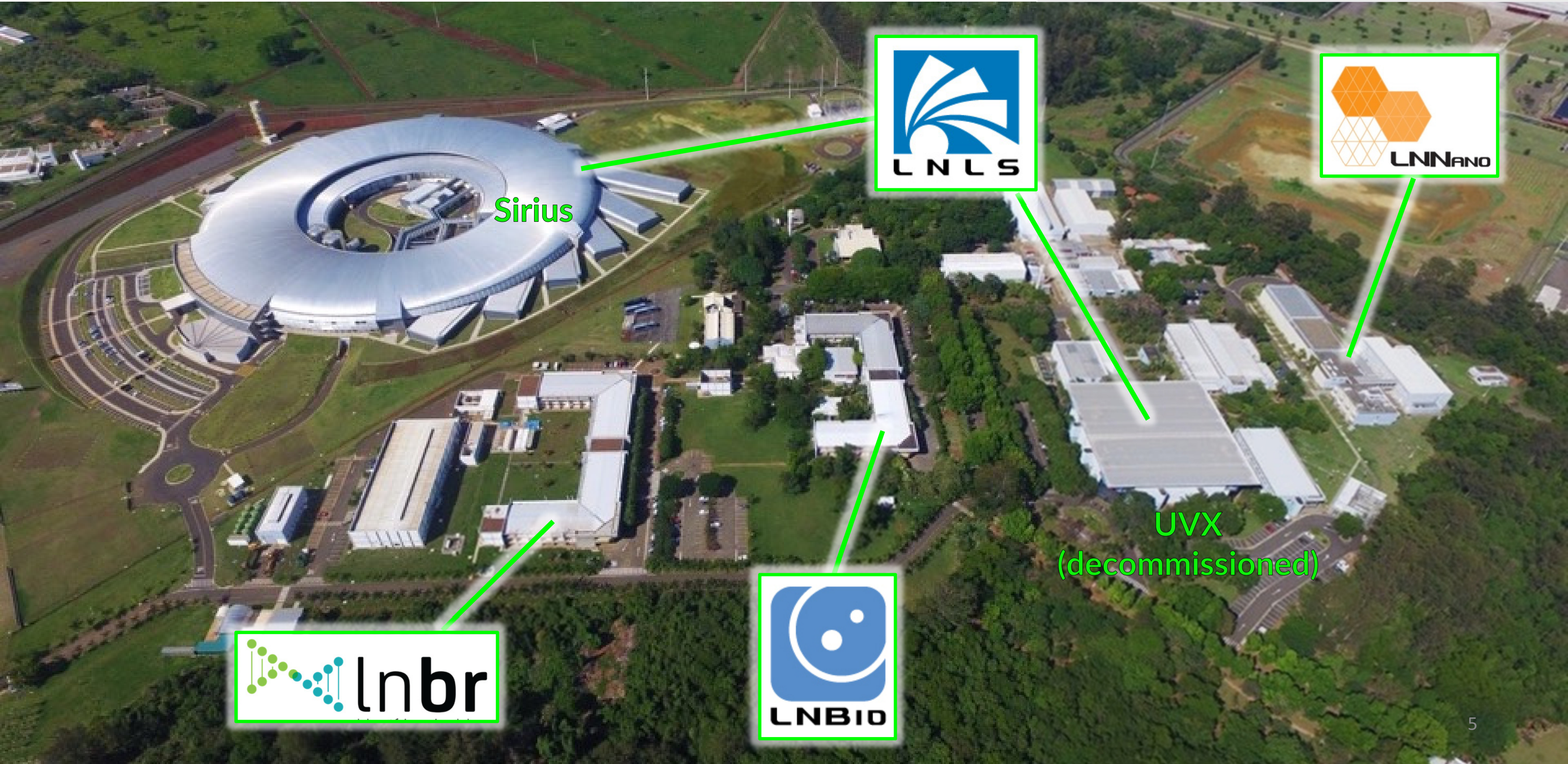


Cryogenic X-ray Mirror Systems



The TARUMÃ nanoprobe

# 2. The CNPEM and the LNLS



# 2. 4th Generation Storage Rings Worldwide

## APS-U

| | |
|---|---|
| Energy | 6.0 GeV |
| Circumference | 1103 m |
| **Natural emittance** | **42 pm.rad** |
| Current (top-up) | 200 mA |

## MAX IV

| | |
|---|---|
| Energy | 3.0 GeV |
| Circumference | 528 m |
| **Natural emittance** | **330 pm.rad** |
| Current (top-up) | 500 mA |

2024/2025

## SIRIUS

| | |
|---|---|
| Energy | 3.0 GeV |
| Circumference | 518 m |
| **Natural emittance** | **250 pm.rad** |
| Current (top-up) | 350 mA |


## HEPS

| | |
|---|---|
| Energy | 6.0 GeV |
| Circumference | 1360 m |
| **Natural emittance** | **< 60 pm.rad** |
| Current (top-up) | 200 mA |

## ESRF-EBS

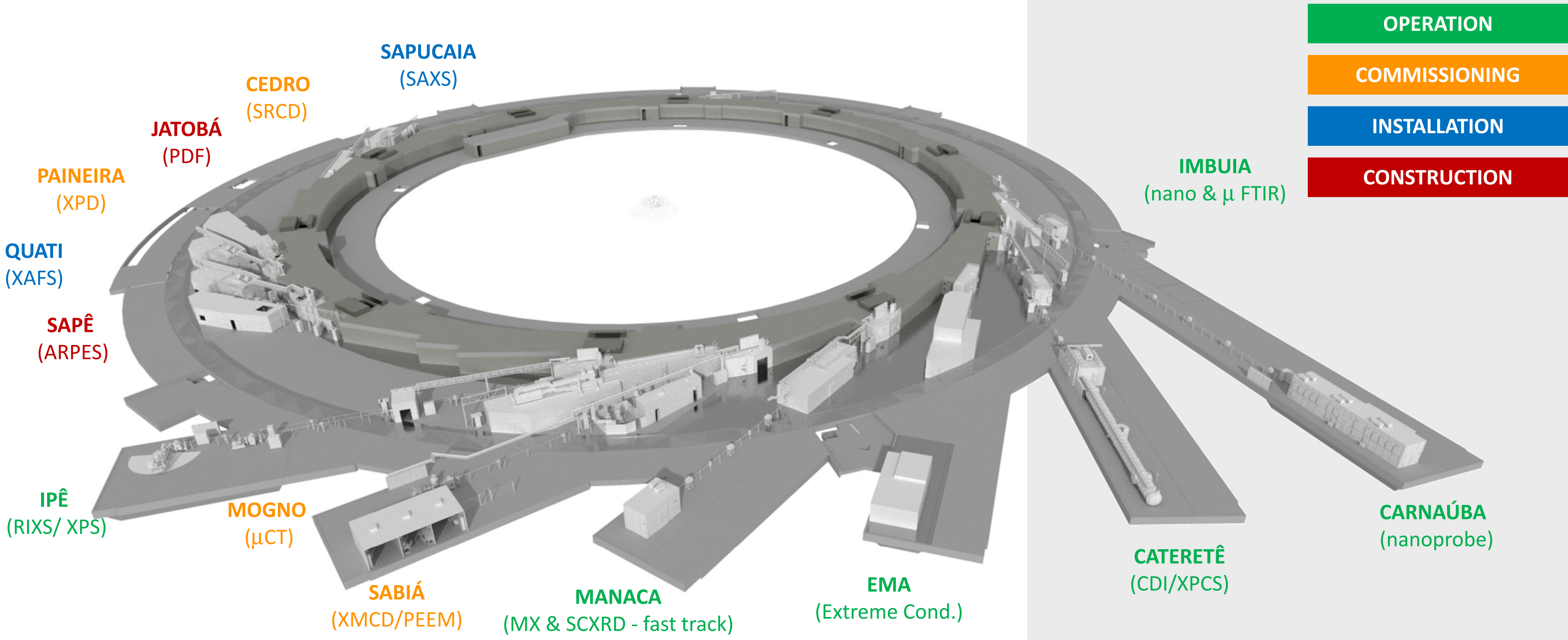
| | |
|---|---|
| Energy | 6.0 GeV |
| Circumference | 844 m |
| **Natural emittance** | **133 pm.rad** |
| Current (top-up) | 200 mA |

**Sirius Project goals**

- Optimized for **coherence** in tender X-rays
- High-brilliance **hard X-rays** for Spectroscopy and Imaging
- Maintaining the **IR and UV** science programs

# 2. Sirius Beamlines – Phase 1

https://www.lnls.cnpem.br/beamlines/



# 2. Sirius Beamlines – Phase 1

https://www.lnls.cnpem.br/beamlines/

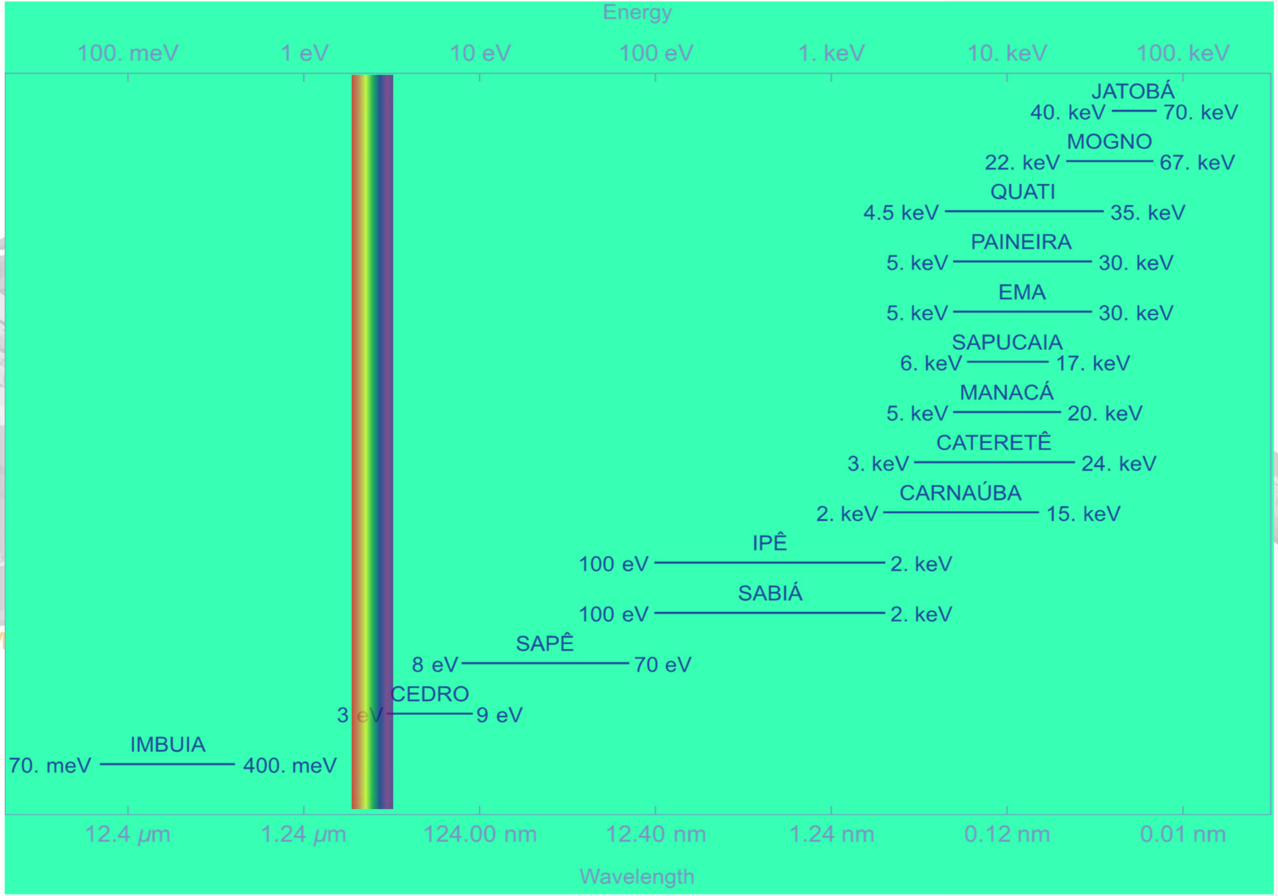
**JATOBÁ**
(PDF)

**PAINEIRA**
(XPD)

**QUATI**
(XAFS)

**SAPÊ**
(ARPES)

**IPÊ**
(RIXS/ XPS)

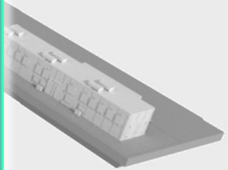



**OPERATION**

**COMMISSIONING**

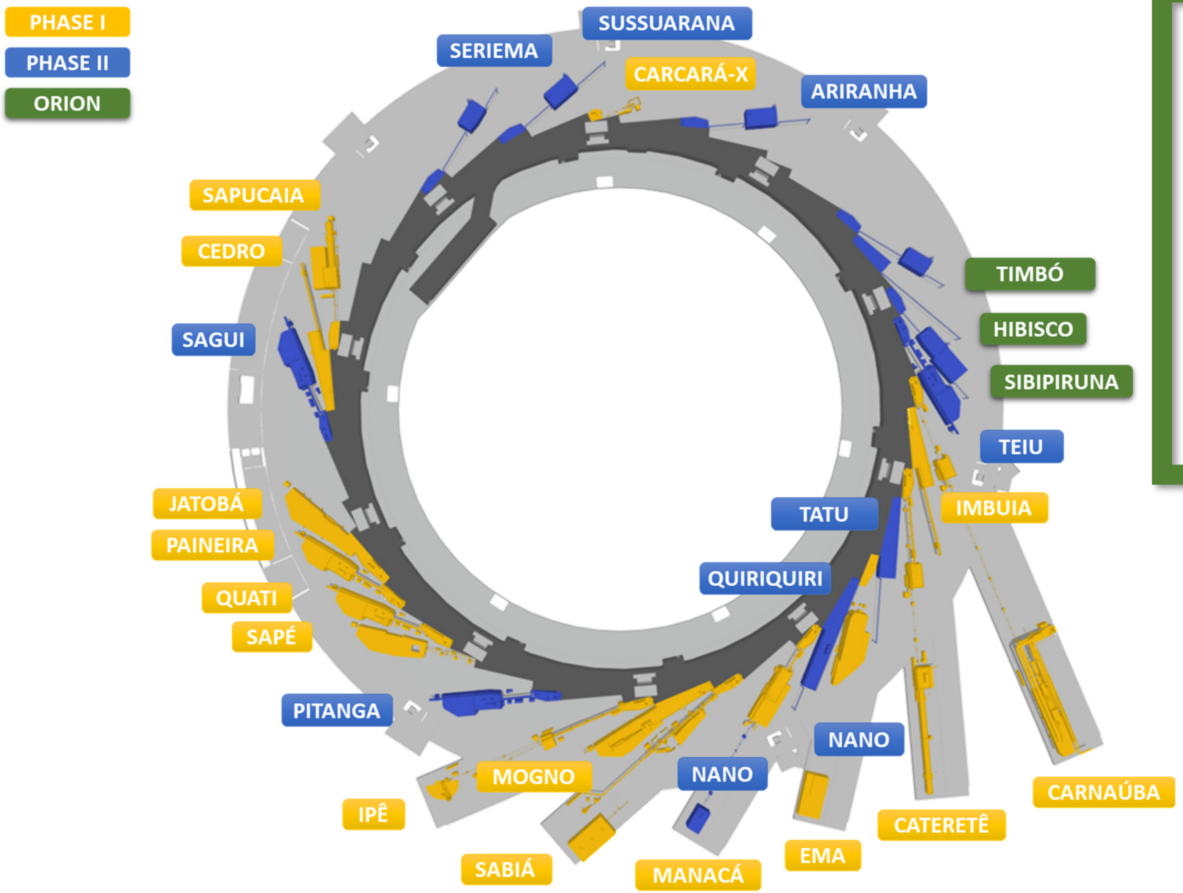
**INSTALLATION**

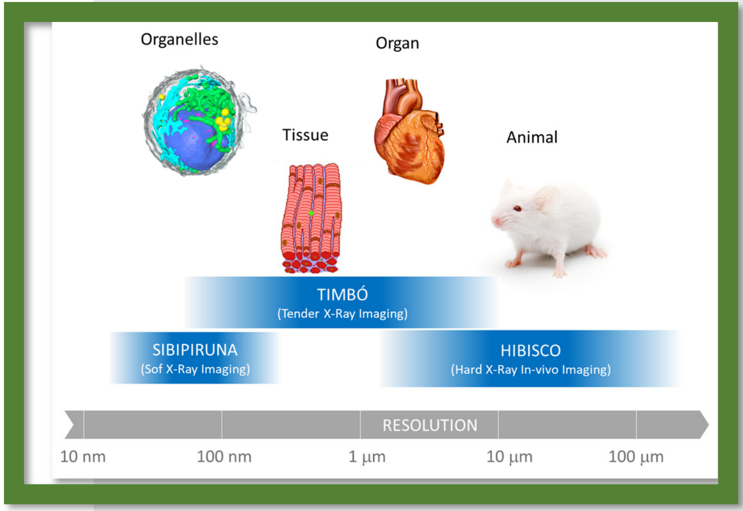
**CONSTRUCTION**

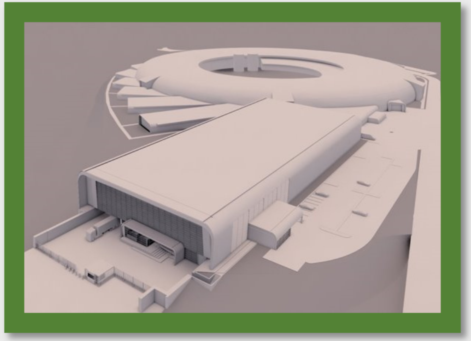


**CARNAÚBA**
(nanoprobe)

# 2. Sirius Beamlines – Phase 2 and Orion



# Outline: Nanopositioning

- Introduction
- Motivation: **Why** do we need it?
- Commercial Scenario
- Development Framework
- Examples
- Conclusions & Perspectives

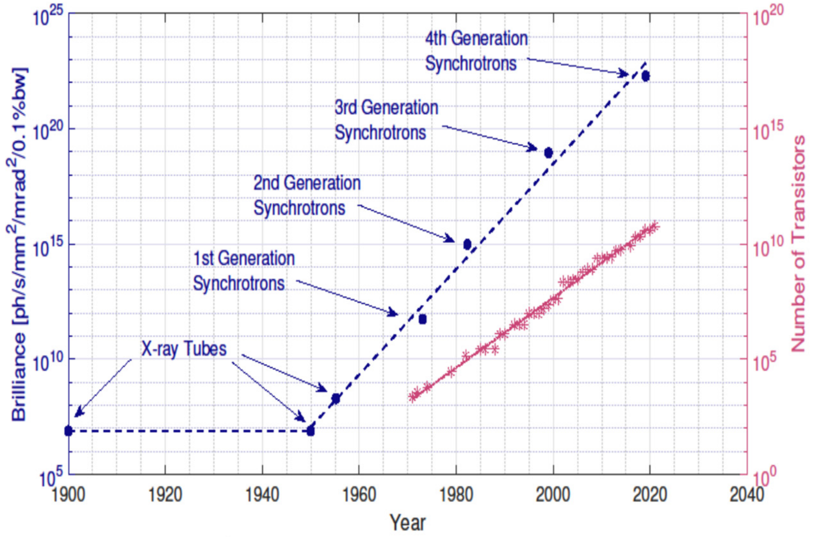
**1. New light sources**

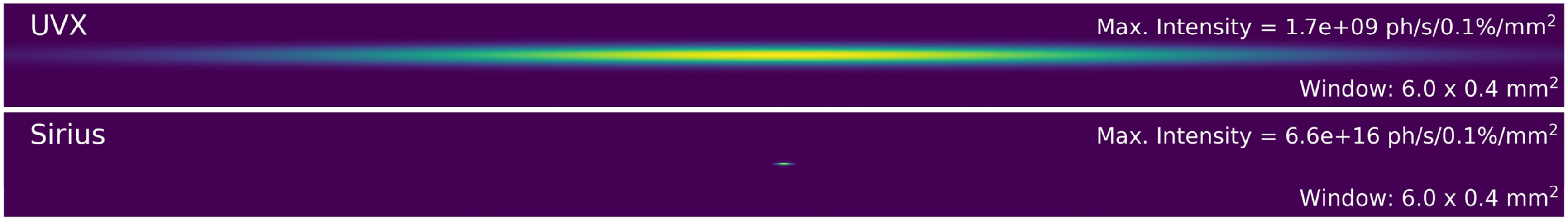
**2. Beam delivery**

**3. Experimental Methods**

# 1. New-generation light sources

- Increased brilliance/flux
  - **Smaller sources** → Higher stability
  - **Higher flux** → Faster processes
- Increased **coherence** fractions
  - Coherence-based methods (ptycho)
  - Higher stability requirements




2nd Generation UVX to 4th Generation Sirius at the LNLS

# 2. Beam Delivery

2.1. Mirrors

2.2. Double-Crystal Monochromators

2.3. Plane-Grating Monochromators

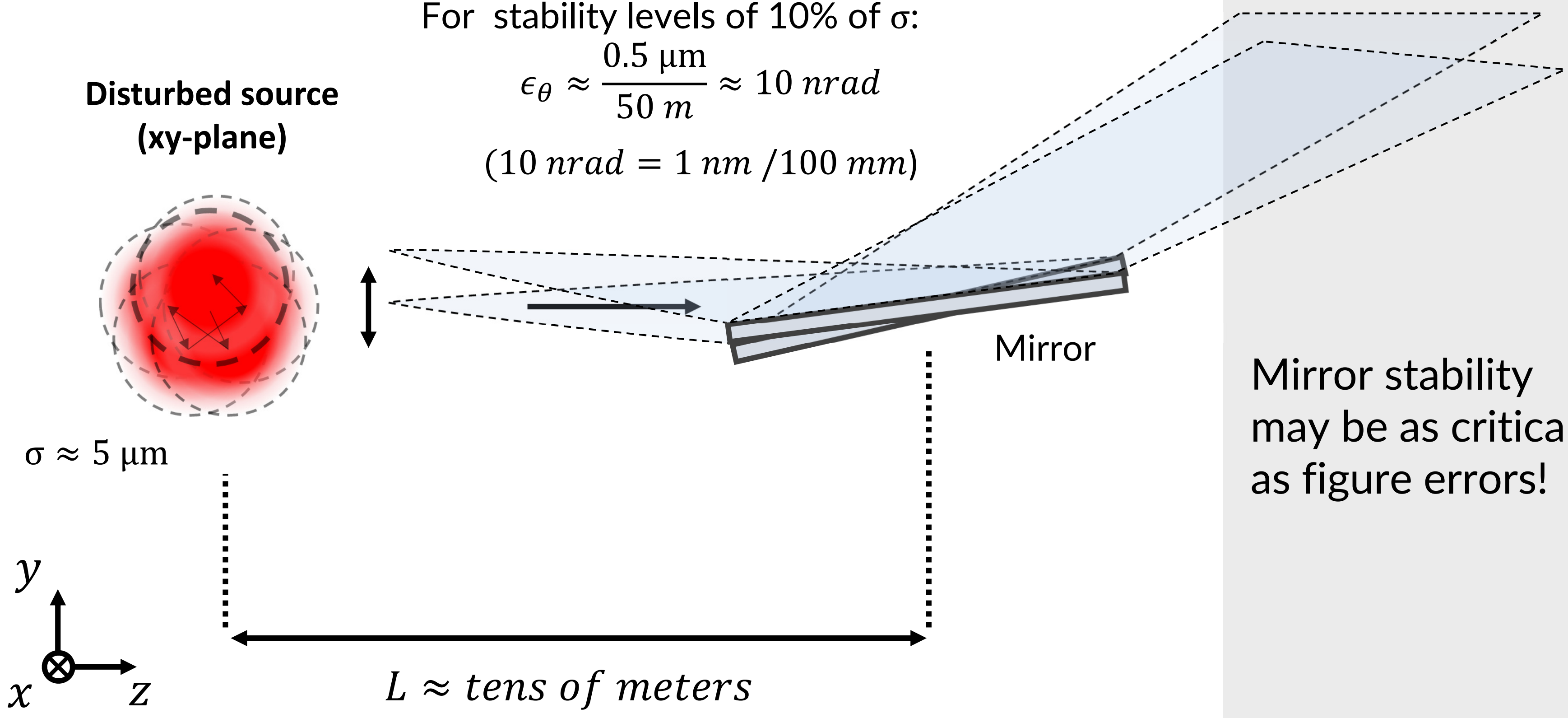
2.4. KB Mirrors

# 2.1. Mirrors

For stability levels of 10% of σ:

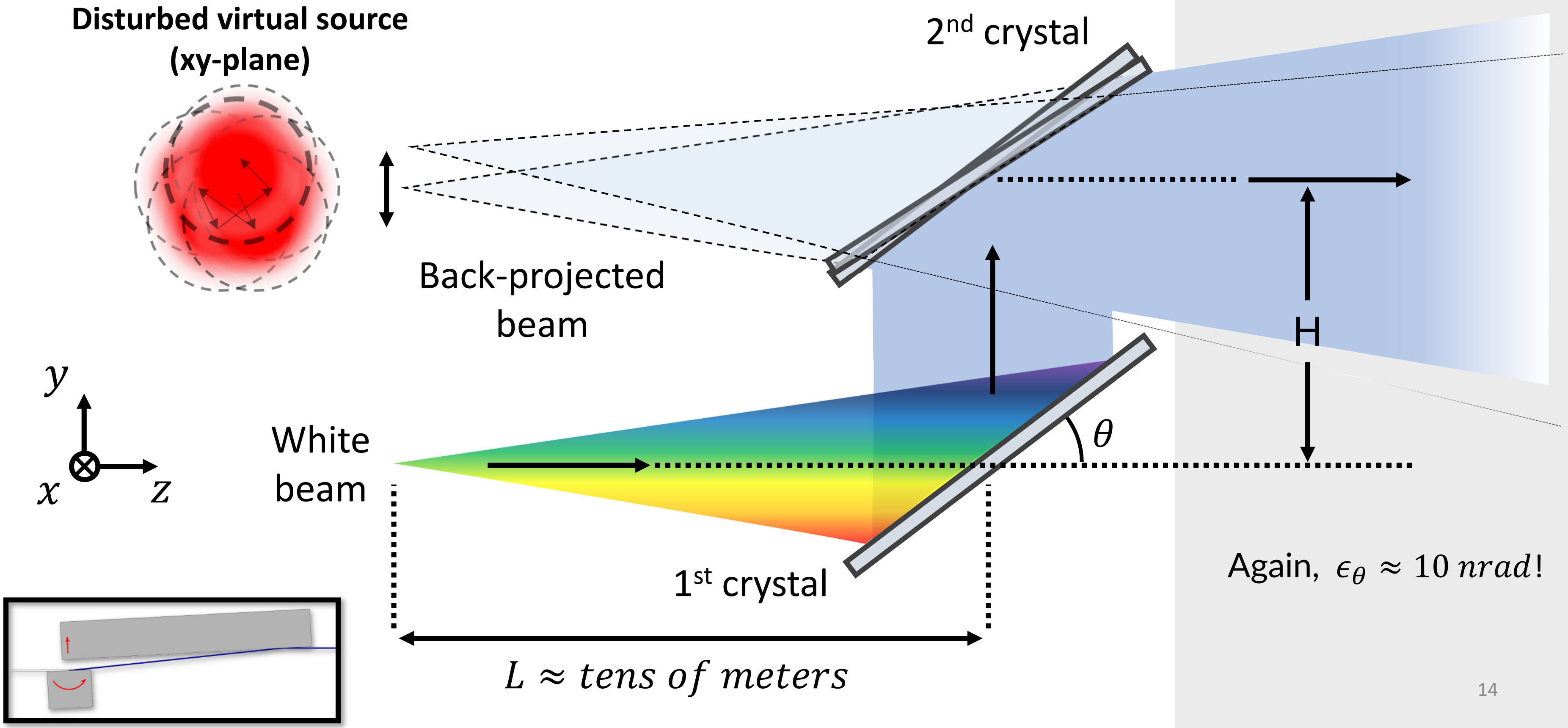
$$\epsilon_\theta \approx \frac{0.5\ \mu m}{50\ m} \approx 10\ nrad$$

$$(10\ nrad = 1\ nm\ /100\ mm)$$




Mirror stability may be as critical as figure errors!

# 2.2. Double-Crystal Monochromators




Again, $\epsilon_\theta \approx 10\,nrad$!

# 2.3. Plane-Grating Monochromators

(doi:10.1107/S1600577520000843)

## Veritas @ Max IV

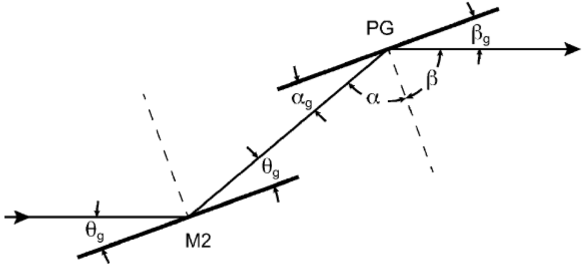



**Figure 1**
Schematic picture of the geometry of the collimated plane grating monochromator. M2 denotes the mirror and PG the plane grating. The light comes in from the left and exits towards the slit to the right. The incoming and outgoing beams are parallel to each other.

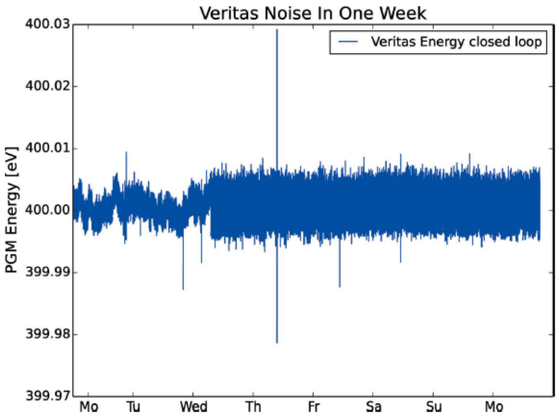



**Figure 22**
Veritas PGM in closed loop was standing still for one week while the energy was sampled. Mid-week, the cooling water was turned on increasing the noise from 3 meV to 7 meV.

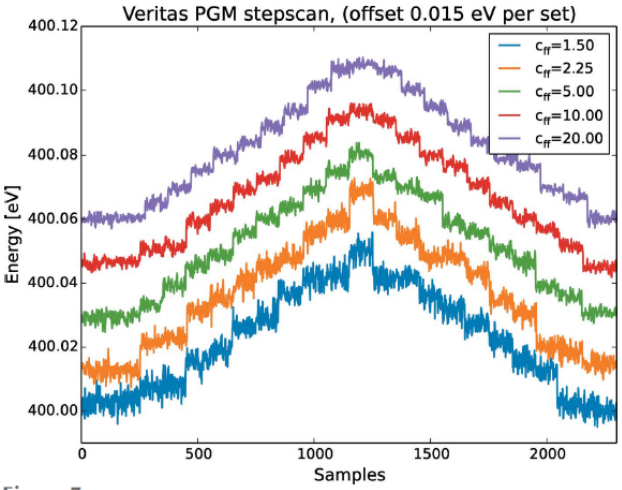
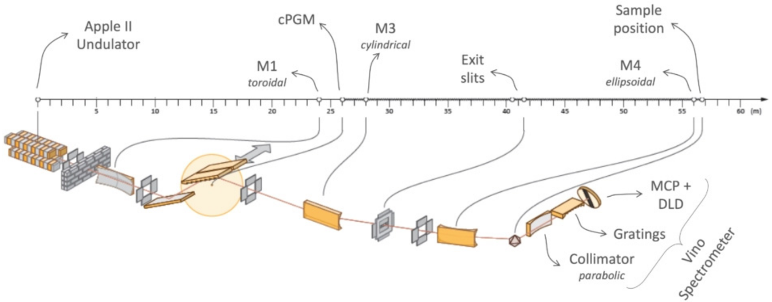
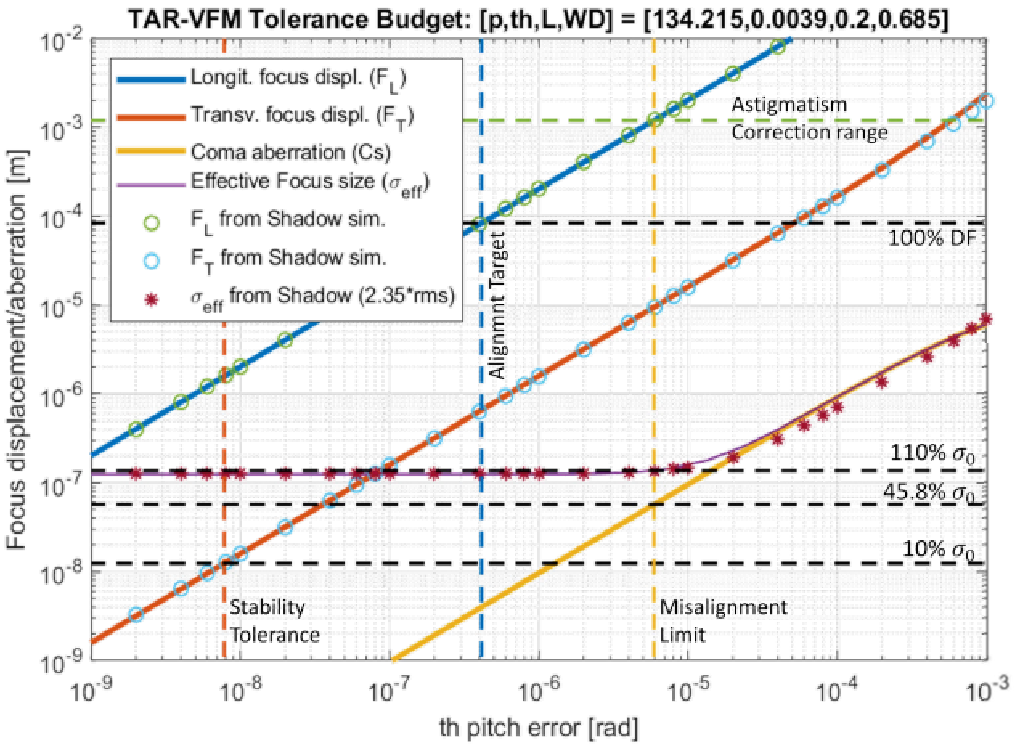



**Figure 7**
The sampled angular noise in encoder position converted to energy for small energy steps for different $c_{ff}$ values at Veritas. Each step is 5 meV and 10 s at 400 eV giving a resolution of 80000. The system behaviour is better at higher $c_{ff}$ values. The cooling water is turned off.




Angular stability, affecting energy resolution!

# 2.4. KB (Kirkpatrick-Baez) Systems

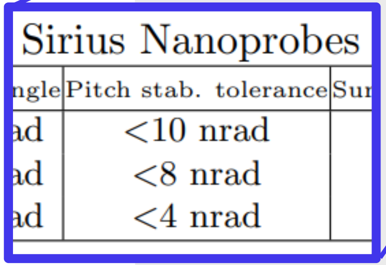


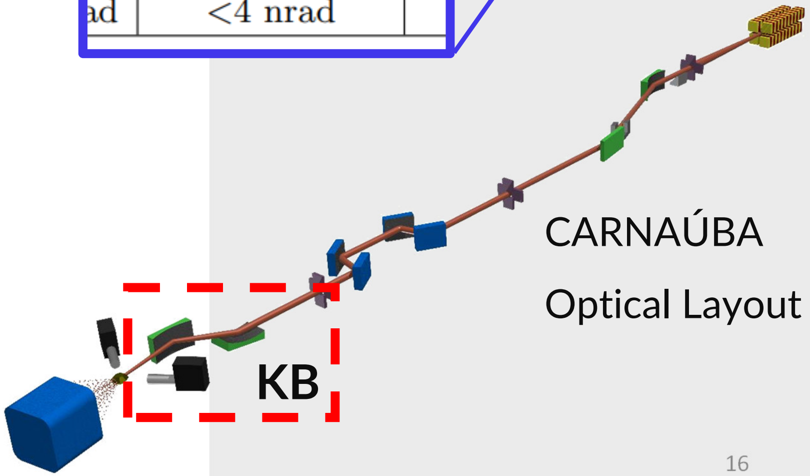

(doi: 10.1088/1742-6596/2380/1/012074)

[Credit: Gabriel Moreno]

**Table 1.** KB set specifications for first Sirius Nanoprobes

| KB set | Focus size | Depth of Focus | Max.mir. Length | Working distance | Grazing angle | Pitch stab. tolerance | Surface error tol. | #stripes |
|---|---|---|---|---|---|---|---|---|
| TARUMÃ | 120 nm | 80 µm | 210 mm | 450 mm | 3.9 mrad | <10 nrad | <1 nm | 1 |
| MOGNO | 100 nm | 20 µm | 450 mm | 175 mm | 3.8 mrad | <8 nrad | <1 nm | 2 |
| SAPOTI | 35 nm | 5 µm | 390 mm | 55 mm | 3.9 mrad | <4 nrad | <1 nm | 1 |




CARNAÚBA

Optical Layout

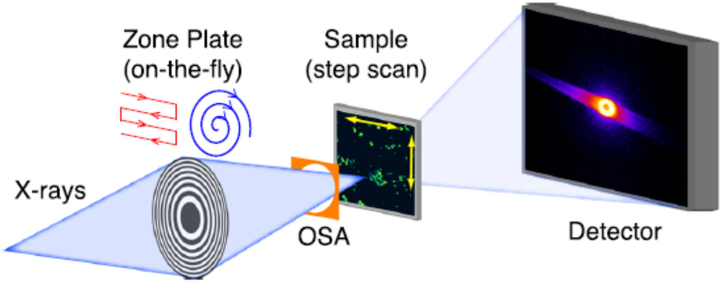
# 3. Experimental Methods

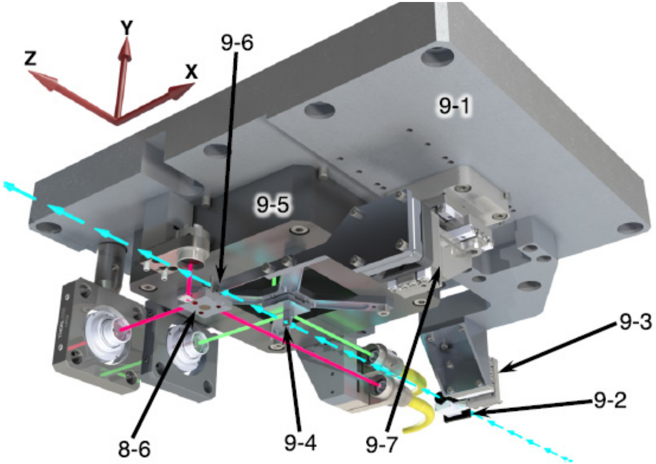
Scanning Microscopes

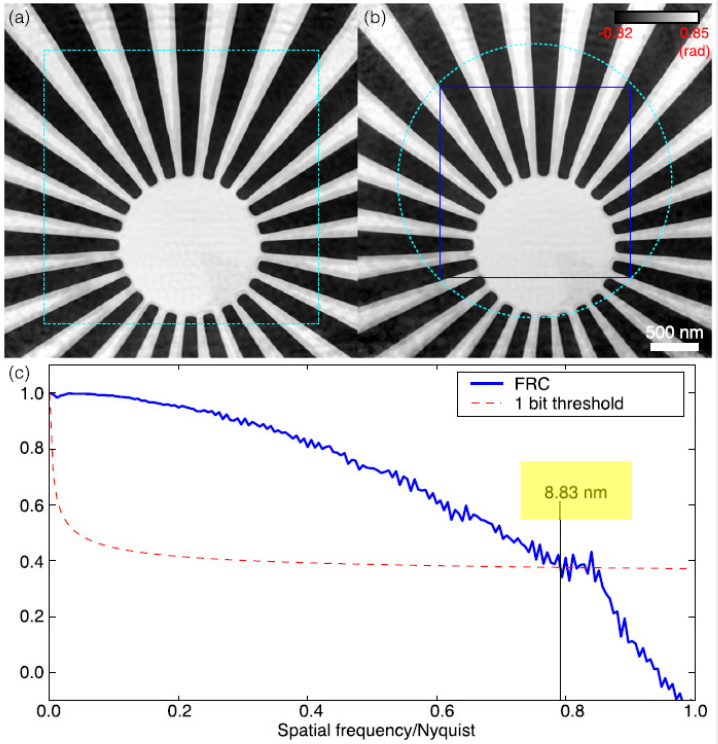
- 2D images (STXM, Ptychography, Fluorescence)
- 3D Tomography

# 3. Experimental Methods: Ptycho-Tomography

## Velociprobe @ APS



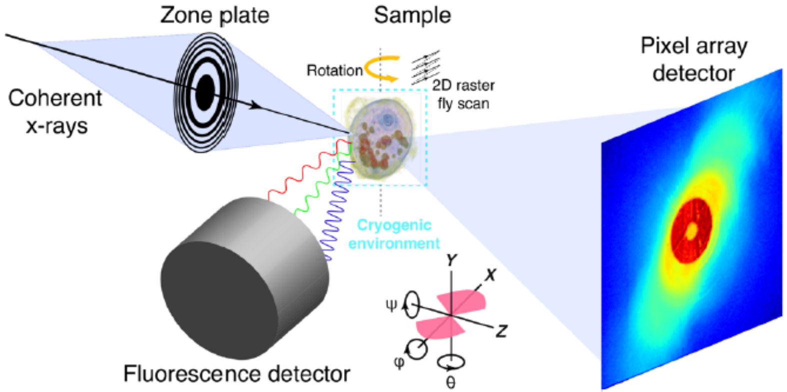



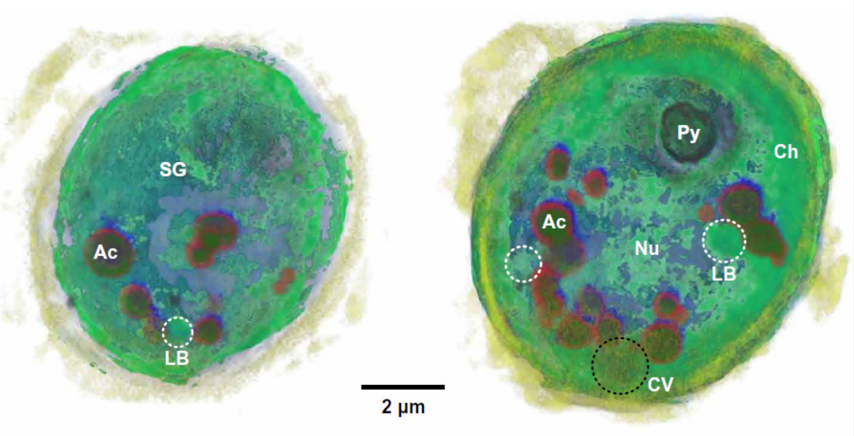

(doi: 10.1063/1.5103173)

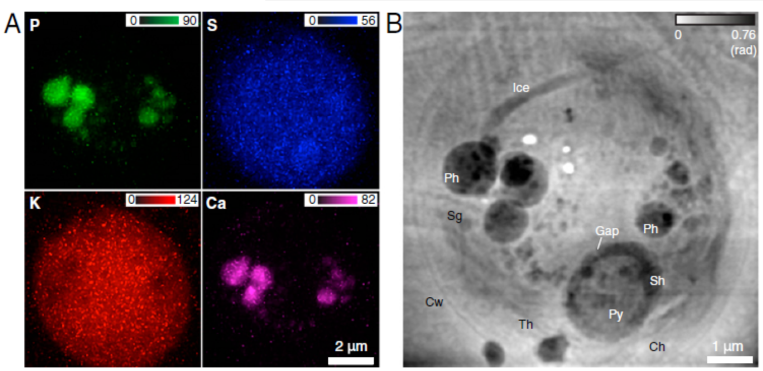
# 3. Experimental Methods: Ptycho-Fluoro-Tomography

## Bionanoprobe @ APS




(doi: 10.1126/sciadv.aau4548 )




(doi: 10.1073/pnas.1413003112)

# Outline: Nanopositioning

- Introduction
- Motivation
- Commercial Scenario: **What** is out there?
- Development Framework
- Examples
- Conclusions & Perspectives

1. **Commercial Systems**
2. **Standards and Procedures**

# 1. Commercial Systems

1.1. Positioning Systems

1.2. Complete Instruments

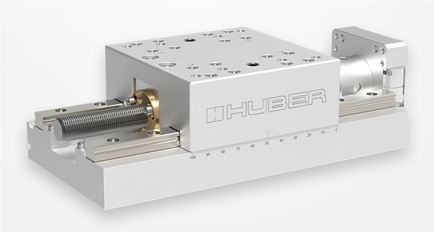
# 1.1. Positioning Systems

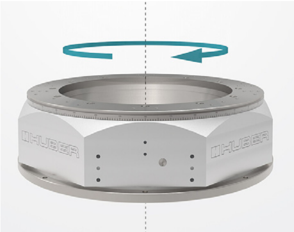
and many others...

LNLS

CNPEM

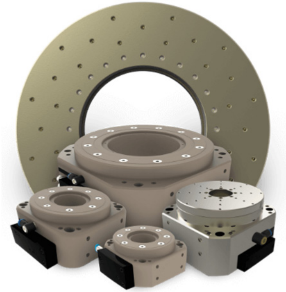
HUBER
Diffraction and Positioning Equipment



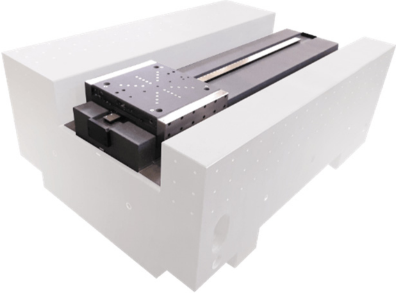





Symétrie



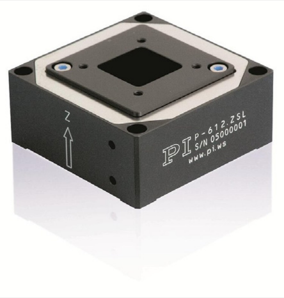
LAB
MOTION SYSTEMS



SYMC



PI

# 1.1. Positioning Systems

and many others...

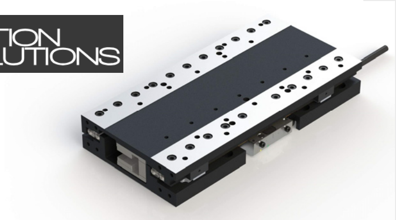
LNLS sirius

CNPEM


ALIO 6-D

An Allied Motion Company


MOTION SOLUTIONS



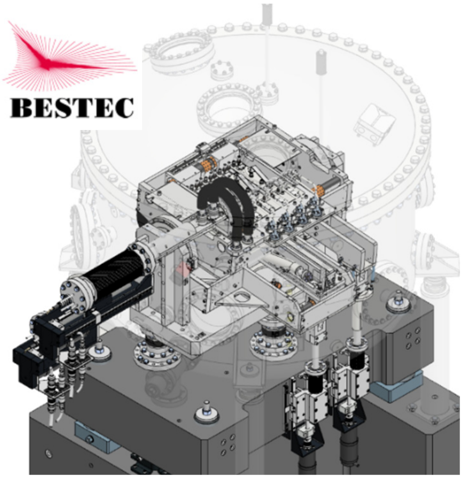
AEROTECH

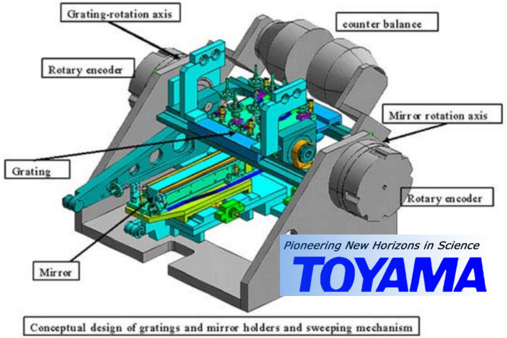

SmarAct

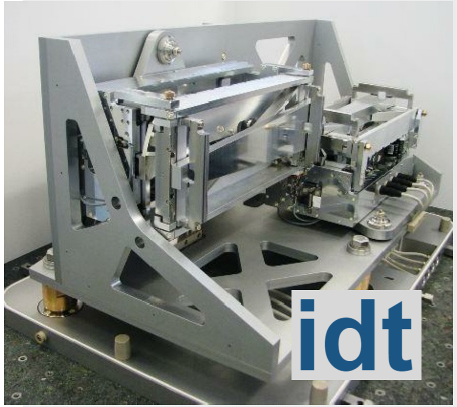
# 1.2. Complete Instruments

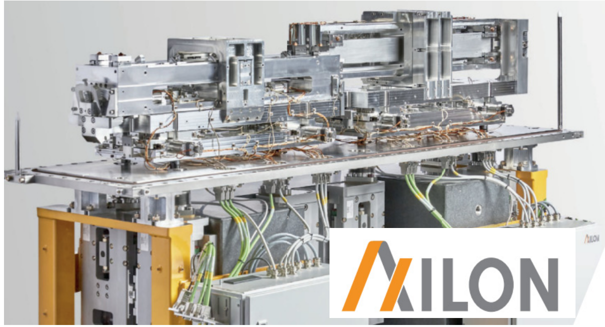
and many others...

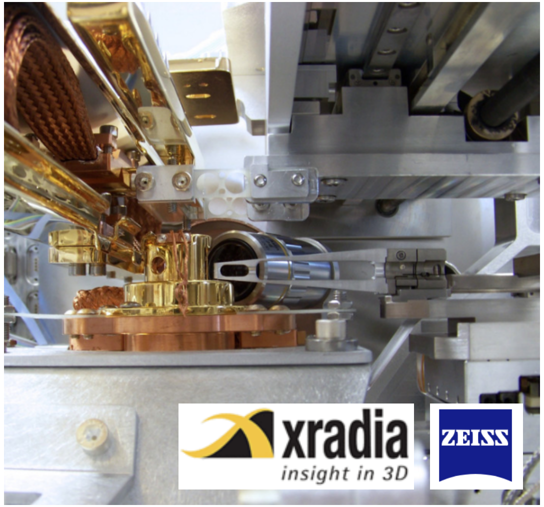
LNLS CNPEM

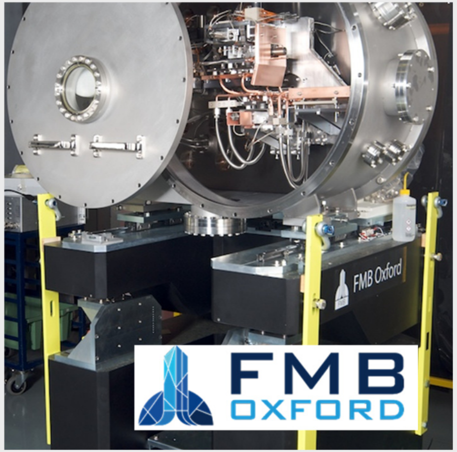


# 2. Standards and Procedures

2.1. Linear Positioning Systems: ASME B5.64

2.2. Rotary Systems: Spindle Metrology

*Comparing complete instruments being very challenging.

# 2.1. Linear Positioning Systems: ASME B5.64

## ASME B5.64

- Characterization Guide
- Performance Tests
- Unified Terminology
- Statistics and Correction Methods

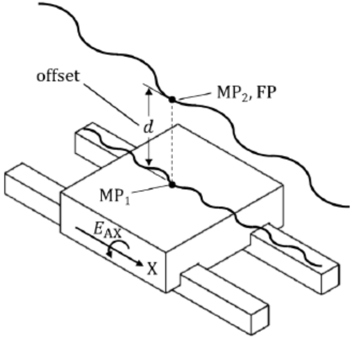
**Greg Vogl** is an Engineer in Production Systems Group @ NIST

**Steve Ludwick** is Director of Sustaining Engineering @ Aerotech

**Jimmie Miller** is Chief Engineer of Center for Precision Metrology @ UNCC

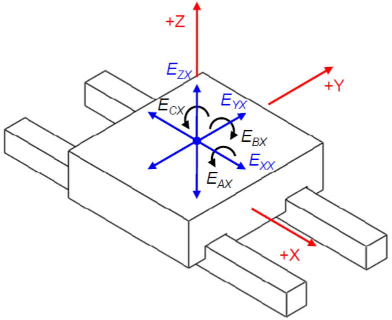
**Axel Grabowski** is Head of R&D of Sensor Technologies Department @ Physik Instrumente (PI)

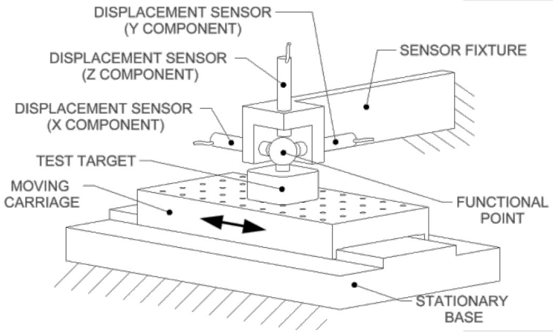
**ASPE 2022**




**Measurement Point (MP) vs Functional Point (FP)**

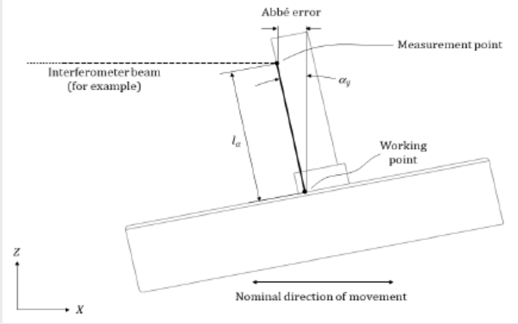
**Positioning Error Motion Nomenclature**




**Point Repeatability**

**Metrology Corrections**



# 2.1. Linear Positioning Systems: ASME B5.64

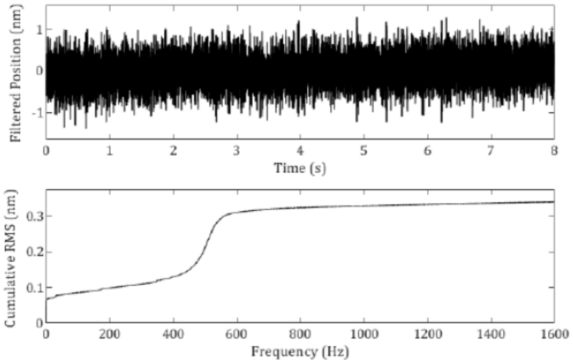
**In-Position "Jitter"**

- Setup/assembly
- Sensor type
- Acquisition (period, filters, etc.)
- Uncertainty Analysis
- Data presentation

**Move and Settle**

- In-position remarks +
- *Travel distance*
- *Settling Criteria*

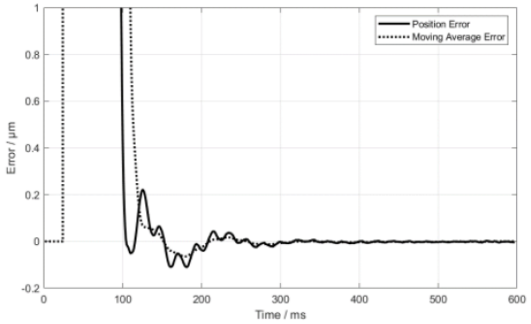
Filtered Data Plots




In-Position Jitter Test Results

| In-Position Jitter Metric | Metric Value (nm) |
|---|---|
| Standard Deviation | $0.34 \pm 0.10$ ($k = 2$) |
| Peak-to-Peak Value | $2.68 \pm 1.9$ ($k = 2$) |

Plot of Data




Move and Settle Test Results

| Settle Metric | Move-and-Settle Time (ms) |
|---|---|
| Moving Average Error | $115 \pm 5.2$ ($k = 2$) |
| Moving Standard Deviation Error | $147 \pm 4.9$ ($k = 2$) |
| Moving Peak Error | $189 \pm 9.2$ ($k = 2$) |

[Credits: Greg Vogl, Steve Ludwick, Axel Grabowski, Jimmie Miller]

# 2.1. Linear Positioning Systems: ASME B5.64

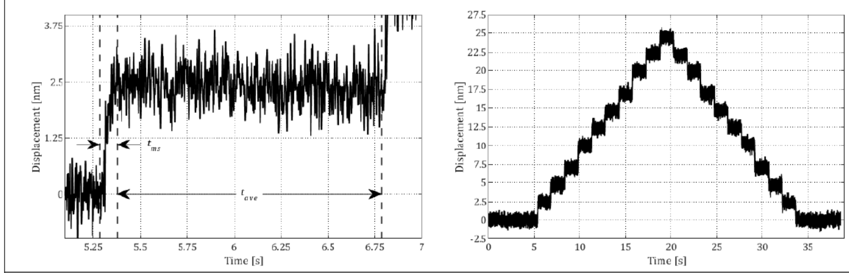
## Incremental and Minimum Step Motion Test

- In-position remarks +
- *Step size*
- *Uni/bidirectional*
- *Number of steps*
- *Step reversal error*
- *Minimum incremental motion*

## Corrections

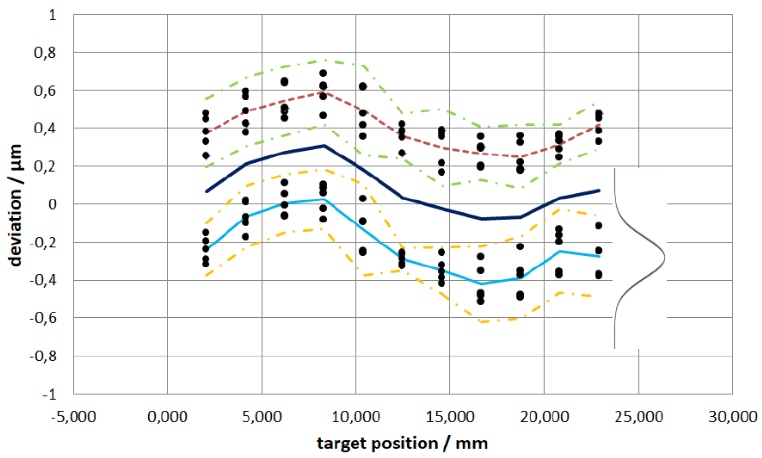
- Thermal drift
- Abbé errors (angle meas. and compensation)
- Uni/bidirectional deviation
- System reversal error
- Linearity correction methods

Plots of Filtered Data



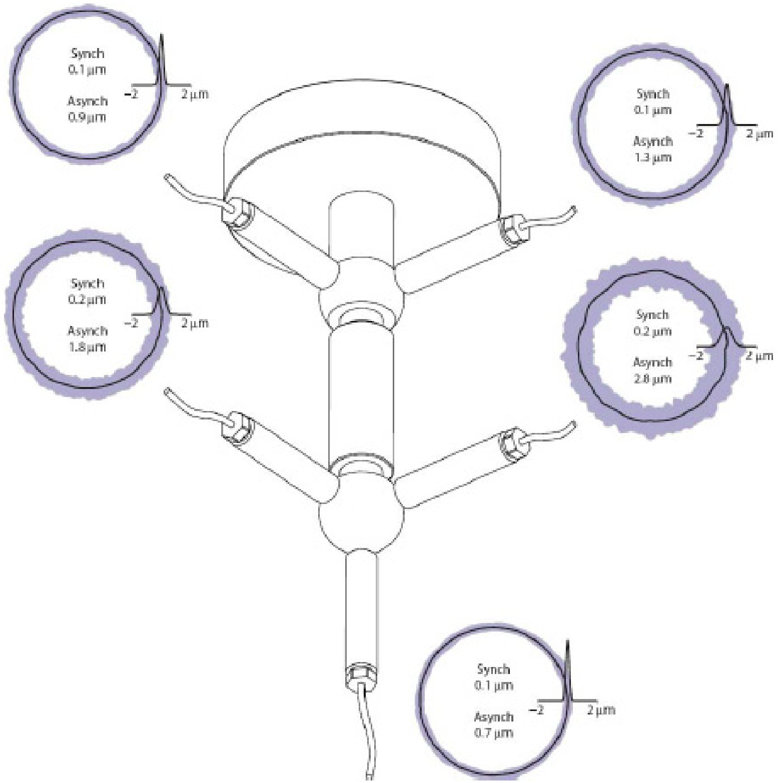

Incremental Step Test Results

| | Direction of Motion | | |
|---|---|---|---|
| | Forward | Reverse | Combined |
| Sample Mean, $\bar{X}_{inc}$ (nm) | 2.51 | 2.53 | 2.52 |
| Sample Standard Deviation, $s_{inc}$ (nm) | 0.051 | 0.074 | 0.065 |




[Credits: Greg Vogl, Steve Ludwick, Axel Grabowski, Jimmie Miller]

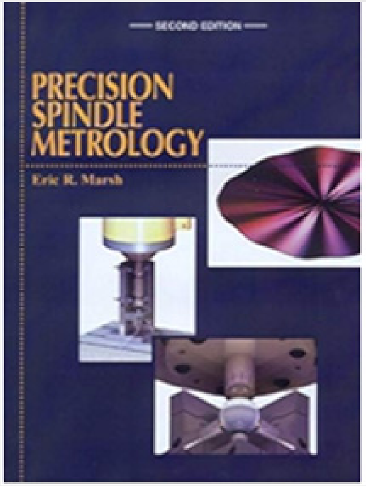
# 2.2. Rotary Systems: Spindle Metrology




*Tests using capacitive probes

**Precision Spindle Metrology (by Erik Marsh)**

- Metrology concepts
- Test Instrumentation
- Data acquisition
- Data analysis




Erik Marsh

https://www.ibspe.com/machine-qualification/spindle-analyzer-systems

# Outline: Nanopositioing

- Introduction
- Motivation
- Commercial Scenario
- Development Framework: **How** can we think about it?
- Examples
- Conclusions & Perspectives

**1. Systems Engineering (SE)**

**2. Design Principles**

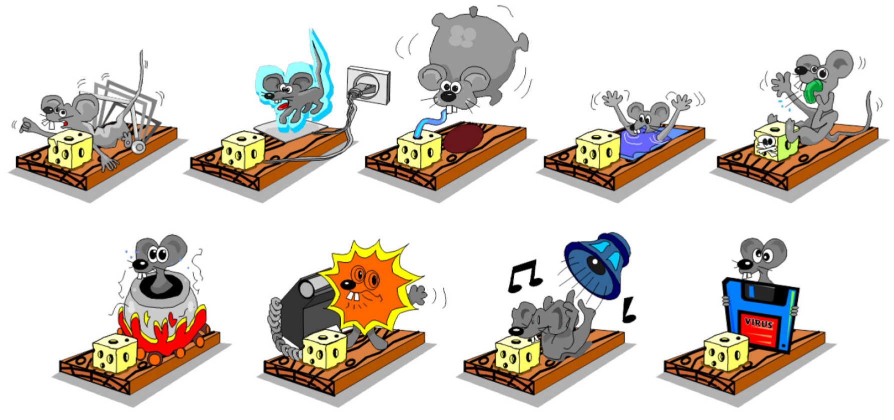
**3. Integration**

# 1. Systems Engineering

- Requirements engineering (Problem Domain vs Solution Domain)
- Modularization (Product Breakdown)
- Functional Breakdown
- Competence Management
- Error Budgeting
- Modeling

**Meant to increase efficiency and reduce redesign/rework!**

[ Credit: Prof. Jan van Eijk]




https://hightechsystems.nl/artikel/kijk-buiten-de-grenzen-van-je-eigen-koninkrijkje/

# 2. Design Principles

2.1. References

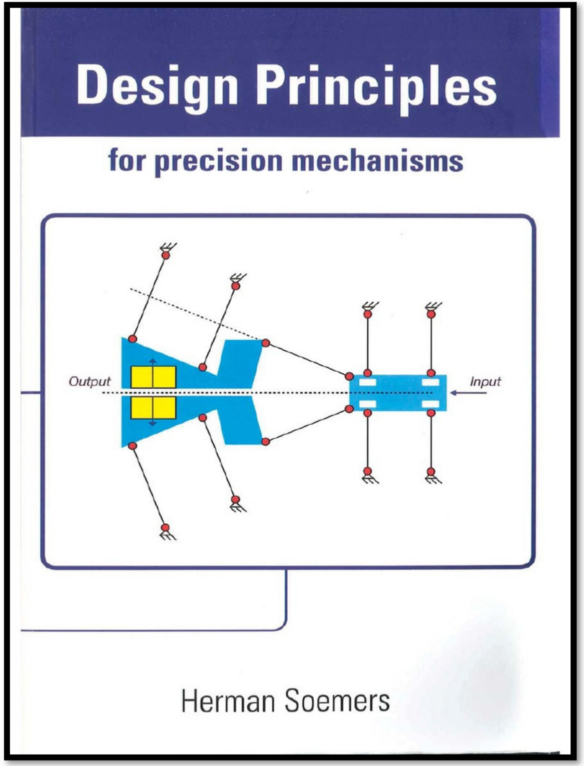
2.2. The 11 Design Principles of High-Precision Machines

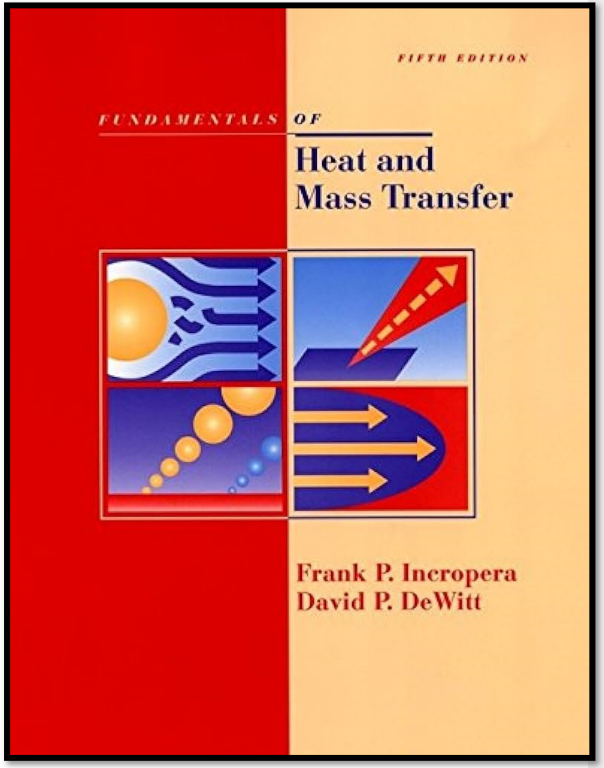
2.3. Mechanical

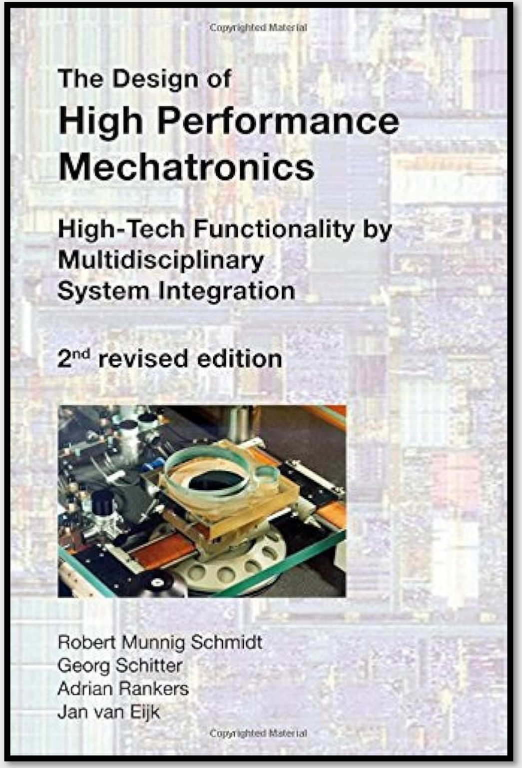
2.4. Dynamics

2.5. Thermal

# 2.1. References



# 2.2. The 11 Design Principles

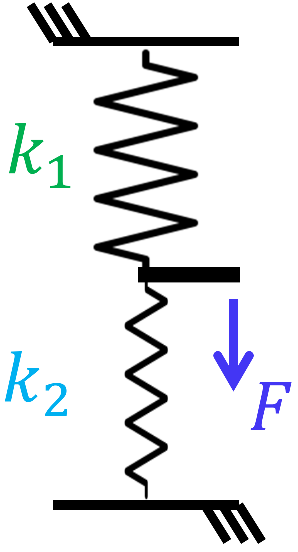
**Design of High Precision Machines:**

1. Structure (symmetry, stiffness, dynamics, damping)
2. Kinematic/Semi-kinematic design (isostatic)
3. Abbé Principle (metrology)
4. Direct measurement
5. Metrology frames (isolated from force frames)
6. Bearings
7. Transmission drives
8. Thermal effects
9. Control
10. Error Budgeting (static, dynamic, thermal)
11. Error Compensation

*From Cranfield Precision Engineering Short Course (2014)

# 2.3. Mechanical: Design for Stiffness

## Parallel Arrangement




$$k_{eff} = k_1 + k_2$$

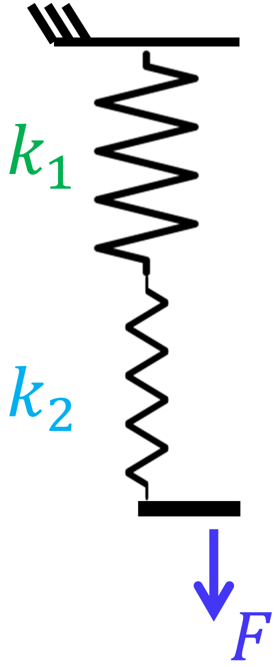
↓

*Dominated by the strongest element*

$(k_{eff} > \max(k_1, k_2))$

$$k_1 > k_2$$

## Series Arrangement



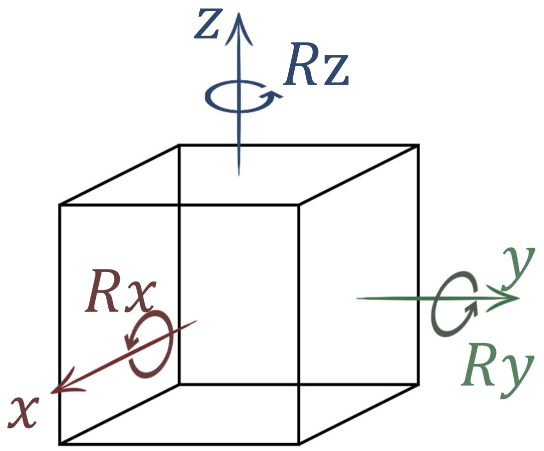

$$k_{eff} = \left(\frac{1}{k_1} + \frac{1}{k_2}\right)^{-1}$$

↓

*Dominated by the weakest element*

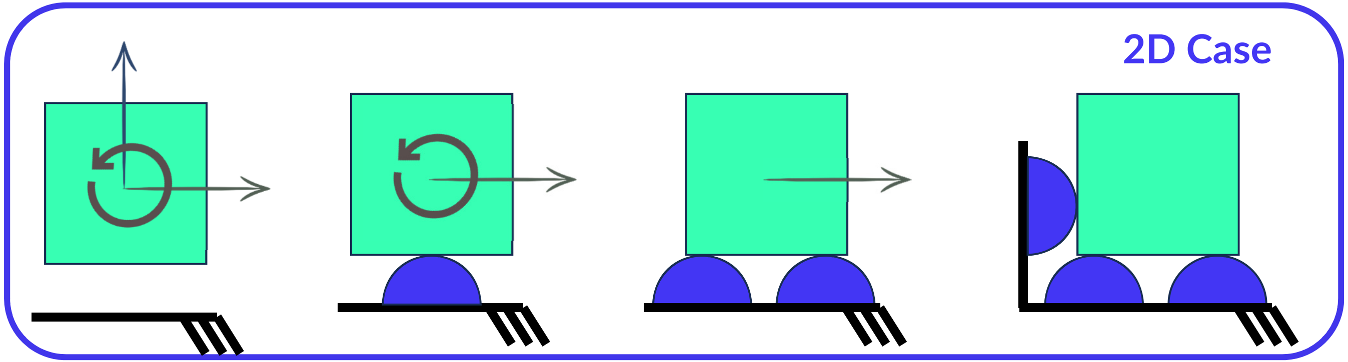
$(k_{eff} < \min(k_1, k_2))$

# 2.3. Mechanical: Control of Degrees of Freedom (DoF)




**Restriction of Degrees of Freedom by single-point contact:**

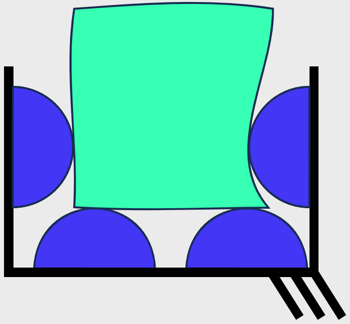
- Hertz contact theory
- Friction/preload based
- Limited stiffness

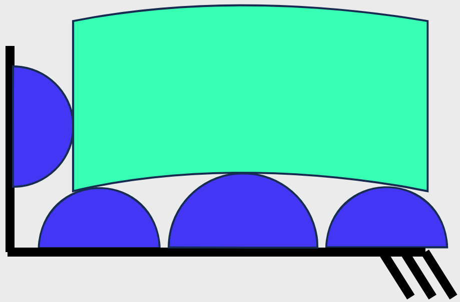



*Overconstraining*

=

*deformation*





# 2.3. Mechanical: Bearings

and many others...

**Ball Bearings**

[SKF]

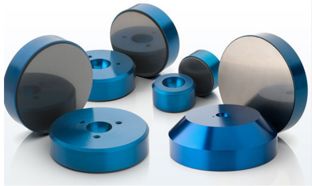
**Roller Bearings**

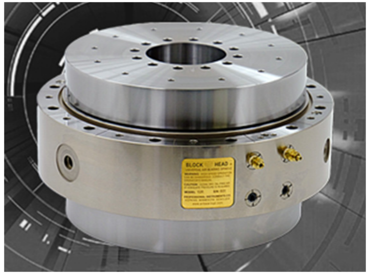
**Needle Bearings**

**Linear Air Bushings**

[Newway]

**Flat Air Bushings**



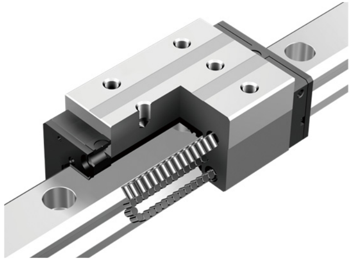


**Air Bearing**

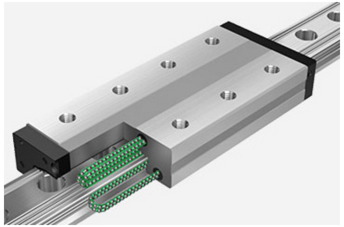
**Spindles**

[Professional Instruments]

**Needle Linear Guides**



[THK]



**Ball Linear Guides**

[SKF]

**Linear Ball Bush**

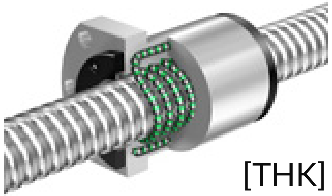
**Critical aspects**

- Stiffness
- Motion errors
- Lubrication
- Friction
- Preload
- Noise levels
- Non-linearities
- Vacuum compatibility
- Temperature compatibility

# 2.3. Mechanical: Transmissions

and many others...

**Ball Bearings**



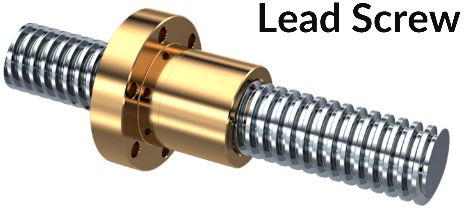
[THK]

**Screw Transmissions**

[Rollvis]

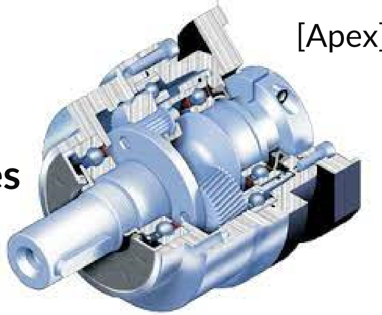
**Rack-Pinion Sets**

**Square/Trapezoidal Lead Screw**



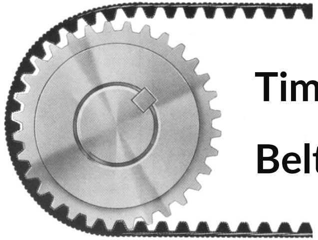
**Gearboxes**

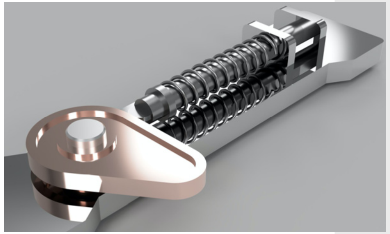
[Apex]



**Worm-gear sets**

**Timing Belts**





**Critical aspects**

- Stiffness
- Efficiency
- Lubrication
- Friction
- Preload
- Noise levels
- Non-linearities
- Vacuum compatibility
- Temperature compatibility

**Cams**

[Autodesk]

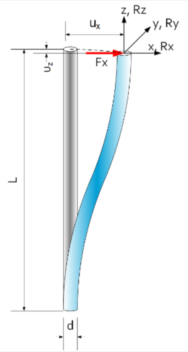
# 2.3. Mechanical: Flexural Mechanisms

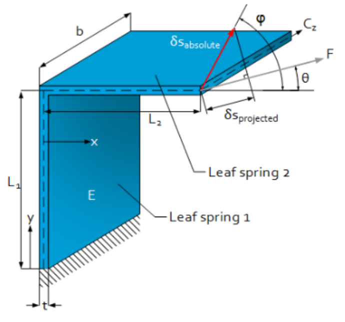
**PROs**

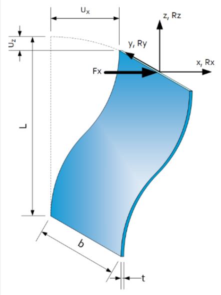
- Predictable behavior/modeling
- Less dependent of friction
- Higher repeatability and resolution (reduced friction effects)
- Free of lubrication
- Lower (or negligible) level of maintenance

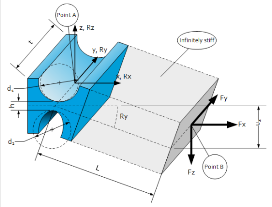
**CONs**

- Limited motion range
- Limited load capacity
- Non-linear behavior





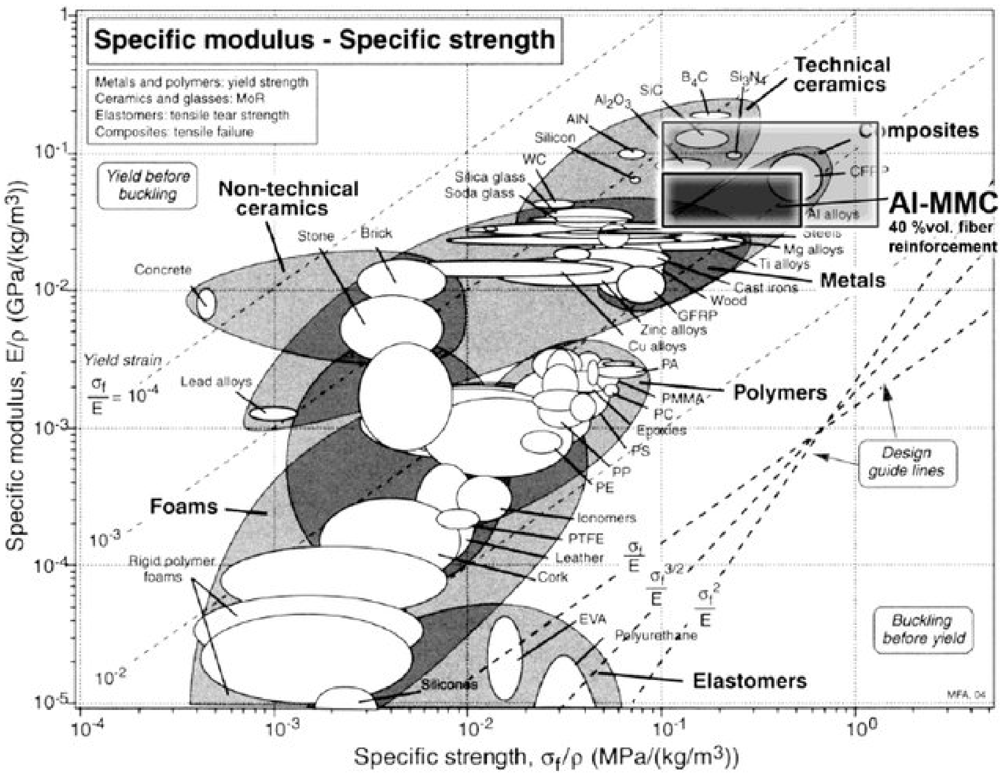



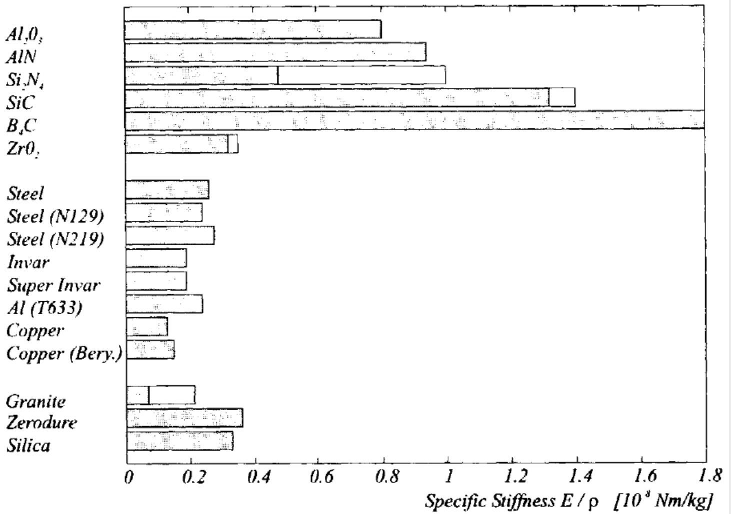


Images by:

https://www.jpe-innovations.com/precision-point/

# 2.3. Mechanical: Material Properties




T. Ruijl (2001)

https://doi.org/10.4028/www.scientific.net/kem.425.217

**Parameters of interest:**

- Elastic modulus
- Yield strength
- Density
- Vacuum compatibility

# 2.3. Mechanical: Actuators

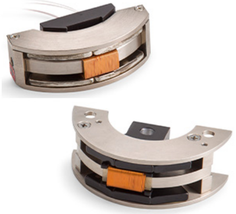
and many others...

**Piezo Stacks**

[PI]


**Voice-coil Actuators**

[Akribis]

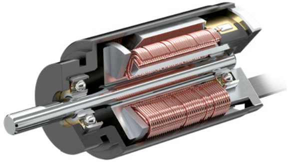


[Sensata]

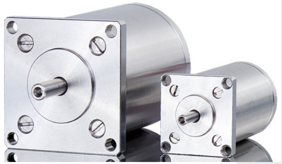
**Piezo Walkers**


[PI]

**Stepper Motors**



[Faulhaber]



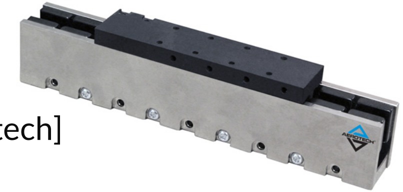
[Phytron]

**Picomotors**


[JPE]


[Newport]

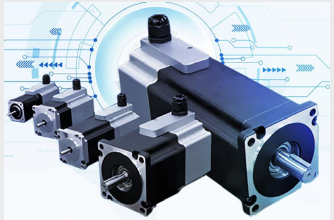
**Linear Motors**



[Aerotech]

**Critical aspects**

- Actuation principle
- Force levels
- Actuation range
- Noise levels
- Non-linearities
- Vacuum compatibility
- Temperature compatibility



**Servo Motors**

[Aerotech]

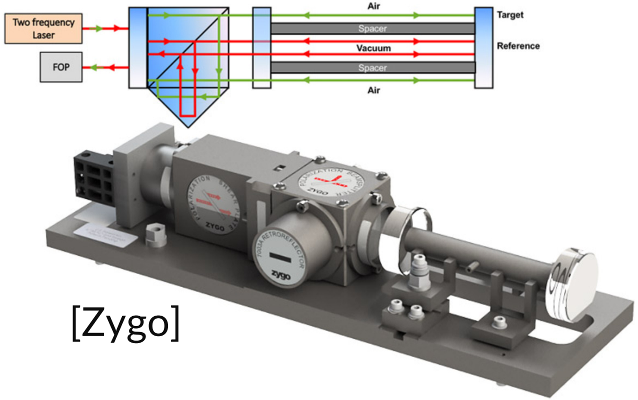
# 2.3. Mechanical: Sensors

and many others...

### Capacitive Probes

[Lion/IBS]

### Laser Interferometers

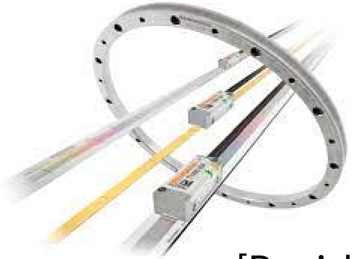


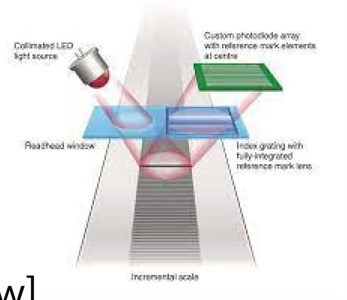

[Zygo]

### Accelerometers


[Kistler]

### Optical Encoders



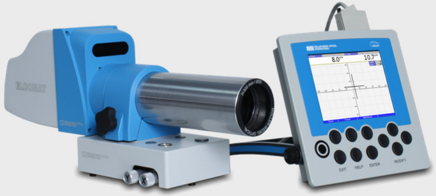


[Renishaw]

### Critical aspects

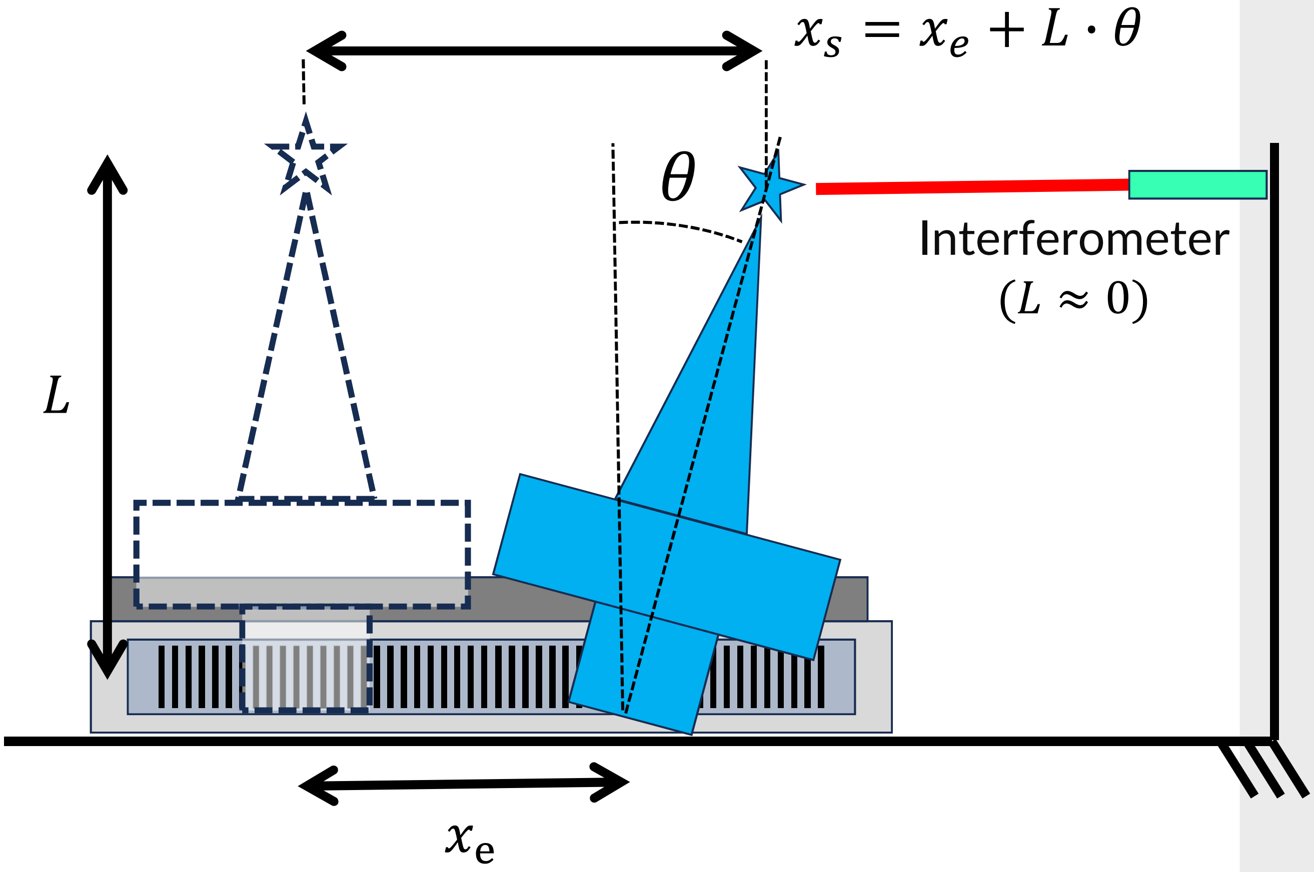
- Absolute vs Relative
- Measurement range
- Communication protocol
- Measurement bandwidth
- Noise levels
- Non-linearities
- Vacuum compatibility
- Temperature compatibility

### Autocollimator



[Möller Wedel]

# 2.3. Mechanical Metrology: Abbé




E.g.:

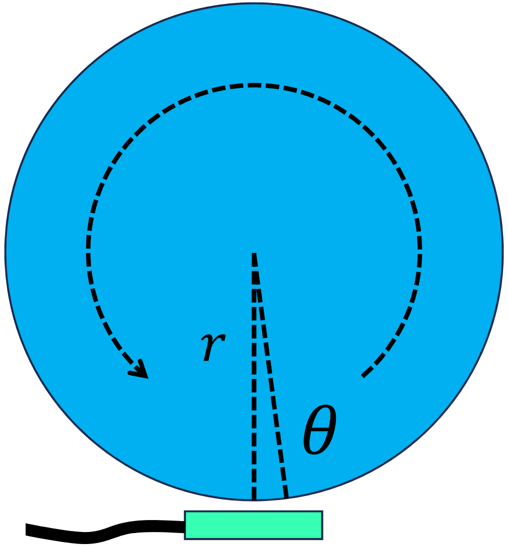
- $L = 25\ mm$
- $\theta = 1\ \mu rad$

$\boldsymbol{\epsilon = 25\ nm}$**!**

**Options:**

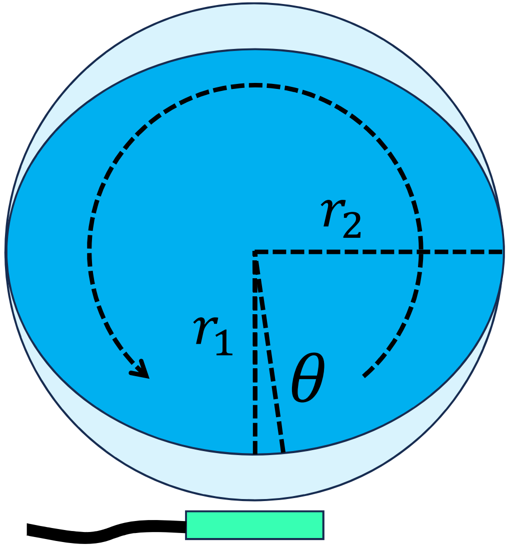
- Reduction of lever-arms as much as possible;
- Measurement of additional DoFs;
- Calibration.

# 2.3. Mechanical Metrology: Angular Measurements



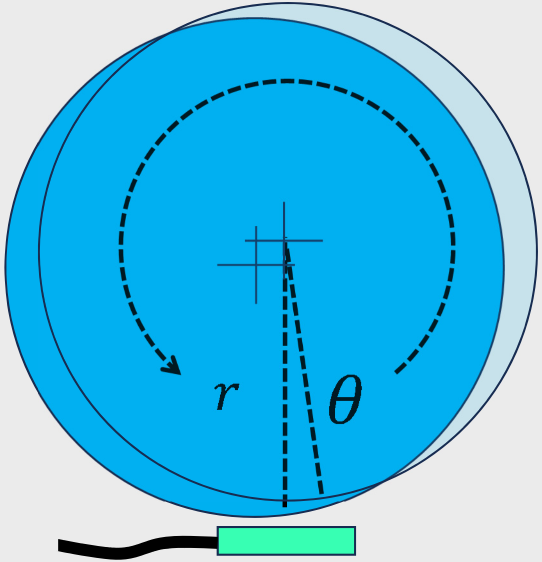

Encoder Head

$$\theta = x_e / r$$



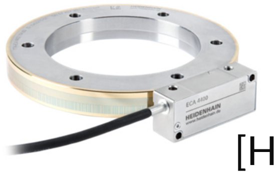

Encoder Head

$$\theta = x_e / r(\theta)$$




Encoder Head

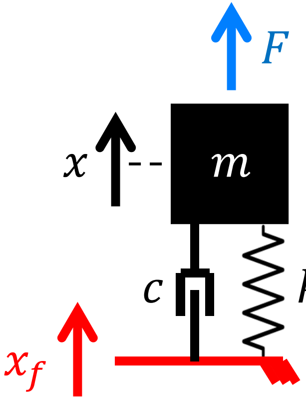
$$\theta = x_e / r(\theta)$$



[Heidenhain]

***Options:** use of multiple heads, calibration, etc.

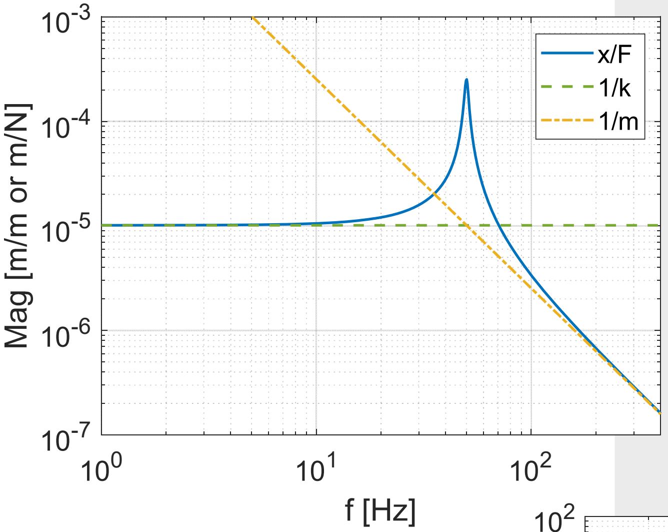
# 2.4. Dynamics



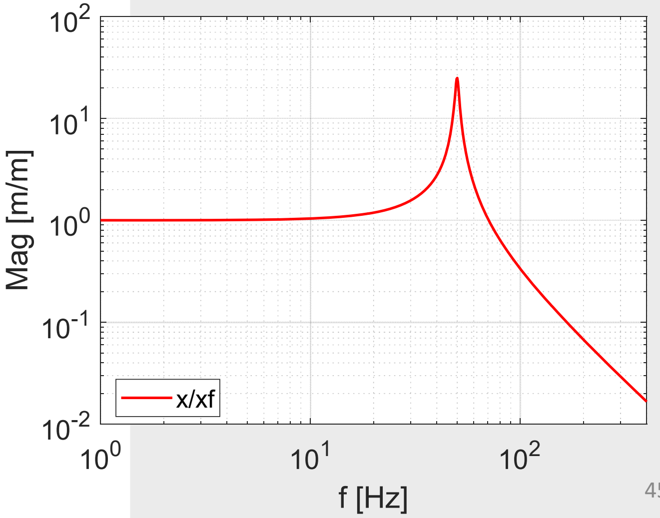

$$m\ddot{x} + c\dot{x} + kx = F + c\dot{x}_f + kx_f$$

Laplace's Transform

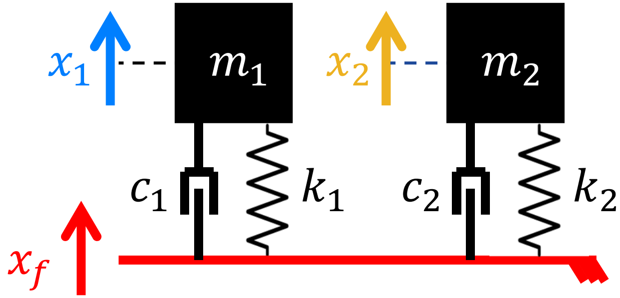
$$ms^2x + csx + kx = F + csx_f + kx_f$$

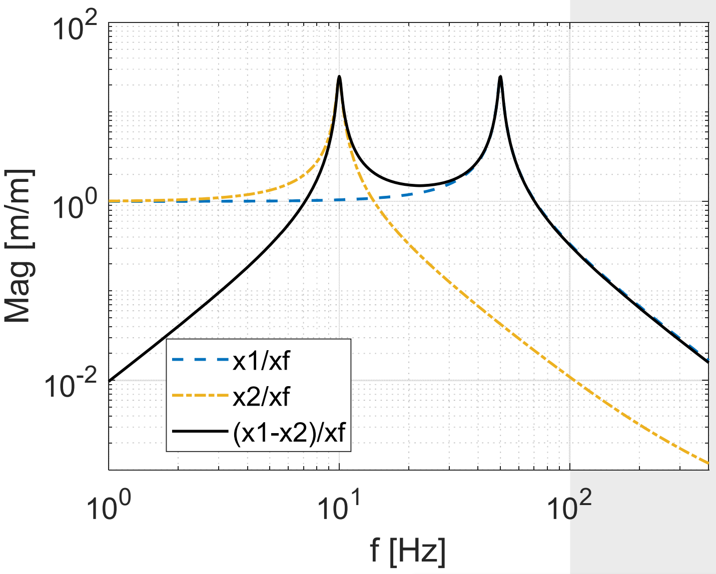



- Shift peaks beyond disturbance sources
- Work on damping (when possible)



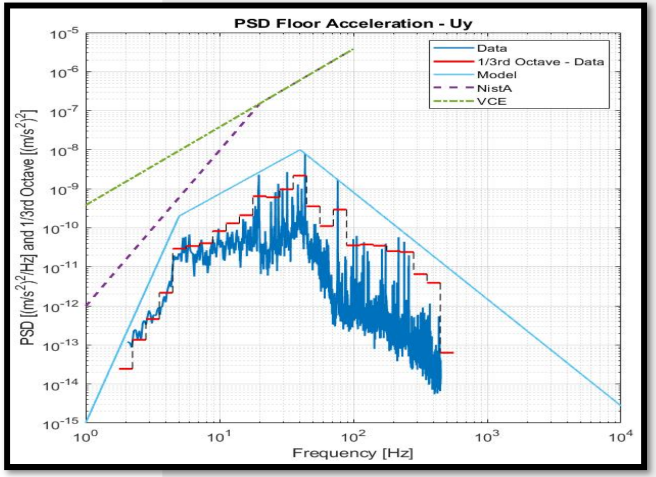
# 2.4. Dynamics



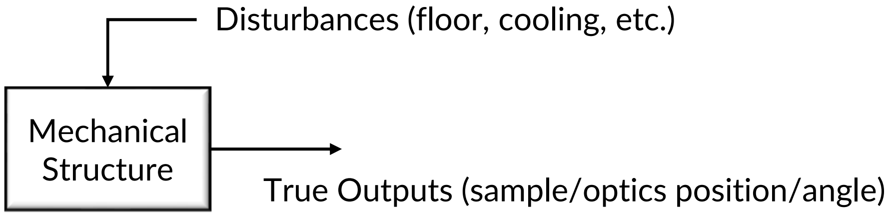

**E.g.:**

- m1: lens (50 Hz)
- m2: sample (10 Hz)

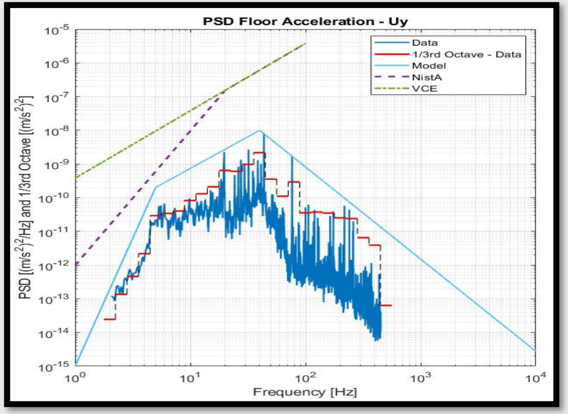


# 2.4. Dynamics: Control

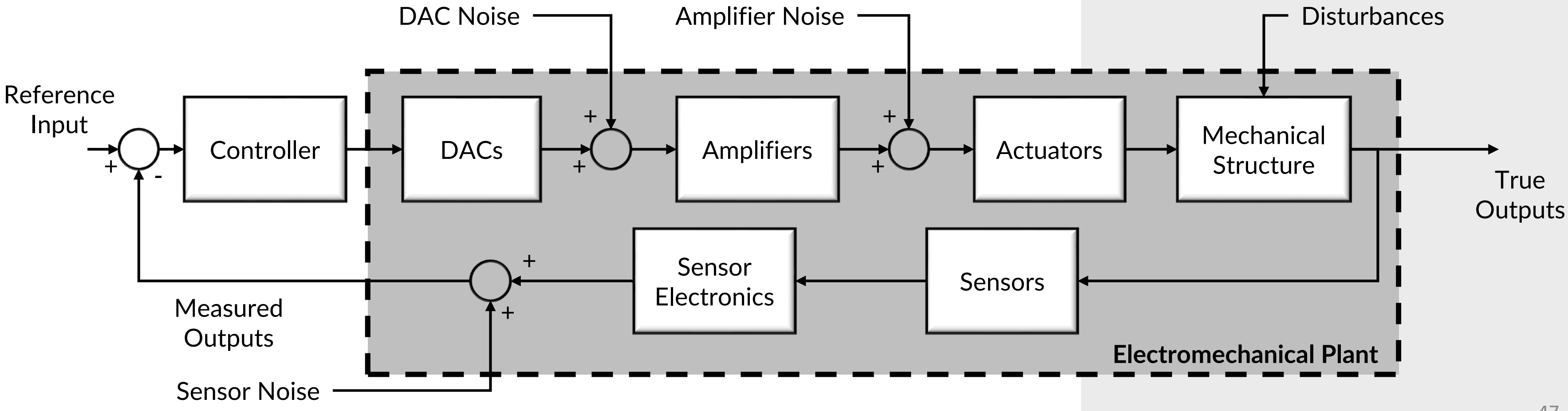
**Passive approach:**



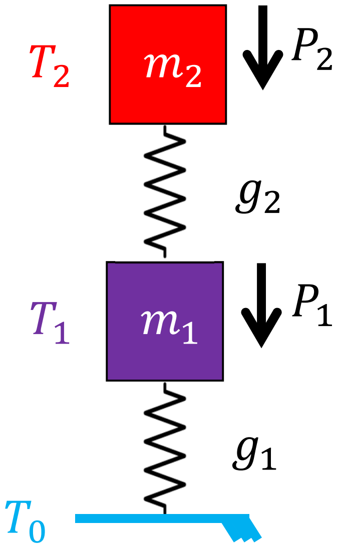

Example:




**Active approach:**

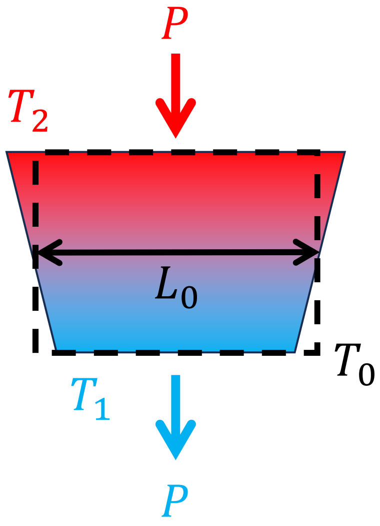


# 2.5. Thermal: Fundamentals




Stead-state approximation:

$$P = g \cdot \Delta T$$



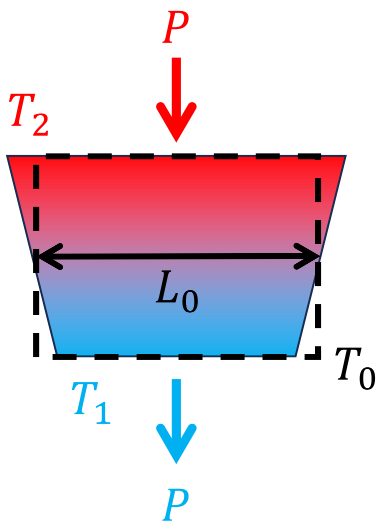

Expansion approximation:

$$\Delta L = L_0 \cdot \alpha \cdot \Delta T$$

**Critical aspects:**

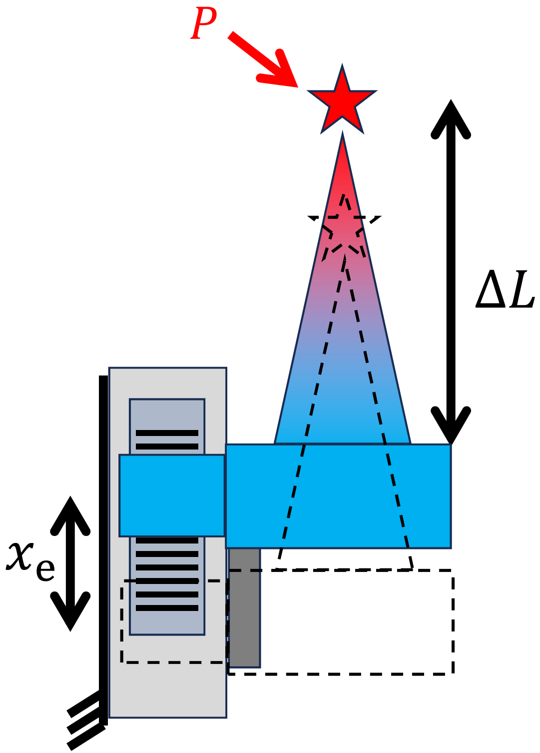
- **Heat sources:** beam, motors, sensors, environment, people ...
- **Heat transfer mechanisms:** conduction, convection and radiation
- **Thermal expansion effects**
- **Measurements**

# 2.5. Thermal: Fundamentals




Expansion approximation:

$$\Delta L = L_0 \cdot \alpha \cdot \Delta T$$

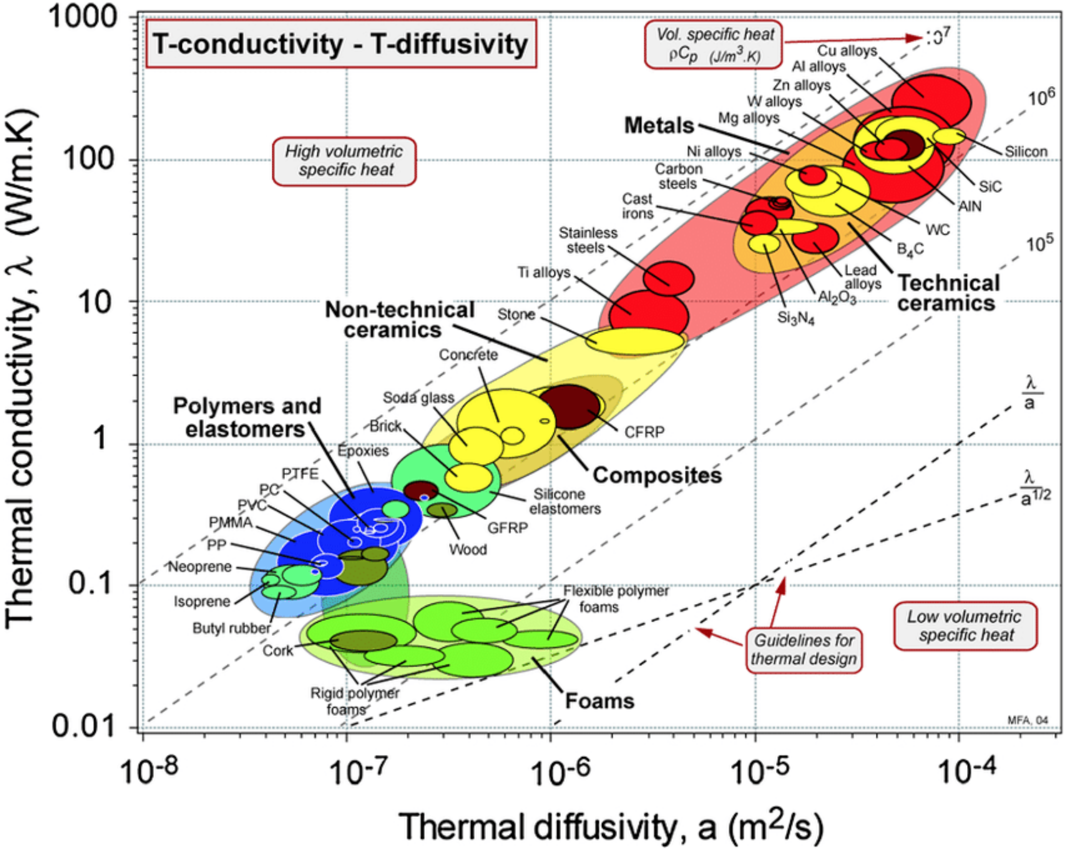



E.g.:

- $L = 25\ mm$
- $\Delta T = 0.1\ K$
- $\alpha = 20\ \mu m/m.K$ (Al)

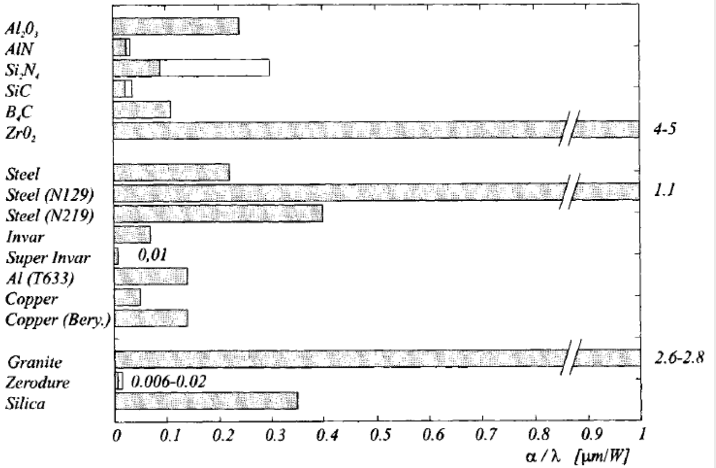
$\mathbf{\Delta L = 50\ nm!}$

# 2.6. Thermal: Material Properties




(doi: 10.1007/s10704-020-00487-7) [$\lambda/(\rho \cdot c_p)$ (temperature wavefront propagation)]

**Bending Sensitivity**




T. Ruijl (2001)

**Parameters of interest:**

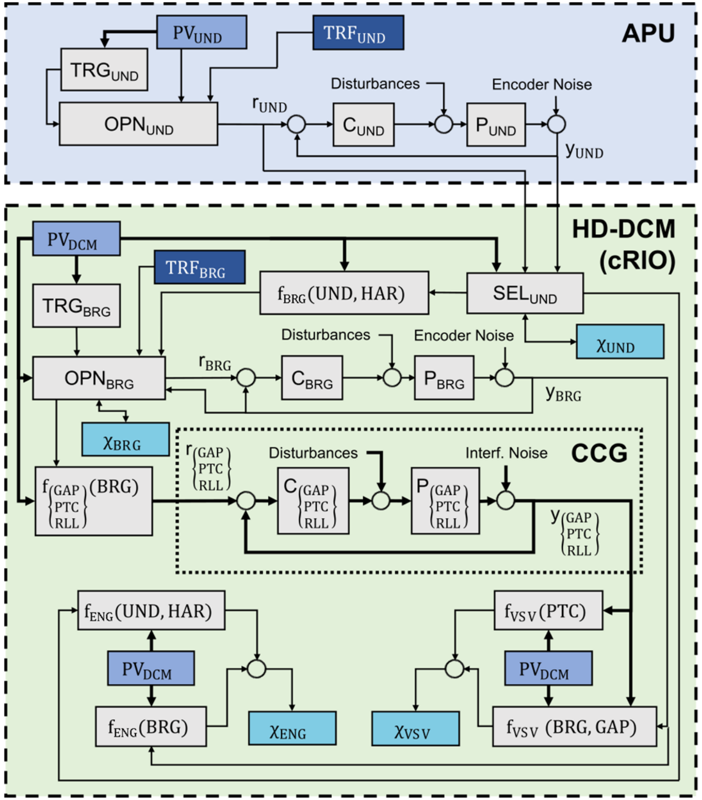
- Coefficient of thermal expansion ($\alpha$)
- Thermal conductivity ($\lambda$)
- Coefficient of heat capacity ($c_p$)
- Density ($\rho$)

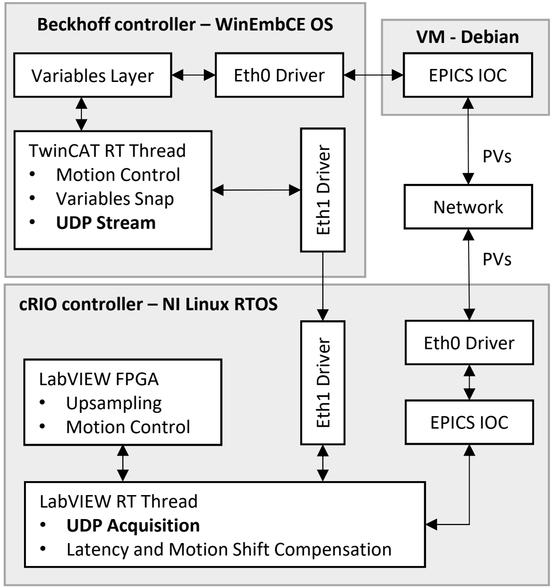
# 3. Beamline Integration

3.1. Double-Crystal Monochromator

3.2. Scanning Microscopes

# 2.6. Integration: DCM (spectroscopy)



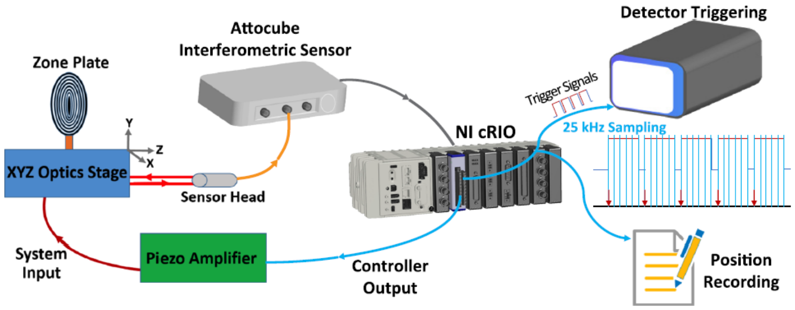




(doi:10.1107/S1600577522010724)

**Critical aspects:**

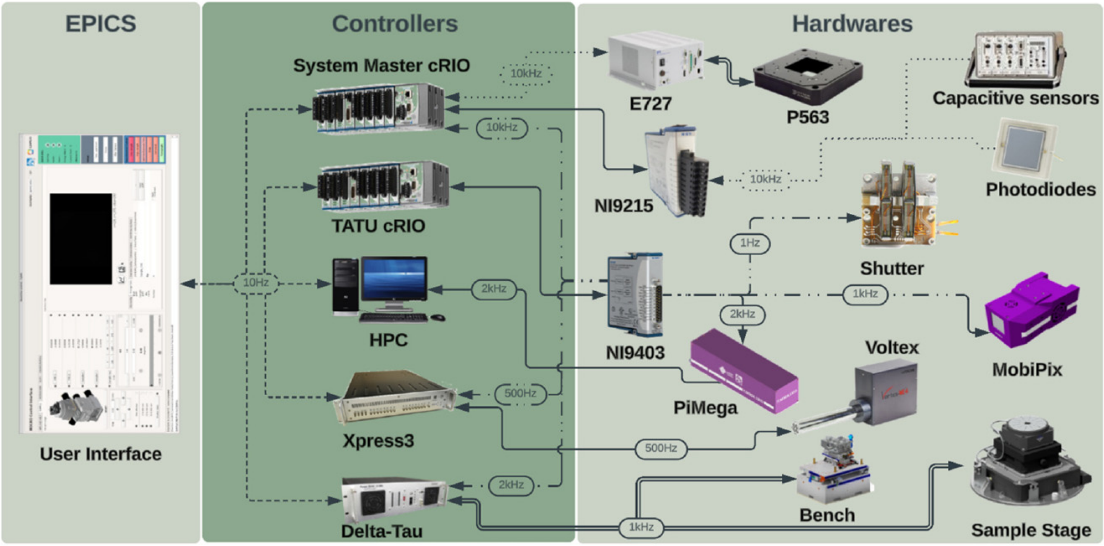
- Multiple instruments
- Master-follower architecture
- Different dynamic performances
- Different protocols
- kHz rates
- Synchronization
- Matching trajectories
- Control complexity

# 2.6. Integration: Scanning Microscopes




(doi: 10.1063/1.5103173)

(doi: 10.1016/ j.elspec.2023.147340)




**Critical aspects:**

- Multiple instruments
- Multiple protocols
- Central orchestrator
- kHz rates
- Synchronization
- Control complexity
- Trajectory optimization
- Software complexity
- Data storage
- Data processing

# Outline: Nanopositioning

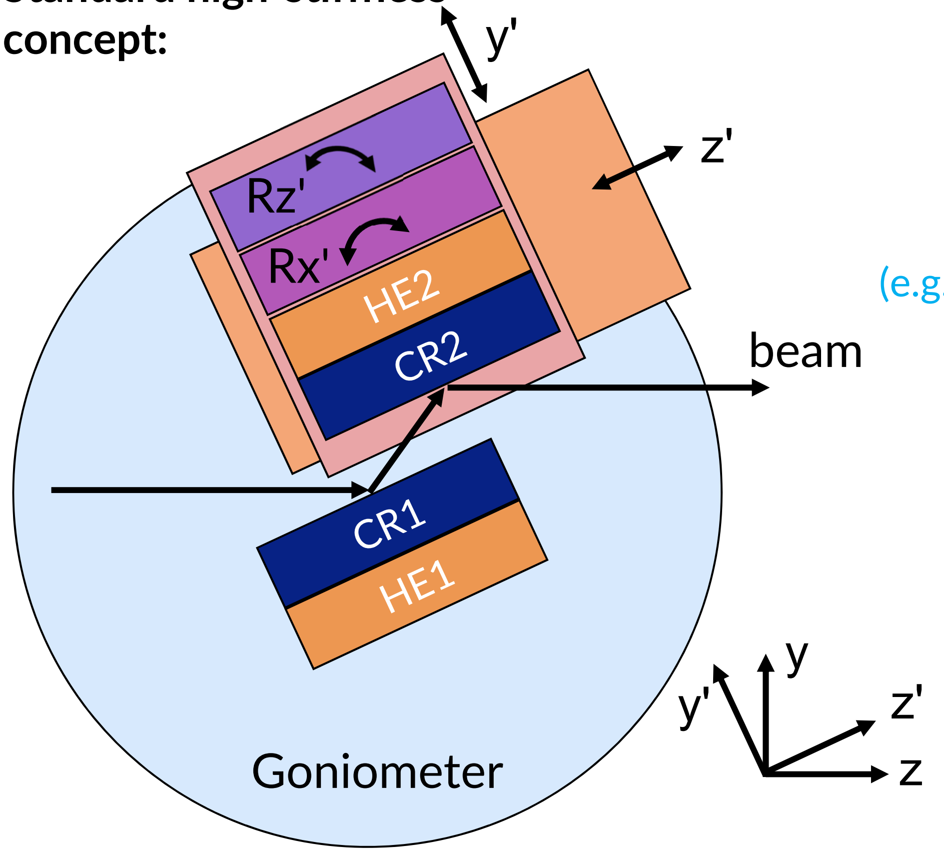
- Introduction
- Motivation
- Commercial Scenario
- Development Framework
- Examples at Sirius
- Conclusions & Perspectives

1. **HD-DCM**
2. **Mirrors**
3. **Nanoprobes**

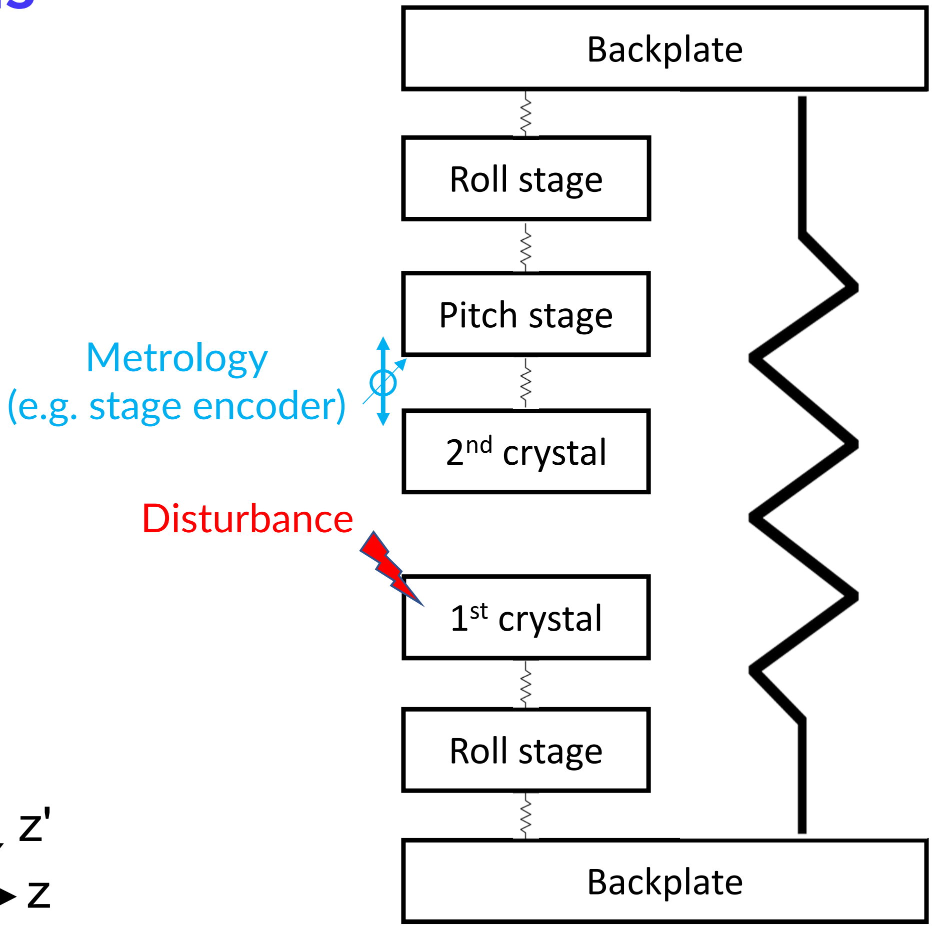
# 1. The HD-DCM

# 1. Standard DCM Designs

**Standard high-stiffness concept:**

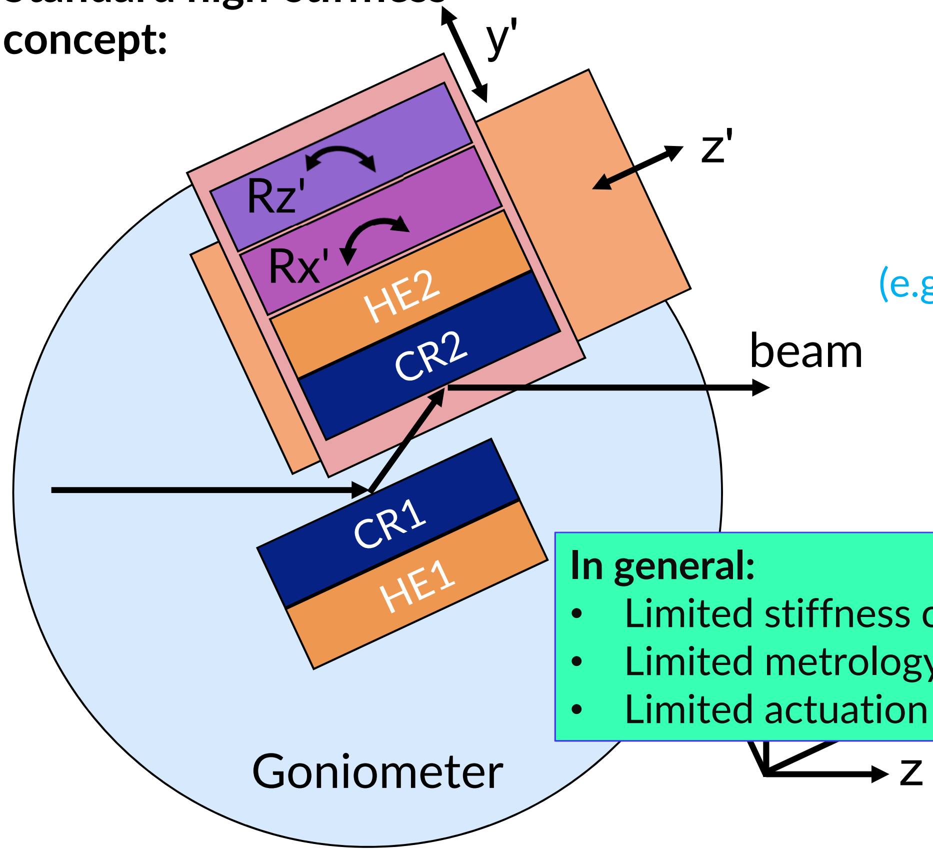



**Illustrative 1D Pitch Stiffness Model**



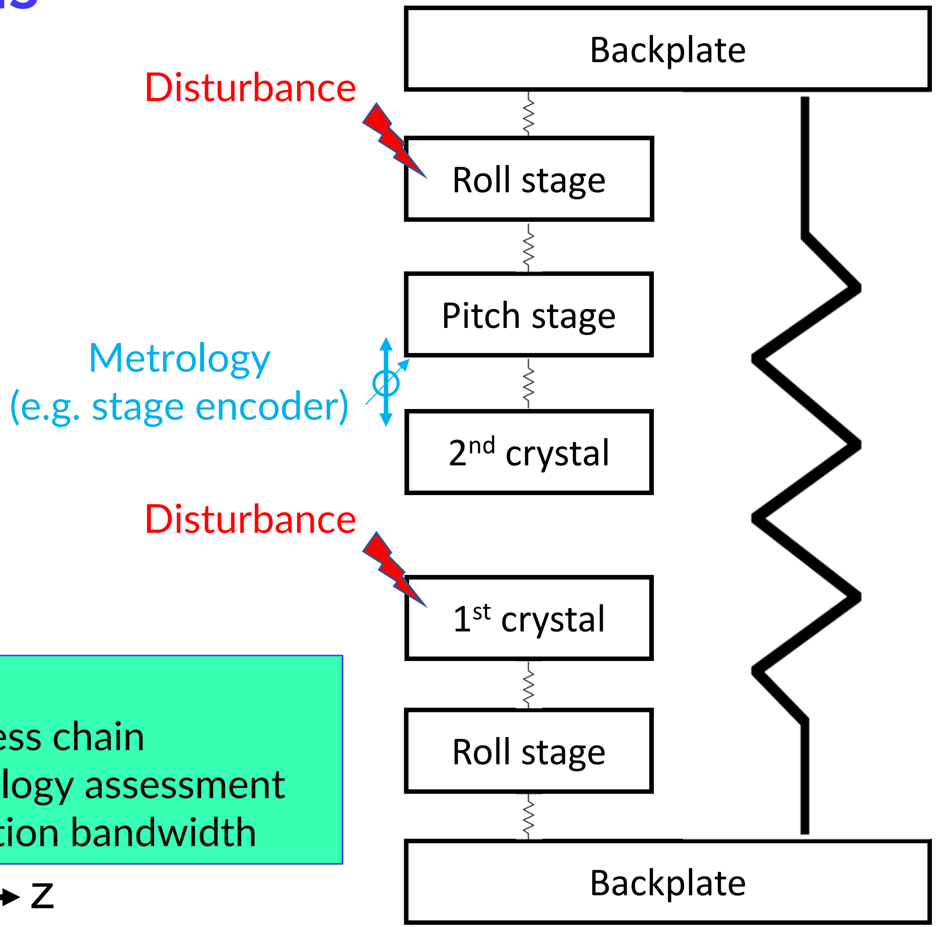
# 1. Standard DCM Designs

**Standard high-stiffness concept:**




**In general:**
- Limited stiffness chain
- Limited metrology assessment
- Limited actuation bandwidth

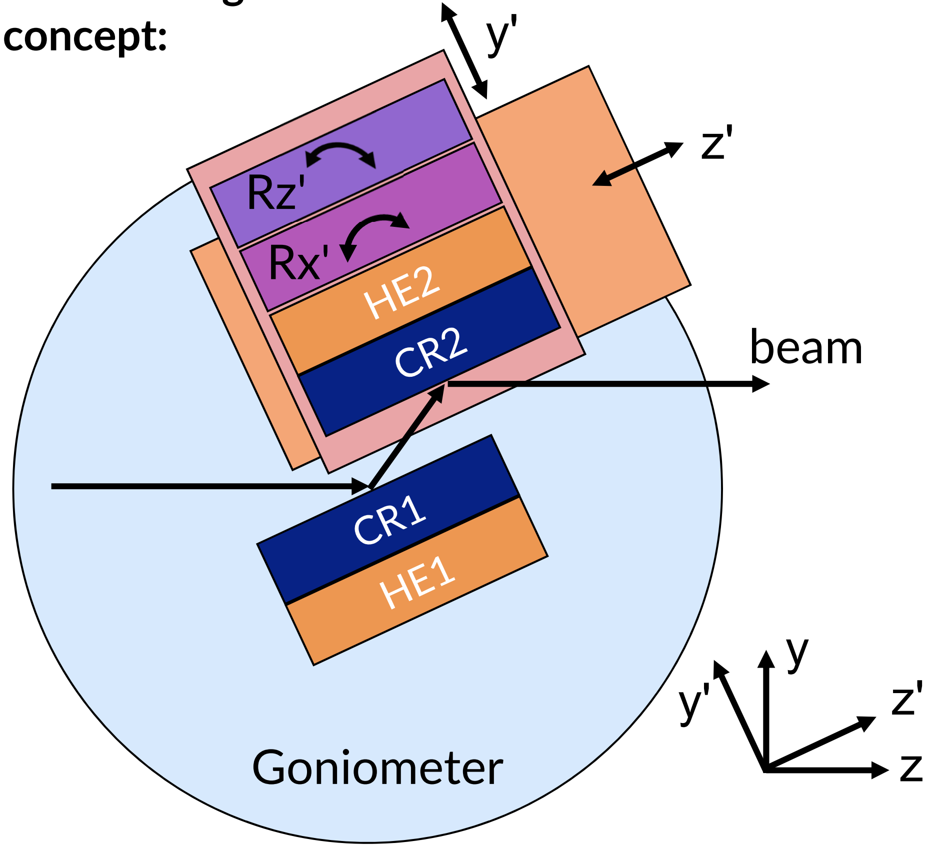
**Illustrative 1D Pitch Stiffness Model**



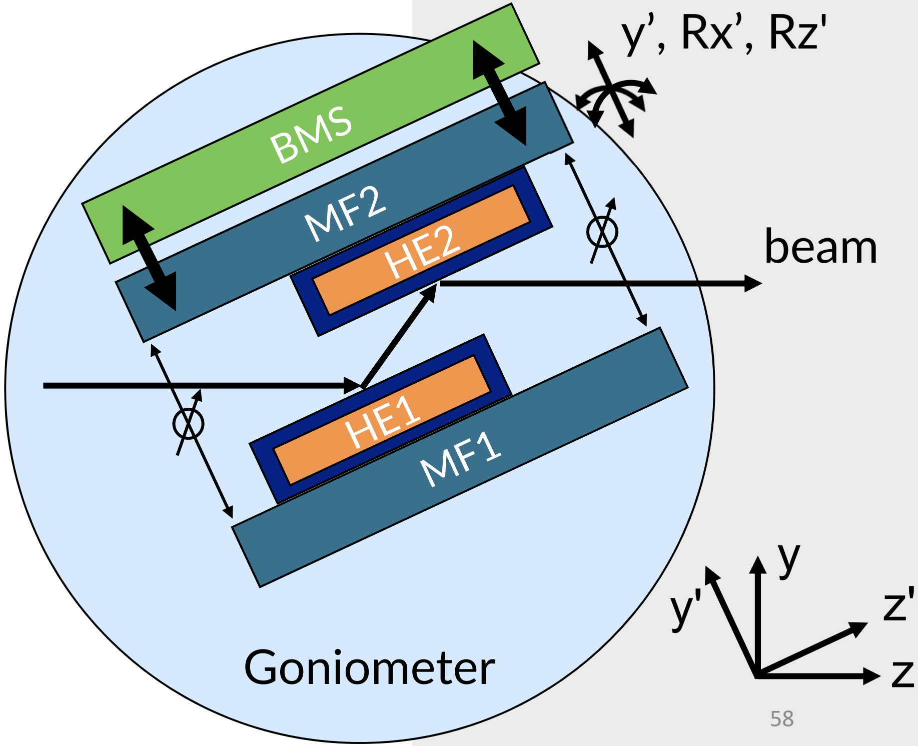
# 1. DCM Architecture Comparison

(doi:10.1088/1742-6596/2380/1/012050 )

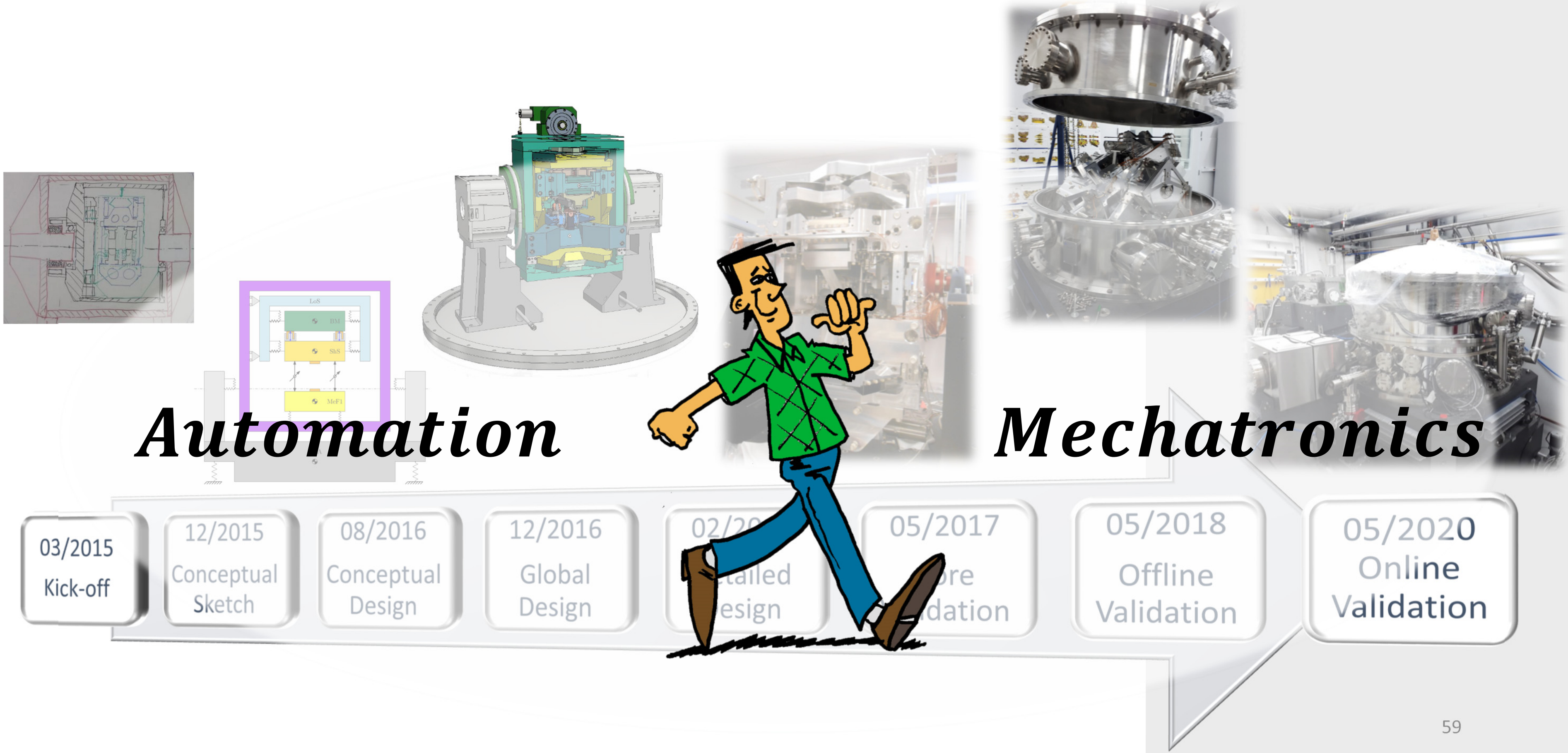
**Standard high-stiffness concept:**



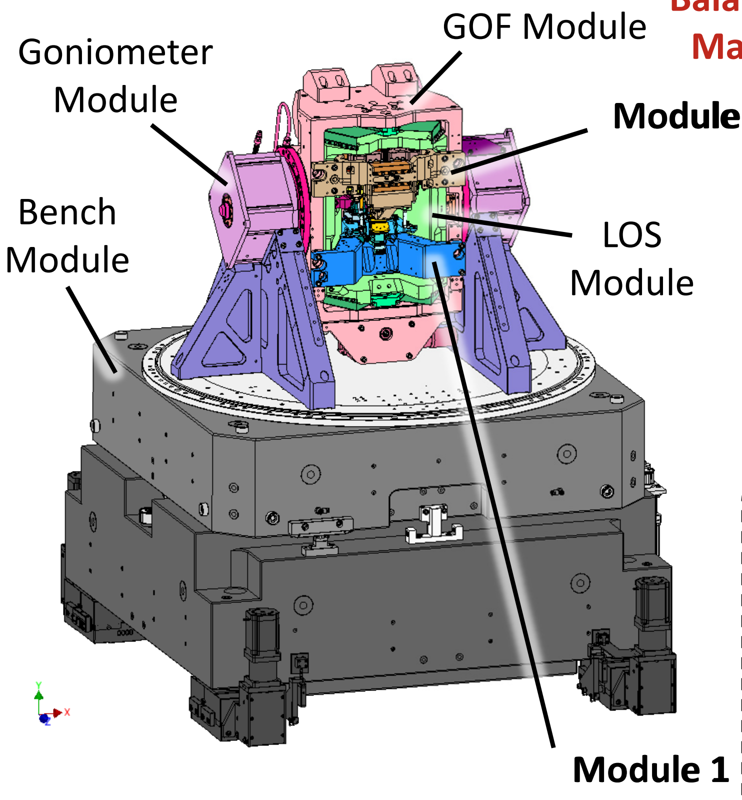

**HD-DCM mechatronic concept:**

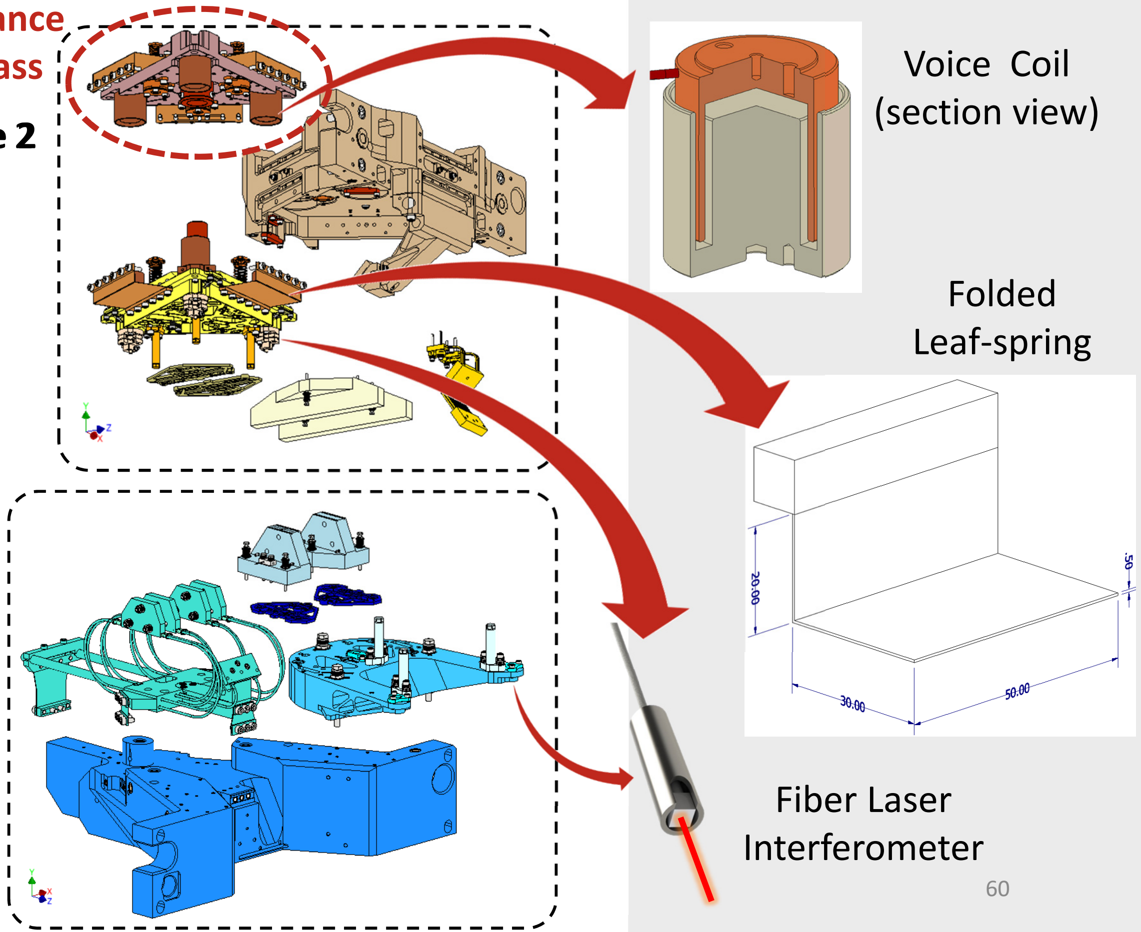


# 1. The HD-DCM Project Timeline



# 1. The HD-DCM Architecture

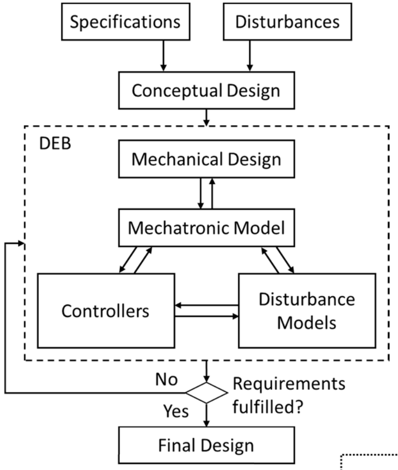


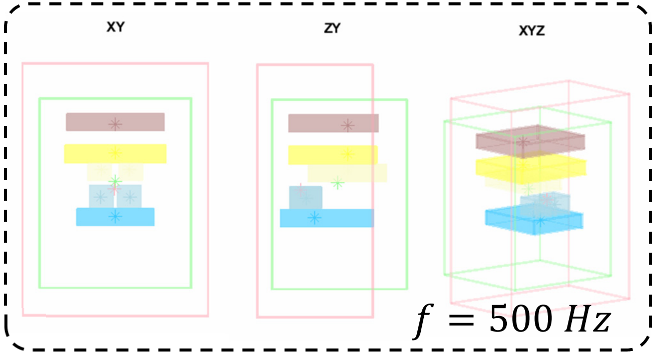

(doi: 10.1016/j.precisioneng.2022.05.009)
(doi: 10.1016/j.precisioneng.2022.04.009)

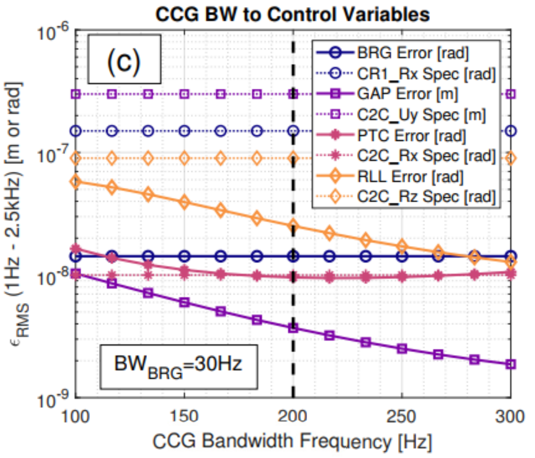
# 1. The HD-DCM Dynamic Error Budgeting

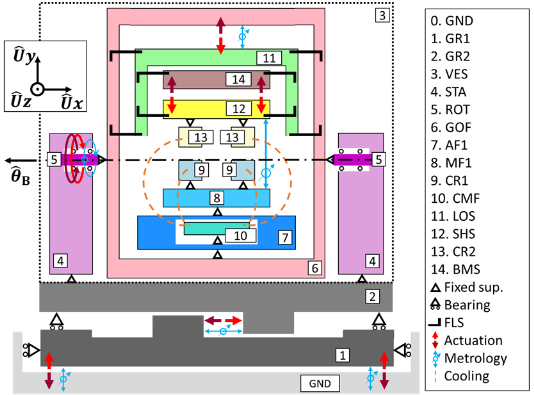
## DEB Framework



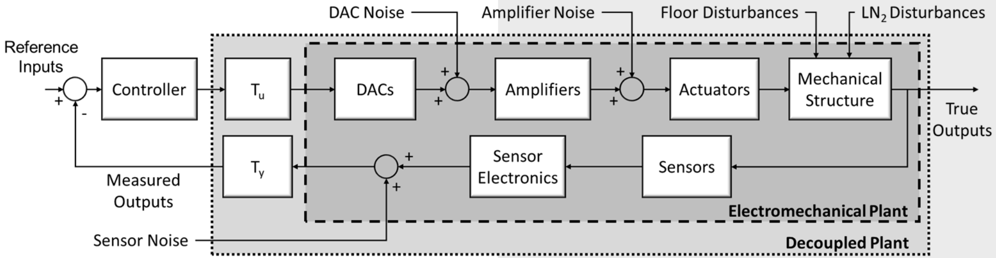

## Mode Shapes



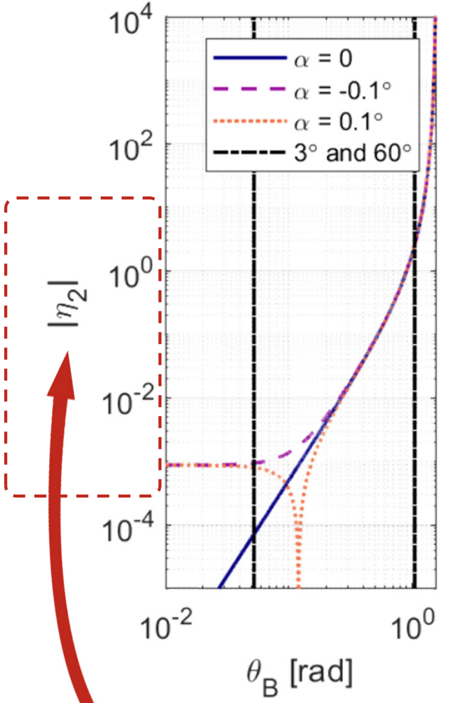

## Lumped Mass Model




## Feedback control loop schematic

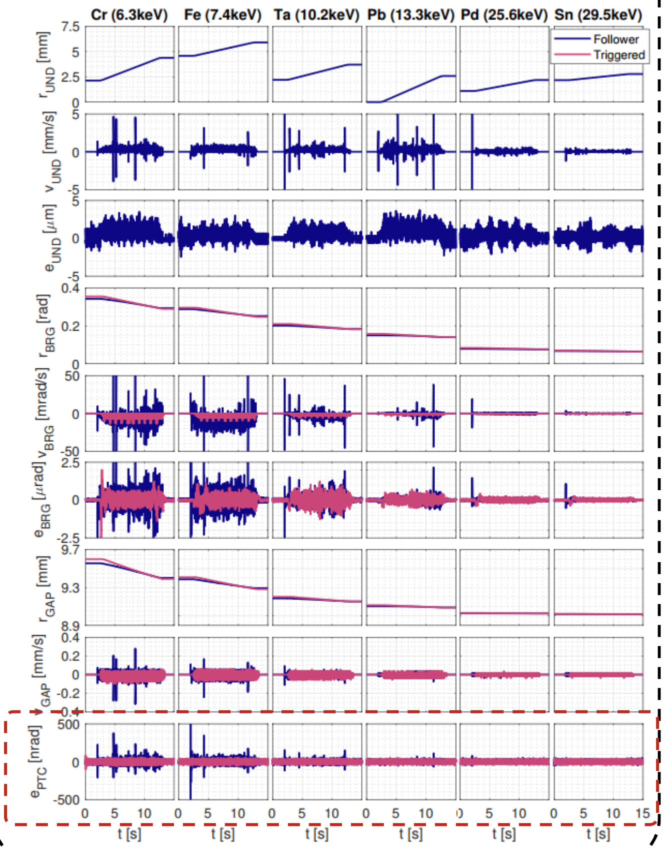
# 1. The HD-DCM Beamline Integration

## Flyscan Analysis

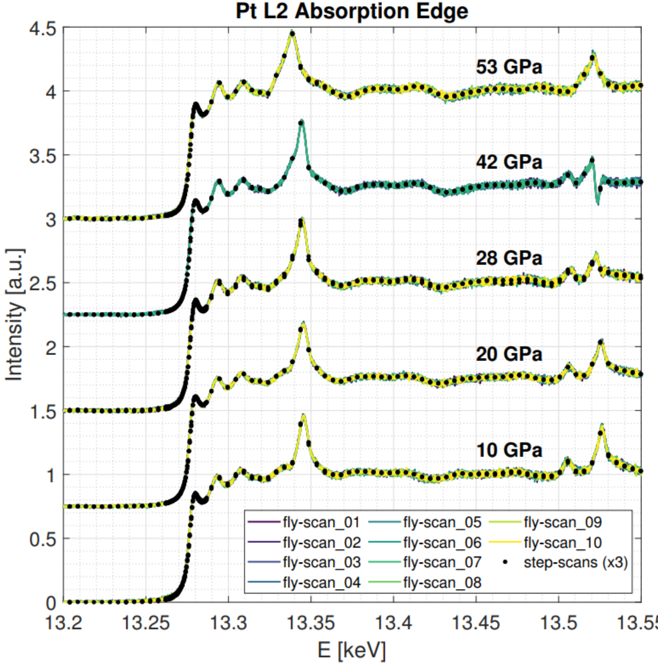



$$\frac{\partial g}{\partial t} = -\eta_2(\theta_B)\frac{2d}{nhc}\frac{H}{\cos(\alpha)}\frac{\partial E}{\partial t}$$

## Undulator-DCM Integration




## Flyscan vs Step-scan Experiment

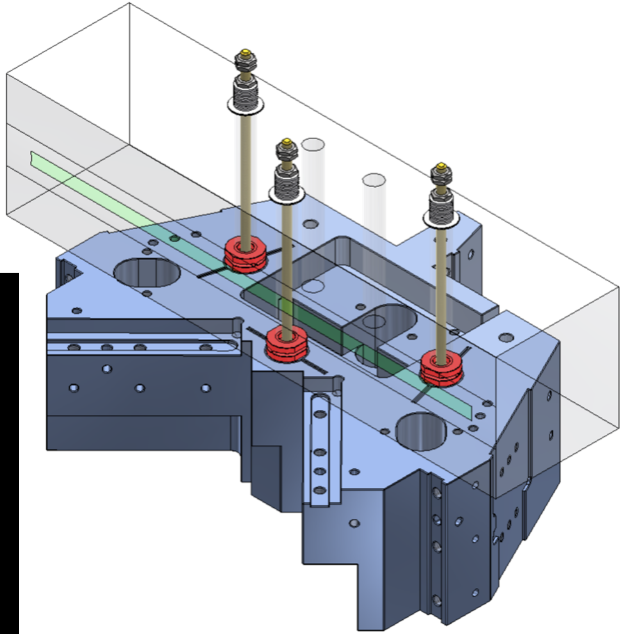


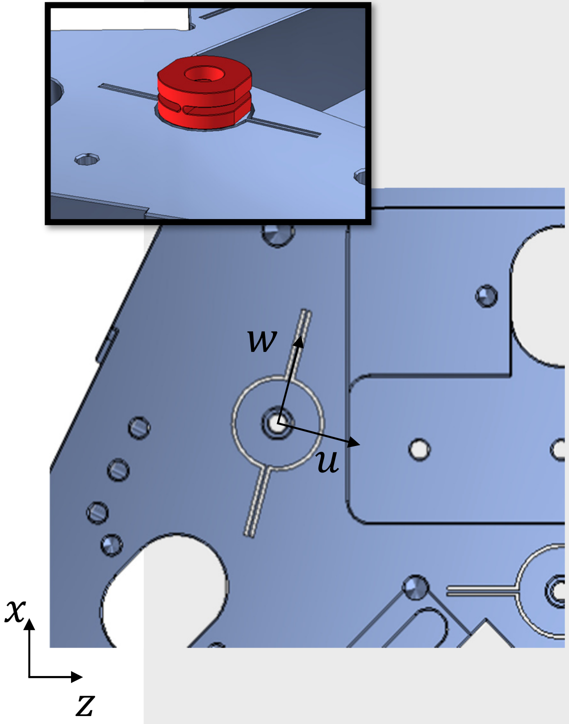

(doi: 10.1107/s1600577522010724)

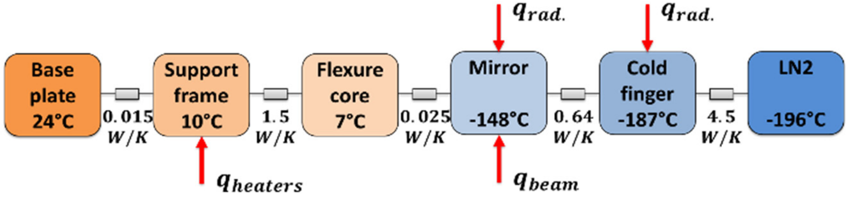
# 2. Mirror Systems

# 2. (Quasi) Isostatic Mirror Fixation

Assembly
and
thermal expansion



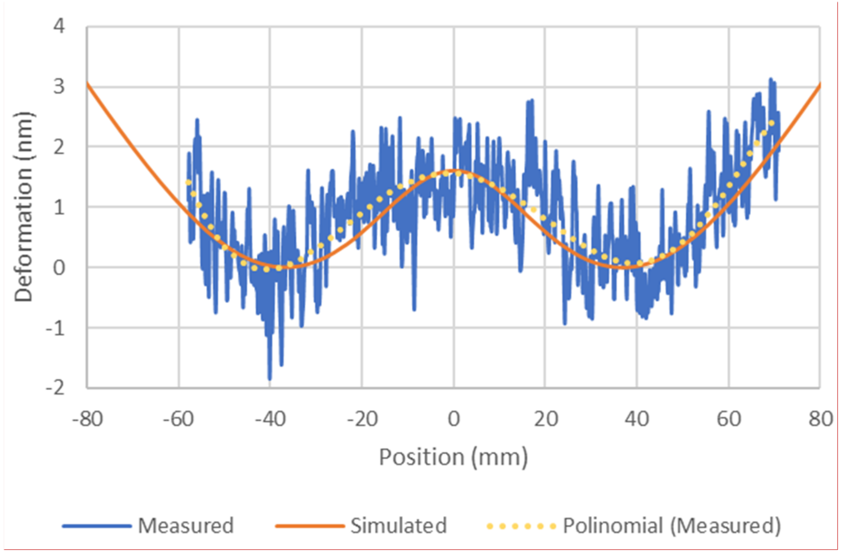


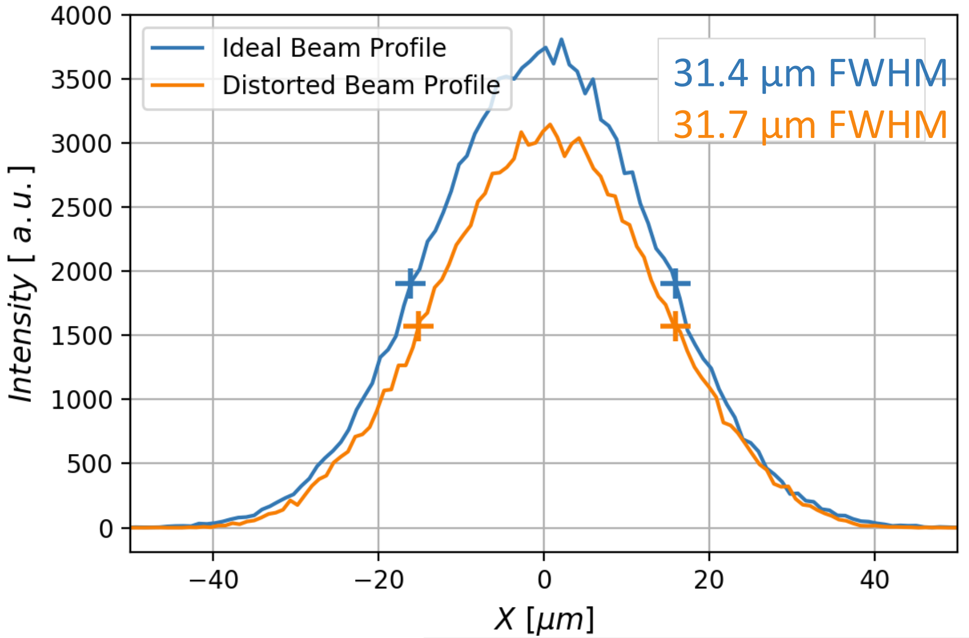

(doi: 10.1364/sxray.1991.the3)
(doi: 10.18429/JACoW-MEDSI2018-WEPH31)

# 2. Mirror Manufacturing and Fixation Effects

## Fizeau Measurements




## Beam Profile Simulations

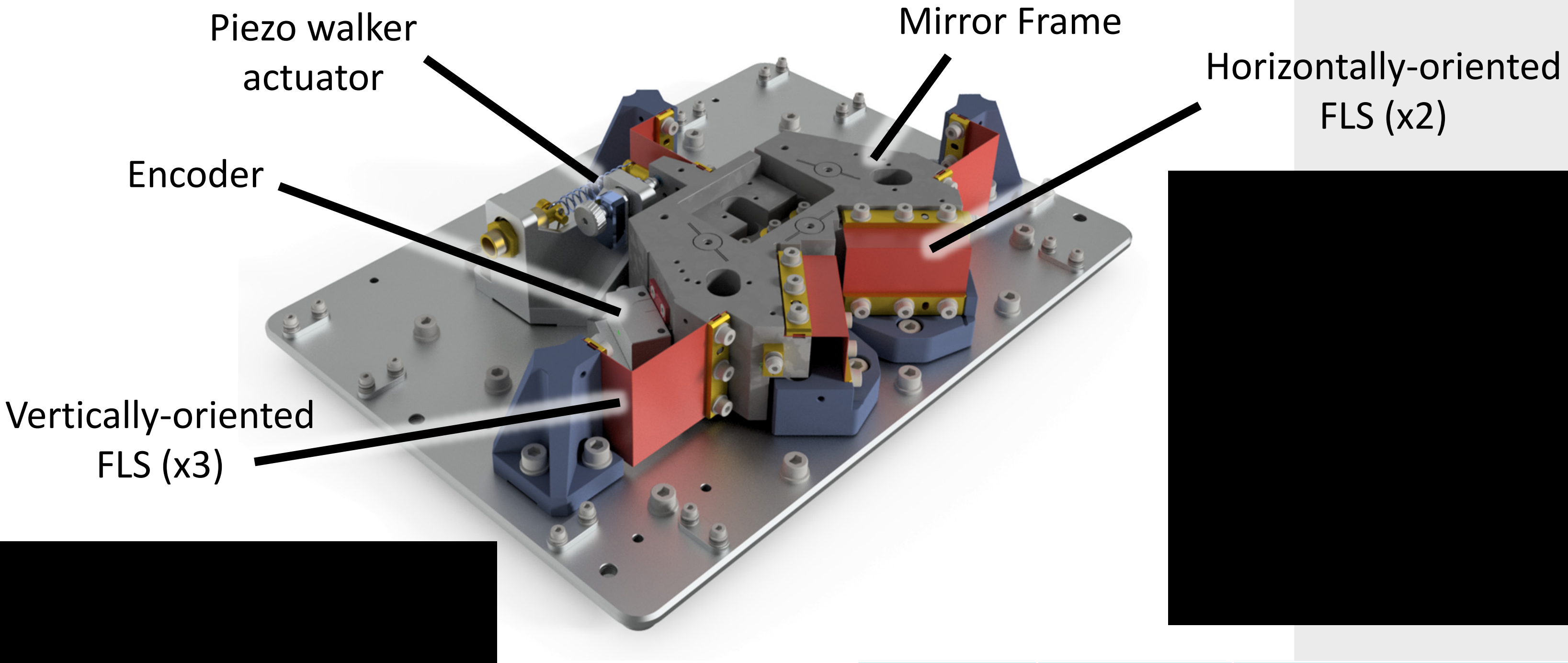



(doi: 10.1364/sxray.1991.the3)
(doi: 10.18429/JACoW-MEDSI2018-WEPH31)

- Gravity
- Thermal
- Bolt tightning

- Mirror polishing
- Manufacturing limitations

# 2. Mirror Isostatic Compliant Mechanism



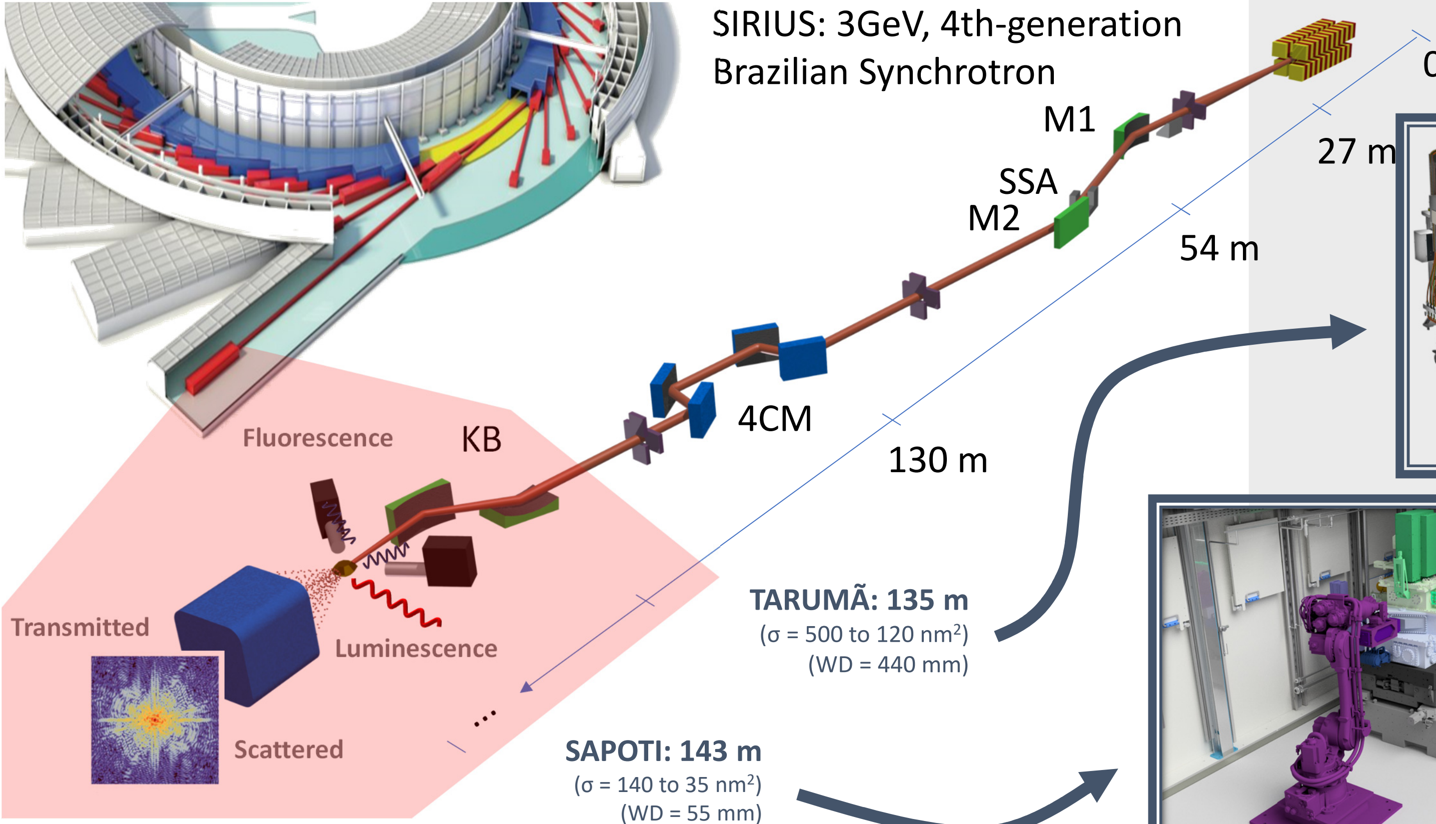

| Mode | FEA [Hz] | Experimental [Hz] |
|---|---|---|
| **1 ($T_x$)** | 249,7 | 250 |
| **2 ($R_y$)** | **312,5** | **313** |
| **3 ($T_z$)** | 342,4 | 341 |

# 3. Nanoprobes

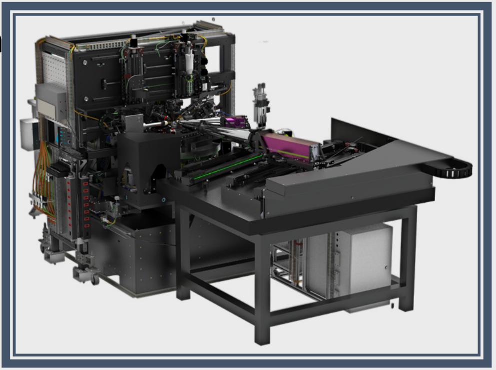
3.1. TARUMÃ

3.2. SAPOTI

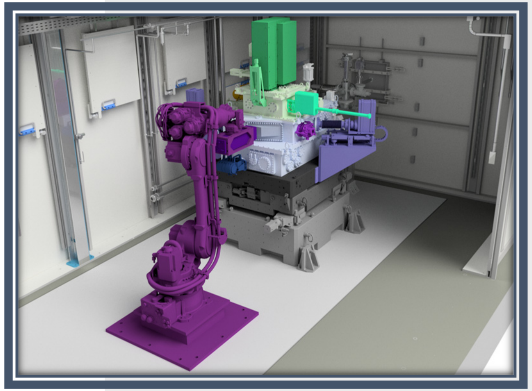
# 3. The CARNAÚBA Beamline



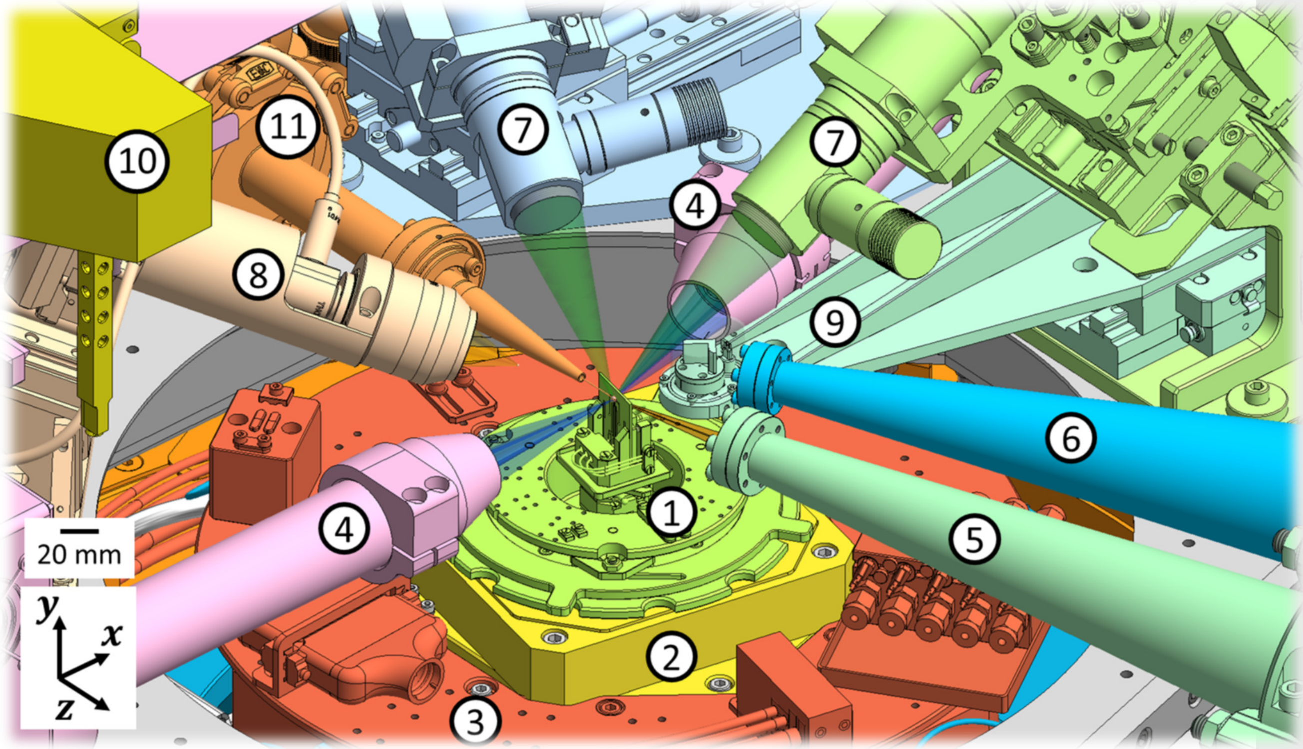

**TARUMÃ: 135 m**
($\sigma$ = 500 to 120 nm$^2$)
(WD = 440 mm)



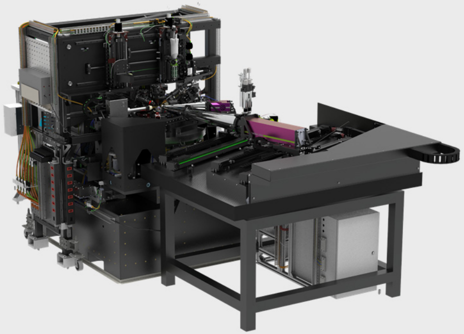
**SAPOTI: 143 m**
($\sigma$ = 140 to 35 nm$^2$)
(WD = 55 mm)



# 3.1. TARUMÃ: Overview



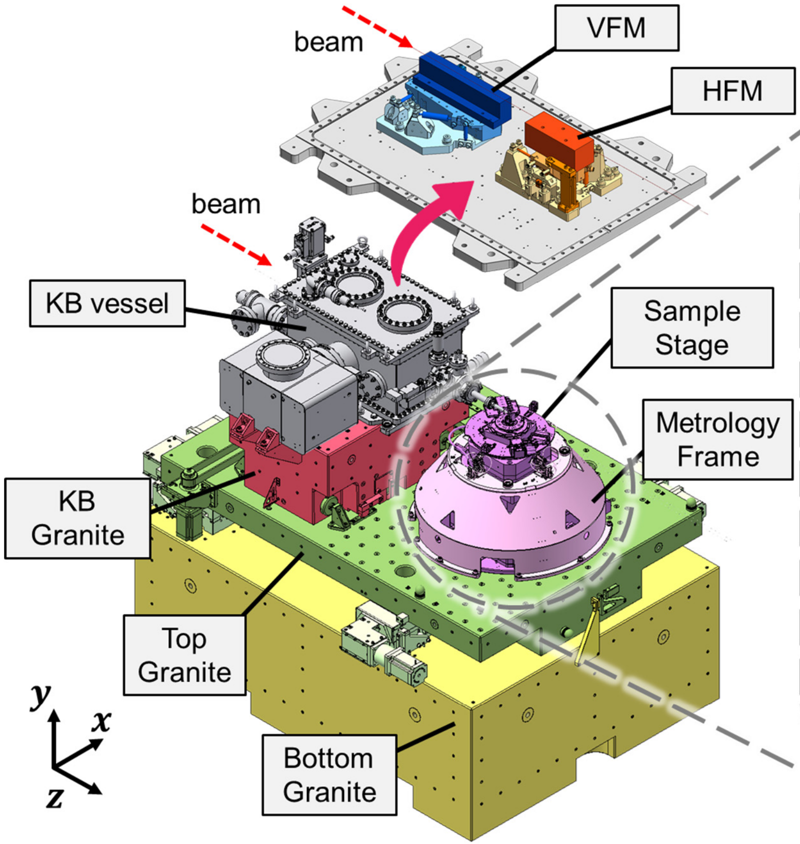

1. Sample setup;
2. XYZ piezo stage;
3. Rotary stage;
4. Fluorescence detectors;
5. Transmission area detector;
6. Diffraction area detector;
7. Optical microscopes;
8. XEOL optics;
9. Crystal analyzer;
10. Pick-and place gripper;
11. KB vessel exit port.

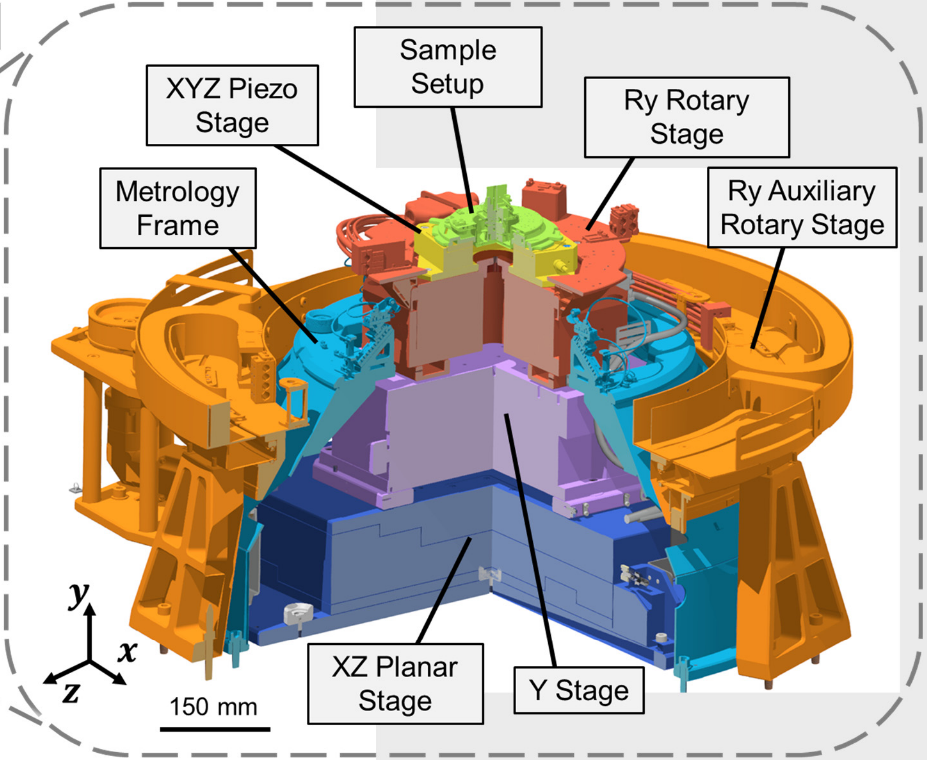


**Techniques:**

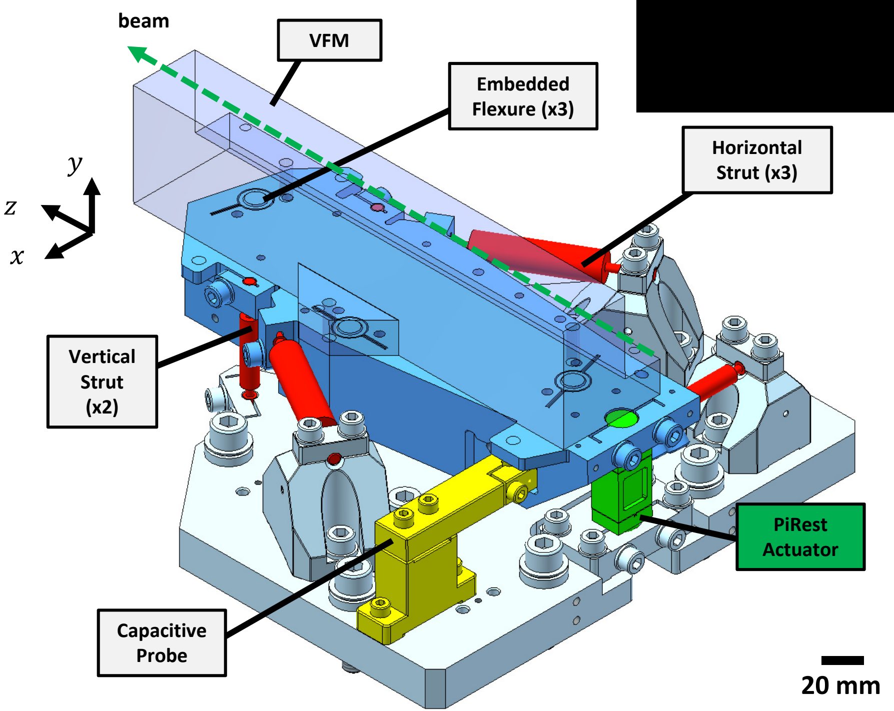
- ❑ **XRD (Diffraction)**
- ❑ **XAS (Absorption)**
- ❑ **XRF (Fluorescence)**
- ❑ **XEOL (Luminescence)**
- ❑ **Ptycho-CDI**
- ❑ **(Ptycho-)Bragg-CDI**
- ❑ **Tomography**

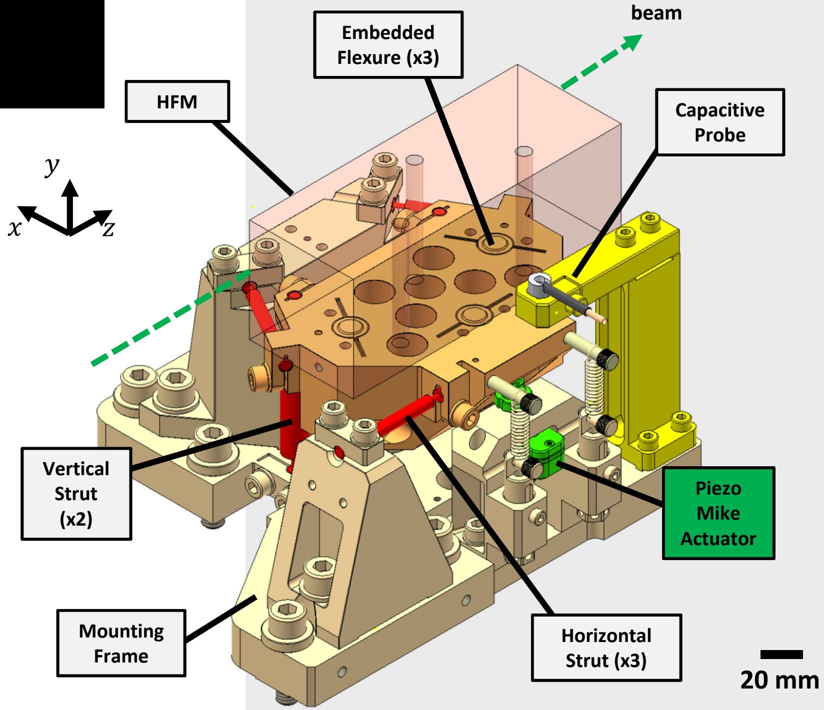
# 3.1. TARUMÃ: Overview



# 3.1. TARUMÃ: Exactly-constrained KB Mirrors

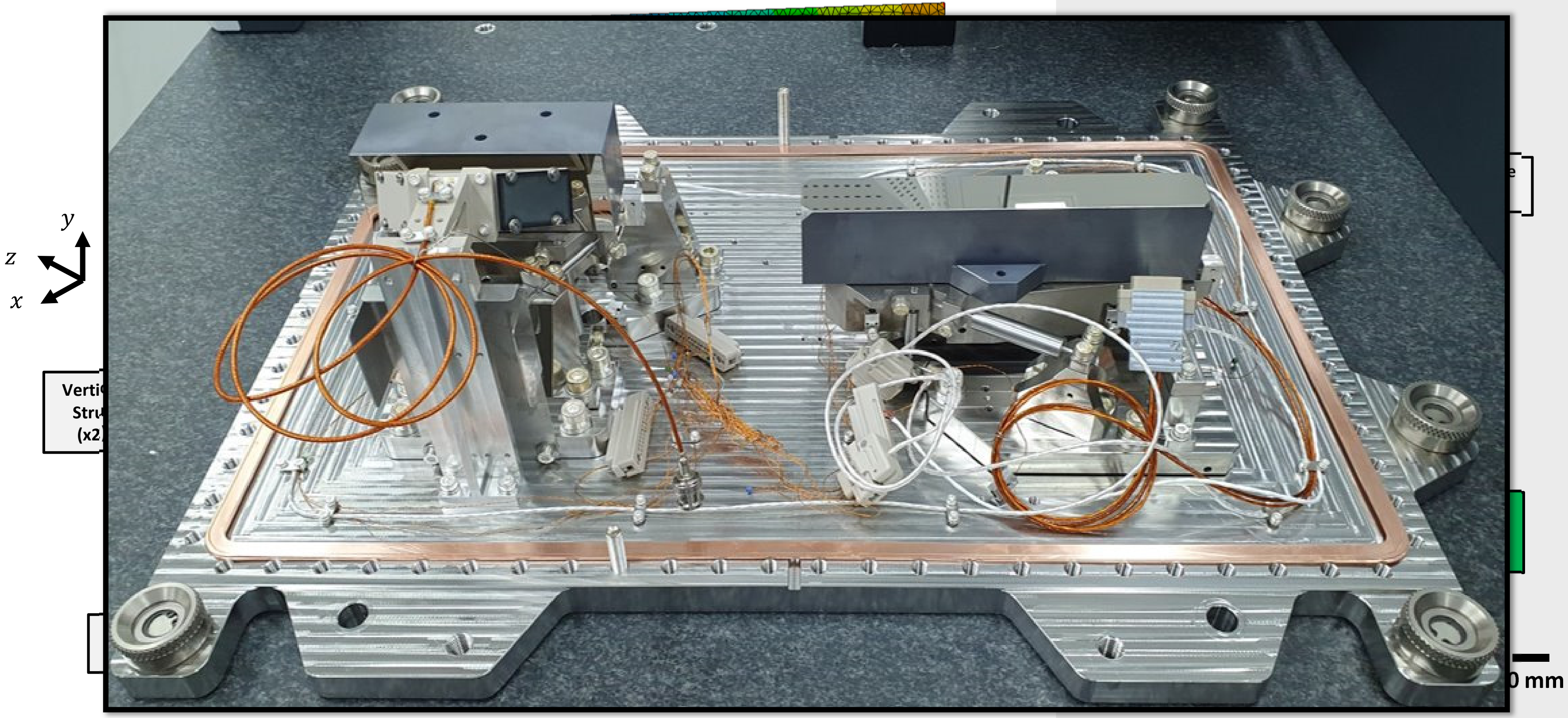



*Pitch modes > 1 kHz

(doi: 10.18429/JACoW-MEDSI2020-TUOB01)

# 3.1. TARUMÃ: Exactly-constrained KB Mirrors

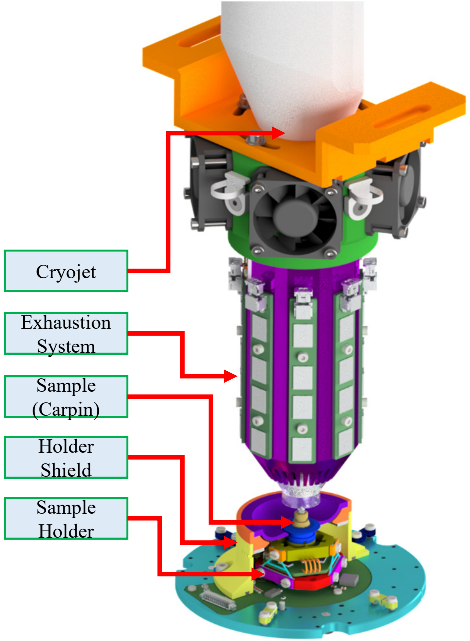



*Pitch modes > 1 kHz

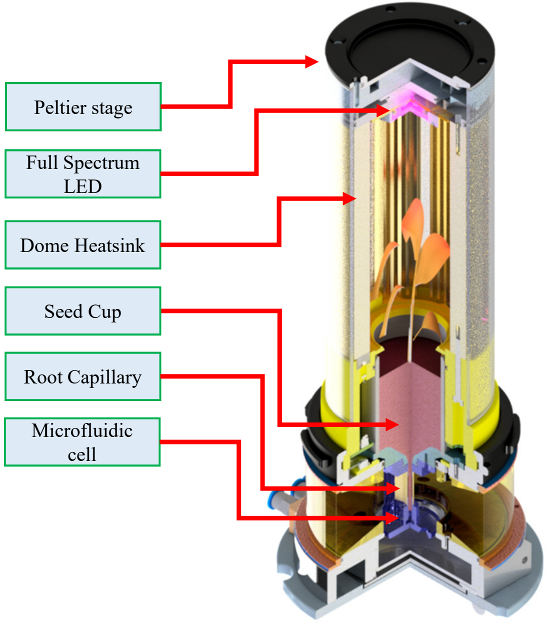
(doi: 10.18429/JACoW-MEDSI2020-TUOB01)

# 3.1. TARUMÃ: Sample Setups

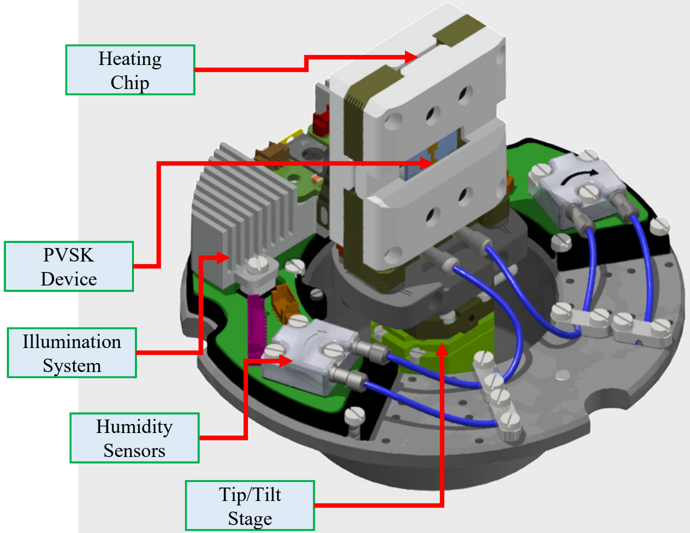
## *Cryogenic Setup*




## *Rhizomicrocosm*



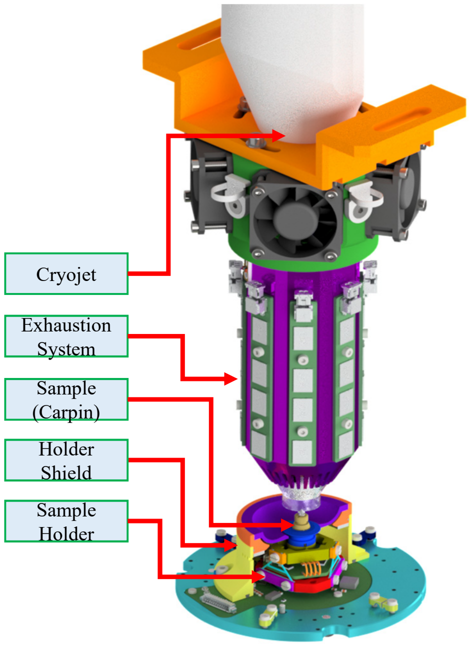

## *Perovskite Setup*

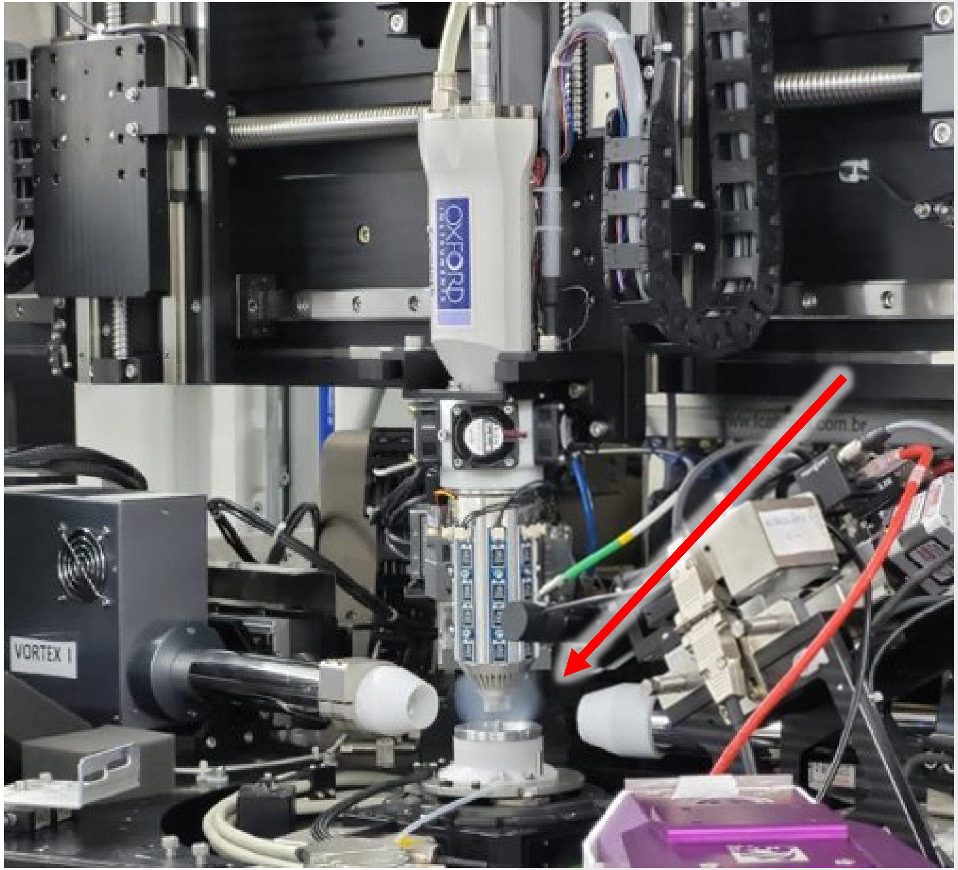



(doi: 10.1016/j.elspec.2023.147340)

# 3.1. TARUMÃ: Cryogenic Setup

## *Cryogenic Setup*




(doi: 10.18429/JACoW-MEDSI2020-WEPC02)
(doi: 10.1088/1742-6596/2380/1/012108)

# 3.1. TARUMÃ: Image Resolution

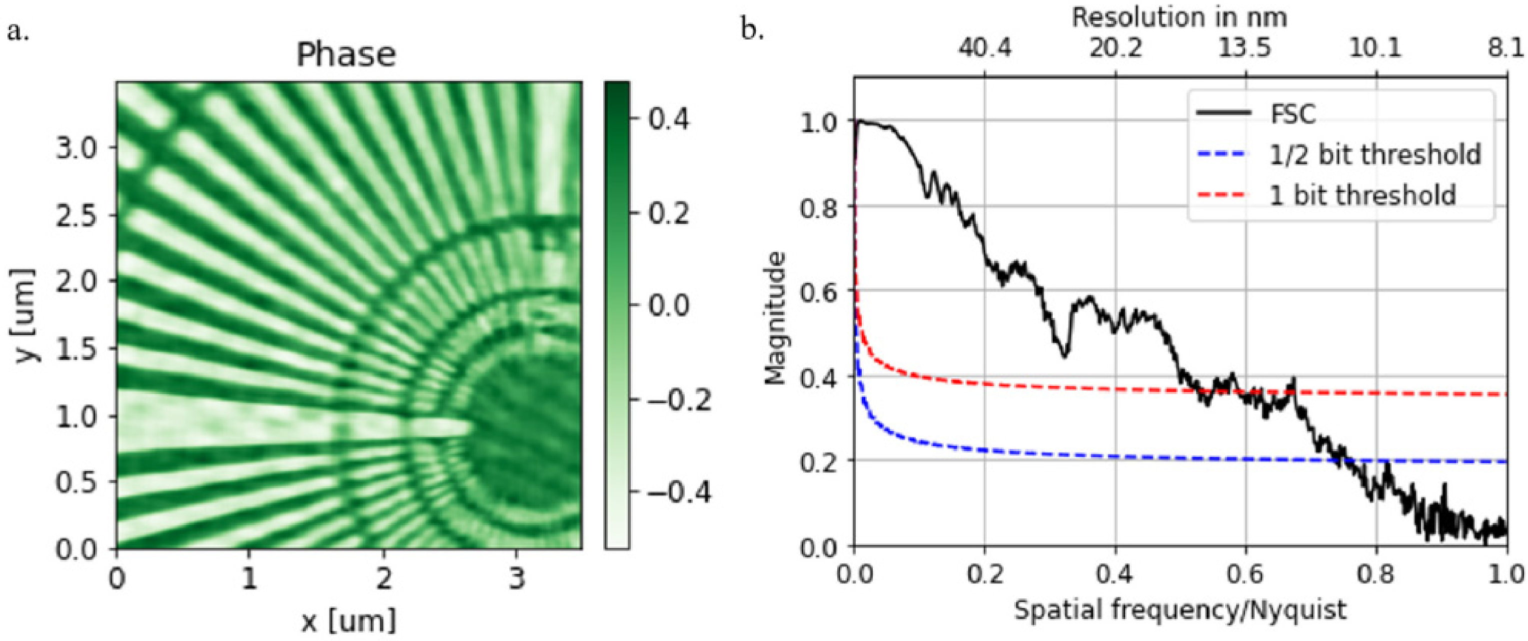
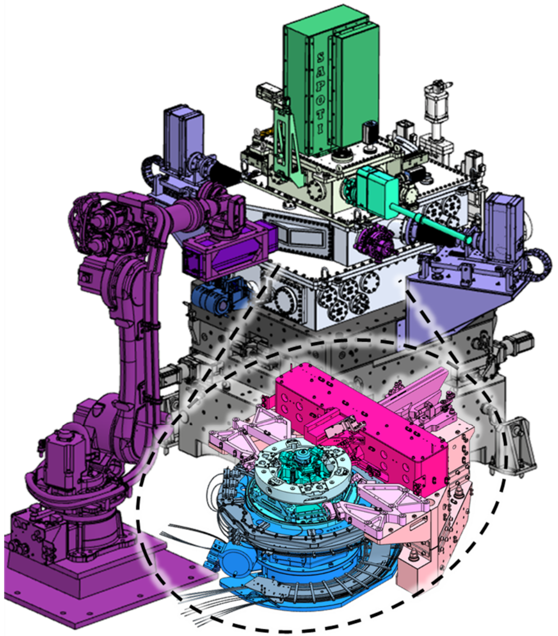
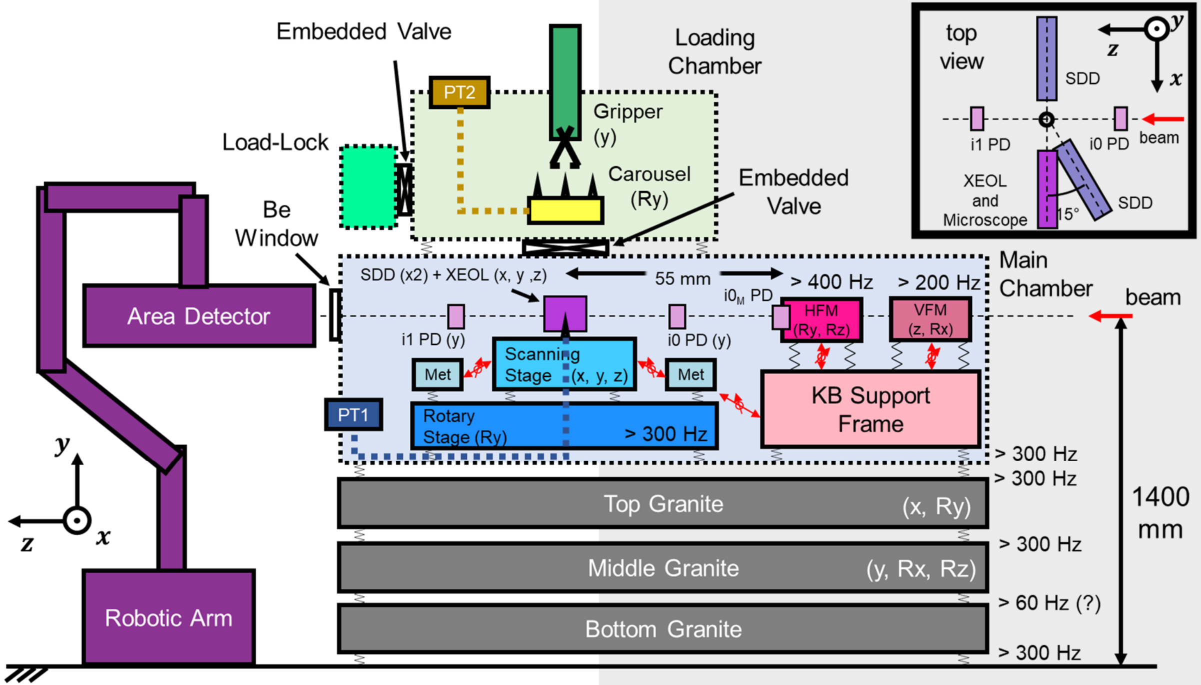



**Fig. 20.** Ptychography reconstruction of the Siemens star. (a) Zoom on the central portion of the image in Fig. 19a, showing the star's finest structures, (b) FSC analysis and comparison to the threshold criteria evaluated with PyNX [89].

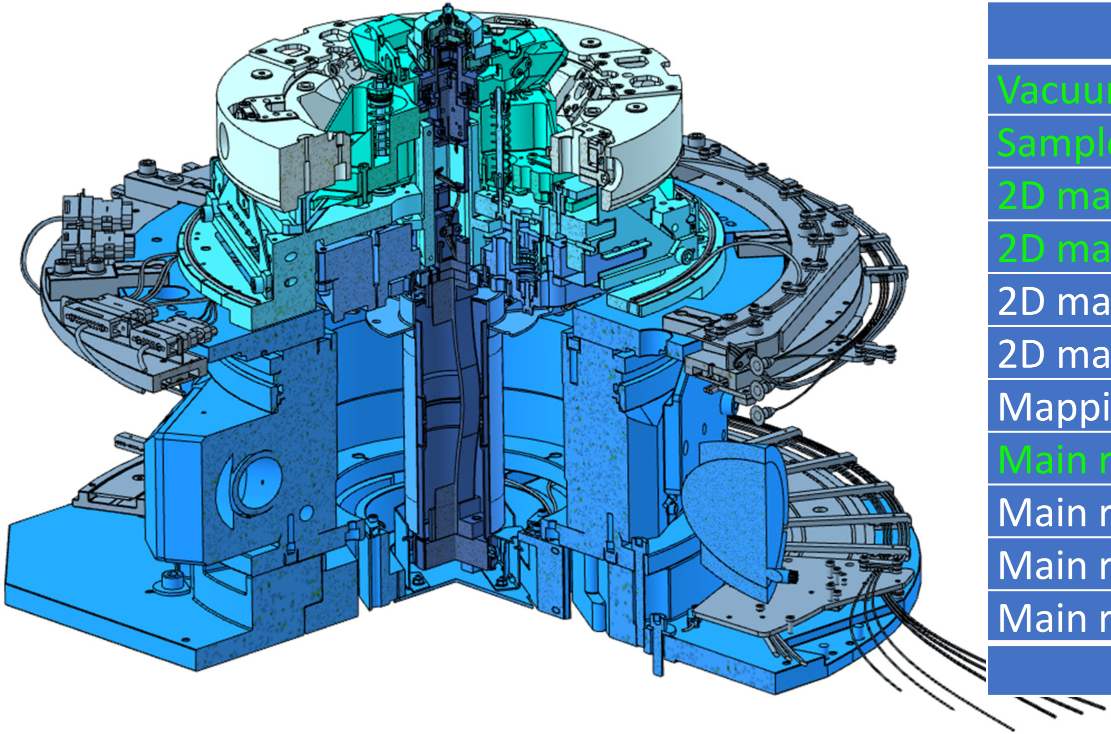
(doi: 10.1016/j.elspec.2023.147340)

# 3.2. SAPOTI: Overview



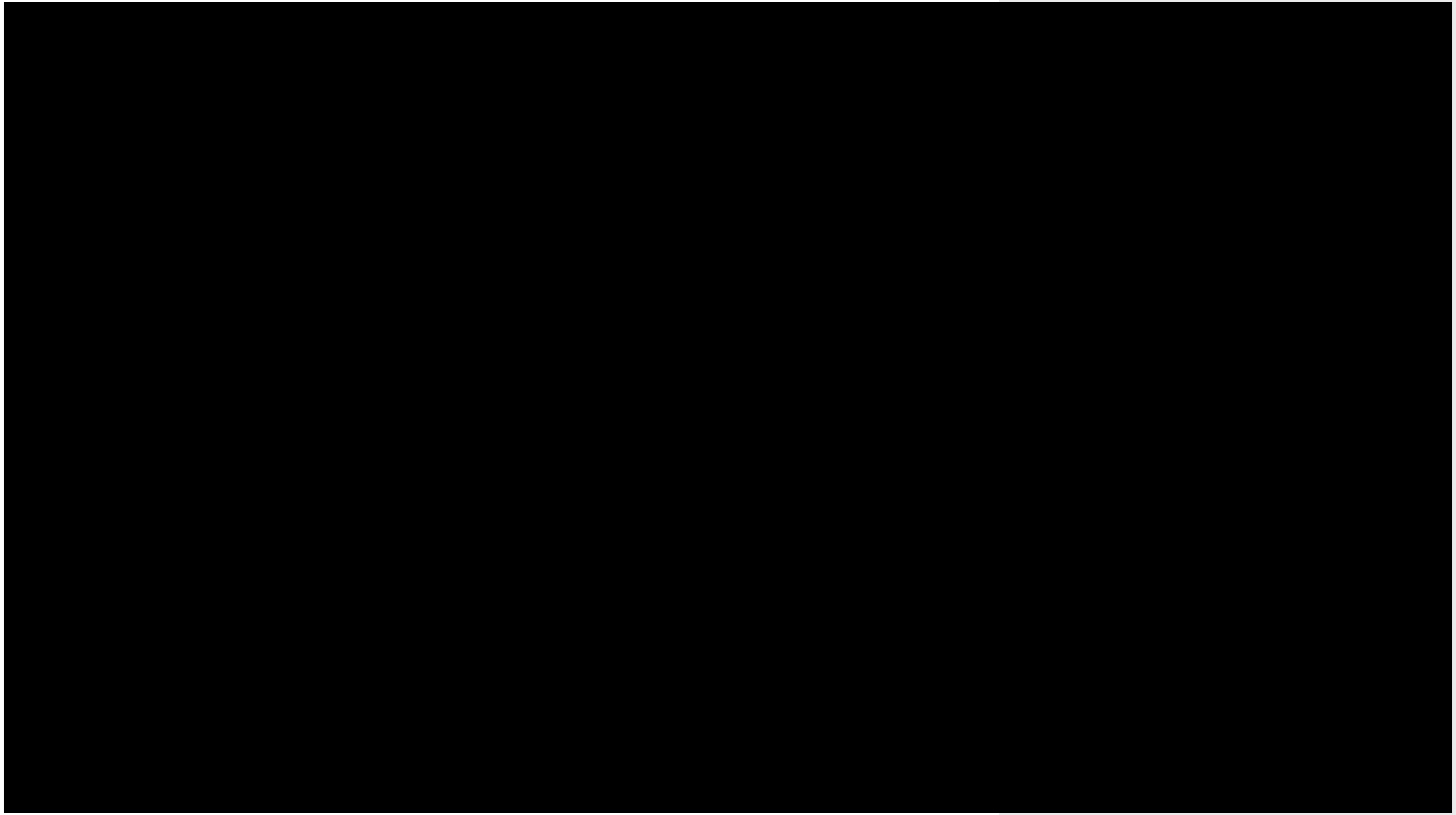


# 3.2. SAPOTI: Sample Stage Specifications



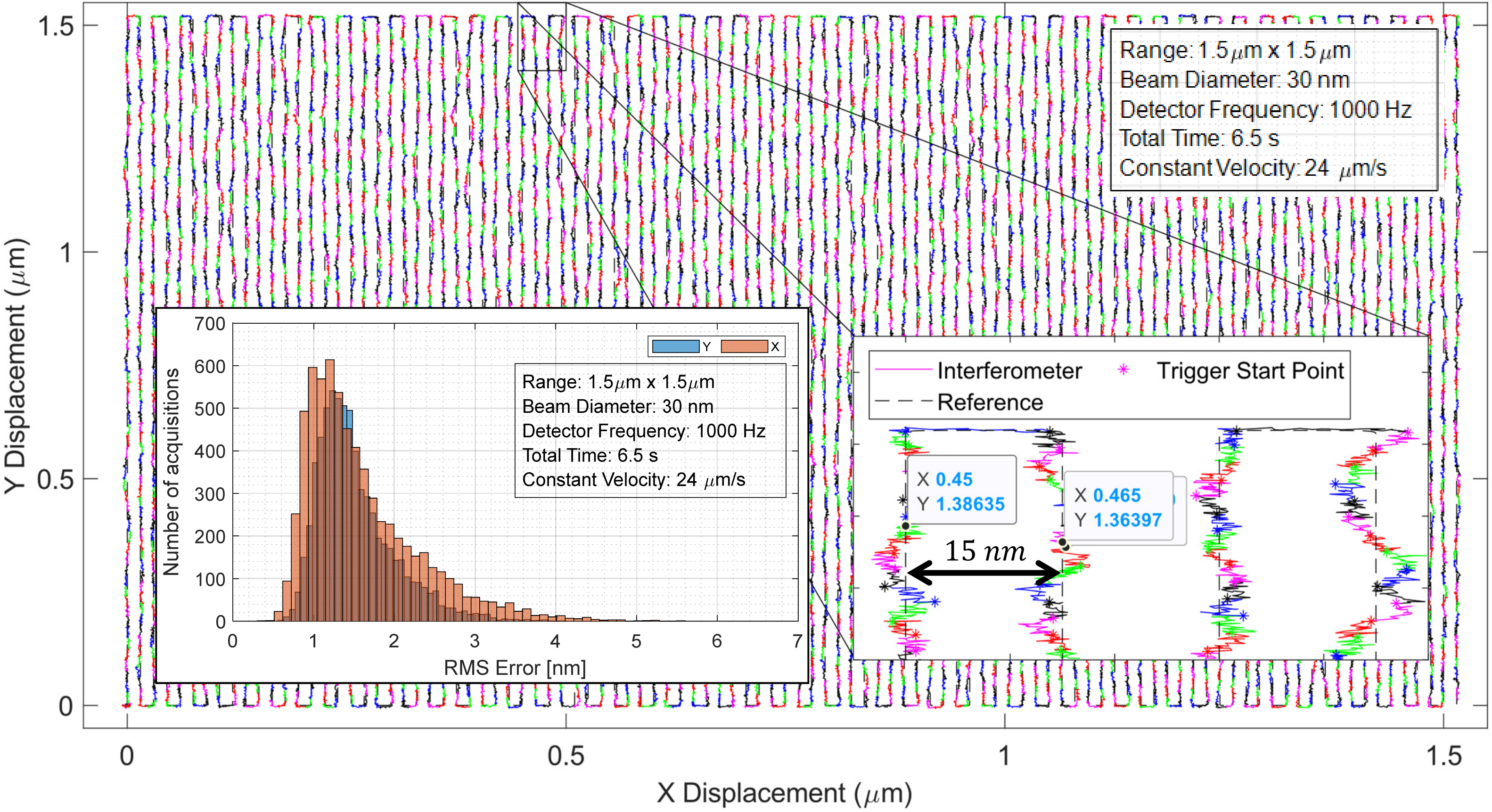
| Parameter | Value |
|---|---|
| Vacuum level | ~ 1e-9 mbar |
| Sample Temperature | < 100 K |
| 2D mapping range (XY) | +/- 1.5 mm |
| 2D mapping stab. (XY) | 1 nm RMS |
| 2D mapping acc. (XY) | < 10 nm |
| 2D mapping repeat. (XY) | 5 nm |
| Mapping velocity | ≤ 50 μm/s |
| Main rotation range (Ry) | 220° |
| Main rotation stab. (Ry) | 2 μrad |
| Main rotation acc. (Ry) | 100 μrad |
| Main rotation repeat. (Ry) | 10 μrad |
| | |

# 3.2. SAPOTI: Sample Stage Motion (XYZ)



8x speed

# Trajectory Optimization (XY mapping)



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# Conclusions

- Design principles and different technologies must be known for optimized solutions;
- Holistic and systemic design approaches should be considered for ultimate performances;
- Predictive design framework and modeling tools can improve design efficiency and assertiveness;
- New-generation beamlines tend to push toward industry-like high-end systems and throughput;
- People training and management may prove to be one of the critical bottlenecks in face of such complex systems.

# Perspectives

- High-end mechatronics is still at an early stage within the beamline environment, but there is room for a quick evolution;
- Full beamline (IDs, slits, mirrors, monochromators, sample, detectors) coordination and calibration in motion and thermal aspects may be required for some ultimate high-performance experiments (e.g. spectroscopy);
- Model-based systems engineering (MBSE) shows great potential in handling ever more complex systems.

# Thank you!

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