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

Modeling the dynamics and disturbances of the MOGNO Microstation

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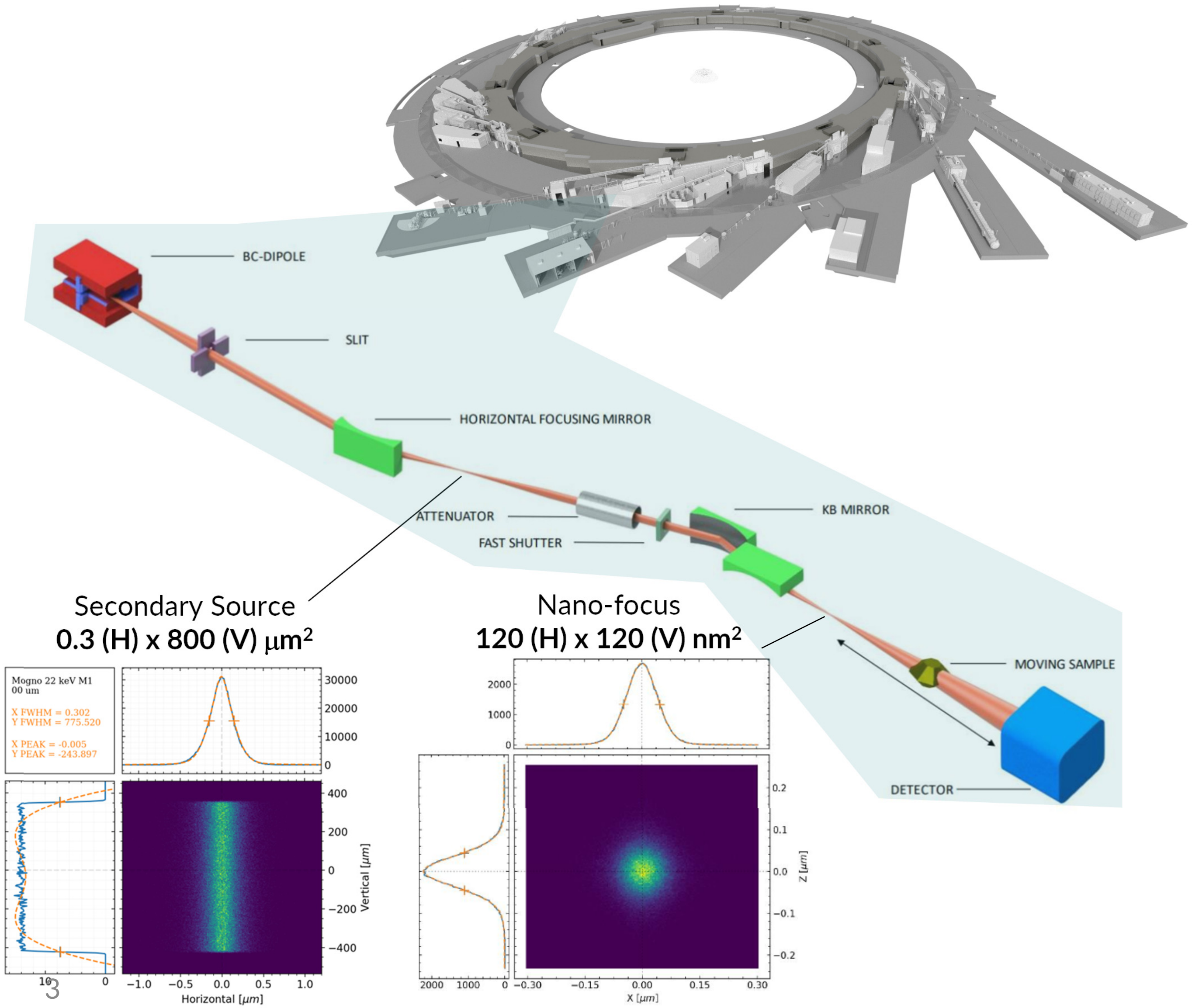
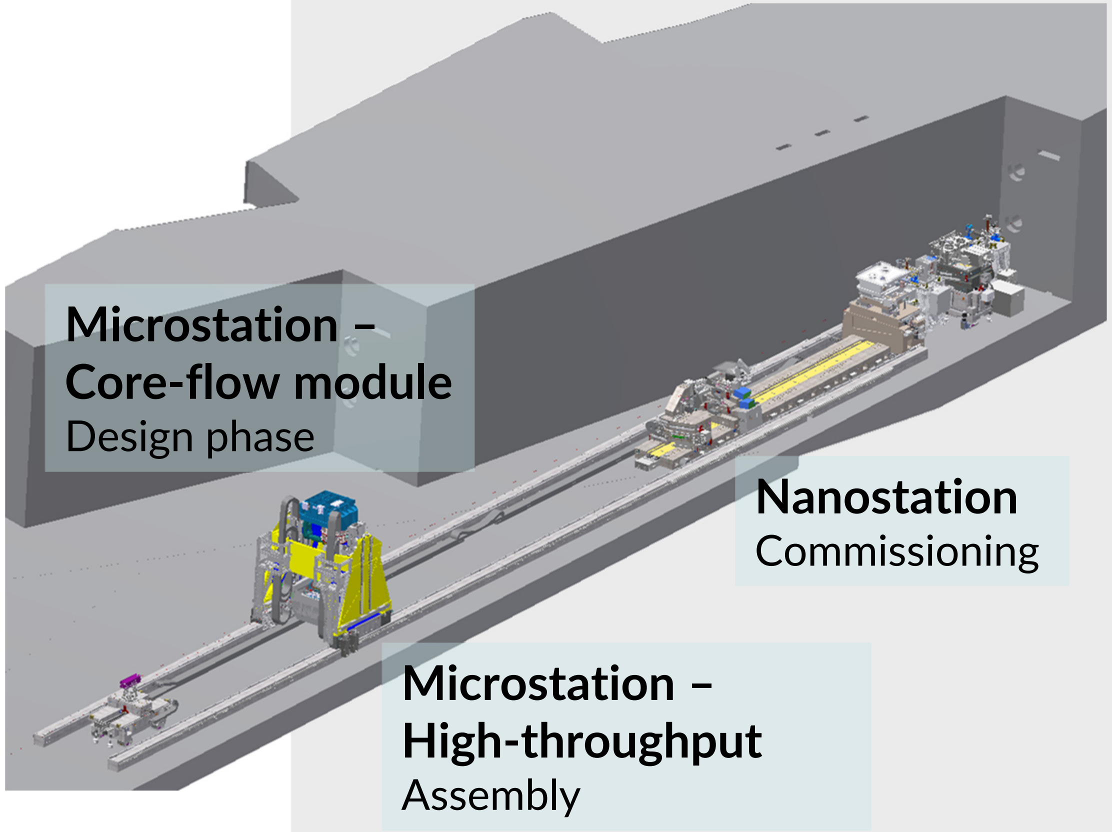
Outline

The MOGNO Beamline





LNLS sirius CNPEM

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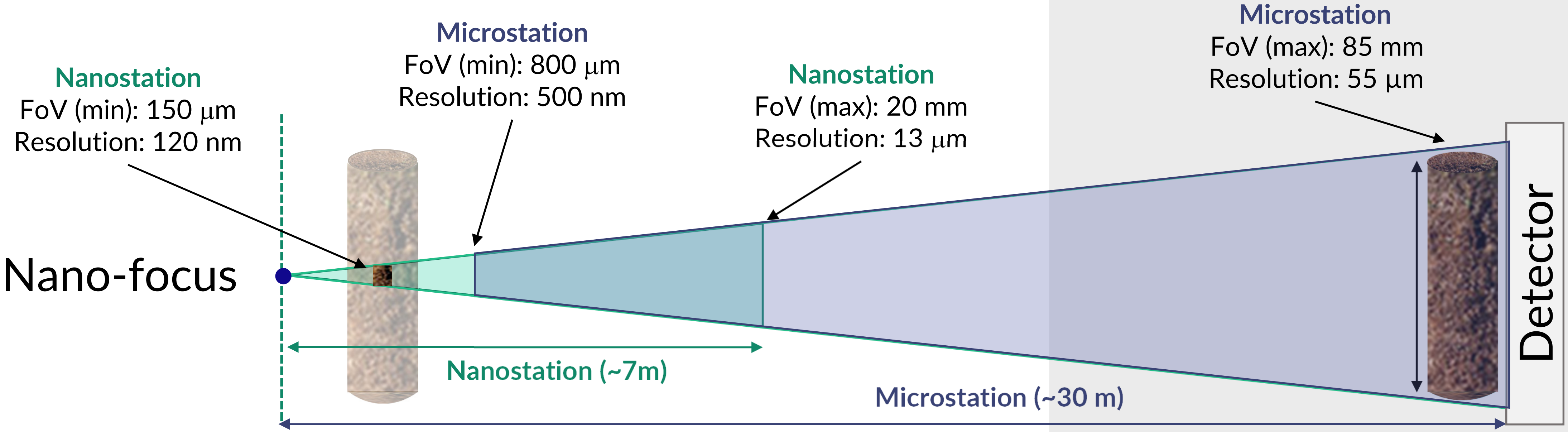

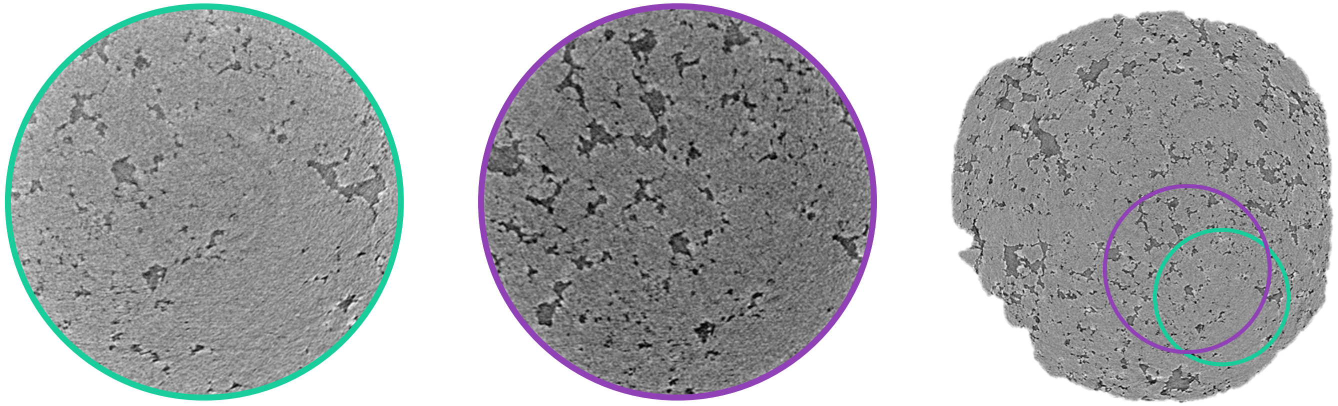

FDK (10k proj) eps 401 nm

FDK (10k proj) eps 701 nm

FDK (10k proj) eps 1156 nm

Images provided by Daphne Pino, Nathaly Archilha (LNLS-CNPEM) and Rodrigo Surmas (Petrobras).

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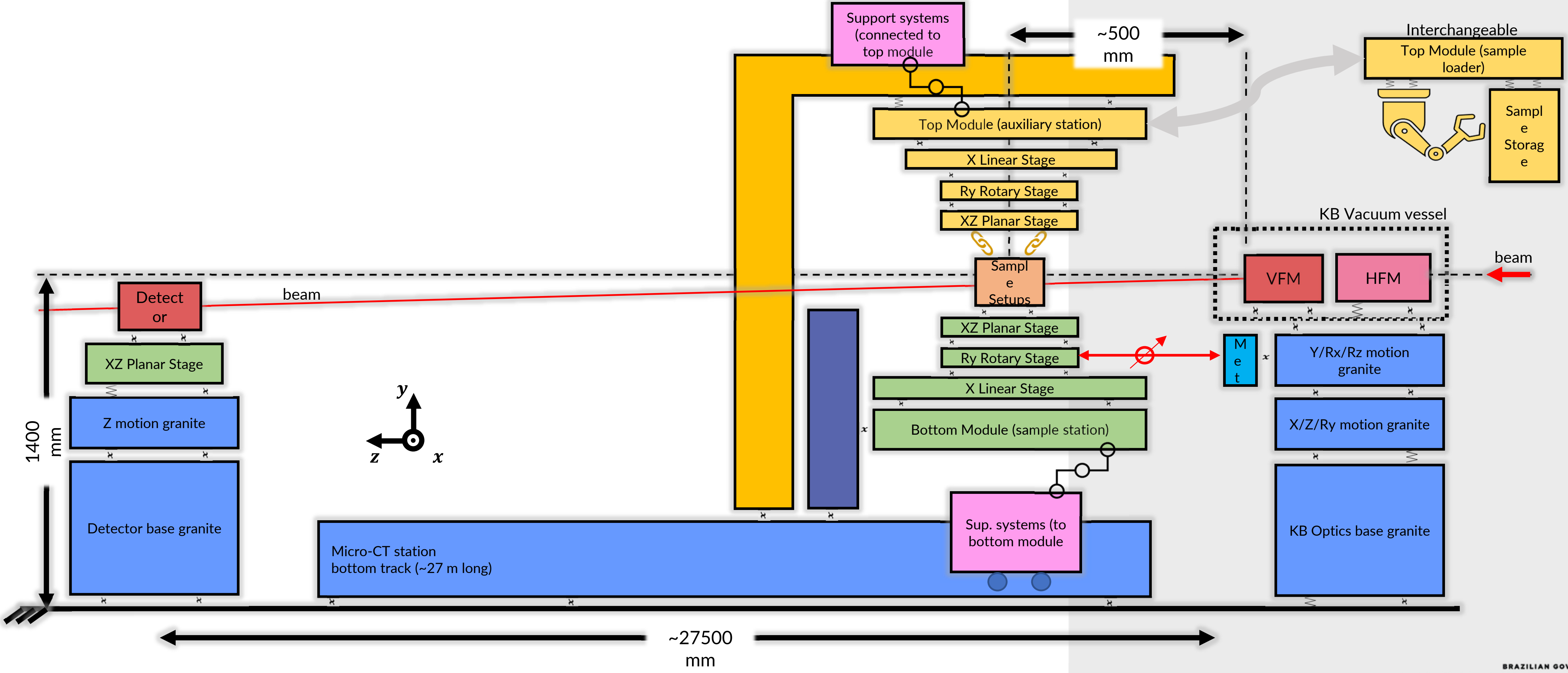
The MOGNO Microstation

Optics overview:
- Bending magnet source
- Up to 9e11 ph/s/100 mA flux
- KB system:
  - 120 nm x 120 nm focus
  - Multilayer mirrors
  - 22 keV; or 39 and 67.5 keV
  - 3.1 mrad x 3.1 mrad divergence

Features:
- High-throughput (30 s/sample)
- Core-flow experiments
- Multi-scale analysis:
  - Zoom
  - 500nm – 55 µm resolution
- High-speed fly scan tomography
- Sample Holder compatibility with other Sirius beamlines
- Direct and indirect detection system

Techniques:
- X-ray tomography
- Zoom tomography
- Time-resolved tomography
- Dual energy tomography
- In-situ tomography
- Absorption and phase contrast regimes
- Helical tomography

The MOGNO Microstation



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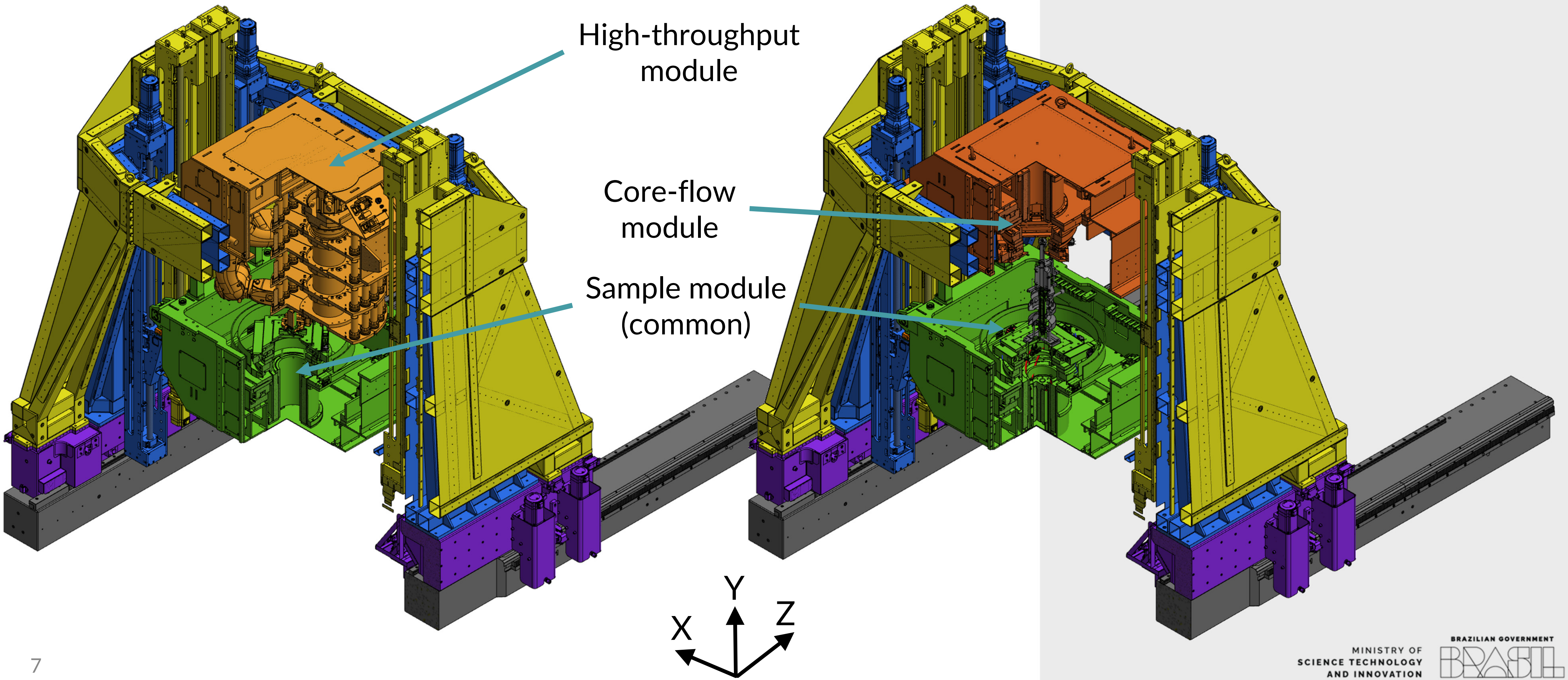
The MOGNO Microstation



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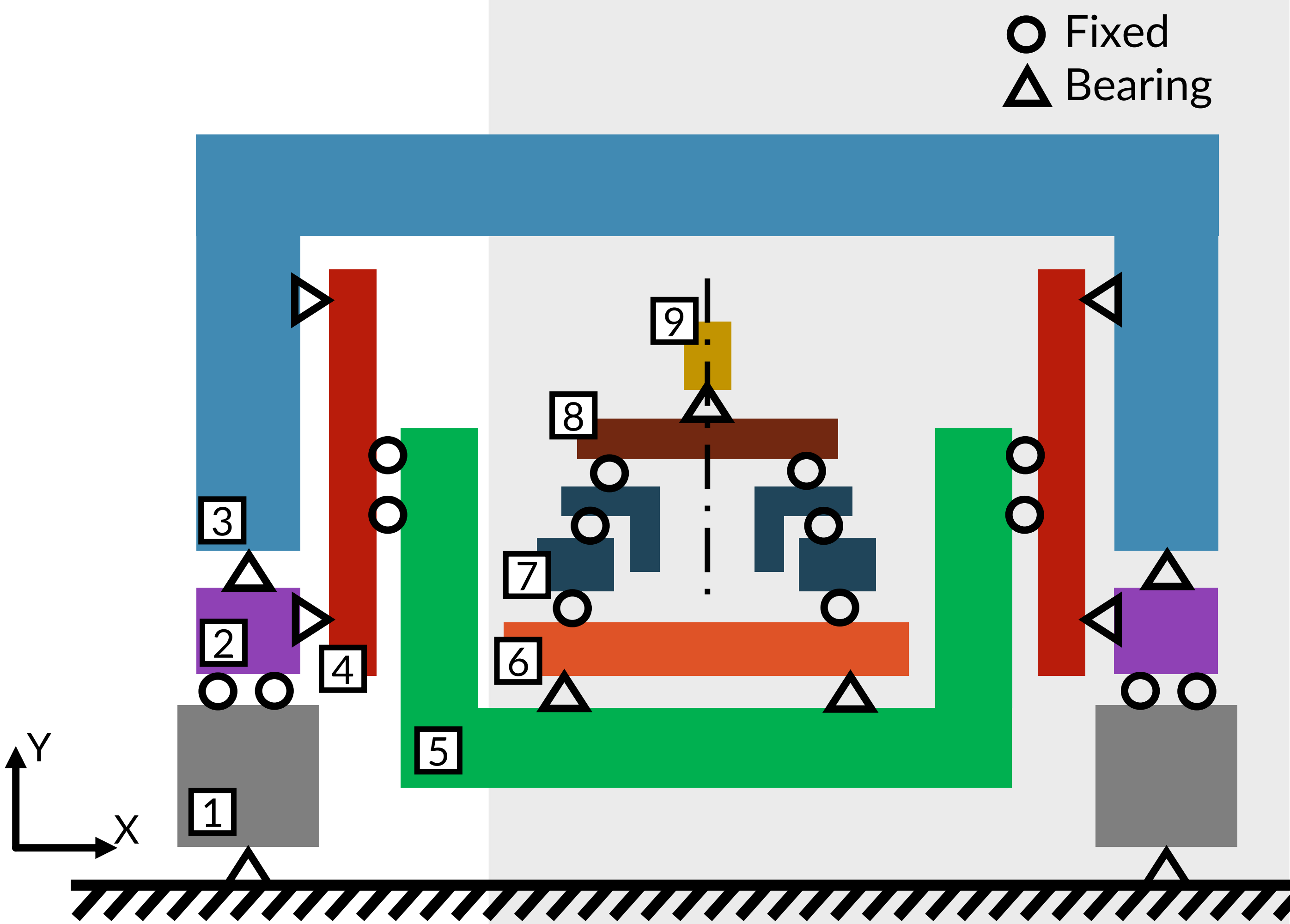
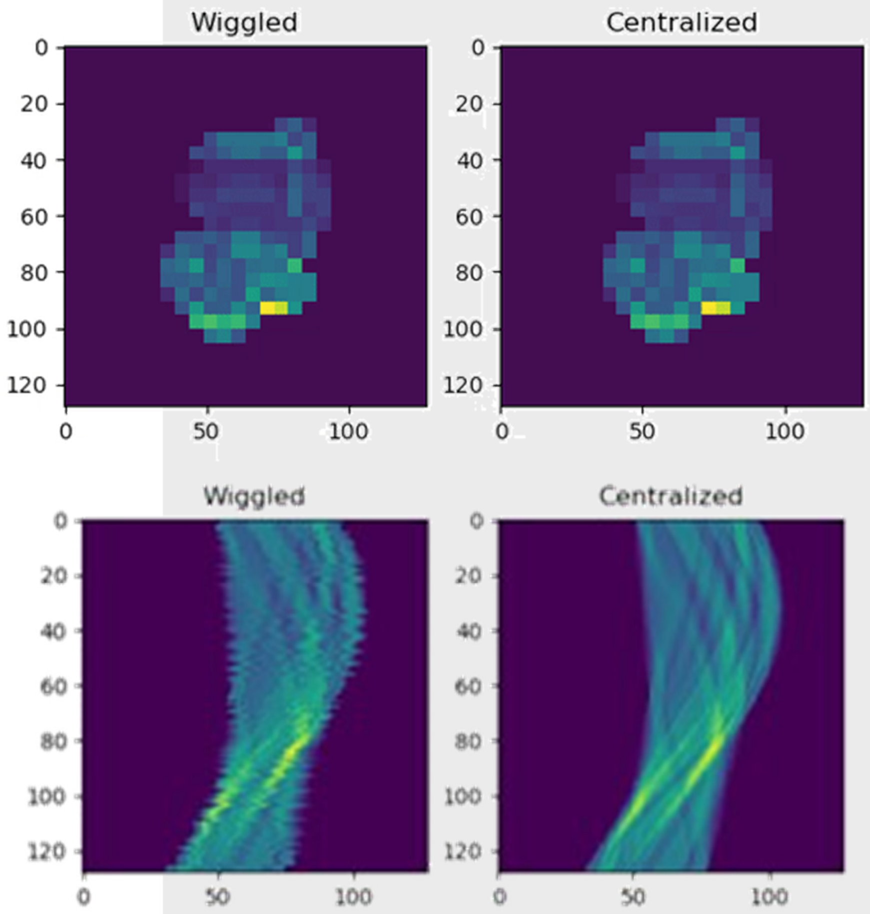
The MOGNO Microstation

1. Granite base
2. Granite feet
3. Structural frame
4. Vertical stages
5. Sample module
6. Long-stroke X stage
7. Rotation stage
8. Planar stage
9. Sample



The MOGNO Microstation

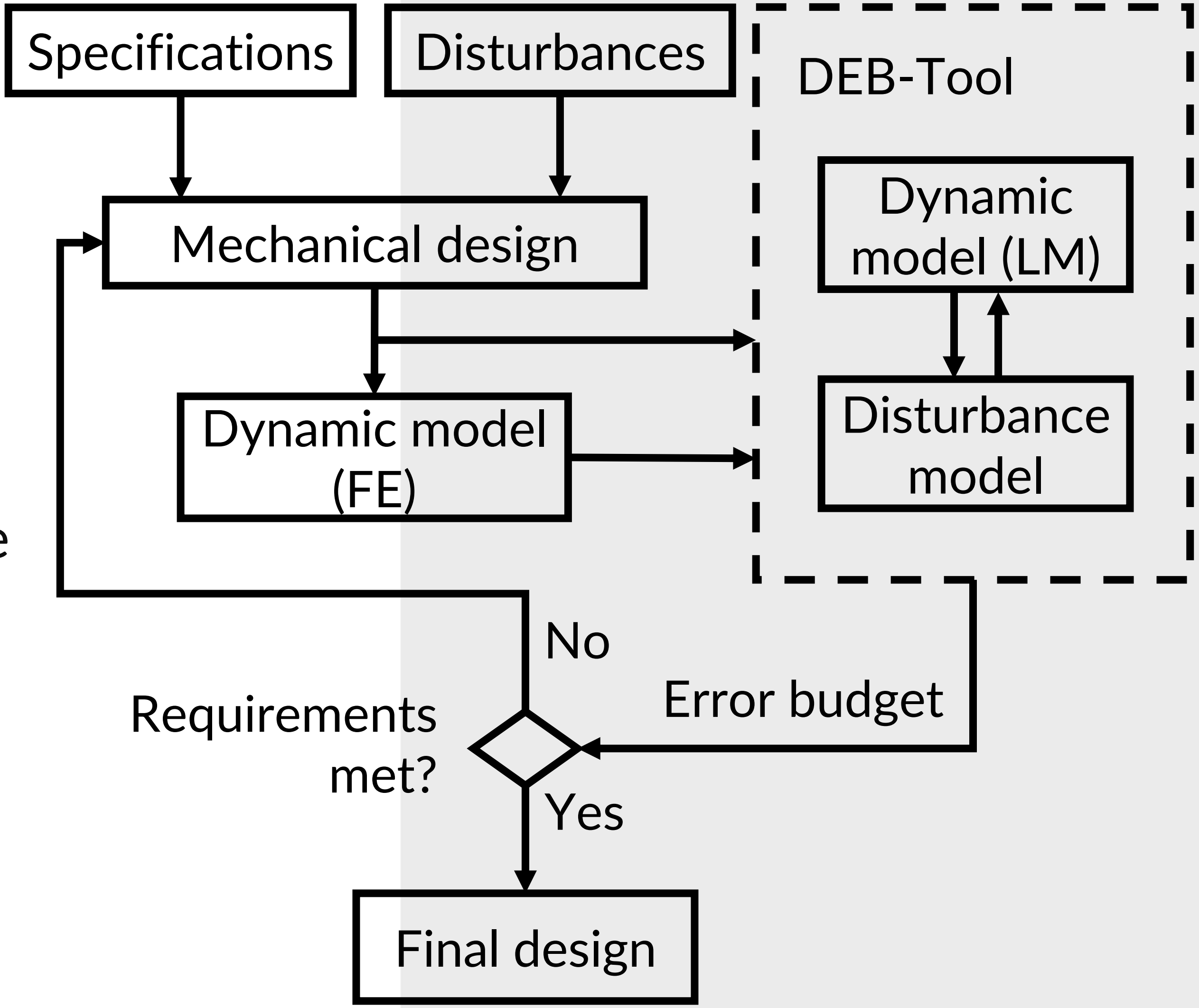
- Reconstruction challenges
  - Sample-to-optics instabilities generate errors
- Compensation:
  - Passive:
    - Reduce sensitivity to disturbances
    - Calibration (systematic errors)
    - In-situ metrology (systematic and random errors to some extent)
  - Active:
    - Reduce disturbance forces (e.g., autobalancing system)
    - In-situ control system



Effects of sample vibration in reconstructed tomography. Simulated data provided by Eduardo Miqueles (LNLS-CNPEM).

Methodology

- Specifications: boundary conditions given by stakeholders
- Disturbances: boundary conditions from the environment
- Mechanical design: conceptual and detailed system design
- Dynamic model: ideal representation of the system's dynamics
  - FE: finite element
  - LM: lumped mass
- Disturbance model: ideal representation of the disturbances
- Final design: Design that meets specifications according to the models



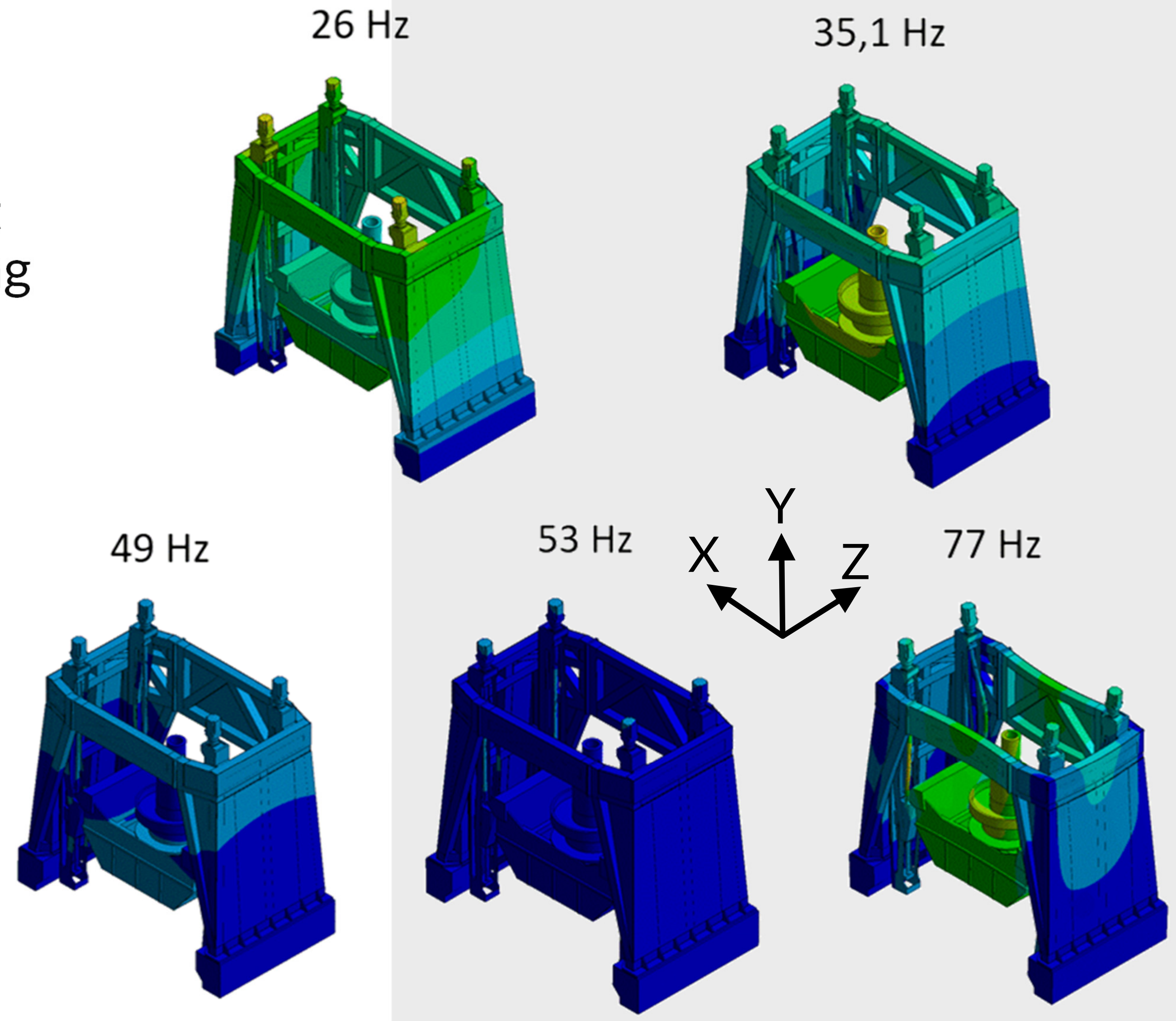
Dynamic model

FE model
- Pros:
  - High fidelity
  - Integration with many kinds of models (thermal, fluids, structural, modal)
- Cons:
  - Harder to prepare
  - Needs detailed design
  - High computational cost
  - Less clear for sensitivity analysis

LM model
- Pros:
  - High computational efficiency
  - Can be used at any design stage
  - Integration with control system modeling
- Cons:
  - Lower fidelity (rigid body only)

Dynamic model

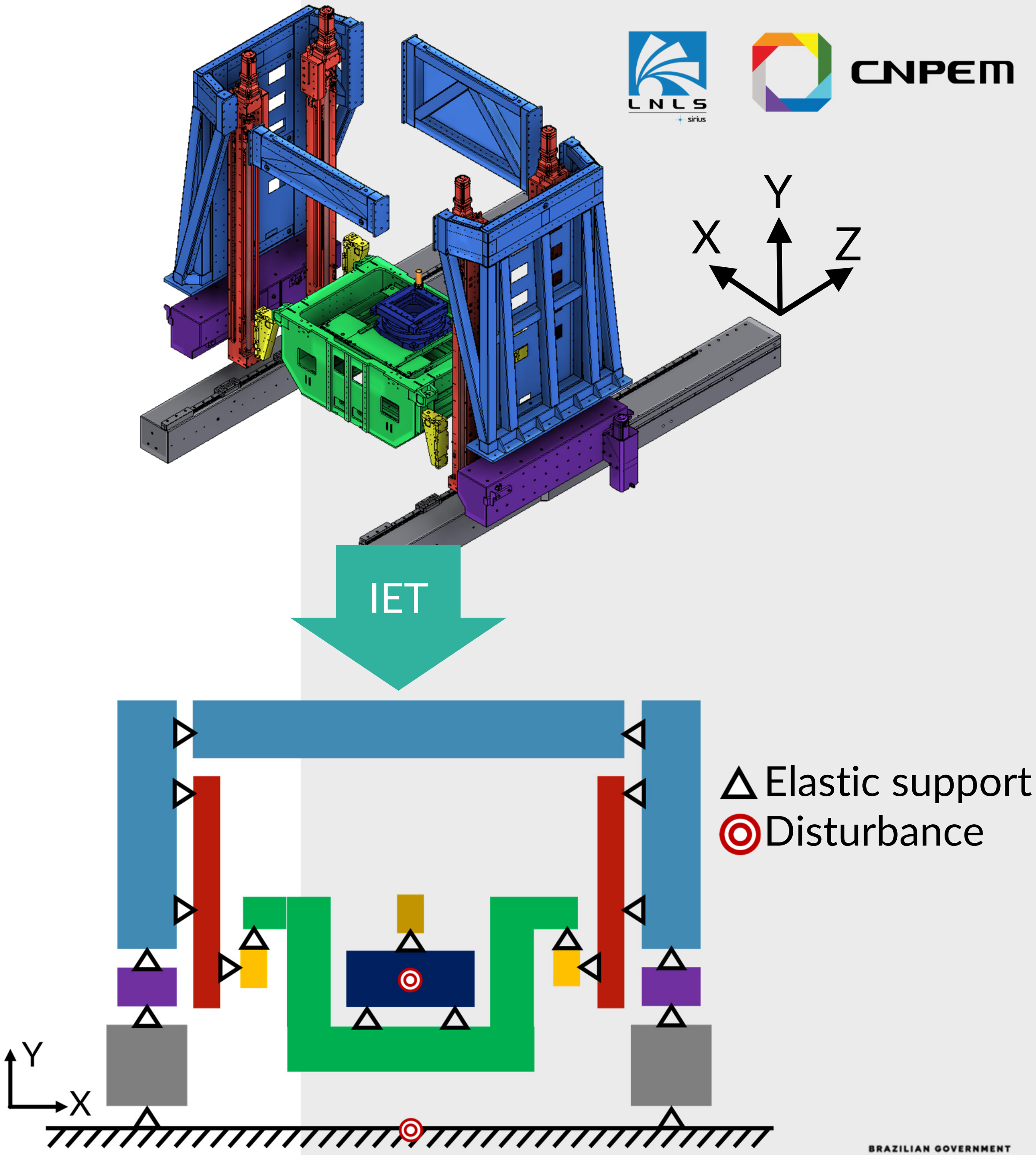
- Microstation's complex geometries make it unfeasible to use FE for error-budget during design phase
- Solution:
  - Have one FE model to use as high-fidelity target to tune the LM model and use the LM model for error-budgeting
- FE model:
  - Modal analysis in ANSYS
  - High performance computer
  - Long process of simplifying geometries
  - Done once main structure is designed
  - Contact stiffness values mostly from experimental data obtained at LNLS



First 5 eigenmodes found in ANSYS. Simulation data provided by André Rocha (LNLS-CNPEM).

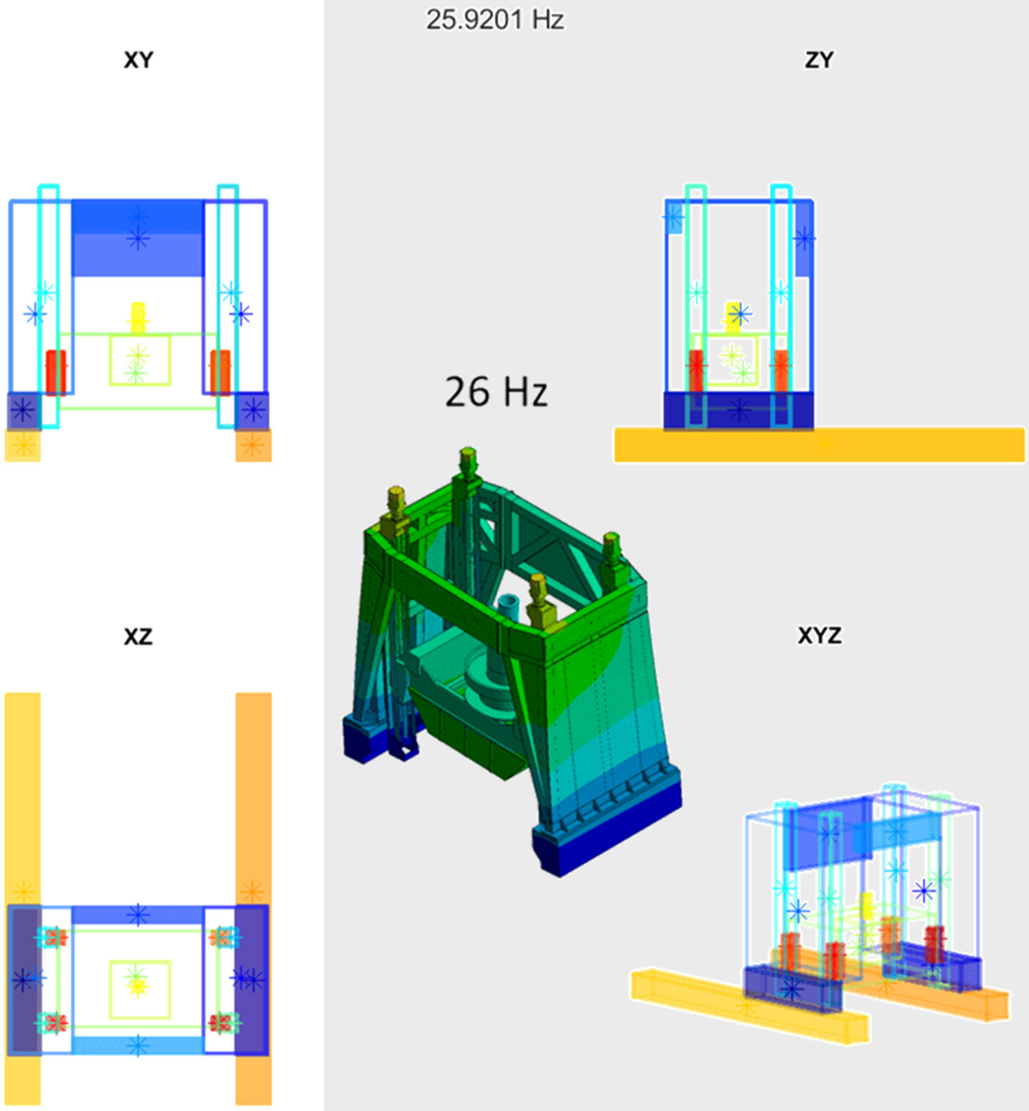
Dynamic model

- LM model:
  - In CAD software, larger bodies divided into smaller bodies to represent flexible body modes from ANSYS
  - Data exported from CAD with IET
  - DEB-Tool to build the model
  - Initial contact stiffness values from experimental data or analytical models (flexures, bolted connections, Hertz contacts)
  - Stiffnesses later tuned to match ANSYS eigenfrequencies



Dynamic model

- Results of tuning process deemed good when difference in eigenfrequency between FE and LM models was less than 5 % for first five eigenmodes
- After that, changes in the design, such as changing position of contact points, adding contact points, changing joint stiffnesses, or changing disturbances, are only applied to LM model



Frequency difference: -0.3%

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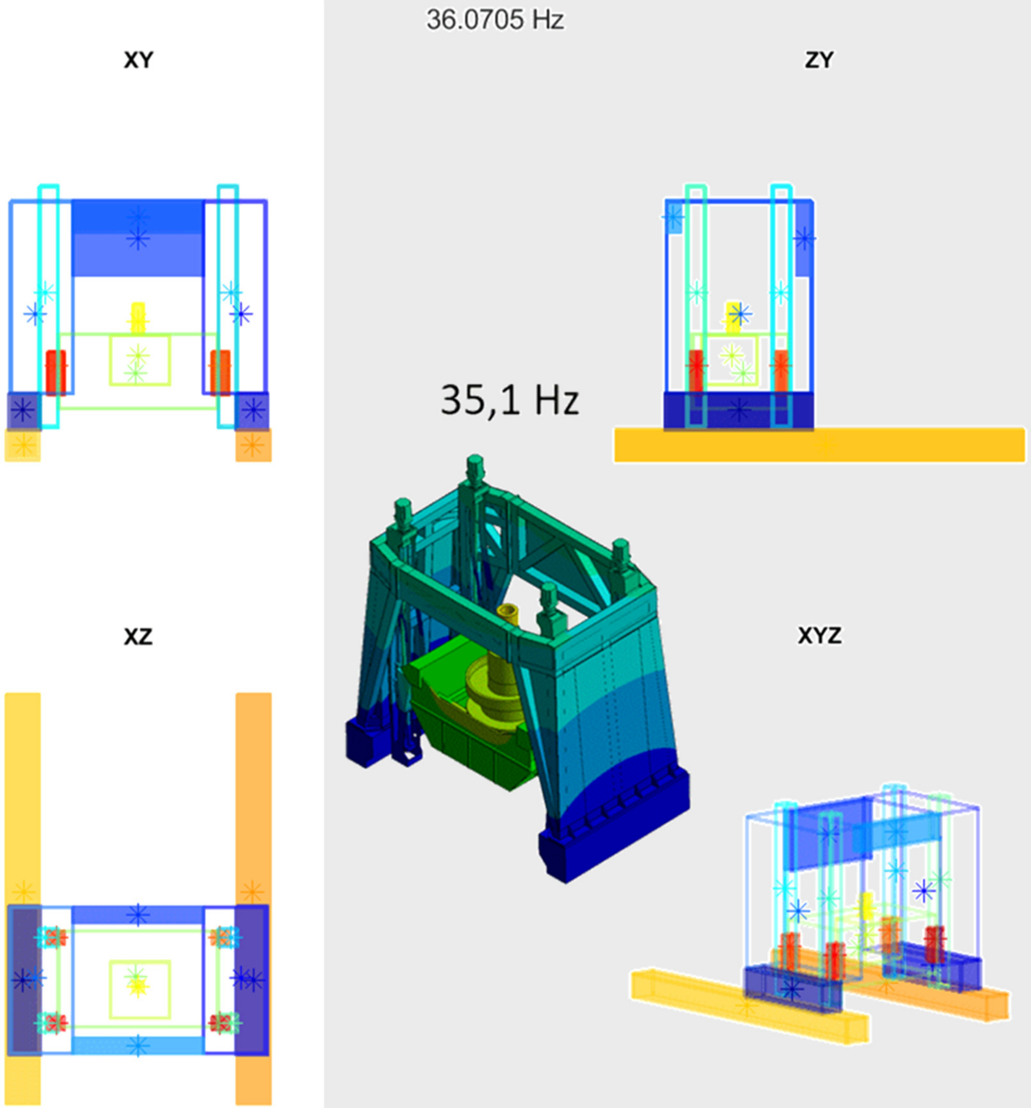

Frequency difference: +3%

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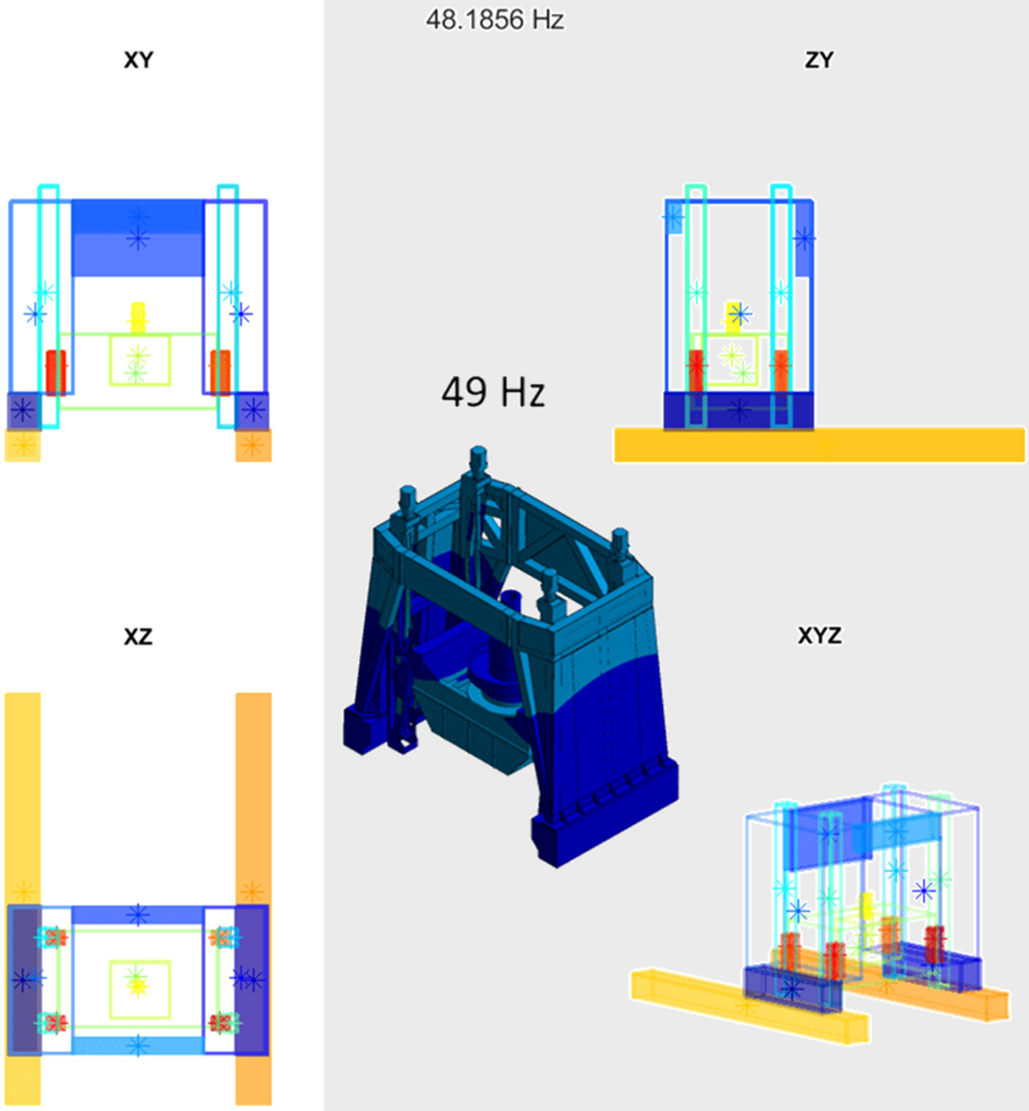

Frequency difference: -2%

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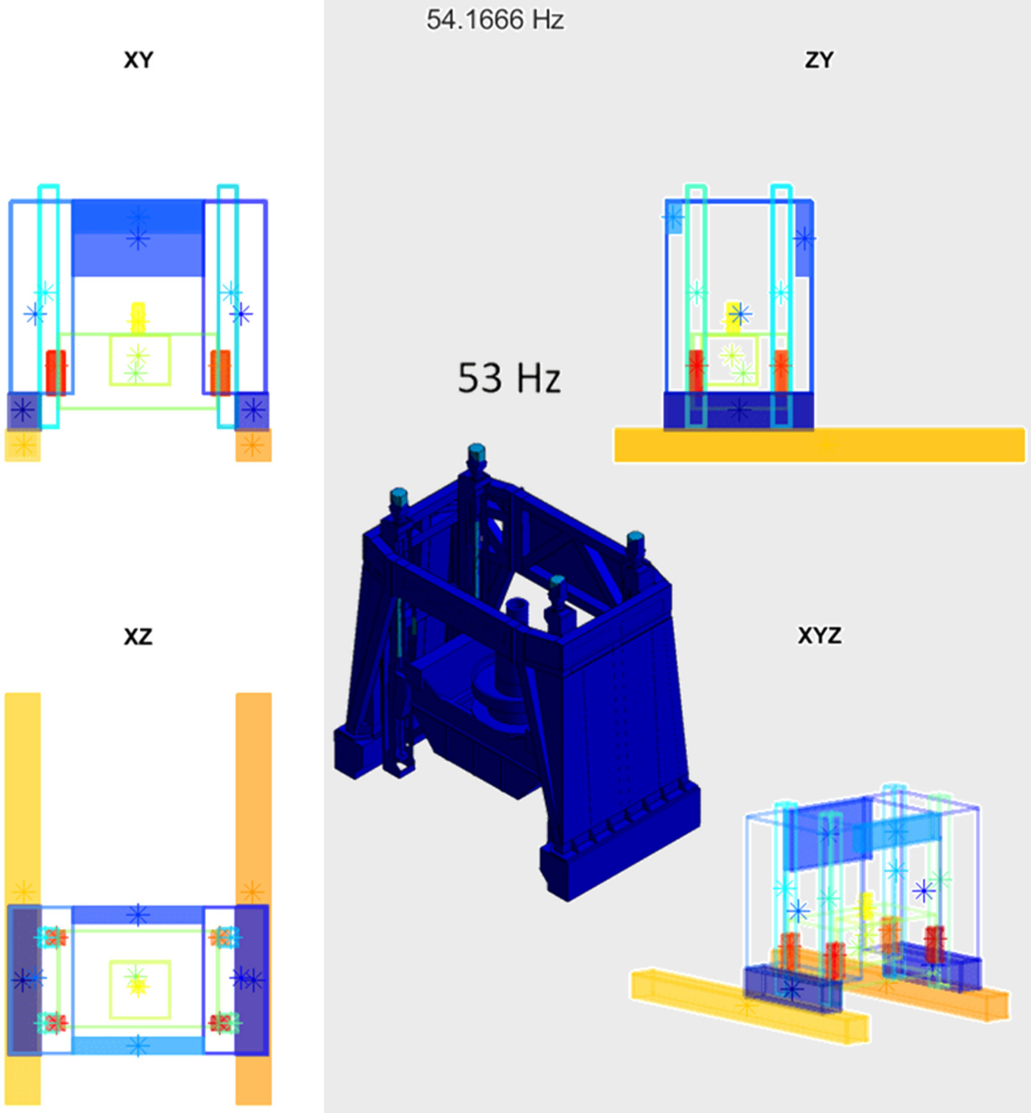

Frequency difference: +2%

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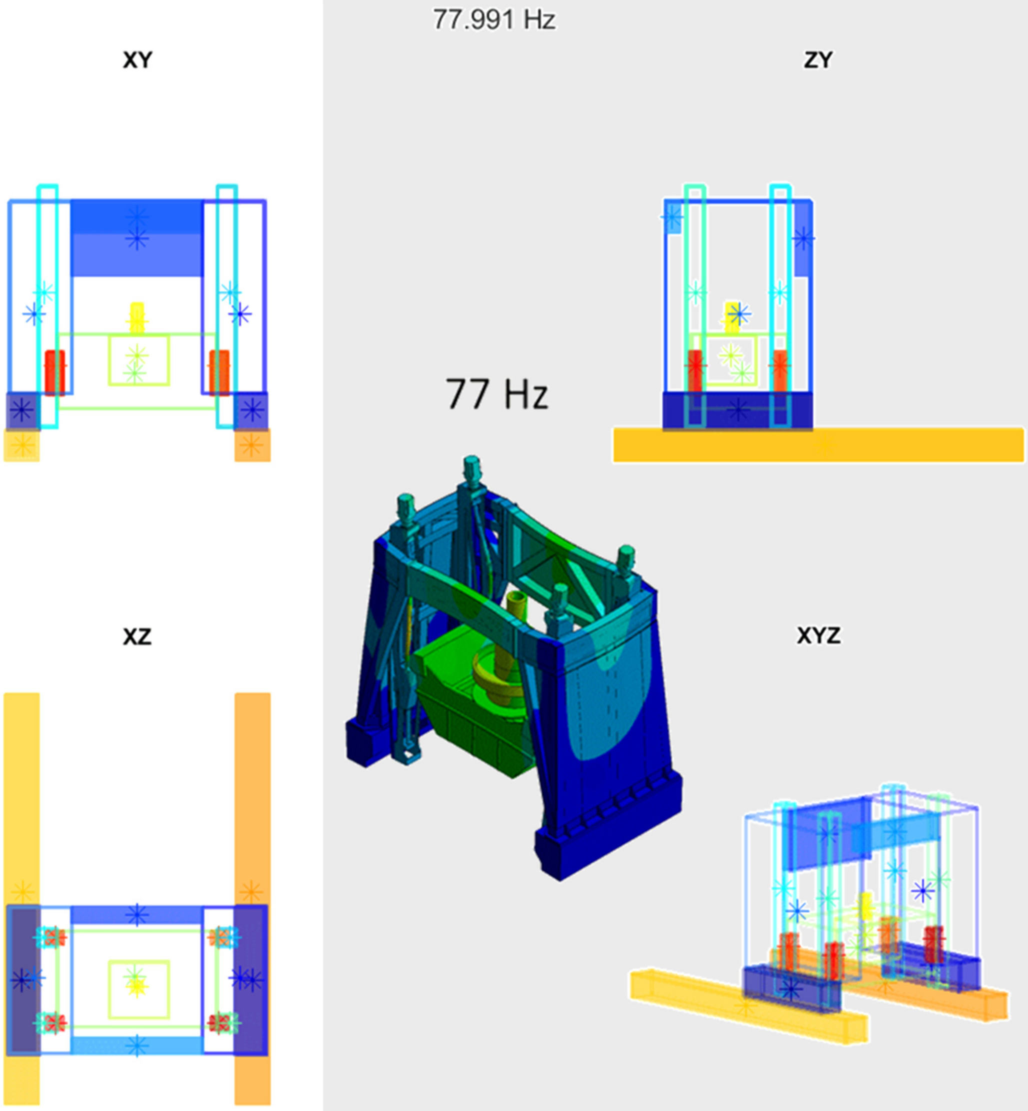
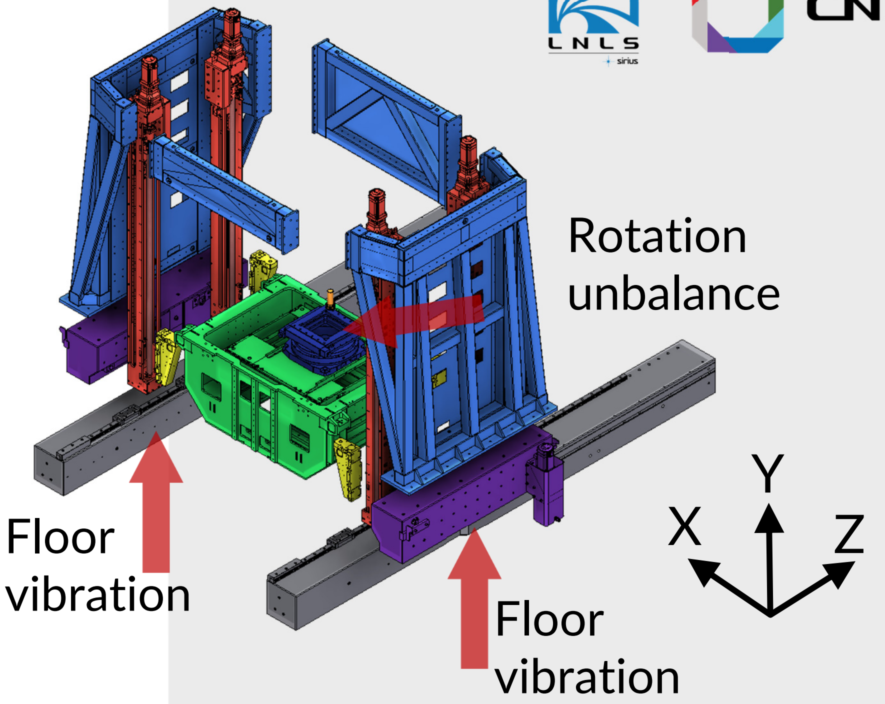
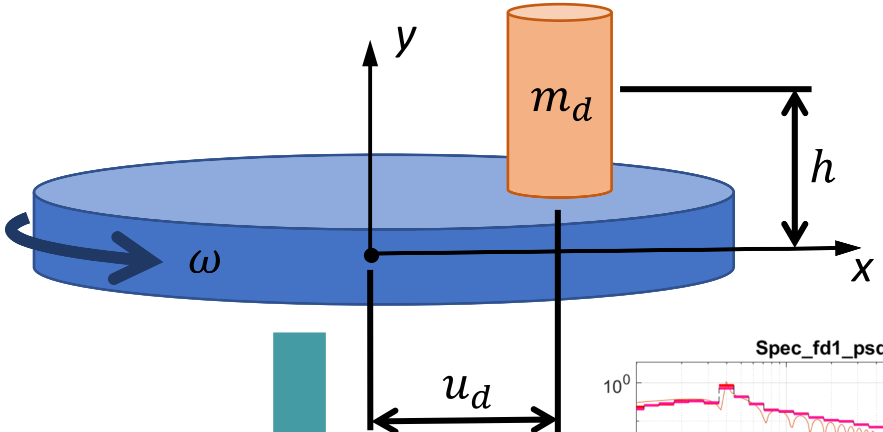


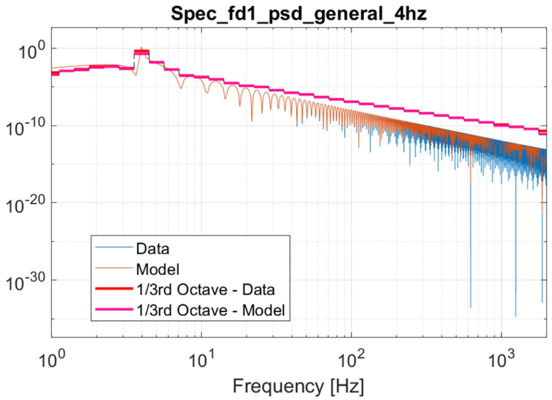
Frequency difference: +1%

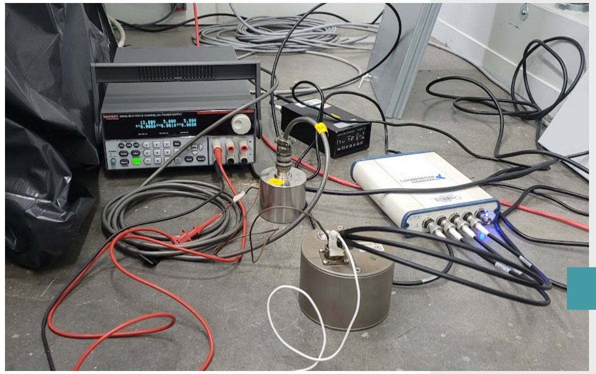
Disturbance model

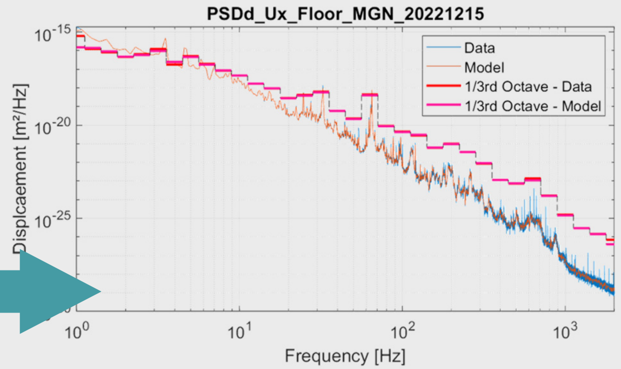
- PSD used to model disturbances
- Floor vibration: 6 DOF measurements
- Rotation unbalance: dynamic model





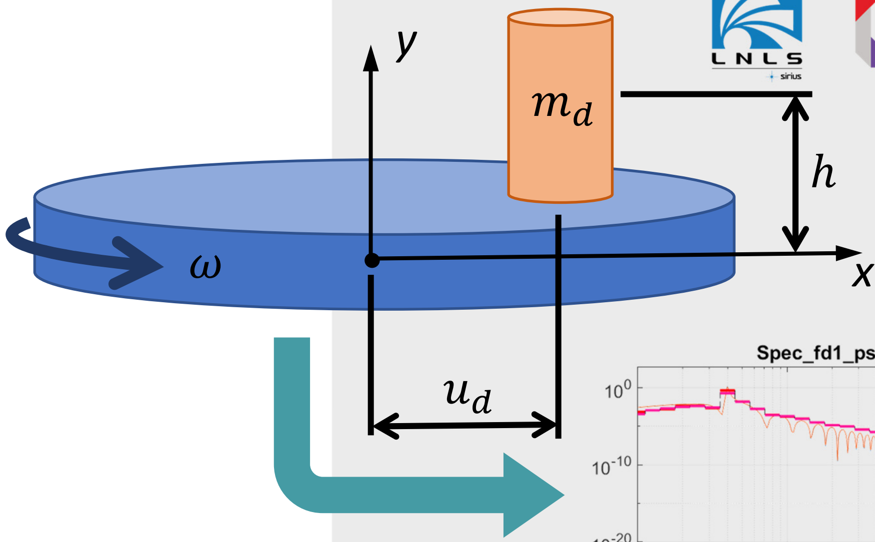


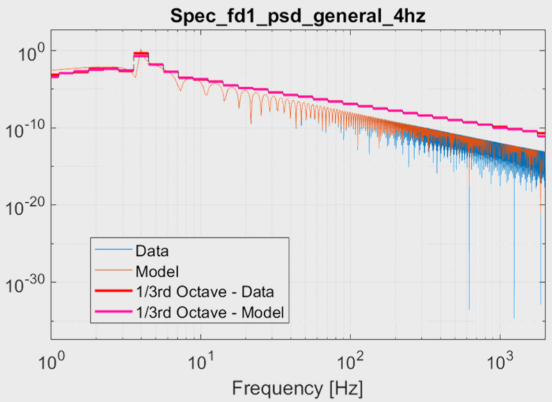




Disturbance model

- Rotating unbalance model
- Models forces acting on rotating stage when sample is out of balance
  - High-resolution tomography of region near the edge of the sample
  - Range: ± 20 mm
  - Maximum unbalanced mass: 40 kg
- Autobalancing system:
  - Reduce unbalanced forces to 1 N
  - Active control
  - Total mass: 70 kg
  - Under development by MI-Partners





$$
\begin{cases}
F_x = F_z = F_d = m_d u_d \omega^2 \\
M_x = M_z = M_d = F_d h + m_d u_d g \\
F_y = M_y = 0
\end{cases}
$$

Parameter	W/o Autobalancing	W/ Autobalancing
m_d [kg]	40	70
h [mm]	120	150
u_d [mm]	20	9e-2
f [Hz]	2	2
F_d [N]	126	1

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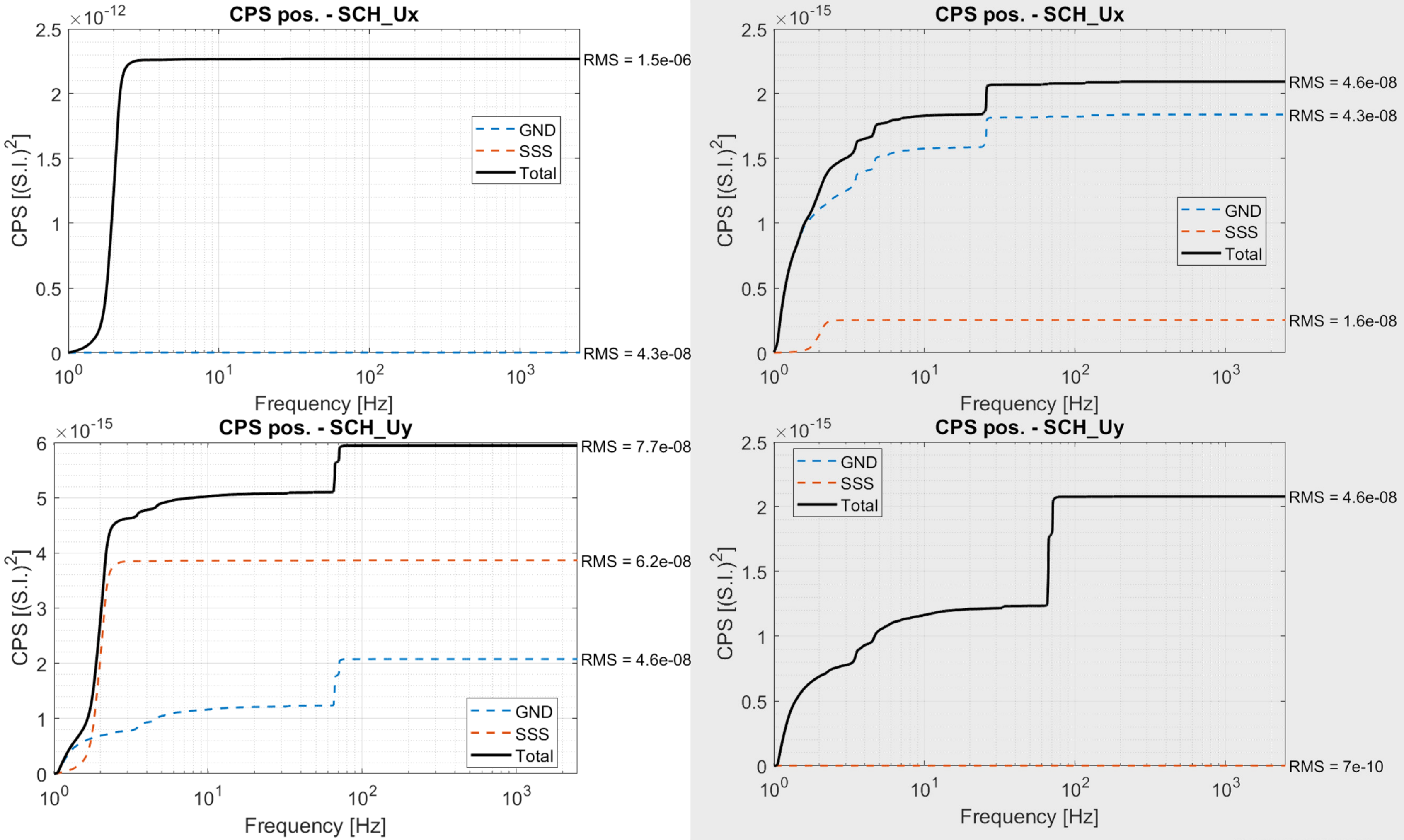
Disturbance model

- Results: PSD, CPS or CAS of sample vibration
  - 40 times more vibration without autobalancing



CPS results for sample vibration from DEB-Tool, in X (top) and Y (bottom) directions. Left side is without autobalancing, and right side is with autobalancing. Cumulative RMS results in meters.

Error Budget

- Errors: sample-to-optics instabilities
  - Dynamics vibration (from DEB-Tool)
  - Spindle error motion (measured at SEA)
- Peak-to-peak total error must sum to less than the resolution
  - Limit: 500 nm PP ≡ 83 nm RMS

Error Budget

- Spindle error motion
  - Measured at spindle error analyzer
  - Synchronous part (repeatable):
    - Mostly form errors on bearing
    - Repeats every rotation
    - Systematic, can be compensated with calibration
  - Asynchronous part (random):
    - From random disturbances
    - Not systematic
    - Usually, lower amplitude than synchronous
    - Can be compensated with metrology

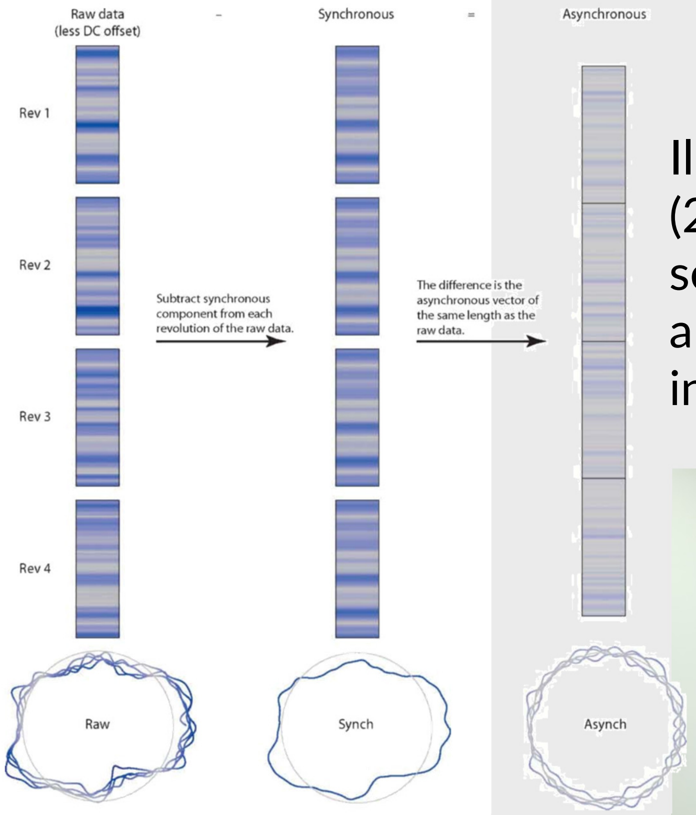
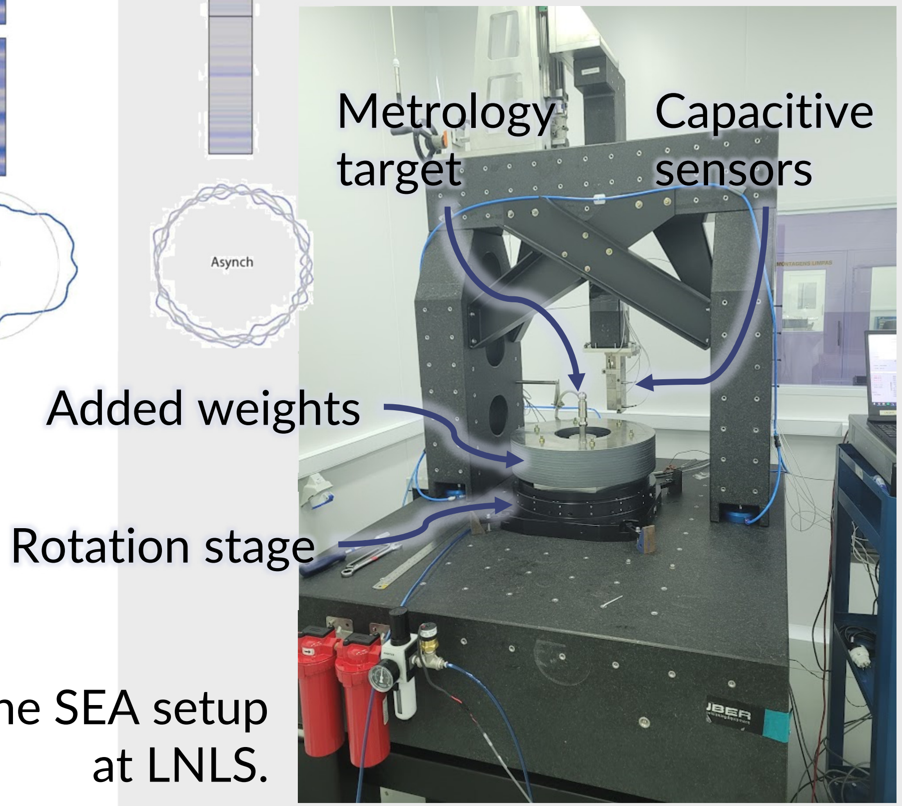


Illustration from Marsh (2010) showing how to separate synchronous and asynchronous errors in SEA measurements.



The SEA setup at LNLS.

Error Budget

- Limit for 500 nm resolution experiments: 83 nm RMS in each direction
- Calibration:
  - By measuring spindle error previously, the repeatable motion error can be compensated during recon
- In-situ metrology:
  - A metrology between the sample module and the rotation stage can measure the motion during the acquisition, compensating both synchronous and asynchronous errors
- Without the autobalancing system and at least a calibration procedure, the microstation is not able to perform to its full specifications

Source	W/o Autoblancing		W/ Autobalancing	
	X	Y	X	Y
Dynamics	1500	77	46	46
Spindle Sync.	220	85	231	64
Spindle Async.	25	27	26	17
Total	1745	189	303	127
Total w/ calibration	1525	104	72	63
Total w/ metrology	1500	77	46	46

Error budget table, values in nm RMS.

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Conclusions and final remarks

- Microstation:
  - Can perform high-resolution experiments, but will have to limit rotation speed and/or unbalance distances
  - In future analyses, more consideration should be taken into the uncertainties of the spindle metrology, since it adds to the error budget
    - Current noise measurements of the SEA for balanced systems are about 10 nm RMS
- The methodology:
  - Using LM models in DEB-Tool allows fast visualization of the impacts of a modification in the design
  - DEB-Tool can also perform dynamic error budget for feedback and feedforward control loops integrated to the dynamic model

Thank you!

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