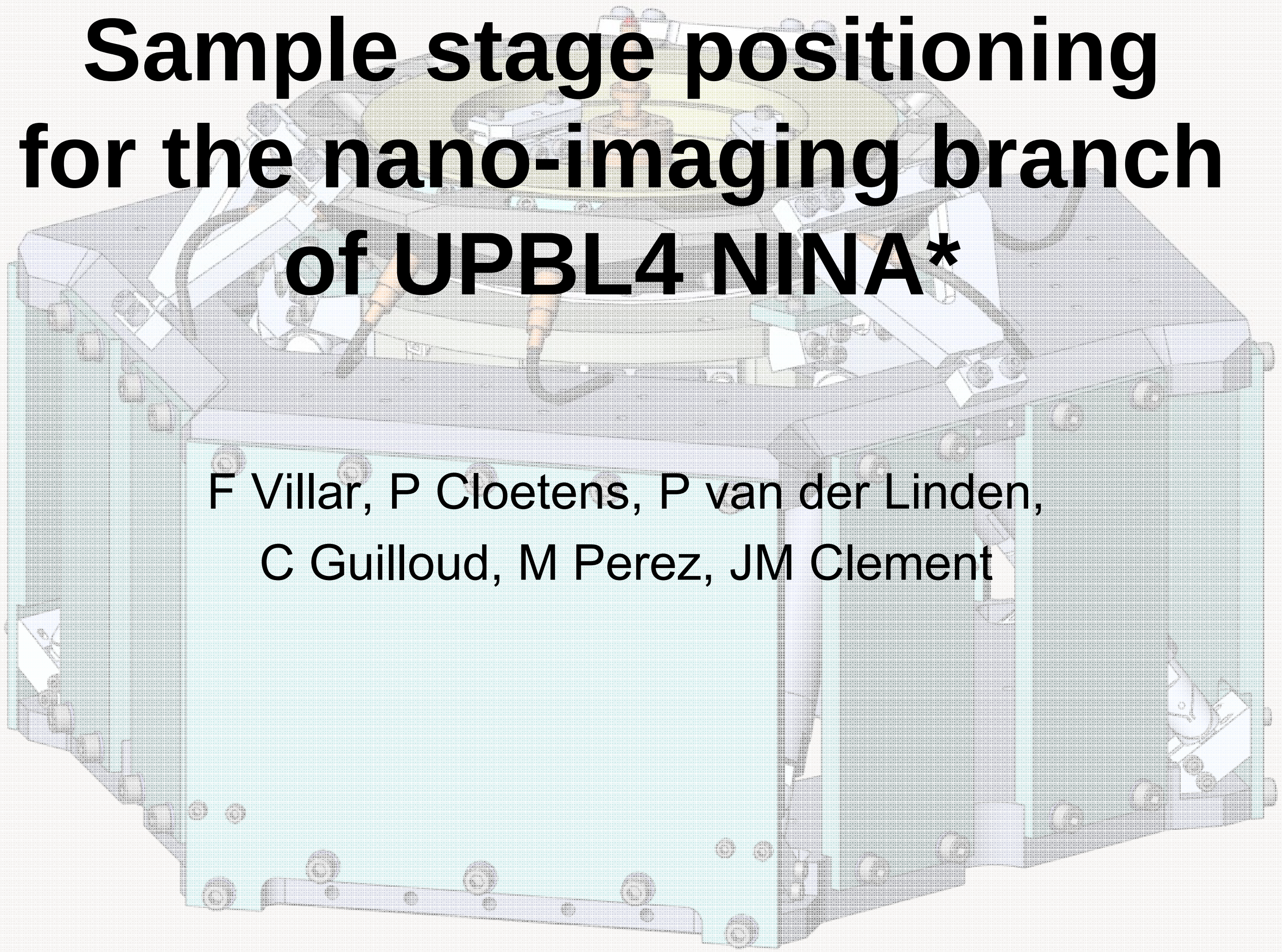
Sample stage positioning for the nano-imaging branch of UPBL4 NINA*



F Villar, P Cloetens, P van der Linden,
C Guilloud, M Perez, JM Clement

*UPgrade BeamLine 4 Nano-Imaging and Nano-Analysis

UPBL4 NINA on ID16

UPBL4 is a long, canted, high β beamline with 2 branches:

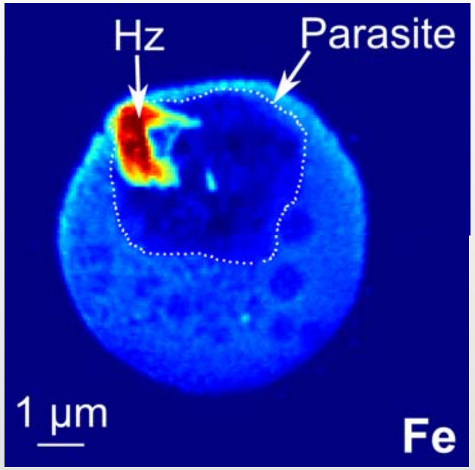
- **NI: ultimate pink beam focus for imaging and XRF**
- **NA: nanofocus monochromatic beam for spectroscopy**

X-ray ultra-microscopy and nano-spectroscopy

	NI	NA
Length	185 meters	165 meters
Spatial Res.	10 – 100 nm	50 nm -1 μm
ΔE/E (%)	1	0.01
Energy range	Discrete 11 – 17 – 33 keV	Scanning 5 →70 keV
Main goals	XRF, coherent XRI-2D/3D Cryo environment	XAS, XRD, XRF, XRI-2D/3D *in-situ* experiments
Main fields	Biology & Life Sciences Nanotechnology & Nanomedicine	Biology, environmental sciences, geoscience, materials sciences, ...

Nano-Imaging branch: scientific drivers

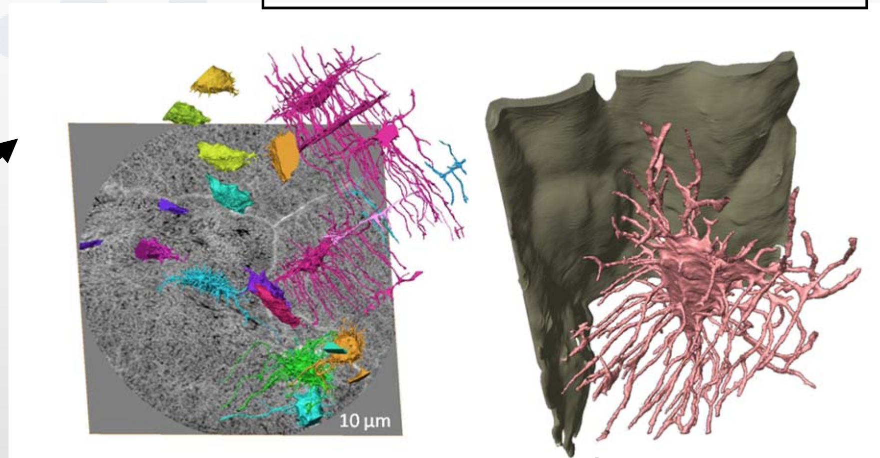
Biomedical Research:
Sub-cellular processes



Anti-malarian drugs
Dubar et al, *Chem. Commun.*

NI

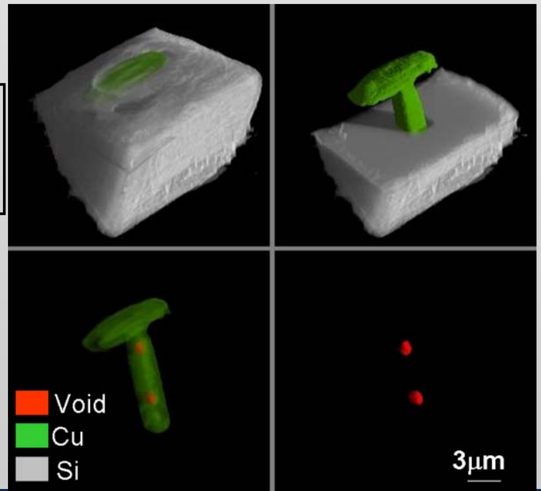
Biomedical Engineering:
Tissue-level



Bone ultrastructure; Langer et al, *PloS One*

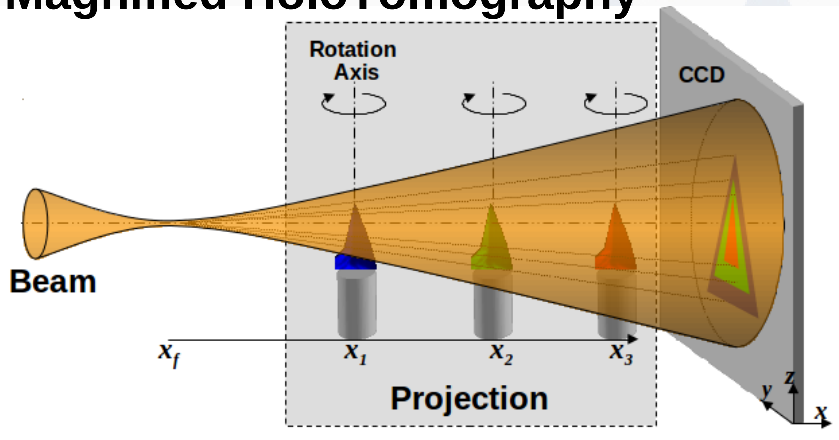
Nano/Micro-Technology:
3D Integration

Voids in Through-Si-via
Bleuet et al (CEA-Leti)

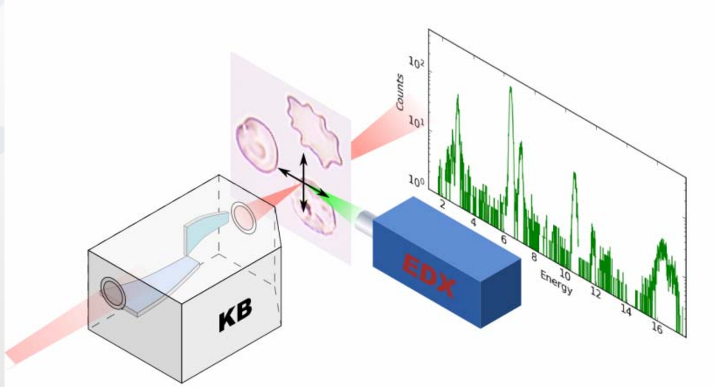


Nano-Imaging branch: experimental techniques

Magnified HoloTomography

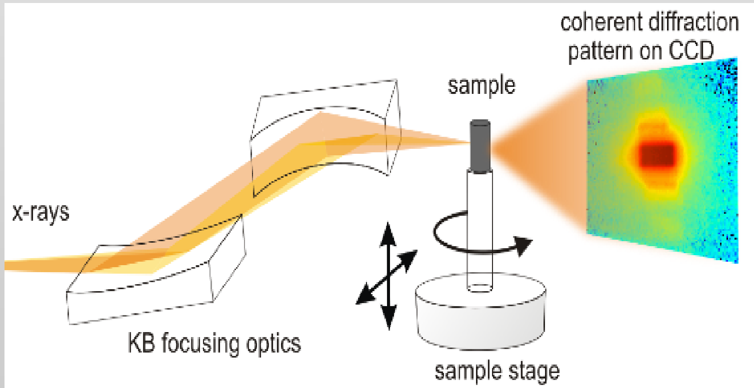


X-ray Fluorescence Microscopy (2D/3D)

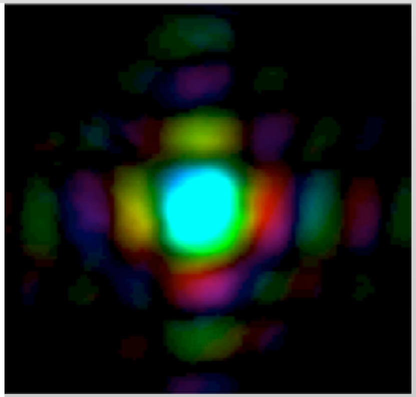


Electron Density distribution ← NI → (Trace) Element distributions

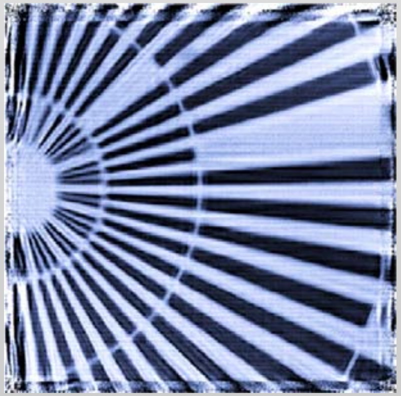
Ptychographic Nano-Tomography (ultimate resolution)



With F. Pfeiffer et al.

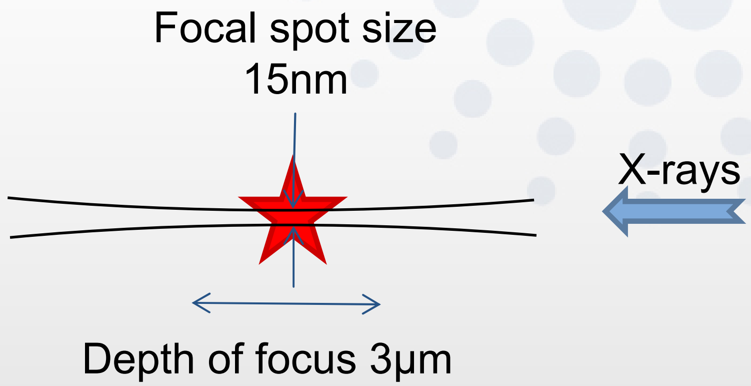


Probe



Object

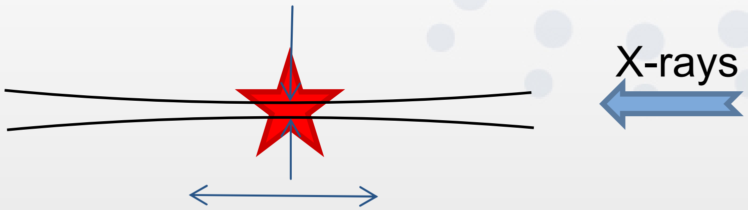
Sample positioning and environment



17keV and 33.6keV
fixed curvature KB optics

Sample positioning and environment

Focal spot size
15nm



Depth of focus 3µm

17keV and 33.6keV
fixed curvature KB optics

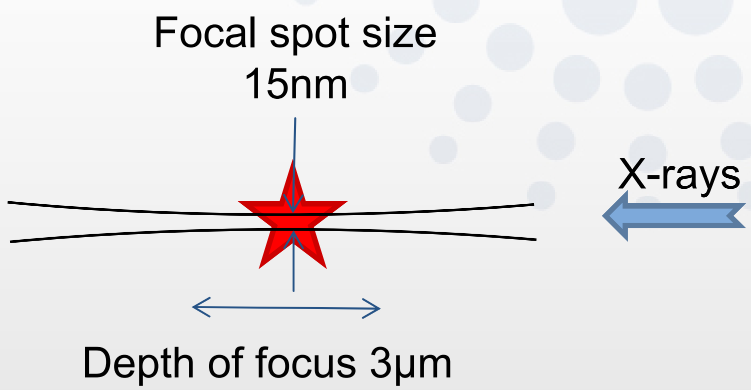
<u>Magnified holo-tomography</u>

- 360° rotation, 1°/s
- parasitic movements < **50nm**

<u>Fluorescence analysis / Ptychography</u>

- 50µm*50µm scanning range
- **5nm** steps

Sample positioning and environment



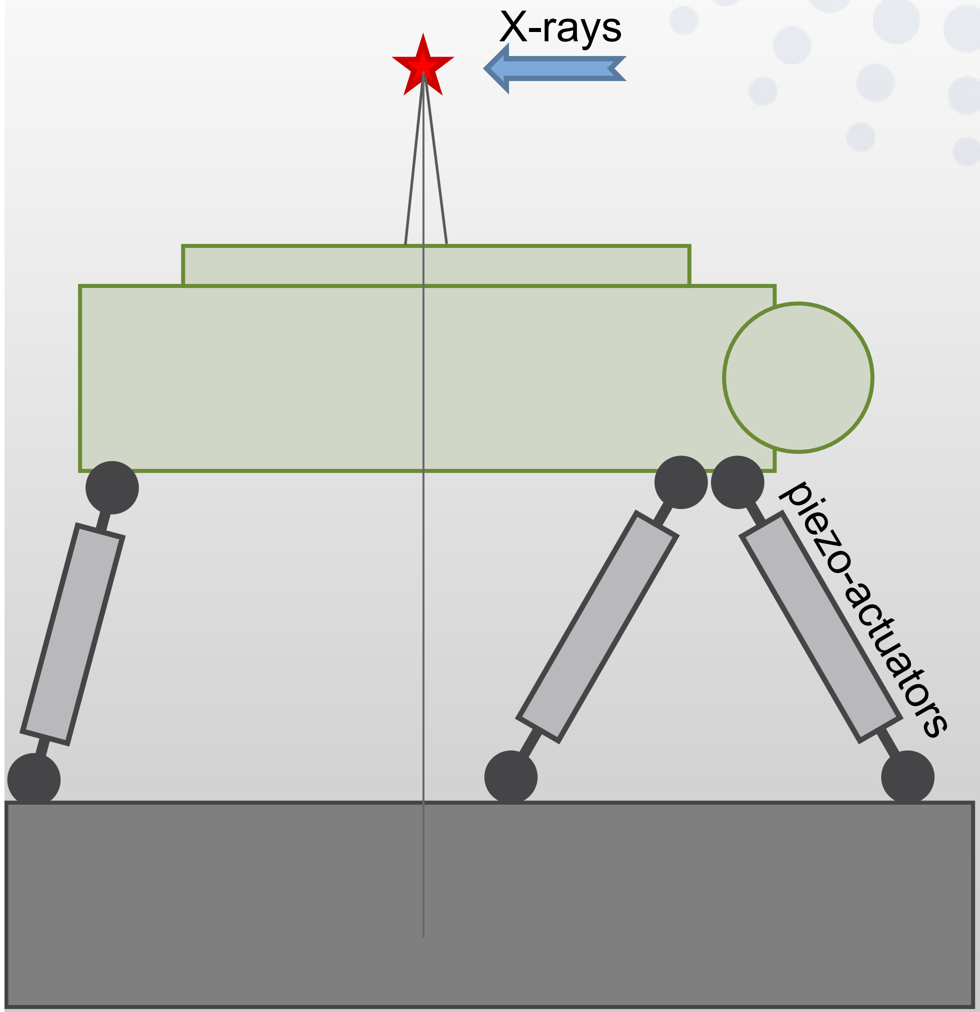
17keV and 33.6keV
fixed curvature KB optics

Magnified holo-tomography
- 360° rotation, 1° /s
- parasitic movements < 50nm

Fluorescence analysis / Ptychography
- 50µm*50µm scanning range
- 5nm steps

To limit the radiation damage :
- sample at 100K and under vacuum (10^{-4} Pa)
- free space for large solid angle fluorescence detectors

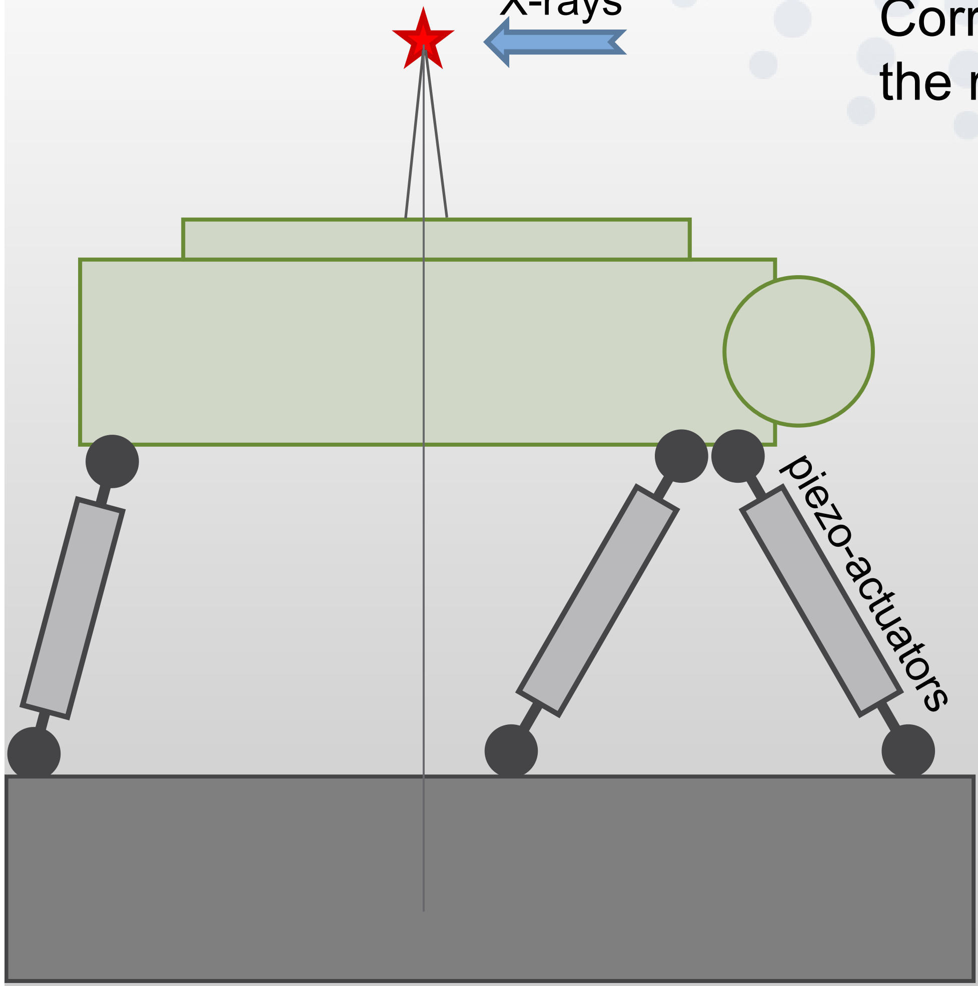
Concept : rotation stage + hexapod



Commercial rotation stage
roller bearings
360° , resolution ~ 0.01°
Parasitic movements ~ 10µm

6 piezo actuators
hexapod configuration
60µm stroke each
resolution ~ 1nm

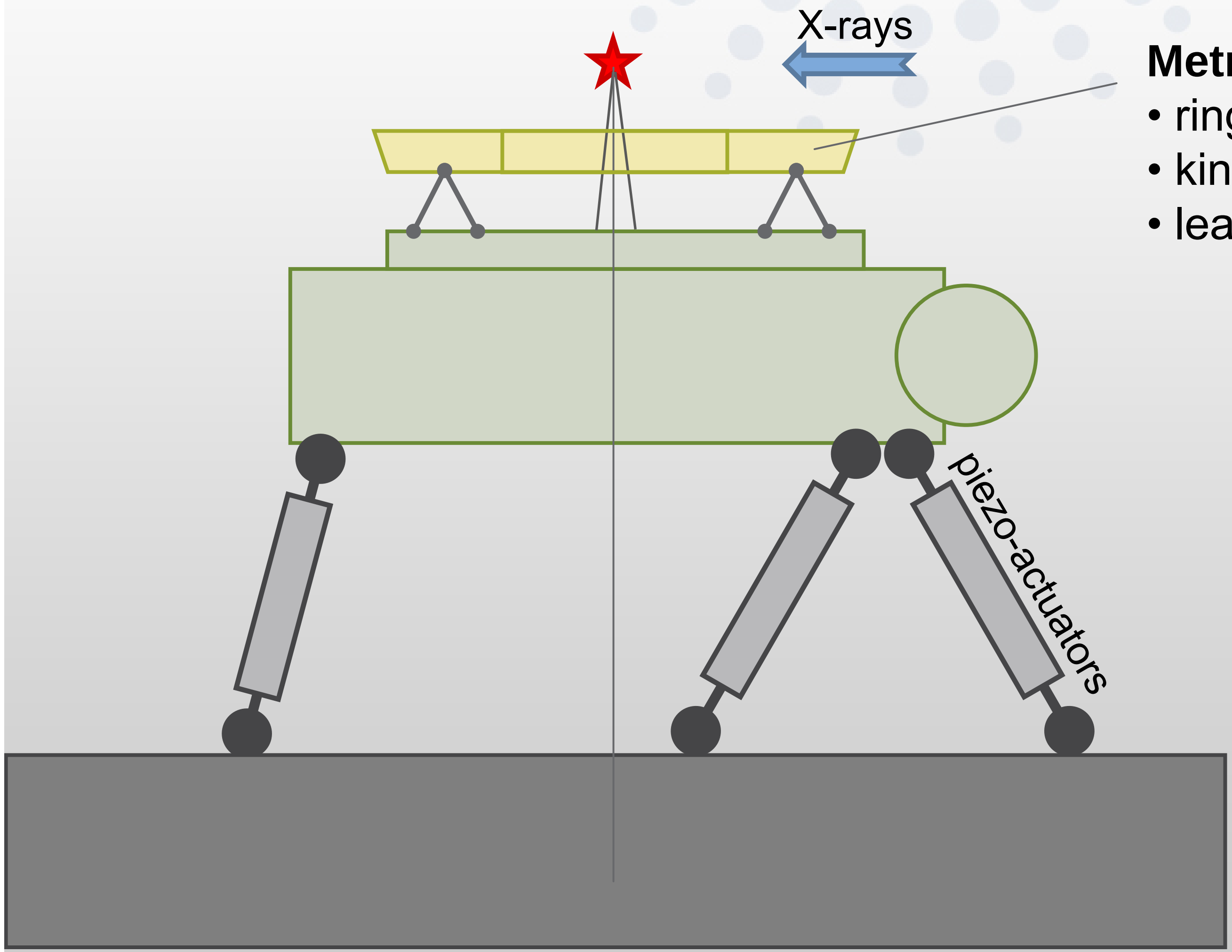
correction and scanning hexapod



TOMOGRAPHY
Correction of the parasitic movements of the rotation stage (limit 50nm)

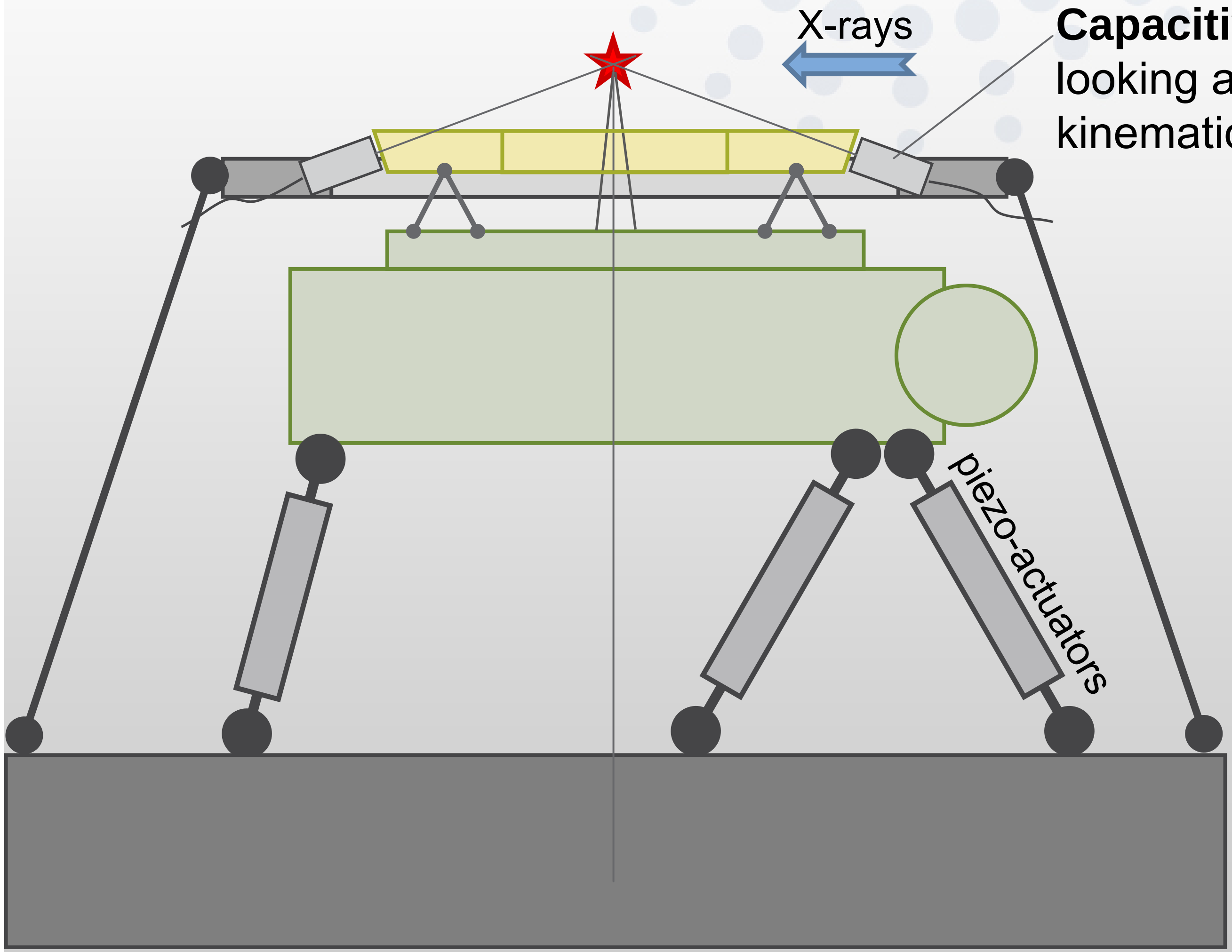
FLUO ANALYSIS, PTYCHOGRAPHY
Fine scan the sample, 50µm*50µm, 5nm steps

Direct metrology of the sample displacements



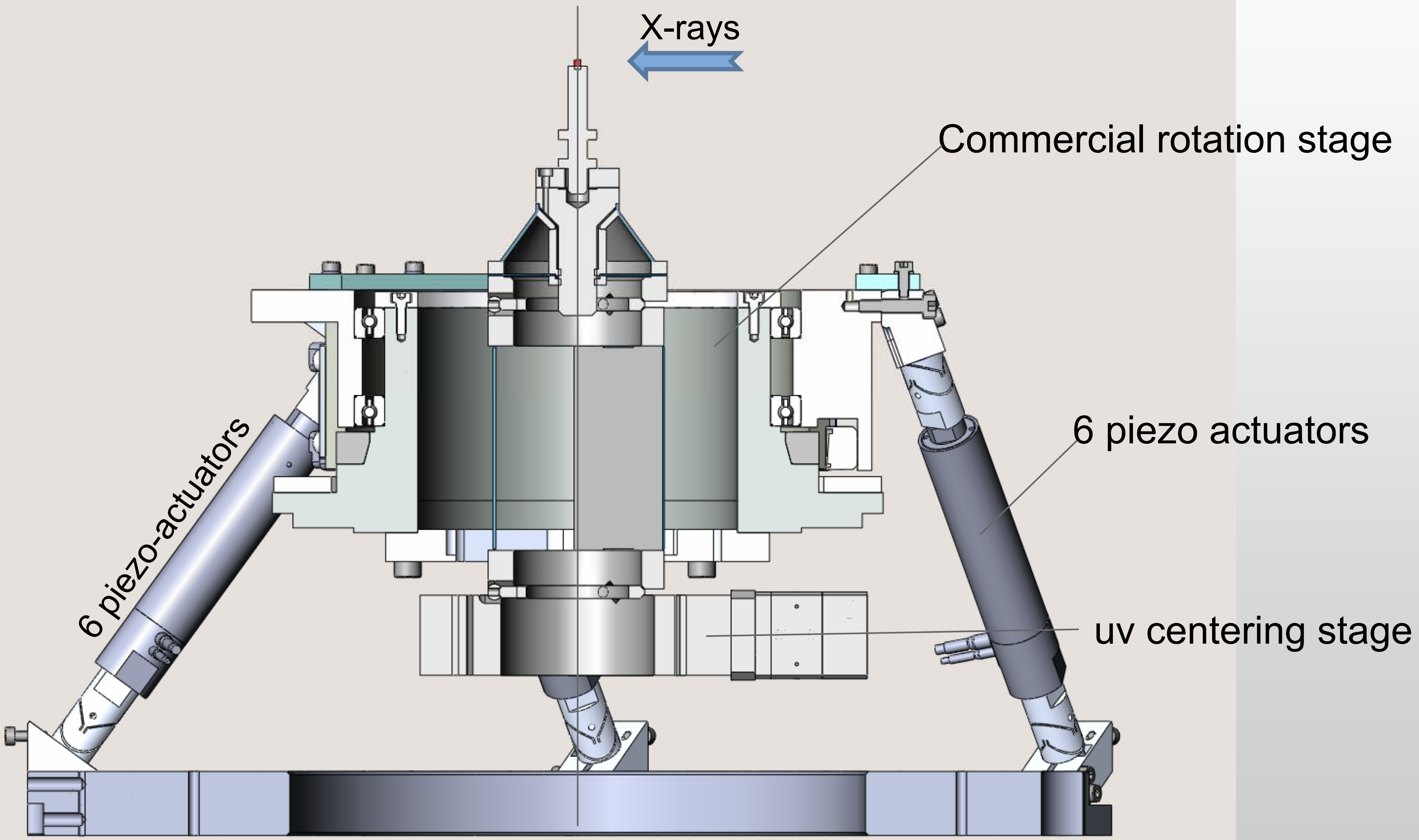
Metrological reference
- ring rotating with the sample
- kinematically mounted
- leave space for detectors

Concept : metrology frame

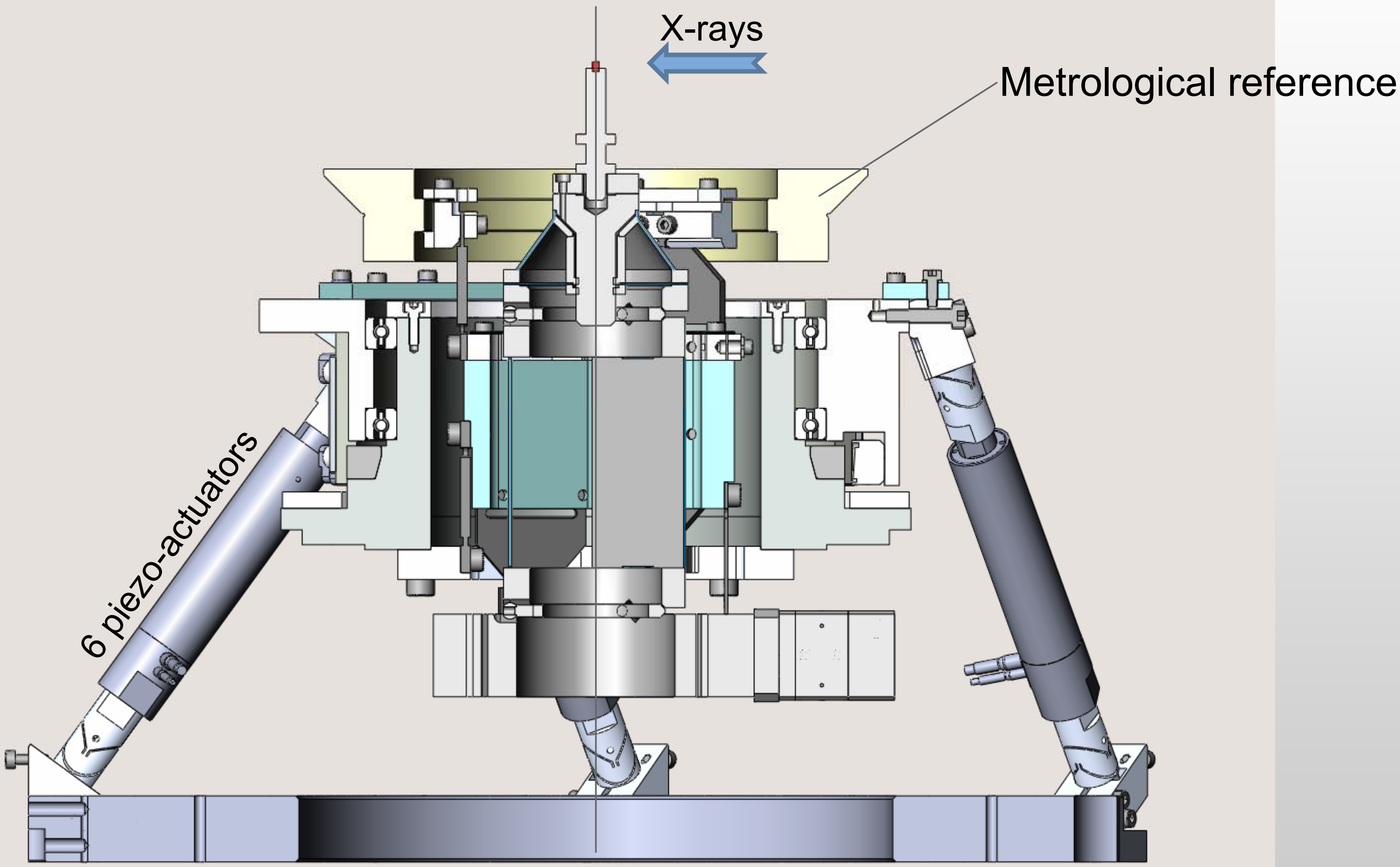


Capacitive sensors
looking at the metrological reference kinematically attached to the frame

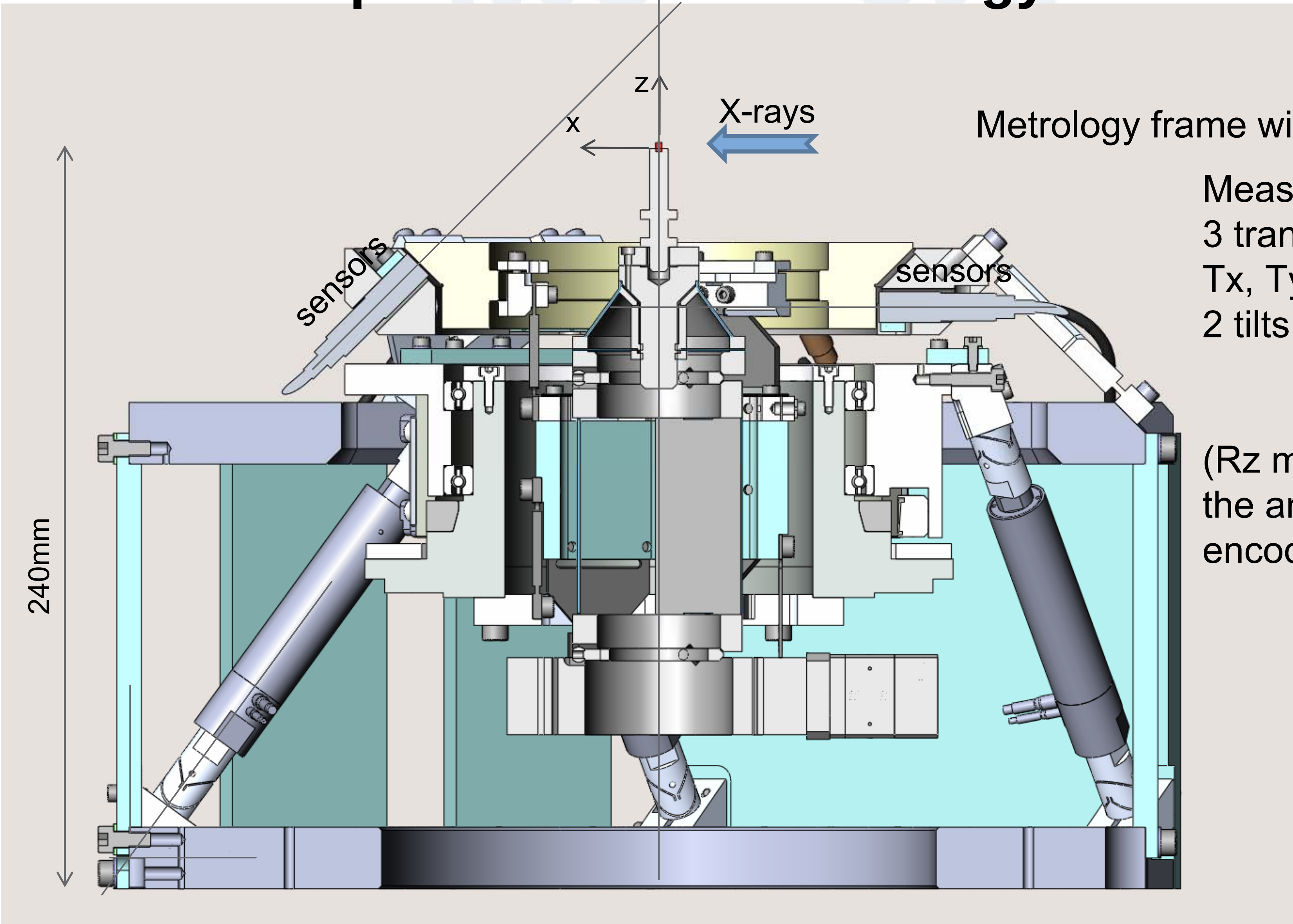
Implementation : piezo-actuated hexapod



Implementation : metrological reference



Implementation : metrology frame



Metrology frame with sensors

Measurement :
3 translations
Tx, Ty, Tz
2 tilts Rx, Ry

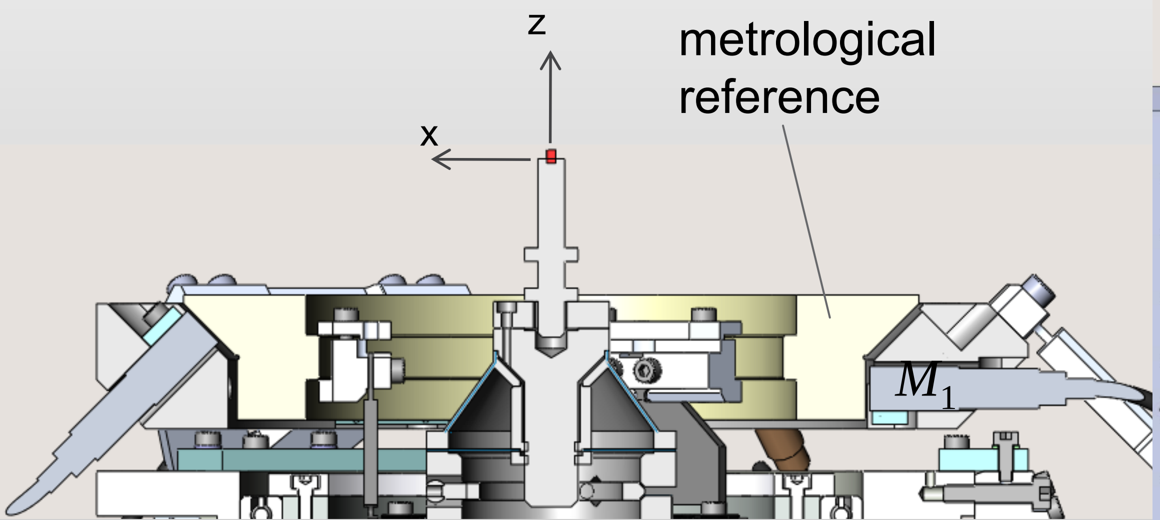
(Rz measured by the angular encoder)

More sensors than parameters : redundancy

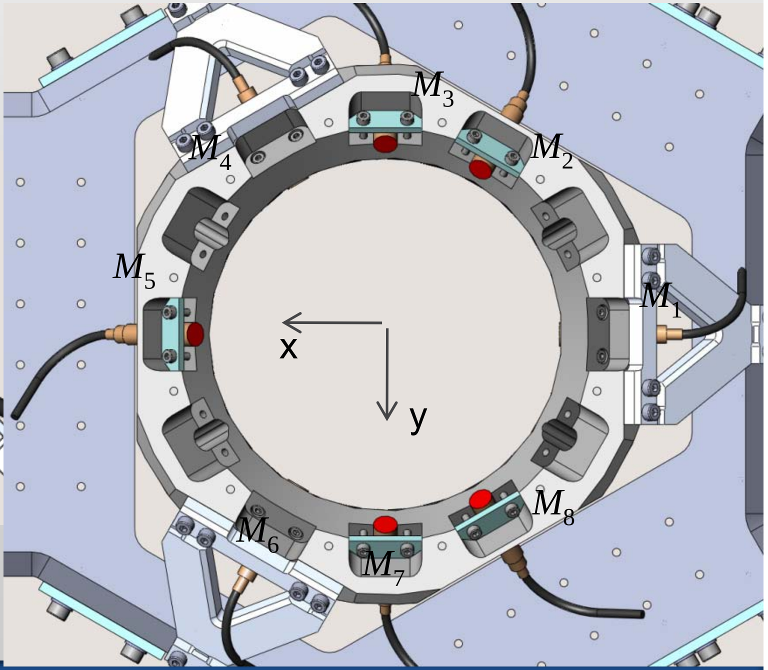
5 parameters to be measured : Tx, Ty, Tz, Rx, Ry

- Reduction of noise by averaging N measurements : √N
- A dysfunction of the system can be identified by the inconsistency of measurement
- Ability to measure other parameters (thermal expansion for example)

+ money + space $\Rightarrow$ 8 (12) sensors



Sensors holder



From the sensors to the displacement of the sample

5 parameters (Tx,Ty,Tz,Rx,Ry) to be determined by 8 sensors
$\Rightarrow$ least square optimization

Hypothesis : **small displacements** (50µm max)
$\Rightarrow$ sensor output is a linear combination of the 5 parameters

8 sensors

5 disp

$$\begin{Bmatrix} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \\ M_6 \\ M_7 \\ M_8 \end{Bmatrix} = [S] \cdot \begin{Bmatrix} T_x \\ T_y \\ T_z \\ R_x \\ R_y \end{Bmatrix}$$

From the sensors to the displacement of the sample

5 parameters (Tx,Ty,Tz,Rx,Ry) to be determined by 8 sensors
⇒ least square optimization

Hypothesis : **small displacements** (50µm max)
⇒ sensor output is a linear combination of the 5 parameters

8 sensors

5 disp

$$\begin{Bmatrix} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \\ M_6 \\ M_7 \\ M_8 \end{Bmatrix} = [S] \cdot \begin{Bmatrix} T_x \\ T_y \\ T_z \\ R_x \\ R_y \end{Bmatrix}$$

Least square fit

$$\frac{\mathrm{d}}{\mathrm{d}T_x} \sum_{i=1,8} (M_i - S_i)^2 = 0$$

Sample displacement

Measurement by the *i*th capacitive sensor

*i*th row of the signature matrix

From the sensors to the displacement of the sample

5 parameters (Tx,Ty,Tz,Rx,Ry) to be determined by 8 sensors
$\Rightarrow$ least square optimization

Hypothesis : **small displacements** (50µm max)
$\Rightarrow$ sensor output is a linear combination of the 5 parameters

8 sensors

5 disp

$$\begin{Bmatrix} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \\ M_6 \\ M_7 \\ M_8 \end{Bmatrix} = [S] \cdot \begin{Bmatrix} T_x \\ T_y \\ T_z \\ R_x \\ R_y \end{Bmatrix}$$

Least square fit

$$\frac{\mathrm{d}}{\mathrm{d}T_x} \sum_{i=1,8} (M_i - S_i)^2 = 0$$

$$\begin{Bmatrix} T_x \\ T_y \\ T_z \\ R_x \\ R_y \end{Bmatrix} = [S'] \cdot \begin{Bmatrix} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \\ M_6 \\ M_7 \\ M_8 \end{Bmatrix}$$

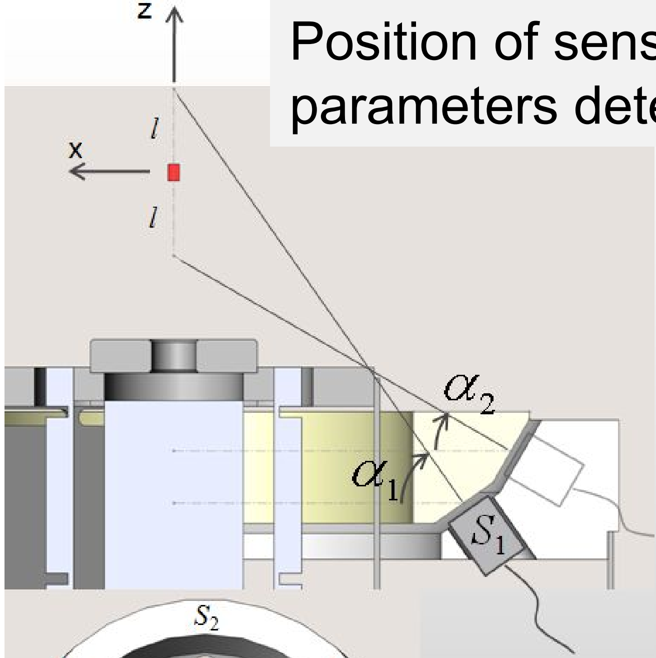
Sample displacement

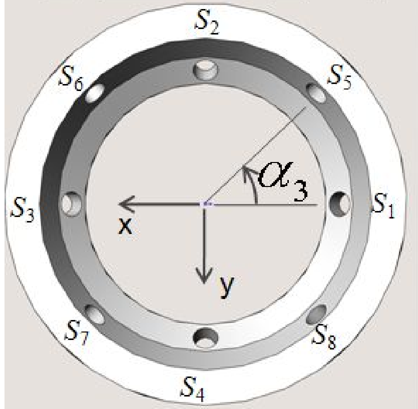
Measurement by the *i*th capacitive sensor

*i*th row of the signature matrix

Sensors position optimization

Position of sensors is *optimized* to reduce the noise on the parameters determination (e.g. Monte-Carlo simulation)

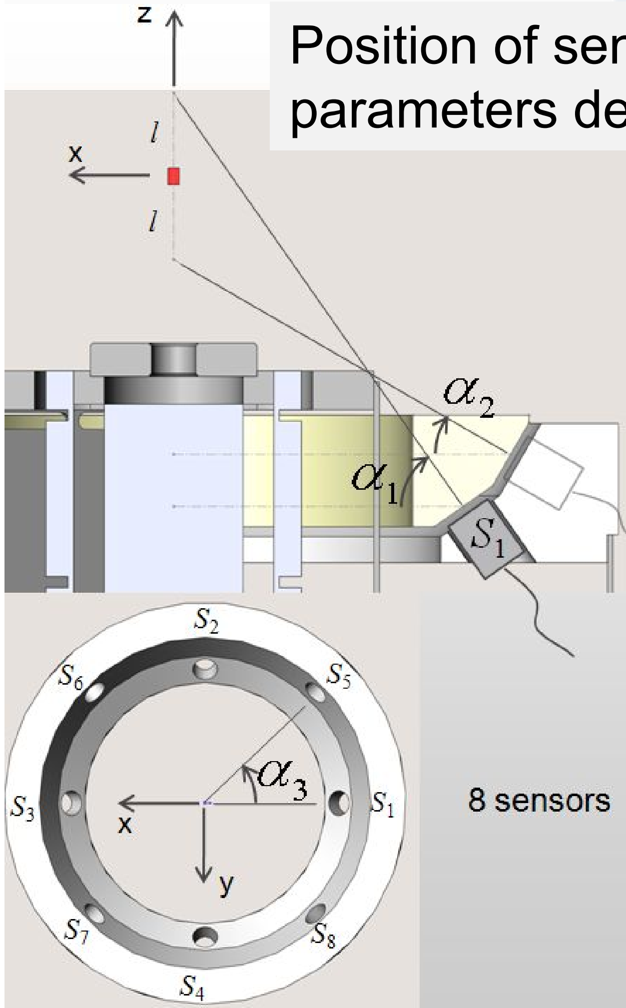


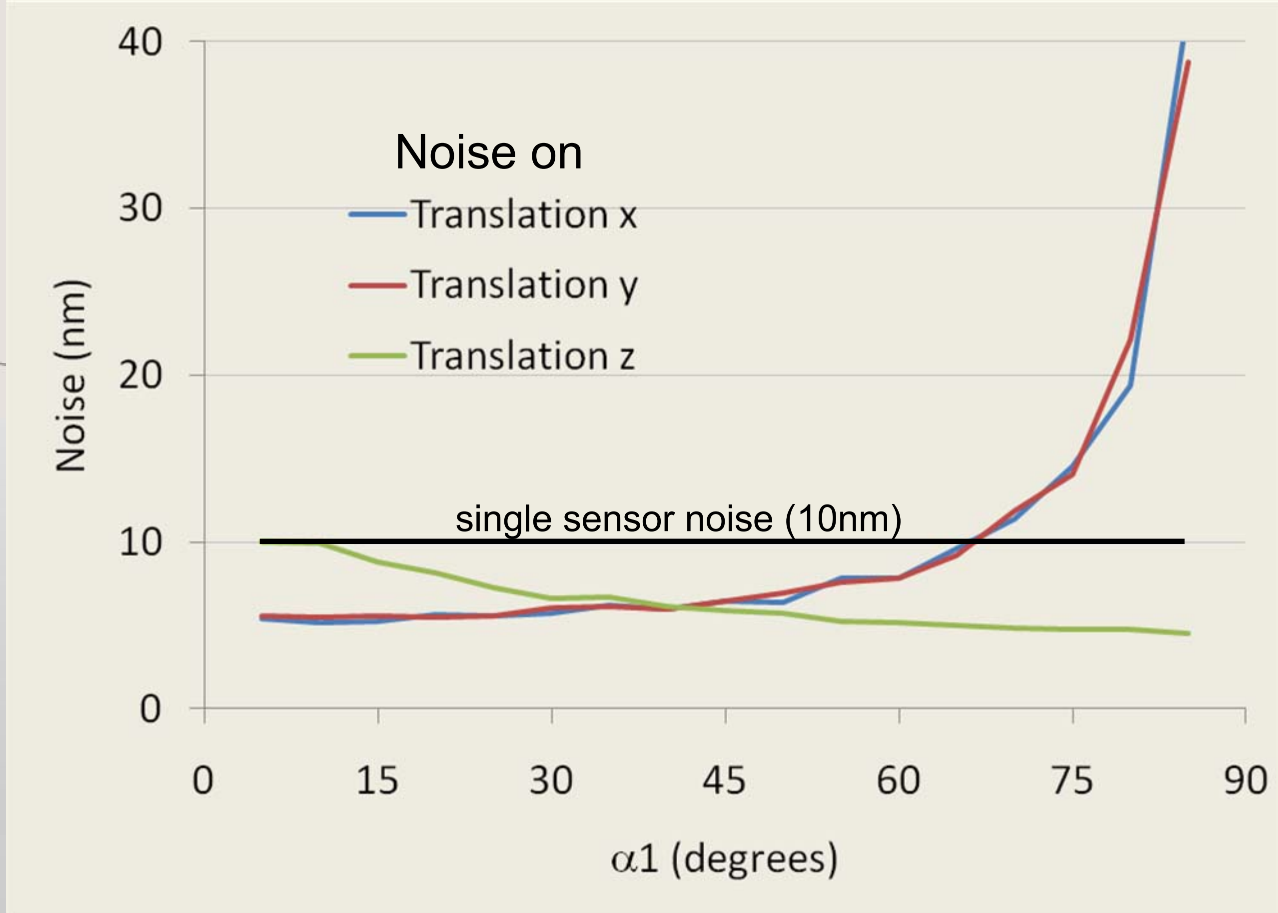


8 sensors

Sensors position optimization

Position of sensors is *optimized* to reduce the noise on the parameters determination (e.g. Monte-Carlo simulation)





Small displacement hexapod control

Fine scan or correction of guiding errors

Piezo-actuators : extension (60µm) << length (150mm)

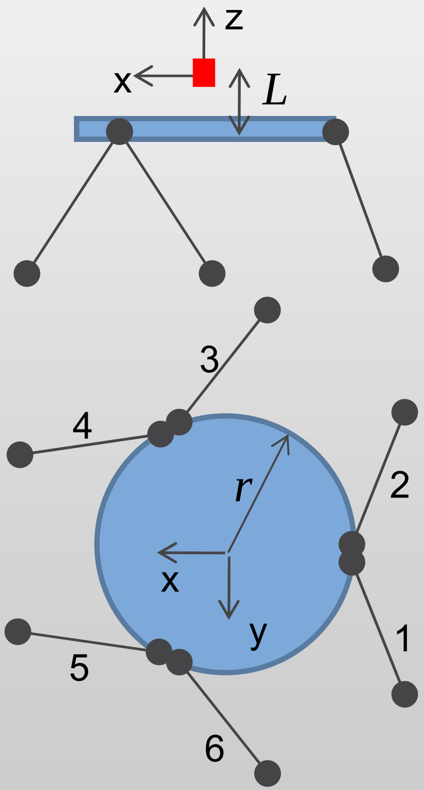
⇒ A linear model is sufficient to approximate the hexapod kinematic

Small displacement hexapod control

Fine scan or correction of guiding errors

Piezo-actuators : extension (60µm) << length (150mm)

⇒ A linear model is sufficient to approximate the hexapod kinematic



$$\begin{Bmatrix} \Delta 1 \\ \Delta 2 \\ \Delta 3 \\ \Delta 4 \\ \Delta 5 \\ \Delta 6 \end{Bmatrix} = \begin{bmatrix} 0.294 & -0.509 & 0.809 & -0.032 & 0.060 & 0.049 \\ 0.294 & 0.509 & 0.809 & 0.032 & 0.060 & -0.049 \\ 0.294 & 0.509 & 0.809 & -0.036 & -0.057 & 0.049 \\ -0.588 & 0.000 & 0.809 & -0.068 & -0.002 & -0.049 \\ -0.588 & 0.000 & 0.809 & 0.068 & -0.002 & 0.049 \\ 0.294 & -0.509 & 0.809 & 0.036 & -0.057 & -0.049 \end{bmatrix} \cdot \begin{Bmatrix} T_x \\ T_y \\ T_z \\ R_x \\ R_y \\ R_z \end{Bmatrix}$$

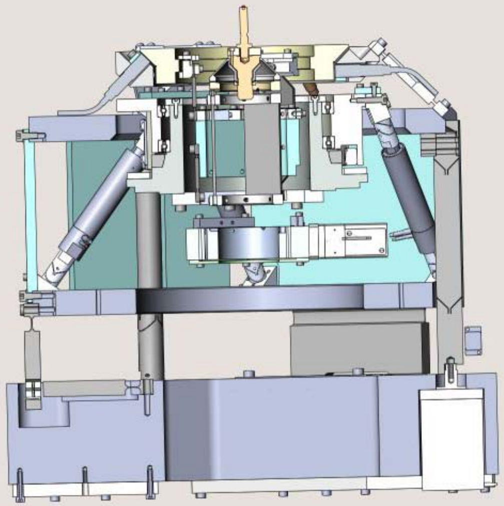
Alignment stages

Z

Translation 10mm

choice of the 50µm zone
to be imaged
+ change in incidence angle

Tripod geometry

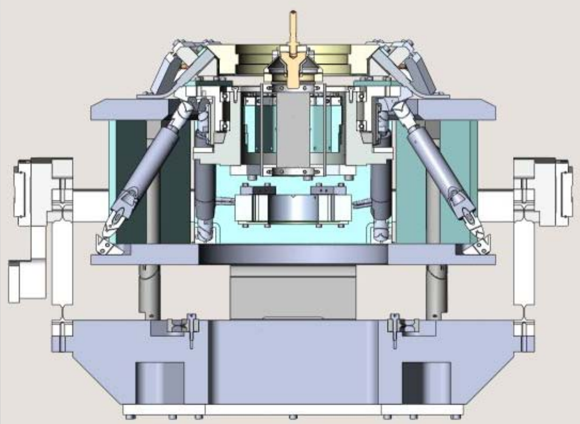


Y

Translation 10mm

choice of the 50µm zone
to be imaged

Circular translation
flexure stage

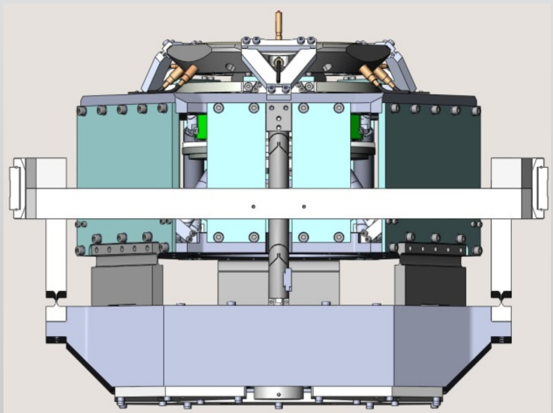


X

Translation 100mm

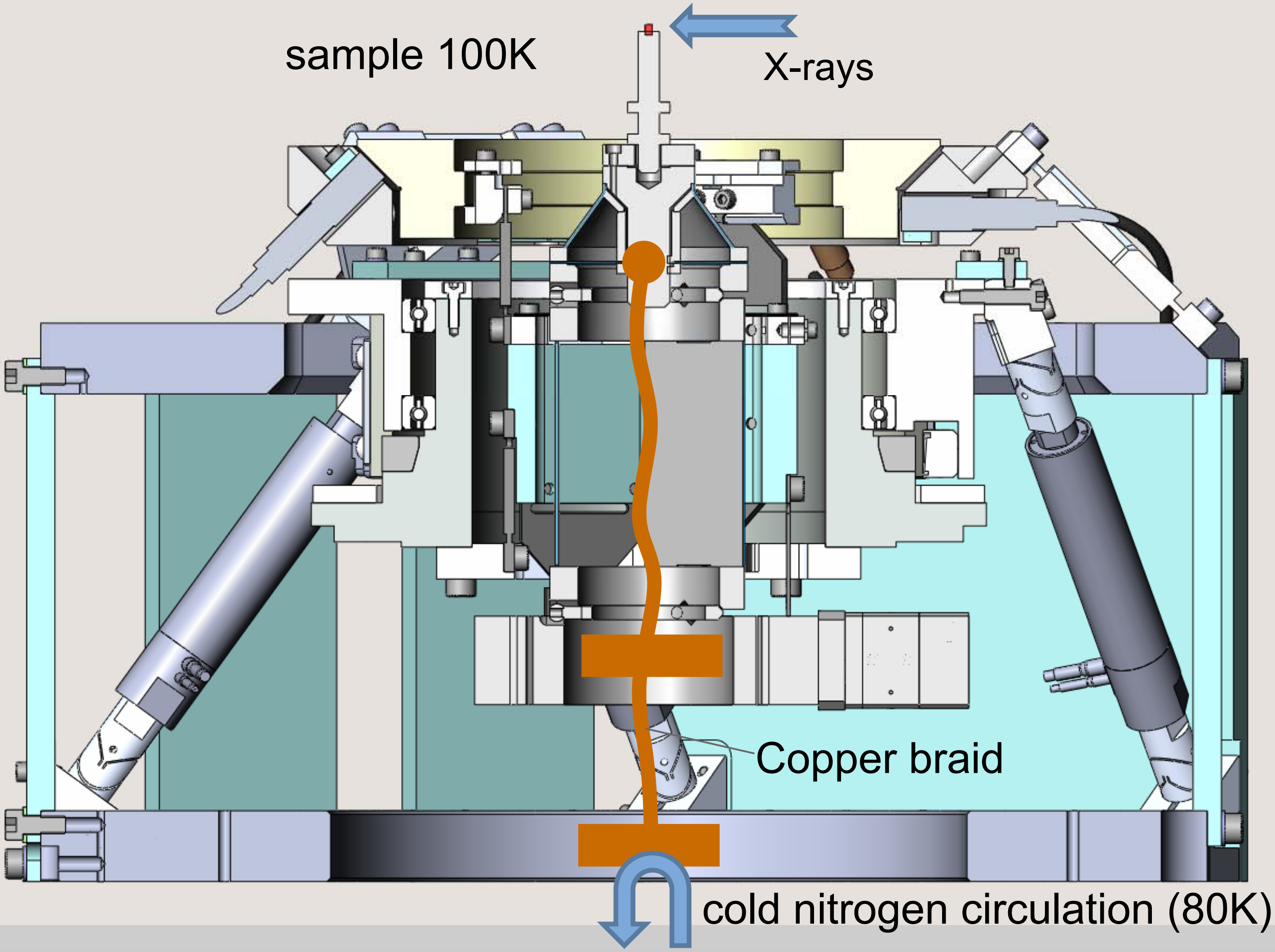
Phase contrast
tomography

Roller bearings

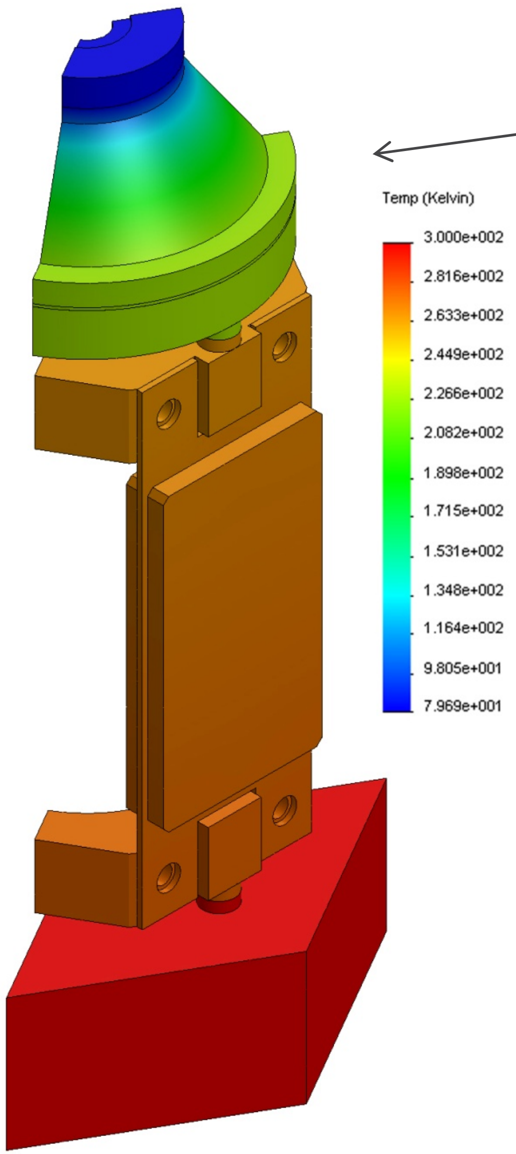


Cryo cooling to limit radiation damage

Heat is evacuated by conduction through a cold braid going through a central bore

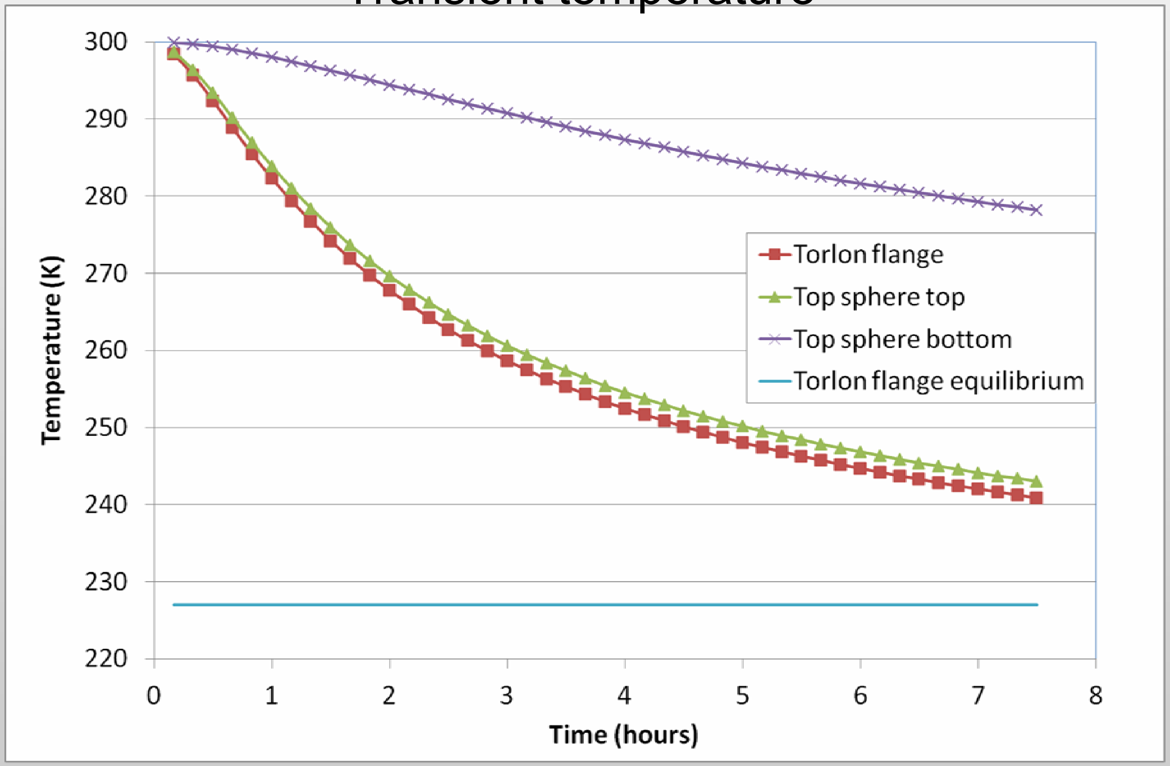


Cryo cooling

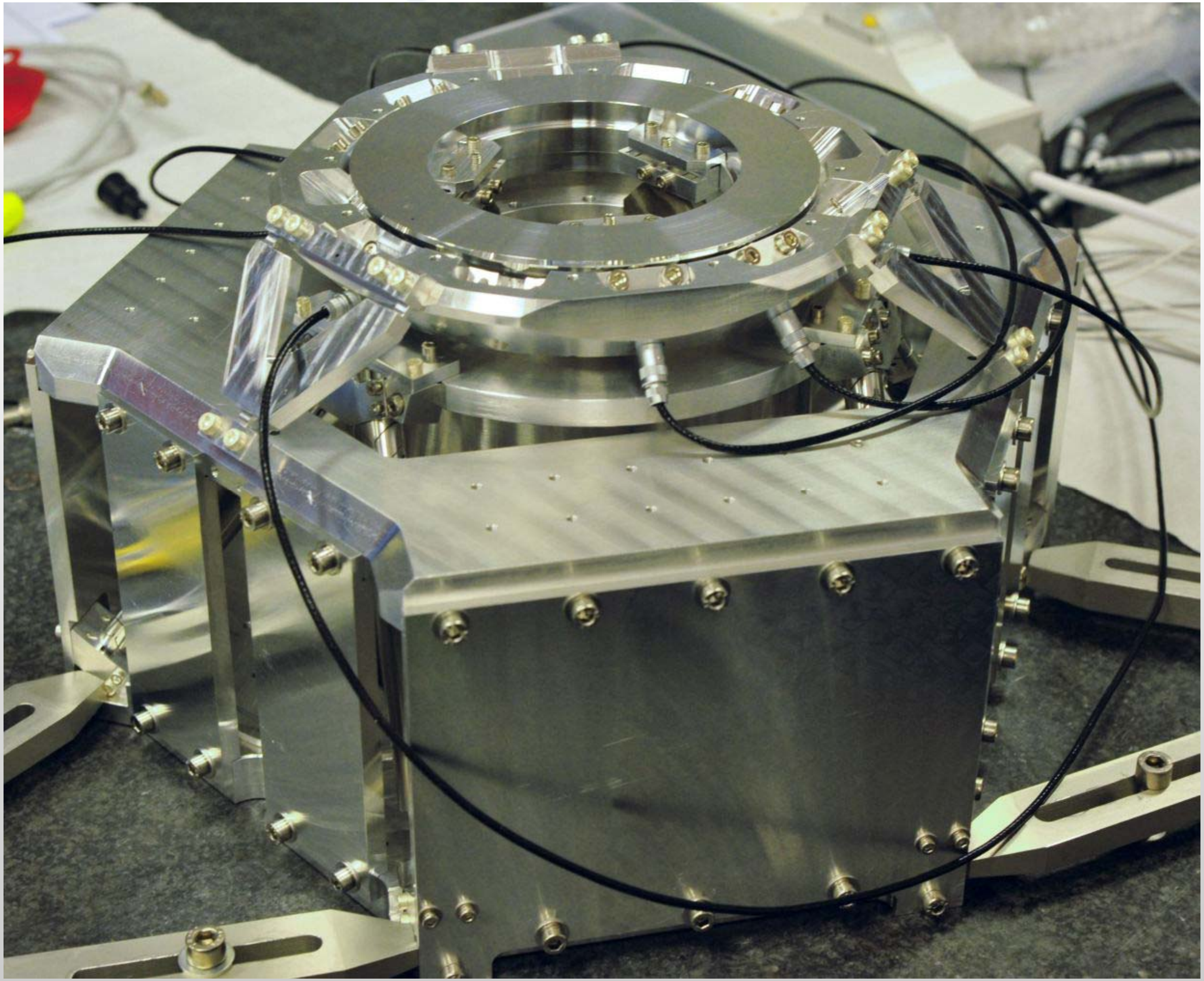


Steady state temperature of the sample holder

Transient temperature

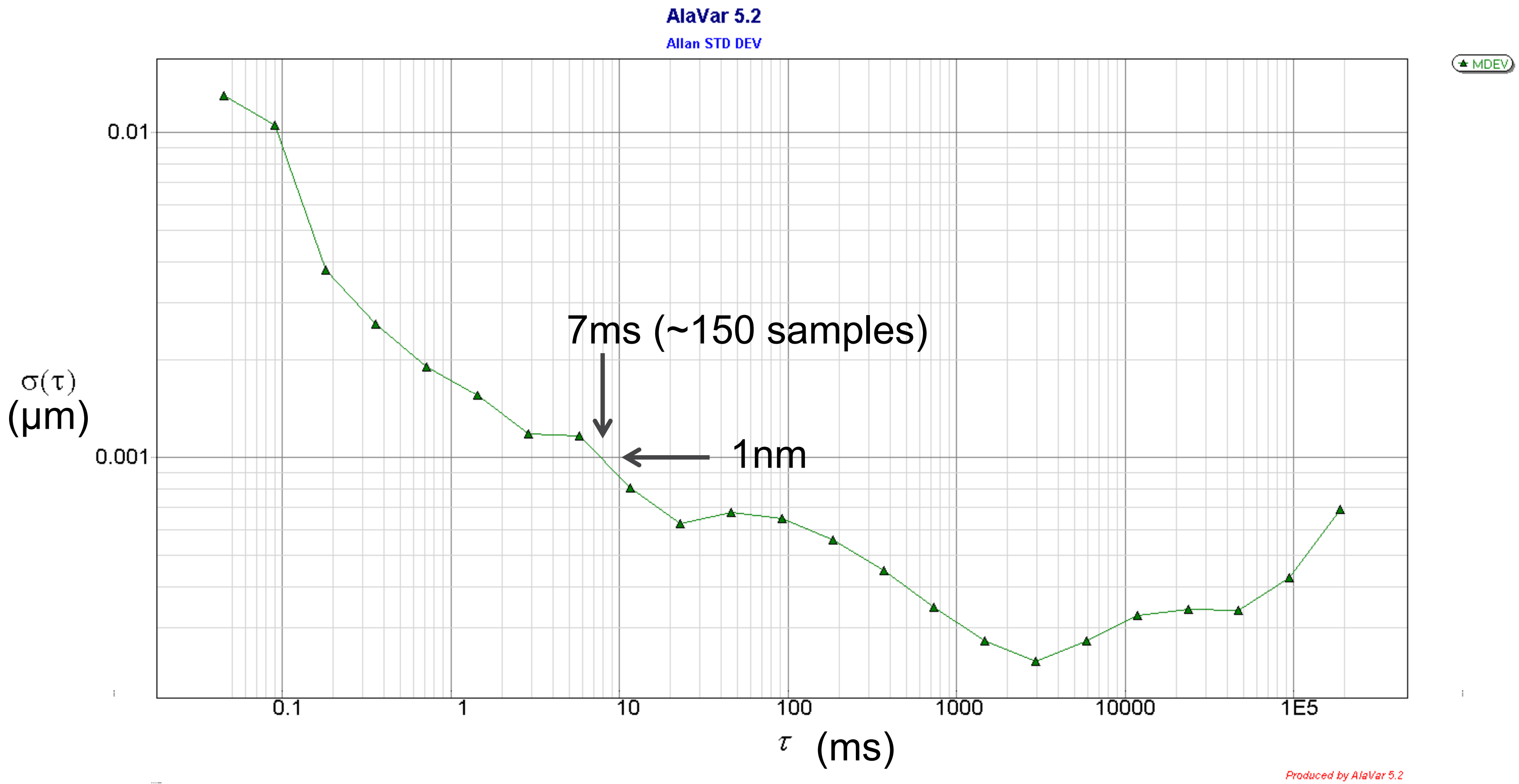


~240mm

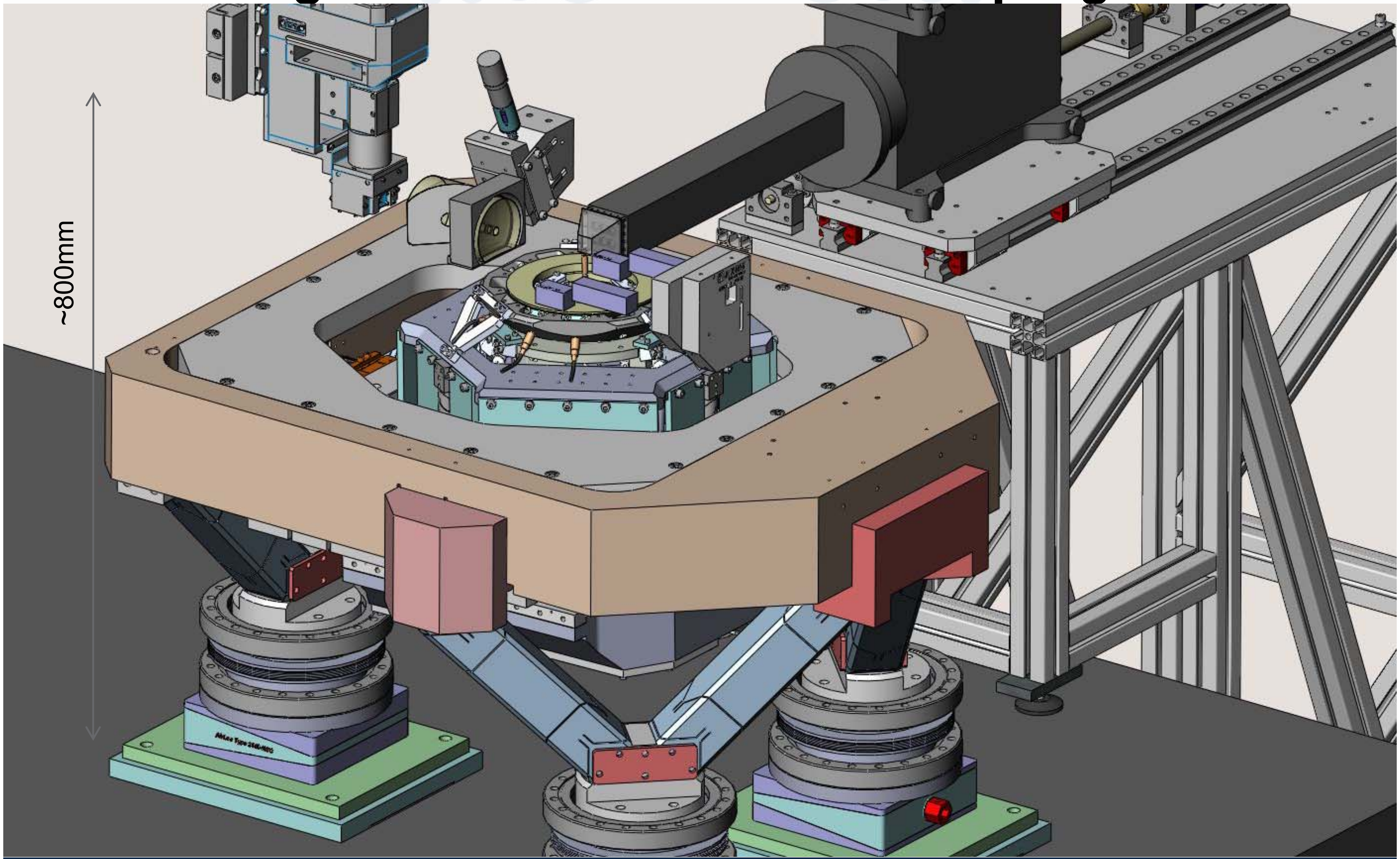


Noise level

Allan standard deviation. One single sensor. 22kHz sampling rate



Design of the endstation under progress



Acknowledgment

Experiments Division ESRF:
S. Labouré, H. Suhonen, R. Tucoulou, L. André

Instrumentation Service and Development Division ESRF:
R. Barrett (Optics)
J.C. Labiche, T. Martin, J. Morse, C. Ponchut, (Detectors)
O. Hignette (Advanced Analysis and Modelling)
R. Baker, P. Bernard, L. Ducotté, Ph. Marion, H. van der Kleij, R. Zerouk (Mechanical Eng)
G. Berruyer,(Software & Electronics)

INSERM, Grenoble Institut des Neurosciences:
S. Bohic

SPRETEC:
D. Baboulin

ENSAM Lille:
J.M. David

Thank you for your attention

Other topic

- KB changer : 17keV and 33.6keV 100mm Ty translation stage
- Cryogenic line + radiation screen
- Videomicroscope + 2mm translation stage
- Sample changer (cryo)
- Pinhole between sample and KB
- Vacuum chamber
- …

Summary

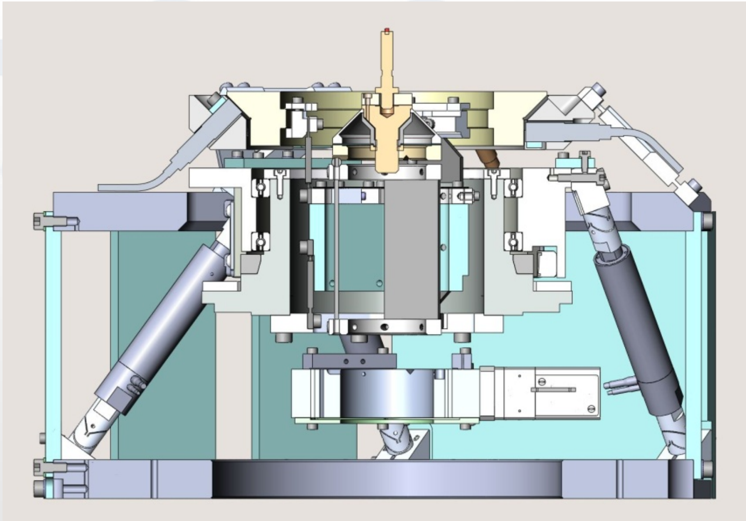
- Piezo actuated hexapod : correction of rotation stage errors + fine scan
- Direct metrology of the sample movements
- Free space for large solid angle fluorescence detectors
- Central bore for cryo cooling
- All flexure stages (except main rotation): vacuum, no hysteresis, high repeatability
- All piezo actuator stages : limit heat generation
- Axial symmetry preserved as much as possible
- Implementation of mechanic hardware and real time controller are starting

Hexapod control during rotation

8 capacitive sensors
+ electronic

0…10V
(0…100µm)

8 AD converters,18 bits
10 000 samples /s



6 piezo-actuators
amplifiers / controllers
in **closed** loop

0…10V
(0…60µm)

6 DA converters
18 bits

REAL TIME CONTROLLER

$\{M_i(\theta_j)\}$ → average → $\{M_i(\theta_0)\}$ (−) (+) → (+) (−) → $\times[S']$ → (+) (−) → $\times -[H]$

Rotation encoder → Angular position θ_j → interpolate shape and concentricity errors

$$\begin{Bmatrix} T_x = 0 \\ T_y = 0 \\ T_z = 0 \end{Bmatrix} \begin{Bmatrix} R_x = 0 \\ R_y = 0 \\ R_z = 0 \end{Bmatrix}$$

Set points of the sample movements

Hexapod control during rotation

Objective : correction made every 10ms

Highest rotation speed :

10° /s

(Typical speed 1° /s)

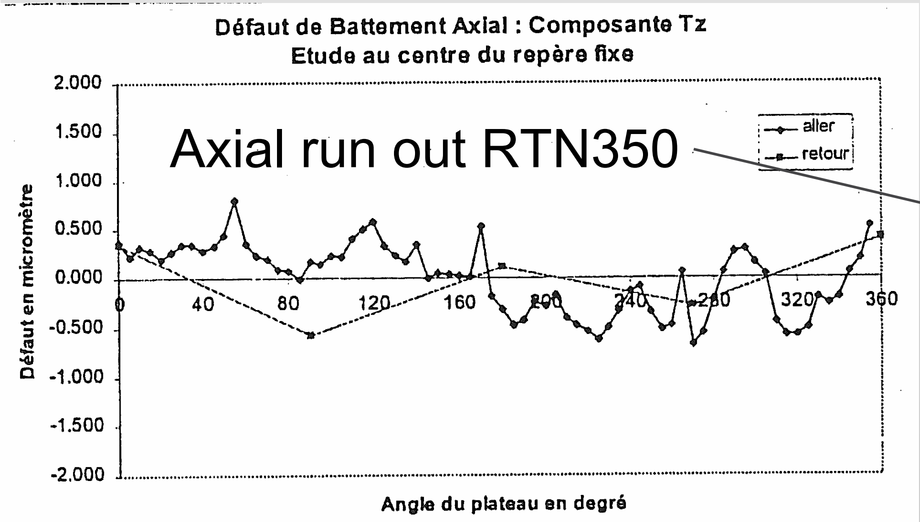
0° 0s

0.1° 10ms

Measure : mean of 40 samples
4ms at a sampling rate of 10000 s^{-1}

Correction calculation
1ms

Command of piezo actuators
4ms



Highest variation rate ~ 2µm in 5°
Command of the actuators : 40nm in 4ms (10° /s)
Command of the actuators : 4nm in 4ms (1° /s)