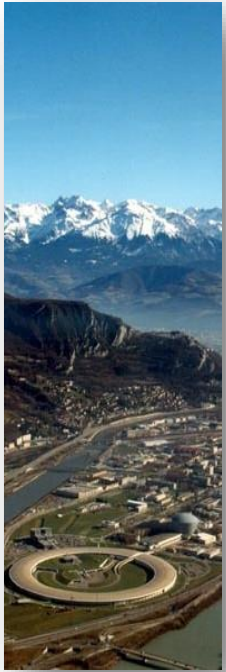
ESRF | The European Synchrotron



# ESRF

# EBS small beam

# Heat load issues

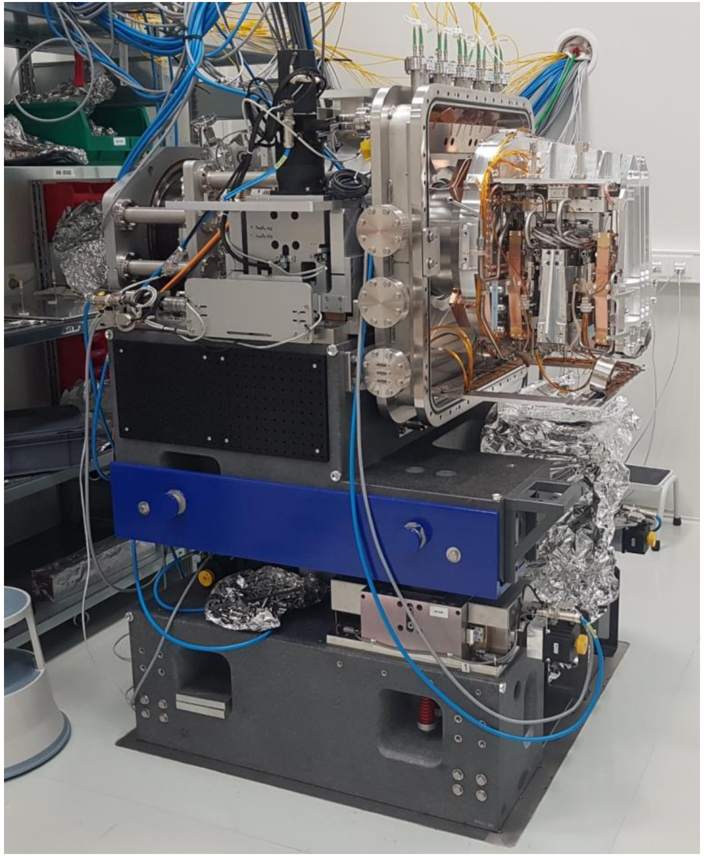
# New positioning requirements

## EIROforum IWG Workshop on Systems Engineering


*Laurent EYBERT*

***I**ntrumentation **S**ervices & **D**evelopment **D**ivision – Mechanical Engineering Group*

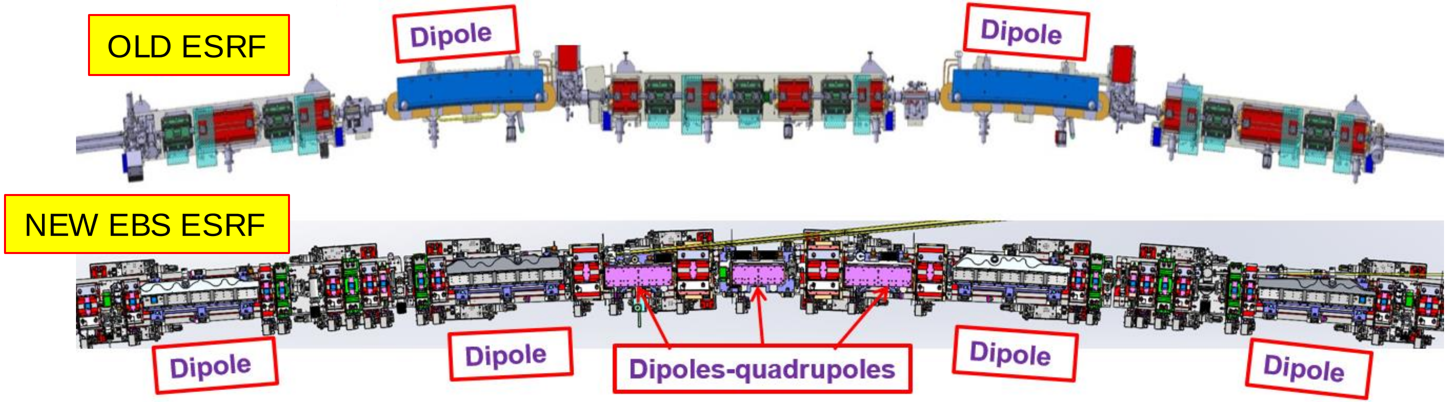
# OUTLINE



- Introduction = EBS beam
- Heat load issues
- New positioning requirements
  - End stations
  - DCM monochromator
- Challenges and Conclusion

# EBS BEAM VS OLD ESRF BEAM

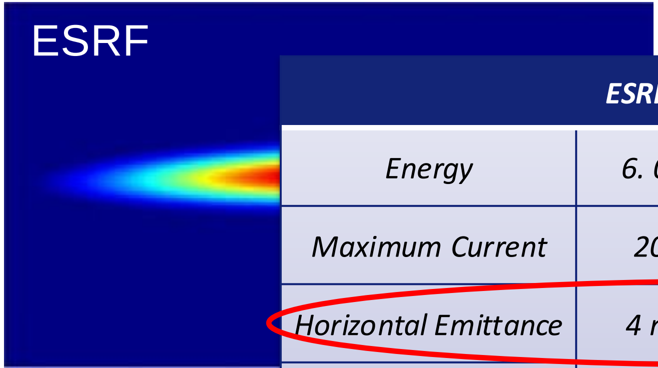
**Open to user since 2020 ESRF has a new storage ring** based on an hybrid multi-bend achromat (HMBA) lattice.

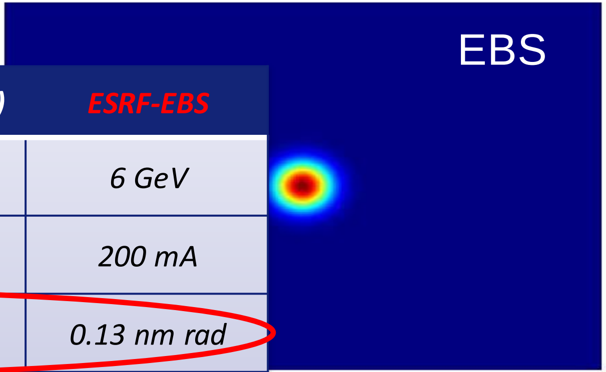



31 magnets per cell instead of 17

# EBS BEAM

*Reduction of the **horizontal** emittance from **4 nm rad** to **0.13nm rad (/30)***




| | *ESRF(low $\beta$)* | *ESRF(High $\beta$)* | *ESRF-EBS* |
|---|---|---|---|
| *Energy* | *6. 04 GeV* | *6. 04 GeV* | *6 GeV* |
| *Maximum Current* | *200 mA* | *200 mA* | *200 mA* |
| *Horizontal Emittance* | *4 nm rad* | *4 nm rad* | *0.13 nm rad* |
| *Vertical Emittance* | *0.005 nm rad* | *0.005 nm rad* | *0.005 nm rad* |
| *Horizontal source size (rms) at low beta source* | *50 um* | *390 um* | *28 um* |
| *Horizontal beam divergence (rms) at low beta beam line* | *105 urad* | *10 urad* | *7 urad* |

***Beam-li***

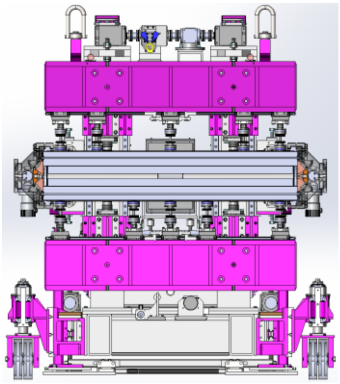
*r. plane)*

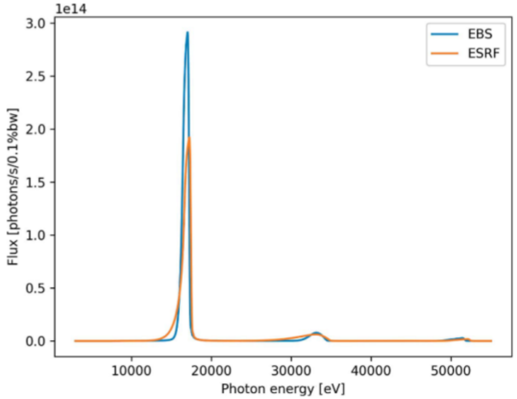
# EBS BEAM – NEW LATTICE BUT ALSO NEW SOURCES

New lattice but also new ID sources = 2*2m CPMU (Cryogenic Permanent Magnet Undulators)
smaller gap (now 5mm, 4 mm in future)
in future possible HTS (High Temperature Superconducting) IDs


| | Room temp invac | Cryogenic invac |
|---|---|---|
| Cell03 | | |
| Cell06 | | |
| Cell09 | x 2 | |
| Cell11 | | |
| Cell13 | | |
| Cell14 | | |
| Cell15 | | |
| Cell16 | | |
| Cell22 | | |
| Cell27 | | |
| Cell28 | x 2 | |
| Cell29 | | |
| Cell30 | | |
| Cell31 | | |
| | 9 | 9 |

The European Synchrotron | ESRF



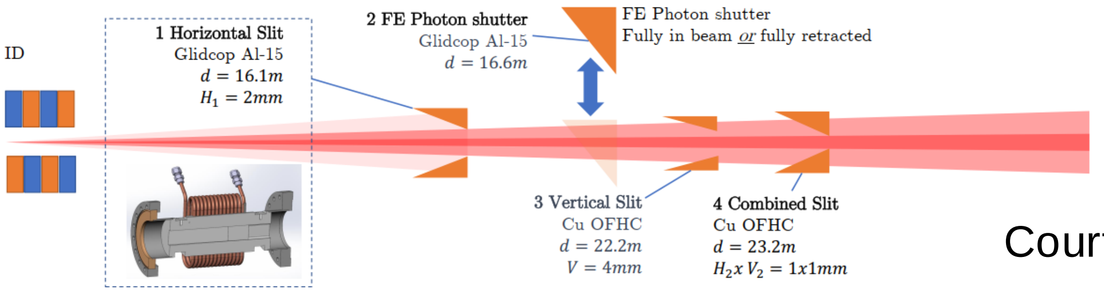



ID status – January 2025

# EBS BEAM – NEW ID SOURCES

=> More power on FE components (slits, shutter) , more power densities on Beamline components

| **Insertion device** *(length)* | **Gap** *(mm)* | **Total Power** *(kW)* | **Power Density (in 16.1m)** *(W/mm2)* | Comment |
|---|---|---|---|---|
| CPMU16.4 (2m) | 5.0 mm | 12.9 | 1545 | Installed and used on ID03 |
| CPMU16.4 (2m) | 4.0 mm | 20.1 | 1947 | ID03 - 4mm (“mini-beta”) |
| CPMU20.5 (4m) | 5.5 mm | **29.6** | **2716** | Plan for double CPMU ID20/ID14 |

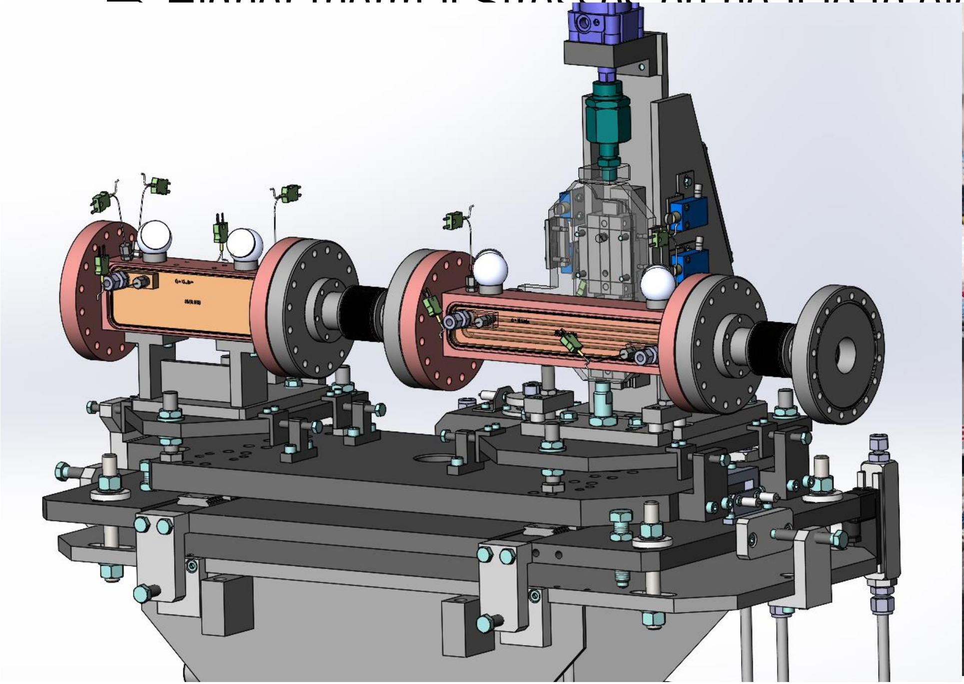


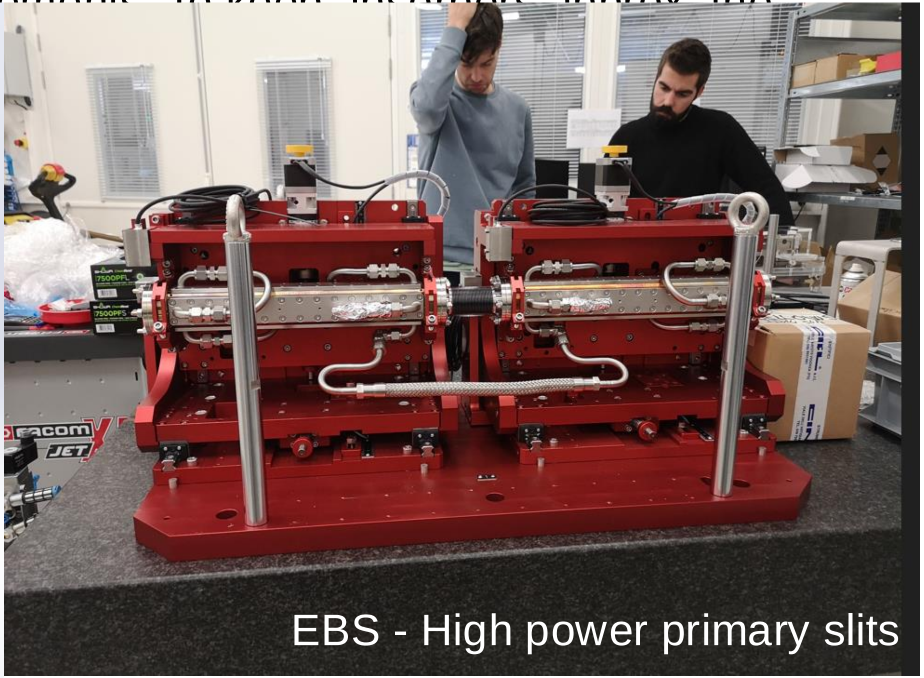

Courtesy P. Brumund

# EBS BEAM – HEAT LOAD ISSUES

Increased emission of photons and linked thermal power Leads to =

→ Higher thermal Stresses on heat load elements. To keep absorbers approx. the






Number of cycles to failure N (-)

# NEW POSITIONING REQUIREMENTS

EBS
(new lattice and ID sources)

Higher flux

Detector developments

Shorter
Integration times
Keep sample alive

Lower emittance

Focusing optics
Developments(KB)
25 nm beams

Smaller focused beam

**Positioning Specifications**

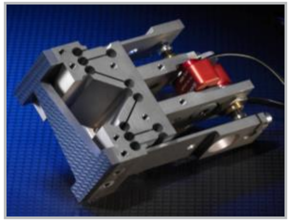
Higher scanning velocity
(up to $1mm/s$)
Control motion up
to higher frequency
($\gg 100Hz$)

Better accuracy (sub $10nm$)

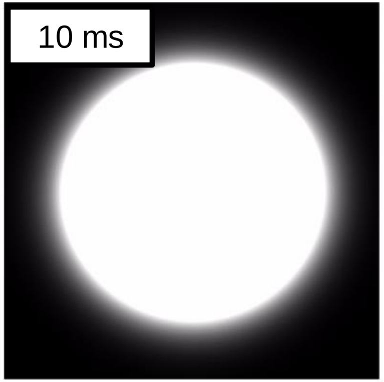
Better stability

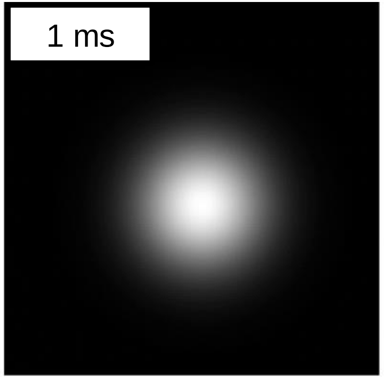
Multi DoF

Long stroke $\approx cm$



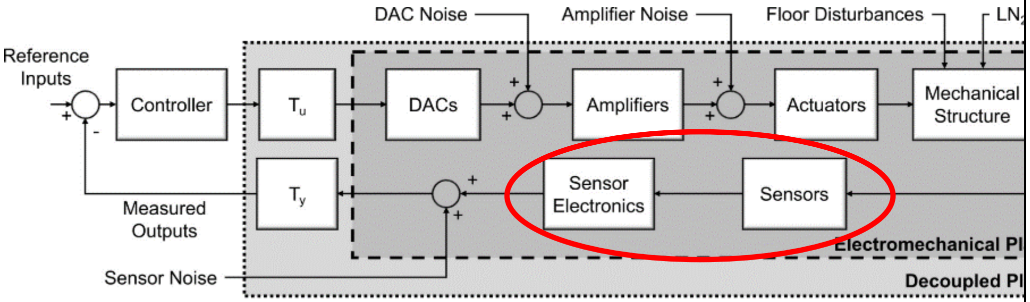
Cannot expect to reach these specifications with stacked stages without fast feedback control

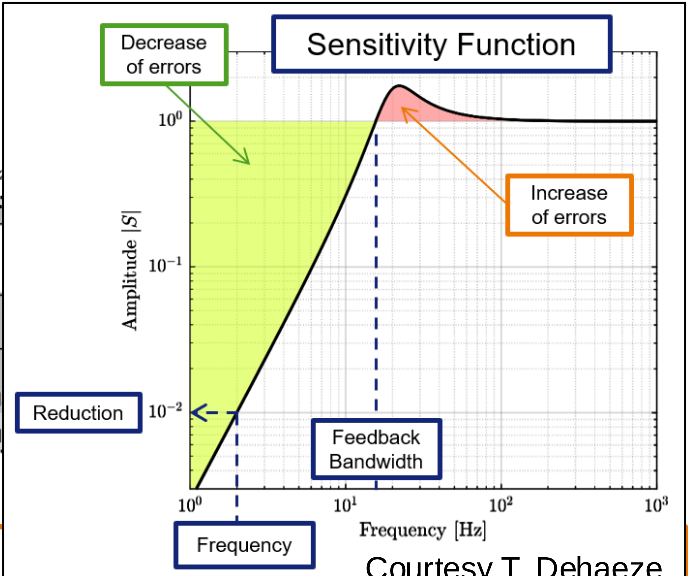


# NEW POSITIONING REQUIREMENTS

Closed Loop control




Courtesy T. Dehaeze

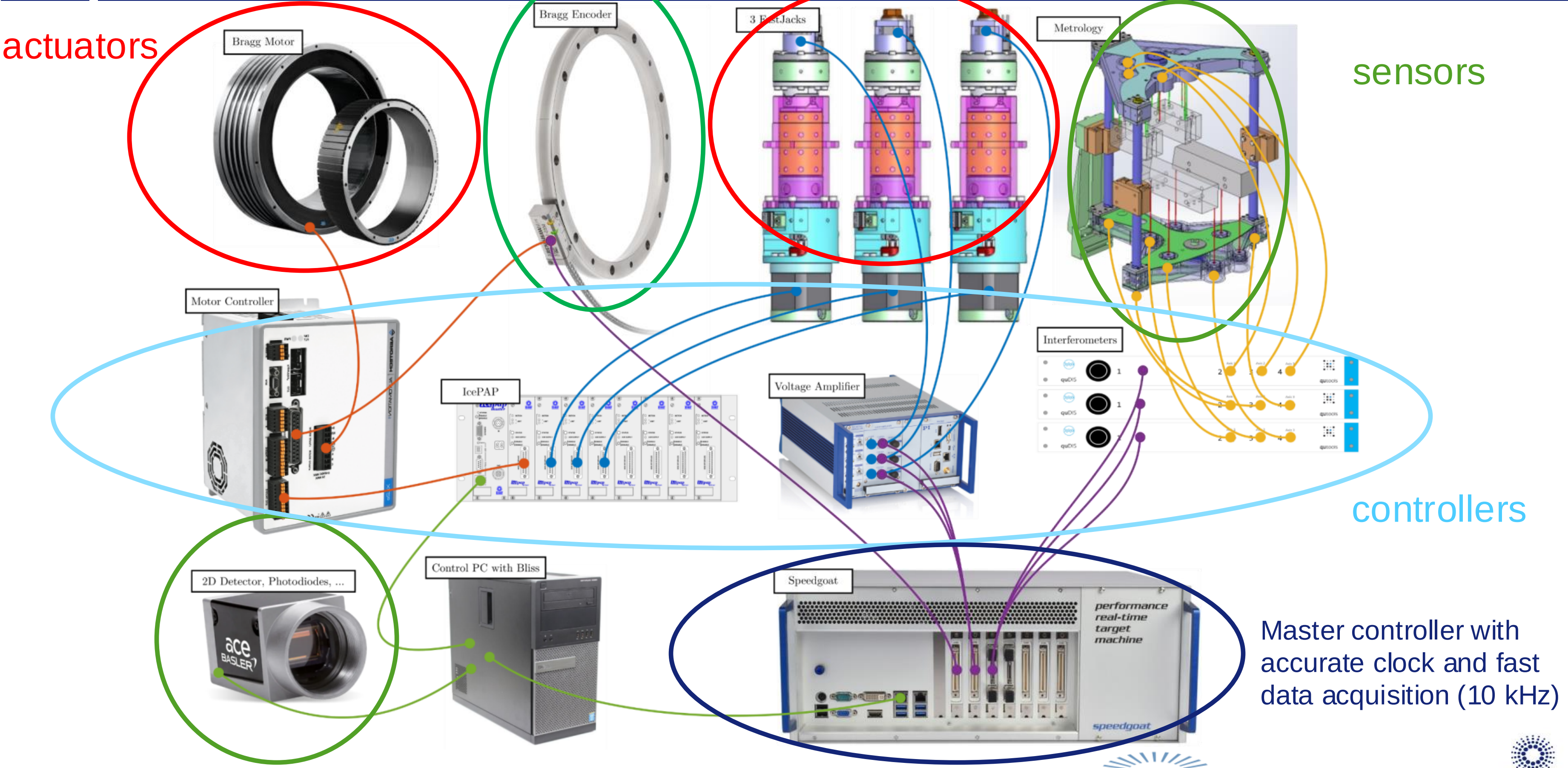
Key points:

- Feedback is used to deal with system disturbances
- Accuracy & drifts determined by the metrology (sensors@#position)
- Feedback only act in a limited **bandwidth** (Sensitivity function)
- How high the bandwidth is depends on the complete system (moving part and and actuators).



EIROforum The European Synchrotron | ESRF

# NEW POSITIONING REQUIREMENTS = COMPLEX ARCHITECTURE




Master controller with accurate clock and fast data acquisition (10 kHz)

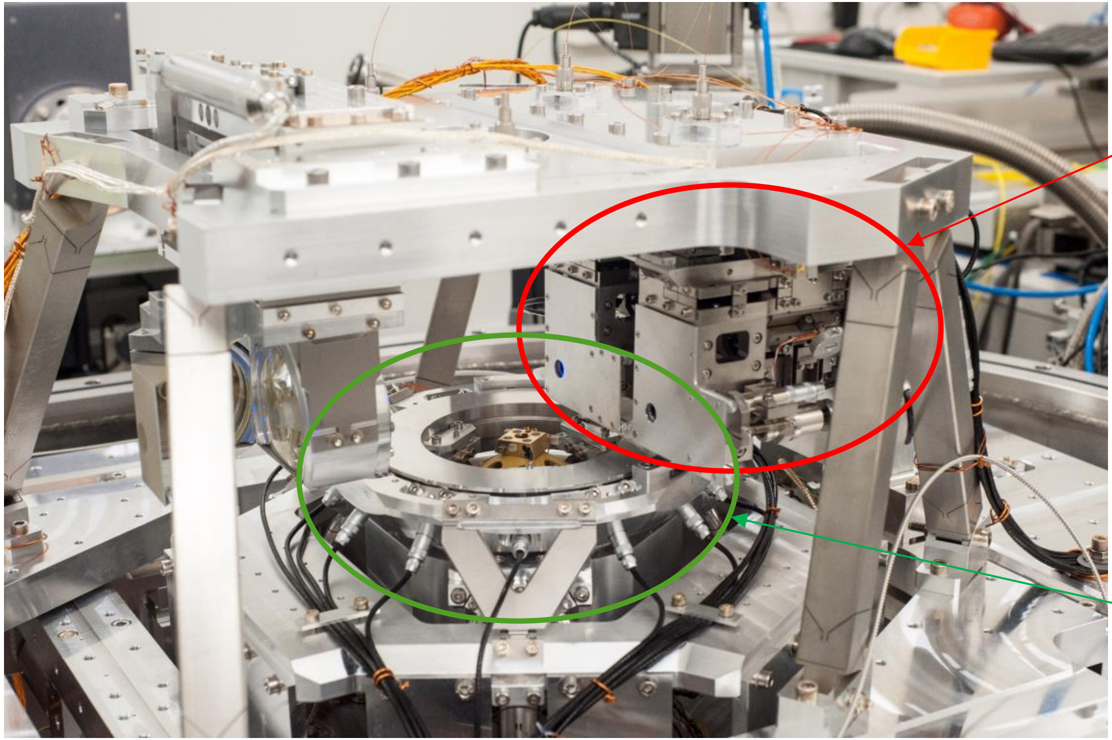
# NEW POSITIONING REQUIREMENTS = EXAMPLES

REAL TIME CONTROL APPLICATIONS

END STATIONS
ID16A – ID31

ESRF- DCM
Fixed Exit Monochromator

# NEW POSITIONING REQUIREMENTS = REAL TIME CONTROL FOR THE ID16A ENDSTATION



KB focalization
25 nm beam sizes

Sample holder

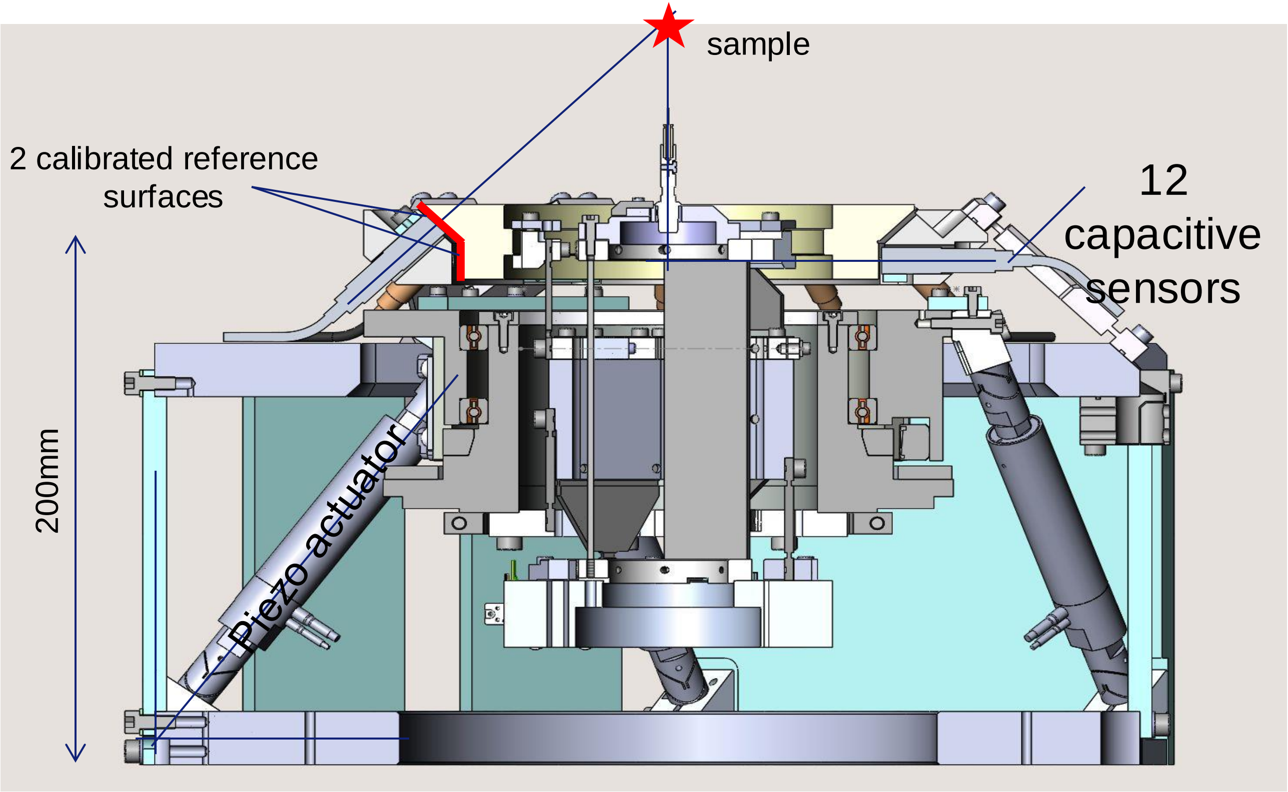
*Courtesy of F. Villar*

# EXAMPLE = ID16A END STATION

Piezo actuated hexapod used to

- Limit rotation errors < 50nm during tomography,
- Scan the sample (10nm steps over ~50µm range)

Movement controlled by capacitive sensors

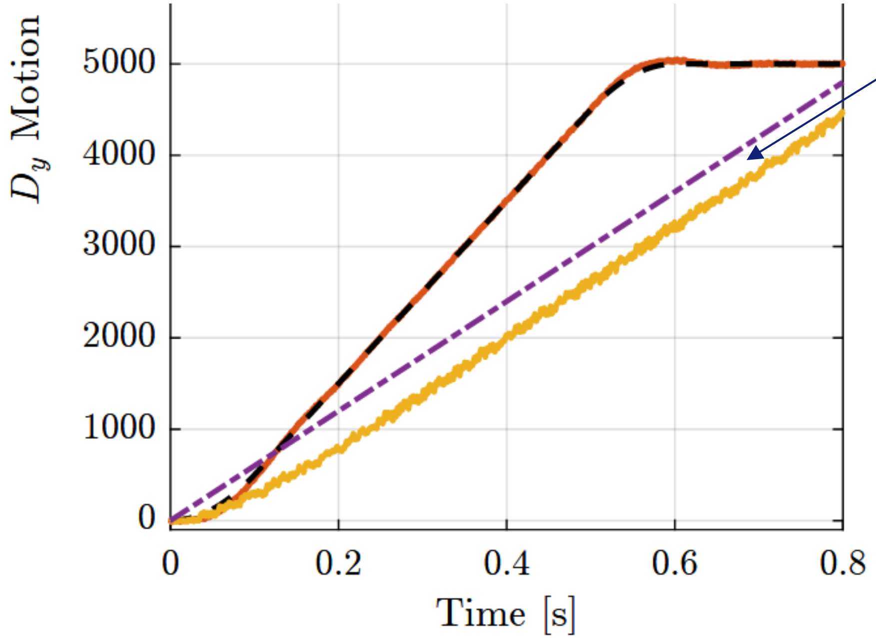


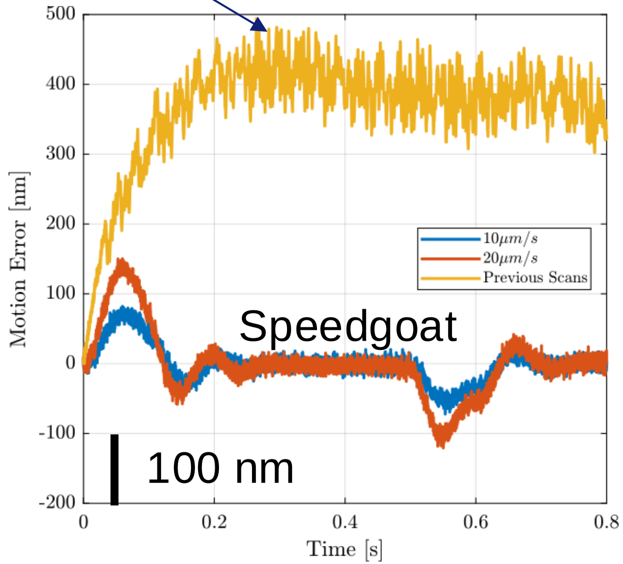

Courtesy of F. Villar

# IMPROVED REALTIME CONTROL (SPEEDGOAT) IMPLEMENTED IN 2024

- Speedgoat based real-time control

**Linux PC controller:**
**delay & vibrations at medium speed**

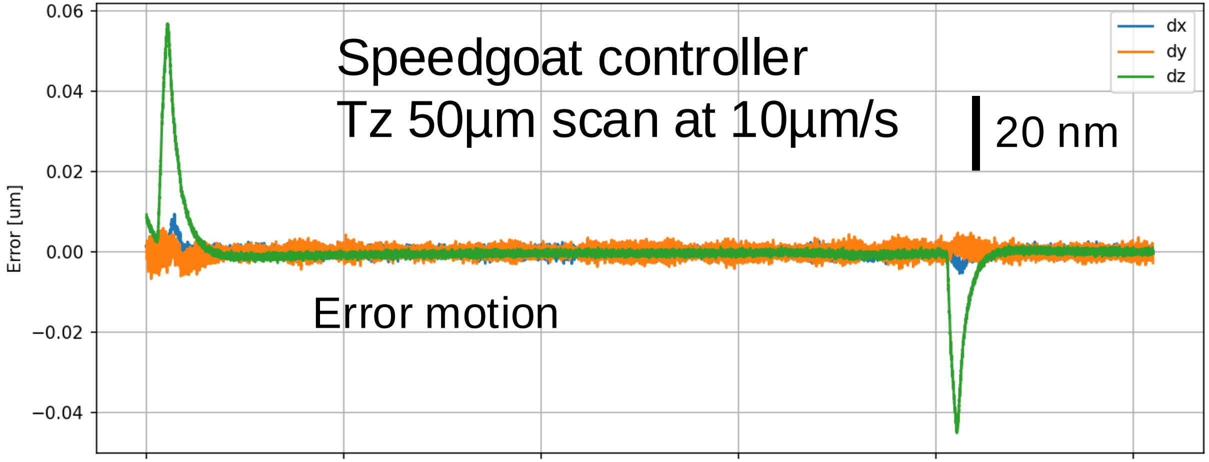



*Courtesy of F. Villar&T. Dehaeze*

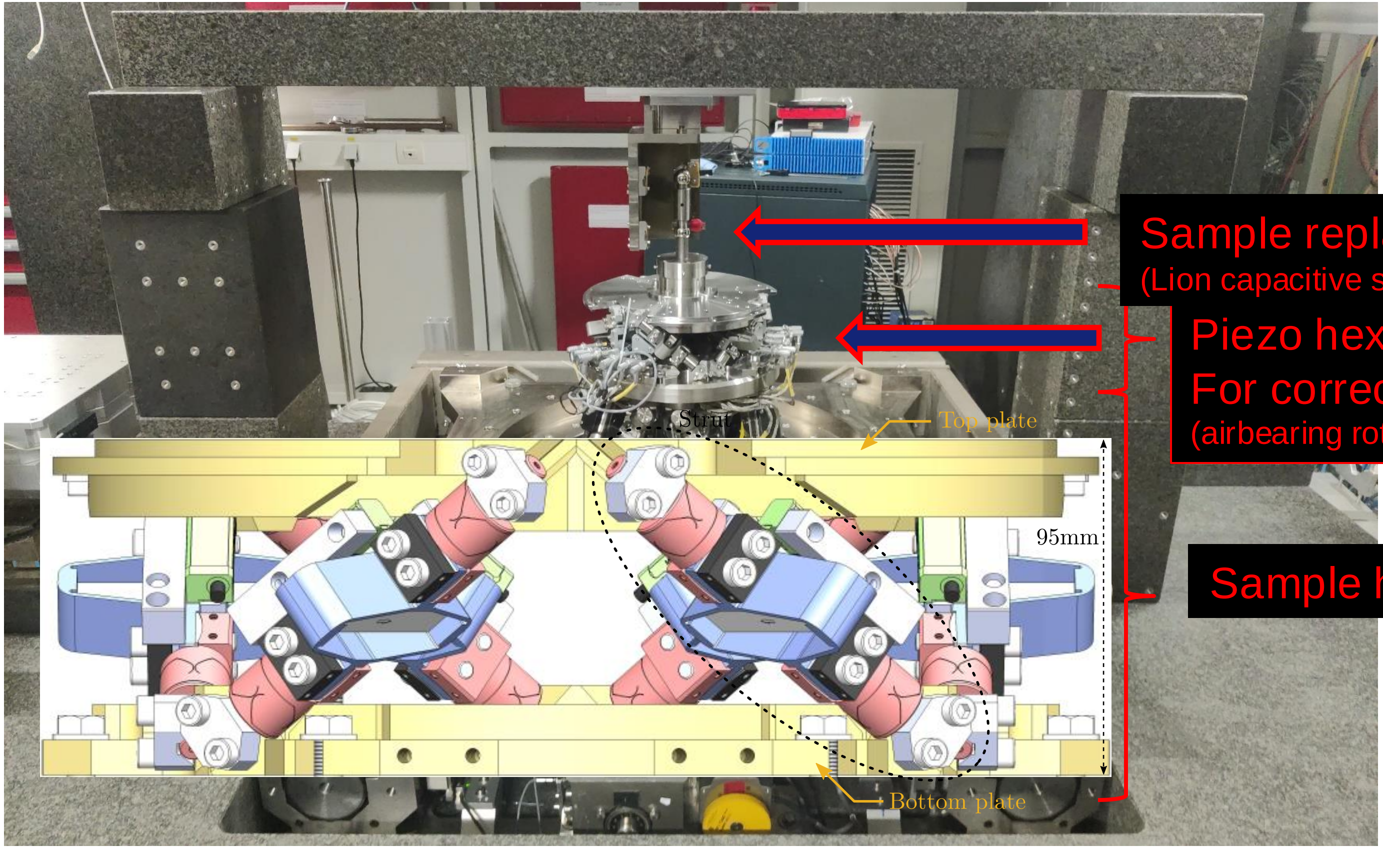
# IMPROVED REALTIME CONTROL (SPEEDGOAT) IMPLEMENTED IN 2024

**Hor focus @ 33keV: 16nm fwhm**




Performance gain (from linux PC to Speedgoat ) :
4 → 20µm/s linear speed (X5)
50 → 2-5ms integration time (/10)
Bidirectional scanning with Horizontal focus < 20nm

# EXAMPLE = ID31 END STATION



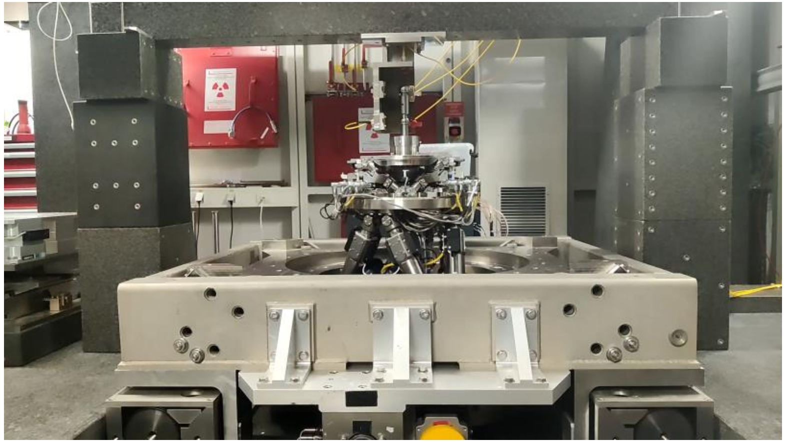

Sample replaced by sensors
(Lion capacitive sensors)

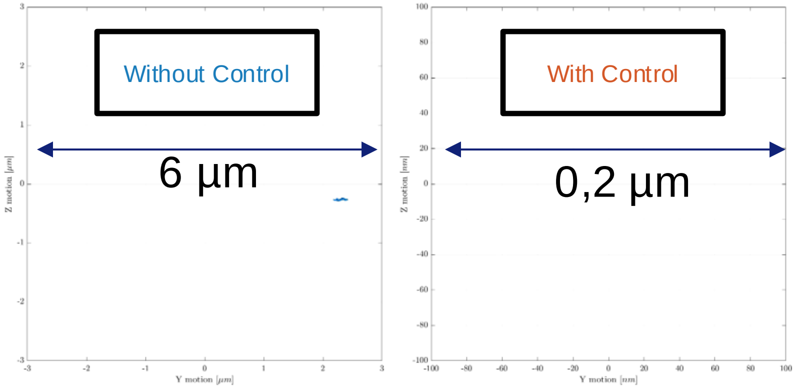
Piezo hexapod used
For corrections
(airbearing rotation errors and vibration)

Sample holder

# EXAMPLE = ID31 END STATION

*Courtesy of T. Dehaeze*



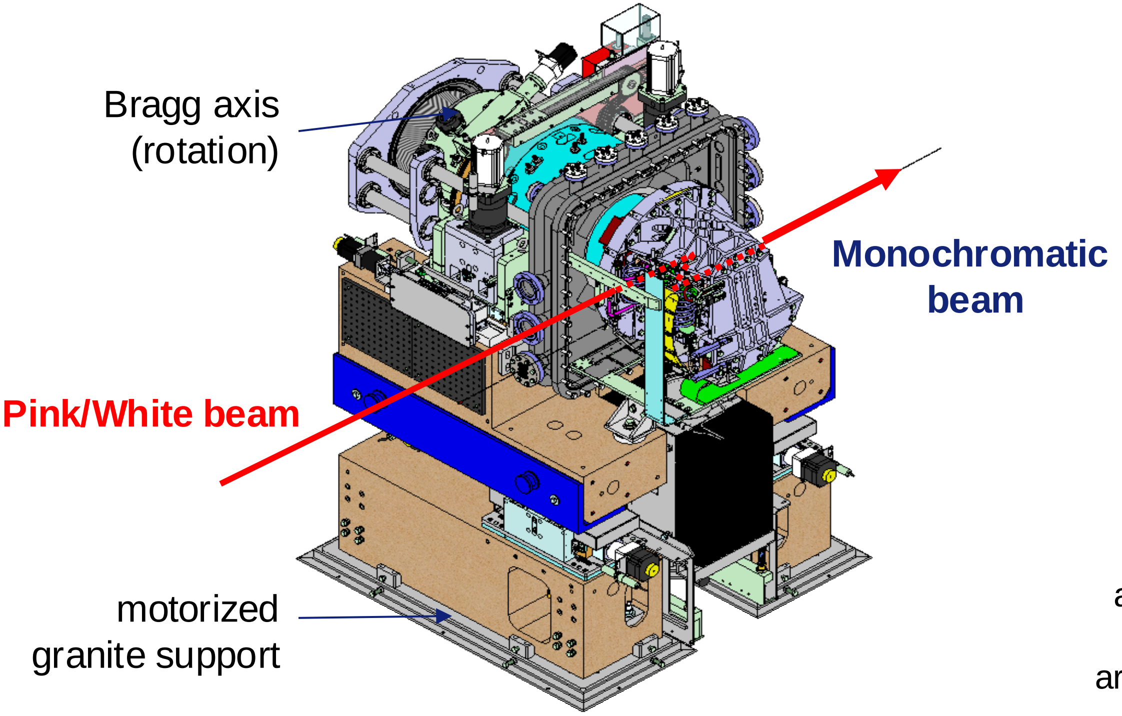


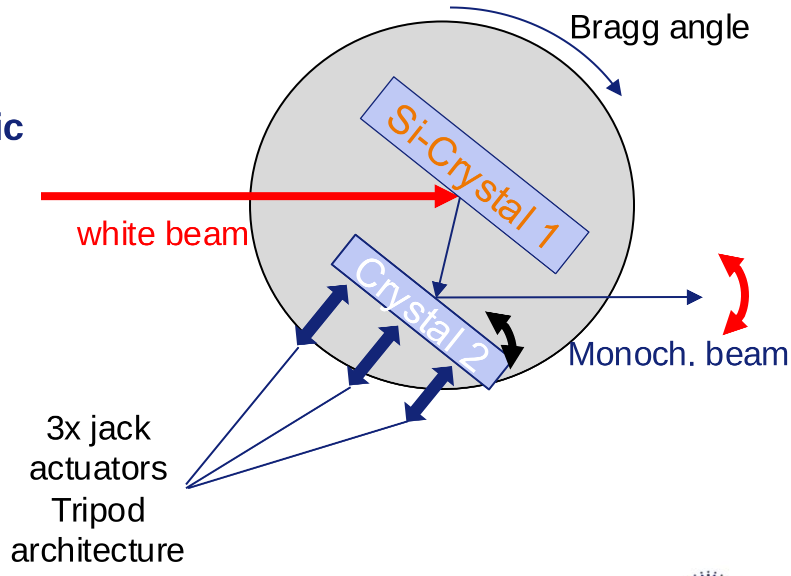

| (RMS) | $D_x, D_y$ | $D_z$ | $R_x, R_y$ |
|---|---|---|---|
| Open-Loop | $2\mu m$ | $25nm$ | $10\mu rad$ |
| Closed-Loop | $35nm$ | $10nm$ | $130nrad$ |

Missing = long stroke (10mm) metrology @sample position

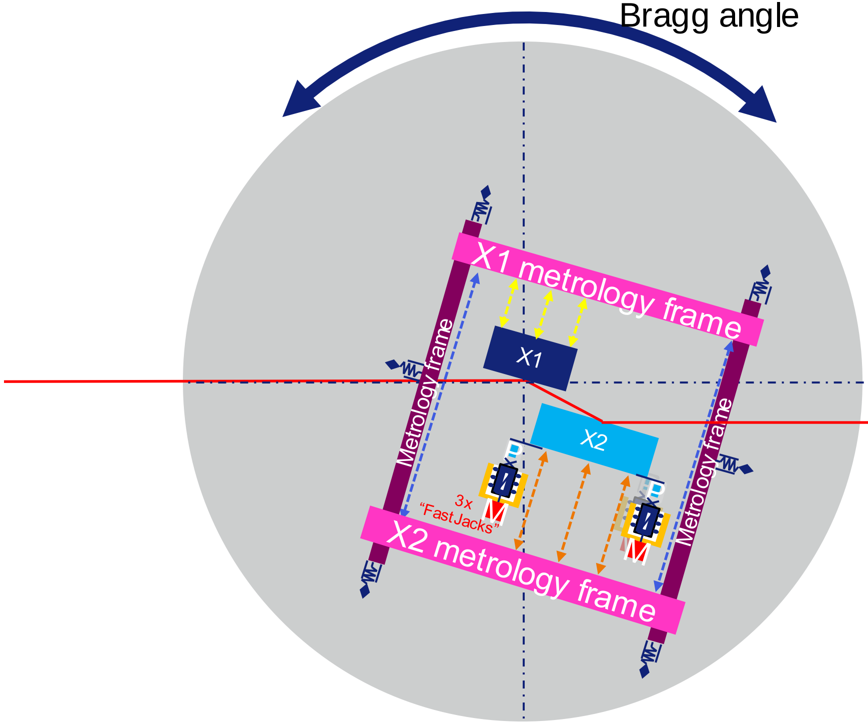
# EXAMPLE = FIXED EXIT ESRF-DCM MONOCHROMATOR

used to perform **scans in energy** (bragg angle rotation) for spectroscopy experiments
► **synchronized 2nd crystals translation** to keep the monochromatic beam at **fixed exit position**

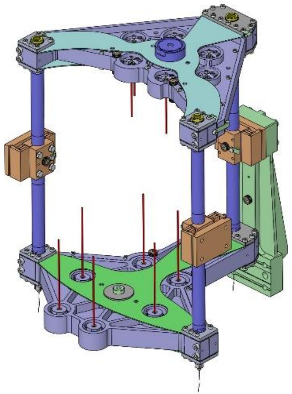


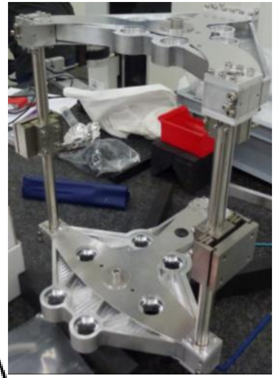



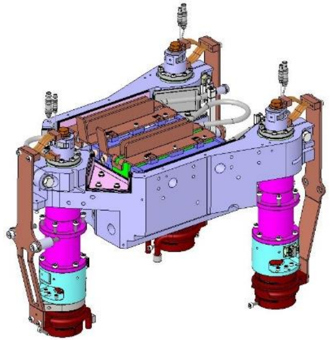
# FIXED-EXIT WITH MECHATRONIC SYSTEM – ONLINE METROLOGY




metrology frame



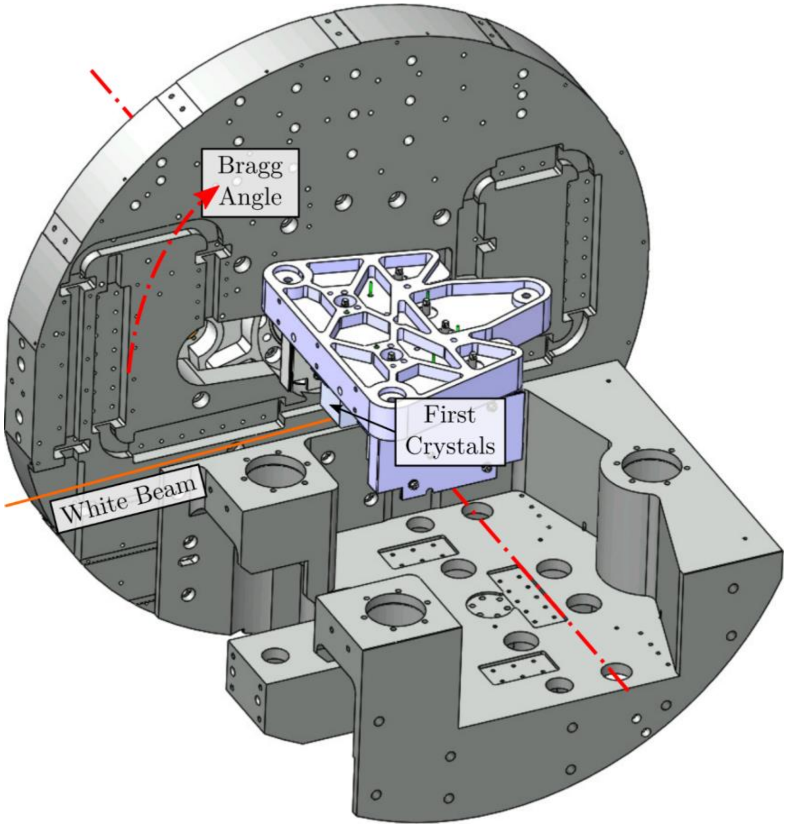


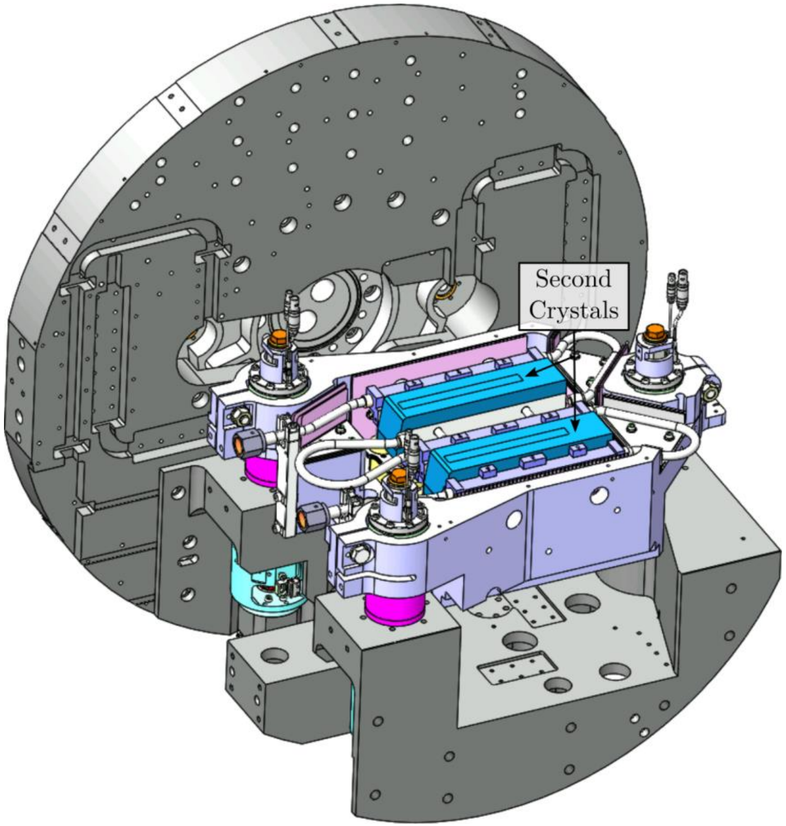


2nd crystal positioning System

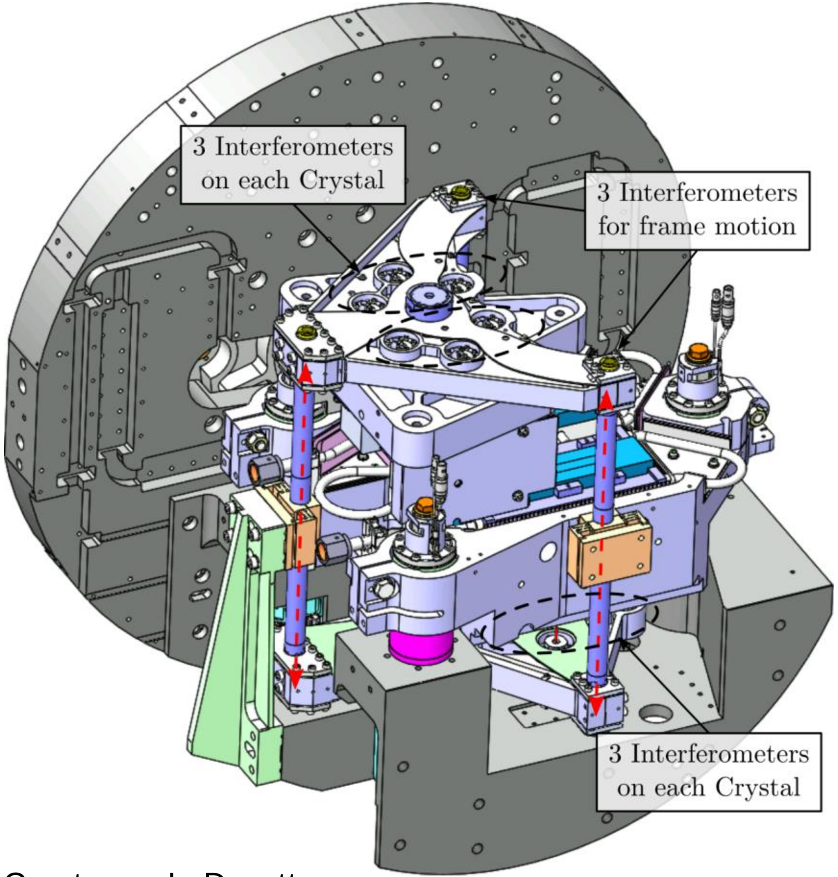
Courtesy = L. Ducotte

# EXAMPLE = FIXED EXIT ESRF-DCM MONOCHROMATOR



# EXAMPLE = FIXED EXIT ESRF-DCM MONOCHROMATOR




Courtesy = L. Ducotte

**Crystal Cage / Bragg Axis**

4 in Vacuum Encoders
Direct Drive Torque Motor

**Tripod Architecture**

Positioning along $D_z R_x R_y$
High rigidity compared to stack stages

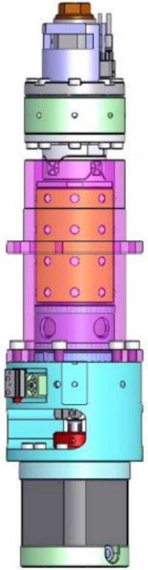
**Fast Jacks**

“Hybrid” Actuator
Piezo for real time error correction

**Mechanically too complex to keep a parallelism <100 nrad**

**Separate Metrology frame**

$D_z R_x R_y$ Indirect measurement
9 interferometers



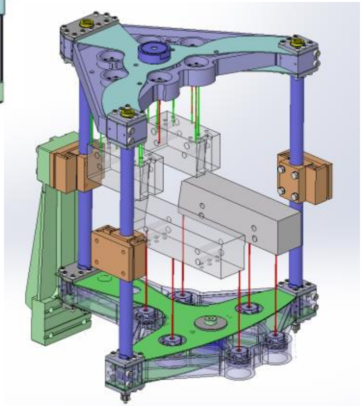
Piezoelectric Stack (15µm stroke)

Flexible Joint

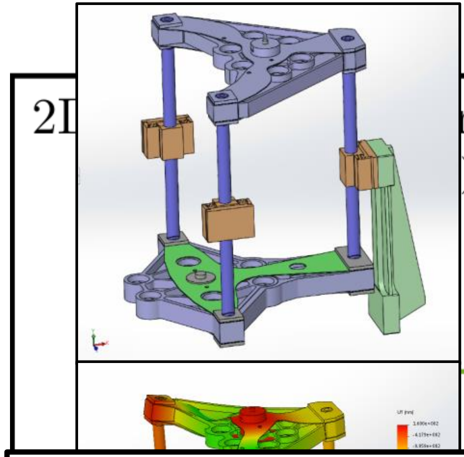
Ball bearing guide

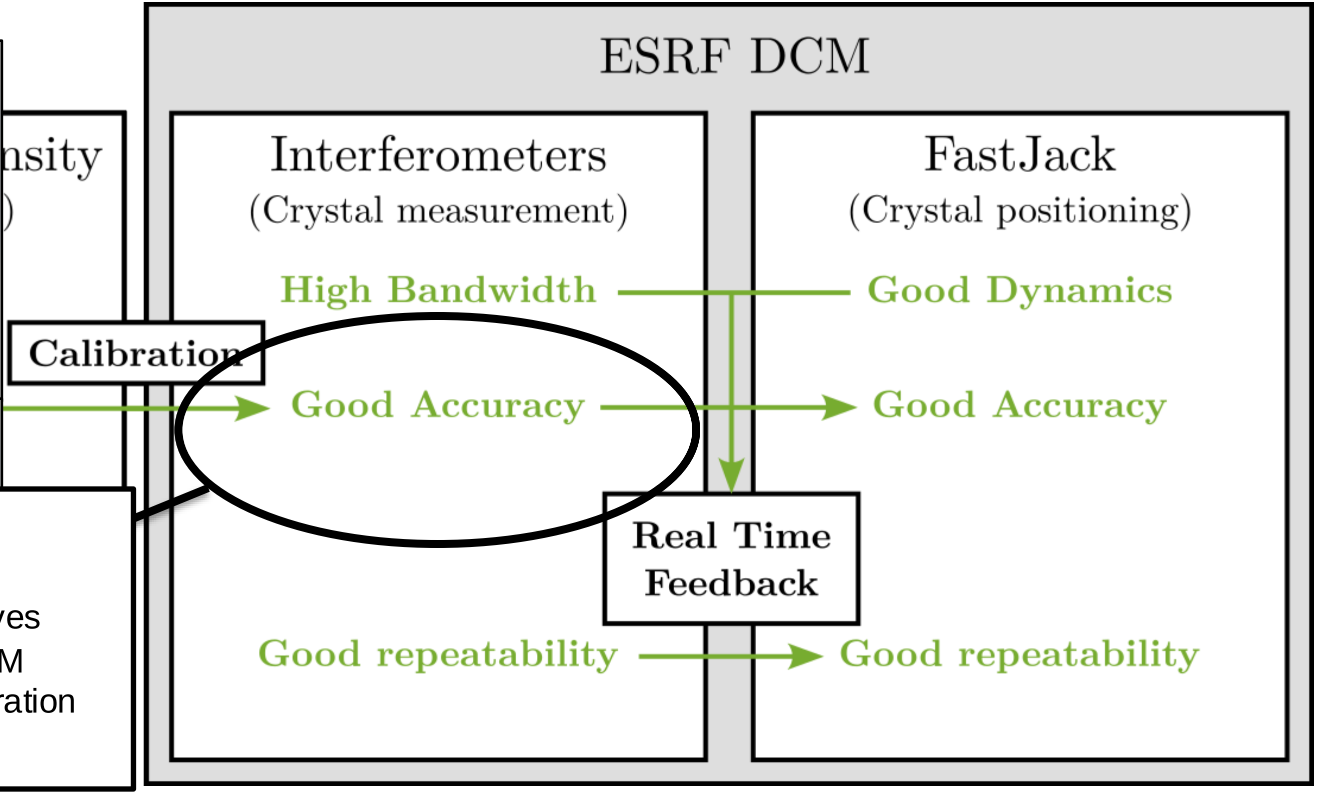
Satellite roller screw (1mm pitch)

Stepper Motor (200 steps/turn)



# DCM – MECHANICAL ARCHITECTURE






**Calibration Procedure**:

1/ $R_y$ calibration: rocking curves
2/ $R_x, D_z$ calibration using BPM
3/ (optional): $R_x$ and $R_y$ calibration using focusing optics

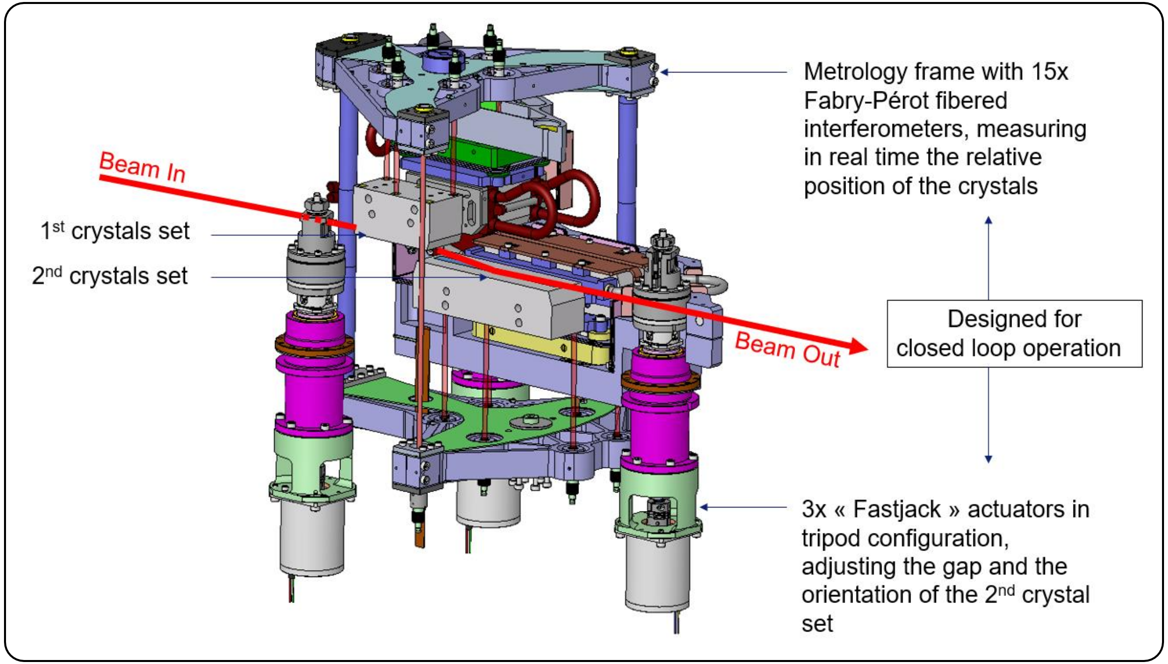
Courtesy = A. Moyne



The European Synchrotron | ESRF

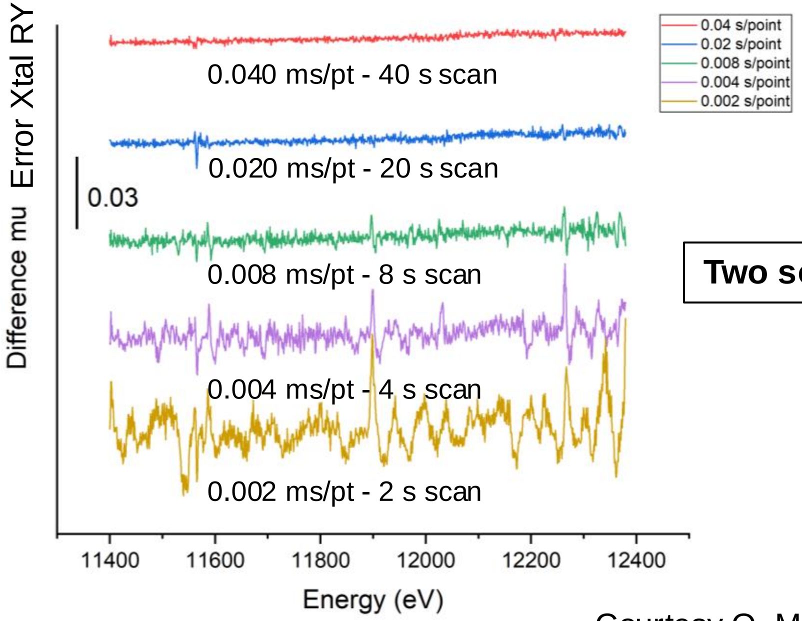
# DCM - RESULTS

- Unprecedented energy stability : < 100 nrad FWHM Bragg stability
- Unprecedented position stability (fixed exit in dynamic mode)
    - $\Delta R_y \rightarrow$ 15 nrad FWHM over 1 deg
    - $\Delta R_x \rightarrow$ 100 nrad FWHM over 1 deg



# DCM LIMITATION / SPEED AND BANDWIDTH

One limitation: bandwidth of the realtime feedback system

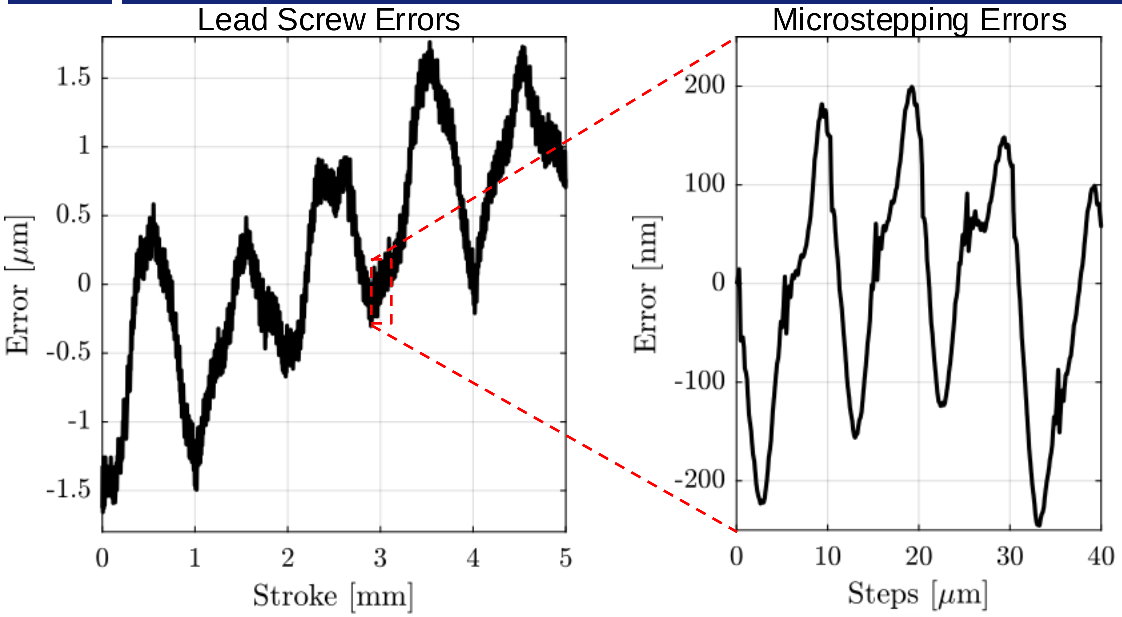


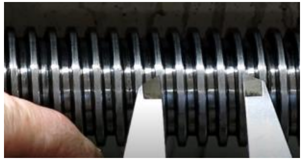

Courtesy O. Mathon

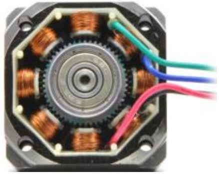
**Two solutions**

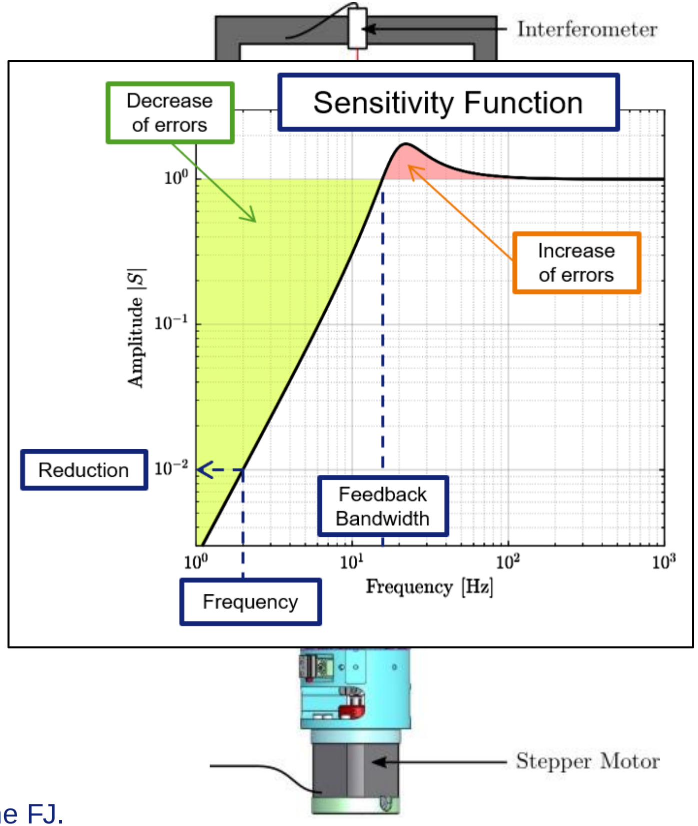
- **Decrease the amplitude of the mechanical excitation**
- **Increase the realtime feedback bandpass**

# FASTJACK DEVELOPMENT







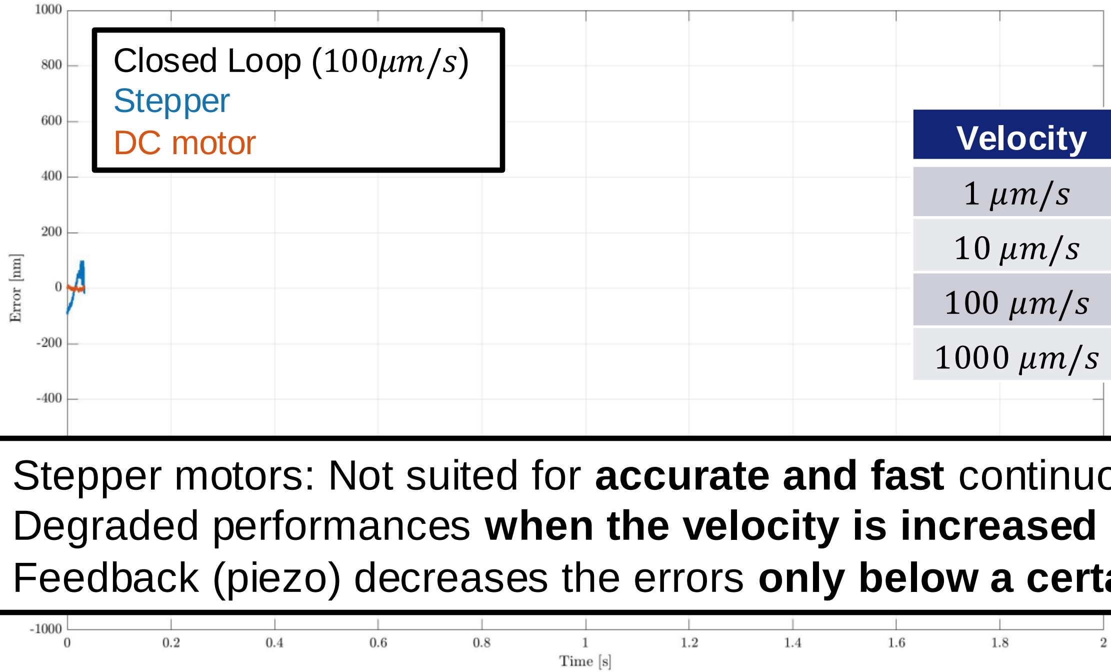

- The cyclic errors are **function of the rotation speed** of the mechanical part of the FJ.
- When the **scanning speed** increase, the **frequency** of the cyclic errors increase

# DCM – FASTJACK WITH DC MOTORS

**Experimental results** with torque motor below :

► **10x faster** scanning speeds would be achievable, **maintaining acceptable accuracy**

► Implementation sheduled on **ID24,** ID21, **ID26, ID16B DCMs**




Courtesy A. Moyne/T. Dehaeze

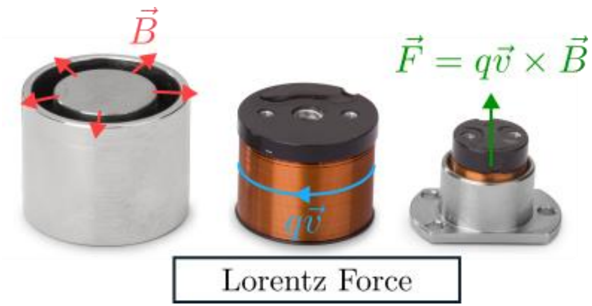
| Velocity | Stepper Motor | Torque Motor |
|---|---|---|
| $1\ \mu m/s$ | 3nm RMS | 3nm RMS |
| $10\ \mu m/s$ | 5nm RMS | 4nm RMS |
| $100\ \mu m/s$ | 50nm RMS | $\xrightarrow{\div 10}$ 6nm RMS |
| $1000\ \mu m/s$ | 670nm RMS | $\xrightarrow{\div 15}$ 40nm RMS |

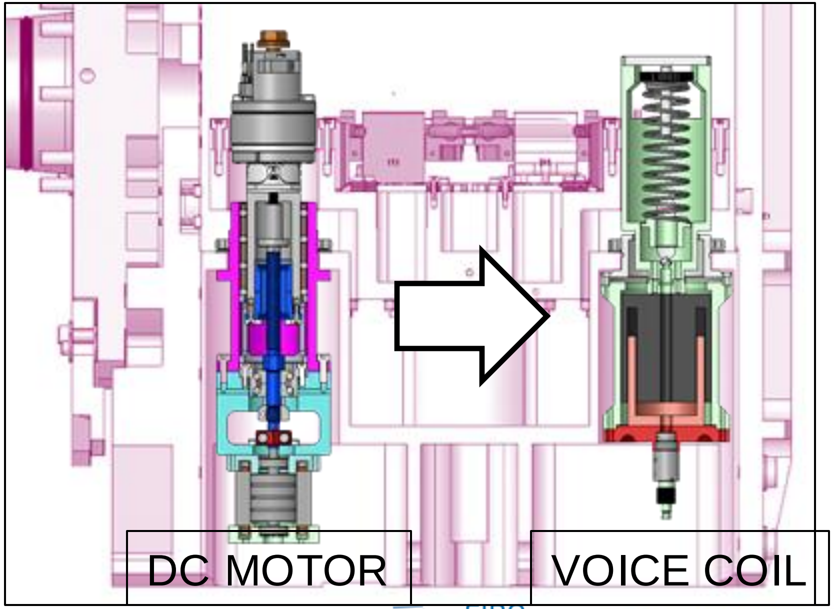
1. Stepper motors: Not suited for **accurate and fast** continuous scans
2. Degraded performances **when the velocity is increased**
3. Feedback (piezo) decreases the errors **only below a certain frequency** (i.e. the **bandwidth**)

# FASTJACK DEVELOPMENT: MAGNETIC ACTUATOR

**Second solution :** Switching from an **hybrid actuator** (mechanical+piezoelectric) to a **magnetic actuator**

- **Advantages :** no more **wear**, cost reduced, **simplified control architecture, Simplified calibration procedure.** bandwidth
- **Drawbacks : Not** compatible with all DCM, new technology at ESRF





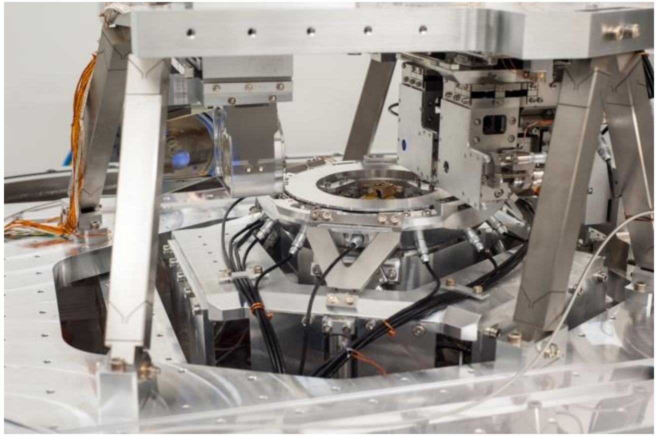

EIROforum serving european science The European Synchrotron | ESRF

# CHALLENGES

**ID16A endstation :**
Closed loop control of movement

Sensor (capacitive + interferometers)
→ Real-time controller (speedgoat)
→ actuator (piezostack)

Achieved performance :
- 20nm resolution @ 5µm/s (scanning)
- 20nm resolution @ 0.5°/s (tomo)



Challenges for the future **ID18 nano-tomo beamline**:

Increase scanning speed x 100 (500µm/s, 50°/s) with same or better resolution ~10 nm

Mechatronics approach imperative :
- System integration of mechanic / software / electronic.
- Use of a real time control system
- Design must include dynamic effects in model

# CONCLUSIONS

- Use of **real time control** is critical to match EBS performance (higher flux, smaller beam)
- real time control systems are implemented and **operational** on ESRF beamlines:
  DCM, ID16A endstation, ID31 NASS (but missing metrology)
- Need for sensors able to measure nm displacements @ sample position (6DOF-long strokes) –
  Leaps innov 5.2
- The implementation requires **transversality** between units (MEG, EU, BCU, BLs)
- Faster scans require supporting **new actuators** : voice coil and direct drive (no stepper motors), ,
  increase real time bandwidth (stiffer/lighter mechanical systems)
- Real time and modeling (including electronic, metrology, mechanics) should be integrated from the
  **early steps** of the design

shorter integration times → larger bandwidths → dynamical design

# ACKNOWLEDGEMENTS / TEAM WORK


- L. Ducotte (Head of PEL), T. Dehaeze (mechatronic engineer), R. Baker, A. Moyne and all ENGU staff involved in DCM activities.

- DEG/EU (ELECTRONIC UNIT) staff involved = H. Gonzalez, R. Hino, M. Girot, M. Lopez-Marrero

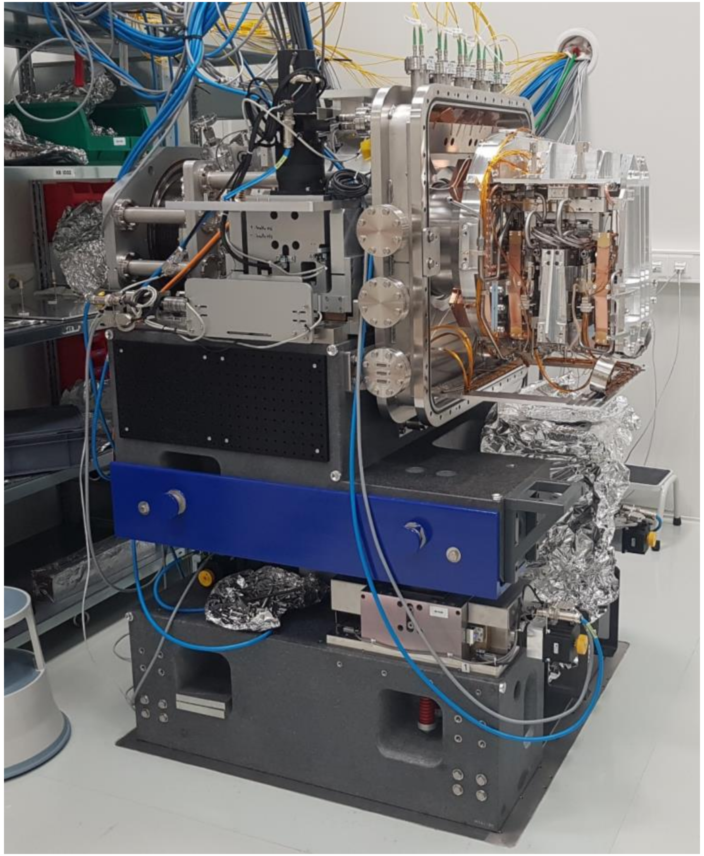
- BCU (COMPUTING UNIT) staff involved G. Berruyer

- F. Villard (Head of modelling team, in charge of ID16A and future ID18 Nano stations)

- Philipp Brumund (heat load management and simulations tasks)

- Olivier Mathon – scientist in charge of ID24/BM23 beamlines (2 DCM)

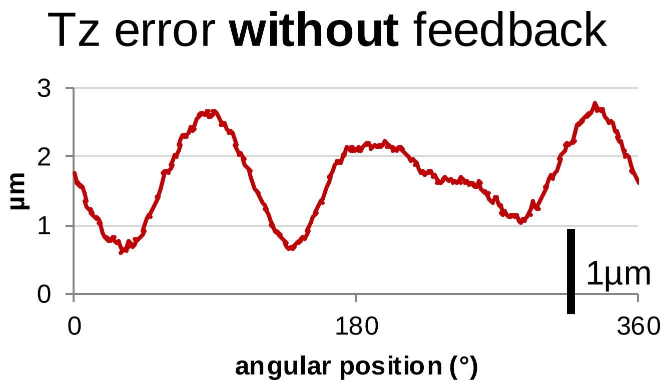
# END OF PRESENTATION

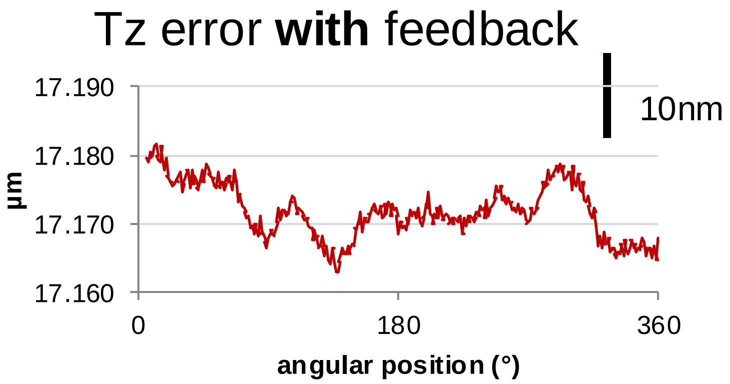


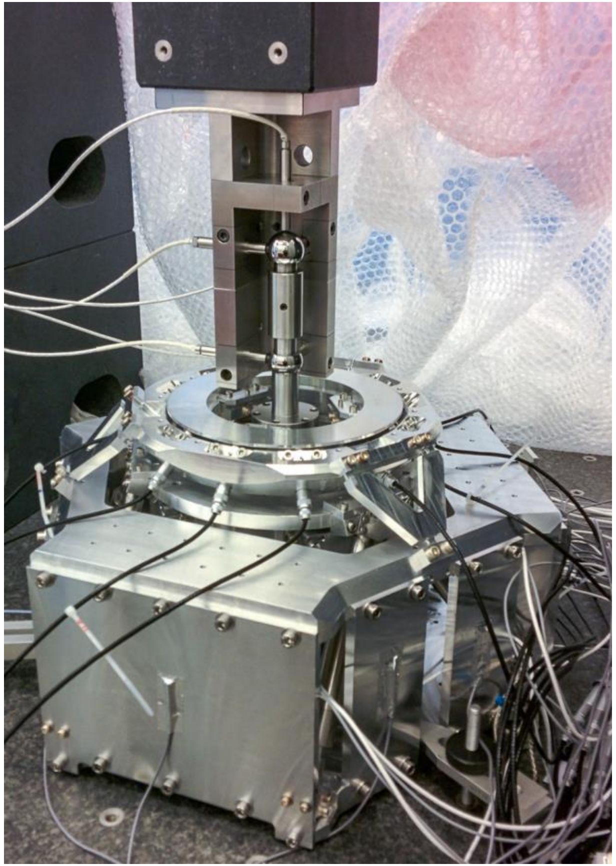
THANK YOU FOR YOUR ATTENTION

# EXTRA SLIDES

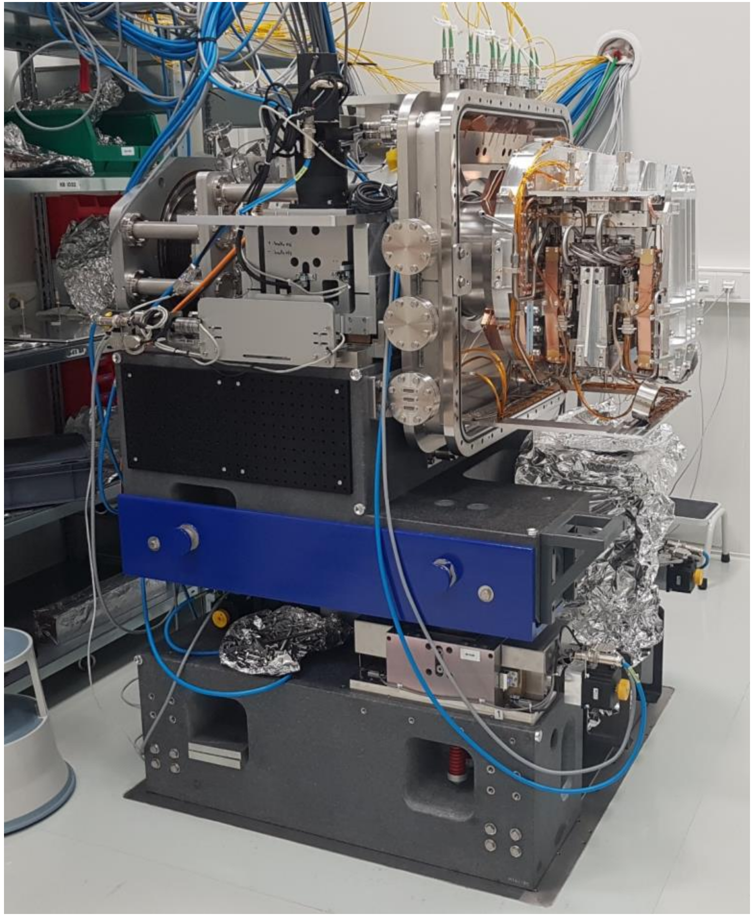
# ROTATION STAGE ERROR COMPENSATION



# DCMs PERFORMANCE



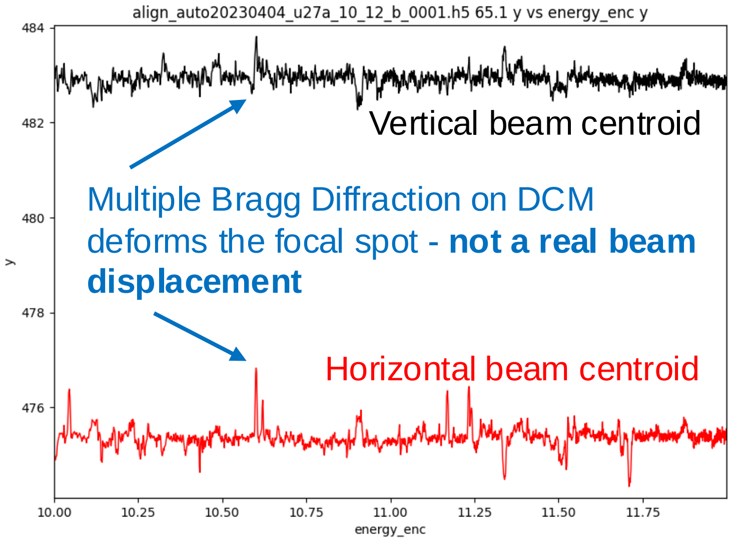
**Many advances in XAS can be obtained by investing in instrumentation**

Development of a new DCM for spectroscopy by the ESRF with
- Continuous acquisition mode as default mode
- Perform full EXAFS spectra at the Hz level
- Unprecedented energy stability
  Bragg stability < 100 nrad FWHM
- Unprecedented position stability (fixed exit in dynamic mode)
  $\Delta R_y \rightarrow$ 100 nrad FWHM over 1 deg
  $\Delta R_x \rightarrow$ 150 nrad FWHM over 1 deg

- Continuous acquisition mode
- EXAFS spectra at 0.5 Hz
- Energy stability, Bragg : 51 nrad rms (DCM ?)
- $\Delta R_y \rightarrow$ 9.48 nrad rms / 50.5 nrad p-p (over 1 deg)
- $\Delta R_x \rightarrow$ < 1.9 $\mu$rad FWHM (over 7 deg): difficult to measure

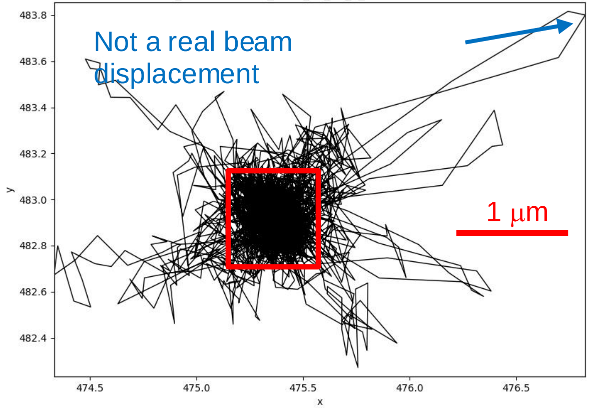
# DCMs PERFORMANCE - BEAM POSITION STABILITY

Commissioning DCM - Si(111) - 11 keV
Continuous scan - Focused beam - Beam Position Monitor

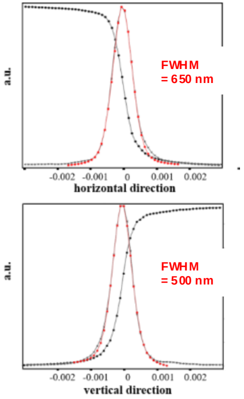


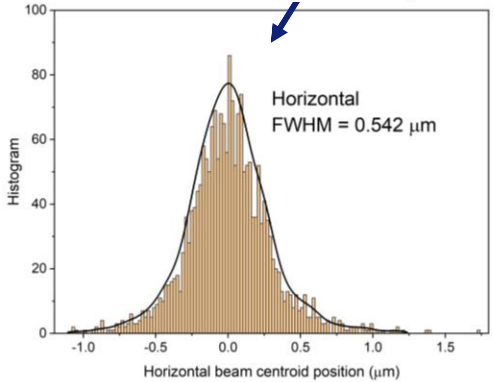

10 - 12 keV - 2 deg
2000 pts - 40 ms/pt

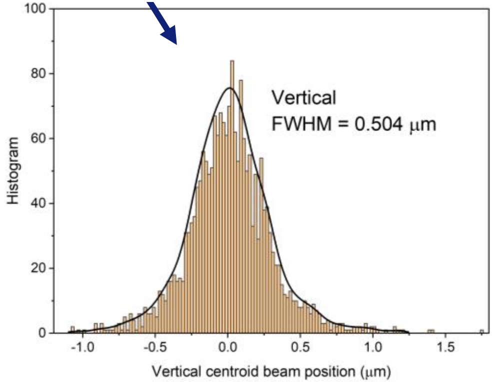
Focal spot trajectory




Focal spot




Beam position stability V/H : 500 nm FWHM → DCM is not the main source of movement

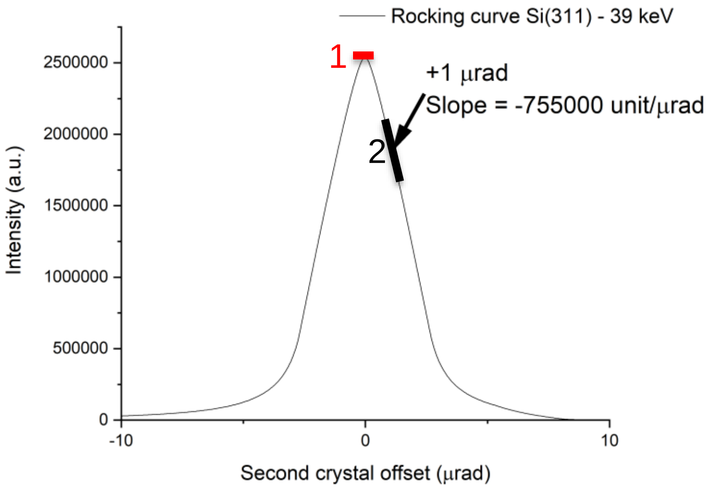
Courtesy O. Mathon

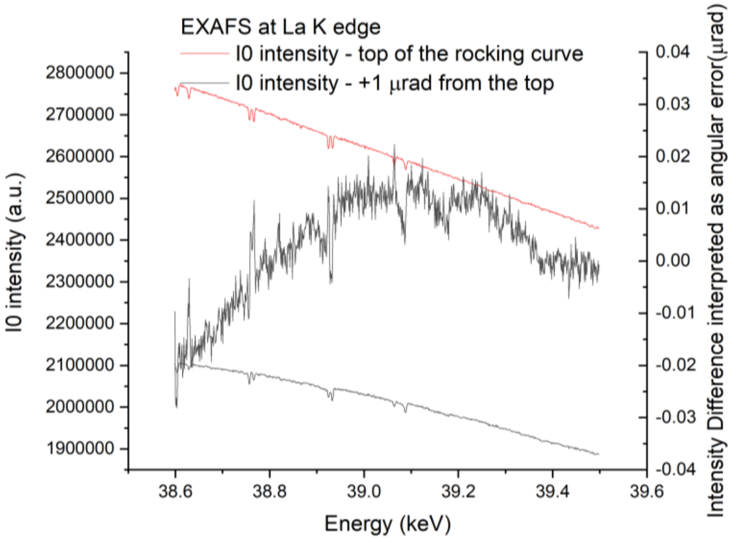
# DCMs PERFORMANCE - ANGULAR STABILITY

Beam intensity is recorded during two (continuous) scans :

1. Regulation around the top of the rocking curve (zero slope)
2. Regulation with a 1 μrad offset (high slope)

The intensity difference between the two scans is interpreted as a pitch error between the crystals.




Result for energy range : 38.6 - 39.5 keV

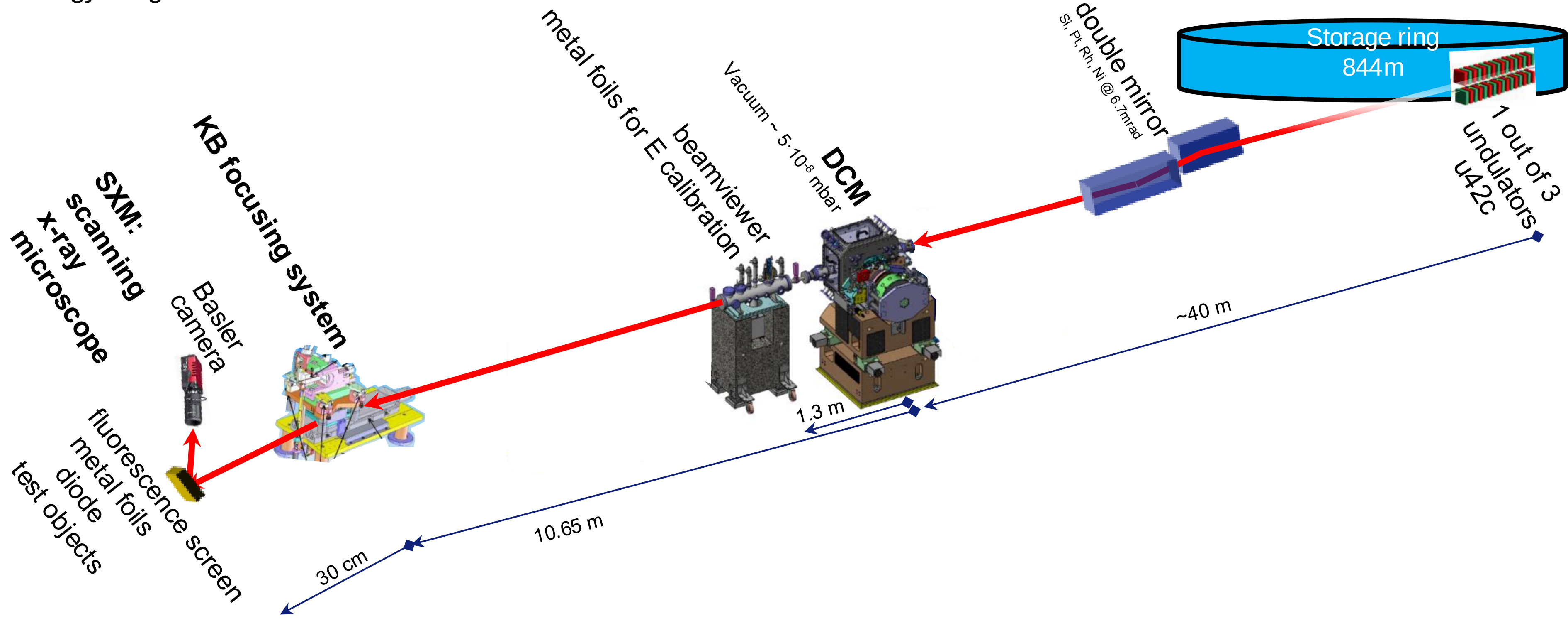
$R_y = 10\ nrad\ RMS$ (50 nrad p-p)



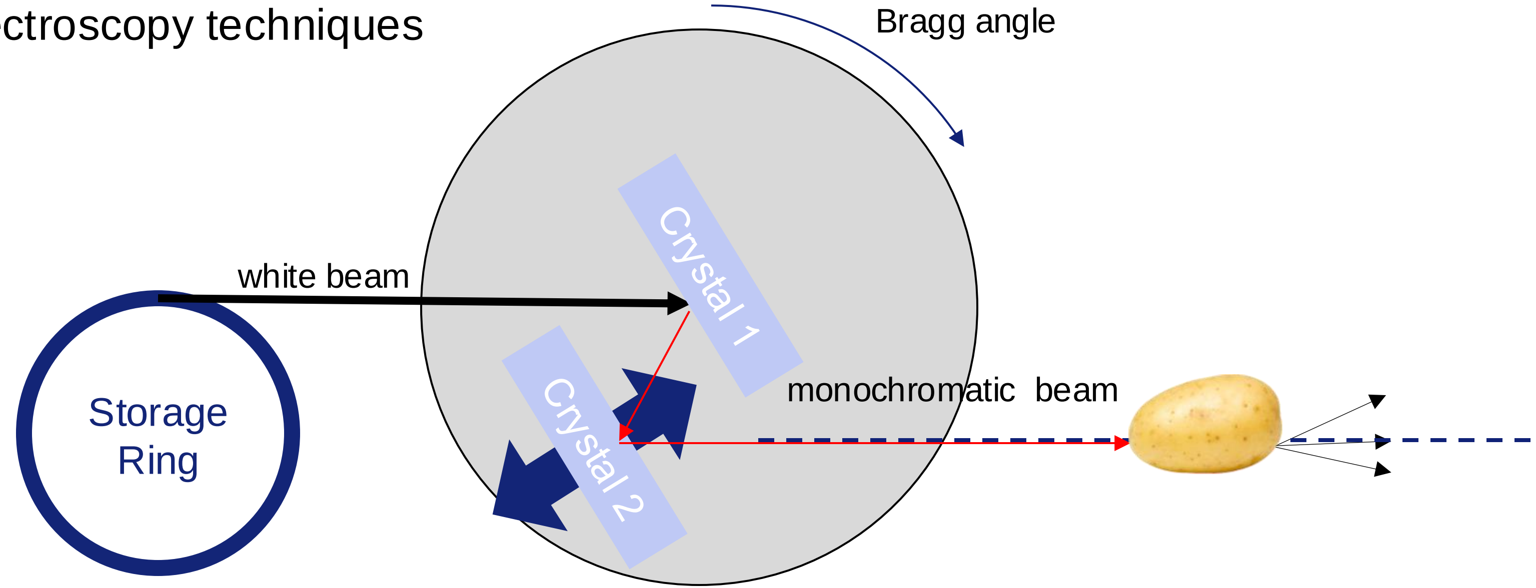
The European Synchrotron | ESRF

# INTRO : WHERE IS A MONOCHROMATOR ON A BEAMLINE

Example ID21
energy range: 2.05 – 11.5 keV



For Beamlines using spectroscopy techniques




Mechanism to change the gap between crystals

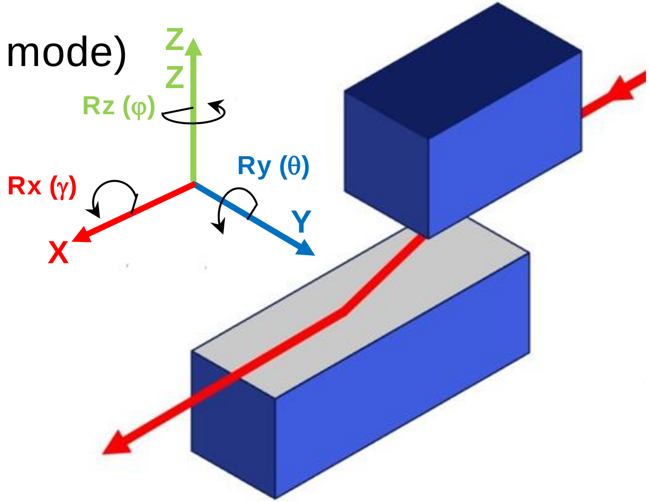
**Development of a new DCM for spectroscopy by the ESRF capable of :**

- **Continuous** acquisition mode as default mode
- Perform full EXAFS* spectra at the **Hz level**
- Unprecedented energy stability :

  **Bragg stability < 100 nrad pp**
- Unprecedented position stability (fixed exit in dynamic mode)

  **$\Delta$ry → 15 nrad FWHM**

  $\Delta$rx → 100 nrad FWHM




*Extended X-Ray Absorption Fine Structure

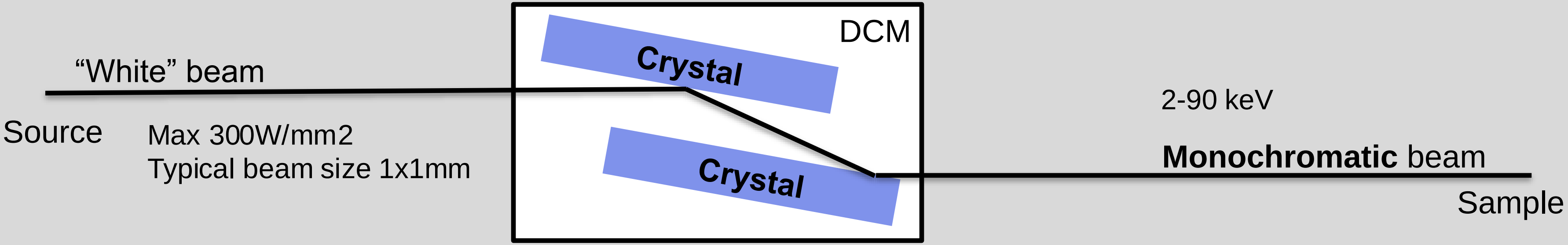
15 nrad ≈ a hair at 5 km

$75\times10^{-6}$

$5\times10^{3}$

# ESRF DOUBLE CRYSTAL MONOCHROMATOR - REQUIREMENTS

**Double Crystal Monochromator,** main characteristics




Main Requirements:

| Energy Stability (Over Time) | Beam Stability (During Scans) | Fast Scanning (e.g. 1x EXAFS/s) |
|---|---|---|

Main Challenges :

| Very low deformation of crystals | Very high thermal stability | Very high positioning precision |
|---|---|---|

# ENGINEERING PROCESS

**Our engineering philosophy :**

1st/ Pre-study to list all sources of perturbations, errors, drifts… → *Error budget*

2nd/ Compare and select the most appropriate design architecture → *Error budget*

3rd/ Best mechanical design together with suitable control design : mechatronic process

## Very low deformation of crystals

### Mechanical design

- Cooling design to obtain magic Si temperature (125K) on beam footprint
- Material CTE
- Thermal insulation
- Flexure based kinematic mounts
- High stiffness

…

## Very high thermal stability

### Mechanical design Thermalisation

- Thermal insulation room vs cryogenic temperatures
- Water cooling circuit to maintain actively structural parts at room temperature
- Symmetric mechanical design to mitigate the effect of thermal drifts

…

## Very high positioning precision

### Mechatronic approach

- Best mechanical design for intrinsic best performances
- Online metrology
- Active control
- Calibration in-situ

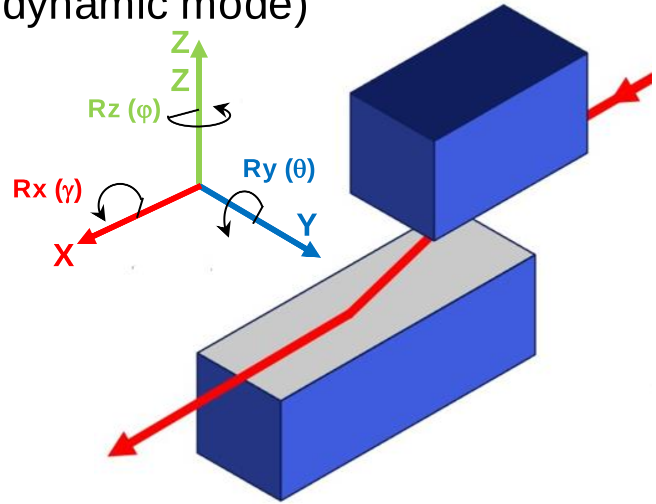
…

Performance vs Robustness

# KEY SPECIFICATIONS (REMINDER)

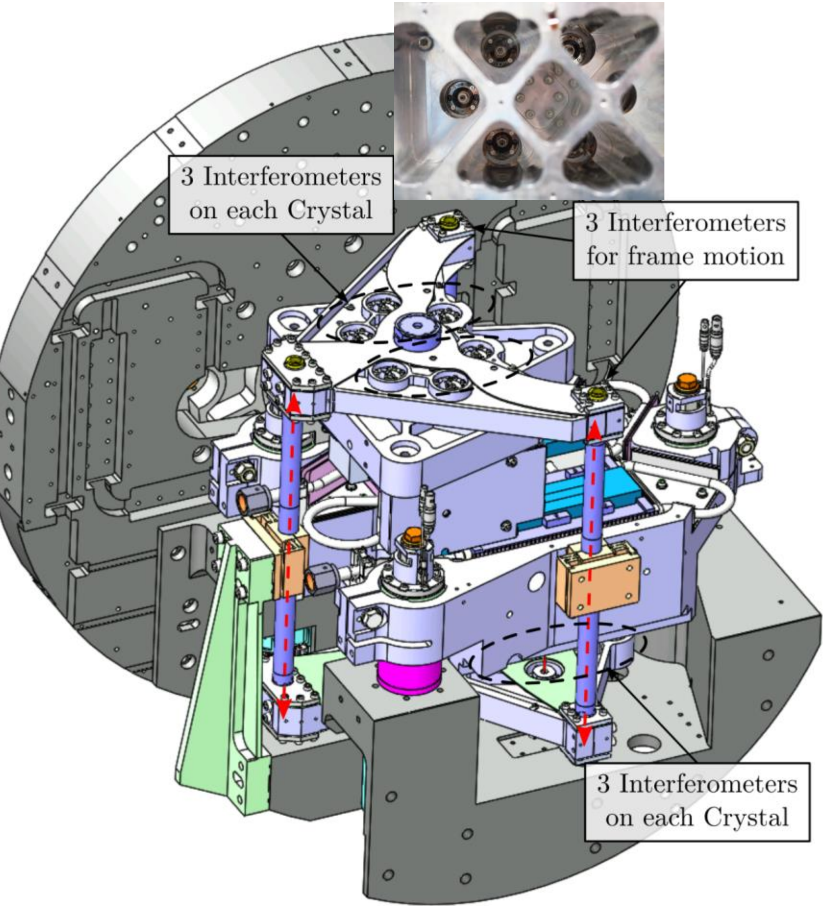
**Development of a new DCM for spectroscopy by the ESRF capable of :**

- **Continuous** acquisition mode as default mode
- Perform full EXAFS spectra at the Hz level
- Unprecedented energy stability :
  **Bragg stability < 100 nrad pp**
- Unprecedented position stability (fixed exit in dynamic mode)
  **Δry → 15 nrad FWHM**
  Δrx → 100 nrad FWHM




**Now possible with the new concept**
**But requires a full study of all sources of error and solutions for compensation**

# MECHANICAL DESIGN FOR HIGH PRECISION POSITIONING – KEY COMPONENTS




**Crystal Cage / Bragg Axis**

4 in Vaccum Encoders
Direct Drive Torque Motor

**Fast Jacks**

"Hybrid" Actuator
Piezo for real time error correction

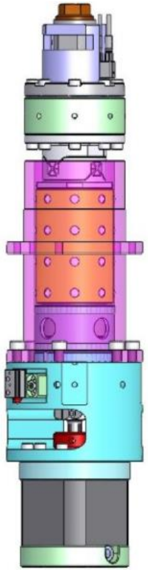
**Tripod Architecture**

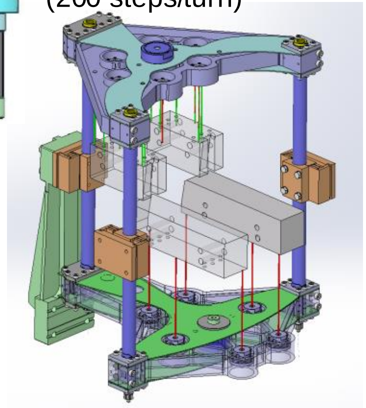
Positioning along $D_z R_x R_y$
High rigidity compared to stack stages

**Mechanically too complex to keep a parallelism <100 nrad**

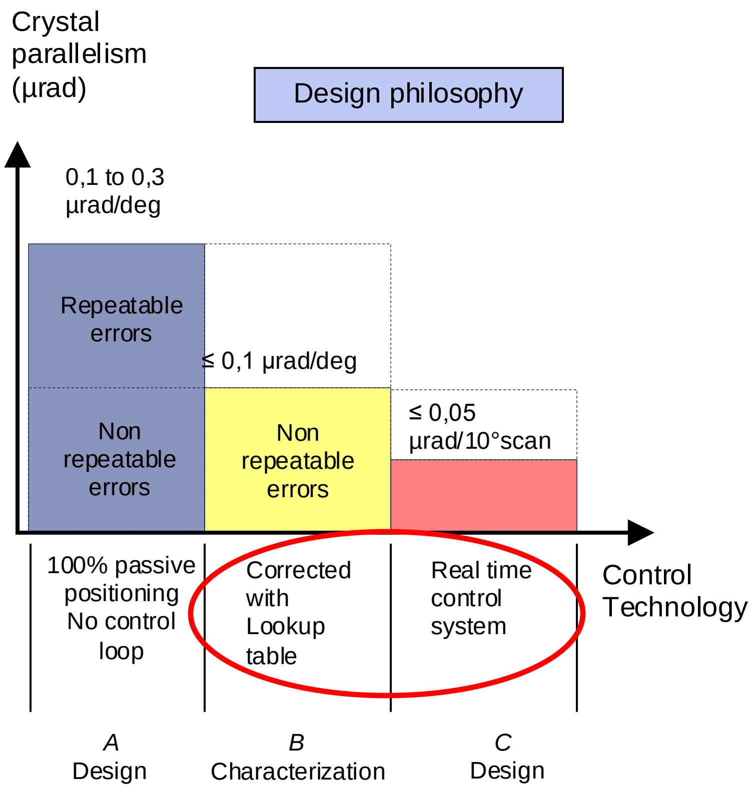
**Separate Metrology frame**

$D_z R_x R_y$ Indirect measurement
9 interferometers per crystal pair

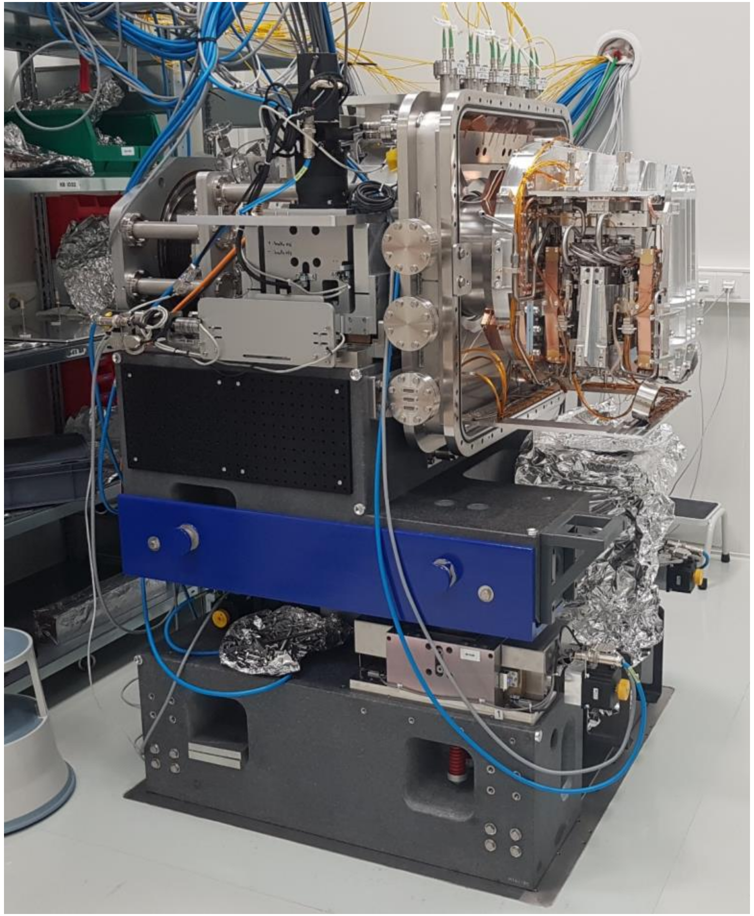


# SUMMARY OF DESIGN PHILOSOPHY



# CONCLUSION



**Many advances in XAS can be obtained by investing in instrumentation**

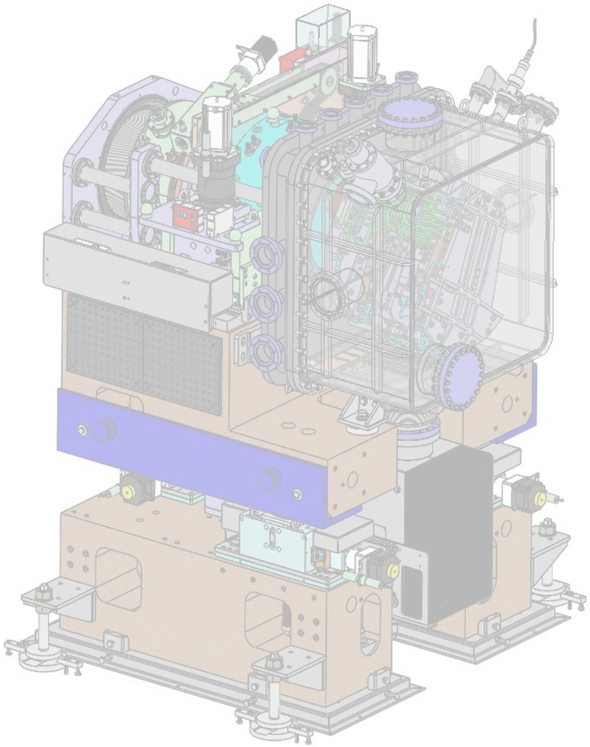
Development of a new DCM for spectroscopy by the ESRF with

- Continuous acquisition mode as default mode
- Perform full EXAFS spectra at the Hz level
- Unprecedented energy stability
  Bragg stability < 100 nrad FWHM
- Unprecedented position stability (fixed exit in dynamic mode)
  $\Delta R_y \rightarrow$ 100 nrad FWHM over 1 deg
  $\Delta R_x \rightarrow$ 150 nrad FWHM over 1 deg

- Continuous acquisition mode
- EXAFS spectra at 0.5 Hz
- Energy stability, Bragg : 51 nrad rms (DCM ?)
- $\Delta R_y \rightarrow$ 9.48 nrad rms / 50.5 nrad p-p (over 1 deg)
- $\Delta R_x \rightarrow$ < 1.9 $\mu$rad FWHM (over 7 deg): difficult to measure

## Future improvements ?

Faster scans keeping stability performance



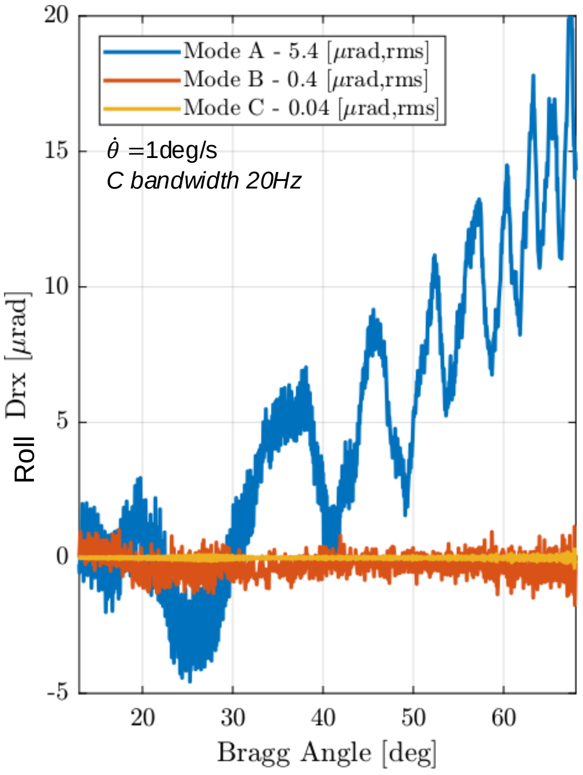
# END OF PRESENTATION

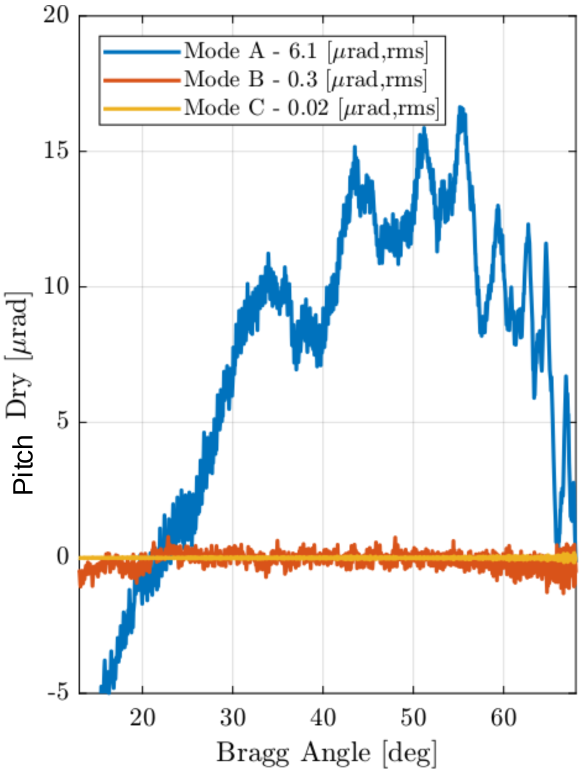
# THANK FOR YOUR ATTENTION

**Thanks to the DCM project and commissioning teams and all those who have contributed to this ambitious project, especially :**

Delphine BABOULIN, Ray BARRETT, Pascal BERNARD, Philipp BRUMUND, Gilles BERRUYER, Julien BONNEFOY, Maxim BRENDIKE, Philipp BRUMUND, David BUGNAZET, Hiram CASTILLO MICHEL, José-María CLEMENT, Marine COTTE, Thomas DEHAEZE, Hervé GONZALEZ, Cyril GUILLOUD, Ricardo HINO, Marc LESOURD, Giovanni MALANDRINO, Olivier MATHON, Alban MOYNE, Manuel PEREZ, Thomas ROTH, Murielle SALOMÉ, Philippe TARDIEU, Remi TUCOULOU, Hans-Peter VAN DER KLEIJ,…

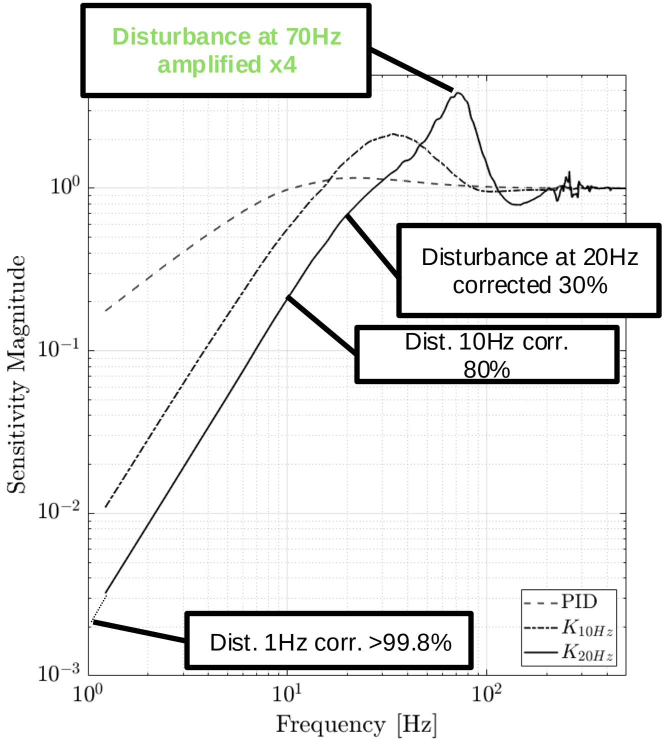
# RT CONTROL LOOP : ACTIVE CORRECTION PERFORMANCE



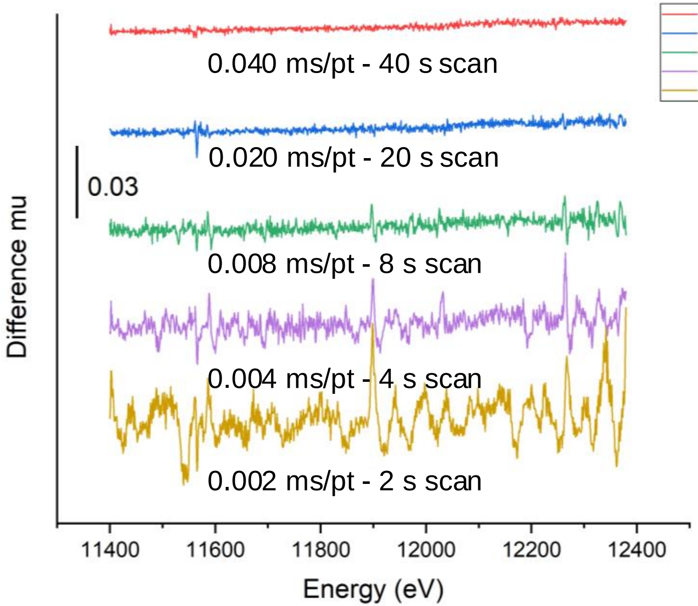

*Sensitivity function*

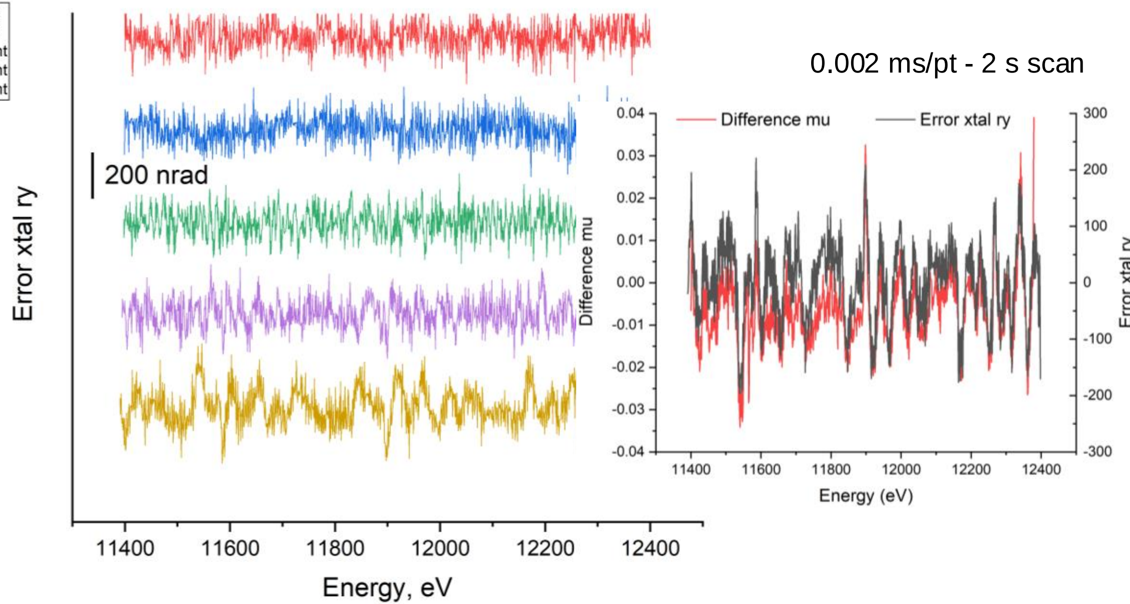
$$|S(j\omega)| = \left|\frac{1}{1+K(j\omega)G(j\omega)}\right| \qquad K: controller\,;\ G: Plant$$



# DCMs PERFORMANCE: BANDPASS

One limitation: bandpass of the realtime feedback system



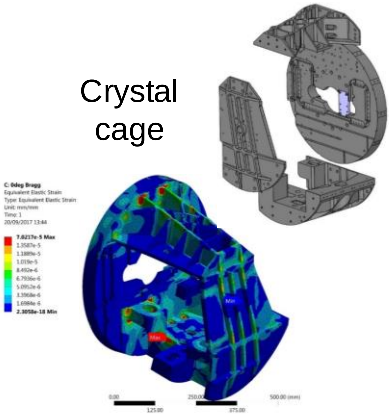

**Two solutions**

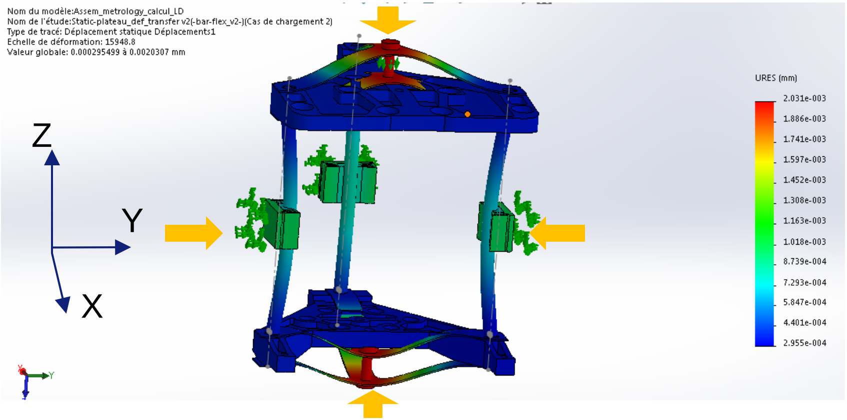
- **Decrease the amplitude of the mechanical excitation**
- **Increase the realtime feedback bandpass**

# ANALYSIS – EFFECT OF CRYSTAL CAGE DEFORMATION

## Deformation induced by thermal expansion of the crystal cage (Al alloy)

| | top/bottom fixtures (membrane flex.) $\vec{Z}$ displacement | sides fixtures (bars and flex.) $\vec{X}$ or $\vec{Y}$ displacement | | Ry | Rx |
|---|---|---|---|---|---|
| ΔT° 0.5K (24hrs) | 2 μm | 1 μm | FEA | 11 | -206 |
| ΔT° 0.2K (8hrs) | 0.75 μm | 0.5 μm | FEA | 7 | -110 |
| ΔT°<0.1K (short term) | < 0.4 μm | < 0.2 μm | Extrap | <4 | <60 |
| | | | | [nrad] | |




**Thermal drift of xtal cage should not induce a metrology frame deformation above the specifications for a short scan range (1 deg), i.e a short term drift.**

**For long term drifts, the xtal cage and the metrology frame are equipped with temperature sensors in order to be able to compensate the parasitic displacement with a TF model.**