ESRF Double Crystal Monochromator - Design and Working Modes

Robert Baker & Ludovic Ducotté

Co authors: Julien BONNEFOY, Thomas ROTH, Maxim BRENDIKE, Pascal BERNARD, Hervé GONZALEZ, Ray BARRETT. Gilles BERRUYER, Philippe TARDIEU

The European Synchrotron | ESRF

SUMMARY

Part 1 - Specifications & design - R. Baker

- Target specifications & design philosophy (reminder)
- Main design principles - Bragg axis
- Main design principles - Crystal cage
- Operating principle
- 1st results

Part 2 - Metrology frame - L. Ducotté

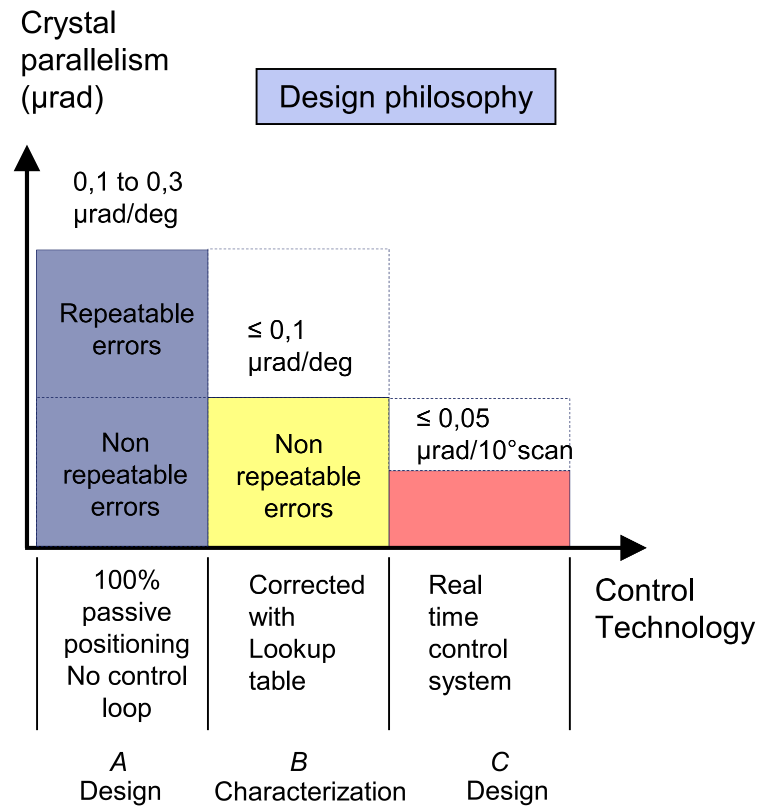
- Design specifications & criteria
- Source of errors - Strategy
- Metrology frame concept
- FEA
- Interferometers cyclic errors
- RT System overview

TARGET SPECIFICATIONS & DESIGN PHILOSOPHY (REMINDER)

MEDSI CHICAGO 2020

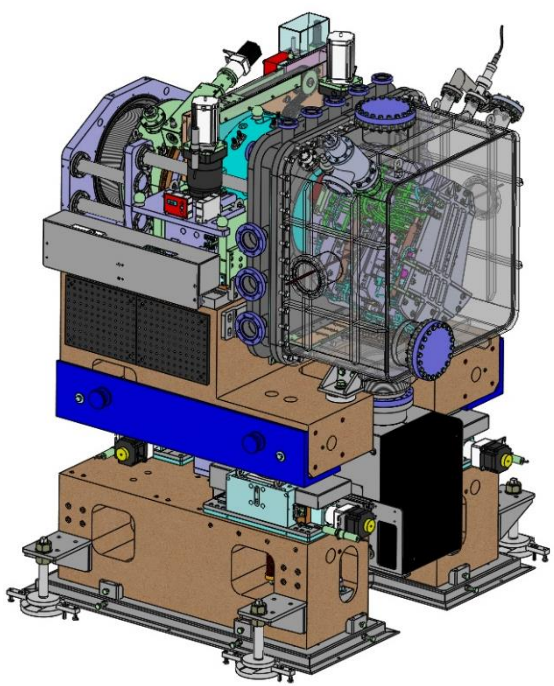
Bragg angle	Units	
Bragg angle range (total)	°	2-80
Bragg angle range (scan)	°	0.1-20
Bragg rotation speed	°/sec	0.001-3
Bragg MIM	*µrad*	0.5
Bragg accuracy	*µrad*	4
Bragg bi-dir. repeatability	*µrad fwhm*	25
Bragg uni-dir. repeatability	*µrad fwhm*	0.1

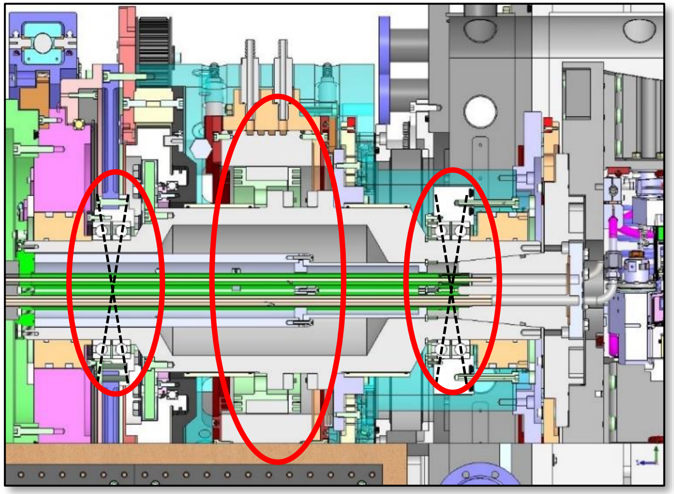
Crystal parallelism	Units	
ΔRY fixed energy	*nrad fwhm*	15
ΔRY for Δθ<1°	*nrad fwhm*	15
ΔRY for Δθ<5°	*nrad fwhm*	28
ΔRX fixed energy	*nrad fwhm*	100
ΔRX for Δθ<1°	*nrad fwhm*	100
ΔRX for Δθ<5°	*nrad fwhm*	300

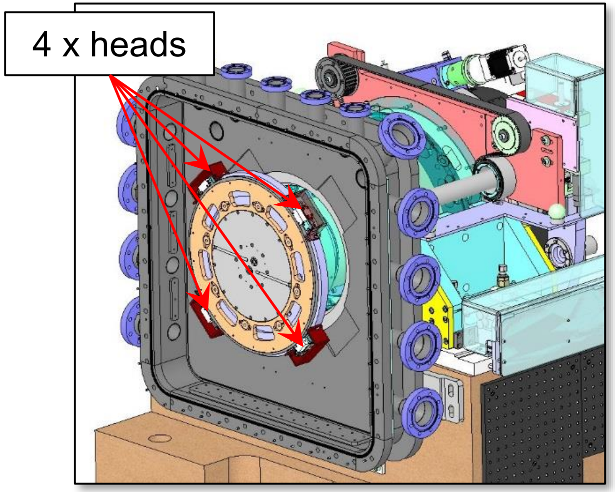


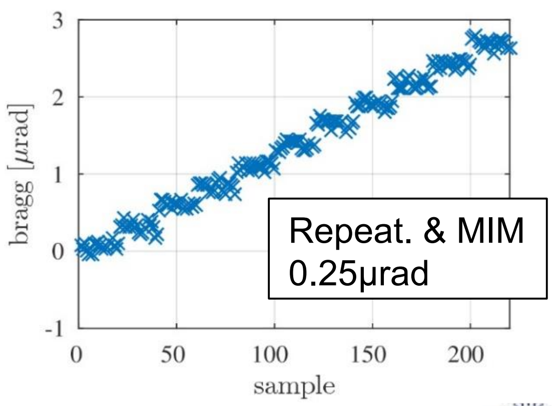
MAIN DESIGN PRINCIPLES – BRAGG AXIS

- Custom angular contact Bragg bearings
- Direct drive torque motor
- In vacuum 4 head encoder



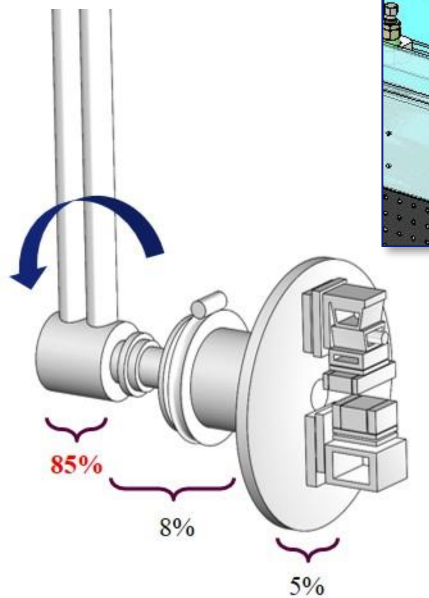


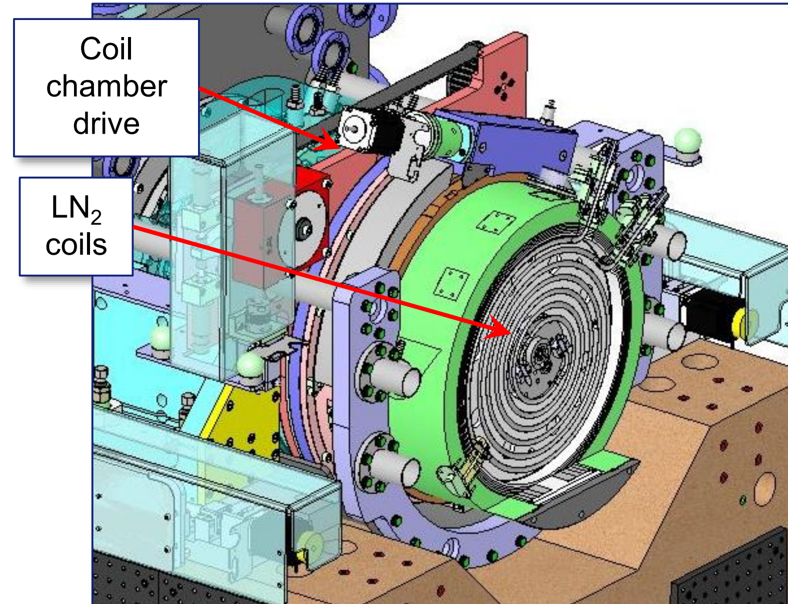




MAIN DESIGN PRINCIPLES – BRAGG AXIS

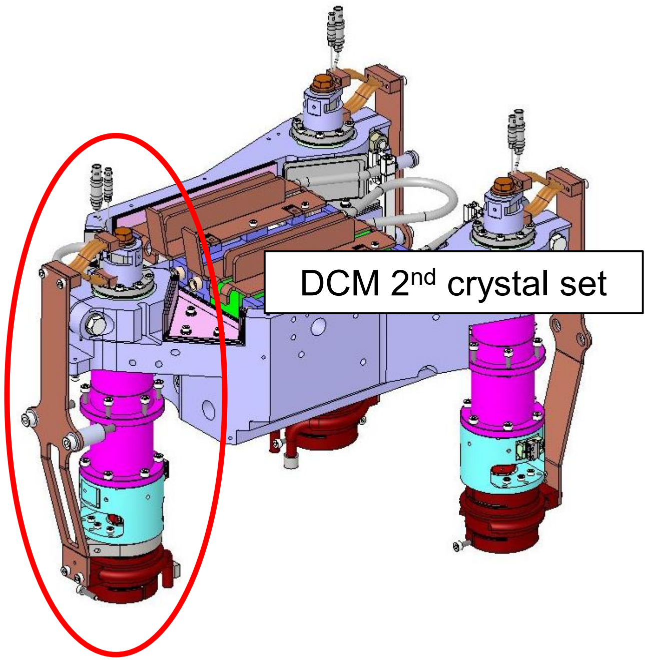
- No internal flexible LN_2 lines
- No following LN_2 feeder lines

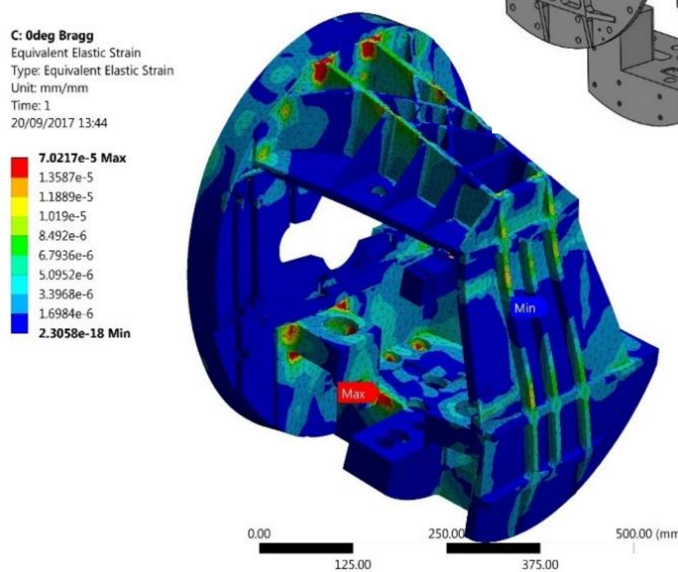


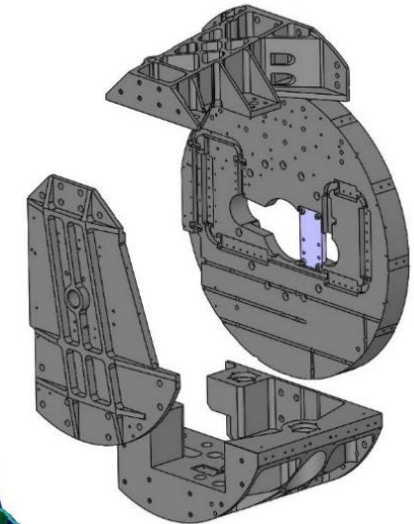


MAIN DESIGN PRINCIPLES – CRYSTAL CAGE

- High stiffness thermalized structure
- No stacked stages
- 2nd crystal tripod concept
- Fastjack hybrid actuator





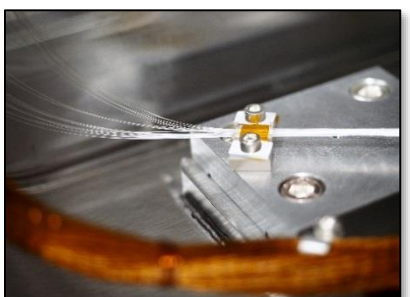


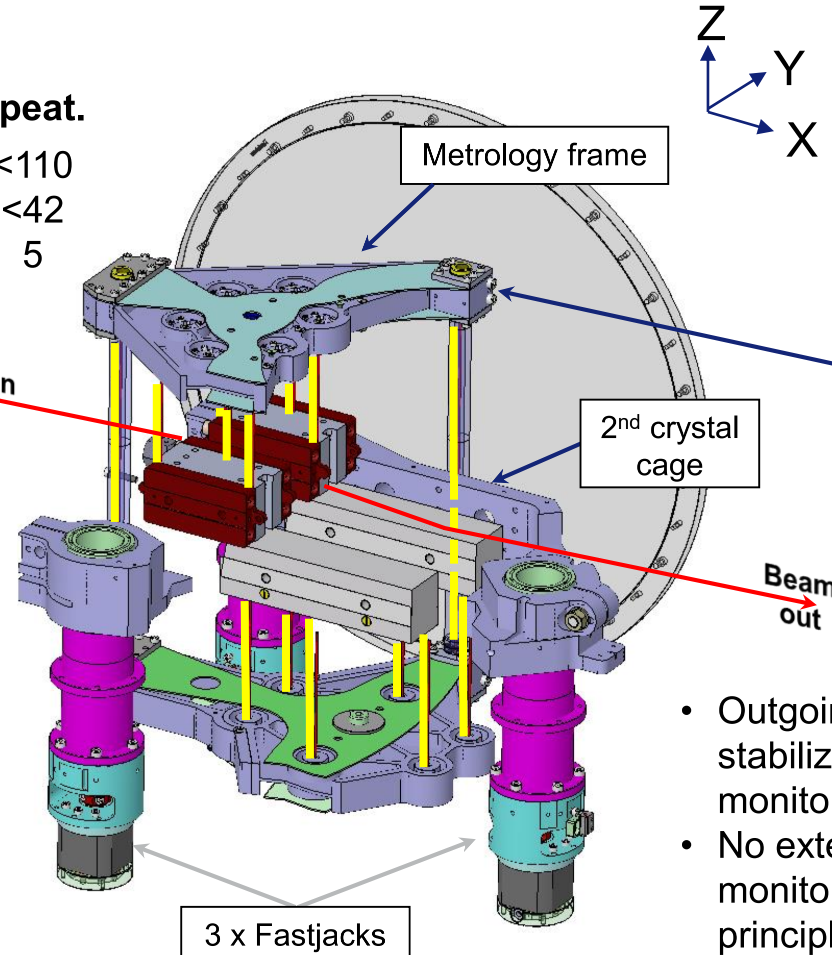
MAIN DESIGN PRINCIPLES - ONLINE METROLOGY

Theoretical performance*

Movement	Resol.	Repeat.
ΔRX (roll) nrad	<8	<110
Δ RY (pitch) nrad	<3	<42
Δ TZ (vertical) nm	0.3	5

**Calculated from suppliers' specified maximum resolution*





Attocube fibre optics:

radiation resistance = 10MGy

PEEK: 3MGy

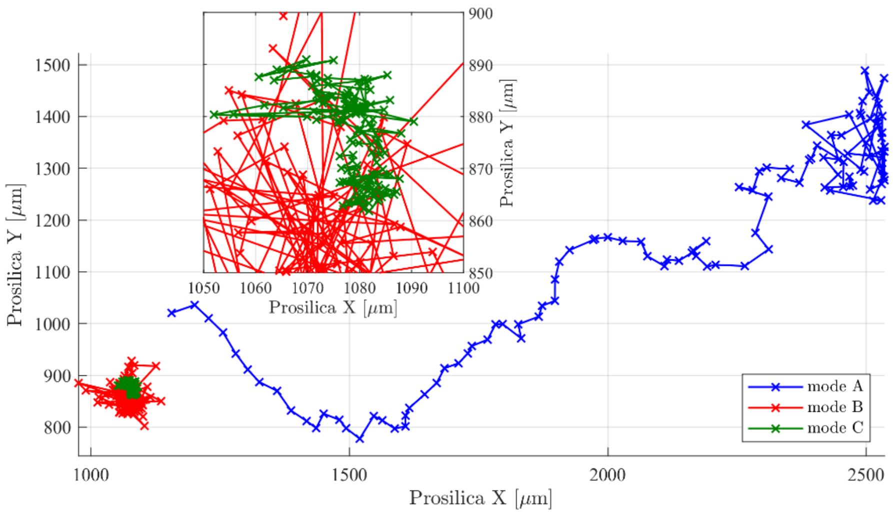
Kapton: 50MGy

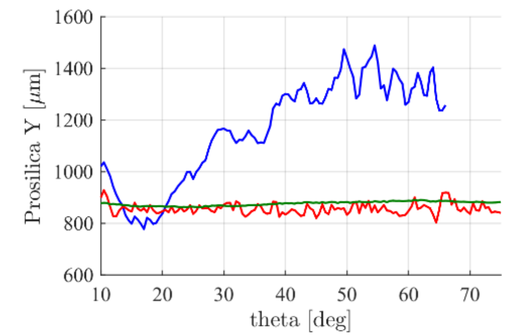
15 Fabry-Pérot interferometer heads (no in-vacuum electronics)

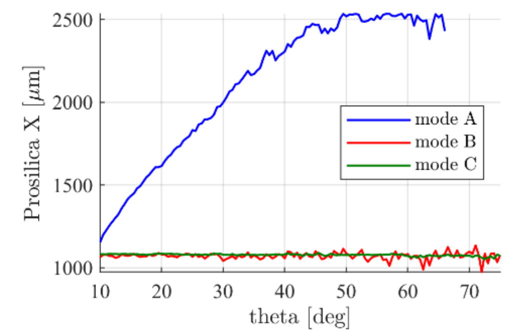
- Outgoing X-ray beam trajectory stabilized by real-time monitoring of crystal positions
- No external beam position monitoring required (but can in principle be added)

FIXED EXIT PERFORMANCE: UNFOCUSED BEAM

- In mode C, the virtual source moves by ~5 x 1.5 beam widths (v x h) over the full angular range
- Locally (over small angles) these values are much reduced

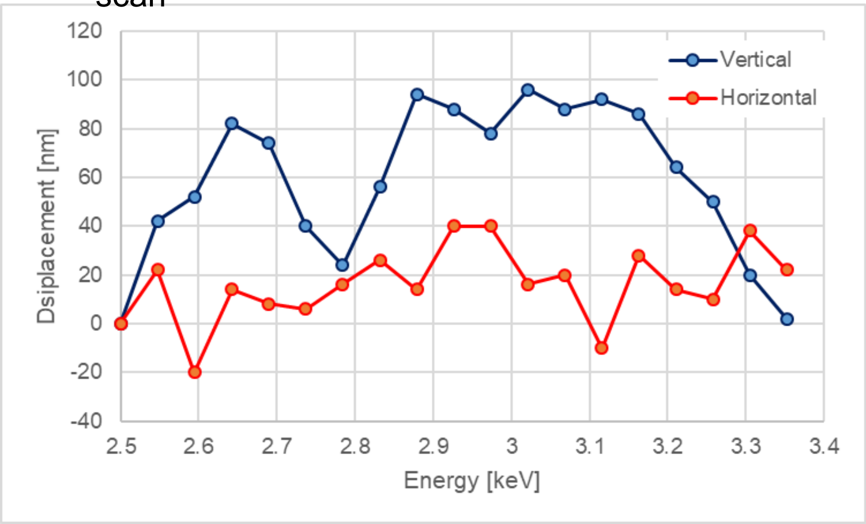


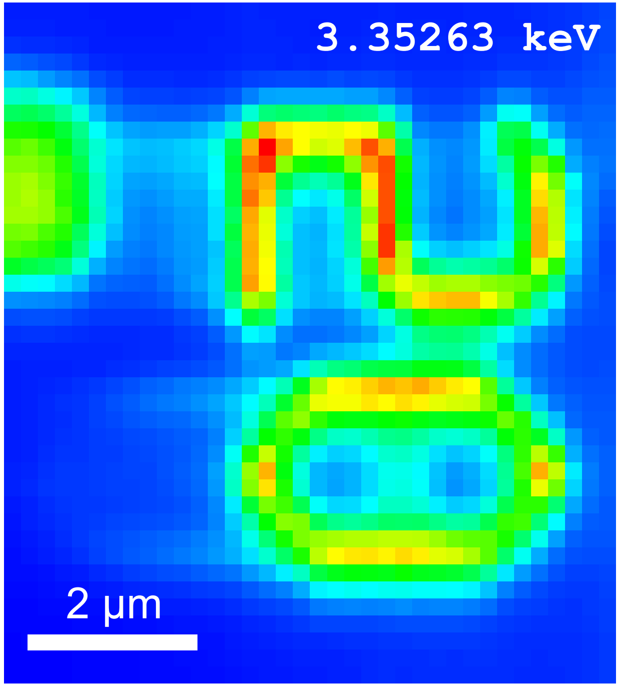




FIXED EXIT PERFORMANCE: FOCUSED BEAM

- Scanning X-Ray microscopy
- 2.5 and 3.35 keV (θ_B 52 - 36°)
- Stacked absorption contrast images of a test object
- No realignment between energies
- Focused Beam moves by < 100 nm over energy scan



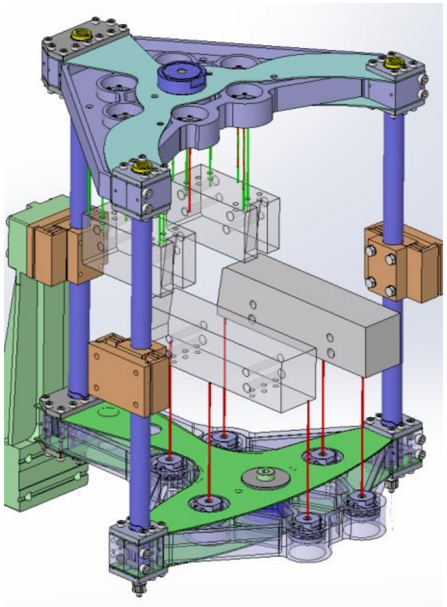


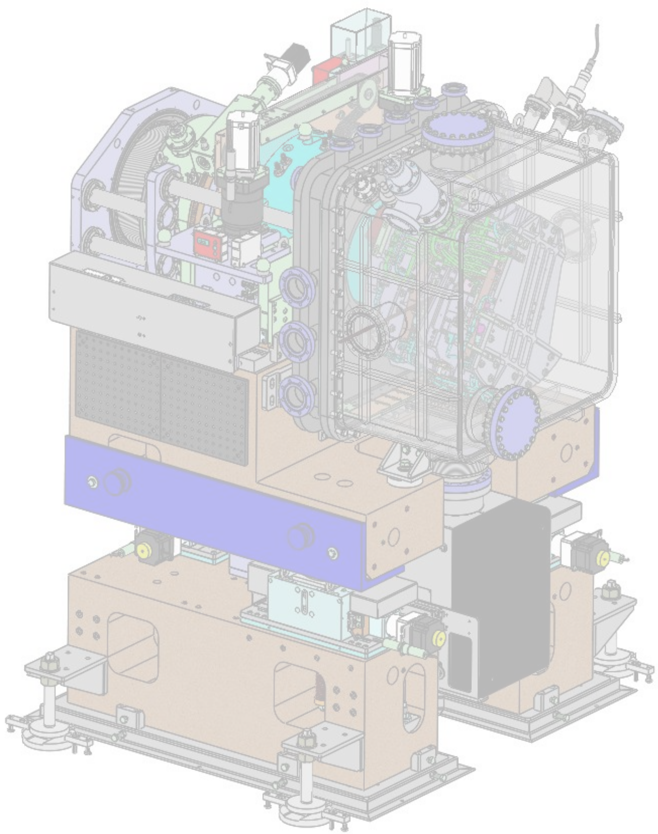
Part 1 - Specifications & design - R. Baker

- Target specifications & design philosophy (reminder)
- Main design principles - Bragg axis
- Main design principles - Crystal cage
- Operating principle
- 1st results

Part 2 - Metrology frame - L. Ducotté

- Design specifications & criteria
- Source of errors - Strategy
- Metrology frame concept
- FEA
- Interferometers cyclic errors
- RT System overview





END OF PRESENTATION

THANKS FOR YOUR ATTENTION

Thanks to the DCM project and commissioning team 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 BUZNAGET, Hiram CASTILLO MICHEL, José-Maria CLEMENT, Marine COTTE, Yves DABIN, Hervé GONZALEZ, Cyril GUILLOUD, Ricardo HINO, Marc LESOURD, Giovanni MALANDRINO, Keith MARTEL, Olivier MATHON, Manuel PEREZ, Thomas ROTH, Murielle SALOME, Philippe TARDIEU, Remi TUCOULOU, Hans-Peter VAN DER KLEIJ…

ESRF Double Crystal Monochromator - Design and Working Modes

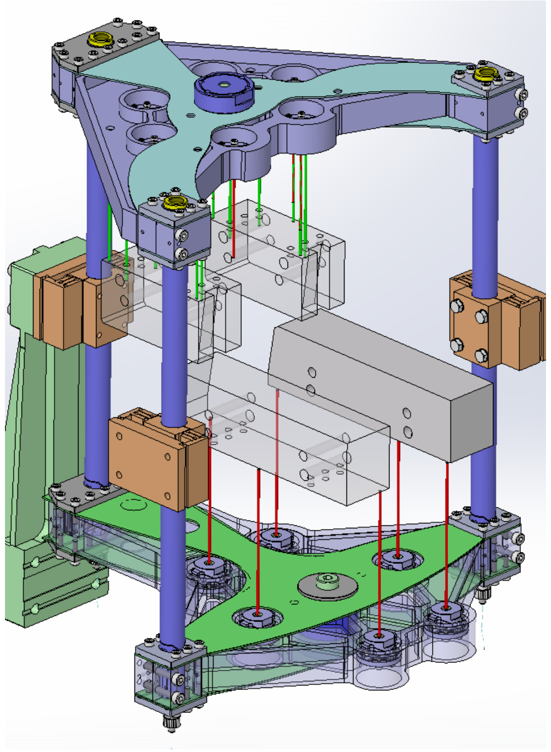
Robert Baker & Ludovic Ducotté

Co authors: Julien BONNEFOY, Thomas ROTH, Maxim BRENDIKE, Pascal BERNARD, Hervé GONZALEZ, Ray BARRETT. Gilles BERRUYER, Philippe TARDIEU

- **Part 1 - Specifications & design - R. Baker**
- Target specifications & design philosophy (reminder)
- Main design principles - Bragg axis
- Main design principles - Crystal cage
- Operating principle
- 1st results

Part 2 - Metrology frame - L. Ducotté

- Design specifications & criteria
- Source of errors - Strategy
- Metrology frame concept
- FEA
- Interferometers cyclic errors
- RT System overview



MEDSI CHICAGO 2020

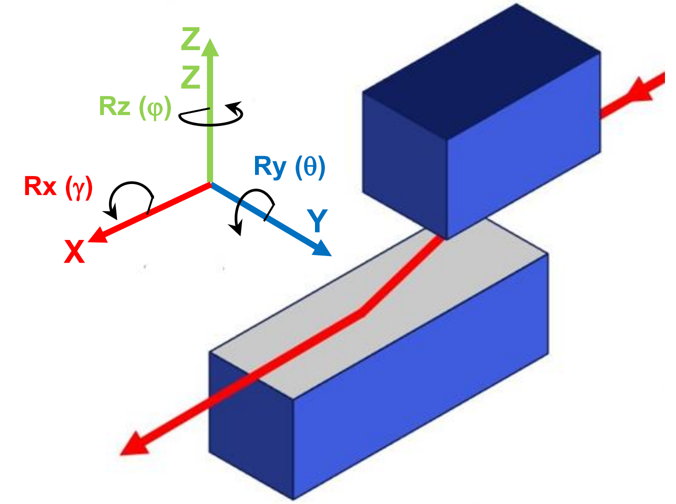
From functional to positioning precision specifications :

- Measurement of **Rx + Ry + Tz variations between 1st and 2nd crystal** (2 pairs)
- Supported by crystal cage (= "*Bragg* axis")
- Bragg angle **2→80deg**
- **2nd Crystals Tz stroke** for a fixed beam exit : **~25mm** for the total Bragg angle range
- UHV and radiations

- Eigen Frequencies **> 250 Hz,** Control BW Fastjack Piezo actuators [0-100]Hz
- **Measured parallelism X1 // X2 :**
  - **Ry < 14nrad , Rx < 100 nrad** for a **scan** of **1deg,** and during **24hrs** at **fixed energy**
  - **Low sensitivity** to **deformation** of crystal cage
  - **Low sensitivity** to **thermal drift**

Scanning mode, sampling Δθ/1000	
Δrx over 1 deg	**100 nrad**
Δry over 1 deg	**14 nrad**
Δrx over 5 deg	200 nrad
Δry over 5 deg	28 nrad
Δrx over 20 deg	500 nrad
Δry over 20 deg	70 nrad
Δtz over 1 deg	0.2 µm
Δtz over 1 to 20 deg	0.4 µm

i 100 nrad ≈ a hair at 1 km



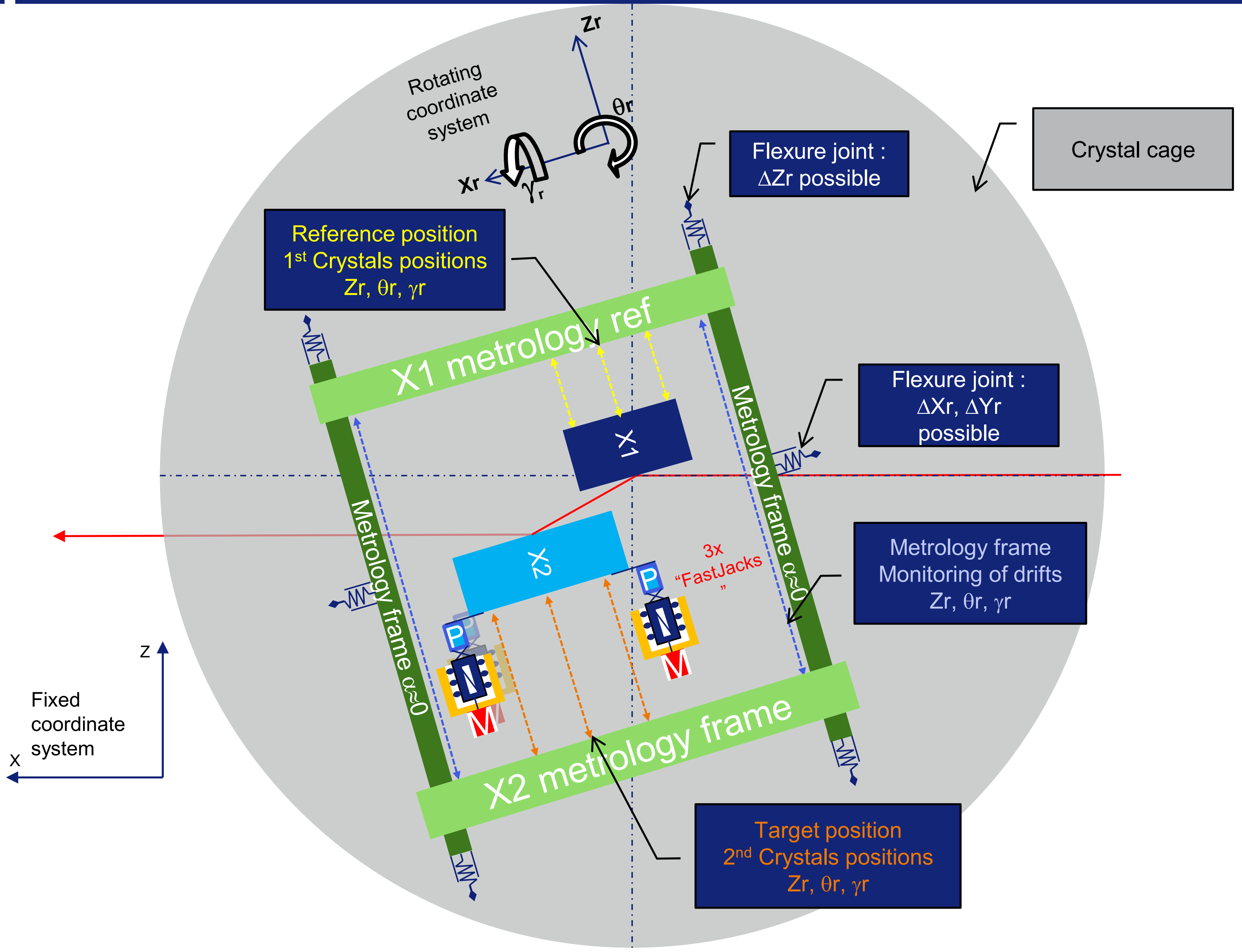
The European Synchrotron ESRF

METROLOGY FRAME – SOURCE OF ERRORS – STRATEGY

Source of error	Effect on accuracy	Calibration possible ?	Effect on repeat.	Effect on stability	Strategy
Gravity $\vec{g}$ vs Bragg angle θ	Yes	Yes, f(θ)	No	No	**Calibration in lab or with X-Rays**
Deformation of crystal cage	Yes	Difficult, f(T,t)	Yes	Yes, low frequency	**Minimised by design**
Thermal drift of metrology frame	Yes	Difficult, f(T,t)	Yes	Yes	**Minimised by design**
Vibration	No	/	No	Yes, [2-100]Hz	**Minimised by design 1st EF > 250Hz**
Interferometers precision	Yes*, linear	Yes, f(θ or d)	Yes*	Yes*	**Calibration in lab or with X-Rays**

*Data in *Attocube* datasheet

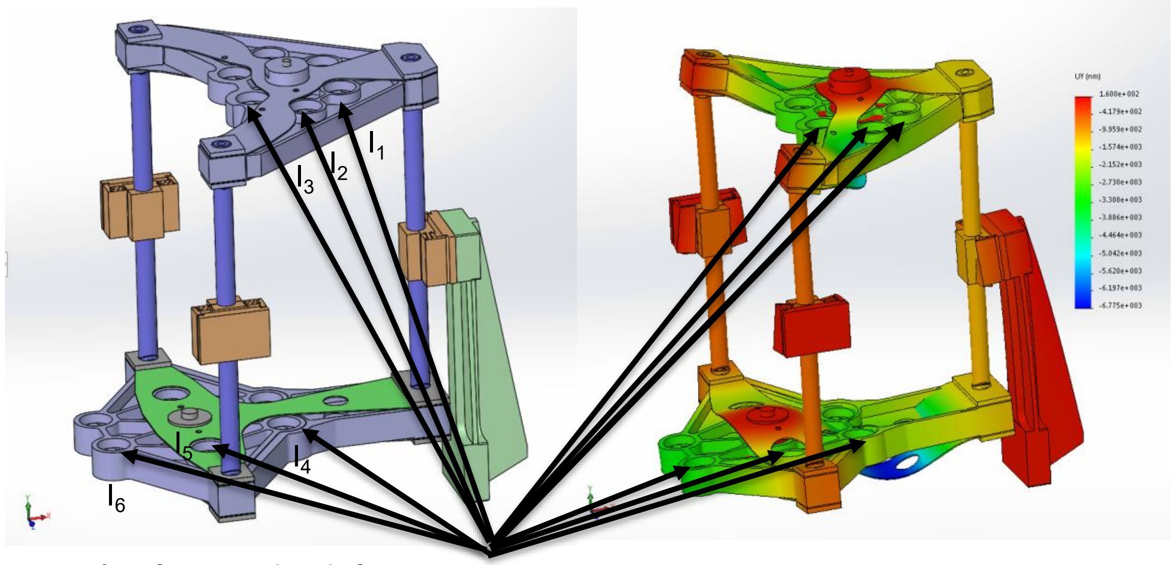
METROLOGY FRAME CONCEPT



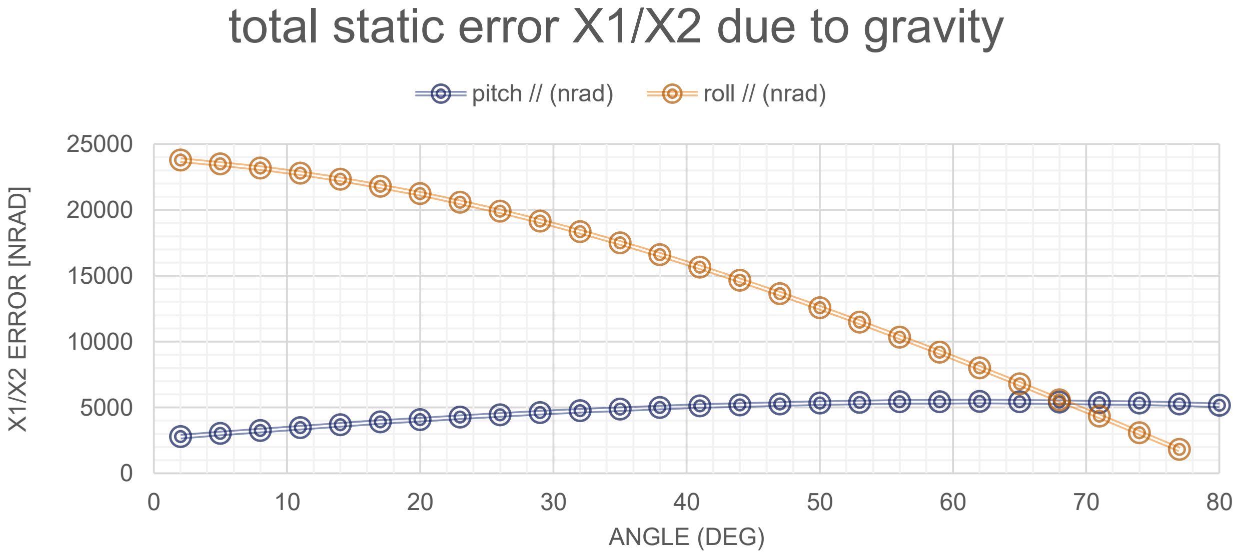
$\theta r \equiv ry$

$\gamma r \equiv rx$

FEA RESULTS ANALYSIS – GRAVITY EFFECT WITH BRAGG AXIS ORIENTATION

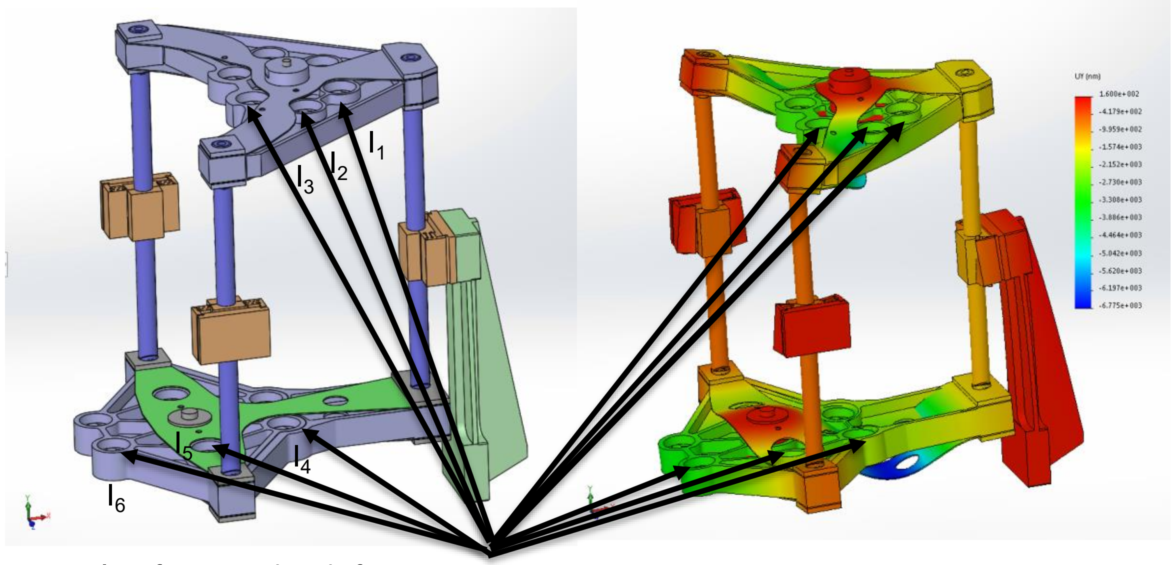


Interferometer heads for measurement of X1 and X2 displacements



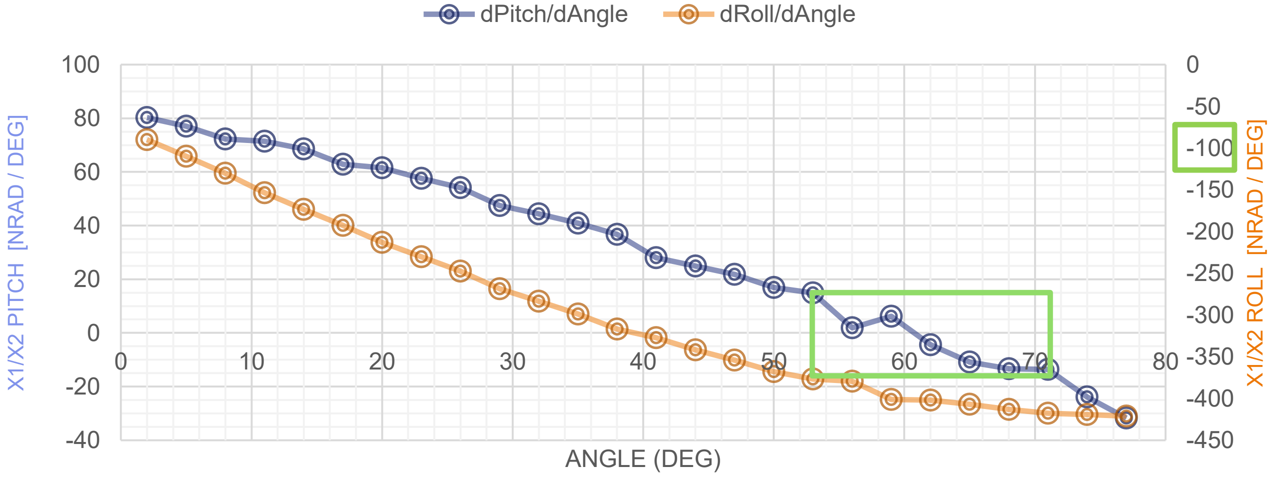
Bragg angle [2-80] deg	
Δ // Pitch (Ry)	Δ // Roll (Rx)
2670 nrad	23200 nrad

FEA RESULTS ANALYSIS – GRAVITY EFFECT WITH BRAGG AXIS ORIENTATION



Interferometer heads for measurement
of X1 and X2 displacements

change of static error X1/X2 due to gravity / deg



Bragg angle [2-78] deg	
d(Ry)/deg	d(Rx)/deg
[0-80]nrad/°	[90-420]nrad/°

<14 | <100

Out of specification on most of Bragg range

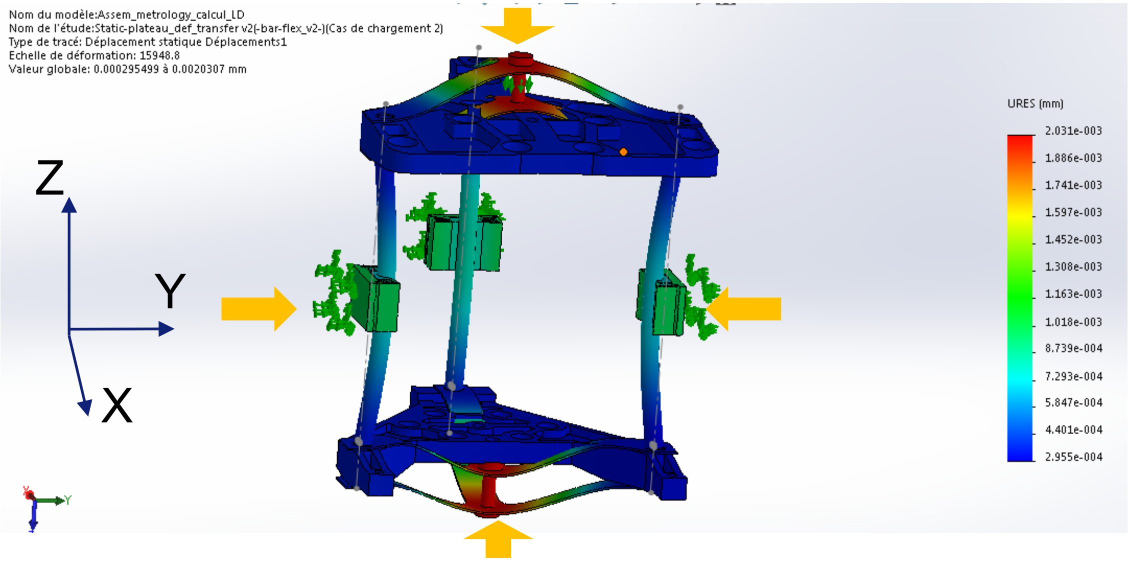
Repeatable and f(Bragg)

Can be calibrated and compensated on RT control system

MEDSI CHICAGO 2020

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.

Not known at implementation of *Attocube IDS* Interferometers

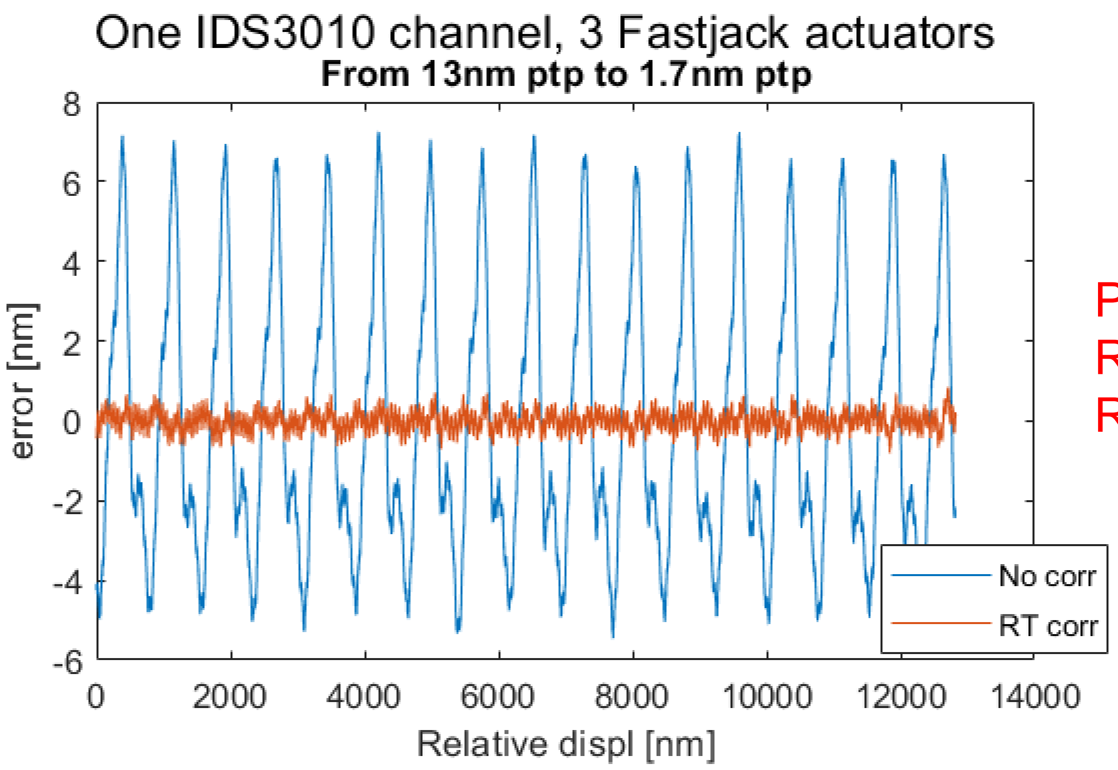
Non-linear errors cyclic modulo ~765nm $\left(\frac{\lambda}{2}\right)$

Significant effect on 2nd crystals' measured angles during a scan:

- Rx ~1 μrad
- Ry ~ 0.15 μrad

Current strategies for improvements :

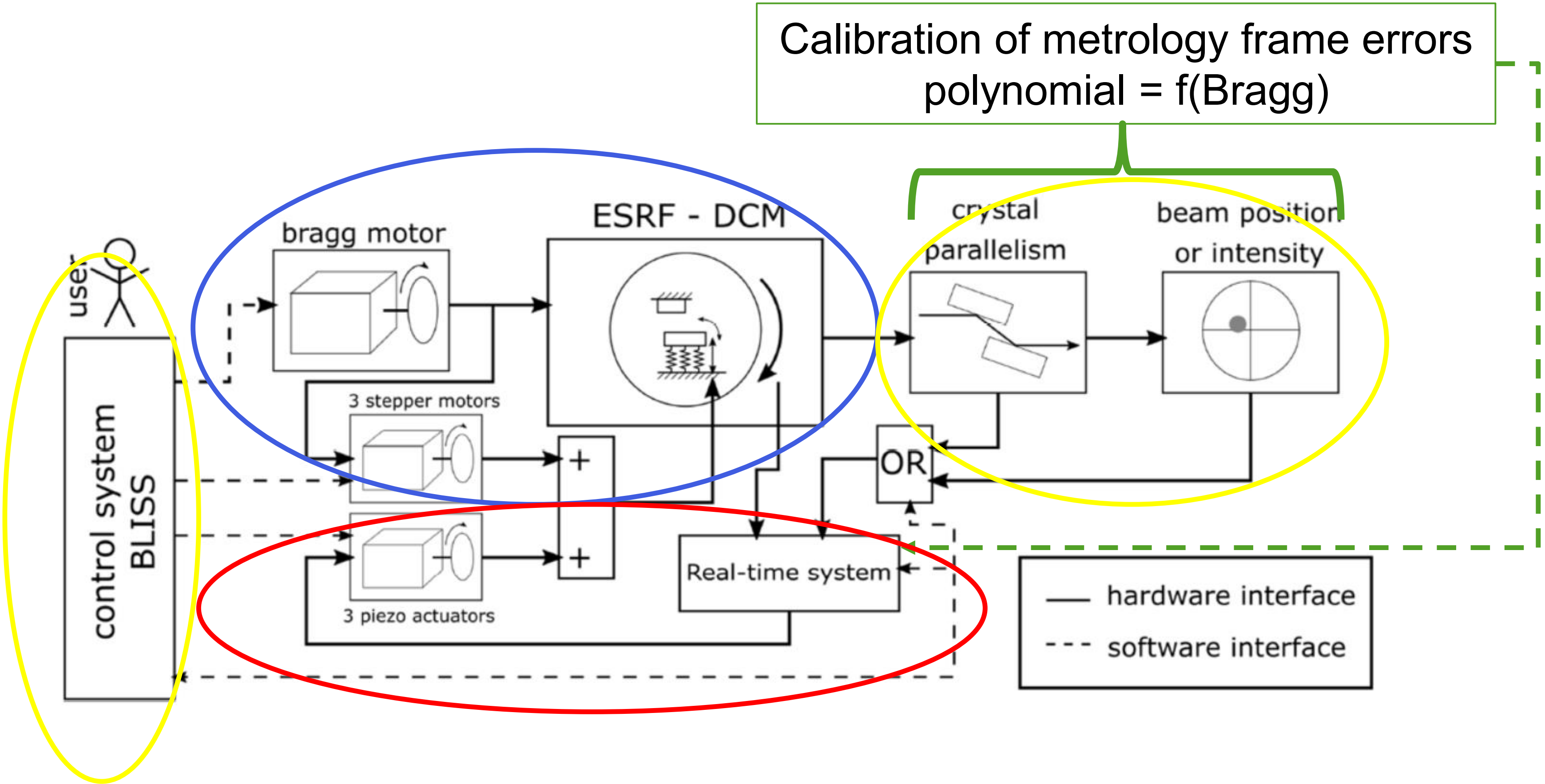
Improvements by supplier, other suppliers, **compensation by our RT system**



Possible improvement :
Rx < 70 nrad
Ry < 15 nrad

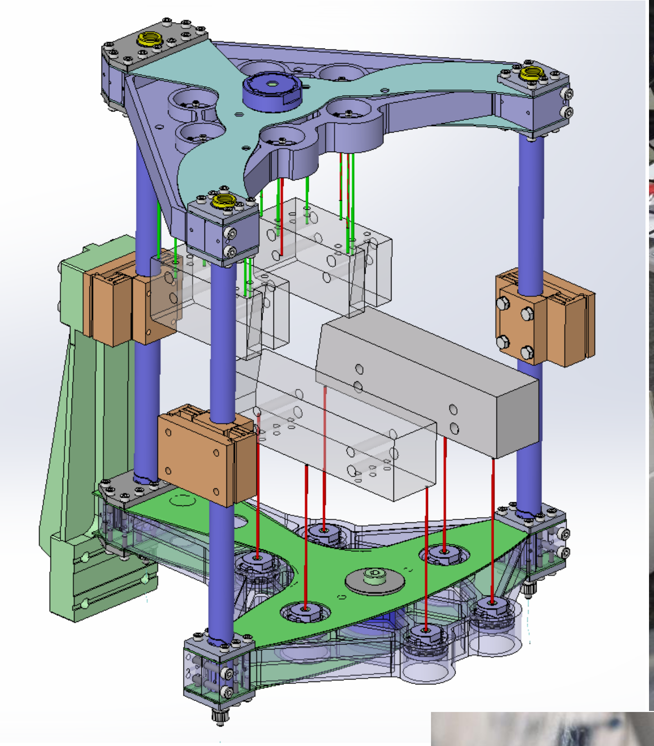
Crystal parallelism, working modes:

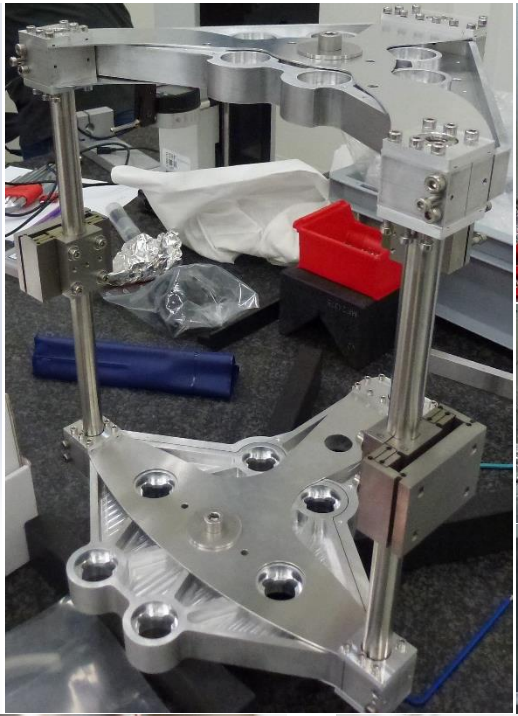
- **Mode A :** Open-loop actuation, no corrections
- Mode B : Open-loop, correction of repeatable errors of stepper motors
- **Mode C** : Active real-time control

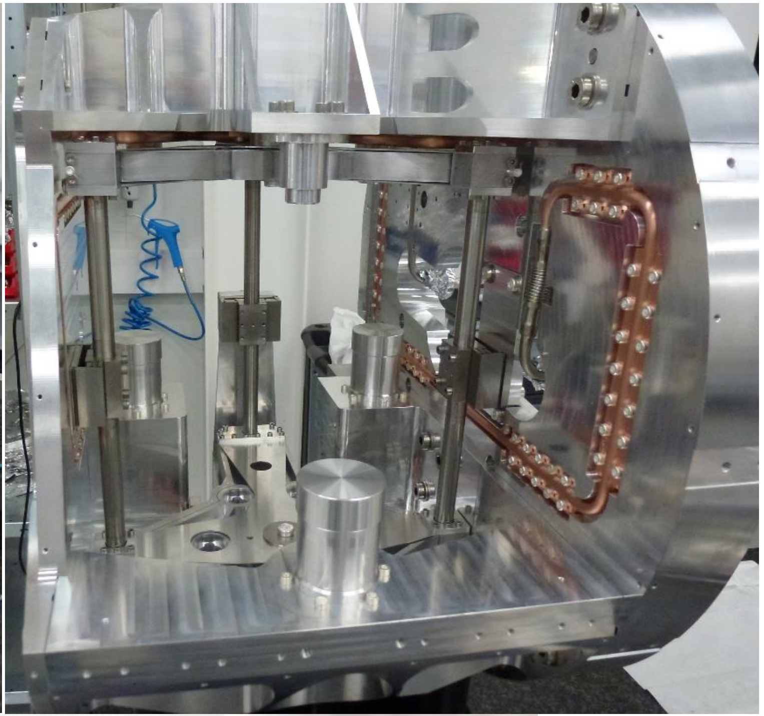


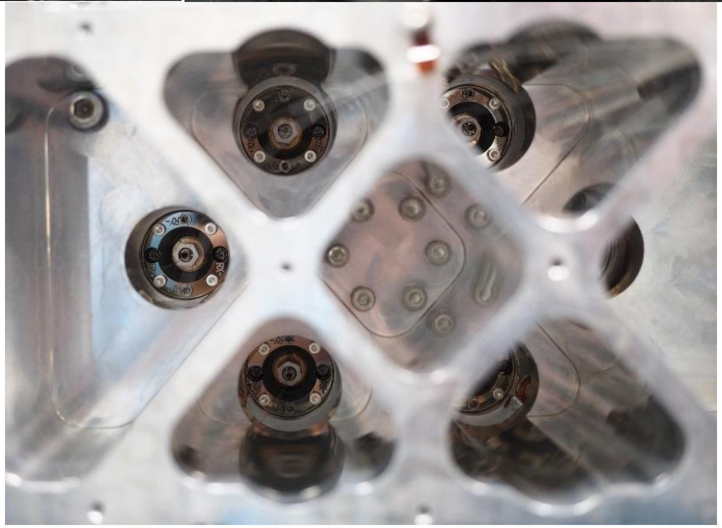
M. Brendike et al., “ESRF-Double Crystal Monochromator Prototype - Control Concept”, presented at the 17th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'19), New York, NY, USA, Oct. 2019, paper TUCPL05.

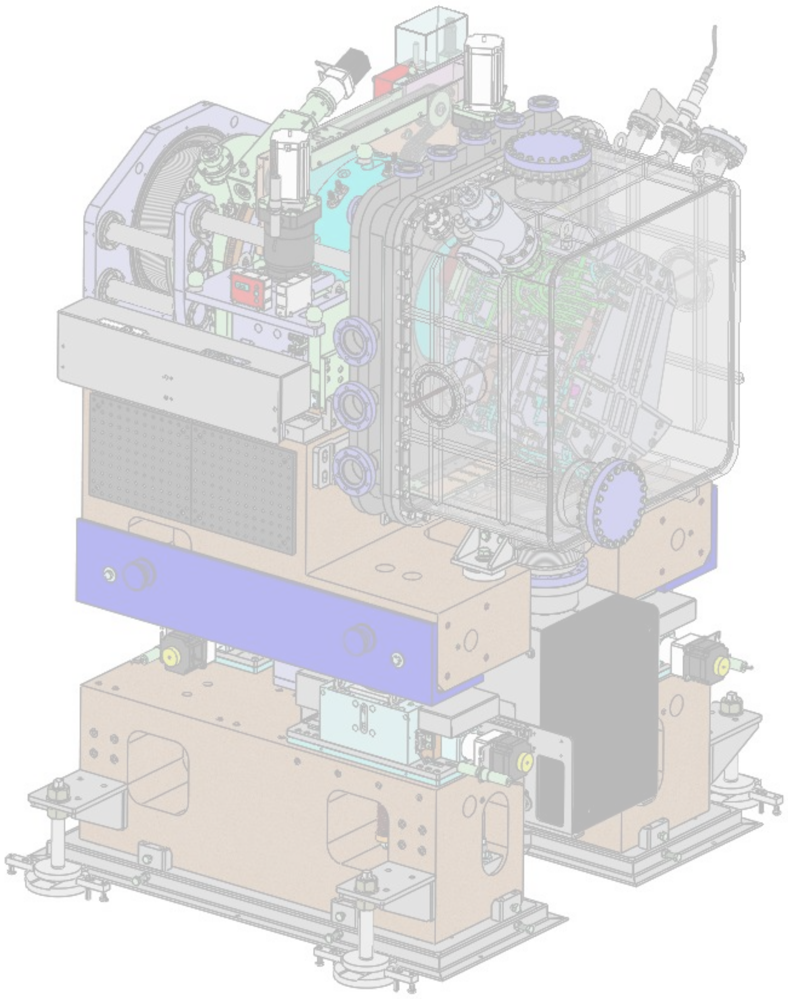
CAD MODEL AND ASSEMBLY ACHIEVED











END OF PRESENTATION

THANK FOR YOUR ATTENTION

Thanks to the DCM project and commissioning team 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, Yves DABIN, Hervé GONZALEZ, Cyril GUILLOUD, Ricardo HINO, Marc LESOURD, Giovanni MALANDRINO, Keith MARTEL, Olivier MATHON, Manuel PEREZ, Thomas ROTH, Murielle SALOMÉ, Philippe TARDIEU, Remi TUCOULOU, Hans-Peter VAN DER KLEIJ,…