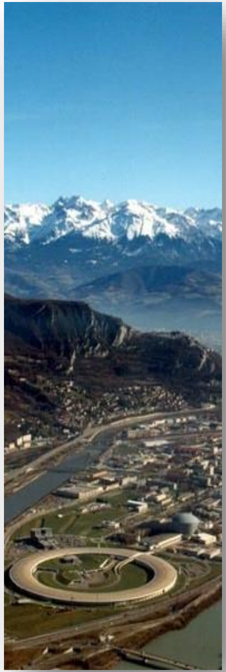
ESRF | The European Synchrotron



ESRF

Double Crystal Monochromator

How mechatronic can enhance the performance of X-Ray optical system

8th EIROforum School on Instrumentation

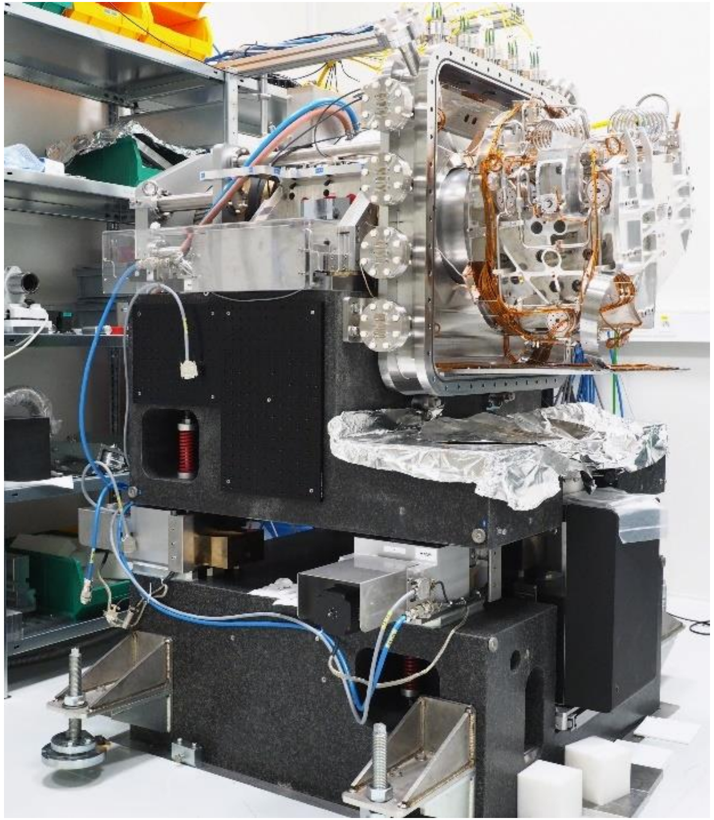
System integration and instrument design

Ludovic Ducotté

Intrumentation Services & Development Division – Mechanical Engineering Group

EIROforum serving european science The European Synchrotron | ESRF

OUTLINE



Introduction

Where a Double Crystal Monochromator (DCM) is used ?

DCM concept

What is a Fixed-Exit DCM
Working principle

ESRF DCM

Specifications for ESRF beamlines
Fixed-exit with mechanical system
Engineering philosophy
Fixed-exit with mechatronic system
Key components
Calibration strategy
Results

Conclusion

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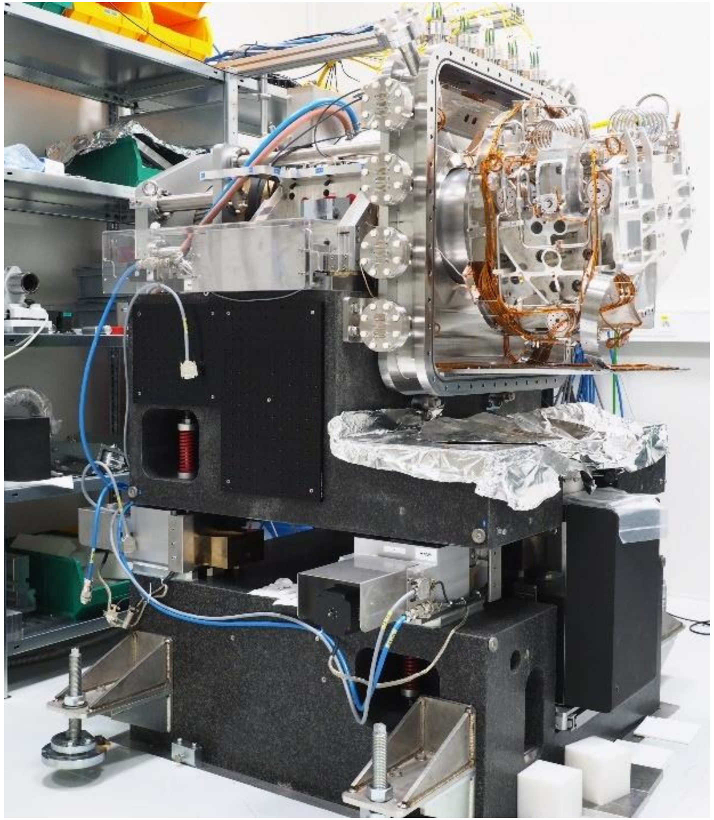

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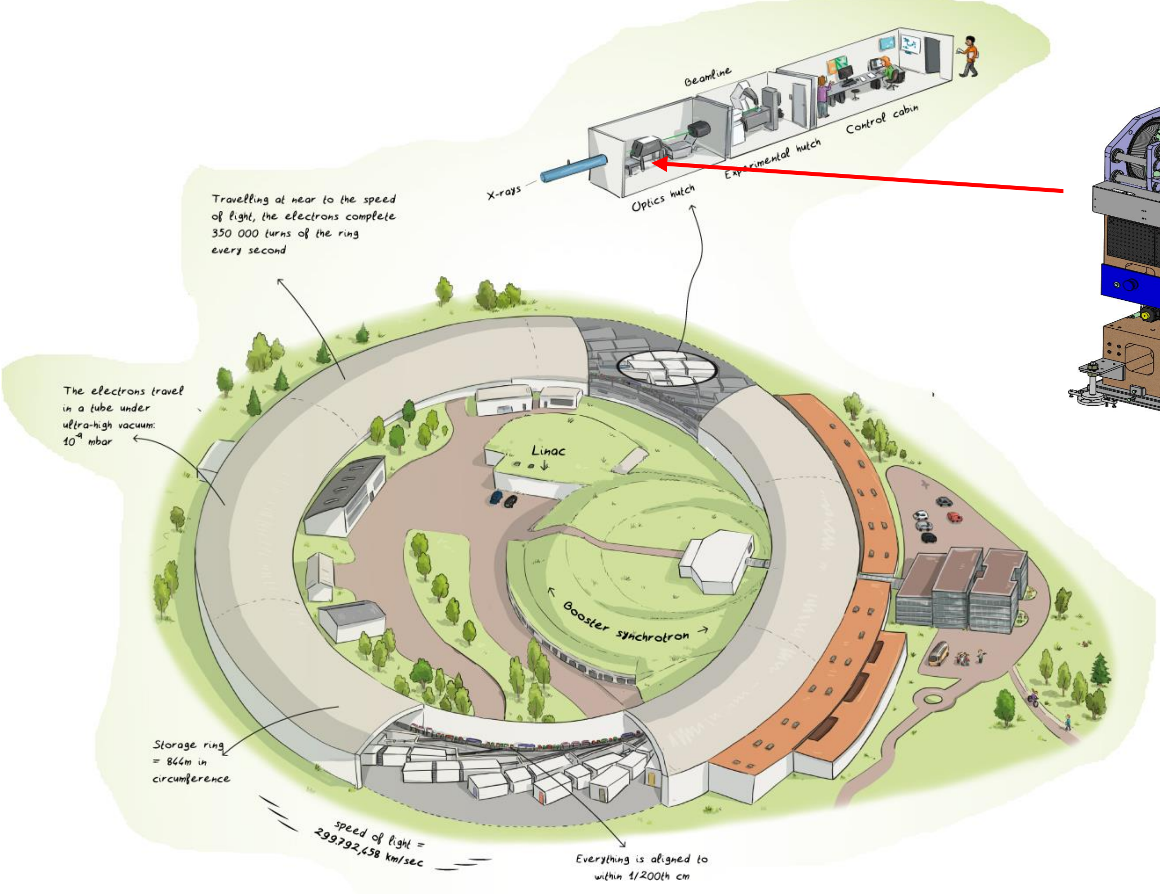
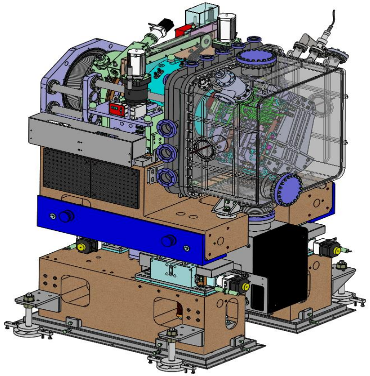
INTRO : WHERE IS A MONOCHROMATOR ON A BEAMLINE





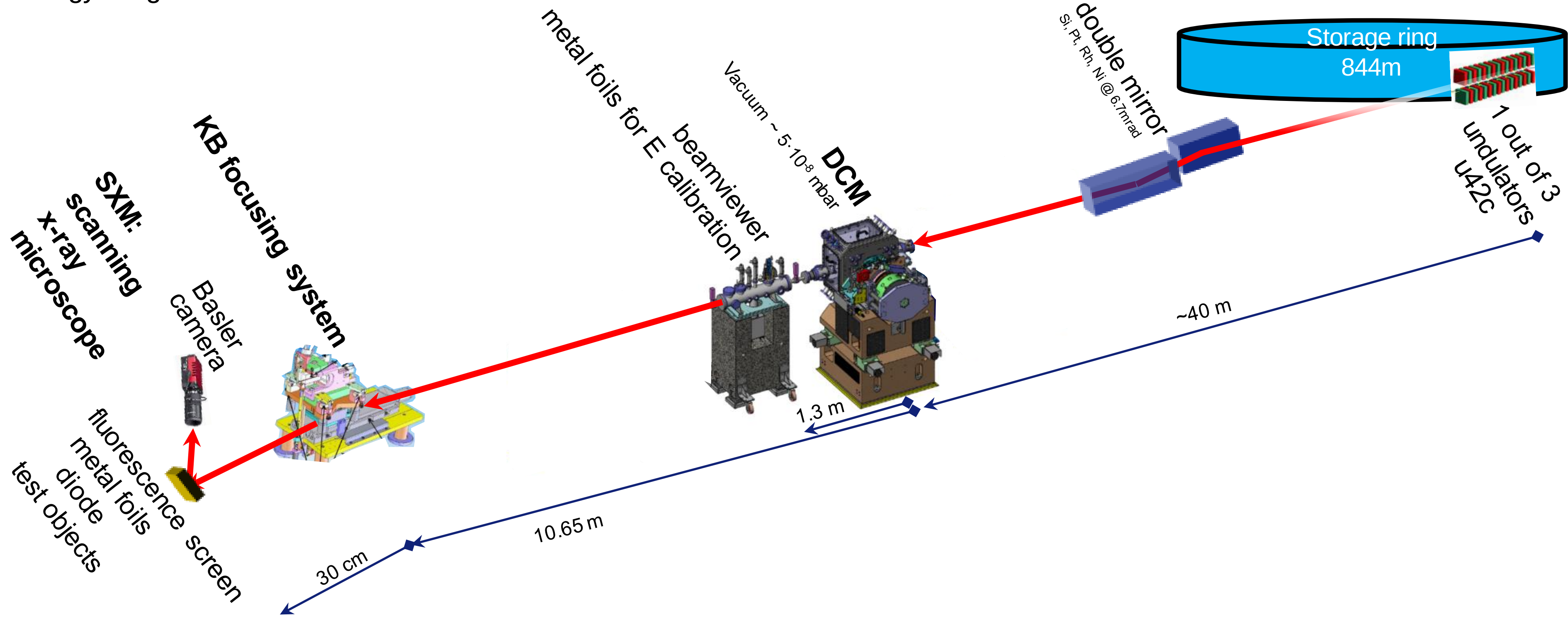
Working environment :

Ultra High Vacuum

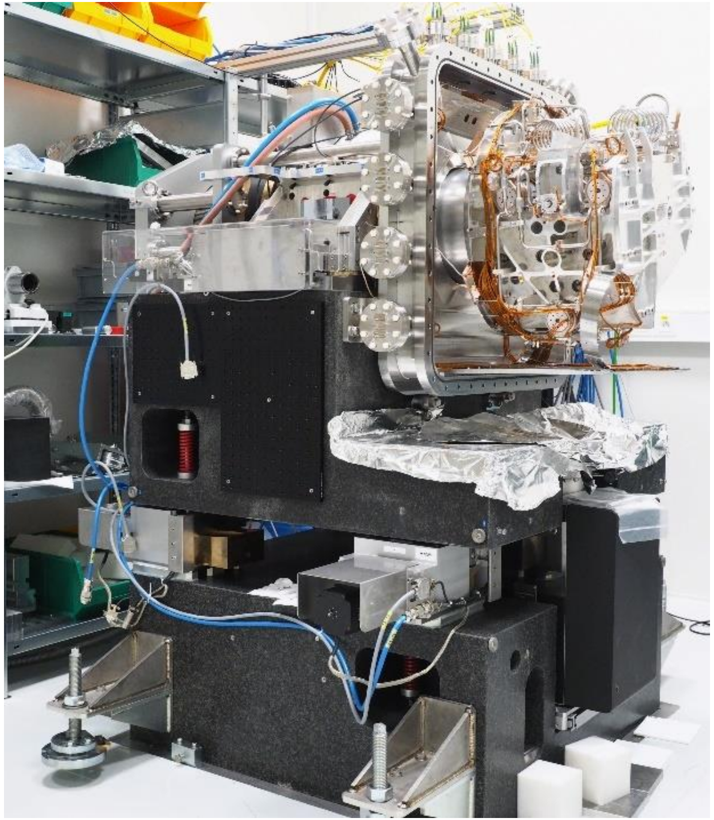
Radiation

INTRO : WHERE IS A MONOCHROMATOR ON A BEAMLINE

Example ID21
energy range: 2.05 – 11.5 keV



OUTLINE



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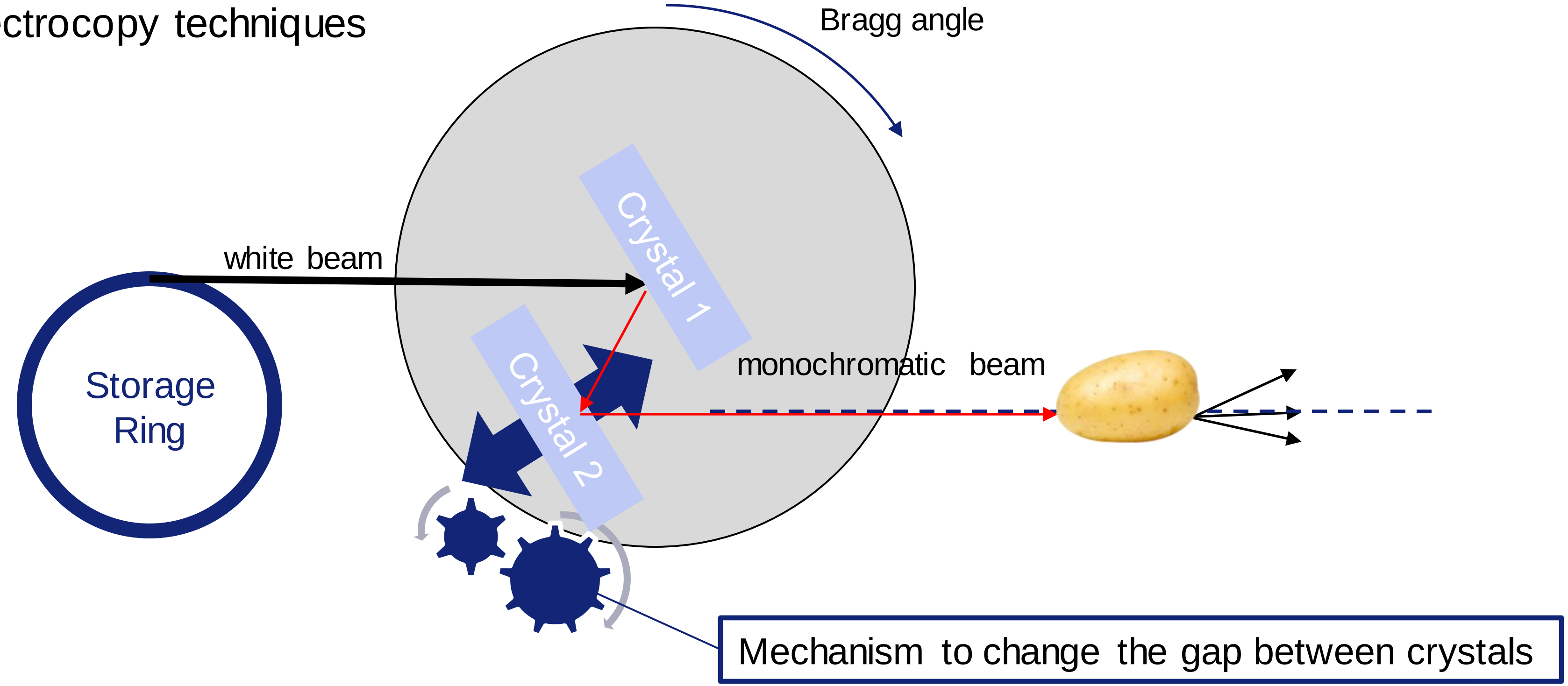
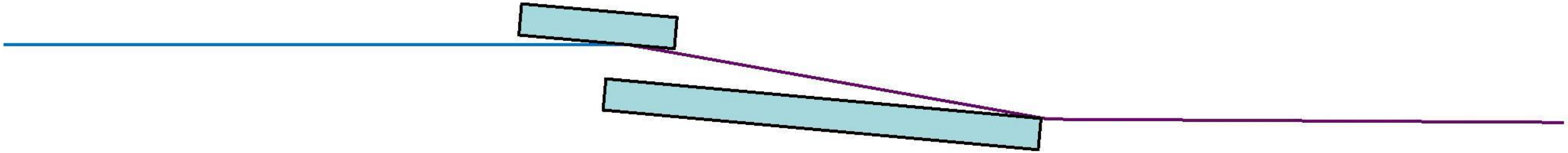
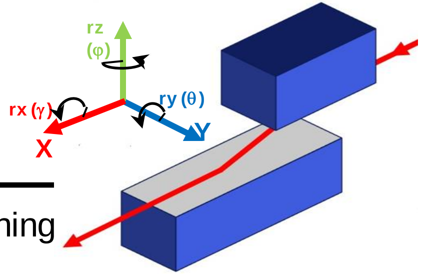
INTRO : WHAT IS A FIXED-EXIT DOUBLE CRYSTAL MONOCHROMATOR

For Beamlines using spectrocopy techniques

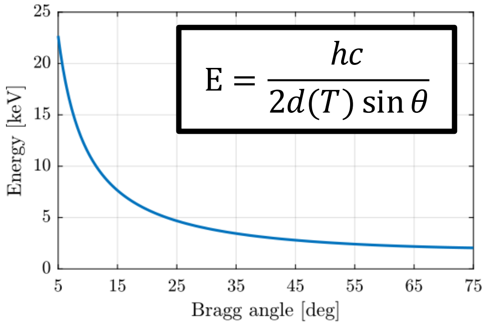


WORKING PRINCIPLE AND MAIN PARAMETERS



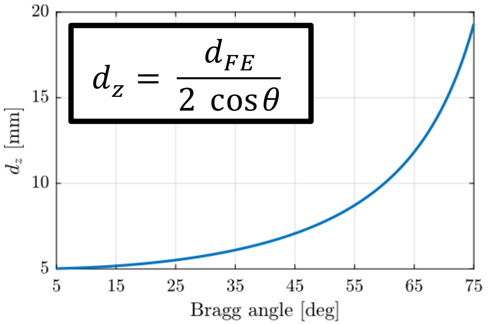


Bragg Diffraction



$$E = \frac{hc}{2d(T)\sin\theta}$$

Fix Exit



$$d_z = \frac{d_{FE}}{2\cos\theta}$$

Effect of Crystal Positioning Errors on the beam

Beam | Crystal

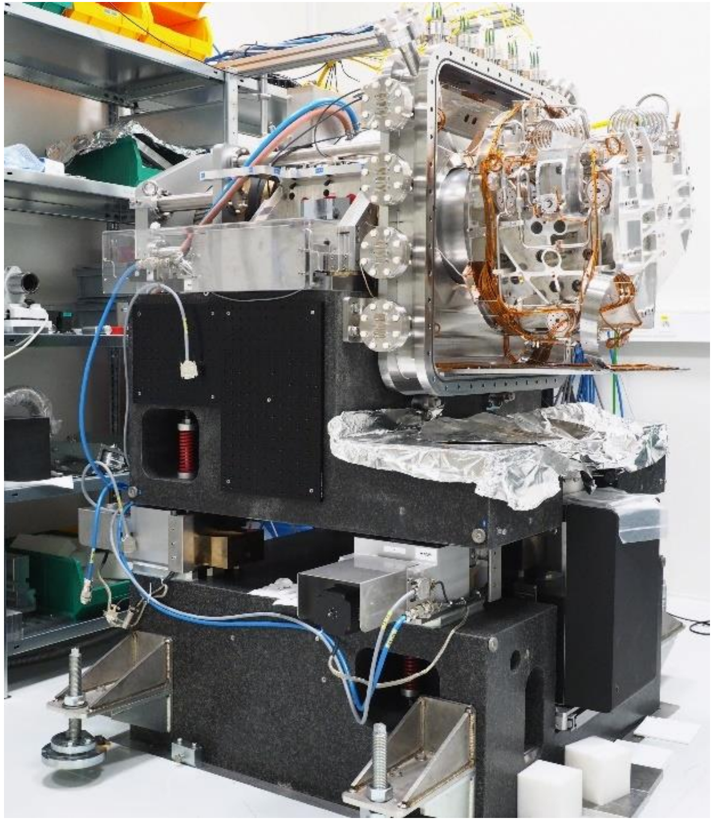
$$\epsilon_z = 2\,\epsilon_{d_z}\cos\theta$$

$$\epsilon_{R_z} = -2\,\epsilon_{r_x}\sin\theta$$

$$\epsilon_{R_y} = -2\,\epsilon_{r_y}$$

Courtesy of T. Dehaeze

OUTLINE



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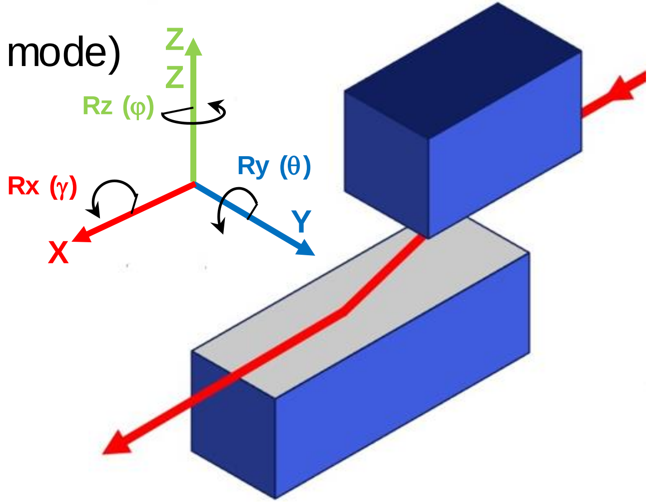
Development of a new DCM for spectroscopy by the ESRF capable of :

- **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



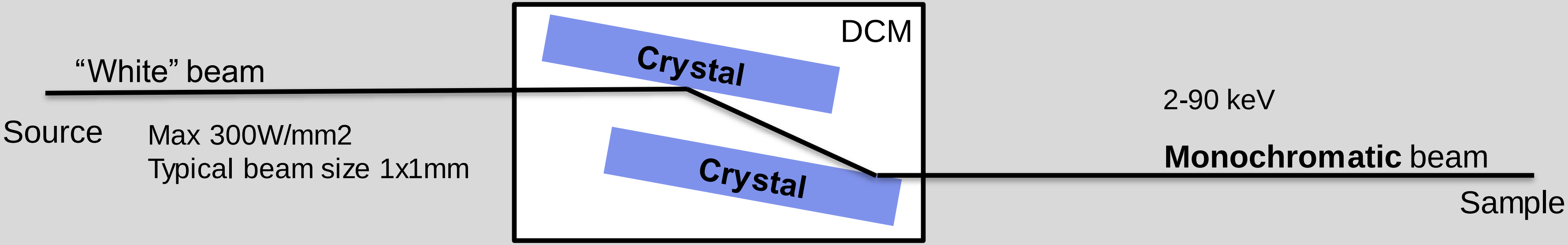
Extended X-Ray Absorption Fine Structure

15 nrad ≈ a hair at 5 km

$75x10^{-6}$

$5x10^{3}$

Double Crystal Monochromator, main characteristics



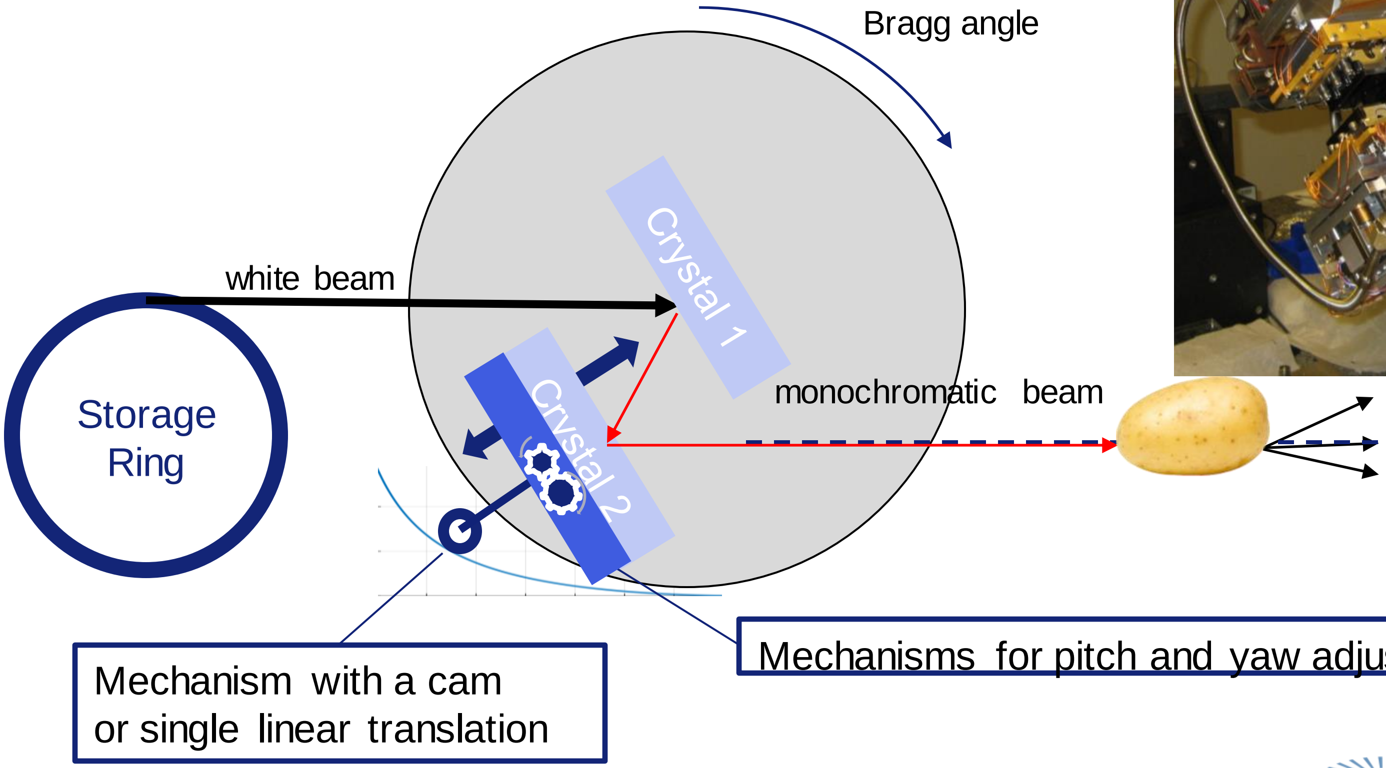
Main Requirements:

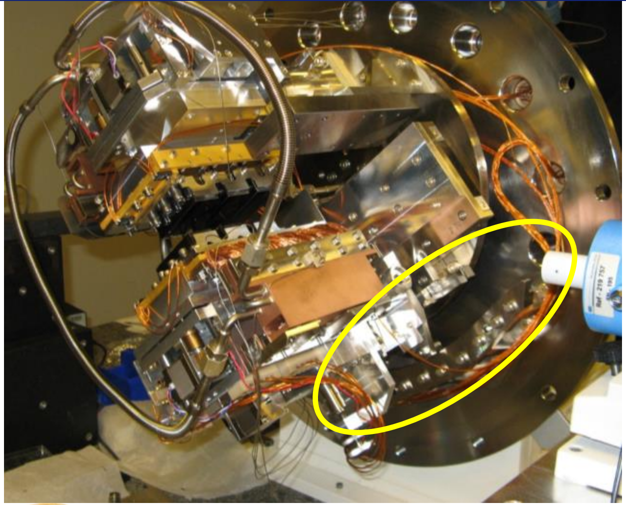
Energy Stability (Over Time)	**Beam Stability** (During Scans)	**Fast Scanning** (e.g. 1x EXAFS/s)

Main Challenges :

Very low deformation of crystals	**Very high thermal stability**	**Very high positioning precision**

DCM EXISTING CONCEPT : FIXED-EXIT WITH MECHANICAL SYSTEM





Kohzu Monochromator at ESRF

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

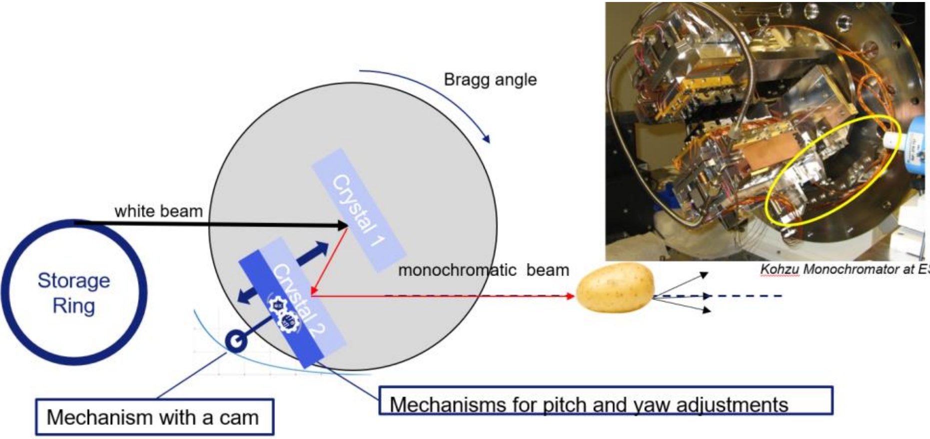
Mechatronic approach

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

…

Performance vs Robustness

DCM EXISTING CONCEPT : FIXED-EXIT WITH MECHANICAL SYSTEM



Kohzu Monochromator at ESRF

Concept not adapted to new requirements

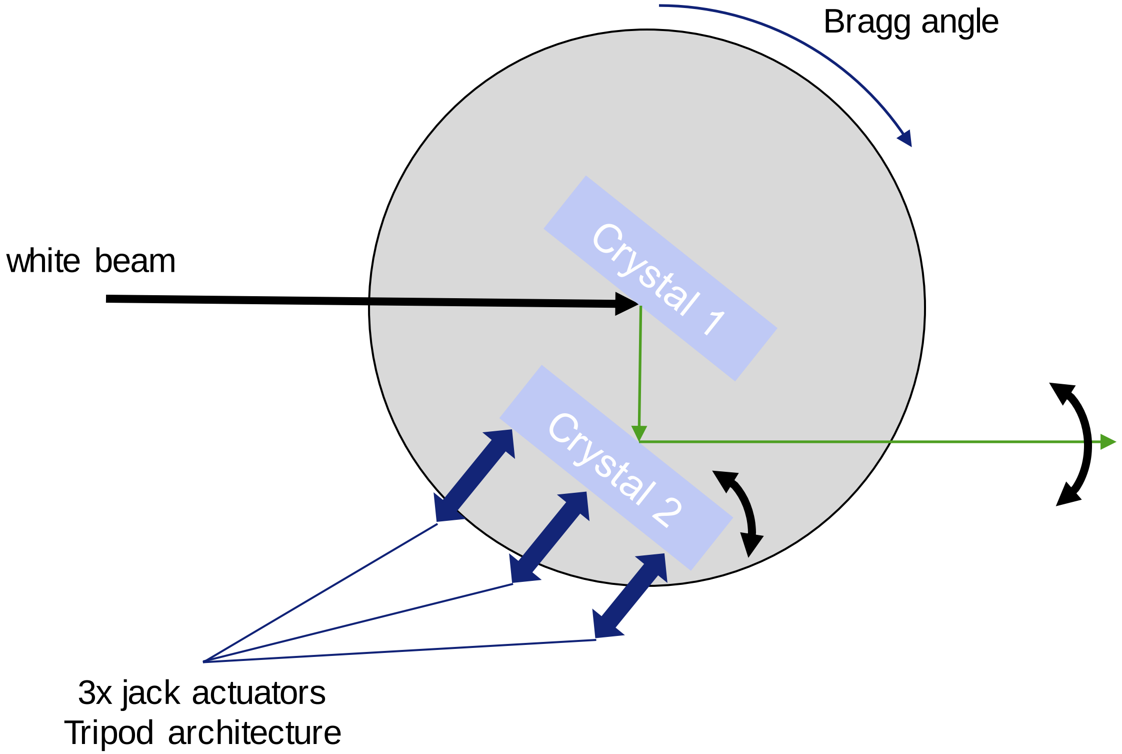
Very high thermal stability ?

- Long natural stabilisation time required
- No internal metrology to monitor drifts of crystals parallelism
- External metrology possible with beam position monitoring (intensity 4Q)

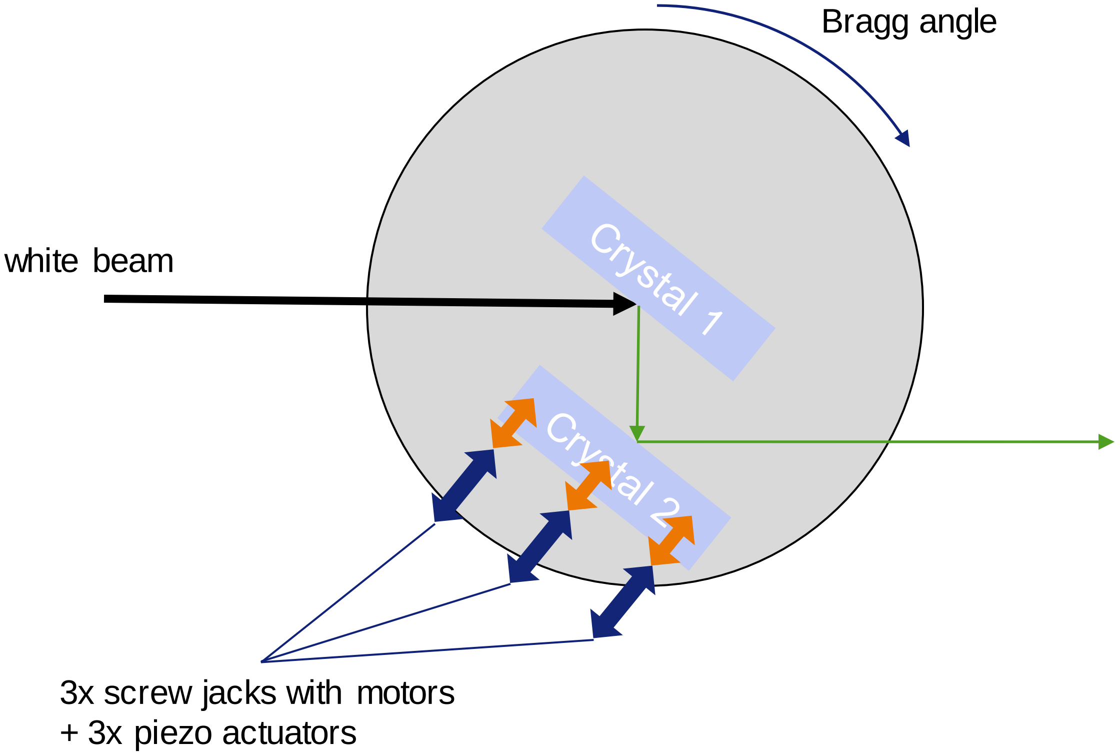
Very high positioning precision ?

- Positioning errors are **not sufficiently repeatable**
- **No internal metrology** to monitor drifts of crystals parallelism
- Continuous scans are difficult to operate for **energy and beam stability**, and the velocity of actuators is not compatible with **fast scanning**

The ESRF-DCM prototype



The ESRF-DCM prototype



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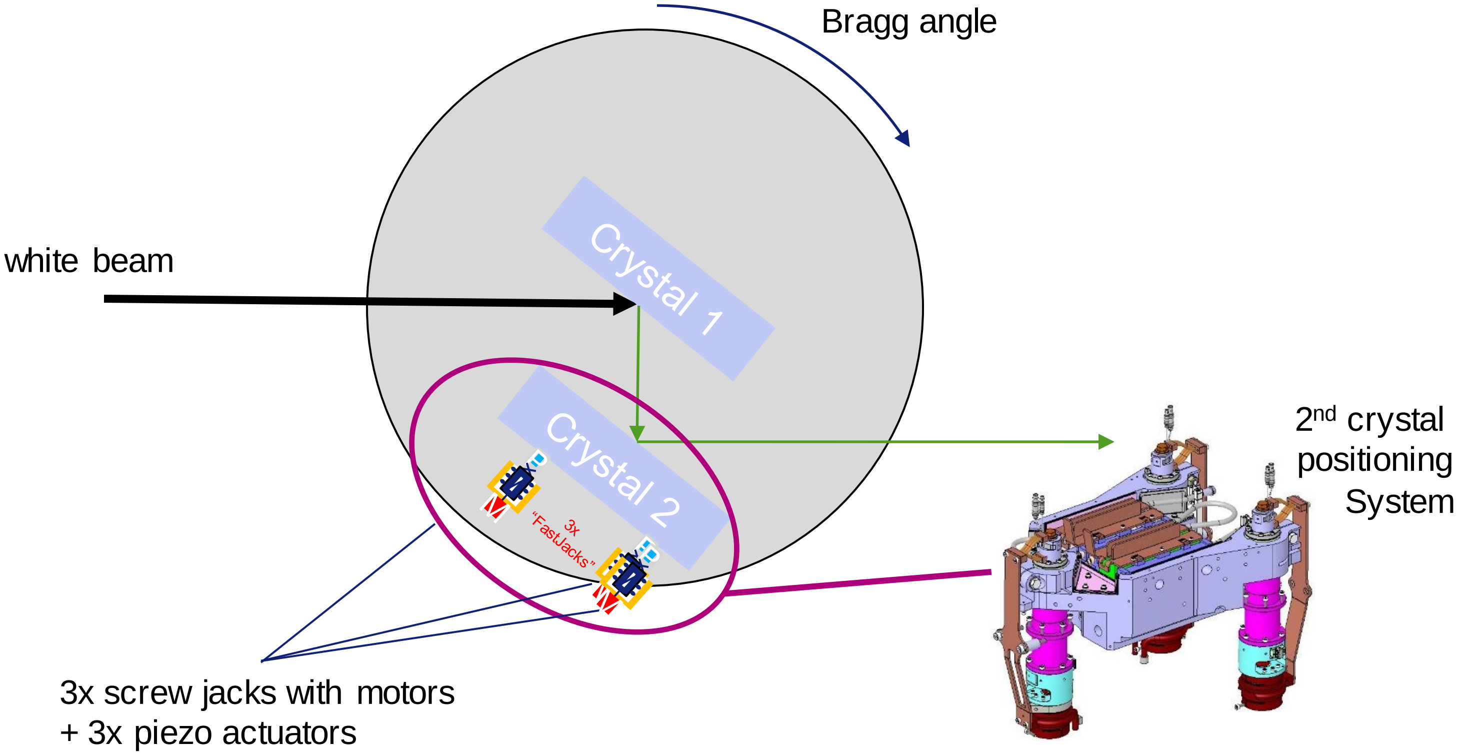
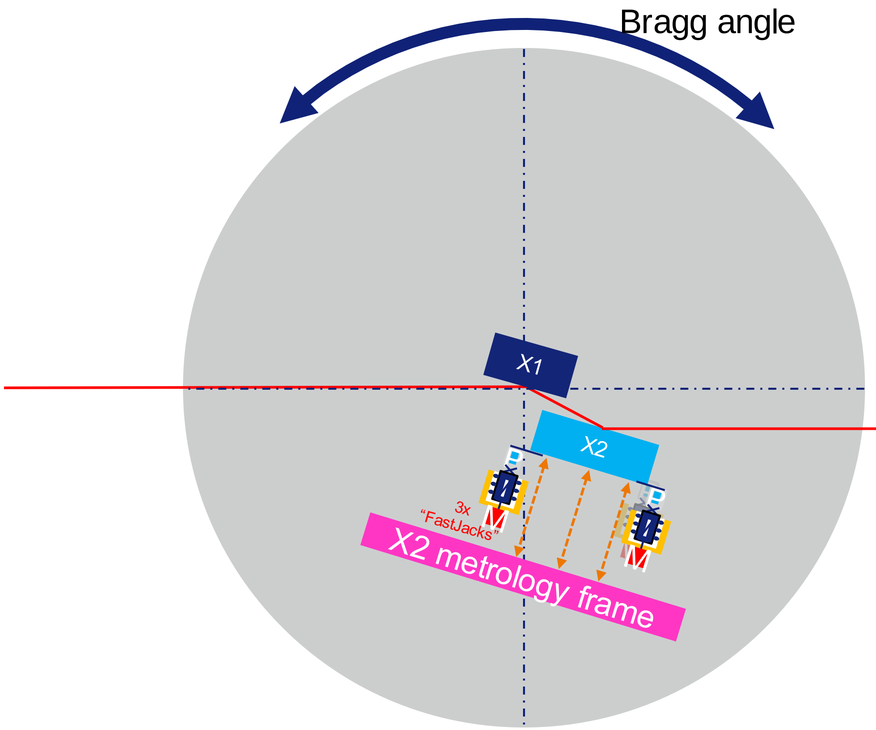
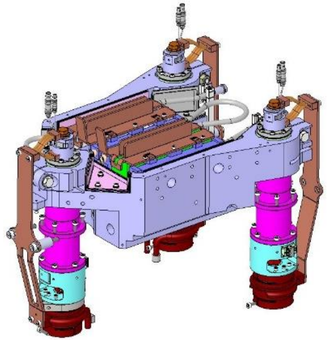


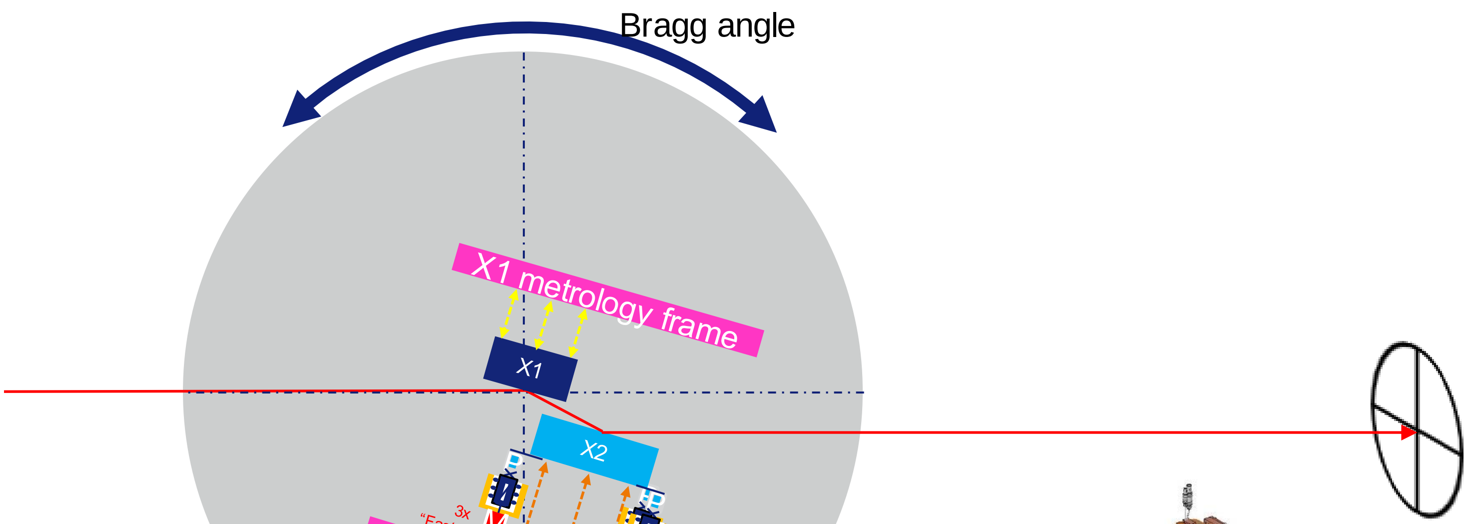
FIXED-EXIT WITH MECHATRONIC SYSTEM – ONLINE METROLOGY

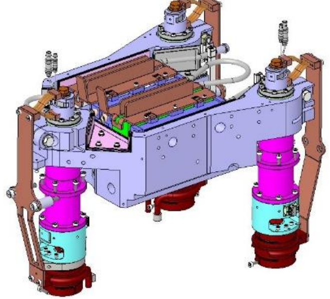




2nd crystal positioning System

FIXED-EXIT WITH MECHATRONIC SYSTEM – ONLINE METROLOGY





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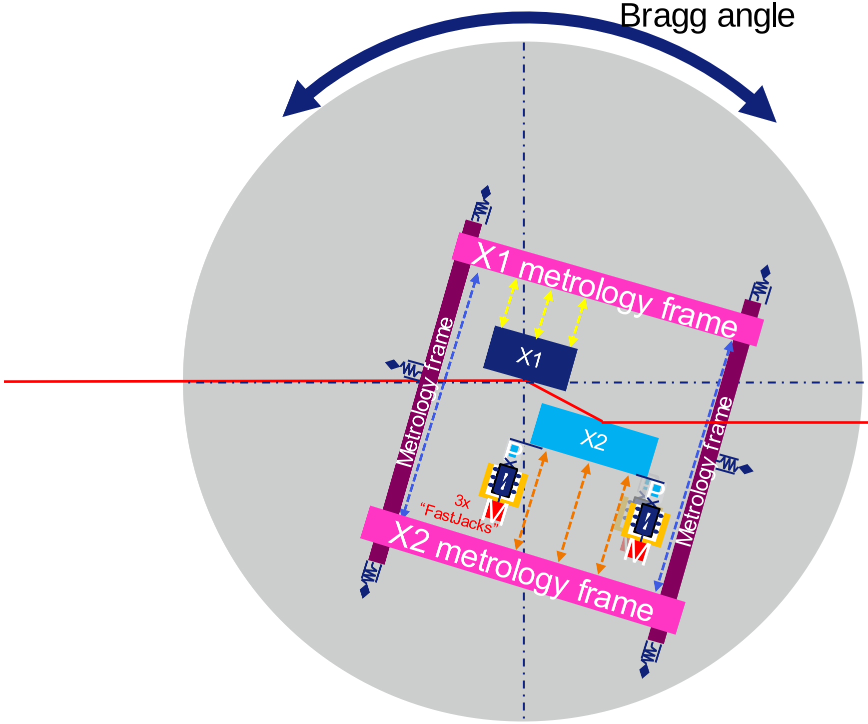
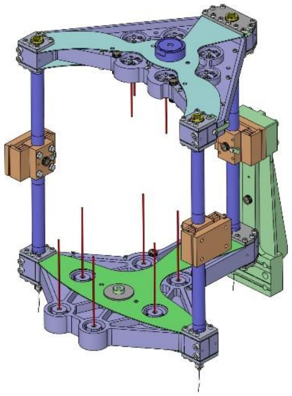
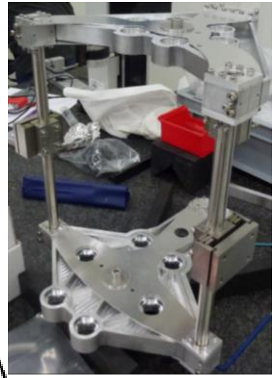
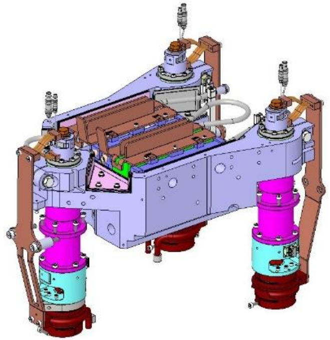


metrology frame







2nd crystal positioning System

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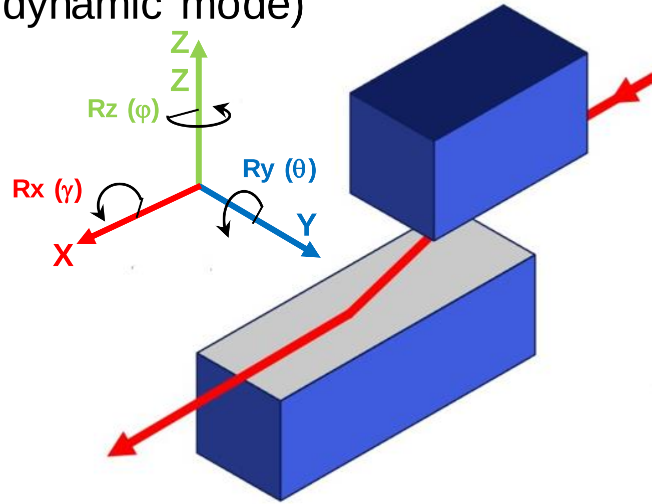
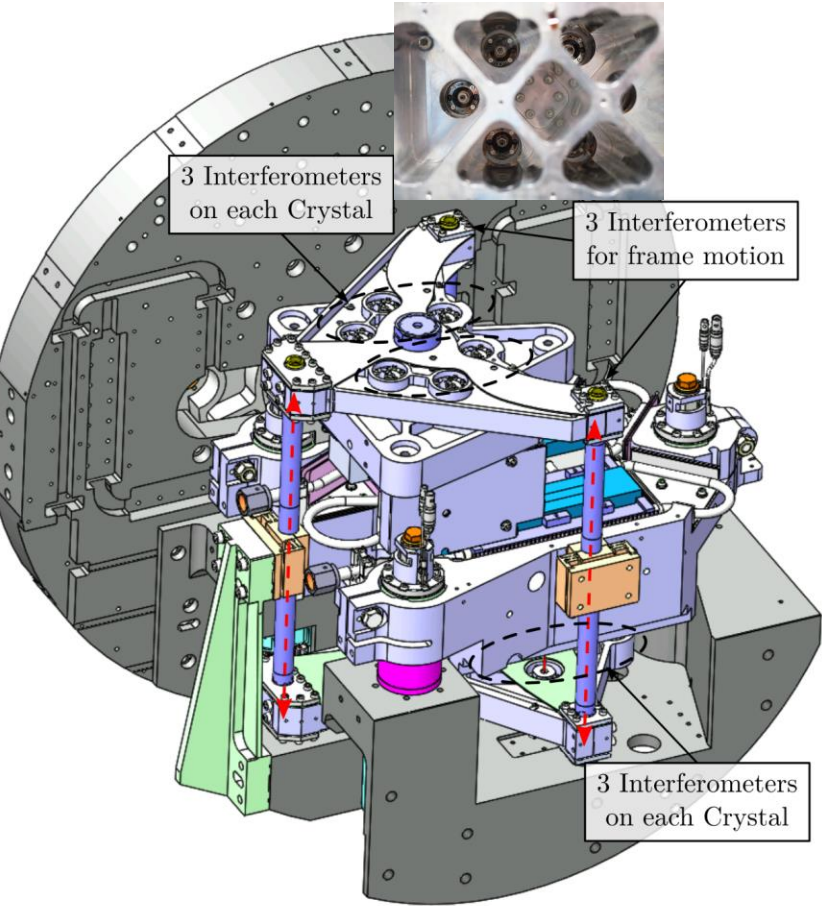


Now possible with the new concept
But requires a full study of all sources of error and solutions for compensation

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

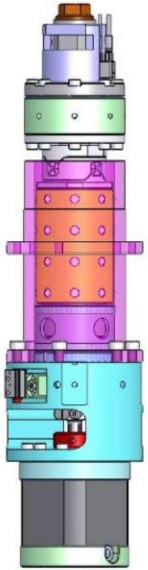
Tripod Architecture

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



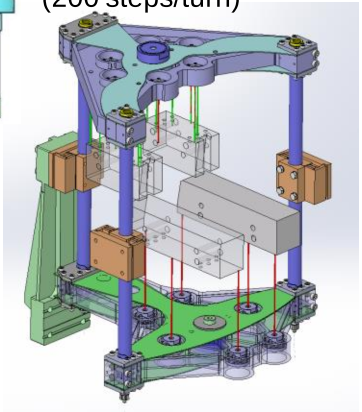
Piezoelectric Stack (15µm stroke)

Flexible Joint

Satellite roller screw (1mm pitch)

Ball bearing guide

Stepper Motor (200 steps/turn)

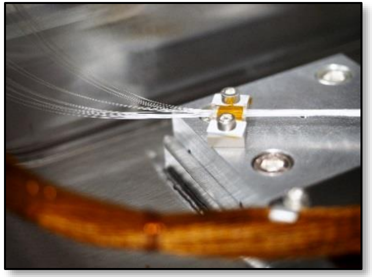


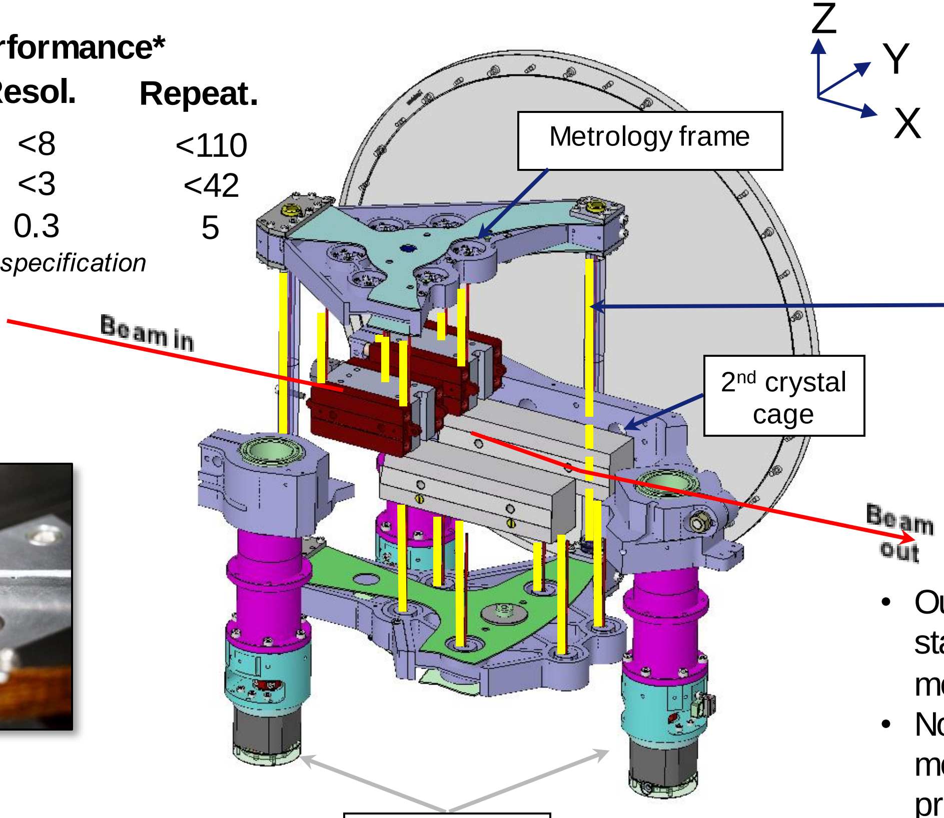
CRYSTAL POSITIONING - ONLINE METROLOGY

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' specification*



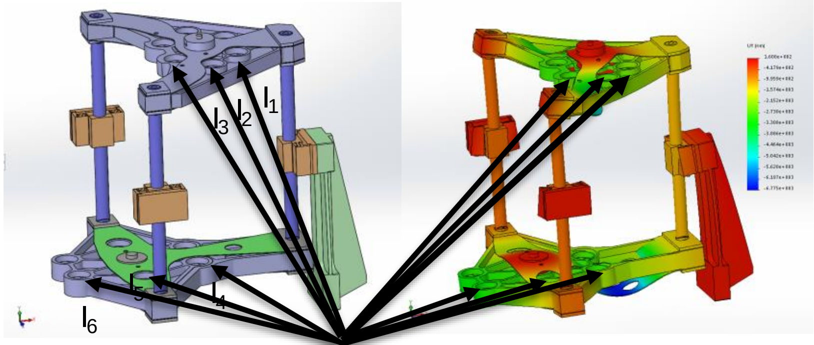


15 optics fiber with *Fabry-Pérot* interferometer heads (no in-vacuum electronics)

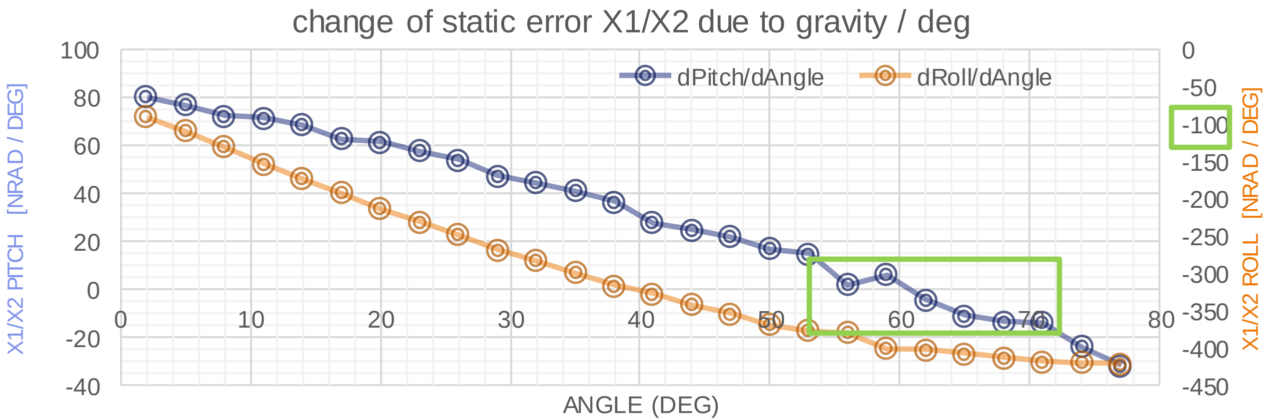
radiation resistance = 10MGy

- 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)

ANALYSIS METROLOGY FRAME– GRAVITY EFFECT WITH BRAGG AXIS ORIENTATION



Interferometer heads for measurement of X1 and X2 displacements



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

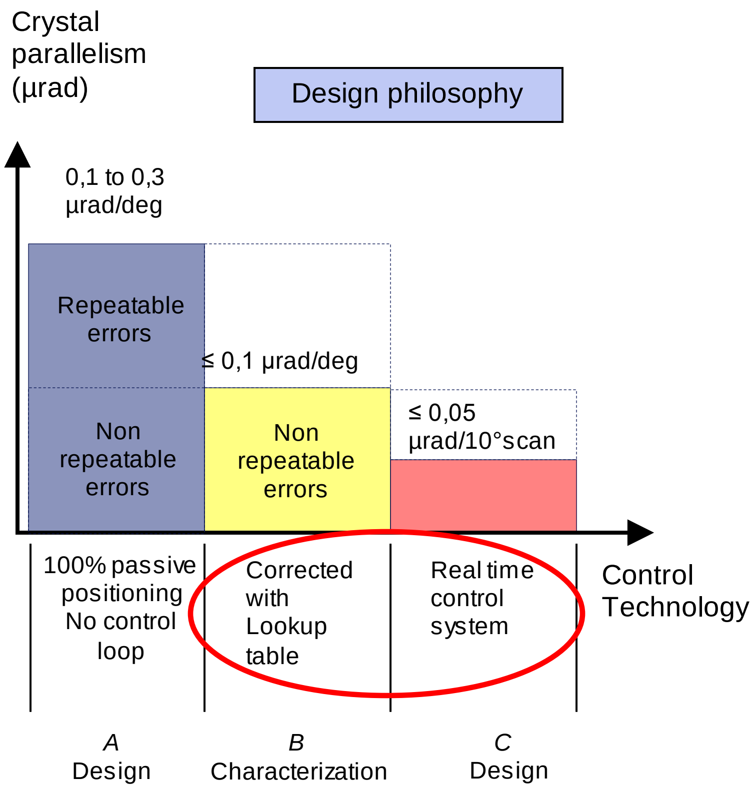
<14 | <100

Out of specification on most of Bragg range

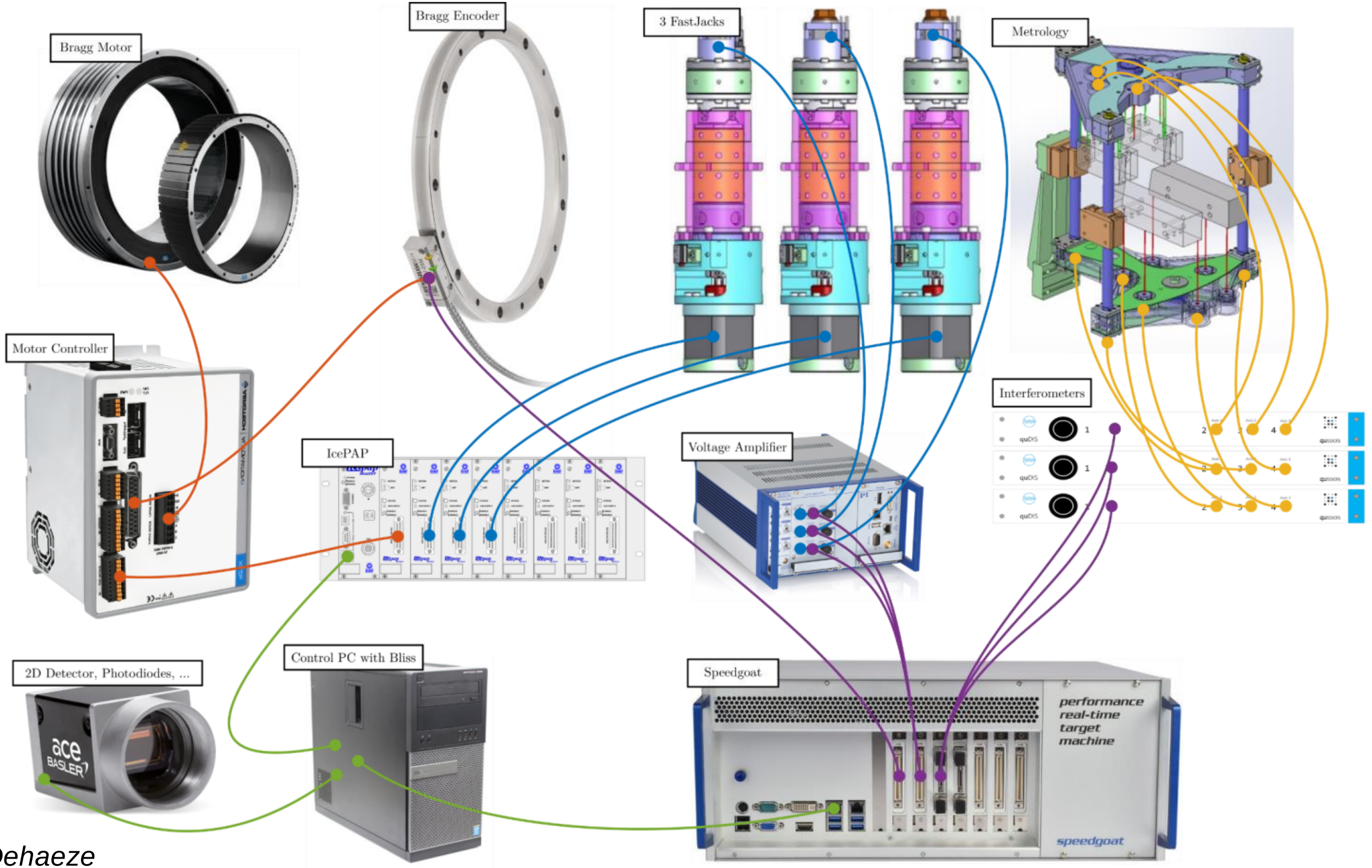
Repeatable and f(Bragg)

Can be calibrated and compensated on RT control system

SUMMARY OF DESIGN PHILOSOPHY

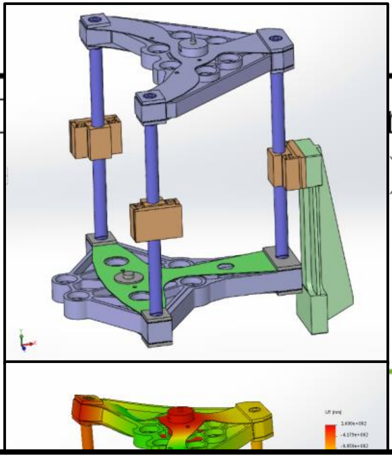


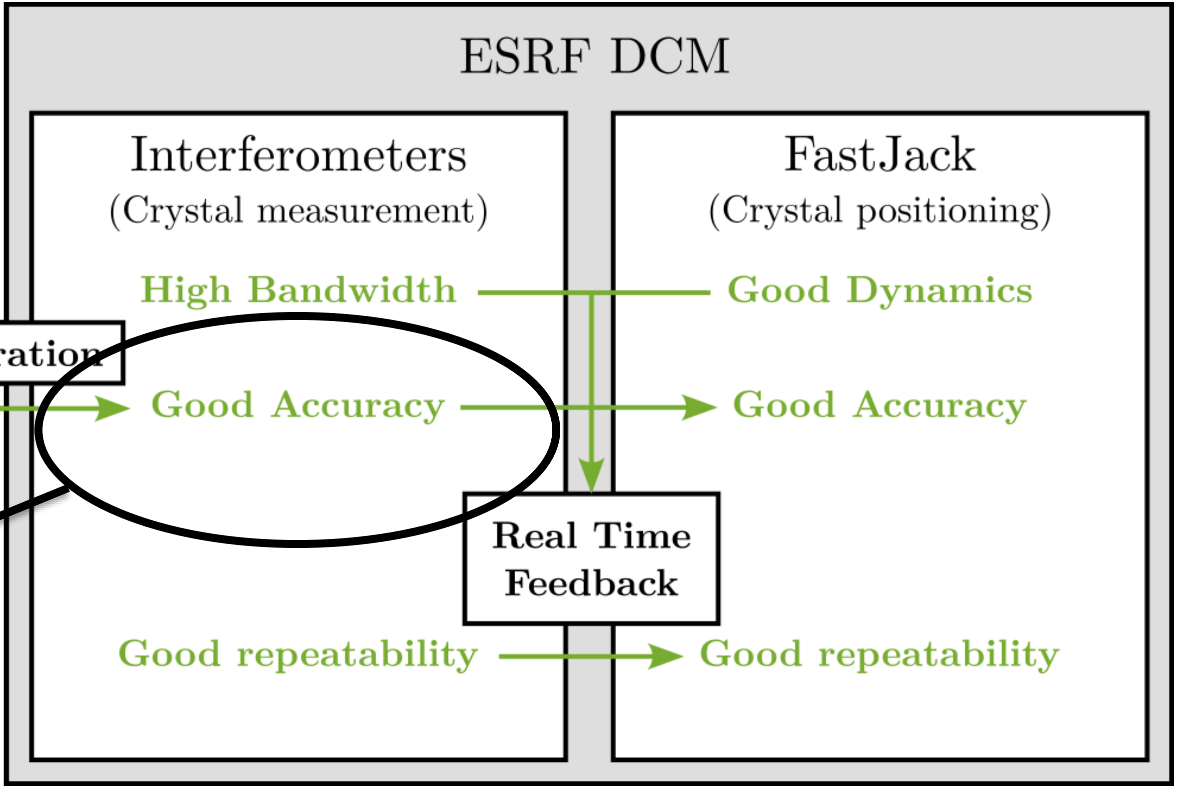
A COMPLEX CONTROL ARCHITECTURE



Courtesy of T. Dehaeze

HOW TO GET AN ACCURATE DCM? CALIBRATION !



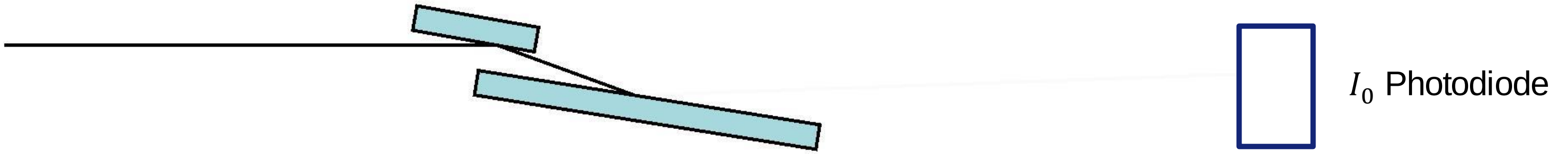


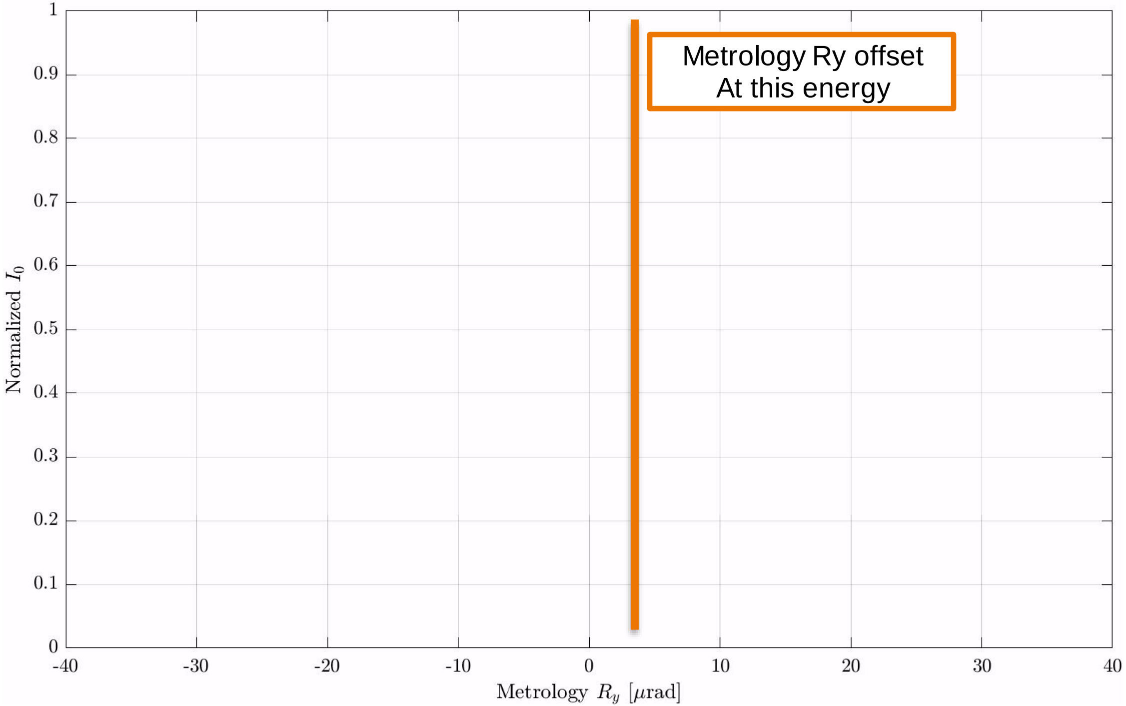
Calibration Procedure:

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 of T. Dehaeze

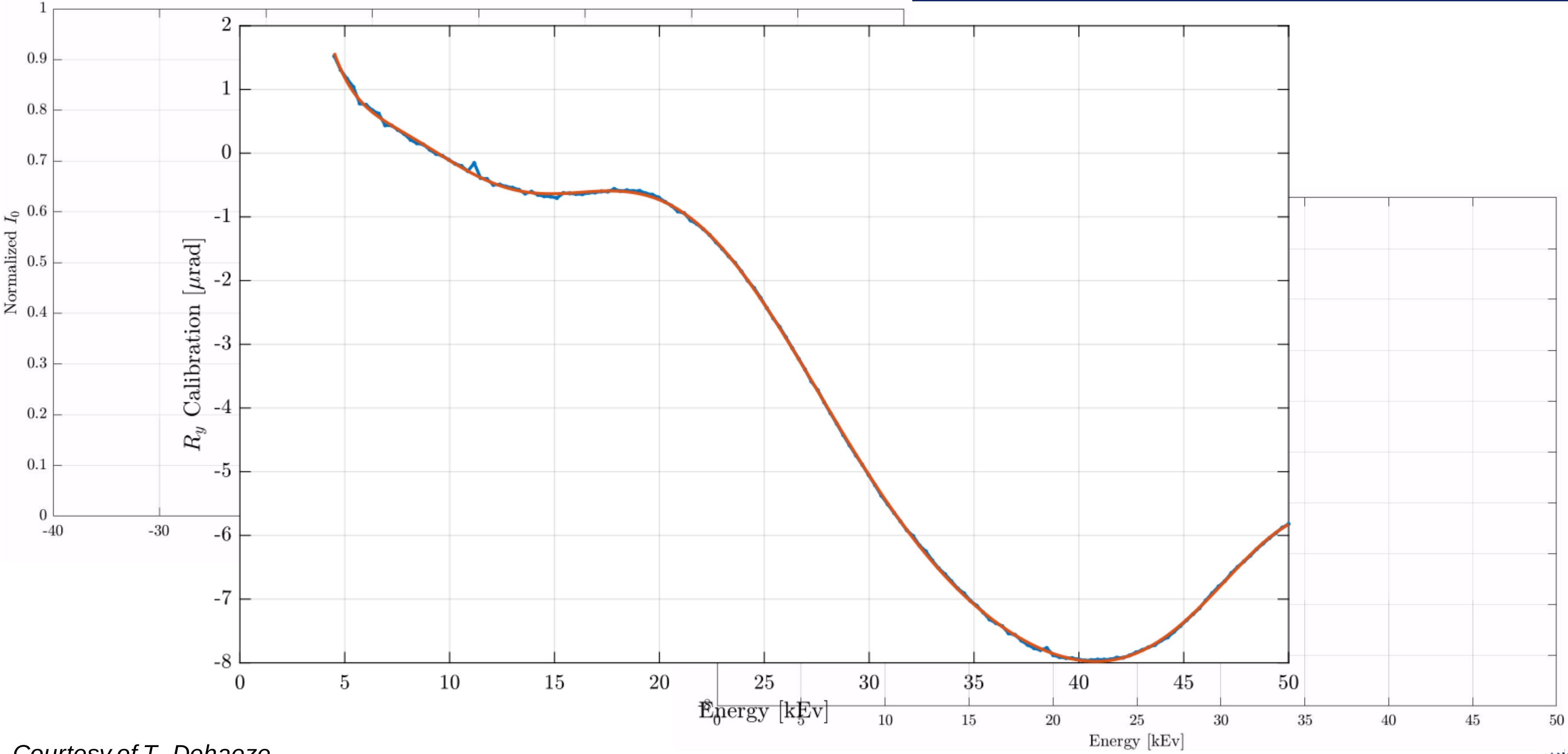
1 - RY CALIBRATION: FINDING THE TOP OF THE ROCKING CURVE…





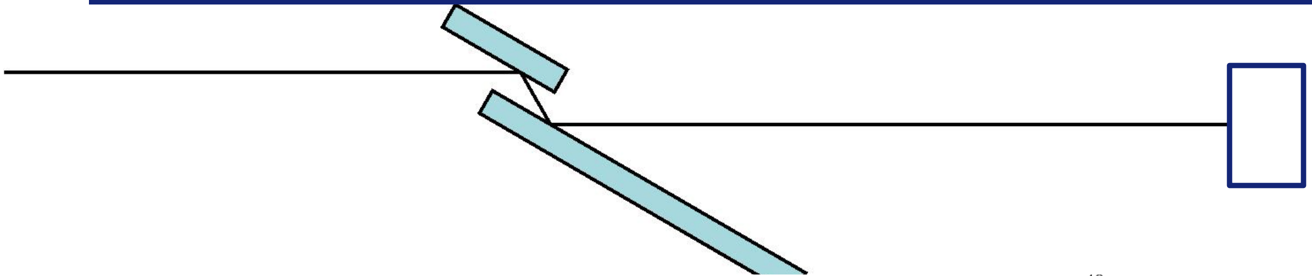
Courtesy of T. Dehaeze

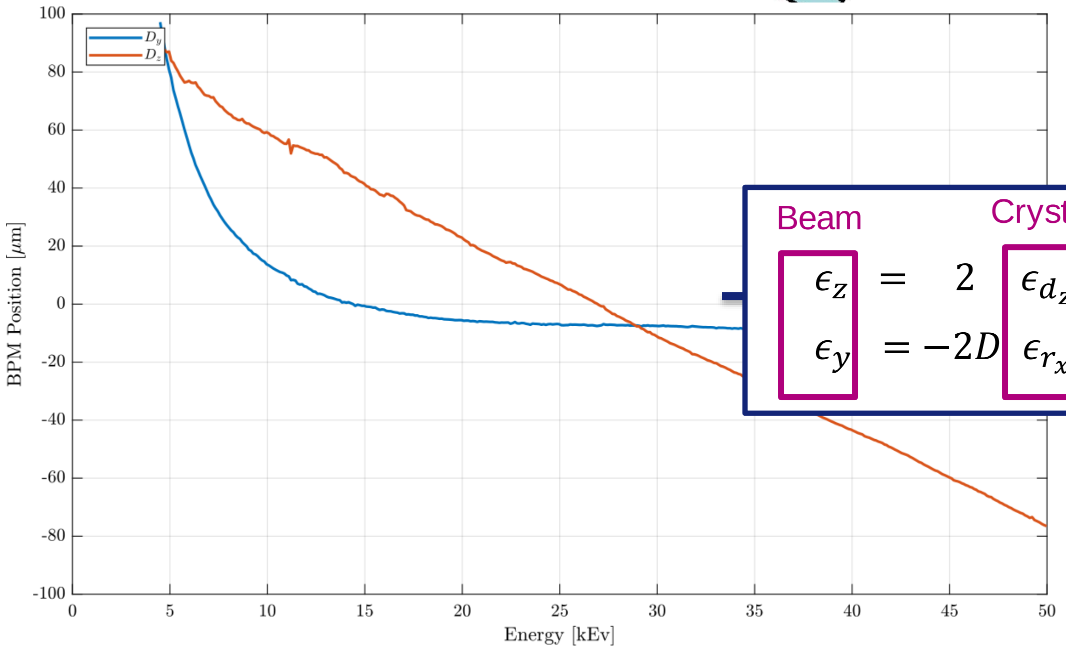
1 - RY CALIBRATION: … AT SEVERAL ENERGIES



Courtesy of T. Dehaeze

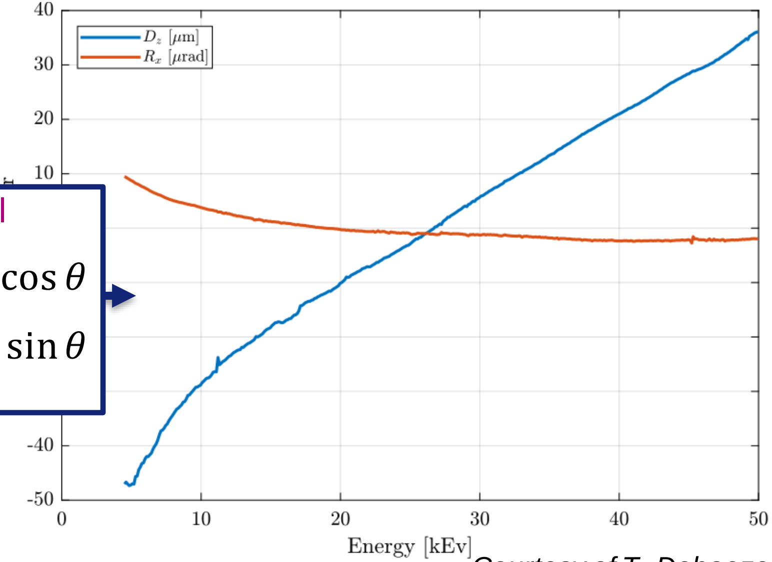
2 - D_z AND R_x CALIBRATION: UNFOCUSED SCAN





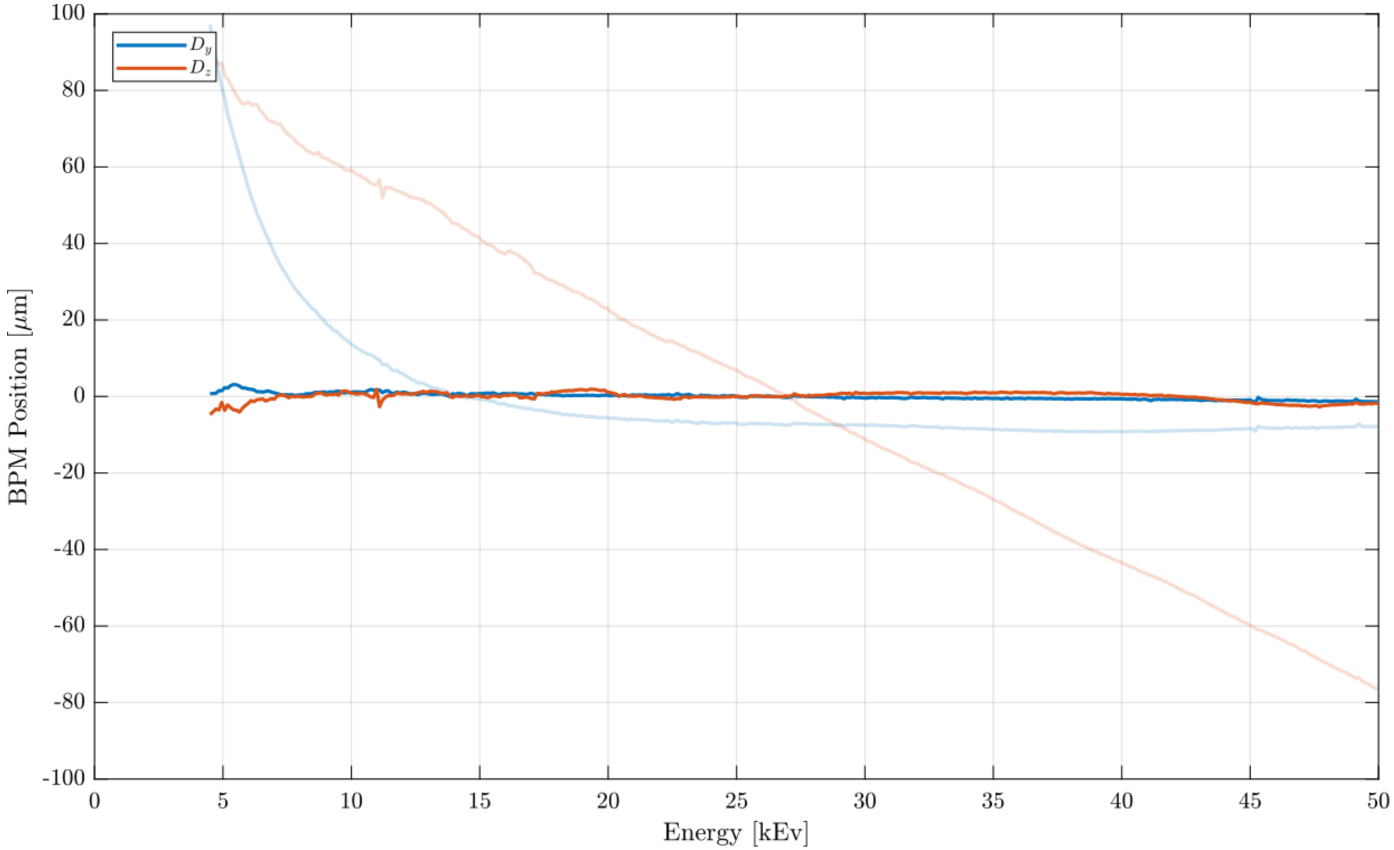
Beam Crystal

$$\epsilon_z = 2\,\epsilon_{d_z}\cos\theta$$
$$\epsilon_y = -2D\,\epsilon_{r_x}\sin\theta$$



Courtesy of T. Dehaeze

2 - D_z AND R_x CALIBRATION: VERIFICATION SCAN

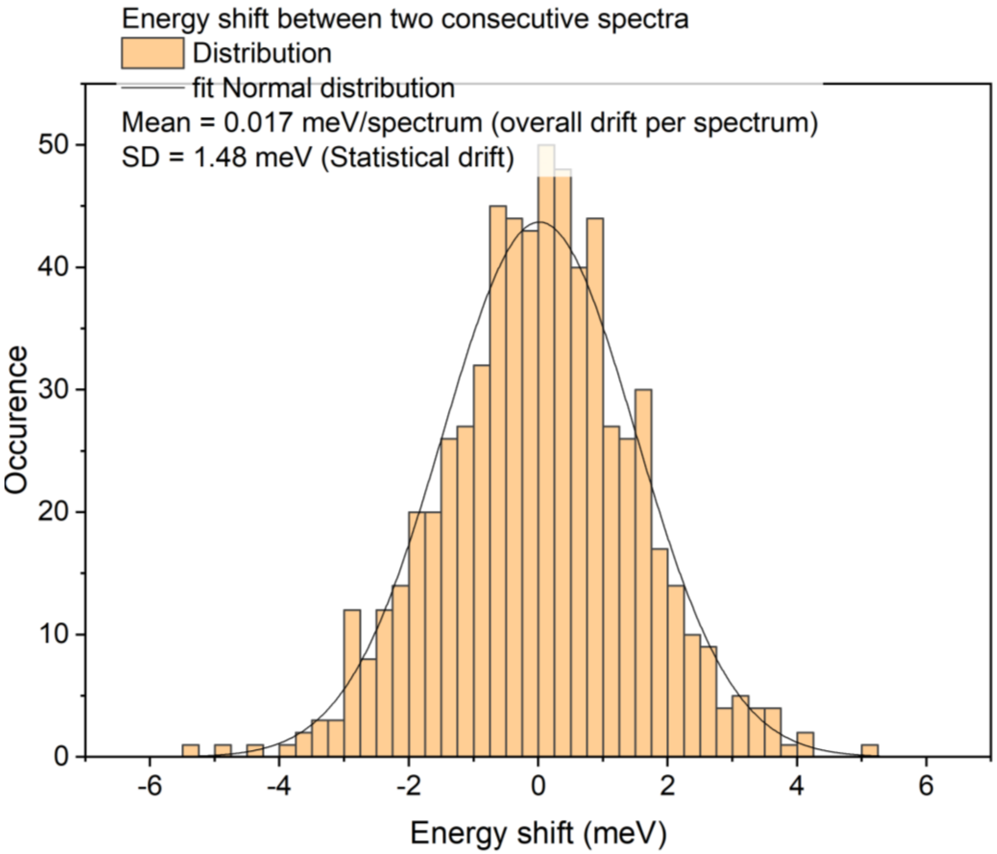


Courtesy of T. Dehaeze

DCM : ENERGY STABILITY

Co K edge for 48H00 : one spectrum (continuous scan, 800 eV, 1600 pts, 100 ms/pt) every 5 mn

Between two consecutive spectra



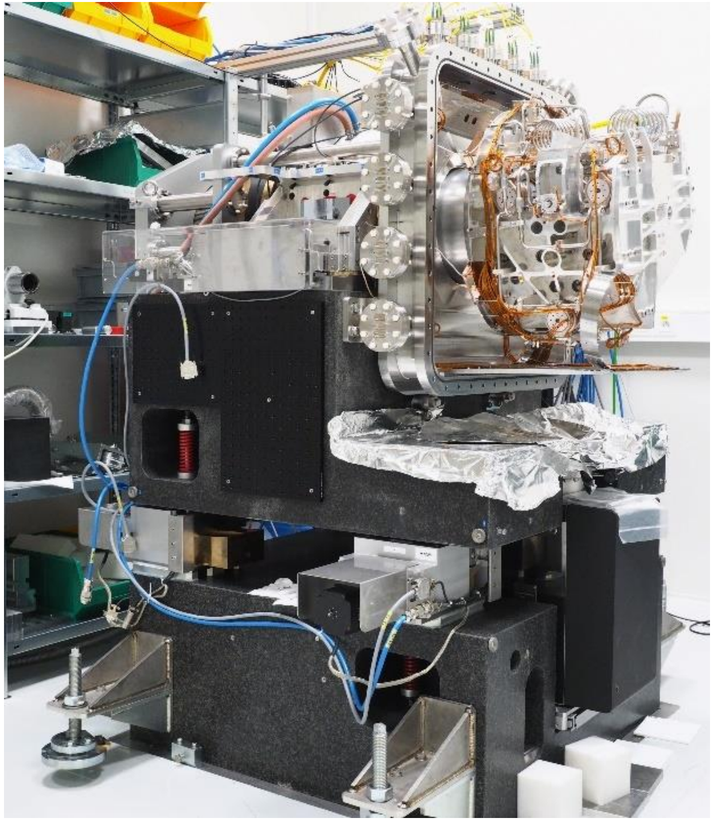
Average drift = 0.017 meV/spectrum

ΔE = 1.48 meV rms

$\Delta \theta$ = 51 nrad rms

Courtesy of O. Mathon

OUTLINE



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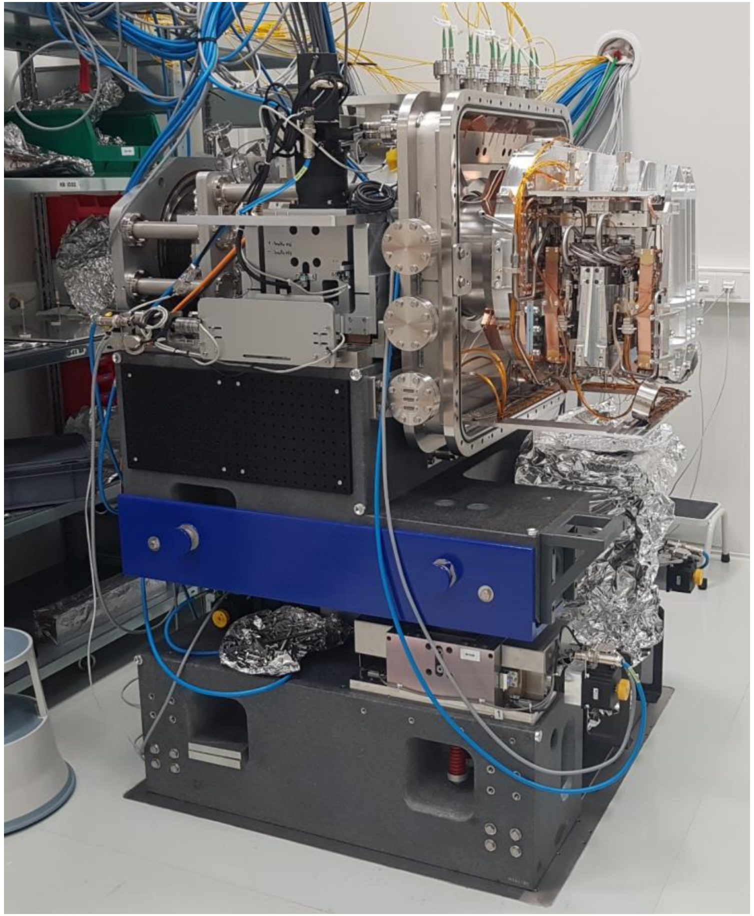

Many advances in XAS can be obtained by investing in instrumentation

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- Unprecedented energy stability
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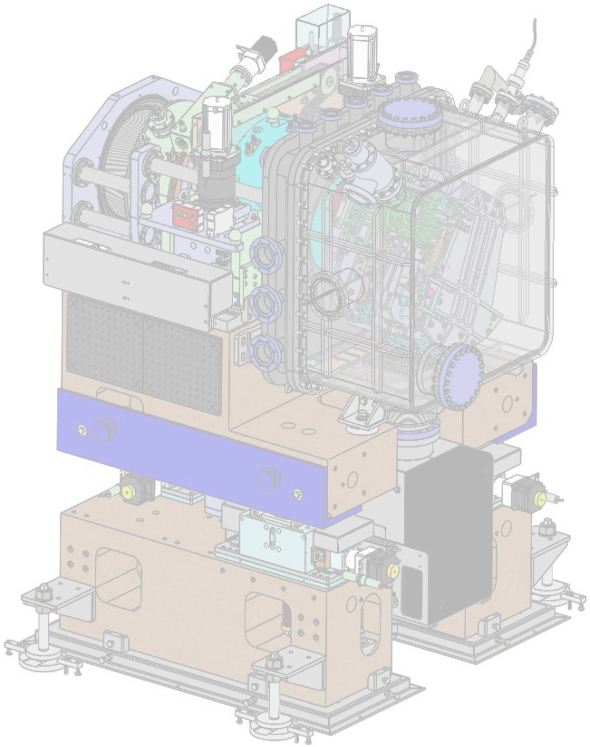
- Unprecedented position stability (fixed exit in dynamic mode)
  $\Delta R_y \rightarrow$ 100 nrad FWHM over 1 deg
  $\Delta R_x \rightarrow$ 150 nrad FWHM over 1 deg

- 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 μrad FWHM (over 7 deg): difficult to measure

Future improvements ?

Faster scans keeping stability performance



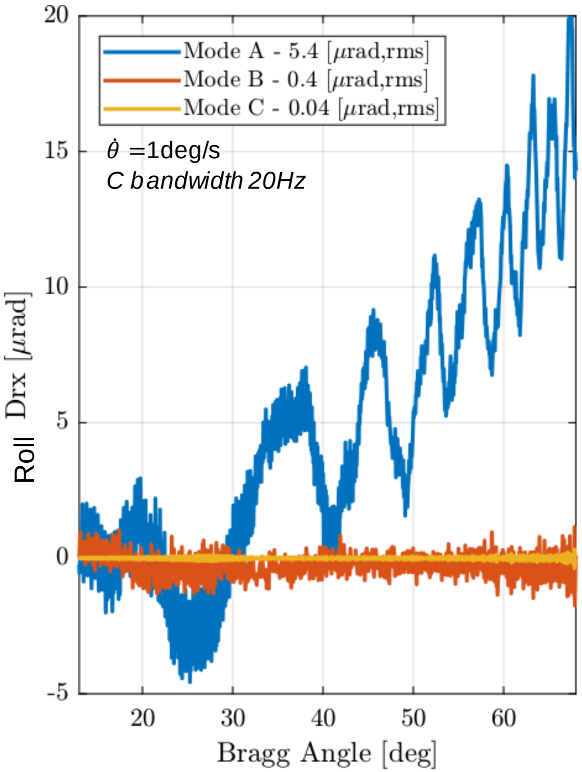
END OF PRESENTATION

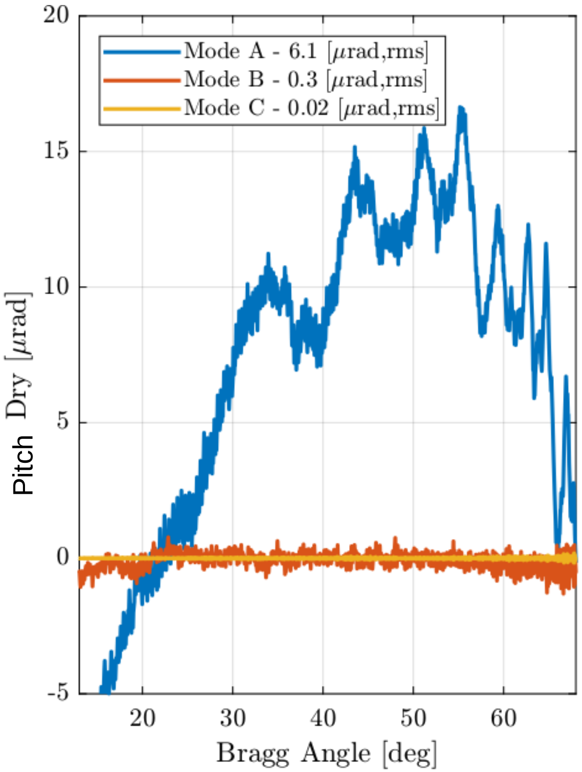
THANK FOR YOUR ATTENTION

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,…

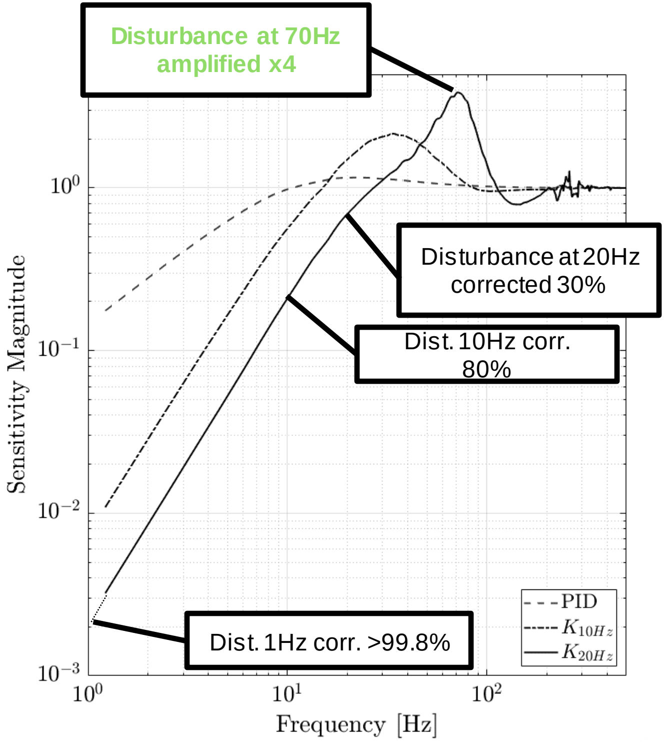
RT CONTROL LOOP : ACTIVE CORRECTION PERFORMANCE





Sensitivity function

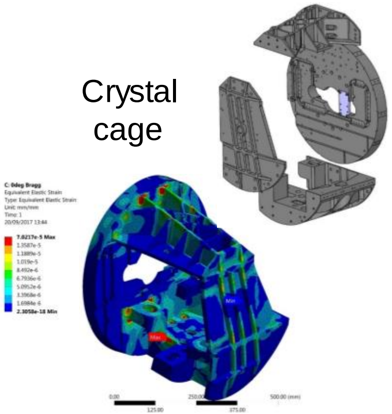
$$|S(j\omega)| = \left| \frac{1}{1 + K(j\omega)\, G(j\omega)} \right| \qquad K: controller\ ;\ G: Plant$$

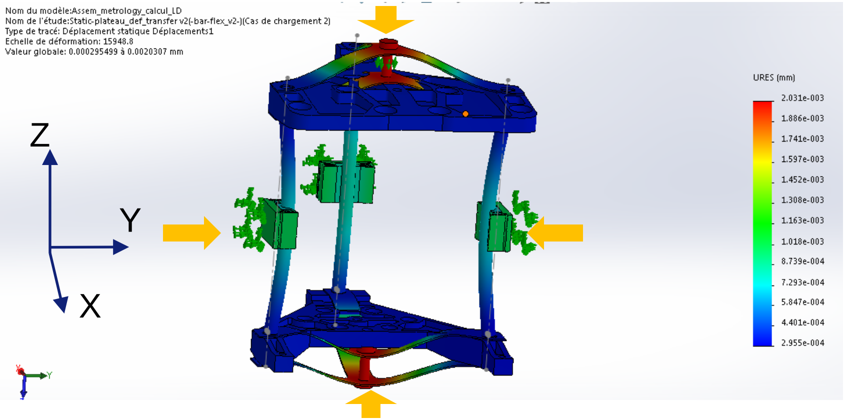


Deformation induced by thermal expansion of the crystal cage (Al alloy)

	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]	

Crystal cage

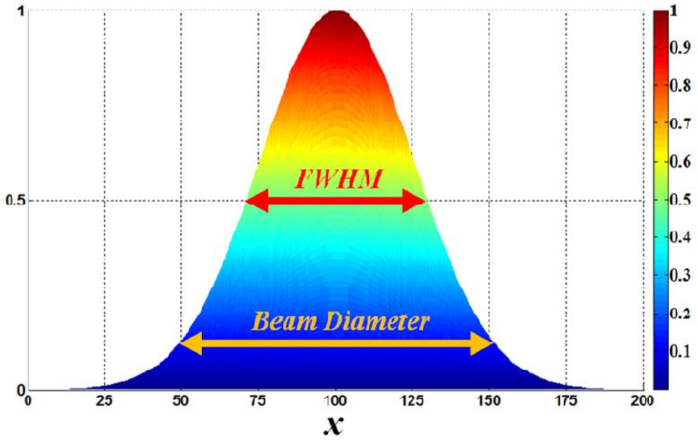


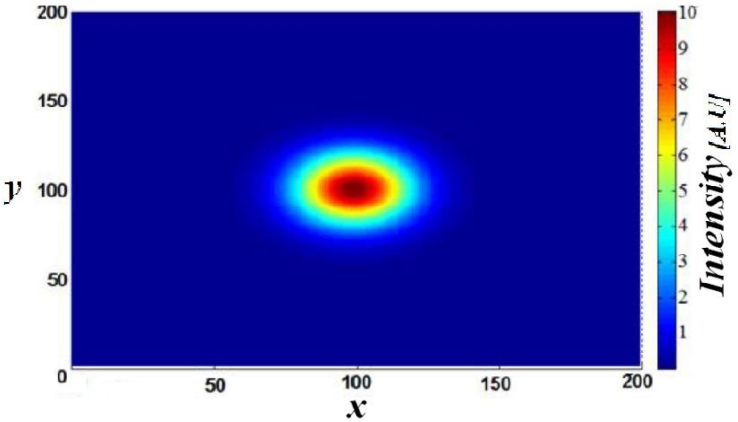


Thermal drift of xtal cage should not induce a metrology frame deformation above the specifications for a short scan range (1 deg), i.e a short term drift.

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.

FWHM


FWHM
Beam Diameter
x
0
25
50
75
100
125
150
175
200
1
0.5
0
0.9
0.8
0.7
0.6
0.4
0.3
0.2
0.1


y
x
200
150
100
50
0
Intensity [A.U]
10
9
8
7
6
5
4
3
2
1