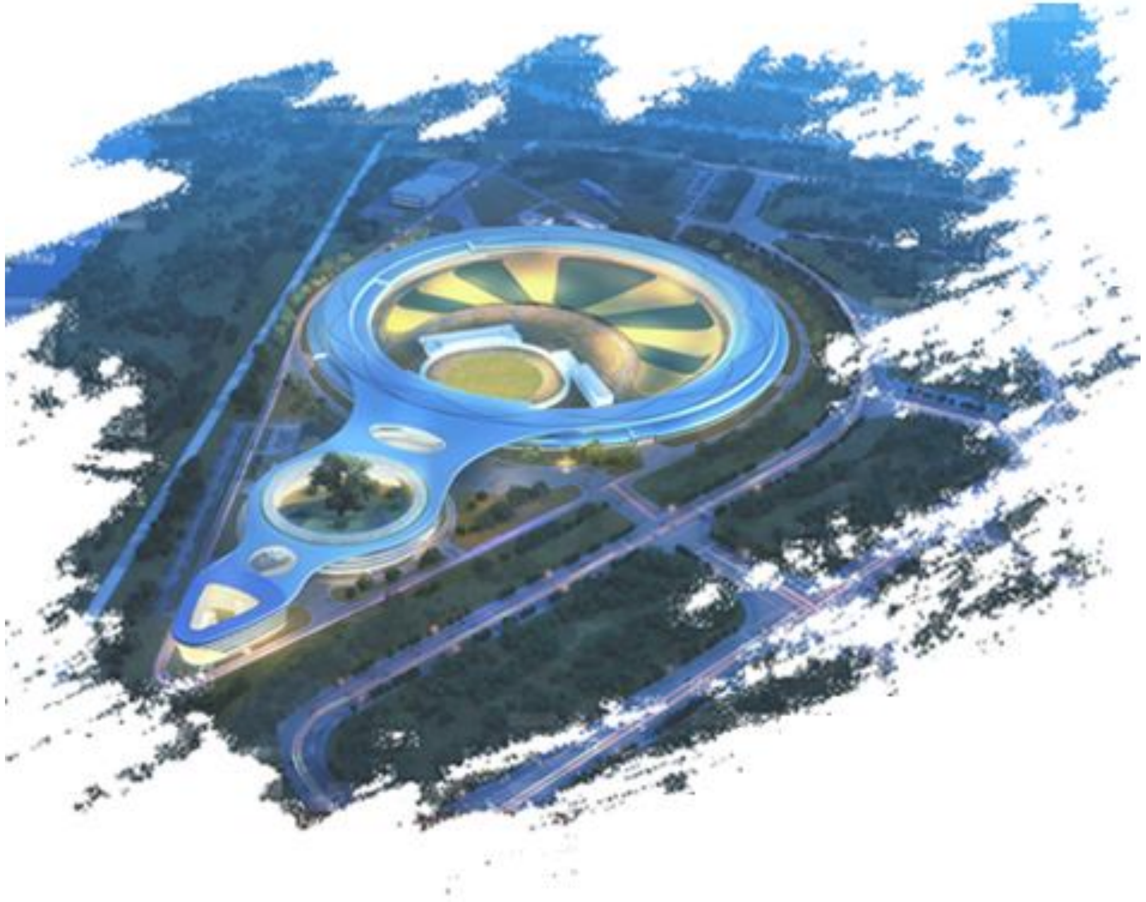
MEDSI 2023 Beijing Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation

Progress and Core Technologies Development of Monochromators for HEPS



Hao Liang

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On behalf of the colleagues of HEPS beamline division

Fine Mechanics system of HEPS

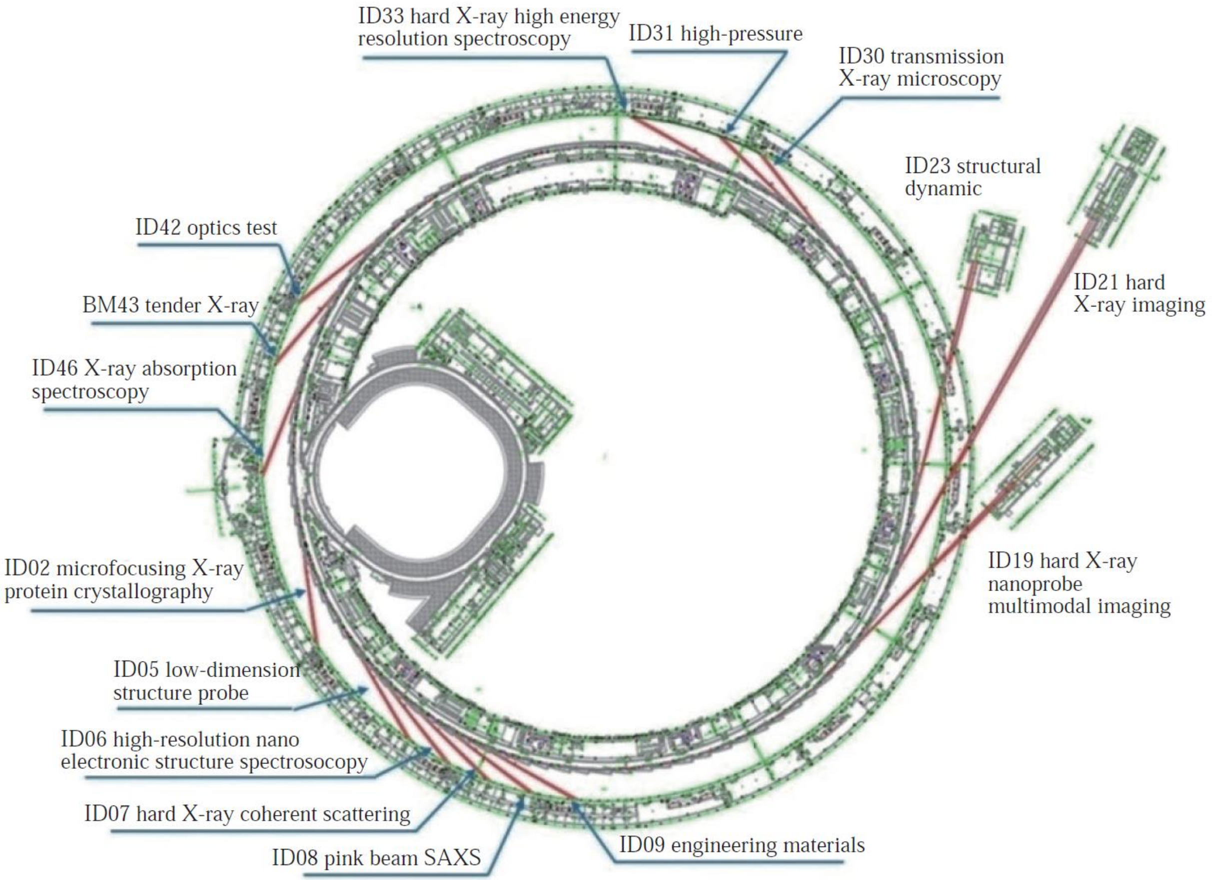
2023.11.09

HEPS

Outline

I. Introduction

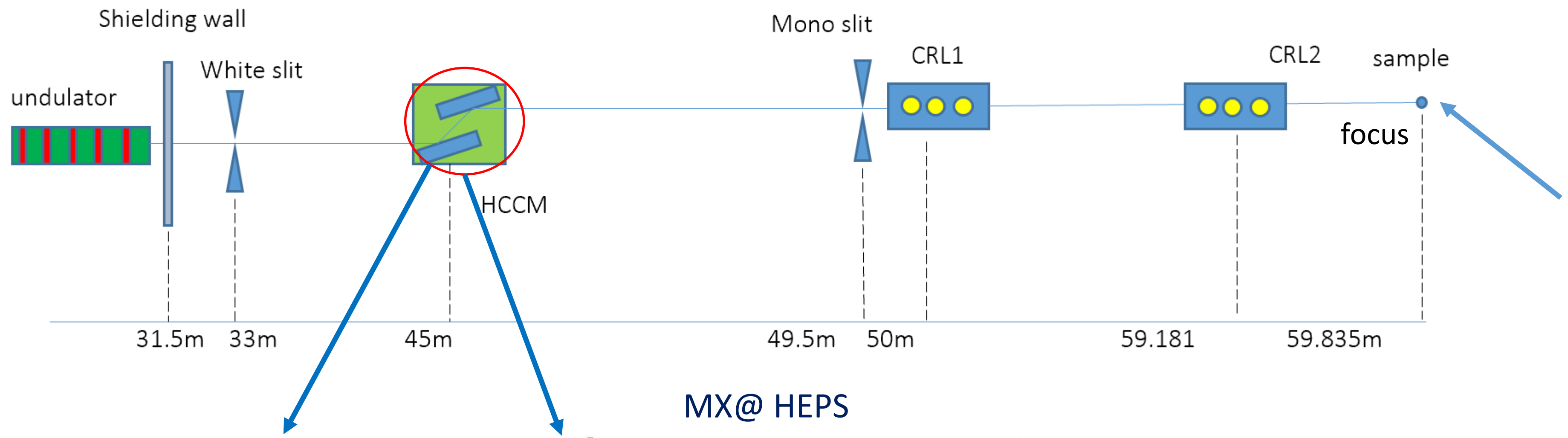
- **Surge of 4th generation light sources in China**
  - HEPS, 6GeV, emittance below 60 pm·rad, Lowest source size ~2μm
  - HALF, Wuhan light source, SSRF upgrade, Shenzhen light source
  - Need to push beamline technologies advance in China
- **Monochromators often limiting performance of beamlines**
  - Especially in stability and slope errors
  - Compared to mirrors, usually worse working conditions and larger slope errors
  - Mono Suppliers from Japan, Germany, UK, Italy
  - No LN2 mono suppliers in China until recently



Beamlines layout of HEPS phase I
curtesy of Xiaodong Li

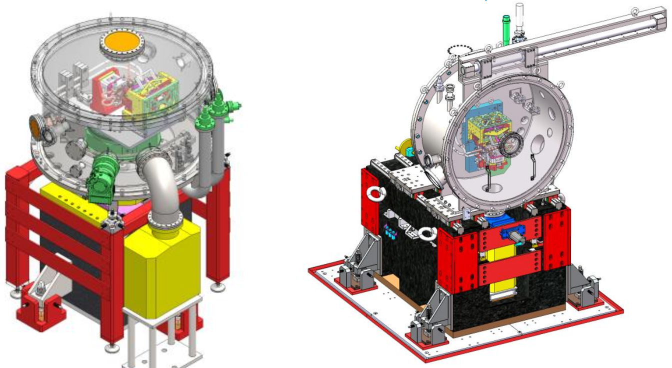
I. Introduction

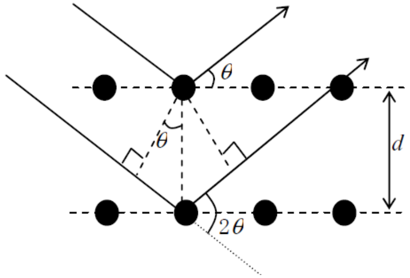
Source



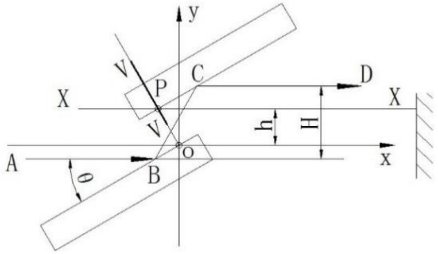
HEPS nanoprobe:
<10nm@10keV

MX@ HEPS





$2d\sin\theta = n\lambda$



Fixed exit, H=2h

Beamline technology has been limiting the performance of a light source

Monochromator, as a core optical component in the beamline, selects energy and conducting energy scans.

High brightness and low emittance:

Requires high stability, low surface slope error.

I. Overview of HEPS monochromators

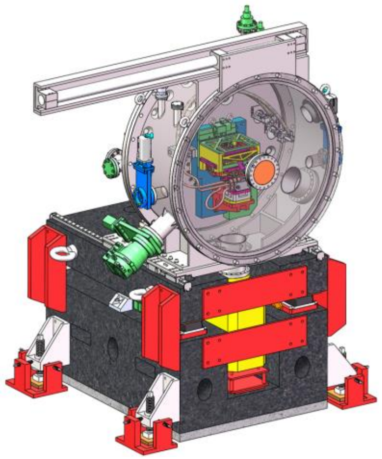
- 8 types, 17 in total. 11 developed by IHEP (yellow), 1 by SSRF, 5 by foreign vender.
- 13 LN2 cooled mono, 3 cooled by water, 2 without cooling

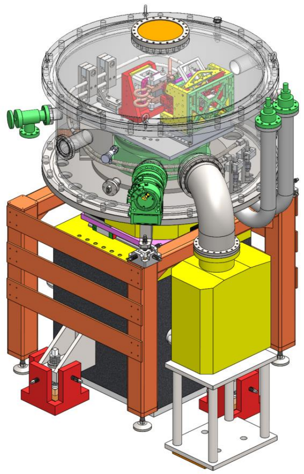
Yellow: in house
Green: purchased

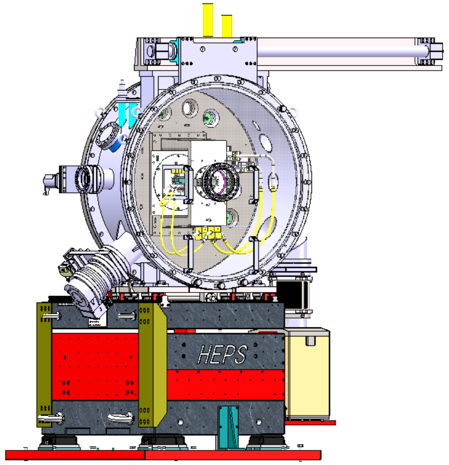
Mono. Type	ID	Beamline	Coolant	Optics	Optics Pair	Energy range (keV)	Slope error （μrad）	Stability in Pitch (nrad)	Stability in Roll (nrad)	Heat load (W)	Peak Power density (W/mm2)
HDCM	B2	Hard X-ray Nanoprobe Multimodal Imaging Beamline	LN2	Si(111)/Si (220)	2	4.8-30,7.8-40	0.1λ	25	50	150	63
	B4	Hard X-ray Coherent Scattering Beamline	LN2	Si(111)/(311)	1	7-25,12-25	0.1λ	25	60	210	99
	B9	Low-Dimension Structure Probe Beamline	LN2	Si(111)	1	4.8-40	0.50	50	100	145	28
	BB	Pink Beam SAXS Beamline	LN2	Si(111)	1	7-30	0.30	100	200	20	19.8
HCCM	B6	High Pressure Beamline	LN2	Si(111)/Si (220)	1	20-42,42-75	0.31	30	350	330	32.7
	BA	Microfocusing X-ray Protein Crystallography Beamline	LN2	Si(111)	1	5-18	0.30	100	150	161.1	
VDCM	B5	Hard X-ray High Resolution Spectroscopy Beamline	LN2	Si(111) /Si (311)	2	5-26	0.50	50	150	144	61
	B8	XAFS beamline	LN2	Si(111) /Si (311)	2	4.8-20,10-45	0.30	100	100	140	45
	BE	Transmission X-ray Microscope Beamline	LN2	Si(111)	1	5-15	0.60	100	350	435	19.14
	BF	Test Beamline	LN2	Si(111)	1	5-40	0.30	100	100	900	11.7
	BD	Tender X-ray Beamline	Water	Si(111)	1	2.1-8	1.00	200	200	50	0.1
QCCM	B8	XAFS beamline	LN2	Si(111)/Si (311)	2	4.8-23,4.83-22.3	0.45			147	22.7
HDMM	B3	Structural Dynamics Beamline	Water	DMM	1	20-70	0.50	50	350	65	0.14
HRM-NRS	B5	Hard X-ray High Resolution Spectroscopy Beamline	None	Si(400)/Si(10 6 4)	2	14.4125	0.50	80	200		
HRM-RIXS	B5	Hard X-ray High Resolution Spectroscopy Beamline	None	Si(400)	2	8-10	0.50	175			
DLCM	B7	Hard X-Ray Imaging Beamline	LN2	Si(220)	1	40-200		100	100	1073	0.245
	B1	Engineering Materials Beamline	LN2	Si(111)	1	50-170		1000	1000	38	38.4
PGM	BC	High Resolution Nanoscale Electronic Structure Spectroscopy Beamline	Water	PGM	3	0.1-2	0.15	50	100	56	0.32

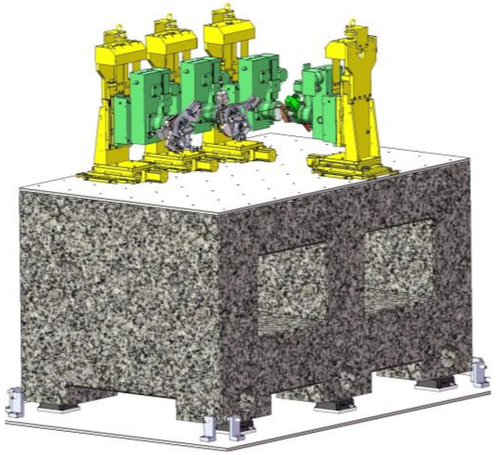
I. Overview of in-house built monochromators for HEPS

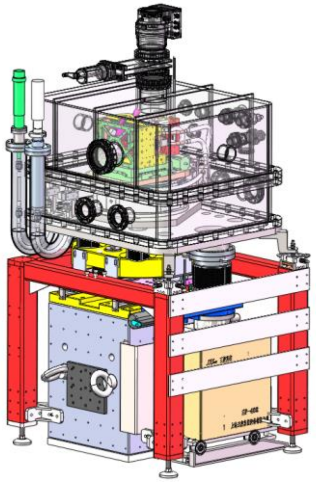
- **Crystal monochromators**
  - Vertical diffracting double crystal monochromators
    - B5/BE/BF
  - HDCM or HCCM
    - BA HPCCM, B6 HCCM
  - Quick scan monochromators for XAFS
    - B8 QCCM
  - High Resolution Monochromator or Medium Resolution Monochromators
- **Multilayer monochromators**
  - B3 HDMM

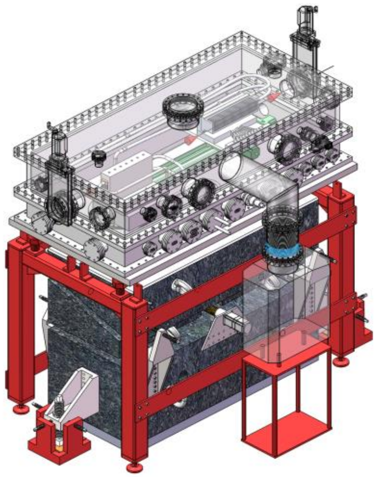

VDCM


HCCM


QCCM

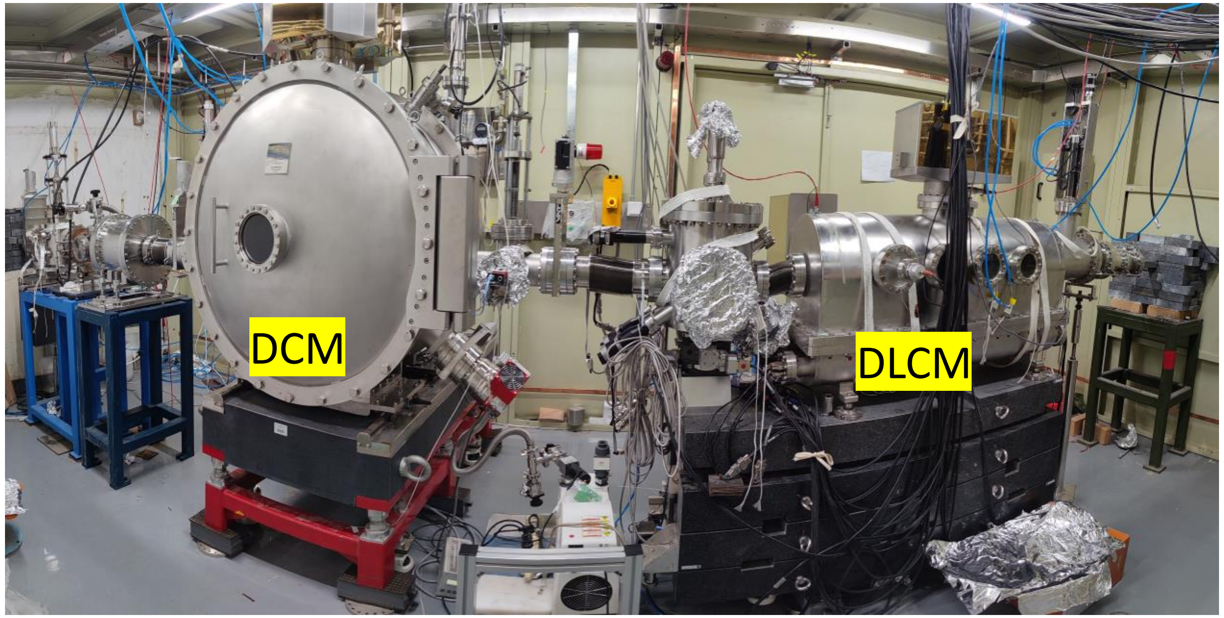

HRM

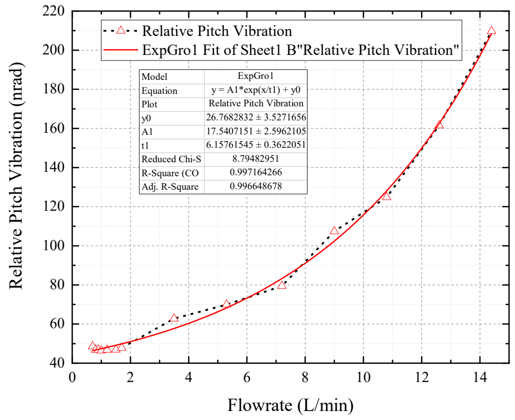

HDCM

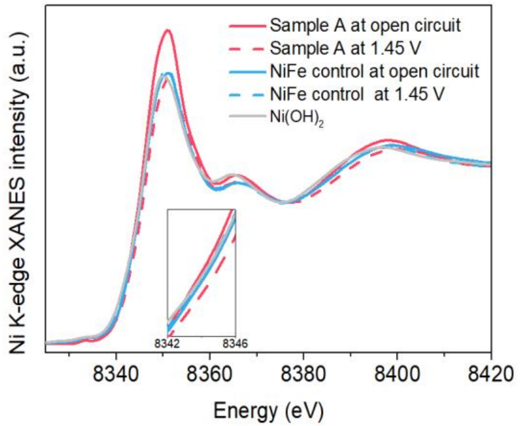

HDMM

I. Experience with monochromators

- **BSRF: 1st generation light source**
  - 0 experience with LN2 monochromators
- **HEPS Test Facility (2014-2018)**
  - High Heat load double crystal monochromator
  - Double Laue Crystal monochromator
  - High Resolution Monochromator
  - Tested and verified by users on BSRF beamline
- **Many challenges**
  - High stability, slope error requirements
  - 1 or 2 design is not able to meet all the requirements
  - Various types of mechanics

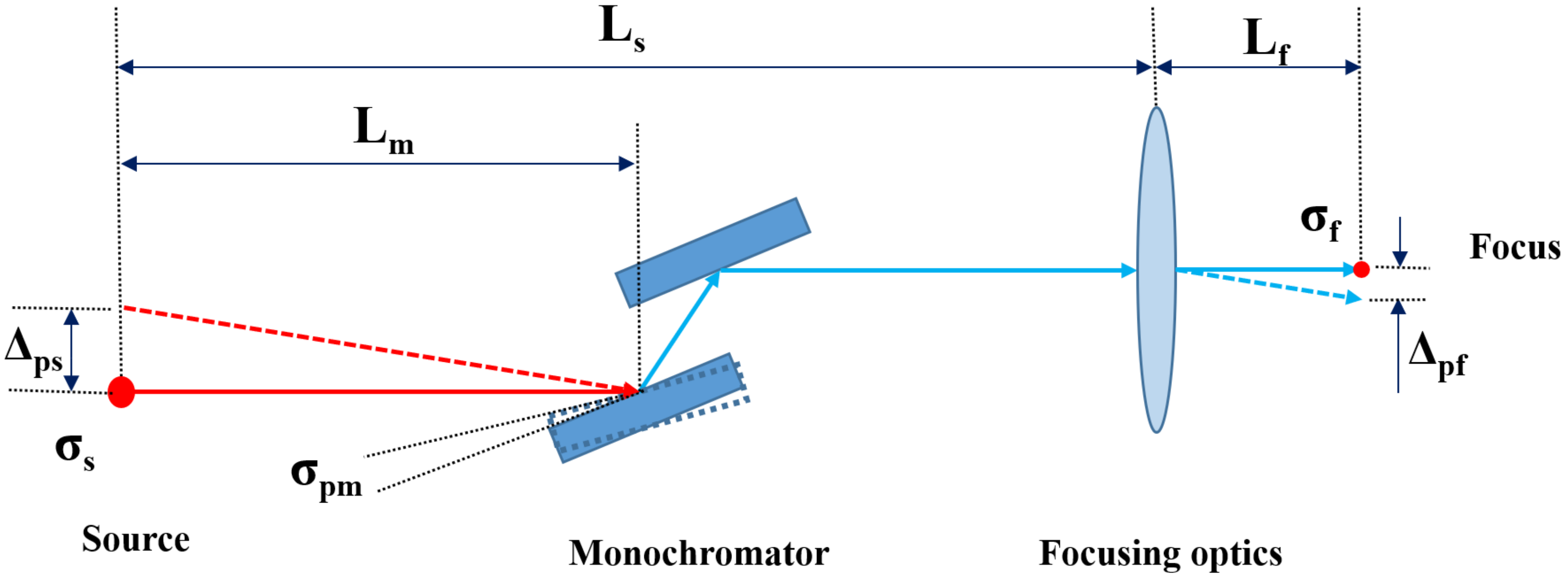






II. Vibration problem of monochromator

- **Beam properties deteriorate**
  - Position, intensity, coherence, energy, energy resolution…

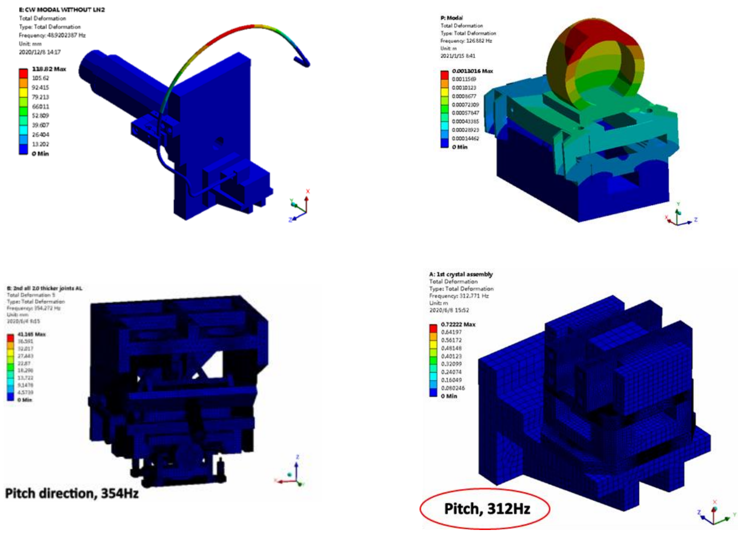


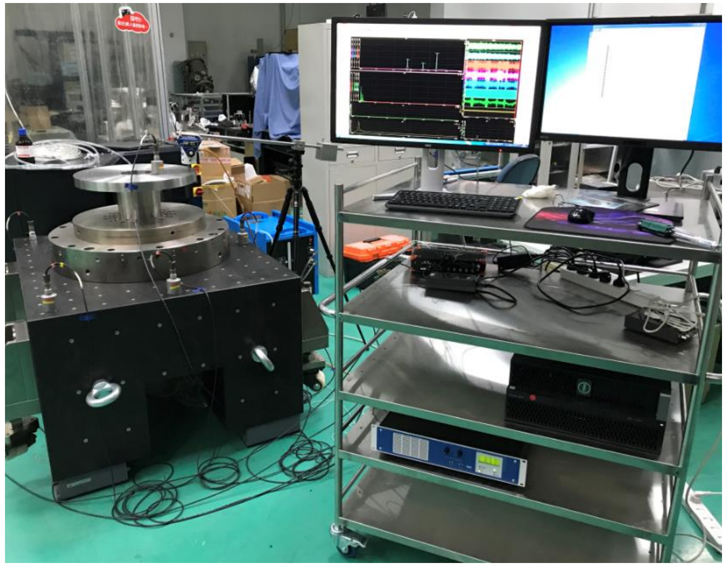
Demanding beamline require 25 nrad RMS

II. Stability

- **Traditional approach:**
  - High stiffness design
  - FEA validation
  - Room for error: higher 1st modal

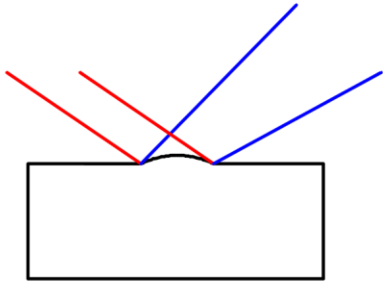
- **Measure it and improve it**
- **Offline measurement:**
  - Accelerometer: modal analysis, shaker, impact hammer
  - Velocity sensor: such as seismometer for ground vibration monitoring
  - Displacement sensor: with laser interferometer, or laser dopler interferometer
  - Impact hammer and shaker
- **Online measurement:**
  - Intensity based measurement, with ion chambers, photodiodes and AD converter





II. Slope error of crystals

- **Slope error of crystals (lattice)**
  - Energy resolution, coherence, spot size, distribution
  - Fabrication, thermal deformation, mechanical clamping and cooling
  - Total deformation need to be ~0.3 μrad RMS after correction

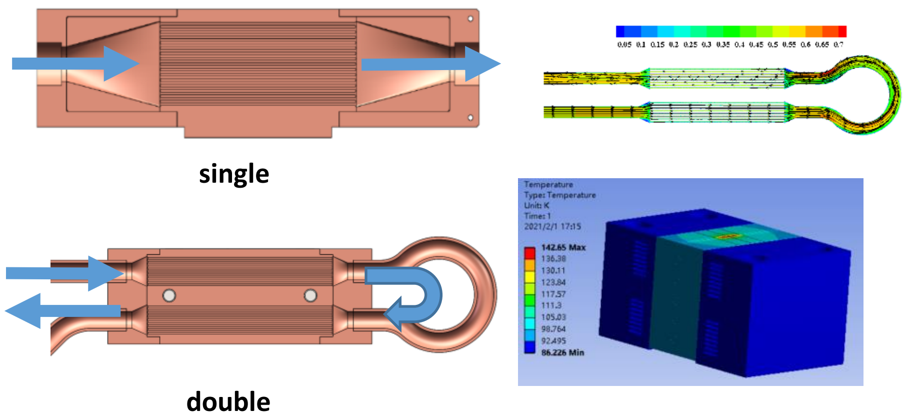


Fabrication and defects
0.17 μrad

TUOBM07, WEPPP014

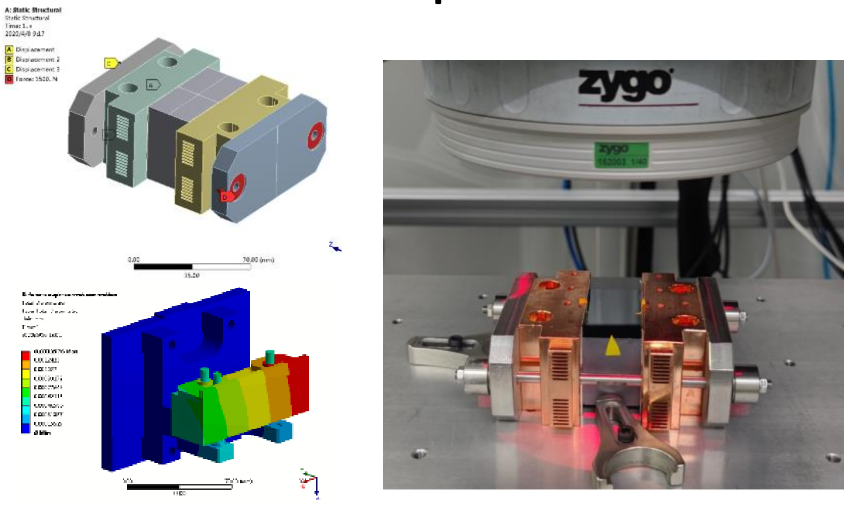
New process by HEPS optics group, Choose of material

Thermal deformation
0.1 μrad



FEA, CFD, reduce flow
Thermal contact resistance study

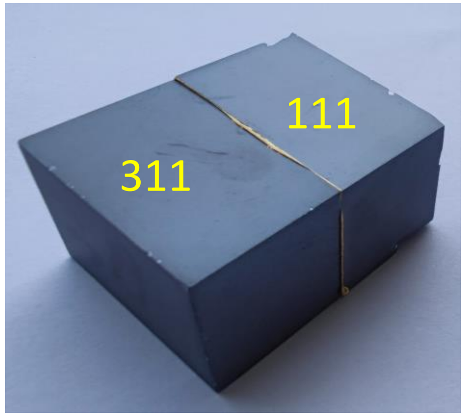
Clamping and cryogenic deformation
0.1 μrad



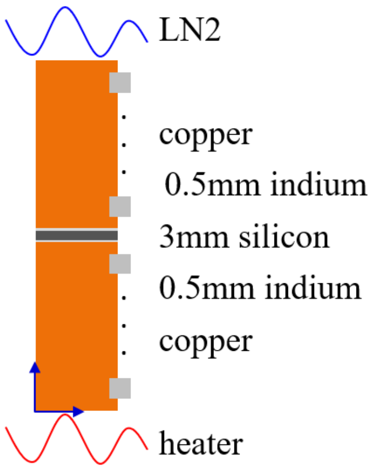
FEA and measurement

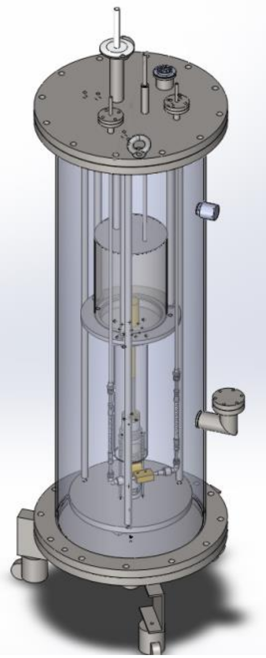
II. Thermal deformation-Thermal contact resistance study

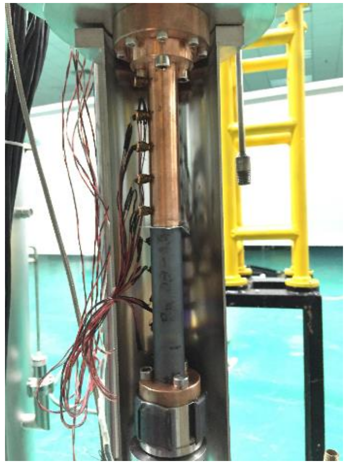
- **High power density of HEPS**
  - Lack of thermal contact resistance data at cryogenic temperature
  - A device was built during HEPSTF, a new measurement scheme was proposed
  - Data under different pressure and with different thickness of indium is measured
- **A new method by eutectic bonding of multi crystals was proposed and measured**
  - **TCR in the range of ~2E-6Km²/W, an order of magnitude lower than that of indium**

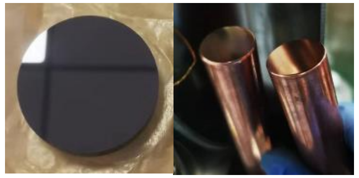


eutectic bonding of multi crystals, to be further developed

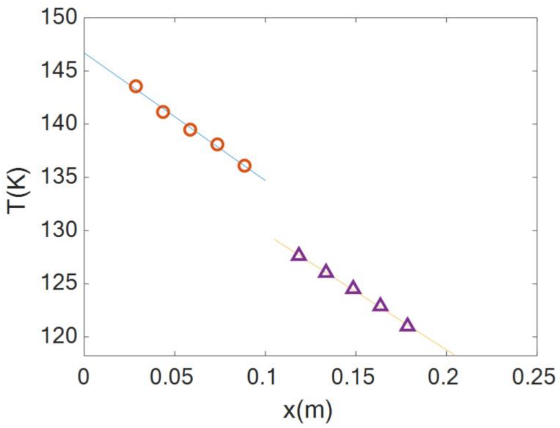




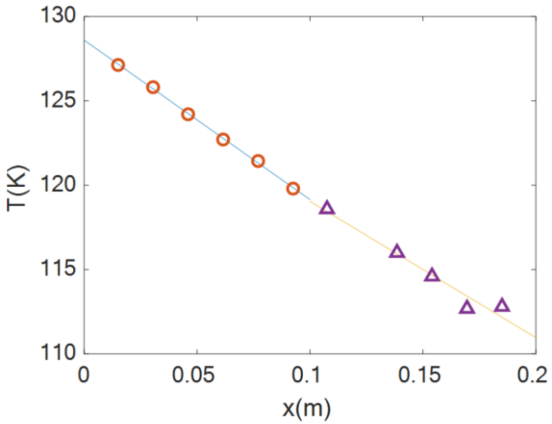




Measurement setup



3 bar, 15W, TCR: 5.14E-5Km²/W
With indium

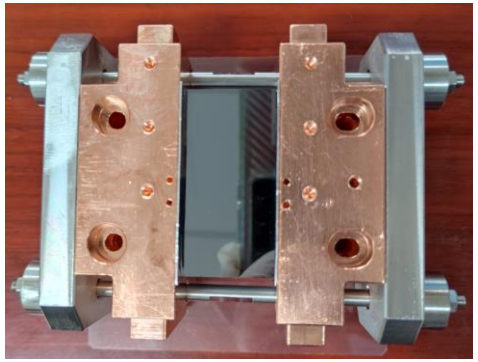


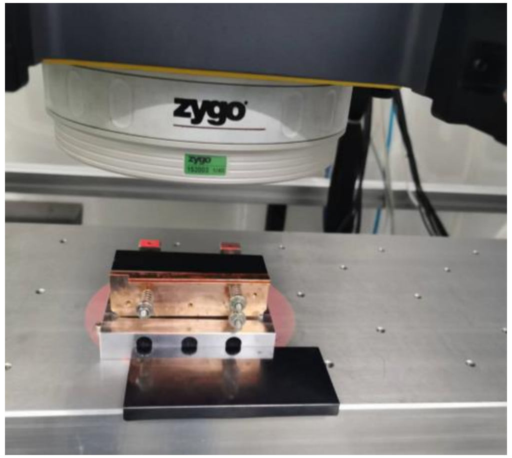
TCR: ~2E-6Km²/W, with eutectic bonding
An order lower

Measured by Minwei Chen & Guang Yang

II. Clamping deformation study

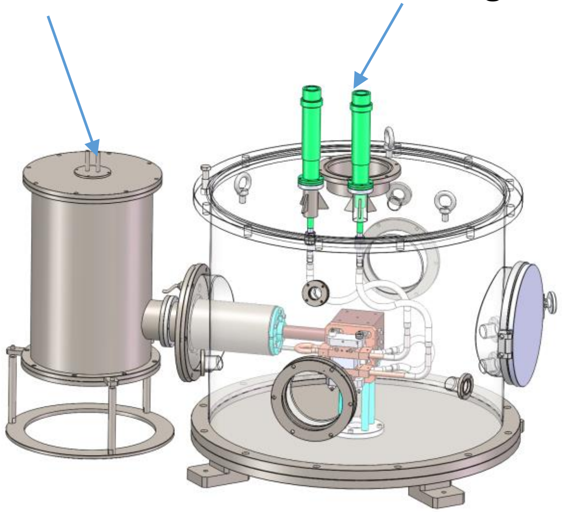
- **Clamping deformation**
  - 0.1μrad RMS
- **New clamping mechanics based on springs were developed**
  - Clamp pressure could controlled
- **The deformation of first and second crystals under room and cryogenic temperatures were measured**
  - A measurement device was designed and built for LN2 temperature
  - Zygo interferometers



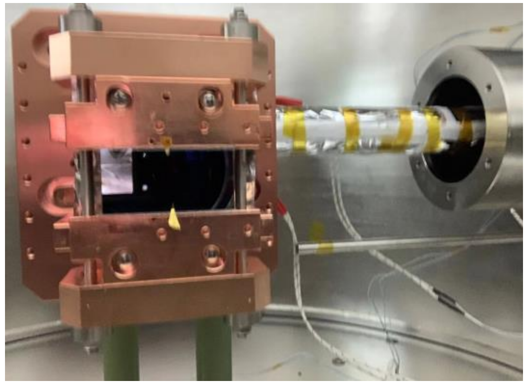


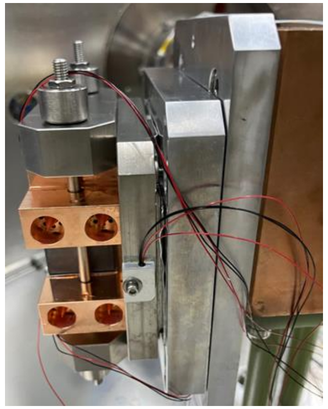
Room temp. measurement

Cryo tem. meas.



Cryo measurement device

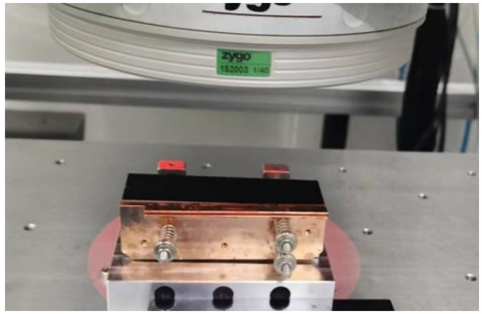


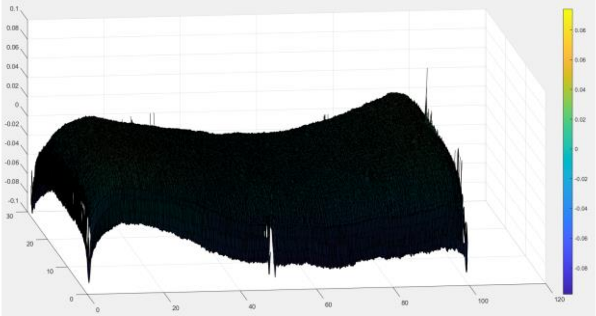


Cryo tem. meas.

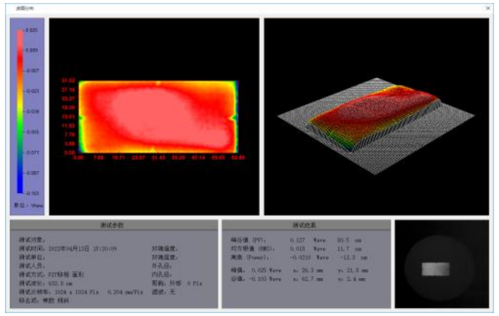
II. Clamping deformation study

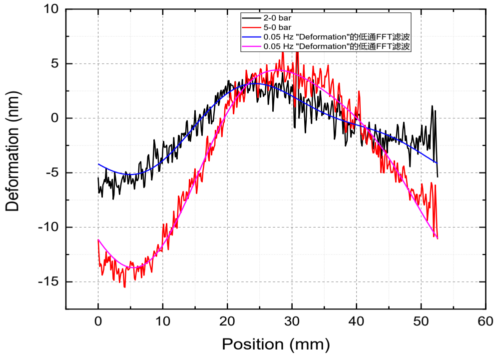
- **Results**
  - ＜0.1 μrad RMS after correction measured for 4 DCMs, first and second crystals, in 10 mm footprint range



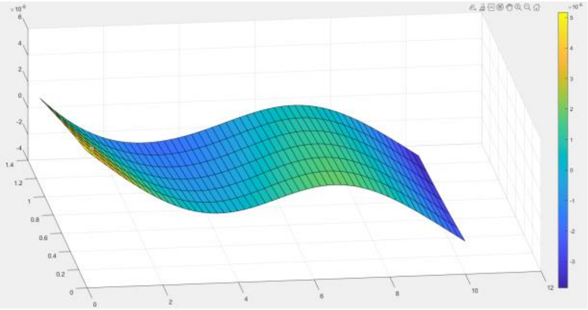


Room temperature



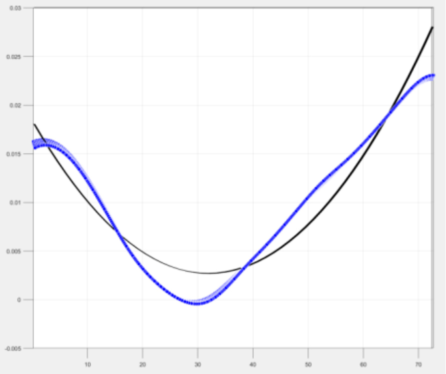


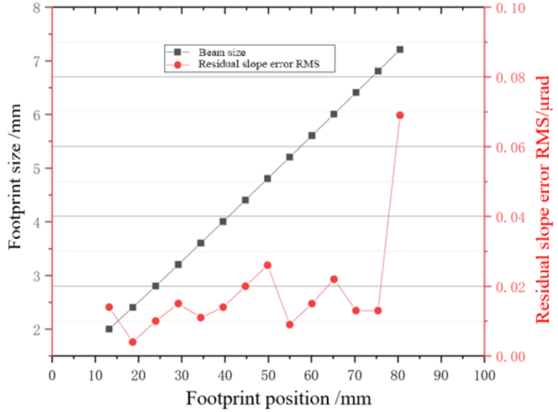
room temperature



RMS 0.085urad @10mm
At cryo temperature

First crystal clamped at room or cryo temperature



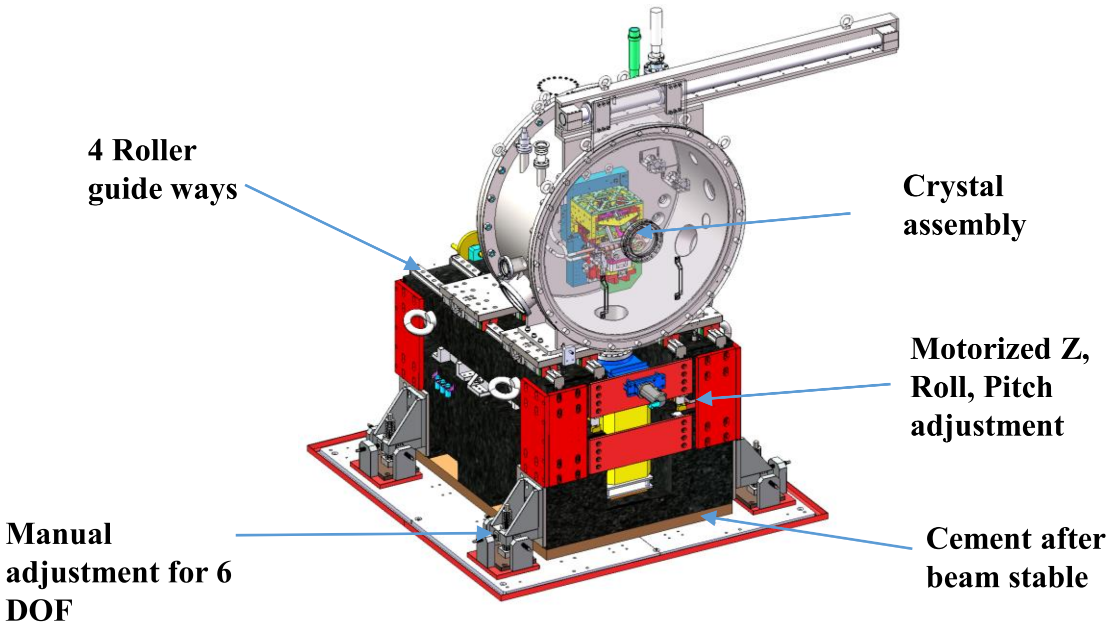


cryo temperature

Second crystal clamped at room or cryo temperature

III. Vertical diffracting Double Crystal Monochromators

- Vertical diffracting layout suitable for high flux application such as spectroscopy
- 3 variation in total

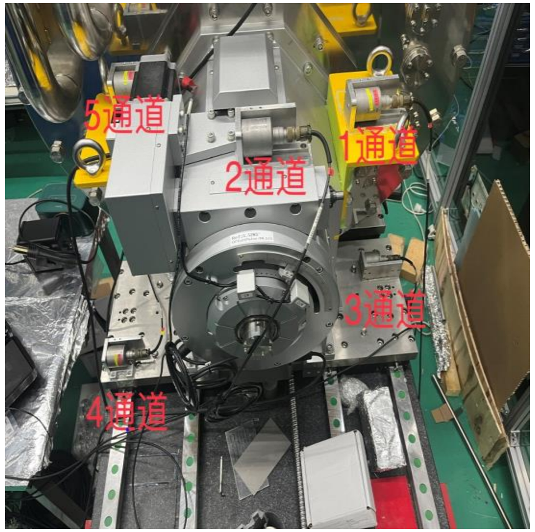


Transmission X-ray Microscope Beamline
Mostly fixed energy, near edge scan

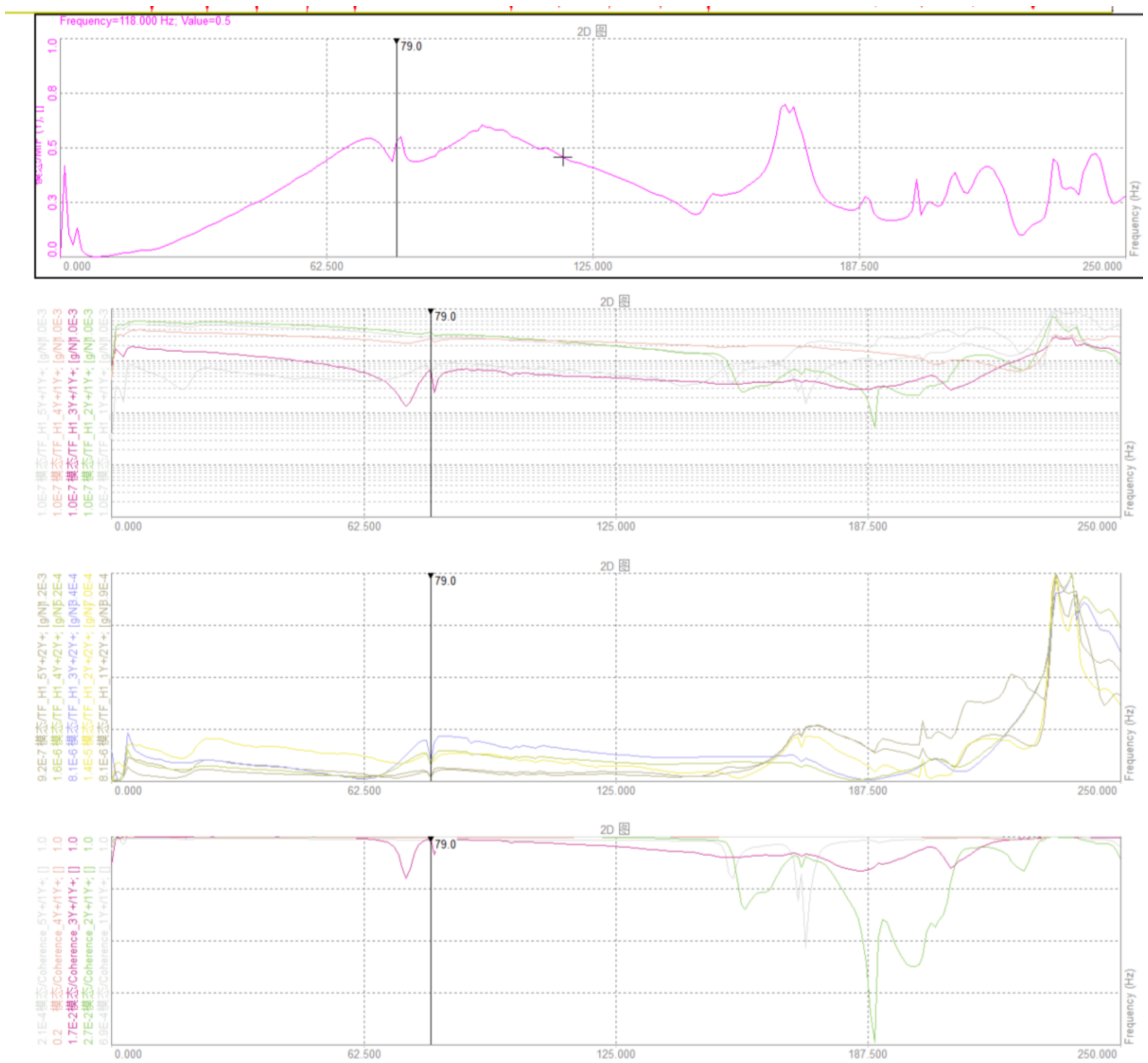
Ready to be installed, at HEPS site

III. Modal test of VDCM

- **Modal test**
  - Dewesoft ADC (24 bit)
  - Dytran accelerometer
    - Up to 1000Hz, 10V/g
  - PCB impact hammer
- **Result on Goniometer**
  - ~77Hz
- **FEA result:**
  - 112Hz, modal shape agrees
- **Considering 1.5 T load, the roller linear guideway and Airloc wedge performs rather good**

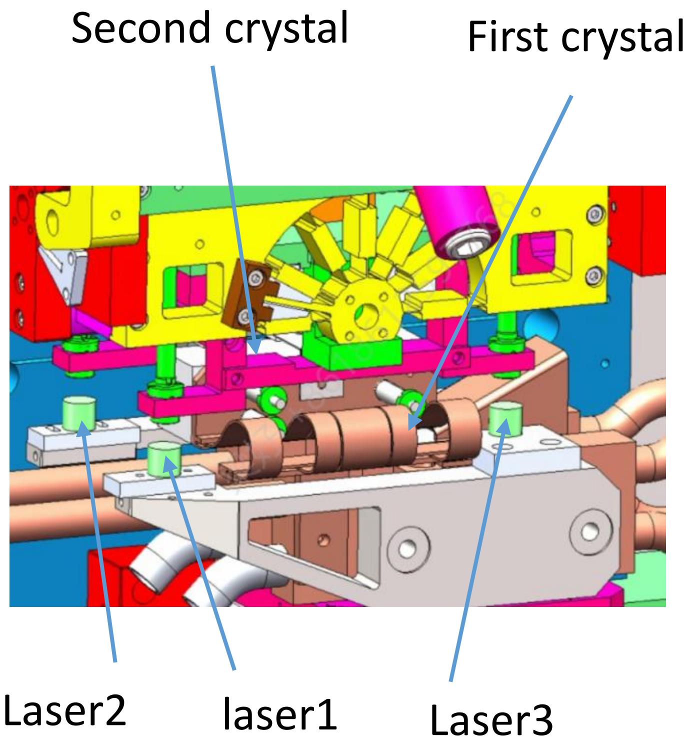


FEA result



III. Stability of VDCM

- **Offline measurement setup**
  - Attocube IDS 3010, with cryo and vacuum fiber and laser heads
  - Sampling rate 1k and 50k
- **With 2 different coolers**
  - Different pump speed
  - Long term monitoring



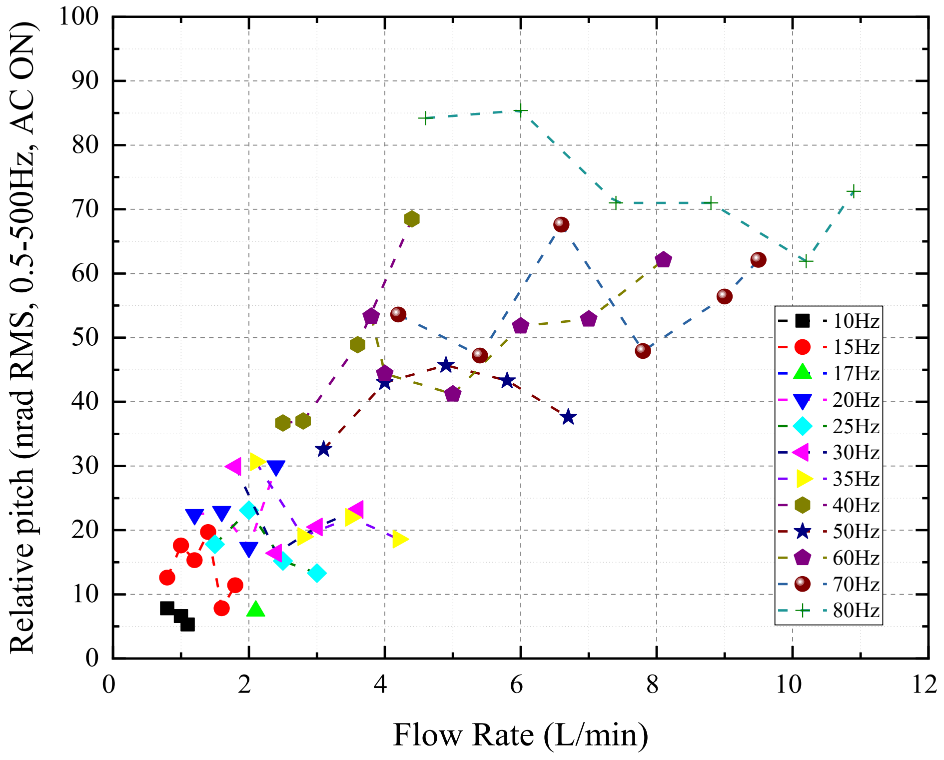
Pitch=(D1-D3)/L13
Roll=(D1-D2)/L12

Sensor	
number of sensor axes	3
working distance	0...5000 mm (depending on sensor head)
sensor resolution	1 pm
sensor repeatability	2 nm[1)]
max. target velocity	2 m/s
measurement bandwidth	10 MHz
signal stability (WD: 77 mm)	0.110 nm (2σ)

III. Stability of VDCM

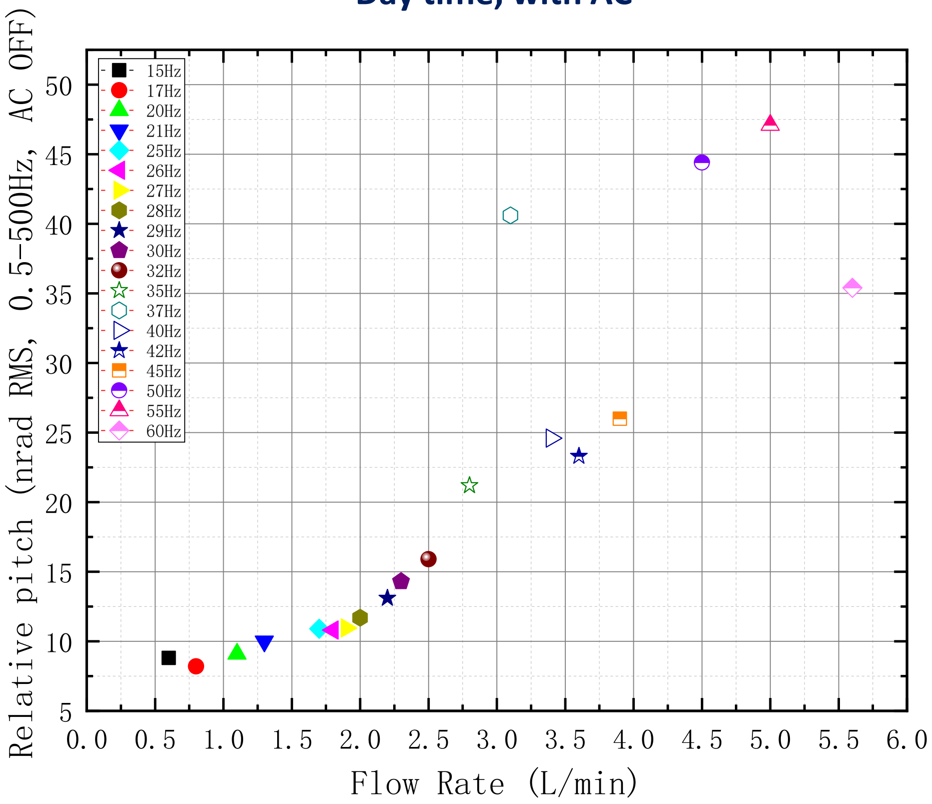
- **Pitch vs flow rate and pump speed**

With cooler A
Evening peak, with AC



As low as 6nrad RMS

With cooler B
Day time, with AC

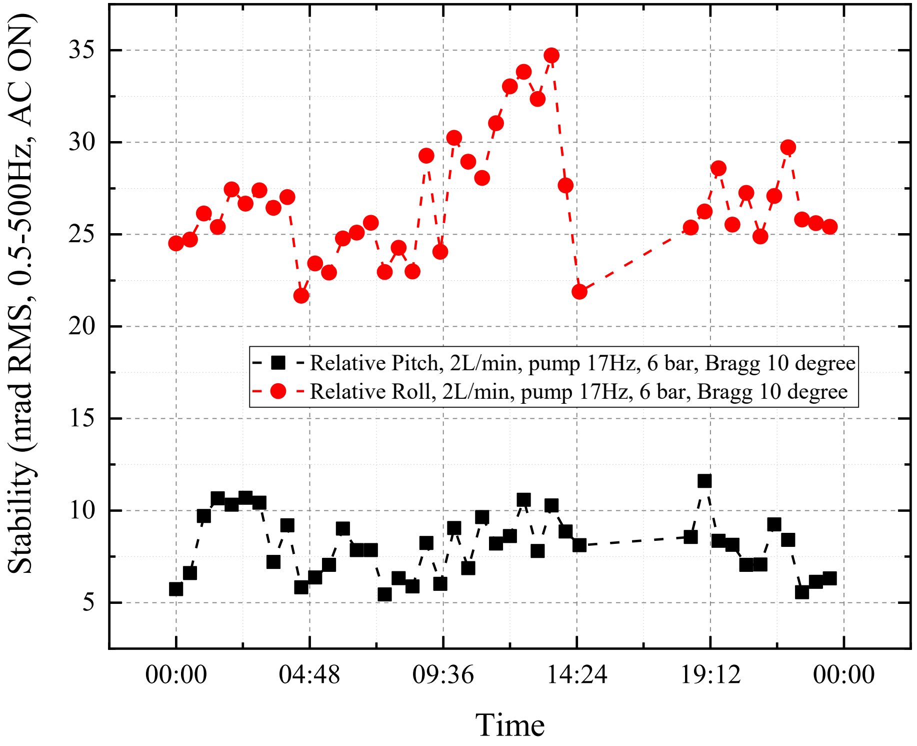


As low as 8nrad RMS

III. Stability of VDCM

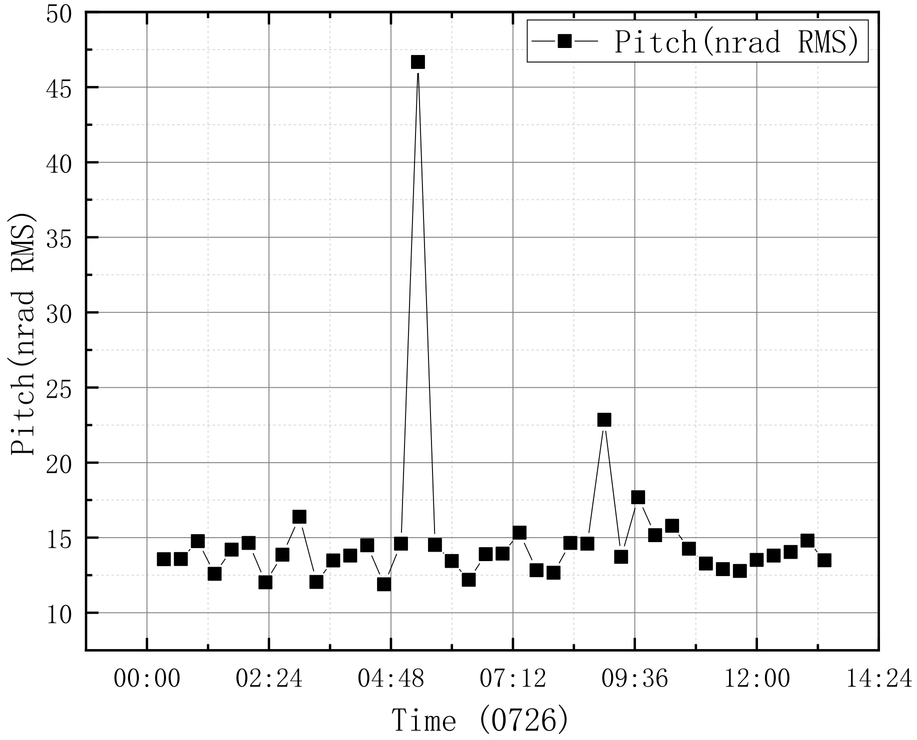
- **Pitch stability over 24 hours at 2L/min (working conditions for 435W heatload)**

With cooler A
Pump 17Hz



RMS stability of Pitch and Roll over 24 hours

With cooler B
Pump 28Hz

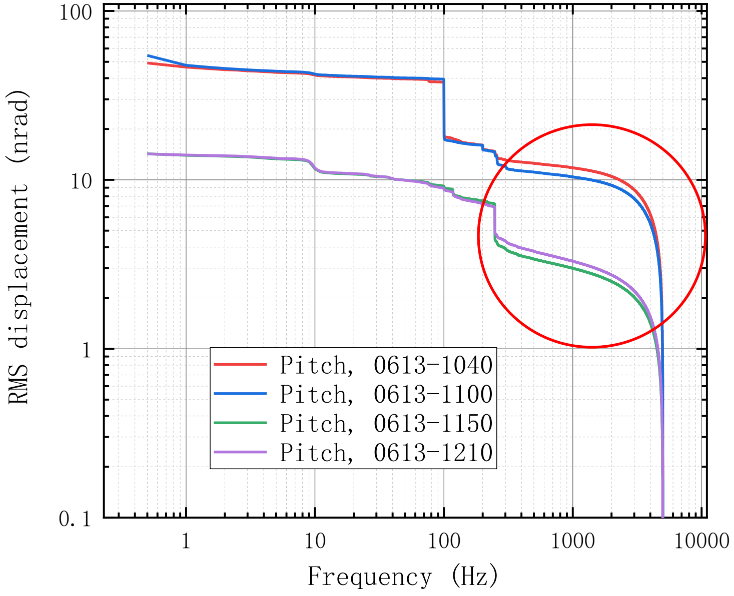


RMS stability of Pitch over 13 hours

III. Stability of VDCM

- **High sampling speed vs low sampling speed**
  - RMS level more or less the same
  - Main issue is the noise at high frequency

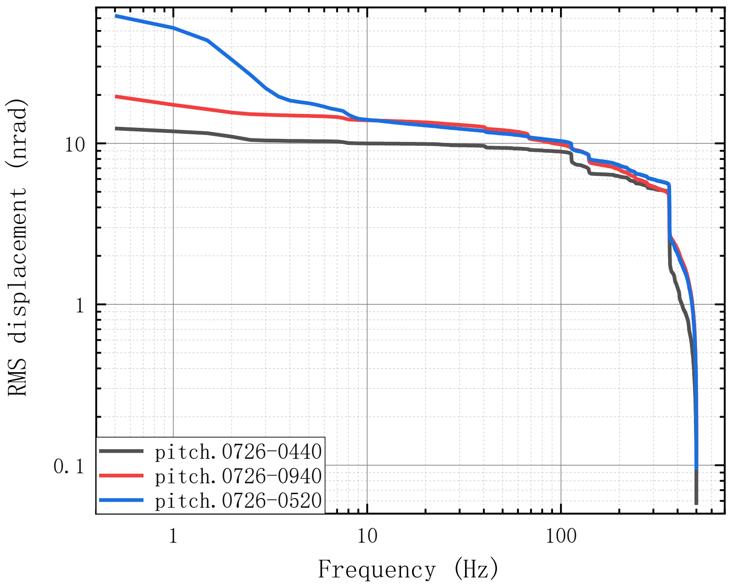
10k



2.0L/21Hz

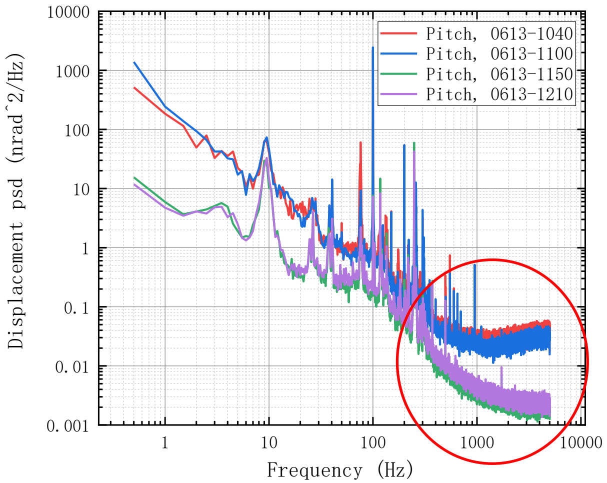
With cooler A

1k

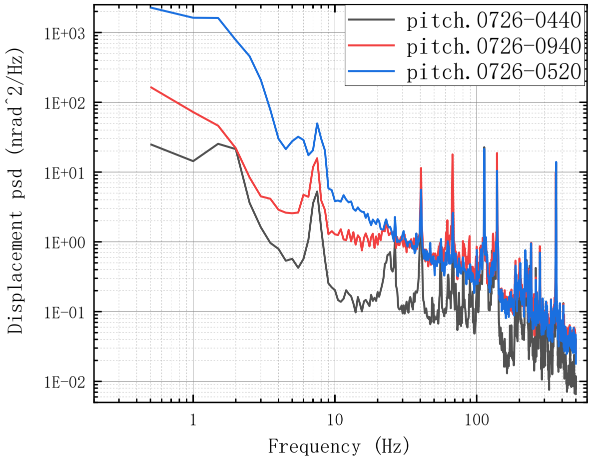


2.0L/28Hz

With cooler B



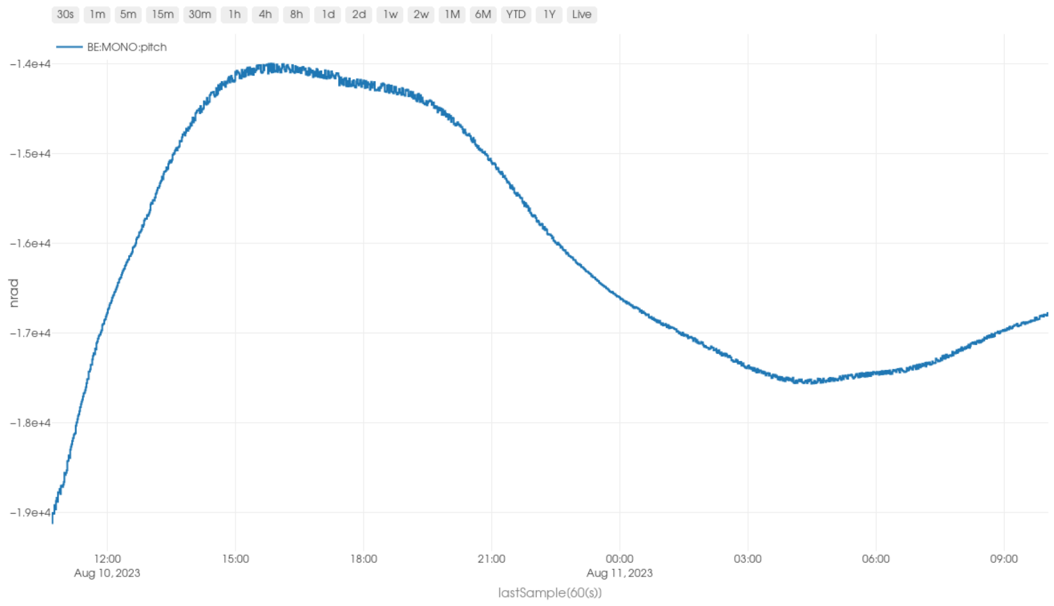
10k



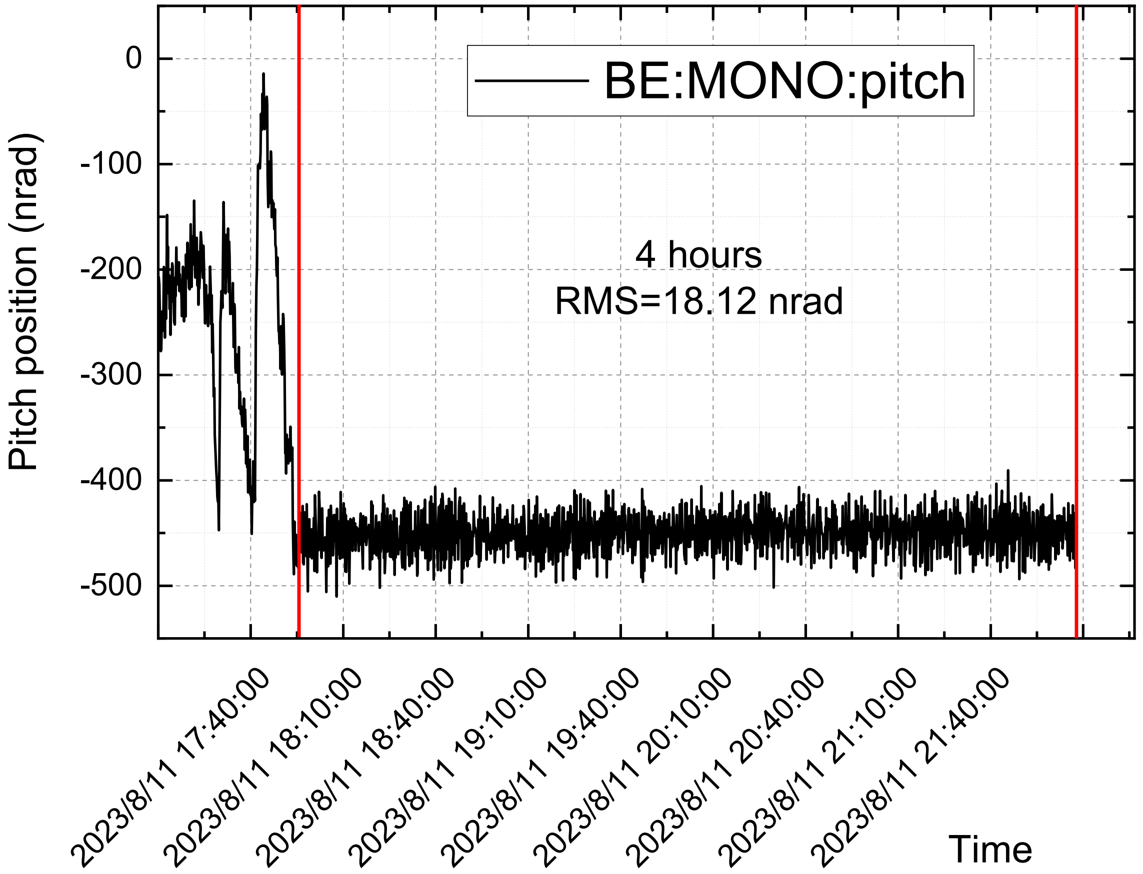
1k

III. Stability of VDCM

• **Long term stability 18 nrad RMS, with feedback by interferometers**



Without feedback

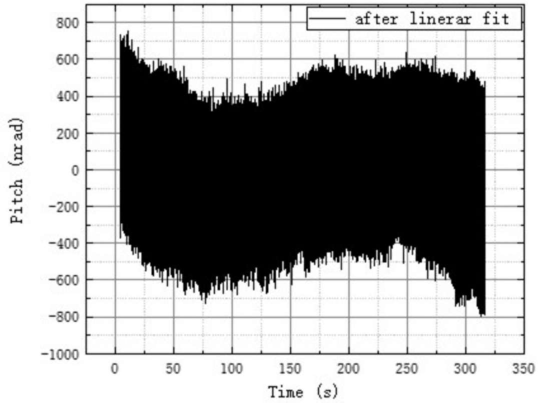


III. Stability of VDCM

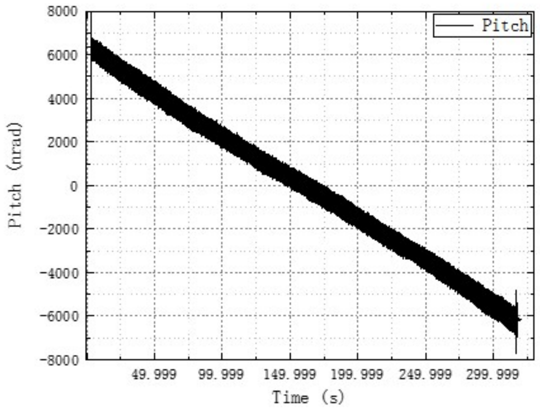
- **Parallelism during scan over full Bragg range, 7.5-23.3 degrees**

1. Bragg Speed 0.05° /s：Pitch：14μrad；Roll：~0.5μrad

2. Bragg speed 0.025° /s：Pitch：14μrad ；Roll：~1μrad

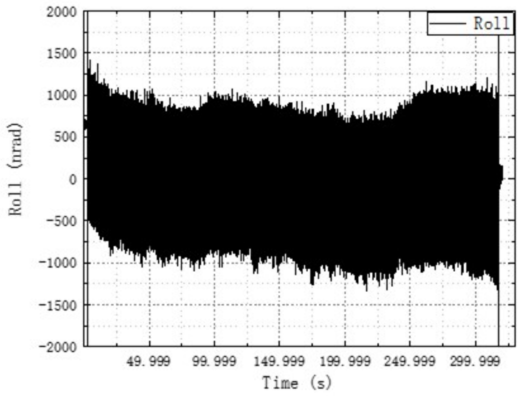


Pitch after linear fit
180 nrad RMS in 1 second

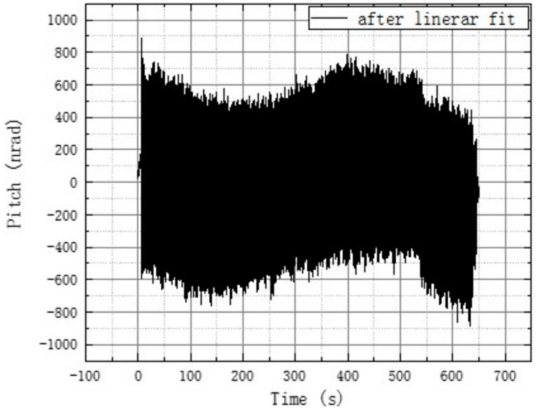


Pitch

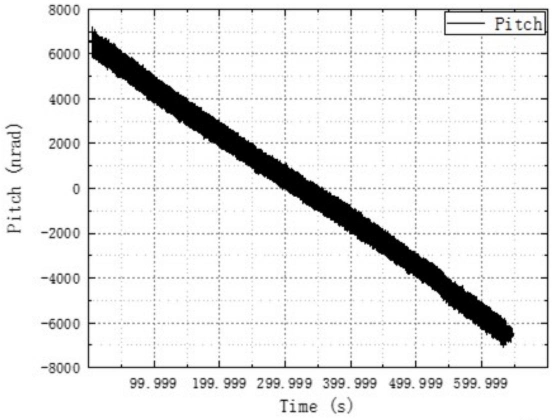
Scan 15-5 keV, 0.05° /s



Roll

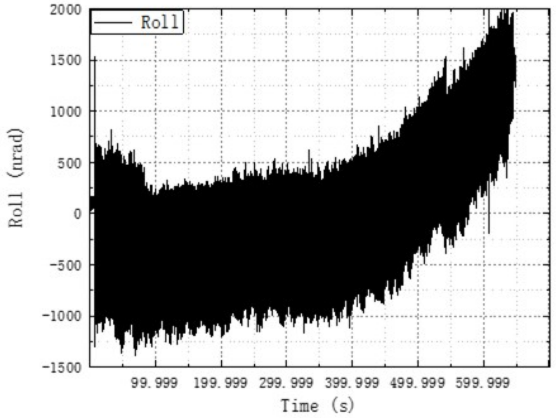


Pitch after linear fit



Pitch

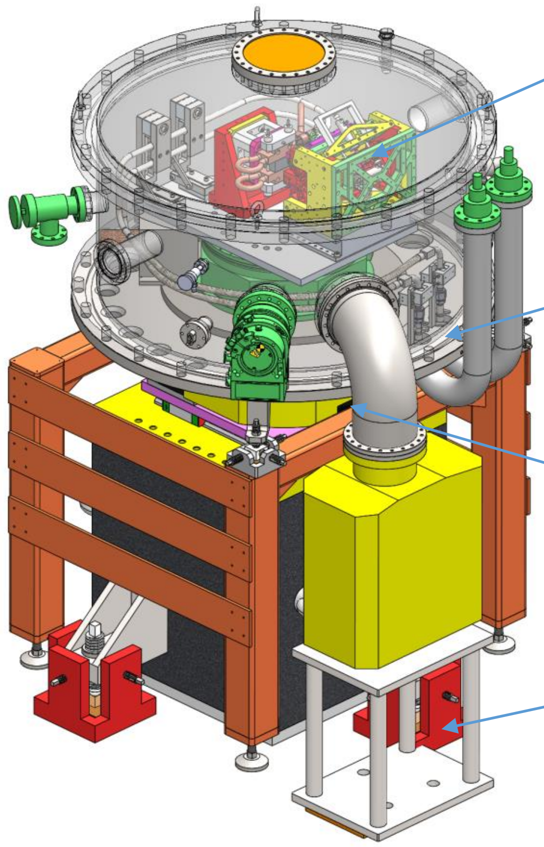
Scan 5-15 keV, 0.05° /s

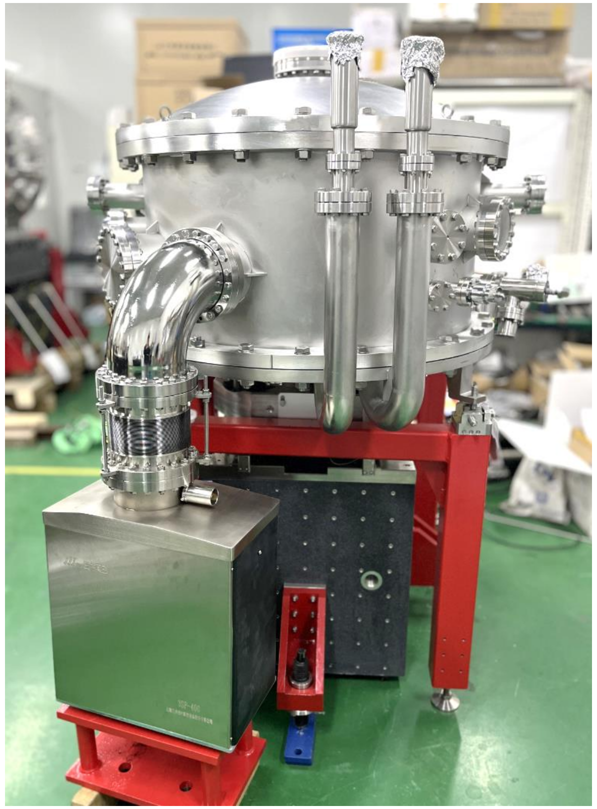


Roll

III. Horizontal diffraction double crystal monochromators

- Developed for beamlines with high stability requirements, due to larger source size in horizontal direction
- With double crystal, pseudo channel cut crystal, and muti-crystal sets variations

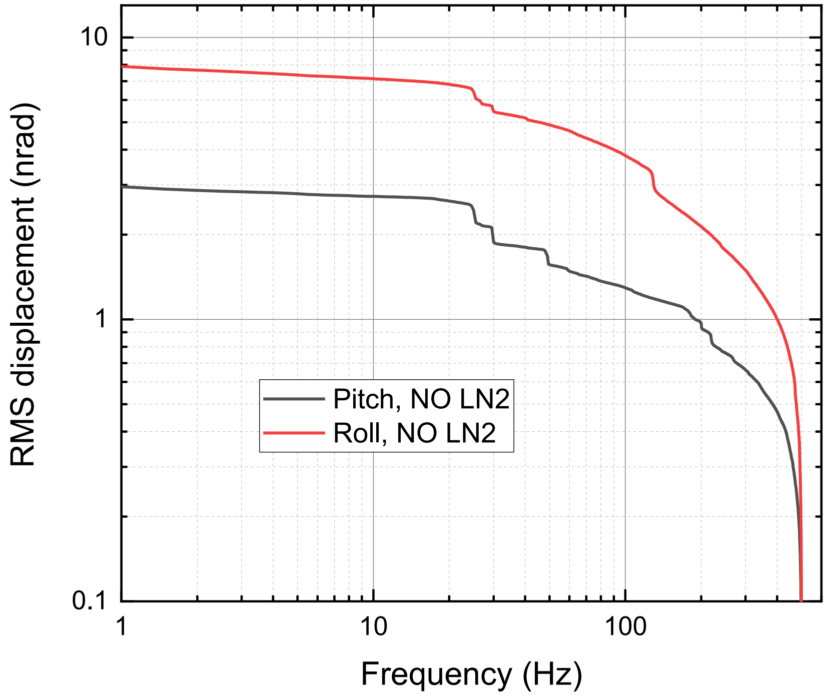




Still under test at IHEP

III. Horizontal diffraction double crystal monochromators

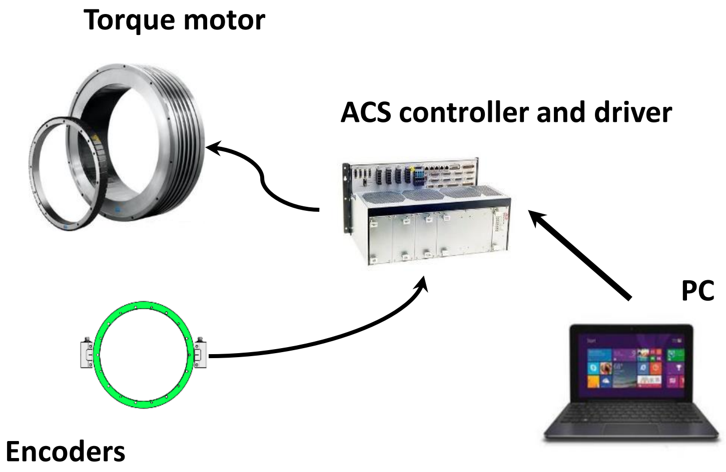
- **In air motion test almost finished**
- **Stability without cooling is below 10 nrad for pitch and roll**



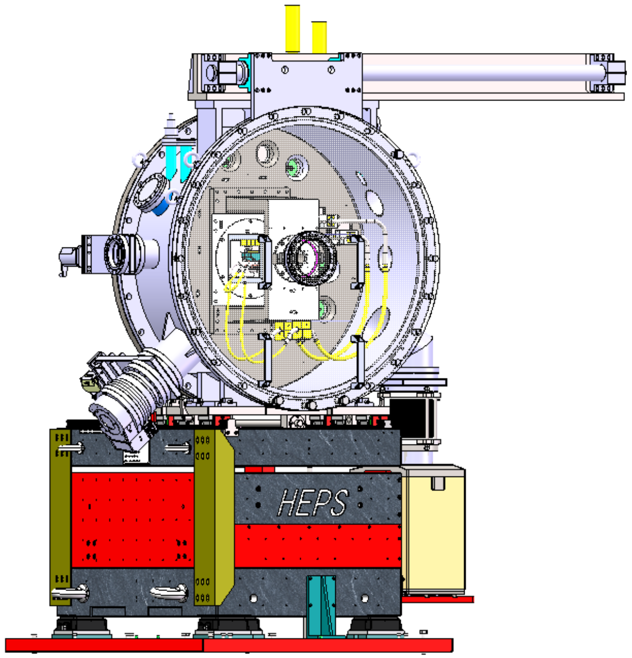
III. Quick scanning EXAFS channel-cut crystal monochromator

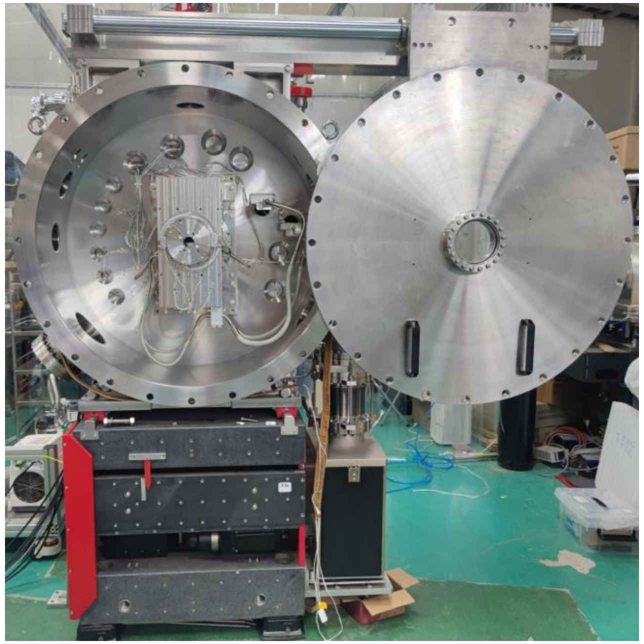
- Time resolved XAFS up to 100 spectra/s, with stepping scan mode and quick scan mode
- Fully in house design, including the servo controlled direct drive Bragg spindle
- Dynamic and Modal FEA validate design
- High modal: >300Hz for the spindle and crystal assembly

Also in WEPPP049



Direct drive scheme

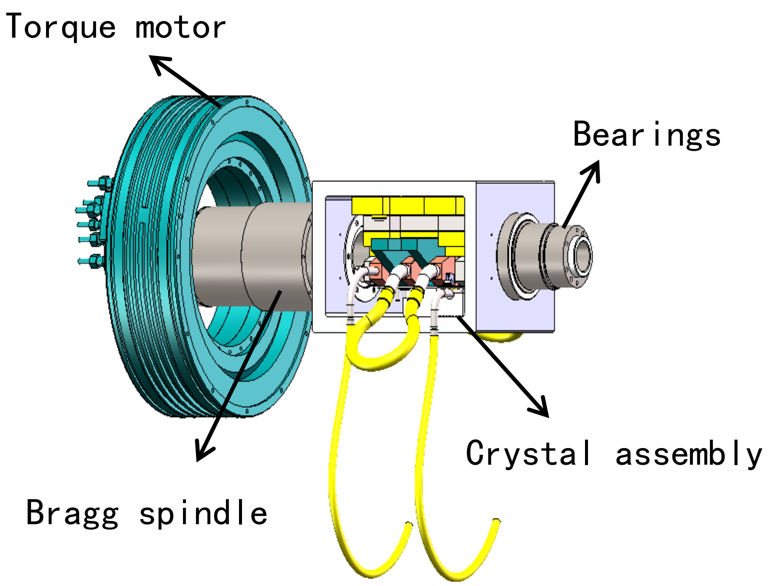




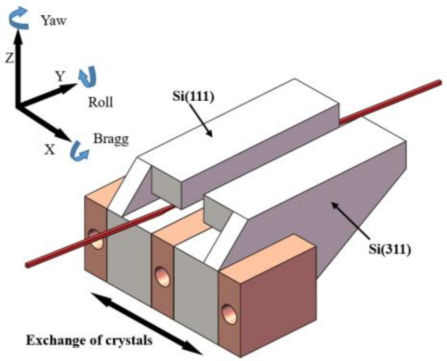
Finished test with LN2

III. Quick scanning EXAFS channel-cut crystal monochromator

- **High stiffness design, with support in the vacuum side**
- **Crystals hang in the support frame, perfectly well balanced, reduce force**



The direct drive spindle

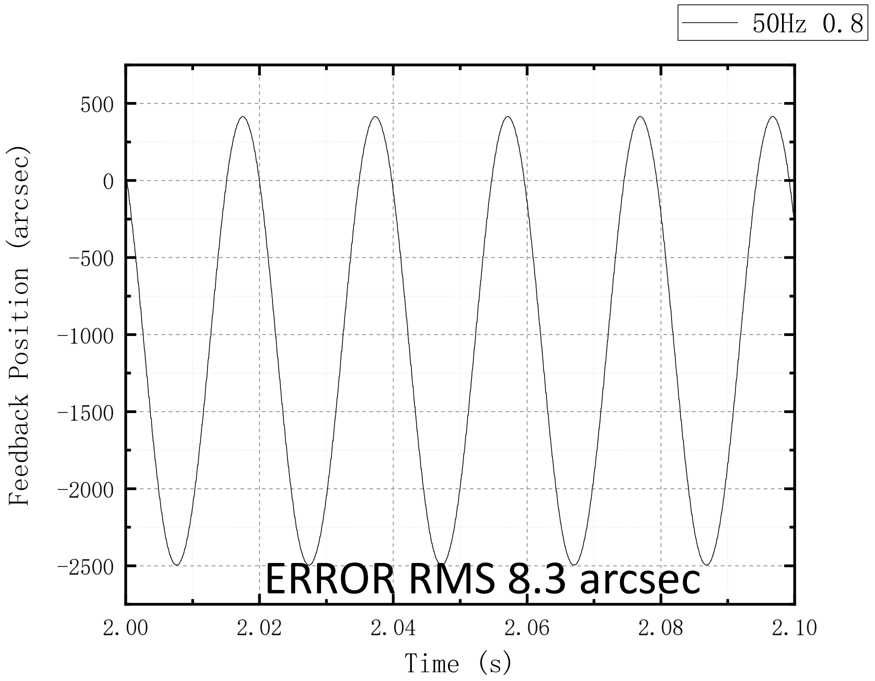


Crystal sets

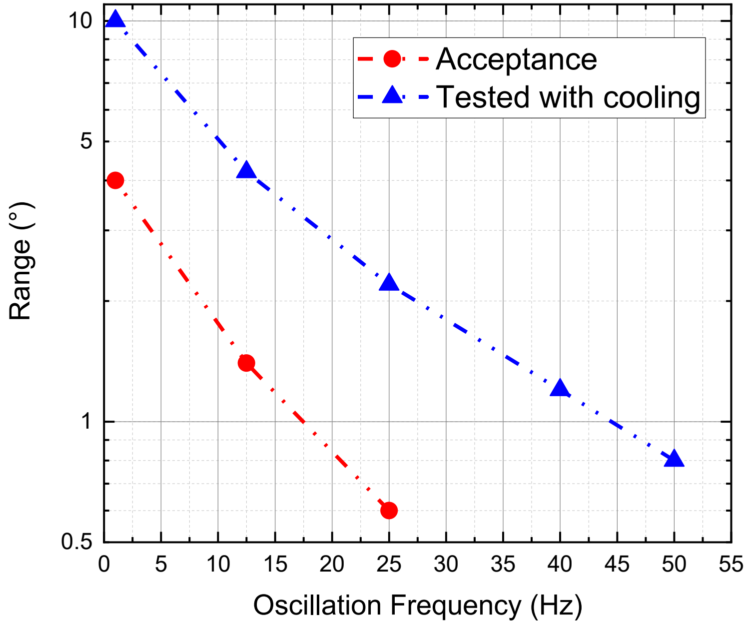
12.5Hz 2.8° with full load

III. Quick scanning EXAFS channel-cut crystal monochromator

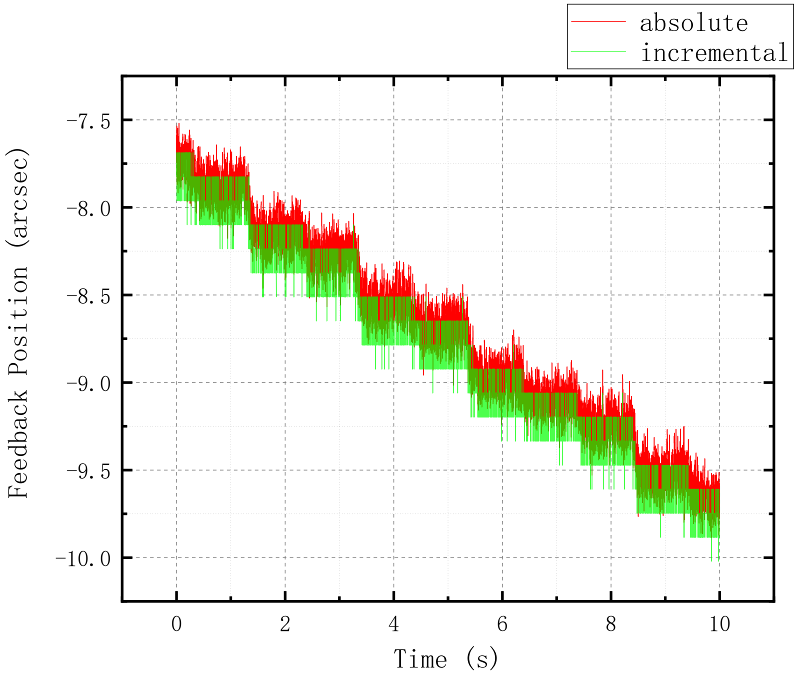
- **Quick scan tested: 0.8 degree at 50 Hz (100 spectrums/s), ~555eV@Cu K edge, Si(111) crystal**
- **Data collected by Pandabox @20000Hz**



50Hz 0.8°



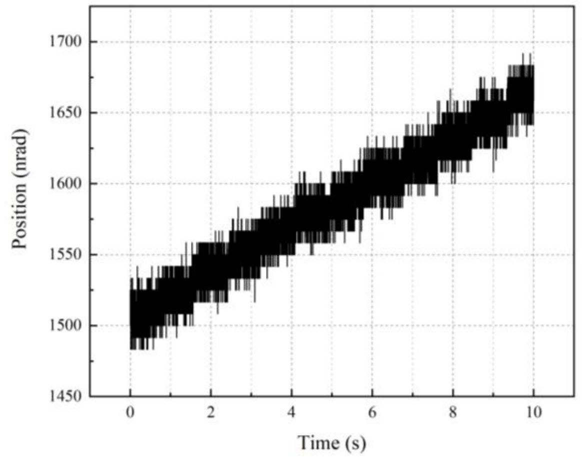
Fast scan results



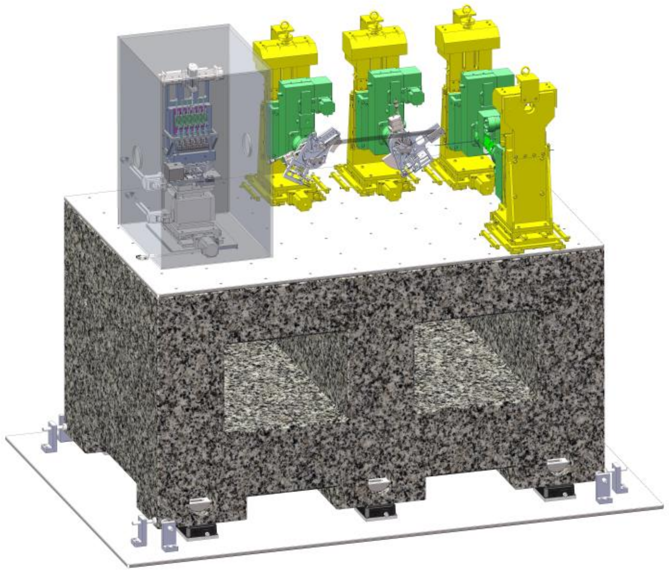
Step scan result

III. High resolution monochromators

- **In house developed large travel range flexure**
  - Step resolution of 8.3 nrad achieved
  - Relative pitch vibration 6.8 nrad RMS measured (Prelimary results)
- **Future plan involves more tests done at HEPS site with optical platform, with some vibration isolation capability**
- **More in TUPYP017**

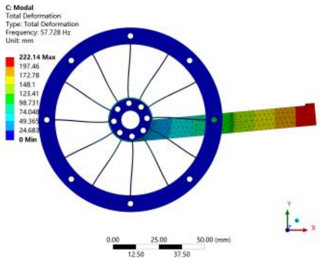


Measured resolution of 10 nrad/step Limited by encoder noise

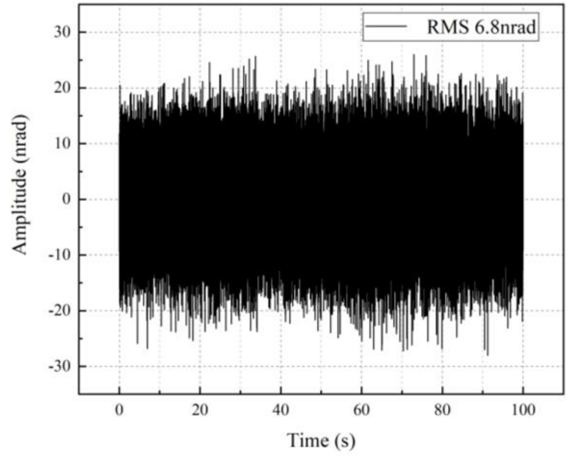


A HRM, a MRM and a CRL transfocator on the same bench

HRM during test



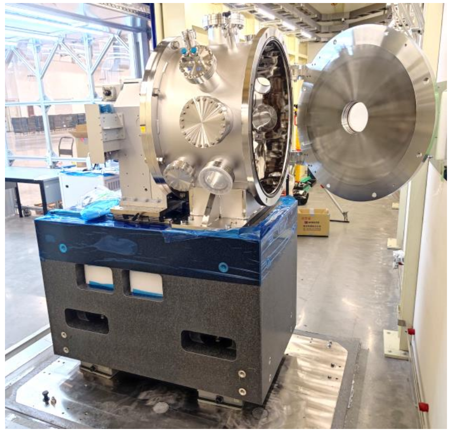
Large travel range up to 2.2 degree



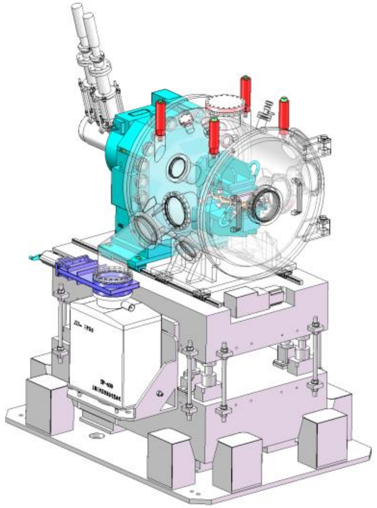
Relative pitch vibration 6.8 nrad RMS

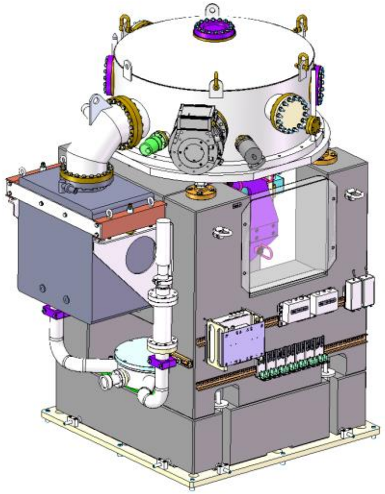
III. Purchased monochromators

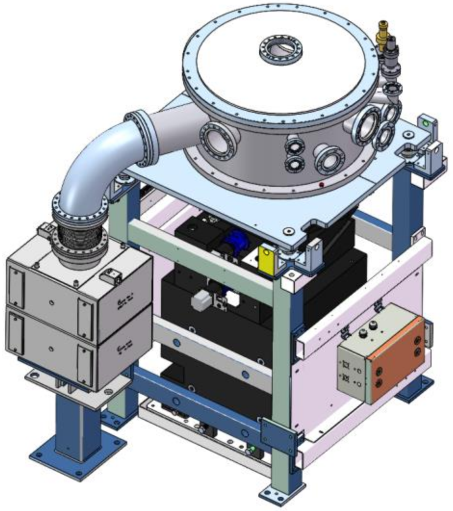
- **5 monochromators from foreign vendors**
  - 2 from Japan, 1 from Italy, 1 from UK, 1(PGM) from Germany
  - 1 already arrived and installed (water cooled)
- **Try collaboration on design phase to achieve final specification**
  - Clamping and cooling
  - Stability considerations, test methods
  - Example: XAFS monochromator vender changed design and meet requirements, ＜0.1μrad RMS for both crystals



Water cooled







3 LN2 cooled (in progress)

IV. Problems and plans

- **Problems**
  - Schedule: tight, no room for errors
  - Quality and process control: vacuum, surface process
  - Foreign suppliers: communication, delay, responsibilities
  - Control: time consuming, errors
- **Plans**
  - First group before June 2024
  - Second group before December 2024
  - Improve performance, reliability

V. Summary

- **R&D on crystal fabrication, clamping deformation, TCR carried out and meet HEPS requirements**
  - Fabrication ＜0.17μrad RMS, Clamping and cryogenic deformation ＜0.1 μrad RMS measured
  - TCR measurements provides data at cryo temperature
  - High stiffness approach to enable high stability
- **Progress on first group in house monochromators show good results but still problems**
  - Stability ＜10nrad RMS for VDCM
  - Scan capability of 0.8 degrees at 50Hz
  - High resolution and high stability (＜10nrad) for HRM
  - Progress with purchased mono is okay but room to improve
- **Further development and improvement still needed**

Acknowledgements

- **HEPS monochromator task group:**
  - Hao Liang, Yuanshu Lu, Yang Yang, Lu Zhang, Zekuan Liu, Shan Zhang, Dashan Shen, Yunsheng Zhang, Zhen Sun, Weifan Sheng, Ming Li
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  - Gang Li, Aiyu Zhou, Xiaobao Deng, Zongyang Yue, etc.
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  - Qinfu Han, Ye Tian, Zebin Zhang, Gang Wang, Weidong Man, etc.
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- **All BSRF Colleagues**
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Thank you for your attention!