X-ray optics technology at High Energy Photon Source (HEPS)

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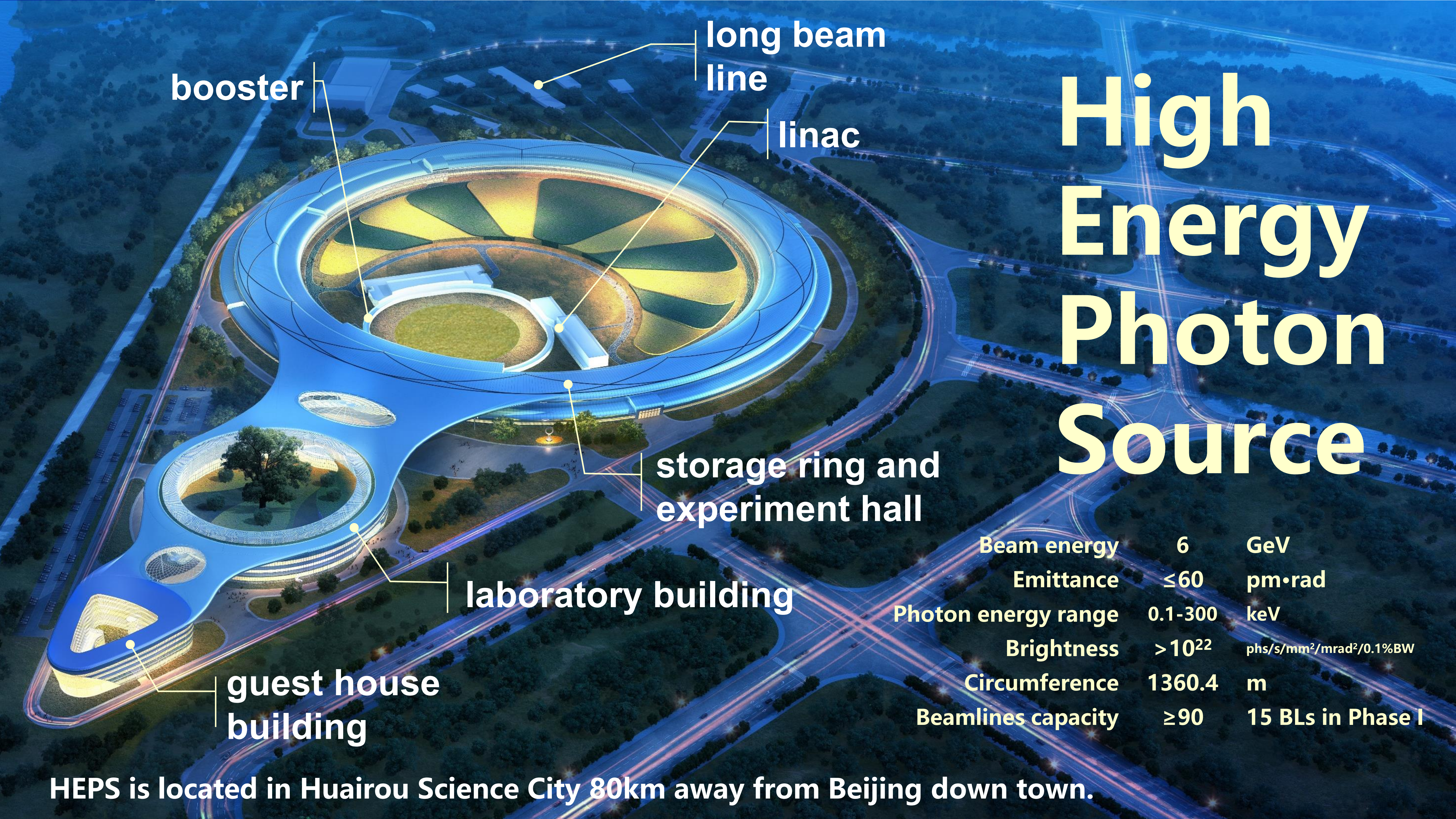
Challenges of optics at HEPS

High Energy Photon Source



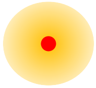
Beam energy	6	GeV
Emittance	≤60	pm•rad
Photon energy range	0.1-300	keV
Brightness	>10^{22}	phs/s/mm^2/mrad^2/0.1%BW
Circumference	1360.4	m
Beamlines capacity	≥90	15 BLs in Phase I

HEPS is located in Huairou Science City 80km away from Beijing down town.

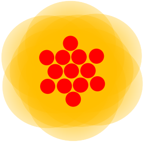
X-ray optics limits the performance of advanced light source

■From DLS to DLSR, X-ray optics is the key.

Low β	HEPS	EBS	APS-U	PETRA-III	ESRF	Spring-8	APS	MAX-IV	NSLS-II
Horizontal Size (μm)	**8.8**	27.2	14.5	34.6	37.4	301	275	42-54	42
Vertical Size (μm)	**2.3**	3.4	2.8	6.3	3.5	6	10	2-4	2.9
Horizontal Diver. (μrad)	**3.1**	5.2	2.9	28.9	106.9	12	11	4.7-6.1	21
Vertical Diver. (μrad)	**1.2**	1.4	1.5	1.6	1.2	1.1	3.5	1-2	2.7



Theoretical diffraction limit (~100%)



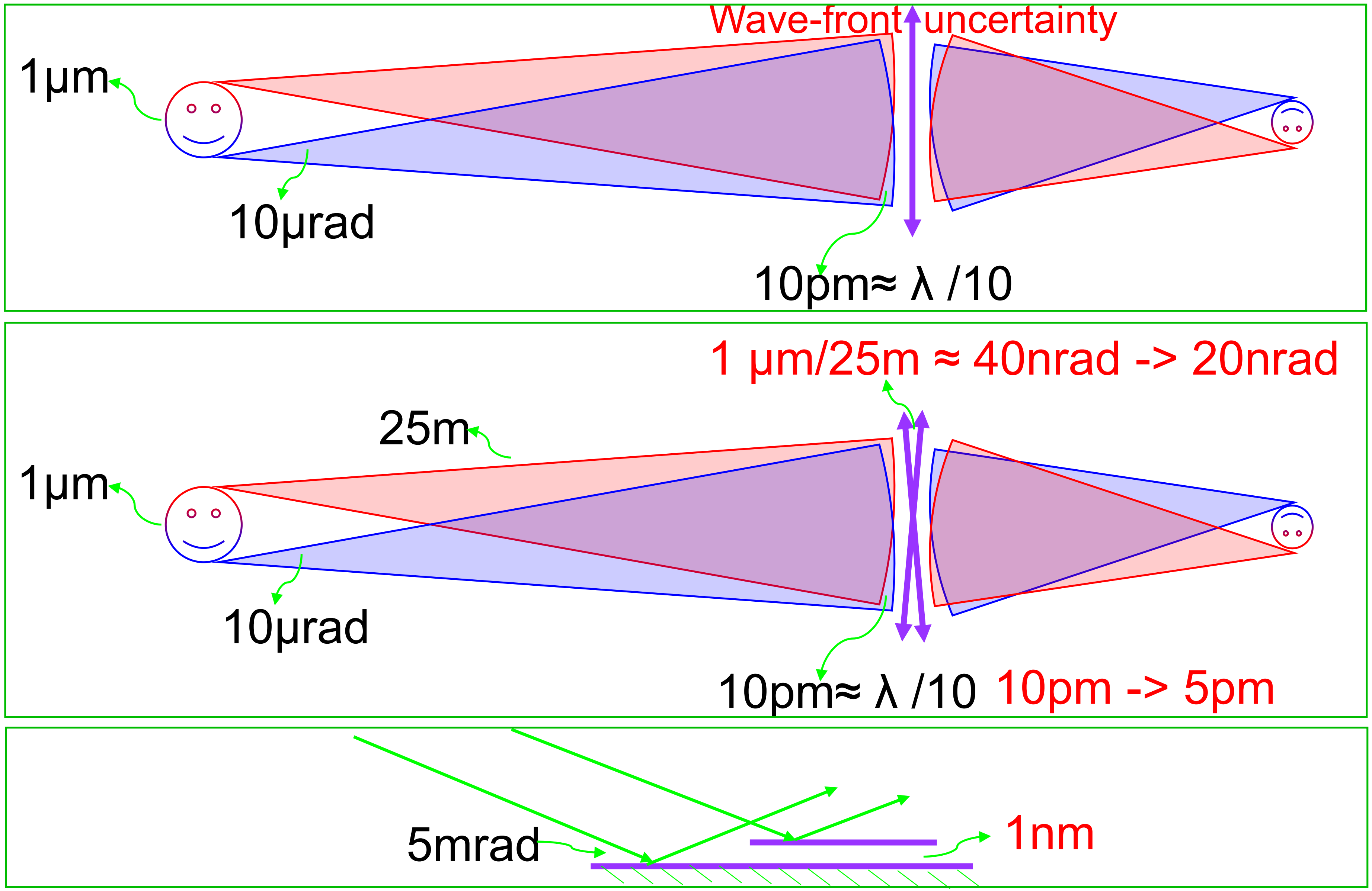
Technical diffraction limit (~25%)

Advanced 3G SR -> HEPS

Coherence ratio ~0.2% -> ~20%

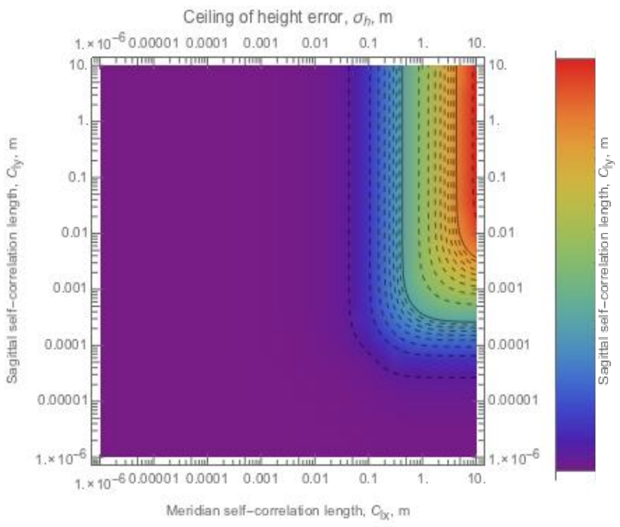
Challenges

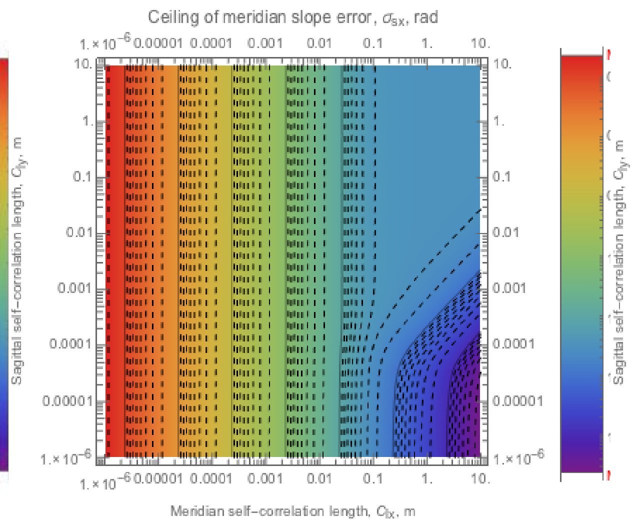
Why dose ~μm size electron beam，require ~sub-nm optics?

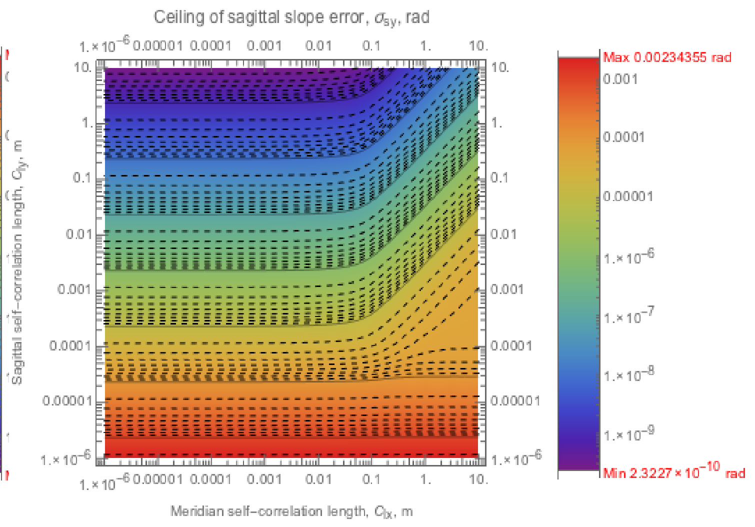


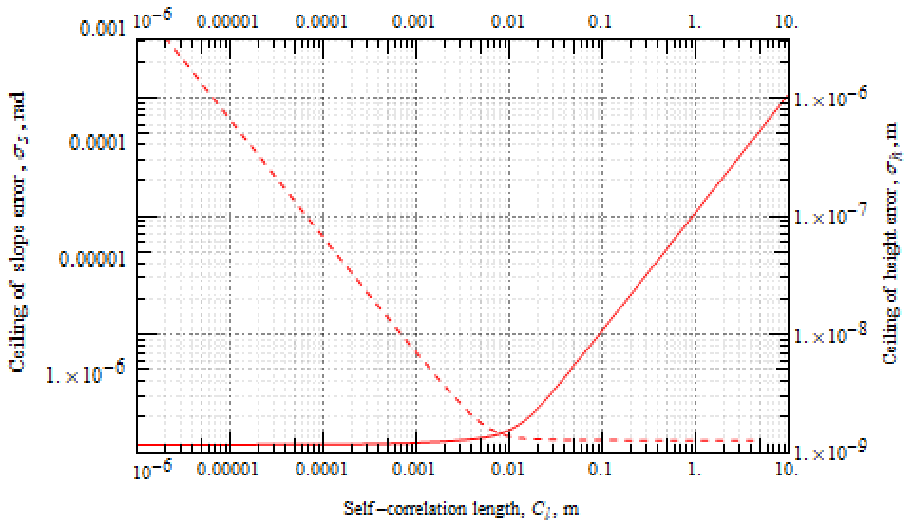
Challenges

Accuracy requirements of HEPS mirror based on partially coherent optics









- ~20nrad for low frequency
- ~1nm for high frequency (Large range)

Challenges

■ R&D of optical elements and equipment

<table>
<tr><th rowspan="2">Optical elements</th><th rowspan="2">🔴 Focusing
🔵 mono.
🟢 correction</th><th rowspan="2">🔴 Reflection
🔵 Diffraction
🟢 Refraction</th><th rowspan="2">Processing</th><th rowspan="2">Metrology</th><th colspan="3">Manipulation</th></tr>
<tr><th>Dynamic</th><th>Thermal</th><th>Environment</th></tr>
<tr><td>Mirror</td><td>🔴🟢</td><td>🔴</td><td rowspan="9">Ultimate precision</td><td rowspan="9">Ultimate accuracy</td><td colspan="3" rowspan="6">Ultimate resolution and stability

Dynamically adjustable</td></tr>
<tr><td>Crystal</td><td>🔴🔵</td><td>🔴🔵</td></tr>
<tr><td>Grating</td><td>🔴🔵</td><td>🔴🔵</td></tr>
<tr><td>Bragg ML</td><td>🔴🔵</td><td>🔴🔵</td></tr>
<tr><td>Laue ML</td><td>🔴</td><td>🔵</td></tr>
<tr><td>Zone plate</td><td>🔴</td><td>🔵</td></tr>
<tr><td>Kinoform Lens</td><td>🔴</td><td>🔵🟢</td><td>Shape</td><td>Cooling</td><td>Temperature</td></tr>
<tr><td>CRLs</td><td>🔴🟢</td><td>🟢</td><td>Posture</td><td>Adjustable</td><td>Vibration</td></tr>
<tr><td>Phase Plate</td><td>🟢</td><td>🟢</td><td>…</td><td>…</td><td>…</td></tr>
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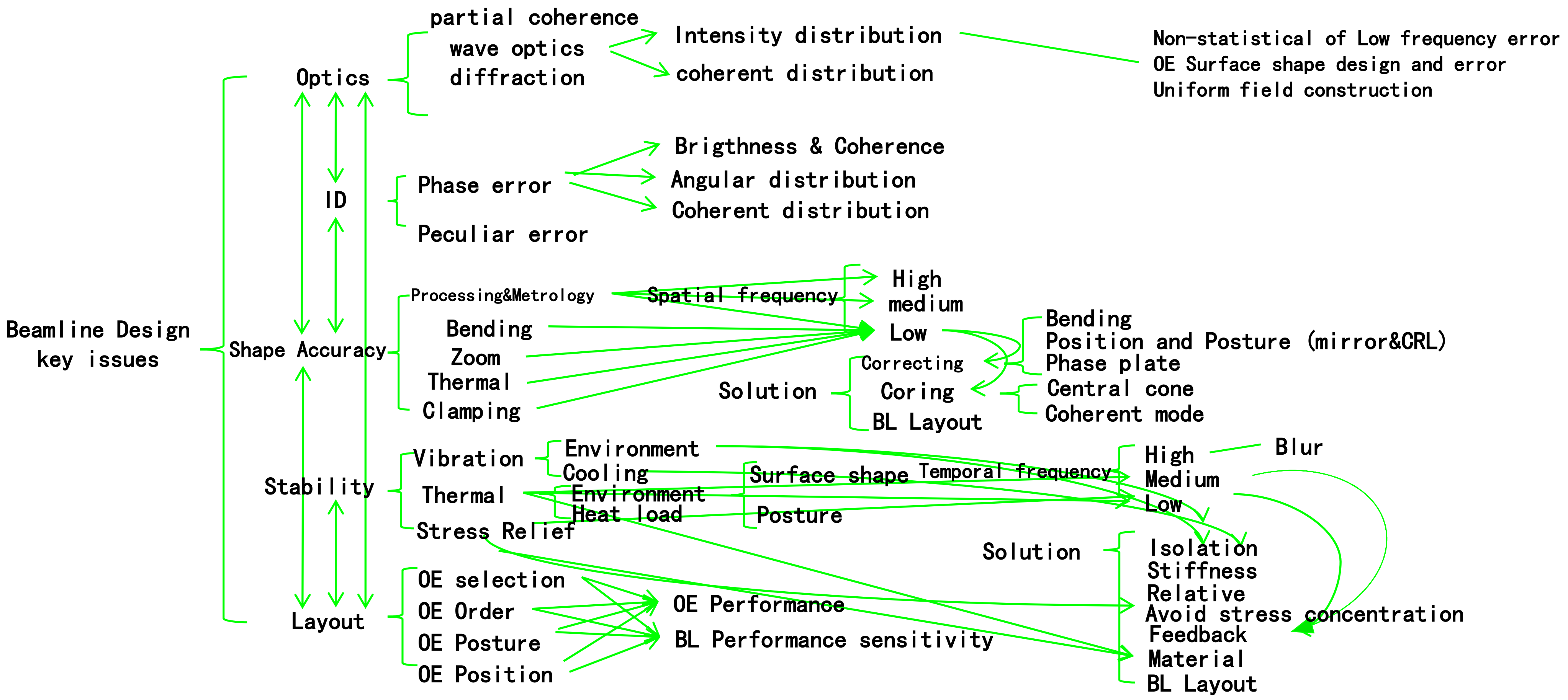
Optics and beamline design

Beamline

■ Revolution in beamline design and construction

- The design concept and organization of the beamline have undergone fundamental changes.
- The transformation towards systematic engineering is the technology integration and optimization under the guidance of the new X-ray optics theory.

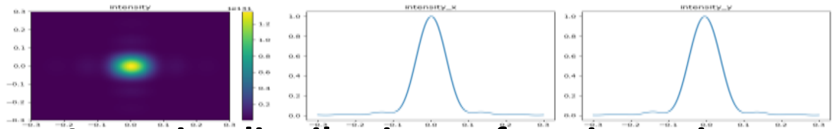


X-ray optics

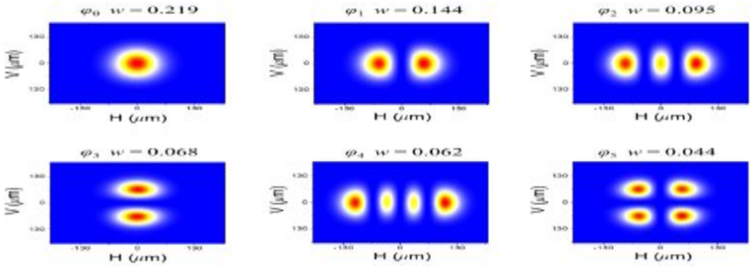
A wave-optics simulation based on a coherent modes decomposition and a wavefront propagation model.
The simulation software, Coherence Analysis Toolbox (CAT)

Used in BL design

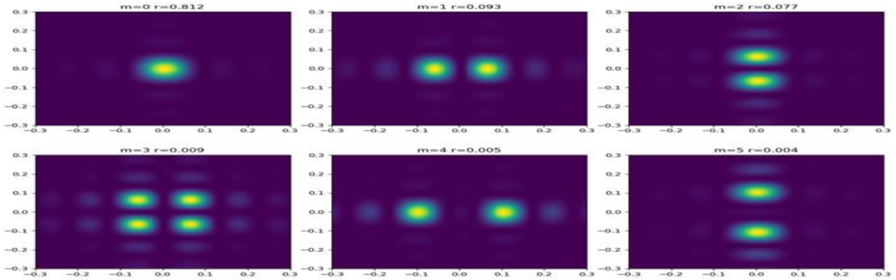
HEPS B4 coherent scattering



Intensity distribution at focusing point



Source (IVU) coherent modes distribution

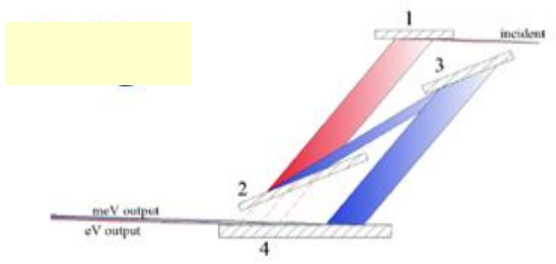


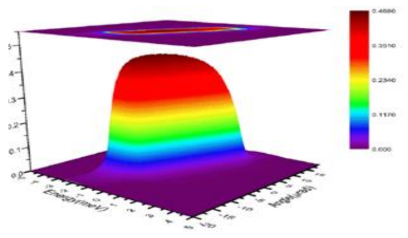
Coherent mode at focusing point

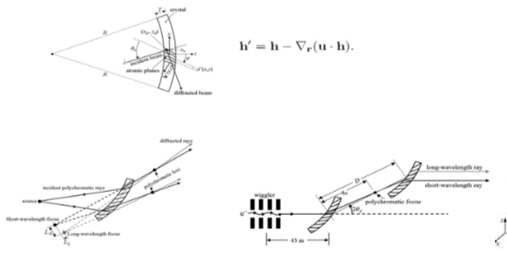
Xu etal. Optical Express 2022, 30, 7625

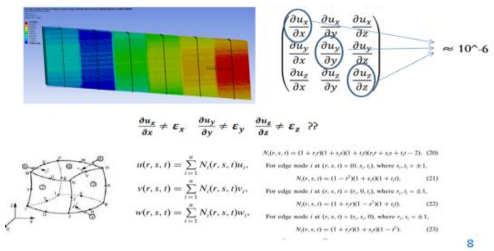
Dynamical diffraction theory

Developing a general numerical framework for X-ray diffractive optics based on the Takagi–Taupin (TT) dynamical theory with a general integral system of the TT equations formed for the FEA

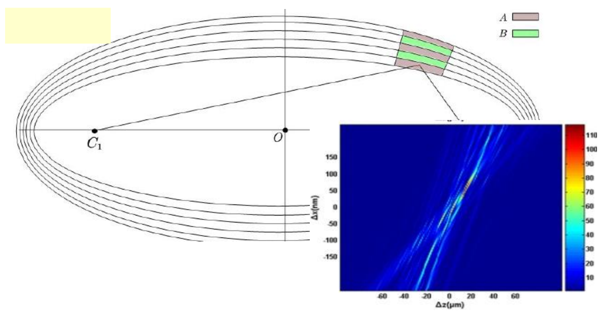


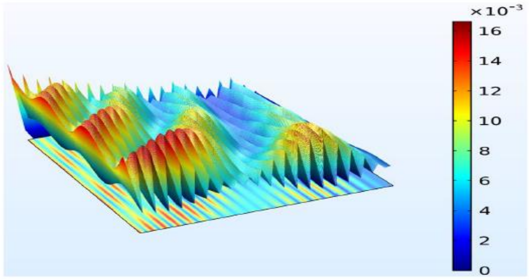


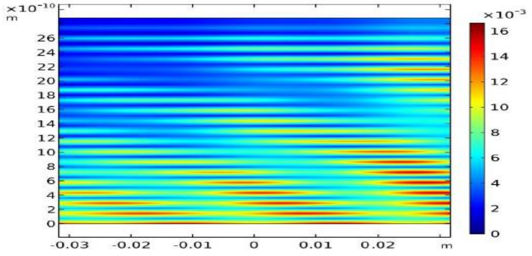




Used in HEPS-TF and HEPS
For high-energy-resolution/high-energy monochromators designs



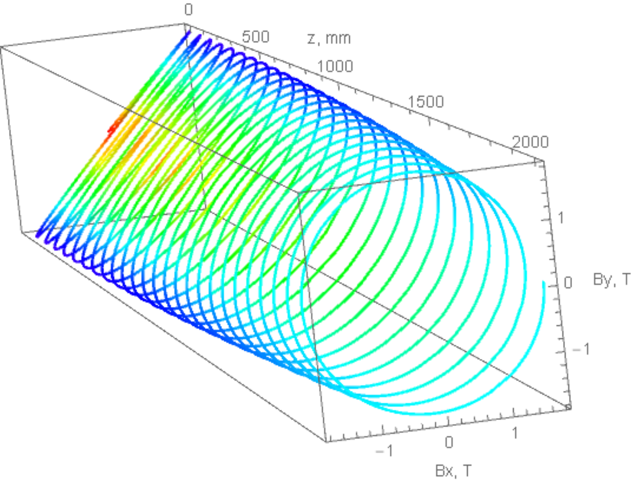


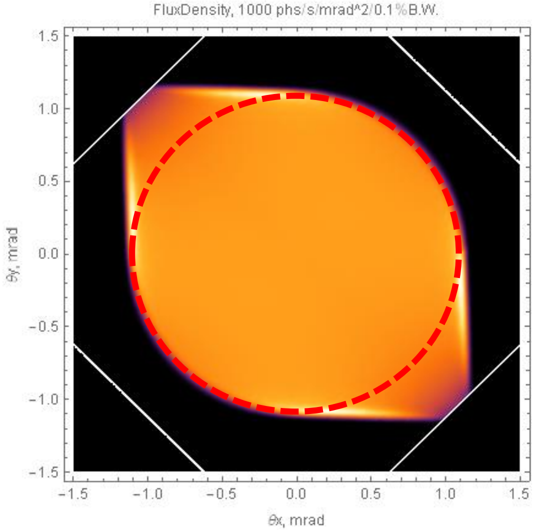


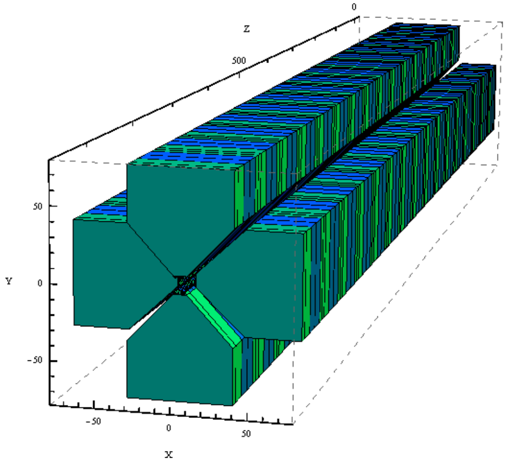
Also used in HEPS-TF and HEPS
For multilayer devices in B2 nano-probe/B3 dynamic structure/B6 high pressure

Yuhang Wang, Optics Express 28（2020）

Mango: A new type of Wiggler for Large FOV Imaging







Magnetic field

Flux angle distribution in FOV

Delta type magnetic structure

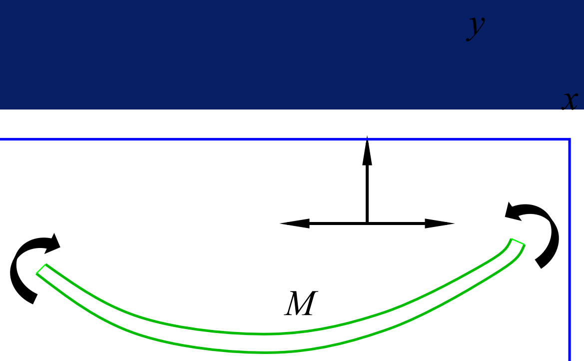
To be published

R&D status of optics technology

Developing the theories of bent mirrors

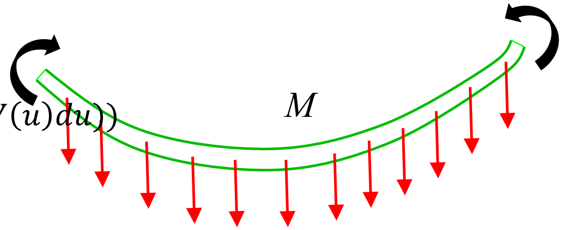
- **Basic Theory:**
  - Pure Bent Beam curvature

$$y''(x) = {M(x)}/{E\ I(x)}$$



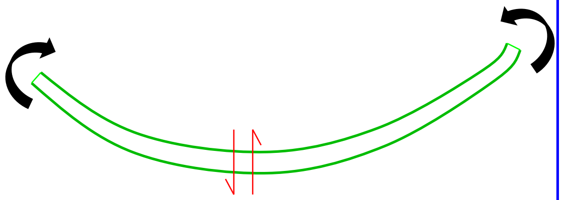
- Extra moment from gravity:

$$M_g(x) = \frac{g\rho_m T}{4L}\left(-4L\int_x^{\frac{L}{2}}(u-x)W(u)du + (L-2x)\left(L\int_{-\frac{L}{2}}^{\frac{L}{2}}W(u)du + 2\int_{-\frac{L}{2}}^{\frac{L}{2}}uW(u)du\right)\right)$$



- Extra transverse shear deformation

$$s_b(x) \equiv \frac{-M_0 k_M}{W(x)*TG},\quad s_g(x) \equiv \frac{g\rho_m\left(\int_x^{\frac{L}{2}}\left(-\frac{L}{2}+u\right)W(u)\,du + \int_{-\frac{L}{2}}^{x}\left(\frac{L}{2}+u\right)W(u)\,du\right)}{GLW(x)}$$

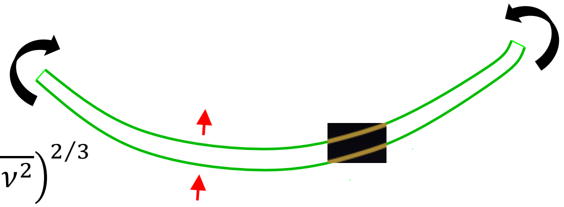


- Extra transverse deformation:

$$h_c(x) \equiv \frac{T^2\ \nu}{12}\frac{M(x)}{E\ I(x)}$$

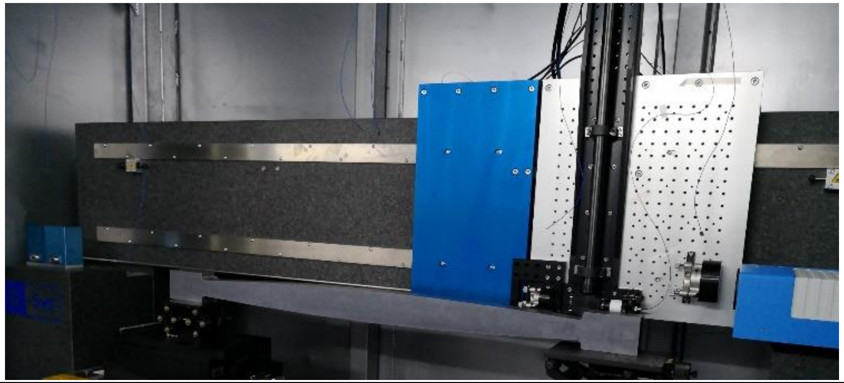
- Curvature (including Influence of saddle deformation)

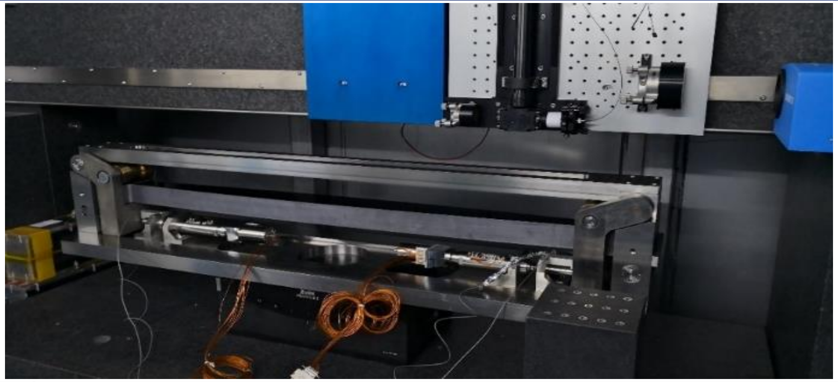
$$y''(x) = \frac{-2\times 5^{2/3}\ E^{2/3}T^{8/3} + 2\times 5^{1/3}\left(9M(x)W(x)\nu + \sqrt{5E^2T^8 + 81M(x)^2W(x)^2\nu^2}\right)^{2/3}}{W(x)^2\nu\left(ET\left(9M(x)W(x)\nu + \sqrt{5E^2T^8 + 81M(x)^2W(x)^2\nu^2}\right)\right)^{1/3}}$$



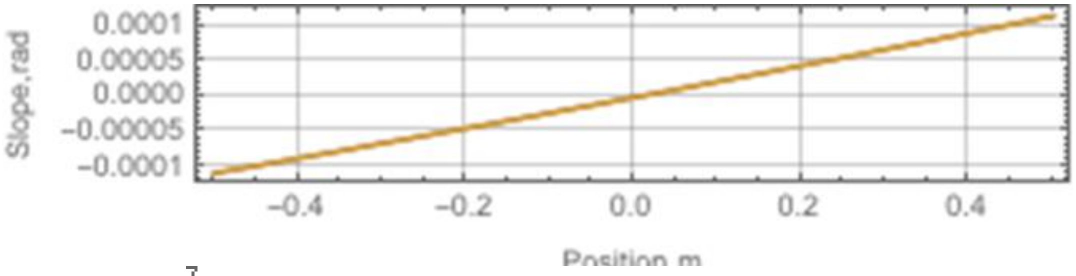
To be published

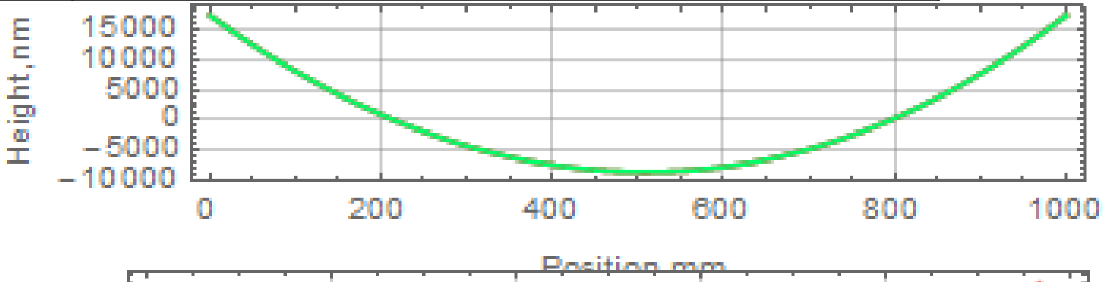
1m ellipitical bent mirror

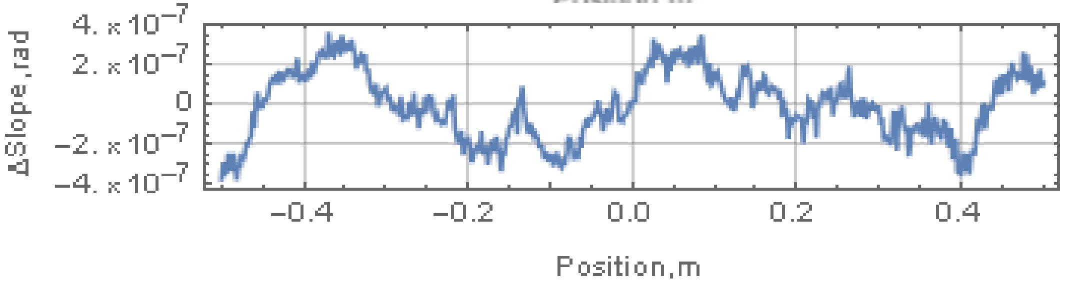




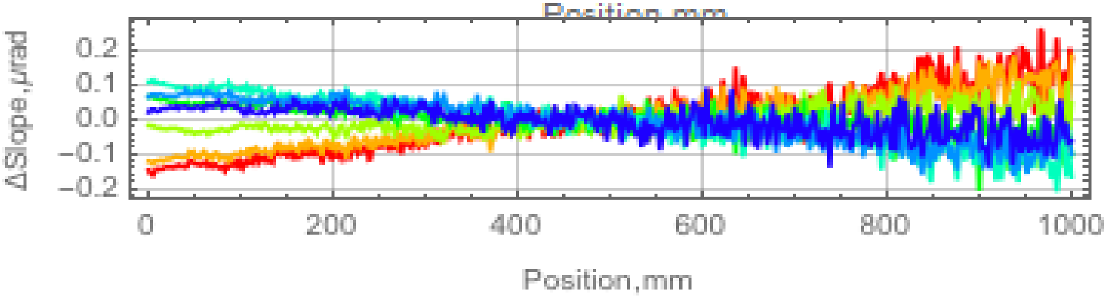
	Measuring Results
Effective length	1000mm
Elliptical Bending shape accuracy	0.17μrad (elliptical)







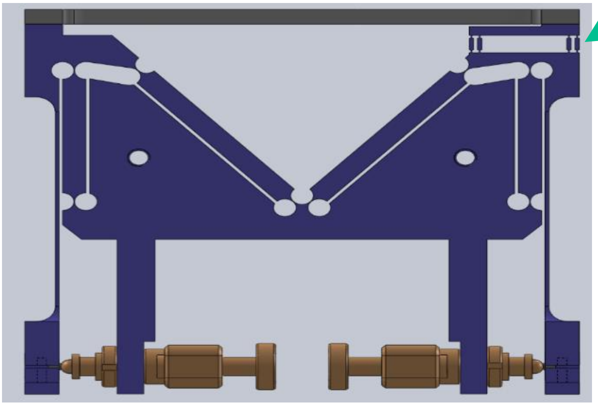
Bending shape accuracy RMS 0.17μrad

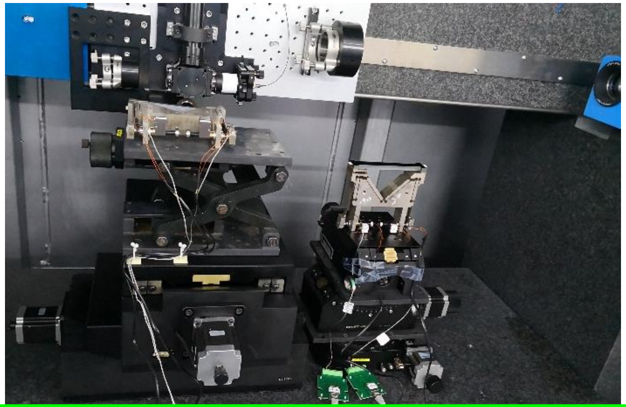


Stability: 72h, deformation 66nrad RMS

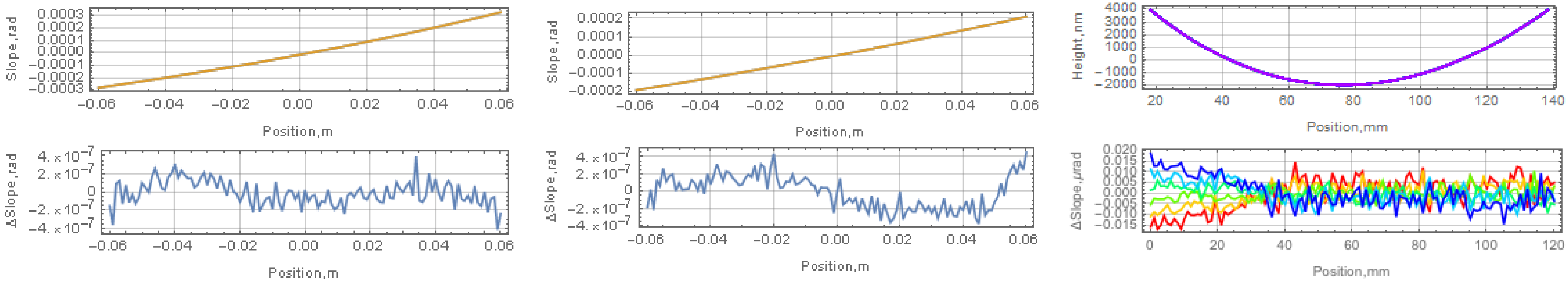
Short bent mirror

We use this longitudinal translation structure firstly in the world.





	Measuring Results
effective length	120mm（146mm total）
Bending Shape	Designed Ellipse(40m, 120mm, 3mrad)
Bending shape accuracy (Bent mirror shape – Bare mirror shape – Designed ellipse)	0.13μrad(HFM) 0.19μrad (VFM)

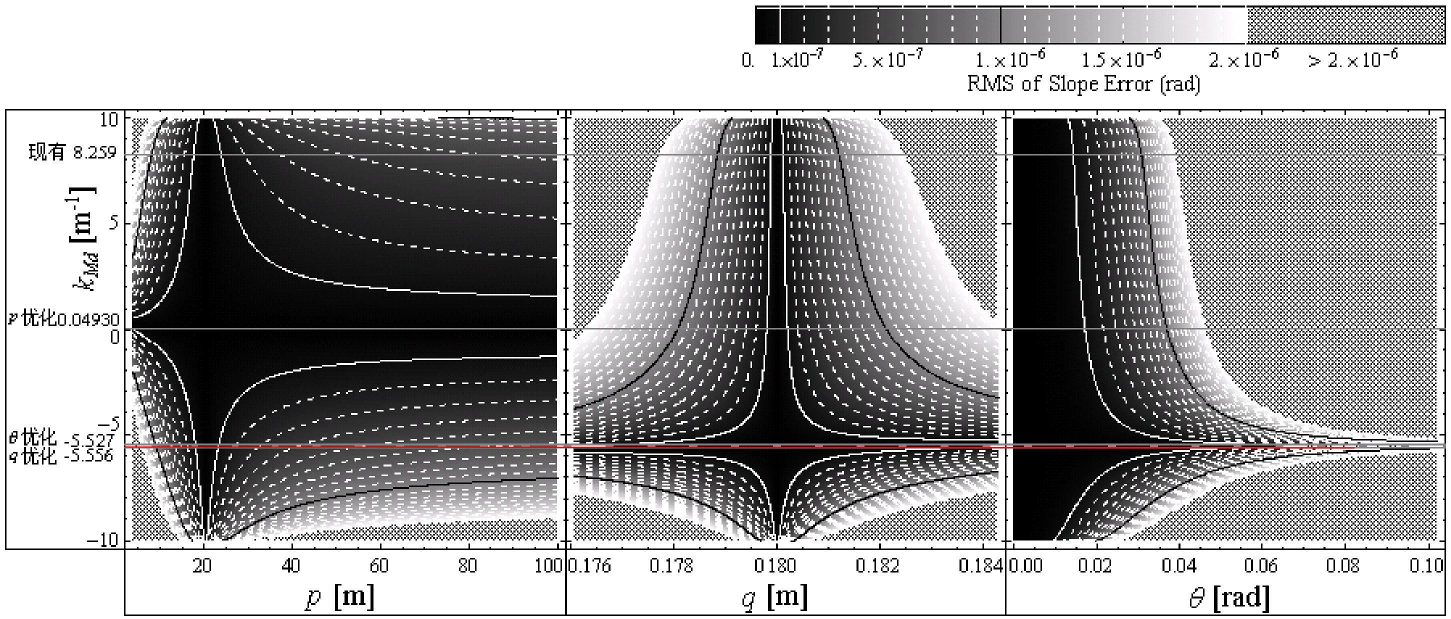


Bending shape accuracy RMS 0.13μrad & 0.19μrad   Stability：72h，**transformation** 6nrad RMS

Next Bending Techniques in HEPS

—— Zoom capability and optimized design

For example: p=20.3m, q=0.18m, L=0.2m, θ= 2.2mrad HFM

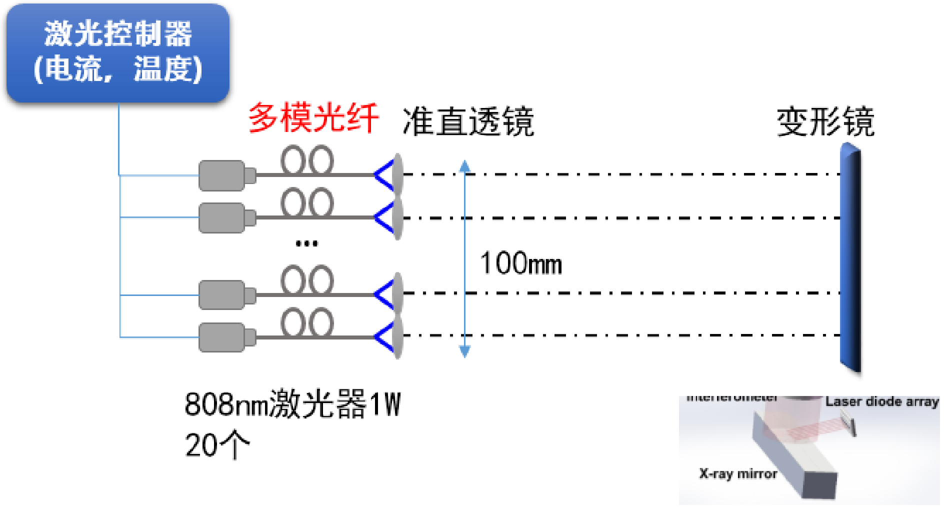


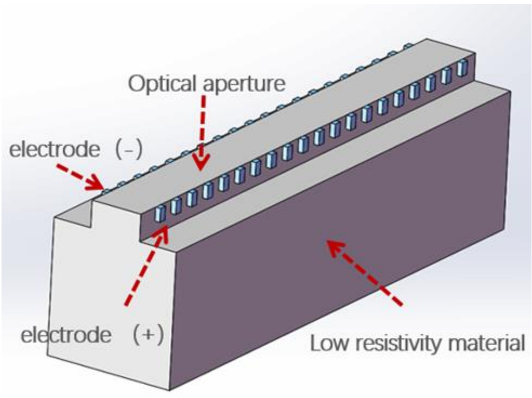
$$k_{Md} = -\frac{\cos\theta_d}{q_d} - \frac{\sin\theta_d \tan\theta_d}{p_d} \approx -\frac{1}{q_d}$$

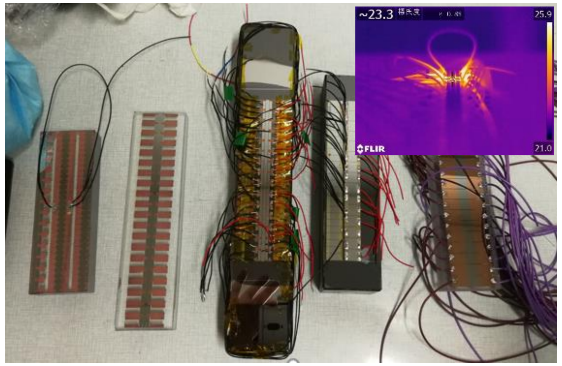
Subscript “d” means design value.

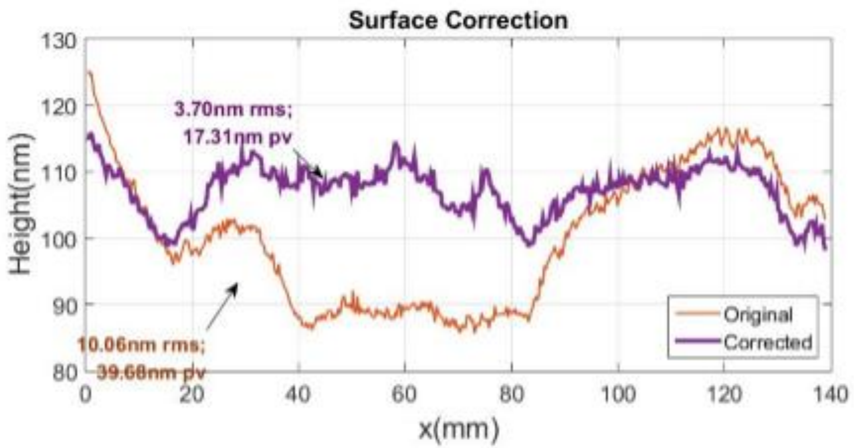
To be published

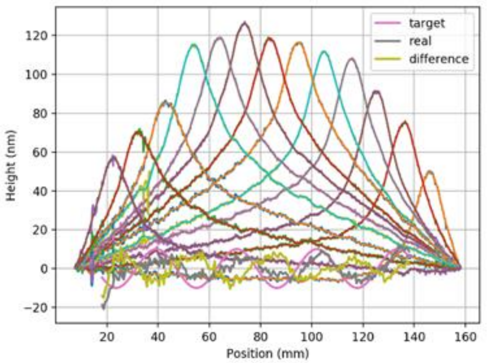
Active mirror

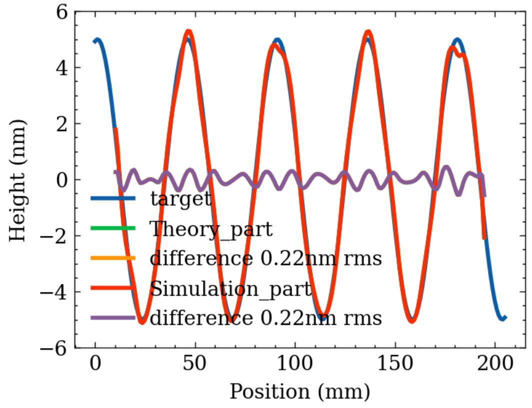










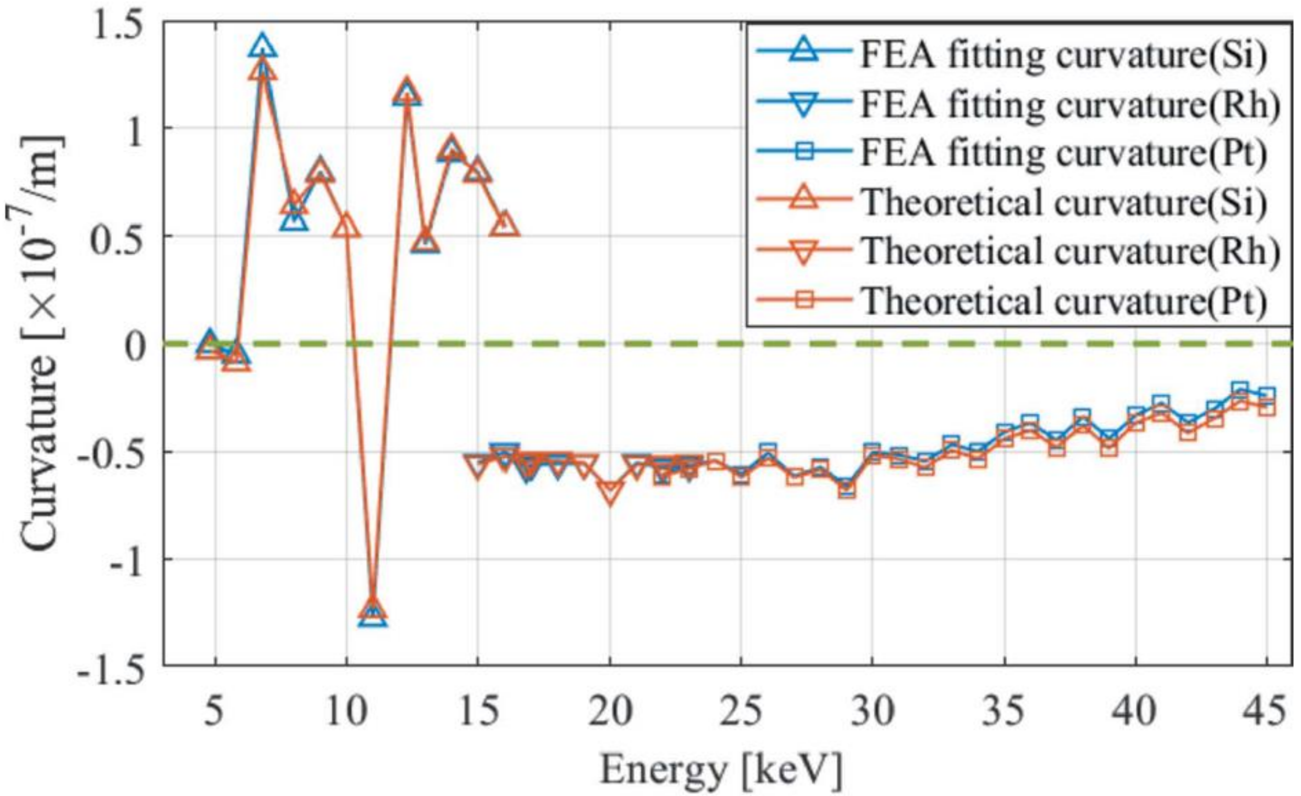


0.2nm RMS

Fugui Yang, Ming Li*, Lidan Gao, Weifan Sheng, Peng Liu, and Xiaowei Zhang, "Laser-heating-based active optics for synchrotron radiation applications," *Opt. Lett.* 41, 2815-2818 (2016)

Thermal management

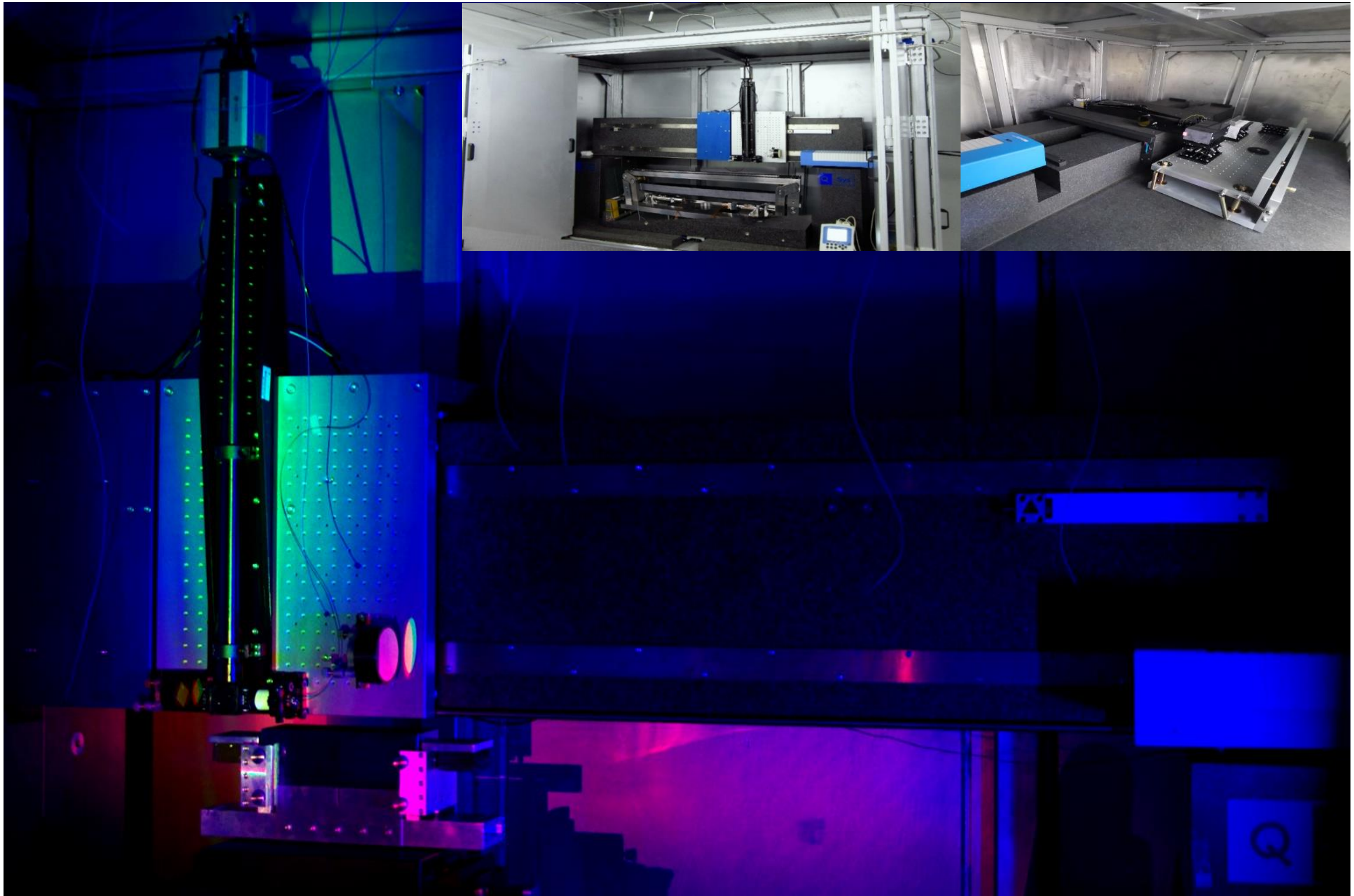
- Highly efficient thermal deformation optimization method
- Smart-cut mirrors over the entire photon energy range
- By optimizing the notches of water-cooled white-beam mirrors, the RMS of the curvatures of the thermal deformation of the white-beam mirror over the entire photon energy range is minimized. Considerably simplifies design of all of the water-cooled white-beam mirrors



The method has been used for all the thermal deformation analysis of all mirrors.

Shaofeng Wang‡, Dongni Zhang‡, Ming Li*, Lidan Gao, Minwei Chen, Fugui Yang and Weifan Sheng, “Highly efficient thermal deformation optimization method for smart-cut mirrors over the entire photon energy range” J. Synchrotron Rad. (2022). 29, 1152–1156

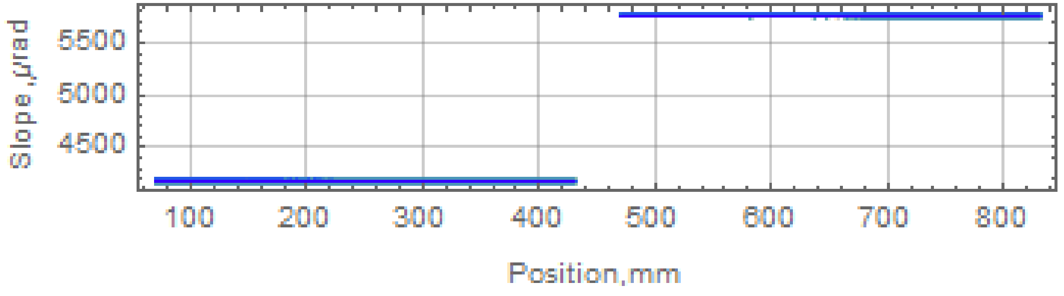
Optical metrology (Flag-type Surface Profiler, FSP)



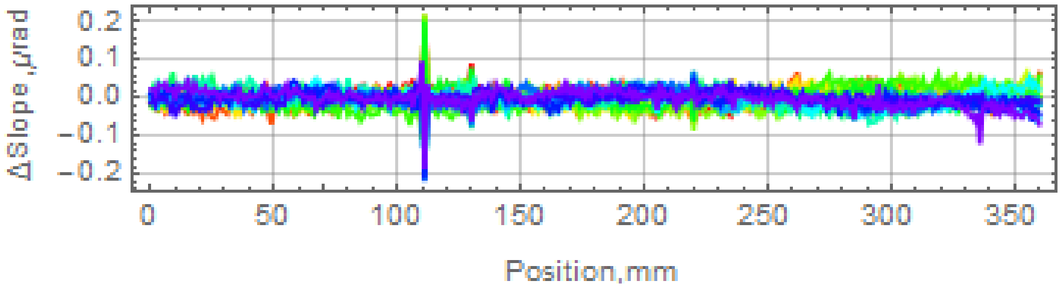
To be published

Accuracy of measurement for plane/curved mirror

360mm plane mirror measurement: tilt 1.6mrad and translate 400mm, scan 8+8 times

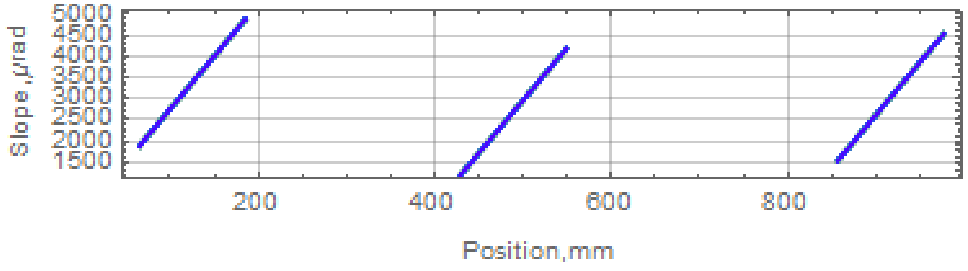


Spatial resolution 1mm
(Slope error is sensitive to spatial resolution)

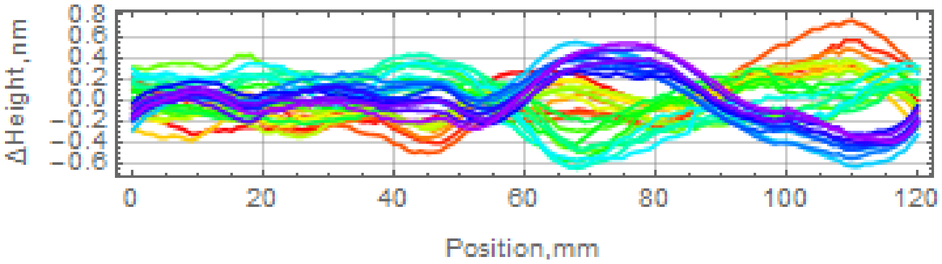


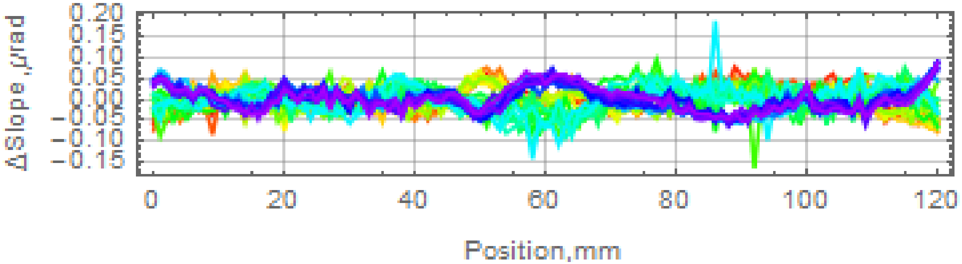
Accuracy for plane mirror measurement：
RMS 24.5 nrad

3mrad range 120mm curved mirror measurement: tilt 0.35mrad / 0.7mrad and translate, scan 10+10+10 times



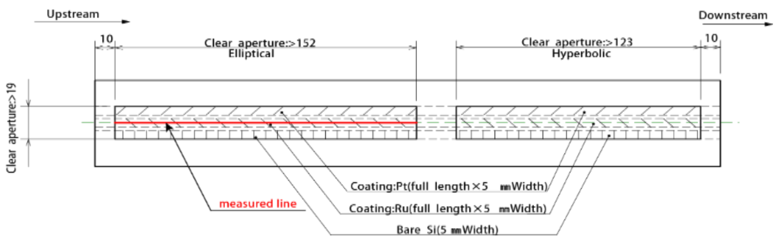
Accuracy for Curved mirror：
RMS 29.0 nrad / RMS 0.23nm



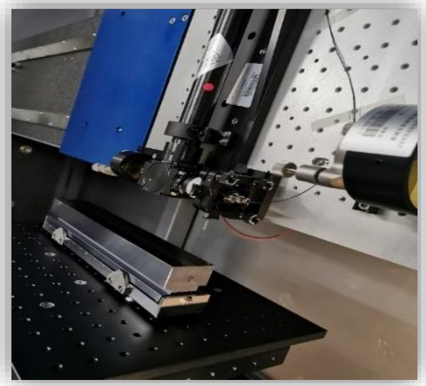


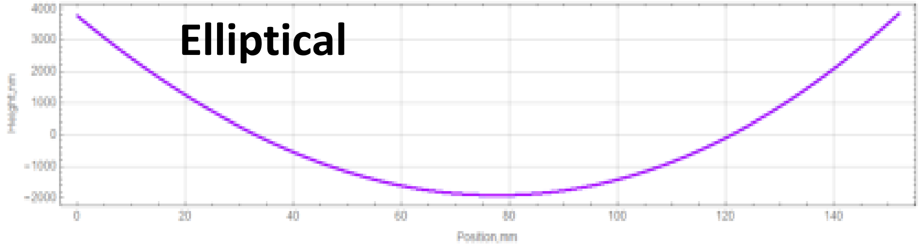
Measurement of the mirror of B4 beamline (Curve, 0.1nm RMS)

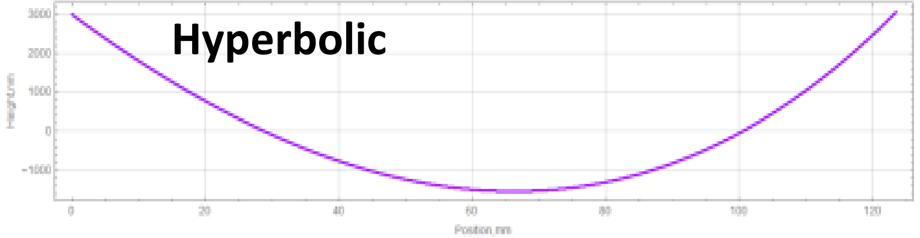
Length 415mm



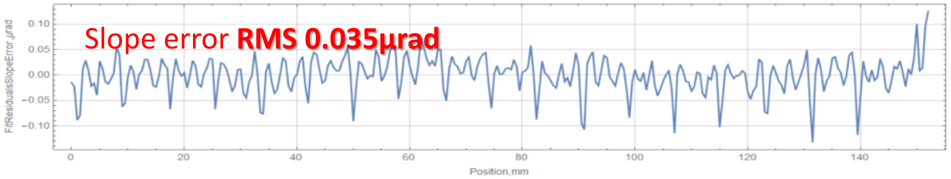
Mirror	Shape	Parameter	Specification	Measurement
B4-Wolter	Elliptical	Slope error RMS	50nrad	35nrad
	Hyperbolic			41nrad
	Elliptical	Height error RMS/PV	0.4nm / 6nm	0.11nm/0.59nm
	Hyperbolic			0.12nm/0.7nm

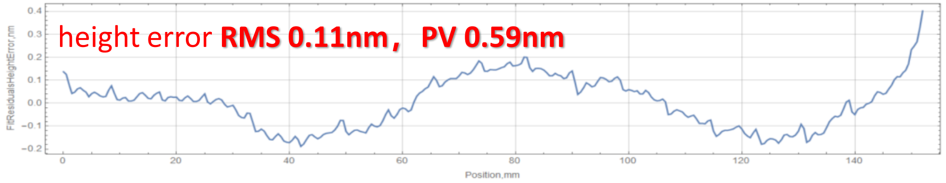




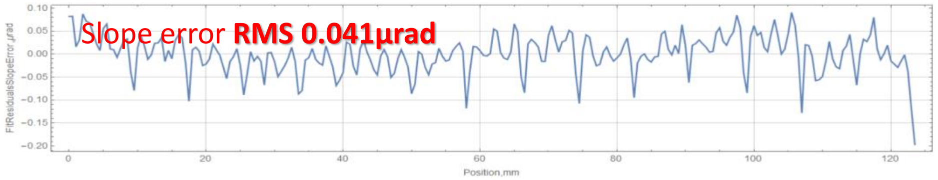


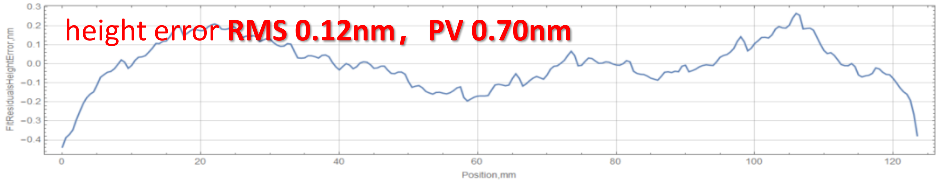
1mm resolution





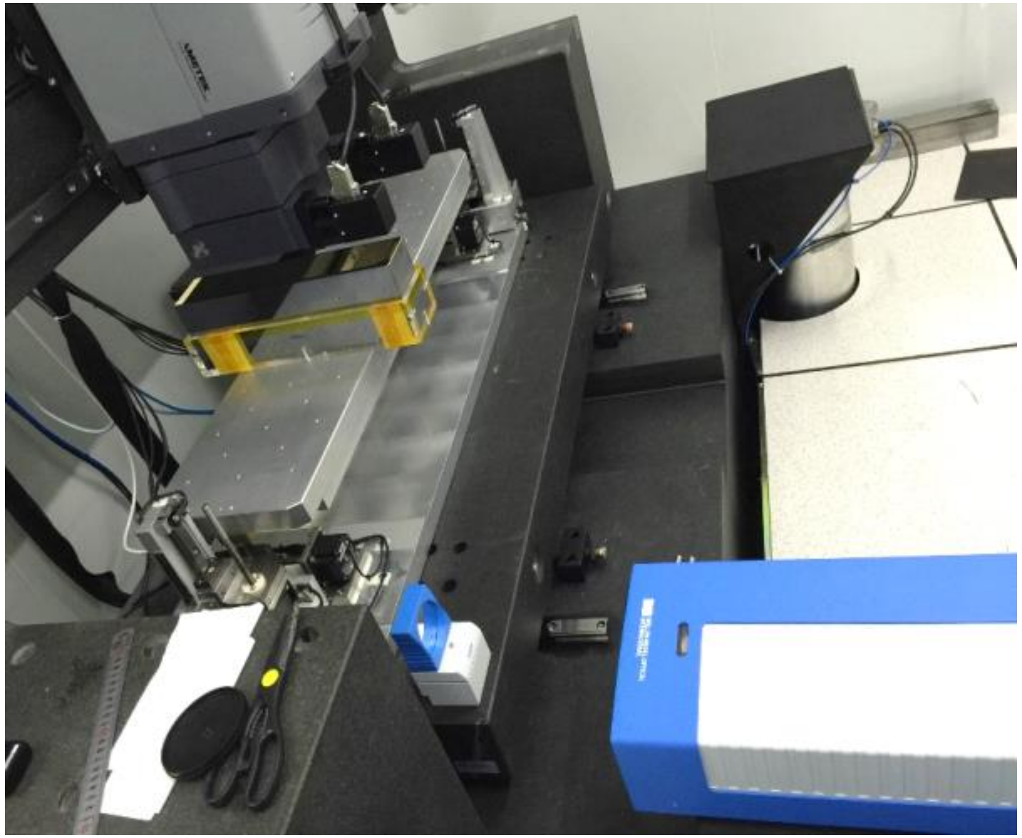
1mm resolution



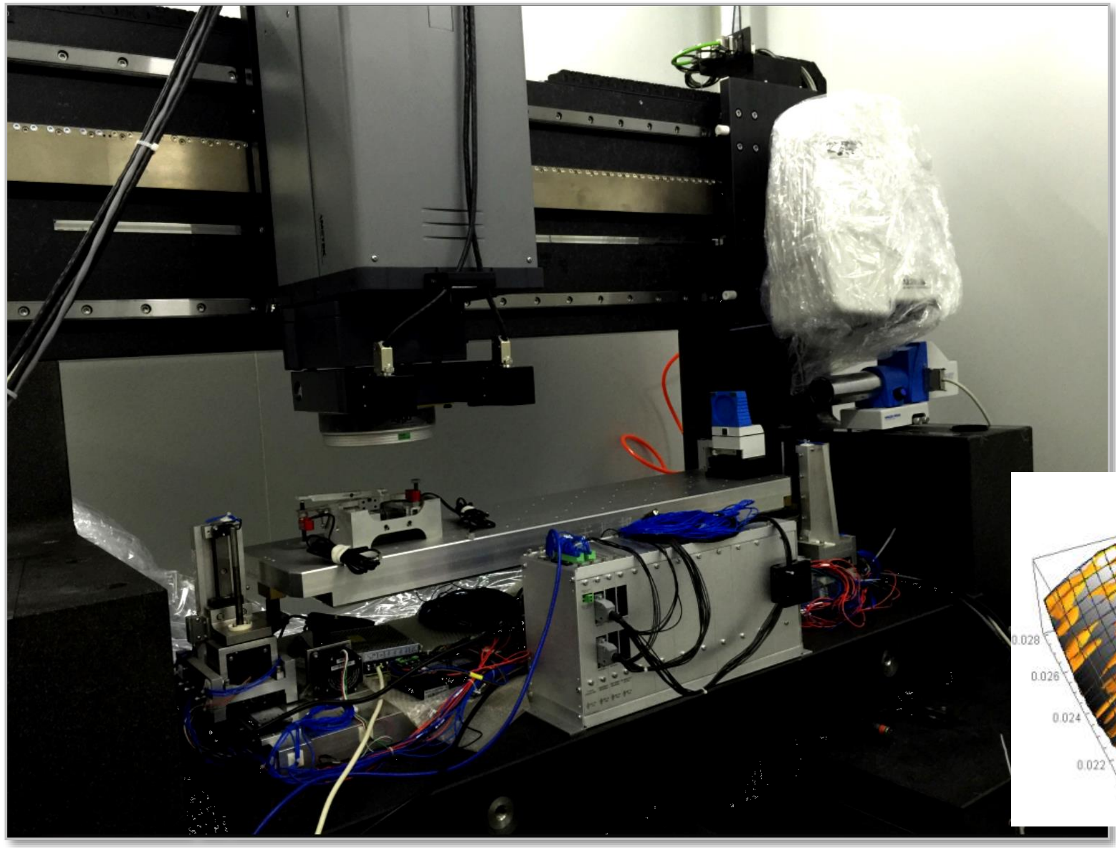


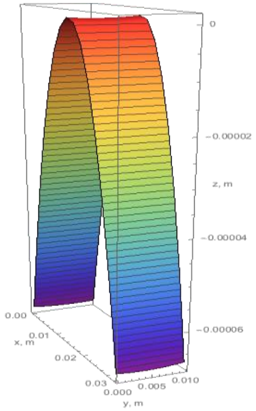
Stitching Interferometer

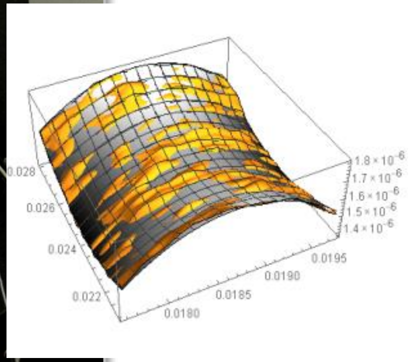
- **Surface metrology during fabrication**



Proposed SI based on angular measurement

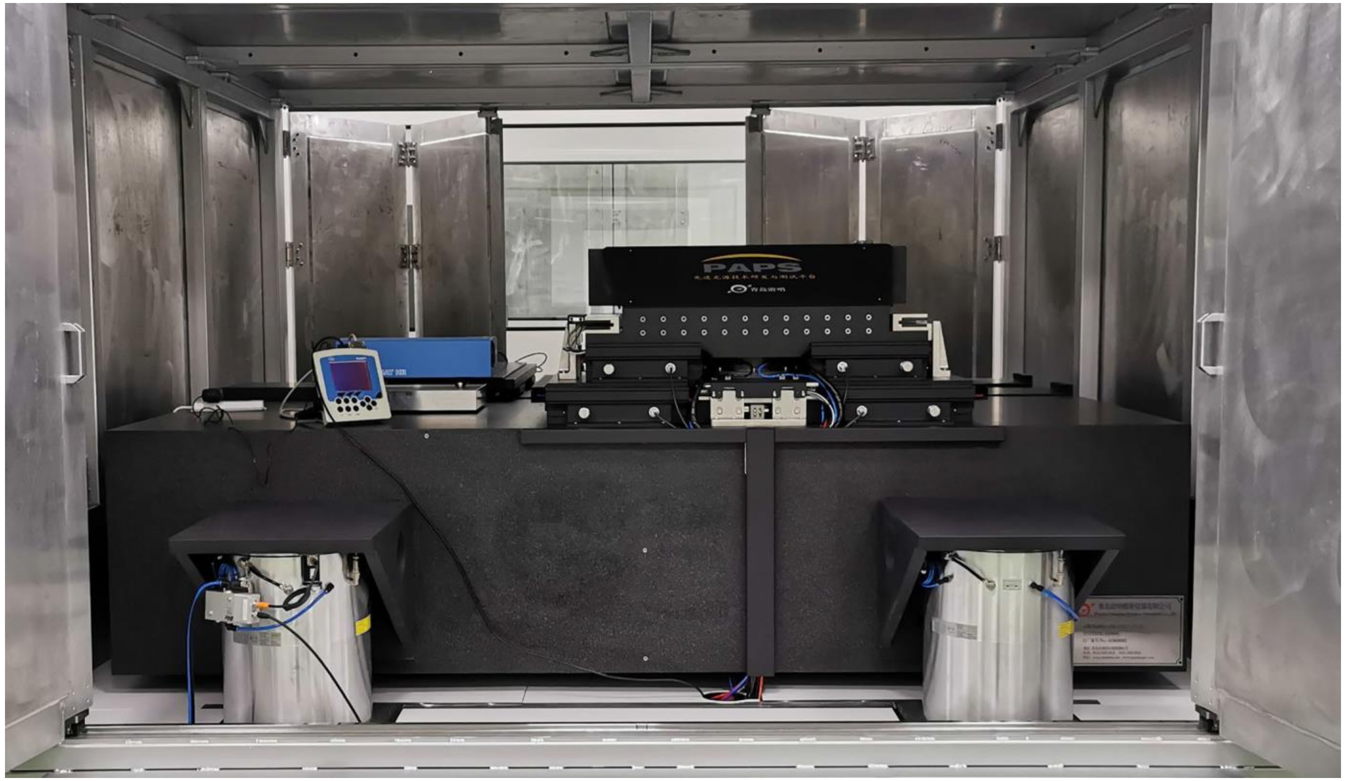


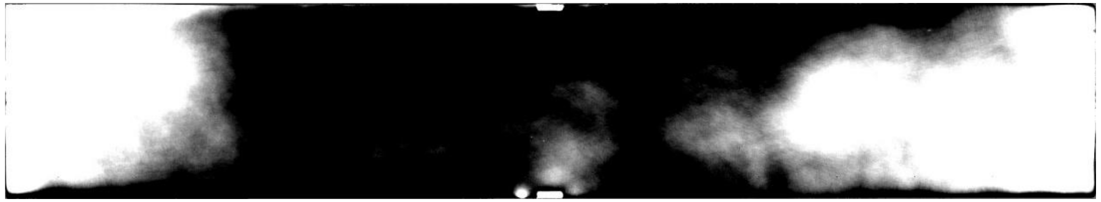




The proposed θ-R method is used in metrology of severe curvature crystal

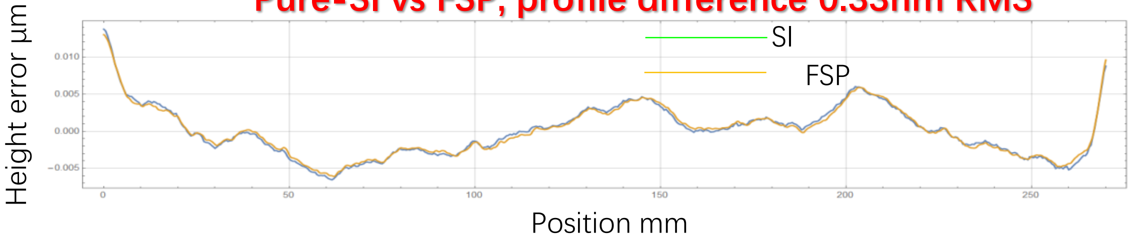
Stitching Interferometer





Stitching result

Pure-SI vs FSP, profile difference 0.33nm RMS



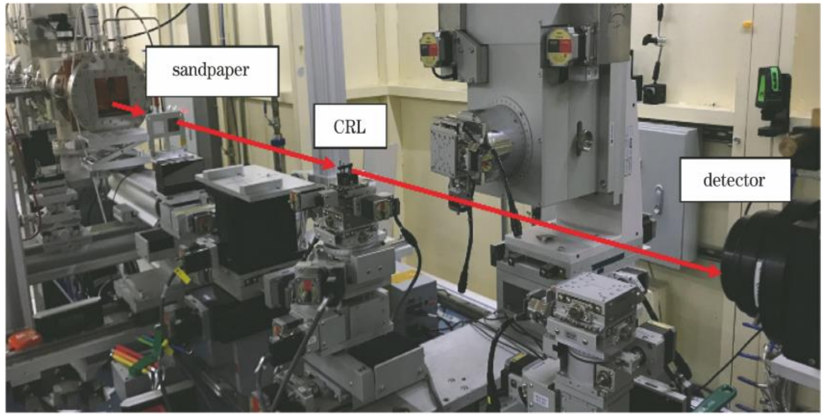
FSI vs FSP, profile difference 0.12nm RMS

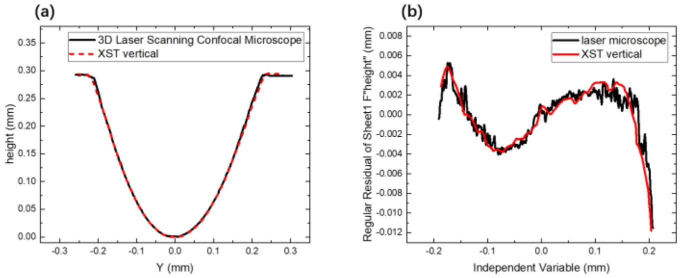
A Frequency-decomposed Stitching Interferometer (FSI) has been proposed and developed , which can provide feedback for mirror processing with sub-nanometer accuracy.

To be published

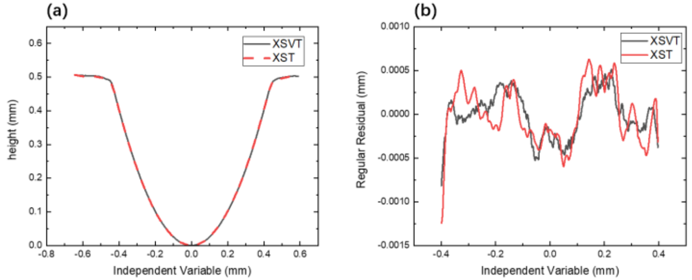
Near-Field Speckle Based Wavefront Metrology

- **Develop speckle based wavefront metrology at SSRF**



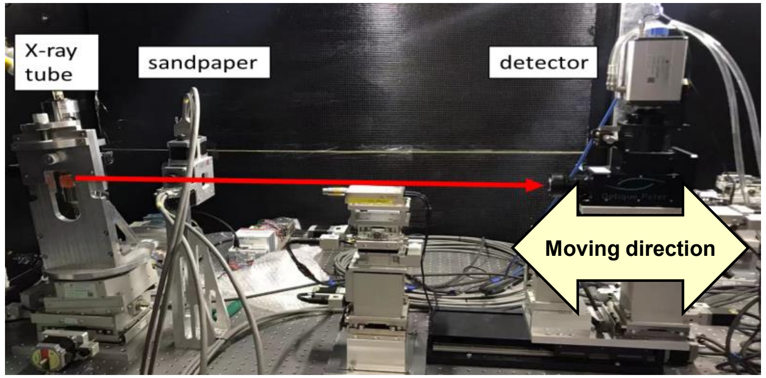


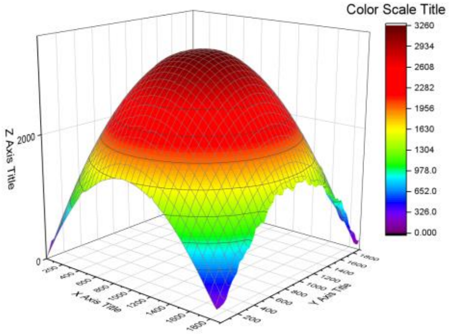
CRL measurement results compare with confocal laser scanning microscopy, (a)Height profile, (b)Residual error



Measurement results comparison between XST method and XSVT method for CRL sample, (a) Height profile, (b)Residual error

- **Develop speckle based wavefront metrology based on X-ray microfocus source**

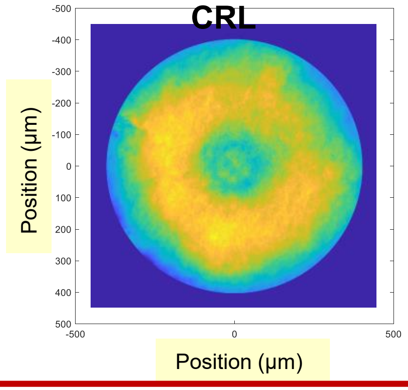




Reconstructed wavefront

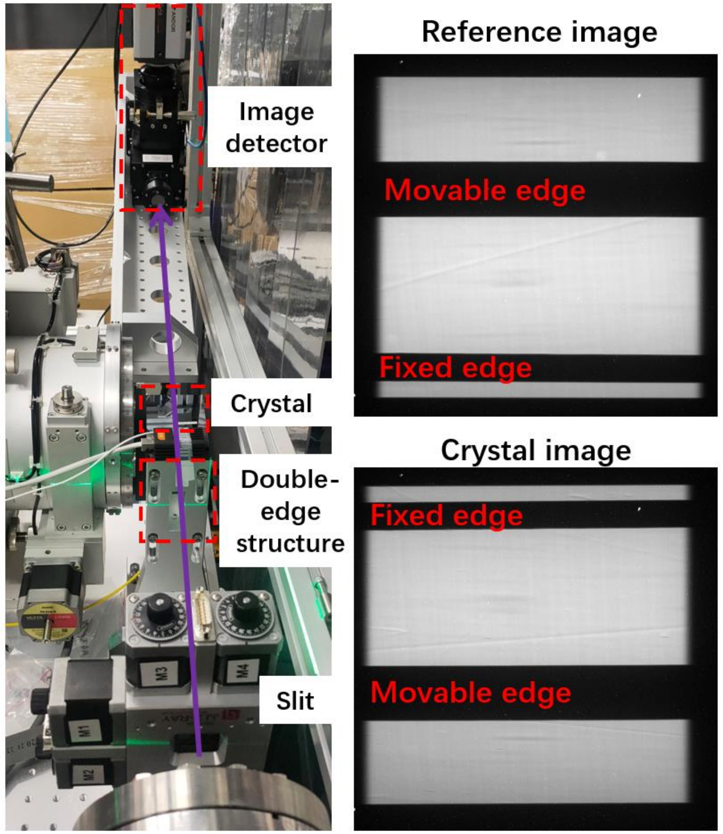
Use XSVT method for commercial CRL checking ⇨

Residual error of CRL

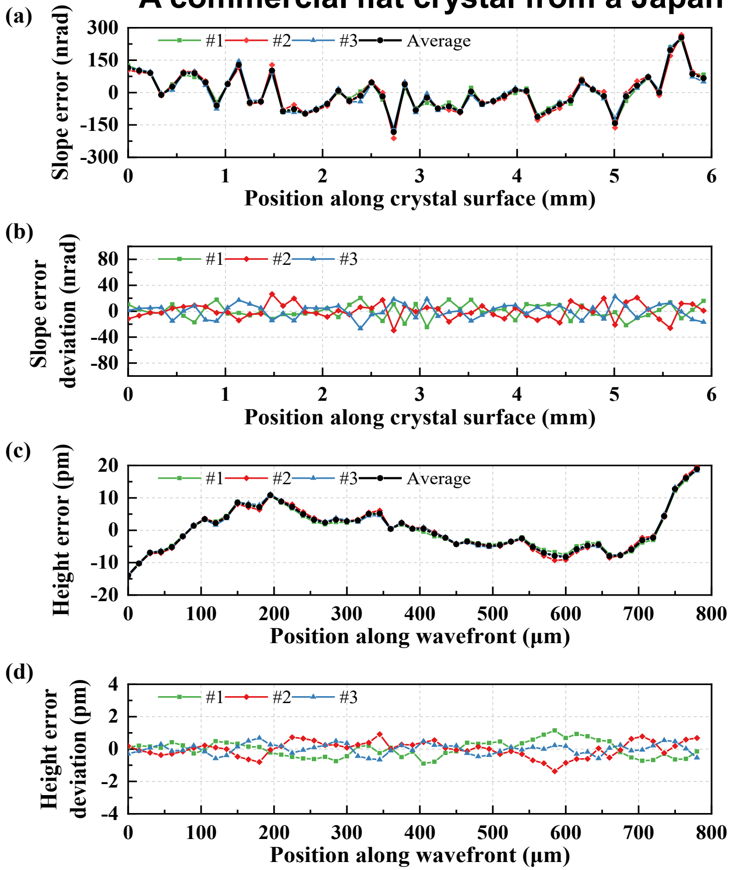


Online wavefront measurement

Double-edge scan wavefront measurement



A commercial flat crystal from a Japan company (EXCEED)



Average slope errors:

82.08 nrad RMS

Repeatability:

13.51 nrad RMS

Average wavefront height error:

6.71 pm RMS

Repeatability:

0.54 pm RMS

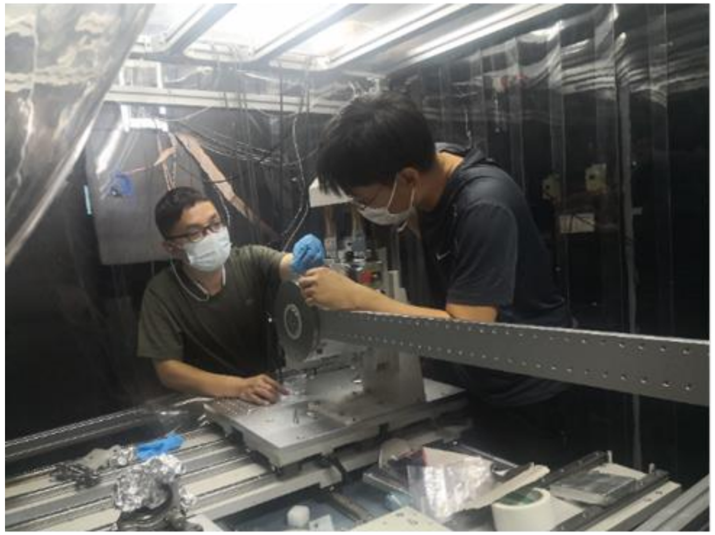
(a) Equivalent Bragg diffraction surface slope error profiles of three measurements and average profile. (b) The deviations from the average of the three measurements slope error profiles. (c) Wavefront height error profiles of three measurements and average profile. (d) The deviations from the average of the three measurements wavefront height error profiles.

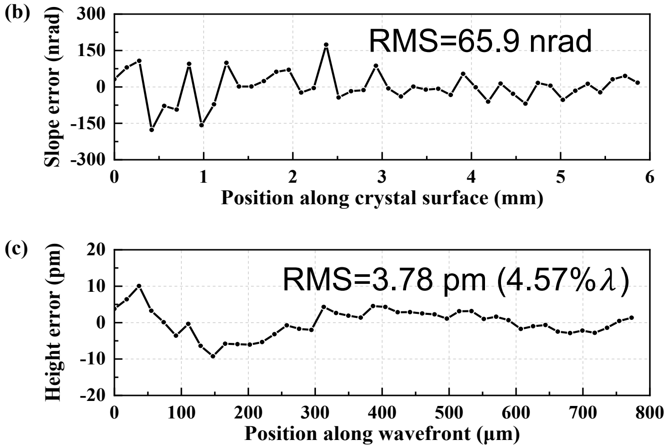
- **Solving the problems of coherence, stability, distortion of wavefront in 1GSR**
- **Successful application in BSRF <1pm precision**

Measurement precision ~14 nrad and <1 pm RMS

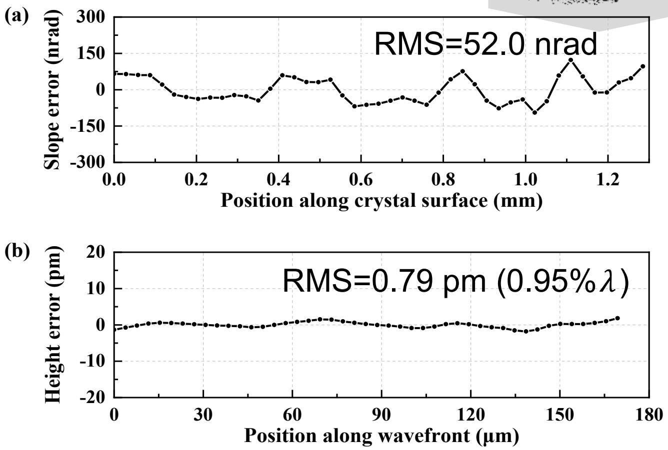
To be published

Fabrication of wavefront-preserved crystals

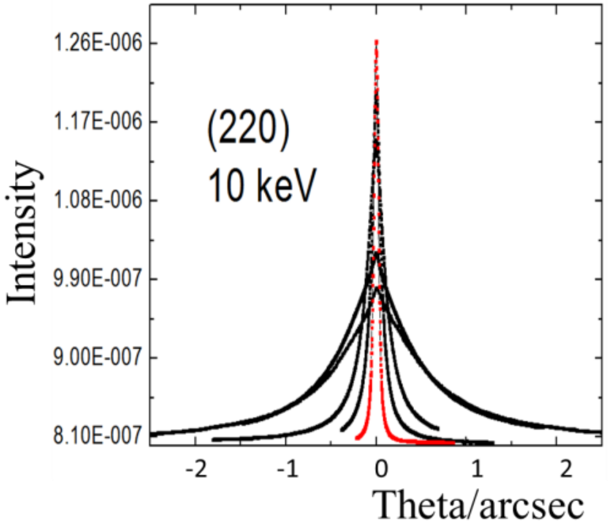




(a) Equivalent Bragg diffraction surface slope error profile in ~6 mm range; (b) Wavefront height error profile.



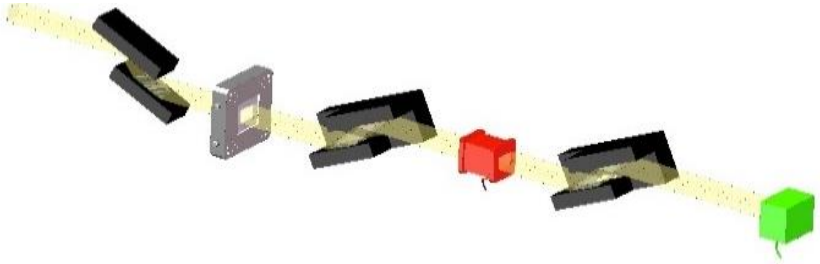
(a) Equivalent Bragg diffraction surface slope error profile in ~1.3 mm range; (b) Wavefront height error profile.



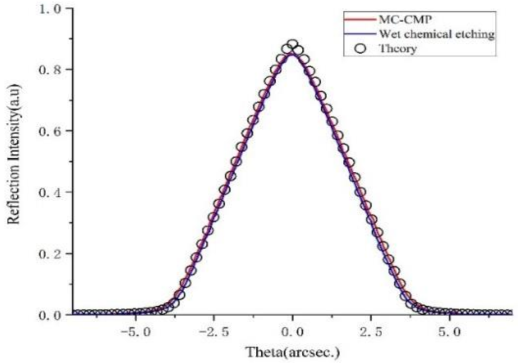
Crystal	Wavefront
BSRF	65.9±6.5nrad
From Japan	81.7±1.1nrad
From France	185.8±10.3nrad

The quality of crystals satisfy the requirements of 4GSR.

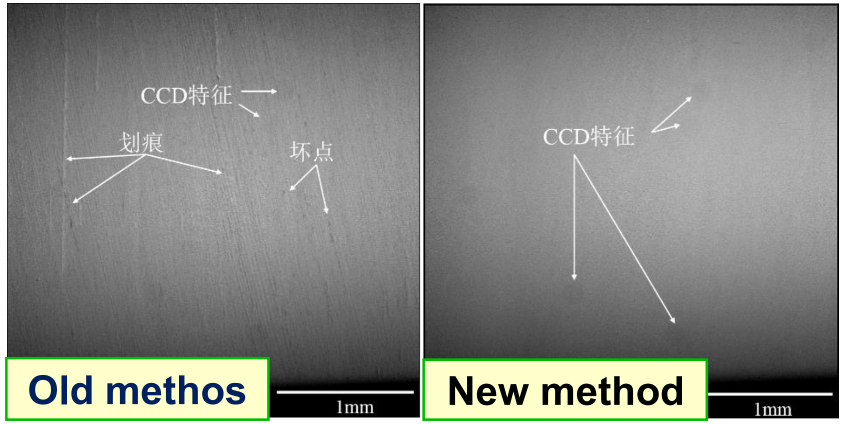
Channel-Cut crystal



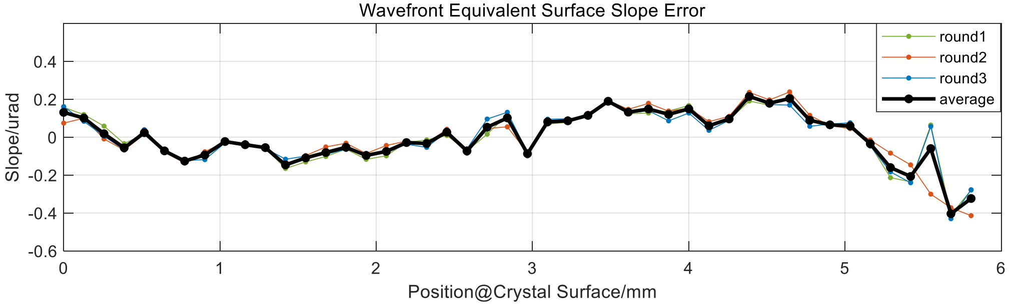
Rocking curve measurement layout

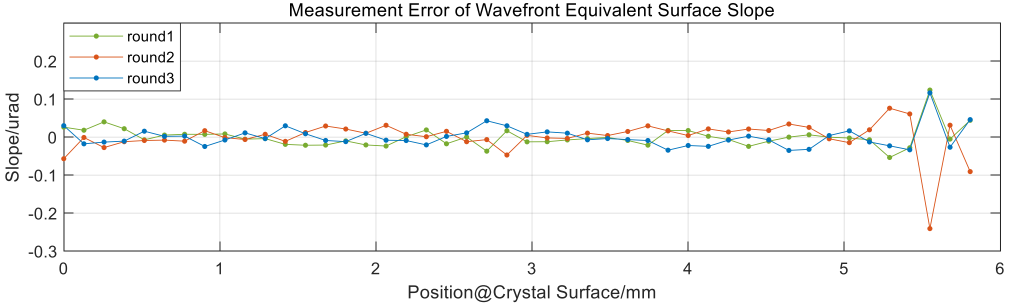


Rocking curve



Morphology





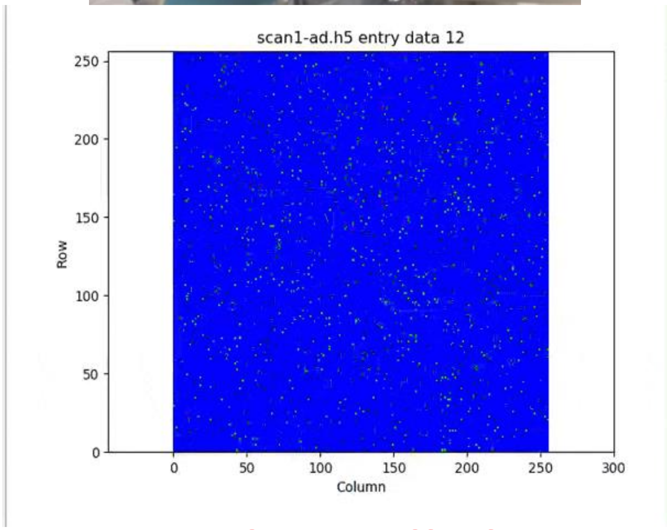
Double-edge wavefront measurement

Reflectivity: **85.1%VS.88.3%**(theory)
Homogenous morphology
Wavefront error: **130nrad** RMS

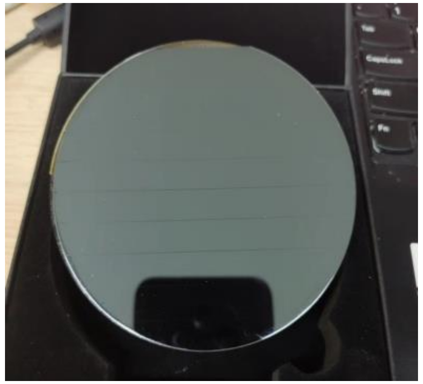
The qualities are better than commercial products

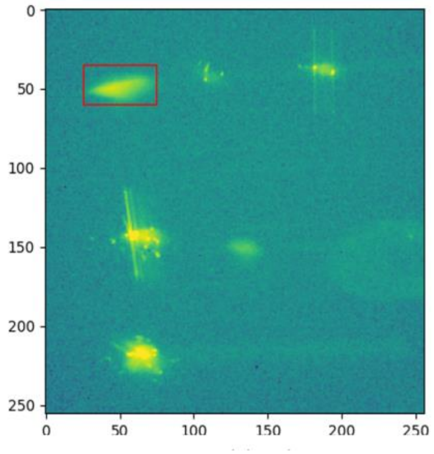
Analysis crystals

Spherically bent Si(660)
~1eV @9.7keV

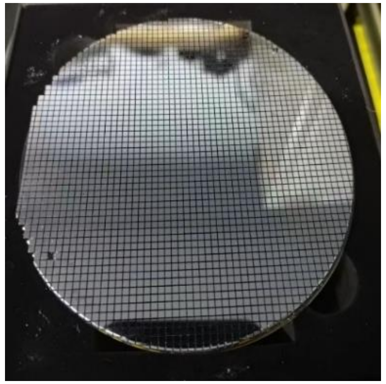


Bent striped Si(660)
~0.53 eV@9.7keV



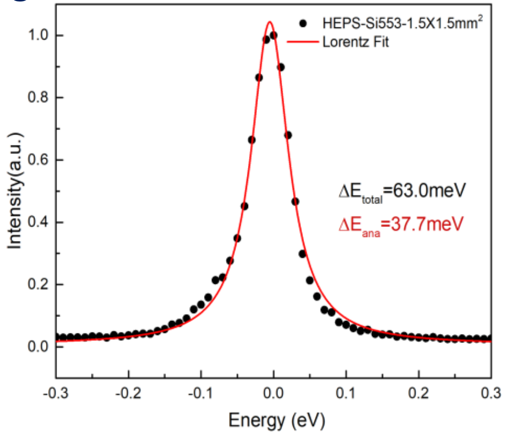


Mosaic-diced Si(553)
~0.037 eV@8.9keV



glued

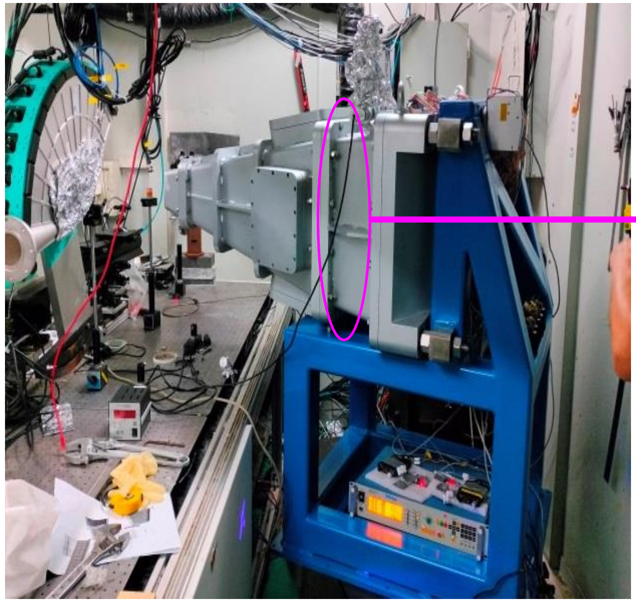
Vacuum mounted



- **Spherically bent analyzers for XRS: excellent focusing & energy resolution**
- **Bent-striped analyzers for XRS: energy resolution improved**
- **Mosaic-diced analyzers for RIXS: highly improved energy resolution**

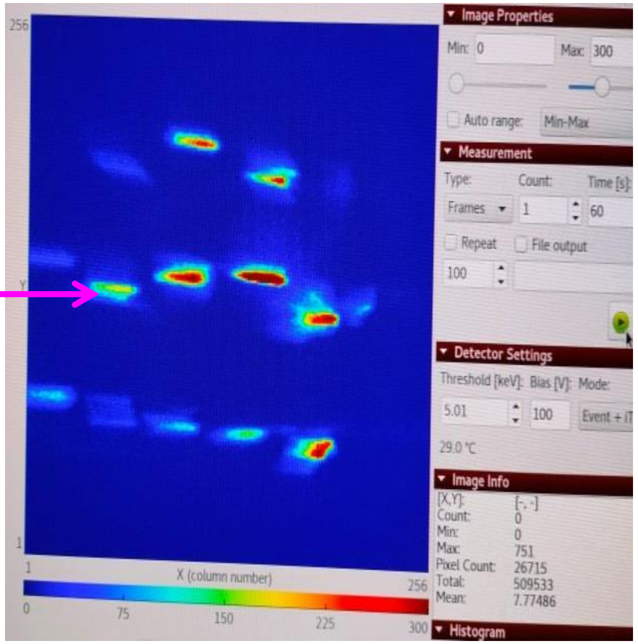
Test and installation- endstation instrumentation

X-ray Raman spectrometer prototype module tested at BSRF



Prototype module

15 analyzer crystals/module

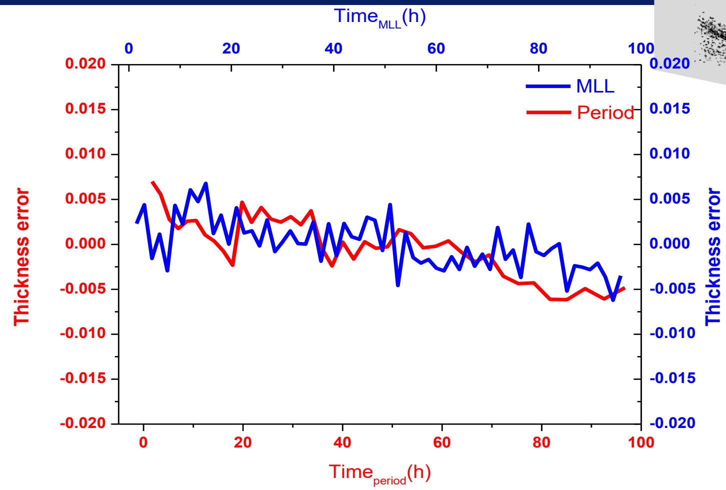


X-ray Raman signals

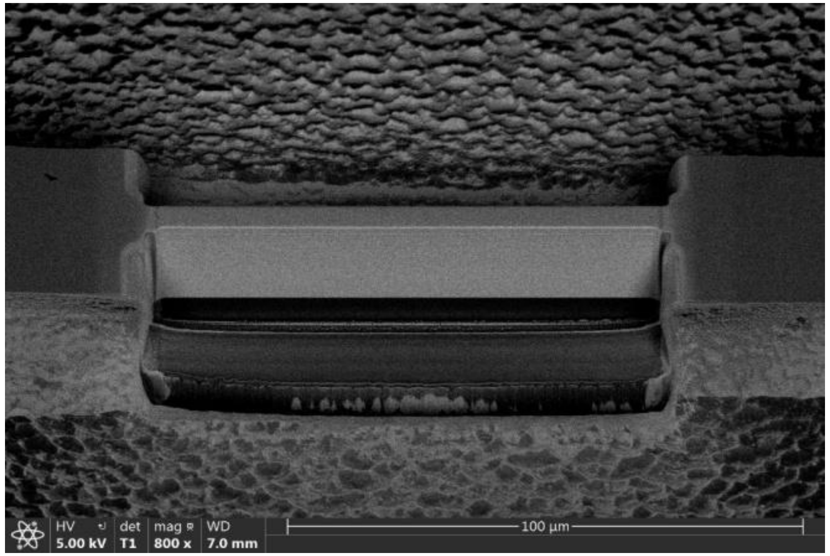
Multilayer Laue Lens (MLL)

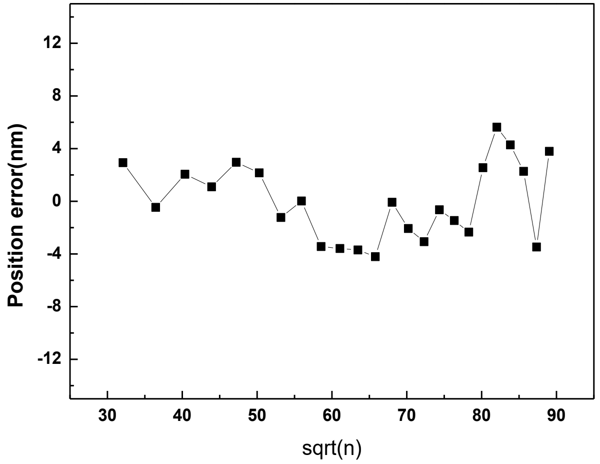
Para.	Req.
Material	WSi_2/Si
N. Layer	13030/ 8030
Thickness	64μm/ 44μm
Focus	$8\times8nm^2$

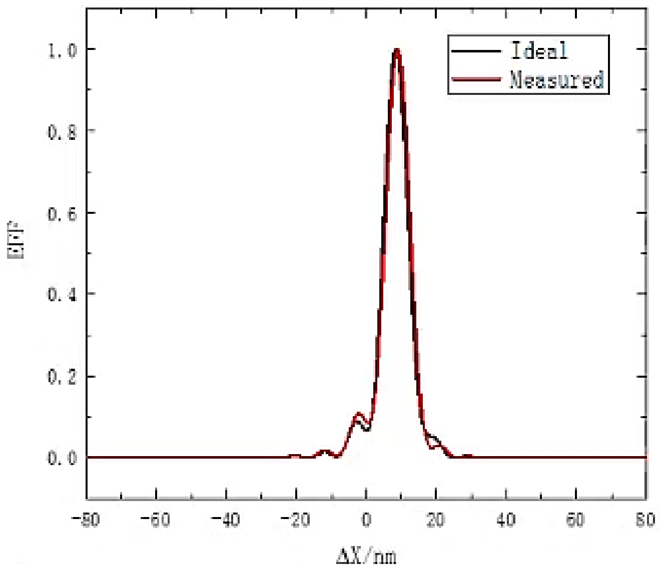
Magnetron sputtering



Growth rate drift 0.3%



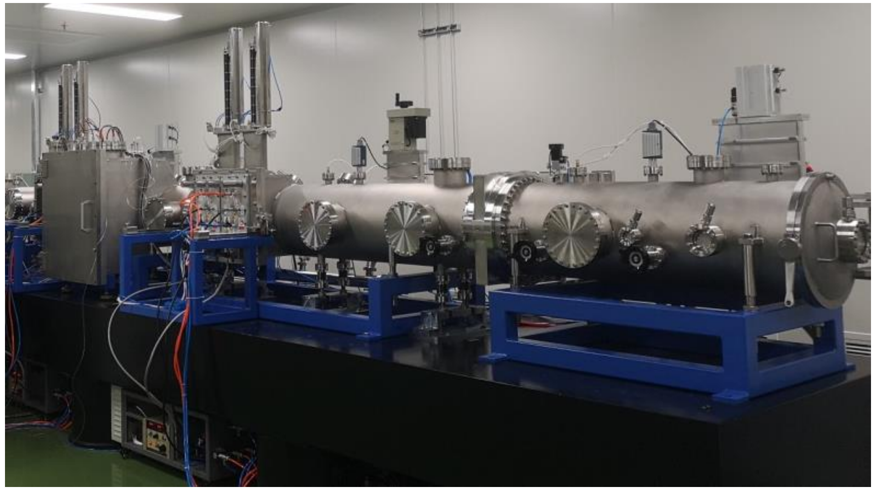


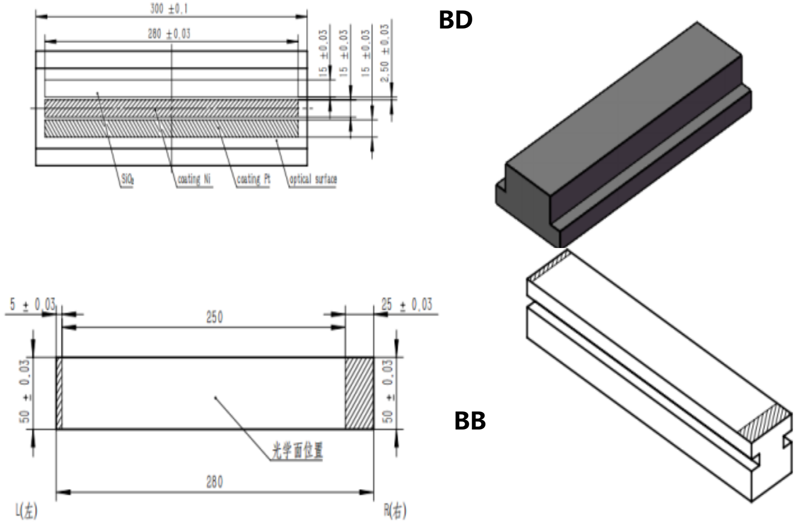


Position error (PV) ±5nm, simulated focus spot 8nm. Fulfilled the demand of nano-probe

Multilayer devices

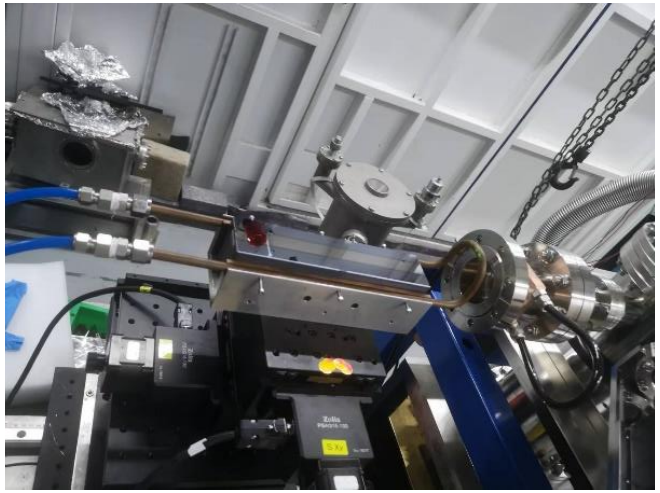
Coating on mirrors

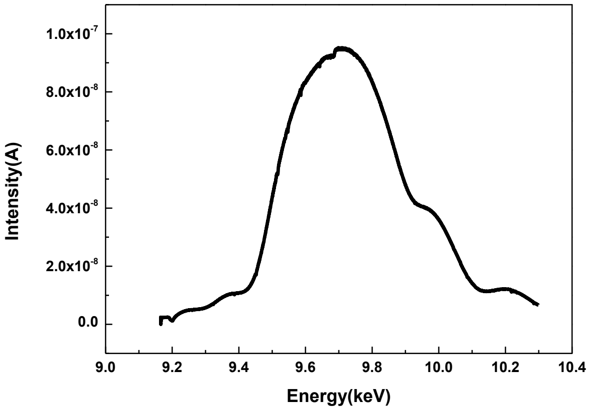




Coating: Pt, Ni, B4C

Multilayer mono.

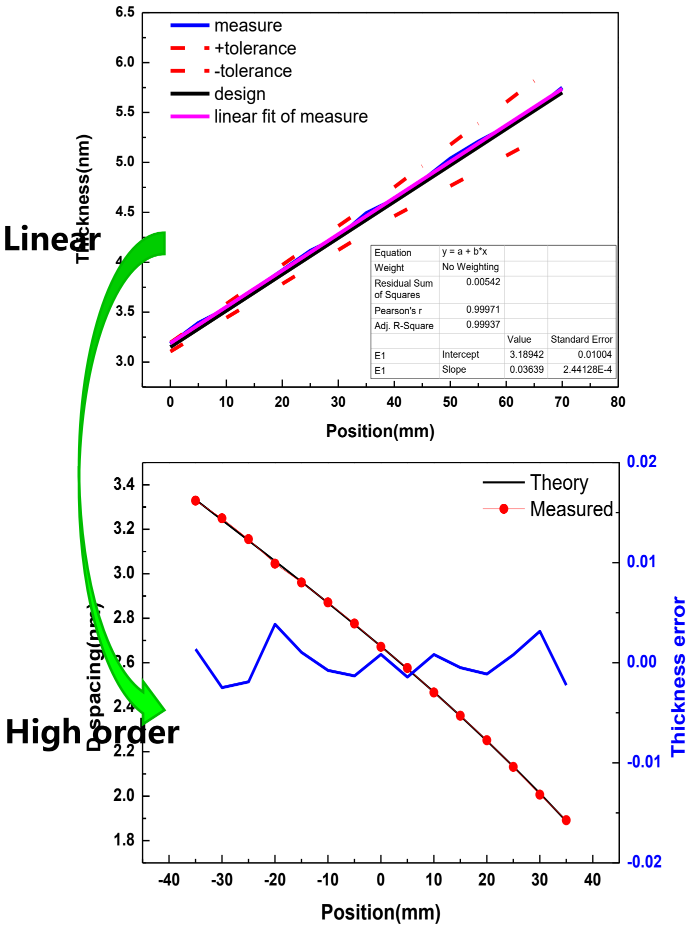




Energy resolution: 4.1%

Reflectivity: 75%

Gradient multilayer mirror



Thickness error ±0.35%(pv)

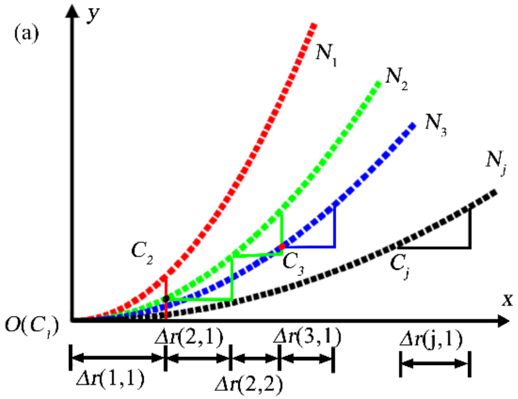
Precision: 6.5pm(rms)

Refractive lens

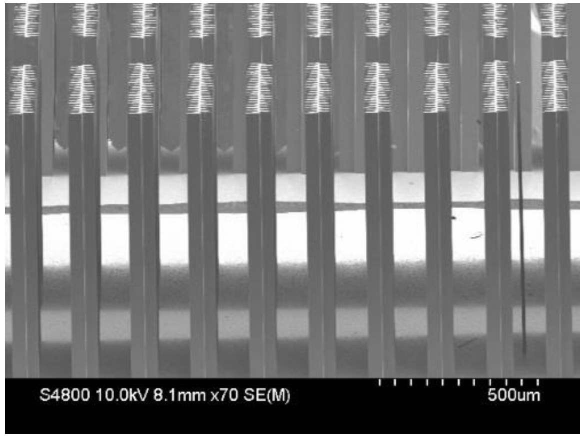
Ni-based kinoform

Tested in PETRA III, focus spot 4µm@87keV

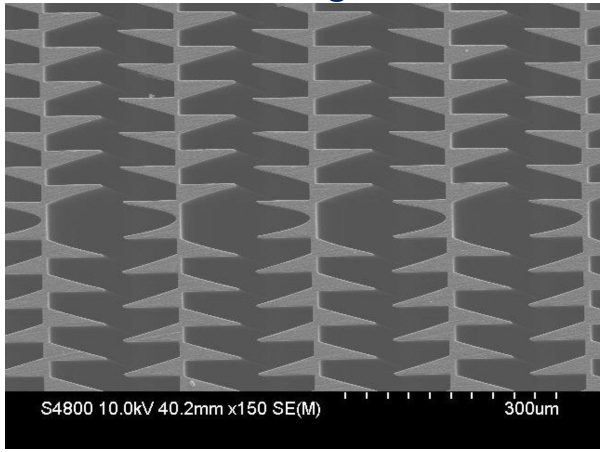
Used in HEPS B1



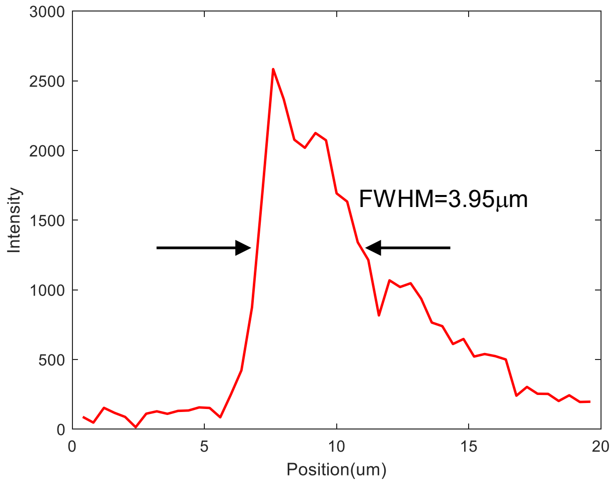
Design



Ni-based kinoform

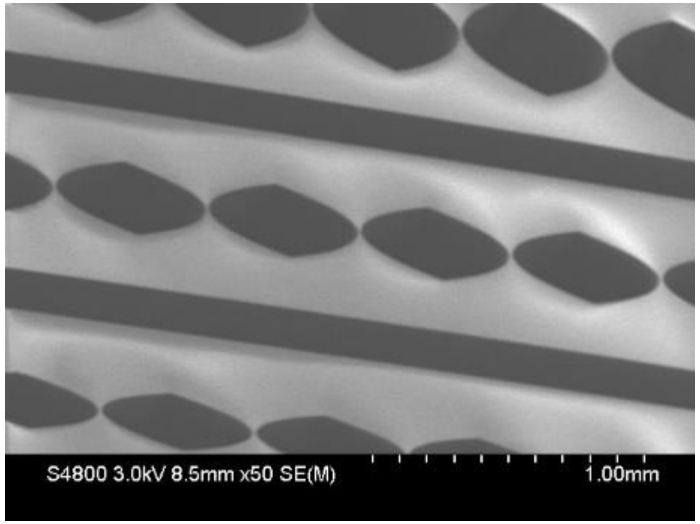


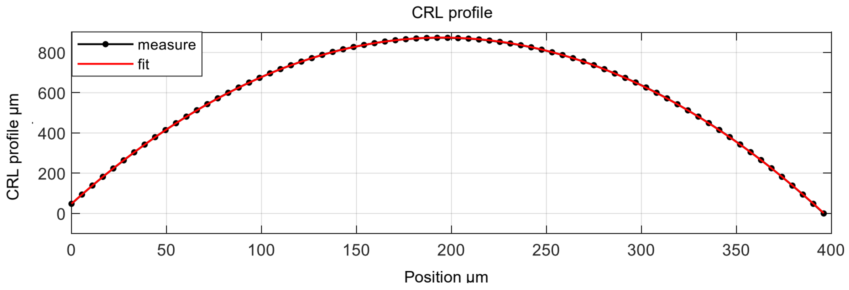
Ni-based kinoform

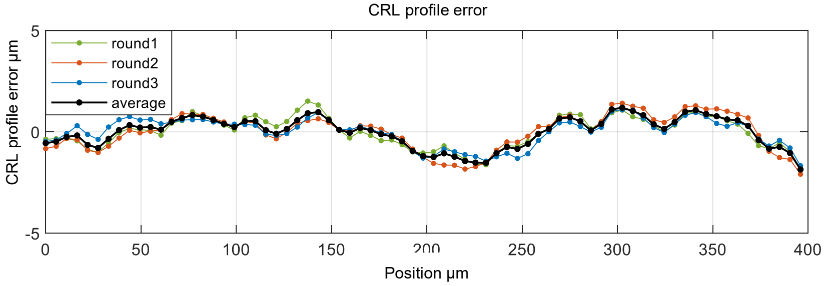


Focusing

1D SU8-based CRL





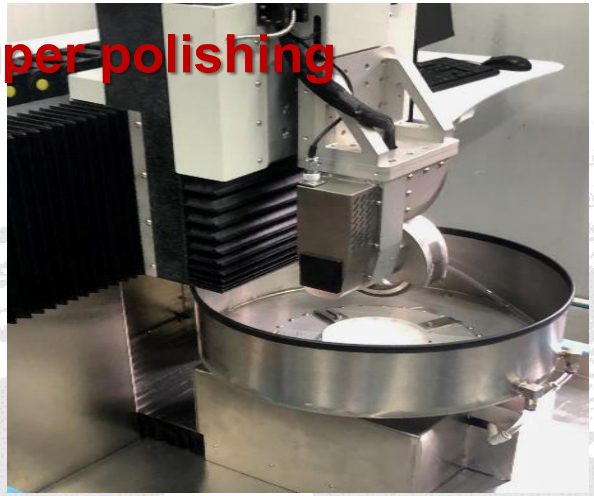


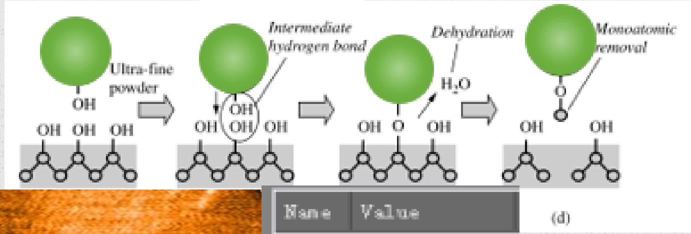
Shape profile error 0.75µm RMS

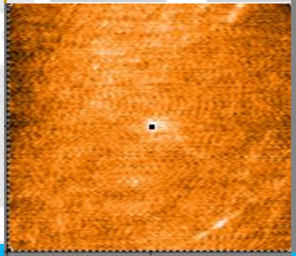
Mirror Fabrication (collaborate with other Chinese institute)

- 500mm 0.3μrad flat mirror
- 300mm 1μrad elliptical mirror
- 0.2nm~0.3nm roughness

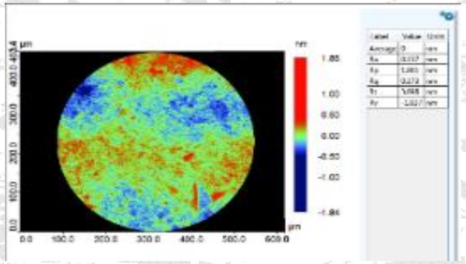
Super polishing

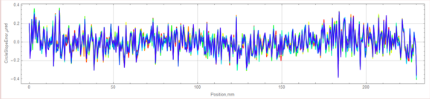
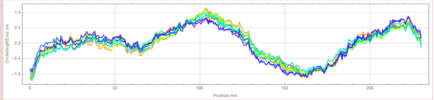
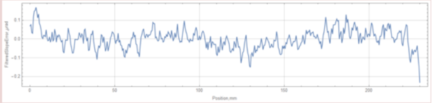


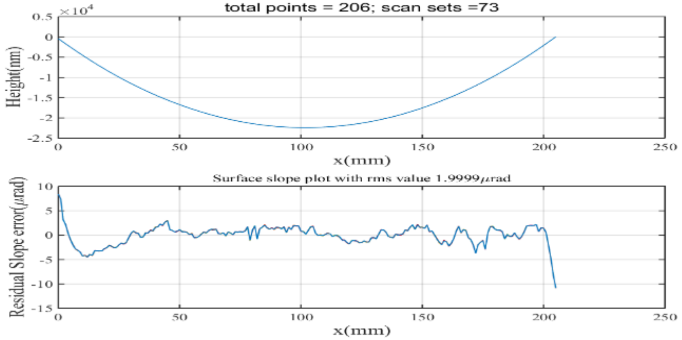




Name	Value
Area	4.031pm^2
Sa	92.375pm
Sq	117.81pm
Sy	1292.2pm
Sp	592.44pm
Sv	-699.76pm
Sm	-9.6318fm



Mirror	Slope error RMS	110nrad	
Flat mirror Made in China Clear aperture: 230mm	Height error RMS	0.51nm	
	Slope error RMS 2mm Filtered	50 nrad	

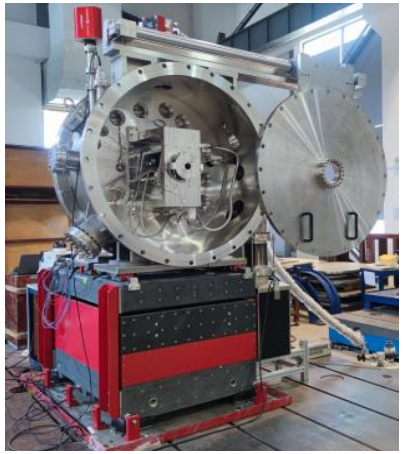


230mm elliptical
~1μrad @ 2mm resolution

Monochromators for high stability and coherence preserving

VDCM

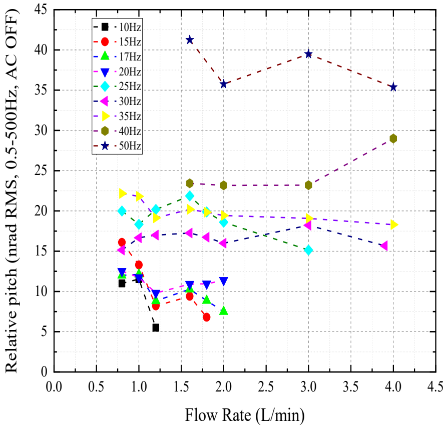
HDCM



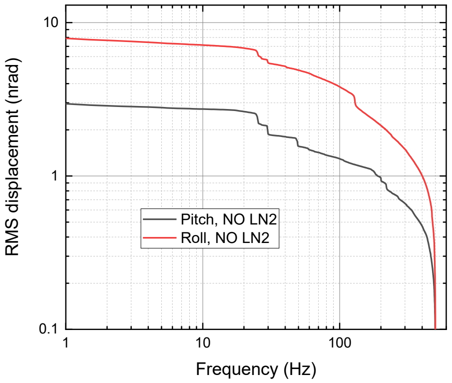
Fast-scan DCM
Time resolved XAFS

HR-4BCM
High energy resolution

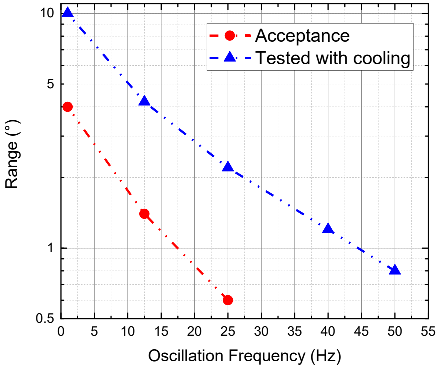
Details also in THOBM03



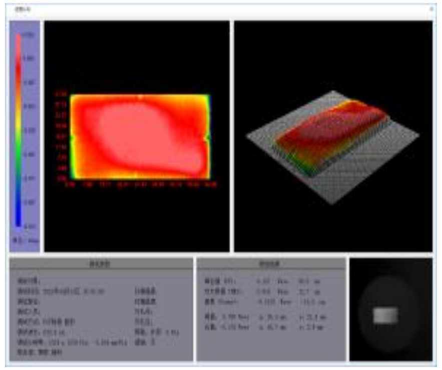
Stability of VDCM
<10nrad RMS
Under cooling



Stability of HDCM
Without cooling



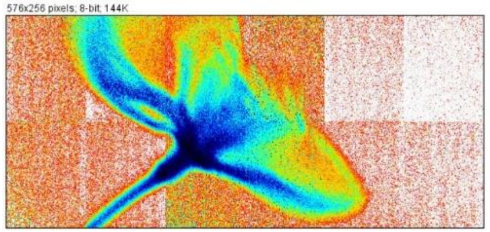
Fast-scan DCM
100 XAFS spectra /s
@50Hz 0.8°

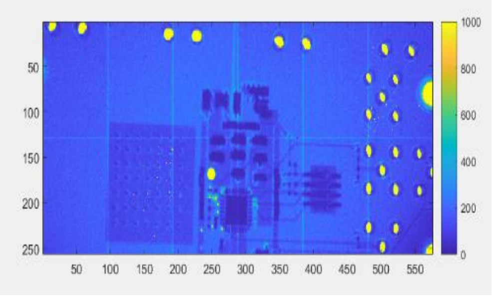


Deformation of crystals with clamping under cryo temperature
< 0.1μrad RMS （after removal of 2nd order）

Detector

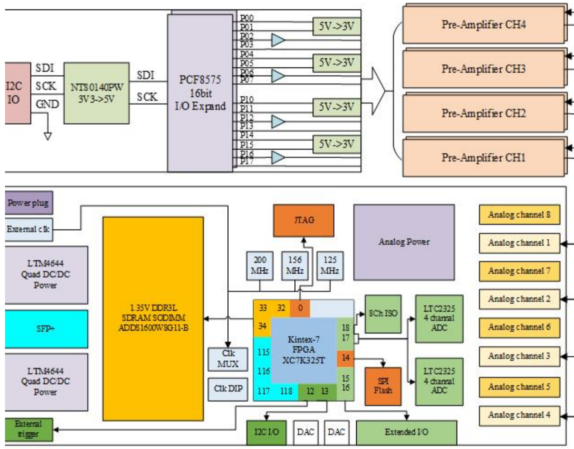
1、 Pixel array detector

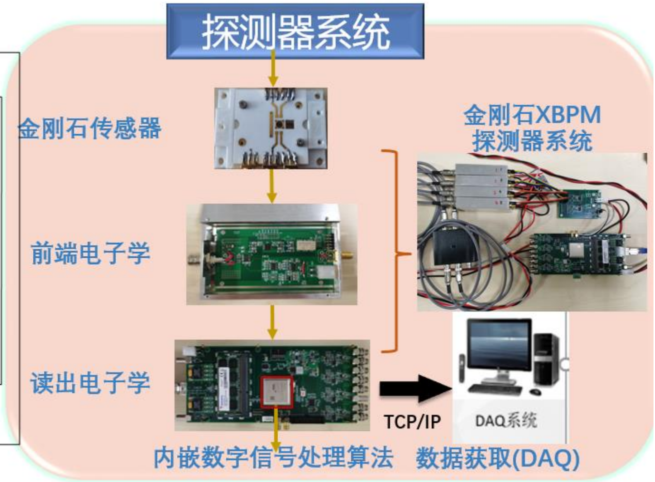




Parameters	1st generation	2nd generation –new
Sensor	320um silicon PIN	320-500μm
Pixel size	150umX150um	140umX140um
Pixel array	1248X1728 (single module 208X288, 4X6 modules)	Single module 256×576 pixels (3.6cm×8cm)
Counting rate	1Mcps	>1Mcps
Dynamic range	20bit	20bit
Flame rate	1KHz (design), continuous read-out 100Hz	1KHz continuous read-out
Energy range	8-20keV	>6keV
Threshold	single	Double
Death point	<1‰	<1‰
Gap	1.6mmX2.5mm	1.2mm×2.8mm

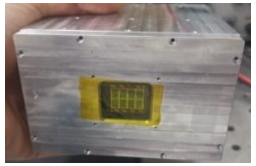
2、XBPM：（Diamond four-quadrant XBPM）





- Senser
- Electronic

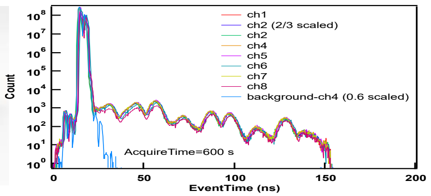
3、nanosecond time resolution detector. (APD)



sensor

Electronic module

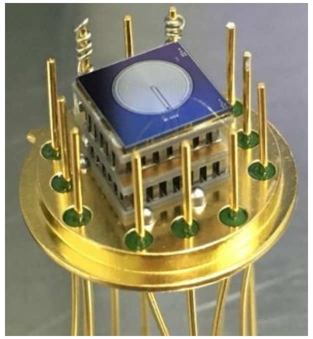
DAQ



Test @ APS

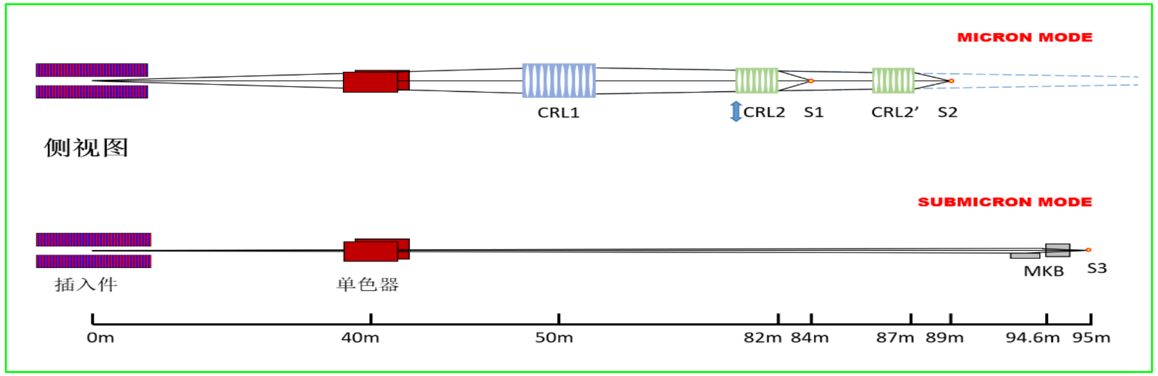
4、SDD

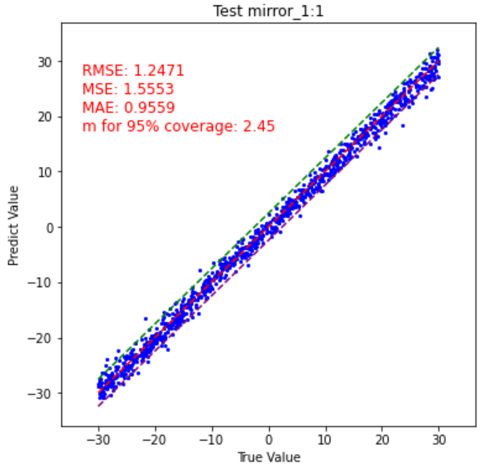
- ■ **Senser + ASIC + Packaging**
- ■ **150eV@5.9keV，1Mcps/channel。**

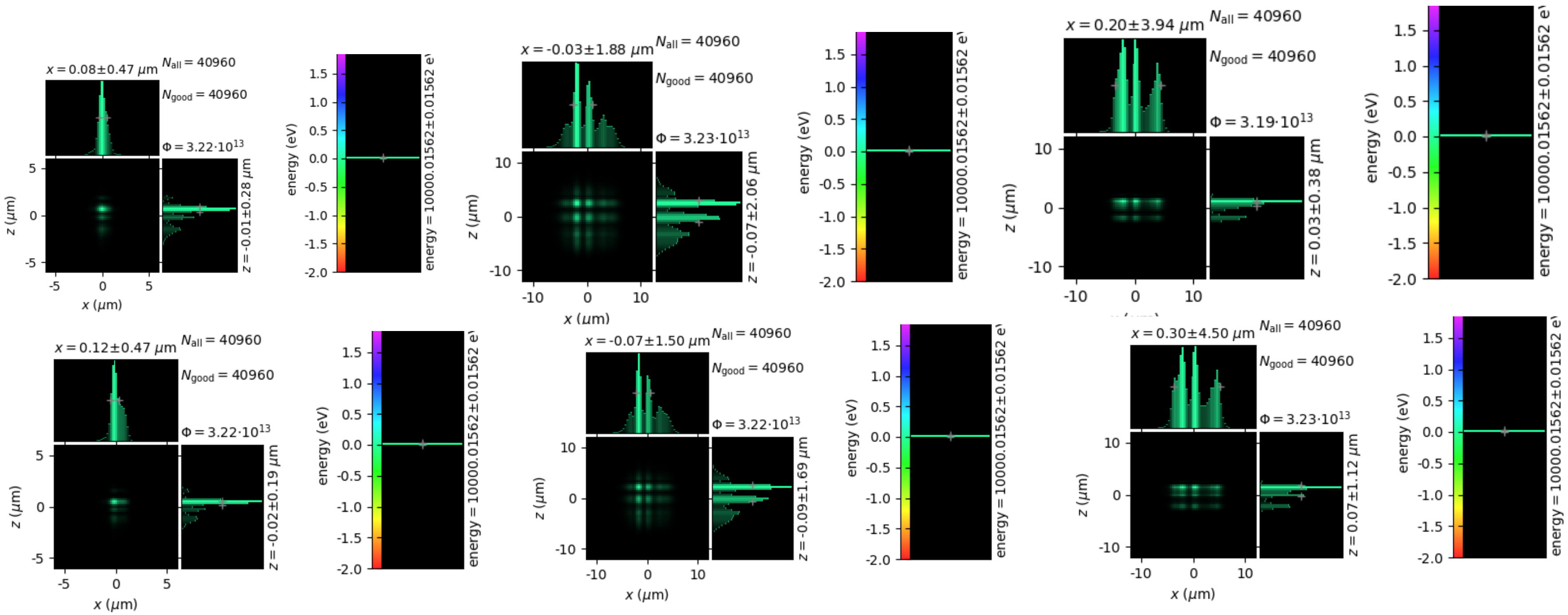


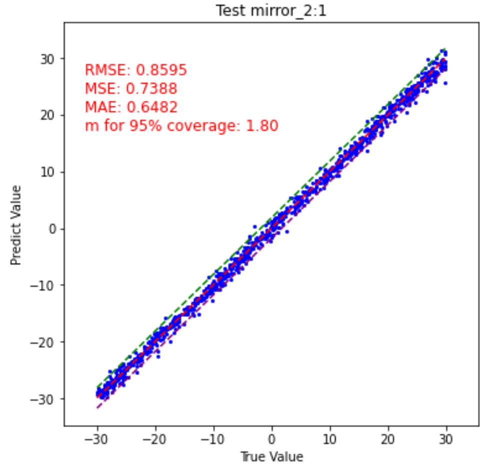
AI-drived optics manipulation

Beamline alignment：

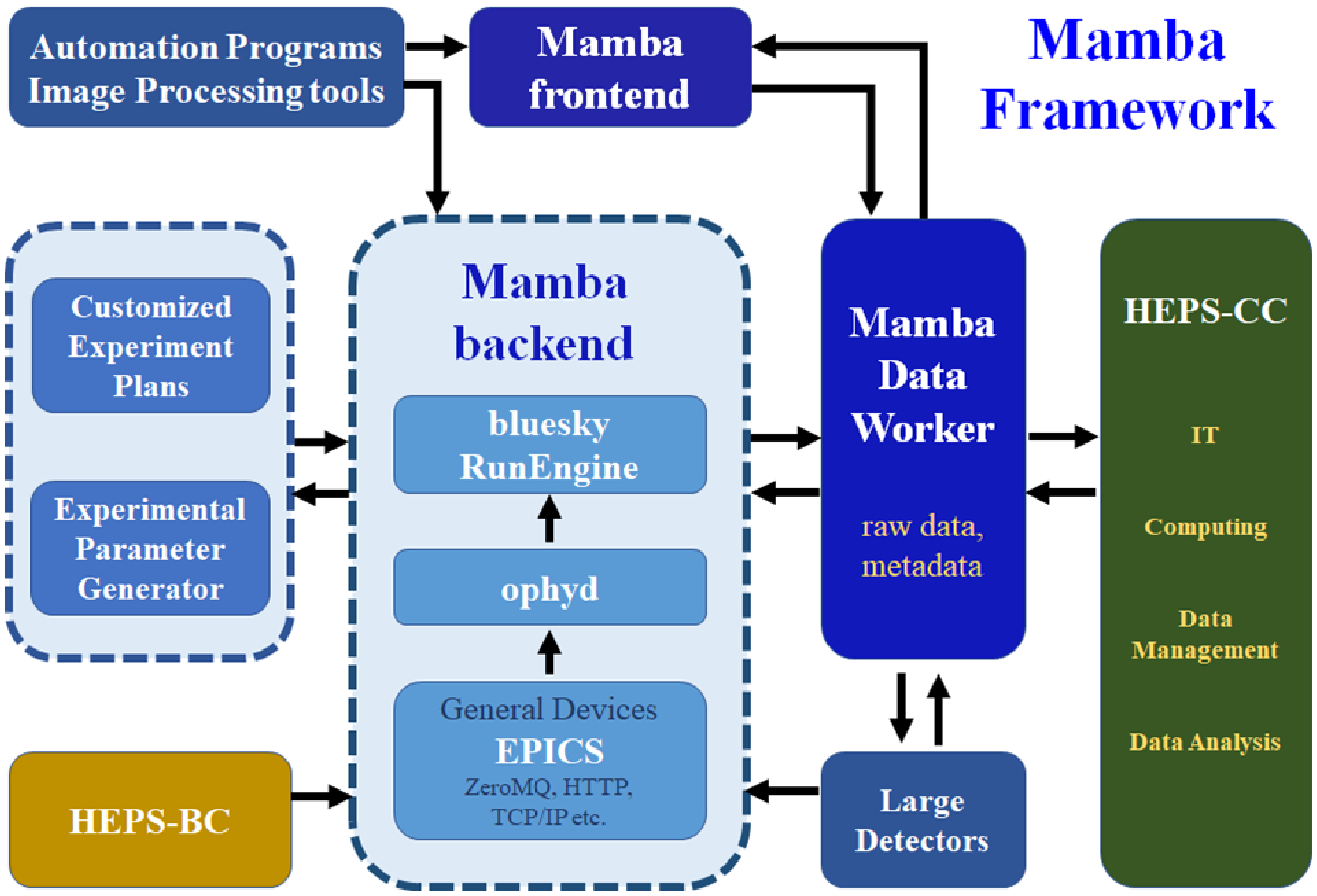


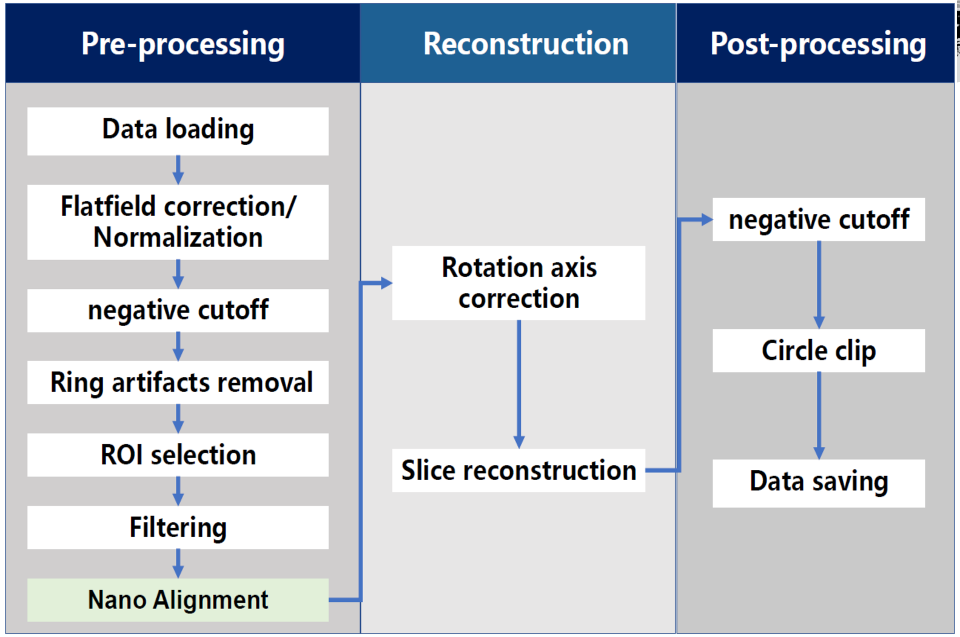


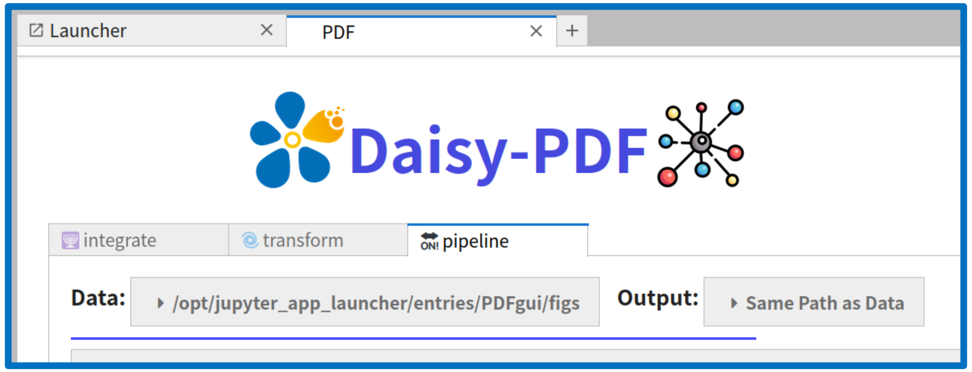




Data management and analysis







Data acquisition and beamline/end-station control: MAMBA
Data management: DOMAS
Data analysis: DAISY

Summary

- HEPS, a powerful 4G light source, brings severe challenges to optics technology.
- Towards the challenges of diffraction limited optics, we have done a lot of R&D work, including metrology, processing, manipulation, detector and so on.
- Some challenges of optics technology have been solved by ourselves.


Thank you for your attention!