High Energy Photon Source (HEPS)

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Outline

Synchrotron Radiation Facilities Worldwide

Europe: 16; America: 11; Asia: 21 (Japan: 12); Australia: 1

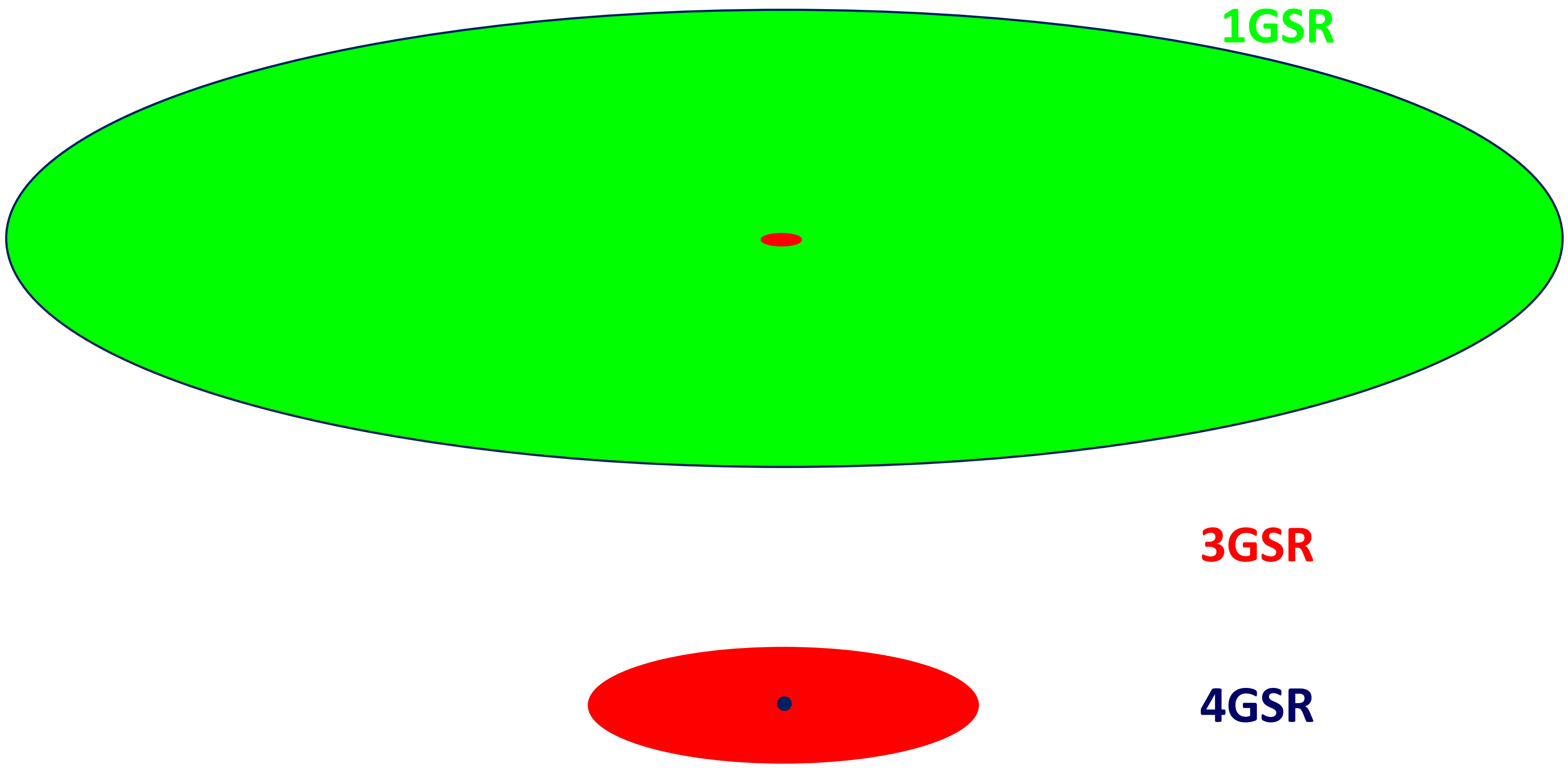
The trends of the SR sources

- ✓ **Lower emittances (4 ↘ <0.1 nmrad)**
- ✓ **Higher brilliances (↗2~3 orders)**
- ✓ **More advanced beam lines and end-stations (Better resolutions, higher speeds, etc.)**
- ✓ **SR-based research centers**

Emmitance of SR

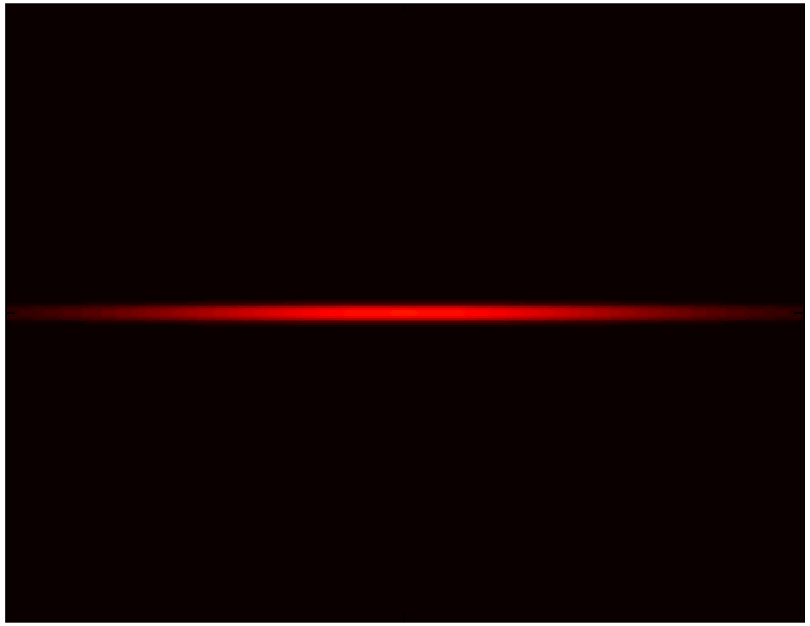
Facilities		e_x (nm•rad)	e_y (nm•rad)
DESY-DORIS III	1^{st}	410	12
BNL-NSLS	2^{nd}	66	20
ESRF	3^{rd}	4	0.025
DIAMOND	3^{rd}	2.74	0.0274
BNL-NSLS II	3^{rd}	0.55	0.008
DESY-PETRA III	3^{rd}	1	0.01
ESRF-EBS	4^{th}	0.133	0.002
HEPS	4^{th}	0.034	0.0034

Emmitance

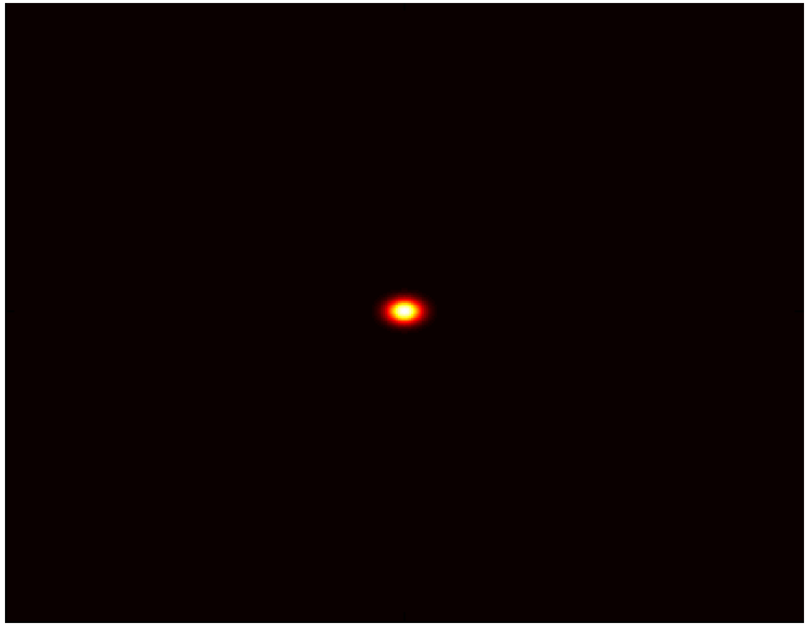


Technology advantage: accelerator

$$\varepsilon \propto \frac{E_e^2}{\left(N_{sect} \cdot N_{dipole}\right)^3}$$

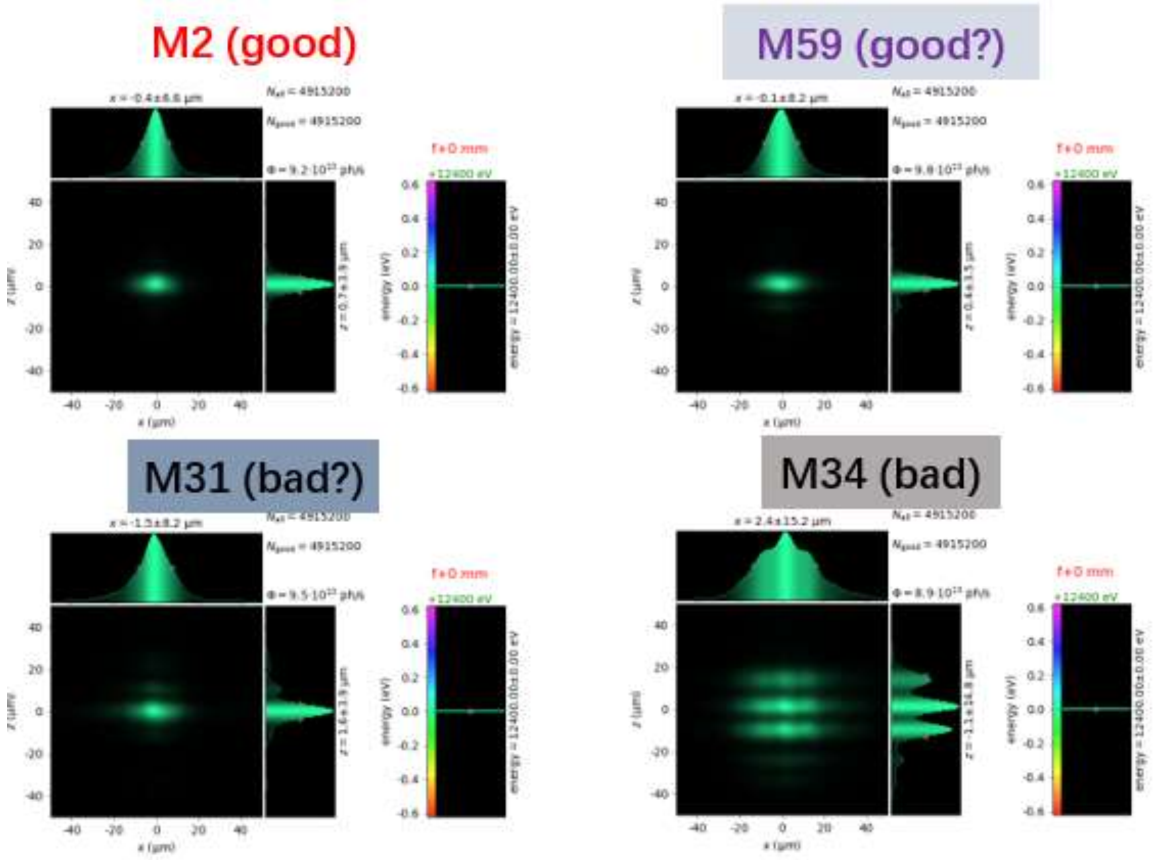


3GSR



4GSR

Technology advantage: beamline



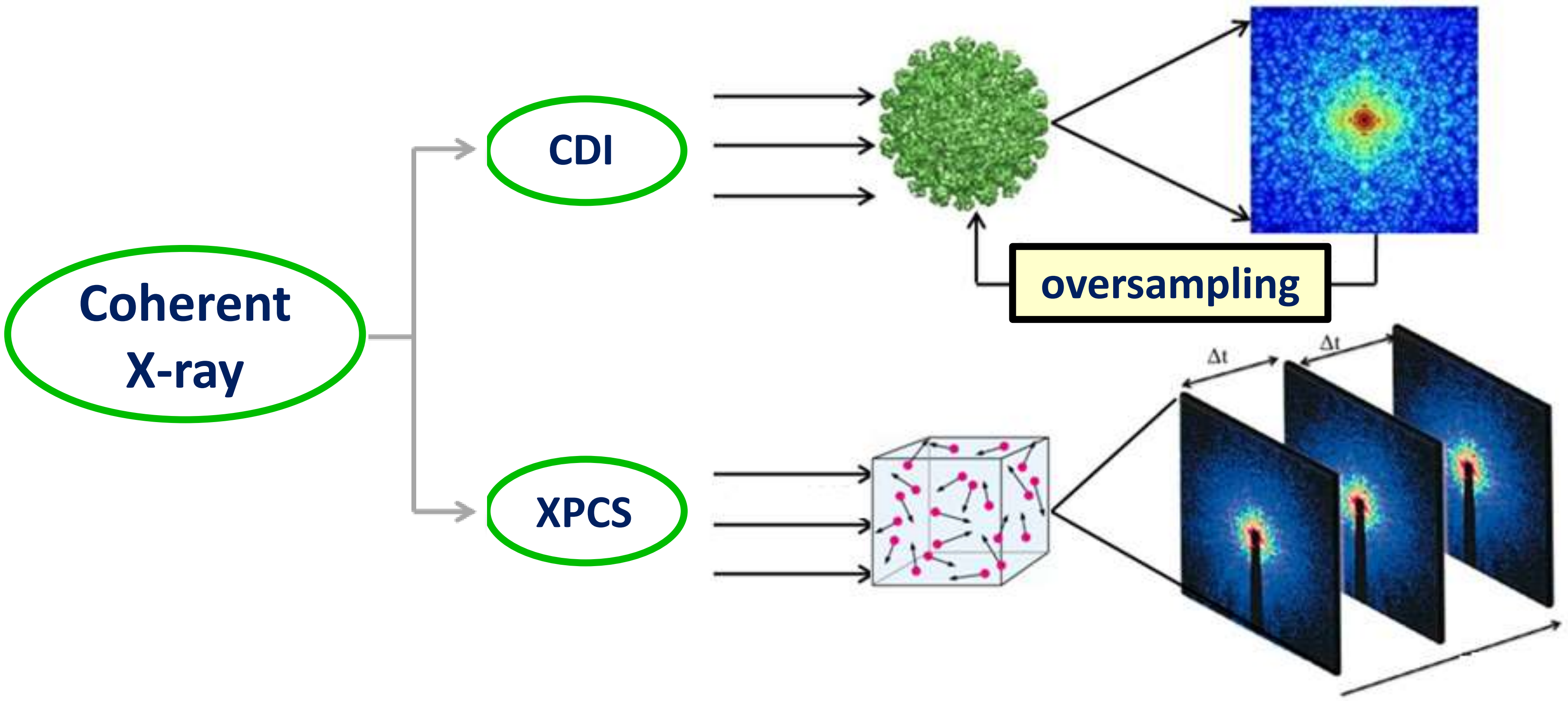
Due to the coherence,

- ➢ Coherent optic must be used
- ➢ The characterization and metrology of optical components (crystals, mirrors, CRL, etc.) are different, the parameters used before (slope of error, roughness, etc.) are not enough for identify the qualities of optical behaviors
- ➢ Extremely high heat-load

We can get:

- ➢ Very small beam: nm size
- ➢ Very high flux: 2-3 order higher than 3GSR
- ➢ Coherent beam

4th generation SR: experiments



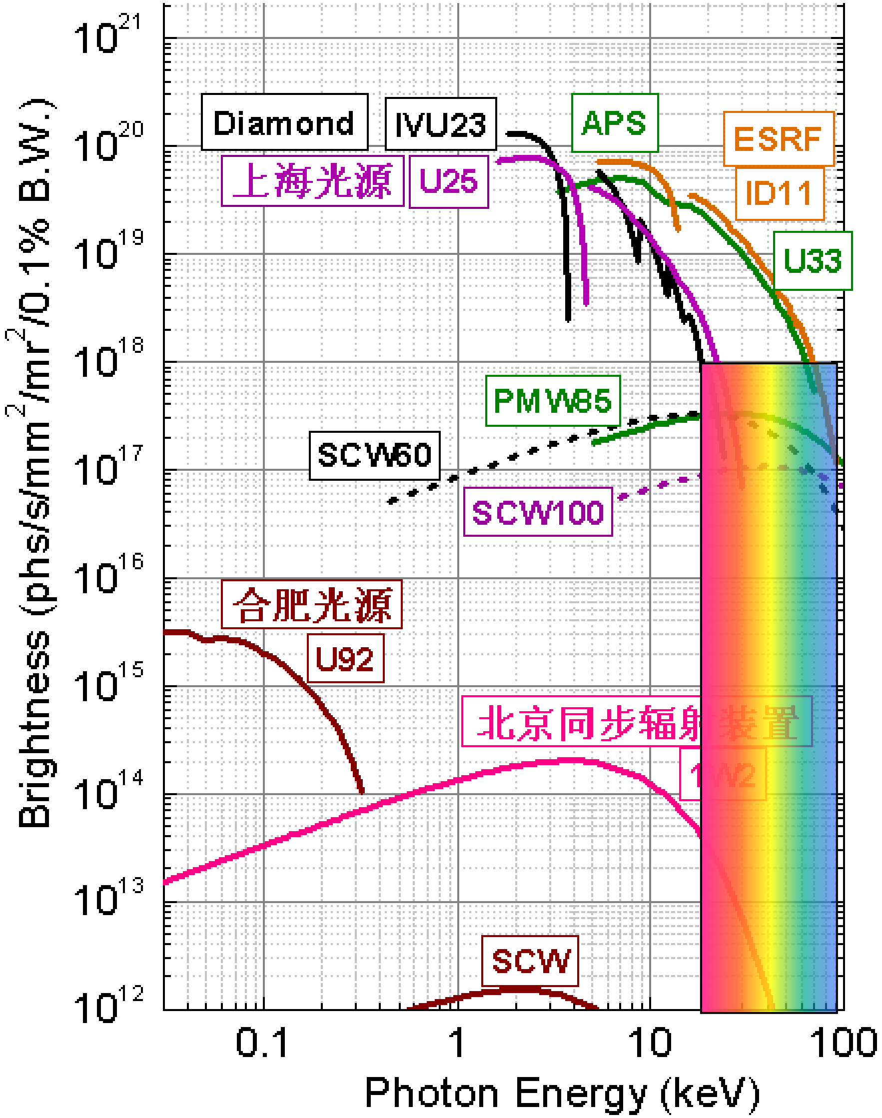
New experimental methods:

- Coherent Diffraction Imaging (CDI): non-crystal, nano-crystals (Cells, organelle, nano-catalyst, etc.);
- X-ray Photon Correlation Spectroscopy (XPCS): dynamic properties;
- Nano-probe;
- New methods?

The SR facilities in mainland of China

BSRF (2.5GeV, 1GLS)

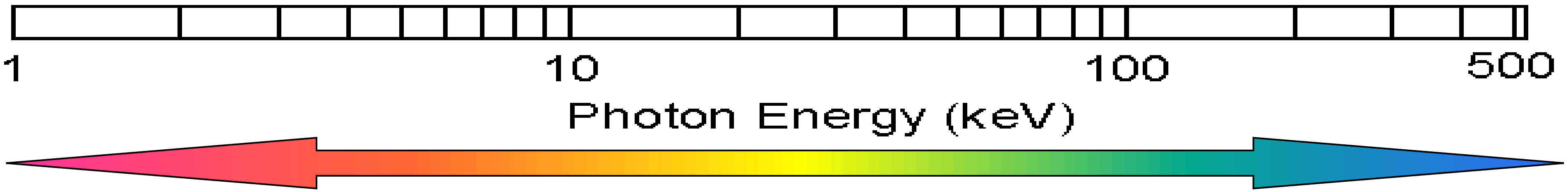
HLS (0.8GeV, 2GLS)



SSRF (3.5GeV, 3GLS)

Hard X-ray is required.

Energy Ranges of Synchrotron Radiation Facilities

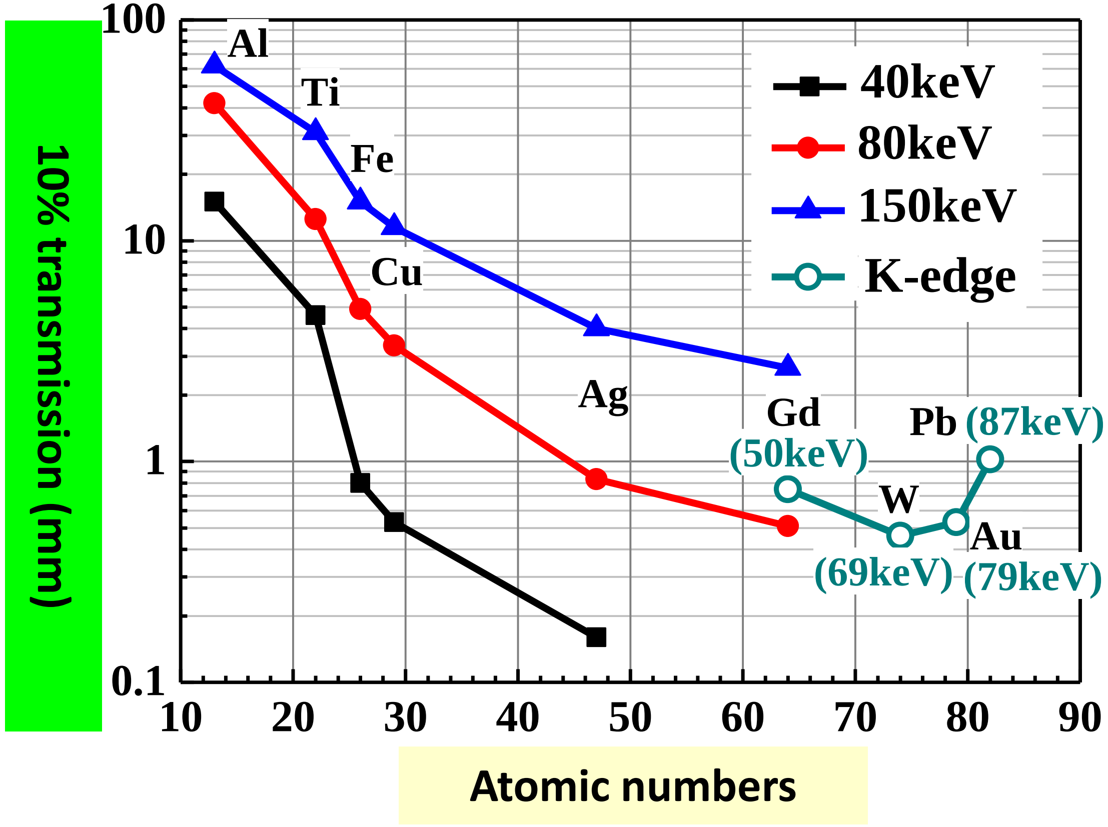


	Low Energy (~1GeV)	Medium (~3GeV)	High Energy (≥5GeV)
Types	Low Energy (~1GeV)	Medium (~3GeV)	High Energy (≥5GeV)
Penetration depth	nm	mm	mm-cm
Samples	Surface	Shallow	Real components Extreme conditions

High-energy synchrotron radiation sources are suitable for "real materials under real conditions".

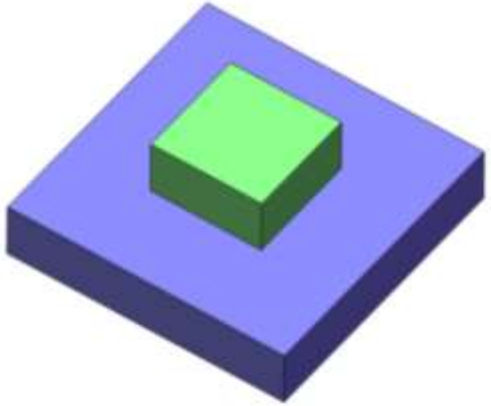
The Penetrative ability of Hard X-ray

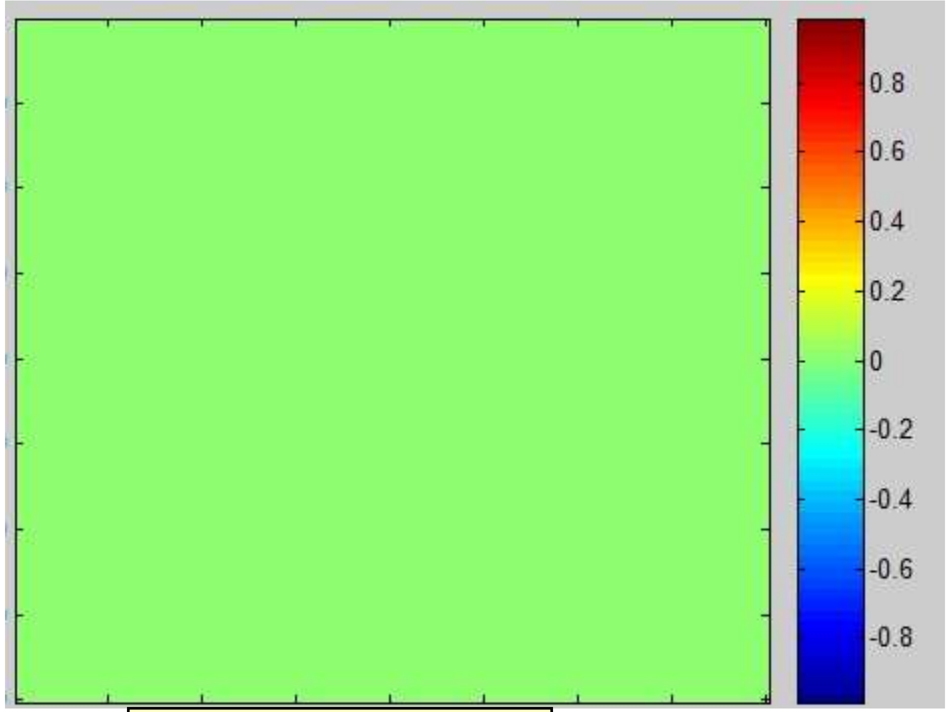
Hard X-ray:
Penetration
Atomic resolution
Real conditions: high/low temperatures, high pressure, high fields, reactive atmospheres



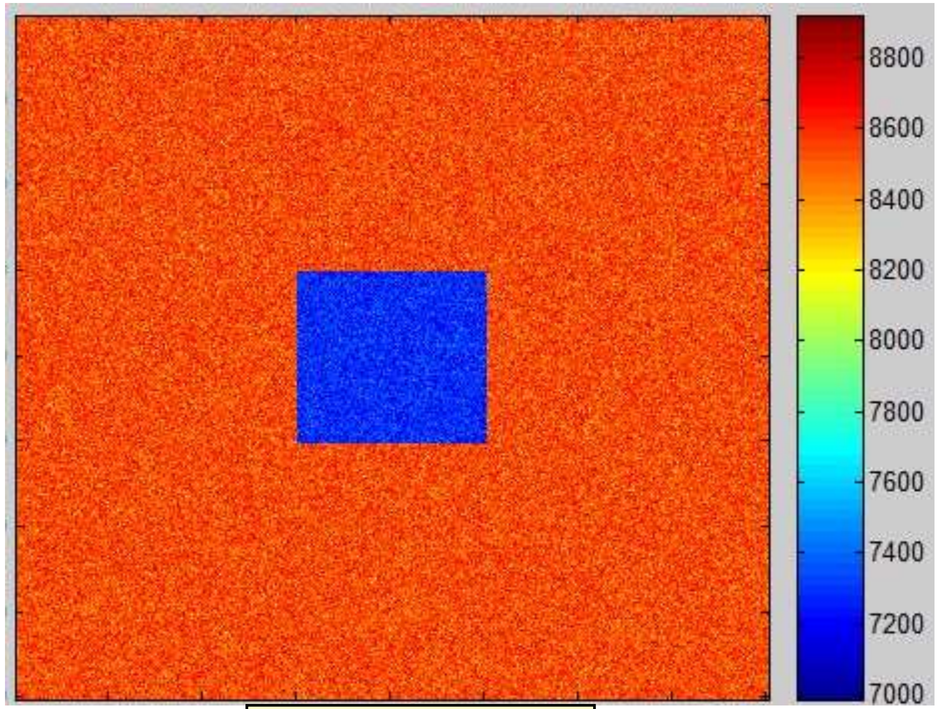
Hard X-ray: Providing better chances for materials studies, especially the materials under conditions.

A simple simulation: 1mm-thick Fe on another 1mm-thick Fe plate: imaging by X-ray with different energies





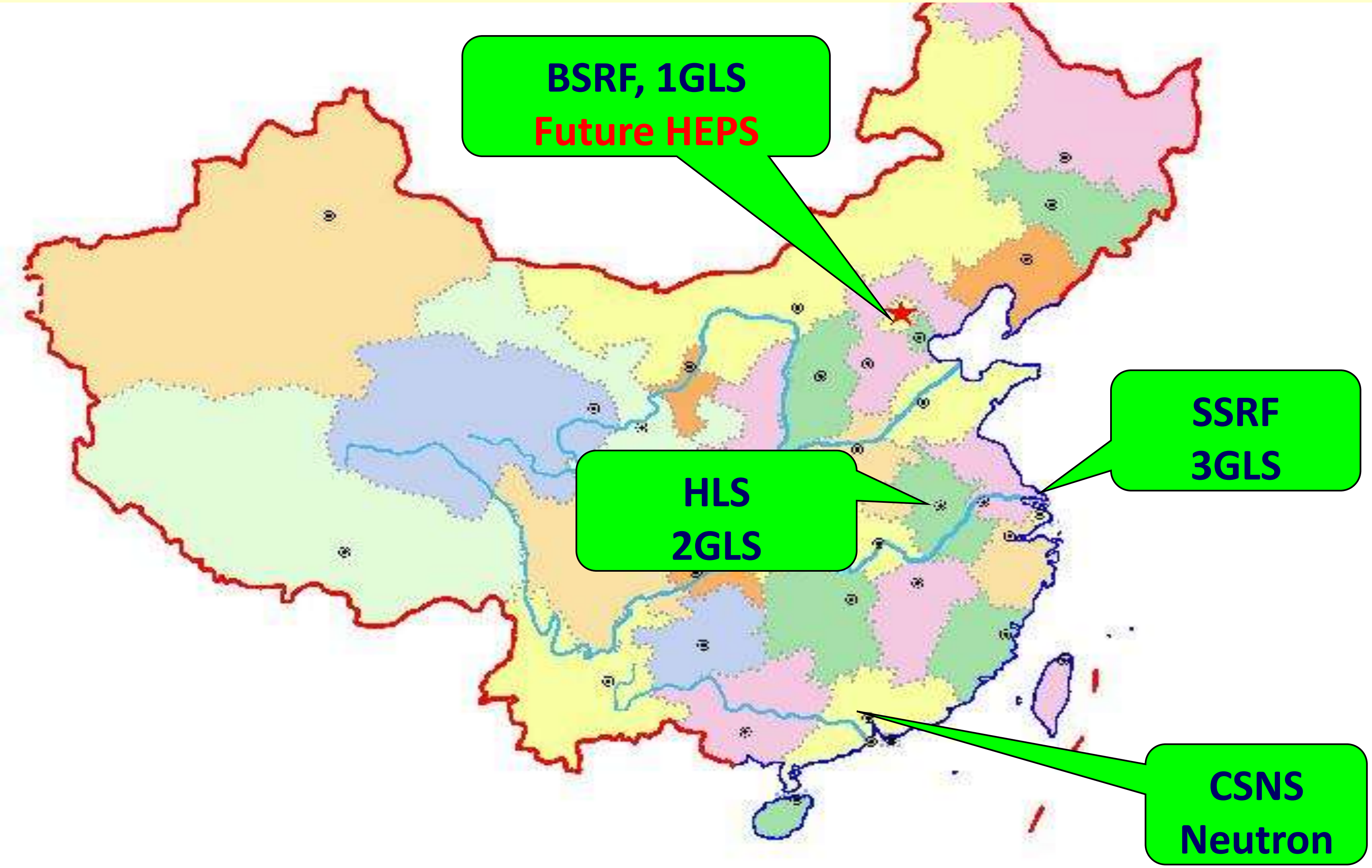
10keV



100keV

Distribution of the research population in mainland China

The distribution of SR facilities in mainland of China



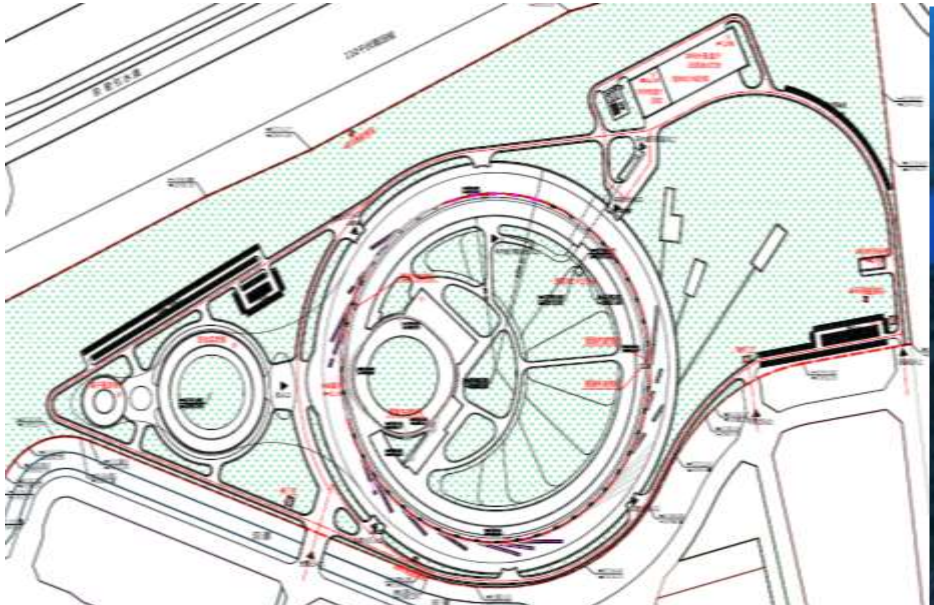
The strongest research teams in the fields of condensed matter, structure biology, nano-science, chemistry, engineering around Beijing area need an advanced light source.

Next SR facility in mainland of China

- The imminence demand for SR facility requires

  a high-energy, low-emittance SR facility

  around Beijing area
- High Energy Photon Source (HEPS) (Beijing Advanced Photo Source, BAPS)
- 6GeV, ε<0.1nmrad 4th generation SR machine



Location

~80km away from IHEP main campus

- **Huairou Science City** (an area of 233 acres)

  - Five big science facilities: **HEPS**, SECUF (Synergized Extreme Condition User Facility), CMP Phase II (Chinese Meridian Project Phase II), EarthLab (the Earth System Numerical Simulation Facility), Multi-mode, Multi-scale Biomedical Imaging Facility

  - Series research platforms in energy, environment, biology, materials, etc.

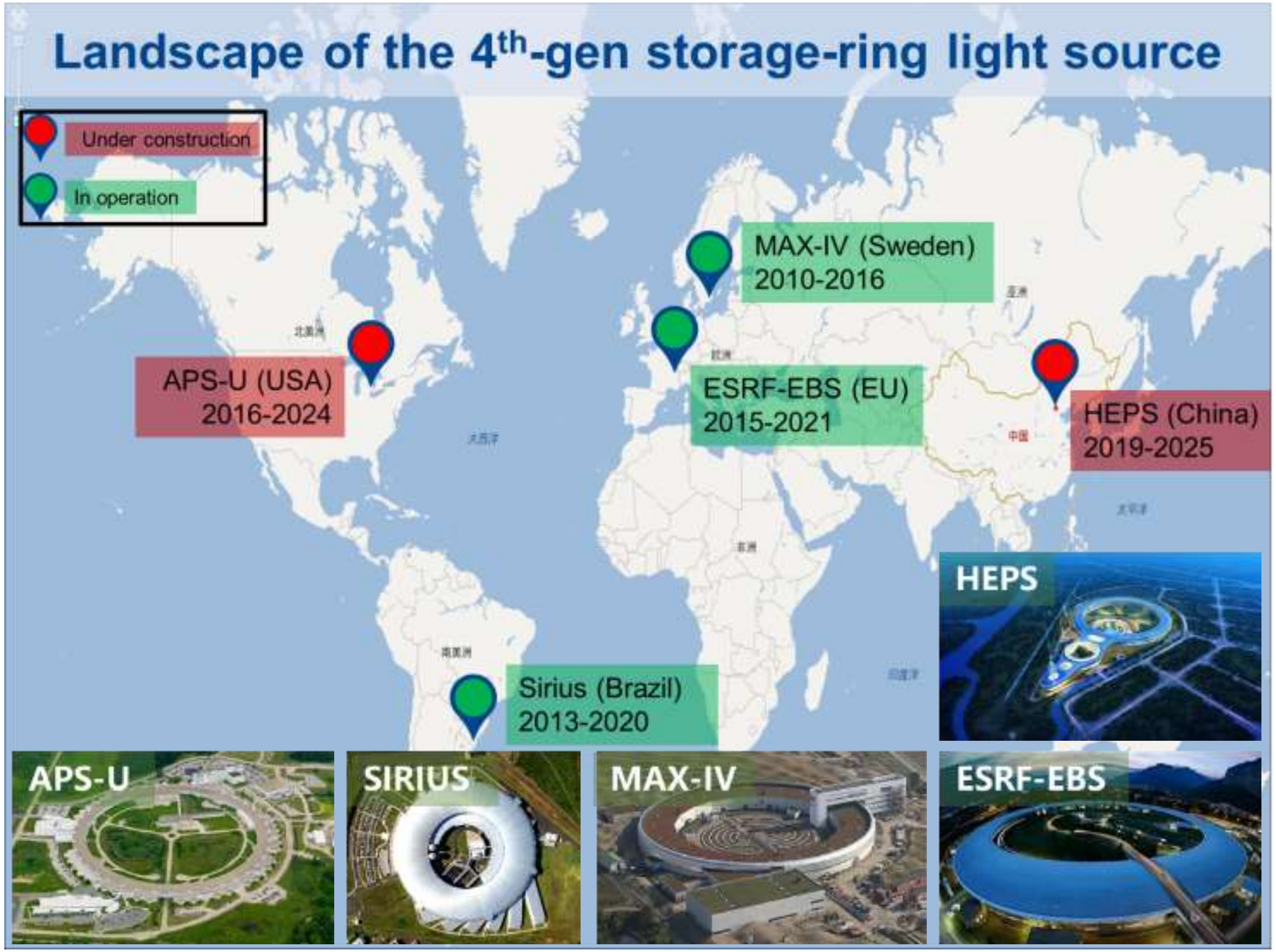
Projects related to HEPS @Huairou

- High Energy Photon Source (HEPS), RMB 4.67B (2019-2025)
- Auxiliary project for HEPS, office & lab. building and guesthouse, RMB 205M (2020-2023)
- Platform for Advanced Photon Source Technology R&D (PAPS), RMB 497M (2017-2021)
- High Energy Photon Source Test Facility (HEPS-TF), RMB 3.216B (2016-2019), R&D of HEPS
- A series of research projects from MOST, NSFC and Beijing city (X-ray detectors, SR methodology)

Overview of HEPS

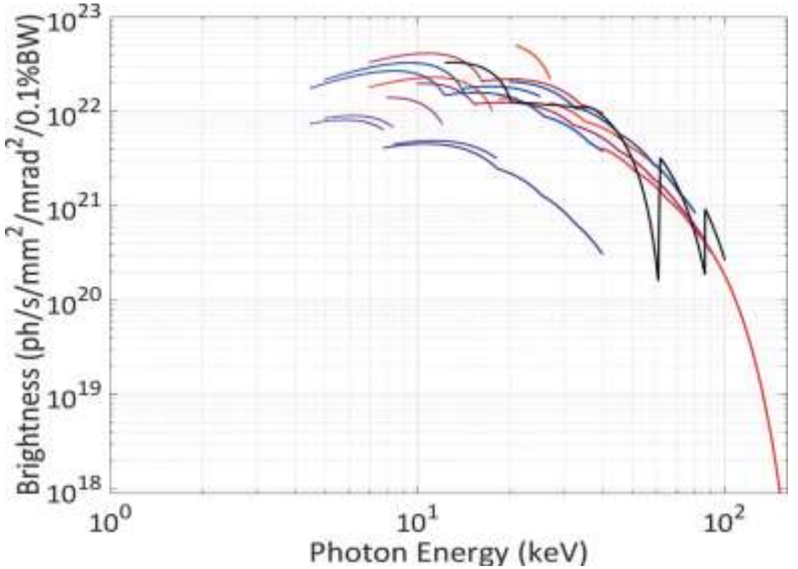
HEPS: a 4th-gen high-energy synchrotron LS

- One of the brightest fourth-generation synchrotron radiation facilities in the world

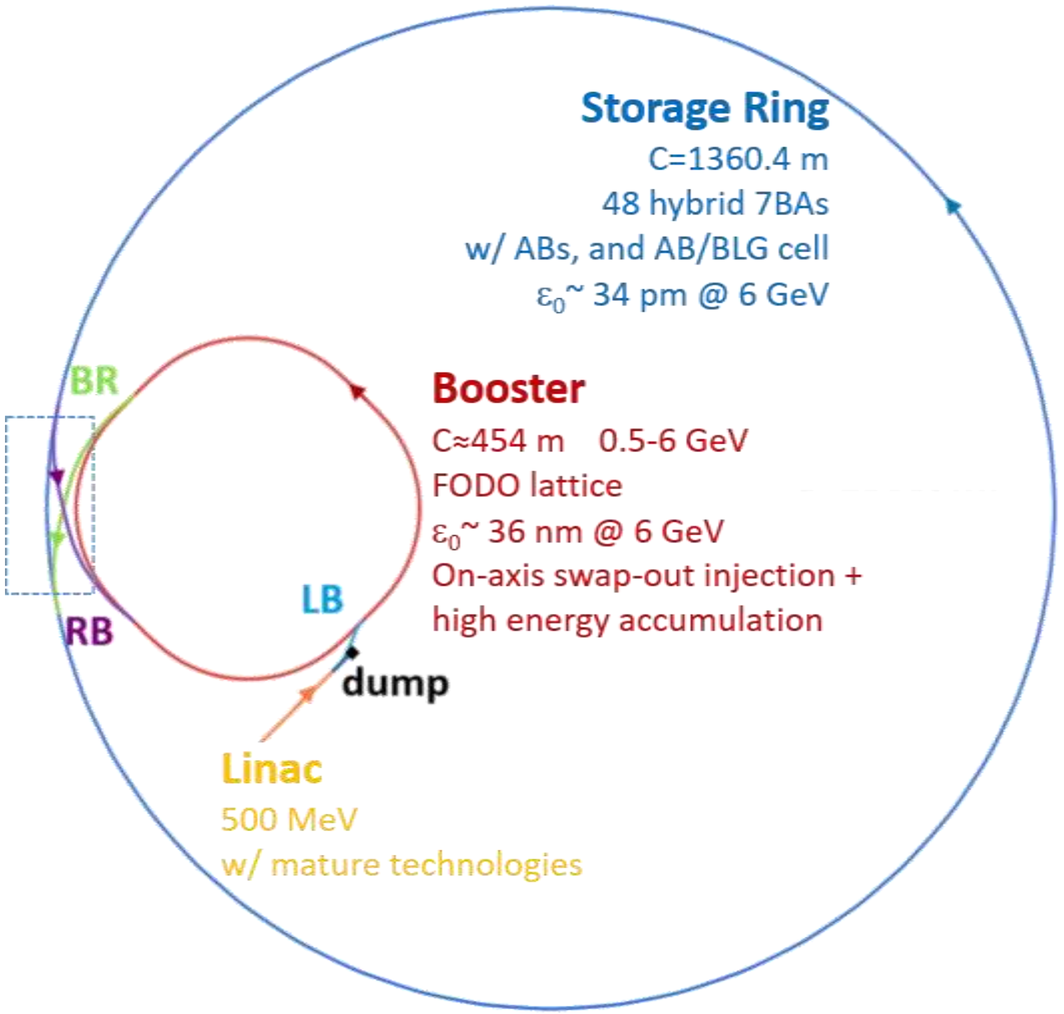


Main Parameters	Design goals	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Hori. natural emittance	<60	pm·rad
Brightness	$>1\times10^{22}$	BU
Beam current	200	mA
Injection mode	Top-up	-

BU: phs/s/mm²/mrad²/0.1%BW



Design goals of HEPS



Main Parameters	Value	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Hori. natural emittance	<60	pm·rad
Brightness	$>1\times10^{22}$	BU
Beam current	200	mA
Injection mode	Top-up	-

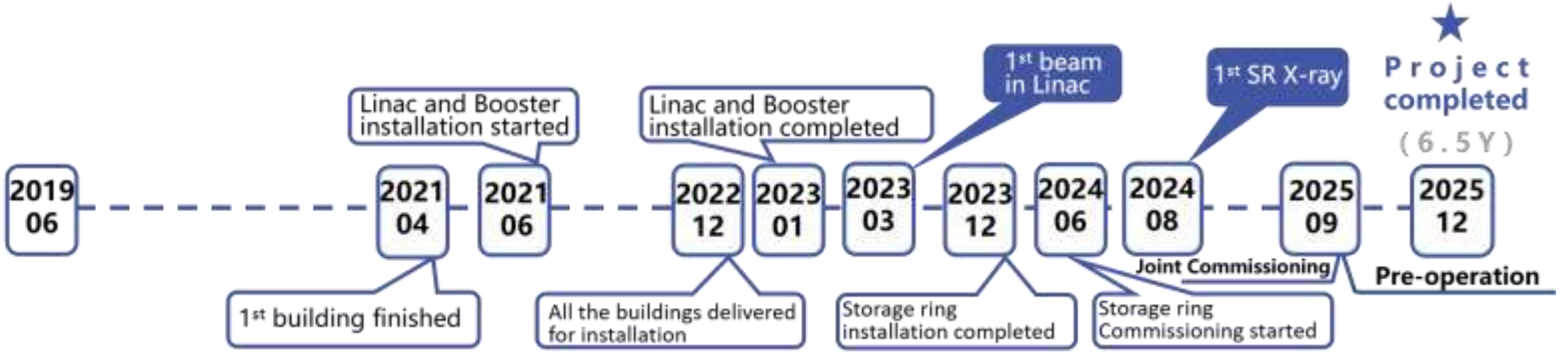
BU: phs/s/mm^2/mrad^2/0.1%BW

Schedule (2019-2025)

- **The construction period was estimated to be 6.5 years.**

  - Date of Groundbreaking ceremony: Jun. 29, 2019

  - Project is scheduled to be completed in 12.2025



Aug. 8, 2022, the installation in the booster tunnel began.

Jun. 28, 2021, HEPS Installs First Piece of Accelerator Equipment in Linac Tunnel.

Milestones

June 29, 2019
Groundbreaking ceremony

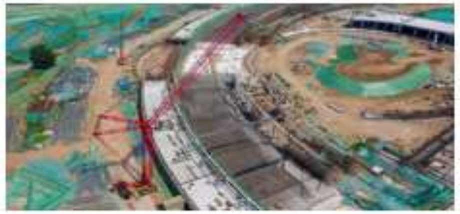
May 12, 2022
The Linac Vacuum-sealing in the tunnel completed

Jan. 13, 2023
The Booster Vacuum-sealing in the tunnel completed

Feb. 1,2023
The first girder was installed in the storage ring tunnel

Mar. 14, 2023
The first electron beam

July 1, 2020
The first steel beam was installed



Apr. 13, 2021
Utility installation in NO.2 Hall commenced

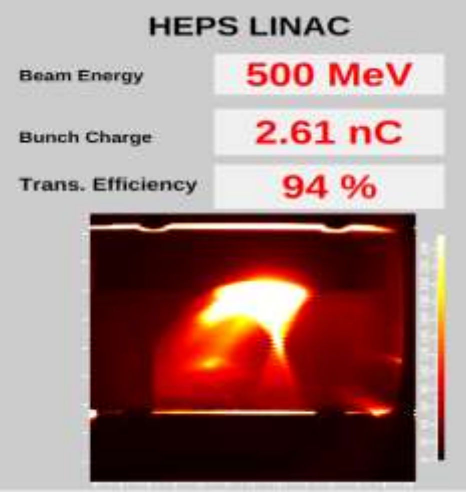
June 27, 2021
Roof-sealing work for the main ring building completed

June 28, 2021
HEPS Installs First Piece of Accelerator Equipment in Linac Tunnel.

Nov. 18, 2021
Roof-sealing work for ancillary buildings completed

Progress of Linac

LINAC



The first electron beam of the HEPS was accelerated to 500 MeV with better than 2.5 nC of bunch charge by the Linac on March 14, which was a key milestone of the HEPS project—HEPS beam commissioning had begun.

Milestones of the HEPS Linac

29/06/2019: Design completed

28/06/2021: Electron gun, the first piece of accelerator equipment, was installed in the Linac tunnel.

08/03/2022: Installation in the Linac tunnel begun

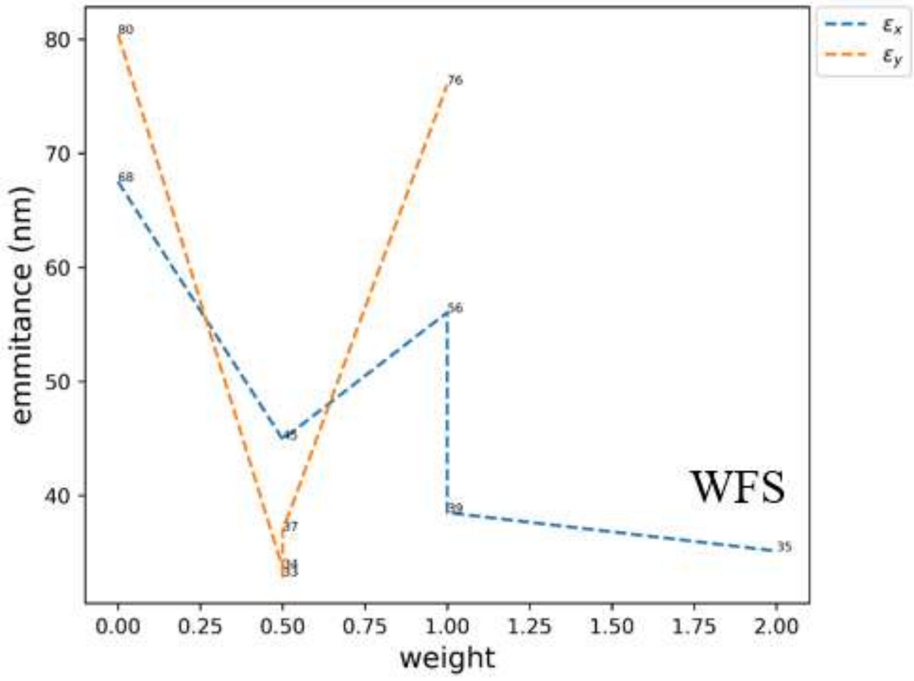
12/05/2022: Linac vacuum-sealing in the tunnel completed

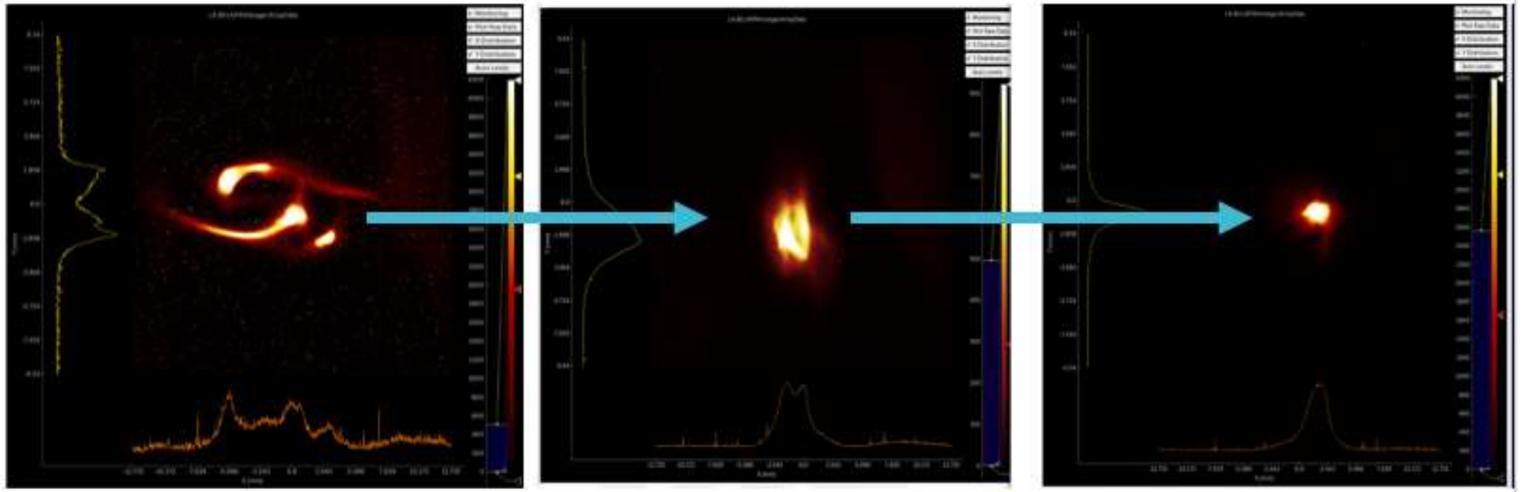
23/09/2022: Linac online RF conditioning completed

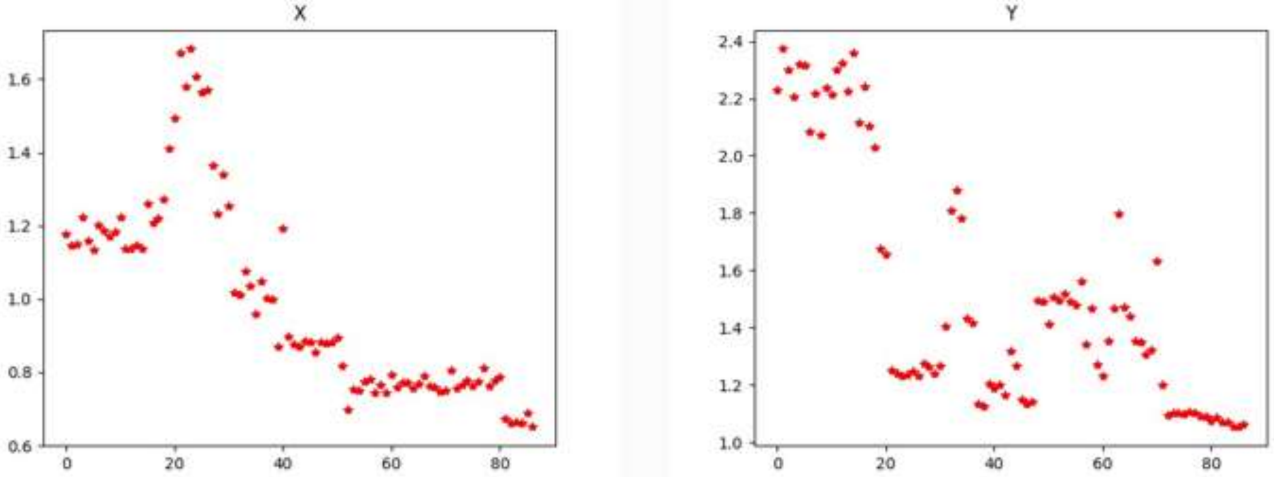
09/03/2023: Linac commissioning began

Emittance optimization: Wakefield

- Beam size optimization
- Wakefield-free steering（WFS）







Progress of booster

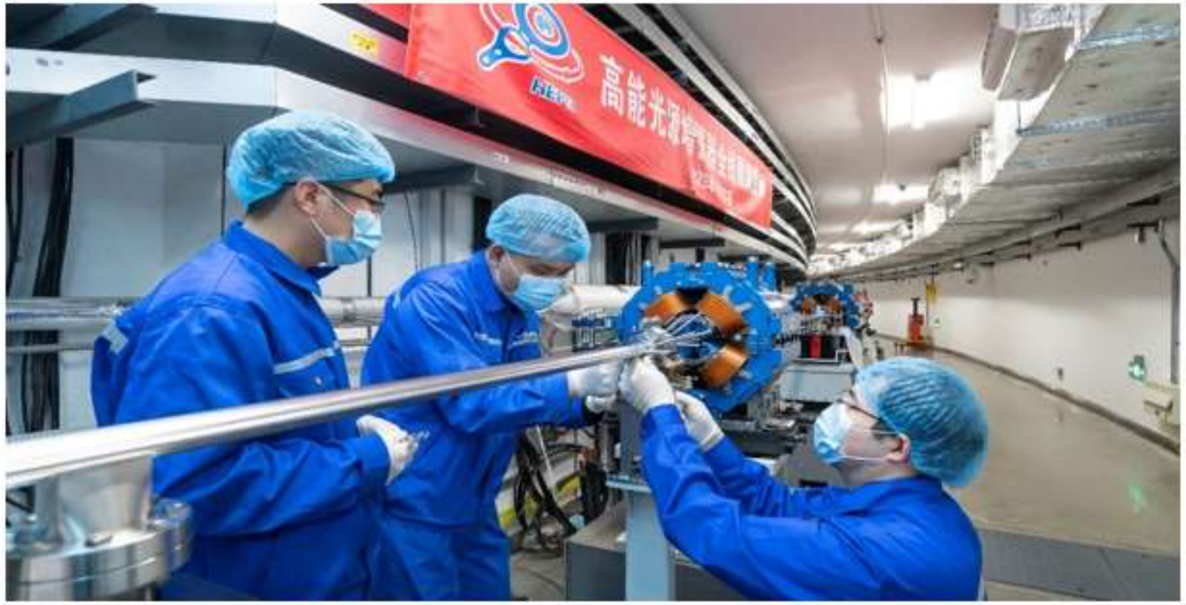
RF conditioning started on May 25, 2023 and beam commissioning began last month.

The Booster was vacuum-sealed on Jan. 13, 2023.

Sep. 30, 2022, The pre-alignment of the booster installation cells completed.

Aug. 8, 2022, The installation in the booster tunnel began.

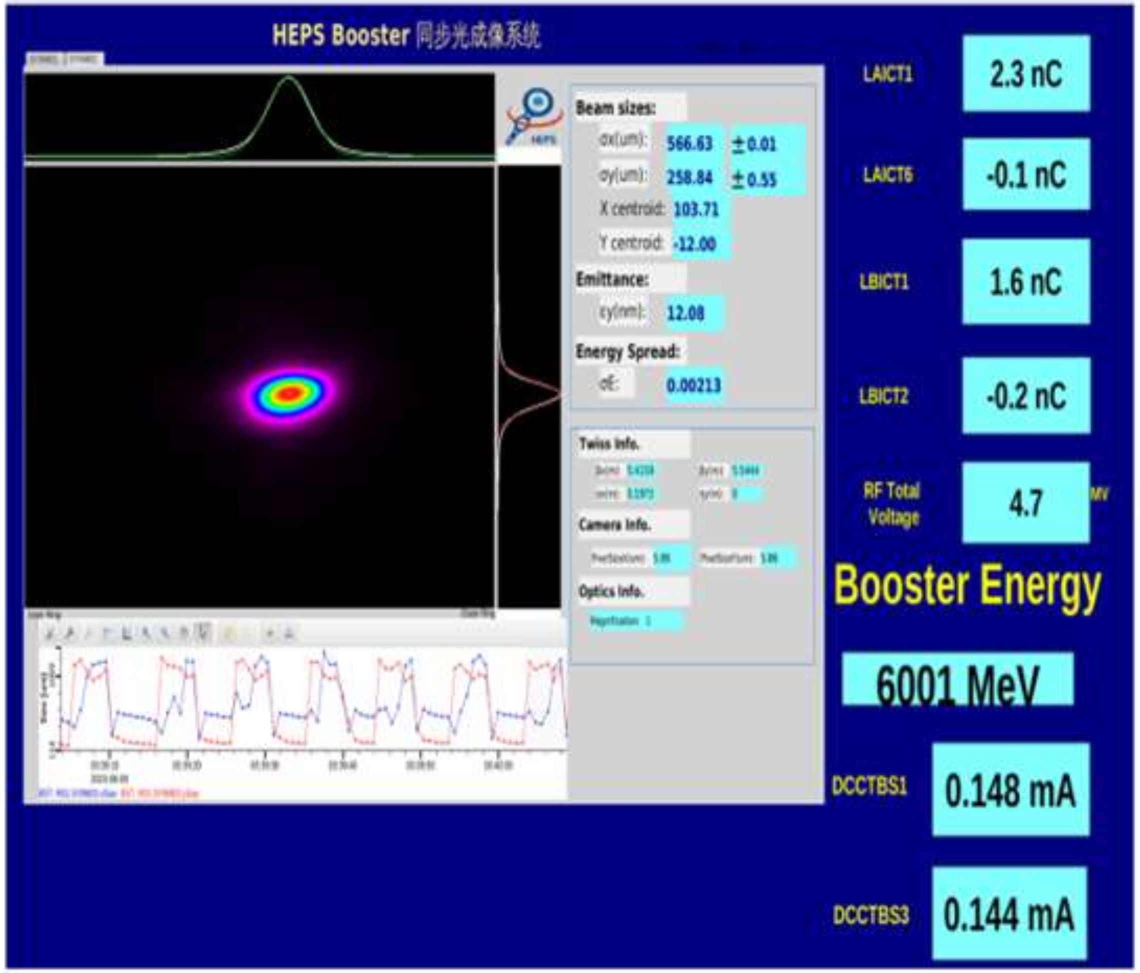
Dec. 14, 2021, Booster tunnel building moved to installation phase.

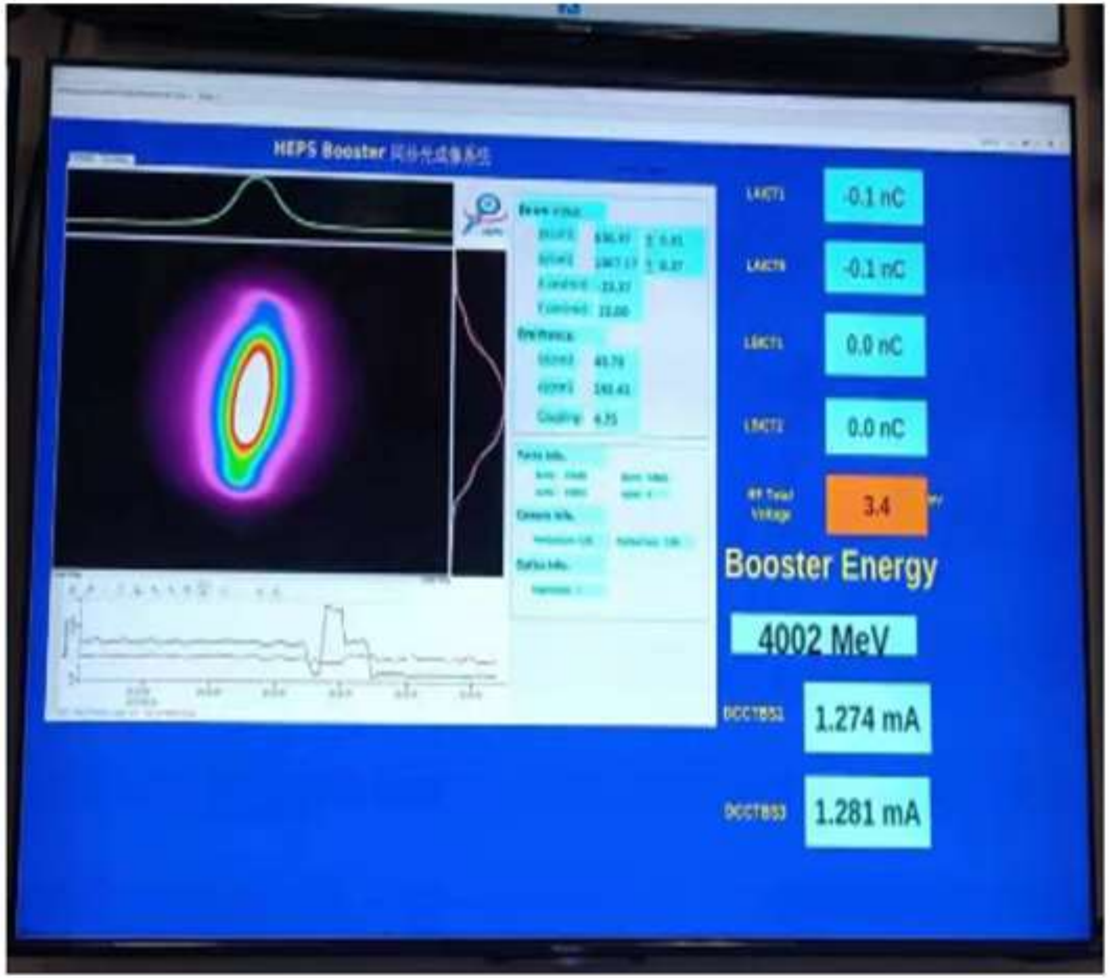


132 pre-alignment cells

Booster commissioning

Beam energy ramping to 6.0 GeV (with RF)





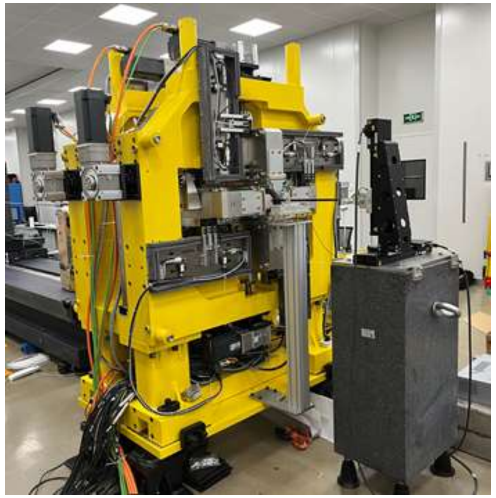
Progress of storage ring

1776 magnets **288** girders

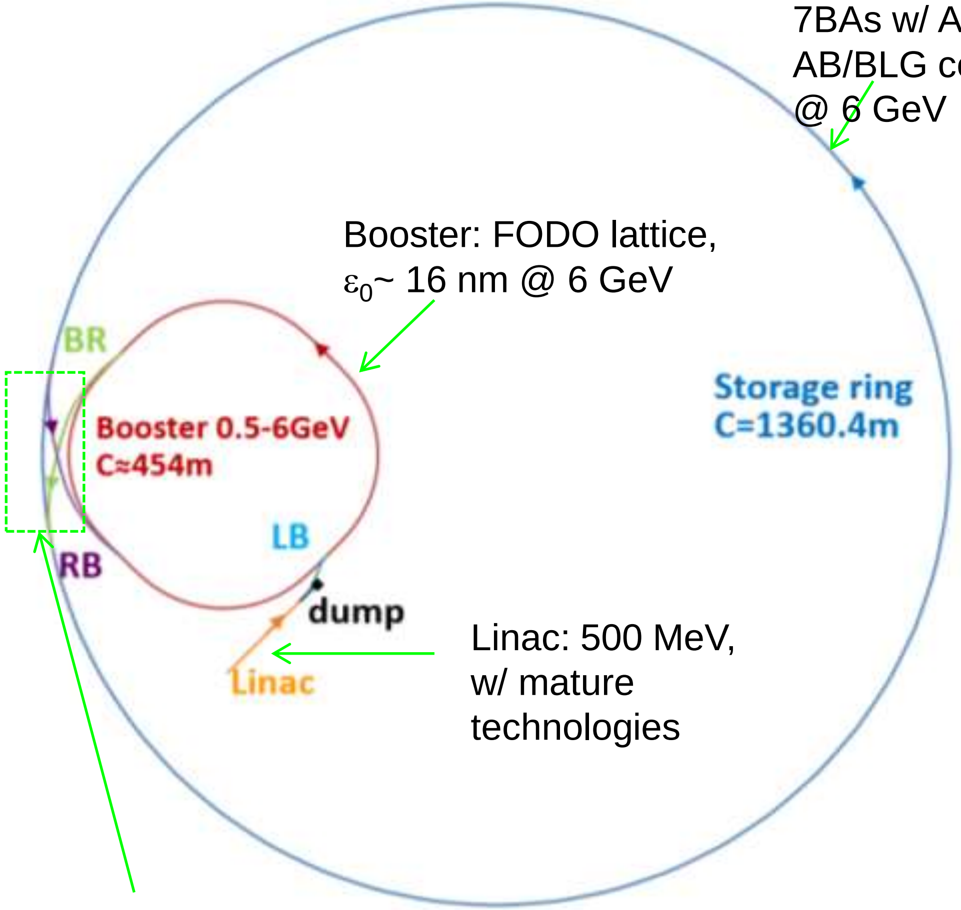
- The installation of a 7BA cell of the storage ring on the experiment bench was successfully finished to optimize process flow.
- The pre-alignment for the storage ring magnet girder began on July 13, 2022.
- The tunnel installation of the storage ring started on Feb. 1, 2023.
- Up to date, ~75% girders has been installed.

Progress of storage ring

19 insertion devices (including IAU, IAW, CPMU and IVU AK Mango) were manufactured and received.



Accelerator Physics

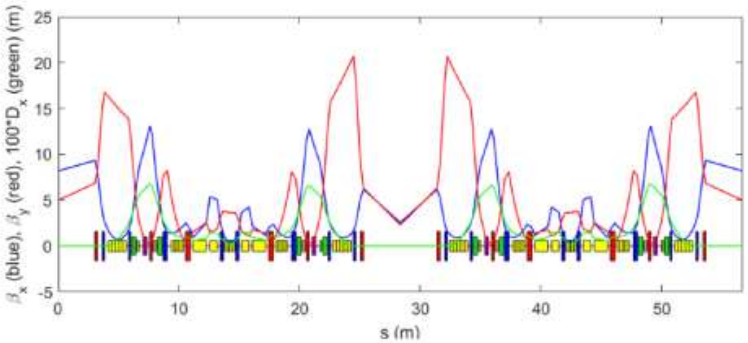


Storage ring: 48 hybrid 7BAs w/ ABs, and AB/BLG cell, ε_0~ 35 pm @ 6 GeV

Booster: FODO lattice, ε_0~ 16 nm @ 6 GeV

Linac: 500 MeV, w/ mature technologies

On-axis swap-out injection + high energy accumulation

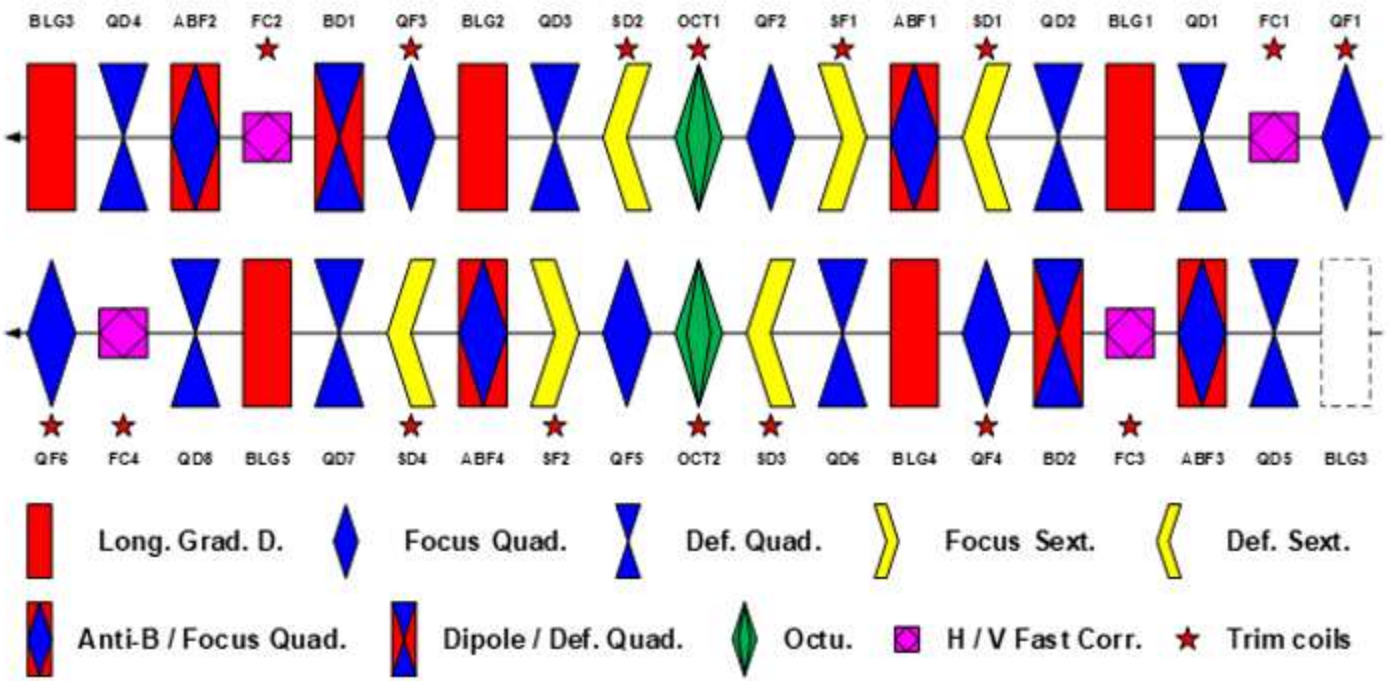


To deal with challenges from technical and engineering design, the accelerator physics design was updated

- Storage ring lattice: enlarged drift space in arc (1.1 m more space/7BA), slightly larger magnet aperture (25->26 mm), emittance preserved (34.2->34.8 pm) with however smaller dynamic acceptance
- Booster design: higher bunch charge (2->5 nC), and emittance reduced by more than 50% (35->16 nm)
- Linac design: higher bunch charge (5->7 nC) and optimized layout
- Transfer lines: updated accordingly

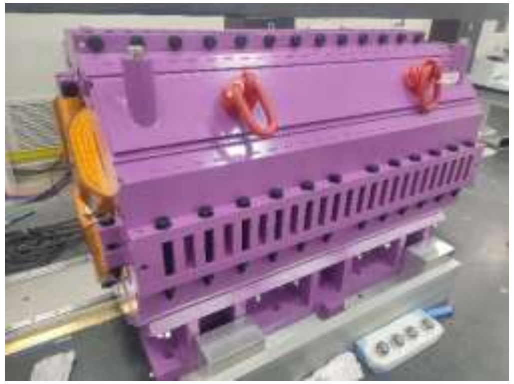
Storage-ring magnets

- Magnets
  - 37 magnets in one 7BA cell
  - BLG 0.11 – 1 T
  - Quad 82 T/m
  - BD 66 T/m
  - Sext 6082 T/m²
  - Oct 512600 T/m³
  - Fast Corr 0.08 T



BLG2

ABF2/3



BD1/2

QD4

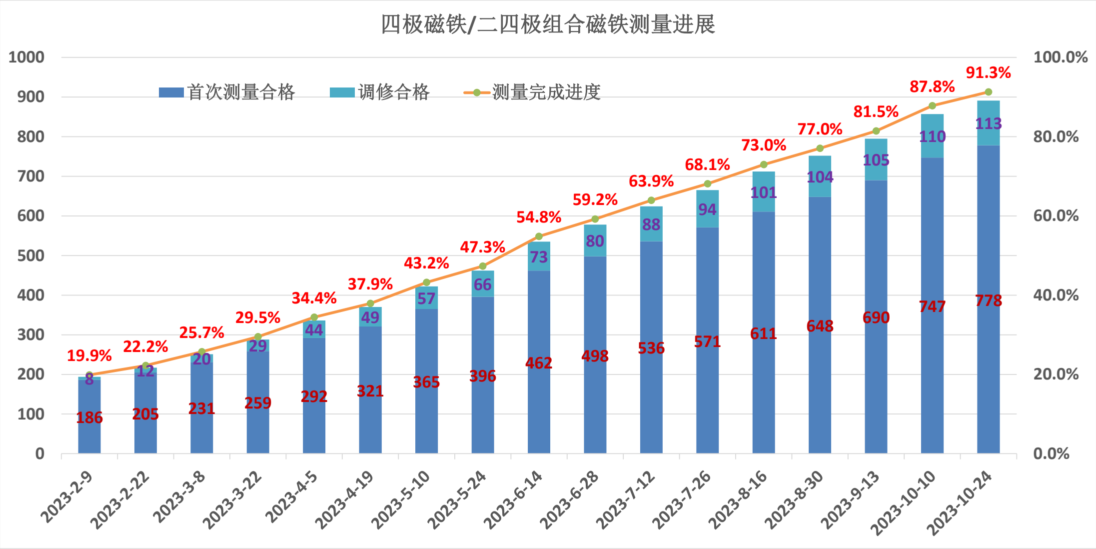
Magnetic field measurement

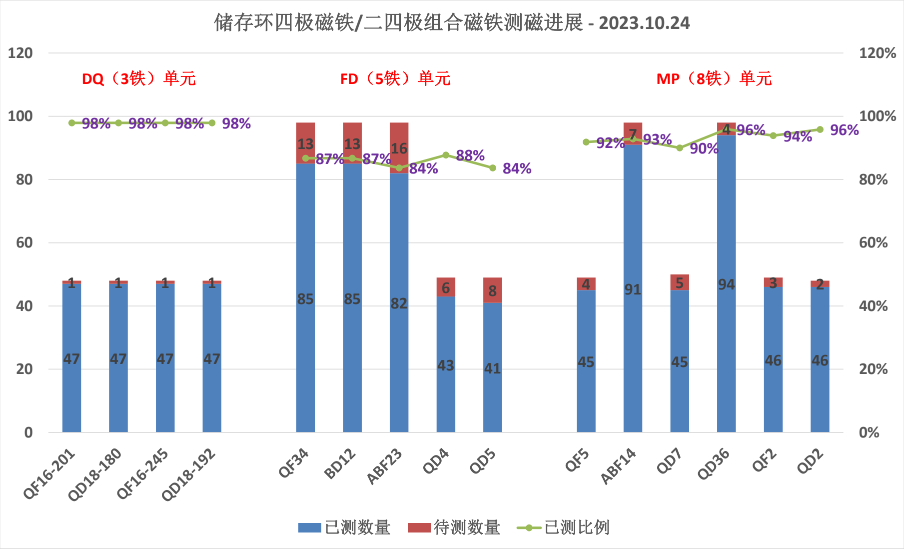
- **Measurement and pre-alignment move on schedule**

 - Measurement of the dipoles, quadrupoles and dipole/quadrupole combined function magnet will be finished by the end of November

 - All sextupoles, octupoles and fast correctors have been measured

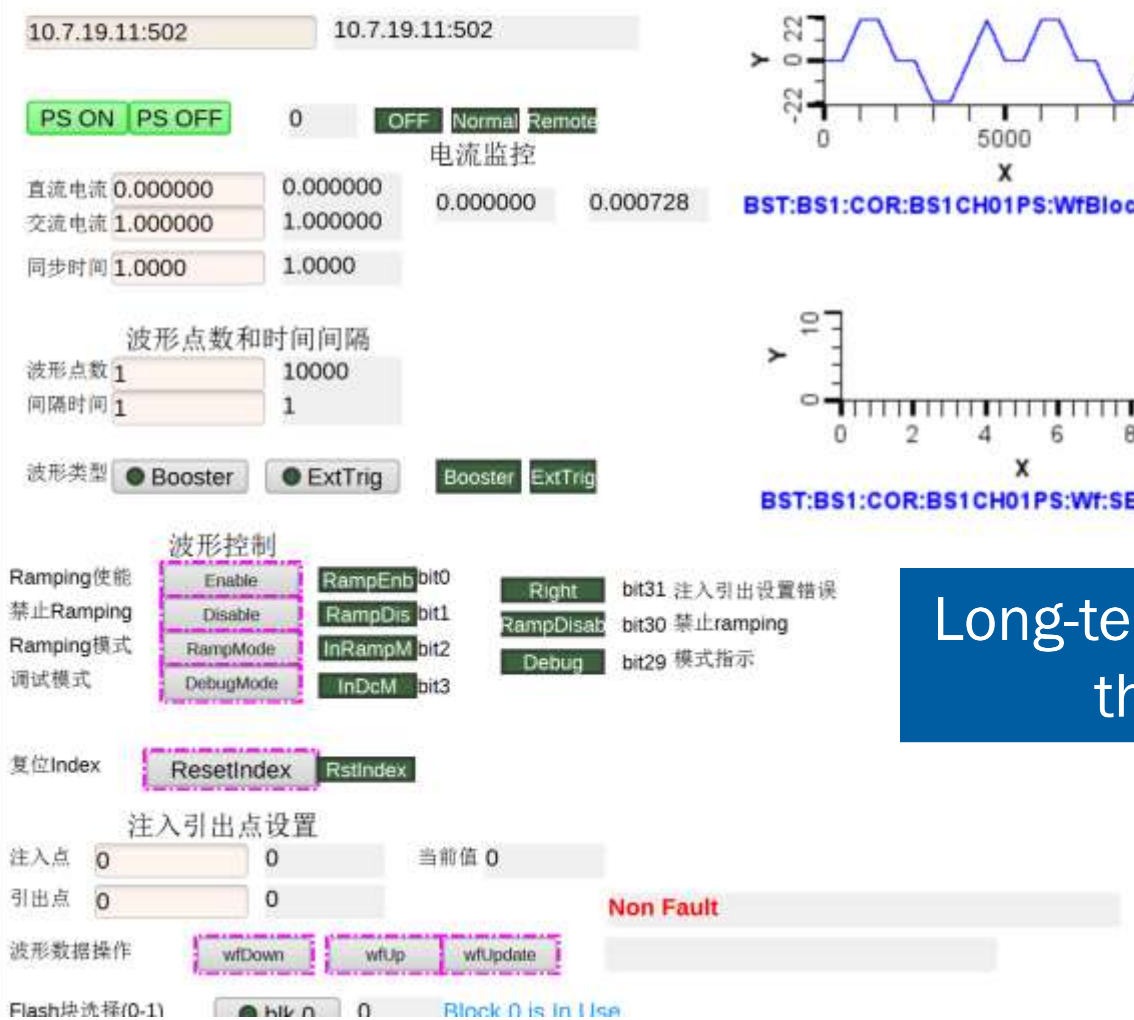
 - Fine tuning of the BLGs field integrals is performed by using adjustable screw. All the BLGs are within 5x10^{-5} after tuning

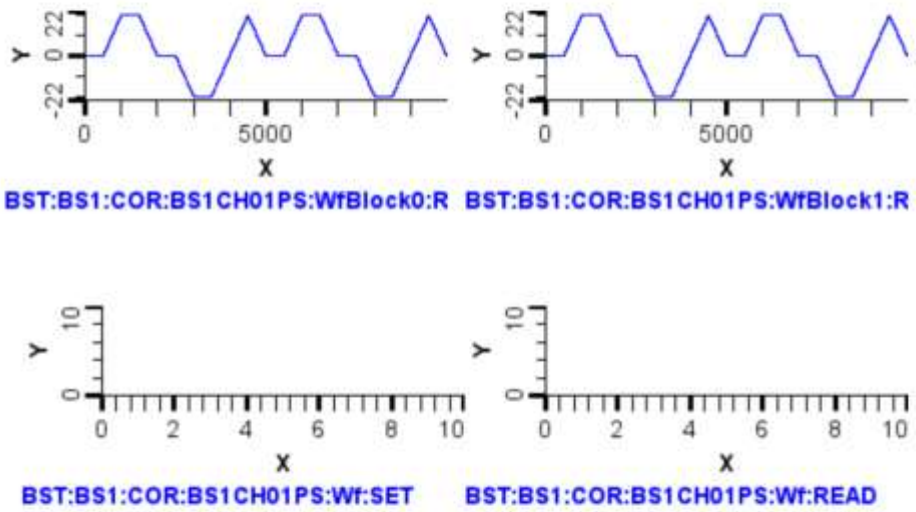




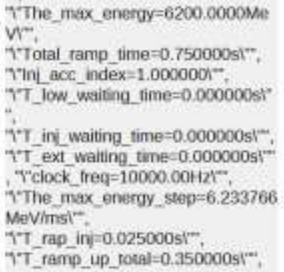
Magnet power supply

- All power supplies installed （total number 2804） at 10 PS Halls and M01-48
- PS for Linac, Low energy transport and Booster started commissioning





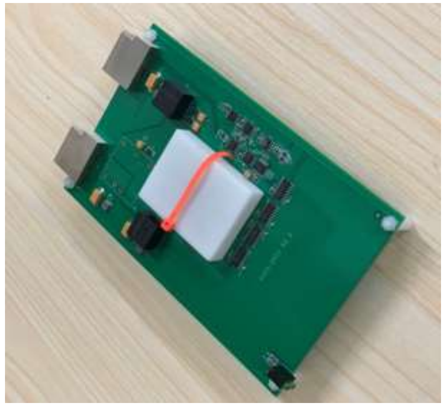
Long-term stability better than 10 ppm

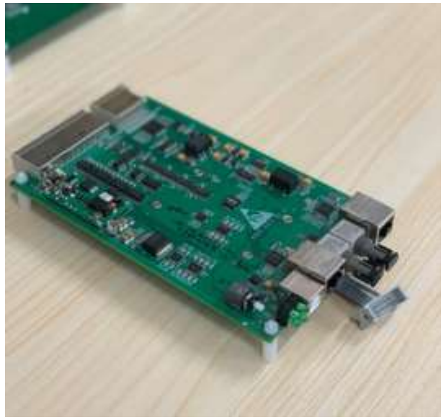


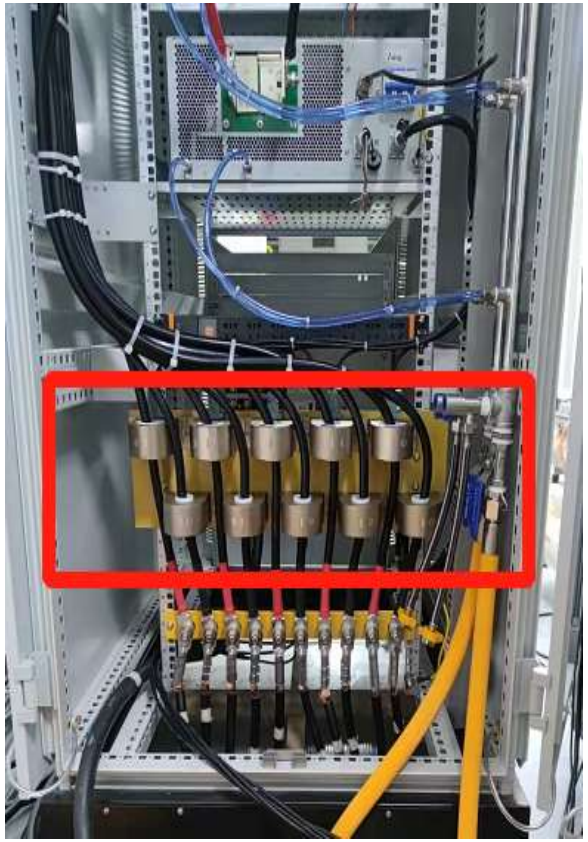
Magnet power supply

- All power supplies are digital-controlled with self-designed DPSCM(Digital Power Supply Control Module) and DCCT(two scales with 20A and 300A).

DCCT: DC Current Transformer (Accuracy < 2 ppm)





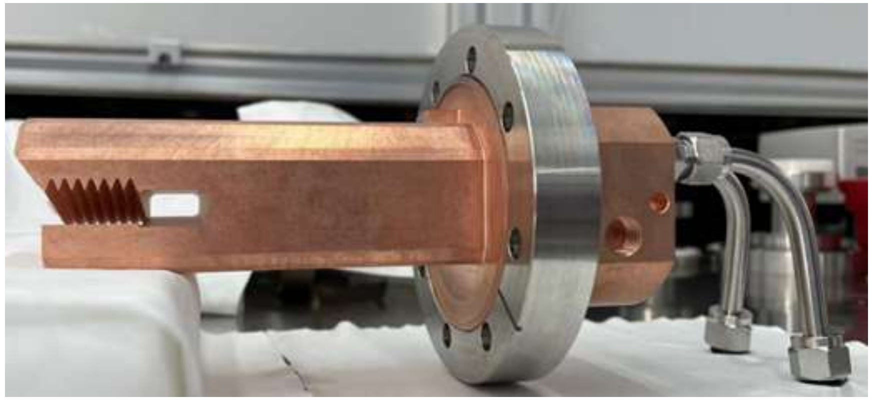


Storage-ring vacuum

- The vacuum components in the storage ring are being mass-produced, and the vacuum equipment of a standard arc cell have been installed and verified

Stainless steel chamber with pumps, photon absorbers and end mask, and copper is coated inside.

Extruded Cu-Cr-Zr (C18150) antechamber



Cu-Cr-Zr /dispersion-Cu crotch photon absorber

RF shielding bellows with double-fingers type, and BPM module is integrated.

NEG coating facilities

- 3 sets of NEG coating equipment have been built

  - 1 for coating small aperture circle vacuum chambers, and 6*3.5m vacuum chambers can be coated simultaneously
  - 1 for antechambers paralleled with 4 groups in a length of 1.5m, and the NEG coating have been verified in a slit height of 6mm with a length of 1.2m
  - A 6m long vacuum chamber can be coated in the 3rd setup by moving solenoid vertically.

NEG coating pumping speed ~ 0.72 L/(s·cm^2)(H2)



Girder & Magnet support

SR magnet support system

- Prototypes developed and engineering design scheme finalized
- Contradiction between the precise motion and stability compromised effectively

- Eigen frequency： ≥71Hz
- Motion resolution : 1μm

- Concrete plinths grouting finished in tunnel and passed the final test acceptance.
- Girder mass production finished and installation is in progress, 70% completed.

LA & BS mechanical support

- All the mass production and tunnel installation have been completed

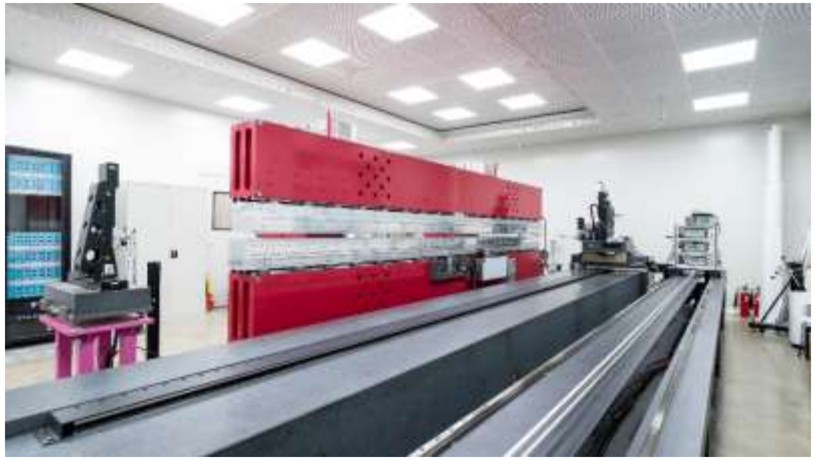
Insertion Device

In-air IDs

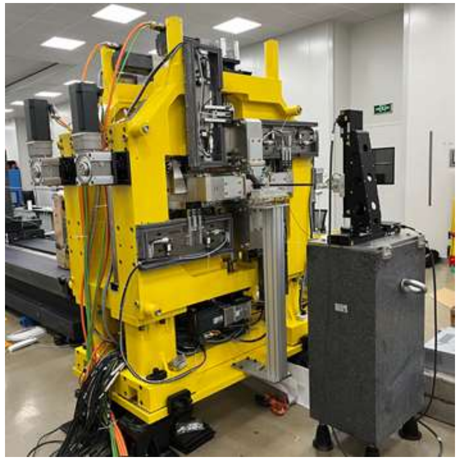
- The **APPLE-Knot undulator** is an innovative device which can achieve both circular polarization and low on-axis heat load. The "**Mango**" wiggler is designed to offer a big radiation spot size for Large - field X-ray diagnosis and flaw detection. They are both successfully realized and through expert review.
- The development of 6 in-air IDs (4 **IAU**s+ 2 **IAW**s) is finished, ready for tunnel installation.

Merged APPLE-Knot: 1st 4 Array AK

Mango: Scan range 0.6mrad*0.6mrad



AK



MANGO

IAU

IAW

Insertion Device

- The mass production of 11 in-vacuum IDs (6 CPMUs + 5 IVUs) completed
- The batch tuning is underway

Short period 12mm

CPMU in Tuning

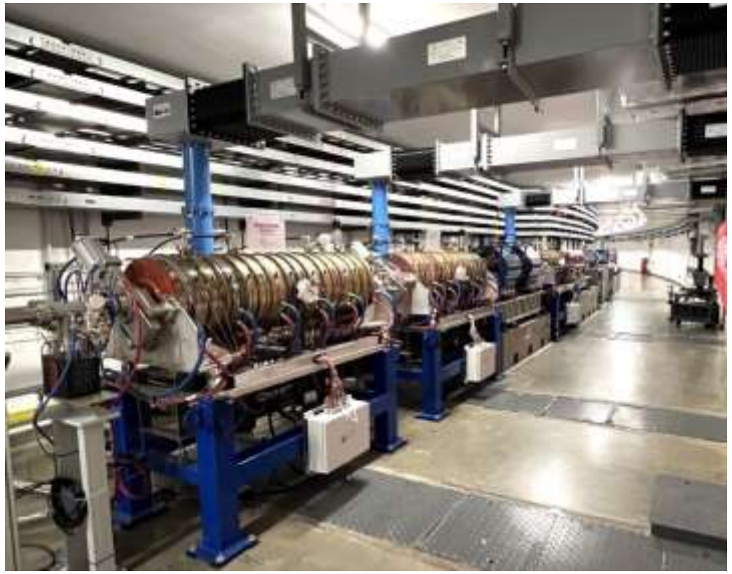
IVU in Tuning

IVU in Baking

RF cavities

- 2022.12, all six 500MHz 5-cell copper cavities passed SAT at PAPS (c.w. 120kW)
- 2023.07, three 500MHz 5-cell **copper cavities installed in the Booster tunnel and commissioned**
- 2021.11, first 166MHz bare SRF cavity passed vertical acceptance tests
- 2022.06, first **166MHz jacketed SRF cavity passed vertical acceptance tests**
- 2023.06, first **166MHz cryomodule assembled** and moved into the horizontal test stand
- 2022.12, four **500MHz bare SRF cavities** produced and **passed vertical acceptance tests**

500MHz 5-cell copper cavities



166MHz SRF cryomodule

500MHz SRF cavity string

High-power RF system

- 2021.10, 166MHz-260kW and 500MHz-150kW prototype SSAs passed essential tests at PAPS
- 2023.04, 166MHz-260kW and 500MHz-260kW **series SSAs production complete and passed FAT**
- 2023.07, **500MHz-100kW series SSAs complete and passed SAT** at Booster RF hall
- 2023.06, first 500MHz-150kW circulator installed at Booster and passed SAT

Low-level RF system

- 2022.12, XILINX-based LLRF in-house developed
- 2023.05, integration of cavity, SSA and LLRF at Booster complete
- 2023.07, **commissioning of booster RF complete**
- 2023.04, RF EPICS database start archiving data
- 2023.04, Booster RF control OPI developed

Cryogenics system

- Layout of the cryogenics system finished and met the technical requirements of HEPS micro-vibration requirement
- All cryogenic equipment of cryogenic hall, tank area and HEPS zone installed

Transport line from cryogenic hall to HEPS

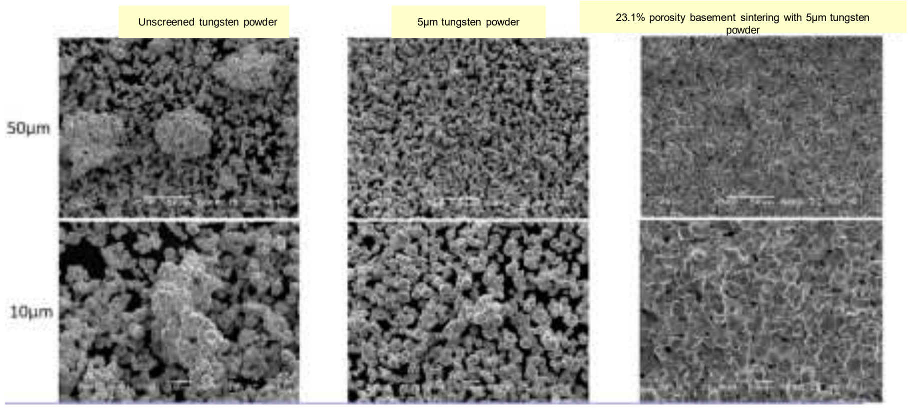
Tank area and cryogenic hall

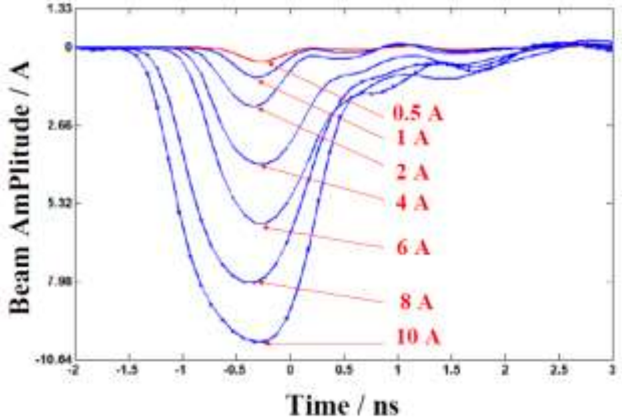
Linac microwave and power source

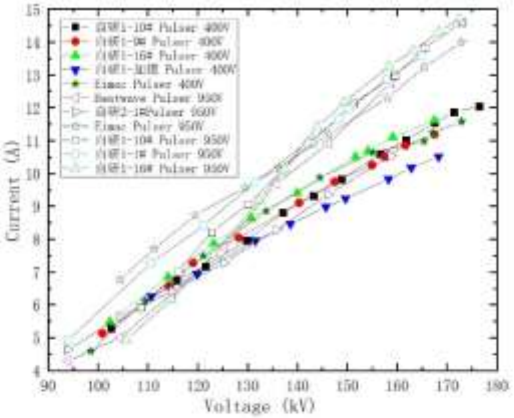
- **Cathode-grid Assembly R&D**

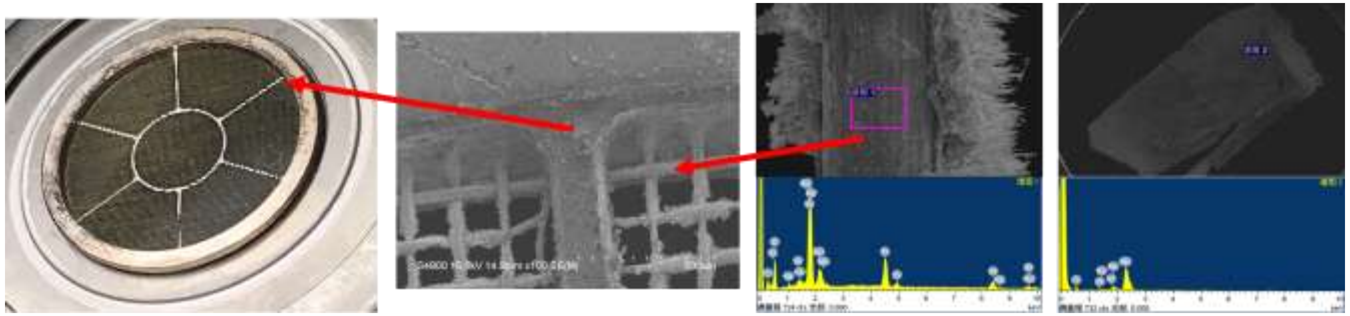
  - Assembly emission current satisfied E-gun of HEPS linac

  - Reliability and lifetime of assembly are under tests







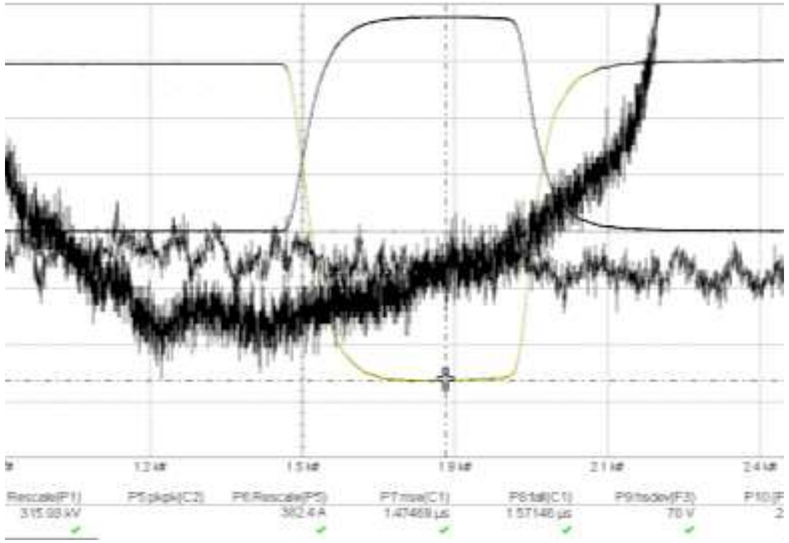


Linac microwave and power source

- **Solid-state modulator**

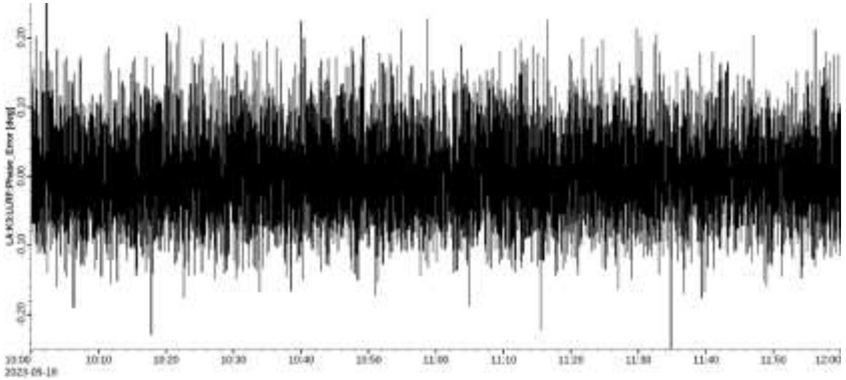
  - Completely eliminate instability and limited lifetime of thyratron
  - Solid-state modulator technology in-housed developed

Modulators in HEPS Linac Gallery



Pulse Repeat stability 0.018%
305kV/354.2A/30min

Microwave phase stability of Linac K3
2 hours p-p stability: 0.4°
2 hours RMS stability: 0.07°



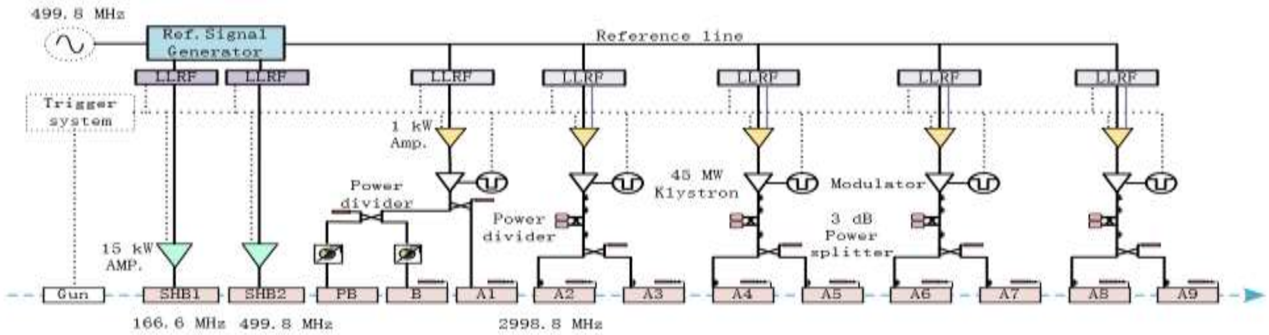
Linac RF system

- **Features**

  - The accelerating structure adopts an round-shaped cavity, an elliptical cross-section iris design, and the coupler design is a single port doubly fed structure
  - The pulse compressor design is a dual cavity structure with dual hole coupling, and internal water cooling
  - The directivity of DC: 40dB, LLRF is fully digital

- **Milestone**

  - 2019.6, microwave system design completed and begin to manufacture the component
  - 2021.3, complete the acceptance of the first accelerating structure
  - 2022.4, complete the installation of the accelerating structure and pass the final acceptance
  - 2022.5, complete the installation and test of the microwave system and begin online high-power practice
  - 2022.9, the energy reaches 500MeV at linac exit

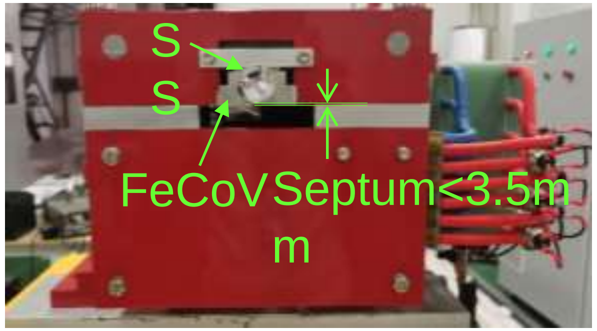


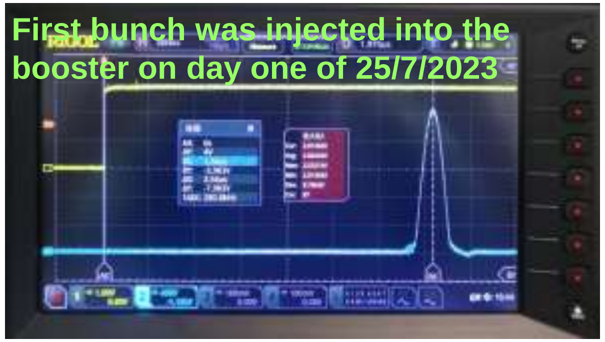
The layout of the linac RF system

Main components

Injection & extraction system

- **Booster**
  - All hardware including Lambertson magnets, kicker magnets and pulsers were delivered for installation in May 2023
  - The low-energy injection system has been put into operation for beam commissioning

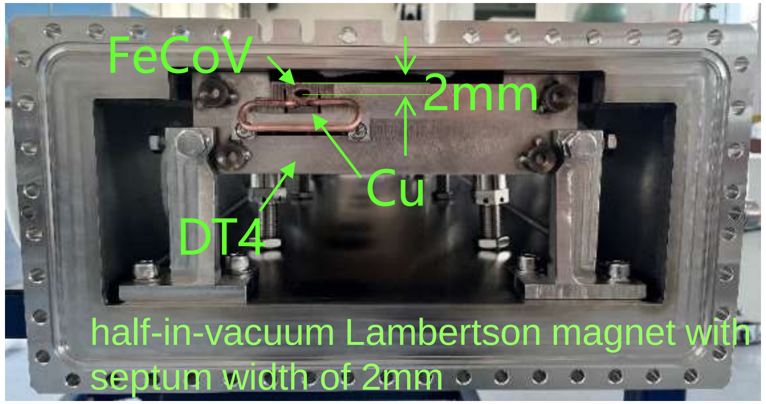




Injection & extraction system

- **Storage ring**
  - Kicker: All strip-line kickers delivered on 24/7/2023
  - Septum: the full-size prototype was completed in Jan. 2023 and 2 sets of final magnets are still under processing.

Fast kicker and pulser: pulse bottom width (3%-3%) < 10ns, pulse peak = ±15kV

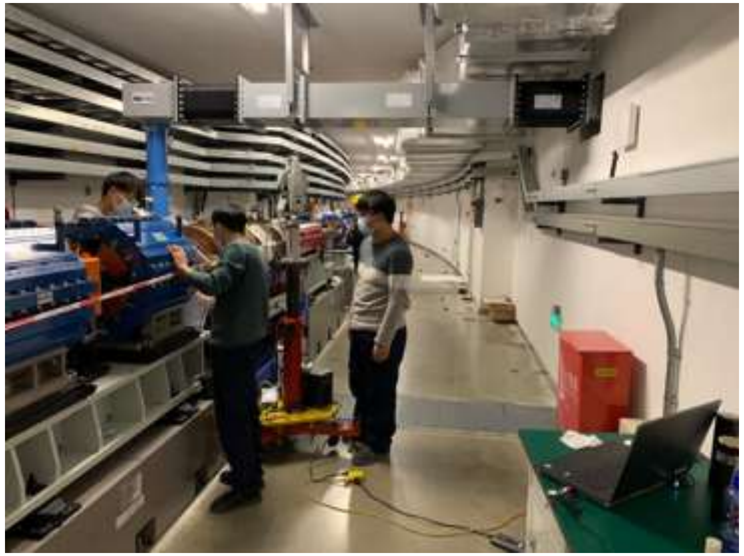


Alignment: Linac and Booster

- The initial alignment and smooth precise alignment of the 50-meter linear accelerator were completed from March to August 2022, with an alignment accuracy of **0.1mm**.
- From October to December 2022, the initial alignment of the 454-meter circumference booster was completed. From February to May 2023, two rounds of smooth precise alignment of the booster 's orbit were conducted with an alignment accuracy of **0.065mm**.
- All these alignment works have effectively improved the efficiency of beam commissioning and ensured stable beam operation. Currently, the linear tunnel is operating successfully, and the booster tunnel has completed beam commissioning. This demonstrates the correctness and practicality of the principle and procedure for achieving smooth precise alignment of the orbit.

Smooth precise alignment of linear accelerator

Smooth precise alignment of booster



Initial alignment of booster

Alignment: storage ring

- For the first time in China, the laser multilateration measurement method is adopted to the pre-alignment of storage ring magnets of HEPS. **The spatial coordinate measurement precision of 6μm within a 6.5-meter control range have been achieved.** The system has reached a world-leading level in terms of stability and measurement efficiency. By August 2023, 217 out of 288 girders have been pre-aligned.
- The initial alignment of the storage ring is currently underway. It is being carried out using a conventional single tracker control network fitting positioning method. The deviations have been adjusted to 0.05mm, the instrument control network fitting positioning error is 0.4mm, and the magnet position error is 0.5mm, meeting the requirements for initial alignment. By August 2023, 156 out of 288 girders has been completed.

Pre-alignment of storage ring magnets

Pre-alignment of storage ring magnets

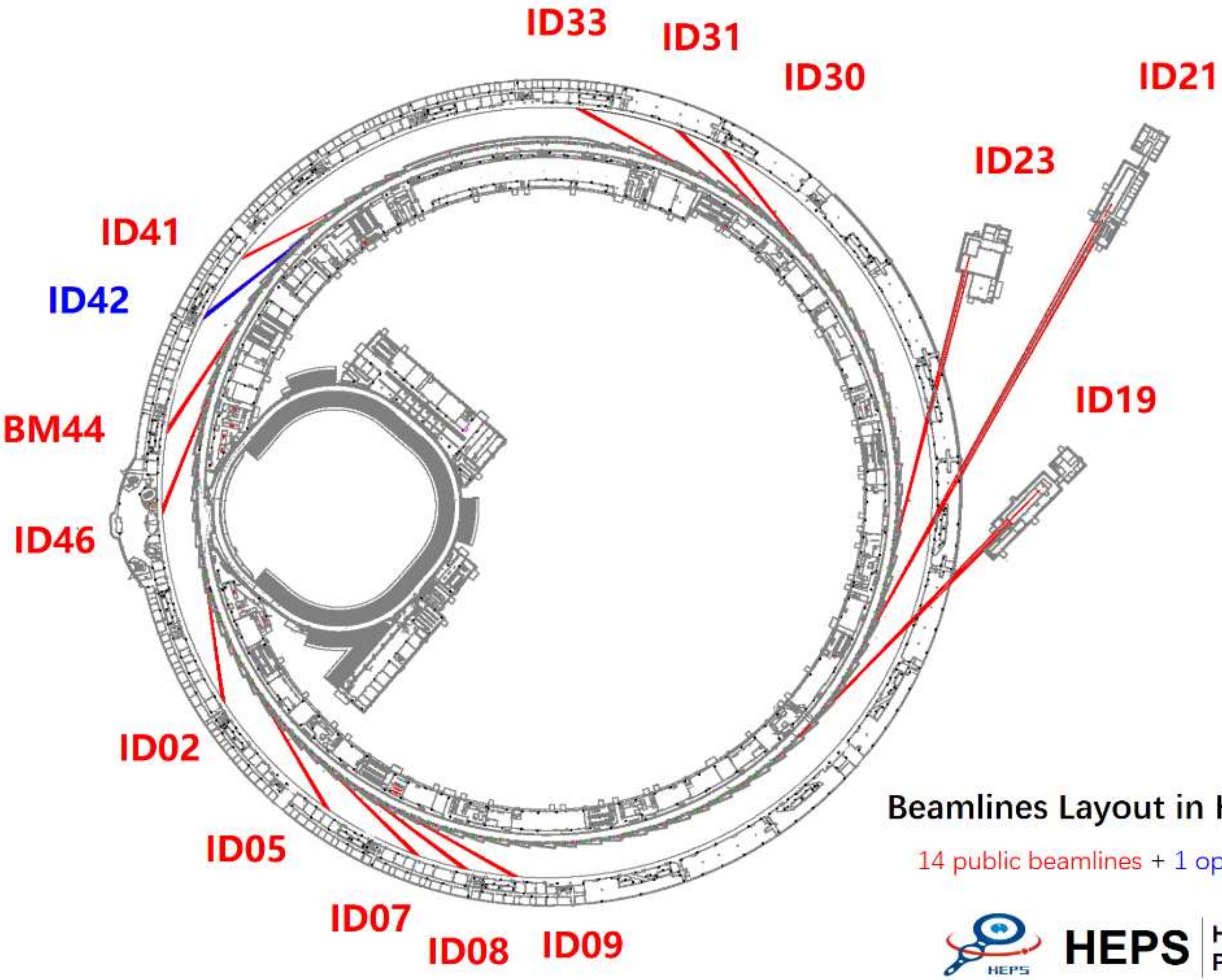
Initial alignment of the storage ring

Mock-up of storage-ring standard cell

- The operation space and interfaces have been checked, and pre-alignment scheme, transport scheme and other critical problems have been thoroughly tested

Aim to verify the feasibility of the magnet, vacuum chamber, BPM, etc. installation procedure

Layout of HEPS Phase I Beamlines



Beamlines Layout in HEPS phase I

14 public beamlines + 1 optics test beamline

HEPS HIGH ENERGY PHOTON SOURCE

HEPS Phase I Beamlines list

	Beamlines	Features
High Energy	Engineering Materials	50-170keV, XRD, 3DXRD, SAXS, PDF
	Hard X-Ray Imaging	10-300keV, Phase and Diffraction contrast imaging, 200mm large spot, 350m long
High Brightness	NanoProbe	Small probe, <10nm; *In-situ* nanoprobe, <50nm; 180m long
	Structural Dynamics	15-60keV, single-shot diffraction and imaging; < 50nm projection imaging
	High Pressure	110nm focusing, diffraction and imaging
	Nano-ARPES	100-2000eV, 100nm focusing, 5meV@200eV, APPLE-KNOT undulator
High Coherence	Hard X-ray Coherent Scattering	CDI(<5nm resolution), sub-μs XPCS
	Low-Dimension Probe	Surface and interface scattering, surface XPCS

Phase I Beamlines list (cont.)

	Beamlines	Features
General beamlines	NRS&Raman	Nuclear Resonant Scattering and X-ray Raman spectroscopy
	XAFS	Routine XAFS, plus 350nm spot and quick XAFS
	Tender spectroscopy	Bending magnet, 2-10keV spectroscopy
	μ-Macromolecule	1μm spot, standard and serial crystallography
	Pink SAXS	Pink beam, lest optics
	Transmission X-ray Microscope (TXM)	Full field nano imaging and spectroscopy
Test beamlines	Optics Test	With undulator and wiggler source for optics measurement and R&D

Status of HEPS Beamline

- Designs
- Key technologies
- Procurement and Delivery
- Test and Installation
- Schedule

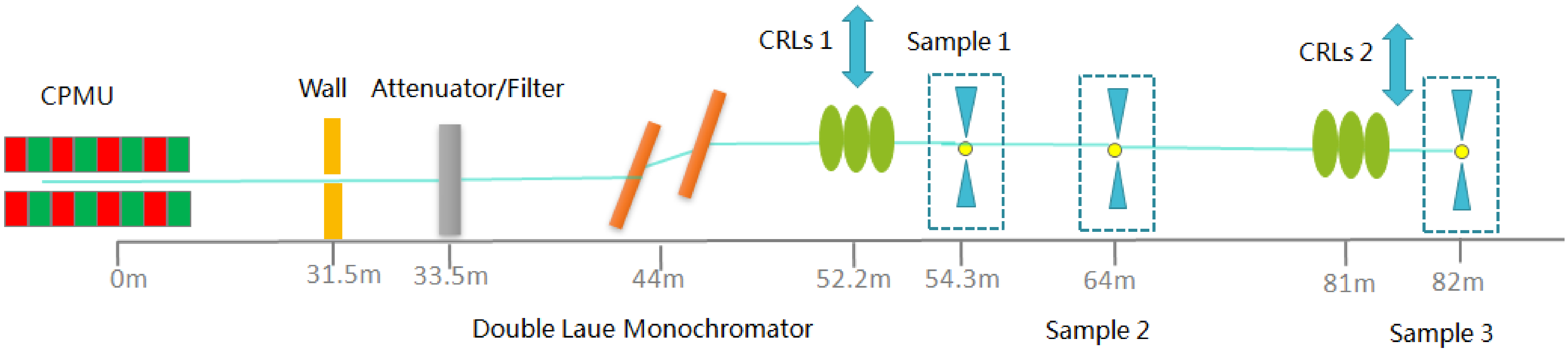
Engineering Materials Beamline

High energy X-ray for engineering materials

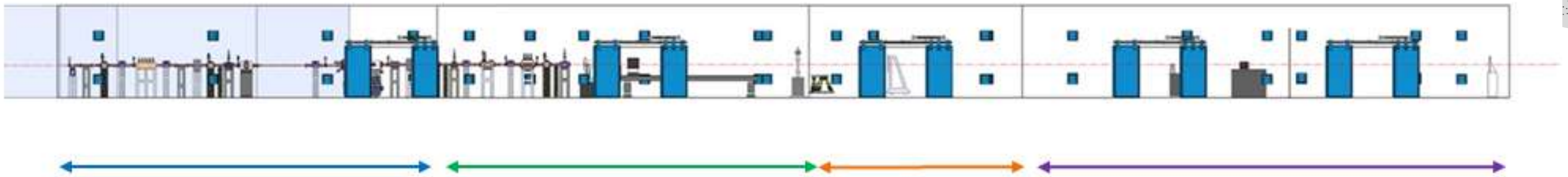
- Source, 2 x CPMUs for **photon flux >1×10^{12} @100keV**
- Mono, Laue monochromator, asymmetrically cut crystal, Double crystal, fixed exit

50keV~170keV , ΔE/E ~1×10^{-3} @100 keV

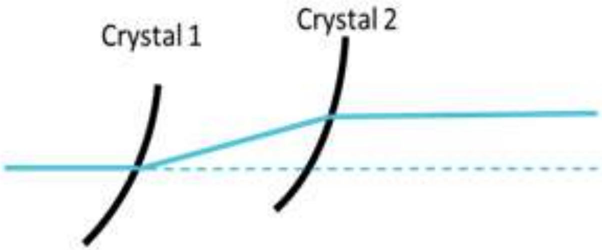
- Focusing, Home made Nickel-based Kinoform, **~2μm×2μm and submicron**

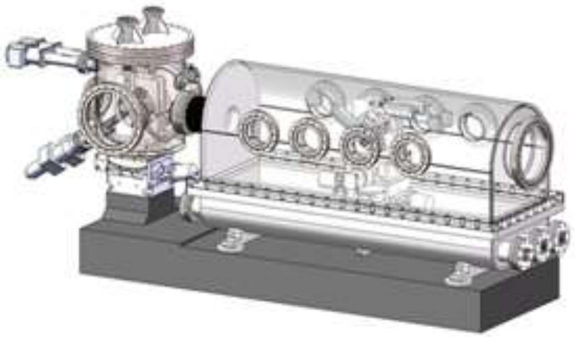


Engineering Materials Beamline

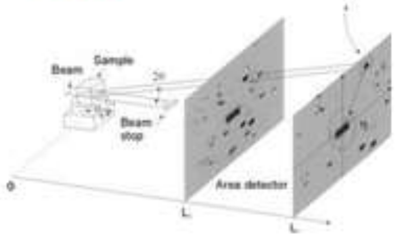


FOE: Laue optics



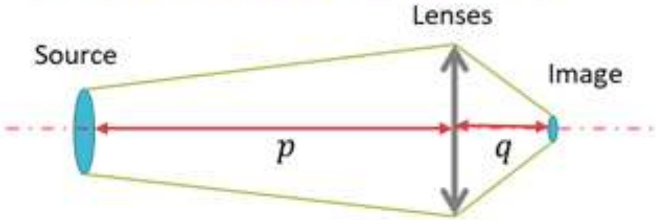


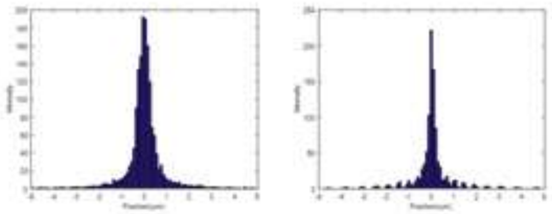
Hutch A: powder diffraction/3D XRD



Hutch B: large samples tensile mode heating mode

Hutch C: SAXS/micro XRD





100keV, ~500nm×200nm, ~5×10^{10}phs/s

Layout of beamline and endstations

Hard X-ray Imaging Beamline

Goals: High sensitivity, Deep penetration, Multiscale mesoscopic spatial resolution, Large FOV, Multiple contrast mechanisms and compatible with diverse sample environments.

Probes: In-line phase contrast imaging; Diffraction Contrast Imaging

Application: Biomedicine: whole organ mesoscopic imaging

Engineering Materials

Fossils and Human Relics

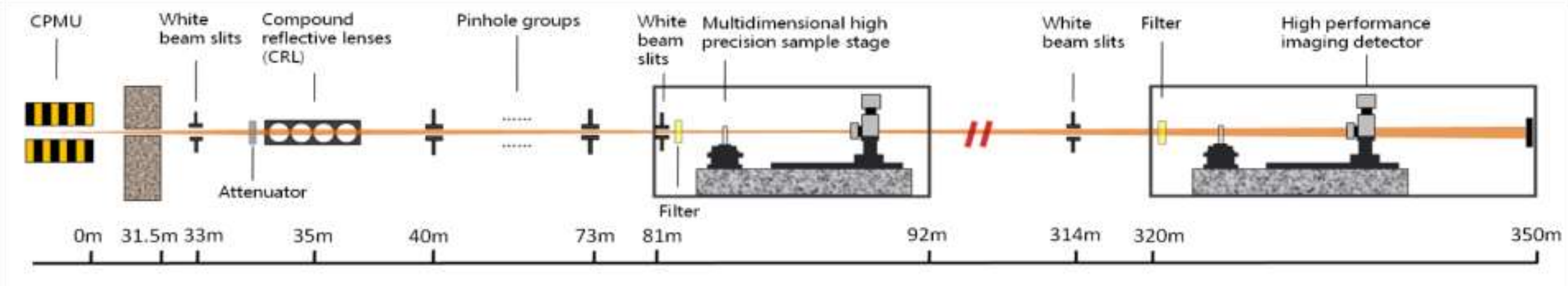
Features: Large FOV and high Resolution

Ratio of spot size and PSF increase from 2k to 20k, 1000 times of voxels one CT

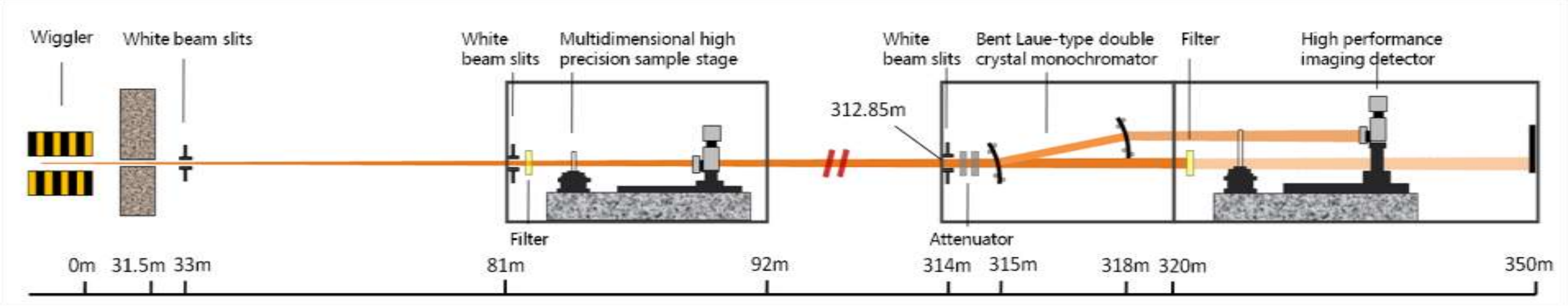
High sensitivity at high resolution & deep penetration case, very small PSF

Hard X-Ray Imaging Beamline

CPMU branch: 10-90 keV



Wiggler branch: 20keV—300keV

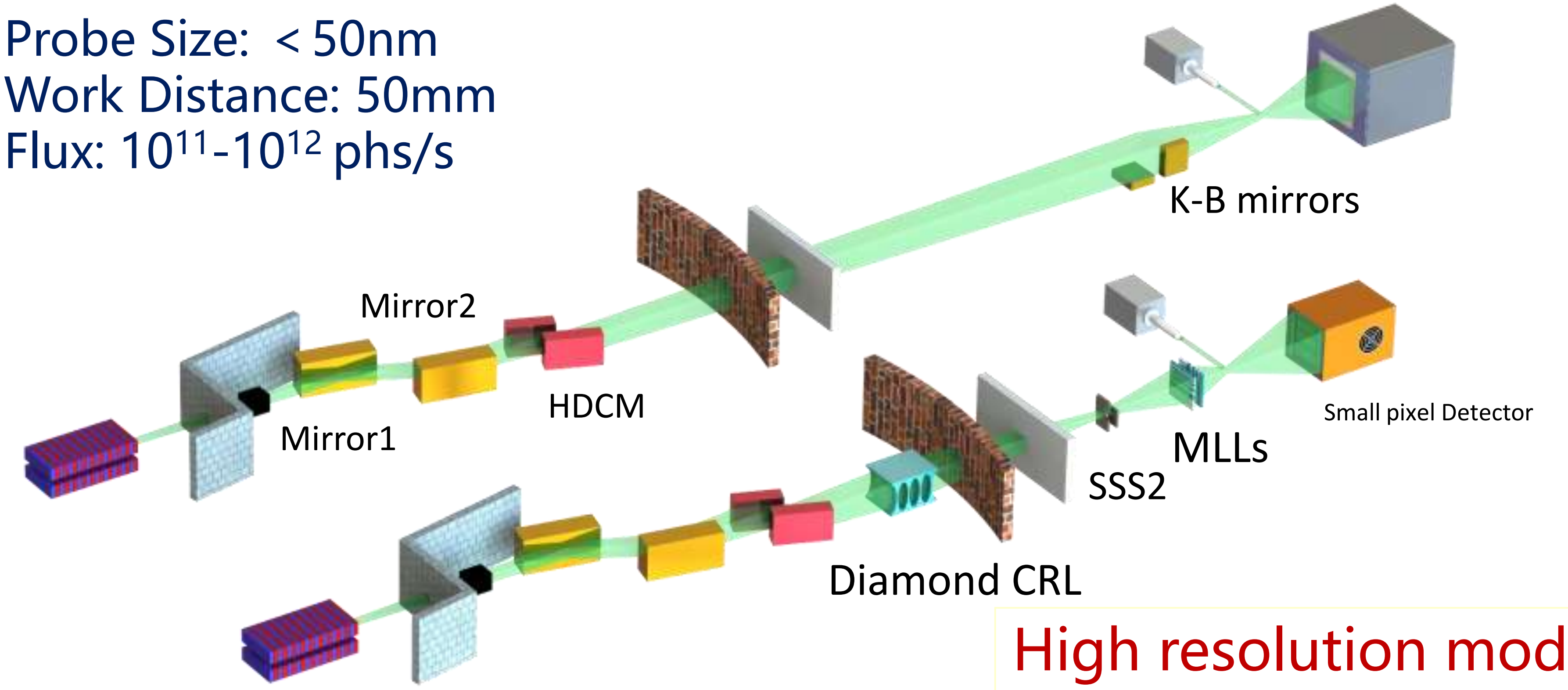


1xCPMU + 1xWiggler+1x Mango Wiggler； 350m long beamline

NanoProbe beamline

In-situ mode (K-B mirror)

Probe Size: < 50nm
Work Distance: 50mm
Flux: 10^{11}-10^{12} phs/s

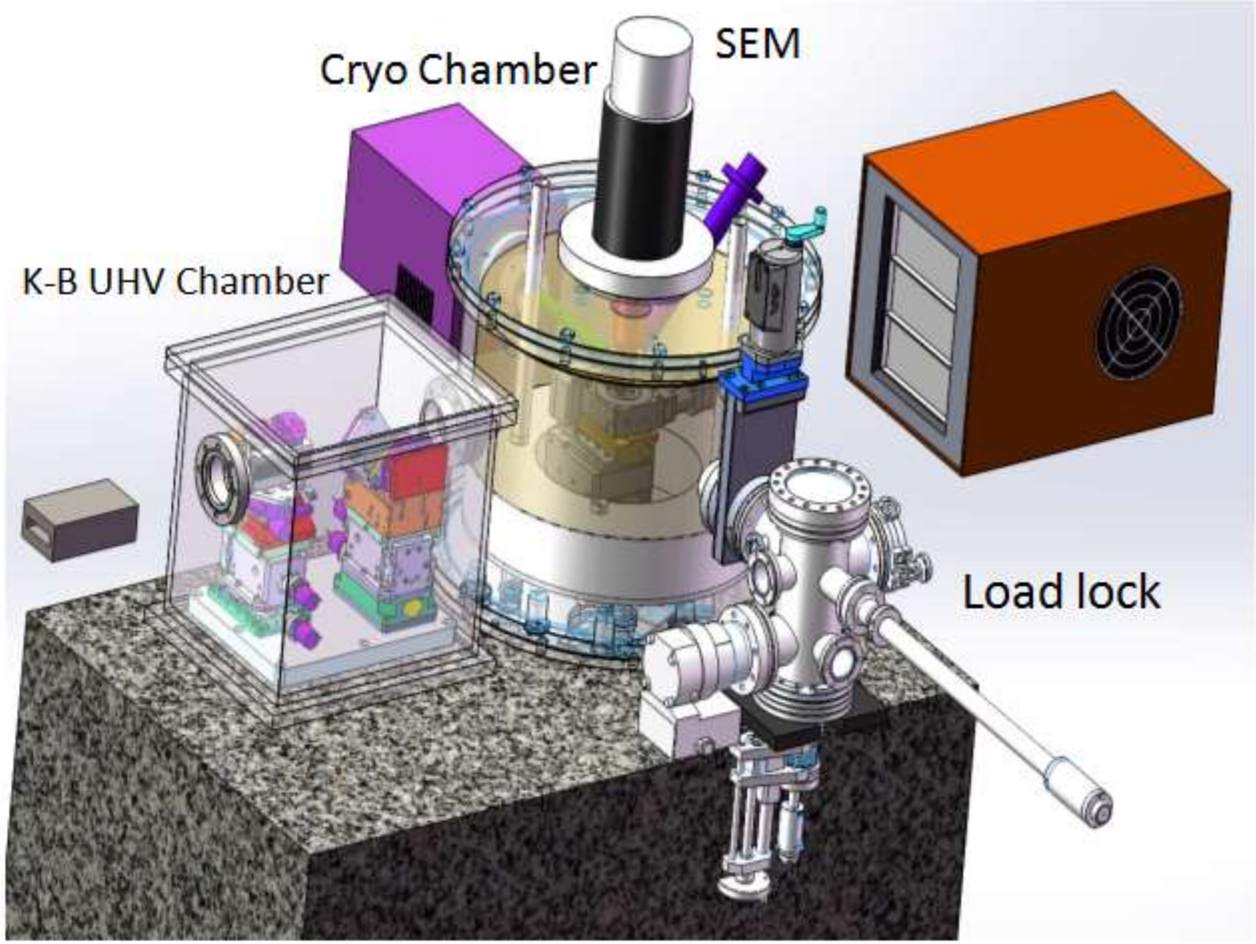


High resolution mode (Mutlilayer Laue Lens)

Probe Size: < 10nm
Work Distance: 2mm
Flux: $10^{10\sim11}$ phs/s

NanoProbe beamline: Multimodal Probing

nano-XRF, nano-XRD, nano-XANES
Ptychography, Spectra-Ptychography

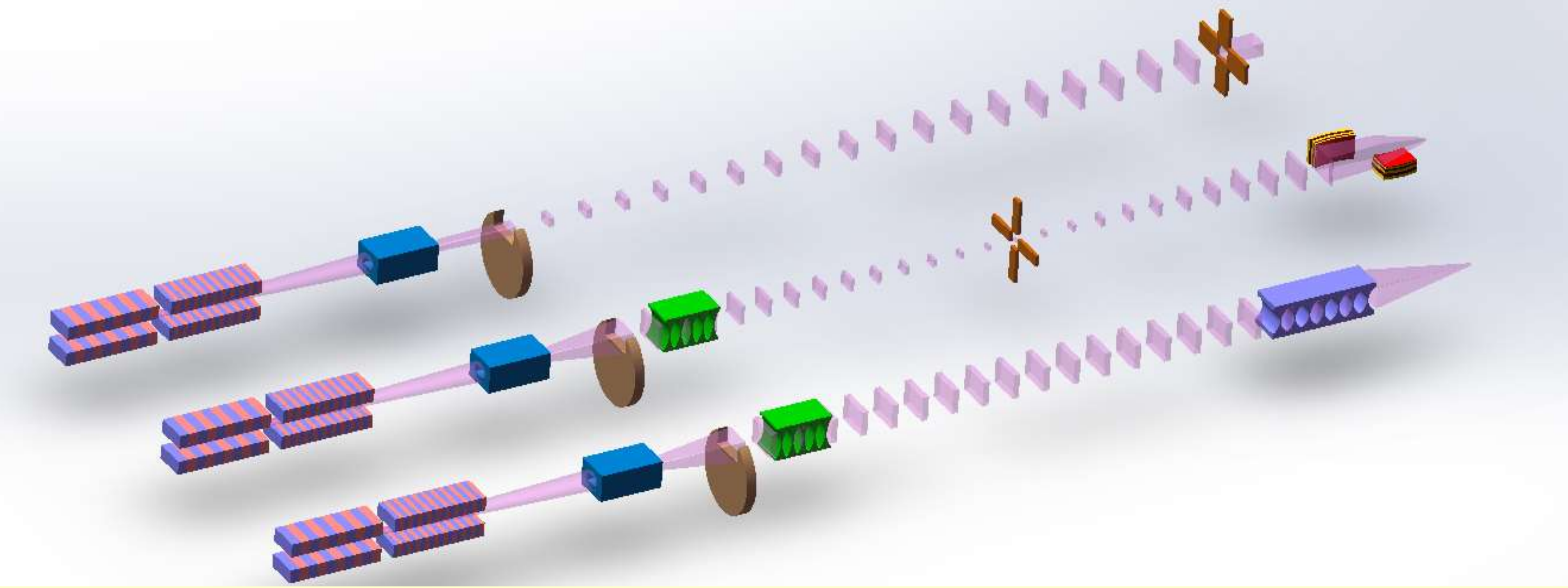


Structural Dynamic Beamline

Single shot probes for Irreversible progress

Energy range	23,44,65 keV
Energy resolution	0.3-10%
Flux per pulse	>10^9 phs/pulse
Temporal resolution	~400 ps

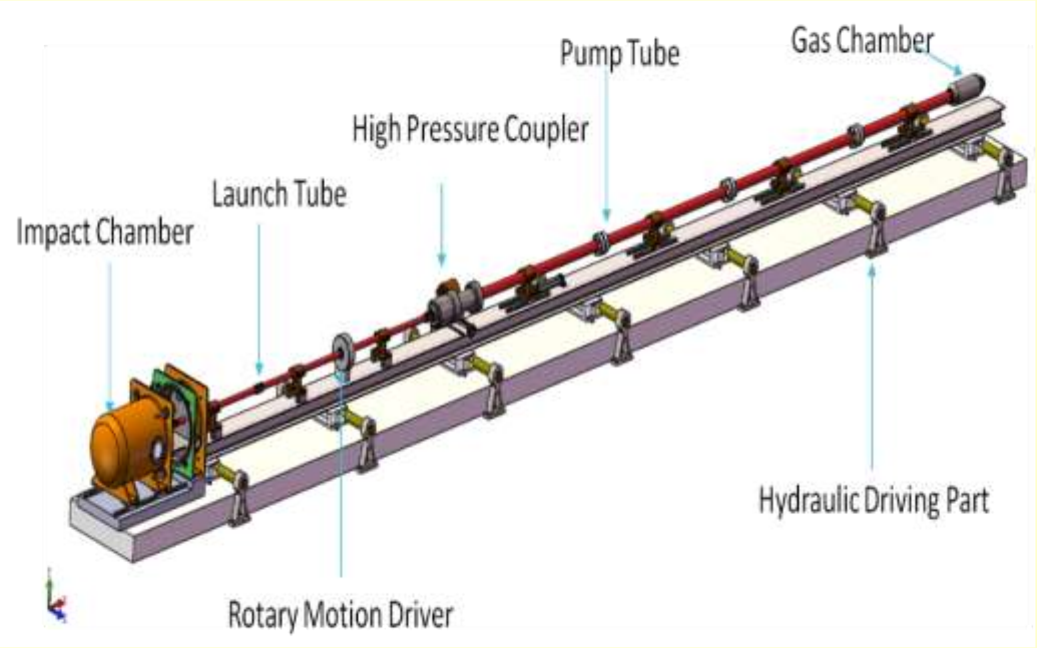
CPMUs: U12+U14.2



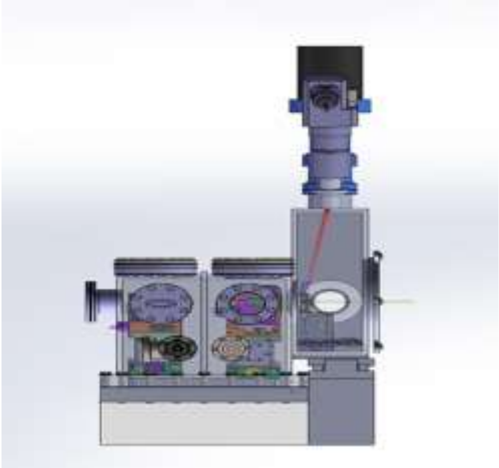
Dynamic experimental instrumentation

Dynamic loading:
Gas gun, Hopkinson bar, High power laser,
Additive Manufacturing

Probes: XRD,SAXS,XPCI,
Magnified nano-imaging



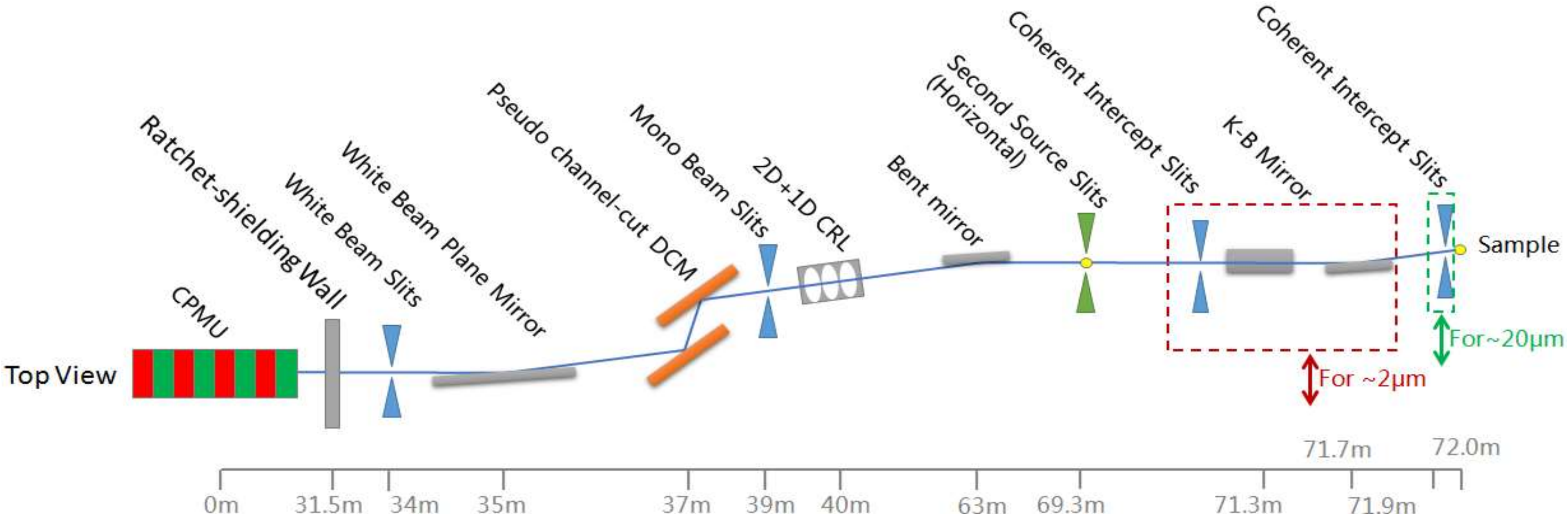
Additive Manufacturing



Hard X-ray Coherent Scattering beamline

Dedicated to CDI and XPCS

	Specifications
Energy range	7-25keV
Energy resolution	10^{-4} Si(111)
Coherent flux	>10^{12}ph/s @12.4keV
Beam size	2μm (WAXS CDI&XPCS) 20μm (SAXS CDI&XPCS)
Endstastion	CDI (resolution<5nm) XPCS (resolution<1μs)

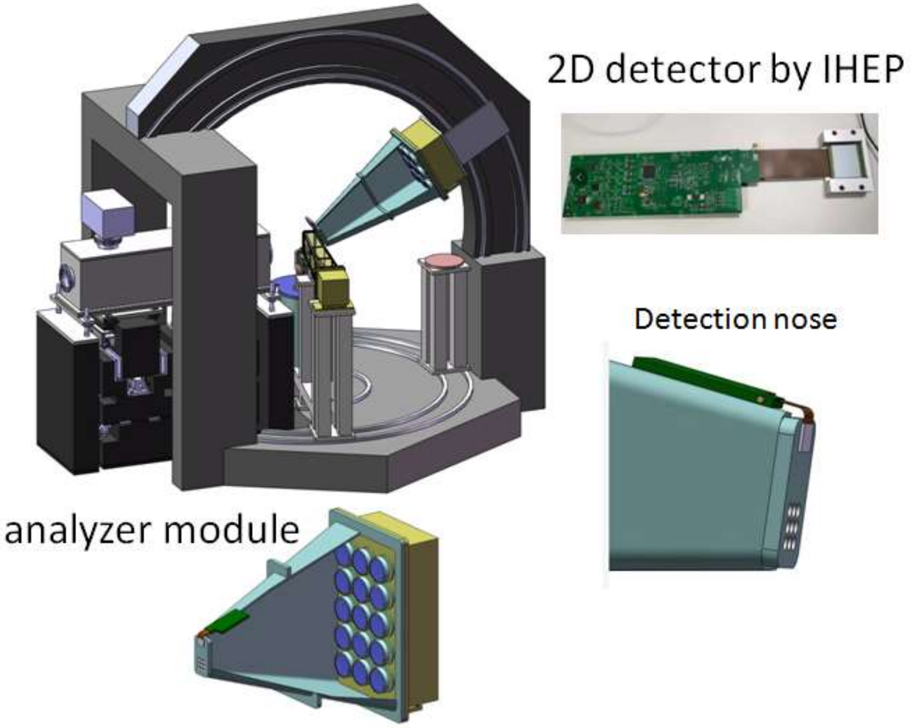


NRS & Raman beamline

Probes	Parameters	Specifications
NRS @Fe-57	Energy resolution	High flux mode: 2.2meV@14.4keV High-resolution mode: 1meV@14.4keV
	4 μm ×2 μm (non dispersive, 2meV) 5.9μm ×20 μm (dispersive, 1meV) Flux at sample position(focused mode)	High flux mode: 2×10^{10}phs/s@100mA High-resolution mode: 9×10^{9}phs/s@100mA
XRS	Energy resolution	0.8eV@10keV
	2μm ×2 μm Flux at sample position	2.6×10^{13} phs/s@200mA

X-ray Raman Spectrometer，low-q + high-q

- Q-dependent XRS, 30 - 130 degree, Vertical and horizontal scattering
- 3*5 array Si(nn0) analyzer crystal, Rowland circle = 1-2m
- 55-µm pixel 2D detector



✓ Larger-solid-angle realized by multiple analyzer modules

✓ Large scattering angle

✓ Home-made analyzer crystals and small pixel array detectors

Key technologies

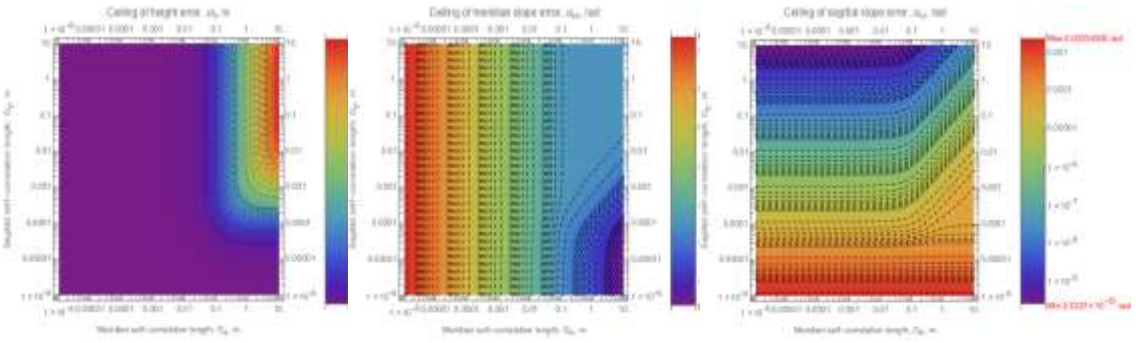
- X-ray optics
- Thermal management
- Optics metrology
- Wavefront preservation and crystal/device fabrication
- X-ray detector
- Data acquisition and analysis

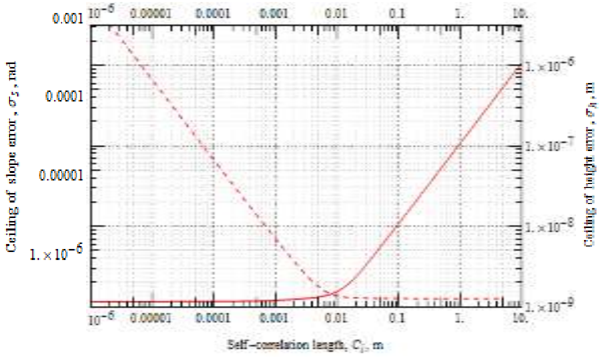
Supported by both HEPS and Platform for Advanced Photon Source Technology R&D (PAPS)

X-ray optics

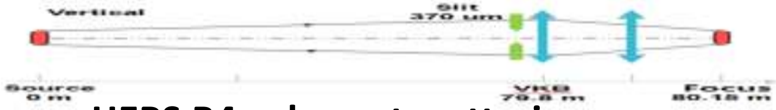
A wave-optics simulation based on a coherent modes decomposition and a wavefront propagation model.

The simulation software, Coherence Analysis Toolbox (CAT)

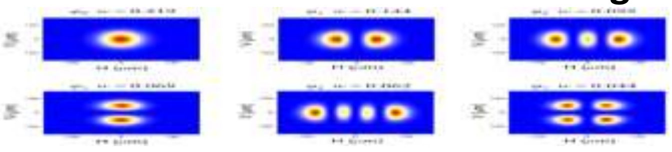




Used in BL design

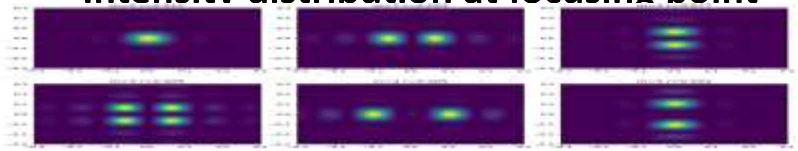


HEPS B4 coherent scsttering



Source (IVU) coherent modes distribution

Intensity distribution at focusing point

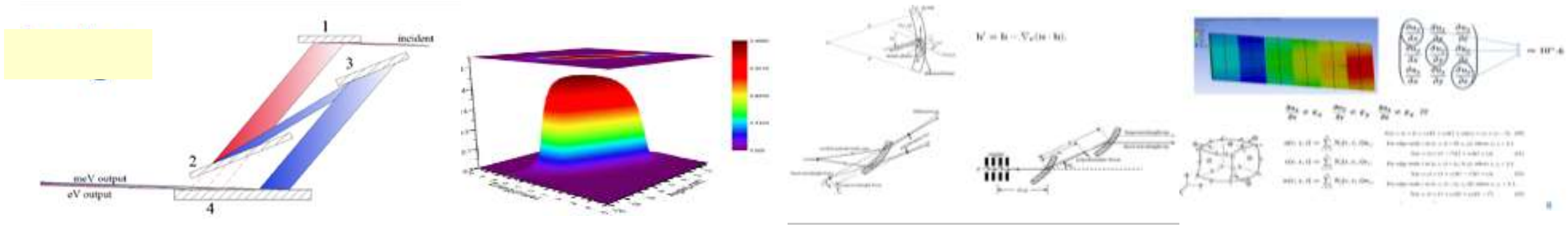


Coherent mode at focusing point

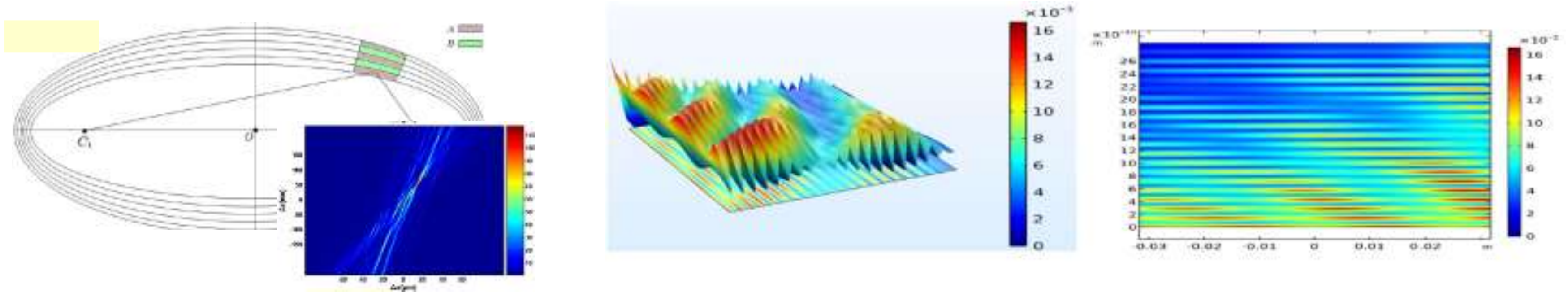
Xu etal. Optical Express 2022, 30, 7625

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



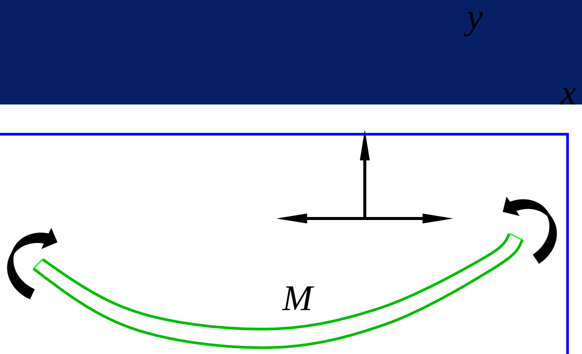
Yuhang Wang, Optics Express 28 (2020)

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

Developing the theories of bending mirrors

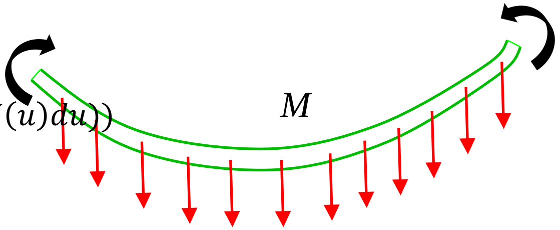
- **Basic Theory:**
  - Pure Bent Beam curvature

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



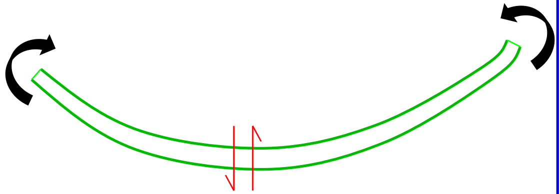
- Extra moment from gravity:

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



- Extra transverse shear deformation

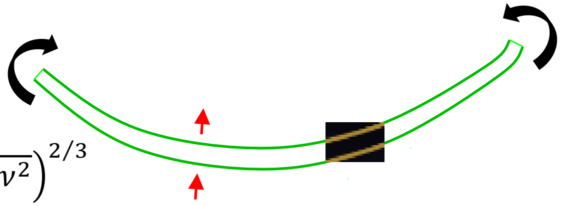
$$s_b(x) \equiv \frac{-M_0 k_M}{W(x)*TG}, \quad s_g(x) \equiv \frac{g\rho_m\left(\int_x^{\frac{L}{2}}\left(-\frac{L}{2}+u\right)W(u)\,du + \int_{-\frac{L}{2}}^{x}\left(\frac{L}{2}+u\right)W(u)\,du\right)}{GLW(x)}$$



- Extra transverse deformation:

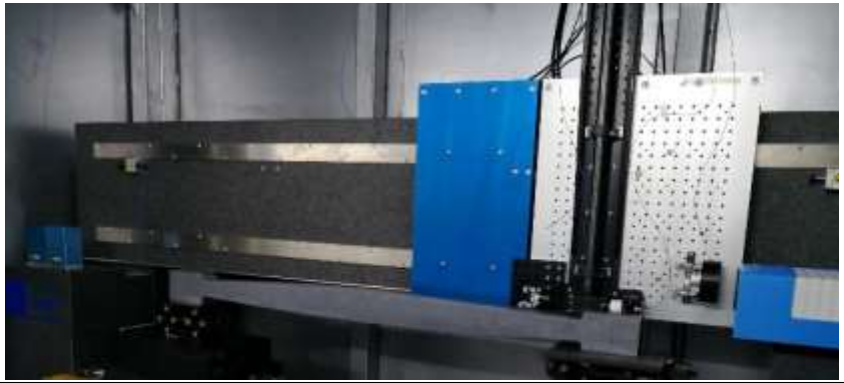
$$h_c(x) \equiv \frac{T^2\,\nu}{12}\frac{M(x)}{E\ I(x)}$$

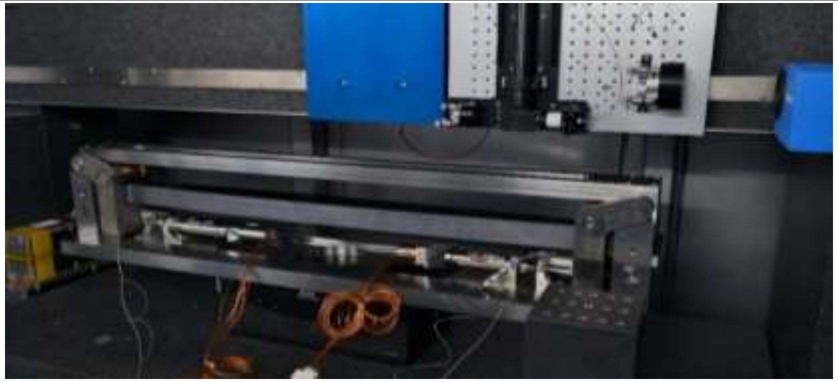
- Curvature (including Influence of saddle deformation)



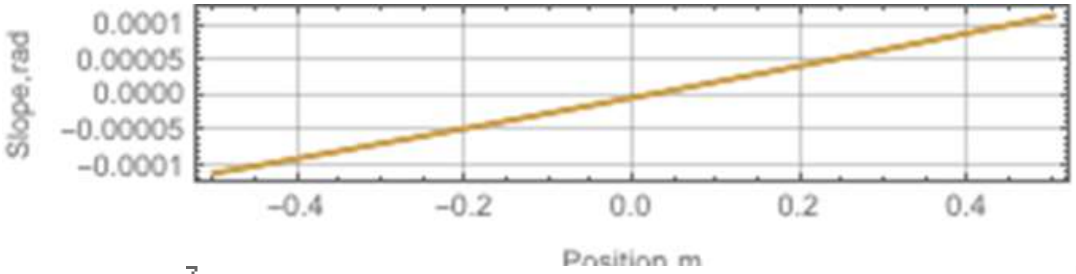
$$y''(x) = \frac{-2\times 5^{2/3}\,E^{2/3}T^{8/3} + 2\times 5^{1/3}\left(9M(x)W(x)\nu + \sqrt{5E^2T^8 + 81M(x)^2W(x)^2\nu^2}\right)^{2/3}}{W(x)^2\nu\left(ET\left(9M(x)W(x)\nu + \sqrt{5E^2T^8 + 81M(x)^2W(x)^2\nu^2}\right)\right)^{1/3}}$$

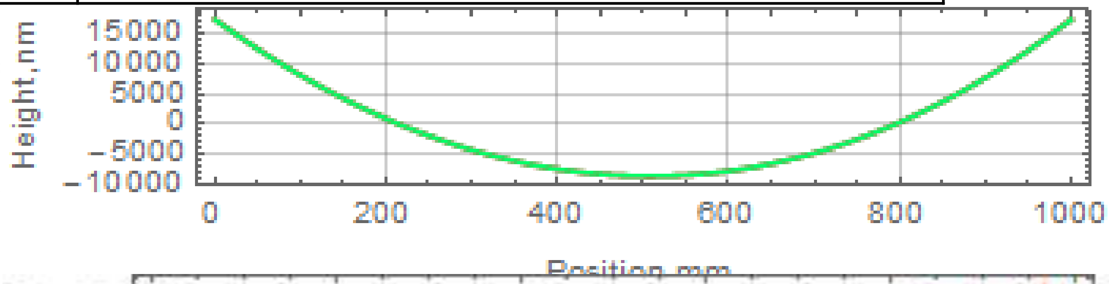
1m ellipitical bending mirror

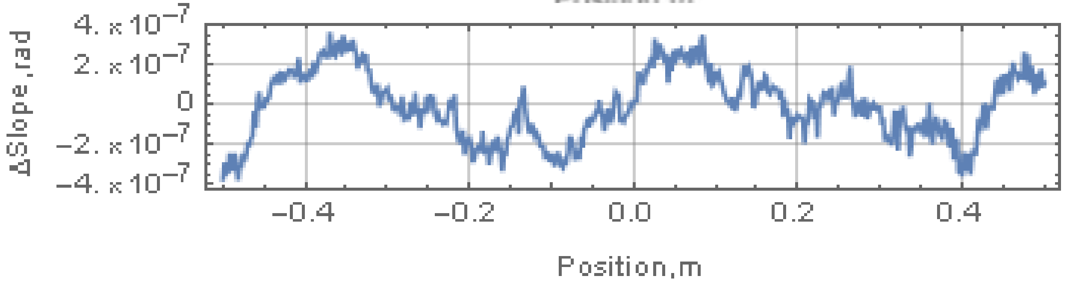


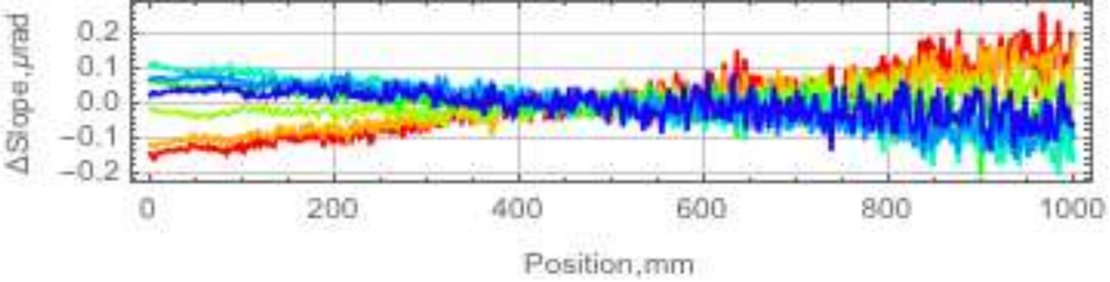


	Measuring Results
Effective length	1000mm
Elliptical Bending shape accuracy	0.17μrad (elliptical)







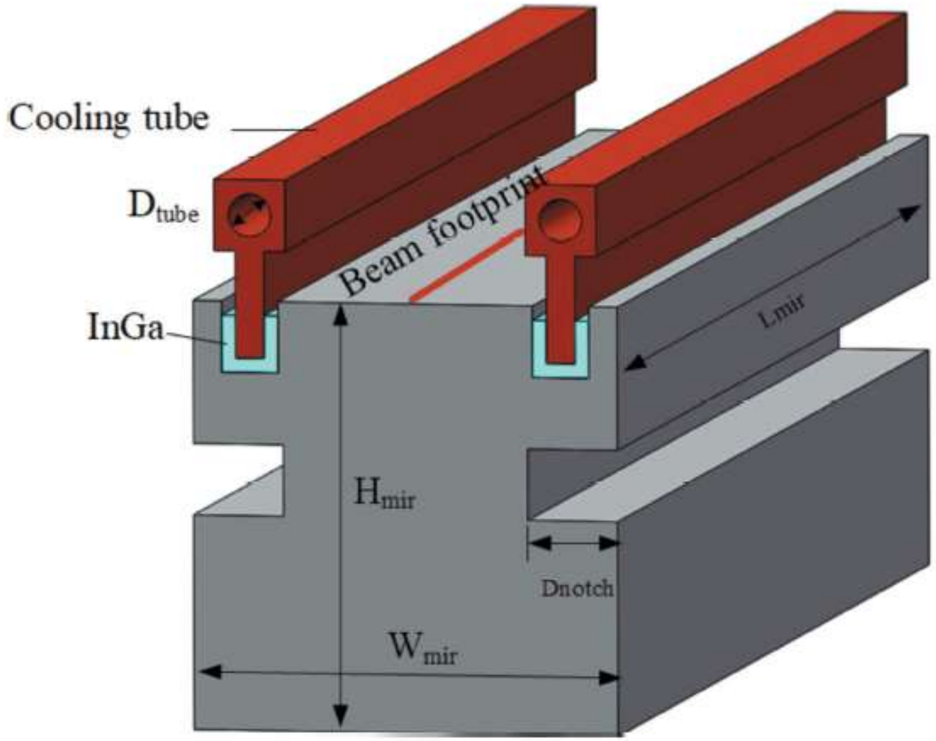


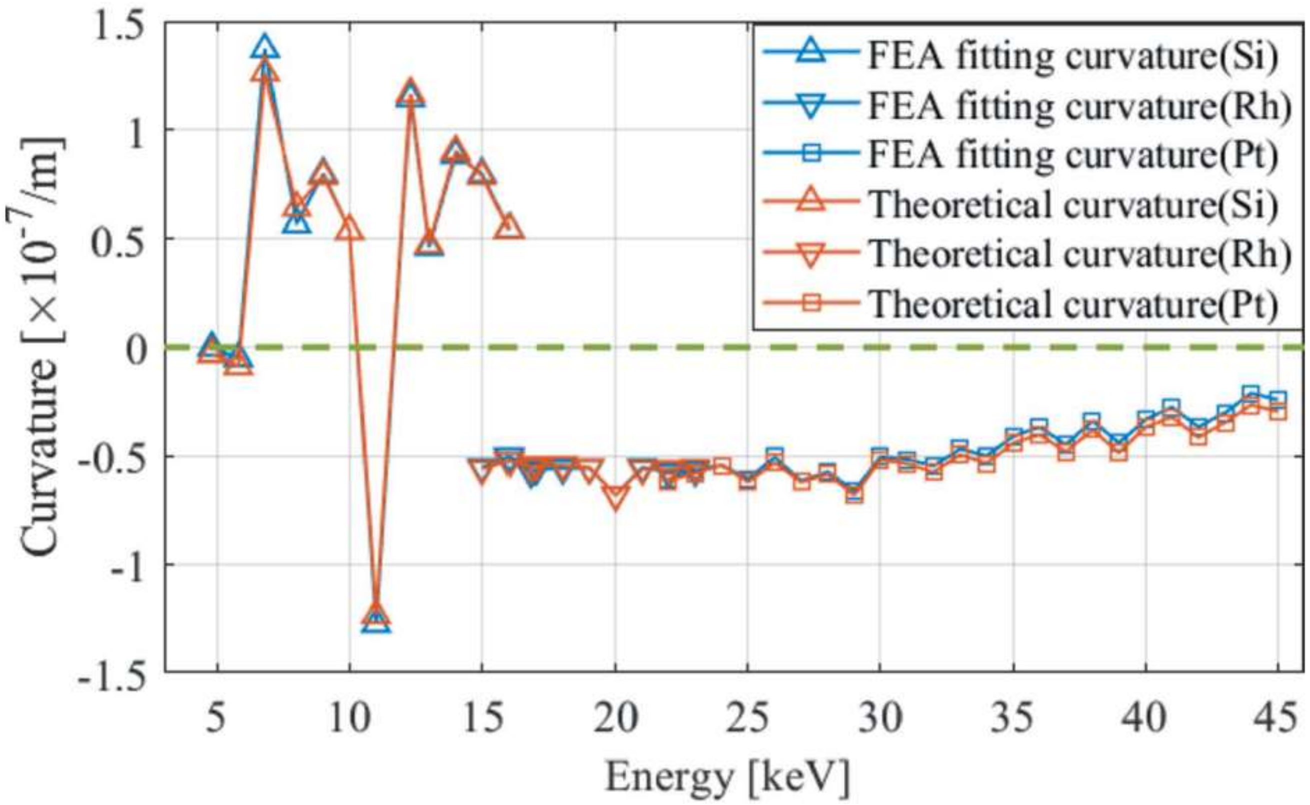
Bending shape accuracy RMS 0.17μrad

Stability: 72h, deformation 66nrad RMS

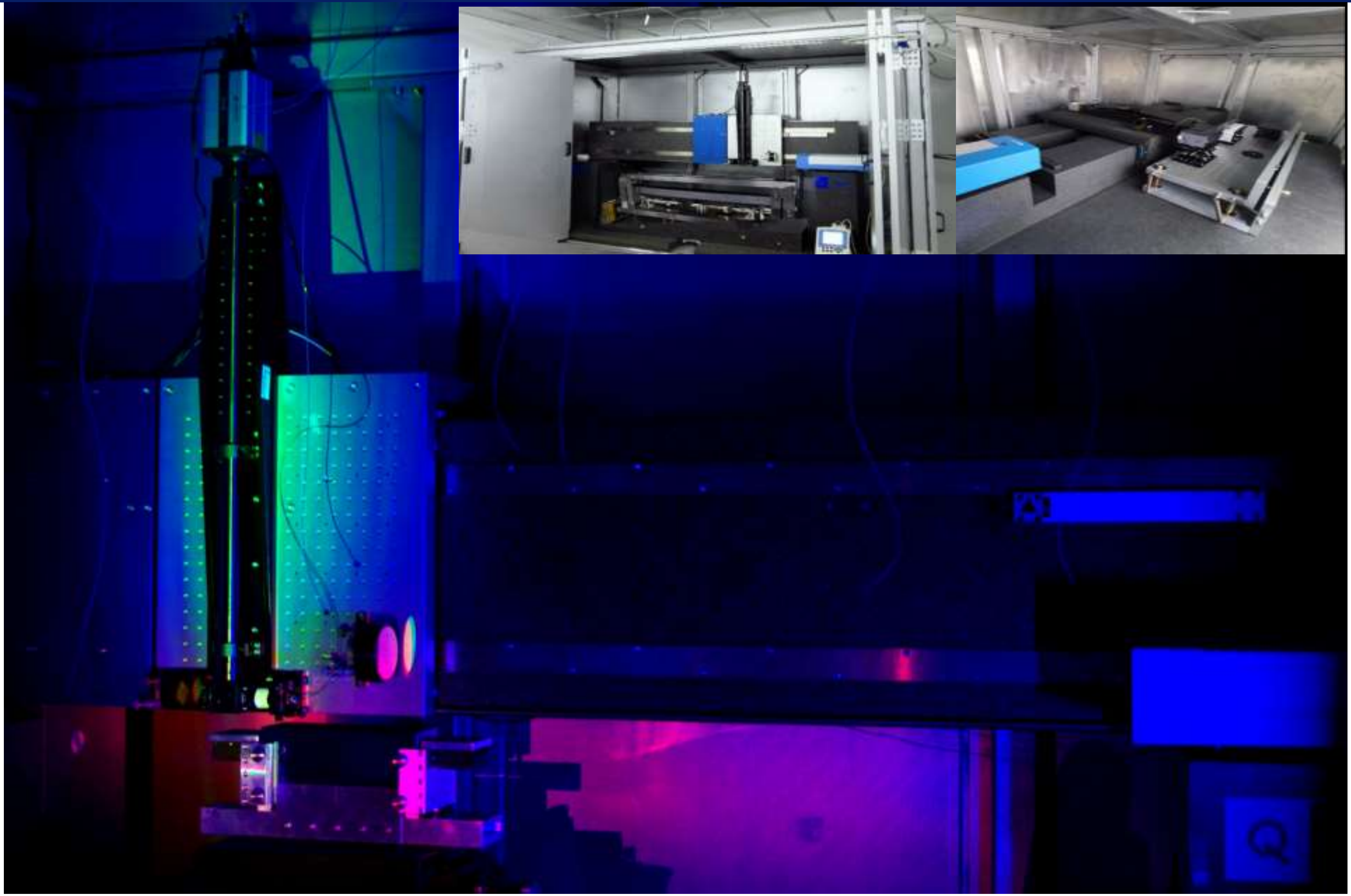
Thermal management

- 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



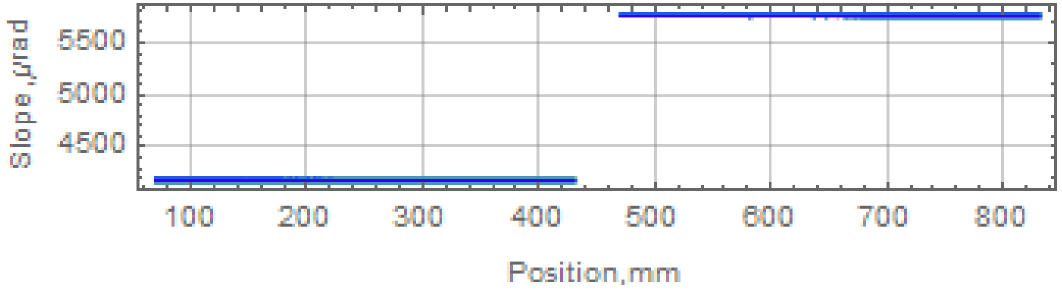


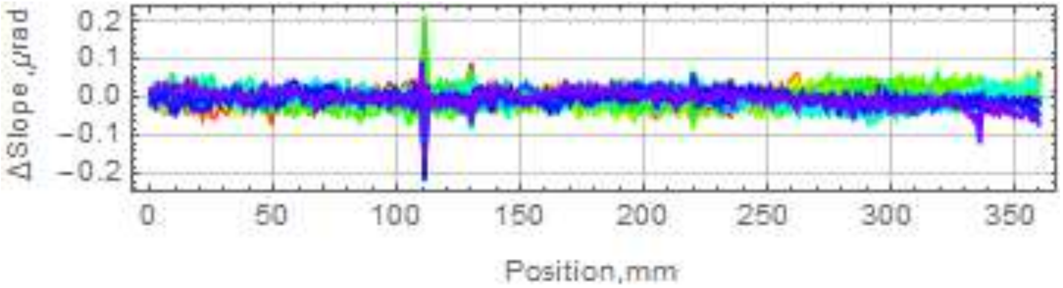
Optical metrology (Flag LTP)



Precision of measurement for flat/curve mirror

360mm flat mirror measurement, Tilt 1.6mrad and translation 400mm, 8+8 times scan

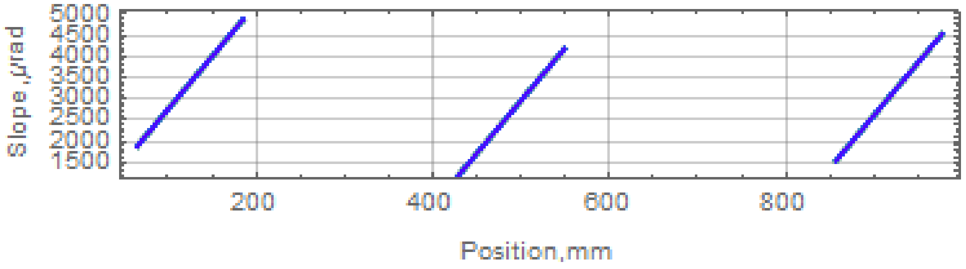




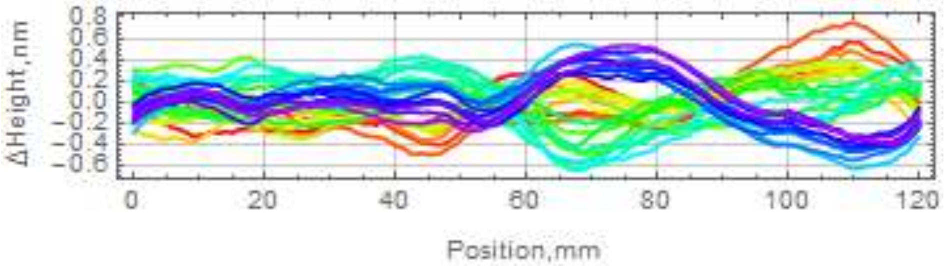
Spatial resolution 1mm
(Slope error sensitive to spatial resolution)

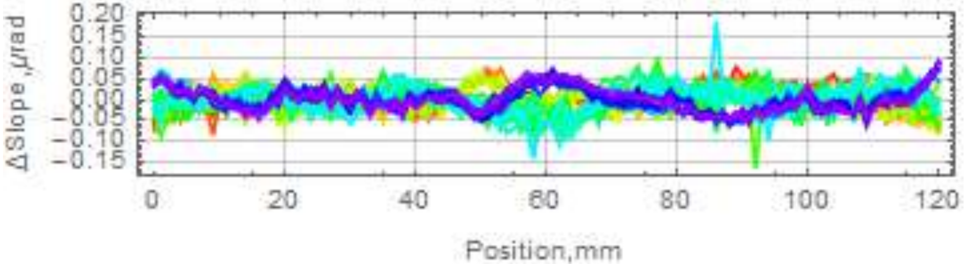
Precision (including systematic error)
RMS 24.5 nrad

3mrad range 120mm curved mirror measurement, Tilt 0.35mrad / 0.7mrad and translation 10+10+10 times scan



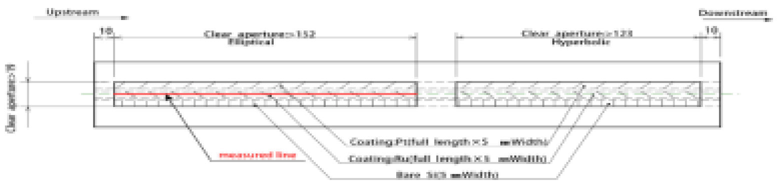
Curve mirror slope/height
RMS 29.0 nrad / RMS 0.23nm





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

Length 415mm

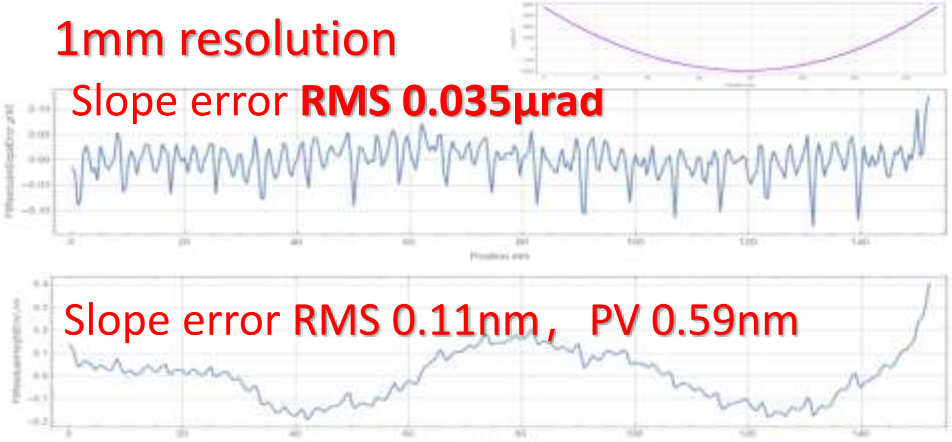


Mirror	Shape	Parameter	Specification	Measurement
B4-Wolter	Elliptical	Slope error RMS	50nrad	35nrad
	Hyperbola			41nrad
	Elliptical	Height error RMS/PV	0.4nm / 6nm	0.11nm/0.59nm
	Hyperbola			0.12nm/0.7nm

1mm resolution

Slope error **RMS 0.035μrad**

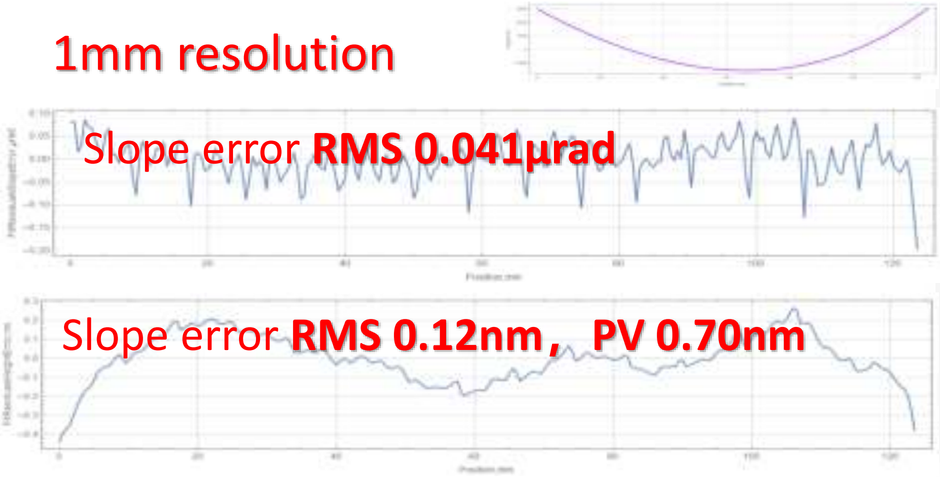
Slope error RMS 0.11nm， PV 0.59nm

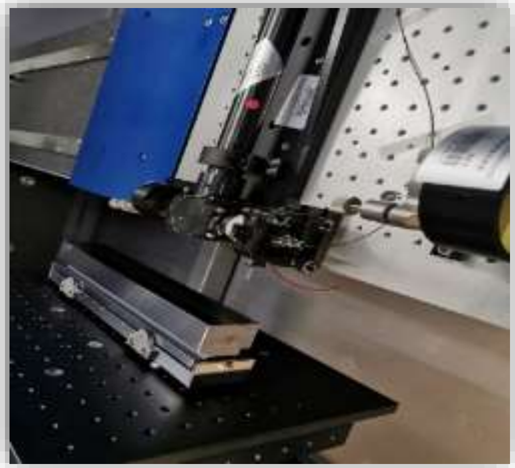


1mm resolution

Slope error **RMS 0.041μrad**

Slope error **RMS 0.12nm， PV 0.70nm**





Optics and Lasers in Engineering

Multi-pitch nano-accuracy surface profiler for strongly curved X-ray mirror metrology

Lei Huang, Lukas Lienhard, Tianyi Wang, Francois Polack, Josep Nicolas

The comparable test results of the ellipse between the NSP in full characteristics manner and JTEC's stitching profiler are presented (Fig. 16)

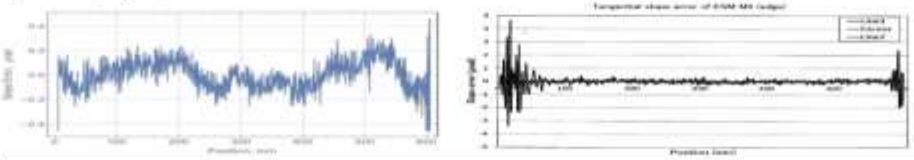


Fig. 16 The comparison tests between JTEC's stitching profiler and the NSP in full characteristics manner
Left: tested by the NSP, **0.133** μrad rms; **Right:** tested by JTEC, **0.227** μrad rms. Both are residuals, the best fit ellipse is removed

MP-NSP： 50nrad and 0.5nm @2.5mm resolution

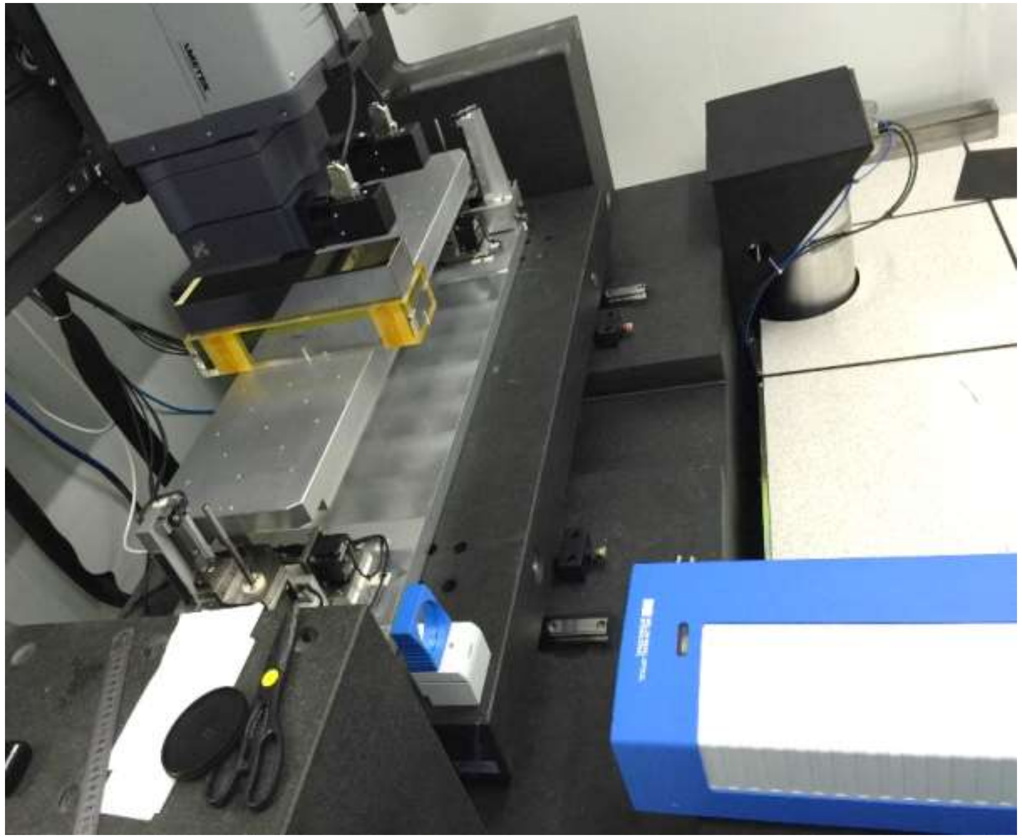
【1】Lei Huang, etc. Optics and Lasers in Engineering, Volume 162, 2023

NSP： 0.133μrad @2.5mm resolution

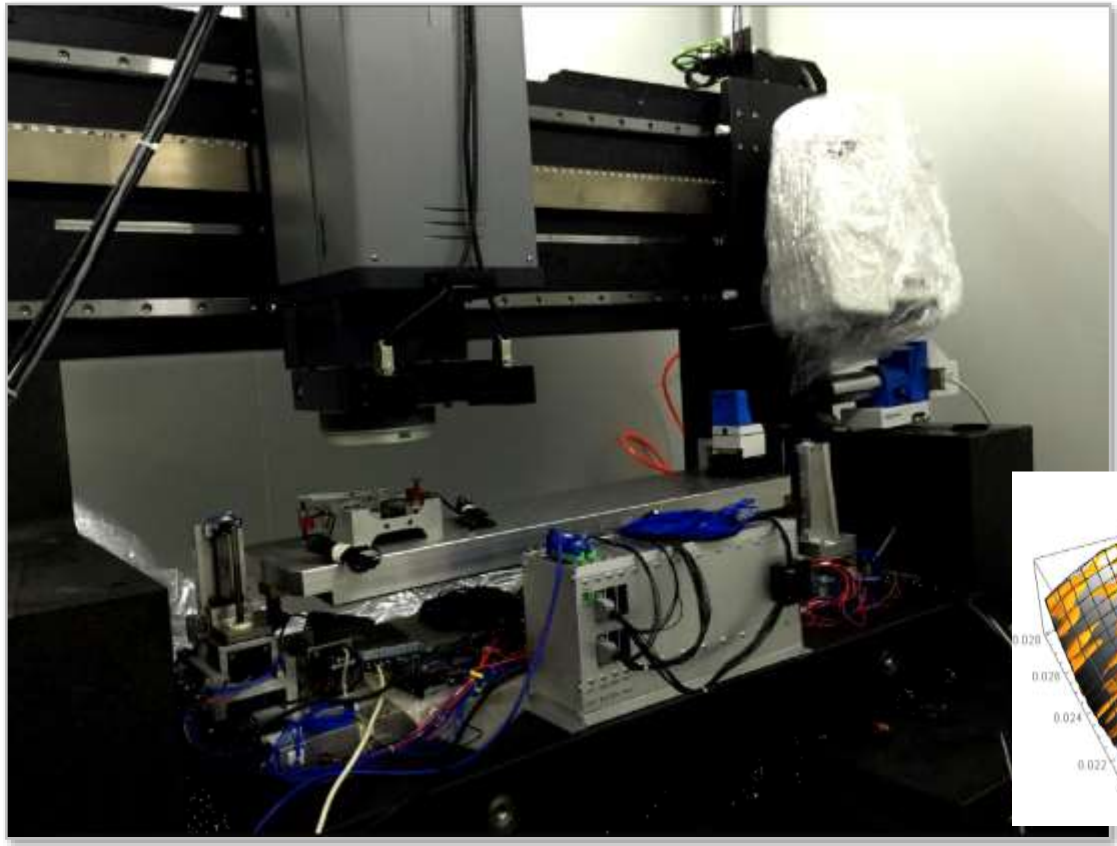
【2】Shinan Qian, etc. Proc. of SPIE Vol. 9687 96870D-1

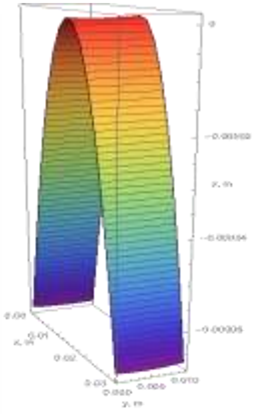
Aspheric Stitching Interferometer

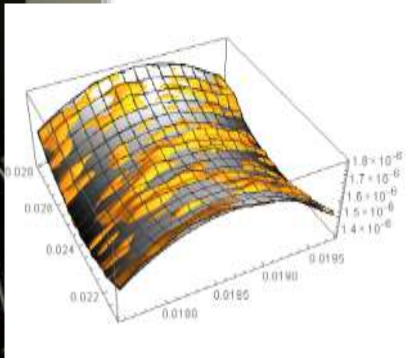
- Surface metrology during fabrication
- Surface metrology for serve curvature of crystal



Proposed ASI based on angular measurement, has been applied in BNL, ALBA.



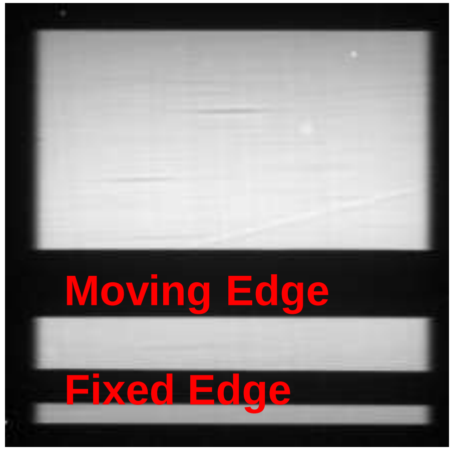




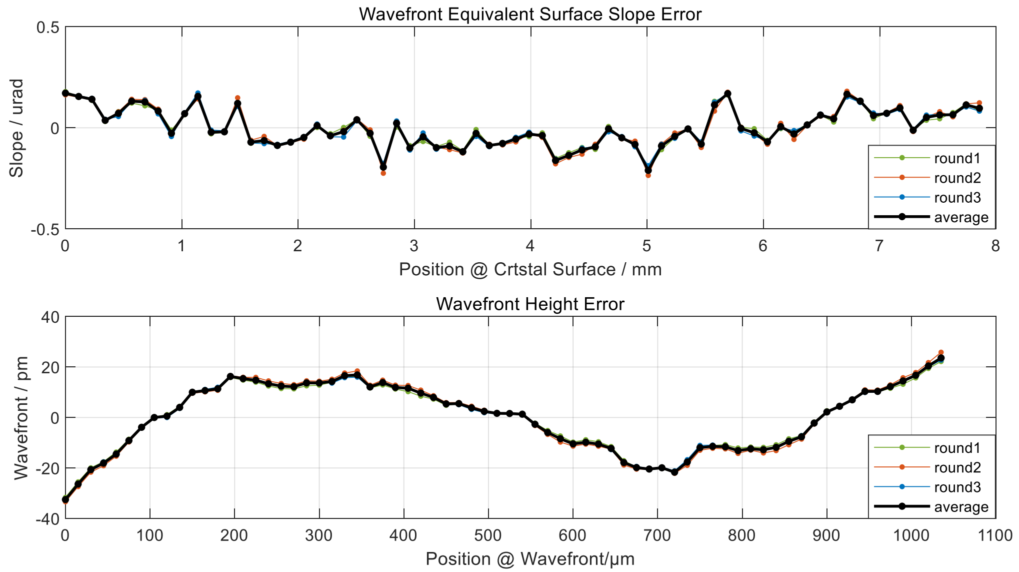
The proposed θ-R method is used in metrology of serve curvature

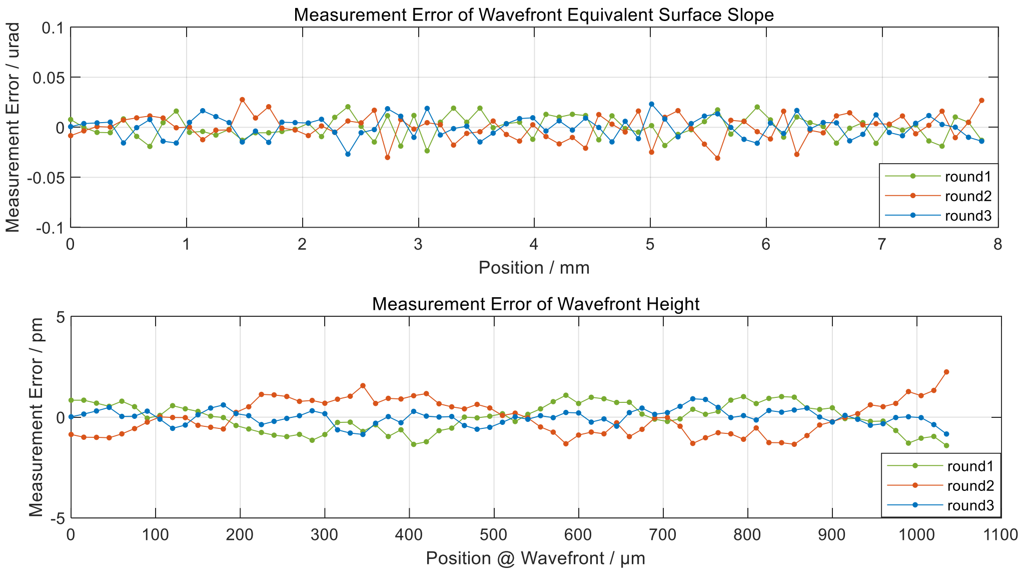
Online wavefront measurement

Double-edge wavefront measurement



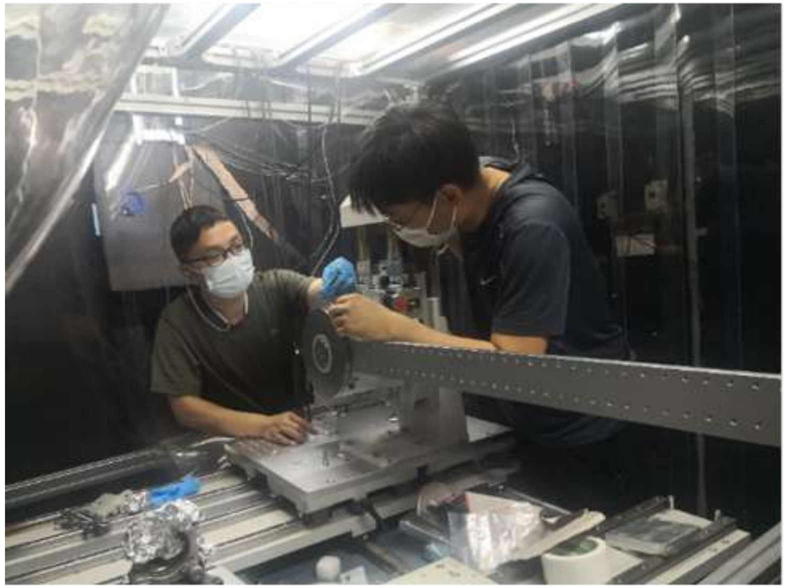
- Innovative method
- Solving the problems of coherence, stability, distortion of wavefront in 1GSR
- Successful application in BSRF: ~1pm precision

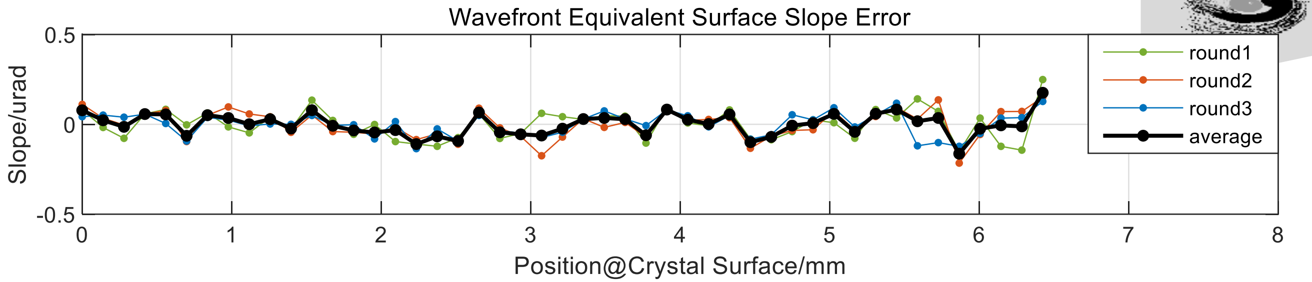


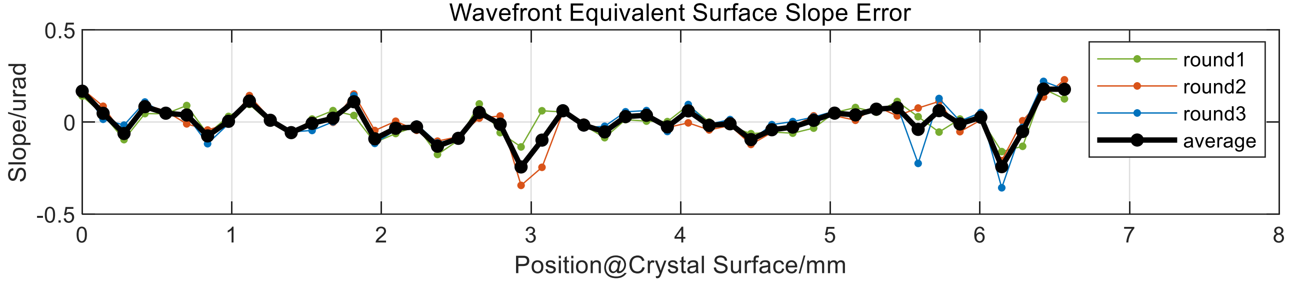


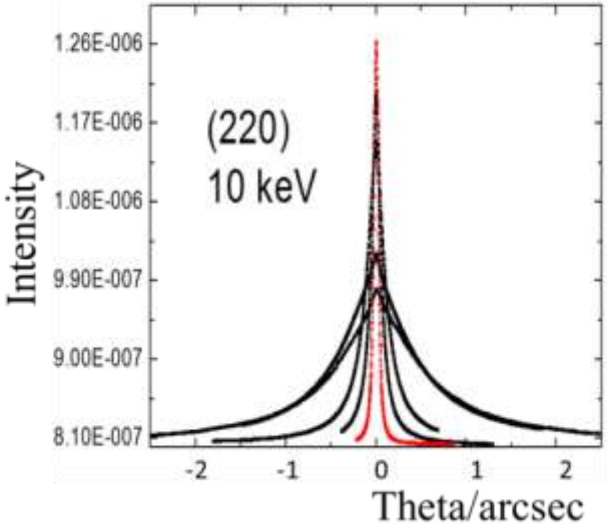
Measurement precision 14 nrad and 1 pm RMS

Fabrication of wavefront-preservating crystals







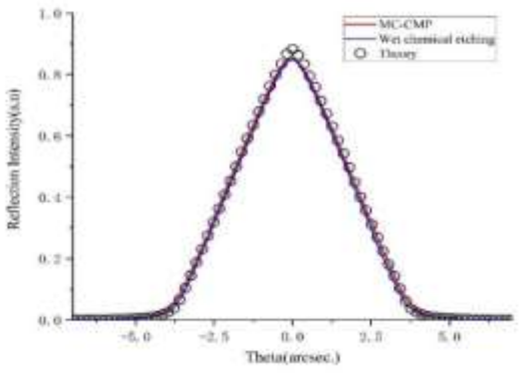


Crystal	Wavefront
BSRF	86.3±16.1nrad
From Japan	91.6±11.8nrad
From France	189.2±23.5nrad

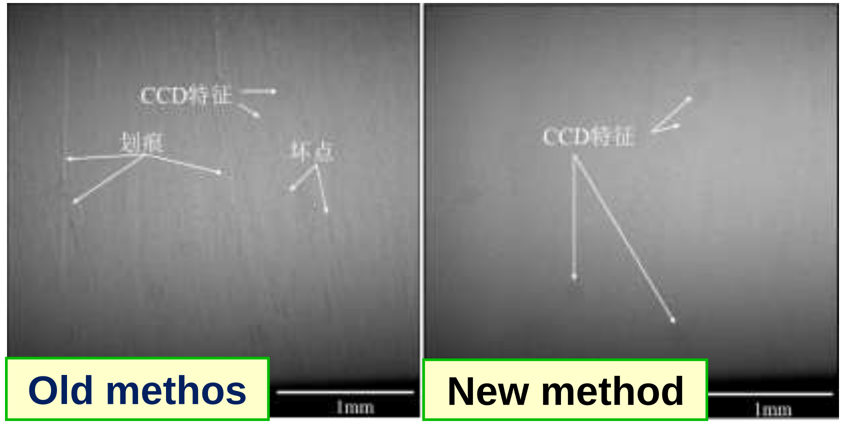
The quality of crystals (170nrad) is satisfied the requirements of 4GSR.

Channel-Cut crystal

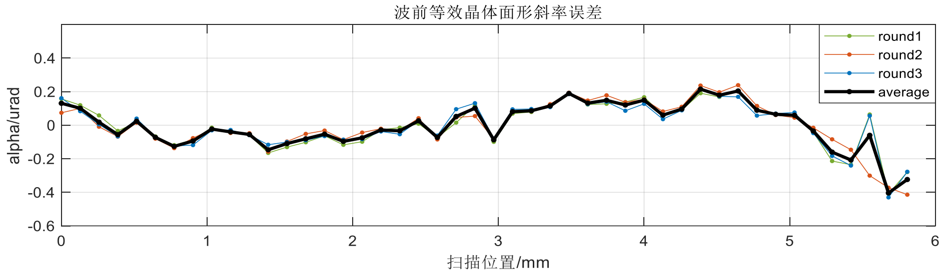
Rocking curve measurement layout

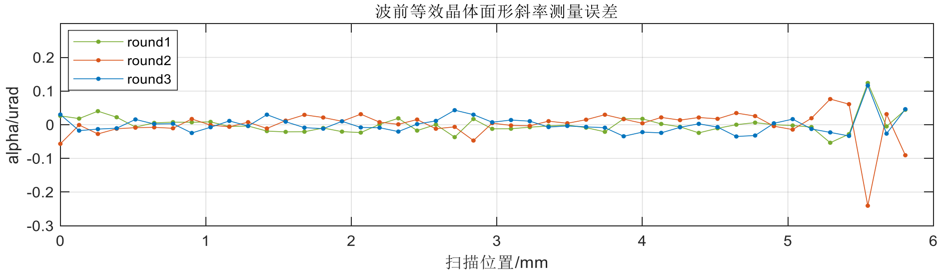


Rocking curve



Morphology





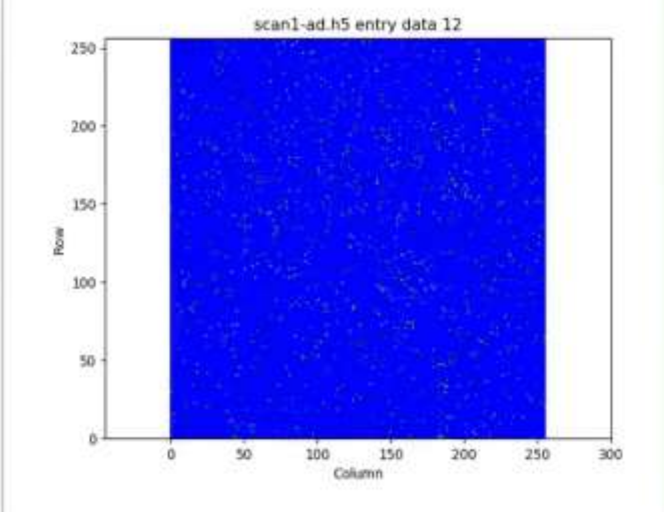
Double-edge wavefront measurement

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

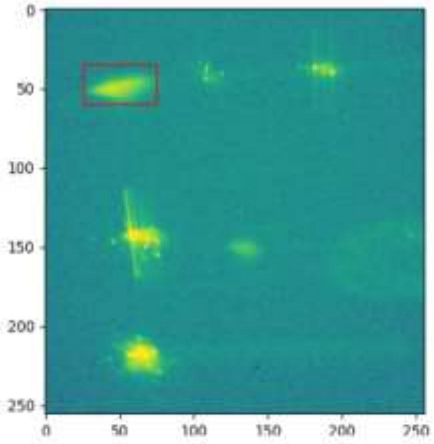
The qualities are better than commercial products

Analysis crystals

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

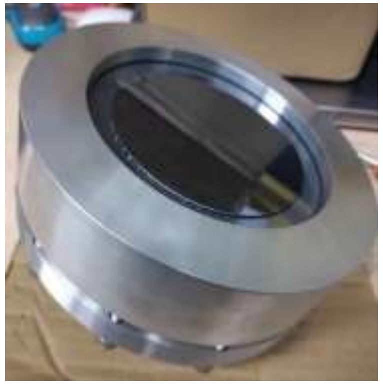


Bent striped Si(660)
~0.53 eV@9.7keV

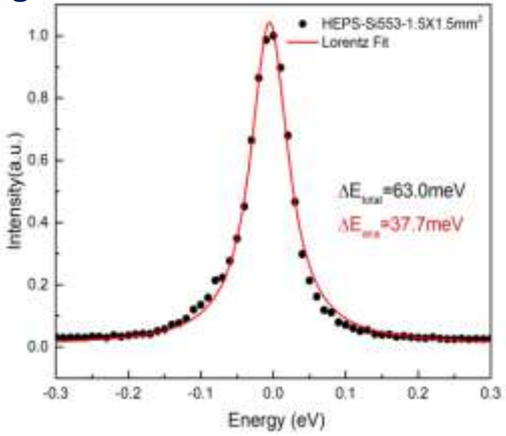


diced Si(553)
~0.037 eV@8.9keV

glued



Vacuum mounted

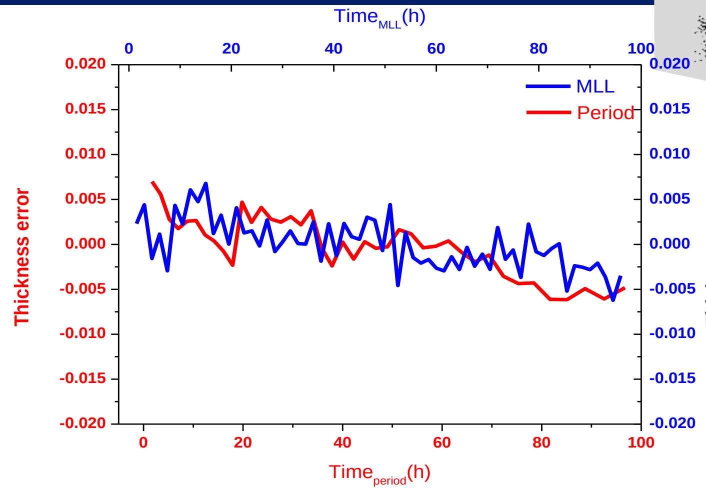


- **Spherically bent analyzers for XRS: excellent focusing & energy resolution**
- **Bent-striped analyzers for XRS: energy resolution improved**
- **Flat-diced analyzers for RIXS: highly improved energy resolution**

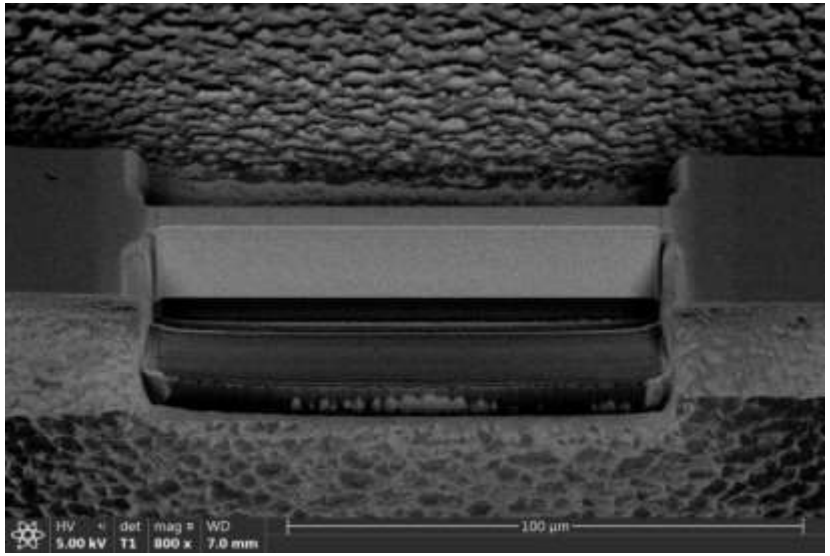
Multilayer Laue Lens (MLL)

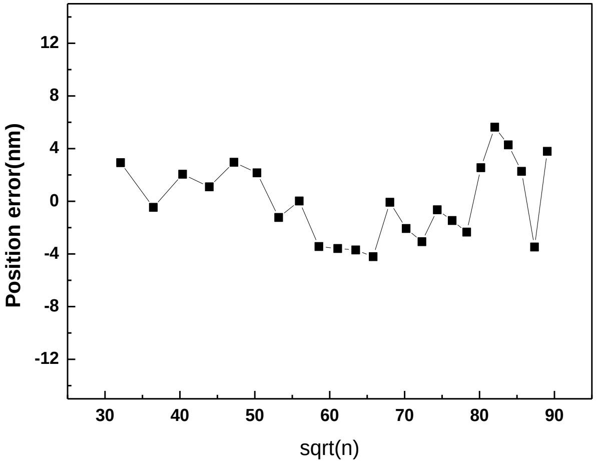
Para.	Req.
Material	WSi_2/Si
N. Layer	13030/ 8030
Thickness	64μm/ 44μm
Focus	$8\times8nm^2$

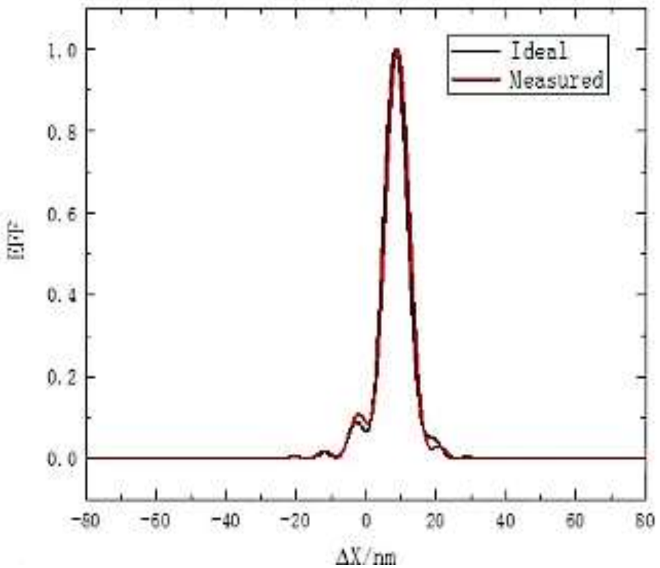
Magnetron sputtering



Growth rate drift 0.3%



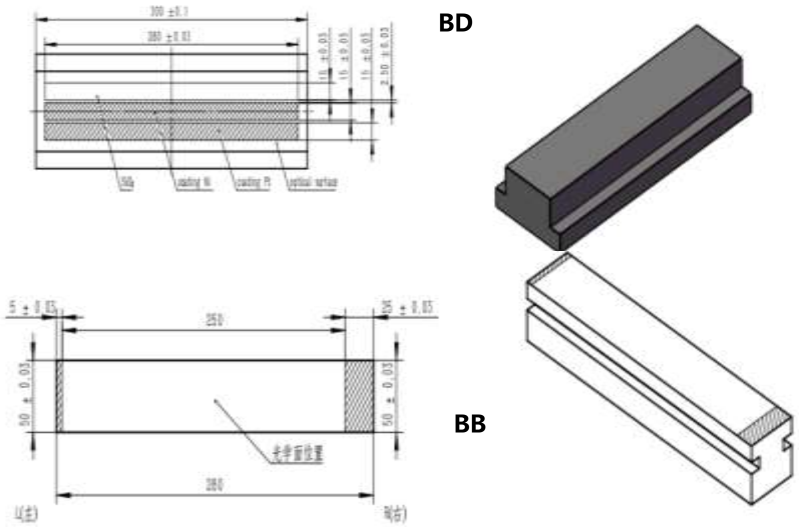




Position error (PV) ±5nm, simulated focus spot 8nm. Fulfilled the demand of nano-probe

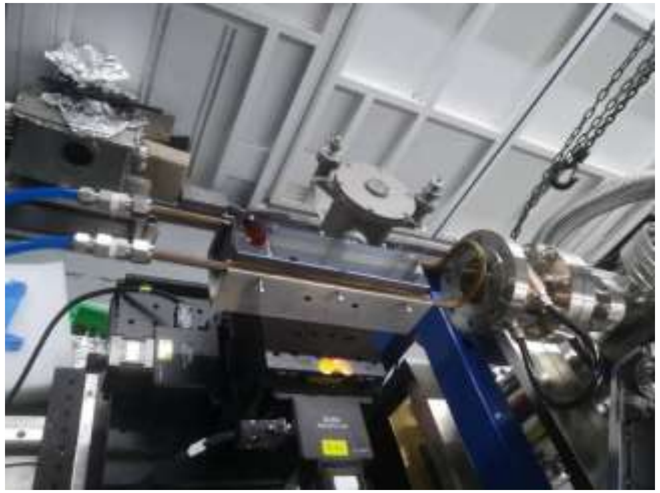
Multilayer devices

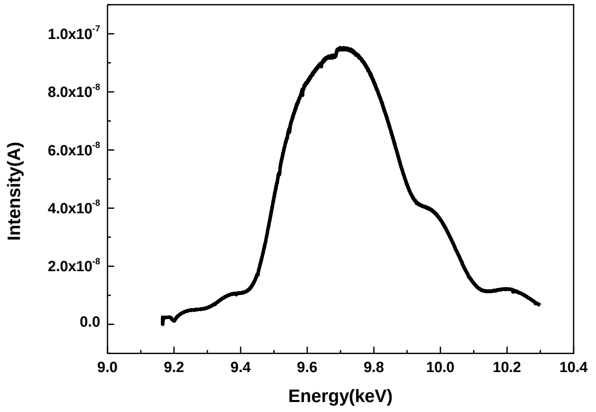
Coating on mirrors



Coating: Pt, Ni, B4C

Multilayer mono.

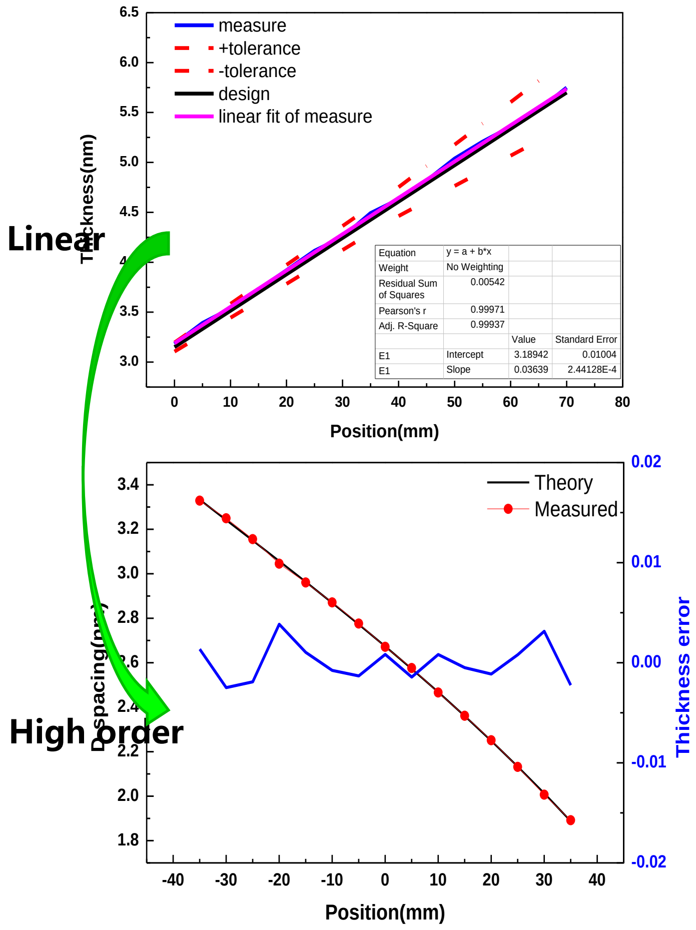




Energy resolution: 4.1%

Reflectivity: 75%

Gradient multilayer mirror



Thickness error ±0.35%(pv)

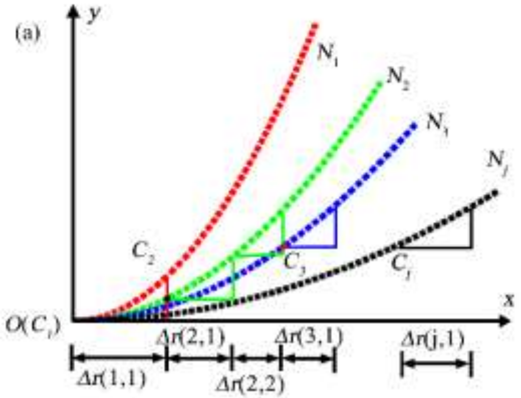
Precision: 6.5pm(rms)

Reflective lens

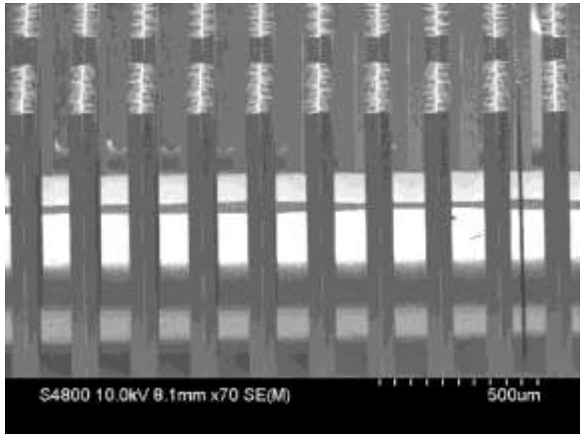
Ni-based kinoform

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

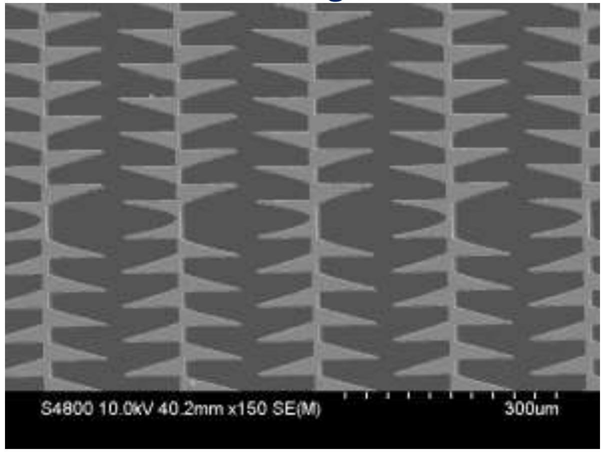
Used in HEPS B1



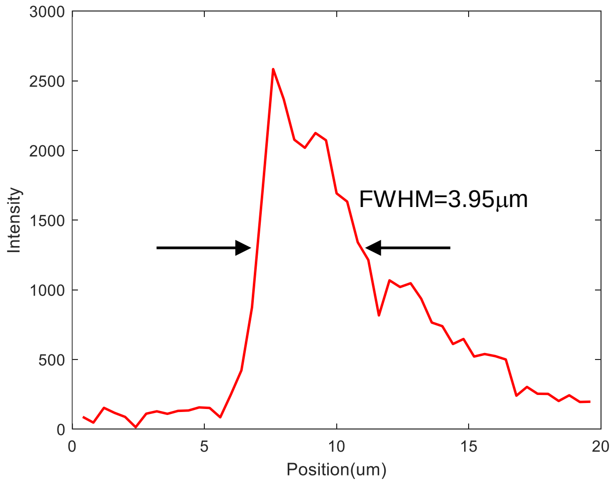
Design



Ni-based kinoform

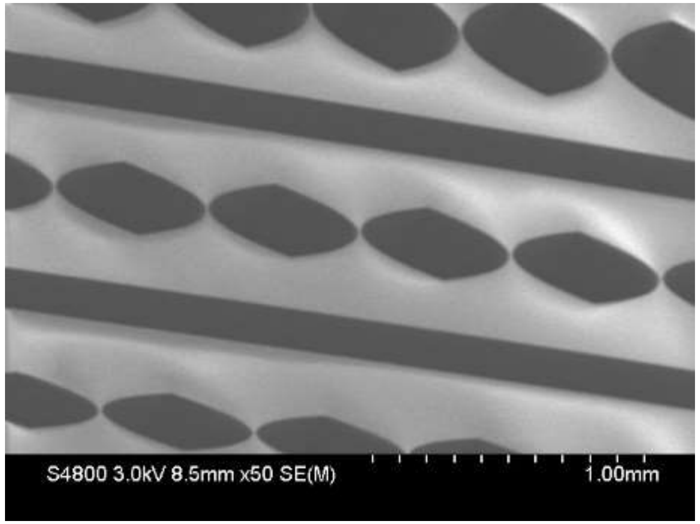


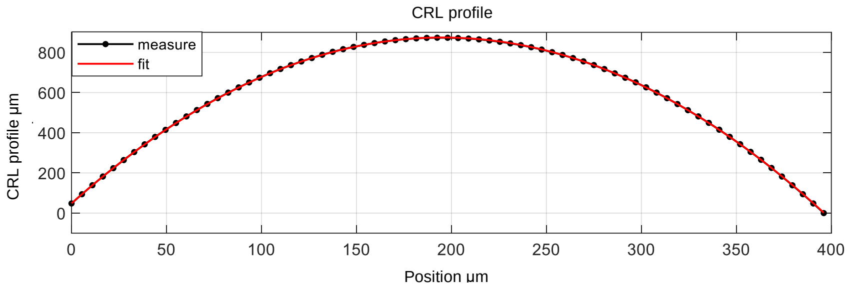
Ni-based kinoform

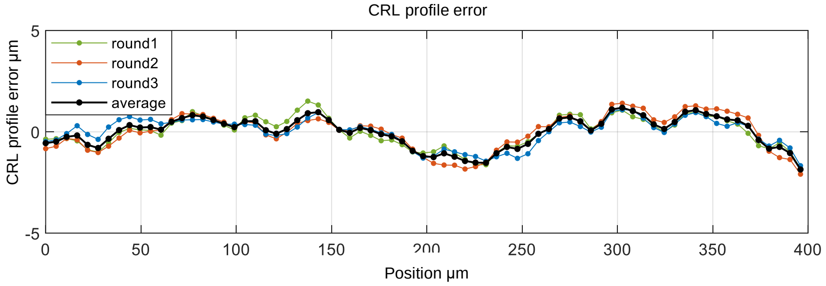


Focusing

1D SU8-based CRL







Shape profile error 0.75μm RMS

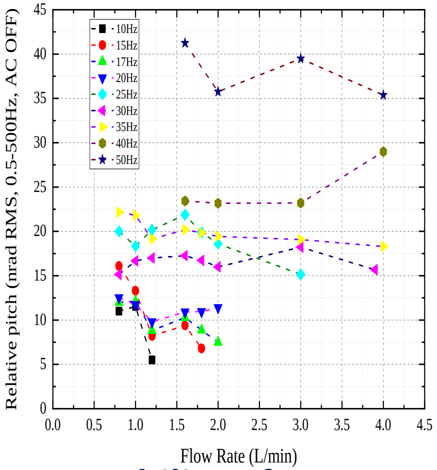
Monochromator for high stability and less deformation

VDCM

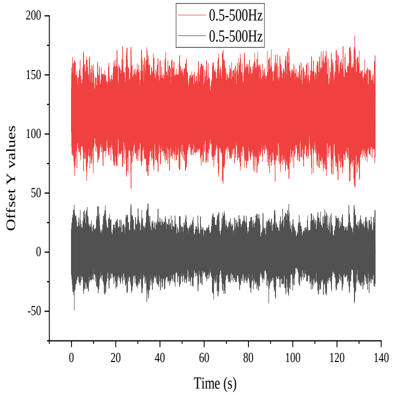
HDCM

Fast-scan DCM

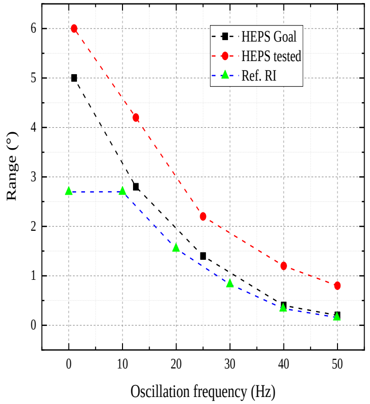
HR-DCM



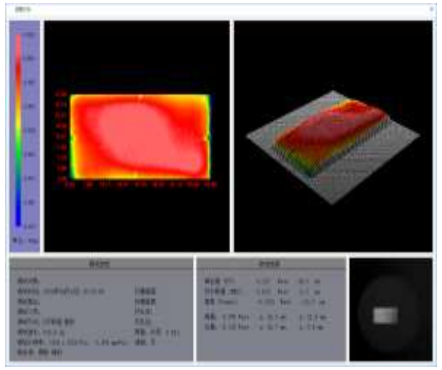
Stability of VDCM
<10nrad RMS
Under cooling



Stability of HDCM
<20nrad

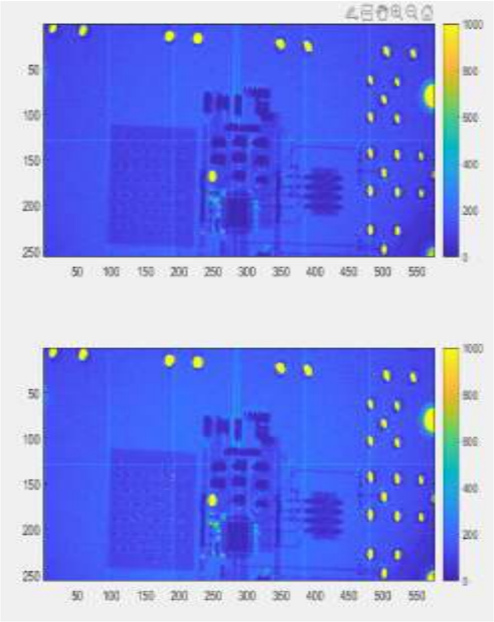


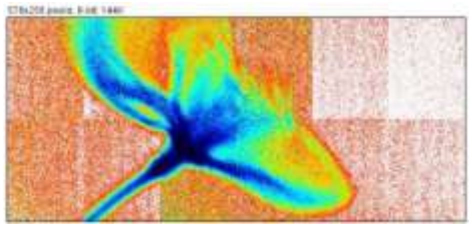
Fast-scan DCM
100 XAFS spectra /s
@0.6°



Deformation of crystals during clamping
< 0.1μrad RMS

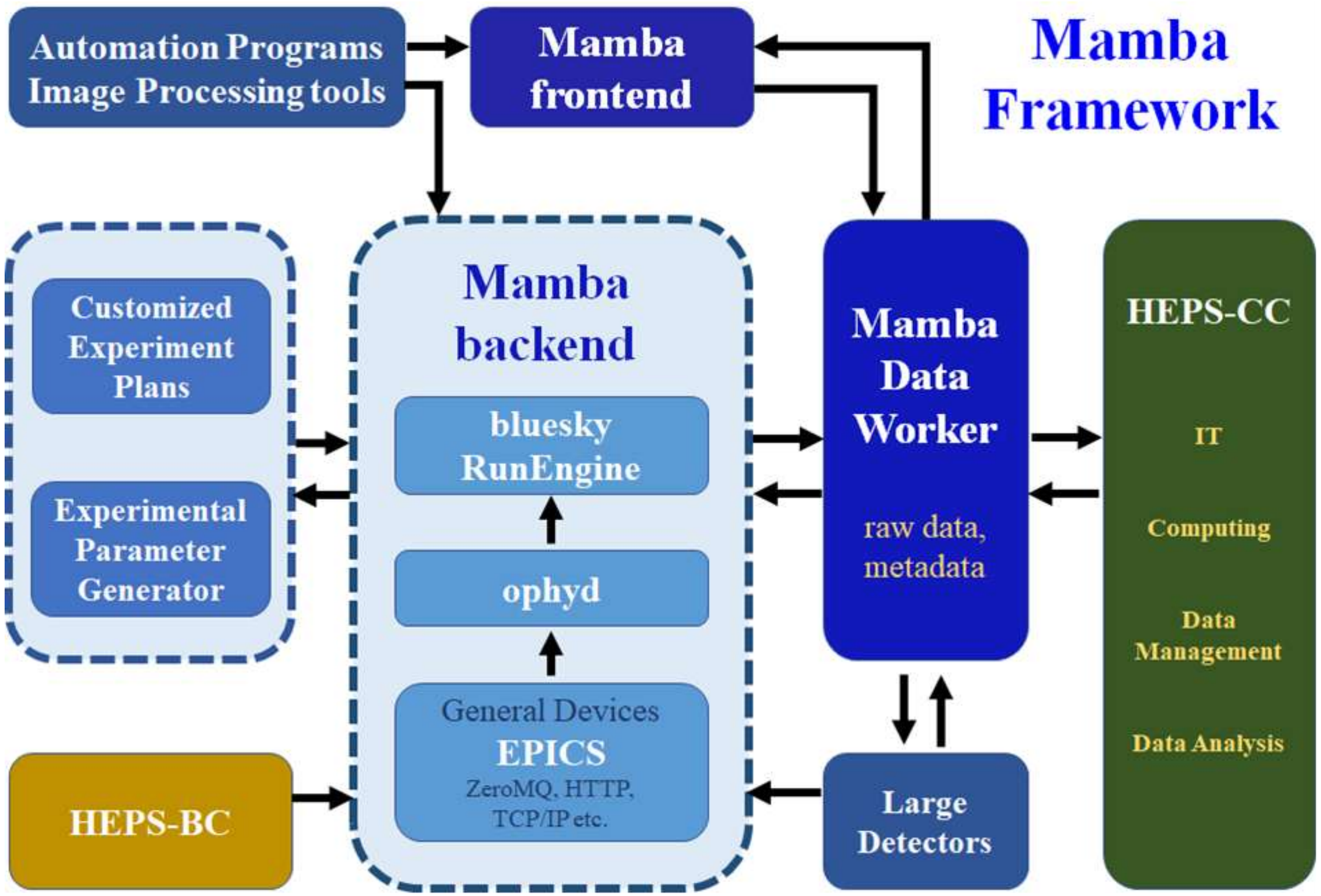
Detector

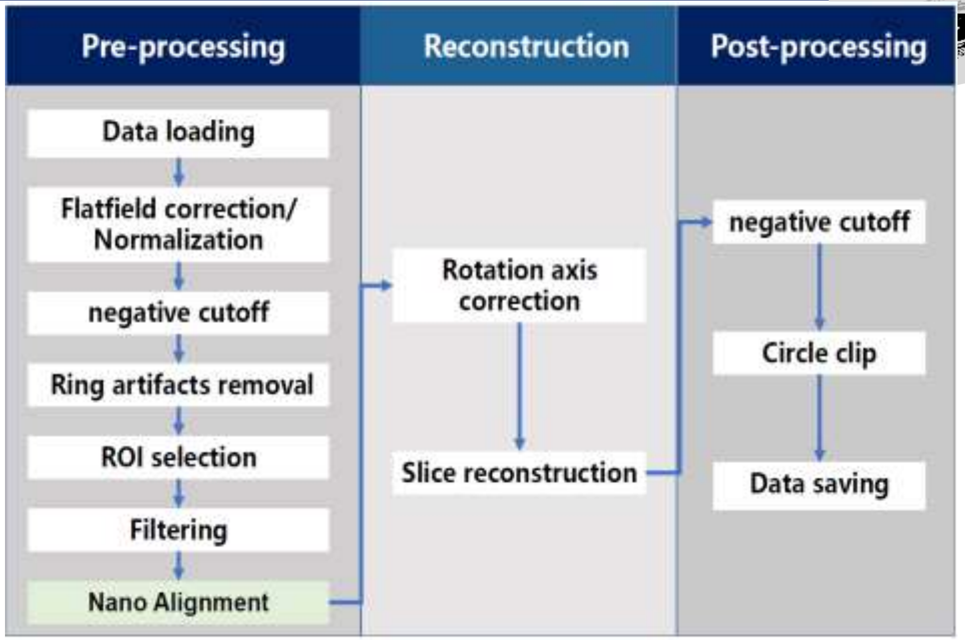




Parameters	1st generation	2nd generation –new
Sensor	320um silicon PIN	320-500µm
Pixel size	150umX150um	140umX140um
Pixel array	1248X1728 (single module 208X288, 4X6 modules)	Single module 256×576 pixels (3.6cm×8cm)
Counting rate	1Mcps	>1Mcps
Dynamic range	20bit	20bit
Flame rate	1KHz (design), continuous 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

Data management and analysis





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

Procurement and Delivery

> 2/3 contracts signed

- Front ends for 15 beamlines delivered by October 2023.
- Enclosures, utilities and safety interlock system delivered 50%
- Optics

  75% mirrors delivered by July 2023.

  First batch of the diamond CRL delivered.
- Opto-mechanics

  All mirror vessel systems for group #1 beamline (Beamlines from BM and in-air insertion devices) delivered.

  4 monochromators delivered.
- Detectors： Advanced pixel array detectors package ordered

Test and installation- Front ends

14 of 17 front-ends delivered

Factory acceptance

Installation start

Test and installation - X-ray Mirror systems

Focusing, collimating mirrors

38/40 are designed by HEPS teams

Factory acceptance

Test measurement after delivery

Test and installation-Monochromators

VDCM

HDCM

Fast-scan DCM

HR-DCM

First Double Crystal Monochromator installed at 2023/7

Test and installation- Enclosures


B8 XAS

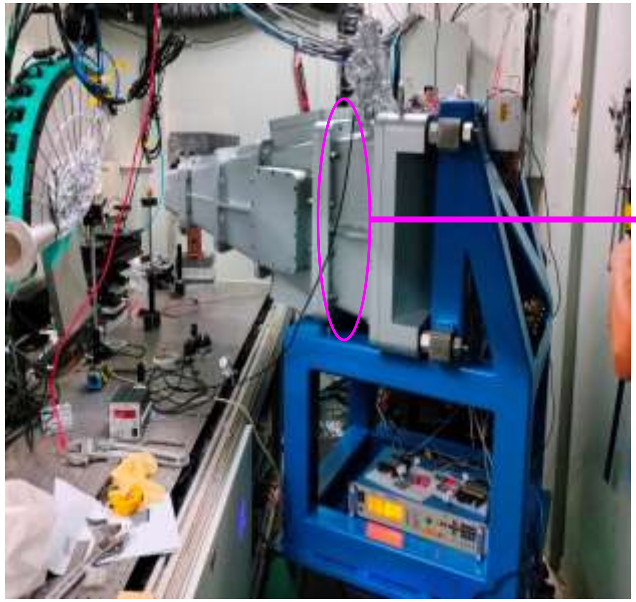

BE TXM


BA PX


B7 Imaging

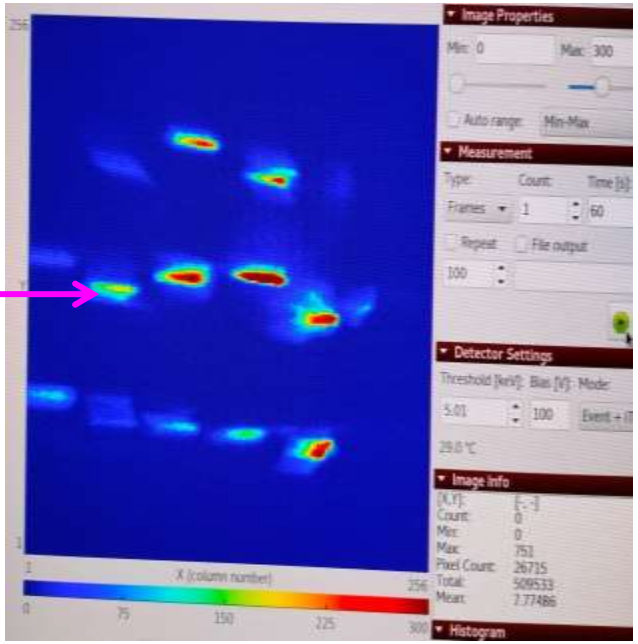
Test and installation- endstation instrumentation

X-ray Raman spectrometer prototype module tested at BSRF



Prototype module

15 analyzer crystals/module



X-ray Raman signals

Schedule

- **Group 1 beamline,**

Test finish in the first half of 2024

Commissioning in the second half of 2024

- **Group 2 beamline**

Test finish in the first half of 2025

Commissioning in the first half of 2025

Future Plans: HEPS follow-up beamlines

- Criteria for HEPS beamline selection: **Scientific and Industrial questions as well as cutting-edge experimental methods motivated in 4GSR.**
- Upon schedule of insertion installation, without impeding the operation of existing BLs, 4-5 ID installed per year
- 32 bls has been planned

Fields	Material	Physics	Chemistry	Envir.	Energy	Industry	Bio.	Meth.
BL	3 ID, 3 BM	5 ID, 1BM	1 ID, 5 BM	2 ID	2 ID, 1 BM	1 ID, 4 BM	2 BM	2 ID

- Organizing institutionalization research teams/projects based on HEPS
- Materials
- Chemistry (Dynamic properties of catalysis)

Summary

- HEPS is a 4th generation, high energy, ultra-low emmitance SR facility. It is the key facility of Huairou Science City.
- A series of projects, HESP-TF, PAPS, Auxiliary building, are also carried on.
- The HEPS project progress in time. Civil construction was finished in Aug. 2022. LINAC is ready. Booster is in commissioning. Storage ring, beamlines and end-stations are in installation and will be commissioning in the beginning of 2024. Whole project will be finished in the end of 2025.


Thank you for your attention!
UCAS
SECUF
(IOP-CAS)
PAPS
HEPS
Dynamic structure
Hard X-ray imaging
Nano-probe
Medicine Imaging facility
(PKU & IBP-CAS)
Earthlab
(IAP-CAS)