Status of HEPS

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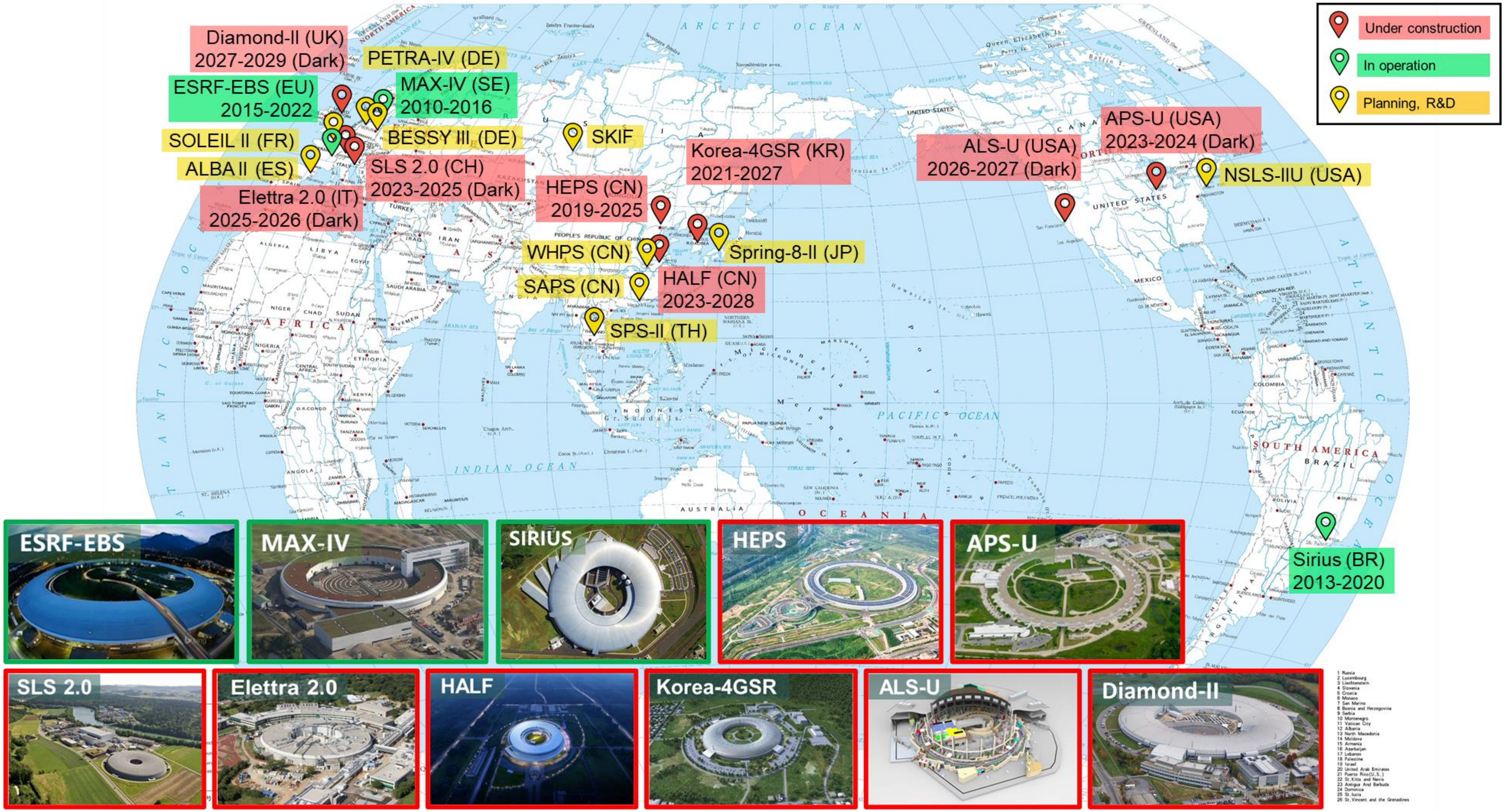
PSI visit, Sep 26, 2024, PSI, Switzerland

Outline

- Project overview
- Accelerator
- Beamlines
- Collaborations
- Future plans

Project overview

Landscape of the 4^{th}-gen SR facilities



Light sources in mainland China

Beijing Synchrotron Radiation Facility (1st-gen)

Hefei Light Source (2nd-gen)

Shanghai Synchrotron Radiation Facility (3rd-gen)

- In operation: 5 light sources (3 SRs + 2 Linacs)
- Under constr.: 3 light sources (2 SRs + 1 Linac)
- Planning, R&D: 4 light sources (3 SRs + 1 Linac)

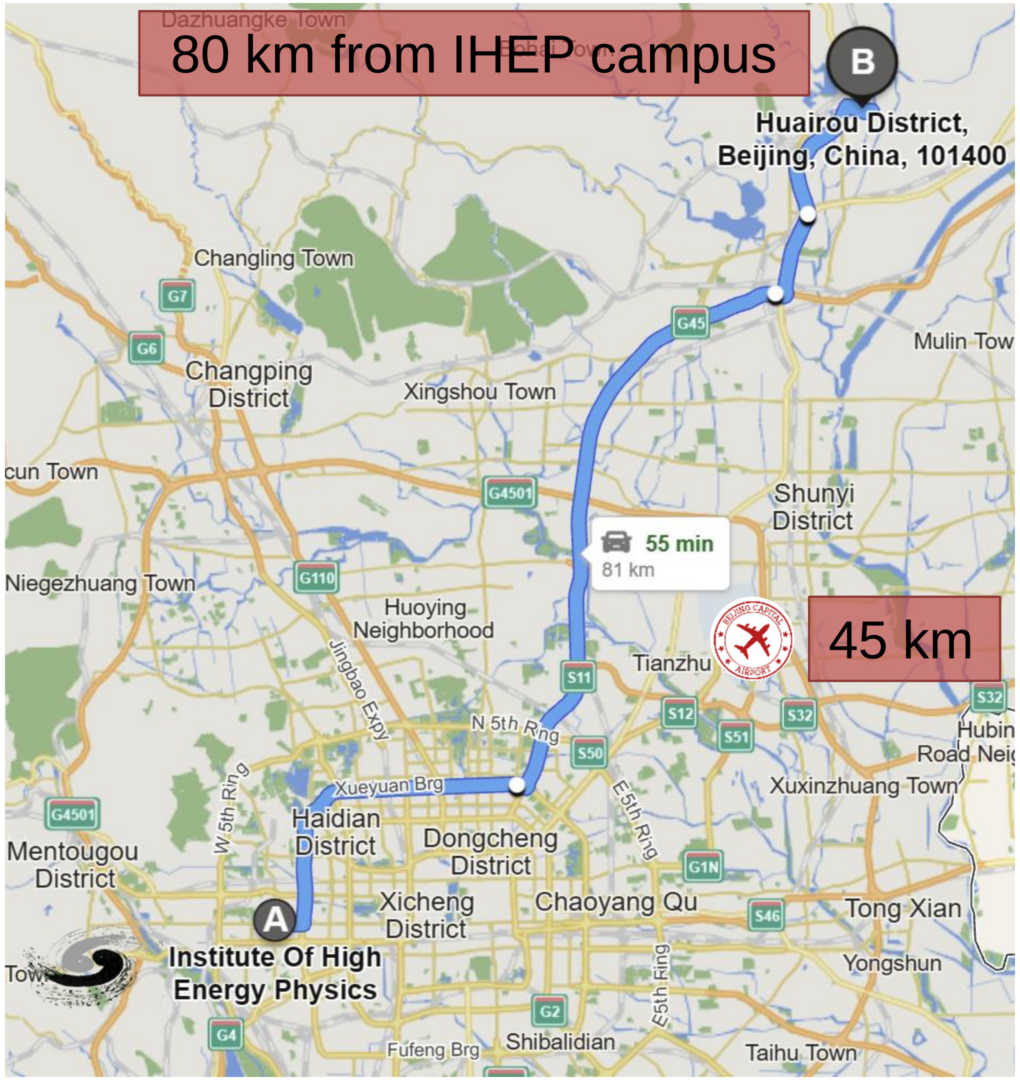
High Energy Photon Source

Hefei Advanced Light Facility

Southern Adv. Photon Source

High Energy Photon Source

- **Project outline**
  - A diffraction-limited SR light source (4^{th}-gen)
  - The 1^{st} high-energy SR light source in China
  - **Location**: Huairou Science City, Beijing
  - **Construction time**: 06.2019 – 12.2025
  - Land: 650,667 m^2, Building: 125,000 m^2
  - **Budget**: 4.76B CNY (~$652M)(incl. materials, civil constr. & commissioning, excl. labor costs)
  - **Support**: Central government + Local government + Chinese Academy of Sciences



SR: Synchrotron Radiation

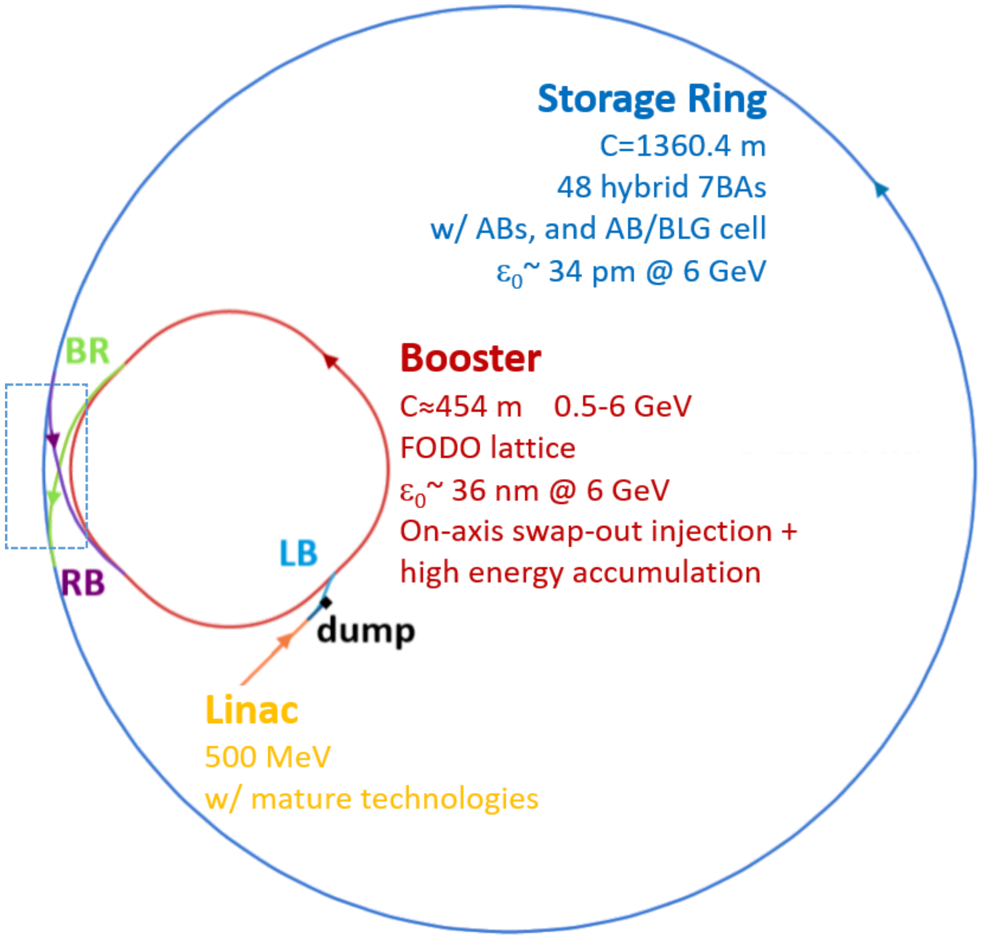
HEPS in Huairou Science City (Beijing)

- World-class Original Innovation Area
- A new highland for strategic and forward-looking basic research
- A key area of Comprehensive National Science Center
- An eco-friendly and livable innovation demonstration zone

100.9 km^2

5 large science facilities

Main parameters: accelerator



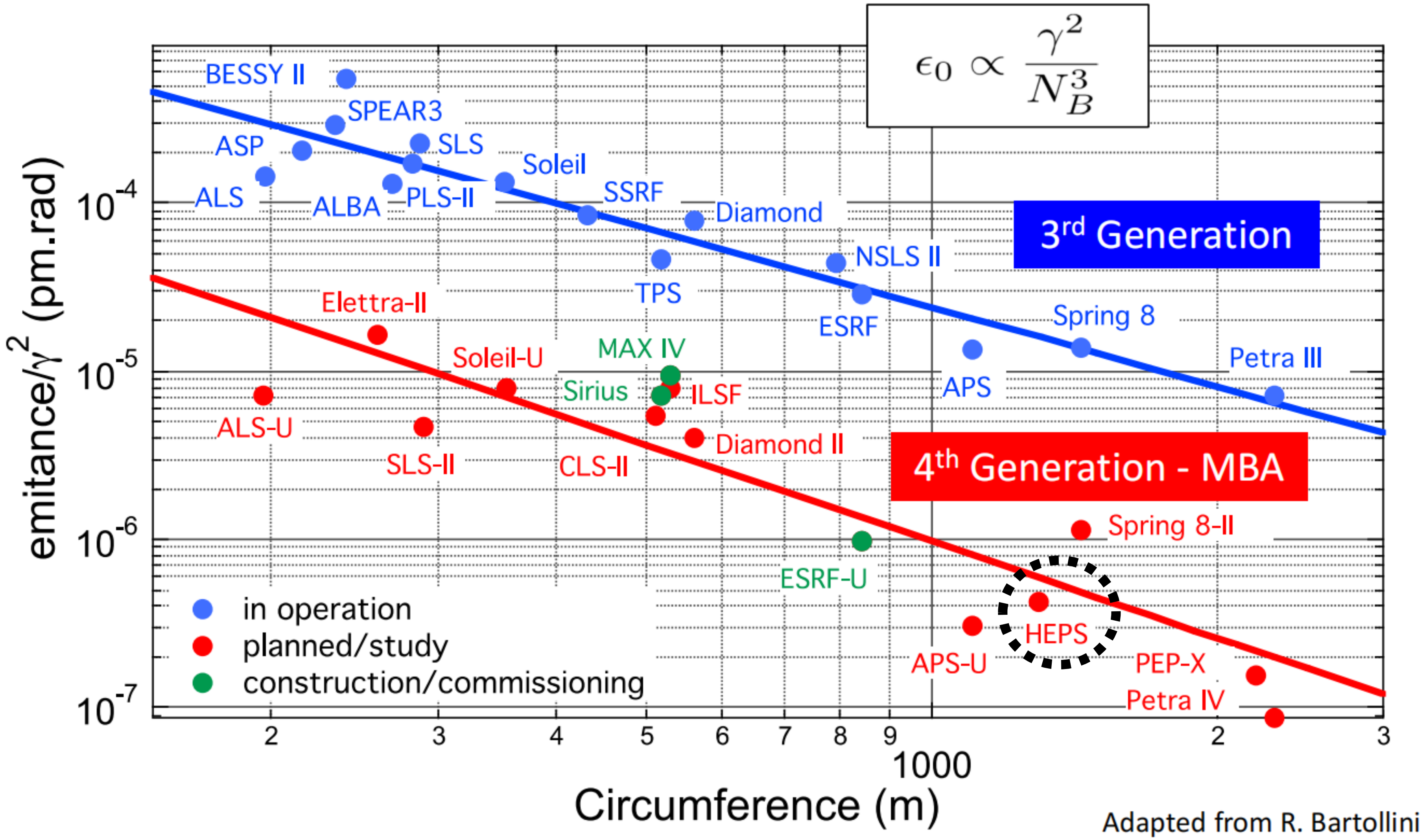
- **Accelerator complex**
  - Linac (500 MeV)
  - Booster (500 MeV to 6 GeV, 1 Hz)
  - Storage ring (6 GeV, top-up)

Parameter	Value	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Lattice type	Hybrid 7BA	
Hori. Natural emittance	<60	pm·rad
Brightness	$>1\times10^{22}$	*
Beam current	200	mA
Injection mode	Top-up	-

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

[1] Y. Jiao *et al.*, *J. Synchrotron Rad.* 25, 1611–1618 (2018).
[2] H. Xu *et al.*, *RDTM* 7, 279–287 (2023).
[3] C. Meng *et al.*, *RDTM* 4, 497–506 (2020).

Main parameters: accelerator

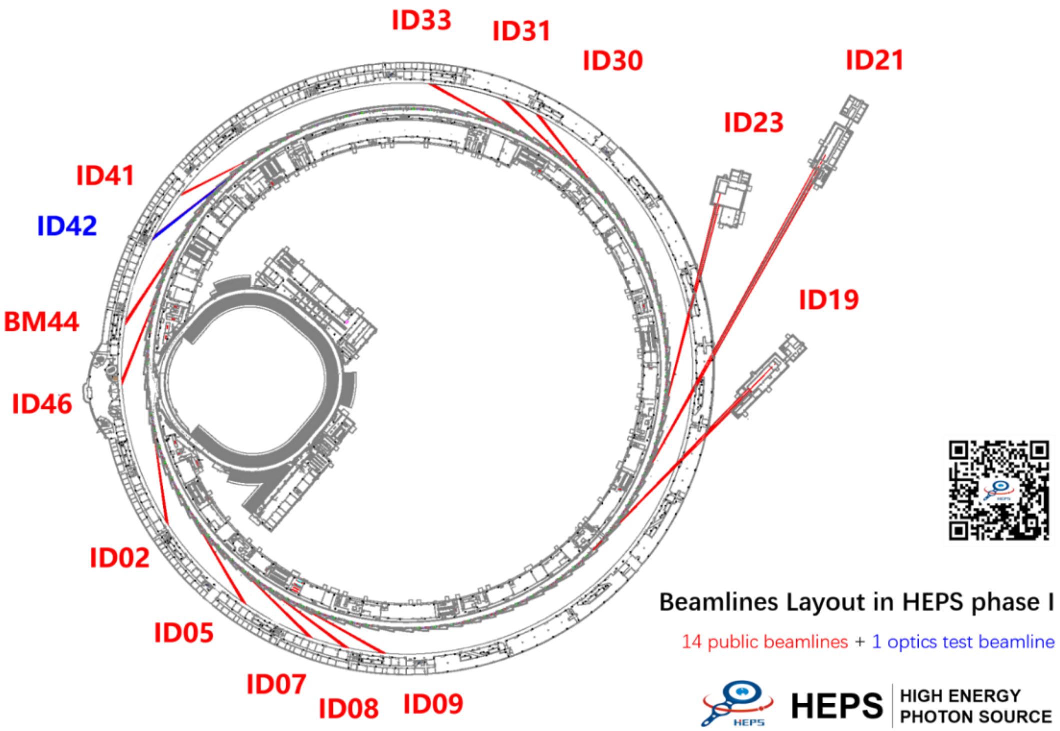


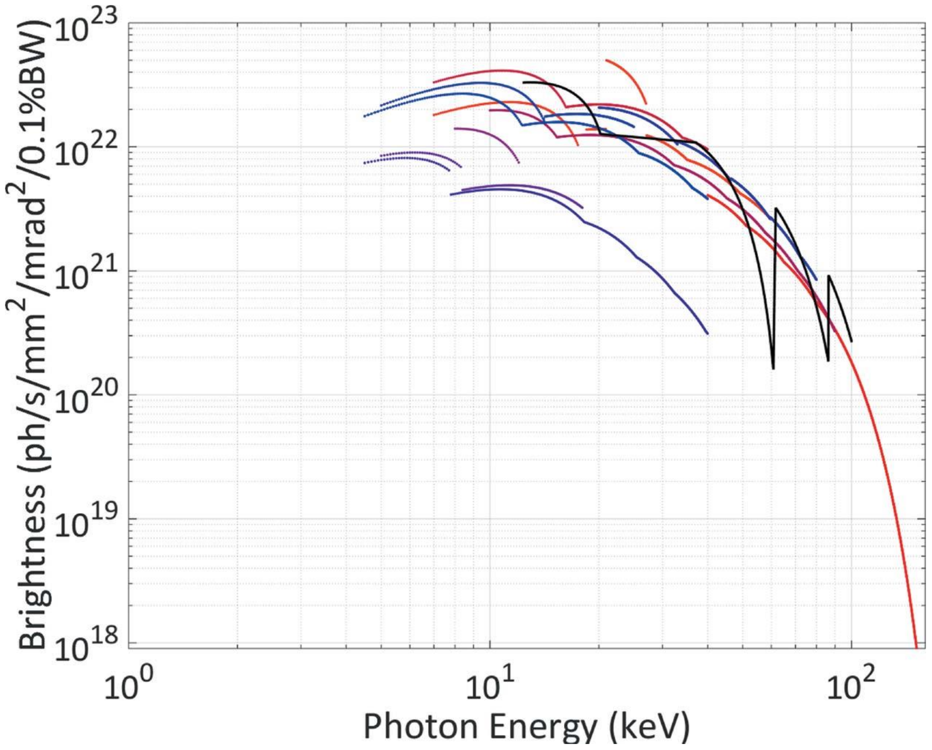
Adapted from R. Bartollini

L. Liu, H. Westfahl Jr., IPAC2017, TUXA1.

Main parameters: beamlines

- One of the brightest 4th-gen SR facilities in the world
- Brightness of 5×10^{22} phs/s/mm^2/mrad^2/0.1%BW at the photon energy of 21 keV, can provide X-ray with energy up to 300 keV
- 14 public beamlines in Phase 1, HEPS can accommodate up to 90 beamlines





Y. Jiao *et al.*, *J. Synchrotron Rad.* 25, 1611–1618 (2018).

HEPS-TF and HEPS: two phases

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
HEPS-TF	Preparation			Execution									
HEPS				Preparation			Construction (6.5 yrs.)						

NOW

HEPS project milestones

- 28.09.2016, Project settled in Huairou (Beijing)
- 15.12.2017, **Project proposal** approved by NDRC (CD0 equivalent)
- 28.12.2018, **Feasibility study** approved by NDRC (CD1 equivalent)
- 22.05.2019, **Preliminary design and budget** approved by NDRC (CD2 equivalent)
- 29.06.2019, Construction started in Huairou (CD3 equivalent)
- 31.12.2025, Construction completed, national acceptance (CD4 equivalent)

HEPS-TF (R&D project before HEPS)

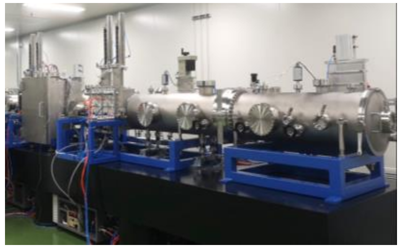
- Schedule： 04.2016 - 10.2018, Budget: 321.6 M RMB (~48 M USD)

NDRC: National Development and Reform Commission

R&D and test infrastructure for HEPS

- **RF lab**: cleanroom, module assembly area, cavity & module test bunker, 400 cavity testing + 20 cryomodule testing per year capability, 2.5kW@4.5K or 300W@2K cryogenic system
- **Precision Magnet Technology Platform:** magnetic field measurement equipment and high-precision alignment equipment, 2500m^2 exp. hall
- **Beam Test System:** photocathode DC gun + 650MHz CM, 10MeV/1~10mA
- **NEG-coating facility**: 6 sets*4.2m + 4 sets*1.6m
- **Optical Metrology Lab**: Frequency-decomposed Stitching Interferometer (FSI) , Flag-type Surface Profiler (FSP)
- **Detector Lab**: Sensor, ASIC, I/O
- **Crystal Fabrication**: Silicon Mono. Crystal, flat and Channel-cut silicon crystals, MLL, Kinoform lens

Platform of Advanced Photon Source technology R&D (**PAPS**)

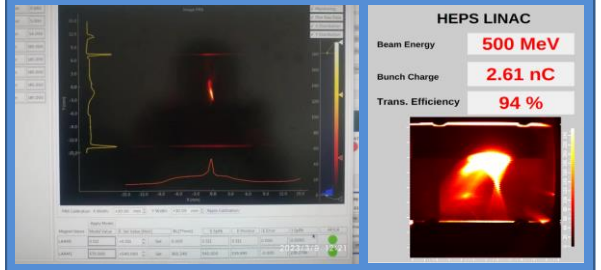


Milestones of HEPS

- Groundbreaking in Jun. 2019
- Civil construction completed in Nov. 2021
- PAPS completed in May 2021, currently in operation
- Booster installation completed in Jan. 2023
- Linac commissioning completed in Mar. 2023
- Booster commissioning completed in Nov. 2023
- Storage-ring installation completed in Jul. 2024
- Storage-ring commissioning started in Jul. 2024
- Beam current exceeds 10mA in storage ring in Aug. 2024

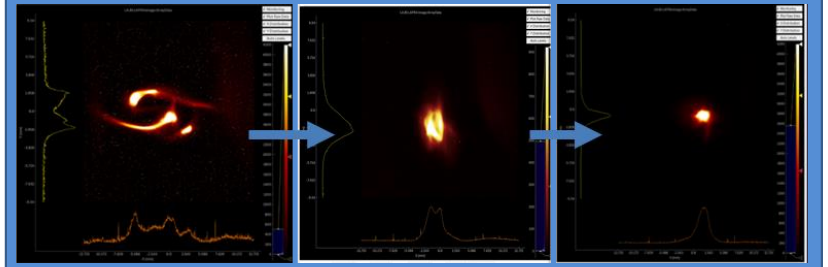
Platform of Advanced Photon Source Technology R&D

Injector commissioning



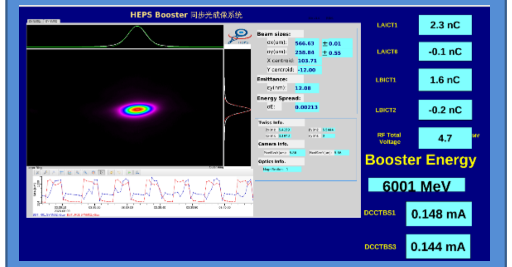
500 MeV, ~2.5 nC

1st electron beam



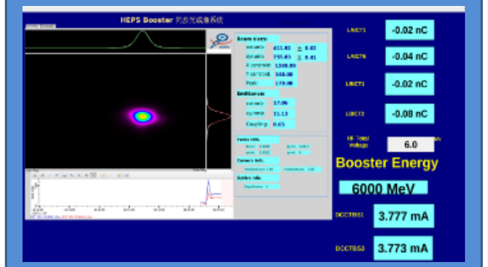
500 MeV, max bunch charge > 7 nC

LINAC passed SAT



Ramped to 6 GeV

1st electron beam in Booster



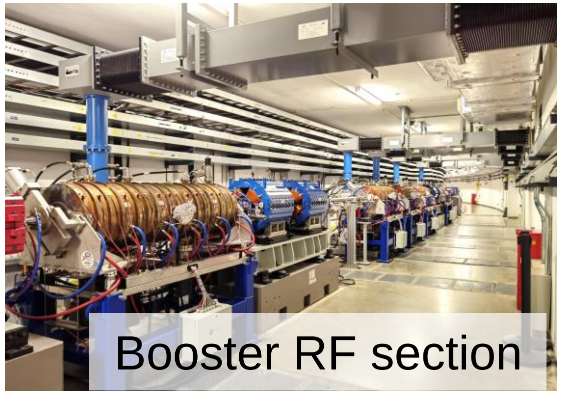
>5 nC of single bunch charge

Booster passed SAT

- 3.9 LINAC CX started
- 3.14
- 6.5
- 7.25 Booster CX started
- 8.9
- 11.17

Linac

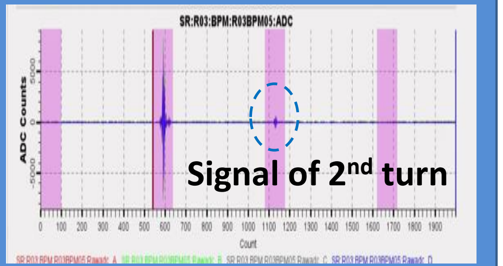
Booster IE sector



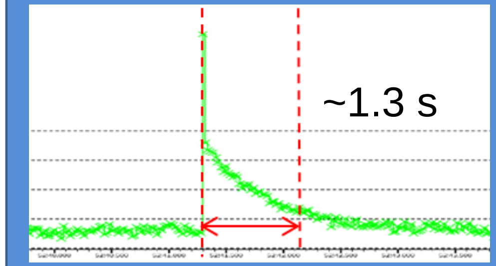
Booster RF section

- **LINAC**: 500 MeV, max bunch charge > 7 nC
- **BOOSTER**: 500 MeV to 6 GeV, single bunch charge > 5 nC

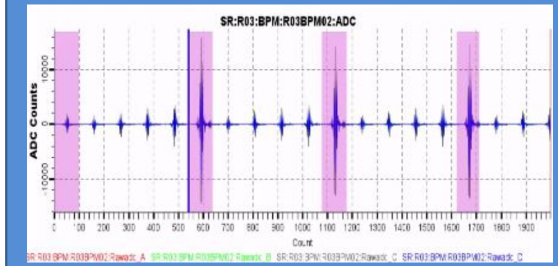
Storage ring commissioning



First turn

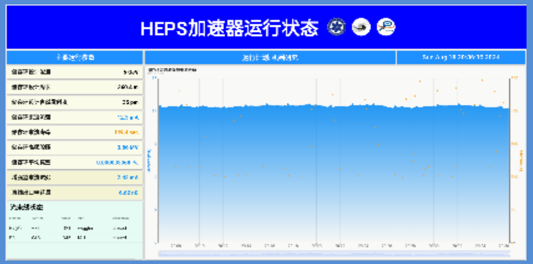


One bunch stored



Current: ~0.4 mA, Life time: ~1 min

Multi-bunch stored



Current: ~12 mA, Life time: ~2 min

12 mA stored

SR CX Started

7.23

7.29 — 10 turns

8.4 — 1000 turns

8.6

8.8

8.15 — 7 mA, 2 min

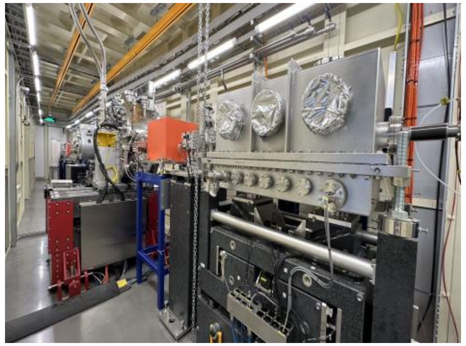
8.18

First light in 2024

Beamline installation & commissioning plan

- **Group 1 beamlines: BM / IAU / IAW**
  - IDs installed in storage ring
  - Installation and commissioning completed
  - Control and data-acquisition software ready
  - Photon beam commissioning scheduled in Oct. 2024
- **Group 2 beamlines: IVU / CPMU / Apple knot / Mango**
  - Installation to be completed in the end of 2024
  - Commissioning scheduled in Apr. 2025
- **All front-ends, FOEs, Hutches are ready**

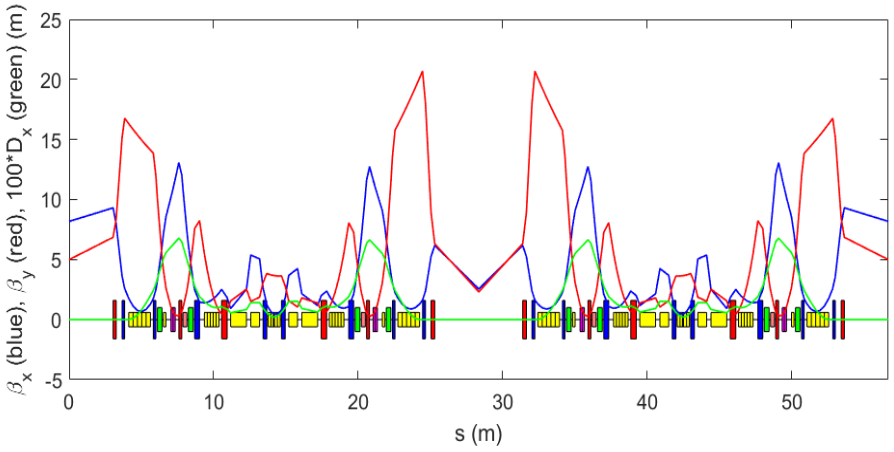
Group 1	Hard X-Ray Imaging	IAW/Mango/IVU(G2)
	TXM	IAU
	XAFS	IAU
	Tender spectroscopy	BM
	Pink SAXS	IAU
	μ-Macromolecule	IAU
	Optics Test	IAW/CPMU(G2)
Group 2	Engineering Materials	CPMU
	Nano-probe	CPMU
	Structural Dynamics	CPMU
	High Pressure	IVU
	Nano-ARPES	Apple knot
	Hard X-ray Coherent Scattering	IVU
	Low-Dimension Probe	IVU
	NRS&Raman	IVU

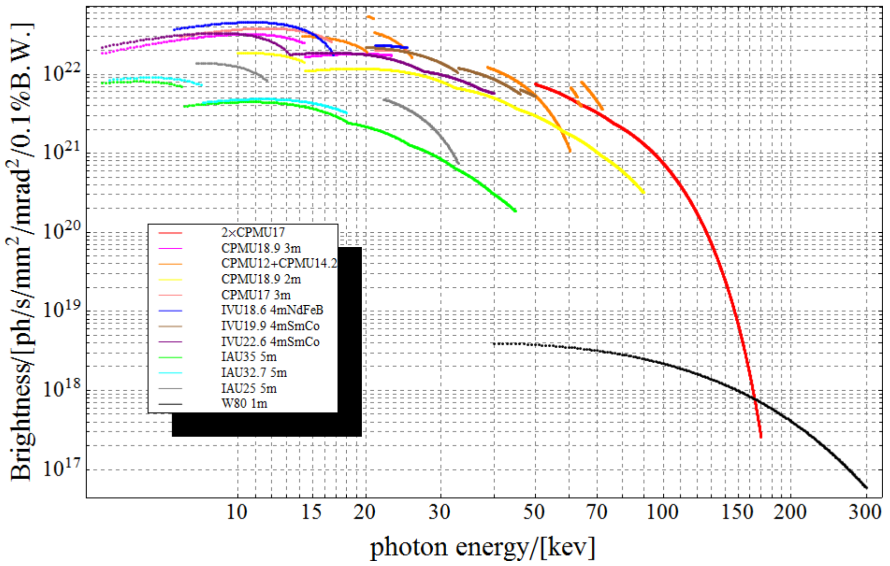


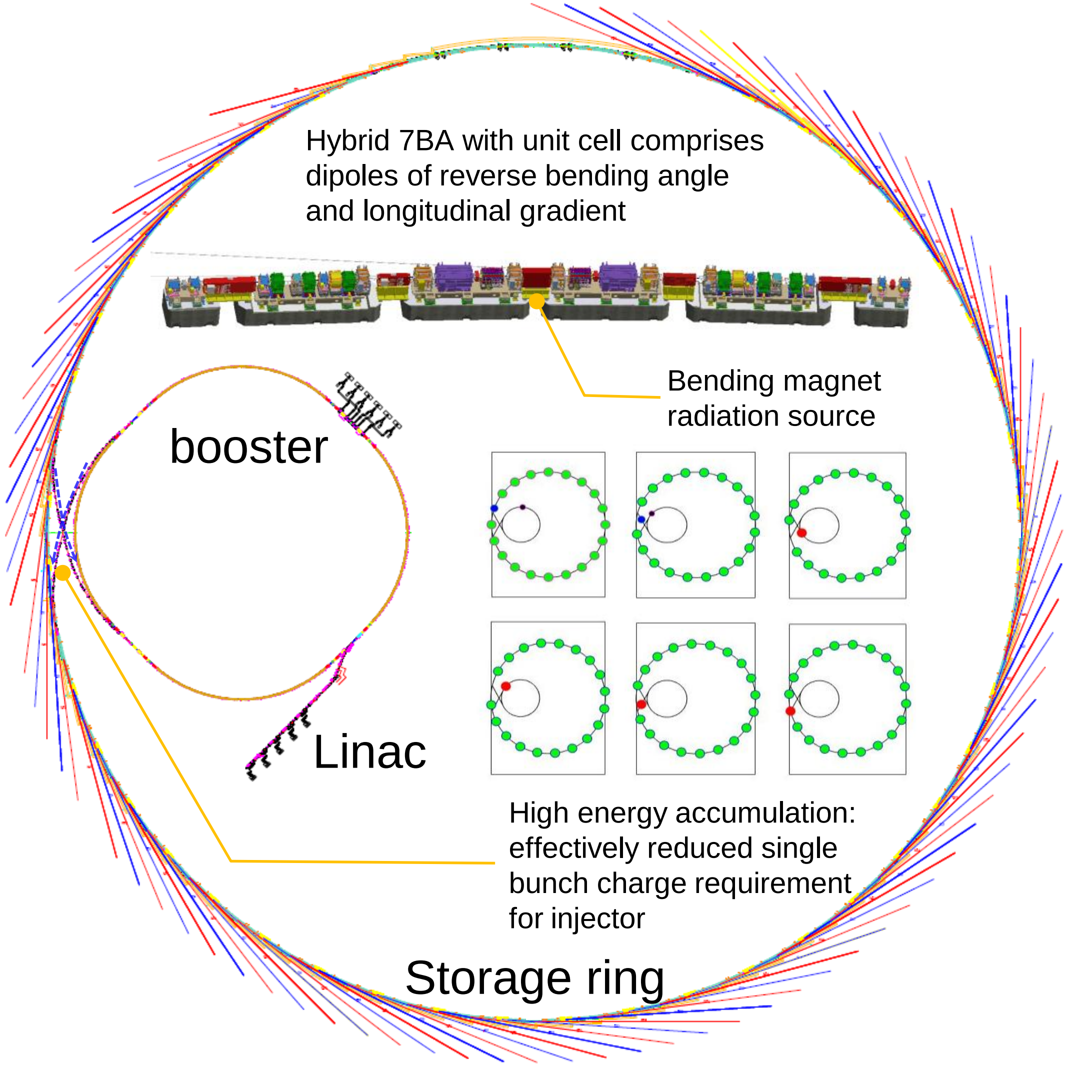
Accelerator

Lattice design

- Accelerator Physics group completed the physical design of the accelerator complex







HLA framework: *Pyapas*

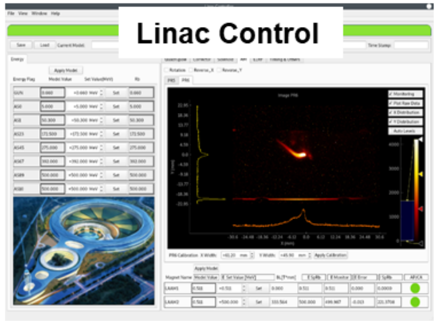
- Developed beam commissioning software and its underlying architecture

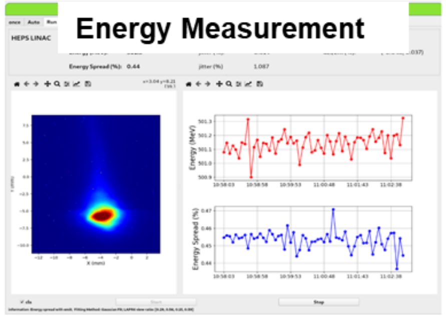
✓ Based on Physical Quantities

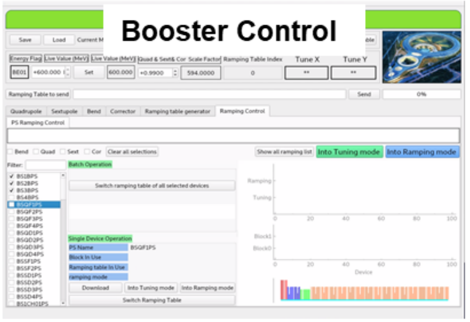
✓ Model-Based

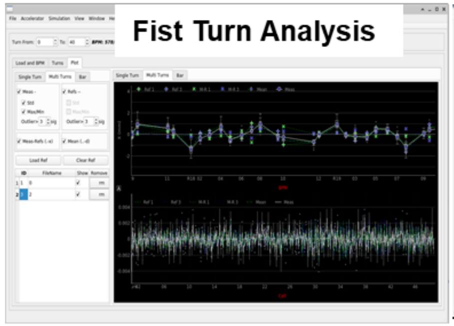
✓ Modular Design

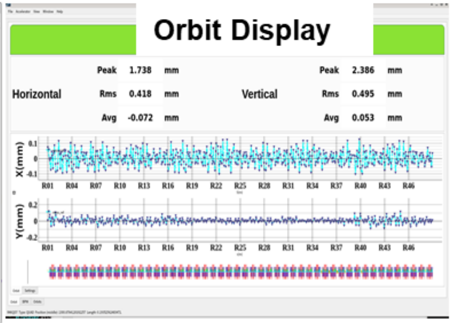
① Dual-layer physical module
② Friendly user interface module
③ Hardware communication module
④ Database connection module
⑤ Client-Server development module
⑥ Various phyisical algorithm toolkits

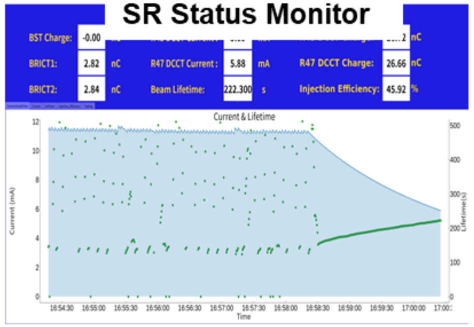




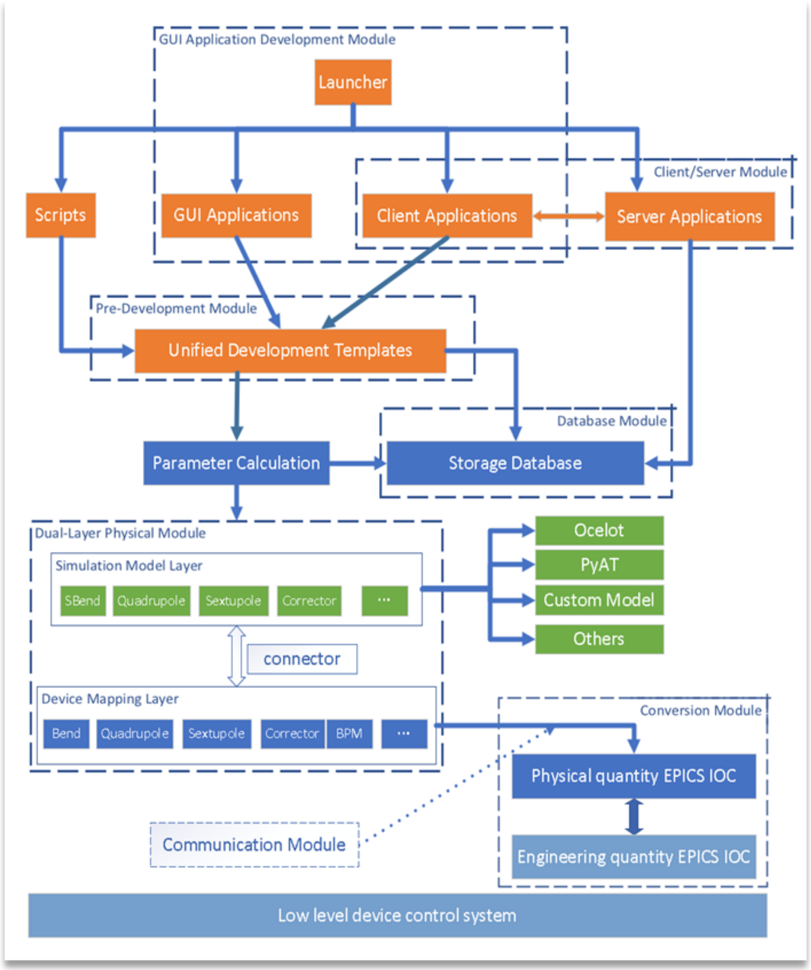








Pyapas framework



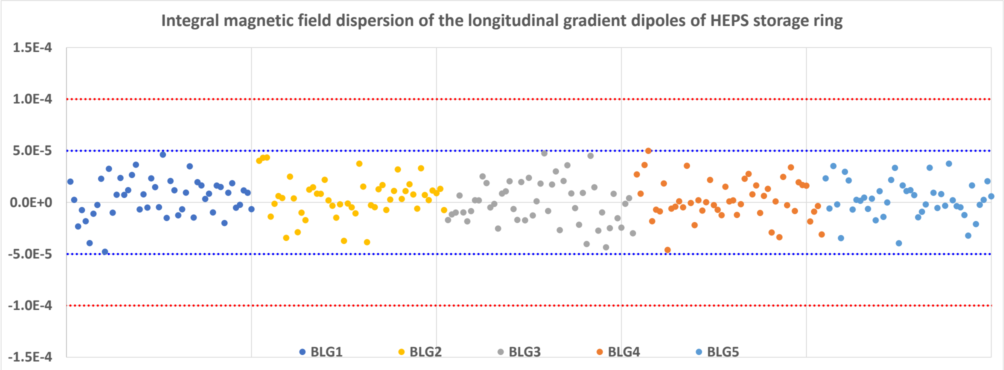
Magnet system

Magnet type	Abbr.	Qty
Longitudinal grad. dipole	BLG	245
Dip./quad. comb. magnet	BD/ABF	294
Quadrupole	QF/QD	686
Sextupole	SF/SD	294
Octupole	OCT	98
Fast corrector	FC	196
Magnet field measurement system		
Rotating coil system	RCS	3
Hall probe system	HPS	3
Planar moving coil system	MCS	1
Stretched wire system	SWS	1
Trans. field meas. system	TFS	1

All magnets and measurement systems developed in-house by the Magnet group.

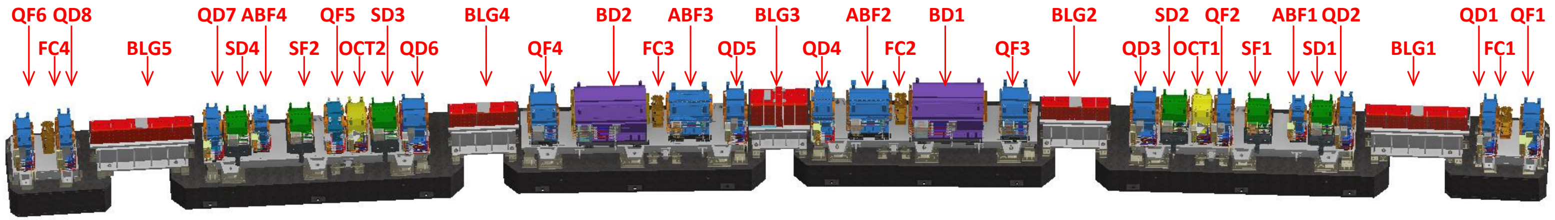
- **Features of key magnets & system**

- BLG: permanent magnet, field tuning to 50 ppm, temperature compensation to 50 ppm/°C
- QF/QD: 80 T/m, $B_n/B_2 < 4\times10^{-4}$, harmonics compensated by "Magic finger"©
- RCS: based on coordinate measuring machine (CMM), automatic alignment with 10 μm precision
- MCS: automatic alignment with 20 μm precision



Measuring BD magnet with CMM based Rotating coil system

Measuring BLG magnet with Arm based planar moving coil system



Magnet power supply

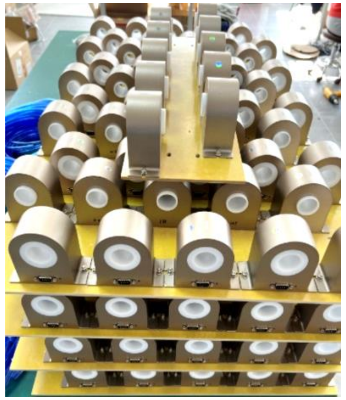
Power Supplies	Qty.	Type
Linac	51	DC
Trans.	123	DC
BS Bend.	4	DC+AC
BS Quad.	8	DC+AC
BS Sext.	6	DC+AC
BS Corrector	84	DC+AC
SR Quad.	960	DC
SR Sext.	12	DC
SR Oct.	4	DC
SR FC	384	DC+AC
SR Corr.	864	DC
IDs related	105	DC

All power supplies, DCCTs and digital controllers developed in-house by PS group

- **Features of the magnet power supply system**
  - **High precision** current-stable power supplies: long-term stability 10 ppm, accuracy 50 ppm, repeatability 20 ppm
  - **High bandwidth** high precision fast corrector power supplies: small-signal step response time 75us, current ripple 20ppm
  - **High power dynamic** power supplies: tracking error 0.1% vs. operating value, from injection to extraction point
  - **In-house developed digital power supply controller and DCCT**: all power supplies are fully digital-controlled with digital controllers and installed DCCTs as the current feedback component

Storage ring PS hall

Booster PS hall



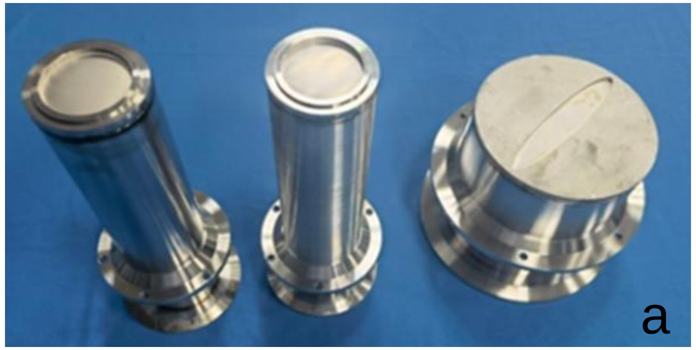
DCCT

Digital controller

Vacuum system: key components

SR requirement:
1.3e-7 Pa (dynamic)

Parameter	Value	Type/Qty
Thickness of electron beam window (a)	0.1 mm	3/4
Dimension of the booster vacuum chamber (b)	36*30*0.7 mm	87/423
Contact force of RF shielding bellows (c)	125±25 g	42/1125
Material of photon absorber (d)	C10100 C15715 C18150	11/288
Magnetic permeability of Stainless Steel vacuum chamber in storage ring (e)	1.02	7/532
Inner dimension of the CrZrCu vacuum chamber (f)	Di22mm Di22mm w/ antechamber, Di8 mm, etc.	27/1019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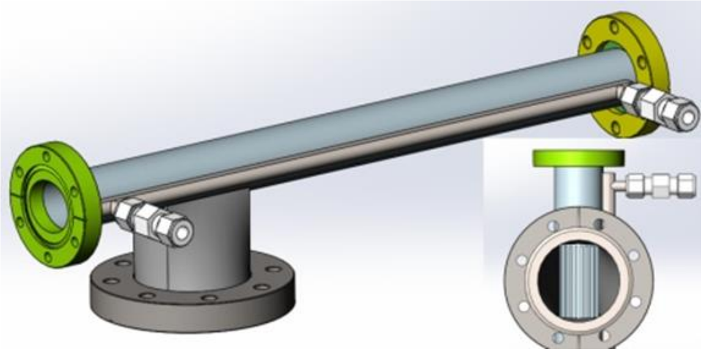
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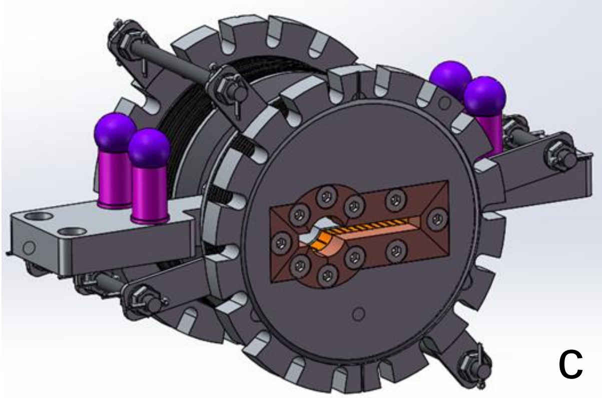
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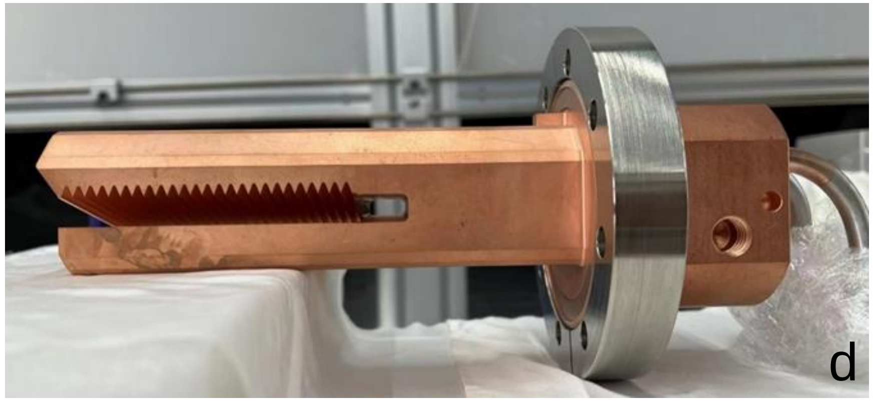
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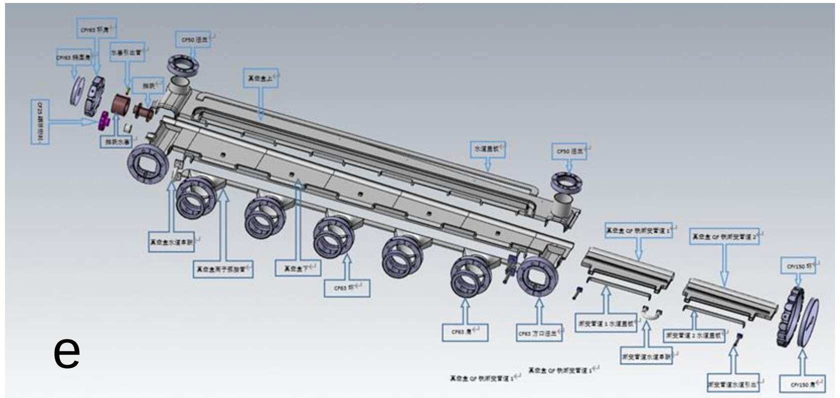
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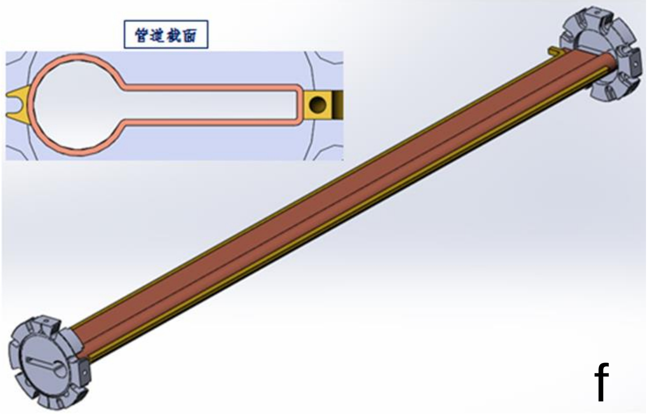
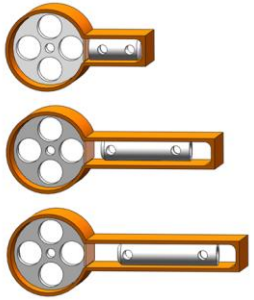
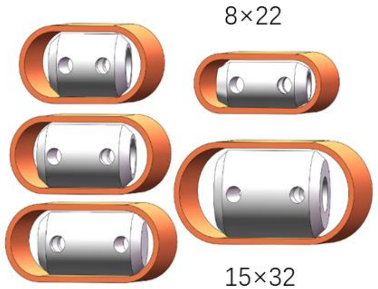


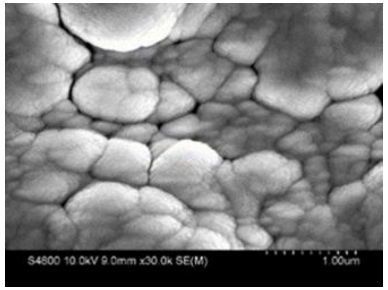
f

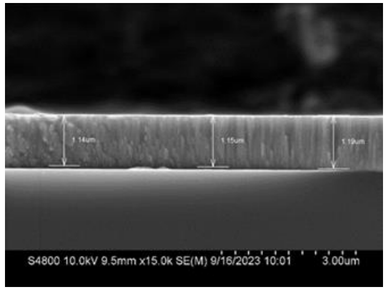
Vacuum system: NEG coating

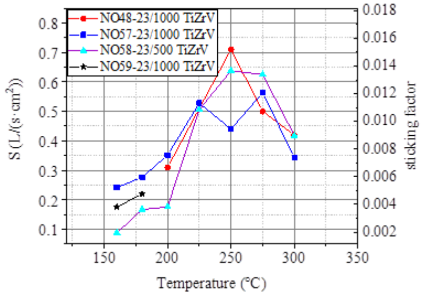
Parameter	Value
Film thickness	1±30% μm
Composition of Ti/Zr/V	~30％
Film structure	Columnar
Pumping speed of H_2	0.2-0.6 L/(s.cm^2)
Activation temperature	180-250 °C
Capacity of CO	>1.0 ×10^{-5} mbar·L/(s·cm^2)
Inner dimension of the coated chambers	Di22mm, Di22mm w/ antechamber, Di8mm, 8×22, etc.
Number of coated chambers	918



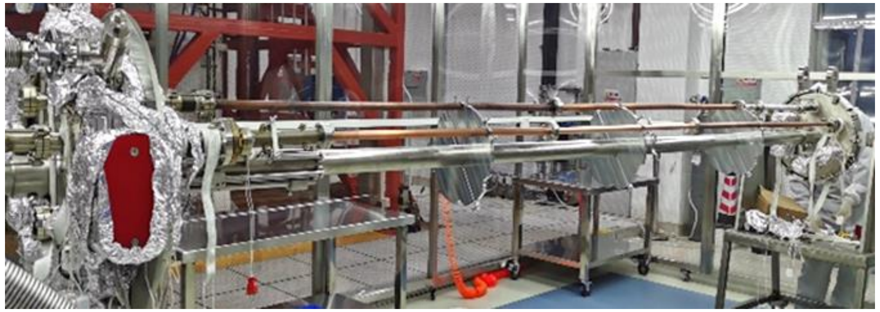








In-house

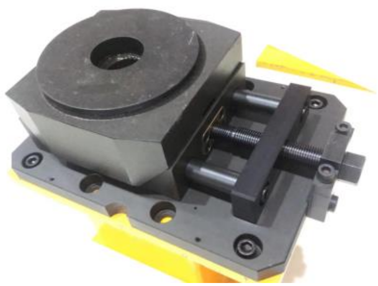


Girder & Magnet support

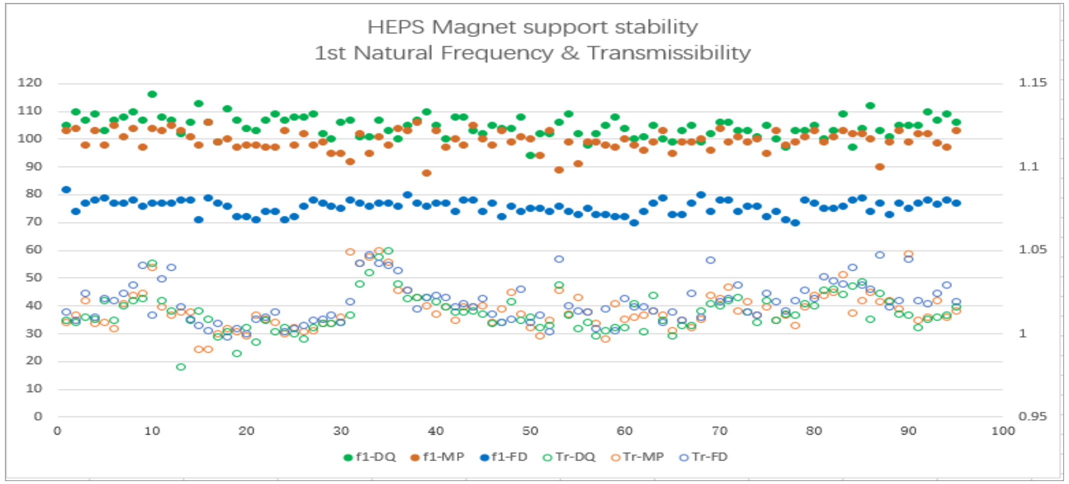
SR magnet support system

- Ultra-high stability & micron-level motion resolution
  →contradictory requirements
- Improve system stiffness : Self-developed wedge mechanism, high-stiffness concrete plinth & grouting installation process
- 288 support modules installed and met the requirements.
  - Eigen frequency： ≥70 Hz
  - Transmissibility: ≤1.05
  - Motion resolution : 1 μm

Parameters		Requirement
Resolution	X/Y	≤5μm
	Z	≤15μm
Adjusting range	X/Z	±10mm
	Y	±7mm
Natural frequency		≥54Hz



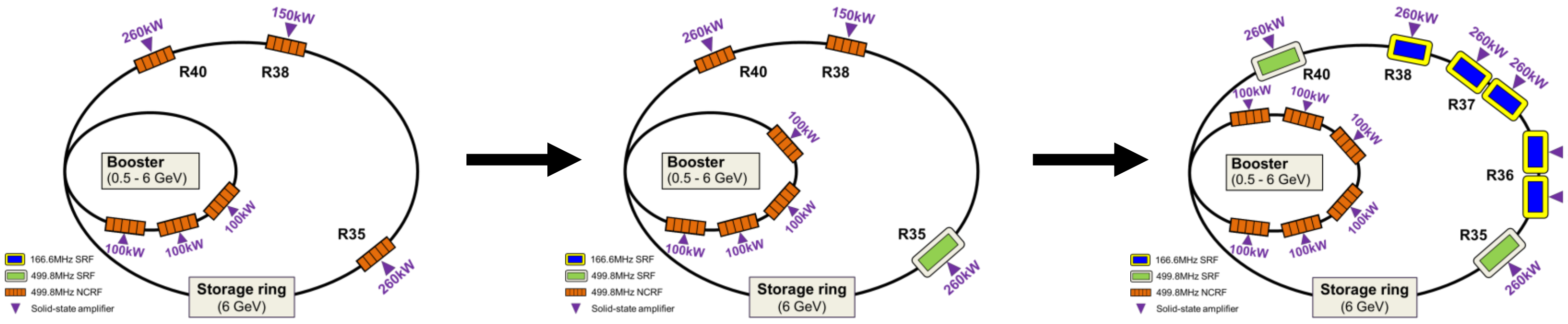
Wedge leveler

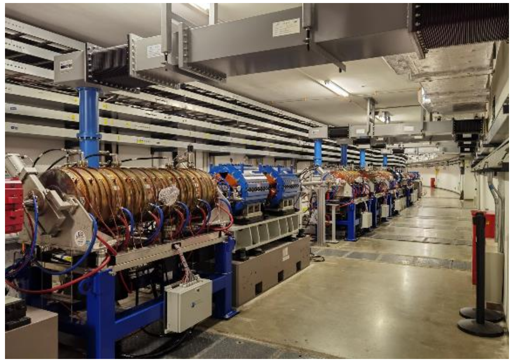


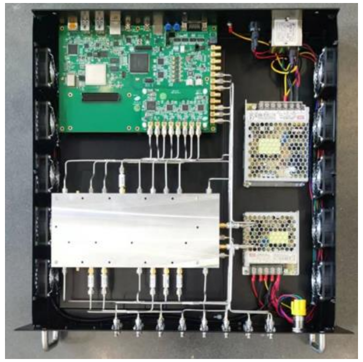
RF system: booster

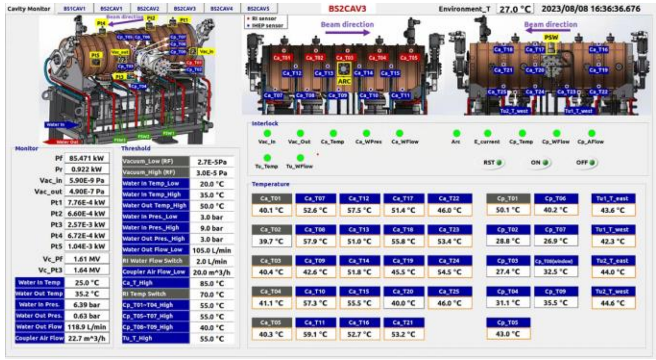
Parameter	Value	Unit
Beam energy	0.5-6	GeV
U_0 @ 6 GeV	4.02	MeV
I_b @ 6 GeV	13	mA
RF frequency	499.8	MHz
RF voltage	2-8	MV
Rep. rate	1	Hz
RF power per cavity	70	kW

- **Features of the Booster RF system**
  - **Cavity**: 5-cell PETRA-type normal-conducting cavity (RI GmbH)
  - **HPRF**: 100 kW SSA (joint dev.) + 150 kW circulator (procured)
  - **LLRF** (**in-house**): digital LLRF (w/ beam: ±0.06%, ±0.04°)
  - **Setup**: 6 cavities with individual SSAs, occupying 1.5 straights









P. Zhang *et al.*, "Radio-frequency system of HEPS", *Radiation Detection Technology and Methods* 7, 159-170 (2023).

RF system: storage ring

Parameter	Value	Unit
Beam energy	6	GeV
U_0 (w/ IDs)	4.14	MeV
Beam current	200	mA
Fundamental RF		
RF frequency	166.6	MHz
RF voltage	5.14	MV
No. of cavities	5	-
RF power per cav.	170	kW
Q0 at 1.5MV	>1e9	-
Harmonic RF		
RF frequency	499.8	MHz
RF voltage	0.91	MV
RF power abs from beam	105	kW
Q0 at 1.75MV	>1e9	-

- **Features of the storage ring RF system**
  - **Cavity (in-house)**: 166.6 MHz β=1 SC QWR (1.1e9 @ 1.6MV) + 499.8 MHz 1-cell SCC (2.6e9 @ 1.75MV), heavy HOM damping, individual cryostat per cavity
  - World's 1st main accelerating cavity of β=1 SC quarter-wave type
  - **HPRF**: 260 kW SSA (joint dev.), 300 kW circulator (joint dev.)
  - **LLRF** (**in-house**): digital LLRF (±0.05%, ±0.1°, 1.2MV)
  - **Setup**: each cavity with individual SSA, occupying 4.5 straights

166.6 MHz cryomodule

499.8 MHz cryomodule

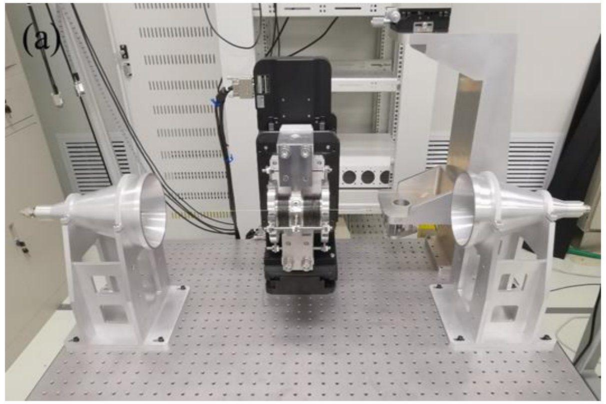
SSA

[1] P. Zhang et al., *Rev. Sci. Instrum.* 90, 084705 (2019). [2] L. Guo et al., *Rev. Sci. Instrum.* 95, 074702 (2024).

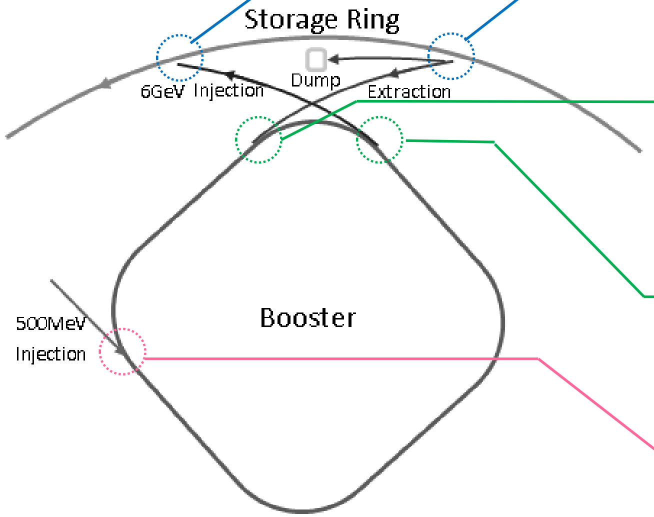
Beam instrumentation system

Instrument	Linac	LB	BST	BR	RB	SR
BPM	10	8	80	11	11	**578**
ICT	7	2	-	2	2	-
DCCT	-	-	2	-	-	2
BCM	-	-	1	-	-	1
OTR/YAG	7	2	-	2	2	-
SLM	-	-	2	-	-	2
Tune	-	-	1	-	-	1
BLM	-	-	4	-	-	**192**
BBFB	-	-	3	-	-	3
Displacement monitor	-	-	-	-	-	8

- **Features of the BI system**
  - **BPM electronics** (**in-house**) resolution: SA 0.06 μm, FA 0.16 μm, TBT 0.39 μm
  - **BPM blocks** (**in-house**): calibrated with a step of 0.5 μm in Goubau line stand, electro-mechanical offset STD 53 um (horizontal plane) and 52 um (vertical plane)
  - **Beam size measurement**: KB mirror and pinhole, spatial resolution 2 μm
  - **Beam loss monitor** (**in-house**): turn by turn beam loss data
  - **BPM support** (**in-house**): 1st-order frequency 66 Hz, thermal stability: ±20 nm


Injection & Extraction system



- BTS: SR 6GeV injection system
- STB: SR 6GeV extraction system

(Bunch by bunch/on-axis swap out injection)

- STB: Booster 6GeV injection system

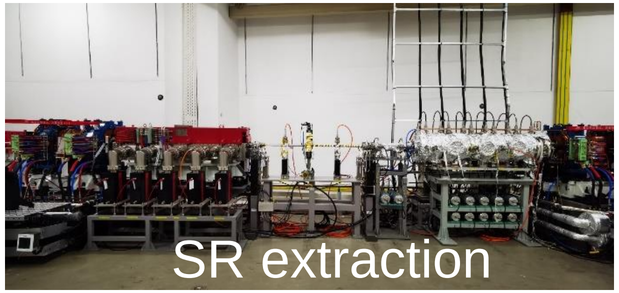
(Pulsed local bumped injection by 2 kickers)

- BTS: Booster 6GeV extraction system

(Bunch by bunch/fast extraction assisted by 4 slow bumpers)

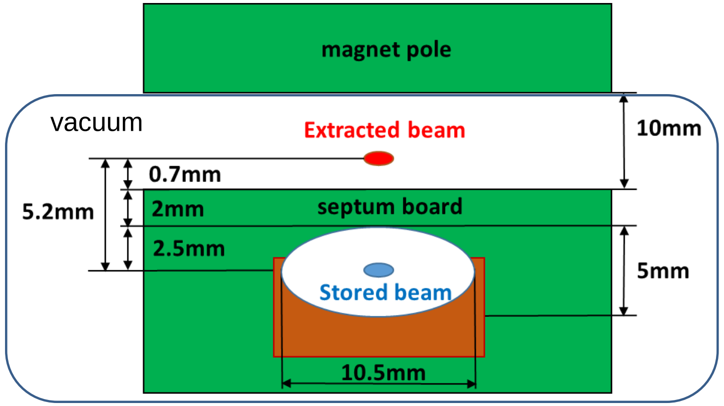
- LTB: Booster 0.5GeV injection system

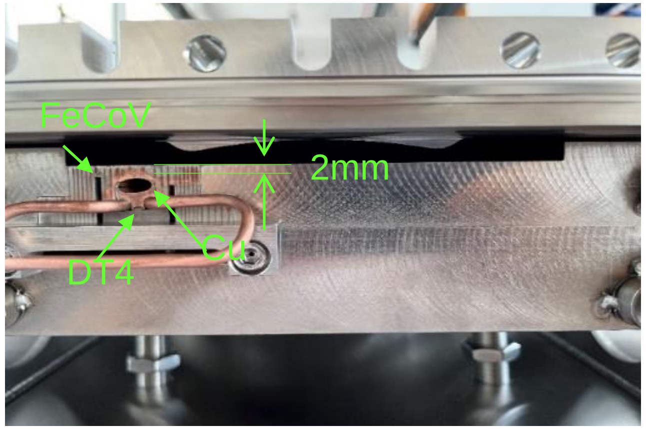
(Bunch by bunch/one turn/on-axis injection)

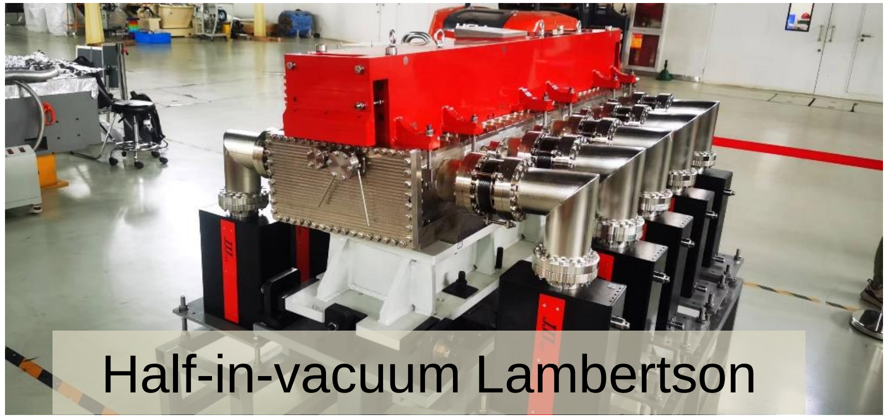


DC Septum Magnets (Lambertson magnet)

Parameters2	Unit	BST1-LSM	BST3/BST4-LSM	R48/R03-LSM
Quantity	-	1	2	2
Energy	GeV	0.5	6	6
Deflection angle	mrad	200	79.945	79.95
Insertion length	m	0.5	1.6	1.6
Magnetic field strength for injected/extracted beam	T	0.7	1	1
Min. Septum thickness（including septum board, wall of beam pipes, installation gap)	mm	≤6	≤3.5	**≤2**
Field uniformity	-	<±0.05%	<±0.05%	<±0.1%
Leakage field	-	$\leq 1\times10^{-3}$	$\leq 1\times10^{-3}$	≤0.002T·m
Clearance of stored beam at lambertson（H×V)（refer to stored beam orbit)	mm	10×10	22×28	8×5
Clearance of inj.&ext. beam at lambertson（H×V)（refer to inj.&ext. beam orbit)	mm	22×28	10×3	6×1.4
Physical aperture of stored beam vacuum chamber	mm	28×28	28×28	10.5x5
Structure	-	In-air	In-air	Half-in-vacuum

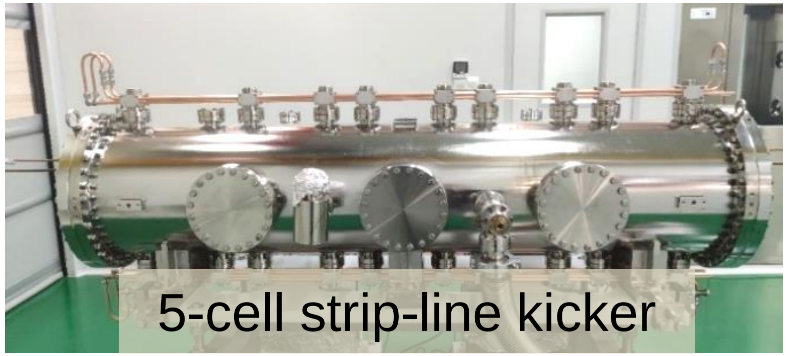




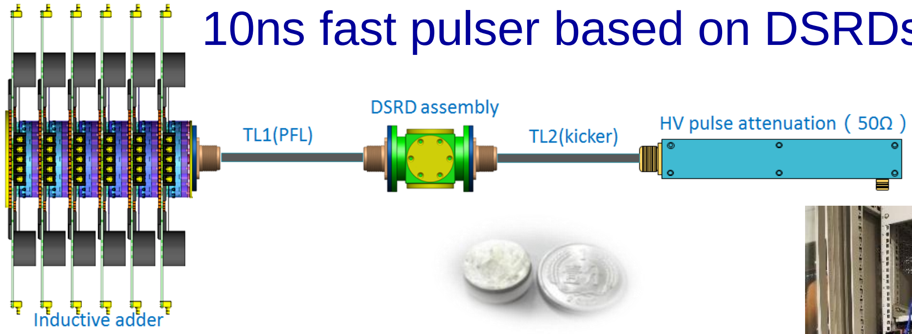


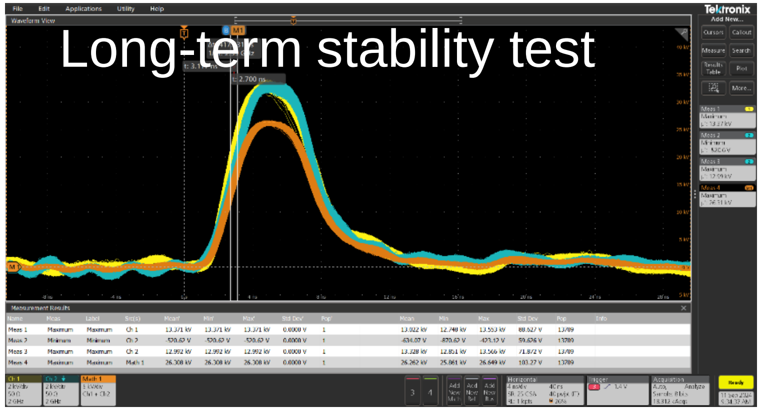
Fast kicker and pulser

Parameters	Unit	injection	extraction	
Name	-	R03K1~5	R48K1~5	R48PK
Total kick angle	mrad	1.6108		0.2~0.075
Kick direction	-	Vertical		Horizontal
Length of strip-line kicker electrode	mm	300		300
Gap between two electrodes	mm	8		16
Quantity of Strip-line kicker	-	5	5	1
Longitudinal space between strip-line kicker electrode	mm	6		-
Odd mode impedance	Ω	50±1		50±1
Even mode impedance	Ω	<65		<65
Amplitude of electrical pulse (into 50Ω)	kV	±15		±7.5
Bottom width of electrical pulse (3%-3%)	ns	<4 *	<10	<10
FWHM (50%-50%)	ns	>2 *	>4	>4
Electrical Pulse Amplitude Stability	-	<2% (RMS)		<2% (RMS)
Repetition rate (CW)	Hz	50		50
Time jitter between electrical pulse and timing clock	ps	<200		<200
Time jitter between channels (bipolar)	ps	<100		<100



10ns fast pulser based on DSRDs (in house)





Accelerator control

- **Features of the Control system**
  - Control System Network Online IP :~9,000
  - PV: ~400K
  - Archiver Data Storage :150TB/year
  - Power Supply:~2700
  - Vacuum equipment: 1724
  - Vacuum equipment Temperature sensors: ~4000
  - Container-based PS Control
  - IOT based Temperature sensor DAQ
  - Comfortable CrontrolRoom
  - ProxmoxVE OpenSource Hyper-Converged Cluster
    - Server Virtualization
    - High Availability (HA) Cluster
    - Ceph RBD Storage
    - SDN
  - HuaWei **High bandwidth low latency network**

Insertion device system

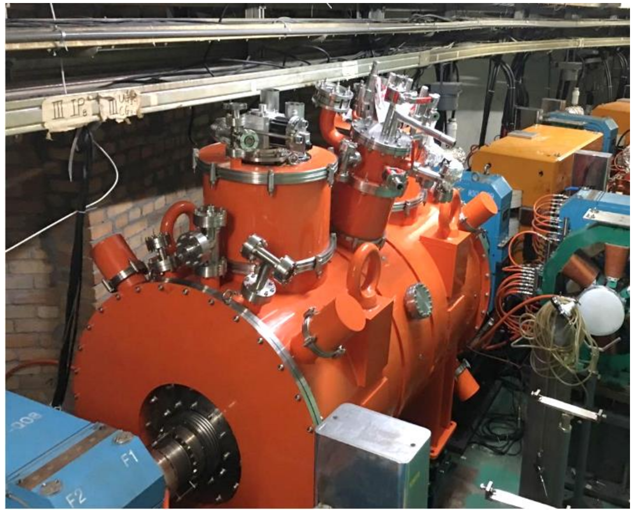
Type		No.	L [m]	Min. Gap [mm]	Max. peak field [T]	Min. phase error RMS [Degree]
In Air	IAU	4	5	11	0.88	4
	IAW	2	1	11	1.64	-
In Vacuum	CPMU	6	2	5.2	1.35	3
	IVU	5	4	5.2	1.1	3
Special	AK	1	5	11	-	5
	Mango	1	1	11	1	-
Total		19				

- **Highlight**
  - **CPMU12**: min. period length in the world, phase error and multiple error in the world's leading level
  - **Mango wiggler**: completely new idea, offer a big radiation spot size for Large - field X-ray diagnosis and flaw detection
  - **AK undulator**: realized by 4 arrays, both circular polarization and low on-axis heat load achieved

[1] X.Y. Li, et al., STATUS OF HEPS INSERTION DEVICES DESIGN, *IPAC 2021*, MOPAB090, P339-341.

Insertion device development

- **Progress on other projects**
  - Superconducting ID: SCW, SCU15
  - ID for European XFEL: U40
  - ID for Hefei LS: QPU, Wiggler
  - Phase shifter for EXFEL and Pohang LS
- **Magnetic measurement system**
  - Hall bench: 2 in-Air, 2 in-vacuum
  - Stretched wire: 3 in-Air, 2 in-vacuum
  - Flipping coil: 1



3W1-SCW ran on BEPCII

SCU15

U40 ran on EXFEL

ID for HLS

PS for EXFEL

Hall bench in-vacuum for IVU

Beamlines

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, **Mango Wiggler**
High Brightness	**NAMI-NanoProbe**	Small probe, <10nm; *In-situ* nanoprobe, <50nm; 220m 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 U
High Coherence	Hard X-ray Coherent Scattering	CDI(<5nm resolution), sub-μs XPCS
	Low-Dimension Probe	Surface and interface scattering, surface XPCS
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	Full field nano imaging and spectroscopy
Test BL	Optics Test	With undulator and wiggler source for optics measurement and R&D

Engineering Materials Beamline (07U1A)

Dedicated to studying the physical and chemical properties of materials under **real working conditions**. By using high-brightness, high-energy X-rays and integrating a variety of on-site sample environments, it can provide **rapid, non-destructive** characterization across scales for **full-life cycle** material research.

Materials Engineering → Processing / Service → Metallurgy, Additive Manufacturing; Aviation, Automobile; Structural Materials, Functional Materials; Microelectronics

Materials Chemistry → Chemical Reaction → Catalysis; Energy

50-170keV

MODE
- time-resolved
- grain-resolved
- depth-resolved
- scanning
- grazing

\+

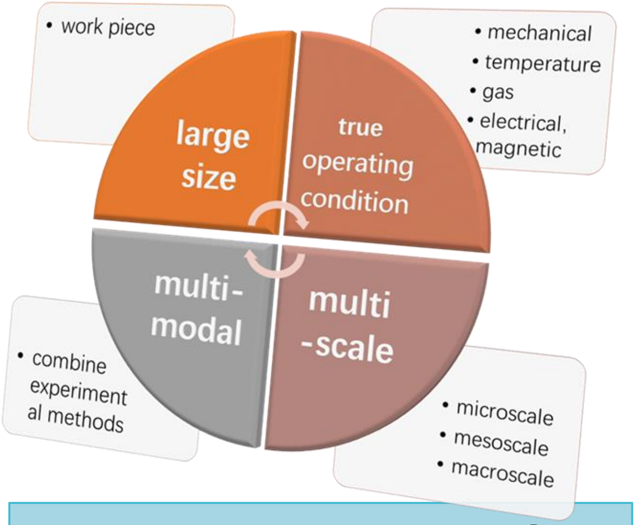
SAMPLE SYSTEM
- single crystal
- powder
- polycrystal
- amorphous

\+

METHOD
- XRD
- PDF
- SAXS
- WAXS
- Imaging

\+

COMBINATION
- CT
- multi-modal

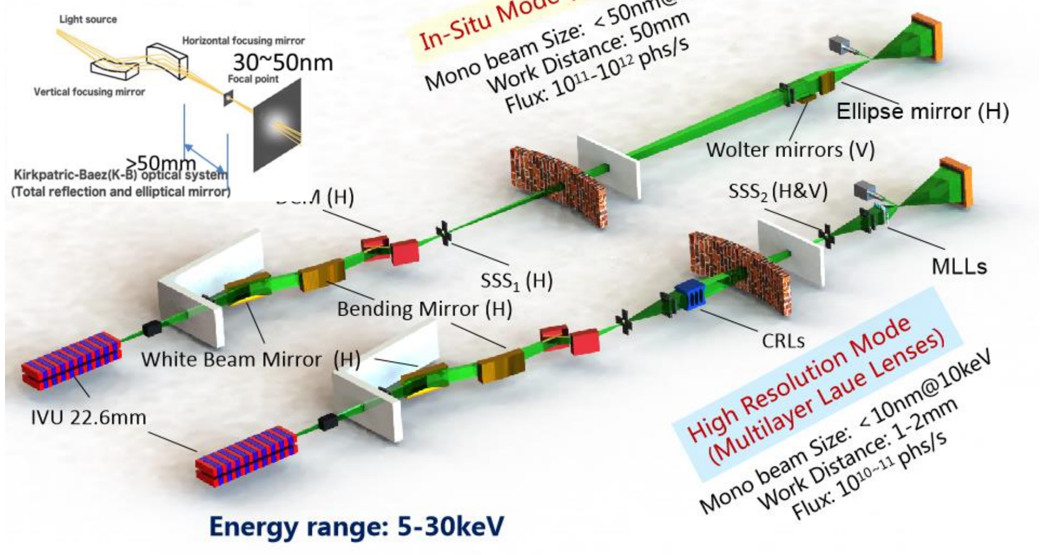


Free combination!

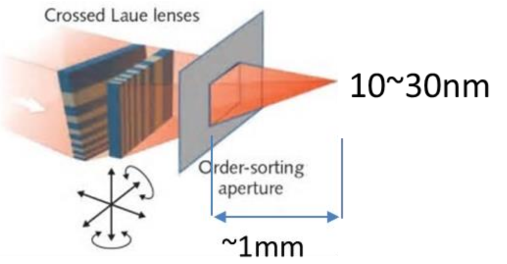
Hard X-ray Nanoprobe Multimodal Beamline (NAMI, 19U1A)

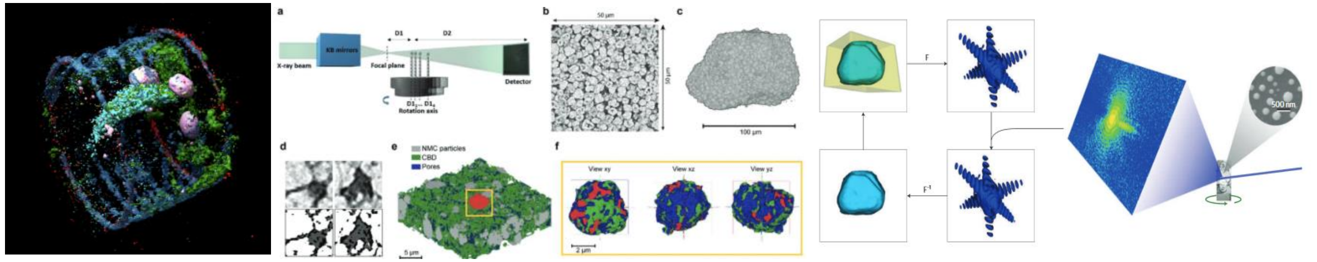
NAMI is one of the long beamlines in HEPS.
The total length is over 220m from the source.
The feature of NAMI is the smallest beam size (<10nm) and multimodal coherent imaging methods.

In-situ Mode: Energy Scan



High Resolution Mode: Fixed Energy





De Jonge, Martin D., et al. PANS, 2010

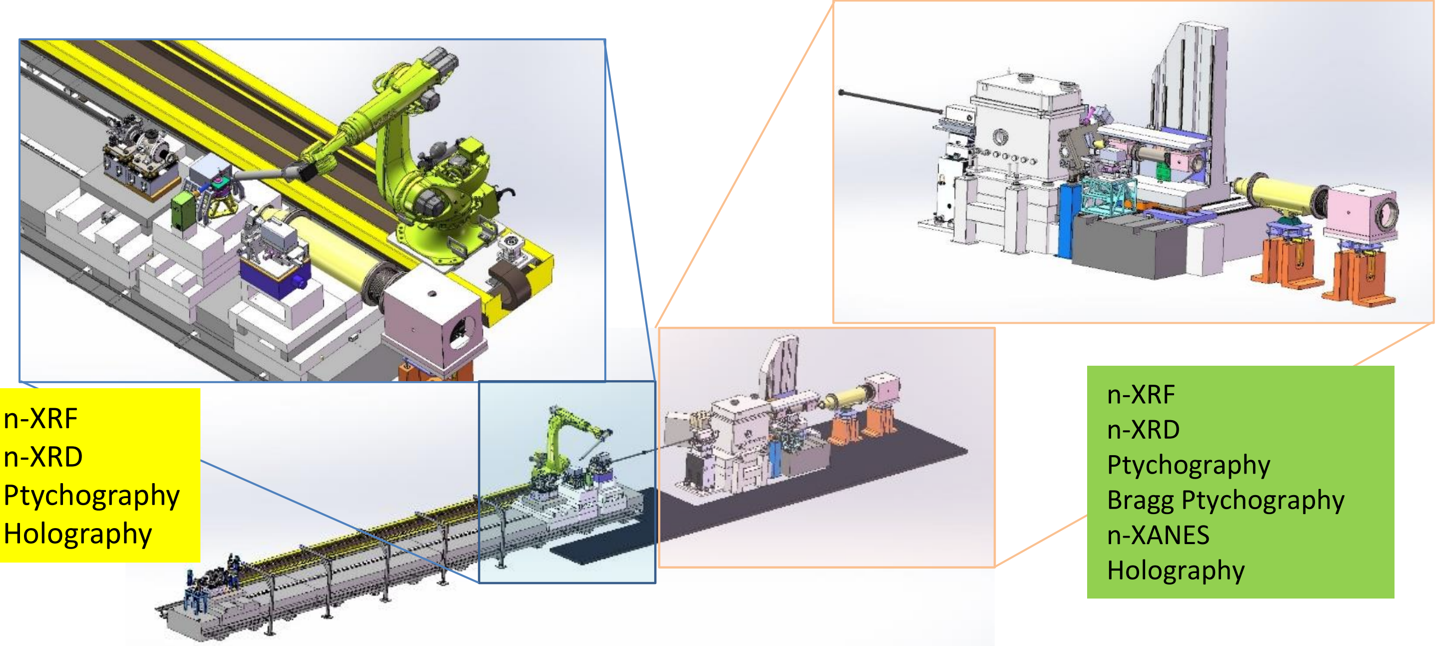
Tuan-Tu Nguyen, et,al. Adv. Energy Mater., 2021

Ian Robinson, Nature Materials, 2009

Nanoholotomography

Nano-XANES

Ptychography CT | BCDI | Nano-XRD | Nano-XRF



Hard X-Ray Imaging Beamline (21I1A)

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

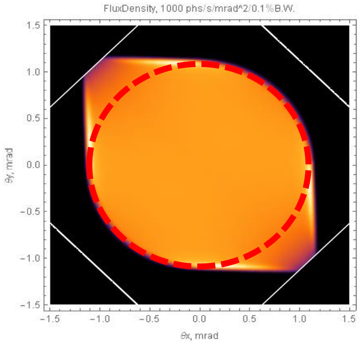
Probes: In-line phase contrast imaging; Diffraction Contrast Imaging

Application: Biomedicine: whole organ mesoscopic imaging

Engineering Materials

Fossils and Human Relics

Features: **Large FOV and high Resolution**



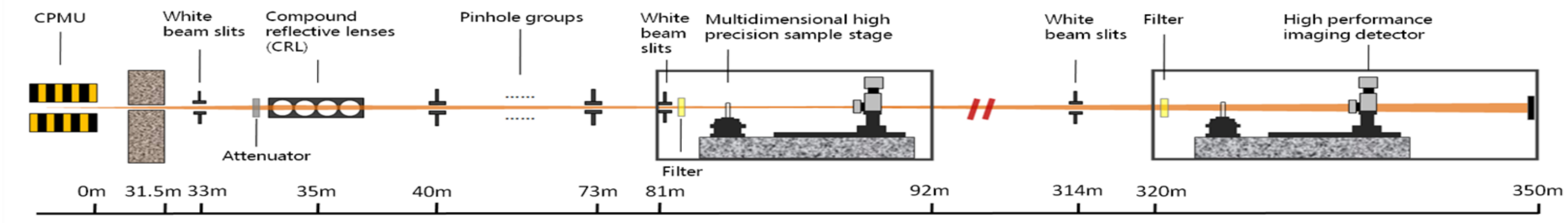
1 CPMU

1Wiggler + 1Mango Wiggler

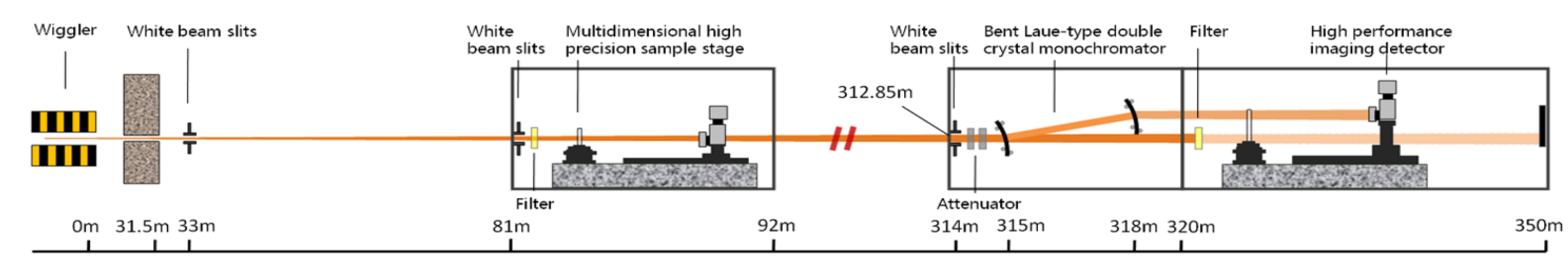
Longest Beamline in Phase I

350m long

CPMU branch: 10-90 keV



Wiggler branch: 20keV—300keV

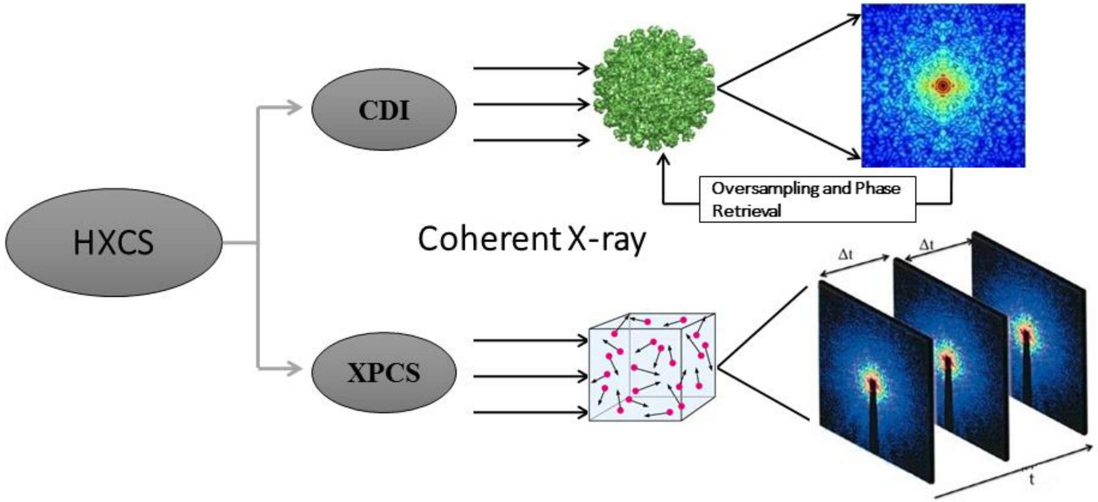


Ratio of spot size and PSF increase from 2k to 20k, 1000 times of voxels one CT

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

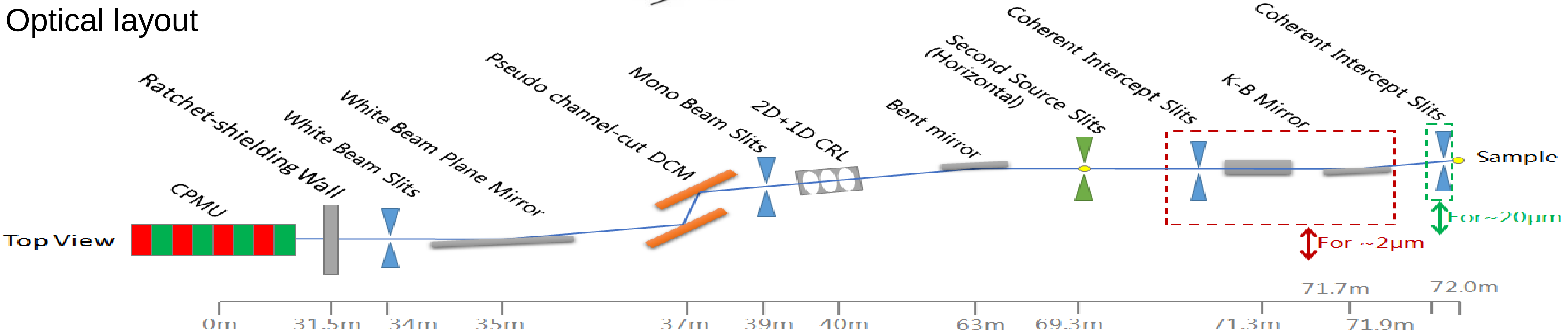
Hard X-ray Coherent Scattering Beamline (09U1A)

Dedicated to Coherent Diffractive Imaging (CDI) and X-ray Photons Correlation Spectroscopy (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)
End-station	CDI (resolution<5nm) XPCS (resolution<1μs)

Optical layout



Beamline technology

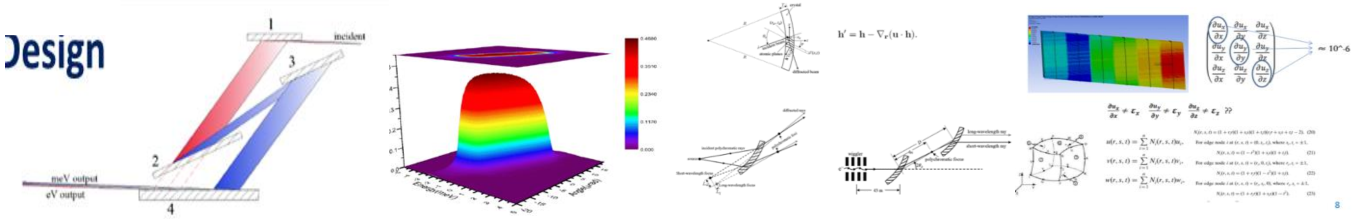
- Optical Theory
- Optical metrology
- Optics Fabrication
- Optical Modulation
- X-ray detector

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

Optical Theory

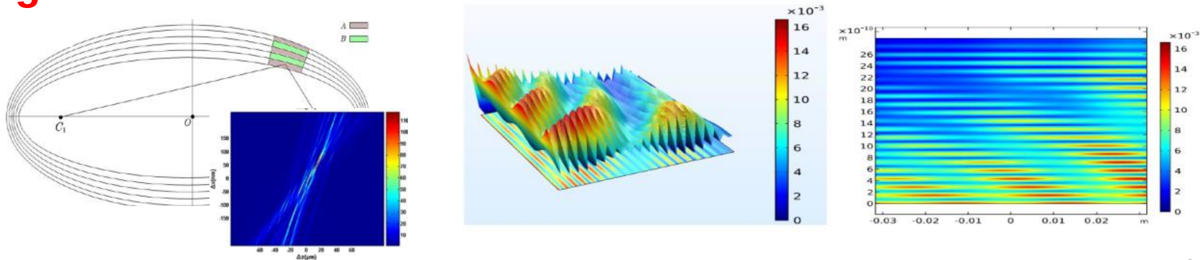
Dynamical diffraction theory

Developed 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, et al. J. Appl. Cryst. (2024). 57



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

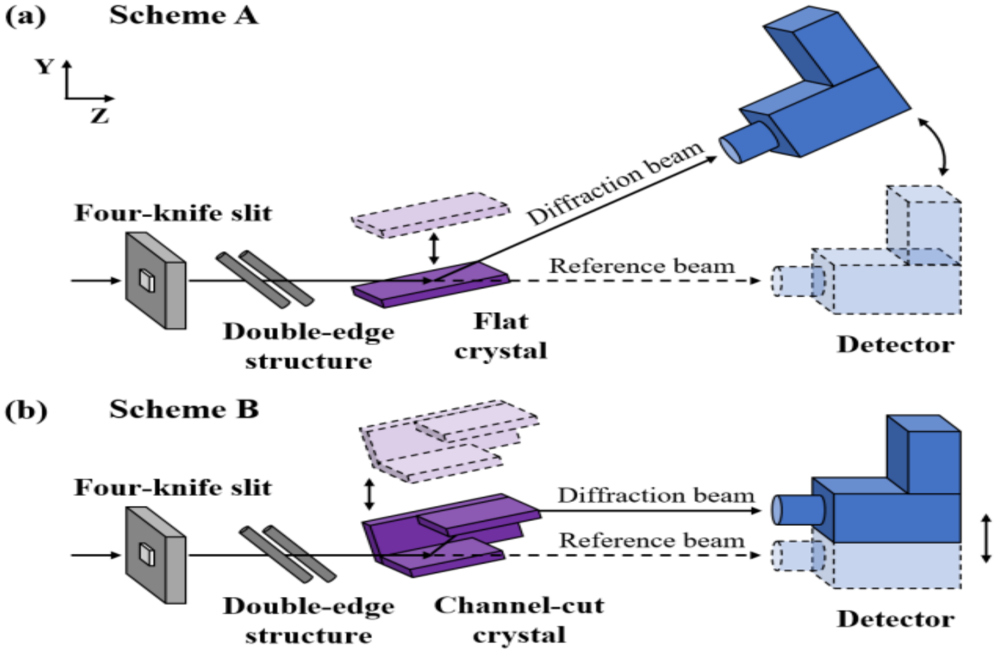
Yuhang Wang et al. Optics Express 28 (2020)

Double-edge Method for wavefront measurement

Overcome the wavefront blurring effect from:

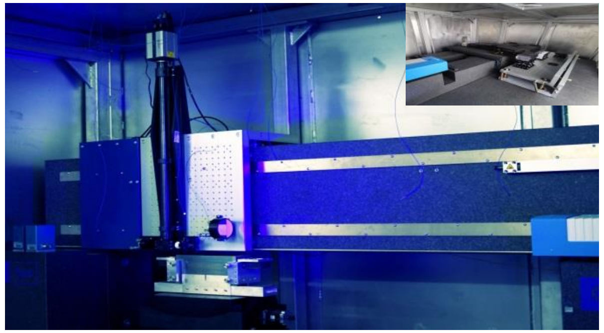
- **Low coherence source @ 1st G SR (eg. BSRF)**
- **Crystal extinction**

Realize diffraction-limited level measurement in a Full beam range.



Optical metrology

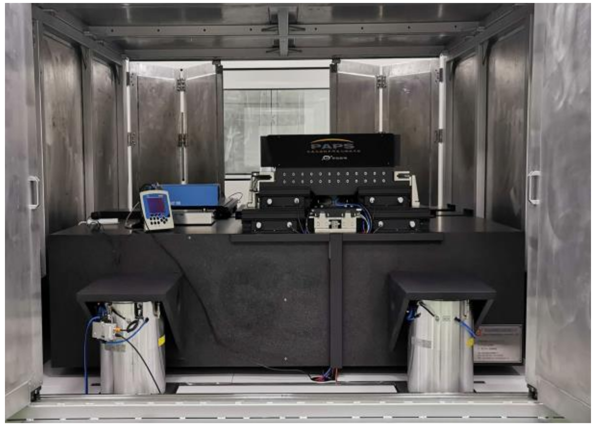
FSP FSI

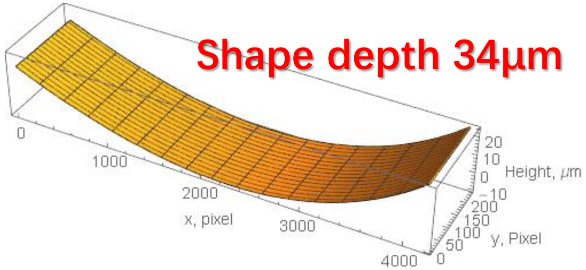


Mirror	Shape	Parameter	Specification	VAKB Measurement	HAKB Measurement
B4-AKB	Elliptical	Slope error RMS	50nrad	17nrad	30nrad
	Hyperbola			26nrad	38nrad
	Elliptical	Height error RMS/PV	0.4nm / 6nm	0.11nm/0.59nm	0.051nm/0.27nm
	Hyperbola			0.12nm/0.70nm	0.052nm/0.35nm

FSP-Flag-type Surface Profiler

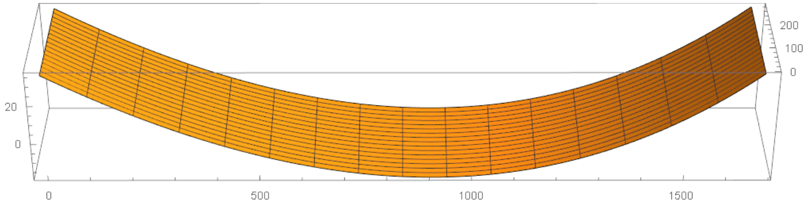
FSI-Frequency-decomposed Stitching Interferometer





Elliptical mirror FSI measuring result (B8-HKB)

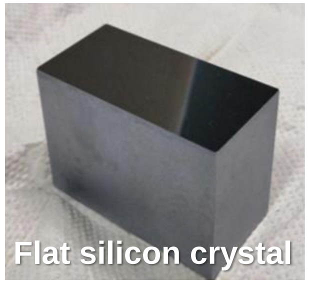
Shape depth 57μm, Slope range 3.9mrad, Minimal radius 17m



FSI result for nano-focusing Mirror polishing (B3-VKB)

The Frequency-decomposed Stitching Interferometer (FSI) has been proposed and developed, which combines the SI & FSP, and can provide feedback for mirror processing with 2D sub-nanometer accuracy measurement.

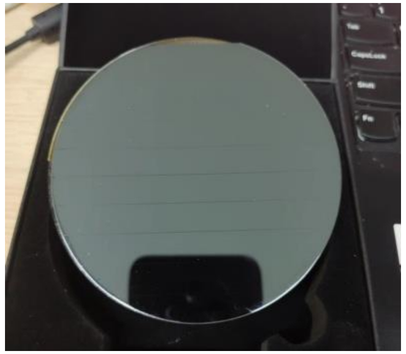
Crystal fabrication



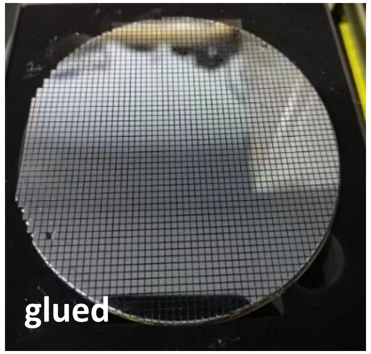
The fabricated **flat and Channel-cut silicon crystals** qualified sub-nanometer surface roughness, X-ray topography with uniform contrast

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

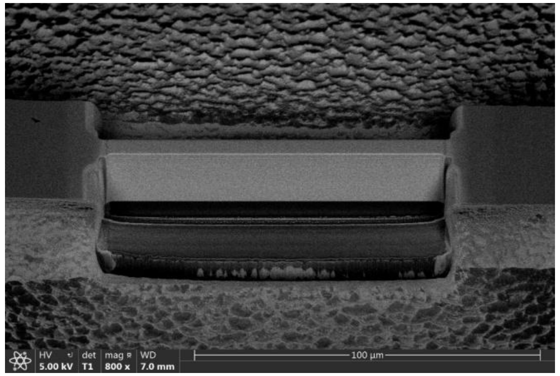
Bent striped Si(660)
~0.53 eV@9.7keV



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

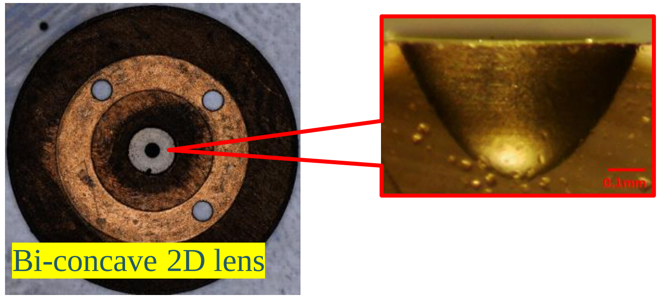


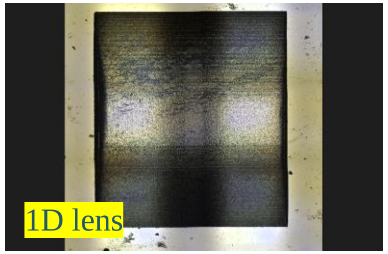
Analyzers for XRS and RIXS: excellent focusing & energy resolution



MLL Para.	Req.
Material	WSi_2/Si
N. Layer	13030/8030
Thickness	64µm/ 44µm
Focus	8×8nm^2

MLL fabrication





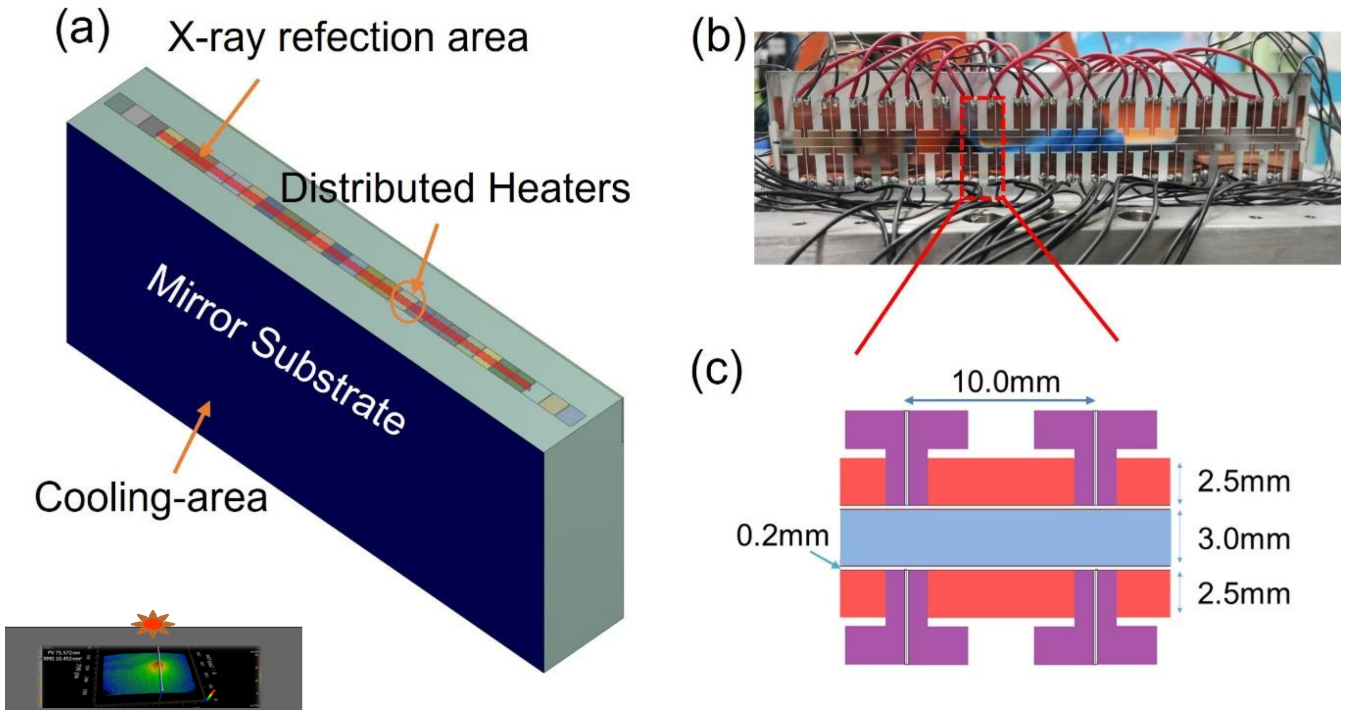
Shape error of 2D lens: 0.7µm RMS, 1D lens: 1.2µm RMS

1D & 2D diamond CRLs fabrication

Mirror Fabrication

X-ray active mirror using electric-heating

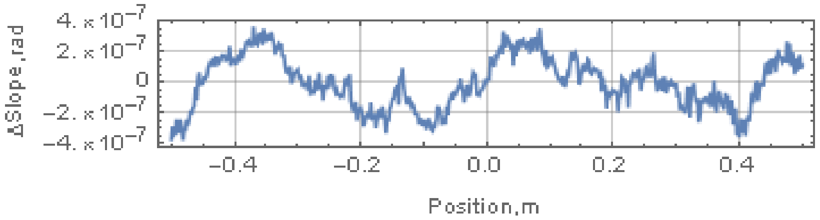
- Deformable mirror is fabricated by MEMS process
- Surface actuation ensures the deterministic deformation
- Modulation accuracy < 0.5 nm RMS has been achieved



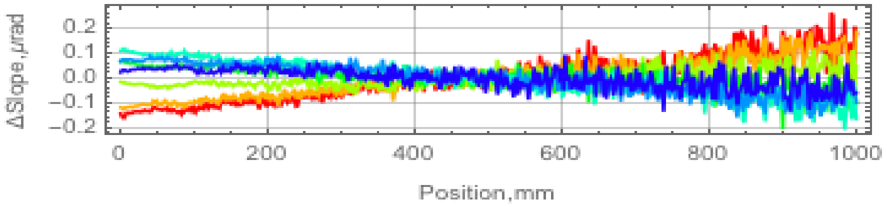
Elliptical bending mirror

Large Flat mirror and Elliptical mirror is under going

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



Bending shape accuracy 0.17μrad RMS

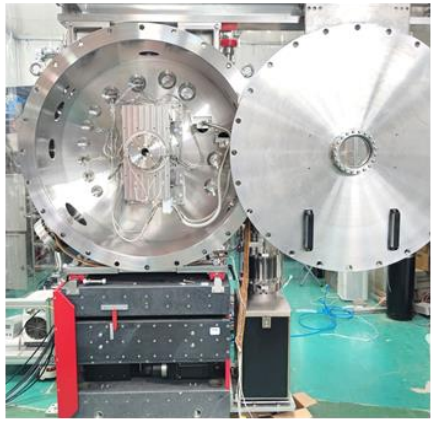


Stability: 72h, deformation 66nrad RMS

Monochromator

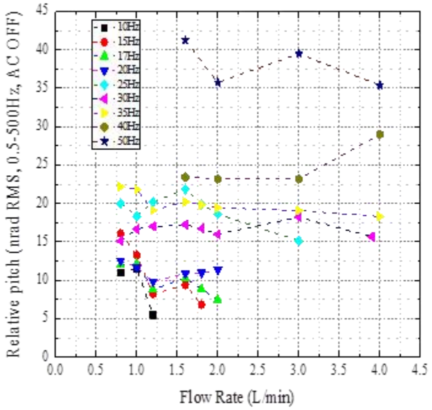
VDCM

HDCM

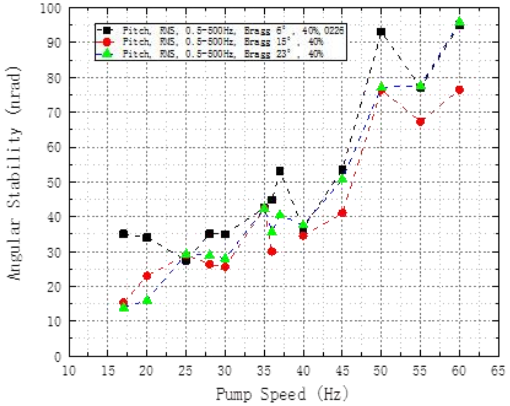


Quick-scan DCM

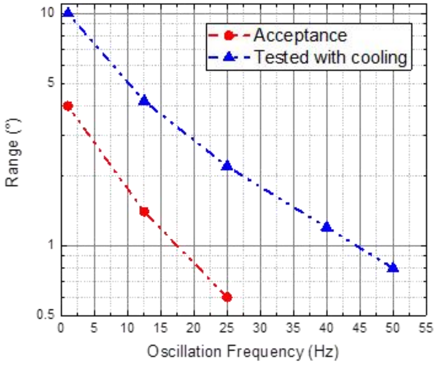
HRM
High energy resolution



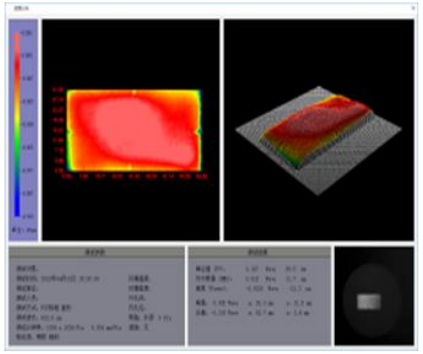
Stability of VDCM
<10nrad RMS
Under cooling



Stability of HDCM
<20nrad RMS
Under cooling



Quick-scan DCM
100 XAFS spectra /s
@50Hz 0.6°



Deformation of crystals with clamping under cryo temperature
< 0.1μrad RMS

Mirror Mechanical System (MMS)

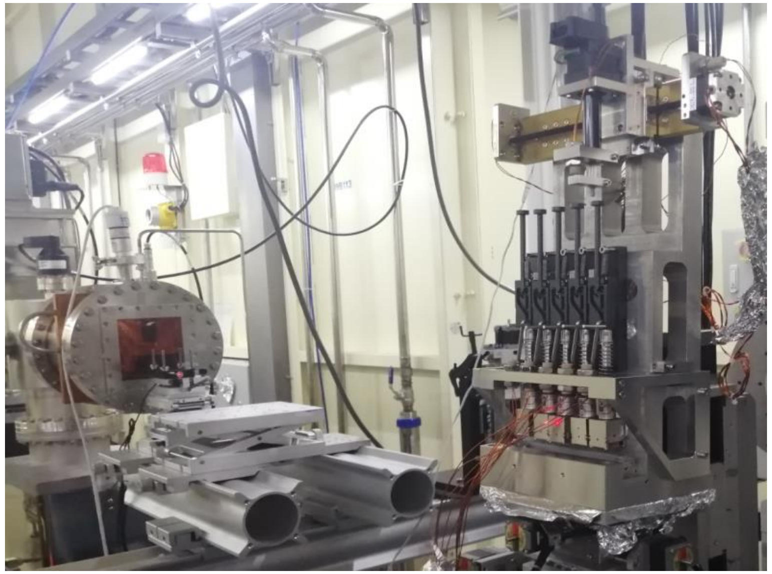
Generic-MMS has been developed

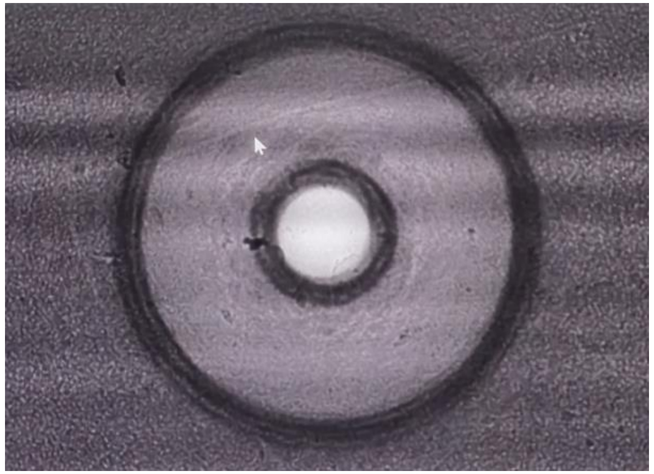
white beam mirror (WBM), harmonic suppression mirror (HSM), combined deflecting mirror (CDM), bending mirror, Nano-KB, and transfocator, etc. .

- **Multi-DOF bench: ≥100 Hz@1st eigenfrequency**
- **High stability: ≤25 nrad rms@1-120 Hz**
- **Fine pitch mechanism: ≤0.1 μrad @ res.**
- **20 pieces of equipment （batch production）**

The transfocator has successfully developed and applied with batch fabrications of ≥20 sets at HEPS.

Transfocator is a special kind of manipulator of CRLs for the variable focus. A novel transfocator with compact is presented, which just employs two driver with orthogonal parallel layout instead of traditional series *N* sets of the driver corresponding to *N* sets of the switched arms.

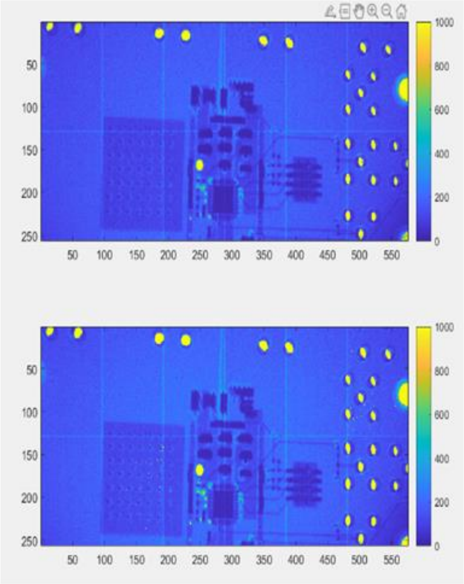


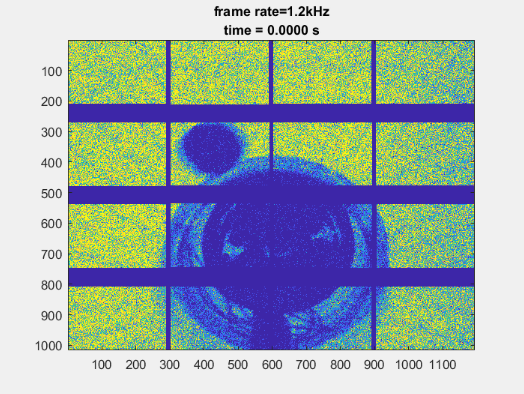


Experimental result for the transfocator at BL09B at SSRF

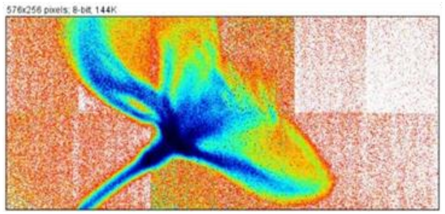
In-house detector development

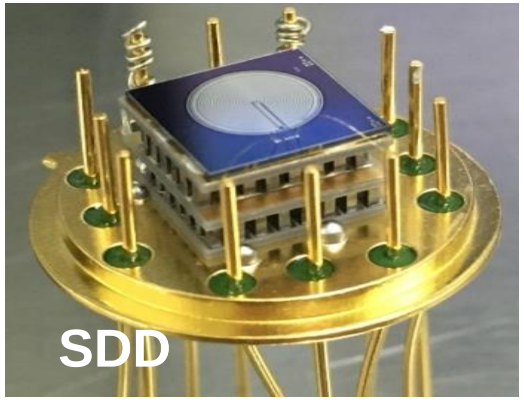
- HEPS officially started the research on pixel array detectors in 2014 and have completed a series of relevant technological developments and verifications.
- A 6M system will be assembled before 2025

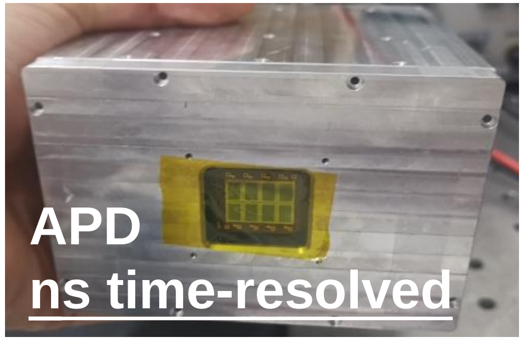




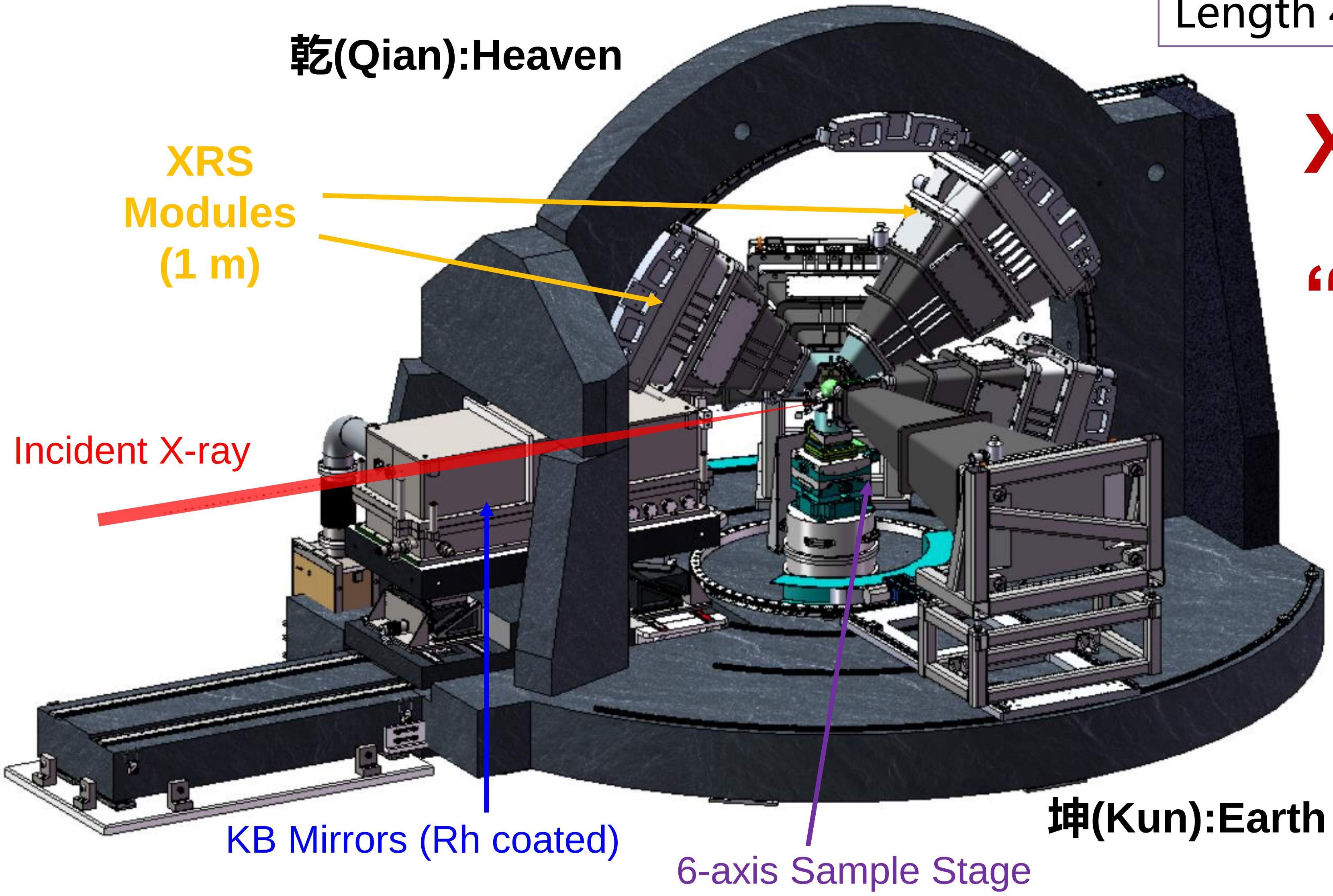
Specs	BPIX-20	BPIX-40
Pixel size	150μmX150μm	**140μmX140μm**
Pixel Array	104X72	**128X96**
Threshold	1	**2**
Gain	Fixed	**2 bits tunable**
Counting rate	> 2Mcps	**> 2Mcps @ Med gain**
Frame rate	1.2kHz	**2kHz**
Counting Depth	20 bit	**14 bit**
Detector Module	2X4 (208X288)	2X6 (256X576)
Module Gap	3mm by TSV	**2.7mm by WB**







In-house detector development

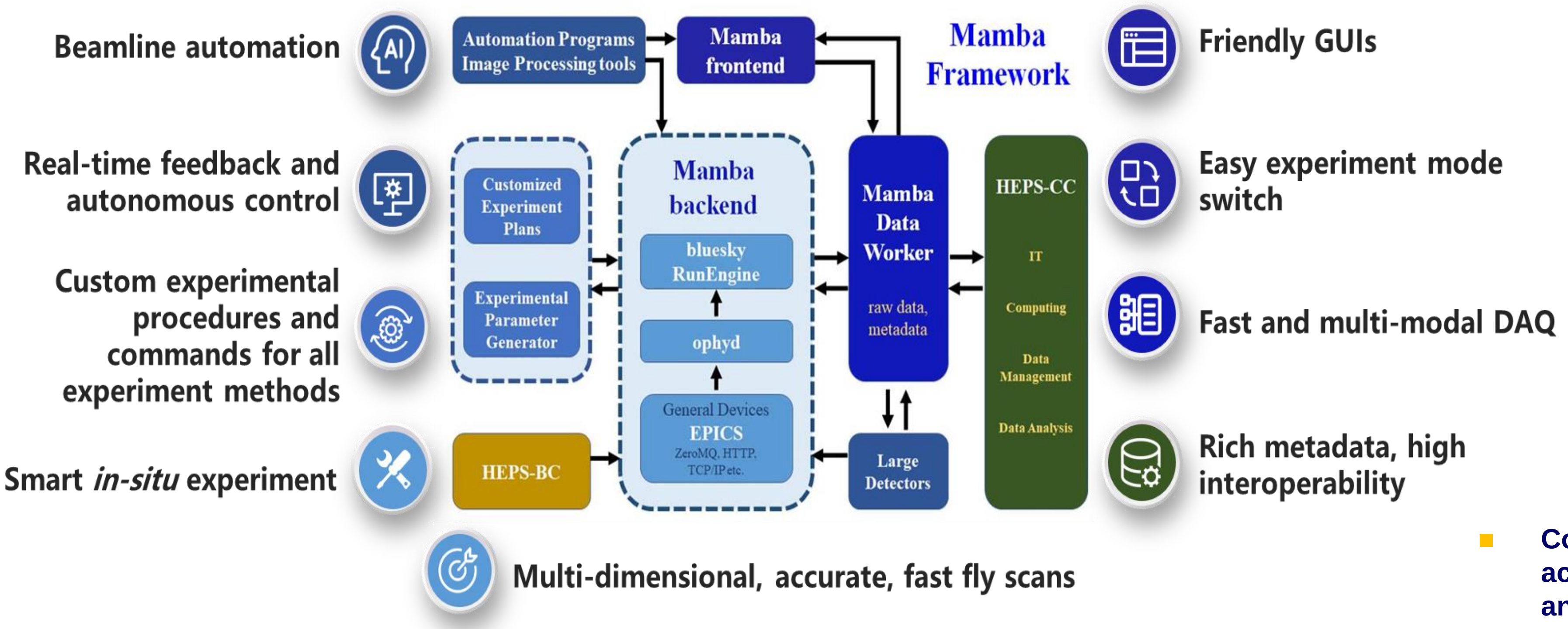


Length 4.8m× Width 4.3m× Height 3.3 m

XRS Spectrometer "Qiankun(乾坤)"

- Working energy: **~10 keV Si(660),** ~13 keV Si(880), ~16 keV Si(10 10 0)
- Energy resolution ~0.7 eV @~10 keV with 1 m Rowland circle
- 140 mm space for sample environment
- High-resolution IXS/RIXS/XES modes with 2m Rowland circle

Scientific software and computing



HEPS has taken the lead at China for the construction of the software system covering the entire life cycle of synchrotron experiments

- Control, data acquisition and analysis
- Data management
- Computing
- AI for Science

Mamba: A new generation synchrotron experiment operating software system

Unified framework for all HEPS beamlines

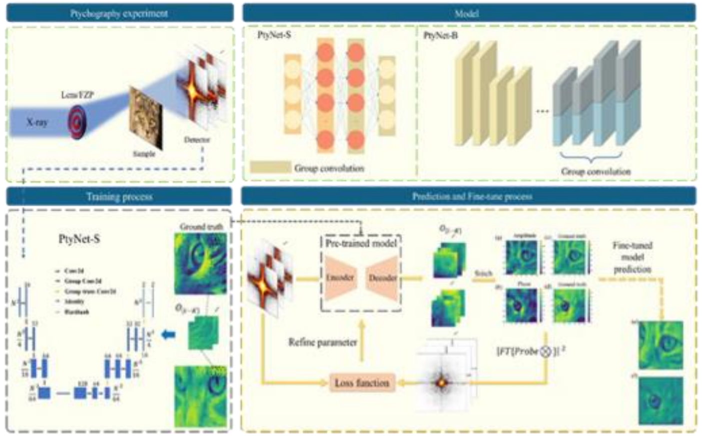
Unified data format and standards

DOMAS: Data Organization and Management Software
- Metadata catalogue, Metadata acquisition, Data transfer, Data service (User GUI)
- Data policy & Data format(HDF5)

Daisy: Data Analysis Integrated Software sYstem
- Basic, common, scalable framework
- Data engine, Workflow engine, Computing engine, GUI
- Released *https://daisy.ihep.ac.cn/*

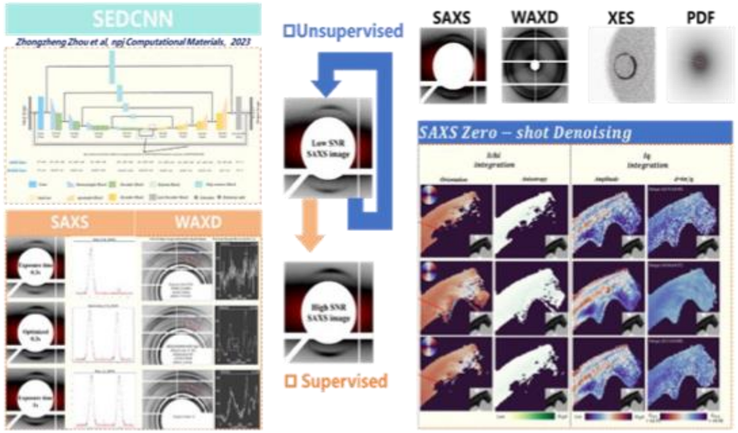
AI for Sciences

☐ Large AI model solves ptychographic phase retrieval problem



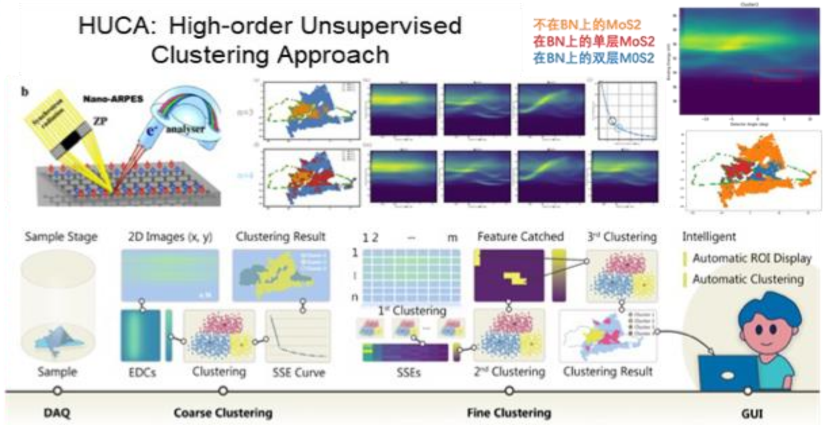
X.Y. Pan et al. *iScience*, 2023
X.Y. Pan et al. *Acta Physica Sinica*, 2023

☐ Physics-informed denoising solution



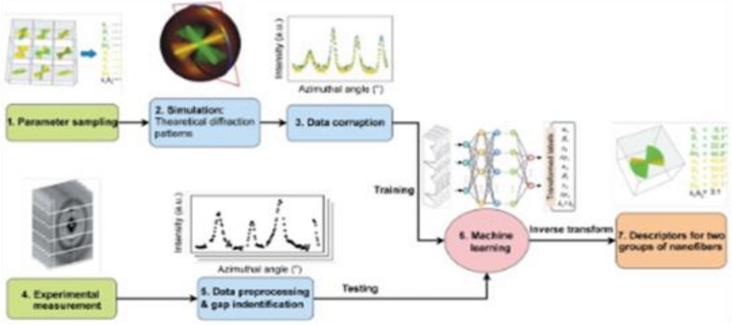
Z.Z. Zhou et al. *npj Comp. Mater.*, 2023
Z.Z. Zhou et al. *Journal of Appl. Crystallogr.*, accepted

☐ Clustering of Nano-ARPES experimental spectra



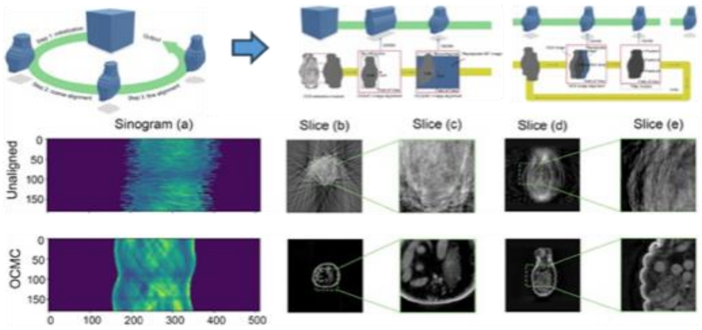
L.Z. Bian et al. *Commun. Phys.*, under review

☐ Physical information retrieval from massive diffraction data using machine learning methods



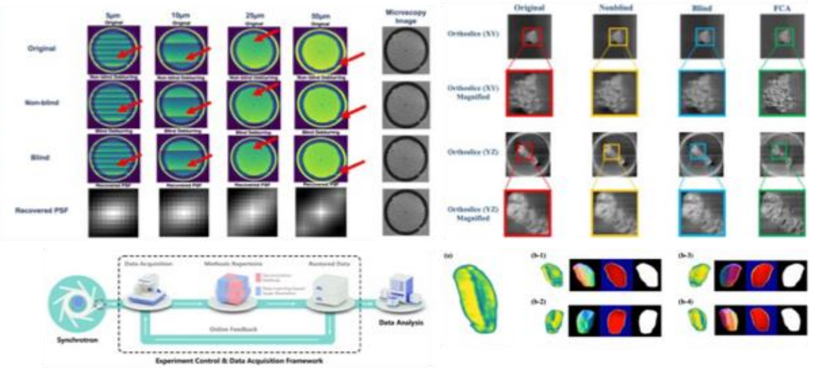
M. Sun et al. *IUCrJ*, 2023
X. Zhao et al. *IUCrJ*, 2024

☐ End-to-end image misalignment correction method for tomography



Z. Zhang et al. *iScience*, 2023

☐ Deconvolution and super-resolution pipeline

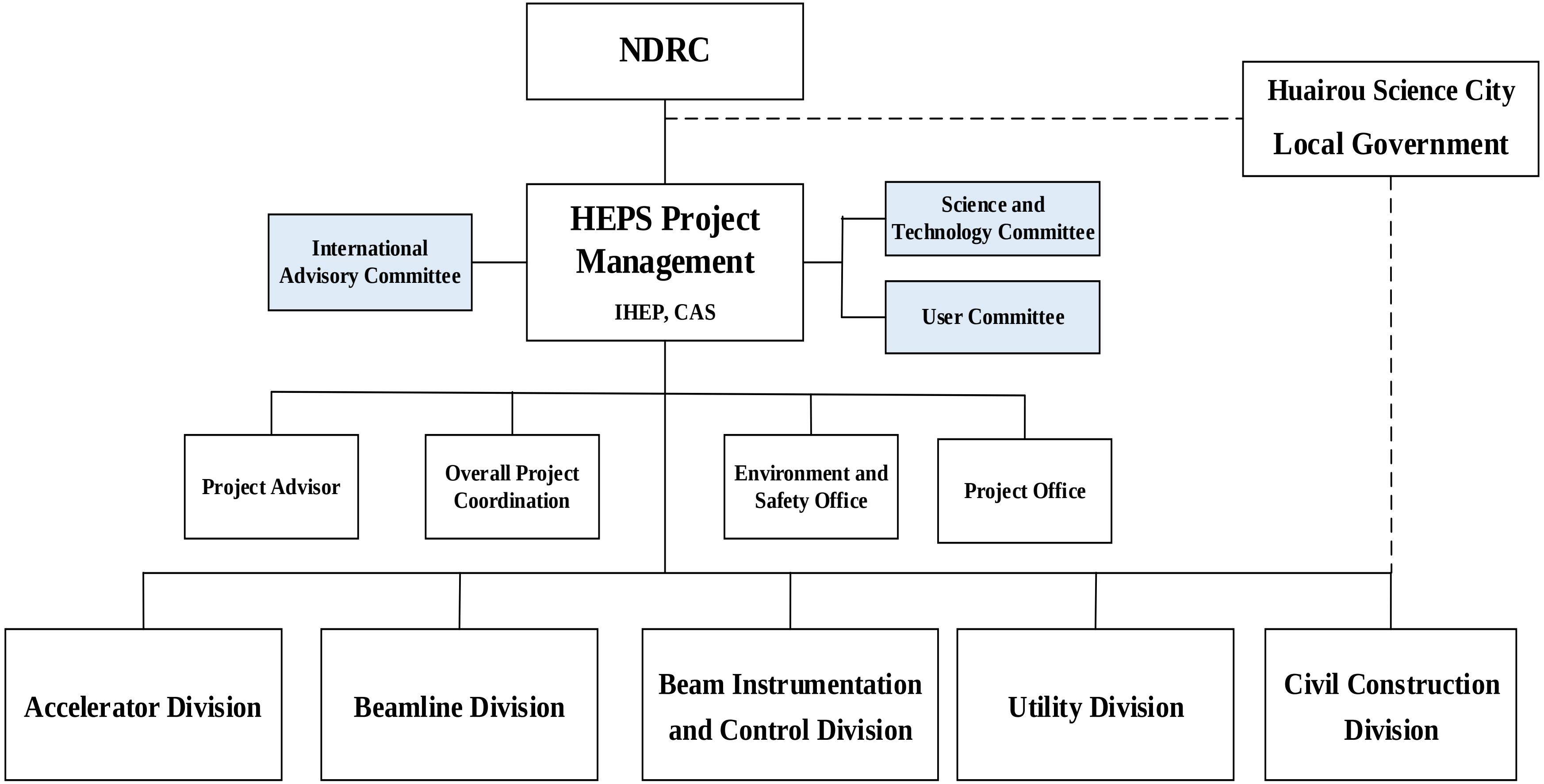


C. Li et al. *Nucl. Sci. Tech.*, accepted

Collaborations

Project governance

5 divisions **52** systems



Weimin PAN — **Director**

Yuhui DONG — **Exec. Dep. Director**

Yuhui LI, Gang XU, Jian LIANG

Deputy Directors

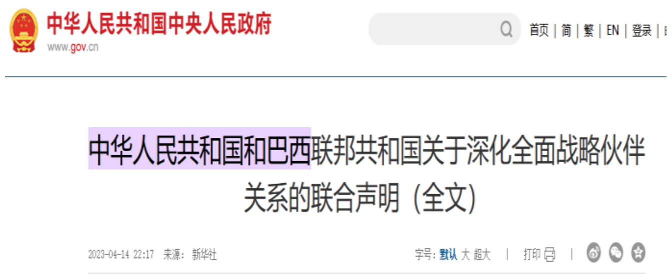
International Advisory Committee

- Dec. 5-7, 2016, Beijing, 1st HEPS-TF IAC Meeting (Chair: Robert Hettel, SLAC)
- Nov. 15-17, 2017, Beijing, 2nd HEPS-TF IAC Meeting (Chair: Robert Hettel, SLAC)
- Dec. 11-14, 2018, Beijing, 1st HEPS IAC Meeting (Chair: Pedro Fernandez Tavares, MAX-IV)
- Dec. 16-18, 2019, Beijing, 2nd HEPS IAC Meeting (Chair: Pedro Fernandez Tavares, MAX-IV)
- **Jan. 14-17, 2025, Beijing, 3rd HEPS IAC Meeting** (Chair: Harald Reichert, DESY)

Collaborations


May, 2023, Brazil

- MoU signed between HEPS and Sirius based on the joint statement on deepening comprehensive strategic partnership between China and Brazil.



Brazilian Synchrotron Light Laboratory


Jun., 2023
HEPS team at SIRIUS


Dec., 2023
HEPS team at SIRIUS


Aug., 2024
Sirius team at HEPS

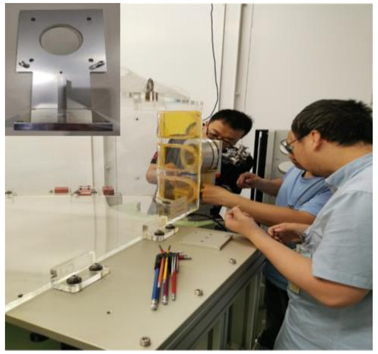
34. Recalling that Brazil is one of the few countries with fourth-generation synchrotron light technology and that China is also developing fourth-generation synchrotron light technology, the two parties will work together to develop the next generation of synchrotron technology. They welcomed the cooperation between the National Centre for Research in Energy and Materials (CNPEM) of the Ministry of Science, Technology and Innovation of Brazil (MCTI) and the Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences (CAS) for collaboration between Sirius and HEPS.

- IHEP signed MoU with DLS to cooperate on synchrotron radiation facility construction on April 17, 2019
- MoU between IHEP and NSRRC signed on Sep. 30, 2020.
- MoU between IHEP and RIKEN-SPring-8 was renewed in July, 2024.
- MoU between IHEP and PSI signed in 2009, appendix in 2018.

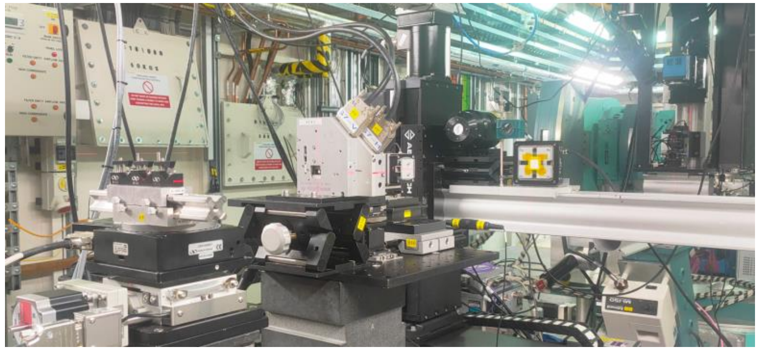

DLS


RIKEN
SPring-8

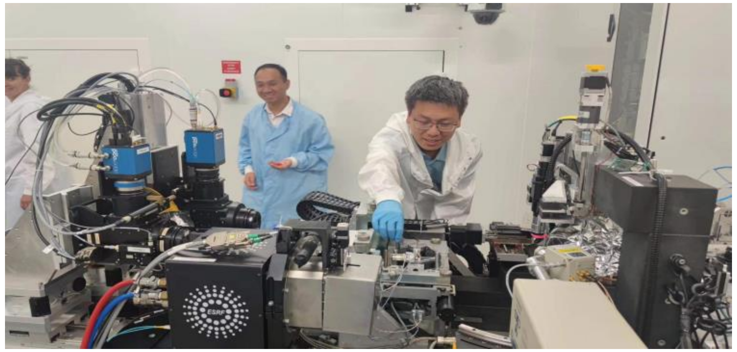
Experiments and reviews



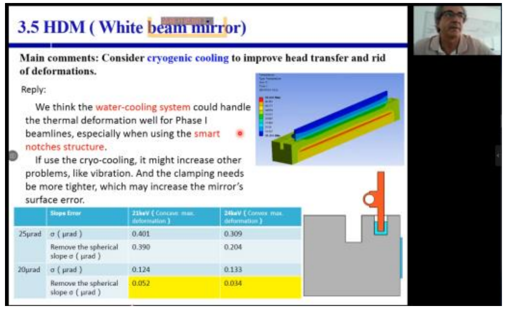

May 2023 SPring-8 HEPS Vacuum-Mounted Flat-Diced Analyzer RIXS



Sep. 2023 Diamond HEPS CRL tested online



June 2023 ESRF ID16B Ni-based alloy materials, holotomography, 6 shifts



International reviews on optical design of beamlines, HEPS RF system, HEPS injector design

International conferences and workshops

IBIC 2024--13th International Beam Instrumentation Conference

MEDSI2023--12th International Conference on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation

LINAC 2018--29th Linear Accelerator Conference

Meeting Rooms, Hostel and Canteen in HEPS campus

Visiting

Helmholtz Association

IHEP international assessment

CEPC IAC

RF international review

CERN Council Chair

Nobel Laureate Prof. D. Gross

Elettra Sincrotrone Trieste

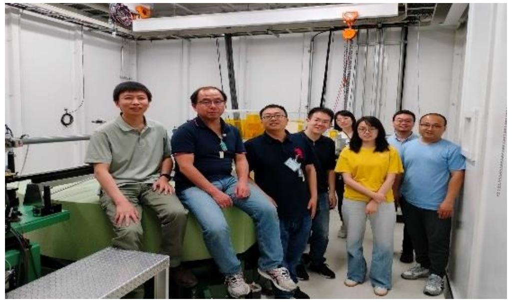
SLS and ETH Zurich

HGTD week

KEK DG

HEPS beamline control team at Diamond

HEPS HX-HERS team at SPring-8



Future plans

HEPS phase II

- Preparing Science Case and Project Proposal for the next 5-year plan
- Multiple reviews underway

- ✓ 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
- ✓ 30 BLs to be built in Phase II

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

~**90** Total capacity

14 IDs**+ 3** BMs Phase I

~**15** IDs**+ 15** BMs Phase II

HEPS phase II beamlines

Candidate beamlines in Phase II (38 preliminary)		
Pink beam Nano-Coherent Imaging	ED-XAFS	Soft RIXS
High Energy X-ray Nano Coherent Imaging	Environment Spectroscopy	HE-NRS
Fly-scan Nano Coherent Imaging	High resolution powder diffraction	nano-NRS bemaline
Surface Interface Nano Coherent Imaging	High energy total scattering	Magnetic Material
Pink beam Coherent Imaging and Scattering	Large volume (multi-anvil cell) high-pressure (LVP)	High Magnetic field Nano-Coherent Imaging
Chemical Catalysis Nano-Coherent Imaging	High-pressure (DAC) synergic method	High-throughput Protein Crystallography for drug screening
High Energy-XPCS	Chemical crystallography	ED-XRD for material genome
Multiscale diffraction imaging	Laue crystallography	Material Synergy
High Energy Compton Scattering and Imaging	SAXS for Industrial application	Energy materials and devices Multimodal
X-ray Chemical imaging	High energy SAXS	Energy materials and devices multimodal spectroscopy
Biomedical 3D imaging	Hard X-ray PES	Earth/planetary Science
Flat Samples 3D Nondestructive Imaging	High Energy Resolution IXS	Multispectral X-ray lithography
High-throughput XAFS	Medium Energy Resolution RIXS	

Beamline built in Phase I
Hard X-ray nanoprobe multimodal beamline
Engineering materials beamline
Structural dynamics beamline
Hard X-ray coherent scattering beamline
Hard X-ray high resolution spectroscopy beamline
High pressure beamline
Hard X-ray imaging beamline
X-ray absorption spectroscopy beamline
Low-dimensional structure probe beamline
Microfocusing X-ray protein crystallography beamline
Pink beam SAXS beamline
High resolution nanoscale electronic structure beamline
Tender X-ray beamline
Transmission X-ray microscopic beamline

	Material	Physics	Chemistry	Envir.	Energy	Industry	Bio.	Meth.
Phase II	3 IDs, 3 BMs	5 ID, 1 BMs	1 ID, 5 BMs	2 IDs	2 IDs, 1 BM	1 ID, 4 BMs	2 BMs	2 IDs

International collaborations

- **HEPS is open to global users**
  - ✓ HEPS beamtime applications open to scientists from around the world, reviewed by SAC (international experts)
  - ✓ **5-10 invited user teams**, new technologies and methods, guaranteed beamtime, evaluation criteria, more funding opportunities
- **International collaborations on SR technologies**
  - ✓ X-ray Optics, Detectors, AI for Sciences
  - ✓ HEPS and Sirius joint LAB (under construction)
  - ✓ HEPS and MAX-IV, DLS, SPring-8
  - ✓ Global calls for proposals of HEPS new beamlines
  - ✓ Strong interests joining international collaboration programs, for example: Human Organ Atlas, European X-ray Connectomics Alliance

Open

Collaborative

Inclusive

- **Schemes**
  - ✓ International exchanges and agreement, collaborative research (PIFI, etc.)
  - ✓ IAC meeting (MAC and SAC in 2026), regular international review meetings, international summer schools, international conferences

HEPS and PSI

- PSI and IHEP signed MoU in 2009 on comprehensive collaborations
  - Appendix to the MoU on beam instabilities signed in 2018 (valid until 30.06.2021)
  - Renewal of the MoU covering more topics of mutual interests?

- Expert from SLS joined the international review of the HEPS beamlines
  - Suggest a replacement of Philip Willmott for HEPS IAC due to his absence

- Welcome PSI colleagues to join the commissioning of HEPS accelerator and beamlines (the SR will restart commissioning on Oct 6th, 2024)

HEPS and PSI

- Potential collaborations between HEPS and PSI
  - **Accelerator physics**, collective effects, etc.
  - **Accelerator hardware**: RF, undulator, control, …
  - **Hard-X-ray imaging beamline**: Interests in fast CT in Tomcat beamline and Tomcat's interests in HEPS's large field-of-view high-resolution optical coupling system for imaging detector.
  - **Nanoprobe beamline**: Lamino ptychography and multi-beam ptychography methodologies and its applications in archeology and biomedical imaging.
  - **Hard X-ray High Energy Resolution Spectroscopy beamline**: Interests in small pixel size MÖNCH detector for high-resolution RIXS. X-ray RIXS spectrometer instrumentation with SwissFEL Bernina beamline.
  - **Nano-ARPES beamline**: Interests in ADRESS beamline.

Summary

HEPS is in good shape to have its first light in 2024