High Energy Photon Source (HEPS) and its status

TAO, Ye
Beamline Division of HEPS, Institute of High Energy Physics (IHEP)

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

HEPS
高能同步辐射光源

SFR-2020 online
conference, BINP,
Novosibirsk, July 13th

Acknowledgement

HEPS Team

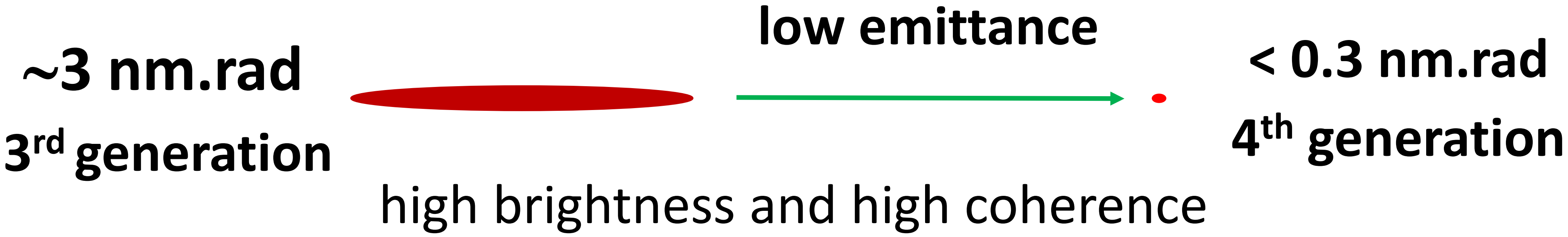
Accelerator Division
Beamline Division
Technical Support Division
Utility Division
Civil construction Division

Supported by Central and Beijing local governments

Outline

1. Brief introduction
2. Accelerator design
3. Beamline design
4. R&D for beamline technologies

1. Brief introduction



~3 nm.rad

3rd generation

low emittance

< 0.3 nm.rad

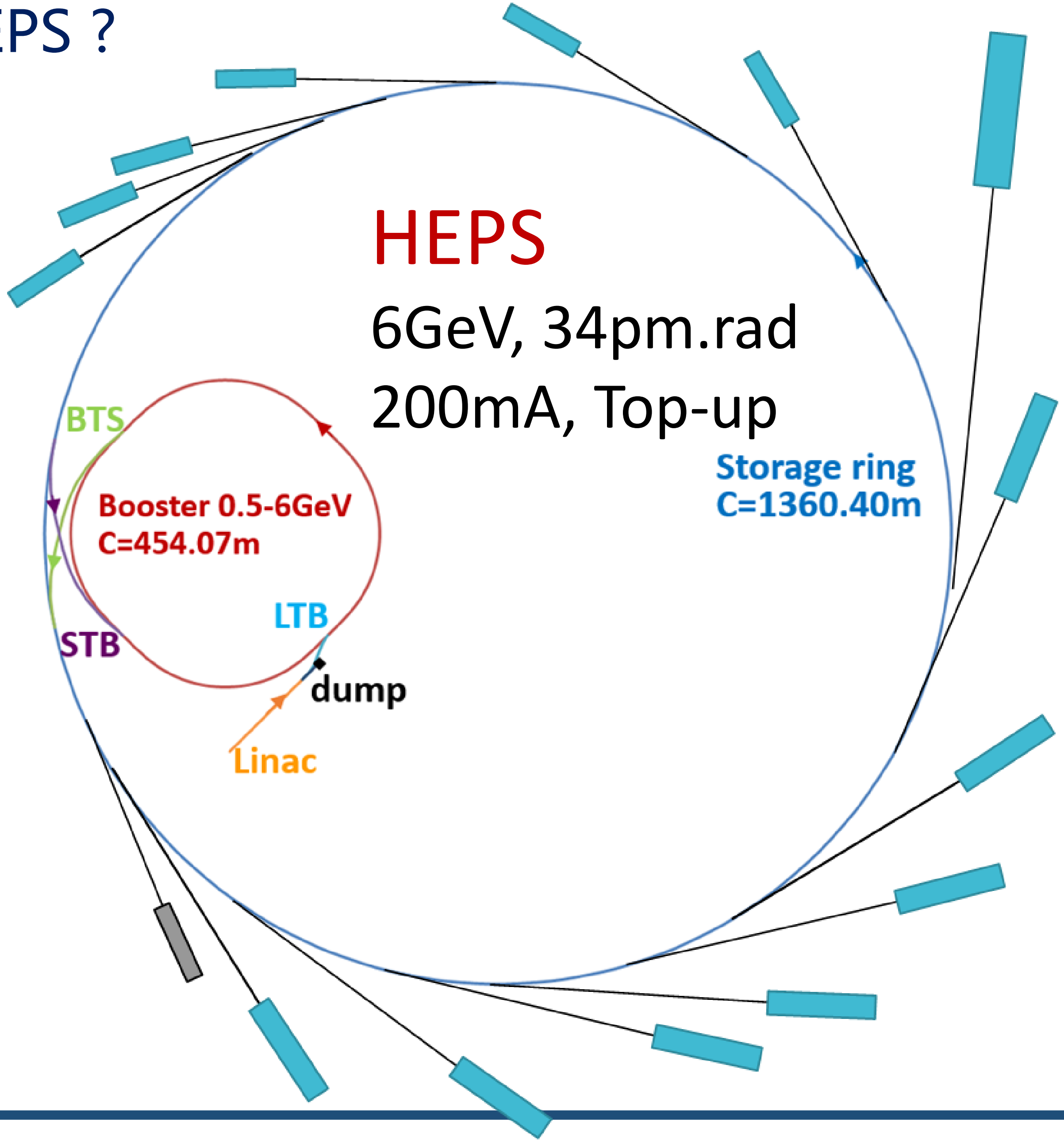
4th generation

high brightness and high coherence

4th generation High-energy machine

source	GeV	emittance (pm·rad)	status	
ESRF-EBS	6.0	115	commissioning	upgrade
APS-U	6.0	42	start	upgrade
SPring-8-II	6.0	142	proposal	upgrade
PETRA IV	6.0	<20	proposal	upgrade
One in Russia	6.0	?	proposal	new
HEPS	**6.0**	**34**	**Under construction**	**new**

What is HEPS ?



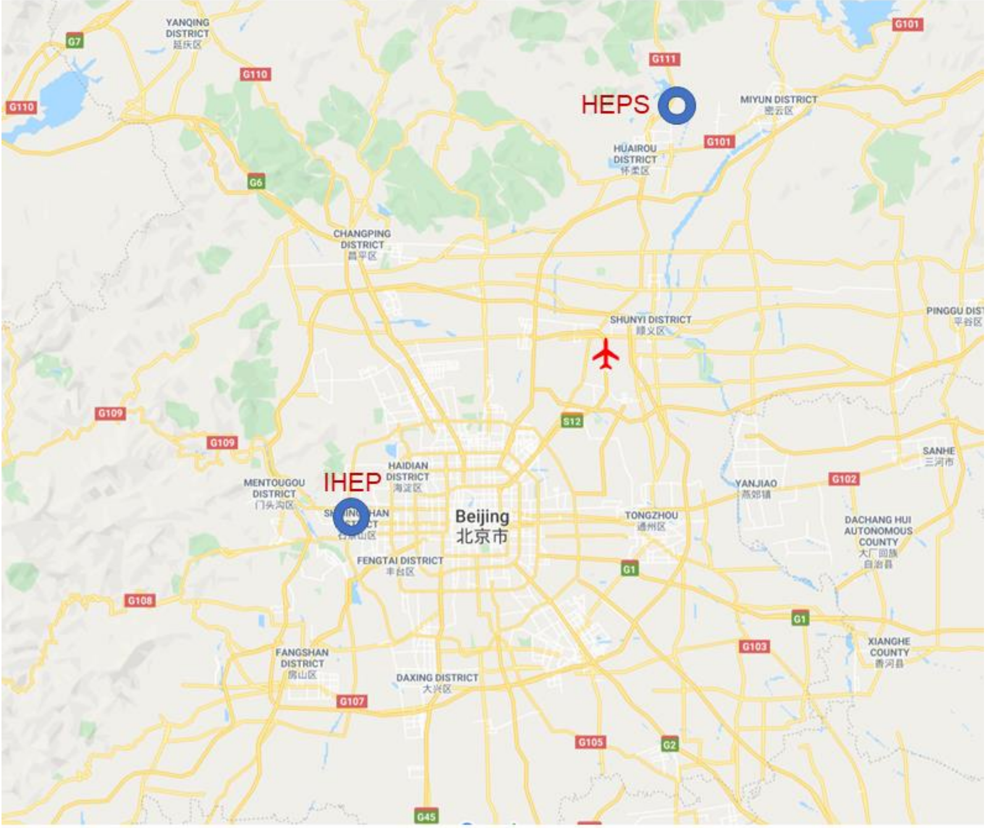
HEPS

6GeV, 34pm.rad

200mA, Top-up

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

Where - HEPS , Located in Huairou Science Campus, Northeast of Beijing. Flagship Facility in campus.



HEPS logo: a magnifying glass

HEPS

高能同步辐射光源

When - Milestones of HEPS project

- Initiative, HEPS-Test Facility, 2010
  ●
  ●
- 04/2016, HEPS-TF approved and started
- 12/2017, HEPS CDR approved by government
- 06/2018, Review of HEPS Feasibility Study Report (FSR)
- 08/2018, Review of HEPS Preliminary Design Report
- 12/2018, HEPS FSR approved by government
- 01/2019, HEPS-TF finished

- 29/06/2019, groundbreaking

HEPS Groundbreaking on 29/06/2019

Groundbreaking Ceremony at the High Energy Photon Source in Beijing, SRN, 32(2019)40

Milestone (cont.)

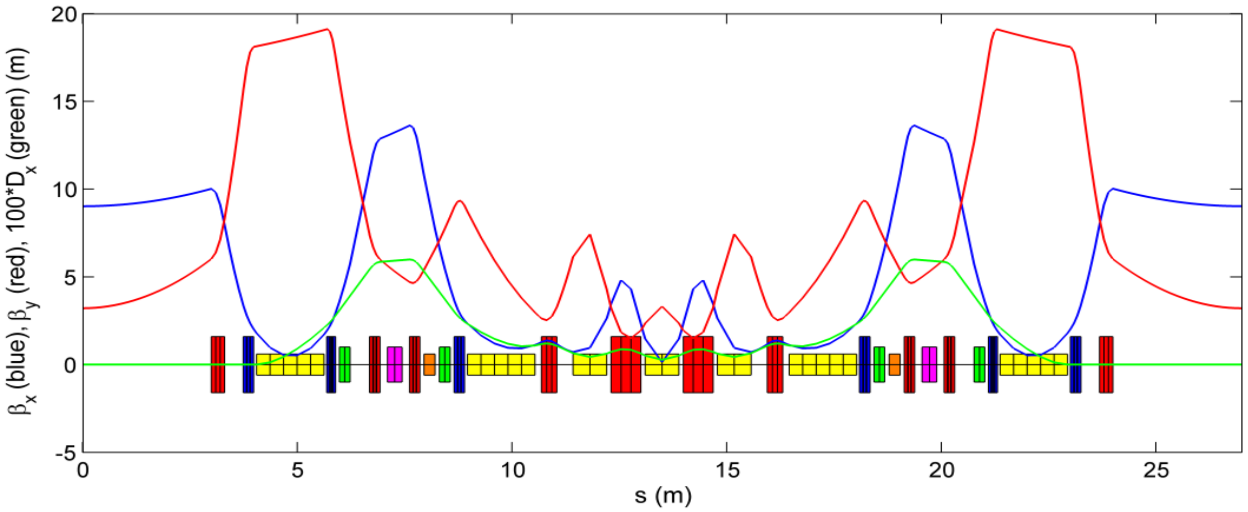
- 10/2023, commissioning of the storage ring
- 01/2024, commissioning of the first batch of beamlines
- 01/2025, commissioning of the second batch of beamlines
- 12/2025, open to users

2. Accelerator design

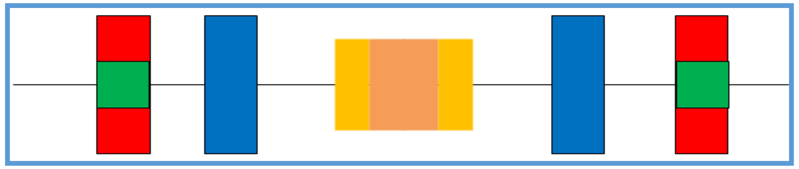
Main parameter	Design	Test goal @ end of 2025
Beam energy	6 GeV	6 GeV
Beam current	200 mA	100 mA
Circumference of SR	1360.4 m	
Circumference of booster	454.5 m	
Hori. Natural emittance	34 pm·rad	100 pm.rad
Brightness	$>5x10^{22}$ phs/s/mm^2/mrad^2/0.1%BW	$2x10^{21}$ phs/s/mm^2/mrad^2/0.1%BW

Accelerator physics design of storage ring

- C=1360.4 m, 48 hybrid 7BAs with AB/BLG cell



The middle cell replaced with AB/BLG cell



Central slice of BLG used for bending magnet beam linein the ring

Combination of Anti-Bend (AB) and Bending magnet with Longitudinal Gradient (BLG) in one cell promises lowest possible emittance [1-3].

Emittance optimized to 34 pm.rad with 48 hybrid

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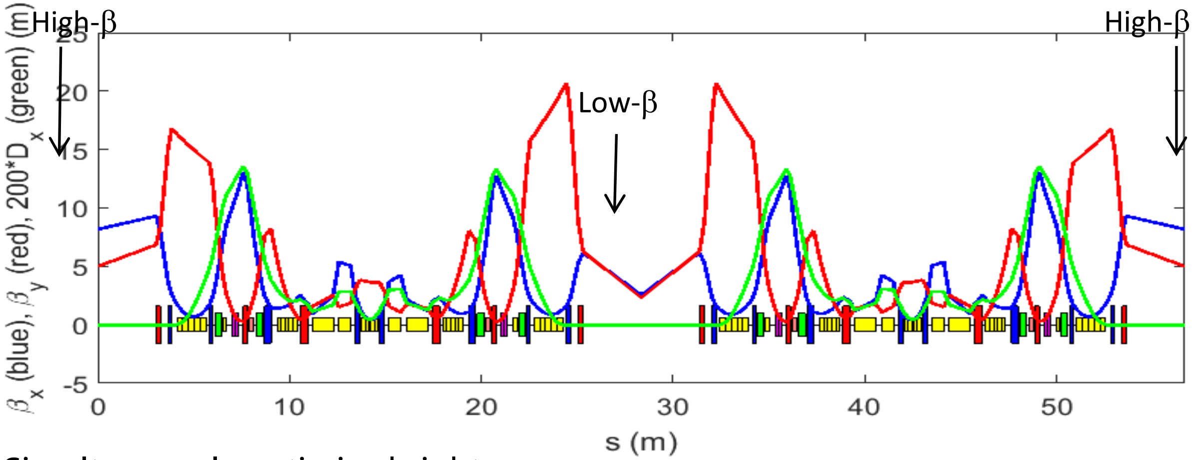
[1] *A. Streun, A. Wrulich, NIM-A 770, 98 (2015).*

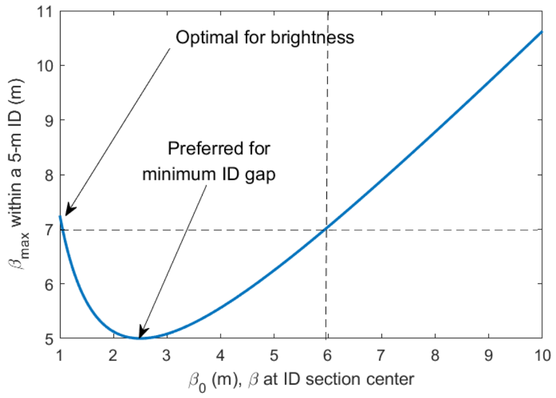
[2] *Y. Jiao, X.Y. Li, G. Xu, IPAC2018, TUPMF054.*

[3] *B. Riemann, A. Streun, PR-AB 22, 021601 (2019).*

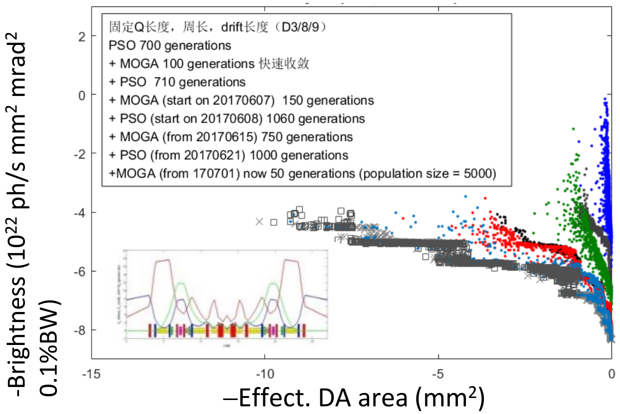
Storage Ring Lattice (cont.)

- Alternating verical high- β (~5m) and low- β (~2m) sections
- 48x 6m sections



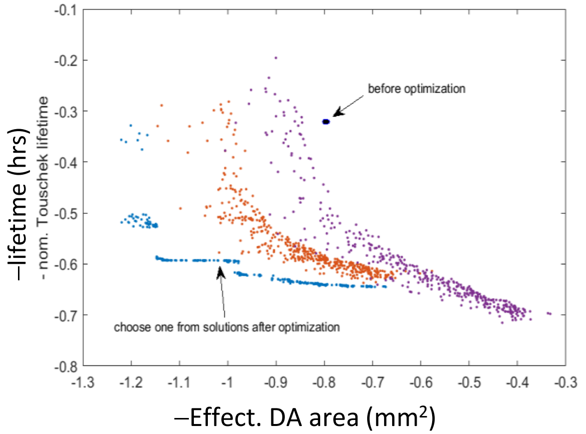


- Simultaneously optimize brightness and DA with PSO/MOGA

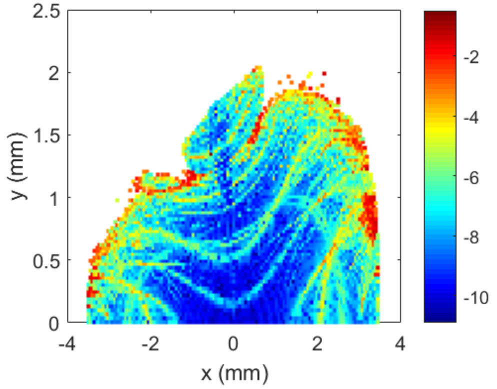


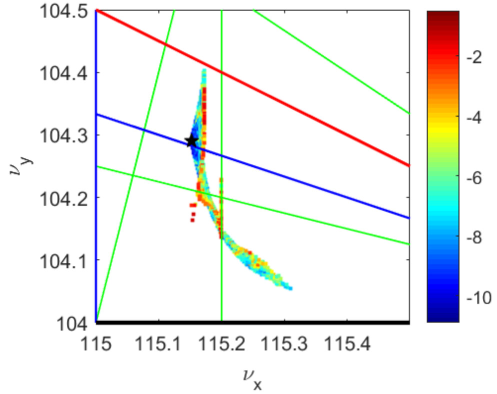
固定Q长度，周长，drift长度（D3/8/9）
PSO 700 generations
\+ MOGA 100 generations 快速收敛
\+ PSO 710 generations
\+ MOGA (start on 20170607) 150 generations
\+ PSO (start on 20170608) 1060 generations
\+ MOGA (from 20170615) 750 generations
\+ PSO (from 20170621) 1000 generations
+MOGA (from 170701) now 50 generations (population size = 5000)

- Touschek lifetime also optimized



- Dynamic aperture (H/V): 3.5/1.9 mm w/o error but w/ physical aperture





Main parameters of storage ring

Parameters	High-brightness mode, 200 mA	High-bunch-charge mode, 200 mA [1]	Units
Beam energy	6	6	GeV
Number of bunches	680	63	
Bunch Duration (rms)	106	160	ps
Bunch spacing	6	72	ns
Coupling factor	0.1	0.1	
Horizontal emittance	27.5	33	pm·rad
Vertical emittance	2.75	3.3	pm·rad
Horizontal beam size (rms) (high-/low-β section)	14.3/8.5	15.6/9.3	µm
Vertical beam size (rms) (high-/low-β section)	4.4/2.3	4.8/2.5	µm
Lifetime	~4	~0.8	hrs
Time between two refills	~30	~8	s

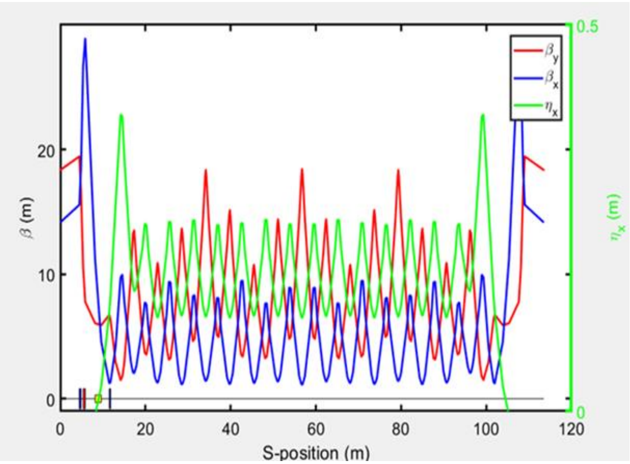
Accelerator physics design of booster

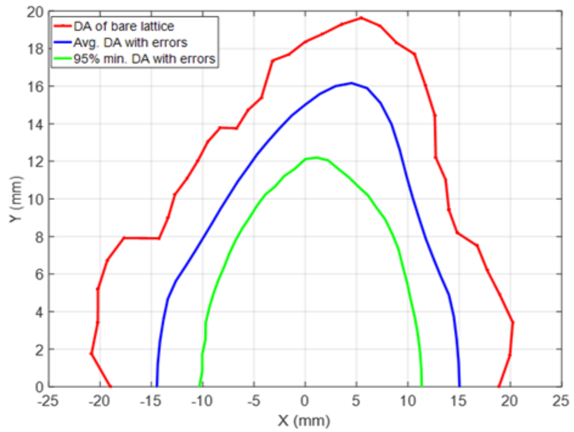
Requirements from storage ring (SR)

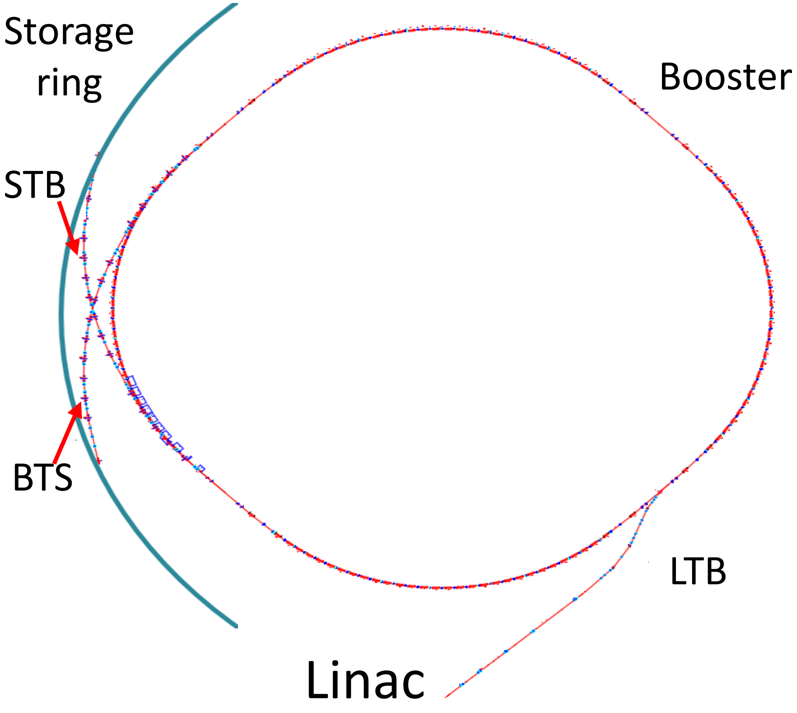
- Emittance less than 20nm
- 15nC for high bunch charge mode
- Setting in a separate tunnel

Design consideration

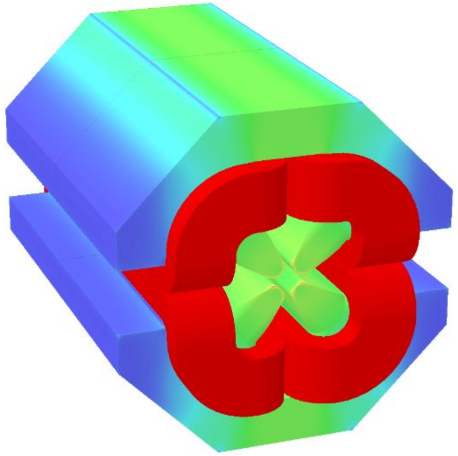
- "High energy accumulation" to reduce the affect of TMCI @500MeV
- The emittance as lower as better , with α_c>2E-3 (requirement from TMCI)
- π section for 2 kicker re-injection



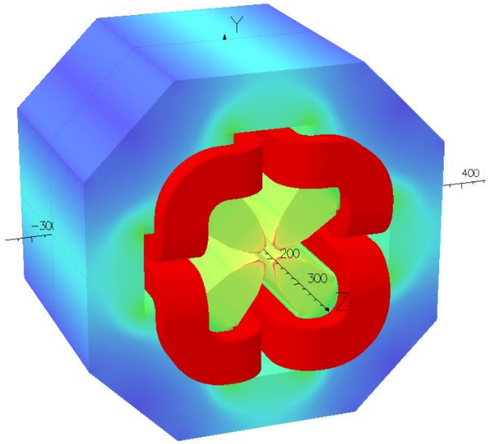




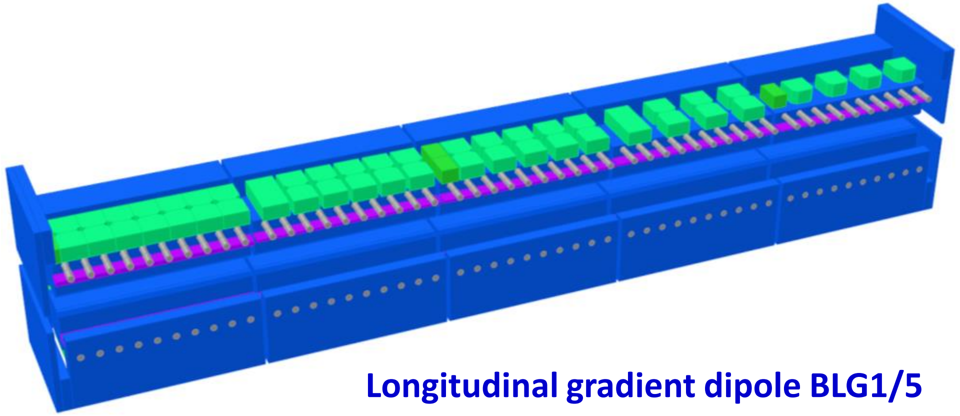
- Physical design of the magnet finished
  - Longitudinal gradient dipoles (permanent magnet), anti-bend quadrupoles, quadrupoles, sextupoles and octupoles → Done
  - Dipole/quadrupole combined magnets → Under design



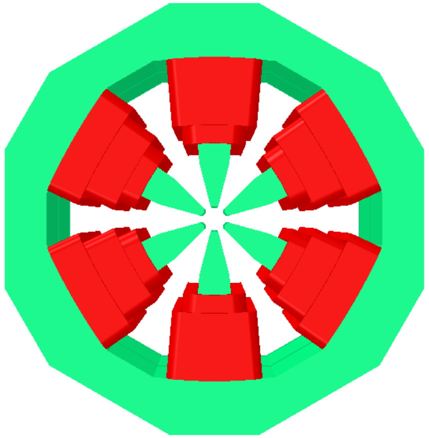
Anti-bend quadrupole ABF2/3



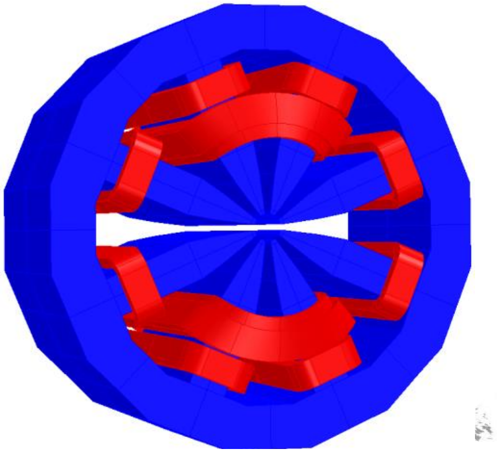
Quadrupole QF3/4



Longitudinal gradient dipole BLG1/5



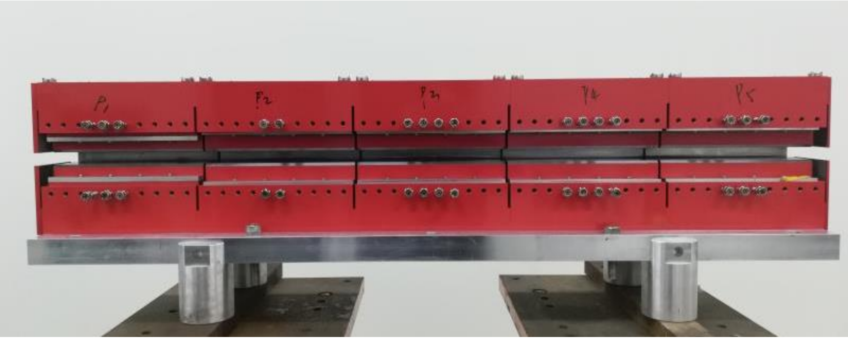
Sextupole SD2/3

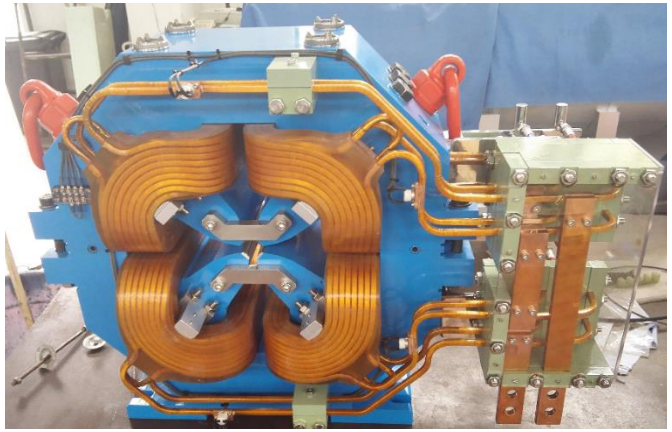


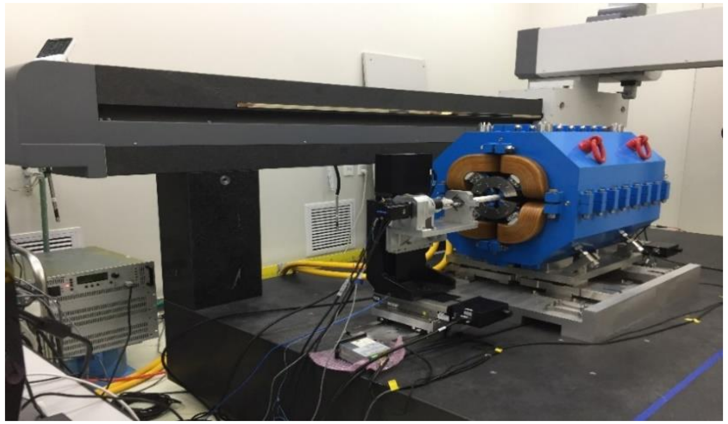
Octupole OCT1/2

- Magnets
  - 37 magnets in one 7BA cell

– BLG	0.11 – 1 T
– Quad	82 T/m
– BD	66 T/m
– Sext	6082 T/m^2
– Oct	512600 T/m^3
– Fast Corr	0.08 T





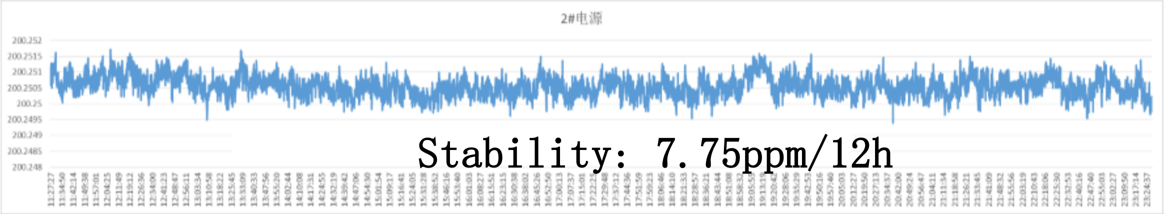


Power suppliers for magnets

- Finish the design of Digital Power Supply Control Module
- High precision PS developed, designed and tested
  - Long-term stability: better than 10ppm
  - Current resolution: better than 17bits
  - Current ripple: better than 10ppm

FPGA-based main board of Digital Power Supply Control Module

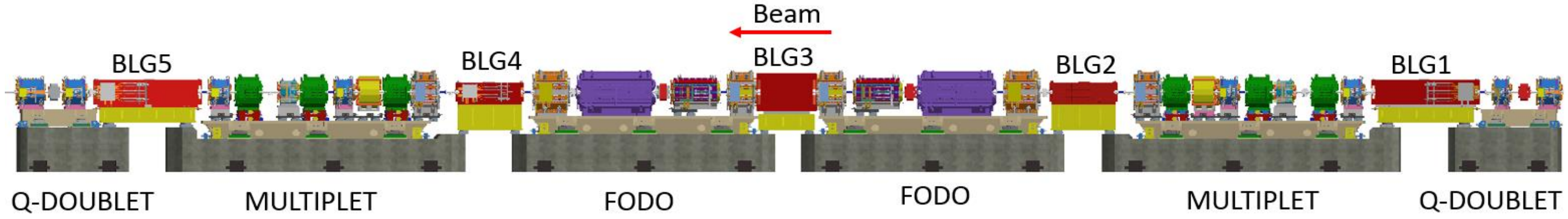
300A50V prototype



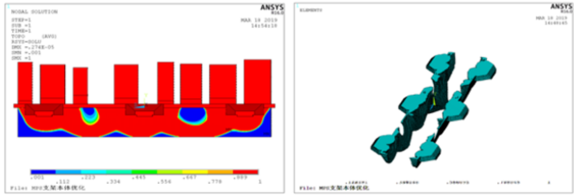
Stability: 7.75ppm/12h

Mechanical support

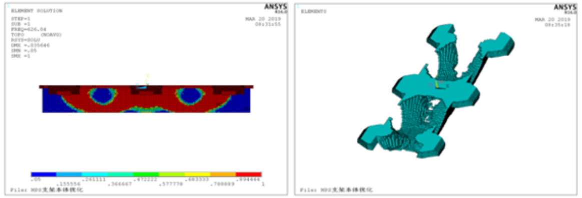
- Optimize stability, alignment, transportation.



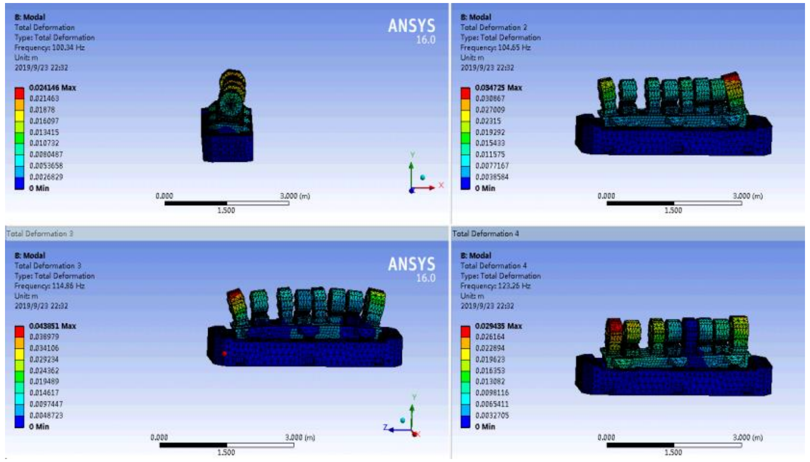
- Eigenfreq. >54Hz from vibration control requirement



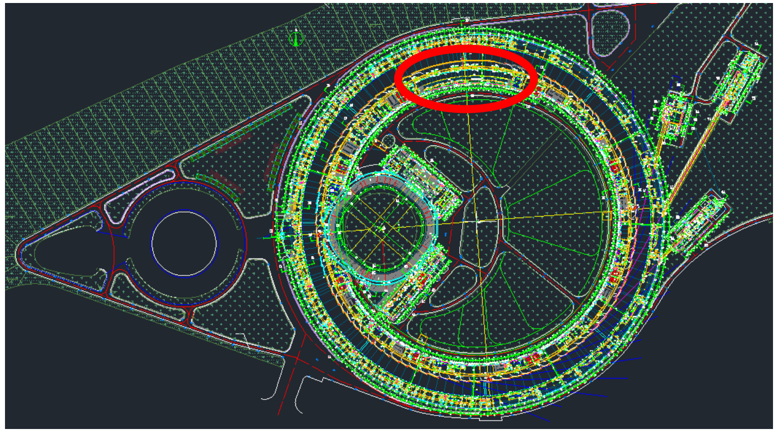
Static Optimization



Modal Optimization



RF system



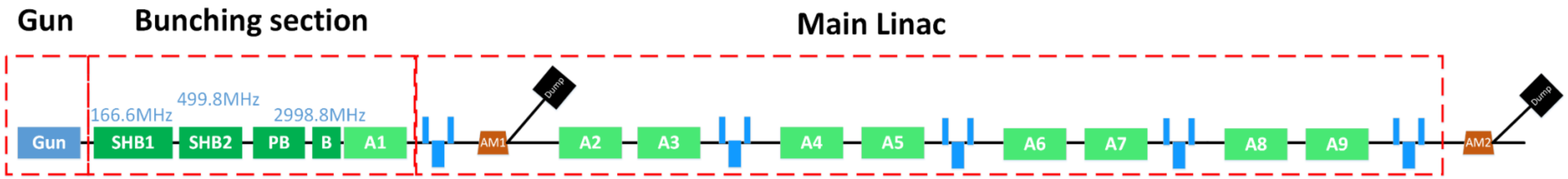
- Number of linear sections for RF: 6 (48 in total)
- Frequency: 166.6MHz (fund.) + 499.8MHz (3rd harm.)
- Technology choice: SRF cavity + Solid state amplifier + digital LLRF

- Energy loss per turn: 4.4MV (14 IDs)
- Total RF voltage: 5.4MV
- Beam power: ~900kW
- Number of RF cavities: 5 fund. + 2 HHC

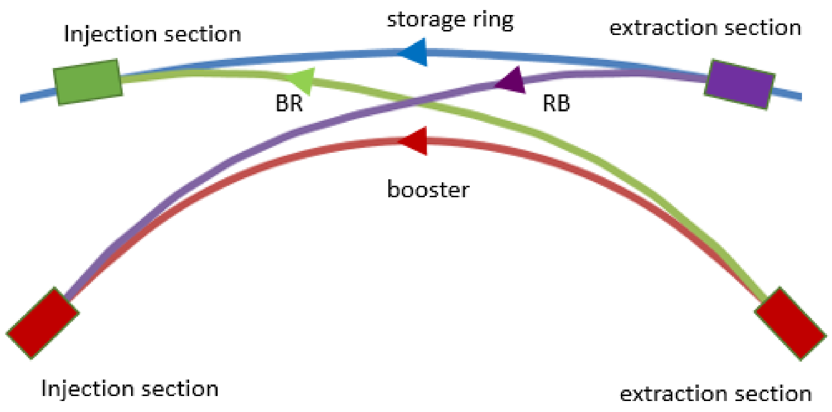
on-axis swap-out injection scheme:

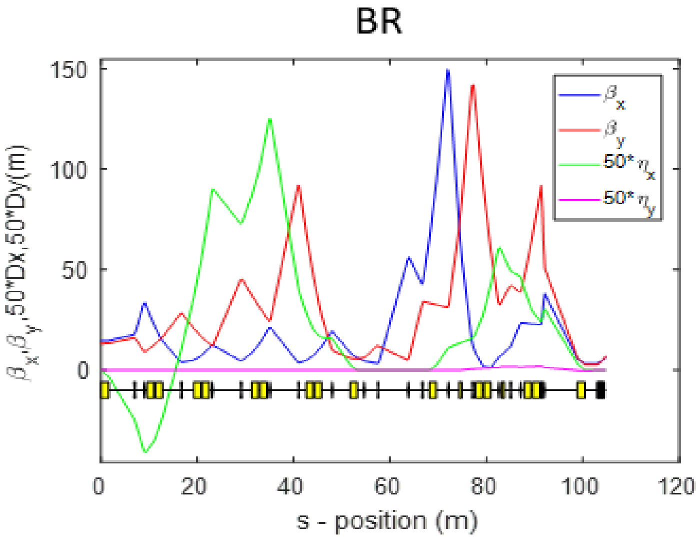
Linac

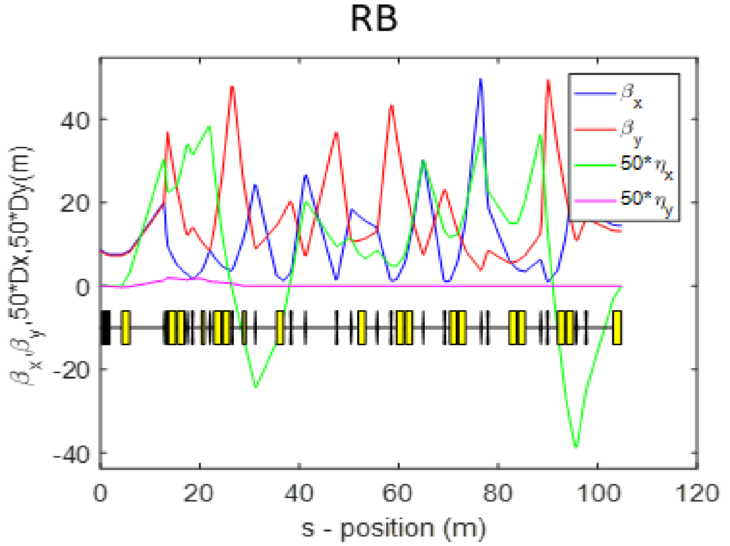
- Linac is designed to meet the requirement from the booster.
- Two sub-harmonic bunchers are introduced for the high bunch charge.



Transport lines

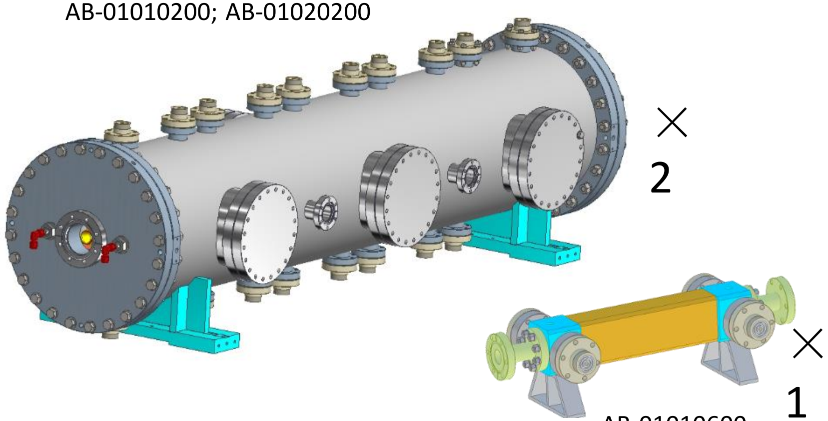






Injection hardware developed

Strip-line kicker



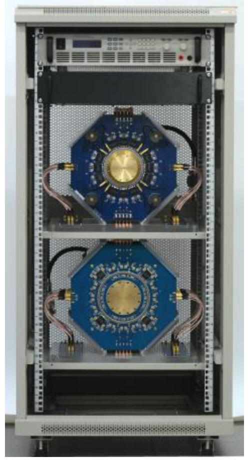
AB-01010200; AB-01020200

× 2

AB-01010600

× 1

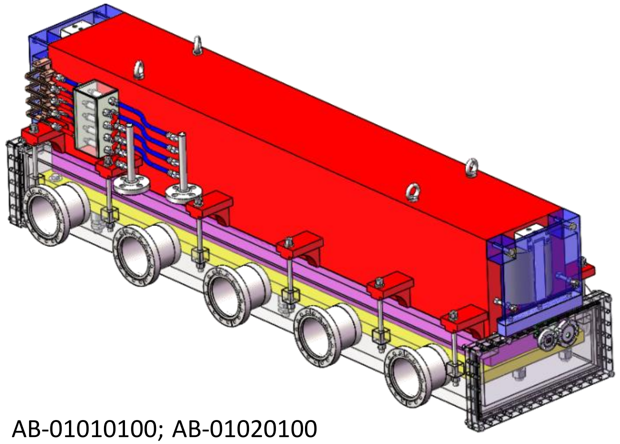
10ns pulser



× 11

AB-01010300; AB-01020300

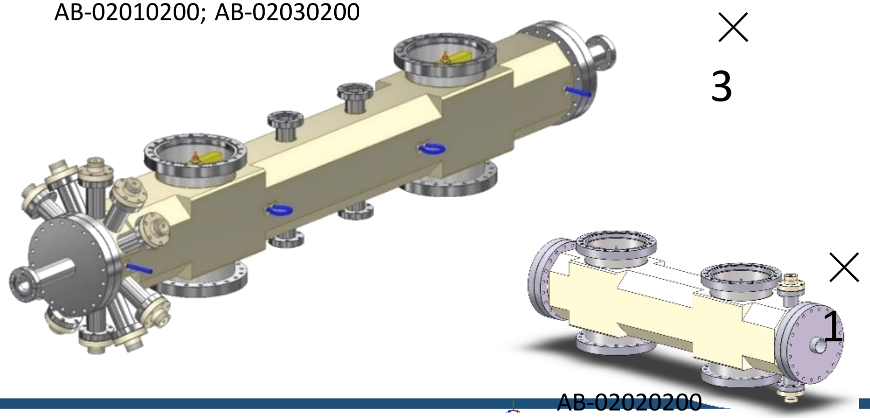
In-vacuum Lambertson



× 2

AB-01010100; AB-01020100

Slotted-pipe kicker



AB-02010200; AB-02030200

× 3

× 1

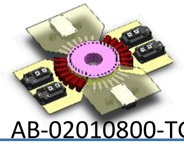
AB-02020200

300ns pulser

× 4

AB-02010300; AB-02020300; AB-02030300

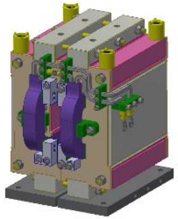
1ms pulser



× 4

AB-02010800-TG

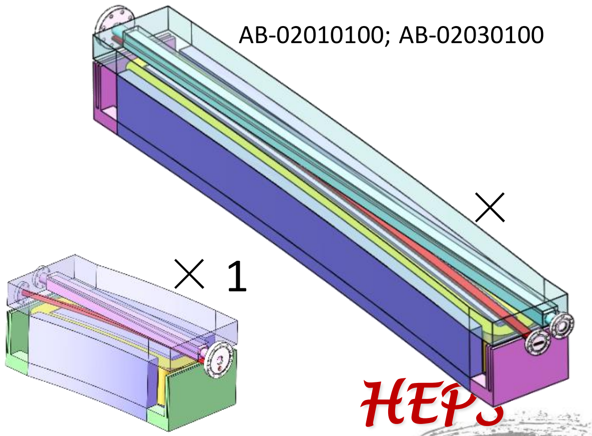
Bumper



× 4

AB-02010600-TG

Out-vacuum Lambertson



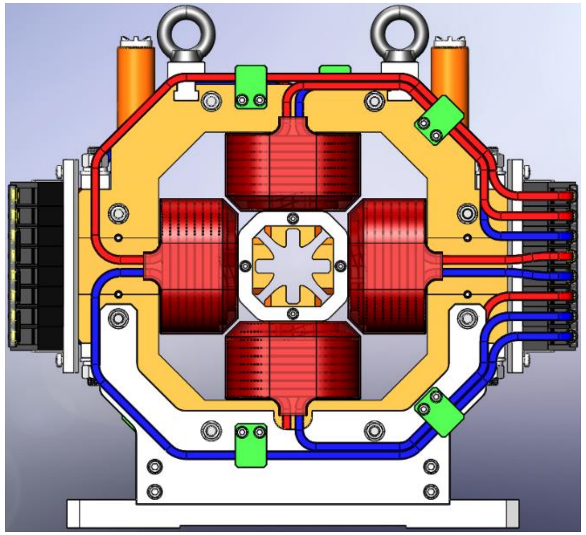
AB-02010100; AB-02030100

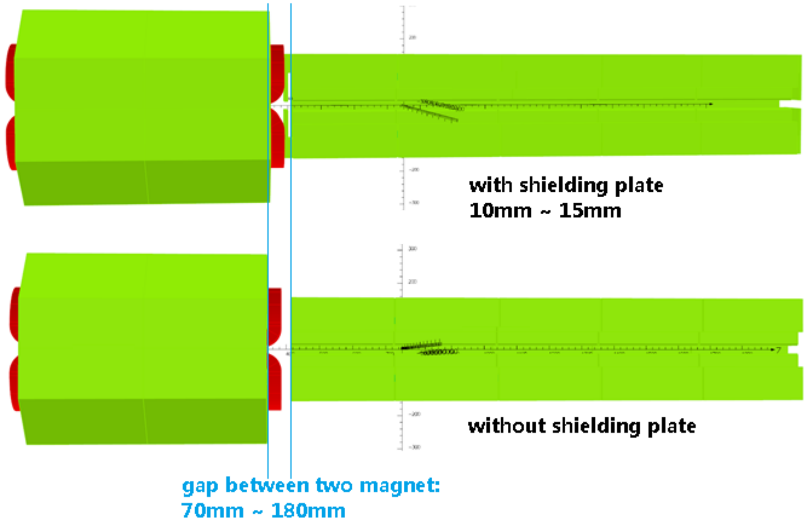
×

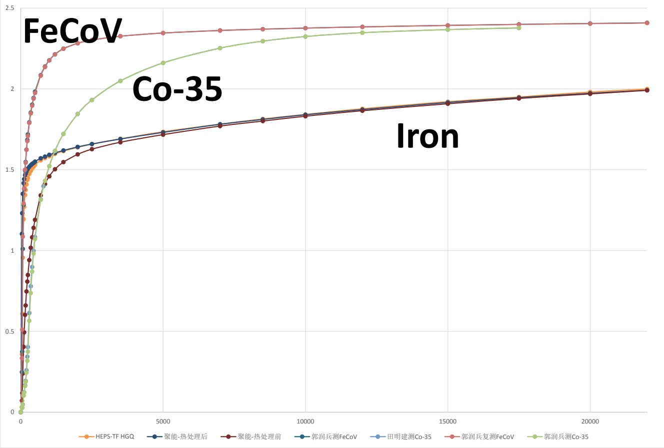
× 1

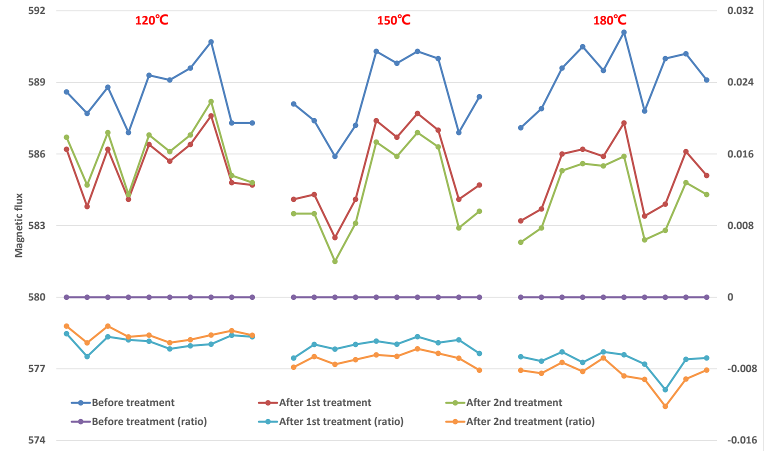
AB-02020100

- Fast corrector prototype is under development
  - Skew quadrupole type with slot on the pole
  - 0.15mm thickness lamination
- Cross talk between dipole and quadrupole is simulated
- Material properties study
  - BH curve for core material
  - Heat treatment for permanent magnet material





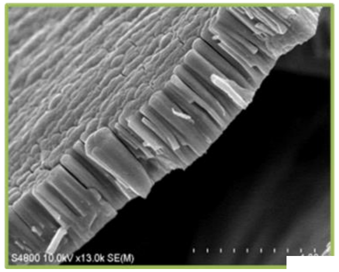




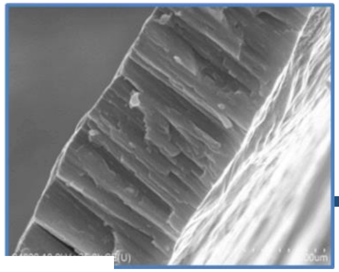
Vacuum: NEG Coating Setup

Two sets of NEG coating equipment have been built and have capability to coat up to **1.5** m long chambers with a diameter of **0.5** m.

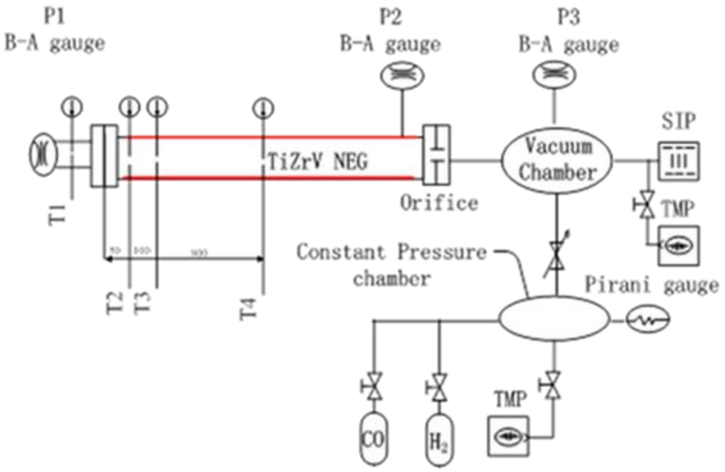
Columnar film for high pumping speed



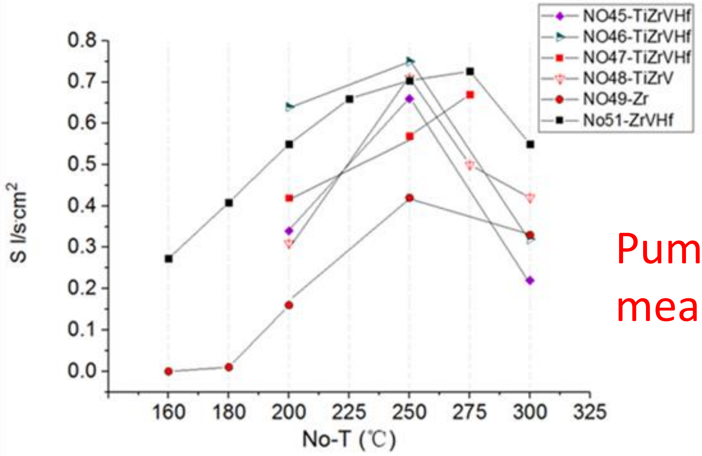
Dense film for low impedance



SEM



From IHEP [1]



[1]. 20 Hours Heating Temperature for Different Times
160℃ is 48 hours and 180 ℃is 22h heating

Pumping speed measurements

Insertion device

Phase I beamlines: 19 IDs, 6 types, including new IDs, APPLE-KNOT undulator and Mango wiggler

Cryogenic Permanent Magnet Undulator (CPMU)

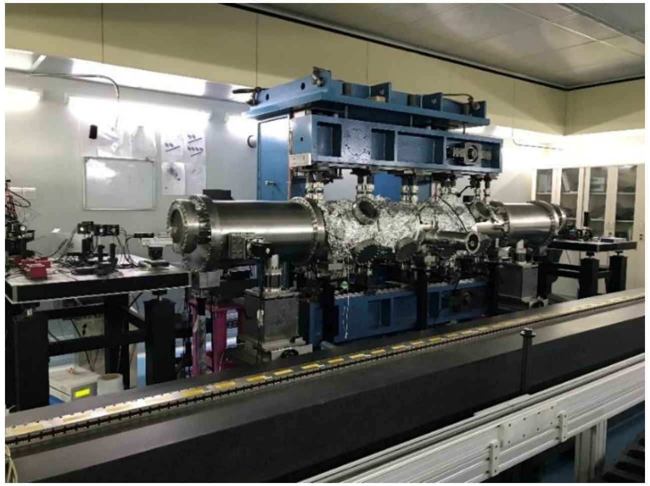
Prototype CPMU

2m in length, short period13.5mm, new magnet PrFeB, liquid nitrogen

peak field 0.98T @80K @ 5mm gap, phase error< 6 degree

2m CPMU prototype

LT in-vacuum magnetic measurement bench



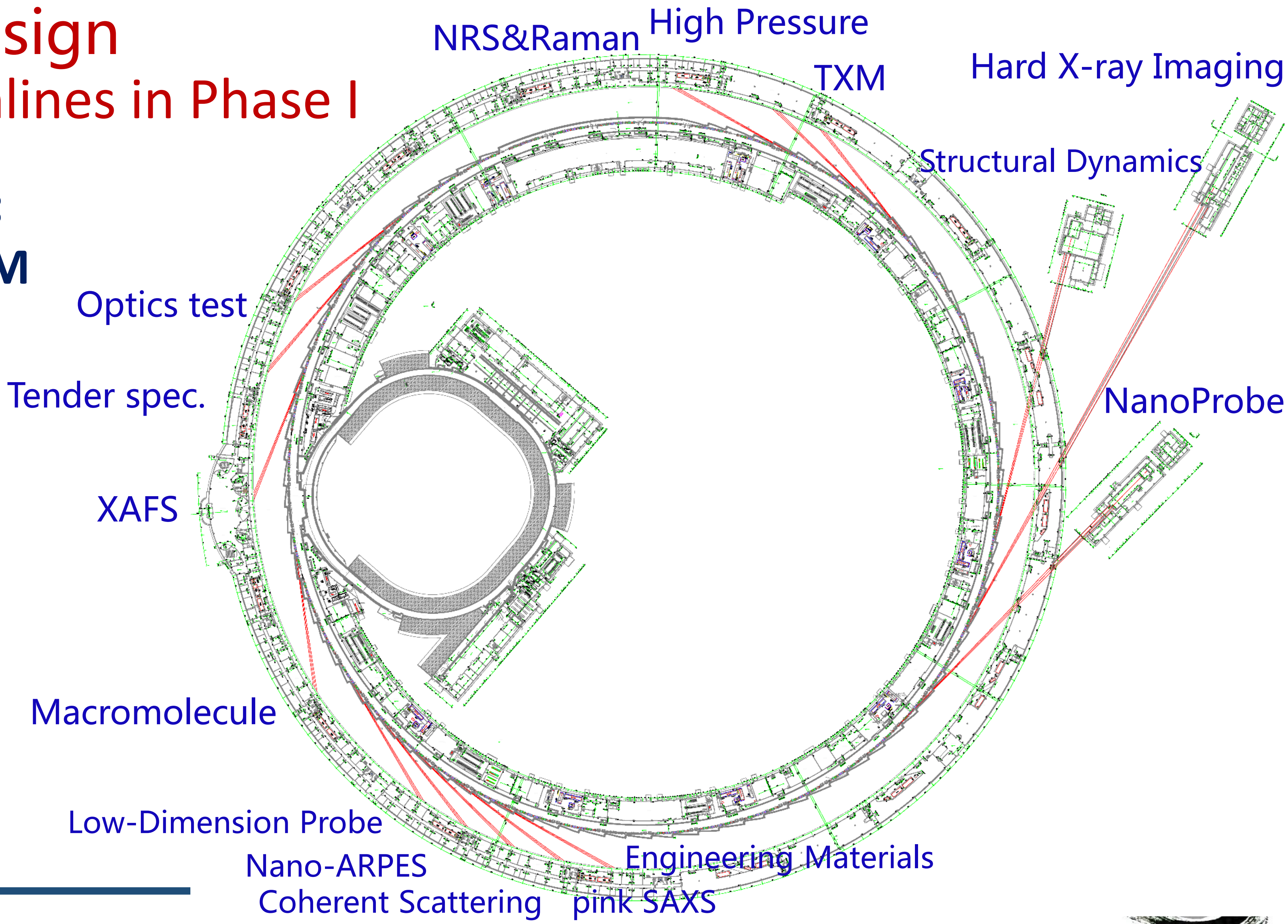
3. Beamlines design

Layout of 15 beamlines in Phase I

14 public beamlines:

13 IDs (3 long) + 1 BM

1 ID beamlines for optics test



Beamlines description

	Beamlines	**Features**
High Energy	Engineering Materials	50-170keV， XRD, SAXS, PDF
	Hard X-Ray Imaging	10-300keV, Phase and Diffraction contrast imaging, 200mm large spot, 350m long
High Brightness	NanoProbe	Small probe, <10nm; InSitu 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

Beamlines description (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

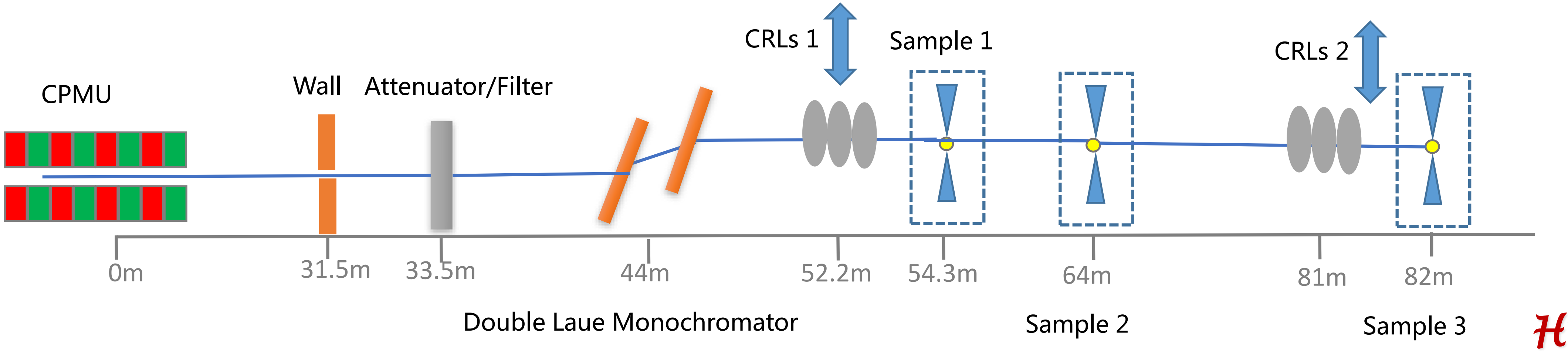
Engineering Materials Beamline (B1)

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**



Hard X-ray Imaging Beamline (B7)

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: (1) Large FOV and high Resolution
Ratio of spot size and PSF increase from 2k to 20k, 1000 times of voxels one CT
(2) High sensitivity at high resolution & deep penetration case, very small PSF

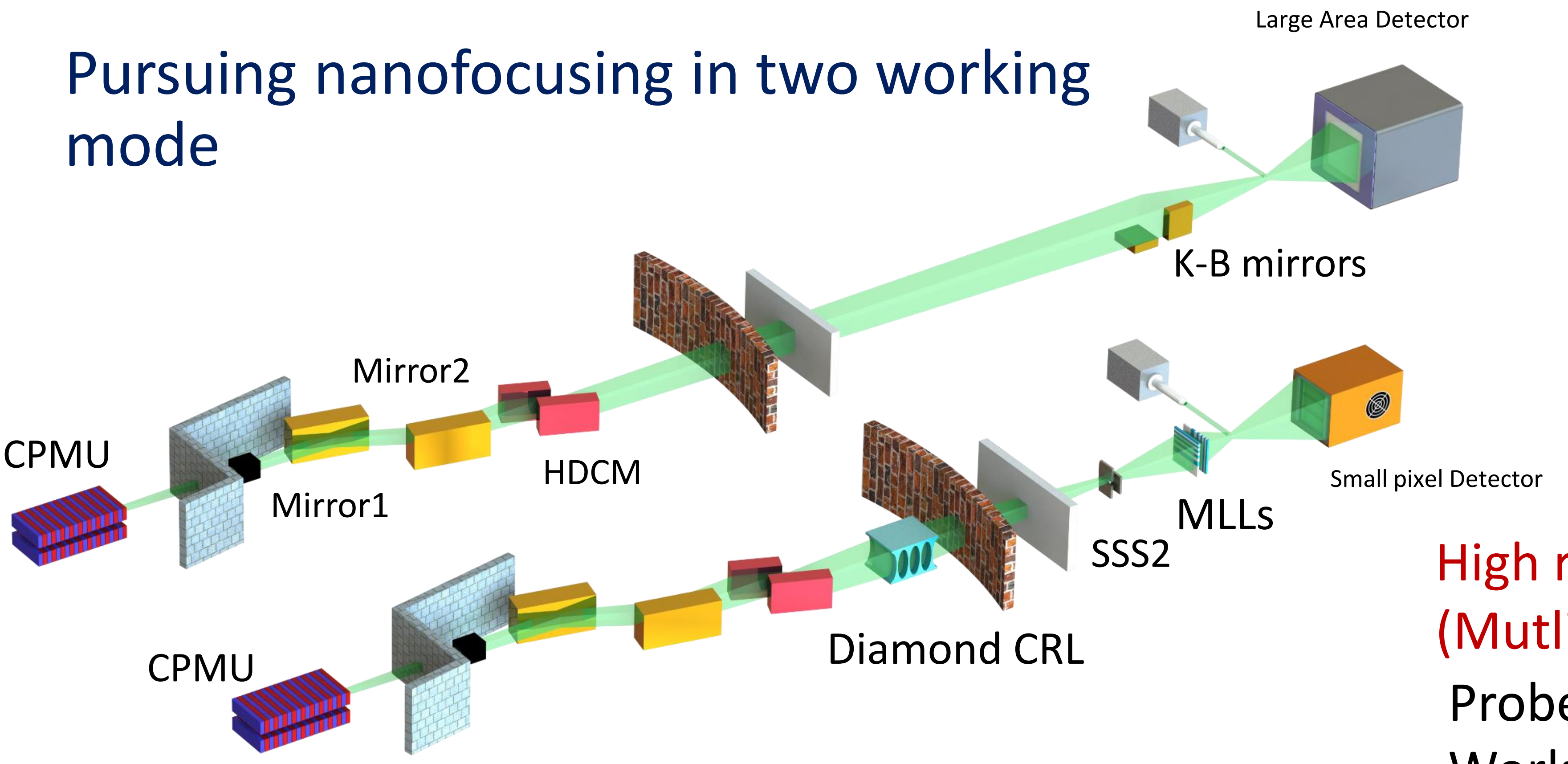
Sources, 1xCPMU + 1xWiggler+1x Mango Wiggler ； 350m long beamline

NanoProbe beamline (B2)

Pursuing nanofocusing in two working mode

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)

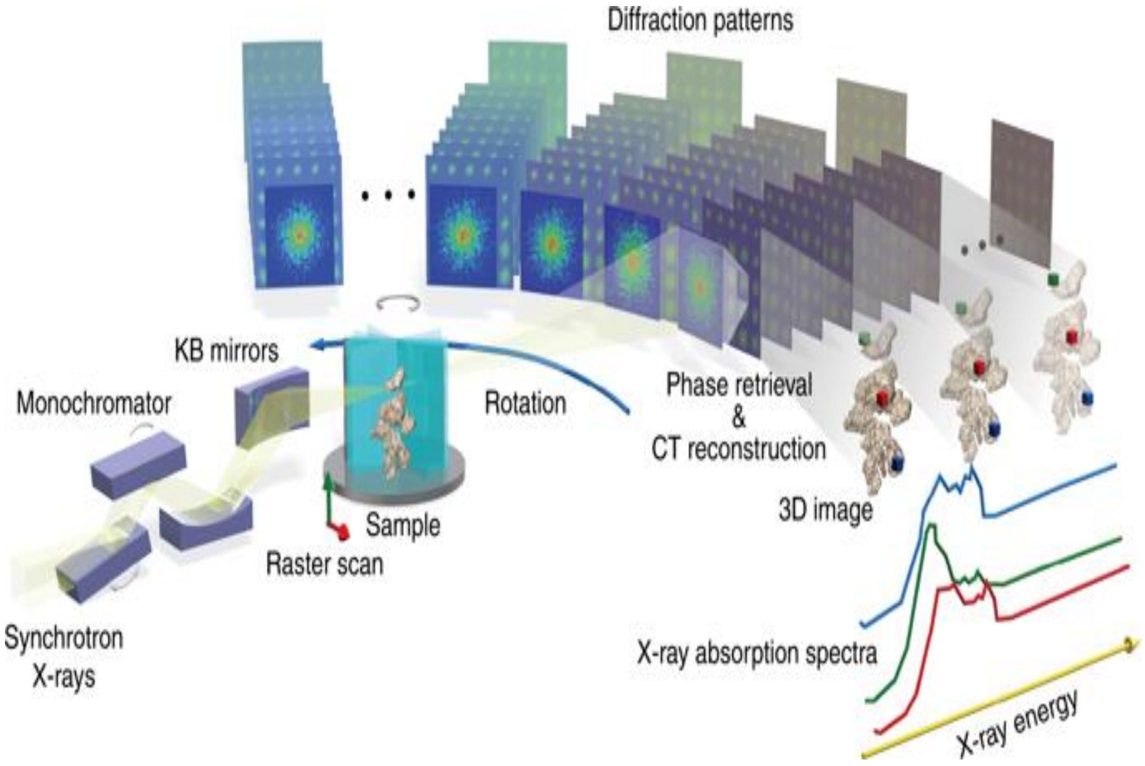
Probe Size: ＜10nm
Work Distance: 2mm
Flux: $10^{10\sim11}$ phs/s

Optical Layout of Nanoprobe beamline

Mirror2
(bent)

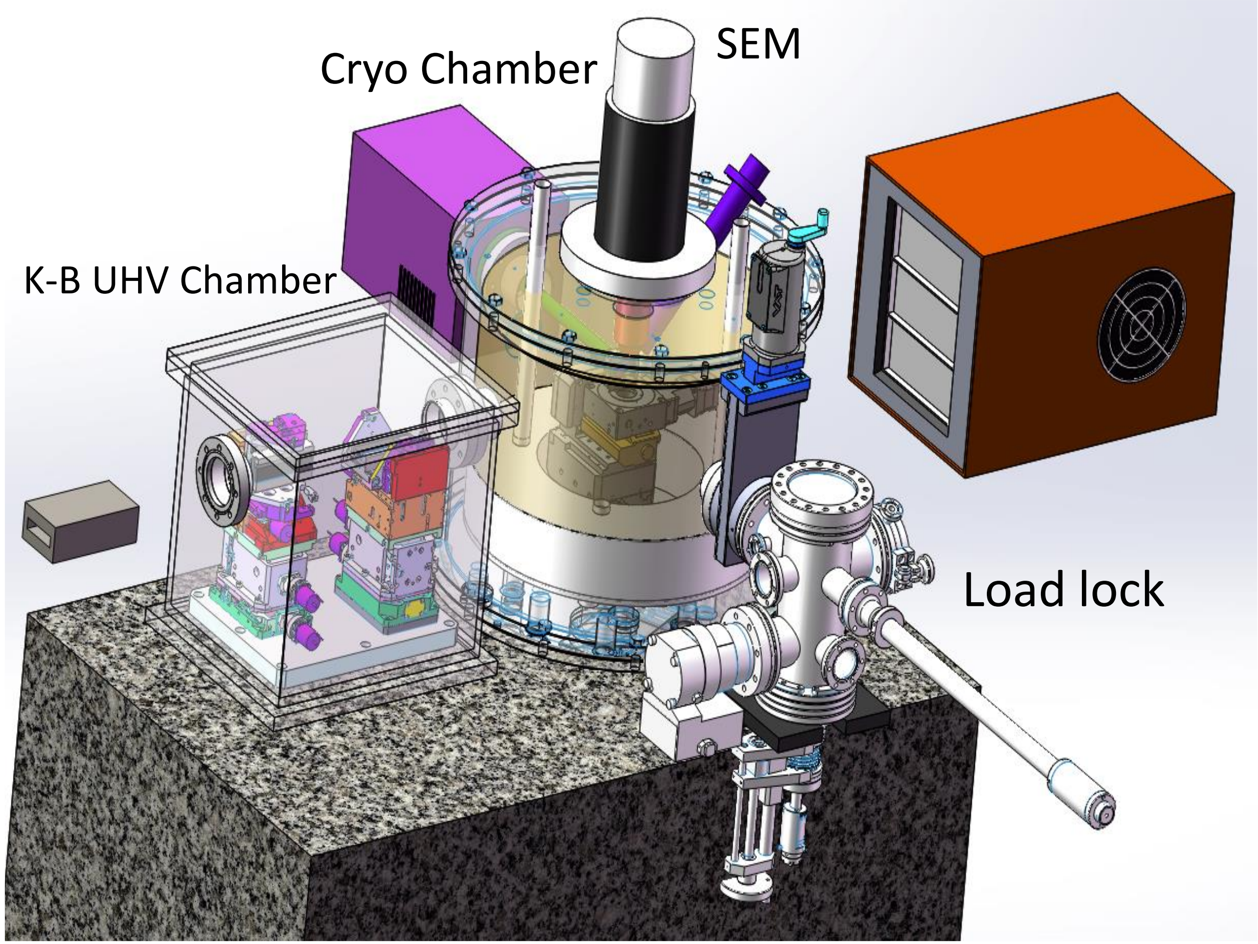
HEPS

Multimodal Probing:
nano-XRF, nano-XRD, nano-XANES
Ptychography, Spectra-Ptychography



M. Hirose, Nature communication,2019

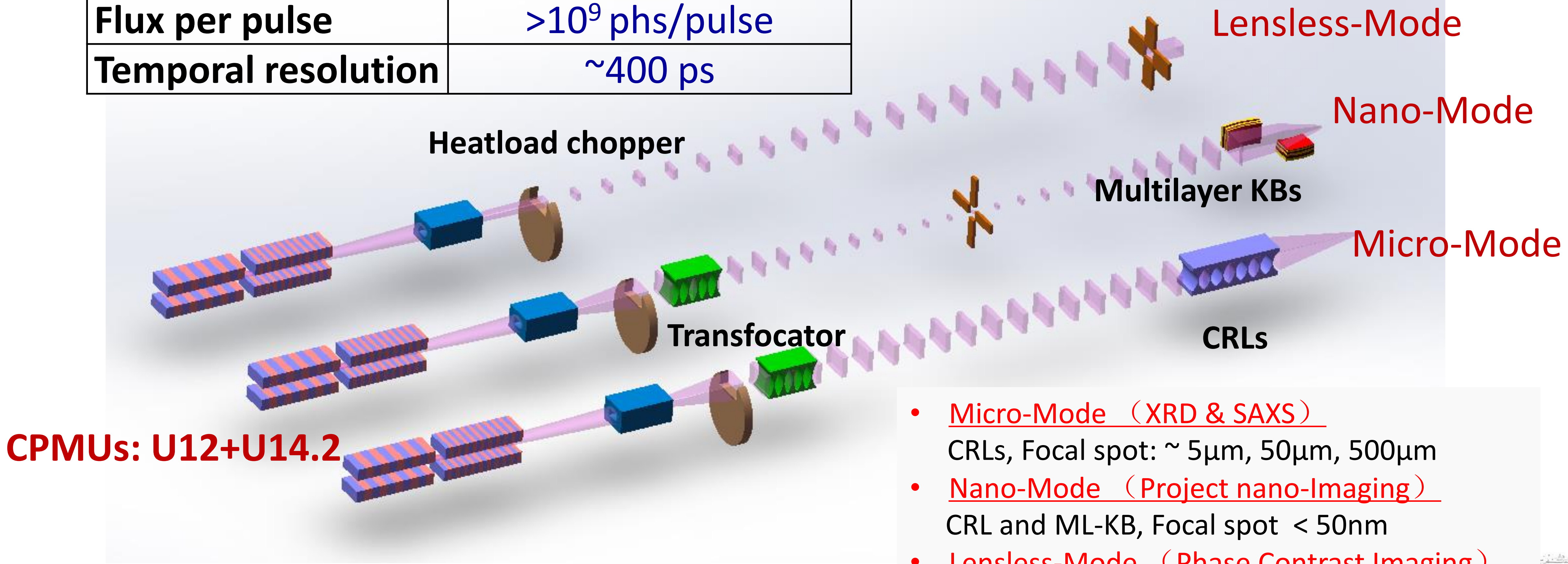
Endstation schematic



Structural Dynamic Beamline (B3)

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



- Micro-Mode （XRD & SAXS）
  CRLs, Focal spot: ~ 5μm, 50μm, 500μm
- Nano-Mode （Project nano-Imaging）
  CRL and ML-KB, Focal spot < 50nm
- Lensless-Mode （Phase Contrast Imaging）
  No optics, FOV 1-5mm

Dynamic loading:

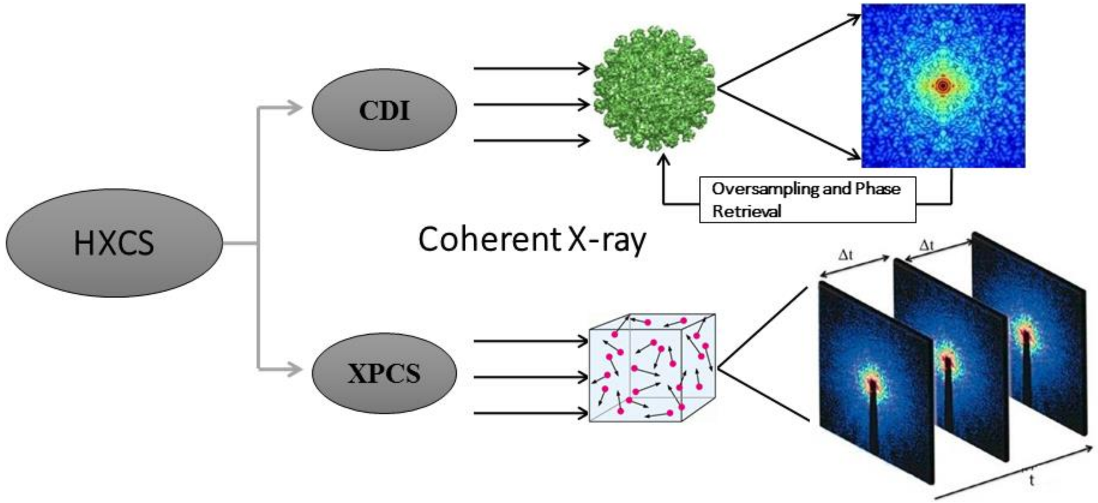
Gas gun, Hopkinson bar
High power laser,

Additive Manufacturing

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

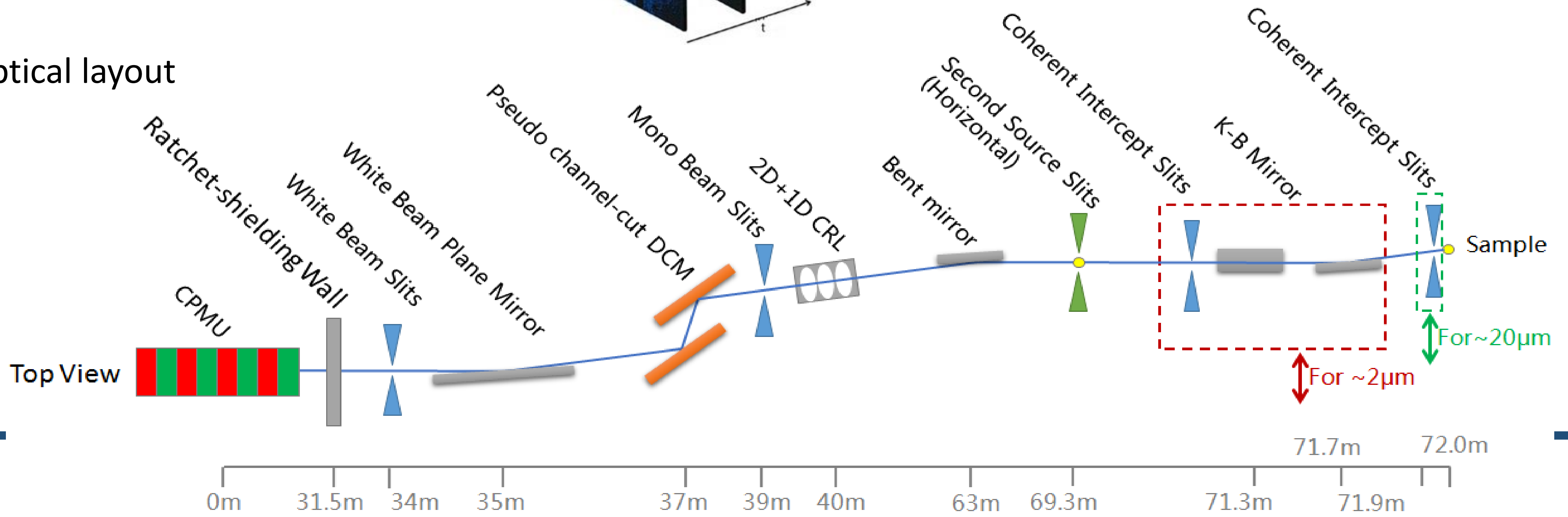
Hard X-ray Coherent Scattering beamline (B4)

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)
Endstastion	CDI (resolution<5nm) XPCS (resolution<1μs)

Optical layout



NRS&Raman beamline

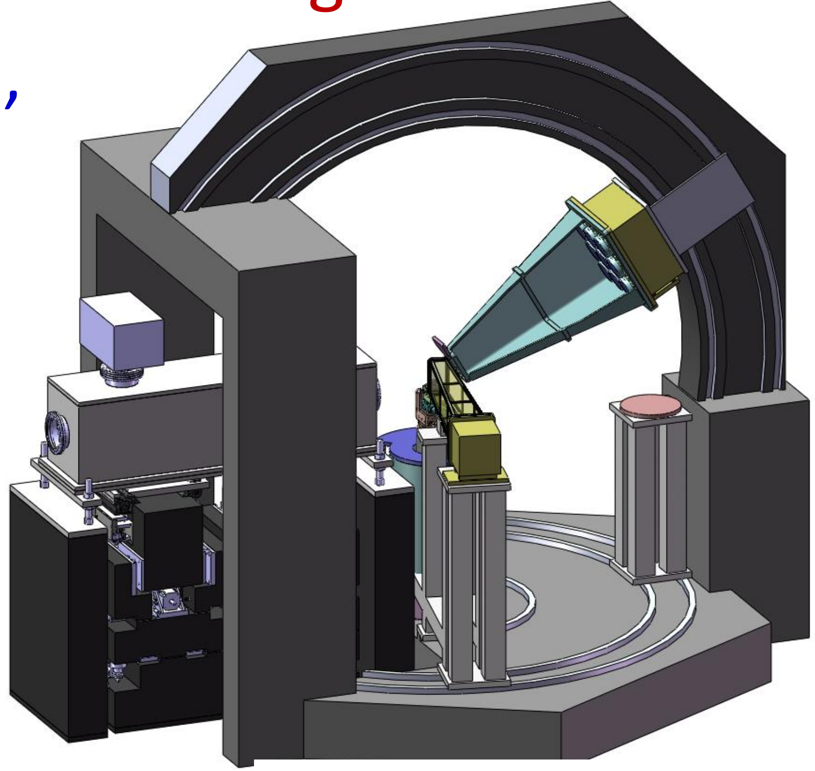
X-ray Raman Spectrometer, referring to the design of ID20 in ESRF

- 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

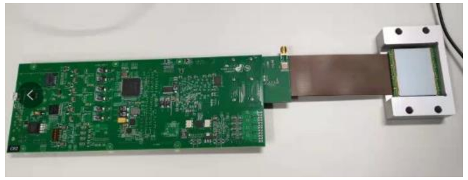
✓ Larger-solid-angle realized by multiple analyzer modules

✓ Larger scattering angle

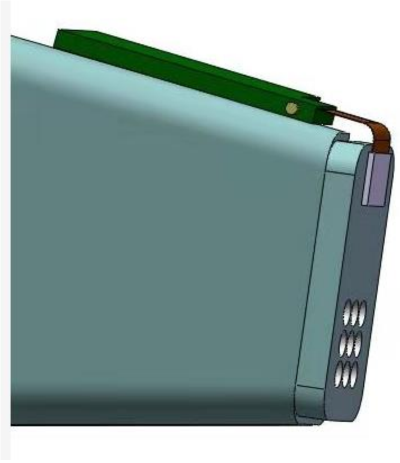
✓ home-made analyzer crystals and small pixel array detectors



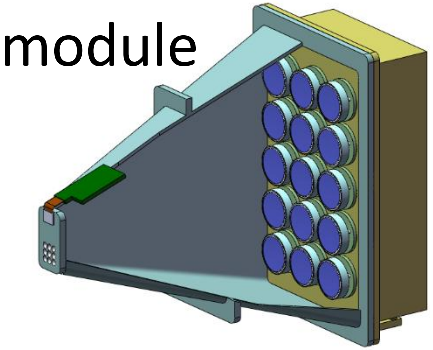
2D detector by IHEP



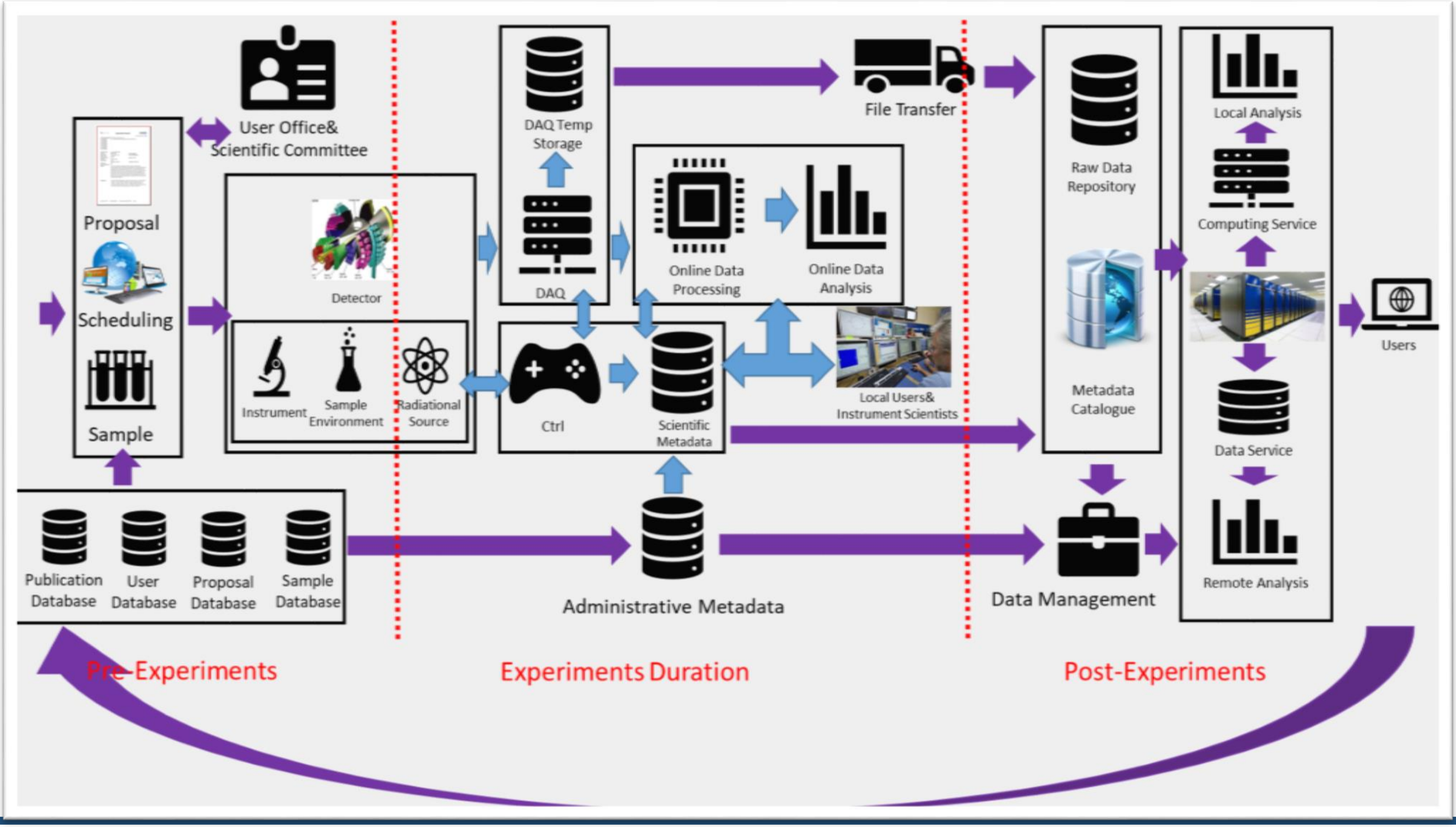
Detection nose



analyzer module



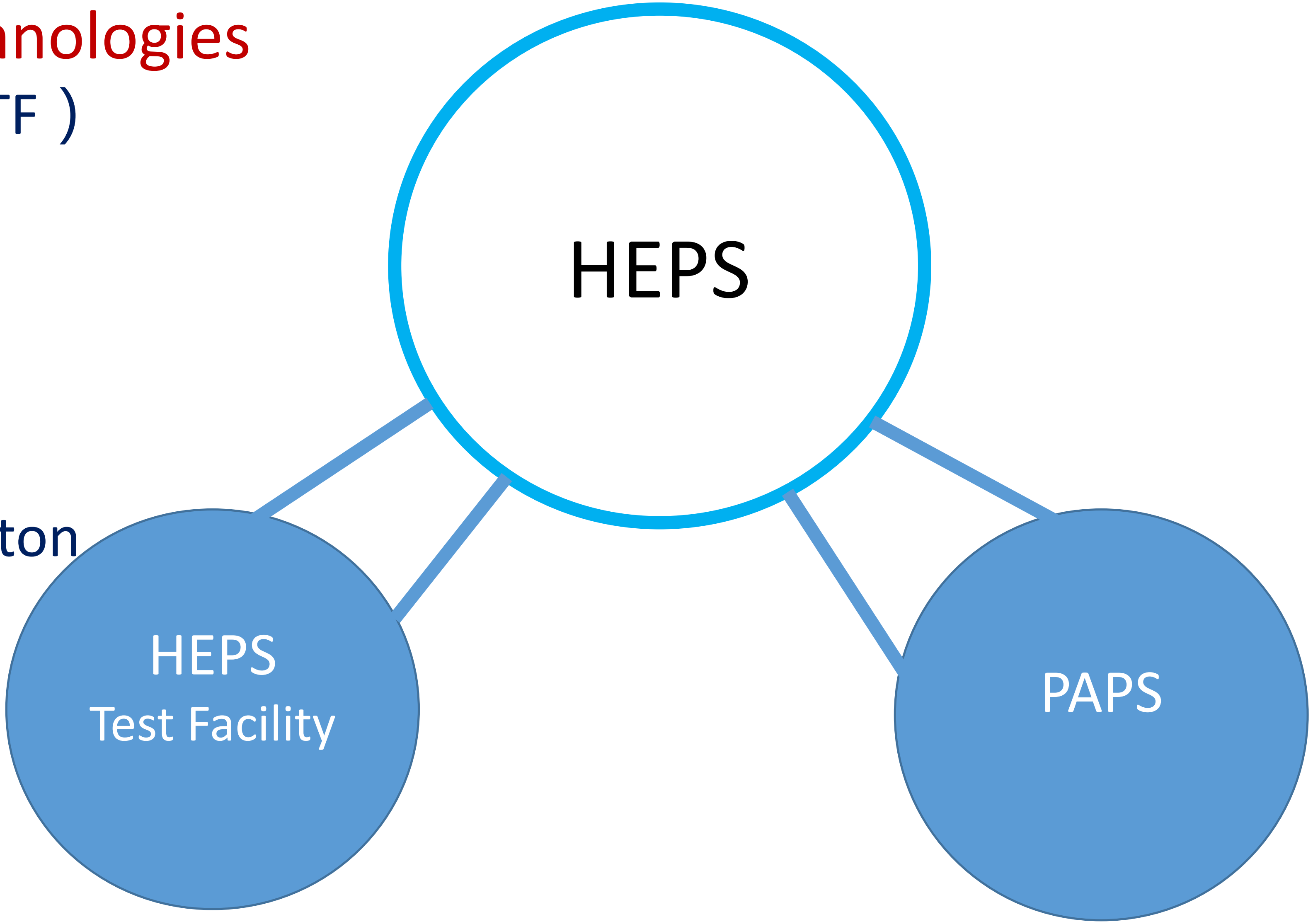
Data Workflow



HEPS

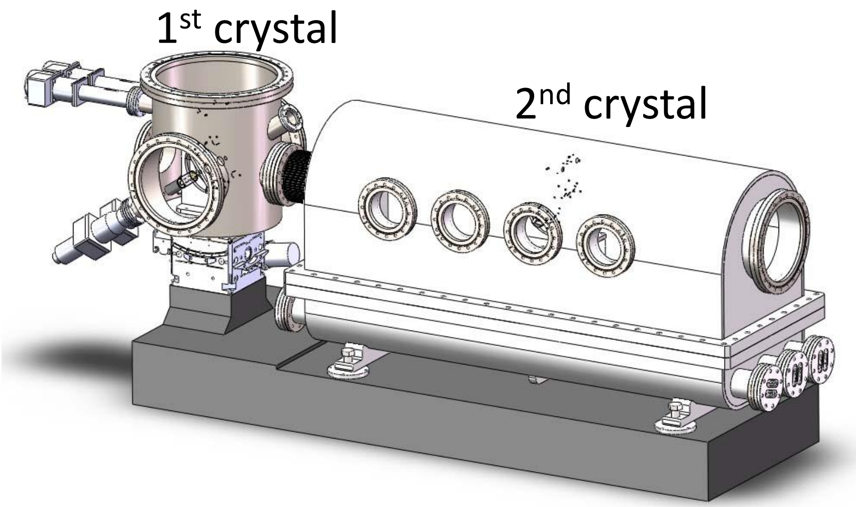
4. R&D for beamline technologies

- HEPS-Test Facility （HEPS-TF） project, 2016-2019
- HEPS
- Platform for Advanced Photon Source （PAPS） project,

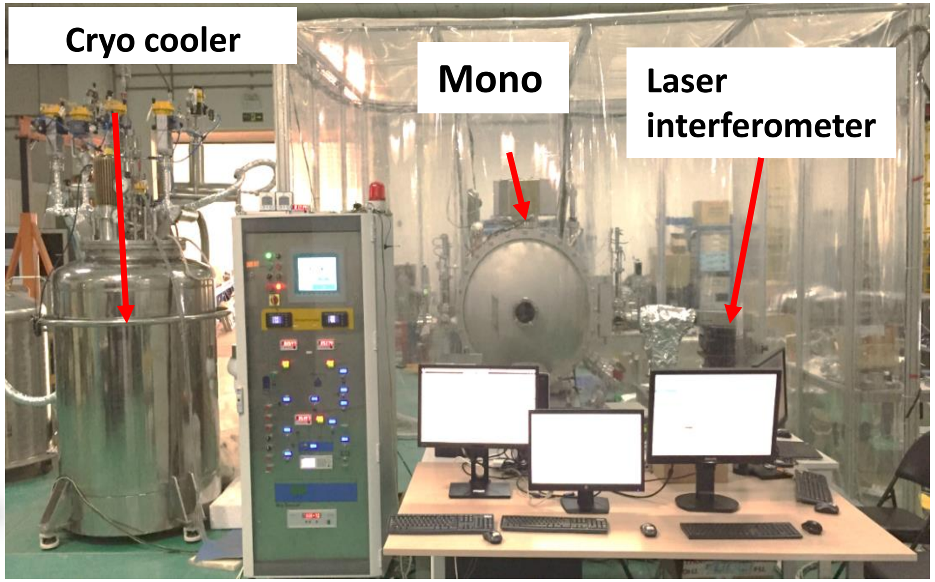


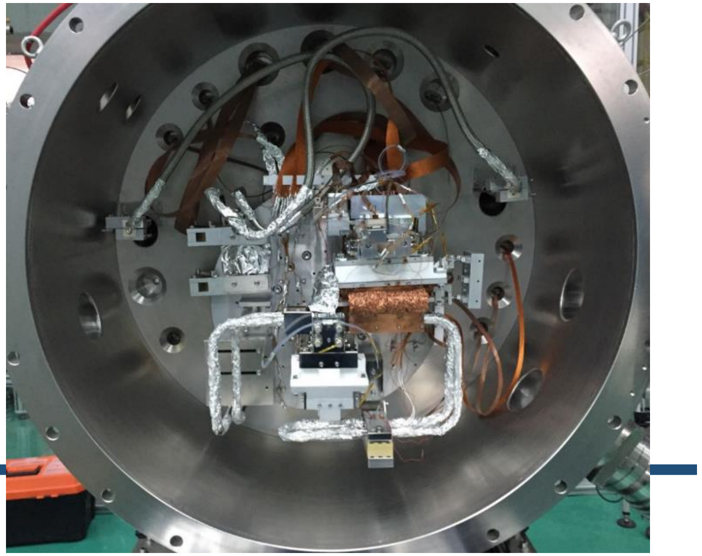
Monochromator (Prototype)

Laue Monochromator: 60-150keV

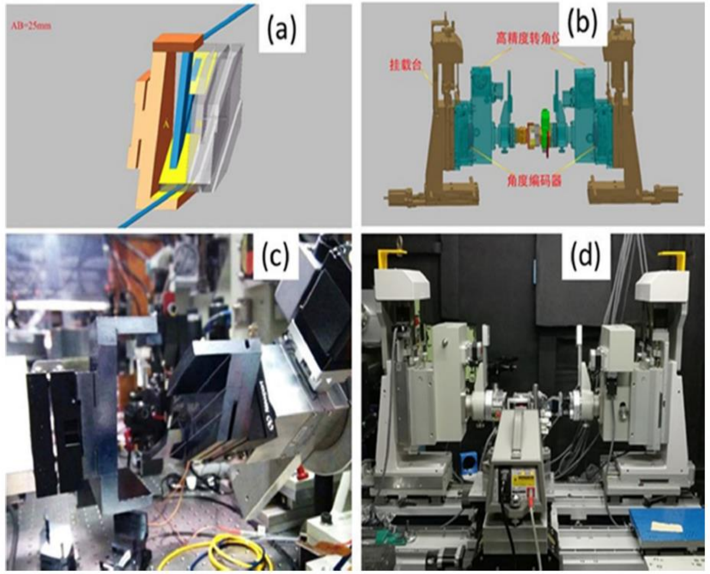


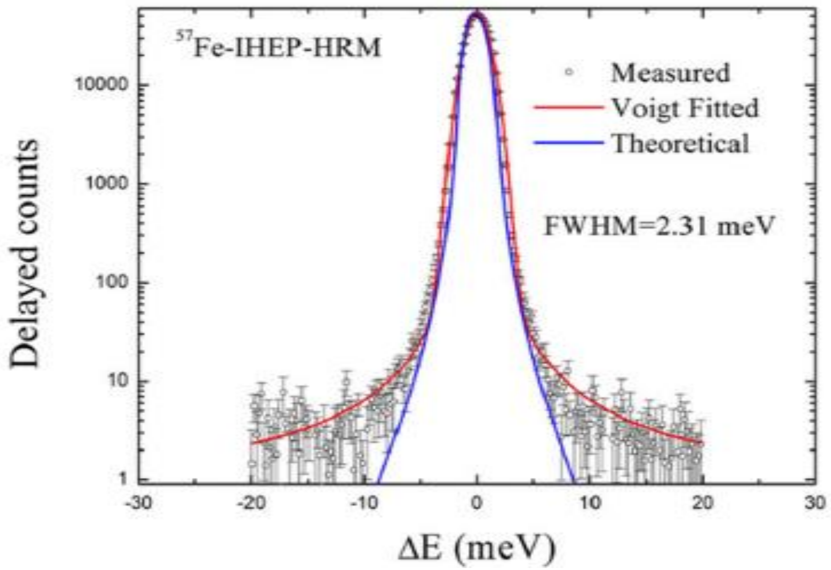
High heatload liquid nitrogen double crystal monochromator



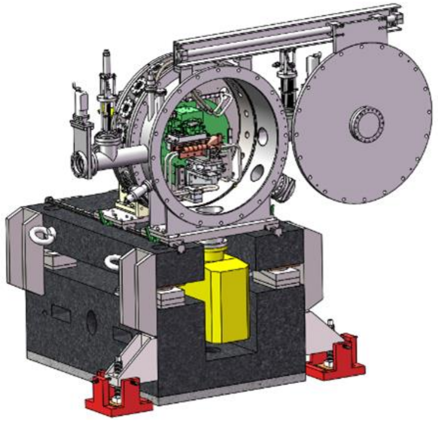


High energy resolution monochromator, meV

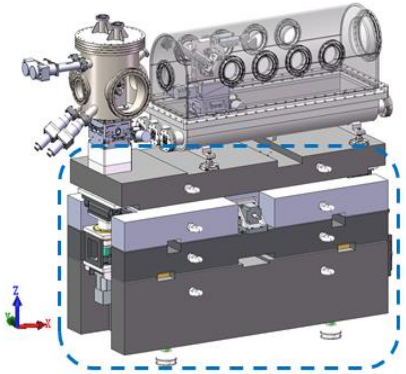




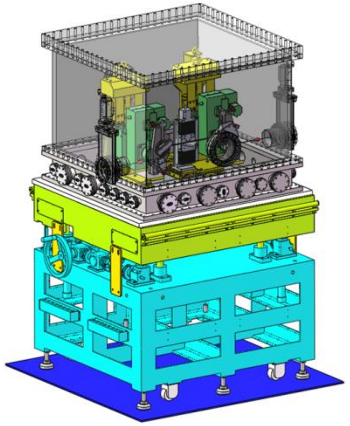
Versatile monochromators： Preliminary designs under the way



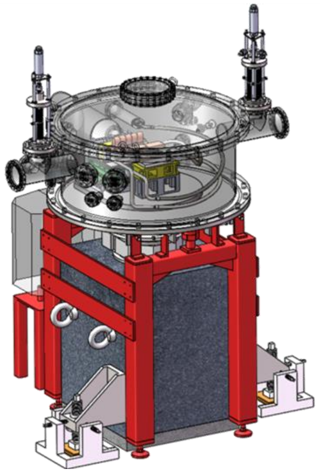
VDCM(update for HEPS)



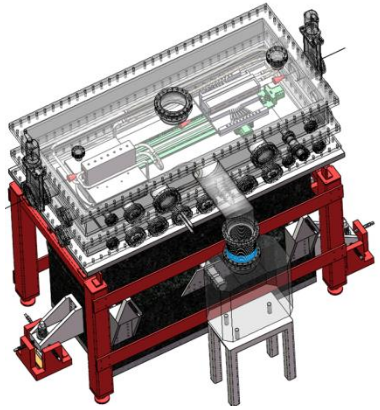
Laue Mono upgrade



HRM upgrade

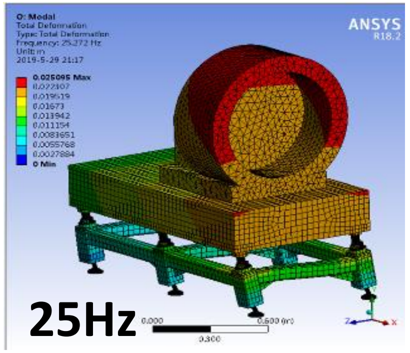


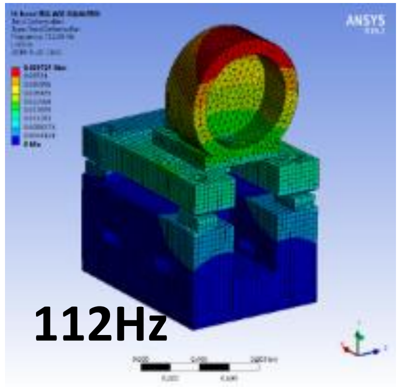
HDCM



HDMM

DCM support redesigned to increase eigenfrequency

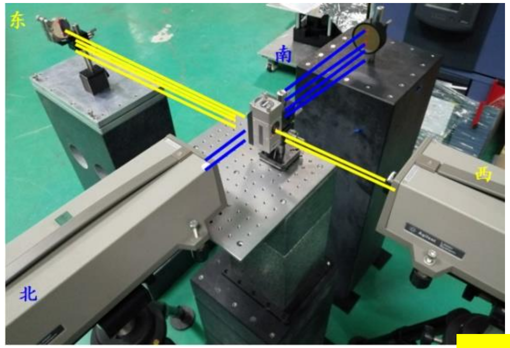


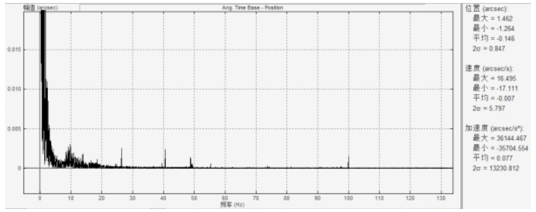


Stability measurement

Building measurement techniques

Granite base



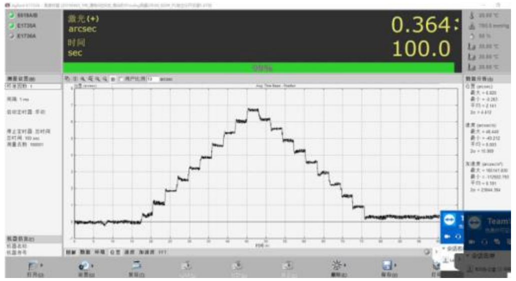


位置 (arcsec):
最大 = 1.462
最小 = -1.264
平均 = -0.146
2σ = 0.847

速度 (arcsec/s):
最大 = 16.495
最小 = -17.111
平均 = -0.007
2σ = 5.797

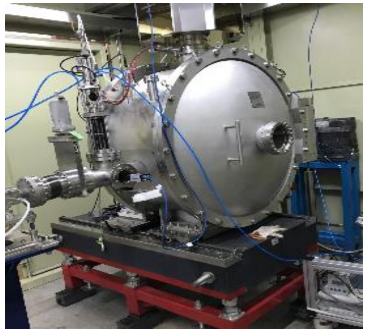
加速度 (arcsec/s²):
最大 = 36144.467
最小 = -35704.554
平均 = 0.077
2σ = 13230.812

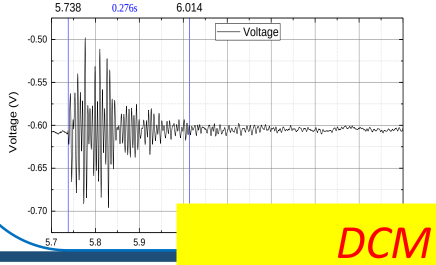
Hexapod

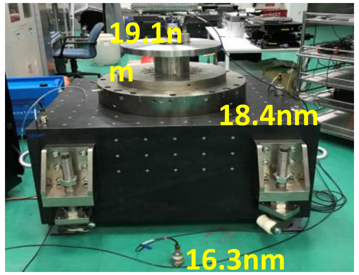


0.364:
100.0

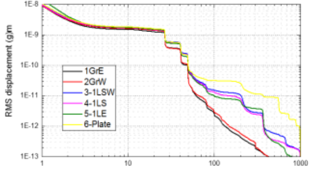
Stability test based on heterodyne interferometer



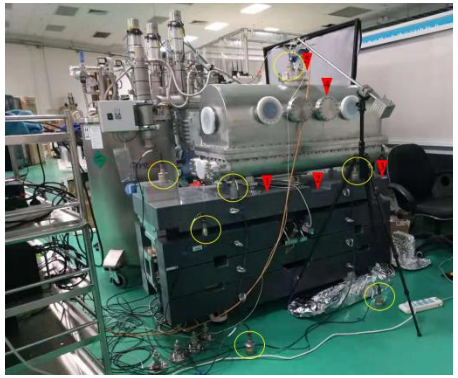


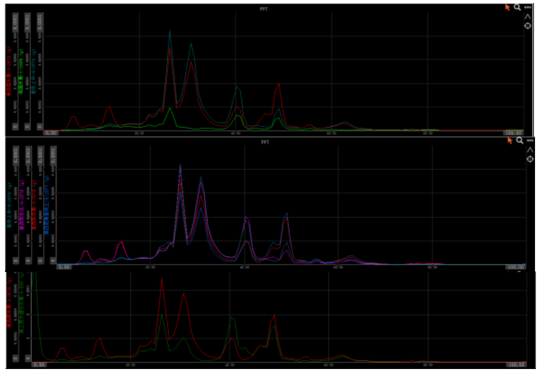


Vibration level of direct drive spindle with air bearing



Prototype vibration test

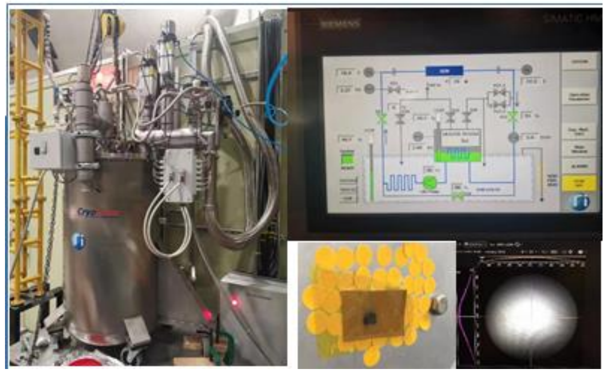




Vibration test by accelerometer

Result: Eigenfrq. revealed

Online test



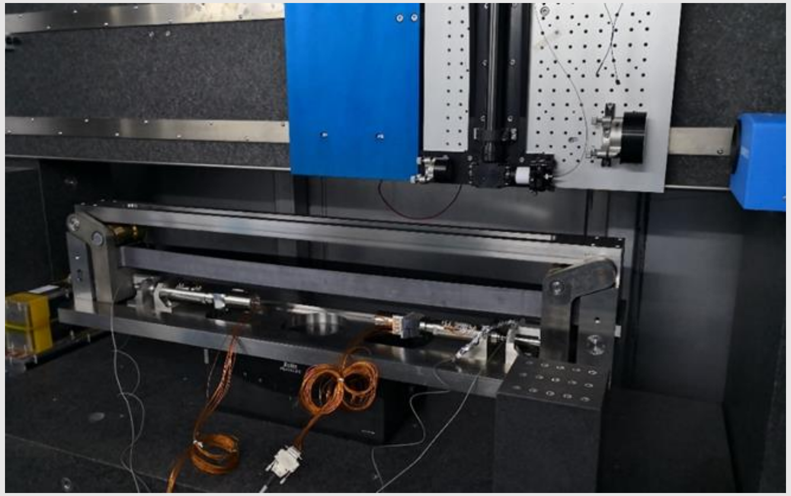
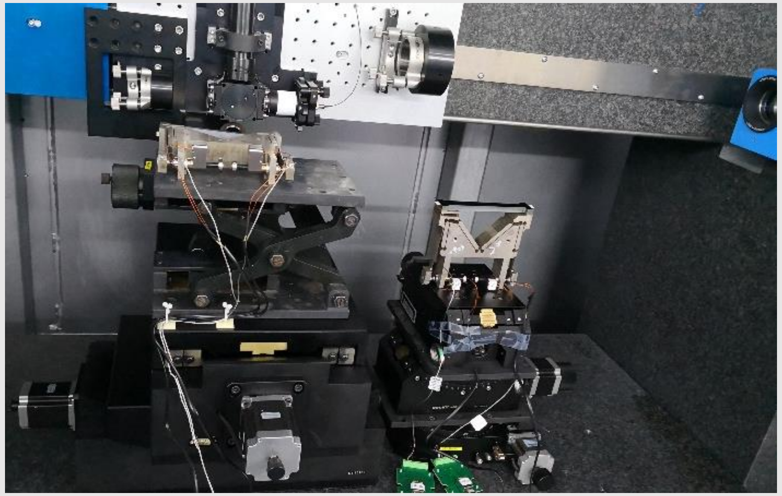
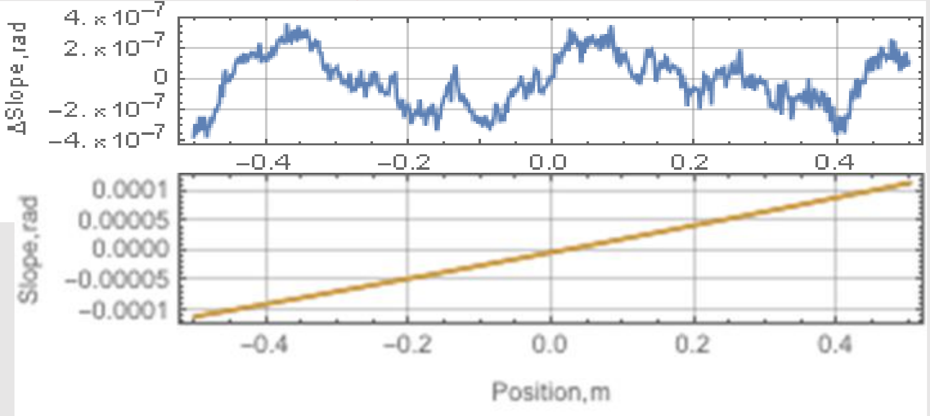
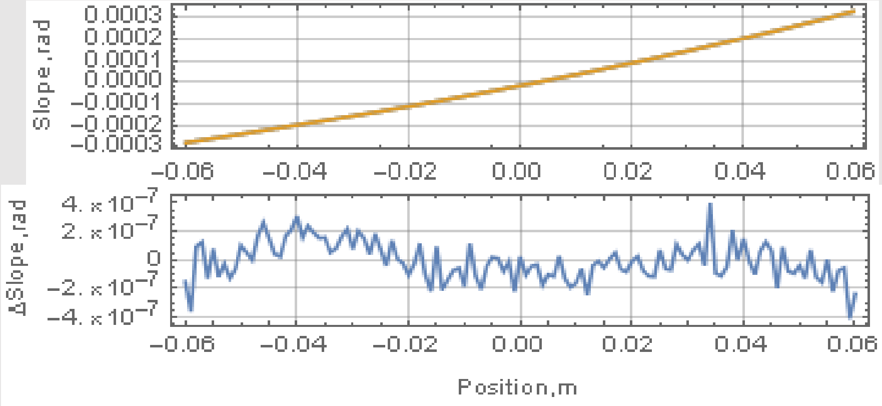
Online test in 3W1 of BSRF

- Laue mono. is running well with cryocooler system（LN cooling） in 3W1 IHEP
- Mono beam at 48.6KeV and 67KeV

DCM prototype and Laue Mono. Prototype vibration test based on accelerometer, and online test

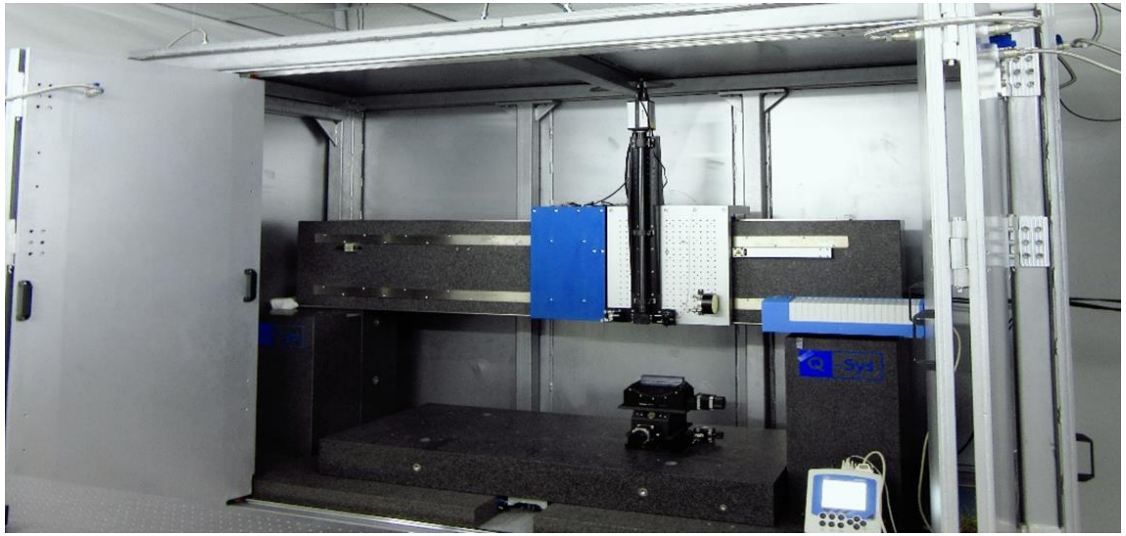
Bent mirrors for sub-micron focusing

Features: Torpedo shape , Non-gravity compensation

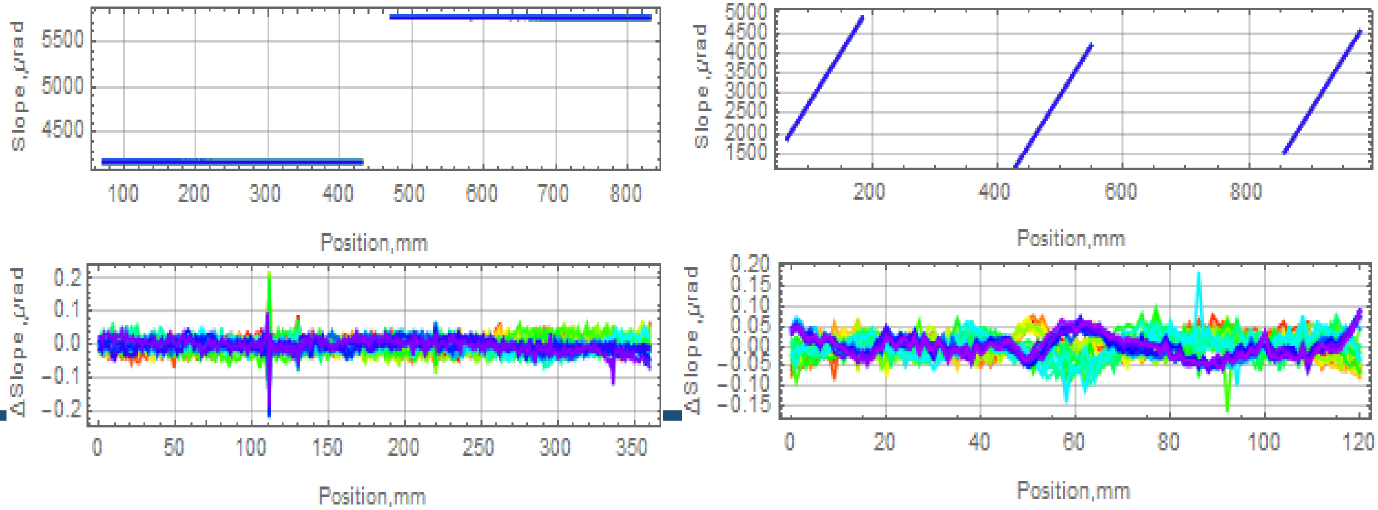
	1m long elliptically bent mirror	120mm short elliptically bent KB mirrors
Bender and metrology setup		
Test results for shape accuracy	**0.17 µrad (Vertical)**  	**0.19 µrad (Vertical) 0.13µrad(Horizontal)** 

X-ray Metrology- Flag-type Surface Profiler(FSP)

Features: High accuracy, High Speed



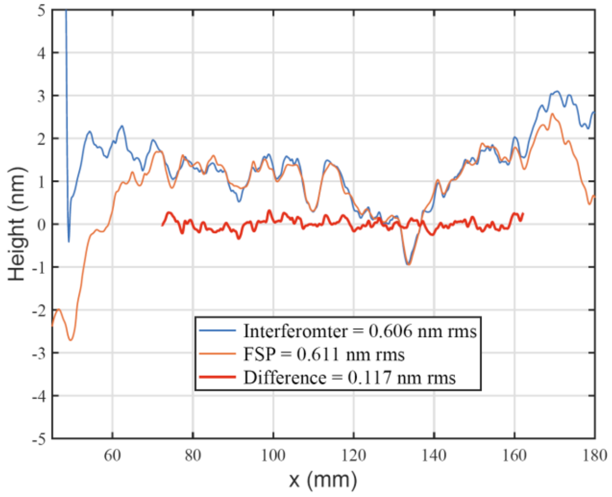
1. Self-comparison Test Accuracy



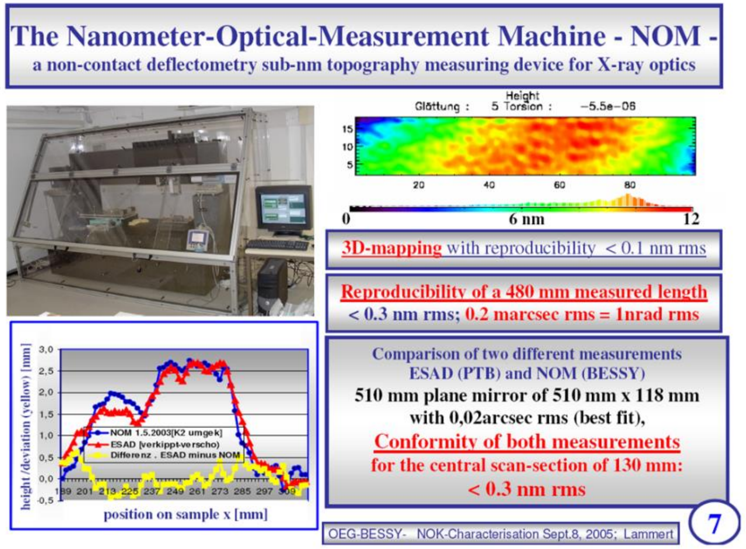
Flat mirror: RMS 25nrad

3mrad Curved : RMS 32nrad

2. Cross-check Test Accuracy



FSP@BSRF
– Interferometer
0.1nm rms



The Nanometer-Optical-Measurement Machine - NOM -
a non-contact deflectometry sub-nm topography measuring device for X-ray optics

3D-mapping with reproducibility < 0.1 nm rms

Reproducibility of a 480 mm measured length
< 0.3 nm rms; 0.2 marcsec rms = 1nrad rms

Comparison of two different measurements
ESAD (PTB) and NOM (BESSY)
510 mm plane mirror of 510 mm x 118 mm
with 0,02arcsec rms (best fit),
Conformity of both measurements
for the central scan-section of 130 mm:
< 0.3 nm rms

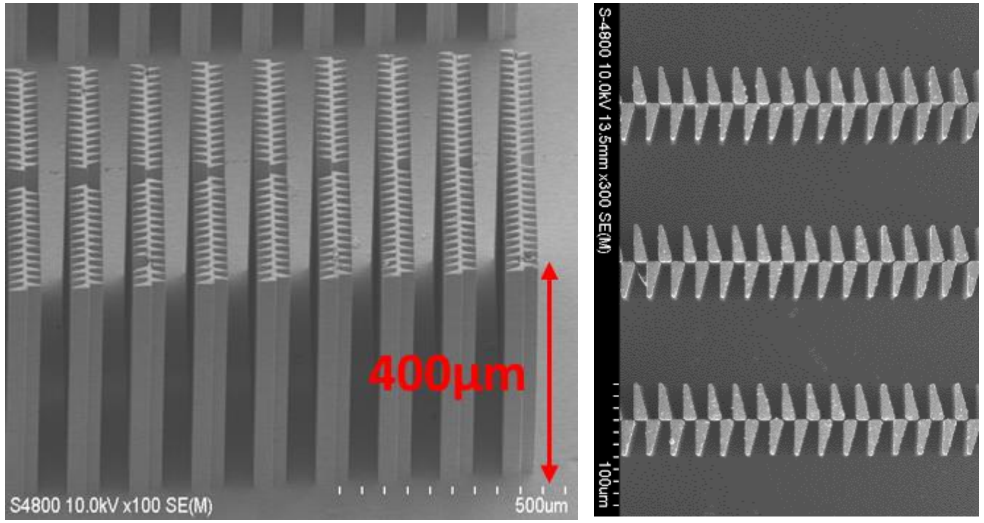
OEG-BESSY- NOK-Characterisation Sept.8, 2005; Lammert

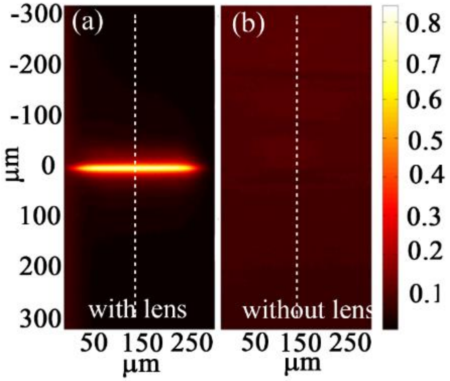
7

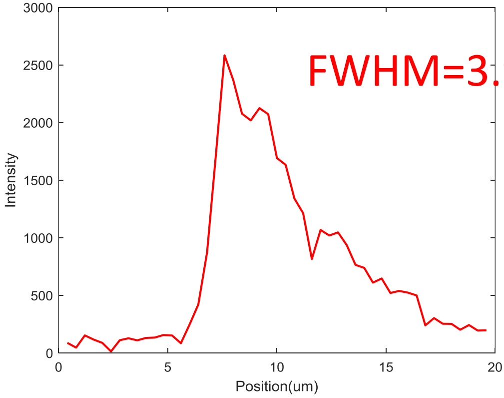
Reference:
NOM@BESSY
– ESAD@PTB
0.3nm rms

X-ray focusing optics (by LIGA using a LIGA beamline in BSRF)

High Energy X-ray Kinoform by LIGA technique
Ni based, 4μm @87KeV measured@PETRAIII

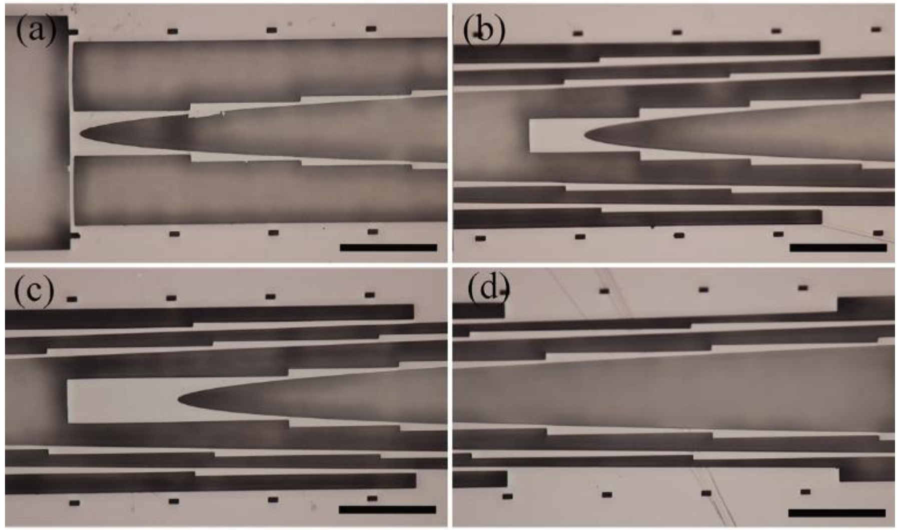


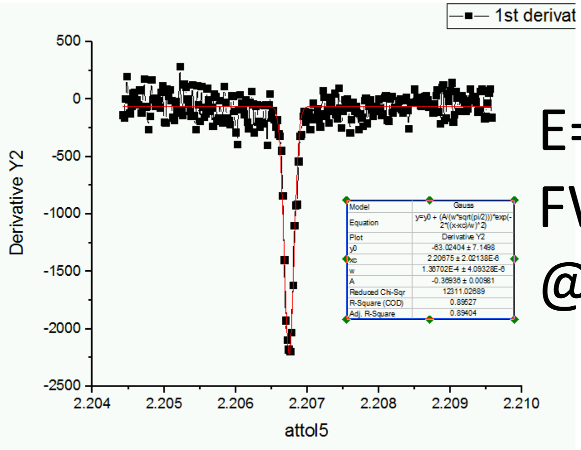




FWHM=3.95μm

X-ray PMMA Kinoform





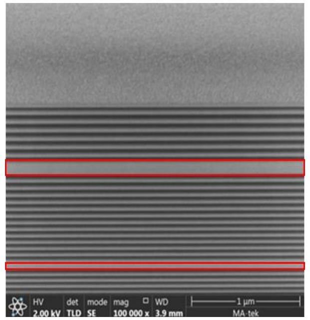
Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	Derivative Y2
y0	-63.02404 ± 7.1498
xc	2.20675 ± 2.02138E-6
w	1.36702E-4 ± 4.09328E-6
A	-0.36936 ± 0.00981
Reduced Chi-Sqr	12311.02689
R-Square (COD)	0.89627
Adj. R-Square	0.89404

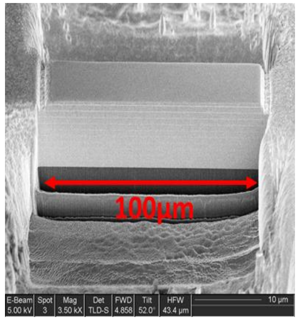
E=12keV
FWHM:~140nm
@Diamond

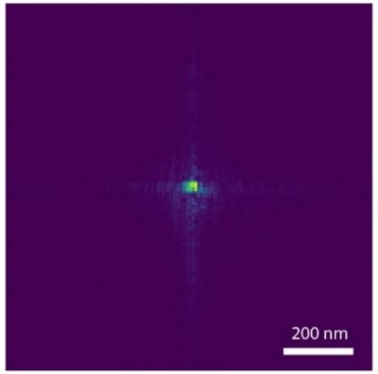
HEPS

Nano-focusing optics and manipulator

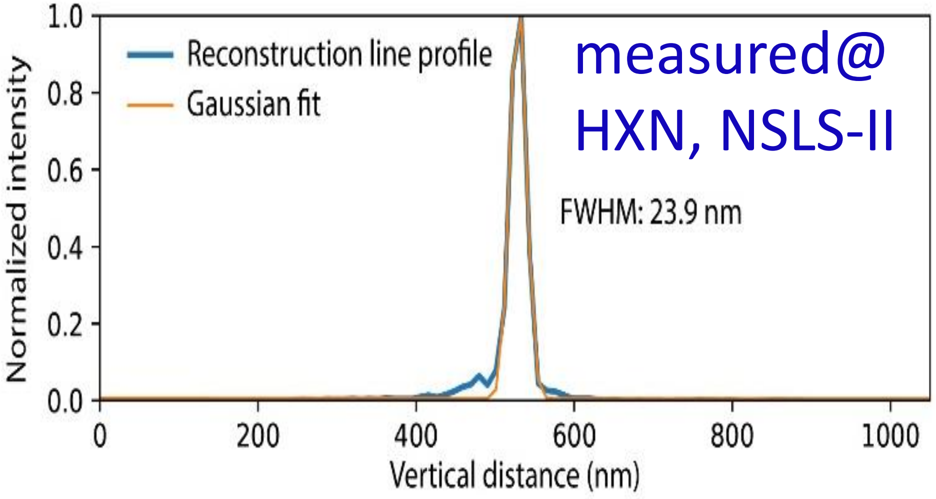
Nanofocusing - Multilayer Laue Lens





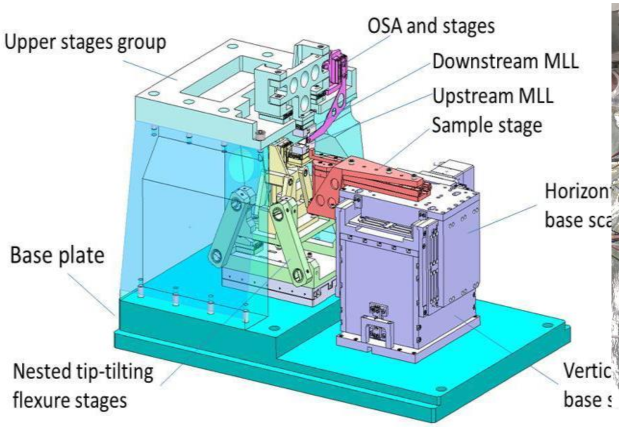


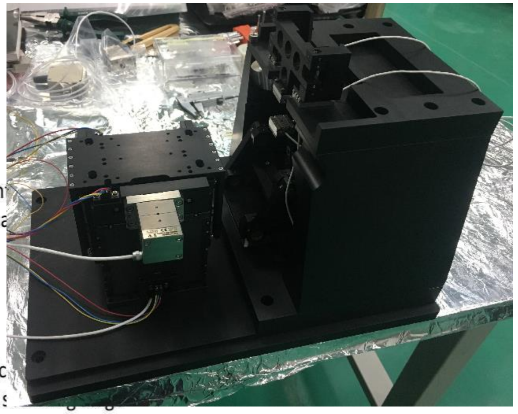
Multilayers and Mark layersFIB Polishing

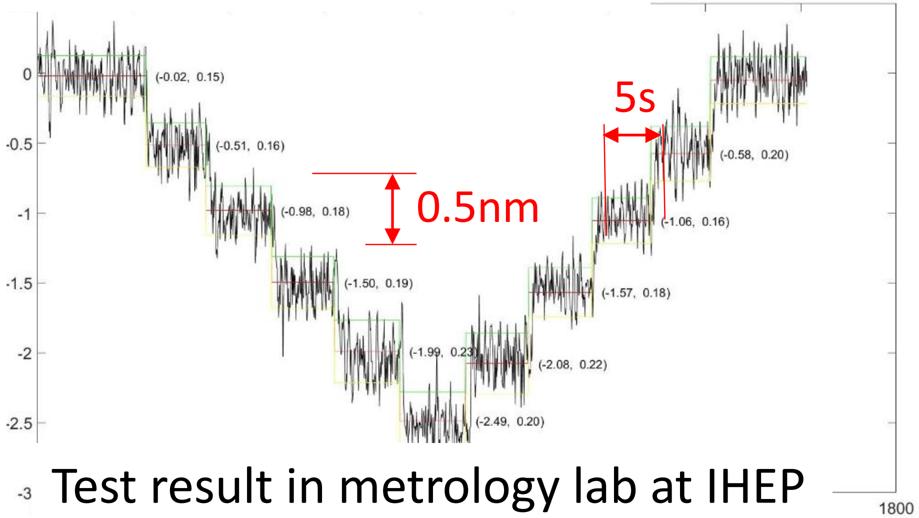


measured@ HXN, NSLS-II

Nano manipulator





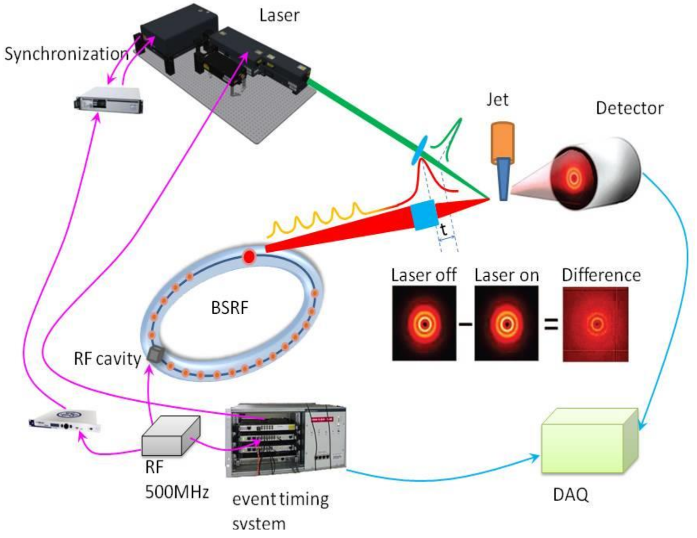


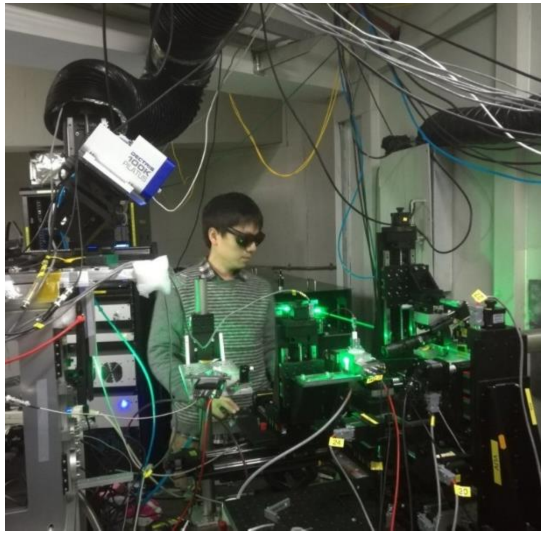
Test result in metrology lab at IHEP

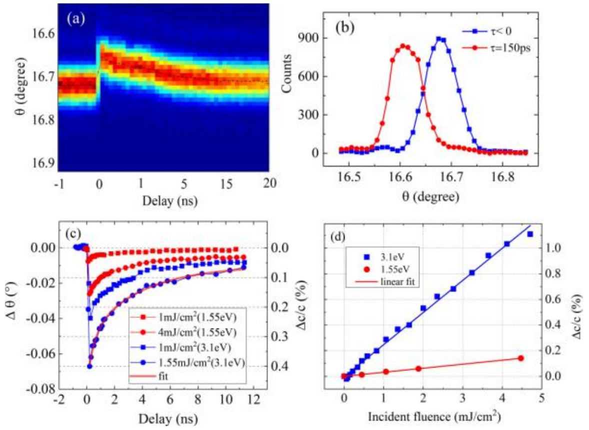
Step scan: 0.5nm, stay time: 5s

Time-resolved:

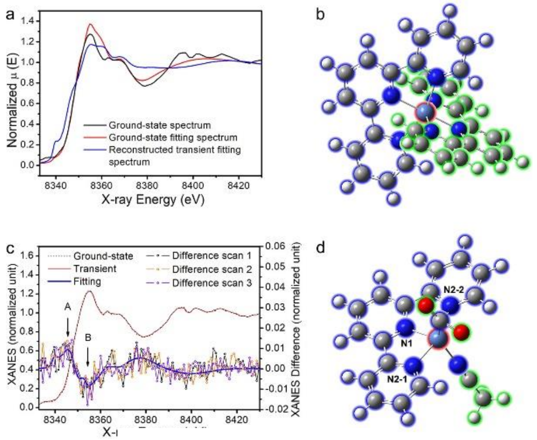
Reversible: High repetition rate laser Pump/X-ray Probe for picosecond XRD&XAS





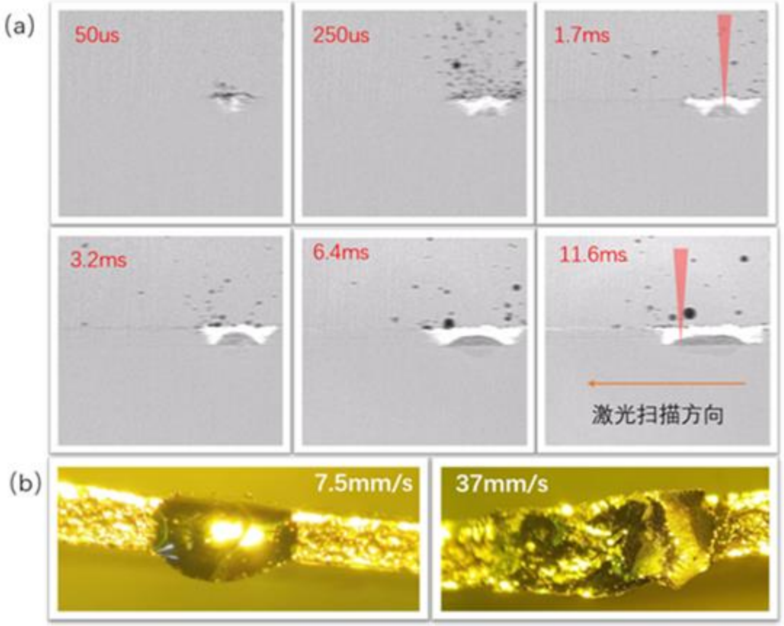


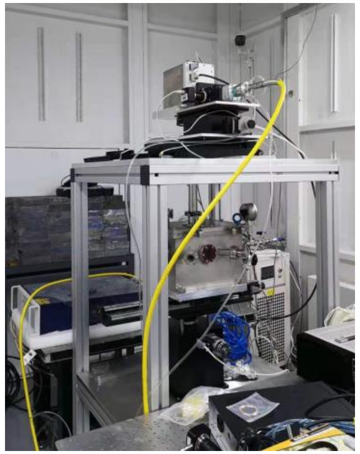
PRB, 2019



JACS, 2020

Irreversible: metal laser 3D printing process by fast X-ray imaging





Demonstration test :

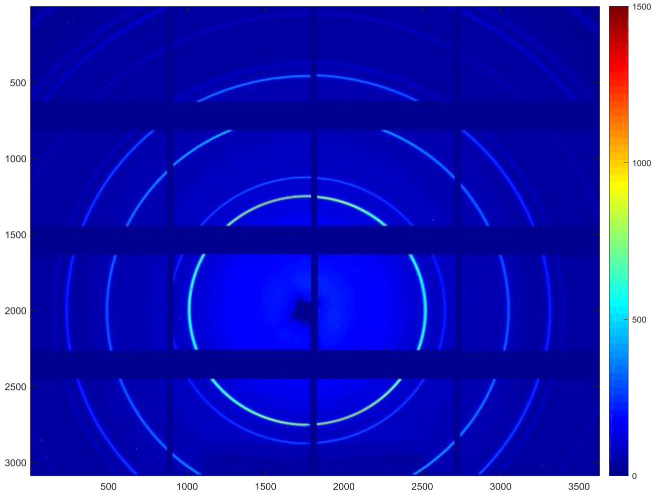
White light from SCW

600 μm Ti alloy powders；

20kfps， 20μs exposure

X-ray Pixel Array Detector

Prototype of 1M PAD



Pixel size： 150 x 150µm

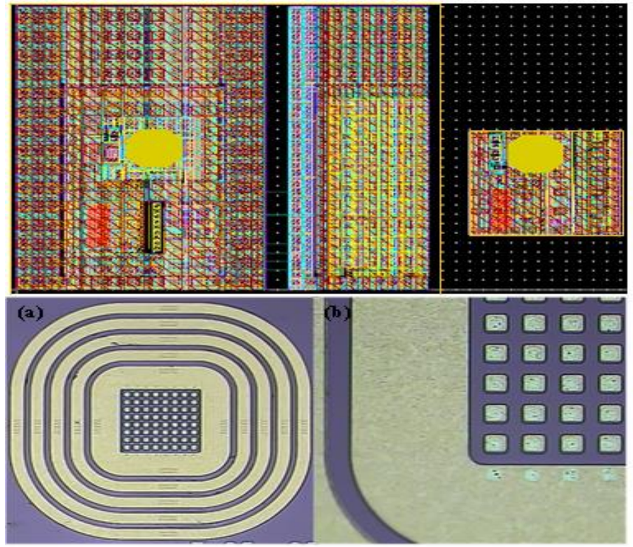
Pixel number: 1M

Active area: 12.24cm×17.28cm

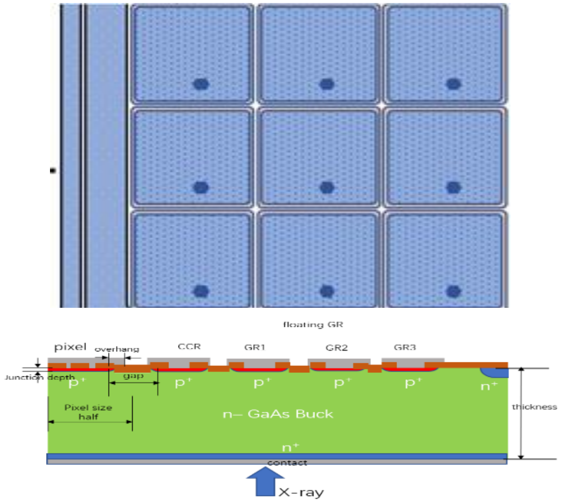
Frame rates： 1 KHz

Dynamic range: 20bits

Energy range: 8-20keV, Si-based



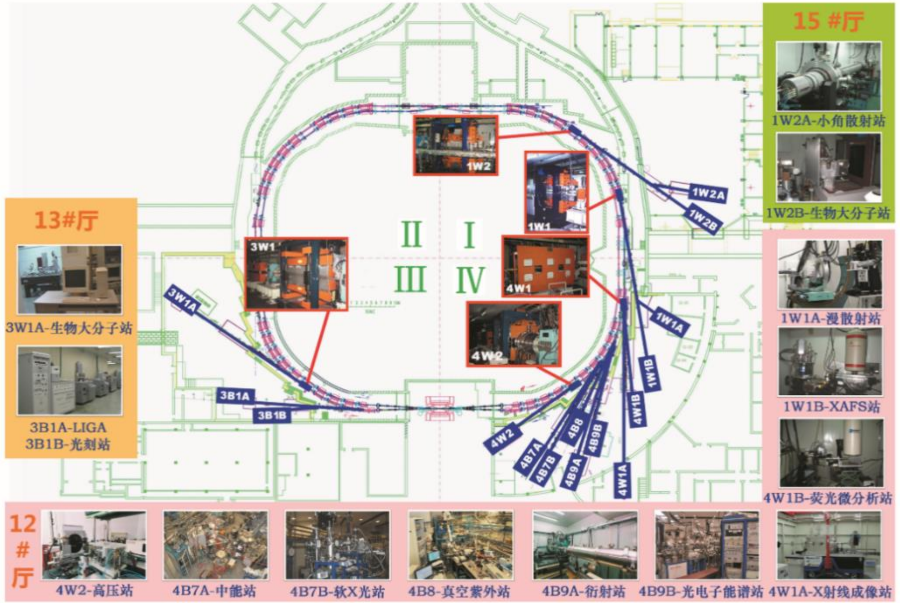
55 µm pixel module nearly finished



Module with high-energy sensor under way

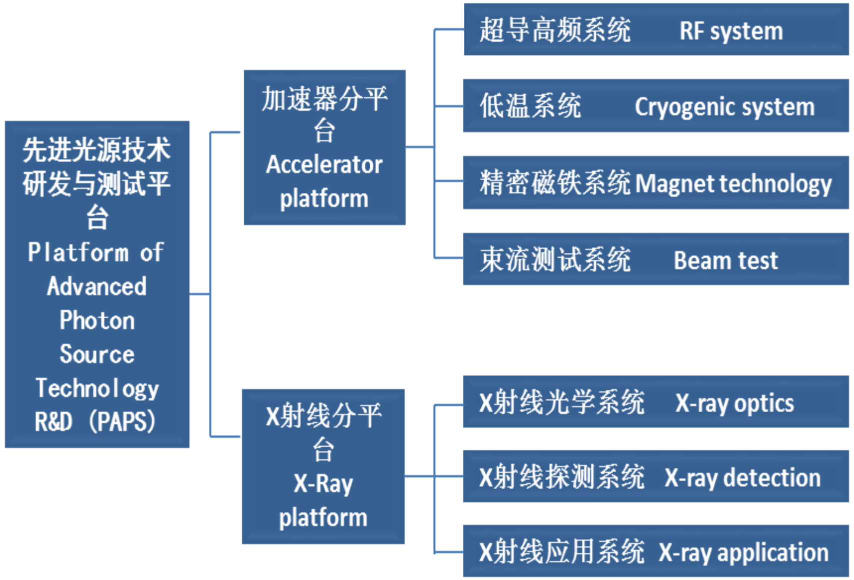
R&D tests also use x-ray from current Beijing synchrotron in IHEP, Beijing Synchrotron Radiation Facility (BSRF)

- BEPCII (Beijing Electron Positron Collider II), a double-ring factory like machine with a parasitic BSRF light source
- BSRF, 2.5GeV , 4 wigglers+1 SCW, 14 beamlines and 15 stations in total
- dedicated 3 months for BSRF per year, Parasitic mode available

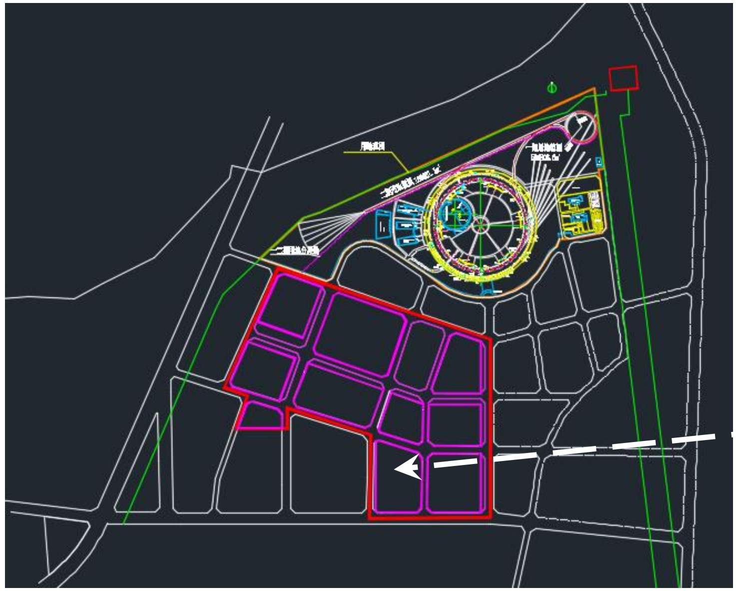


Platform of Advanced Photon Source Technology (PAPS)

- funded by Beijing local government
- Construction period: 2018.5-2021.6
- Providing key technical support for the construction of HEPS
- Platform of core technology development, verification and equipment testing
- Output of new technologies of accelerator and X-ray applications



- 先进光源技术研发与测试平台 Platform of Advanced Photon Source Technology R&D（PAPS）
  - 加速器分平台 Accelerator platform
    - 超导高频系统 RF system
    - 低温系统 Cryogenic system
    - 精密磁铁系统 Magnet technology
    - 束流测试系统 Beam test
  - X射线分平台 X-Ray platform
    - X射线光学系统 X-ray optics
    - X射线探测系统 X-ray detection
    - X射线应用系统 X-ray application



Summary

- HEPS is coming. it aims at the brightest synchrotron in the world at completion

- HEPS construction kickoff on June 29, 2019. Expected to finish at the end of 2025 and open to users
  - Civil construction moving quickly
  - Large scale procurements for accelerator have begun
  - Beamline design under optimization yet, with prototype and key tech studies under the way

Thanks for your attentions and stay Healthy !