NSRL

国家同步辐射实验室

Hefei Advanced Light Facility (HALF)

A VUV, soft X-ray and tender X-ray fourth-generation synchrotron light source in China

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NSRL
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National Synchrotron Radiation Laboratory (NSRL)

History

- The first national Lab. in China (1983)
- The birthplace of China's synchrotron radiation R&D
- 150 permanent and 100 temporary staff members

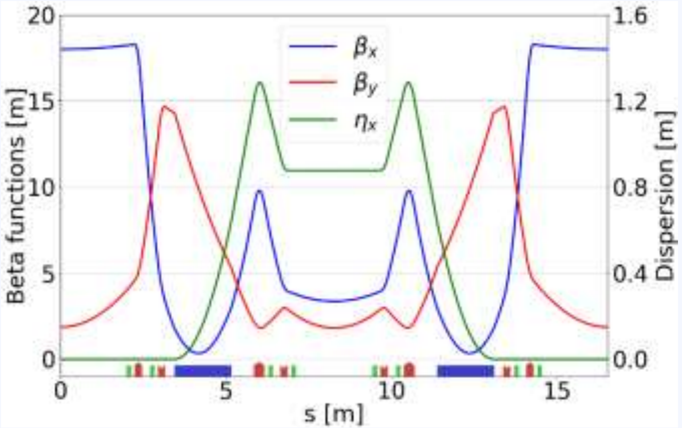
Born in 1991

Hefei Light Source (HLS)

- The first dedicated synchrotron radiation light source in China
- Won the first prize of National Science and Technology Progress in 1995.

Upgraded in 2014

The present HLS storage ring

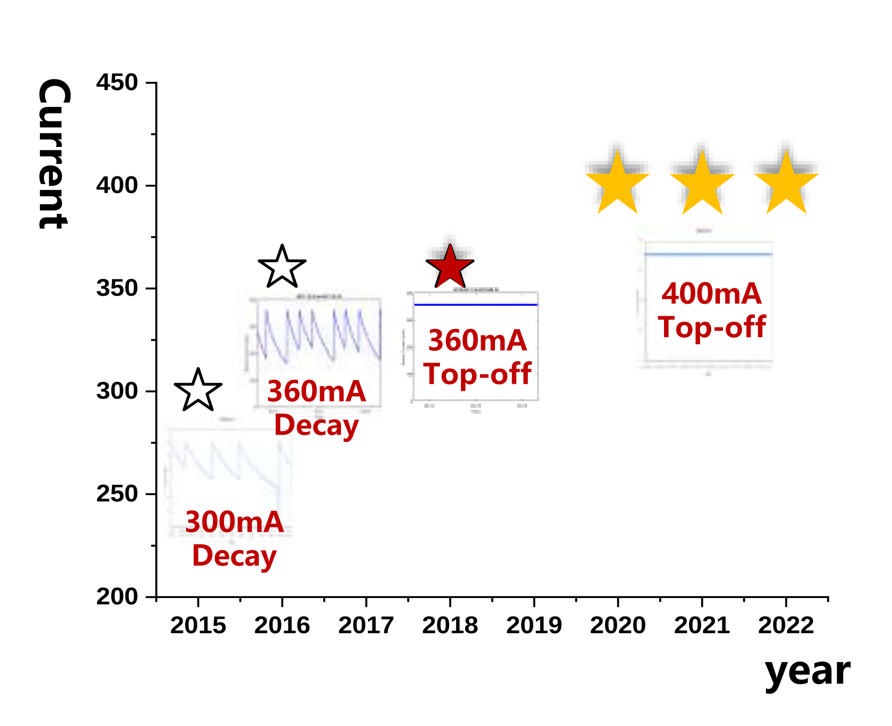


- Full-energy linac + 800 MeV storage ring
- DBA lattice with two straight sections in each cell
- Circumference: 66.13 m, with 4 cells
- Natural emittance: 36 nm•rad
- 8 straight sections: 4×4.0 m + 4×2.3 m

HLS-II Operation Performance

2021.10-2022.9

- **400mA Top-off operation**
- **Current variation: ±1%**
- **Availability: 99.7%**
- **MTBF: 213.14 h**
- **Running time: 7251 h**
- **User time: 43521.83 h**



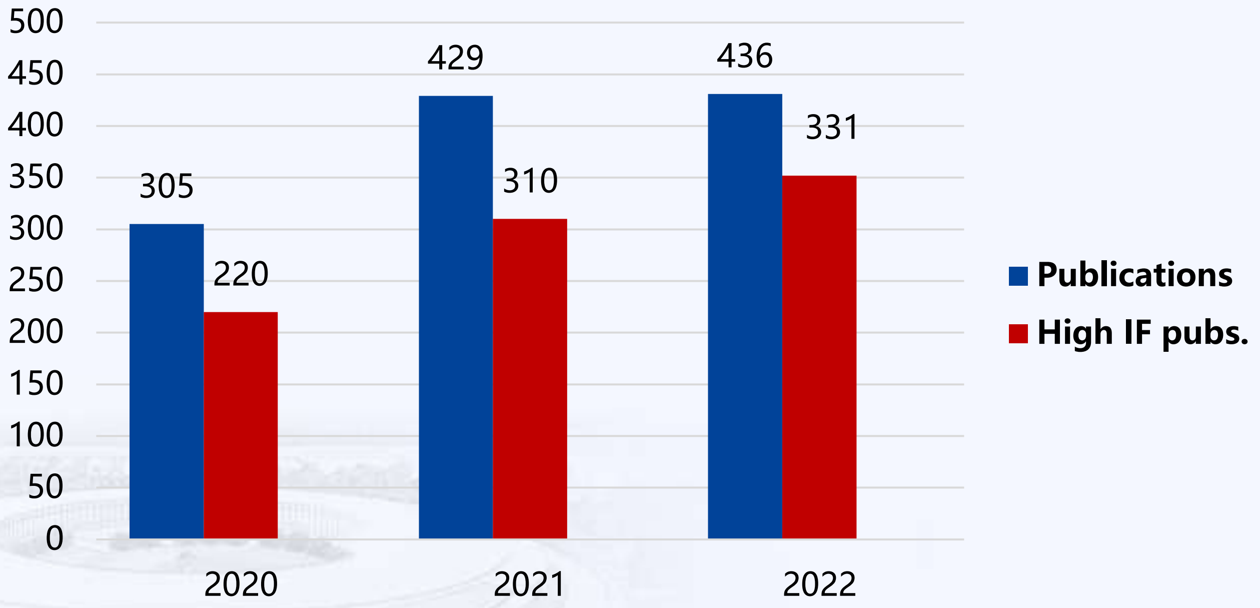
HLS-II beamline construction and upgrade

BL03U	Combustion and Flame	Built in 2014
BL07W	Soft X-ray microscopy	Built in 2014
BL09U	Atomic & molecular Physics	Built in 2014
BL11U	Catalysis and Surface Science	Built in 2014
BL13U	Angle-resolved Photoemission Spectroscopy	Upgraded in 2020
BL01B	Infrared spectroscopy and microspectroscopy	Upgraded in 2017
BL04B	Mass spectrometry	Upgraded in 2022
BL08B	Spectral Radiation Standard and Metrology	Upgrading
BL10B	Photoemission Spectroscopy	Upgraded in 2022
BL12B-a	X-Ray Magnetic Circular Dichroism (XMCD-a)	Upgraded in 2020
BL12B-b	X-Ray Magnetic Circular Dichroism (XMCD-b)	Built in 2020

User statistics

	2017	2018	2019	2020	2021	2022
Institution	78	117	106	78	115	170
Executed proposals	332	370	420	373	532	474
Submitted proposals	517	602	415	426	715	661
Users	1156	1320	1269	1321	1078	1058

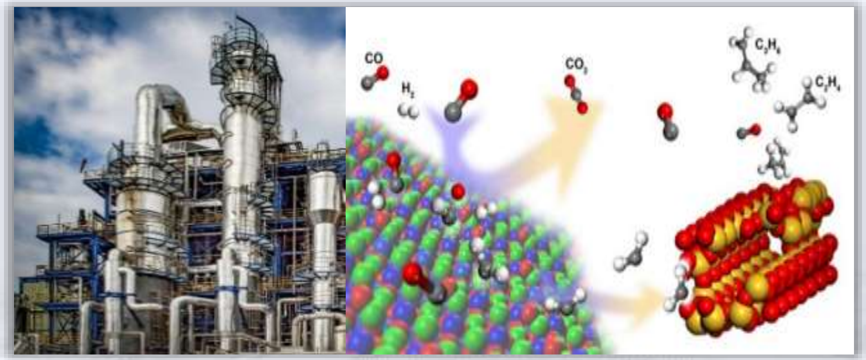
Publication statistics



In 2022, 245 papers are published in journals with Impact Factor above 9

PIMS user research highlights

Clean utilization of coal



Professor Bao Xinhe's team has detected key intermediates in the production of olefin from coal-based syngas, breaking the traditional Fischer-Tropsch limit

Science, 2016, 351, 1065
One of ten scientific advances in China (2016)
National Natural Science First prize (2020)

Infrared FEL (FELiChEM)

- The first FEL user device covering middle and far infrared region in China since 2022.3.
- The first infrared FEL facility dedicated to energy chemistry research.
- The key performance indicators are highly competitive.

Wavelength	2-50 μm (Mid-IR); 20-200 μm (Far-IR)
Electronic beam energy	12-60 MeV
Micro-pulse length	~3 ps
Macro-pulse length	1-10 μs
Macro-pulse Repetition frequency	1-10 Hz
Micro-pulse energy	10-170 μJ (Mid-IR); 0.2-172 μJ (Far-IR)
Macro-pulse energy	10-180 mJ (Far-IR); 0.06-80 mJ (Far-IR)
Bandwidth	0.1-3 %

Infrared FEL (FELiChEM)

- Currently 5 beamlines, space available for 3 more.
- Serving the fields of energy chemistry, catalysis science, materials science, etc.
- Published 62 high-level research papers including Science, Phys. Rev. Lett till now.

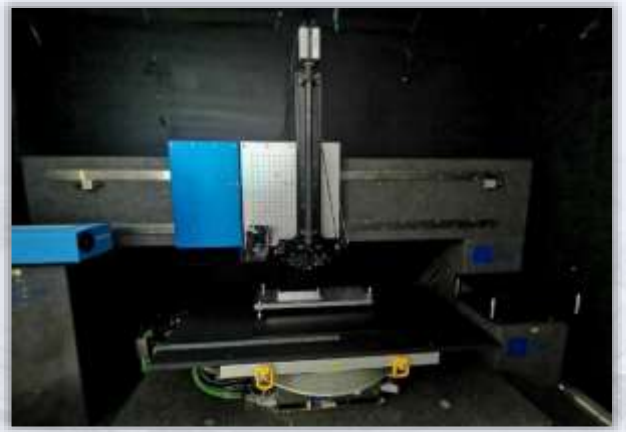
- **Photo Dissociation Spectroscopy:** Chemical structure of clusters
- **Photo Excitation Spectroscopy:** Molecular reaction dynamics of vibrational excited state
- **Sum Frequency Generation Spectroscopy:** High time resolution surface vibration spectroscopy.
- **Atomic Force Microscopy Spectroscopy:** High spatial resolution IR spectroscopy for solid-gas, solid-liquid interface.
- **Reflection Absorption Spectroscopy:** High sensitivity far-IR spectroscopy for solid-gas, solid-liquid interface.





Key Technology
— Optical Validation and Grating fabrication

- Establish the surface interferometric measurement system with high accuracy
- Overcome the "Spillover Effect"
- Establish diffraction grating fabrication technique for blazed grating with the line density of 400-2400 lines/mm, uniformity better than 2E-6



surface interferometric measurement with high accuracy LTP: repeatability of 50 nrad (rms)

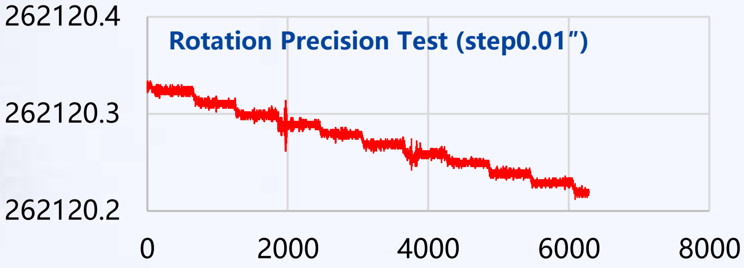
Diffraction grating fabrication

Key Technology
— High resolution grating monochromator fabrication

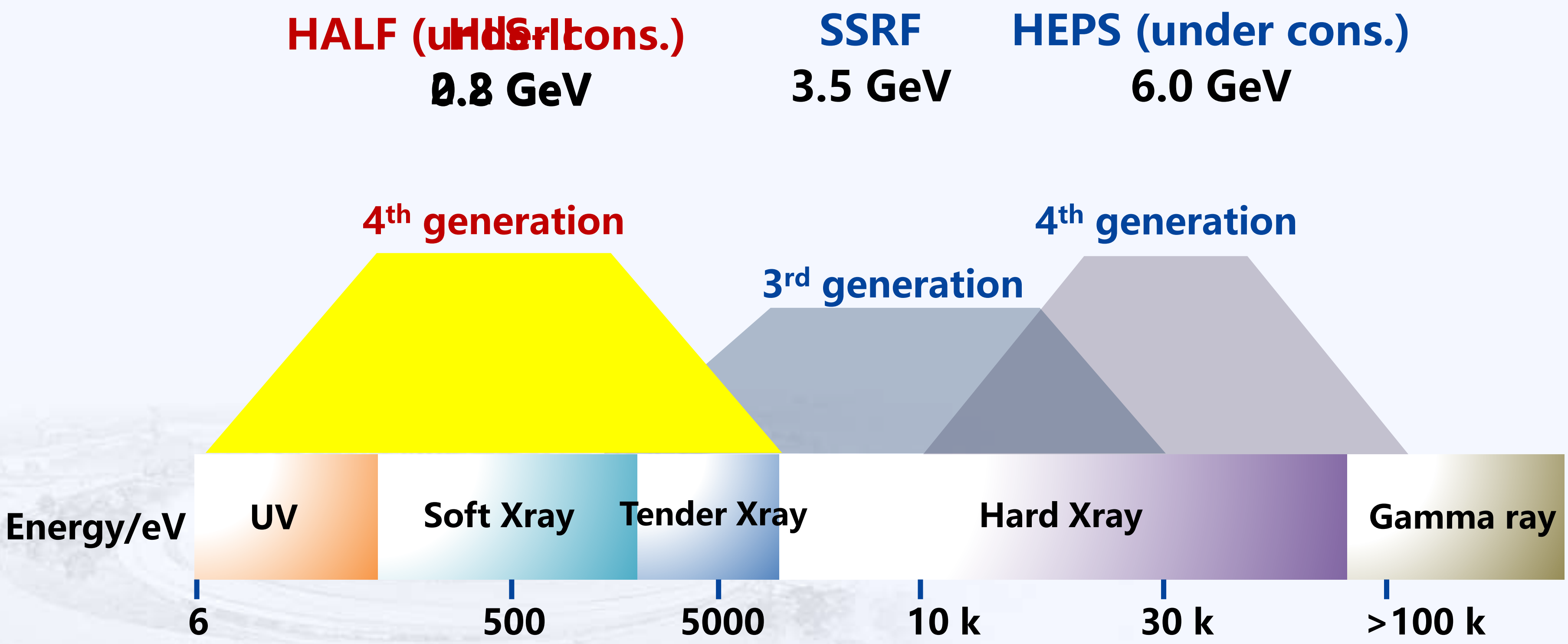
The key device to achieve high energy resolution

Axes Rotation Range	0~16°
Rotation Repeatability	0.1″
Rotation Precision	0.01″
Axes Parallelism	3″
Stability	0.05″/2h

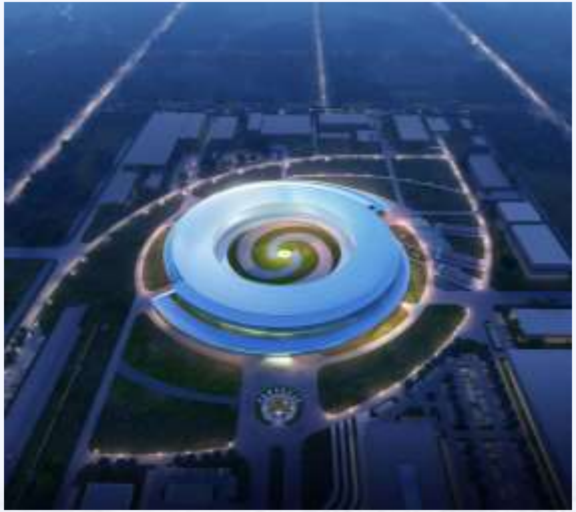
- **Fabrication of high energy resolution grating monochromator**
- **Meet the requirement of 100,000 energy resolving power**

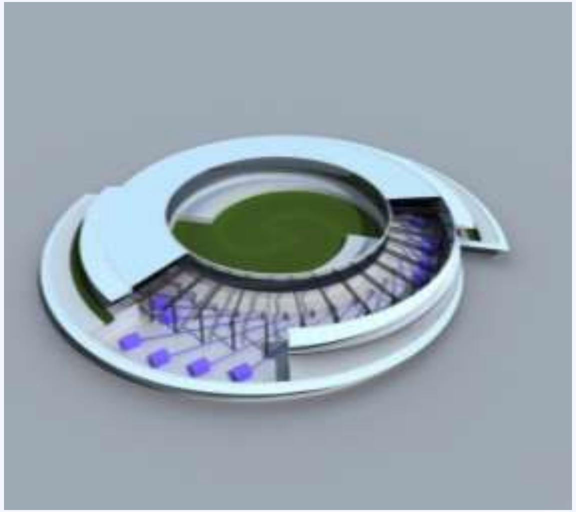


HALF – to complete the energy spectrum



Hefei **A**dvanced **L**ight **F**acility (HALF)





- The big eye to explore the microscopic world
- Hefei city is known for : a city + a university (USTC)
- Facility (Instrument development) + User (Scientific application)
- User participation is extremely important to the construction of HALF

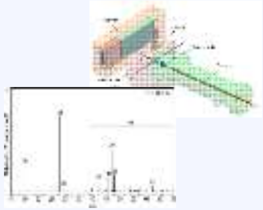
Hefei Advanced Light Facility (HALF)

Scientific goal of HALF

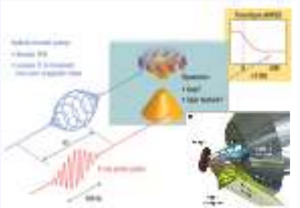
Scientific goal

Accurate measurement of electronic states/chemical states/light element structures of complex systems

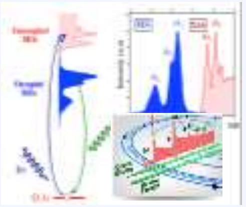
Spectroscopy/ Scattering



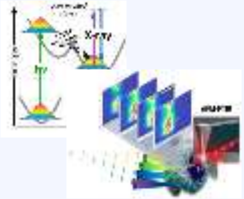
Mass spectrometry



nano-ARPES

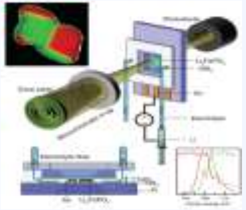


Core-level spectroscopy

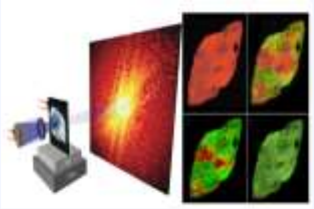


RIXS/REXS

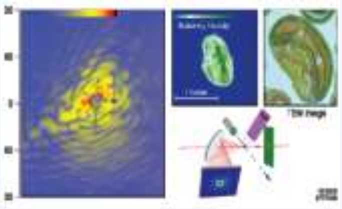
Imaging/ Diffraction



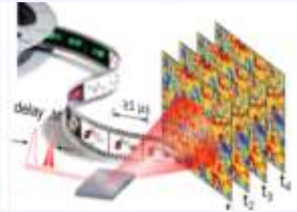
STXM



Ptychography

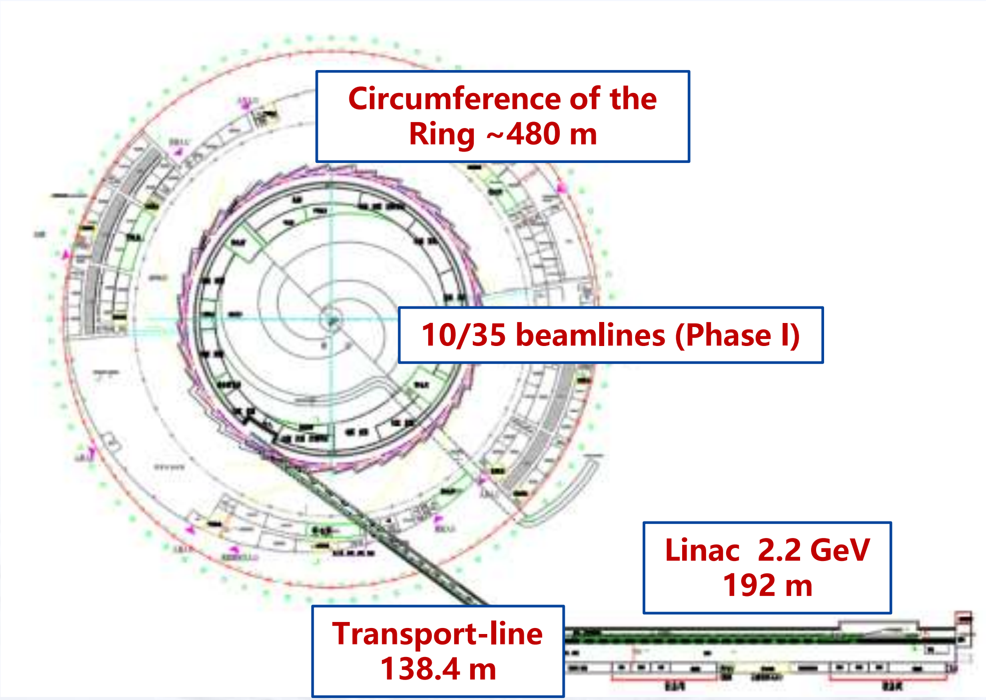


Coherent diffraction



XPCS

Engineering goal of HALF Phase I



- **Construction period:** **64 months (June 2023- Sept. 2028) .**
- **Total budget 2.8 billion RMB.**
- **Total of 35 beamlines planed, 10 of them to be constructed in phase I.**

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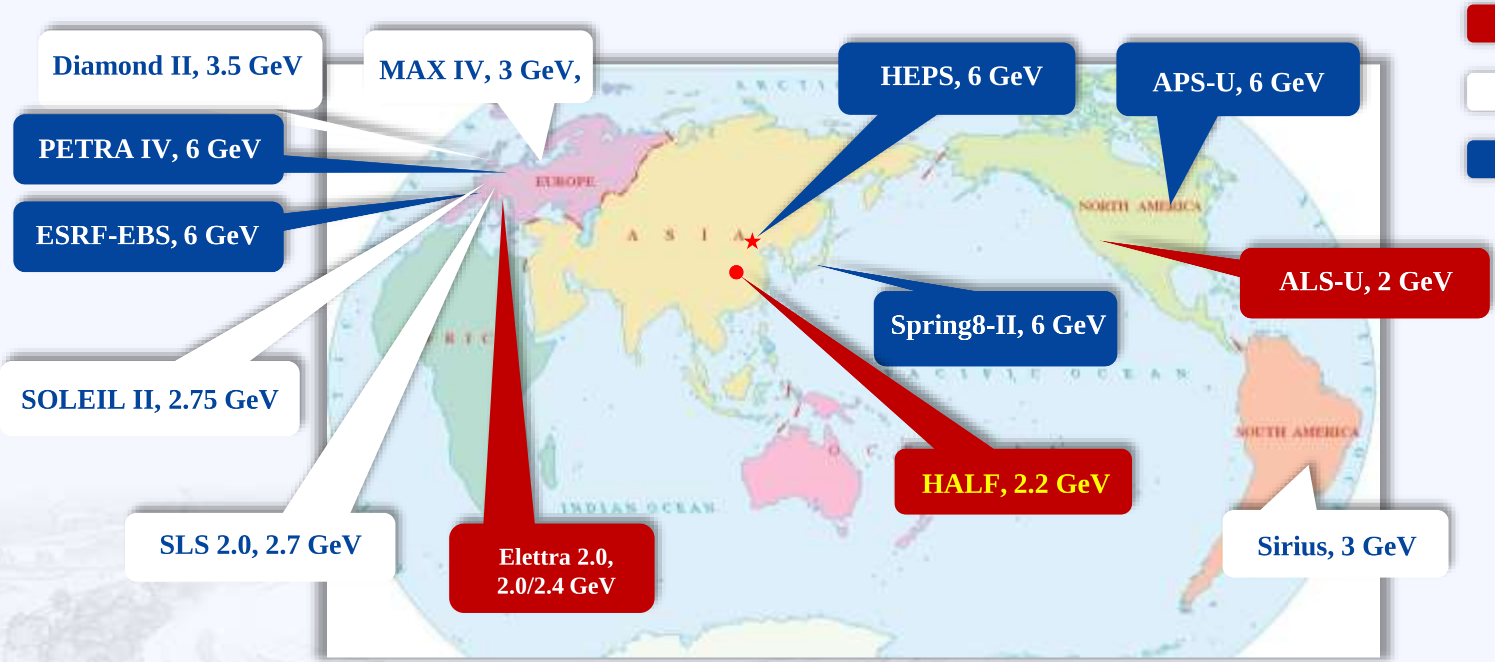
Fourth-generation synchrotron light sources

NSRL National Synchrotron Radiation Laboratory



Low energy

Medium energy

High energy

In operation:

- MAX IV (3 GeV)
- ESRF EBS (6 GeV)
- Sirius (3 GeV)

Forth-generation synchrotron light sources in operation & construction, and to be constructed

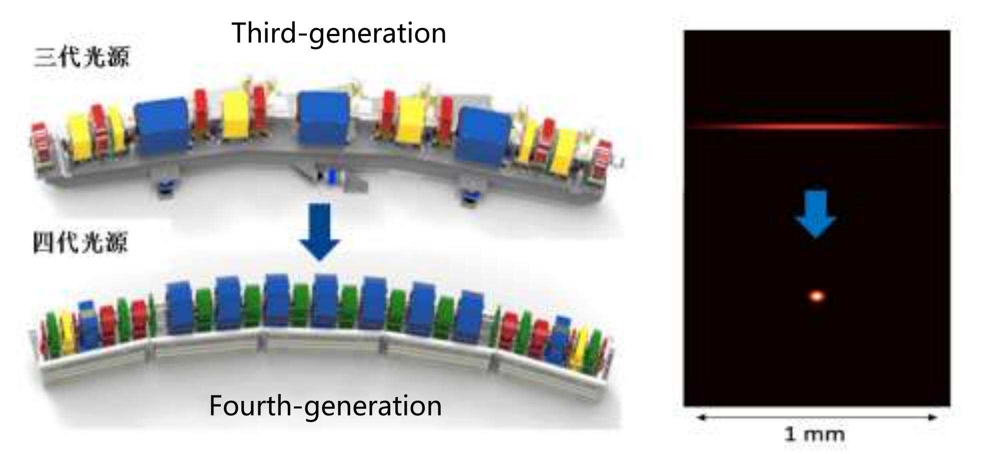
Fourth-generation synchrotron light sources

- **Electron beam emittance: towards diffraction-limited emittance**

  1~2 orders of magnitude lower than those of third-generation sources

  diffraction-limited storage ring

- **Multi-bend achromat lattice**



HALF storage ring physics

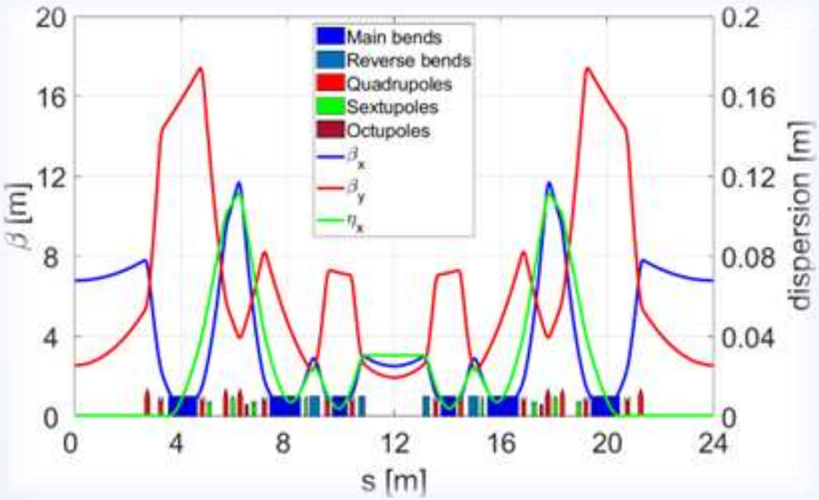
A modified hybrid 6BA lattice structure

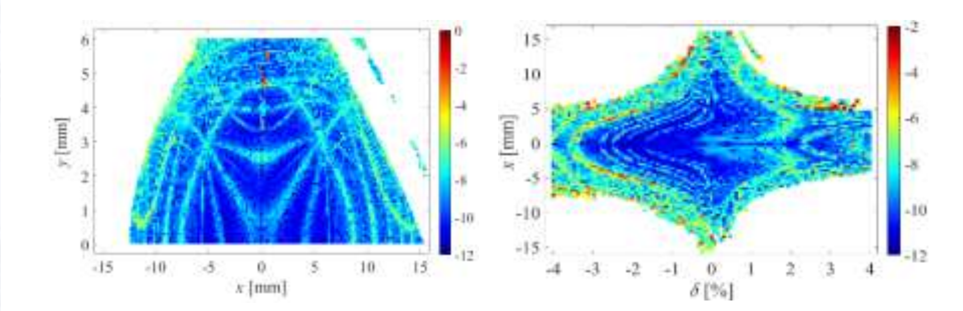
H6BA Lattice

- ESRF-EBS lattice (hybrid MBA) + SLS-2 lattice (LGB/RB cell)

  Low beam emittance + Good nonlinear beam dynamics + Relatively short damping times

- 20 cells, 2 straight sections per cell (5.3 m, 2.2 m) as Diamond II → 40 straight sections





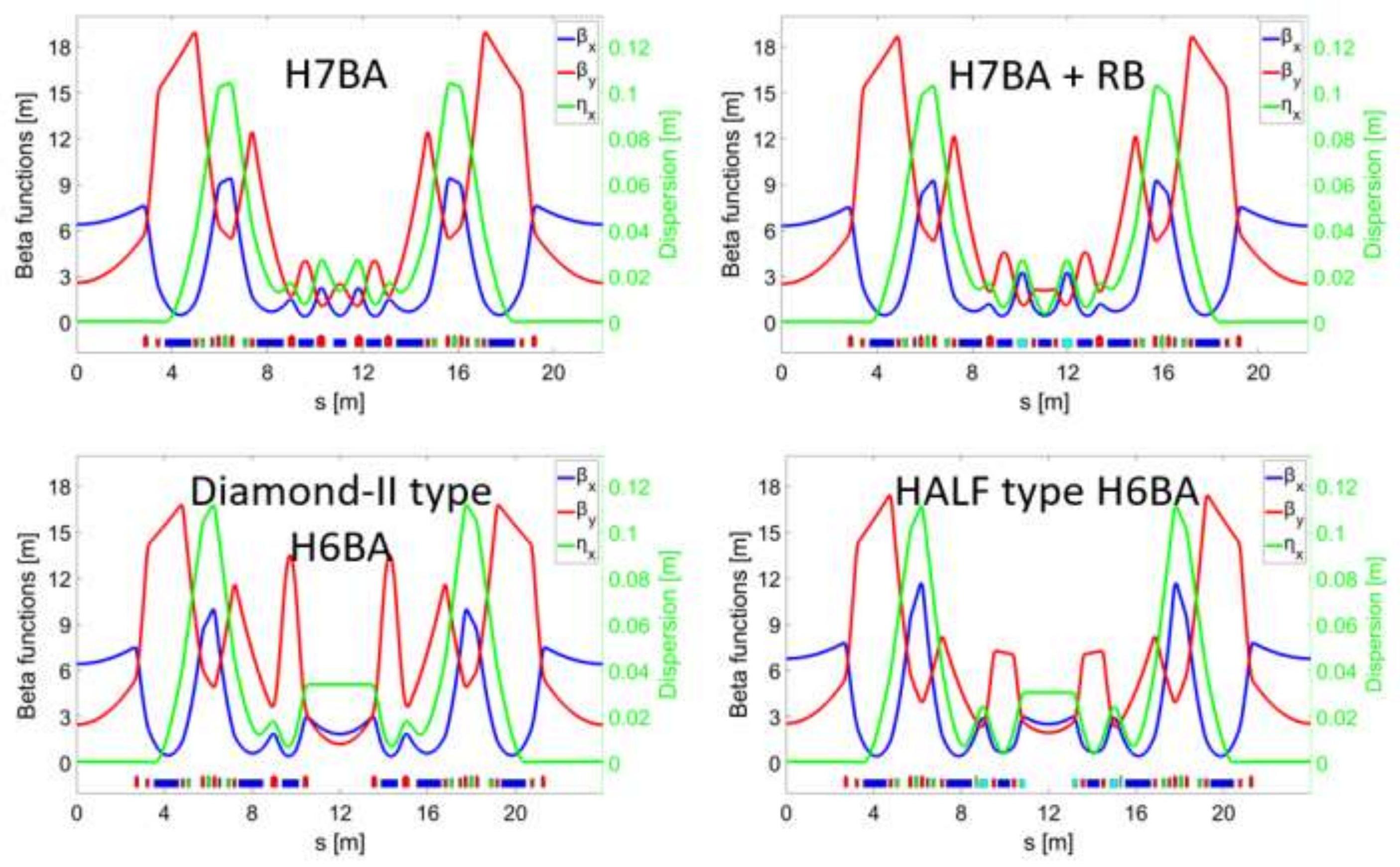
Maximum Field Gradient

Q ~50 T/m, S <2000 T/m², O<1.0×10⁵ T/m³

Main parameters of the HALF storage ring

Parameters	Design Specification
Beam Energy [GeV]	2.2
Average Beam Current [mA]	350
Circumference [m]	479.86
Lattice Structure	6BA
Beam Natural Emittance [pm•rad]	86
Beam Orbit Stability (rms)	<10% Transverse Beam Size
Straight Sections (number and length)	20×5.3 m+20×2.2 m
Brightness @ 1 keV [Flux/mm^{2}mrad^2]	>10^{21}
Coherent fraction of synchrotron emission @ 1 keV	30%

Comparison with other HMBA lattices



Comparison with other HMBA lattices

With the same energy and number of cells, the HALF modified H6BA lattice has:

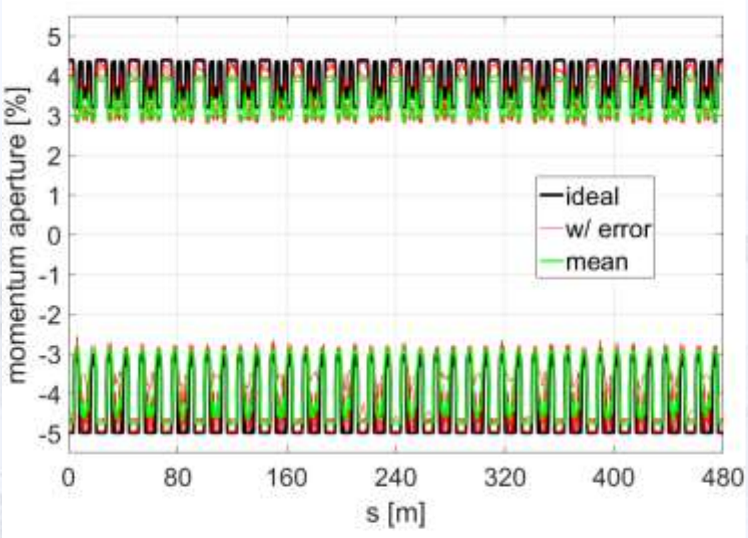
- **almost the same emittance as that of H7BA**
- **relatively short damping times but also relatively small momentum compaction**
- **more straight sections**

Parameters	H7BA	H7BA + RB	Diamond-II type H6BA	HALF type H6BA
Circumference (m)	441.6	441.6	479.86	479.86
Natural emittance (pm·rad)	84.1	71.5	103.3	85.8
Momentum compaction factor	1.73×10^{-4}	1.31×10^{-4}	1.59×10^{-4}	0.94×10^{-4}
Natural damping times (H/V/L) (ms)	36.4/54.6/36.4	26.3/41.2/28.7	43.9/57.3/33.8	28.5/38.8/23.7
Straight sections: number and length	20×5.6 m	20×5.6 m	20×5.3 m + 20×2.9 m	20×5.3 m + 20×2.2 m

Touschek lifetime and IBS effect

Touschek lifetime calculated based on local MA

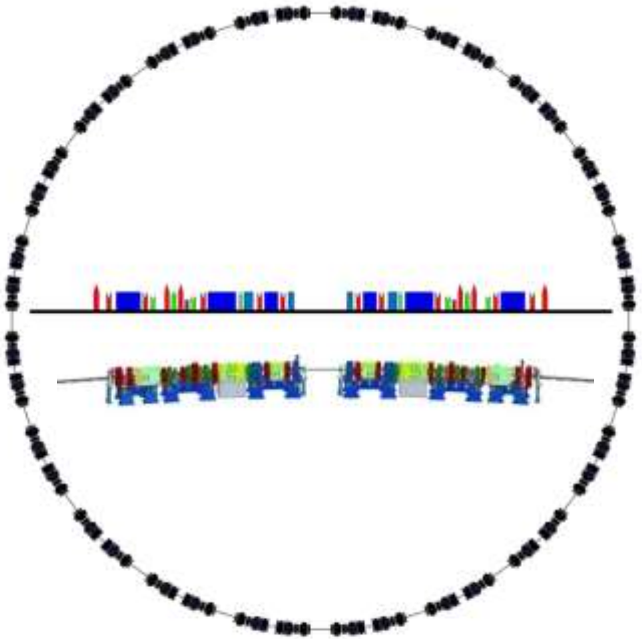
- 1 nC, bunch lengthened by a factor of 3 with harmonic cavity
- Touschek lifetime: >5 hours for 10% coupling beam, >10 hours for full-coupling beam

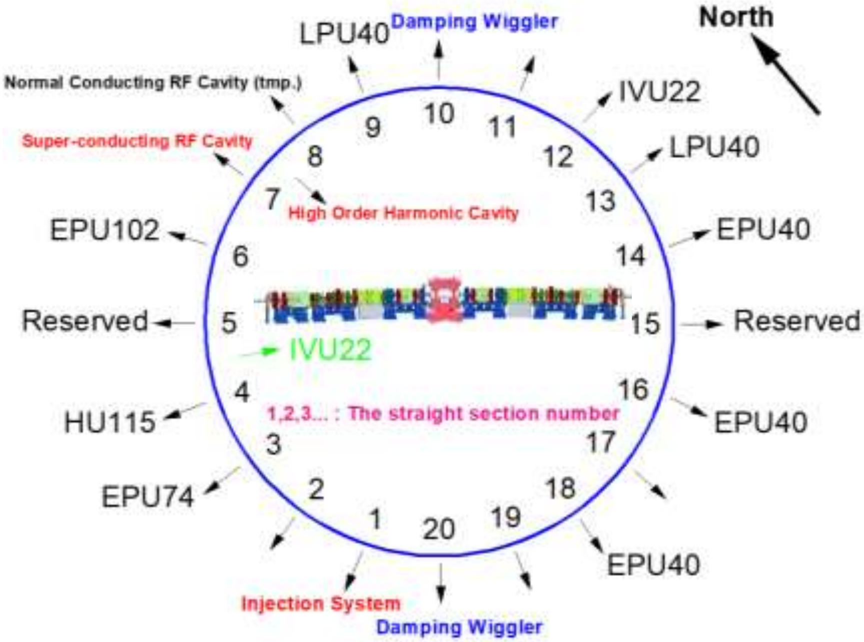


Intra-beam scattering (IBS) effect

- 1 nC, bunch lengthened by a factor of 3, full-coupling beam
- IBS emittance with two damping wigglers and IDs: 60~70 pm·rad

Element layout of the HALF storage ring

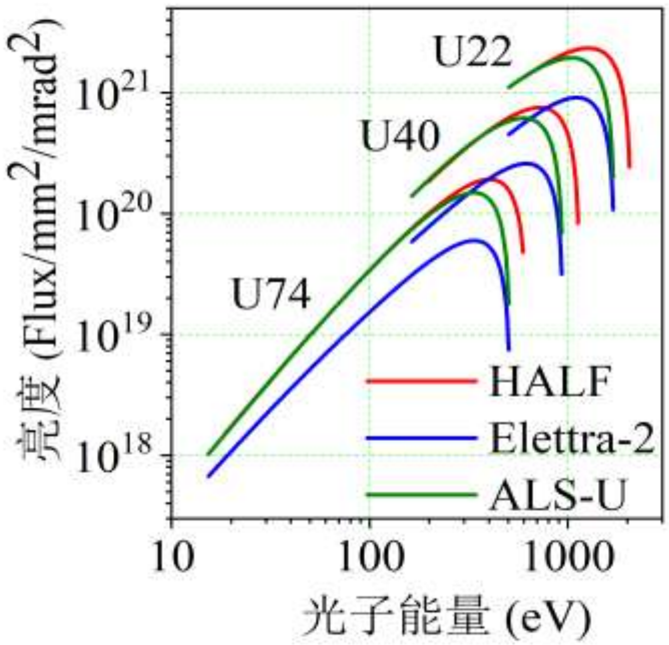




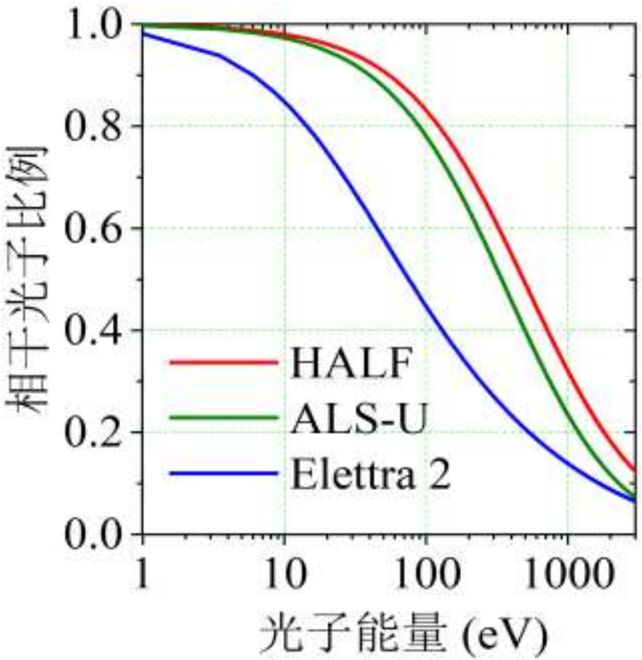
Magnet distribution along the ring (6BA) **Element distribution at the straight sections (Phase I)**

Performance of HALF

Brightness



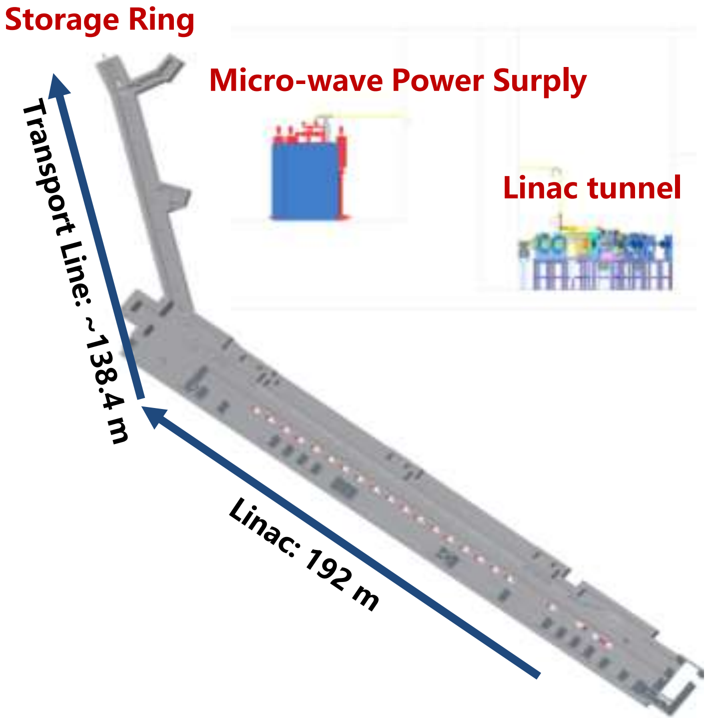
Coherent fraction



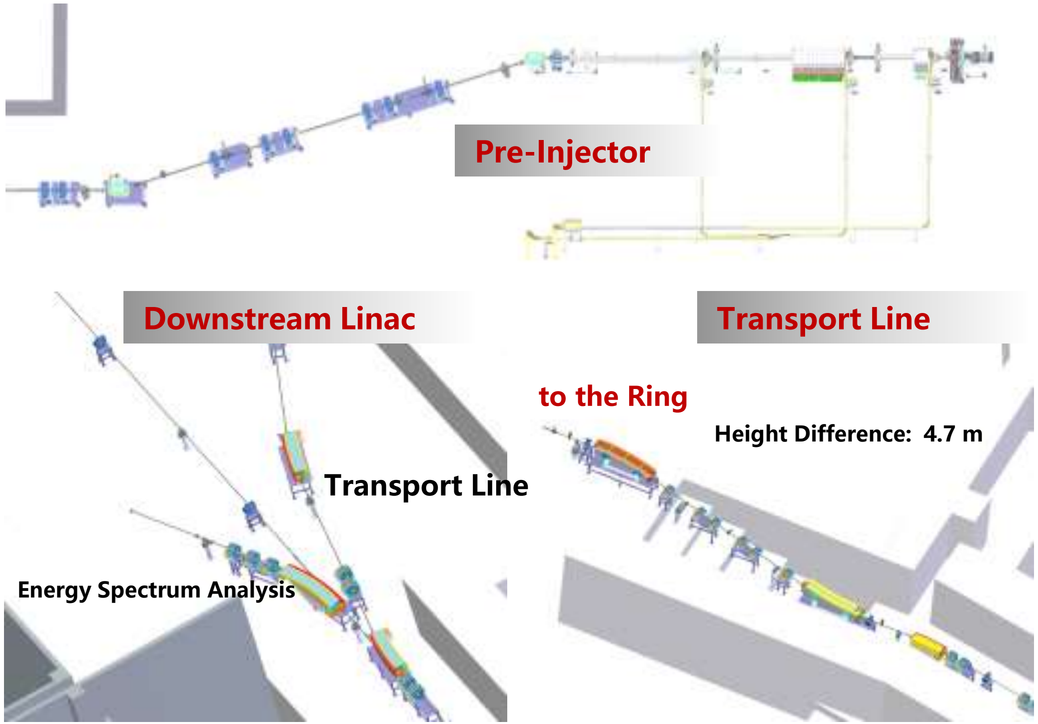
Main parameters of the HALF injector

Parameters	Design Specification
Beam Energy [GeV]	2.2
Bunch Charge [pC]	300
Beam Emittance [nm•rad]	12
Energy Spread (rms)	≤0.2%
Energy Stability (rms)	≤0.1%
Position Error at Injection Point（rms）(dx，dy)	0.1 mm
Angle Error at Injection Point（rms）(dx_p，dy_p)	0.1 mrad

HALF Injector



Layout diagram of the Injector

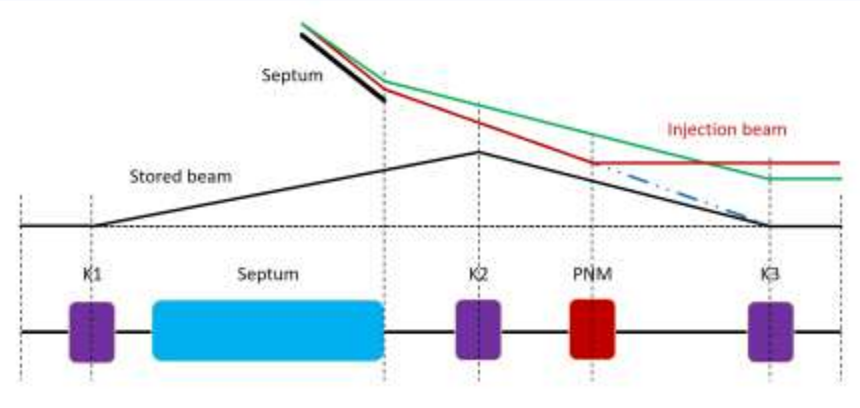


Partial layout of the Injector

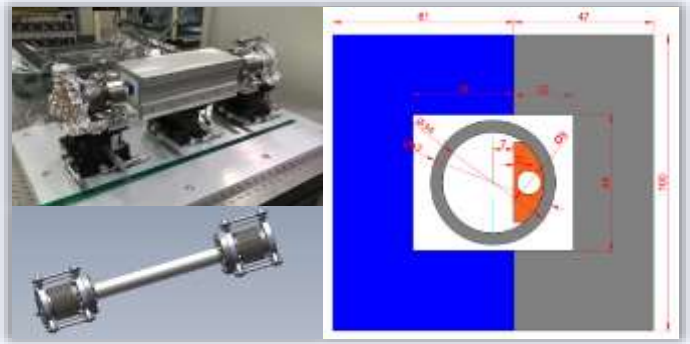
Injection System

Traditional off-axis injection

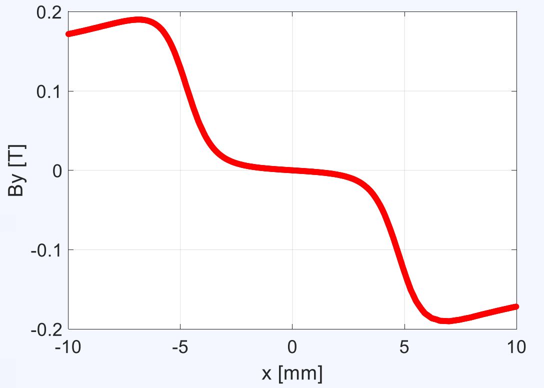
- **3-kicker bump with anti-septum scheme (Septum + K1, K2, K3):** for commissioning and operation in the first stage, required DA > 4 mm
- **Pulsed nonlinear magnet (PNM) injection scheme (Septum + PNM):** transparent injection for the next stage, required DA > 5 mm



Anti-septum

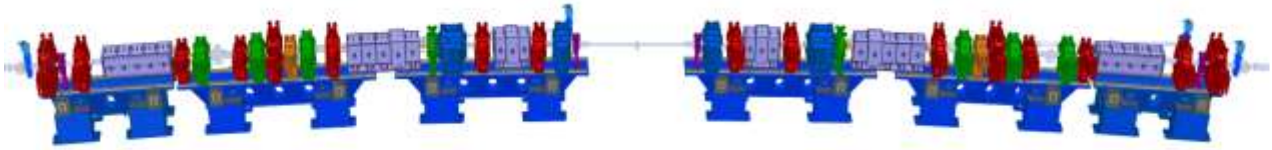


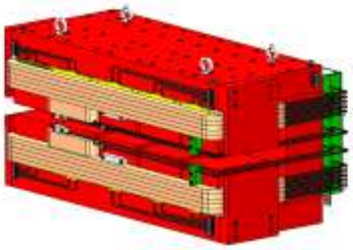
Field strength of PNM



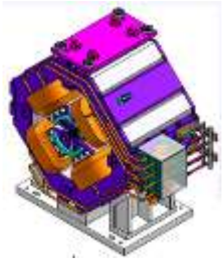
Magnets

- Longitudinal field gradient bending electromagnet (LGB)
- High field gradient quadrupole magnet with small aperture
- Combined function dipole-quadrupole magnet





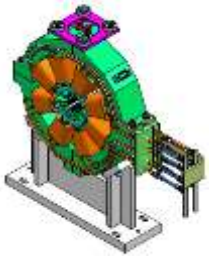
LGB
(6/cell)



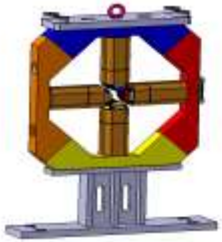
Combined function magnet
(4/cell)

Quadrupole magnet
(16/cell)

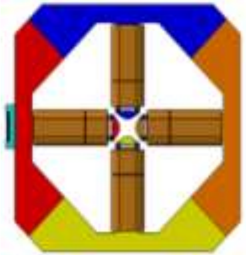
Sextupole
(8/cell)



Octupole
(2/cell)



Fast orbit corrector
(4/cell)



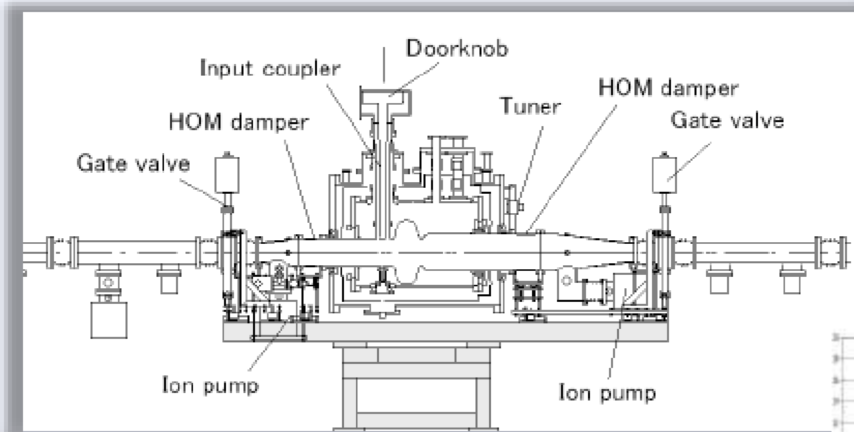
Slow orbit corrector
(4/cell)

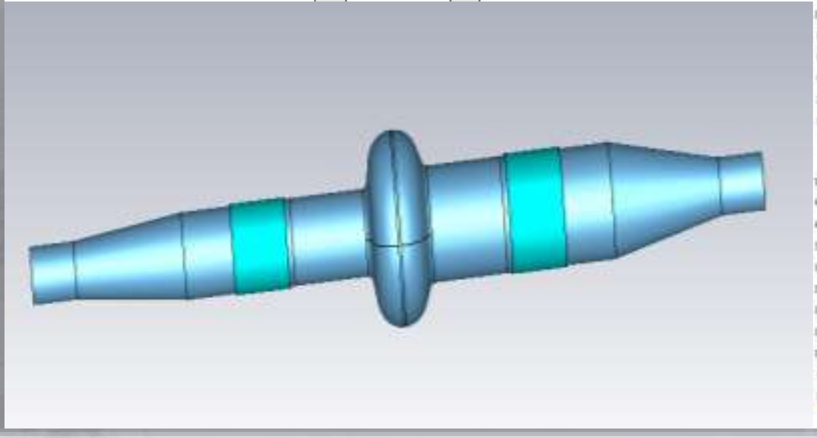
RF System

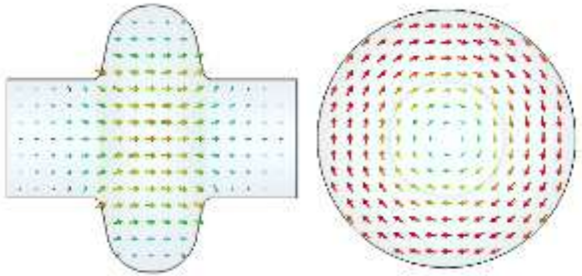
- **500 MHz Superconducting RF Cavity**
  (Low Power Loss、High Cavity Voltage、Efficient HOM Damping、High Q & Large Beam Aperture)
- **1.5 GHz 3rd Harmonic Cavity**
  (Low R/Q，Lengthening Bunch Length、Long Beam Lifetime、 Suppression of Beam Collective Instabilities)

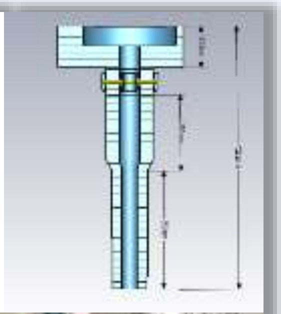
	Main RF System	The 3rd Harmonic RF System / passive
RF Frequency	500 MHz	1.5 GHz
Operation Temperature	4.2 K	4.2 K
Cavity Material	Niobium	Niobium
Maximum RF Voltage	2 MV	0.5 MV
Number of Cavities	2	1
Voltage per Cavity	1.0 MV ($Q_0>5\times10^8$)	0.5 MV (R/Q<45 Ω)
Maximum Input Power Per Cavity	200kW	---

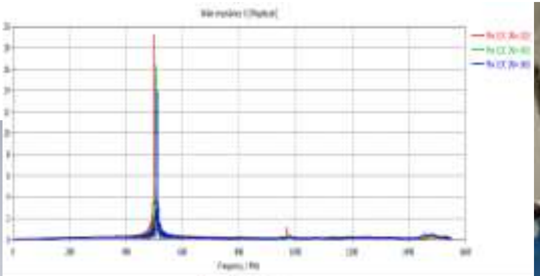
RF System

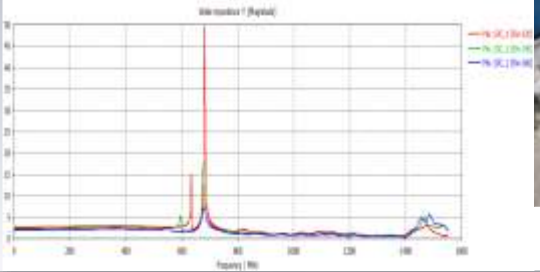












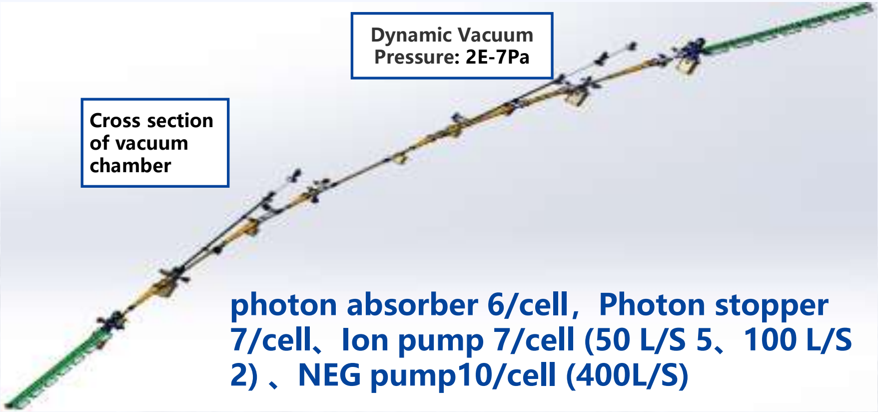
Prototype of the Cavity

Vacuum System

- **High magnetic field gradient➔ small magnetic pole gap➔ small aperture, NEG coating vacuum chamber**

  (26 mm inner diameter, Straight Section, Arc Section, Section with Light Extraction…)

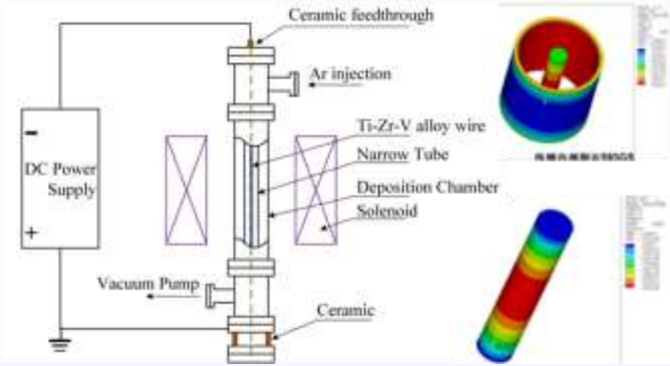
- **Activation, Water Cooling, Photon Absorber, Shielding Impedance …**

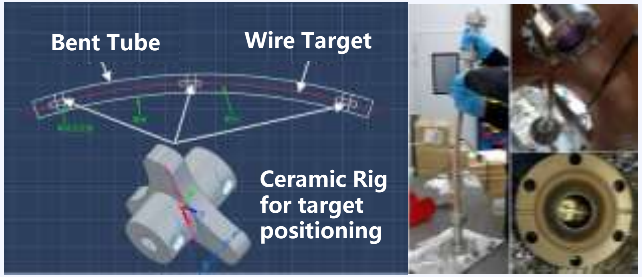


Arc Section

Straight Section with Light Extraction

NEG coating development

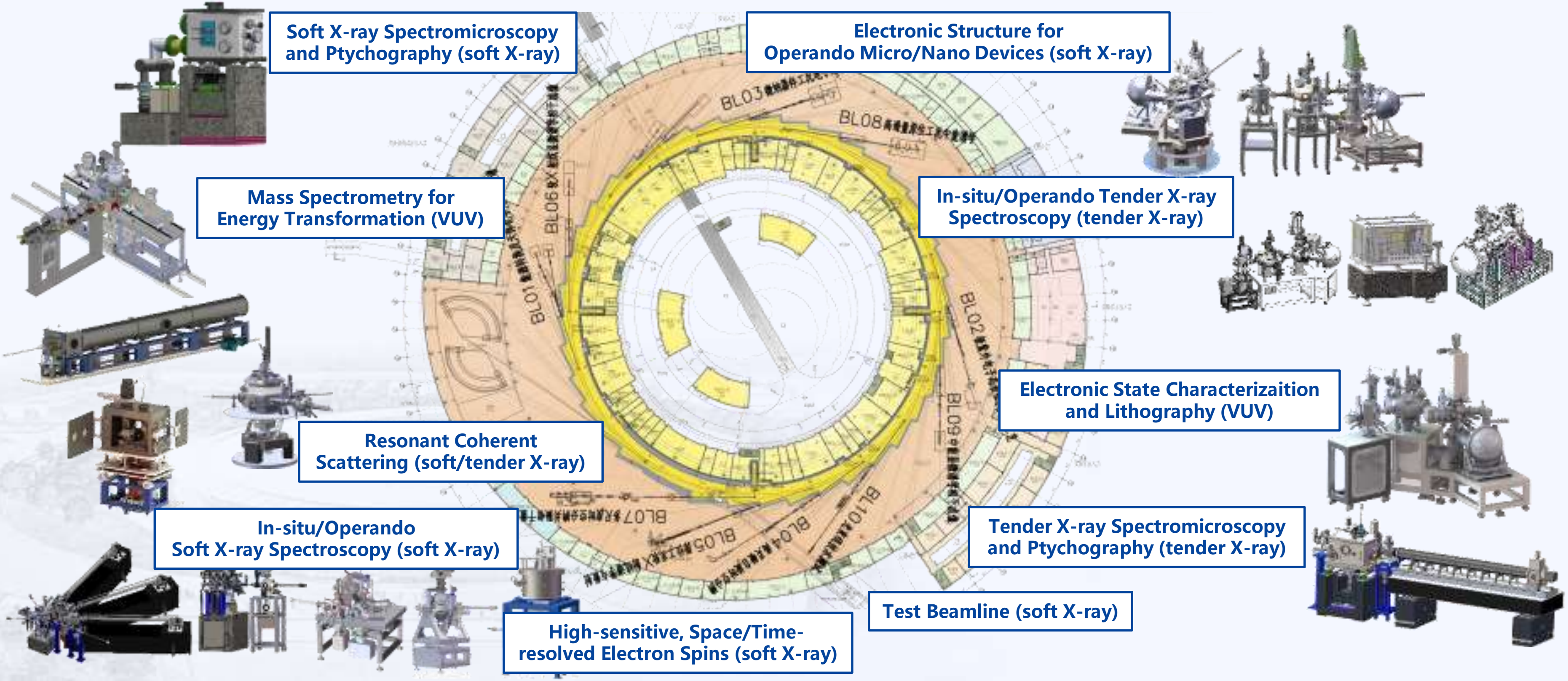




Ceramic rig used to ensure identical curvature between the target and the bent tube. Uniform NEG film deposited in the bent tube of a length of 1000 mm. Ultimate pressure of 1.05×10^{-8} reached.

Beamline list of HALF Phase I

Focus on low energy region，complementary to other light sources in China



Research fields: Energy storage / Industrial Catalysis / Quantum Materials / Integrated circuits / low-z materials / Life science...

	Beamline	Energy/eV	Advantage	Experimental method
1	Mass Spectrometry for Energy Transformation and Astrochemistry	5-20	High sensitivity detecting of transient intermediate states	PIMS
2	Extreme Ultraviolet Electronic Structure Characterization and Lithography	6-135	High energy resolution and high spatial resolution	VUV-ARPES Lithography
3	Electronic Structure Characterization for Operando Micro/Nano Devices	80-1000	High spatial resolution, spin-resolved, operando measurement of the electronic structure of devices	SX-ARPES nano-ARPES
4	High-sensitive, Space-Resolved and Time-Resolved Electron Spin Dynamics	250-2000	High spatial resolution, high sensitivity magnetism measurement	XMCD PEEM
5	In-situ/Operando Soft X-ray Spectroscopy and Scattering	180-2500	High precision In-situ/Operando measurements of electronic structures	NAP-PES RIXS
6	Soft X-ray Spectromicroscopy and Ptychography	250-2500	High spatial resolution and chemical imaging	STXM Ptychography
7	Multiscale Time-Space Resolved Resonant Coherent Scattering	250-4000	Multi-scale dynamics studies	XPCS RSoXs
8	High Throughput In-situ/Operando Tender X-ray Spectroscopy	2300-6500	Operando measurement of the electronic structure of devices	TX-PES TX-APPES
9	Tender X-ray Spectromicroscopy and Ptychography	2100-6500	High spatial resolution and chemical imaging	TXM Ptychography
10	Metrology Beamline	250-2000	Wave optics, inspection of key optical devices	N/A

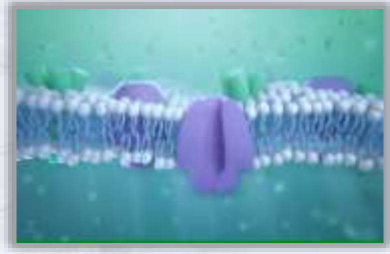
BL07 Multiscale Resonant Coherent Scattering Beamline

Structural and dynamic investigations of soft matters/ sustainable energy materials/quantum materials

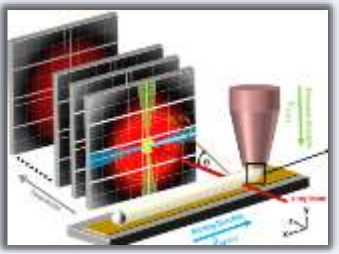
- **Energy Range:** 250-4000 eV
- **Characterization Methods**
  RSoXS, XPCS
- **Beamline Features**
  Sensitivity toward **elemental, chemical, spin** of soft matters and quantum materials. Coherent scattering on **amorphous and disordered** materials.
- **Key Performance Parameters**
  Multilength scale structural and dynamical investigation based on highly coherent scattering

Scientific Applications

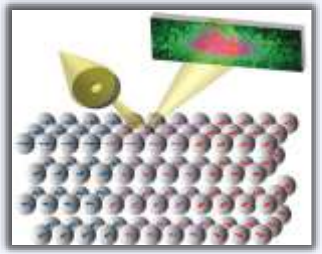
- Composite materials, such as rubber
- Domain structure, phase transition and fluctuation
- Optical films, engineering plastics
- Dynamics and kinetics of biomaterials
- Hierarchical structure physics



Transportation behavior of biomaterials



In-situ monitoring of 3D printing



Domain structure

Beamline Overview

Beamline design requirement:

Energy range: 250 ~ 4000 eV

Photon flux:

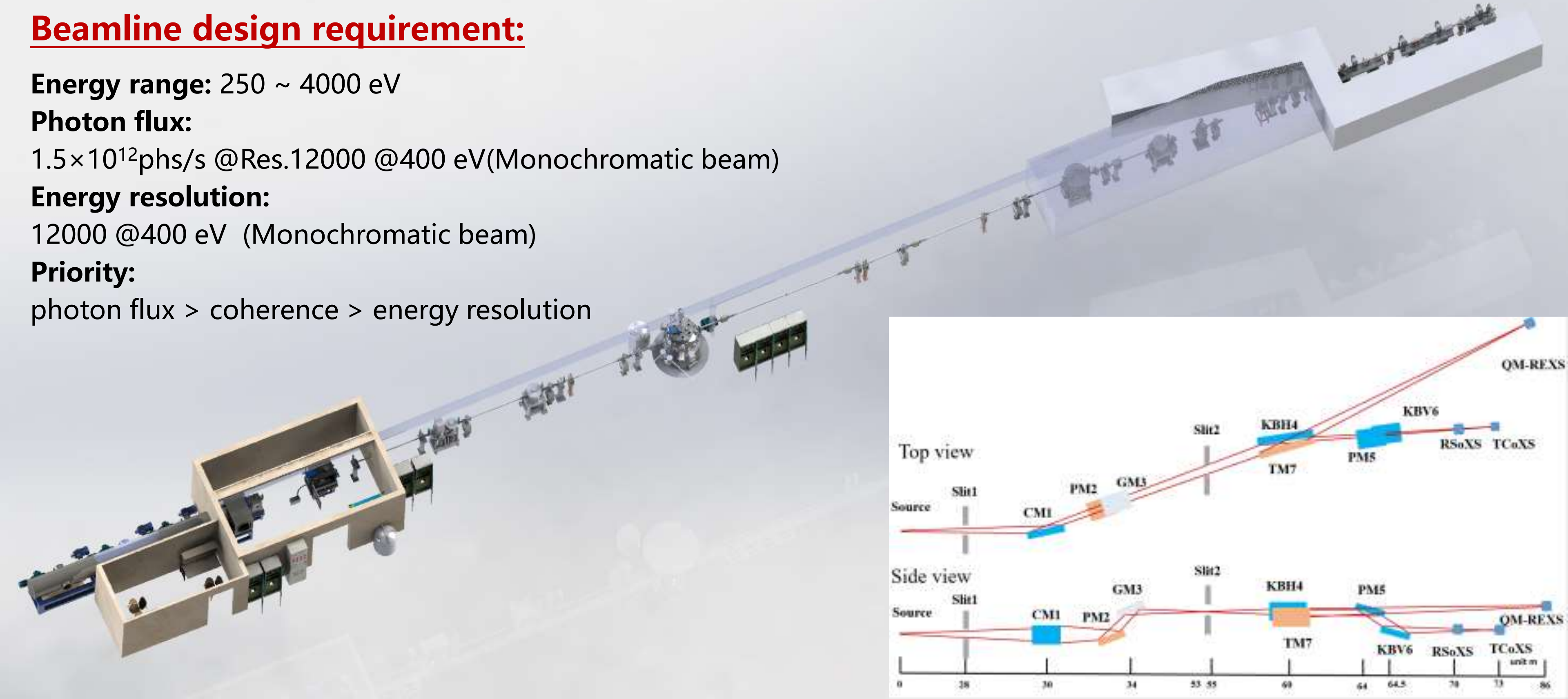
1.5×10^{12}phs/s @Res.12000 @400 eV(Monochromatic beam)

Energy resolution:

12000 @400 eV (Monochromatic beam)

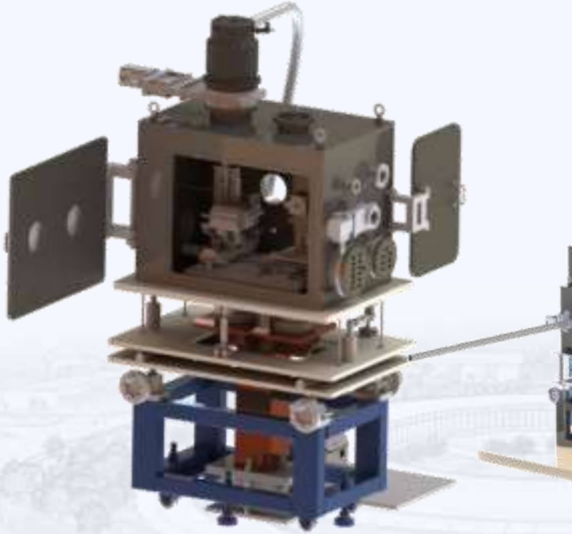
Priority:

photon flux > coherence > energy resolution



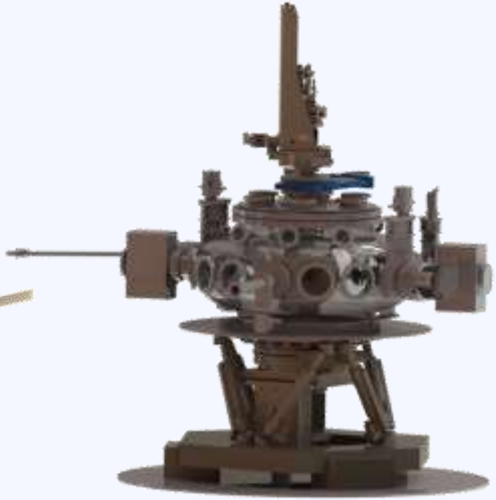
Endstation Overview

Resonant Soft X-ray Scattering Endstation



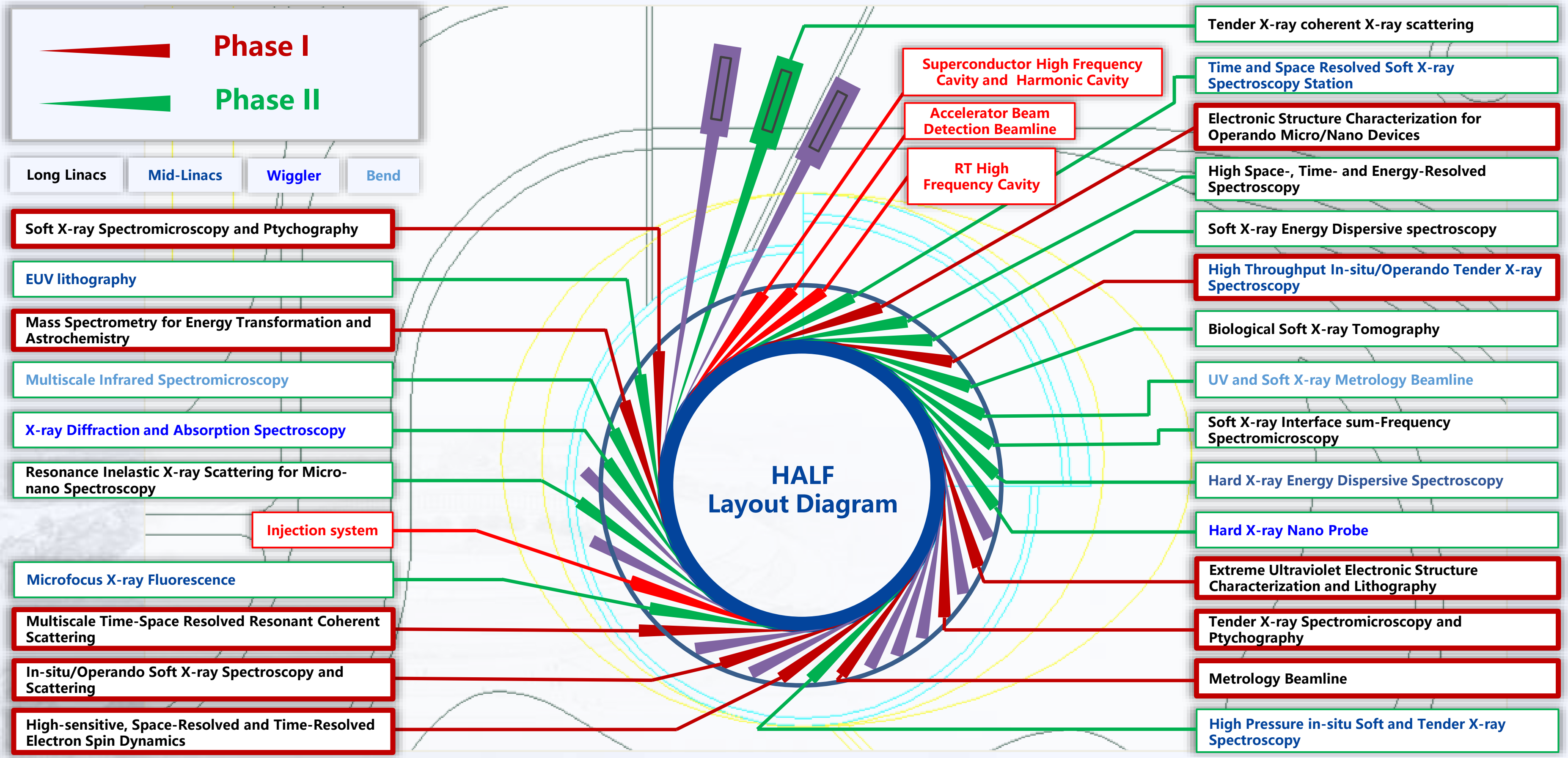
Tender X-ray Scattering Endstation

Quantum Material Resonant Scattering Endstation



Three unique endstations are designed for different research requirement to meet the demands of soft matters and quantum materials.

15 Beamlines planed for phase II



Phase II beamline research field

	Physics	Energy	Chemical Industry	Function Materials	Information Technology	Geoscience	Deep Space Exploration	Environment Science	Biological medicine	Precise manufacturing
UV and Soft X-ray Metrology Beamline							√			√
EUV lithography				√						√
Tender X-ray coherent X-ray scattering		√	√	√				√		
Biological Soft X-ray Tomography				√				√	√	
Hard X-ray Nano Probe		√		√	√		√	√	√	
Microfocus X-ray Fluorescence				√		√		√	√	√
Multiscale Infrared Spectromicroscopy	√	√	√	√	√	√	√	√	√	
Resonance Inelastic X-ray Scattering for Micro-nano Spectroscopy	√	√		√	√					
Soft X-ray Interface sum-Frequency Spectromicroscopy		√	√	√			√	√	√	
High Pressure in-situ Soft and Tender X-ray Spectroscopy		√	√	√		√	√	√	√	
X-ray Diffraction and Absorption Spectroscopy		√	√	√	√					
Soft X-ray Energy Dispersive spectroscopy	√	√		√	√			√		
High Space-, Time- and Energy-Resolved Spectroscopy		√	√	√			√	√	√	
High Space-, Time- and Energy-Resolved Spectroscopy	√	√	√	√	√			√	√	
Hard X-ray Energy Dispersive Spectroscopy	√	√	√	√						

CONTENTS

USTC NSRL

NSRL
National Synchrotron Radiation Laboratory

国家同步辐射实验室

Conclusion

- Accelerator based light sources at NSRL
  - Present HLS-II & Infrared FEL
  - Future HALF

- HALF is a VUV, soft X-ray and tender X-ray fourth-generation synchrotron light source
  - Beam natural emittance: 86 pm•rad @ 2.2 GeV
  - 35 insertion device beamlines
  - The project will be completed in 2028

国家同步辐射实验室
NATIONAL SYNCHROTRON RADIATION LABORATORY

Hefei Advanced Light Facility

——The Eye for Exploring the Microscopic World

Thank you！