Highlights of Accelerator R&D at Shanghai Light Sources Cluster

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Outline

- Shanghai Light Sources Cluster overview
- Accelerator facilities
  - Shanghai Synchrotron Radiation Facility (SSRF)
  - Shanghai Soft X-ray Free-Electron Laser (SXFEL)
  - Shanghai Hard X-ray Free-Electron Laser (SHINE)
- R&Ds of accelerator key technologies
- Summary

Light Source Cluster @Zhangjiang

Zhangjiang High-Tech Park@Shanghai

Large research infrastructures cluster: Zhangjiang Photon Science Facilities

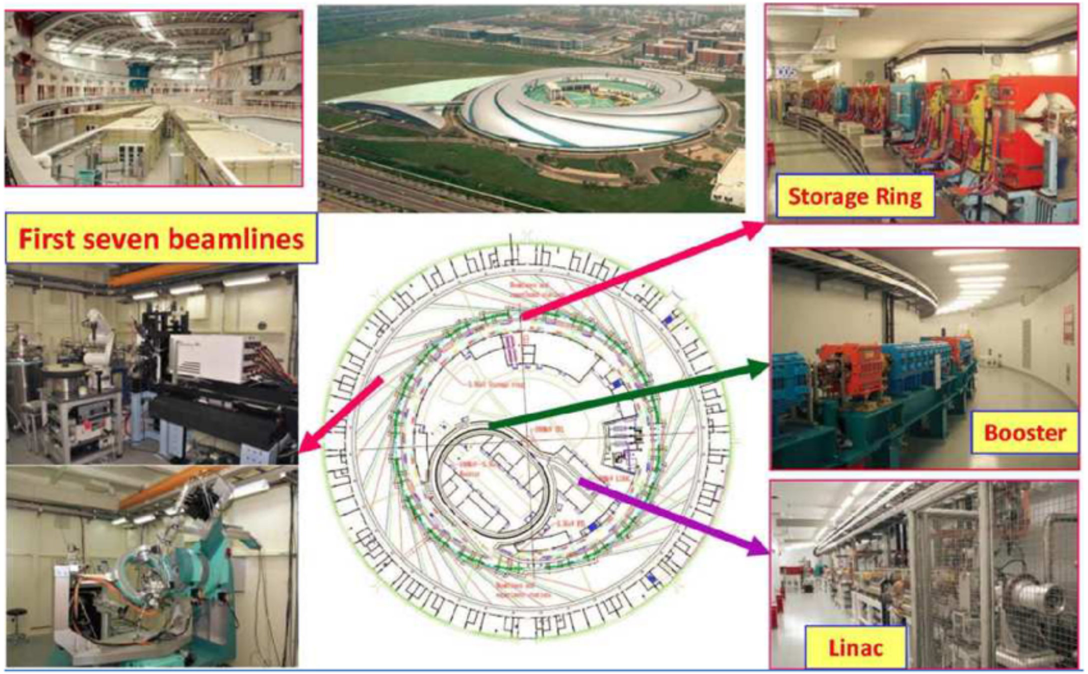
Advanced Light Source Cluster @ Zhangjiang

Accelerator Light Source Facilities

SSRF: Shanghai Synchrotron Radiation Facility

SSRF: Shanghai Synchrotron Radiation Facility

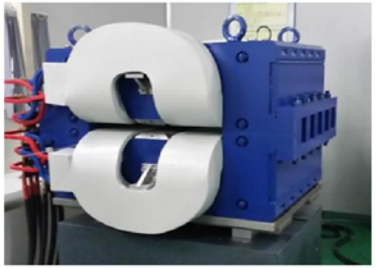
- SSRF is a 3.5GeV third generation light source, consisting of a 150 MeV linac, a full energy booster, and a storage ring with 432m circumference, and currently 23 operating beamlines.
- The SSRF project was launched in Jan. 2004 with the groundbreaking made in Dec. 2004. Its dedication was made in Apr. 2009; Its phase-II beamline project started in Nov. 2016.
- SSRF began its user operation in May 2009. It has served more than 34000 users from with high performance operation fruitful experiment results.



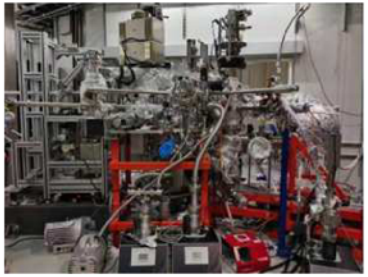
- Energy： 3.5 GeV
- Emittance： 4.2 nm-rad
- Circuference： 432 m
- Current： 260±0.5mA (top-up)

SSRF: Phase-II Beamline project

- **16 New BLs：** to expand the application fields
- **Light Source Improvements：** more short straight sections, more ID devices, bunch stretching system, backup cryogenic system.
- **User supporting system：** labs for sample preparation, including material, chemical, environmental, biological and medical science, in-situ facilities, data center for users
- **Lab for BL engineering：** optics, mechanics, vacuum, control and electronics, FEA, test beamline
- **Utilities and Logistics：** buildings for end station of super-long beamline, user supporting labs, user training and data center

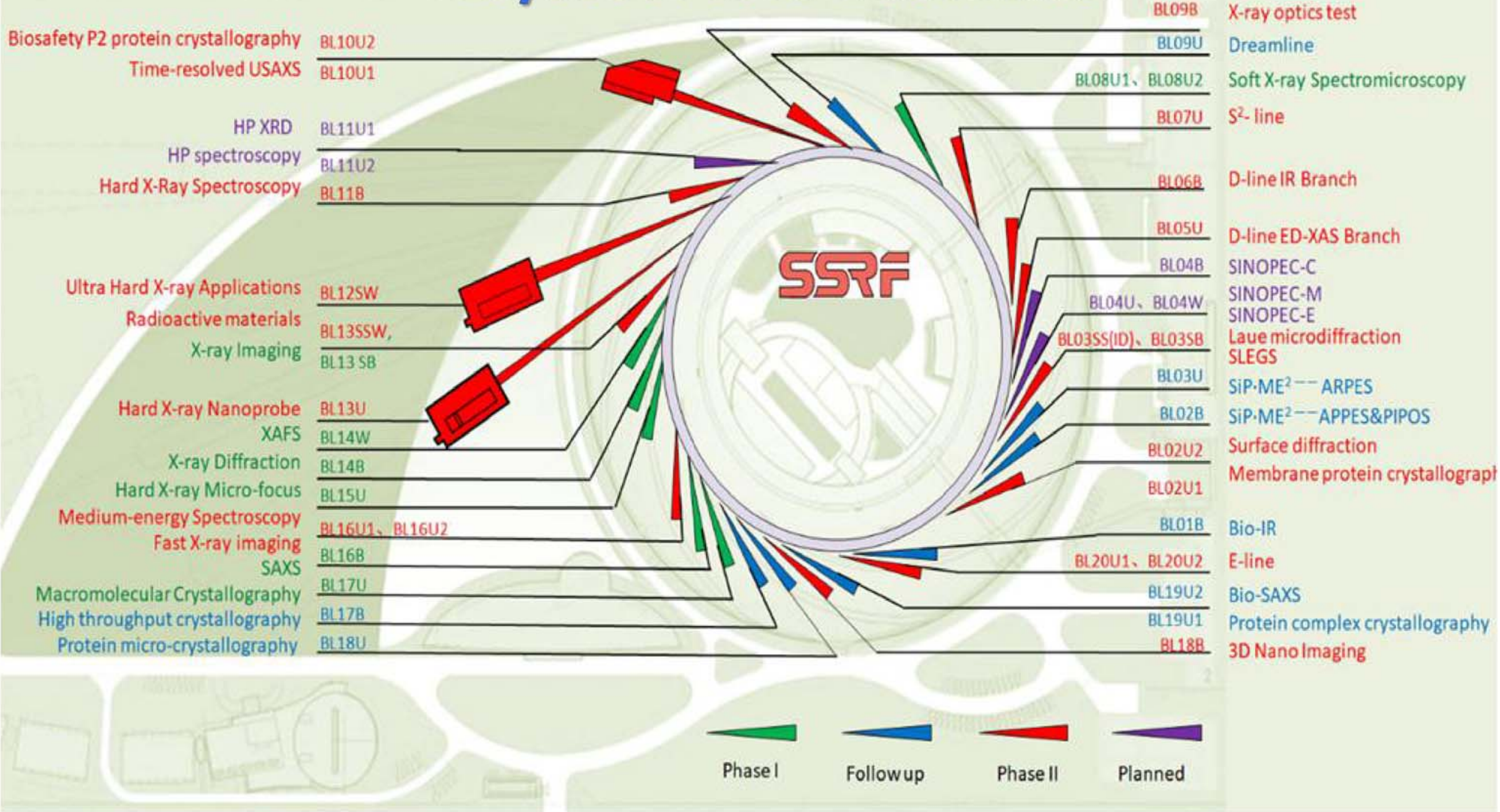


Spin-ARPES



Nano-ARPES

Layout of SSRF Beamlines



SXFEL：Shanghai Soft X-ray FEL Facility

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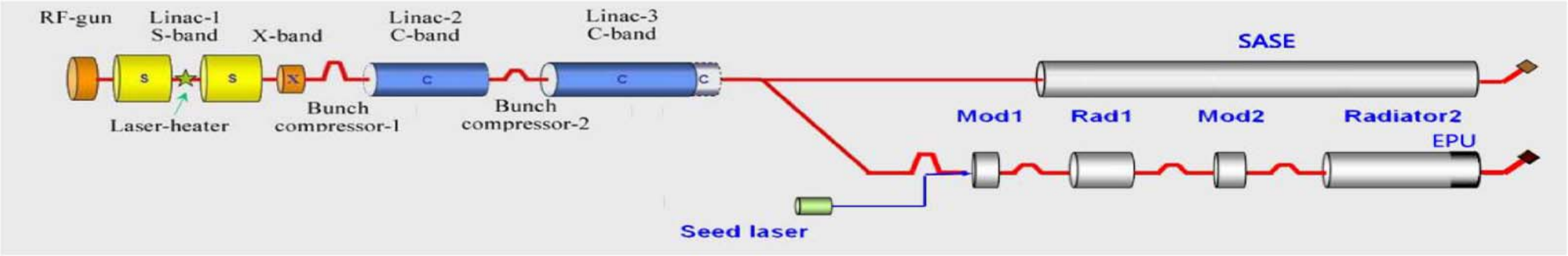
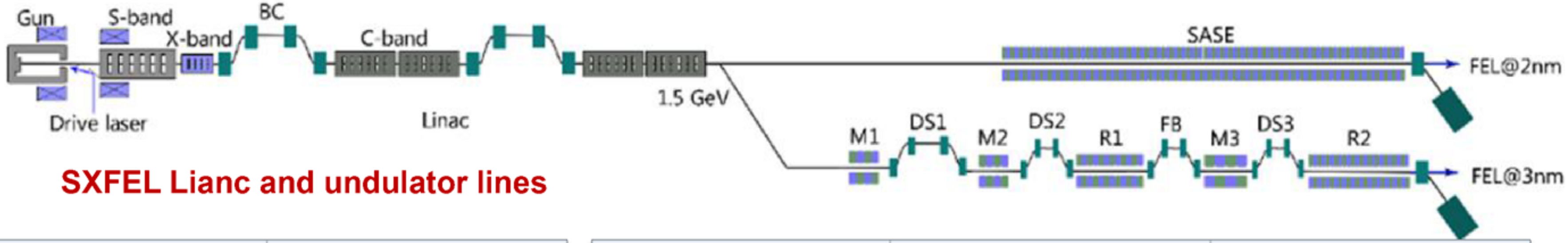


SXFEL：Shanghai Soft X-ray FEL Facility

- **SXFEL Facility,** located in the SSRF campus, consists of a 1.5 GeV linac and two undulator lines with 5 experimental stations in the water window region



SXFEL Lianc and undulator lines

Total length	532m
Electron energy	1.5 GeV
Charge	500pC
Peak Current	700A
Emittance	1.5 nm-rad
Global energy spread	0.1%
Photon energy	0.2 – 0.6 keV
Pulse length	~100 fs
Peak photon power	1 GW
Repetition rate	10 - 50 Hz

	SASE beamline	HGHG beamline
Energy range	1.2-12 nm (100-1000 eV)	2.4~24nm (50~500eV)
Pulse energy	330μJ @100eV,47μJ @620eV	64μJ @56eV , 5μJ @500eV
Photon flux /pulse	4.6×10^{11}@620eV ~1.3×10^{13}@100eV	5×10^{9}@500eV ~2.9×10^{12}@50eV
Energy resolution (ΔE/E)	0.04%~0.2%	0.008%~0.04%
Energy resolving power of spectrometer (E/ΔE)	~3×10^{4} @620 eV	~4×10^{3} @200eV
Spot size	~3μm	~10μm
Pulse width (fs)	117fs@620eV	50 fs@300eV

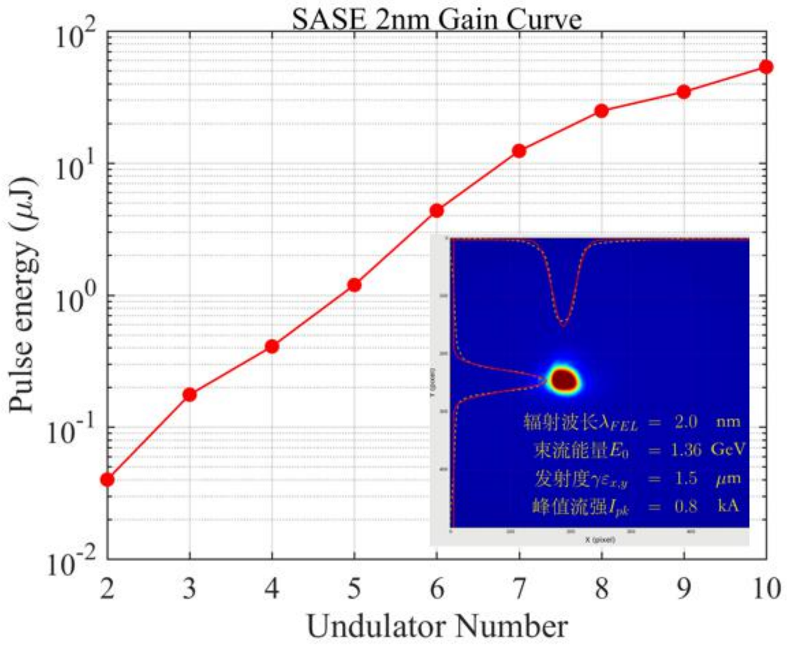
SXFEL-UF undulator lines

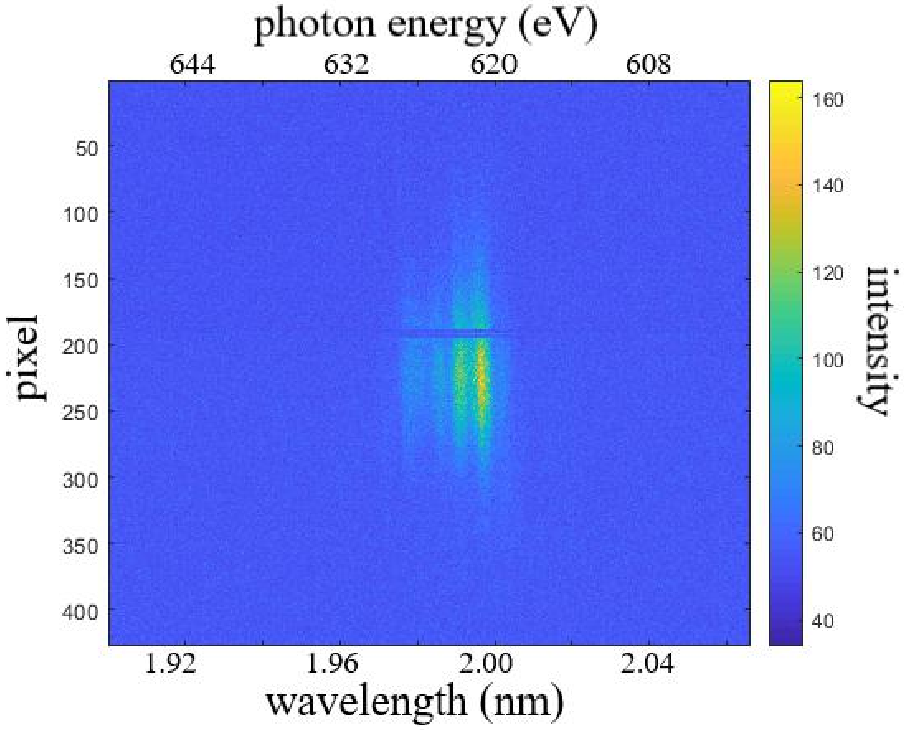
- FEL1: **SASE FEL line with 10 IVUs**

- FEL2: **Seeded FEL line** with 20 **undulators**

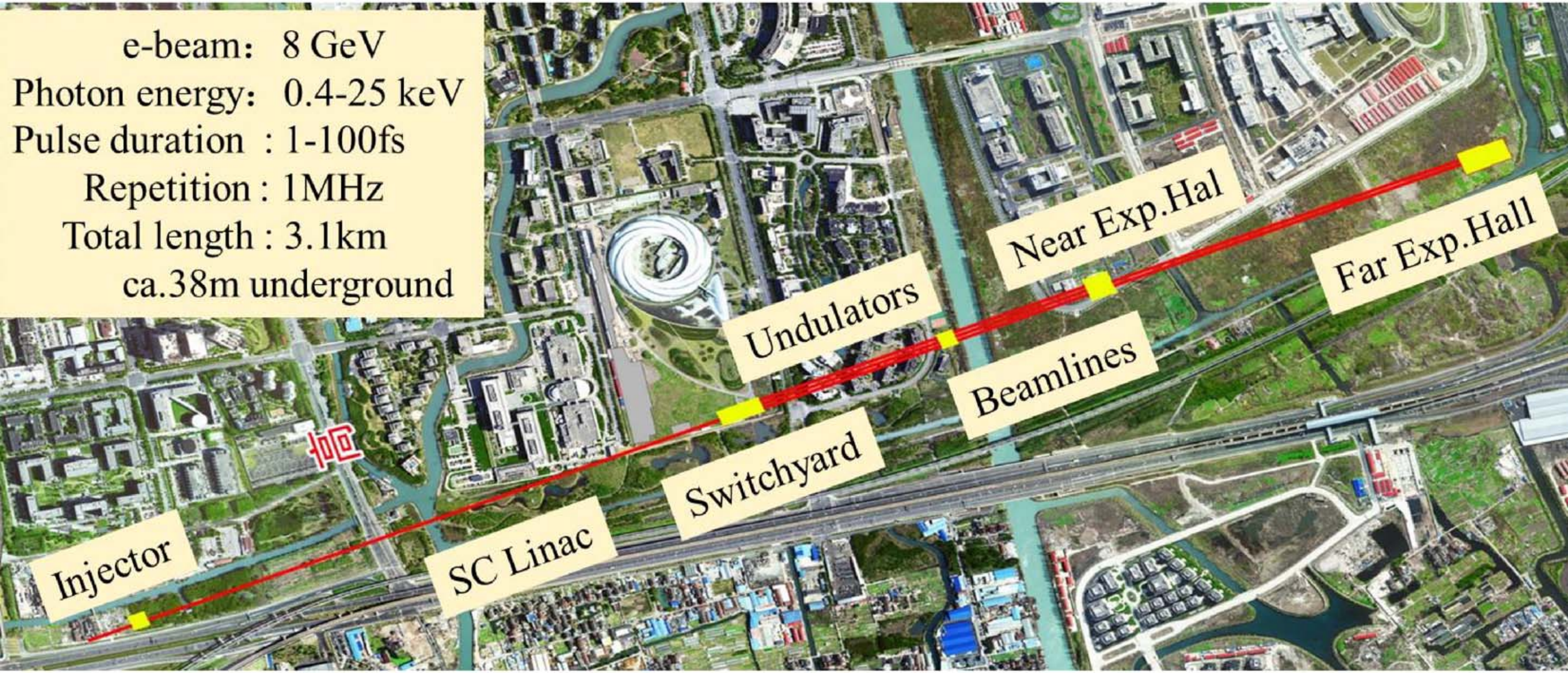
SASE line: lasing at 2 nm!

May 14, 2021

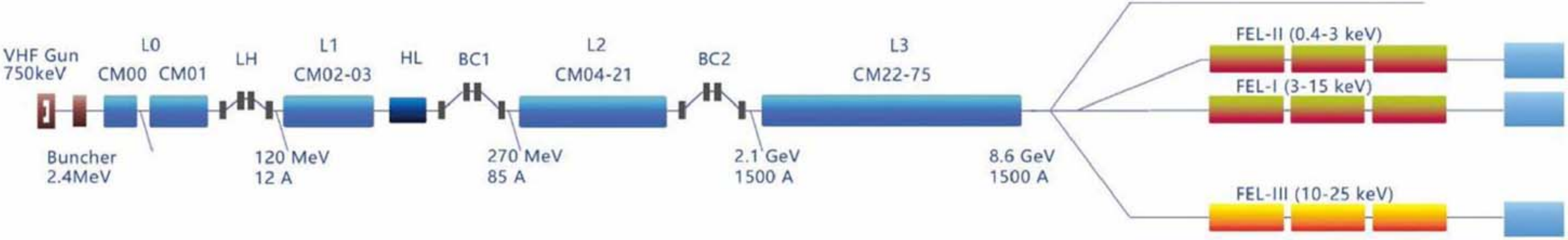




SHINE: Shanghai HIgh repetitioN rate XFEL and Extreme light facility



Accelerator Layout of SHINE



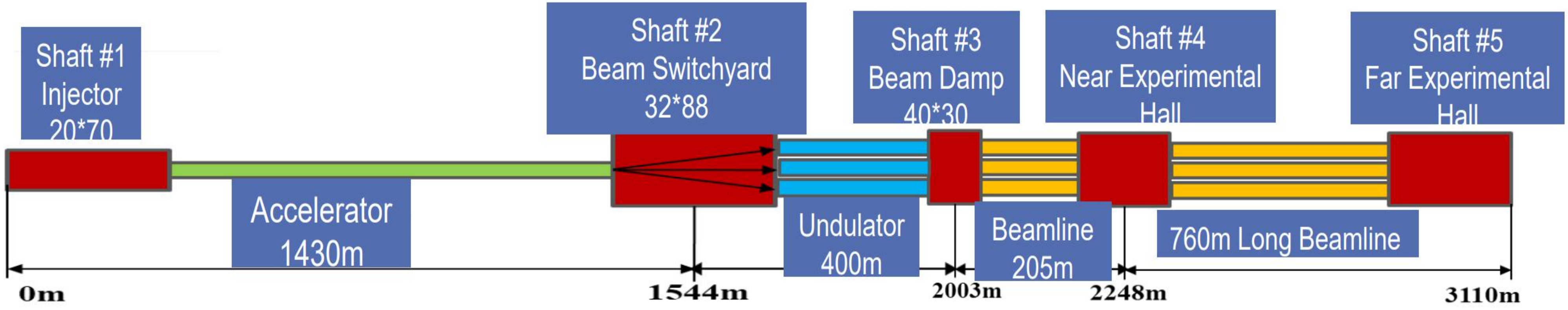
Main Parameters of SHINE

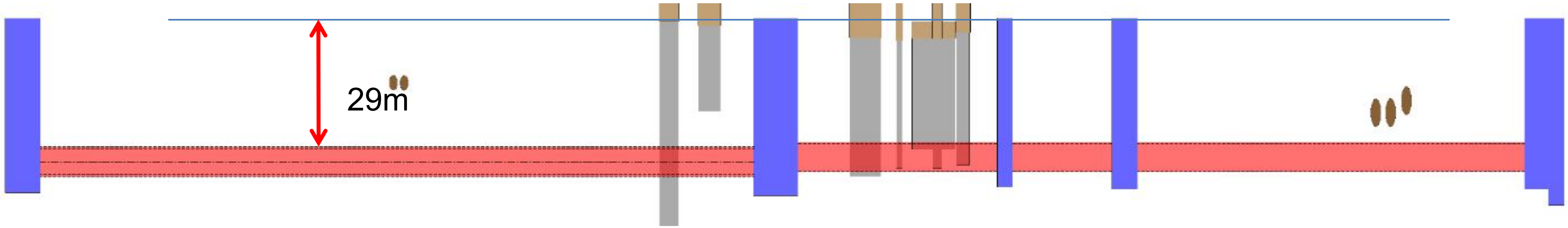
	Nominal	Range
Beam energy/GeV	8.0	4-8.6
Bunch charge/pC	100	10-300
Max rep-rate/MHz	1	up to 1
Beam power/MW	0.8	0 - 2.4
Photon energy/keV	0.4-25	0.4-25
Pulse length/fs	20-50	5-200
Peak brightness	5×10^{32}	1×10^{31}-1×10^{33}
Average brightness	5×10^{25}	1×10^{23}-1×10^{26}
Total facility length/km	3.1	3.1
Tunnel diameter/m	5.9	5.9
2K Cryogenic power/kW	12	12
RF Power/MW	2.28	3.6

FEL Line	Nominal	Objective
FEL-I		
Photon energy/keV	3-15	3-15
Photon number per pulse @12.4keV	$>10^{10}$	$>10^{11}$
Max pulse repetition rate/MHz	0.66	1
FEL-II		
Photon energy/keV	0.4-3	0.4-3
Photon number per pulse @1.24keV	$>10^{12}$	$>10^{13}$
Max pulse repetition rate/MHz	0.66	1
FEL-III		
Photon energy/keV	10-25	10-25
Photon number per pulse @15keV	$>10^{9}$	$>10^{10}$
Max pulse repetition rate/MHz	0.66	1

➢ **XFEL Facility +100 PW Laser Facility**

Facility Layout of SXFEL





SHINE Beamlines and End-stations

FEL-I Hard X-ray End-stations

- **HSS:** Hard X-ray Scattering and Spectroscopy
- **CDS:** Coherent Diffraction Endstation for Single Molecules and Particles
- **SEL:** Station of Extreme Light

➢ **XFEL + 100 PW Laser System**

FEL-II Soft X-ray End-stations

- **AMO:** Atomic, Molecular, and Optical Science
- **SES:** Spectrometer for Electronic Structure
- **SSS:** Soft X-ray Scattering and Spectroscopy

FEL-III Hard X-ray End-stations

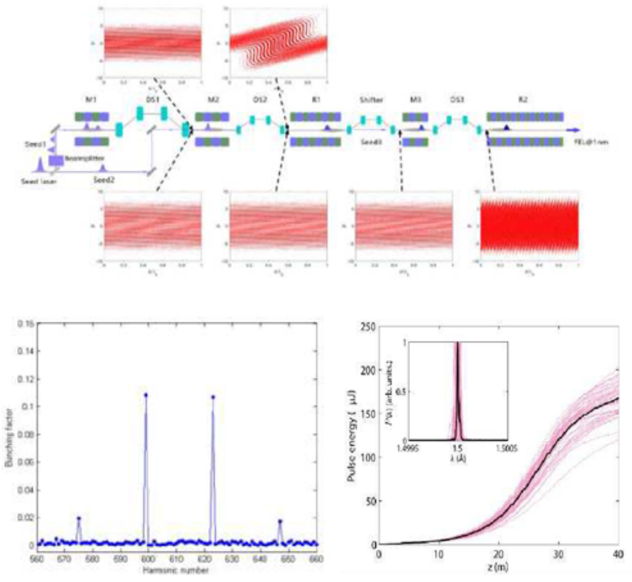
- **HXS:** Hard X-ray Spectroscopy
- **SFX:** Serial Femtosecond Crystallography
- **CDE:** Coherent Diffraction Imaging
- **HED:** High Energy Density Science

R&Ds of Accelerator Key Technologies

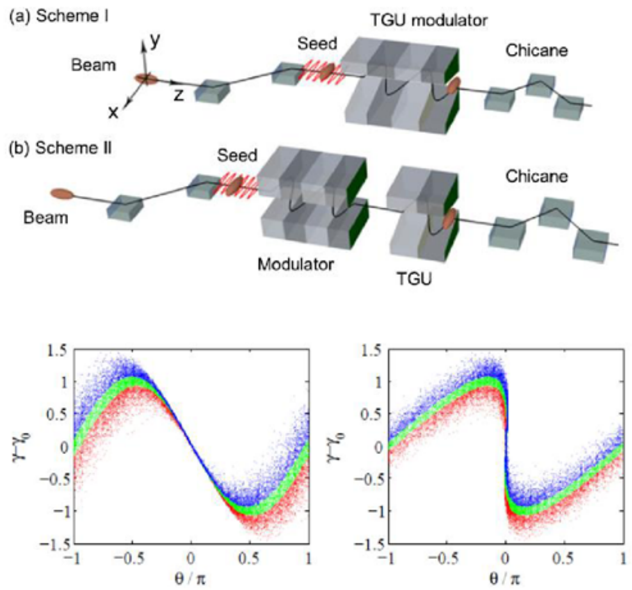
Coherent FEL studies

➢ Novel methods and techniques have been developed for extending the seeded FEL capabilities to shorter wavelength and higher repetition rate

☐ For shorter wavelength: EEHG cascade

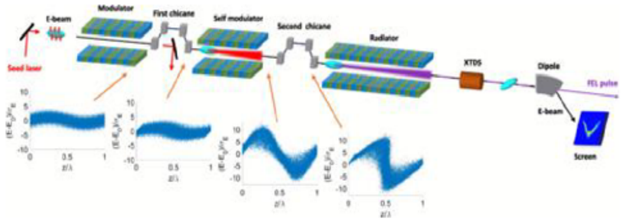


☐ For shorter wavelength: PEHG

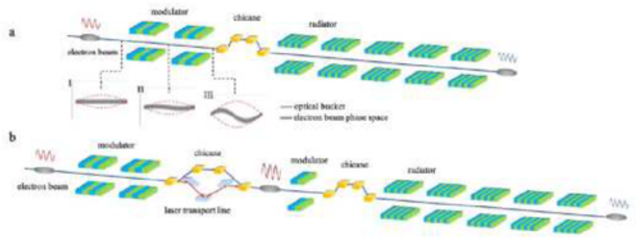


☐ For high repetition rate: self-modulation and DEHG

self-modulation



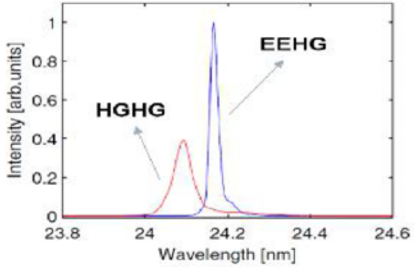
DEHG

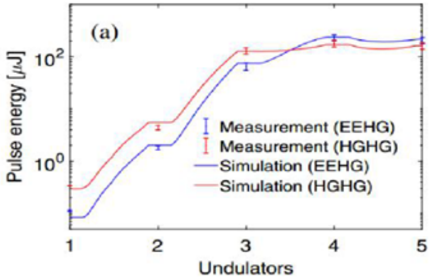


Coherent FEL studies

- A series experiments for EEHG and EEHG-HGHG cascade has been performed for fully coherent soft X-ray FEL

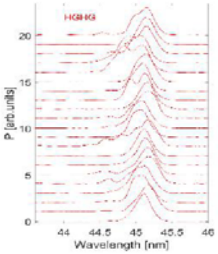
Saturation of EUV EEHG @SXFEL



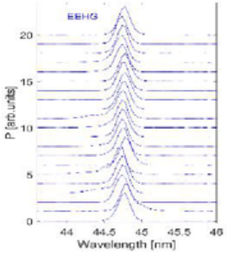


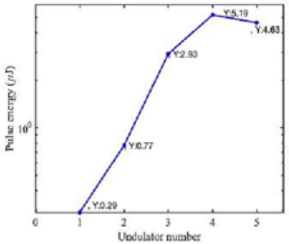
First demonstration of EEHG-HGHG @SXFEL

HGHG spectra



EEHG spectra

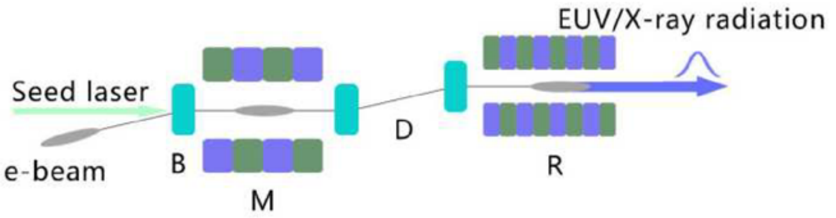


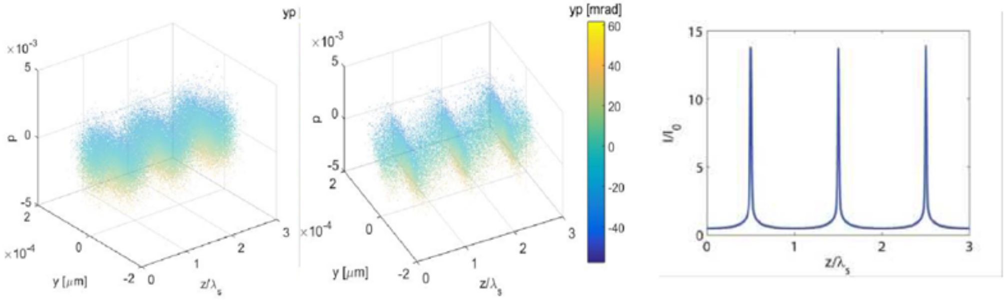


Coherent FEL studies

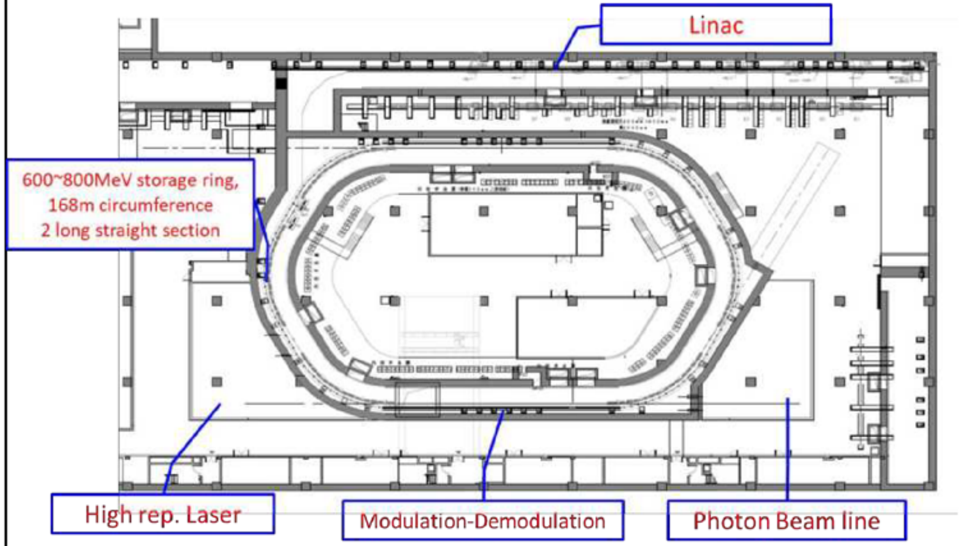
➢ New methods and techniques have been proposed for the next generation light source: fully coherent, high rep-rate radiation based on storage ring.

□ Angular dispersion induced microbunching for fully coherent radiation in storage rings



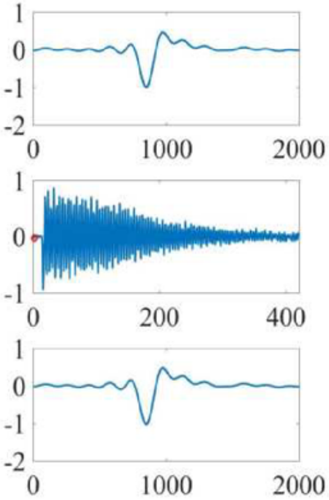


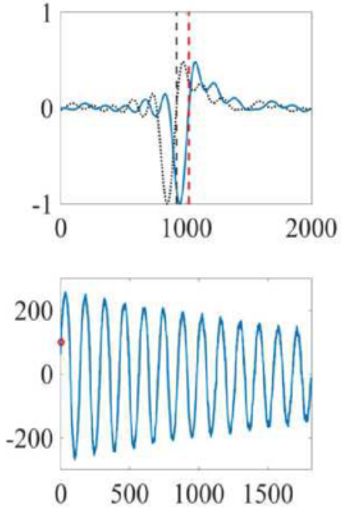
□ A test facility is planned to prove angular dispersion induced micro-bunching(ADM) mechanism.

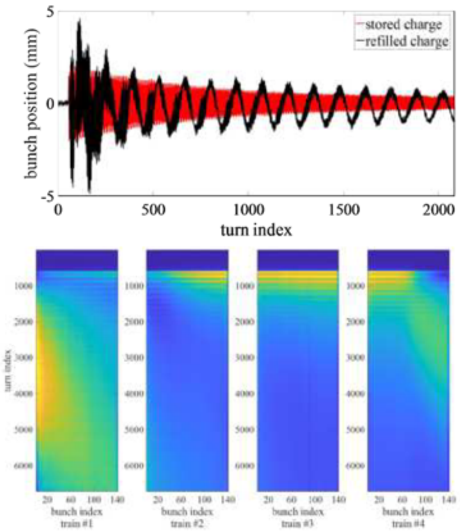


Bunch by bunch 3D position measurement technology

- 1^{st} Bunch by bunch precise 3D position measurement system built @ SSRF in the world
- Very powerful tools for machine study
  - Every individual bunch position can be tracked with resolution of 5um in transverse plane and 0.2ps in longitudinal plane
  - 3D trace of Refilled charge during injection can be extracted
- Open source data analyze package has been developed and release at GitHub, suitable for any other electron storage ring







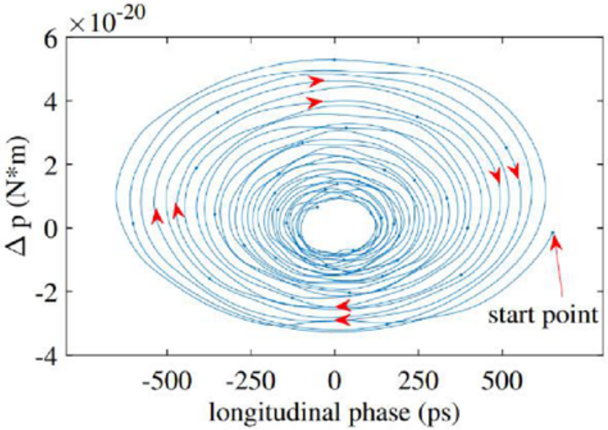


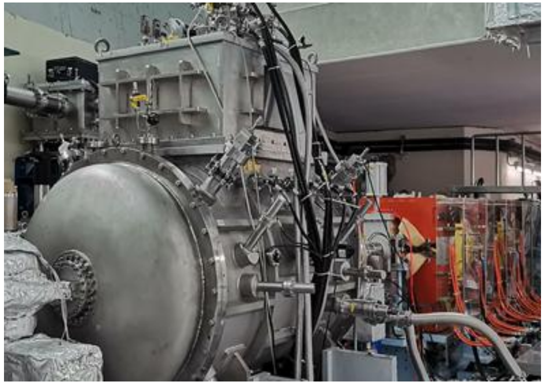
FIG. 11. The evolution in energy phase space of an injected bunch after injection.

Insertion Devices for SSRF

- In-vacuum undulator
- Cryogenic permanent magnet undulator
- Superconducting wiggler
- Superconducting undulator

DEPU in SSRF

CPMU for SSRF



Superconducting undulator for SSRF

Apple knot undulator for SSRF-II

SCW for SSRF

Undulators for SXFEL and SHINE

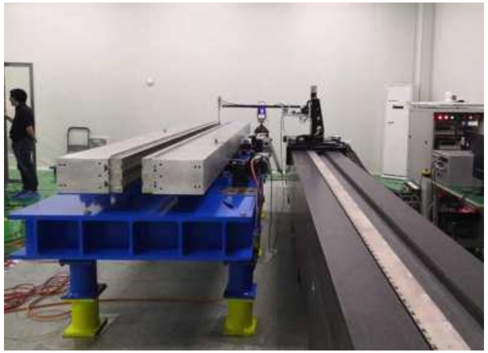
- Short period period in-vacuum undulator for SXFEL
- Small gap undulator for SXFEL
- Elliptical polarized undulator for SXFEL
- Horizontal polarized undulator for SHINE
- Vertical polarized undulator
- Superconducting undulator for SHINE

IVU16 for SXFEL

U235 for SXFEL

EPU for SXFEL

4m H-polarization U68 undulator for SHINE

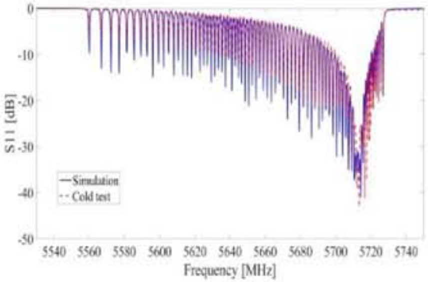


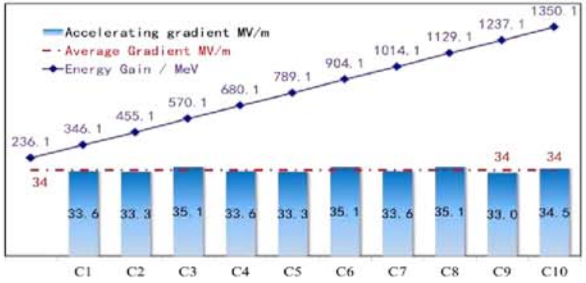
4m V-polarization U68 undulator for SHINE

4m superconducting V-polarization undulator for SHINE

RF accelerating structures

- C-band HG accelerating structure
- X-band accelerating structure
- S-band accelerating structure





C-band high gradient accelerating structure for SXFEL
37MV/m on average, 41.7MV/m on maximum

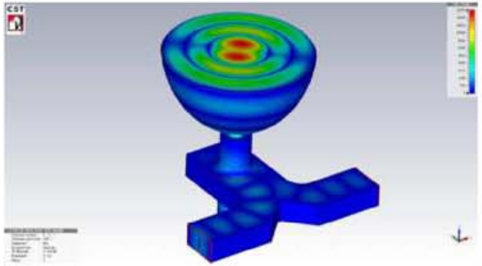
X-band accelerating structure
for SXFEL linearizer

S-band accelerating structure
for SXFEL and Sirius

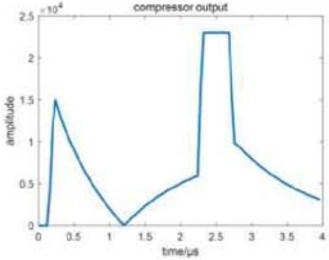
RF pulse compressors

- C-band SLED pulse compressor for SXFEL
- X-band SLED pulse compressor for SXFEL
- S-band SLED pulse compressor for SXFEL
- C&X-band spherical pulse compressor
- Top-flat output controlled by LLRF

RF Mode of Spherical PC

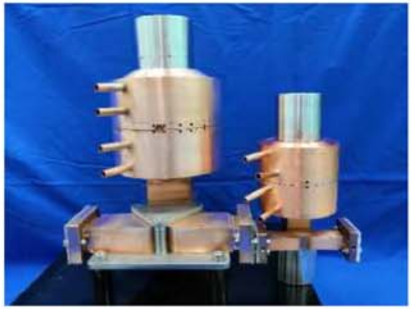


Flat-top output

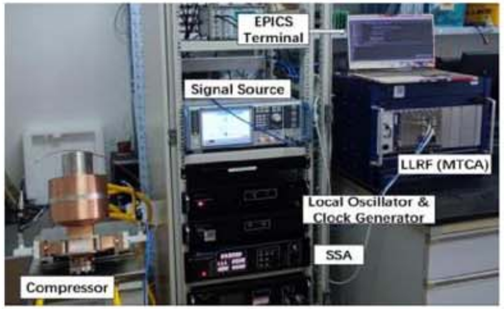


C-band SLED for SXFEL

S-band SLED for SXFEL



C&X-band spherical pulse compressor (PC)

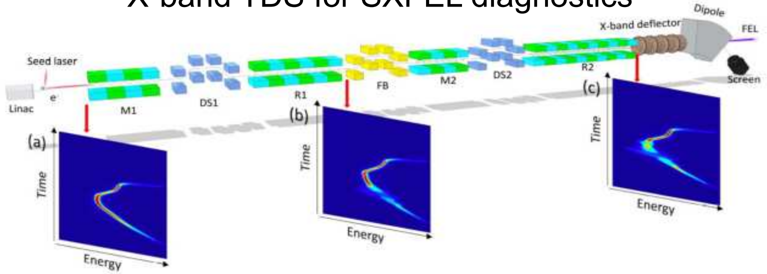


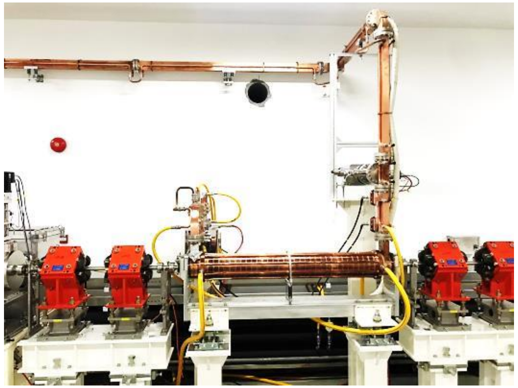
Adaptive control LLRF for Flat-top output

Transverse deflecting systems (TDS)

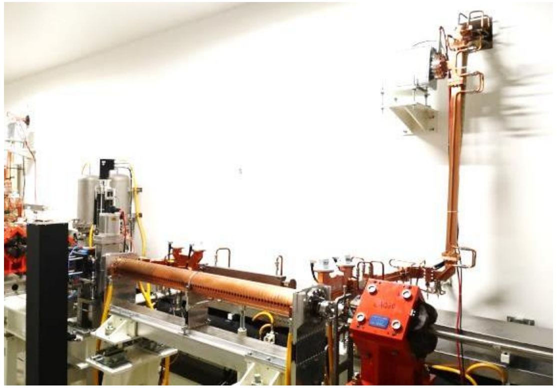
- S-band TDS for bunch length (BL) diagnostics
- C-band TDS for bunch length (BL) diagnostics
- X-band TDS for BL, fs timing and FEL diagnostics

X-band TDS for SXFEL diagnostics





S-band TDS for SXFEL
10 MV deflecting voltage on maximum
Beam energy is 250 MeV



C-band TDS for SXFEL
30 MV deflecting voltage on maximum
Beam energy is 1500 MeV

X-band TDS for:

1. BL measurement
2. Beam-laser fs timing
3. FEL diagnostics for two undulator lines

1.3GHz SRF Cryomodule for SHINE

- **Cryomodule prototype: SHINE cryomodule design adopts the TESLA technology and refers to EXFEL and LCLS-II**
  - **1.3GHz 9-cell cavity prototype**: (1300.2 +/- 0.1)MHz, from BCP to EP and high-Q0 recipe. Eight BCP_ed cavities (Q0> 1E10 @ 16 MV/m) integrated to the first cryomodule.
  - **Fundamental power coupler:** double-window structure, 7.0 kW full reflection power ability
  - **Cryostat:** double-layer magnetic shielding (< 5 mGauss), thermal shielding, cryogenic pipes
  - **Tuner:** mechanical (450kHz) with piezo tuner (+/- 1kHz), 1Hz resolution
  - **Cryomodule:** first prototype assembled and cooldown to 2.0K, horizontal test system commissioned

Cavity & FPC

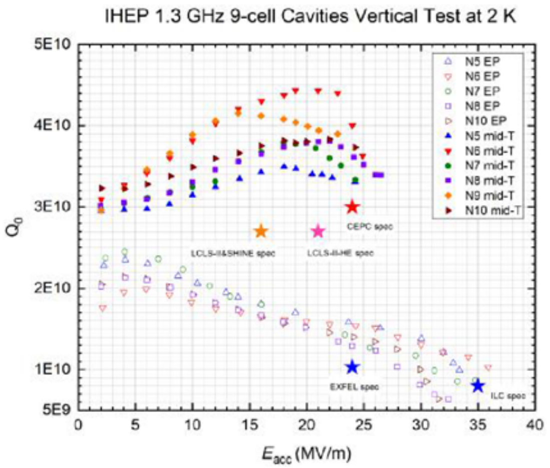
Clean Assembly ISO4

Cold mass

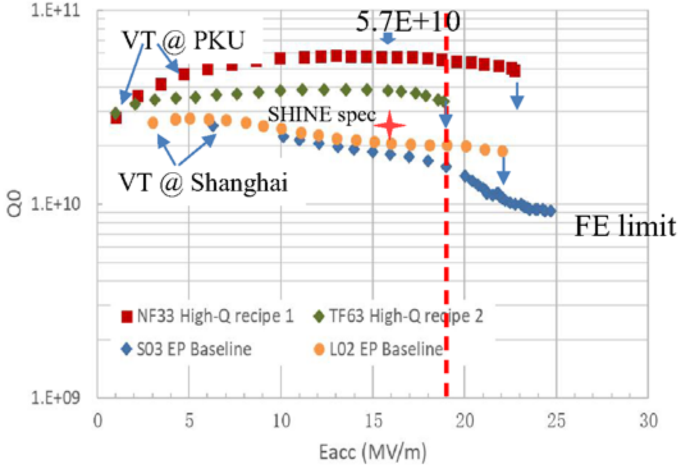
Cryomodule in tunnel

1.3GHz SRF Cryomodule for SHINE

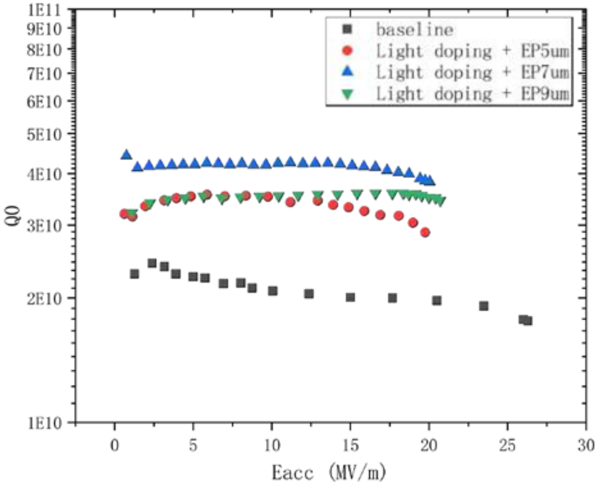
- **High-Q treatment recipe: three groups developed different high-Q0 recipe**
  - IHEP: based on EP and Mid-T, fine grain 9-cell cavity
  - SARI: based on EP and high-Q0 recipe, fine grain single cavity
  - PKU: based on BCP&EP, N-doping, N-infusion and Mid-T, large grain/fine grain single cell cavity



- 6 FG 9-cell cavities, high Q achieved for Q0>3.5e10 @ Eacc=18 MV/m.
- Min gradient 24 MV/m.



- Fine grain single cell cavity
- high Q achieved for Q0>5.7e10 @ Eacc=16 MV/m



- LG3：Light doping N2 2min + A 6min
- Q0~4.1 e10 @16MV/m

500 MHz SRF cryomodule

Cryomodule Composition:

- SC niobium cavity;
- Fundamental power coupler;
- HOM damper;
- Tuner;
- Liquid helium cryostat.

Parameters	Technical Specification
Working frequency	499.654 MHz
Cavity voltage	1.5～2.0 MV
Tuning bandwidth	±150 kHz
Cavity unloaded quality factor	> 5.0×10^8 @Vc = 2.0 MV
External quality factor	(1.5 ±0.3） $\times 10^5$
Module length	3045+/-5 mm

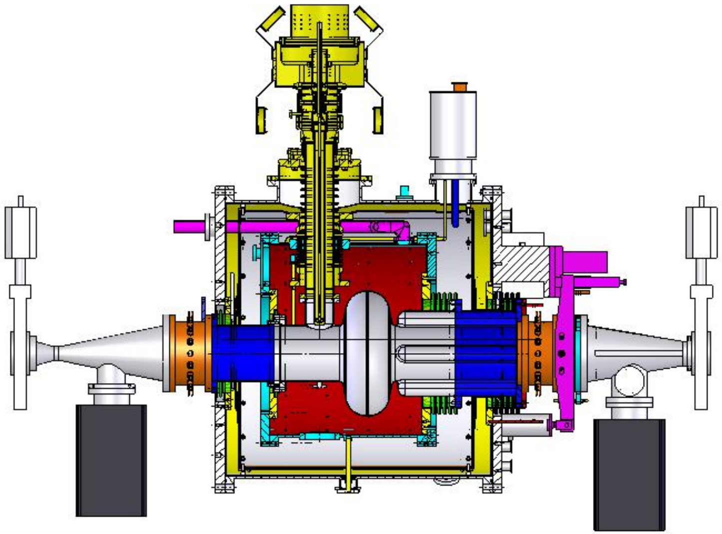


Fig. The structure design of 500 MHz SC cryomodule

Fig. The 500 MHz SC cryomodule integration in the test tunnel

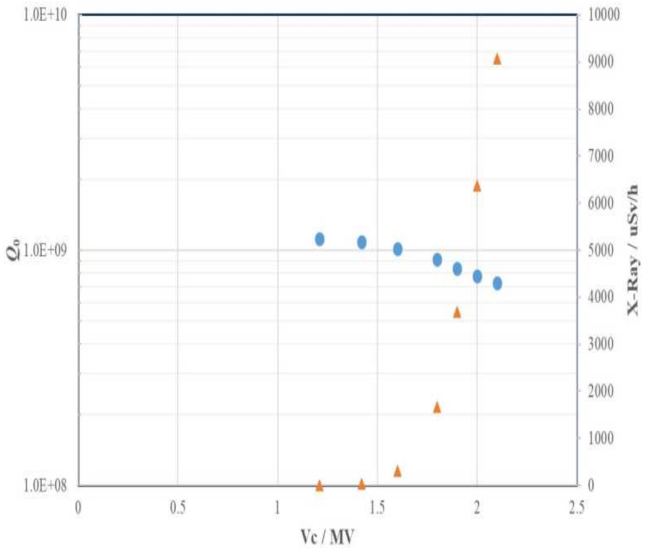
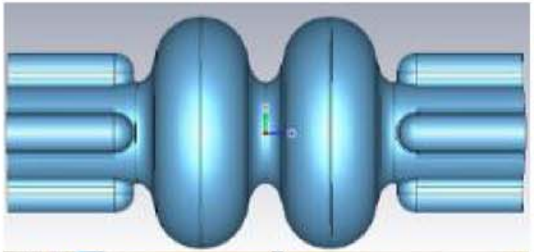
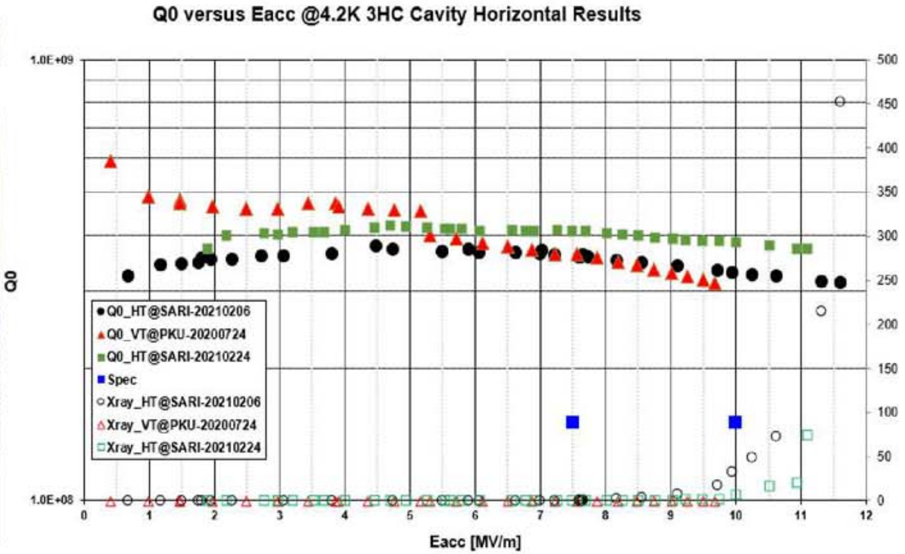


Fig. The Horizontal test results of 500 MHz SC cryomodule

Superconducting Third Harmonic Cavity

- The third harmonic SRF cryomodule was installed into tunnel and cooled down to 4.2 K, frequency detuned, with 200 mA beam;
  - ✓ One 2-cell cavity to provide high harmonic voltage up to 1.8 MV
  - ✓ Compact design to have a shorter cryomodule length, ~ 2.3 m
  - ✓ Lower loss factor of HOM by adopting fluted beam pipe
  - ✓ SiC HOM absorber and mechanical tuner & piezo tuner operated at room temperature





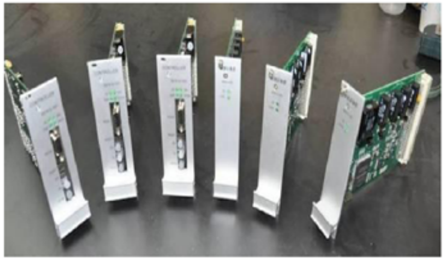
Home-made Digital Instrument Development

- Digital BPM processors
  - 125MHz for SSRF and SXFEL
  - 1GHz for SHINE
- ps timing system
  - White Rabbit timing system for SXFEL and SHINE
  - Event system for SSRF and SAPT
- fs synchronization system
- LLRF control unit
- PS control unit

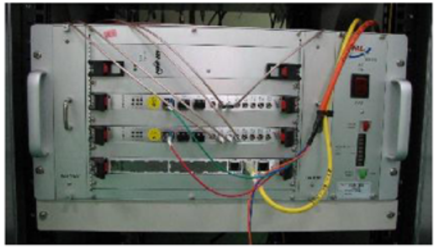
125MHz DBPM for SXFEL and SSRF

1GHz DBPM for SHINE

LLRF controller for SSRF and SHINE



PS controller for SSRF and SHINE

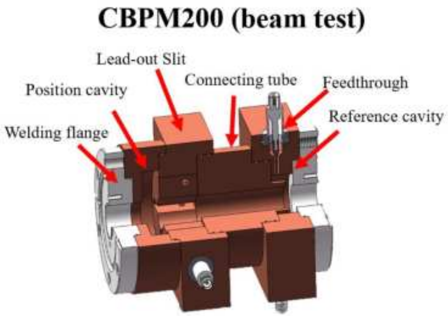


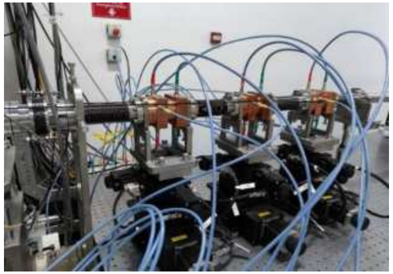
Event timing system

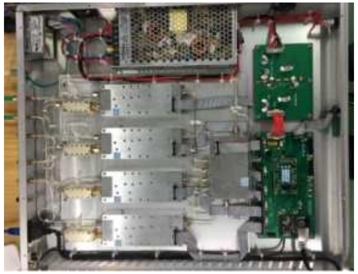
White rabbit timing system

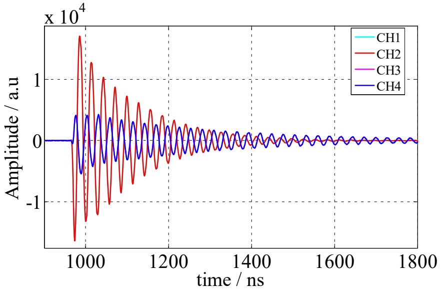
CBPM technology

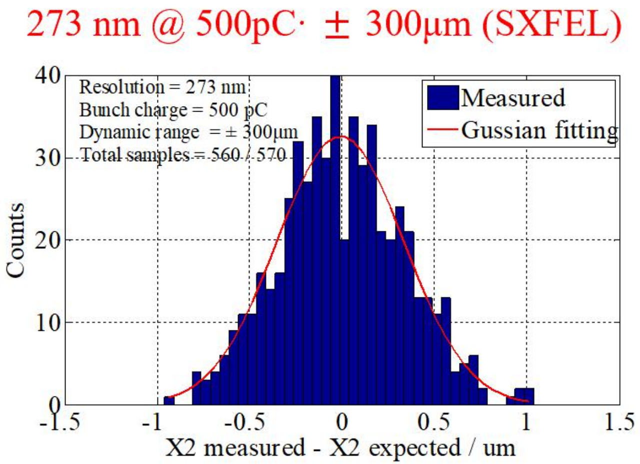
- CBPM technology had been investigated since 2014
- All key components, including C-band sensor, low noise RF front end and high sampling rate (1GHz) DBPM processor, have been designed and fabricated locally.
- Resolution of 300 nm has been achieved and satisfied SXFEL requirement
- Still fighting for 100 nm resolution required by SHINE











Summary

Summary

- For establishing a world-class photon science center at Shanghai, a cluster of accelerator based light sources had been developed.
- SSRF had been in operation since 2009 and 16 more beamlines will be added during SSRF-II project.
- Construction of SXFEL has been making progress, and the SXFEL is in the FEL commissioning stage, aiming at serving users in 2022;
- SHINE is a high rep-rate hard X-ray FEL facility, with an 8 GeV CW SCRF linac, a 100PW laser system, 3 phase-I undulator lines and 10 end-stations, is under development;
- Key technology R&D programs have been initiated to support all facilities construction.


Thanks for your attention!