

### SXFEL & SHINE

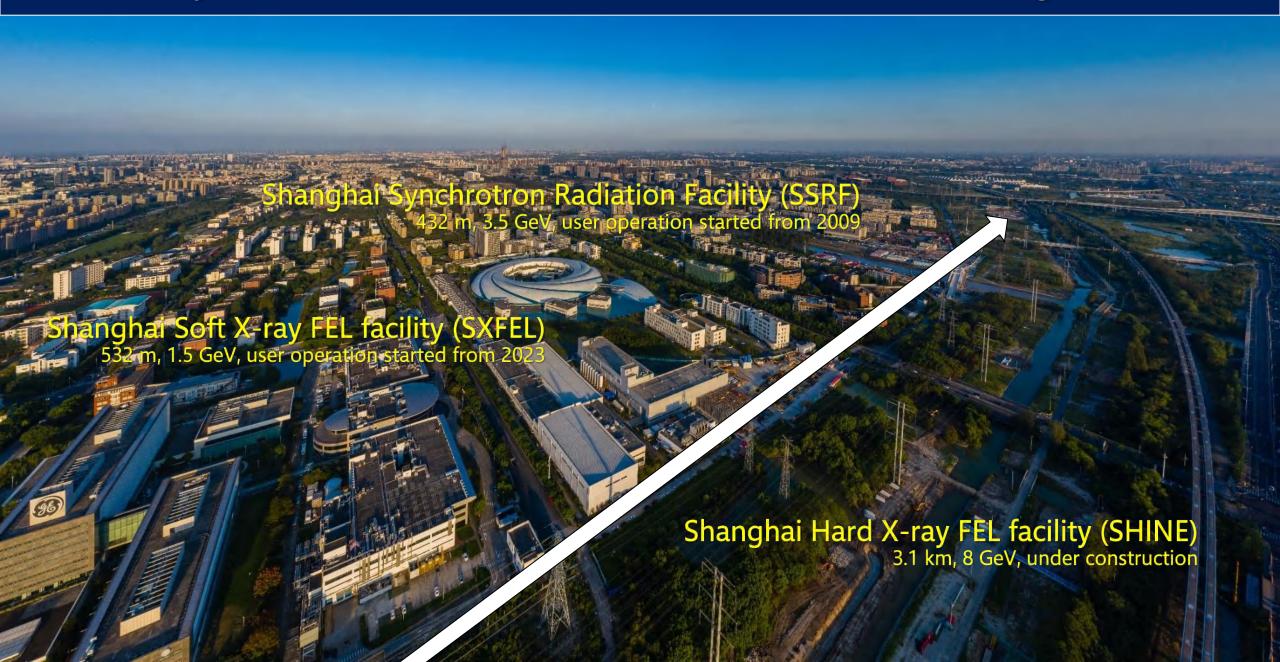
Bo Liu SSRF Center Shanghai Advanced Research Institute, CAS

Aug. 5<sup>th</sup>, 2025

### **Worldwide XFELs**



### Synchrotron Radiation and FEL Facilities in Shanghai





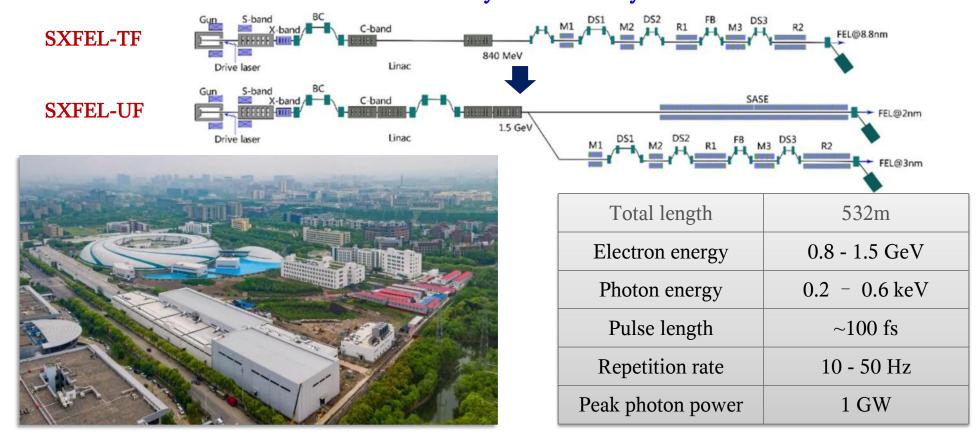


# SXFEL: Shanghai Soft X-ray FEL Facility



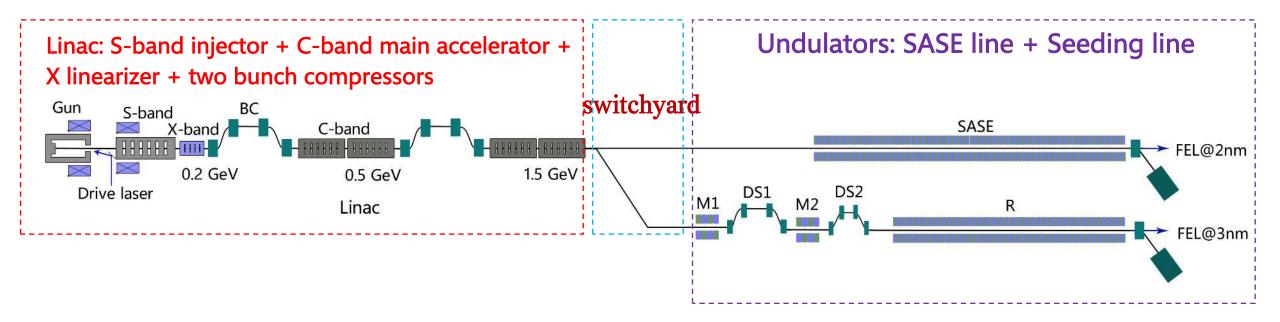
- Two phases of SXFEL Facility: SXFEL test facility (SXFEL-TF) + SXFEL user facility, located at the SSRF campus.
- SXFEL-TF was initiated in 2006 and funded in 2014, its 0.84GeV linac and main undulators started to be installed in 2016. The commissioning of the test facility had been finished in 2020.
- **SXFEL-UF (+SBP)** was funded to upgrade the linac energy to 1.5 GeV for building two undulator lines with 5 experimental stations. The commissioning of the user facility started in 2021 and finished in 2022.

#### From test facility to user facility



# Layout of the SXFEL User Facility











# **SXFEL User Facility**



> Linac



FEL1: SASE FEL line



switchyard



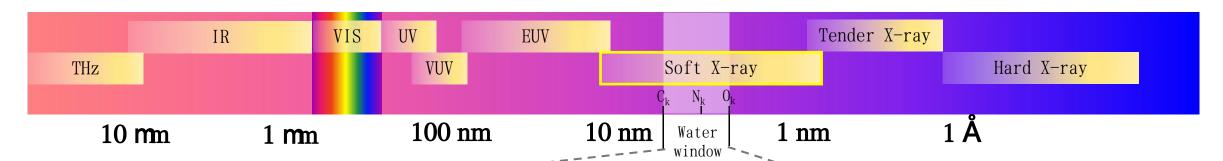
**FEL2:** Seeded FEL line

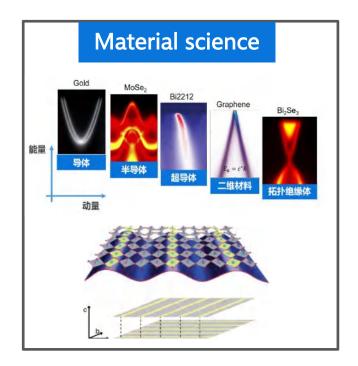


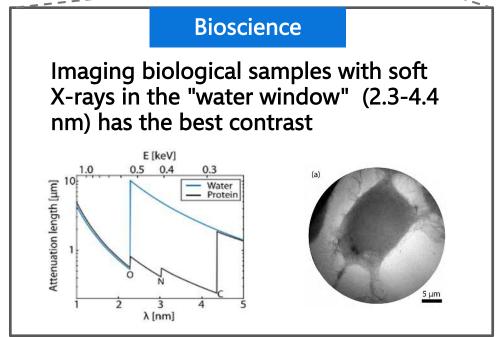
# SXFEL can cover the "water-window" region CPA-2025

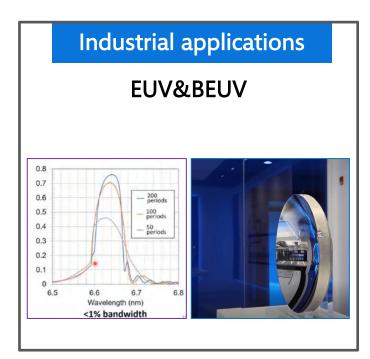


> SXFEL has important application prospects in both scientific and industrial fields



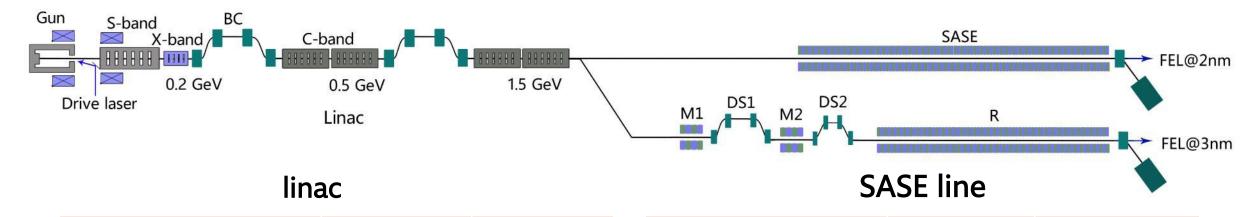






### Main Parameters of the SXFEL





	Design	Realized
Beam energy (GeV)	1.5	1.51
Nor. emittance (mm.mrad, rms)	≤ 1.5	1.2
Bunch charge(nC)	0.5	0.6
Peak current (A)	≥ 700	>1000

	Design	Realized
Wavelength (nm)	2.0	1.98
duration (fs)	~400	<300
Peak power (GW)	≥ 0.1	>1

#### Seeding line

	Design	Realized
Wavelength (nm)	3.0	2.96
duration (fs)	~100	~100
Peak power (GW)	≥ 0.1	>0.2

The main parameters of linac and FEL have all reached or exceeded the design values

### **Main Parameters of Undulators**



> SASE line: IVU16 (in-vacuum undulator)



Parameters	Values
Beam energy	1.5 GeV
Peak current	0.7-1 kA
Undulator period	16 mm (in-vacuum)
Undulator length	4 m*10
FEL wavelength	2-4 nm
Peak power	> 100 MW

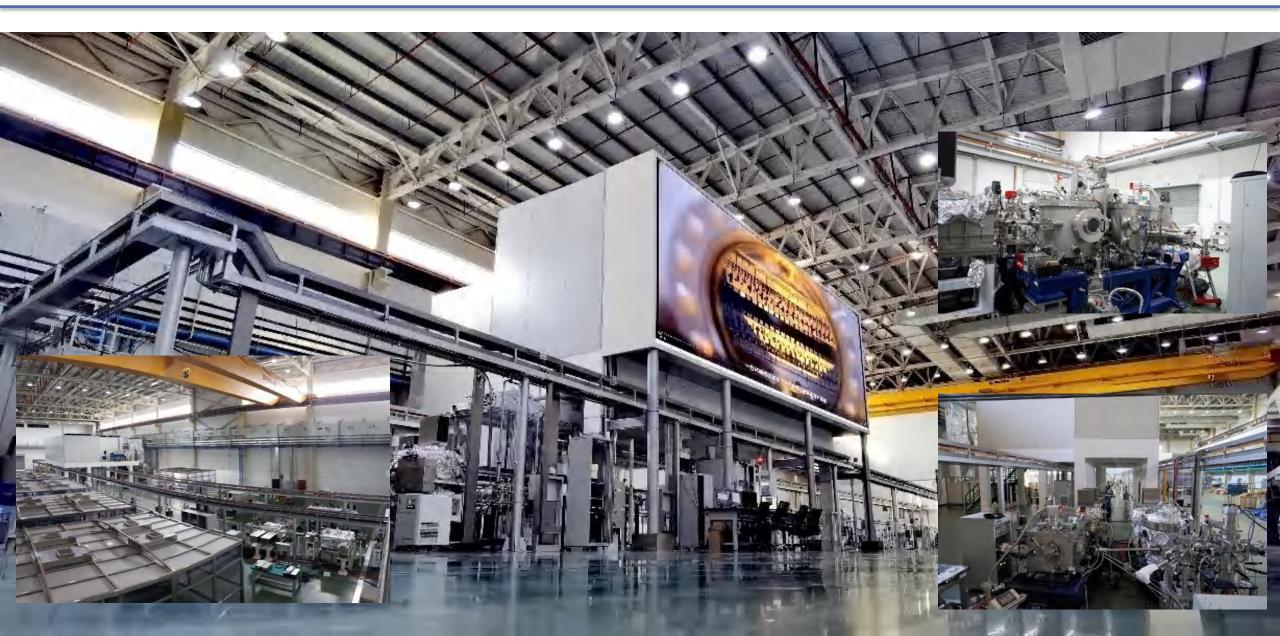
➤ Seeding line: PMU23.5



Parameters	Values
Modulator	80 mm*2
DS1	12 m, max R56~20 mm
Other DSs	3 m, max R56~1 mm
Radiator	U30*6+U235*10+EPU*2
FEL wavelength	3-6 nm
Peak power	> 100 MW

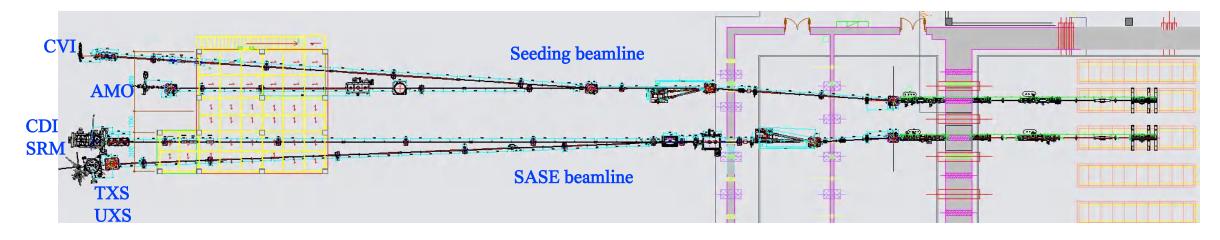
# X-ray Beamlines and End-stations





# X-ray Beamlines and End-stations





#### 2 Beamlines:

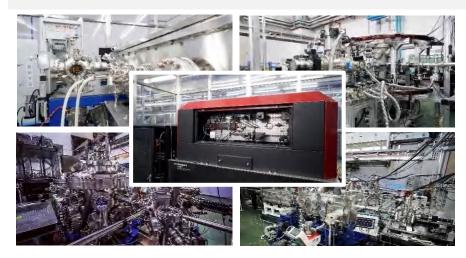
- SASE beamline: two branches, energy coverage 100-620 eV, focusing spot size at sample position  $\sim$ 3  $\mu$  m.
- Seeding beamline: two branches, energy coverage  $50\sim410$  eV, focusing spot size at sample position  $\sim10~\mu$  m.
- Diagnostic tools: online spectrometer, gas monitor detector, timing tool, coherence measurement device etc.





#### 5 end-stations

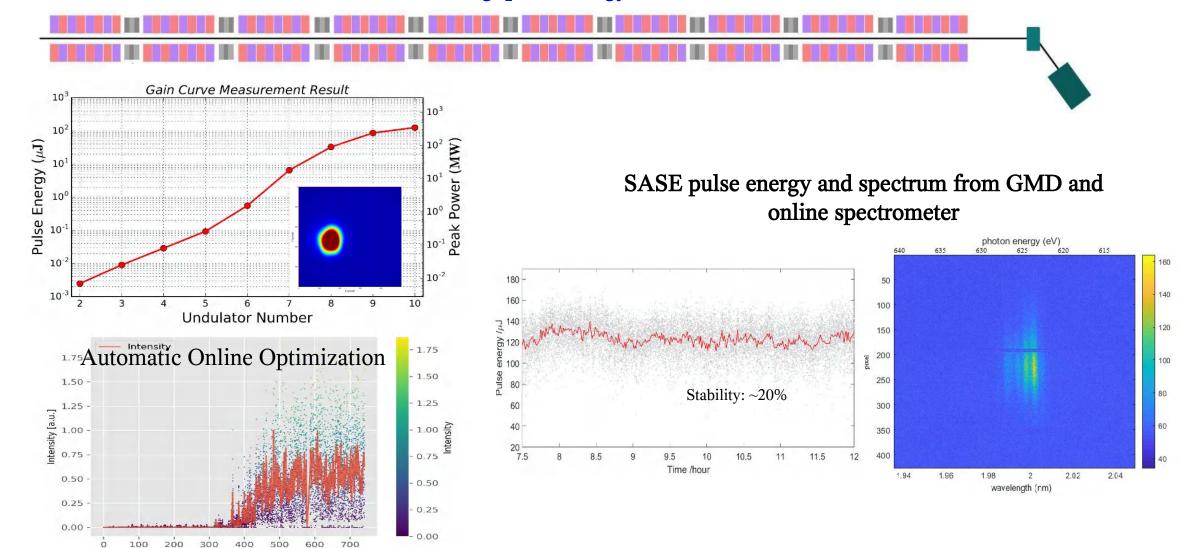
There are 5 phase-I experimental stations: Coherent Scattering and Imaging (CSI), Live-cell fluorescent Super-Resolution Microscope (SRM), Time-resolved X-ray Scattering (TXS), Ultrafast X-ray Spectroscopy for Chemistry (UXS) and Atomic, Molecular and Optical (AMO).



### SASE-FEL Performance at 2 nm



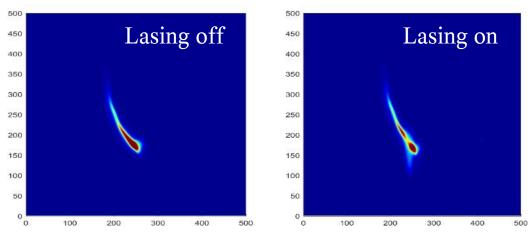
2nm SASE lasing, pulse energy > 200  $\mu$  J

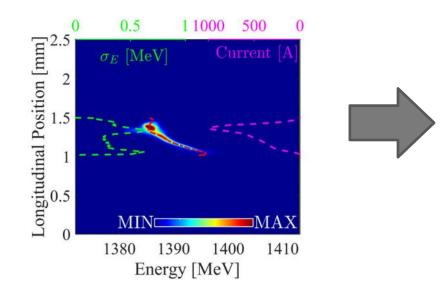


### SASE-FEL Performance at 2.4 nm



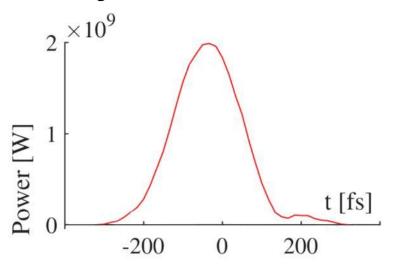
Longitudinal phase space of the e-beam after passing through undulators





- Shorter saturation length (last 3 undulators used for tapering)
- Maximal beam energy loss>1MeV
- FEL peak power>1GW (Peak current~1kA, with only BC1)
- Pulse duration (FWHM)~200fs, only a small fragment in the head lasing, may due to the strong Wakefield of the in-vacuum undulator)
- Pulse energy~200µJ

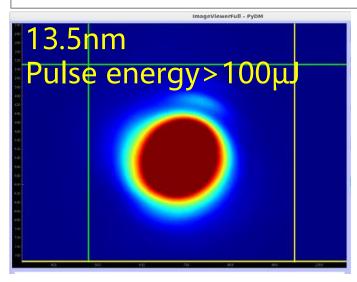
Single-shot reconstruction

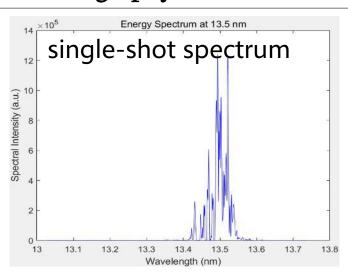


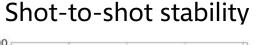
Li Zeng, et al., Fundamental Research 2, 929, 2022

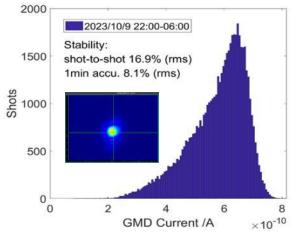
# SASE-FEL Performance at 13.5 and 6.75 nm OCPA-2025

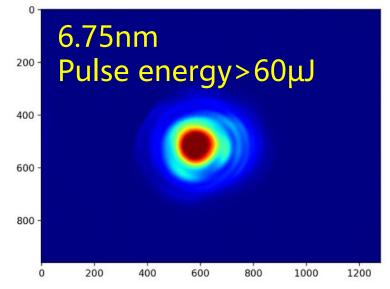
#### > SASE-FEL for EUV and BEUV lithography research

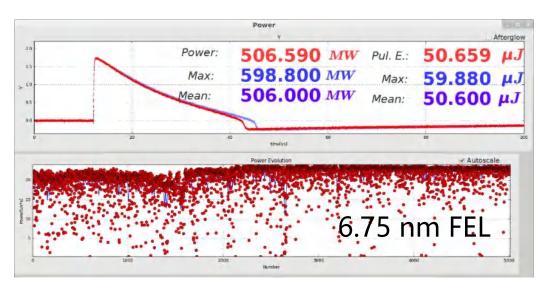






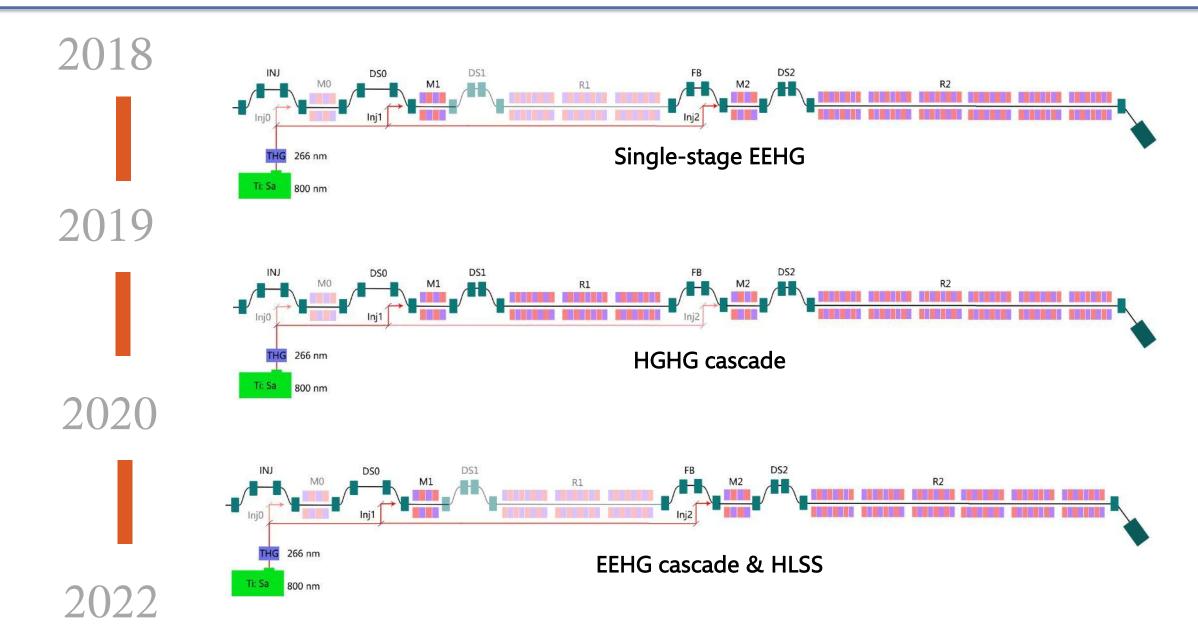






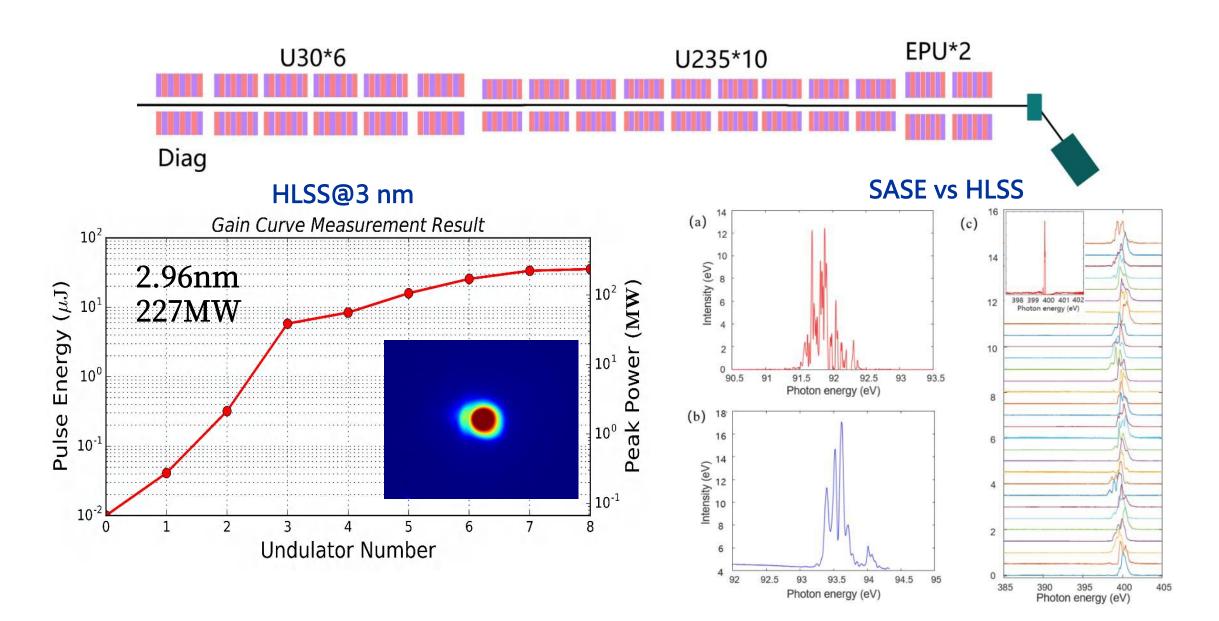
# Seeded FEL Experiments at SXFEL





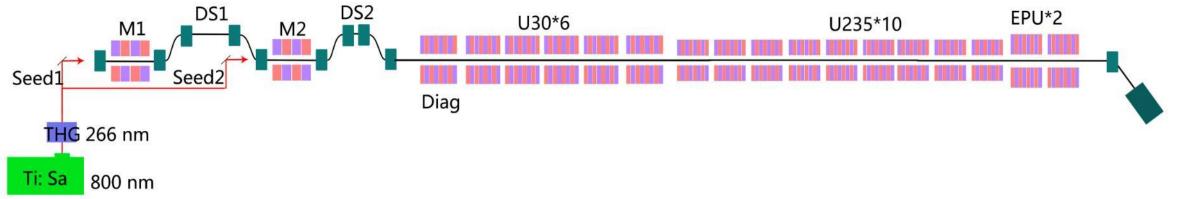
# Harmonic Lasing Self-Seeding (HLSS)



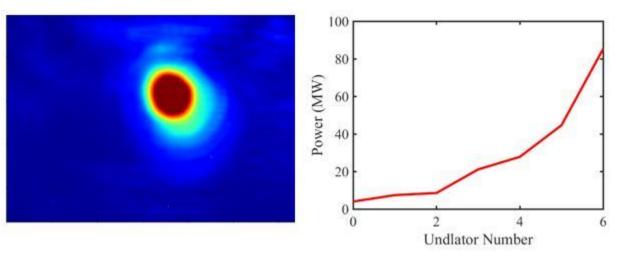


# Single-stage EEHG Experiments





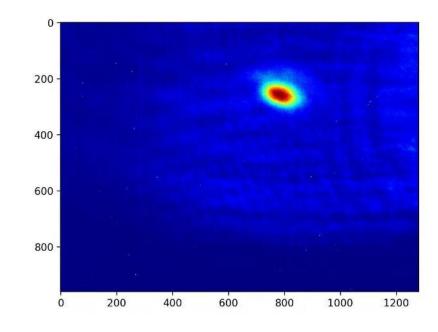
#### EEHG-46<sup>th</sup> (5.78 nm) lasing with U30s



#### **Problems:**

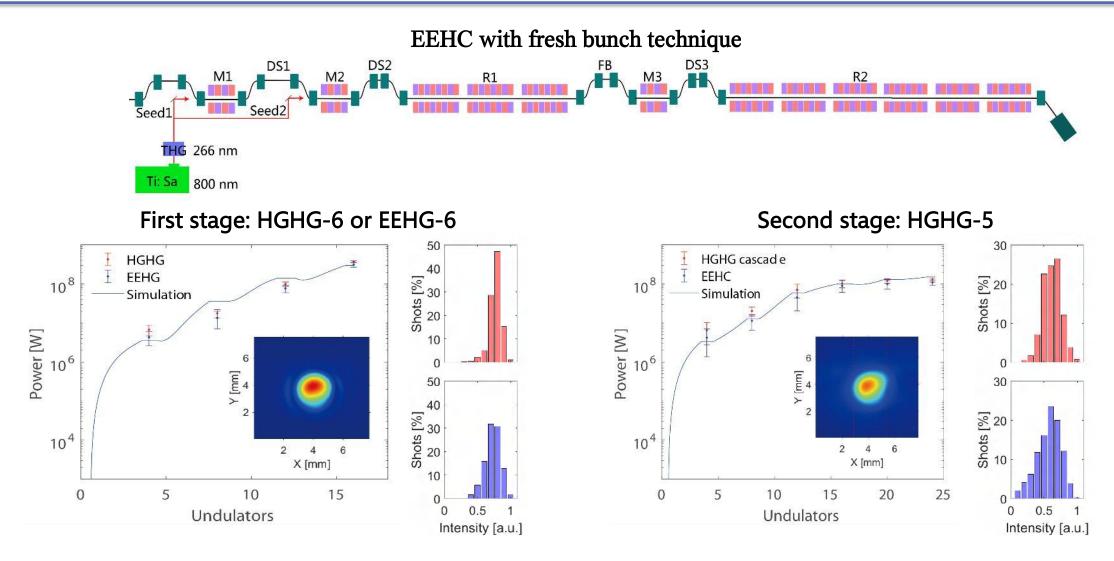
Echo-61 is quite difficult to be amplified with U30s (may due to the relatively weak bunching and undulator field)

#### Coherent radiation from EEHG-61st (4.36 nm)



# **EEHG Cascade (EEHC) Experiments**





> The power fluctuation of EEHG-6 is larger than HGHG-6 due to the jitters of seed1.

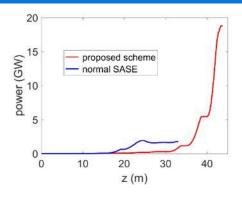
# Plans: Flexible Control of FEL Properties



#### Ultra-short pulse generation

#### **ESASE** modulator

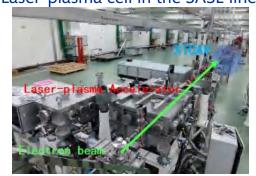


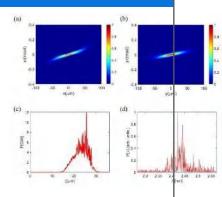


Z. Wang, C. Feng, HPL 11, 33, 2023

#### Spectral bandwidth control with plasma wakefield

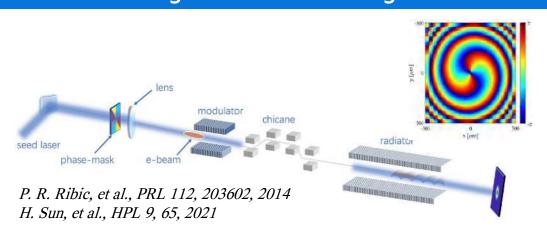
#### Laser-plasma cell in the SASE line





B. Peng, et al., PR Applied 19, 054066, 2023

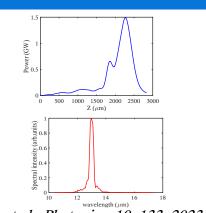
#### OAM generation at Seeding line



#### Intense THz pulse generation

#### THz afterburner





K. Yin, et al., Photonics. 10, 133, 2023

## **Overall Operation Status**

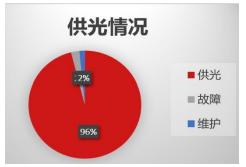


- Modifications have been made during 2023 and 2024, significantly improving reliability and operational efficiency.
- Since 2023: accelerator uptime: ~16,000 hours, beam delivery to users: Over 10000 hours, machine study: ~4,000 hours

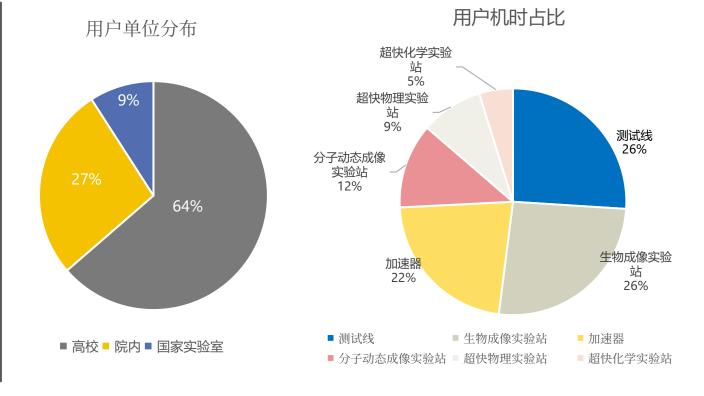
• The maximum photon energy is 2 times higher than similar FEL facilities worldwide.



Early 2023: Beam delivery rate 60%



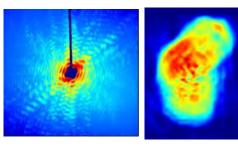
2024: Beam delivery rate 96%

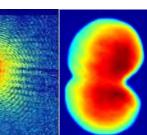


# SXFEL has entered a stable operation phase OCPA-2025

#### □ Supported a series of cutting-edge scientific experiments and strategic national tasks

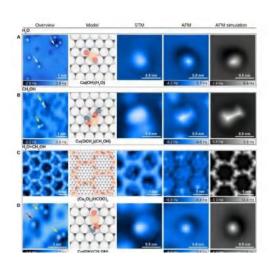
### Non-destructive Structural Imaging of Single Cells





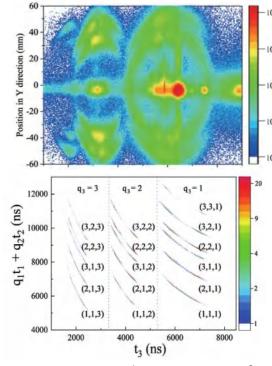
imaging resolution is higher than 25nm, representing the highest biological sample imaging resolution worldwide.

### Surface Dynamics and Reaction Mechanisms



First evidence of the electron transfer intermediate Au-OH+ generated during water oxidation reaction, achieving atomic-level identification of active sites for hydrogen production reactions.

#### Molecular Coulomb Explosion Processes



Coulomb explosion processes of carbon dioxide and nitrous oxide reveal rich dynamic information.

# Next-generation of Photolithography

上海软X射线自由电子激光装置用户证明

上海软 X 射线自由电子激光装置作为国际首台覆盖水窗波 段的软 X 射线自由电子激光用户装置,是国内唯一可提供高亮 度根紫外及更短波长自由电子激光的光源。基于装置建设基础, 张江国家实验室根据《科研任务清单》,面向极紫外波段的战略 需求,增量投入,优化装置功率稳定性,同时建成了极紫外波 段测试线站并通光,可开展光学元件损伤机理、光刻胶材料筛 选等关键技术研究,为国内相关领域先进材料与器件表征提供 了关键平台支撑。

为满足张江国家实验室开展前沿光刻研究的需求,上海软 射线自由由子激光装置实现了国内首个单脉冲能量超过 100uJ

k冲长度在几十飞秒量级的 13.5 nm 极紫外光输出,年度供光

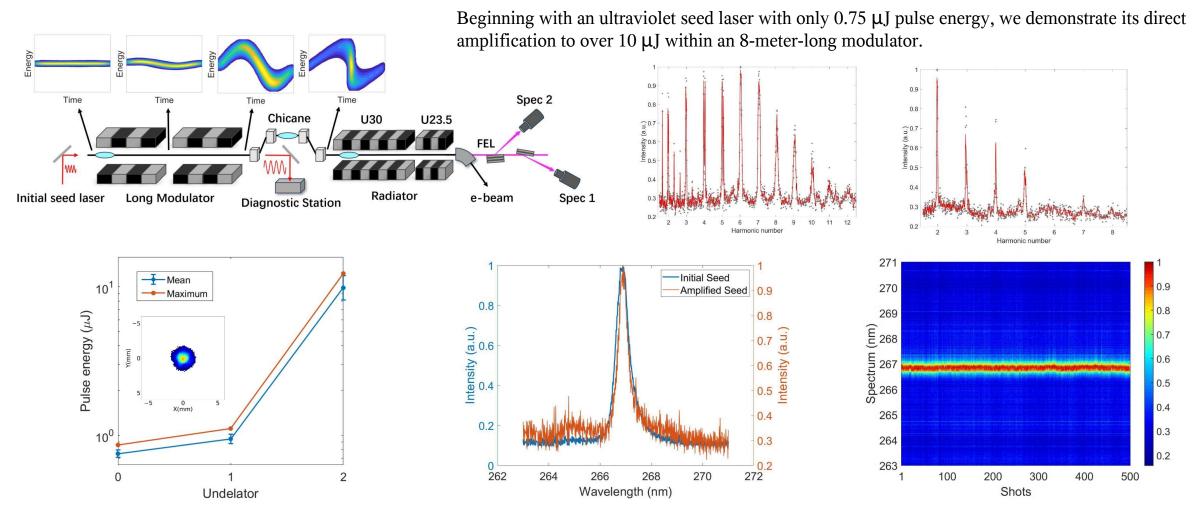
时间超过 800 小时。上海软 X 射线自由电子激光装置兼具高端 值亮度、高相干性、高准直性及波长可调等不可替代的优点, 有力支撑了张江国家实验室在极紫外材料方面的研究,相关要 据结果指导了膜系设计及工艺优化,有效提升了损伤阈值,为 维进国家重大战略任务政关提供了重要保障。



### Recent Machine Studies: DEHG-FEL



#### Towards high repetition rate with reducing the seed laser requirements



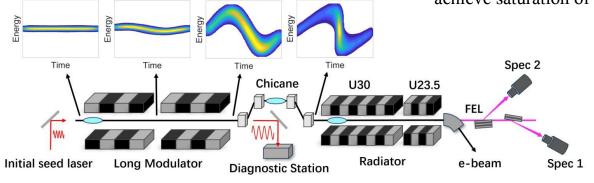
Z. Qi et al., PRL 035001 (2025)

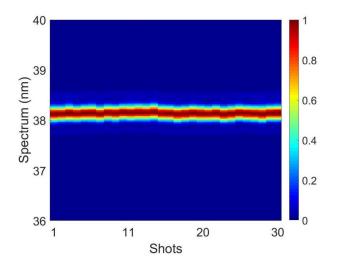
### Recent Machine Studies: DEHG-FEL

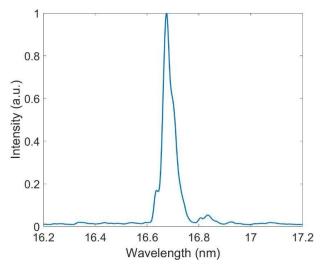


#### Towards high repetition rate with reducing the seed laser requirements

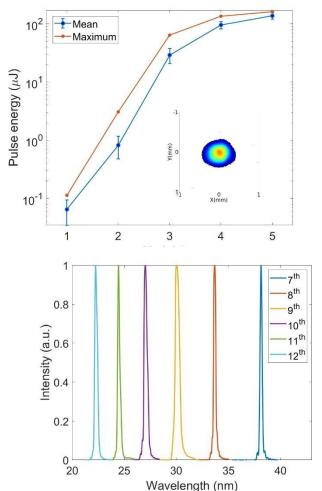
Observe coherent harmonic generation up to the 12th harmonic of the seed and achieve saturation of the 7th harmonic in the radiator.







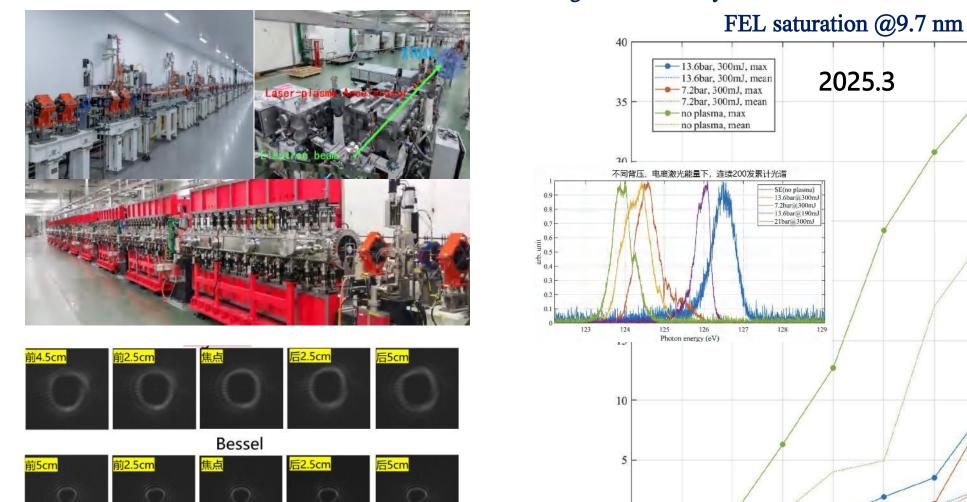
Z. Qi et al., PRL 035001 (2025)



# Recent Machine Studies: PWFA-driven FE OCPA-2025

undulator No.

#### Collaboration with Tsinghua University

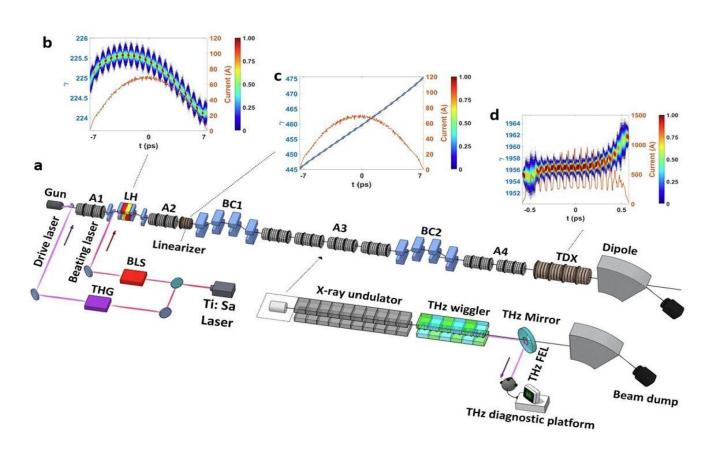


Generation of large-sized (600 µm in diameter) plasma channels

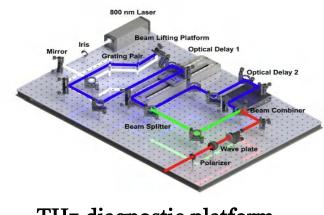
### Recent Machine Studies: THz-FEL



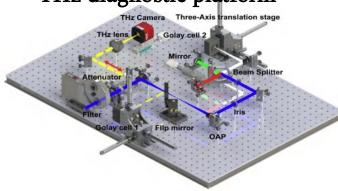
- > Towards THz-X ray pump-probe
- > Pulse duration: 300 fs -1ps
- $\triangleright$  Pulse energy ~100s  $\mu$ J, 1-60 THz (5-300  $\mu$ m)



#### Frequency-beating laser system



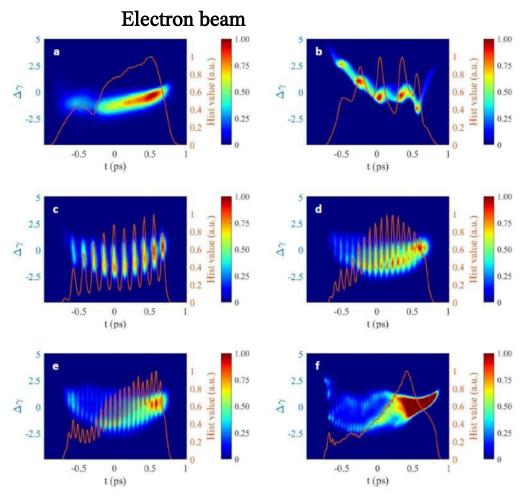




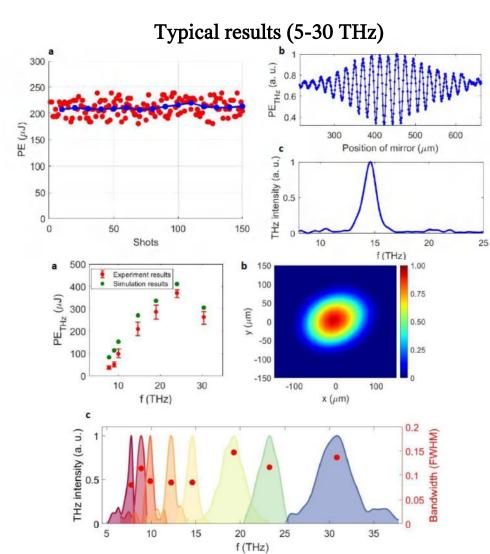
### Recent Machine Studies: THz-FEL



■ Experiment results: stable coherent THz generation with continuously tunable frequency of 1-60 THz



Y. Kang, et al., submitted (arXiv:2504.01391)





# SHINE

# SHINE: Shanghai Hard X-ray FEL Facility



### Shanghai HIgh repetitioN rate XFEL and Extreme light facility (SHINE)

- SHINE is an 8 GeV CW SCRF linac based high rep-rate XFEL facility, it will be installed in a 3.1 km long tunnel underground at Zhangjiang High-Tech Park, across the SSRF campus to the southwest corner of ShanghaiTech University;
- This XFEL facility, assisting with a super-intense laser facility, has several undulator lines, beamlines and experimental stations in phase-I, and it can provide the XFEL radiation in the photon energy range from soft X-ray to hard X-ray.
- This project was launched by the central government in April 2017, and its groundbreaking was made in April 2018.

This facility is being developed by Shanghai-Tech Univ., SARI and SIOM of CAS.

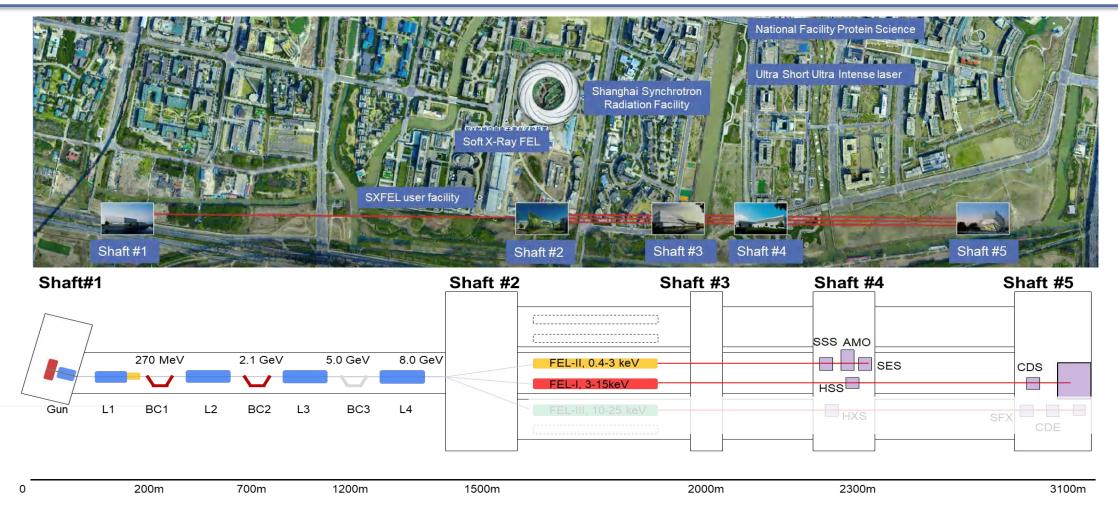






# **SHINE: Layout and Main Parameters**

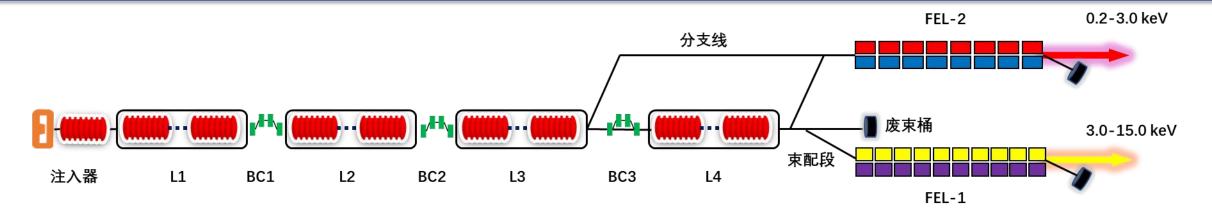




An 8 GeV SCRF linac, 2 undulator lines to deliver photons from 0.2-15 keV in the first stage, up to 1 MHz pulse train with pulse duration of 1-100 fs

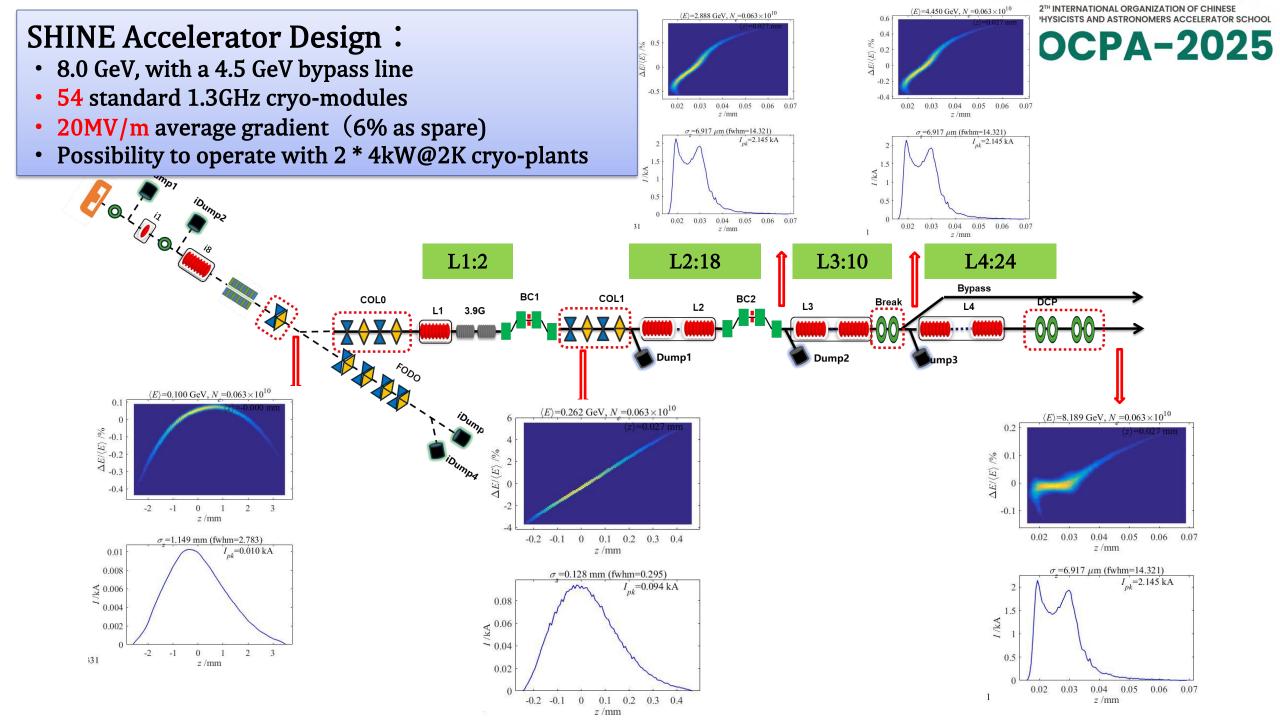
- X-ray beamlines and End-stations
- Super-intense Laser Facility
- Total length 3.1 km; ~33 m underground

# SHINE: A High-rep Rate XFEL Based on SCRFOCPA-2025



	Objective
Beam energy /GeV	8.0
Bunch charge /pC	100
Max rep-rate /MHz	1
Beam power /MW	0.8
Photon energy /keV	0.2-15
Pulse length /fs	20-50
Peak brightness	$5 \times 10^{32}$
Average brightness	$5 \times 10^{25}$

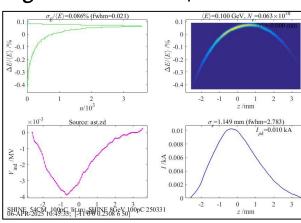
FEL Line	Objective
FEL-I	
Photon energy /keV	3-15
Photon number per pulse @12.4keV	>1011
FEL-II	
Photon energy /keV	0.2-3
Photon number per pulse @1.24keV	>1012

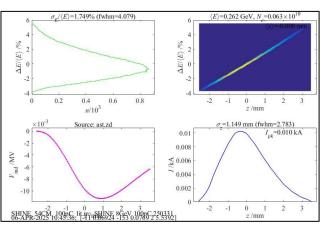


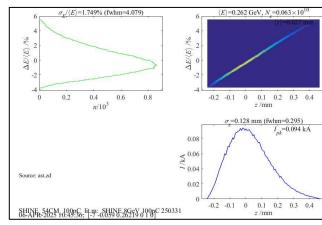
# SHINE Acceledator Design

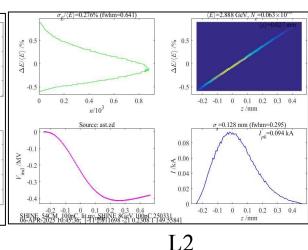
Baseline: Linac 8.0 GeV, Bypass line 4.5 GeV

gradient: 20MV/m



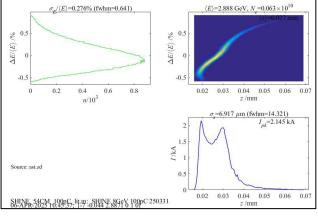


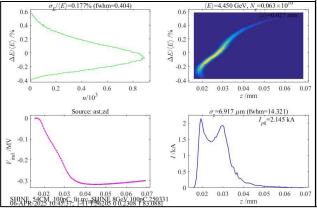


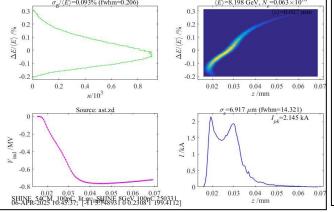


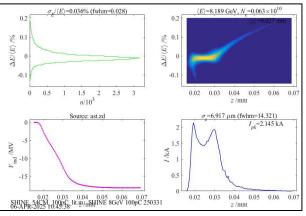
Injector

L1 BC1









BC2 L3 & Bypass

L4

Linac Exit

# SHINE Accelerator Design - Bypass Line



Entrance

20

40

t (fs)

60

2000

1500 ₹

1000 E 500

2000

1500 ₹

1000 E

4.53

4.52

4.52 4.51 4.50

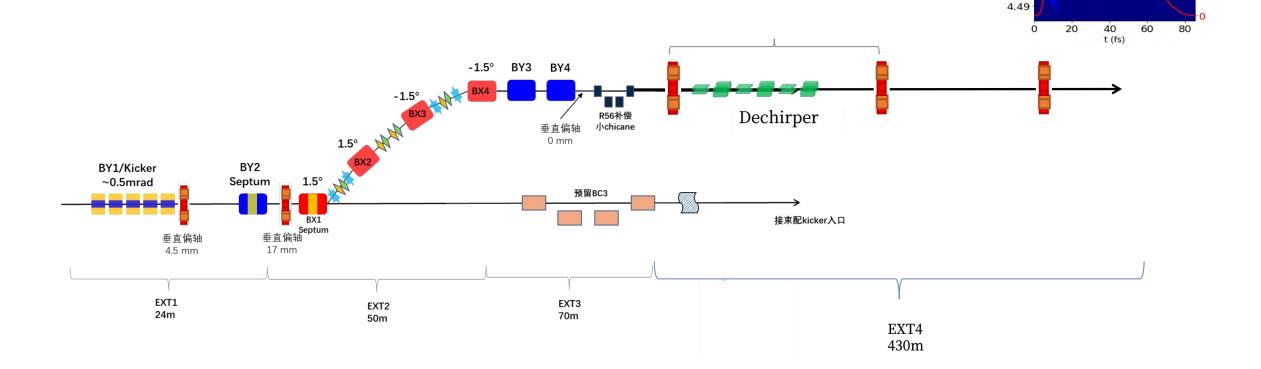
4.49

4.53

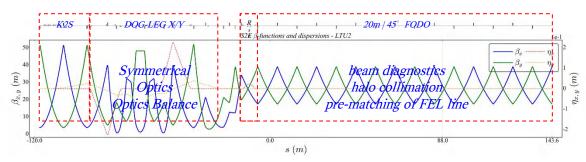
4.52

4.52 (GeV) 4.51 4.50

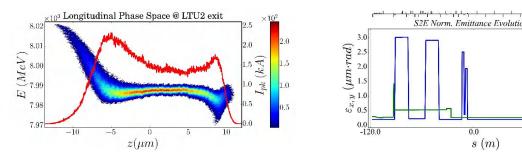
- ➤ A beam bypass line to extract the beam before L4 and generate soft X-ray FEL with lower beam energy
- Extending the FEL-II coverage to longer wavelength
- > Starting the commissioning of FEL-II in an earlier stage, in parallel with the L4 installation
- Operating FEL-II independently with FEL-I/III



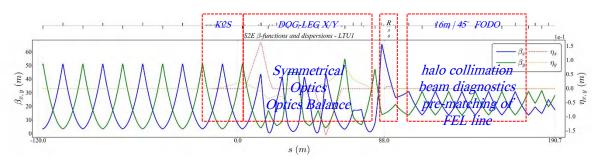
# Switchyard - Beam Transportation Branches OCPA-2025



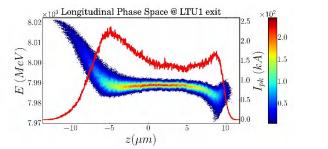
 $\beta$  -functions & dispersion functions of the LTU-2 branch

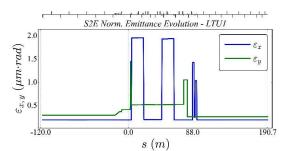


Final longitudinal phase space distribution and emittance evolution of LTU-2 branch



 $\beta$  -functions & dispersion functions of the LTU-1 branch



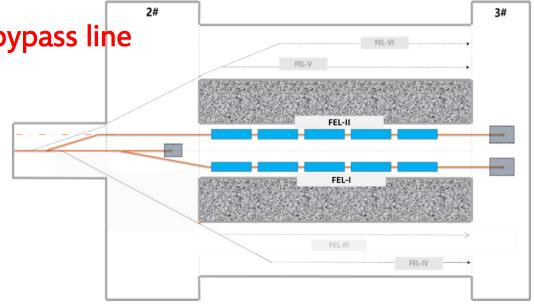


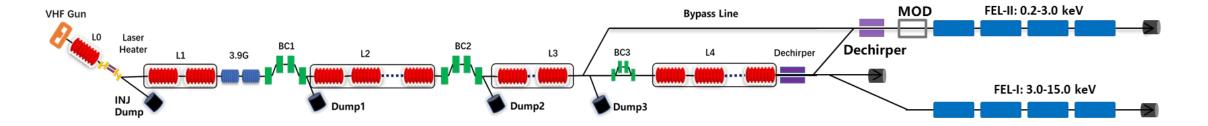
Final longitudinal phase space distribution and emittance evolution of LTU-1 branch

### **FEL Undulator Lines**



- Electron beam parameters
  - 5.8-8.0 GeV @ main line + 3.0-4.5 GeV @bypass line
- FEL revision
  - Number of undulator lines: 3 → 2
  - FEL-I: 3.0-15 keV
  - FEL-II: 0.5-3.0 keV @main line
  - FEL-II: 0.2-1.0 keV @ bypass line
  - FEL-III: suspended





### **Photon Energy Coverage**

0.4

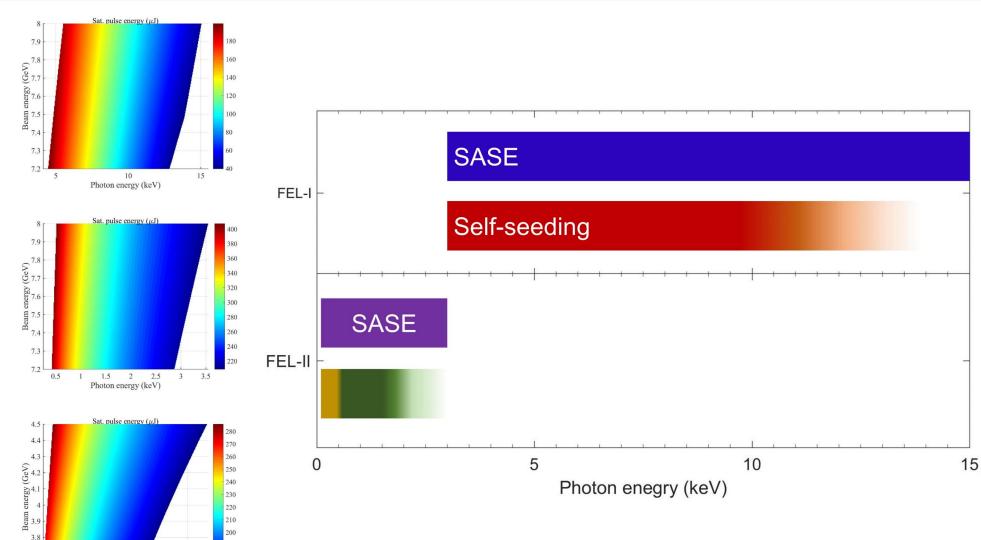
0.6 Photon energy (keV)





FEL-II @ main line





#### **End-Stations @ SHINE facility**



#### 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 + Super-intense 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

## **Progress of Overall Project Construction**



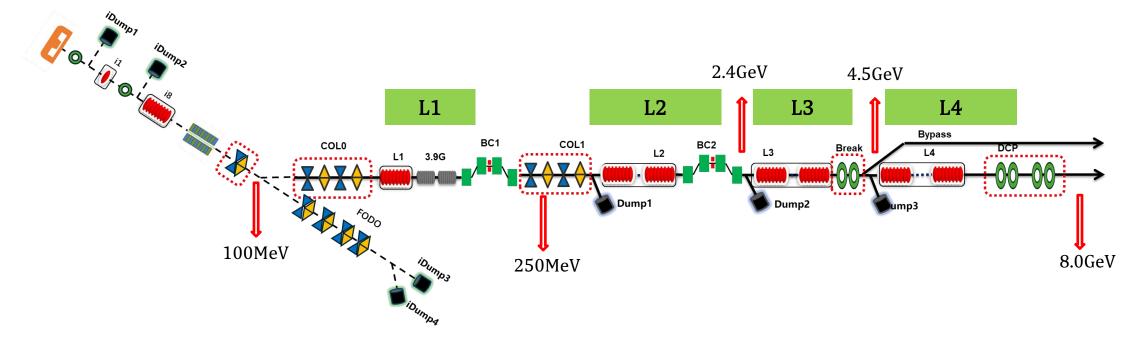
#### > Accelerator Systems

- Injector: installation and beam commissioning
- Main Accelerator: construction and installation of 1.3GHz and 3.9GHz cryomodules
- Undulators: construction and installation of planar U26 and U55/75, APPLE III 68…
- Other accelerator sub systems: RF power system and LLRF…
- Cryogenic Systems: 1kW@2K plant, 3 \* 4kW@2K plants
- ➤ Beamlines and Endstations
- ➤ High-power Super-intense Laser System
- ➤ Civil Engineering & Utilities

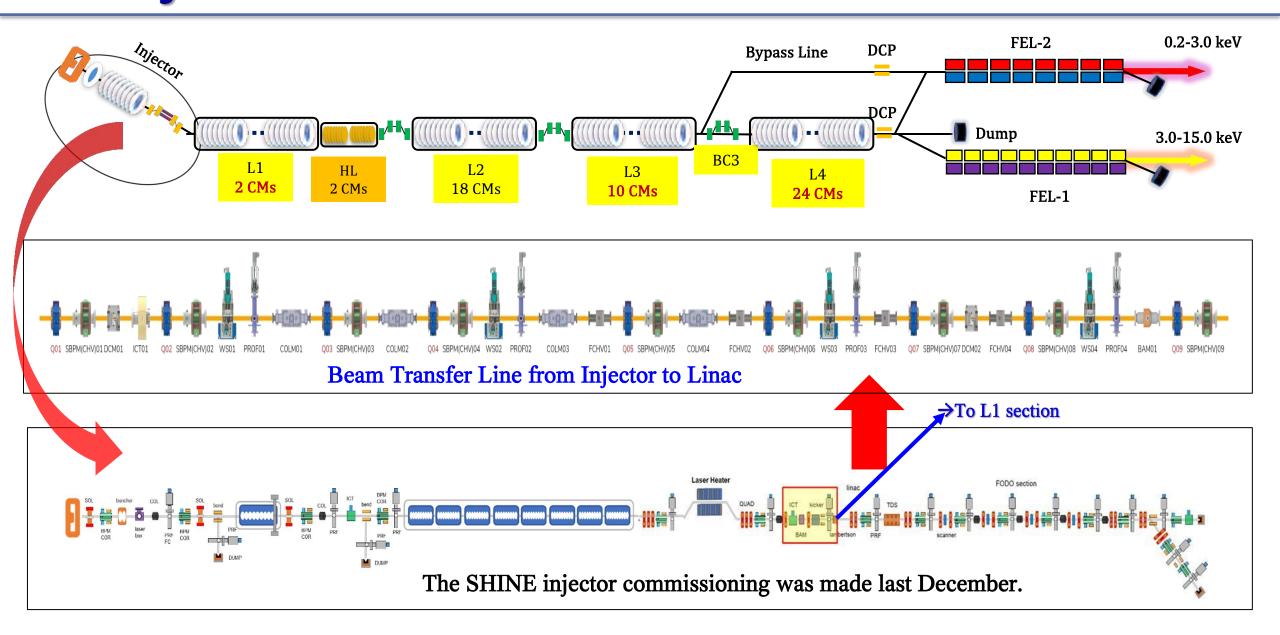
#### The SHINE Linear Accelerator



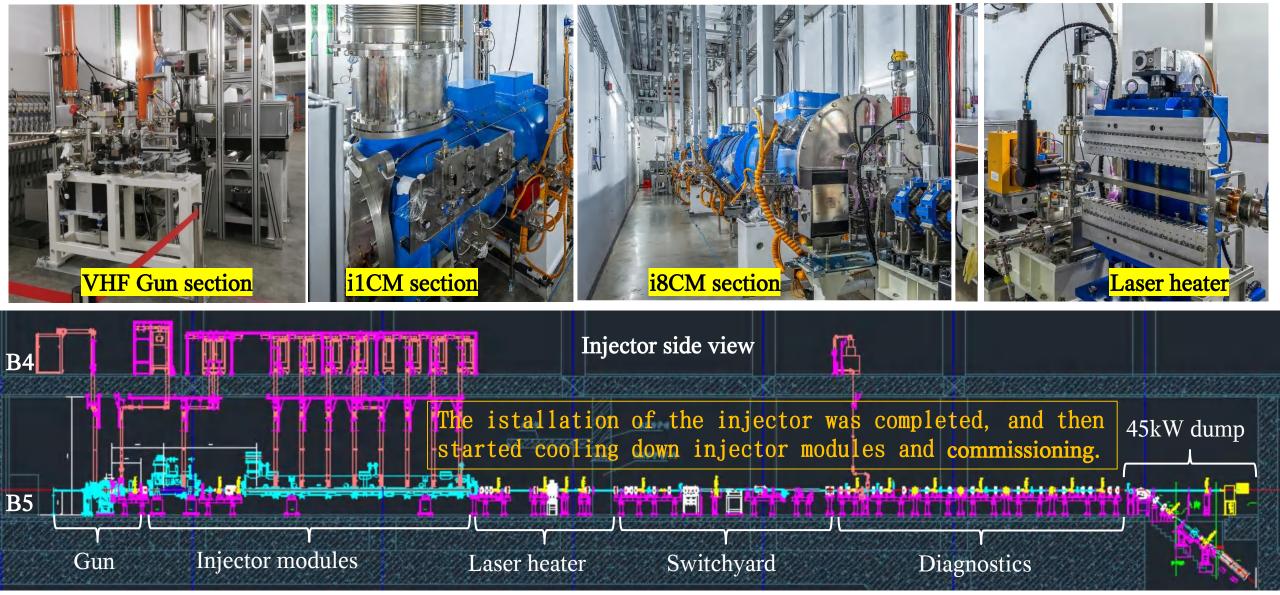
- > The SHINE Linear Accelerator consists of
  - An injector section: 750kV/217MHz photo cathode VHF gun, a normal-conducting two-cell buncher, a single-cavity CM (TFPC-type) and an eight-cavity CM (ABBA-type);
  - A laser heater section; (completed)
  - Four sections of 1.3GHz standard CMs, and one section of 3.9GHz CMs; (on-going now)
  - Three magnetic bunch compression sections and a dechirper section at the end;
  - In addition, a bypass beam transfer line dedicated to FEL-II. (to be installed from Sept.)



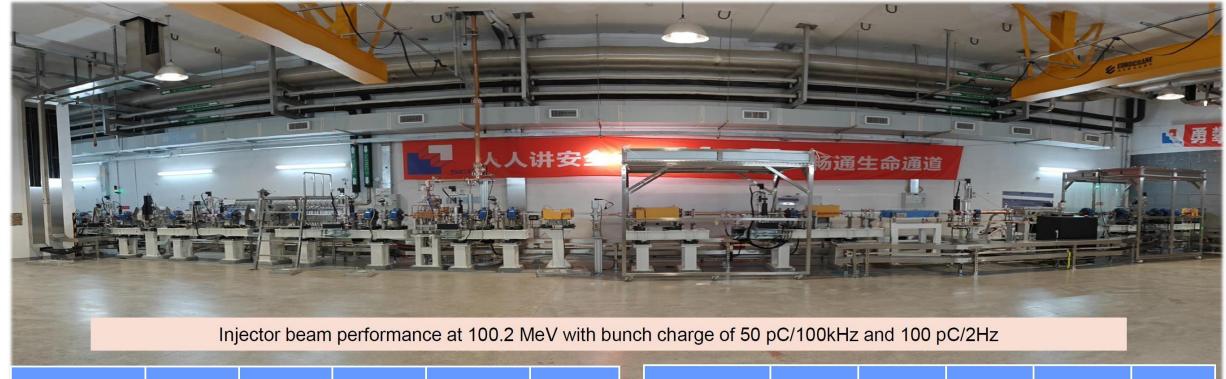
#### The Injector of the SHINE Linear Accelerator OCPA-2025



## Injector: Installation and Beam commission PA-2025



## Injector: Installation and Beam commission PA-2025

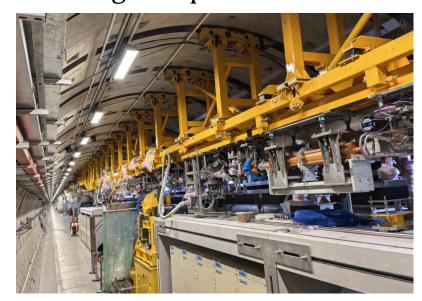


50pC/12.5A	1	2	3	avearge	Unit
X	0.40	0.40	0.44	0.41±0.03	mm mrad
Y	0.50	0.51	0.52	0.51±0.01	mm mrad
Slice	0.328	0.268	0.384	0.33±0.06	mm mrad

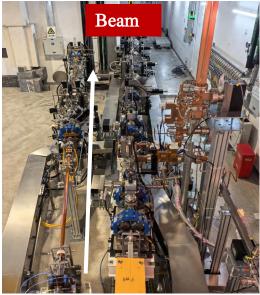
100pC/10A	1	2	3	avearge	Unit
X	0.62	0.53	0.57	0.57±0.04	mm mrad
Y	0.55	0.56	0.55	0.55±0.01	mm mrad
Slice	0.38	0.48	0.46	0.44±0.13	mm mrad

# From Injector to the First Linac Beam Dump OCPA-2025

- ➤ The first linac section L1: begin with a fake module without cavities, then followed by 2 1.3GHz cryomodules CM01~CM02, and 2 3.9GHz cryomodules H-CM01~H-CM02.
- ➤ The first bunch compressor BC1 and COL1 section: including 4 dipole magnets, 10 quadrapoles, 1 analyzing magnet, 5 S-BPMs, 4 profilers, 1 DCM, 1 ICT and 1 S-band defecting cavity;
- ➤ The first linac dump-line: consisting of 2 quadroples, 2 correctors and 1 270W beam tuning dump.

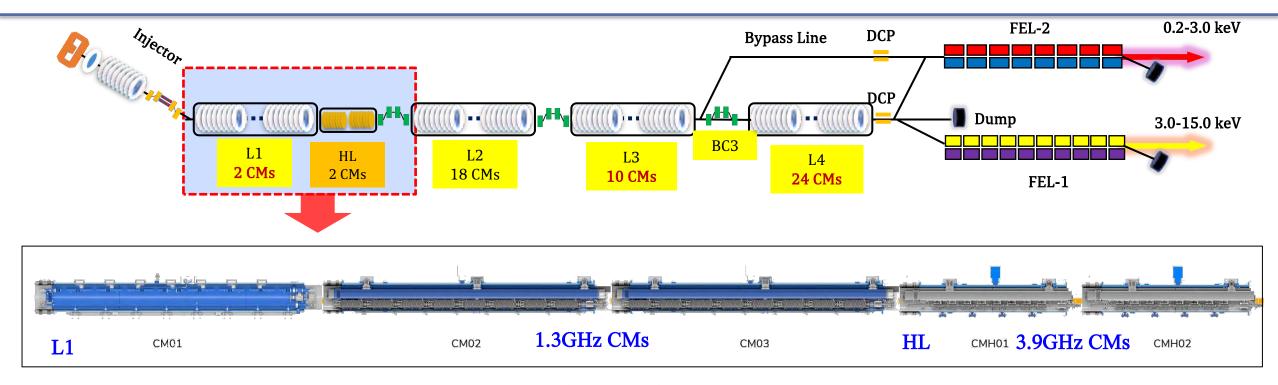




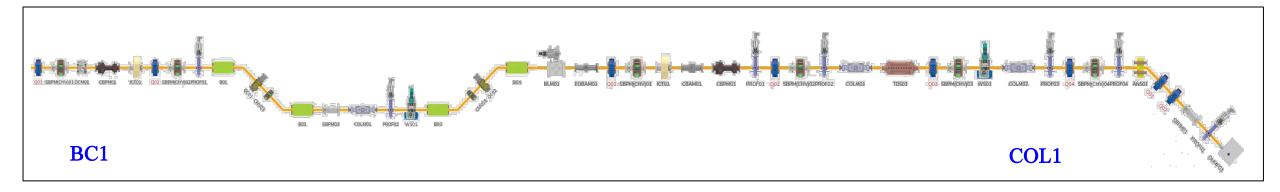


#### The First Linac L1-BC1 Section



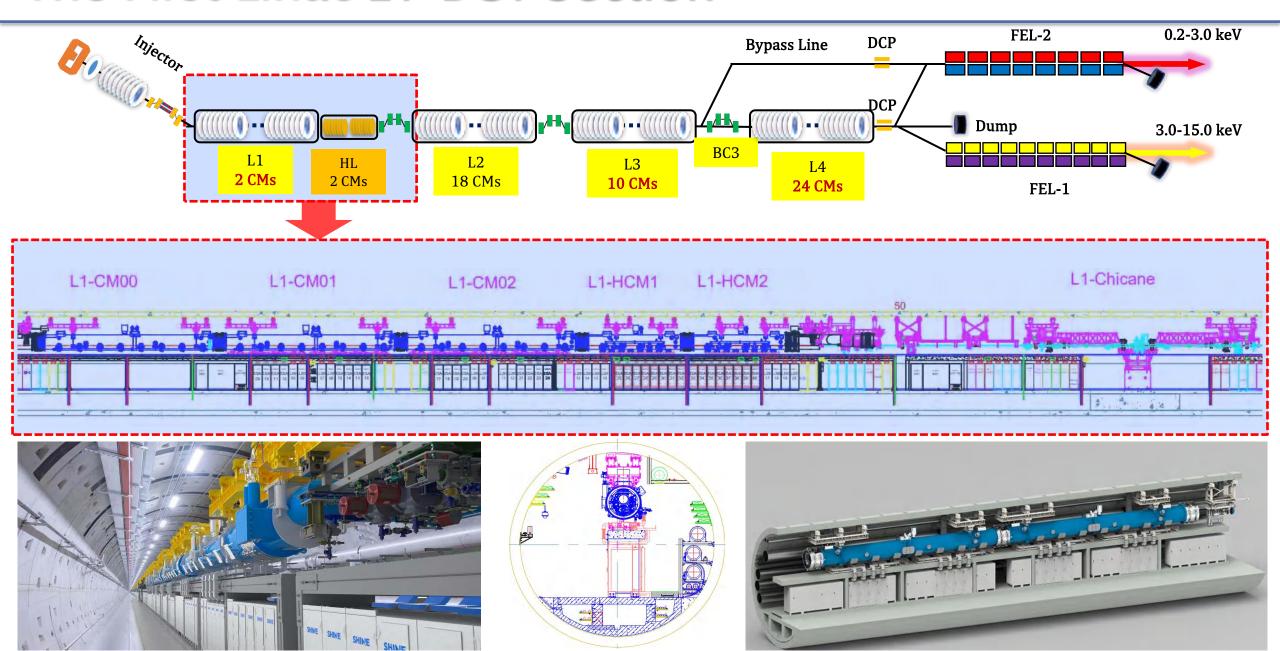


L1 and HL Section



#### The First Linac L1-BC1 Section





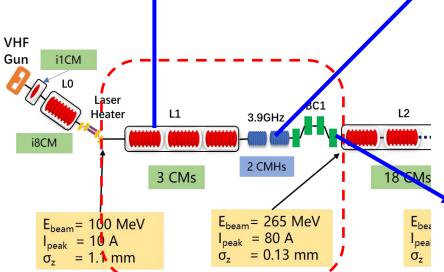
#### The First Linac L1-BC1 Section







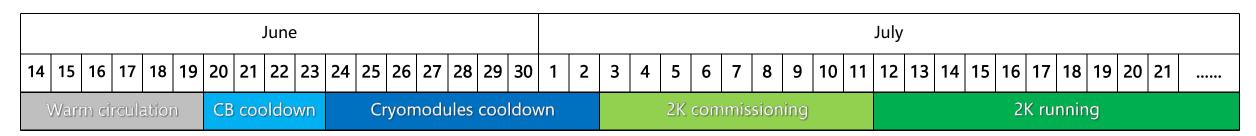


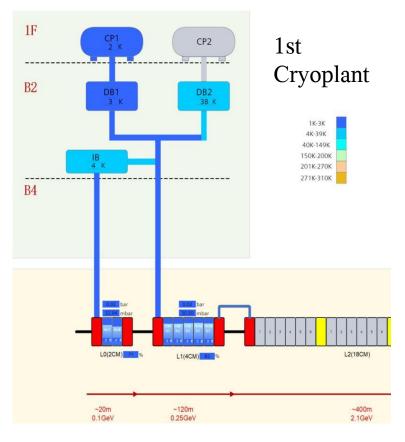


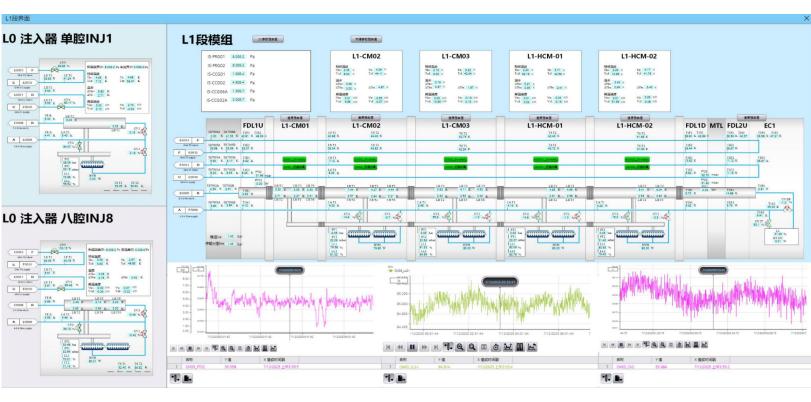




# First Cooling Down of the L1 Cryomodules OCPA-2025







12<sup>™</sup> INTERNATIONAL ORGANIZATION OF CHINESE

2 injector cryomodules + 2 1.3GHz cryomodules + 2 3.9GHz cryomodules

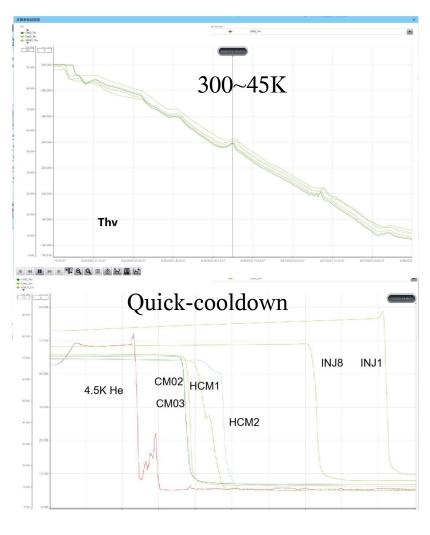
#### 12<sup>™</sup> INTERNATIONAL ORGANIZATION OF CHINESE PHYSICISTS AND ASTRONOMERS ACCELERATOR SCHOOL

## First Cooling Down of the L1 Cryomodules OCPA-2025

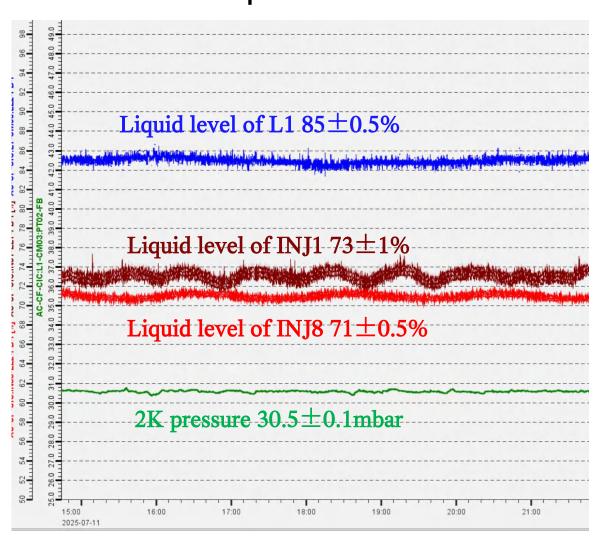


#### Automation





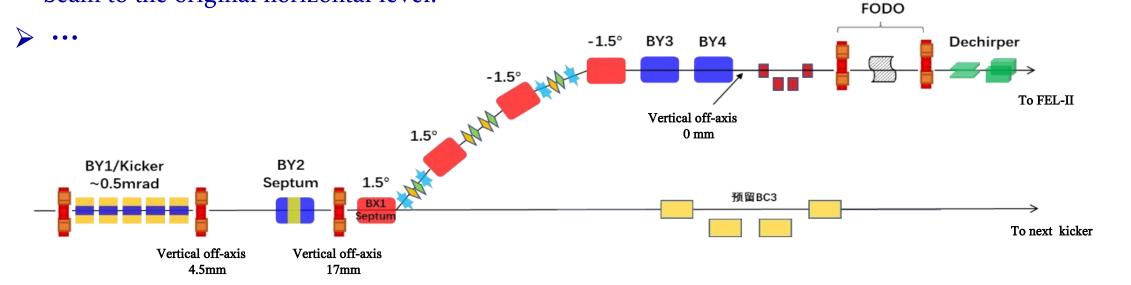
#### 2K performance



#### The Bypass Beam Transfer Line to FEL-II



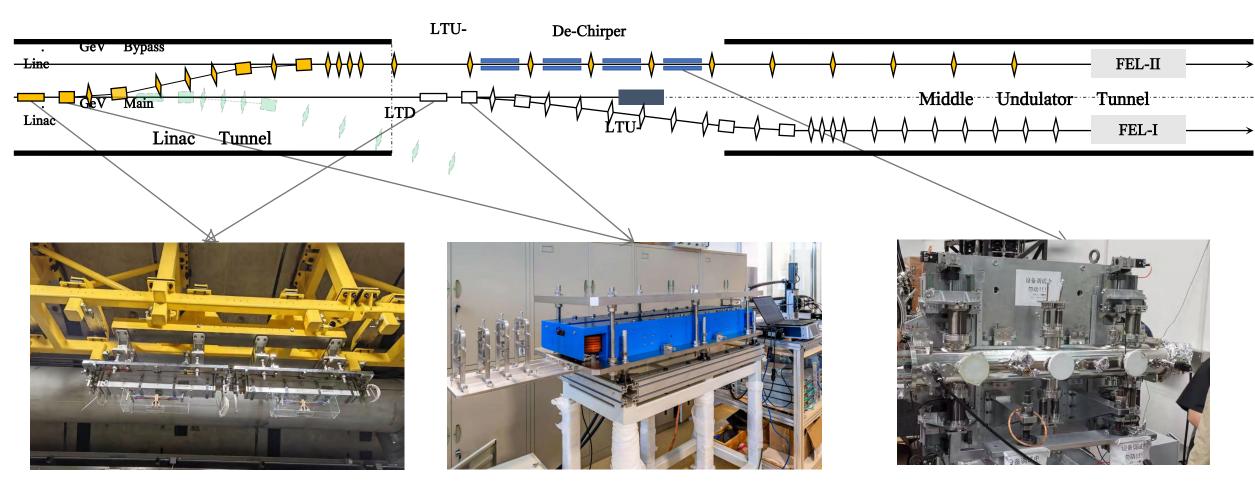
- ➤ The kicker section: a fast vertical kicker system with 5 magnets, for bunch-by-bunch separation up to 4.5GeV, 1MHz(max) electron beam;
- > The Septum BY2: a DC septum for correcting vertical angle of the kicked beam;
- ➤ The Septum BX1: a DC Lamberson septum for horizontally deflecting the kicked beam;
- ➤ **Dipoles:** 3 DC dipoles that form a dog-leg with two DBA cells in horizontal direction
- ➤ The Septum BY3/BY4: 2 DC dipoles that form a dog-leg in vertical direction and deflect the electron beam to the original horizontal level.



Components are in manufacture and will be ready for installation in September 2025.

## The Beam Switchyard @LTU-I and LTU-II @OCPA-2025





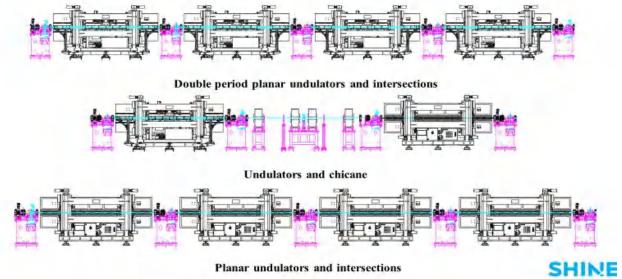
Fast kickers installed in the linac tunnel

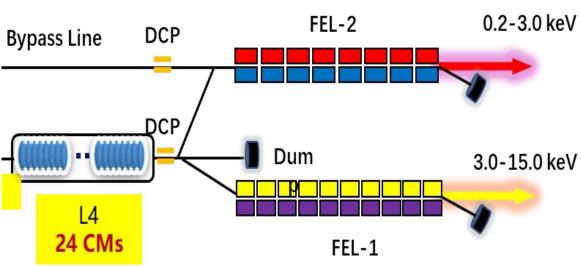
DC Lamberson Septum to be installed

De-chirper under test

#### Installation of the SHINE FEL-I/II Undulators OCPA-2025









#### **Accelerator Systems**



- > Cryomodules
- RF Power System and LLRF
- Kicker and Septa
- Undulators
- **→** High Power Beam Dumps
- Beam Instrumentation
- > Control
- > Timing and Synchronization
- Laser
- Photon beam diagnostics
- **>** .....

Construction of accelerator technical systems is underway.

#### The SHINE Cryomodules



- > The injector cryomodules (a single cavity module and a 8-cavity cryomodule)
- assembled, installed and commissioned with RF and beam;
- > The linearizer cryomodules (two 3.9GHz 8-cavity cryomodules)
- assembled, installed and now in commissioning with RF;
- ➤ The main linac cryomodules (fifty-four + four 1.3GHz cryomodules):
- 16 assembled, 4 under assembly, 14 horizontally measured and 2 under horizontal test;
- Towards to realizing 30 horizontally measured by end of January 2026, with the delivery rate of 2-3 modules per month;
  - ☐ The 1.3GHz SRF dressed cavities status
  - ✓ 2+3 suppliers (Nitrogen doping and Mid-T baking)
  - □ Couplers, HOM absorbers, tuners, SC magnet and Cold BPM
  - ✓ All key components have been technically verified and in batch production for the assembly of the cryomodules.

## **Superconducting Cavity Development**



- > Required Qualified SRF Cavities: ~500 1.3GHz cavities, 16 3.9GHz cavities;
- > Suppliers: RI, ZANON, HE Racing Technology, Eastern SC, ...













1.3 GHz SRF cavity

1.3 GHz SRF cavity

Integration of cavities

3.9 GHz SRF cavity

#### 1.3 GHz Fundamental Power Couplers



- Anhui Huadong (160 sets): 160 batch 1.3GHz couplers have been manufactured and factory acceptance tested;
- AIR CAS (80 sets): 40 batch 1.3GHz couplers have been manufactured and factory acceptance tested;
- HE RACING TECHNOLOGY (8 sets): 8 1.3GHz couplers have been manufactured and factory acceptance tested;





Fig. 1.3GHz FPCs

Fig. FPCs RF conditioning

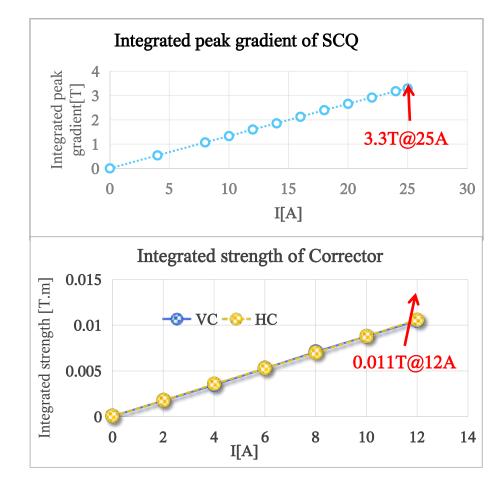
Fig. 1.3GHz cryomodule

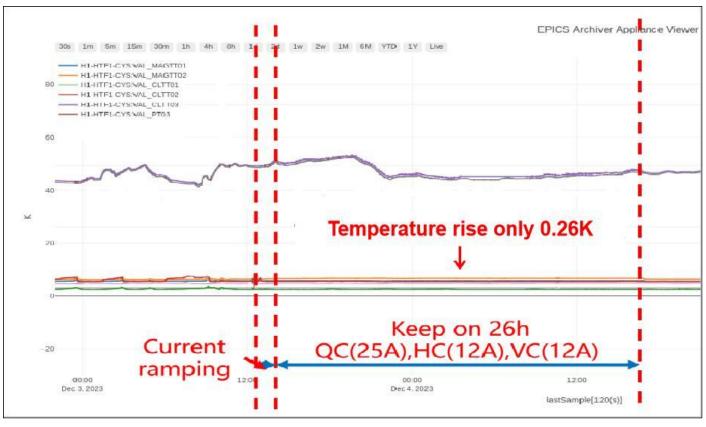
### **Superconducting Magnets**

12<sup>TH</sup> INTERNATIONAL ORGANIZATION OF CHINESE PHYSICISTS AND ASTRONOMERS ACCELERATOR SCHOOL OCPA-2025

- >20 SC magnets have been tested, meeting SHINE requirements.
- 17 SC magnets have been installed in CMs. Quench was not observed with the current up to 25 A (≥24 h).





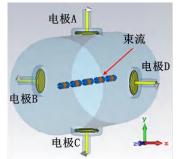


25 A 26h tested in CM01, no quench!

#### Cold BPM



- >20 Cold Button Beam Position Monitors (cBPMs) have been manufactured, tested and verified to meet the requirements.
- Especially, over 110 feedthroughs have been fabricated, and all passed the cryogenic-shock test from 300K to less than 10K.



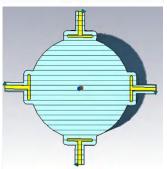










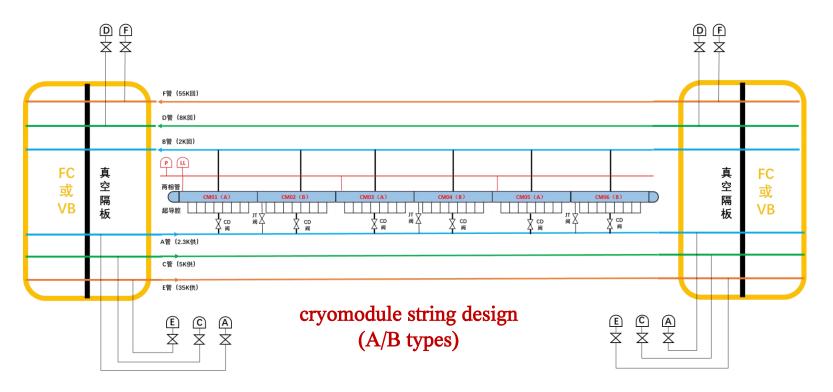
Fig. Cold BPM components

Fig. Partial performance test (Leaking\S-parameters)

### **Cryostat Production**



- Cryostats status
  - 1.3GHz cryostats: 17 assembled in CM
  - 3.9GHz cryostats: 2 assembled in CM and tested





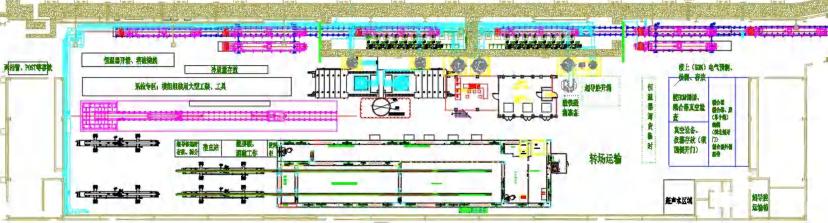


### Infrastructure for CM Assembly and Test COCPA-2025



- Two 3000 m<sup>2</sup> for CM Assembly and Test Halls (ATH1 & ATH2)
- Commissioning and gradually put into operation since 2021
- More than 12 rounds of standard CM assembled and tested











#### **Cryomodules Development**





CM prototype with 8 BCPed cavities



CM prototype with 8 high-Q cavities



Test CM for 1.3/3.9GHz single cavity



i1CM for Injector(1 twin-FPC cav.)



i8CM for Injector (8 midT cav.)



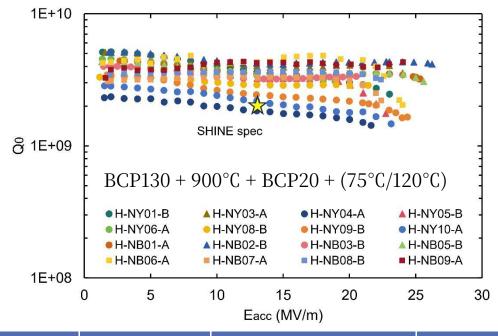
sCM01 for L1(8 N-doped cav.)

#### 3.9 GHz Cryomodule Development





 Nineteen 3.9GHz cavities, fabricated by OSTEC, surface treated at Wuxi platform. tested in Shanghai



Average max Eacc = 22.9 MV/m

Average  $Q_0$ = 3.3×10<sup>9</sup> @ 13.1/15 MV/m

No.	CMs	Specs	Vusable (MV)	<e<sub>usable&gt; (MV/m)</e<sub>	No. of FE cav.	Average Q <sub>0</sub> at 15MV/m	Test time
1	H-CM1	2E+9 @ 36/41.5MV	63.6	23.0	1 (FE_on= 22 MV/m)	3.4E+9	Dec. 2024
2	H-CM2	Ditto	59.8	21.6	3 (FE_on≥ 20.5MV/m)	3.4E+9	Jan. 2025

- Up to now, all special CMs has been developed, including two special CMs for injector, one pipe CM for L1, and two 3.9 GHz CMs.
- Standard CMs: CM01-CM14 have been tested, CM15-CM20 under test or under assembly, more CMs in preparation.
- ◆ Among them, the CM03-MT and H-CM1 as verification CMs showed excellent RF performance, FE free. Standard CMs meets SHINE new specification, except CM02/CM07 with a bit lower  $Q_0$  and CM10 under reassembly.
- FE and MP issues are still challenging for the rest of CMs. Reduction of 2K static heat-load is under investigation.
- CM assembly and test capacity is around  $2\sim3$  CMs per month now. In the future, Cavity delivery and CM test for 3 CMs per month are challenging.



#### • Installation:

- Completed the installation of Inject section in 2023.11, which were used for the electron gun, buncher, twin-feed cavity and injector module.
- Completed the installation of L1 section in 2025.5, which were used for 2 CMs and 2 HCMs.

#### Operating Status:

- Stable operation maintained, no major malfunctions happened.
- Completed the aging test of the injector section modules, and successful beam acquisition was achieved in 2024.11.
- Completed the aging test of 2 CMs and 2 HCMs of L1 in 2025.5.



SSAs' installation for the electron gun

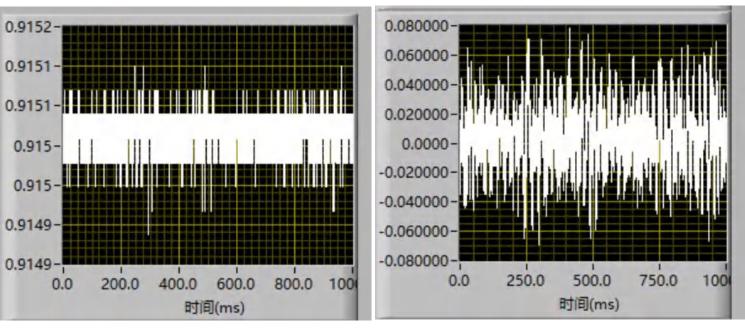


SSAs' installation for L1 section









LLRF Short-term Stability in 1s

LLRF control cabinets have been installed in L1 Section, including two 1.3GHz LLRF systems and two 3.9GHz LLRF systems.

Amplitude RMS Stability (left): 0.0022% Phase RMS Stability (right): 0.021deg (Meets the design specifications)

• Condition: Vc =16.6MV, Qe=4.0e7

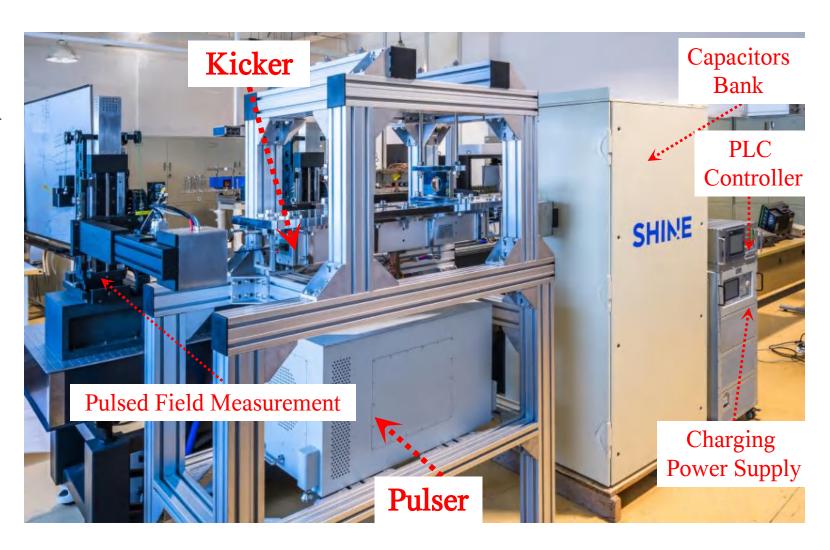
• Operation: >1h

### Kicker System for Beam Switchyard



Three sets of kickers and pulsers of the first batch (10 sets) have been tested with kicker magnet in the lab. The pulser stability and pulsed magnetic field meet the SHINE project requirement.

Peak current	≥ 54 A
Max. repetition rate	0-1 MHz
Stability	< 100 ppm
Pulse width	< 1 µ s
Stray inductance	<b>0.35</b> μΗ
Inductance of Kicker	≤ 1.25 µ H

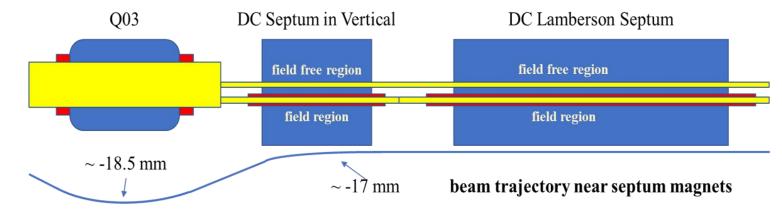


### Septa for Beam Switchyard

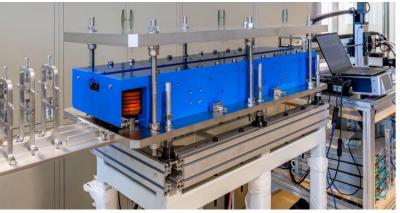


- Direct-drive DC septum magnet for vertical and Lambertson septum for horizontal deflection of beam;
- ➤ All Septa are DC type to achieve a better stability of the magnetic field;
- ➤ The septa for the bypass line are currently ready for installation;

Key p	arameters of the S	eptum
	DC Septum (Vertical)	Lambertson (Horizontal)
Effective length	400mm	600mm-1000mm
Bending angle	3mrad	17.4mrad- 31.4mrad
Distance between two beam centers	17mm	17mm
Beam pipe	Ф8+Ф8	42*8 (rectangular) +Φ8
Field stability (P-P)	<50ppm	<50ppm
Good field region ( $\Delta$ B/B0<1 $\times$ 10-3)	2mm	30mm
Max. integral leakage field	30Gs.m	30Gs.m

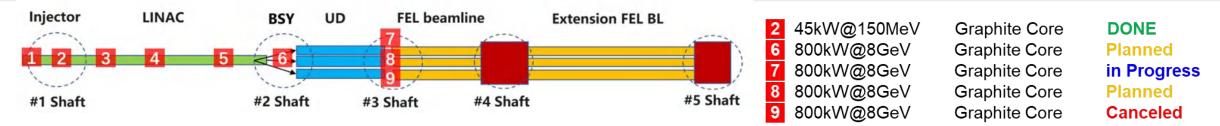




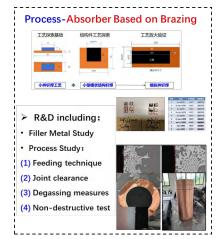


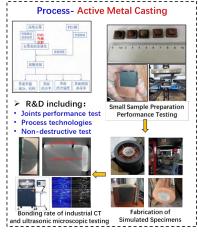
### High-Power Beam Dump





- 45kW@150MeV Dump for Injector
- Two Welding Processes for Large-Scale Graphite and Copper Connecton: Active Brazing vs Active Metal Casting
- Completed development and installed in April 2024







#### 800kW@8GeV Dump for FEL-II

- The first 800kW-Beam-Dump prototype has developed based on larger-scale graphite-to-copper welding
- Installation is scheduled in August 2025



Single-block absorber in brazing



3m-long absorber in electron beam welding



Absorber in sub-assembly

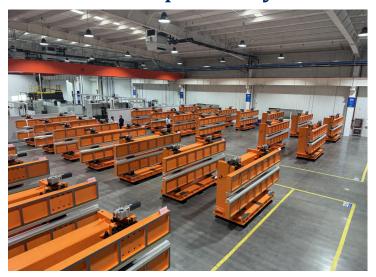


Dump awaiting final assembly

#### FEL-I/II Undulators



- Totally 42/36 undulators (FEL-I: 42×U26, FEL-II: 18×U55, 14×U55&U75, 4×EPU55) have been manufactured, and 24 (11/13) installed in the SHINE undulator tunnel;
- Totally 41/35 phase shifters (FEL-1: 41×PS26, FEL-II: 35×PS55) have been fabricated, and 6 intersections installed in the tunnel;
- Installation of the FEL-II/I undulator-lines will be completed by end of 2025 and middle of 2026 respectively.







FEL-I-U26

FEL-I&II phase shifters

FEL-II-U55

#### Magnets

Location\ Type	Type and quantity of magnets	Status
Injector	Dipole(10),Quad(27),Co rrector(19),Solenoid(3)	Installation completed
SC LINAC	Dipole(17),Quad(72),Co	COL0~BC2 segments under installation
(NC magnet)	rrector(85)	and Rest in production
SC LINAC (SC magnet)	SC magnets (57)	24 SC magnets completed; (21 SC magnets have been installed) 33 SC magnets in production.
SC LINAC (magnetic shielding)	magnetic shielding	Completion of 1.3GHz modules CM7~CM20; Completed the demagnetization of 1.3GHz module CM1~CM15 and the entire 3.9 GHz module CM1~CM2; Batch magnetic shielding currently in processing stage.
Bypass (NC magnet)	Dipole(10),Quad(29),Co rrector(32),Sextu(4)	In production

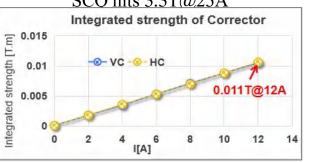


Permalloy	@77K (1-1.3mm)		
grade	$\mu i (\times 10^3)$	$\mu$ m( $ imes10^3$ )	Js(T)
China-1JL0	4-10	20-40	0.80-0.90

Manufacturing and magnetic measurement result of magnetic shielding



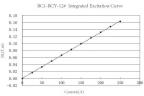
SCO hits 3.3T@25A



Corrector reaches 0.011T@12A Magnetic measurement result of SC magnet







高阶分量@±25mm		高阶分量@±35mm		
B1/B0@25mm	-7.23E-05	B1/B0@35mm	-1.01E-04	
B2/B0@25mm	1.31E-04	B2/B0@35mm	2.56E-04	
B3/B0@25mm	4.05E-05	B3/B0@35mm	1.11E-04	
B4/B0@25mm	-9.68E-04	B4/B0@35mm	-3.72E-03	
B5/B0@25mm	-9.29E-06	B5/B0@35mm	-5.00E-05	
B6/B0@25mm	1.16E-04	B6/B0@35mm	8.72E-04	

Manufacturing and magnetic measurement result of dipole in SCL-Chicane

#### **Magnet Power Supplies**



Injector PS

Low Power (MRPS)

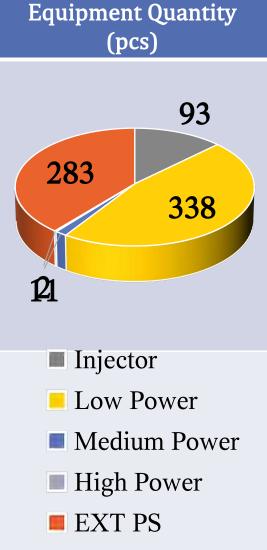
Medium Power

**High Power** 

EXT PS







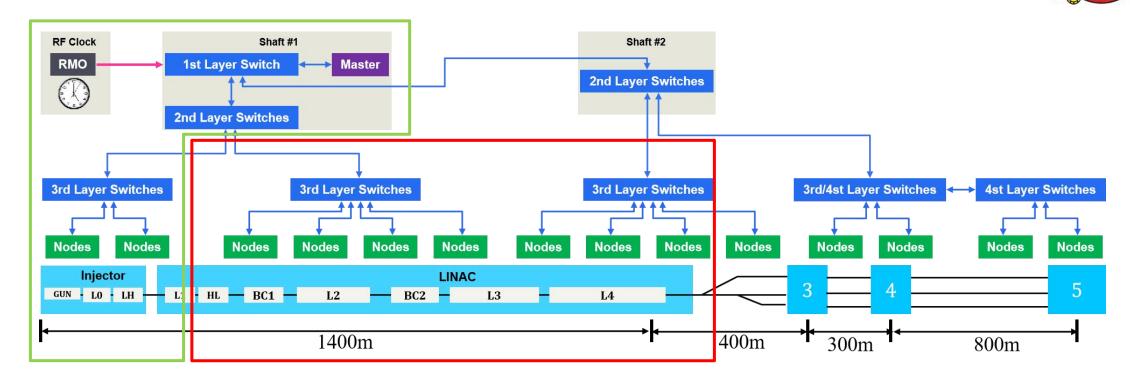
Usage **Injector Magnet** Correcting Coil, Regulating Else: Coil, etc. Compression Magnet, Analysis Magnet, etc. BY Magnet, etc. (1) MRPS: Correcting Coil, Regulating Coil, etc.(2)CPPS: Q Magnet, BX Magnet etc.(3)EXT Medium PS: Analysis Magnet, BC Magnet, etc.

**Current State** Power-on over 6 Months COLO-COL1: **Installed Completed Ex-factory Testing** (Jul 2025 expected to be installed) **Ex-factory Test Completed** (to be installed) In Production (Oct 2025 expected to be installed) In Production (Oct 2025 expected to be installed)

#### **Timing System**



- ☐ SHINE adopts a timing system based on White Rabbit (WR) technology.
  - A new distributed synchronous timing technology. Initially developed as an open-source project by CERN, in collaboration with GSI. Characteristic: high reliability and flexible topology.
  - **The installation and commissioning of the timing system for the Injector section has been completed.**
  - The installation and commissioning of the timing system for the LINAC section is currently underway.



### **Control System**

**DOCPA-2025** 

- The control system is responsible for the facility-wide device control, data acquisition, machine protection, timing, high level applications as well as network and computing platform.
- EPICS V7 + Anolis Operating System + PyDM UI + White Rabbit







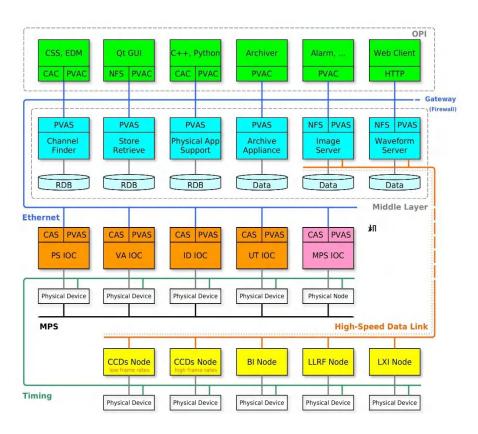
**Core Switchs** 







**Machine Protection System** 









### **Control Room**











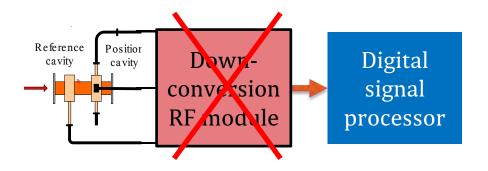
**Shaft #1 Control Room** 

Shaft #2 Control Room

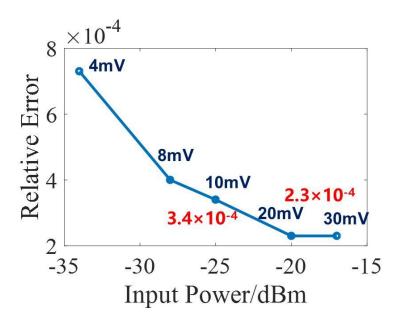
### **Electronics for Beam Instrumentations**



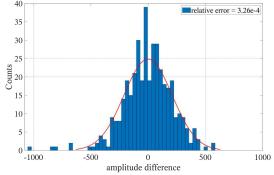
- □ ~300 units of various electronic produced
  - ❖ 1 GSPS generic beam signal processors
  - ❖ 8 channels 1 GSPS beam signal processors
  - ❖ 250 MSPS longitudinal beam signal processors
  - ❖ Fast orbit feedback & interlock processors
- ☐ Direct RF sampling electronics for CBPM
  - 9 GHz bandwidth, 2.6 GSPS sampling rate
  - Sampling 5.254 GHz cavity BPM signal directly without RF down-conversion module







RF source test result



Beam test @ SXFEL

### **Drive Laser & Synchronization System**



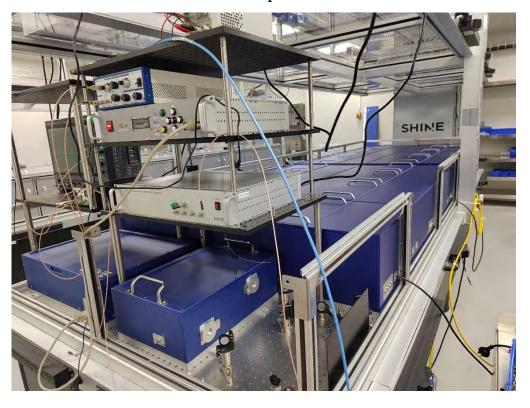
### **Key performance parameters:**

- RF-regeneration with BOMPD: 11 fs [1Hz, 10MHz]
- Laser synchronization with BOMPD: 10.8 fs [1Hz,1MHz]
- Laser synchronization with TCBOC: 8.7 fs [1Hz,10MHz]
- BOC of the FLS: 1.3 fs [1Hz,10MHz]
- FLS long-term drift: 4.8 fs (24hours)

# pulsed distribution system RF station synchro-controller

### Key performance parameters:

- Repetition rate: 1MHz
- IR average power: 240W
- Green average power: > 130W
- UV average power: > 3W
- Pulse duration: 1-2 ps



Local RF Reference modules

Injector laser: ps CPA system

### **Mechanical System**





1.3m-Magnet Support Platform



m-Magnet Support Platform



Feedcap Support



Suspended Support Platform of Cryomodule



Mobile Chicane Platform



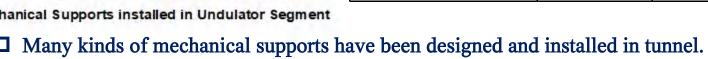
Lifting Platform of Analysing Magnet



Suspended Vibration Induction Platform of Magnet



Mechanical Supports installed in Undulator Segment



Vibration induction platforms of magnet have been installed in Linac and BBA to meet stability requirements of magets.

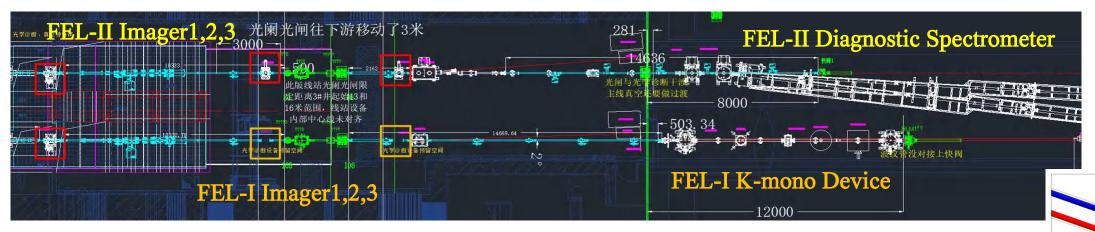


Test Items of BBA	Acceptance Value	Measured Results	
Adjustment range of quadrupole center ( H/V )	≥ ± 0.5mm	≥ ± 0.75 mm	
Adjustment step of quadrupole ( H/V )	≤0.05 µ m	≤0.05 µ m	
Positioning accuracy of quadrupole ( H/V )	$\leq \pm 0.1 \mu$ m	≤ ± 0.1 µ m	
Stability of Magnetic Center Vibration of Quadrupole ( H/V, RMS, >1Hz)	≤0.20 µ m(not less than 90% of the time)	≤0.20 µ m (not less than 98.4% of the time)	

### X-ray Photon Diagnostic System



1) The layout of photon diagnostics at the front-end (installation assessment)



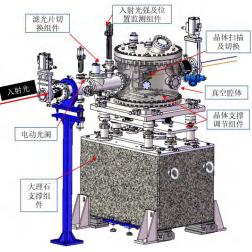
4) Fix the engineering design of K-mono device and start to manufacture

2) Finish fabrication, assembling and onsite test of XFEL invasive intensity and position monitor 3) Complete the key components of FEL-II diagnostic spectrometer, start assembling and test



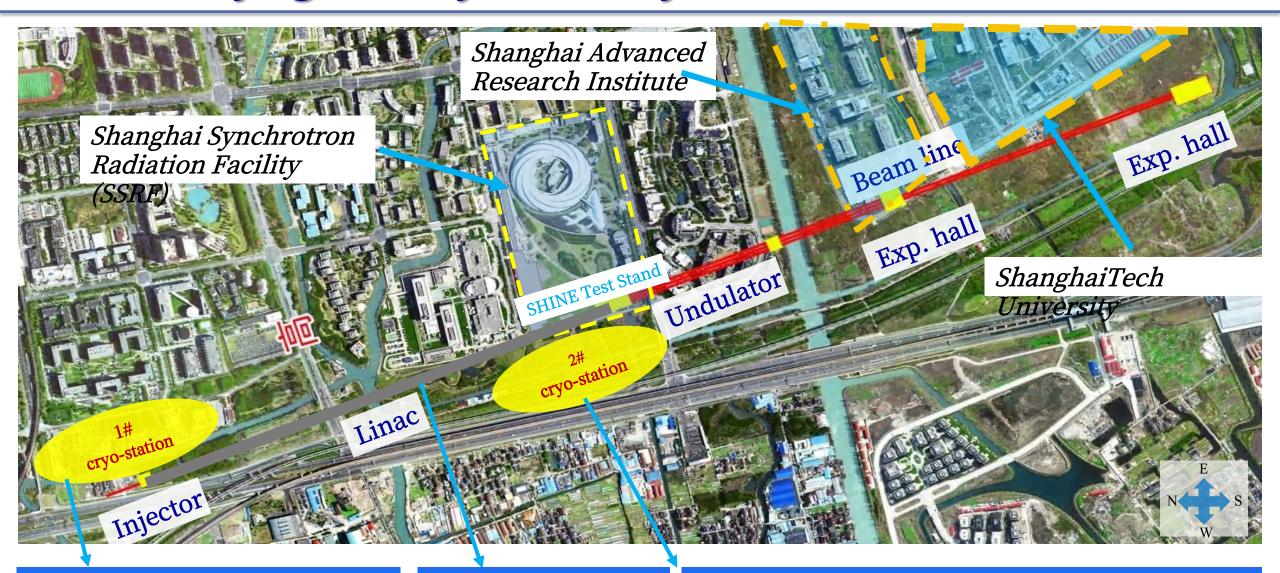






### SHINE Cryogenic System Layout





2 sets of 4kW@2K refrigerators (for SHINE ACCP)

Cryogenic multichannel transfer 1 set of **4kW@2K** refrigerator (for SHINE ACCP) 1 set of **1kW@2K** refrigerator (for SHINE TFCP)

### **SHINE Cryogenic System Construction**



Installation of WCS, 4.5K cold box and 2K cold box had been finished











### **SHINE Cryogenic System Construction**



Installation of CDS had been finished











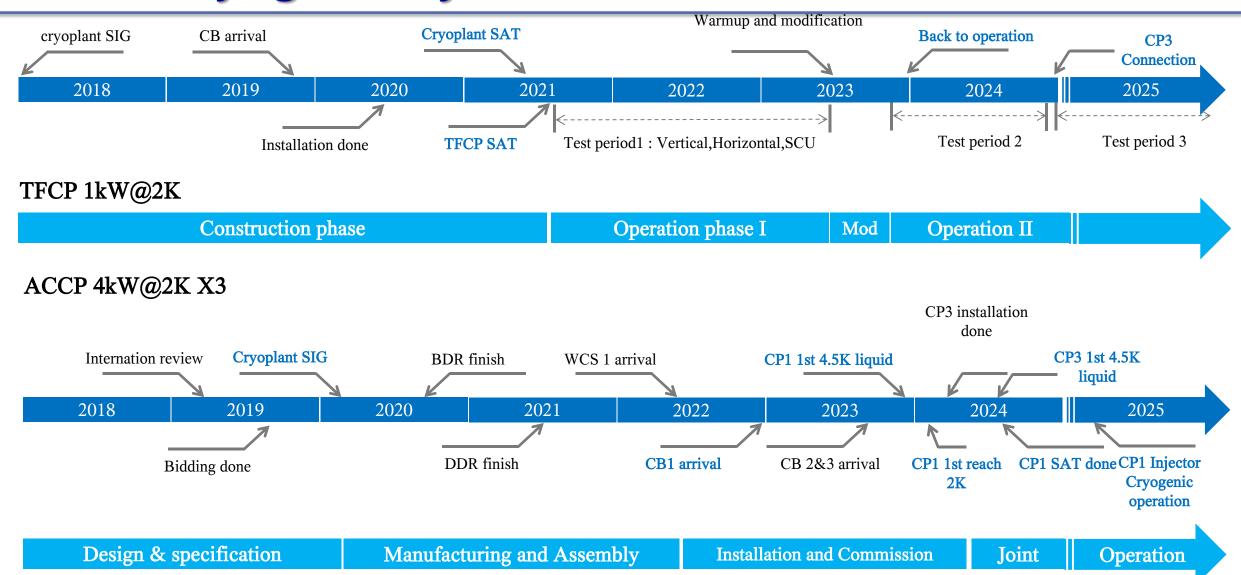






### SHINE Cryogenic System Timeline





### **SHINE Cryogenic System Status**



ACCP1	_	ACCP2	_	ACCP3	TFCP
Auxiliary WCS		Auxiliary		Auxiliary WCS	Auxiliary
4.5K cold box		WCS			Compressor
2K cold box		4.5K cold box		4.5K cold box	Cold box
Helium Dewar		2K cold box		Helium Dewar	PVPS
CDS 4.5K -2K CB		Helium Dewar			Helium Dewar
Distribution box Injector box Test box		Distribution box Cryogenic line		Distribution box  2K cold box  cryogenic line	Cryogenic line Valve box Test bench

Production
Installation
Commission

Operation

> ACCP1 is now under operation to support Injector and Linac SRF

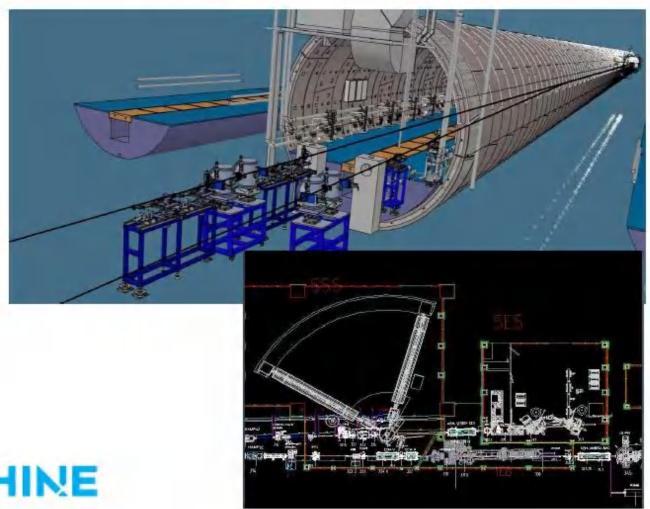
> ACCP2 commissioning finished and passed the SAT

> ACCP3 is under 4.5K operation mode to support test facility for cryomodules R&D

### **Progress of Beamlines and Endstations**



Beamline design has been completed, and end-stations design has been frozen.



### 2022年10月13日

FEL-II实验站 方案设计国际评审



4个实验站,8位国际专家

### 2022年10月28日

FEL-I实验站 方案设计国际评审



2个实验站,6位国际专家

### 2022年11月5日

FEL-III实验站 方案设计国际评审



2024年1月31日

物质电子结构实验站

工程设计国际评审

### 2024年4月17日

单分子/单颗粒相干衍射实验站



4位国际专家、2位国内专家

### 2024年3月5日

原子分子反应成像实验站 工程设计国际评审





8位国际专家

### 2024年6月25日

软X射线高分辨共振散射实





6位国际专家

### 2024年7月26日 相干衍射实验站





7位国际专家

2024年10月15日



6位国际专家



### **Progress of Beamlines and Endstations**



- The construction of the hutch for the 4# shaft experimental station was completed;
- The construction of the main computer server room and the front-end DAQ computer server room at Shaft #4 were completed;
- The FEL-II beamline control network is set-up.







Constant temperature shed completed

The front-end DAQ computer server room

The establishment of the beamline control network



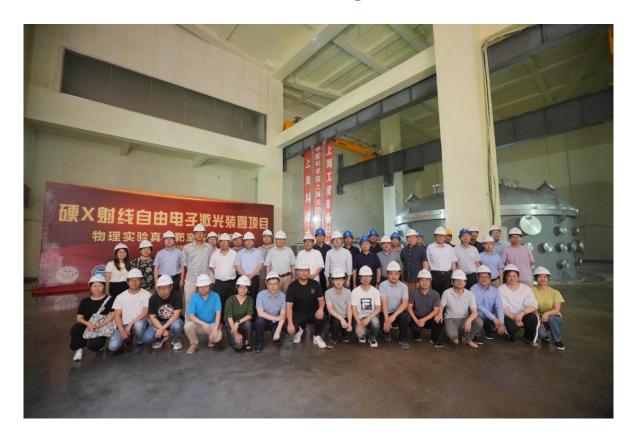
## Progress of Station of Extreme Light (SEL) OCPA-2025

A prototype with peak power of 250TW Measured 13.4 fs Technical and Engineering Design for has been demonstrated, which will be high energy OPCPA main amplifier and installed as the front-end of the 100PW compressor are in process optimization. Mulliunction laser. Experiment Chamber Experiment Diagnostics HighTemporal PW level Rep-High Energy Final Optics Contrast Laser **OPCPA** rate OPCPA Assembly Source Main Amplifier Front-end Pumping Laser for High energy Nd:Glass Beam Diagnostics rep-rate OPCPA Pumping Laser XFEL Synchronization Control System Theoretical and Technical Design for QED experiment is optimized, including experimental chamber, focusing optics and synchronization system. The chamber has been installed

underground.

## Progress of Station of Extreme Light (SEL) OCPA-2025

- ➤ 100PW laser beam of 1000 × 1000 mm<sup>2</sup> coming from top is reflected to off-axis parabola mirror near the chamber wall and then focused to XFEL in the middle of the chamber.
- The chamber was installed underground in 2023.





### **Utilities**



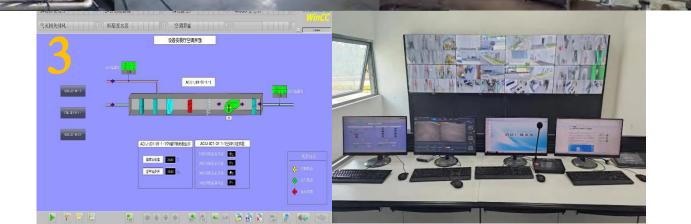
1. High-voltage Power System

2. Cooling Water System

3. Control & Low-voltage Electric System

4. Fire Protection System







### **Civil Engineering**

- Ground breaking of SHINE was made on April 27, 2018.
- The shield tunneling machine began tunneling in January, 2021.
- Construction of 10 tunnels was completed in March, 2023.
- Tunnels for accelerator, FEL I/II undulators and beamlines are all ready for installation in 2024.



Tunnel between Shaft#1and Shaft #2



Eastern tunnel between Shaft #2 and Shaft #3



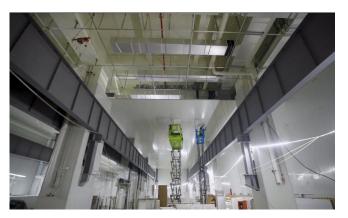
Eastern tunnel between Shaft #3 and Shaft #4



Eastern tunnel between Shaft #4 and Shaft #5



**Near Experimental Hall** 



Far Experimental Hall

- 1. Shaft #1, 2. Shaft #2
- 3. Shaft #3, 4. Shaft #4
- 5. Shaft #5







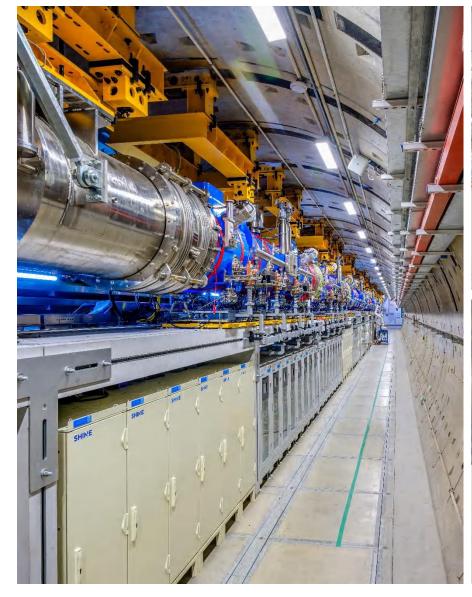






# **Installation Ongoing**

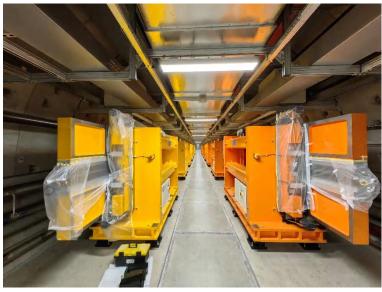






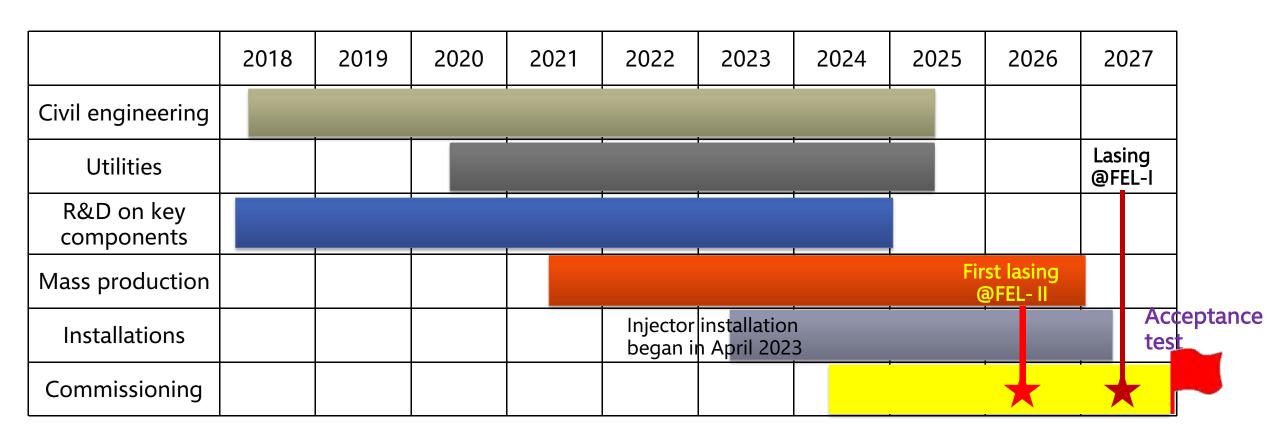






### **Construction Timeline**





Groundbreaking was made on April 27, 2018. First lasing is expected in 2026.

### Summary



- ➤ The Shanghai soft-ray FEL facility (SXFEL) started its user service with a SASE and a seeding FEL/beam lines as well as 5 end-stations in January 2023, now it is gaining momentum to deliver impact experimental results.
- > The Shanghai hard X-ray FEL facility (SHINE) has achieved encouraging progress.
  - $\triangleright$  The injector commissioning was completed with the designed performance by the end of 2024;
  - ➤ The L1-BC1 section of the Linac will start the beam commissioning in August 2025;
  - ➤ Construction of the SHINE cryomodules achieves encouraging progress, but schedule is extremely tight and it still faces the crucial challenge from the yield rate in the production;
  - ➤ Great efforts are being made to realize the first lasing of FEL-II and FEL-I in the first half of 2026 and 2027 respectively, towards completing the project at the end of 2027.

