SHINE工程进展

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SHINE

SHINE: Shanghai Hard X-ray FEL Facility

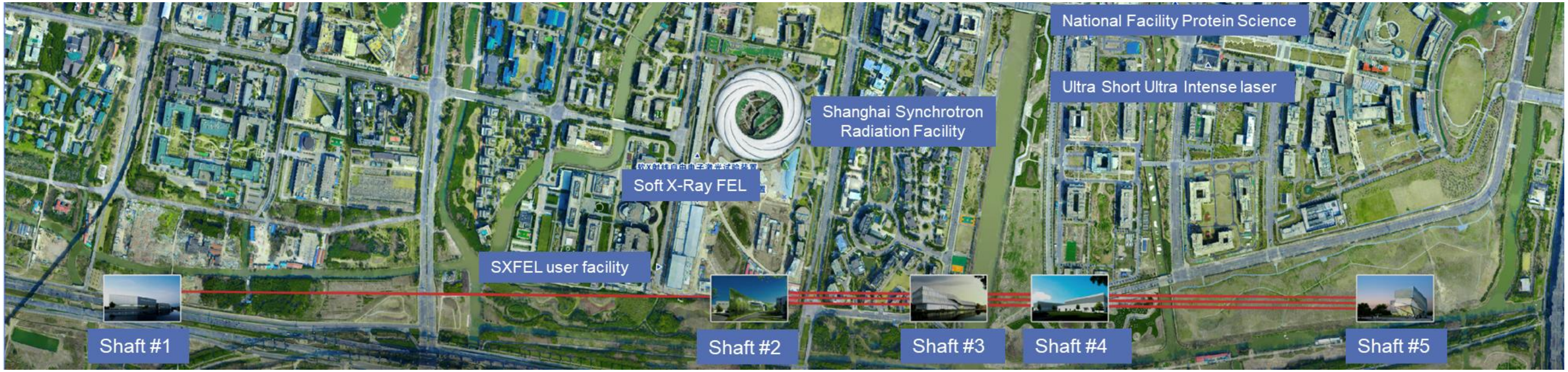
Shanghai HIgh repetitioN rate XFEL and Extreme light facility (SHINE)

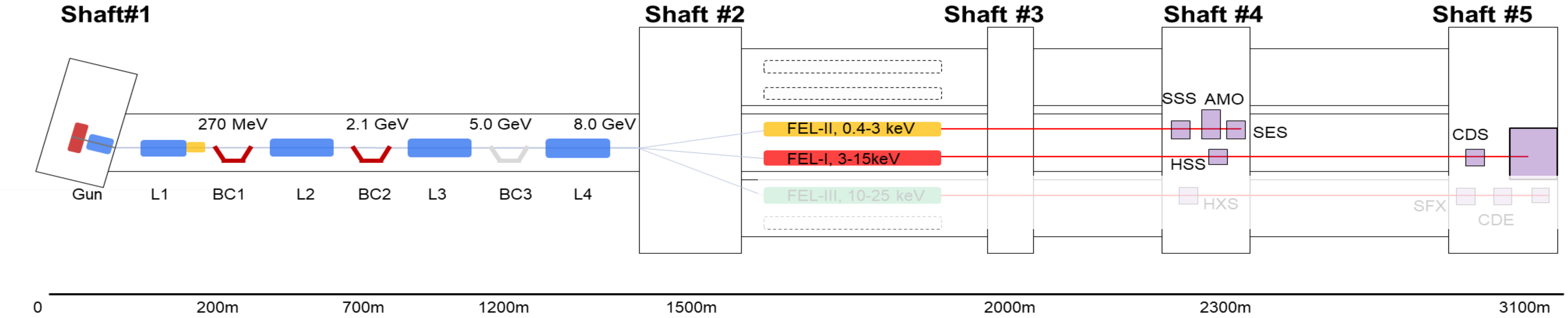
- SHINE is an 8 GeV CW SCRF linac based high rep-rate XFEL facility, it will be installed in a 3.1 km long tunnel underground at Zhangjiang High-Tech Park, across the SSRF campus to the southwest corner of ShanghaiTech University;
- This XFEL facility, assisting with a super-intense laser facility, has 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

SHINE: Layout and Main Parameters

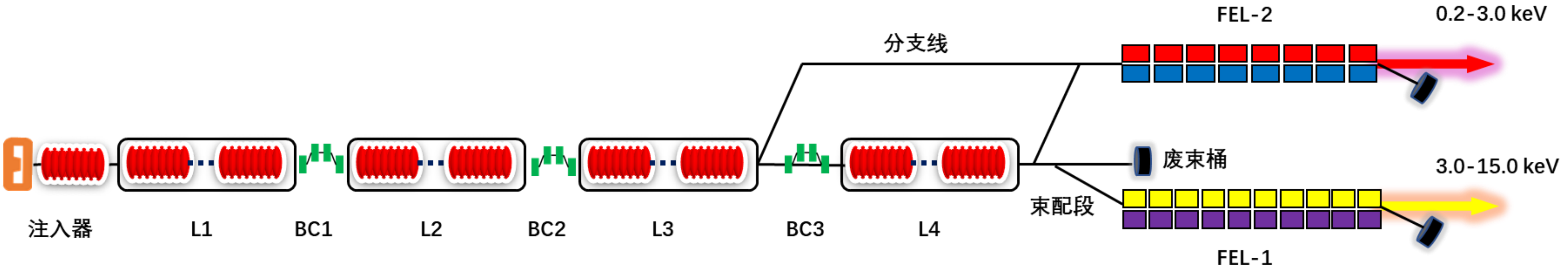




An 8 GeV SCRF linac, 2 undulator lines to deliver photons from 0.2-15 keV in the first stage, up to 1 MHz pulse train with pulse duration of 1-100 fs

- **X-ray beamlines and End-stations**
- **Super-intense Laser Facility**
- **Total length 3.1 km; ~35 m underground**

SHINE: A High-rep Rate XFEL Based on SCRF



	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	5×10^{32}
Average brightness	5×10^{25}

FEL Line	Objective
FEL-I	
Photon energy /keV	3-15
Photon number per pulse @12.4keV	$>10^{11}$
FEL-II	
Photon energy /keV	0.2-3
Photon number per pulse @1.24keV	$>10^{12}$

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

SHINE

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**

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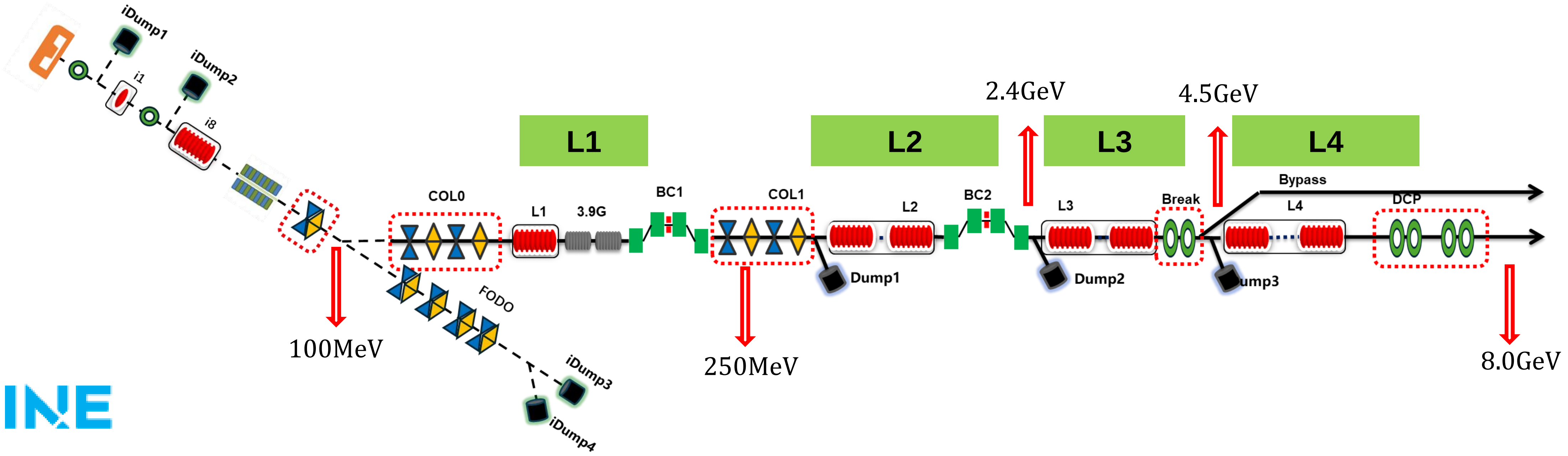
The SHINE Linear Accelerator

➢ **The SHINE Accelerator** consists of

- An injector section: 750kV/217MHz photo cathode VHF gun, a normal-conducting two-cell buncher, a single-cavity SRF CM (TFPC-type) and an eight-cavity SRF CM (ABBA-type);
- A laser heater section;
- Four sections of 1.3GHz standard SRF CMs, and one section of 3.9GHz SRF CMs;
- Three magnetic bunch compression sections;
- A dechirper section at the end;
- In addition, a bypass line dedicated to FEL-II.



The SHINE Accelerator Construction Progress

- The SHINE injector installation and beam commissioning have been completed with the required performance;
- RF power systems (SSAs, coaxial transmission lines and waveguides, circulators) and LLRF for VHF gun, buncher, TDS, and injector cryomodules have been installed, commissioned and operated for the injector beam commissioning;
- Besides the injector modules, totally 16 sets of 1.3GHz and 3.9GHz cryomodules have been assembled and 14 have been horizontally tested with good usable performance; more 1.3GHz cavities and cryomodules are now under manufacture, integration and test;
- The engineering design of the bypass line has been completed and confirmed with technical reviews, manufacture of the bypass line components is underway towards its installation started in July 2025;
- Commissioning and operation of the SHINE cryogenics system achieve good progress with one in operation for the injector commissioning and one for cavity measurements.

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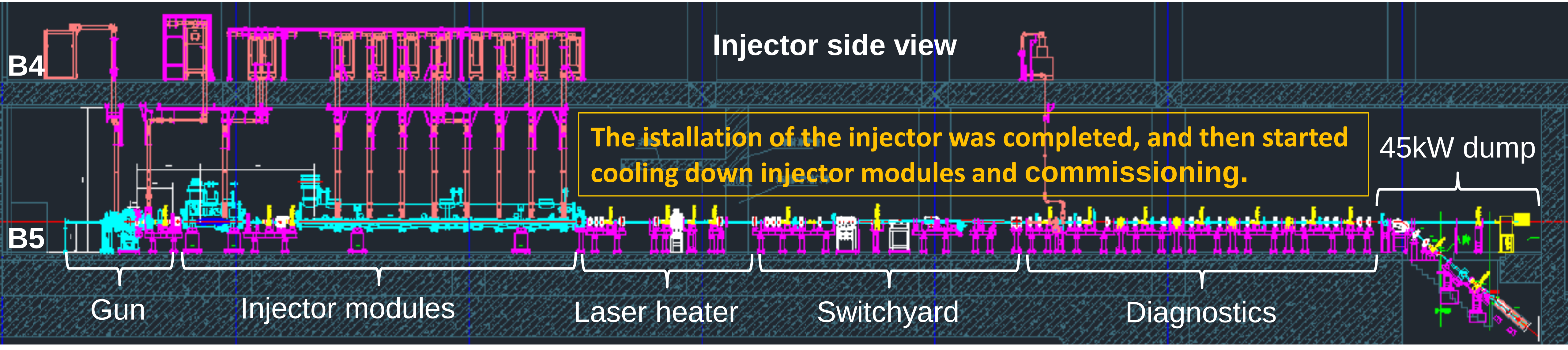
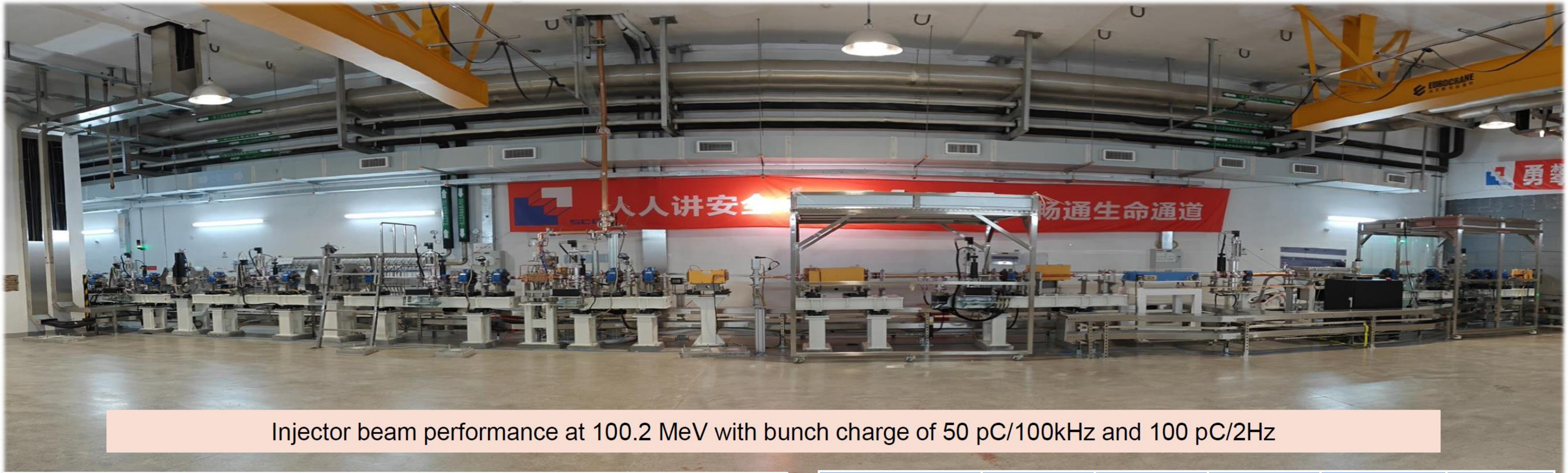
Injector: Installation and Beam commissioning



The istallation of the injector was completed, and then started cooling down injector modules and commissioning.

Injector: Installation and Beam commissioning



Injector beam performance at 100.2 MeV with bunch charge of 50 pC/100kHz and 100 pC/2Hz

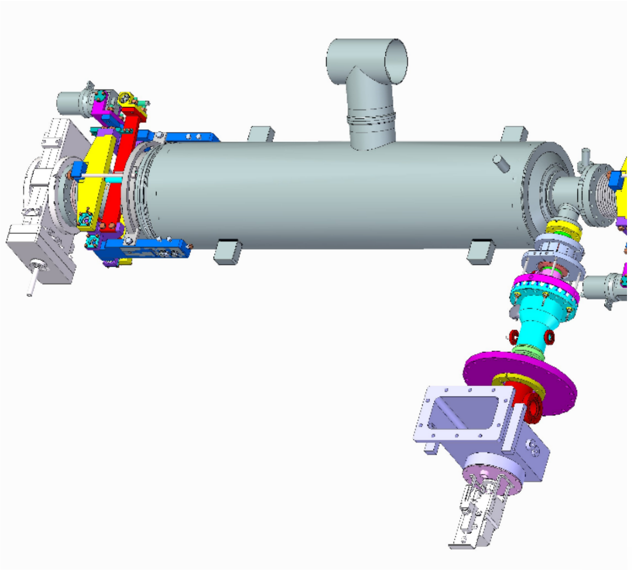
50pC/12.5A	1	2	3	avearge	Unit
X	0.40	0.40	0.44	**0.41±0.03**	mm mrad
Y	0.50	0.51	0.52	**0.51±0.01**	mm mrad
Slice	0.328	0.268	0.384	**0.33±0.06**	mm mrad

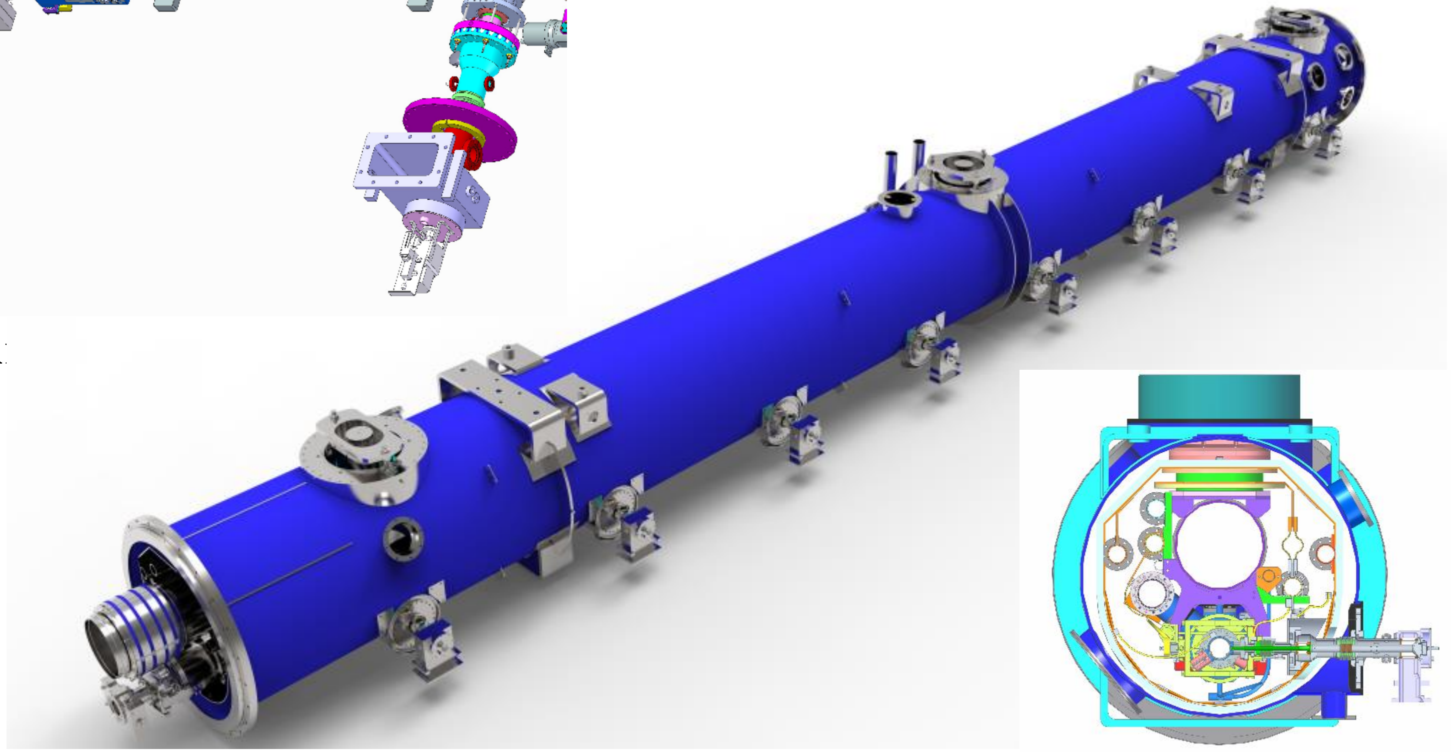
100pC/10A	1	2	3	avearge	Unit
X	0.62	0.53	0.57	**0.57±0.04**	mm mrad
Y	0.55	0.56	0.55	**0.55±0.01**	mm mrad
Slice	0.38	0.48	0.46	**0.44±0.13**	mm mrad

Cryomodule

- **SHINE cryomodule design adopts the TESLA technology and refers to E-XFEL and LCLS-II.**
- **High technical integration of many system components and techniques**

  Superconducting, RF, Magnet, Beam instrumentation, Vacuum, Particle free, Cryogenic, Mechanics, Alignment …
- **Main components in CM**
  - 8 - 1.3GHz, 9-cell cavities
  - 8 - Couplers
  - 8 - Tuners
  - 8 - Magnetic shielding
  - 16 - HOM couplers
  - 1 - HOM absorber
  - 1 - SC magnet
  - 1 - BPM
  - 1 - Cryogenic pipe system and thermal shieldi
  - 1 - Vacuum components and valves
  - 1 - Cold mass support system
  - 1 – Vacuum vessel
  - 1 - Cryomodule support system





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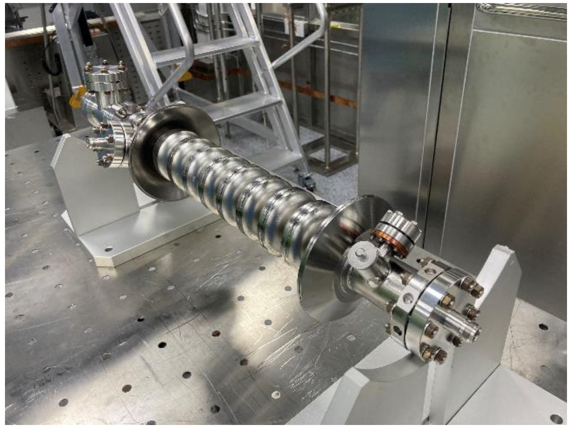
Superconducting Cavity Development

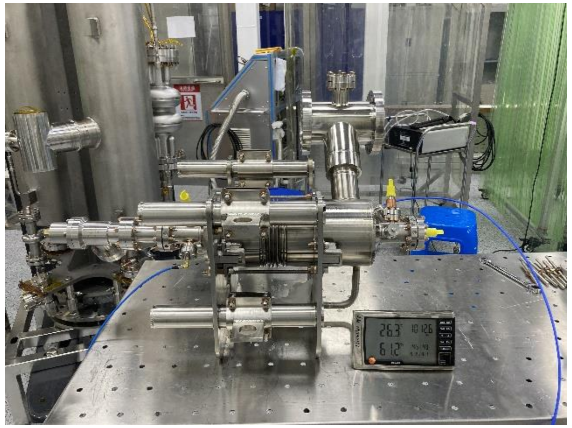
- Cavity numbers: ~500 1.3GHz SRF cavities, 16 3.9GHz SRF cavities;
- Suppliers: RI, ZANON, HE Racing Technology, Eastern SC, …

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

3.9 GHz Fundamental Power Couplers

- **AIR CAS (16 sets)** : 16 batch 3.9GHz couplers have been manufactured and factory acceptance tested;

- **Verified in two 3.9GHz CMs:** SHINE 3.9 GHz FPCs withstanding 2 kW CW power and with an adjustable function have been designed and manufactured, and verified in the two 3.9GHz cryomodules.

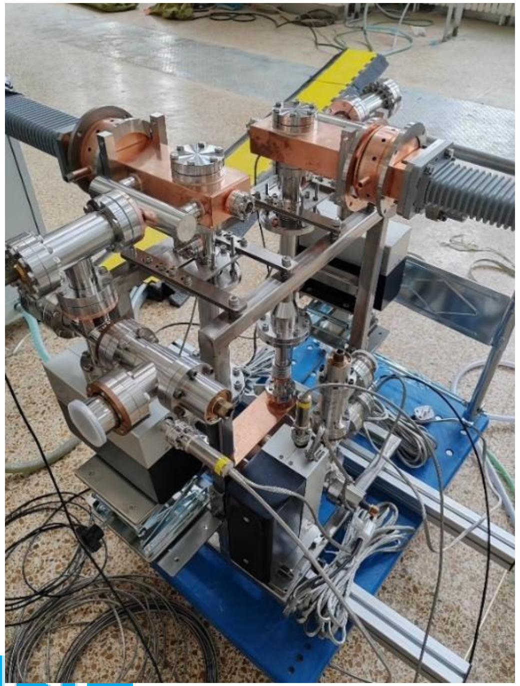


Fig. 3.9GHz FPCs

Fig. 3.9GHz cryomodule

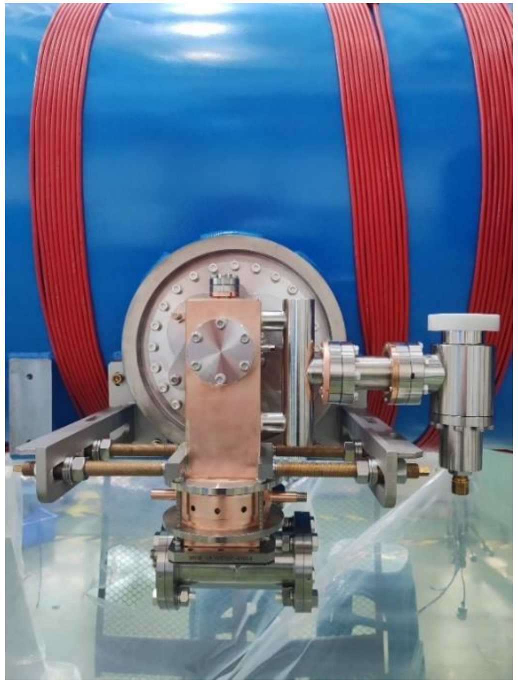


Fig. 3.9GHz FPC in cryomodule

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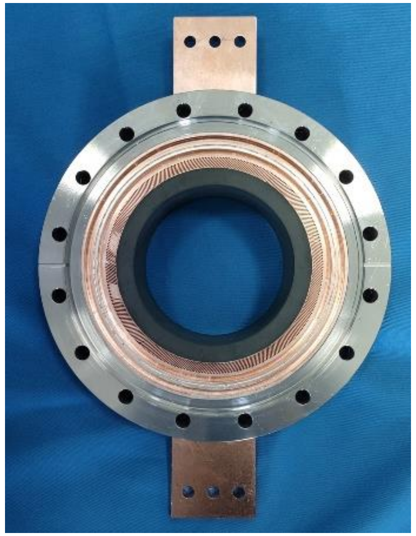
HOM Absorbers

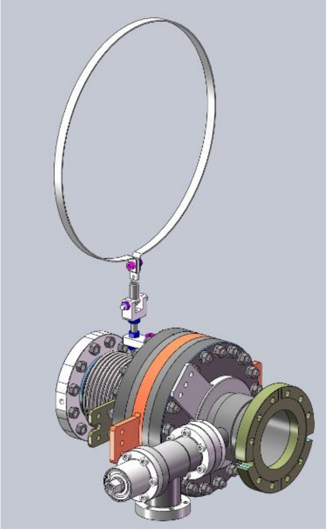
- **Domestic ALN ceramic rings,** RF absorption power test showed higher than **100W** .
- **Small batch** of 8 HOM absorbers with ALN and SiC ceramic （half and half） manufactured and passed FAT;
- **Tunnel installation:** One HOM absorber has been installed between two cryomodule prototypes in the tunnel, verifying the clean installation process of the absorber;
- **Mass production** of 56 HOM absorbers with ALN ceramic are under manufacturing.

ALN ceramic rings



ALN ceramic subassembly

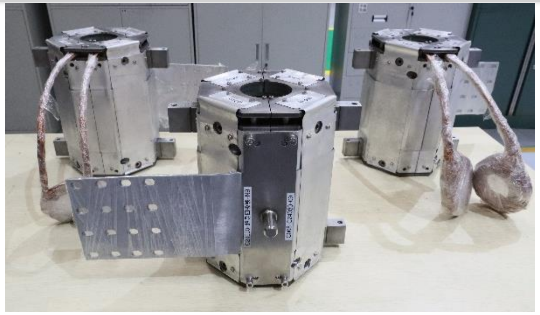
HOM absorber

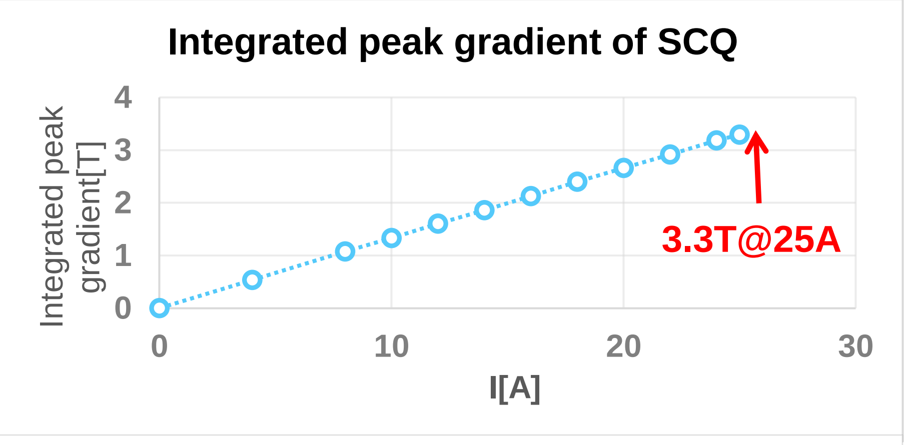


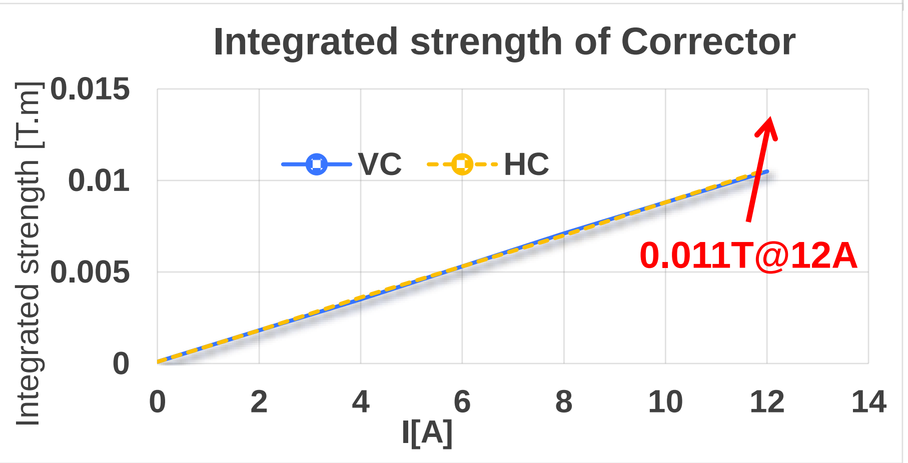
HOM absorber assembly

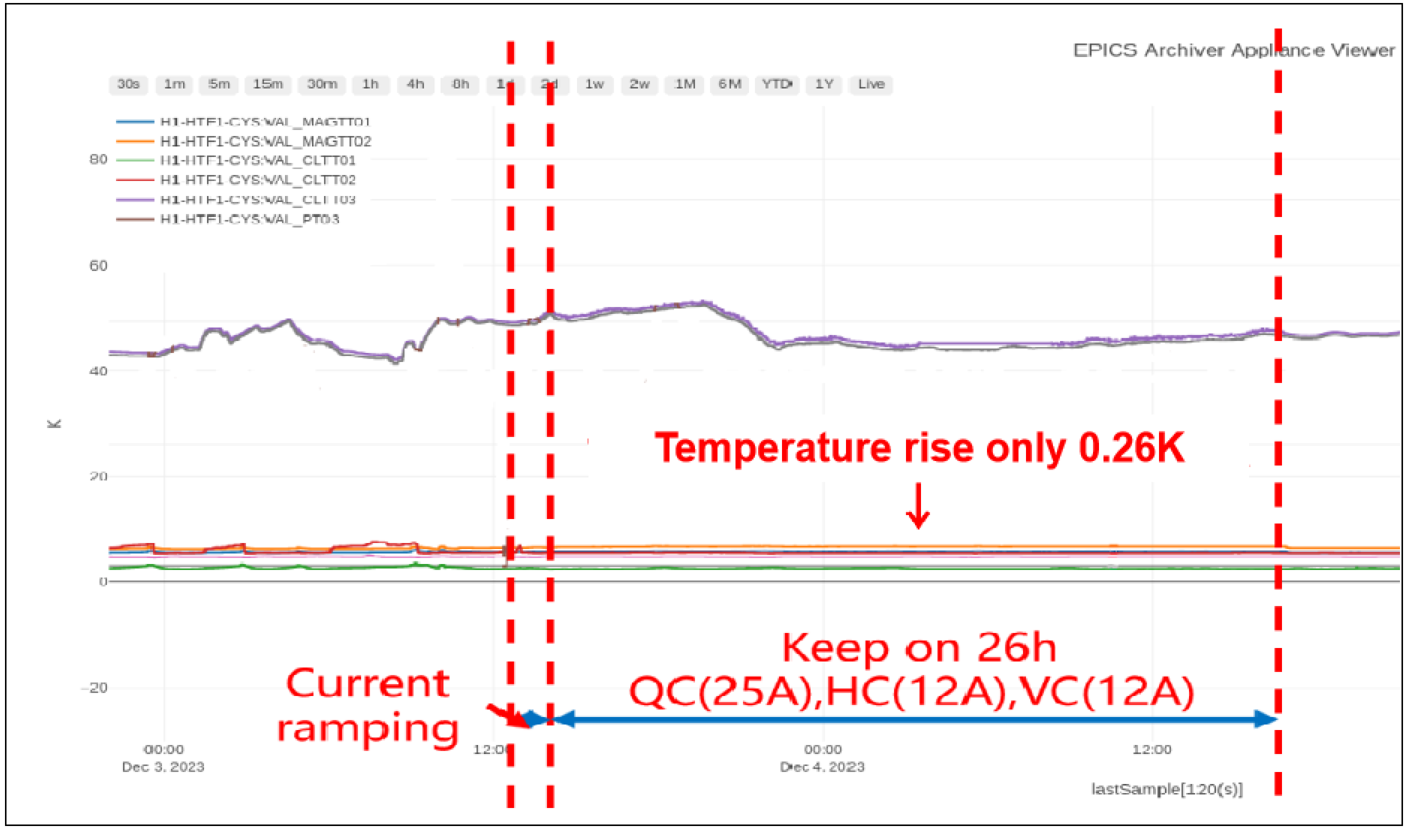
Superconducting Magnets

- 16 SC magnets have been tested, meeting SHINE requirements.
- 10 SC magnets have been installed in CMs, of which 6 magnets have completed stability testing. Quench was not observed with the current up to 25 A (≥24 h).





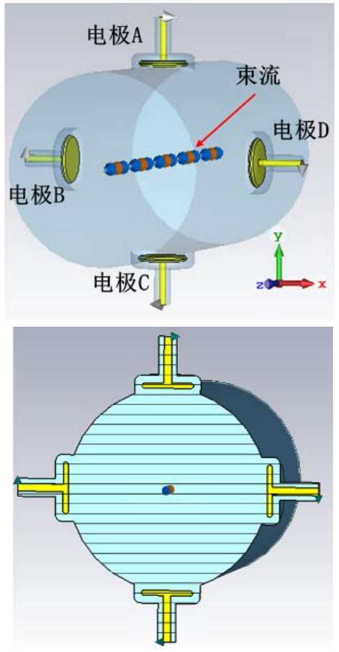


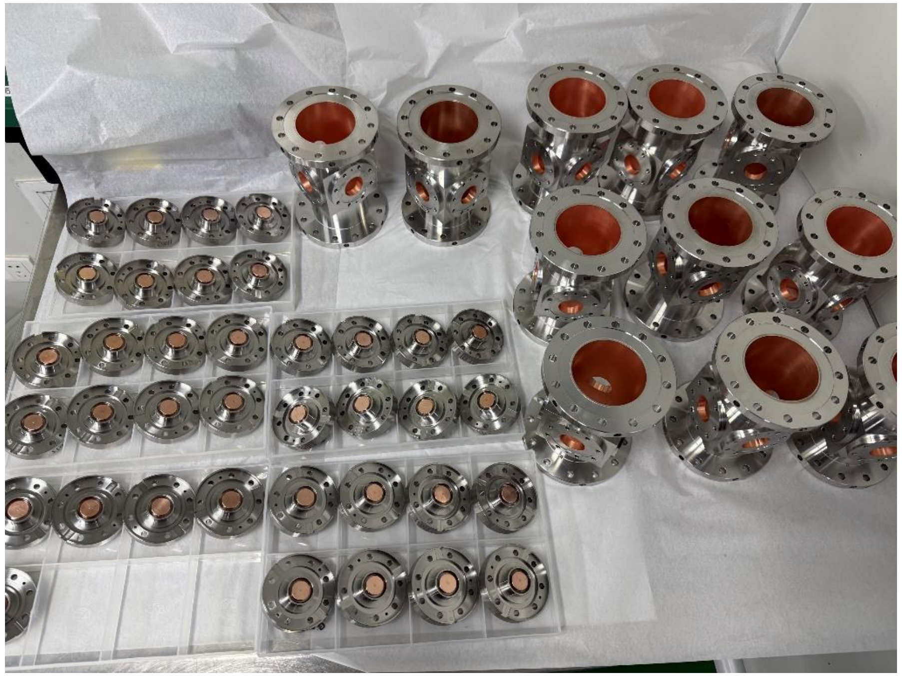


25 A 26h tested in CM01, no quench!

Cold BPM

- In total, 17 Cold Button Beam Position Monitors (cBPMs) have been manufactured, and 11 of them have been 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.





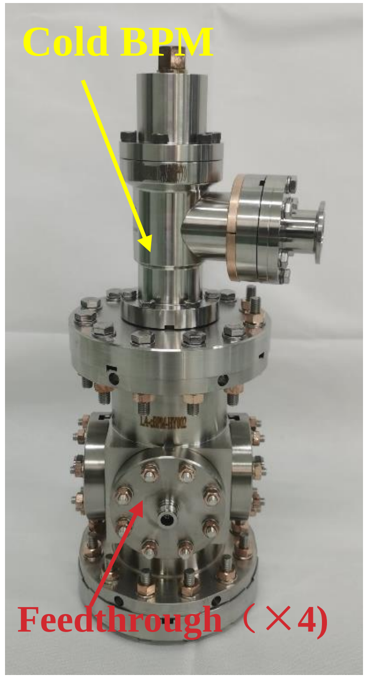


Fig. Cold BPM components

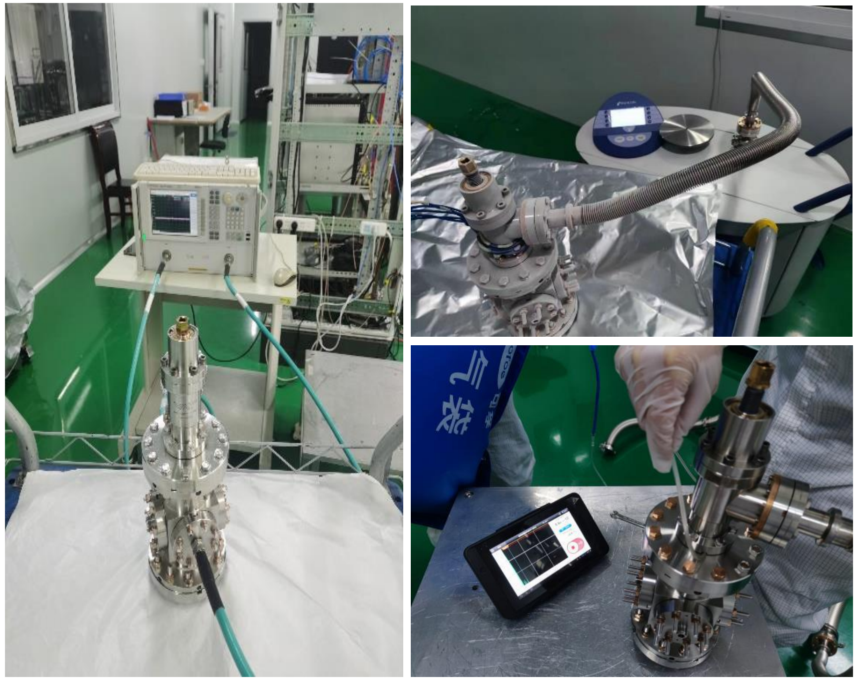
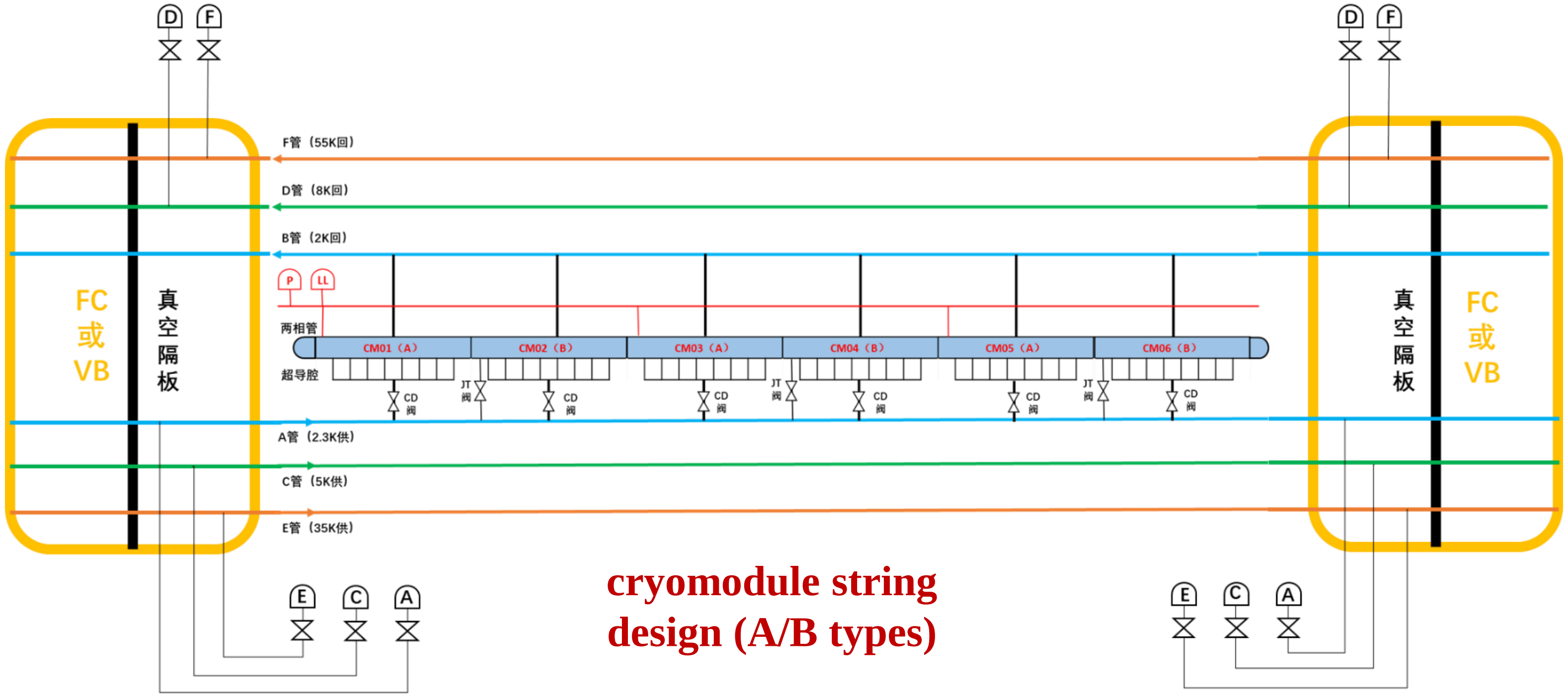


Fig. Partial performance test (Leaking\S-parameters)

Cryostat Production

- **Cryostats status**
  - **1.3GHz** cryostats: 10 assembled in CM + 16 fabrication
  - **3.9GHz** cryostats: 2 assembled in CM and tested



cryomodule string design (A/B types)

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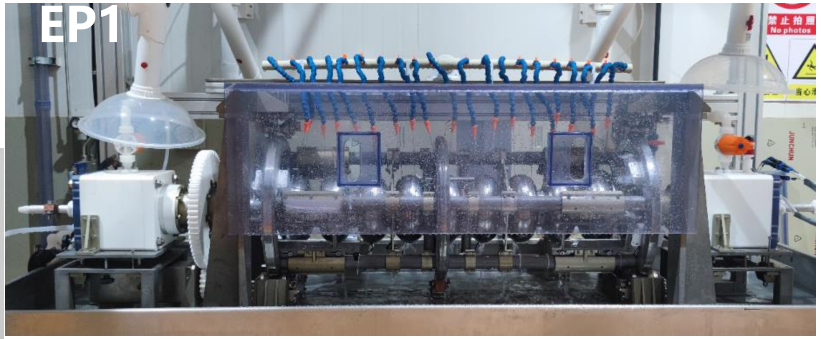
Infrastructure for Cavity Surface Treatment

- **Goal:** undertaking the surface-treatment of SHINE cavities from domestic manufactures
- **Status:** EP2 and HPR3 have been built and put into operation, maximum production capacity around 18 cavities per month now



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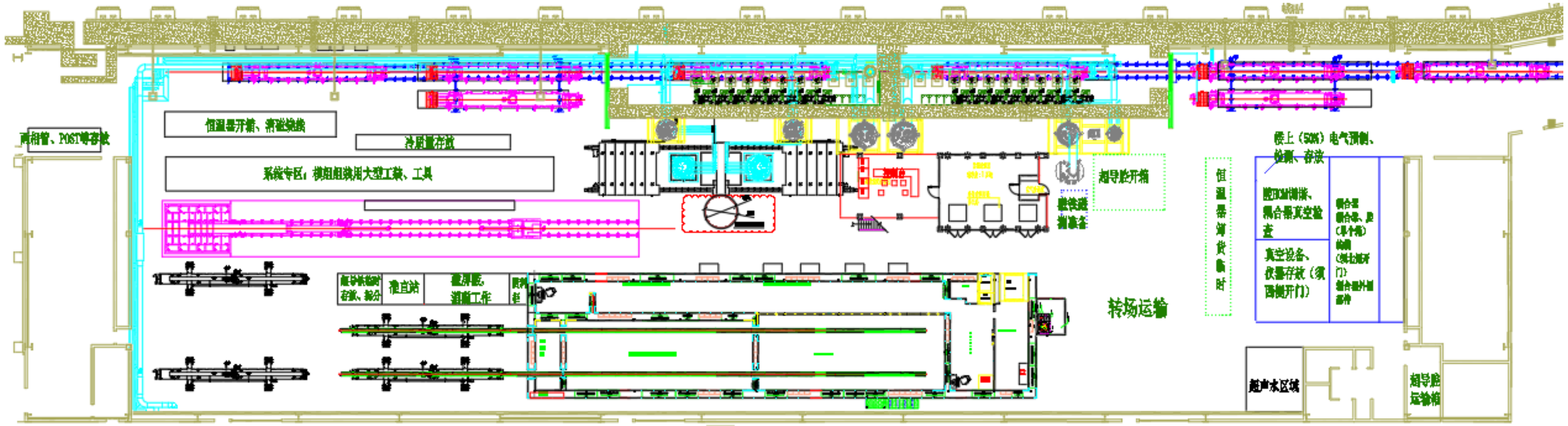
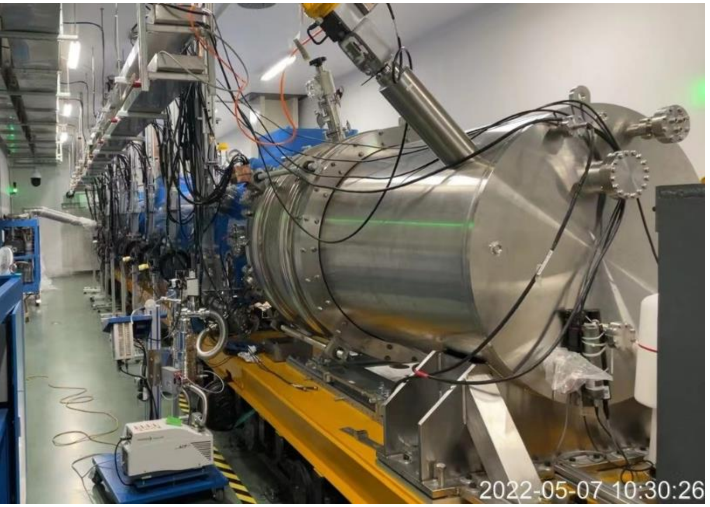
Infrastructure for CM Assembly and Test

- Two 3000 m^2 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

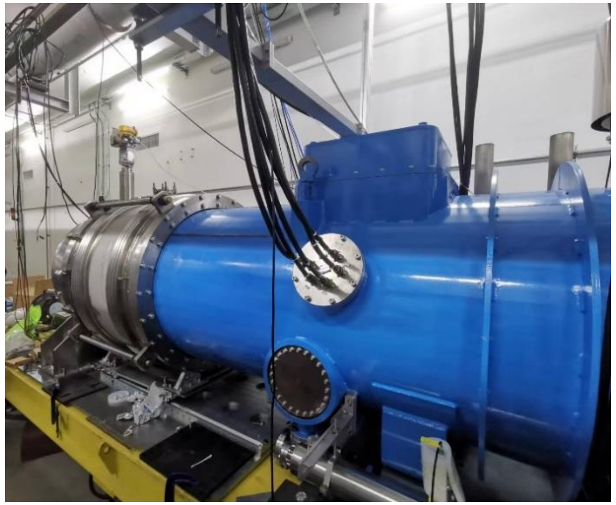


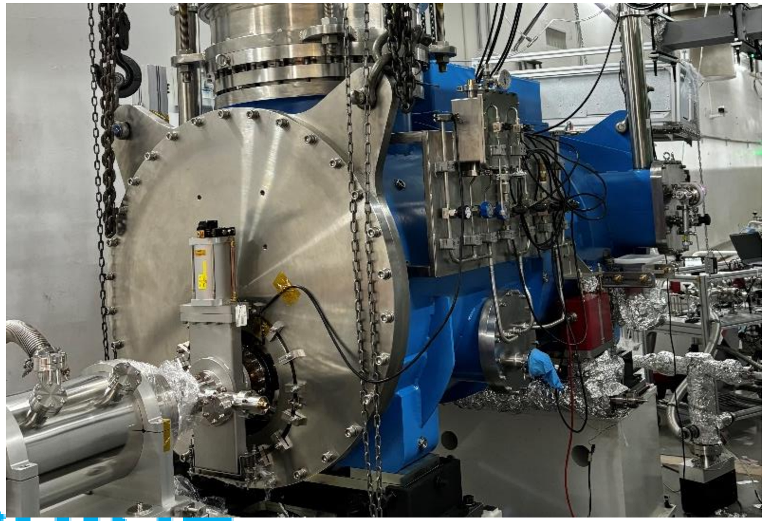
Cryomodules Development



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.)

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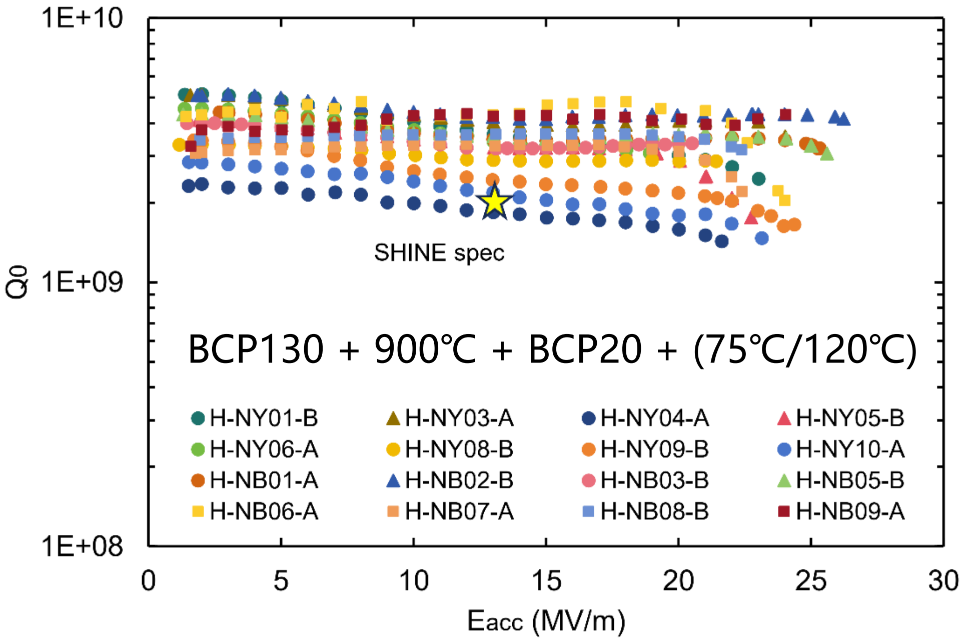
3.9 GHz Cryomodule Development

- 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
= 3.3×10^9 @
MV/m

No.	CMs	Specs	Vusable (MV)	$\langle E_{usable} \rangle$ (MV/m)	No. of FE cav.	Average Q_0 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

Standard 1.3GHz high-Q Cryomodules

ND: Nitrogen-Doping; * MT: Mid-T Baking

1.3 GHz CMs	Goal	Usable Volt.(MV)	Ave. E_{usable} (MV/m)	No. of FE cav.	Ave. Q_0 (E10)	2K static load (W)	Test time
CM01-ND#	**3E10@166MV**	176.7	21.3	3	3.2 @176 MV	18.1	April, 2024
CM02-ND	Ditto	172.8	20.8	4	2.6 @166 MV	21.1	Oct. 2024
CM03-MT*	Ditto	241.3	29.0	0	4.0 @ 166 MV 3.2 @ 241 MV	21.7	Sept,2024
CM04-MT	Ditto	189.4	22.8	3	3.2 @ 166 MV	21.7	Dec, 2024
CM05-ND	Ditto	172.5	20.8	2	3.1 @ 166 MV	21.8	Jan, 2025
CM06-ND	Ditto	171.8	20.7	1 (@VT)	4.0 @ 166 MV	26.5	Mar, 2025
CM07-ND	Ditto	206.6	24.9	1	2.9 @ 166 MV	22.8	Mar, 2025
CM08-ND	Ditto	189.0	22.8	0	4.1 @ 166 MV	27.9	Mar, 2025
CM09-ND	Ditto	200.9	24.2	2	3.1 @ 165 MV	26.5	Apr, 2025
CM11-MT	Ditto	206.6	24.9	2	3.1 @ 166 MV	26.4	Apr, 2025
CM12-ND	Ditto	209.6	25.2	1	3.4 @ 166 MV	25.6	May,2025
CM13-ND	Ditto	180.1	21.7	0	3.8 @ 166 MV	25.2	Jun, 2025
CM14-ND	Ditto	193.7	23.3	0	3.2 @166 MV	20.7	Jun, 2025
CM15-20	Under assembly						

Notes: Admin limit at 26 MV/m since CM04

Summary for Cryomodules Development

- 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 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. Keeping cavity string under vacuum is adopted recently. Reduction of 2K static heat-load is under investigation.
- CM assembly and test capacity is around 2~3 CMs per month now. In the future, Cavity delivery and CM test for 3 CMs per month are challenging.

SHINE

The SHINE Kicker, Septum, and Undulators

- **Prototypes of kicker and Lambertson septum have been developed, and their first pieces are in factory acceptance test;**
  - Single turn inductance type kicker and pulser;
  - DC Lambertson septum;
- **Prototypes of three kinds of warm permanent undulators and two standard intersections between undulators were developed. The mechanical structure of 4m planar undulators for FEL-I U26 and FEL-II U55 are in mass production;**
  - 4m planar undulators with magnetic period of 26mm, 55mm and 55/75mm;
  - 4m APPLE-III with magnetic period of 68mm;
  - Aluminum undulator chambers and photon absorber;
  - Standard intersections: marble supports, phase shifters, CBPMs, quadrupoles and correctors, vacuum chambers, …
- **Prototype of a 4m superconducting undulator has been developed with very challenging experience.**

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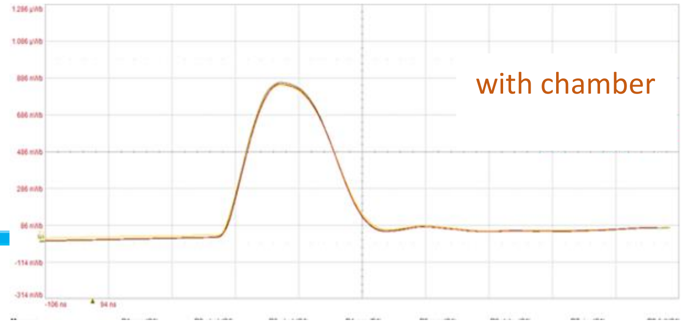
Fast Kicker, DC Septum and Lambertson Septum

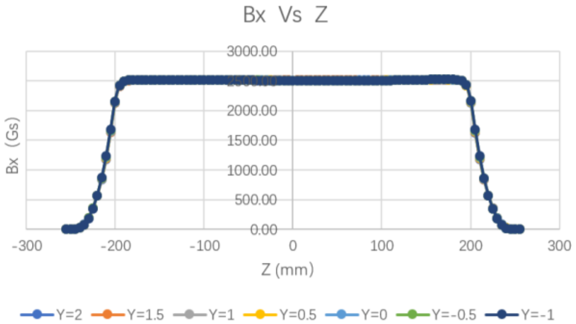
Lumped-inductance Kicker

- Bending angle at 8GeV is 0.07 mrad
- The 100nm Ti coating for the ceramic chamber does not distort the magnetic field
- The temperature of ceramic chamber is under 100℃ at 1MHz
- Stability: <100 ppm @ 1kHz - 1MHz



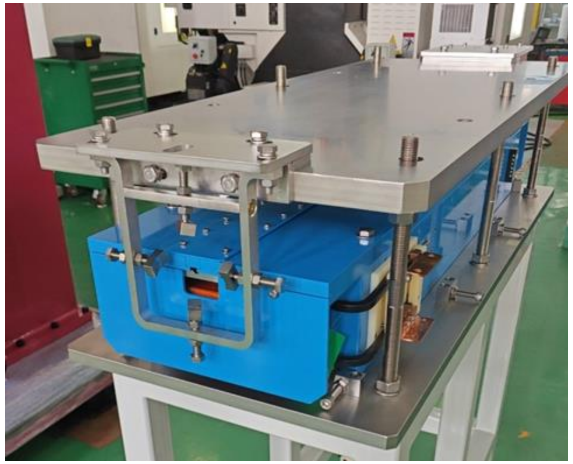
DC Septum

- The integral field reaches 3mrad @8GeV
- The homogeneity of the integral magnetic field is less than 0.1%@2mm
- Integral leakage field in the field-free region is far less than requirement

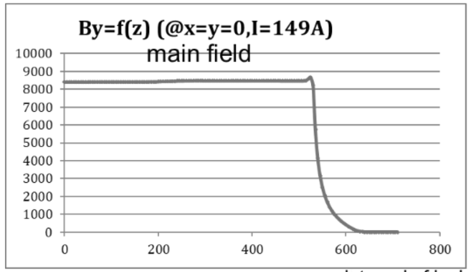


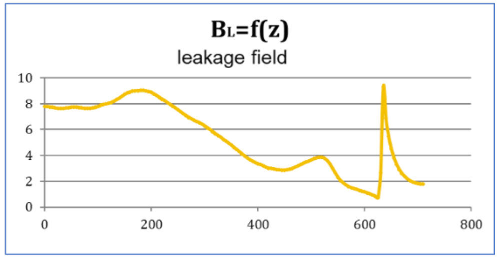
DC Lambertson septum

- The integral field reach the required max bending angle 31mrad@149A
- The main integral field homogeneity is less than 0.1%@±15mm
- Integral leakage field in the field-free region meets the requirement.



field integral of half the core is measured along the beam direction.





$$\frac{\text{Integral of leakage field}}{\text{Integral of main field}} \approx 0.12\% < 0.2\%$$

Permanent Magnet Undulators

Conventional planar undulator

Length: 4 m
Period: 26mm
Peak field: 1.0T
Gap range: 7.2--200mm
rms Phase error: <6 deg
Field integral <50 Gs.cm

Double period Undulator

Length: 4 m
Double Period: 55mm and 75mm
Peak field: 1.25T&1.5T
Gap range: 10.4--200mm
rms Phase error: <6 deg
Field integral <100 Gs.cm

Elliptical Polar. Undulator Prototype

Length: 4 m
Period: 68mm
Peak field: 1.5T
Vertical Gap range: 3.2--150mm
rms Phase error: <12 deg

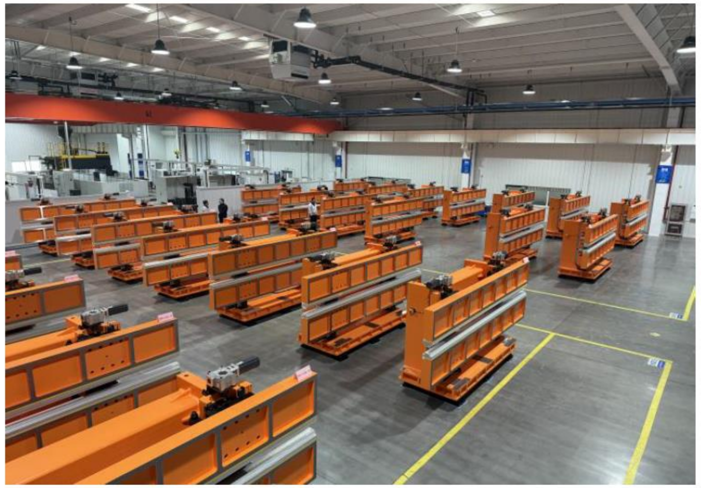
Progress of Permanent Undulator Production

➢ FEL-I SASE-Line

- Magnet, mechanics and control integration of 30 sets of FEL-U26 have been completed;
- 4 sets of U26 finished their magnetic measurements and are being installed in the tunnel.

➢ FEL-II Seeding-Line

- Magnet, mechanics and control integration of 15 sets of FEL-U55 has been completed;
- 5 sets of U55 finished their magnetic measurements and are being installed in the tunnel;
- One double-period U55/75 has been installed in the tunnel and 13 sets are underway.



FEL-I-U26

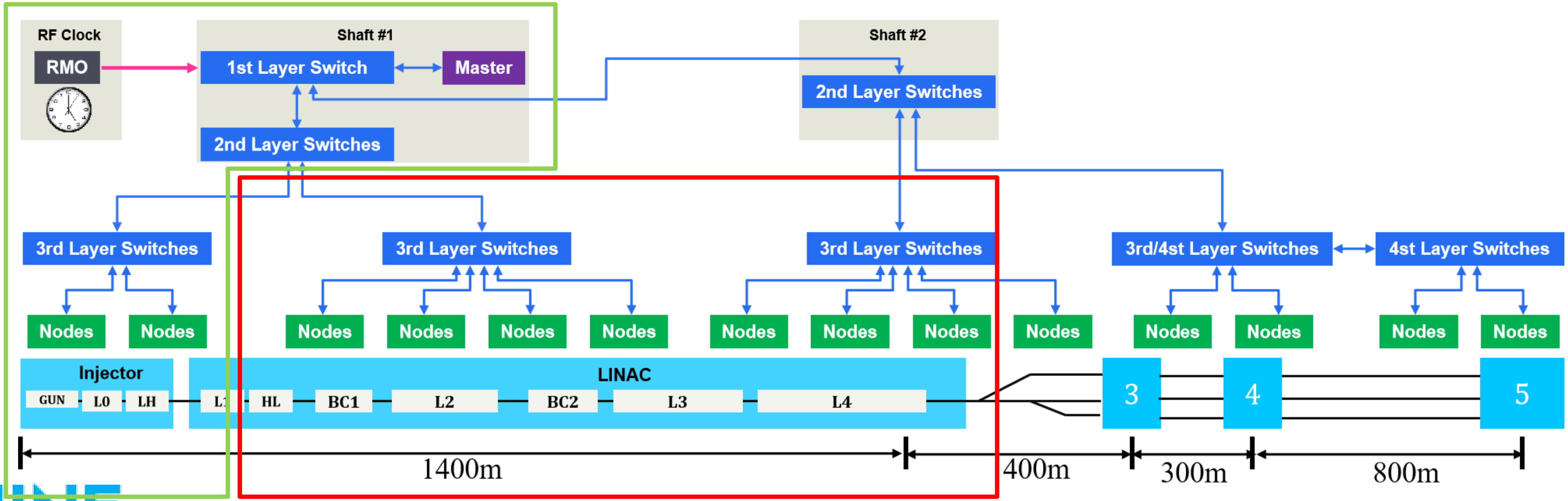
FEL-I&II phase shifters

FEL-II-U55

SHINE

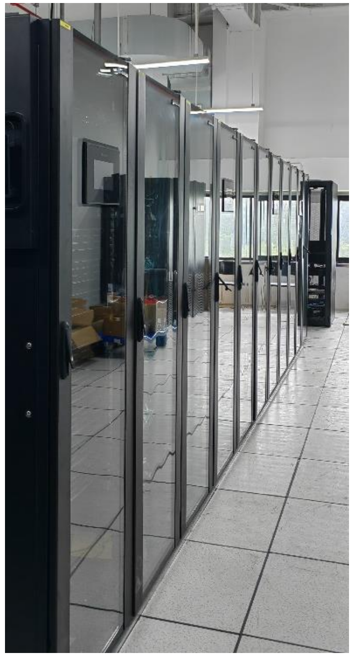
Timing System

- **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

- 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

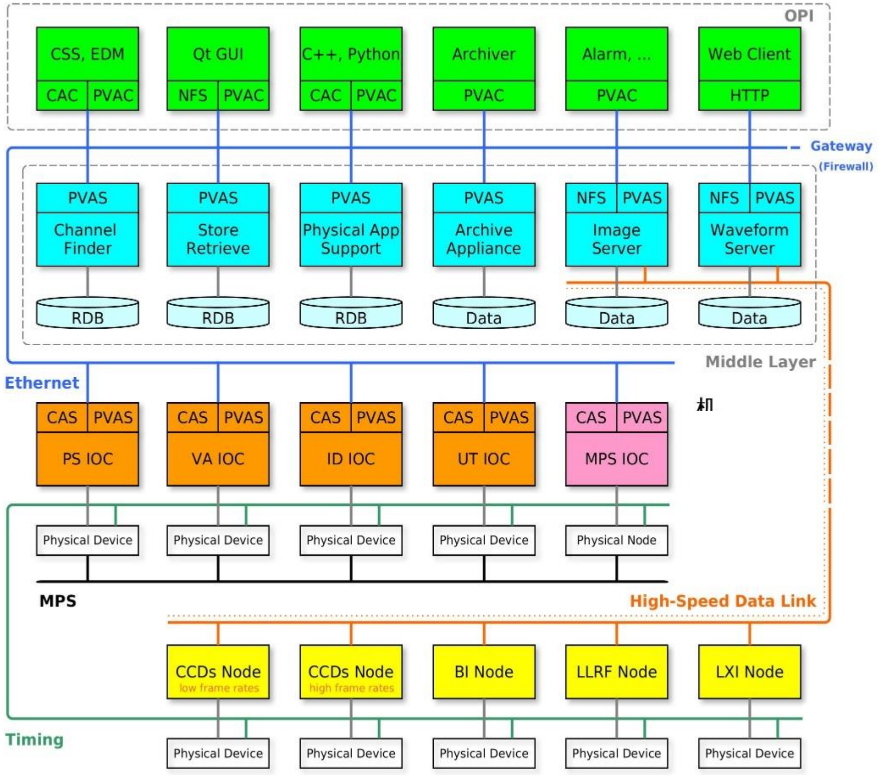


Server Room

Core Switchs

File Servers

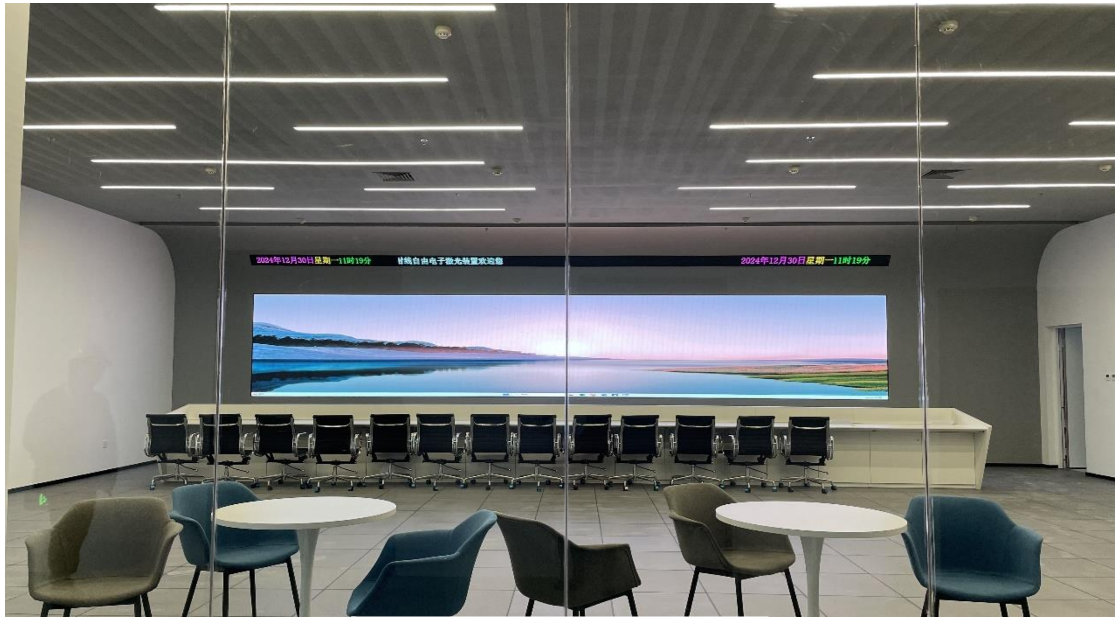
Machine Protection System



SHINE

Control Room

Shaft #1 Control Room



Shaft #2 Control Room

Electronics for Beam Instrumentations

- ☐ **Electronics have been installed in injector**

Electronics in injector

- ☐ **~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

Mass production

SHINE

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)

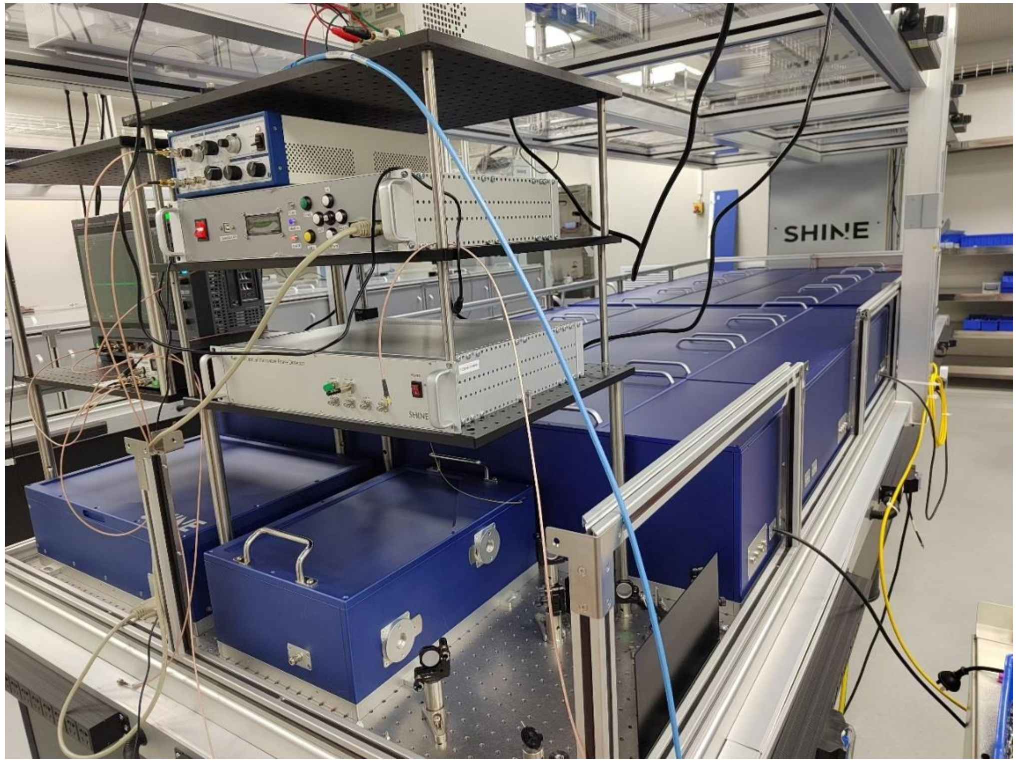
Key performance parameters:

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

pulsed distribution system

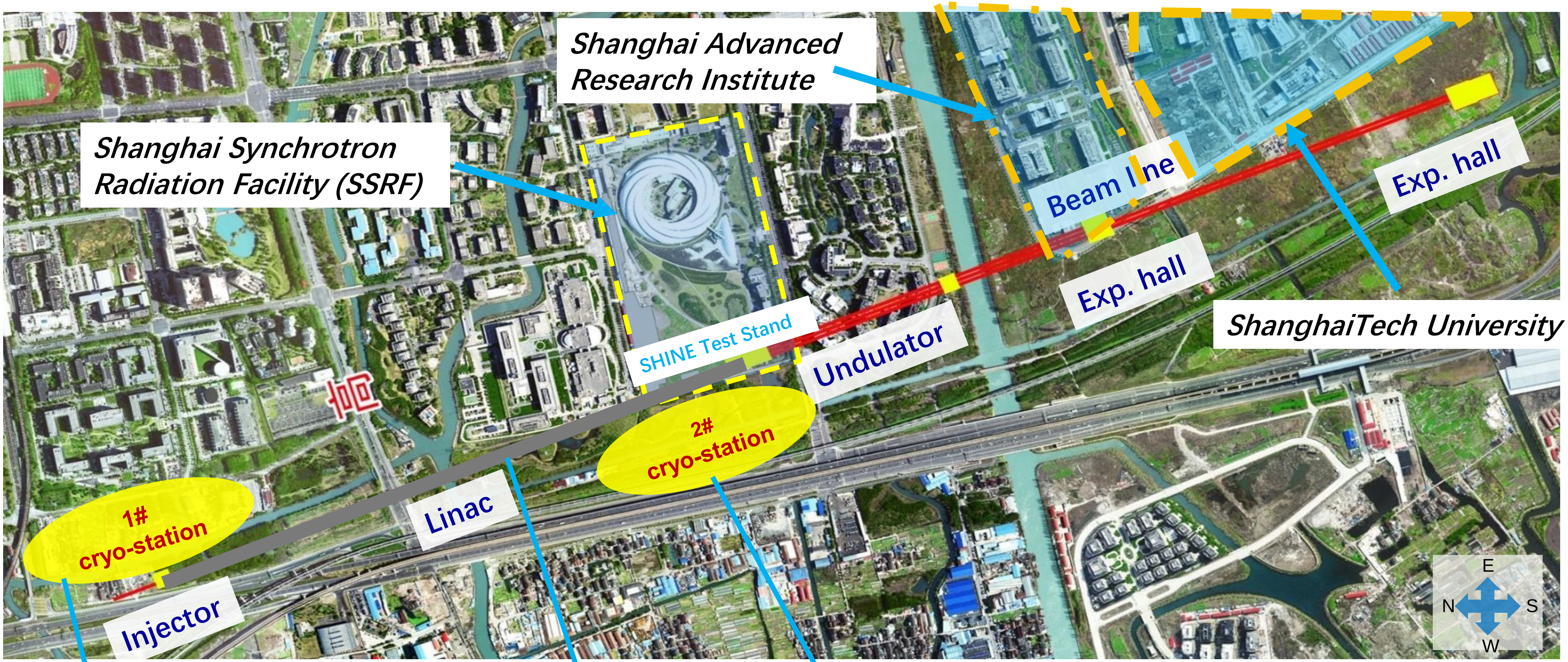
RF station synchro-controller

Local RF Reference modules



Injector laser: ps CPA system

SHINE Cryogenic System Layout



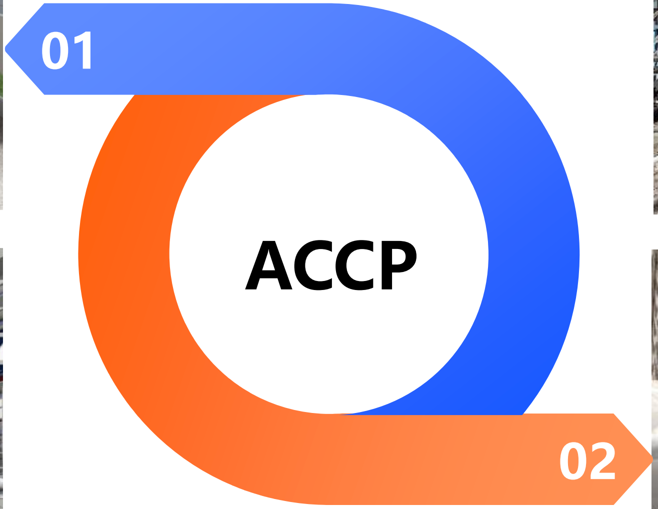
2 sets of **4kW@2K** refrigerators (for SHINE ACCP)

Cryogenic multi-channel transfer lines

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

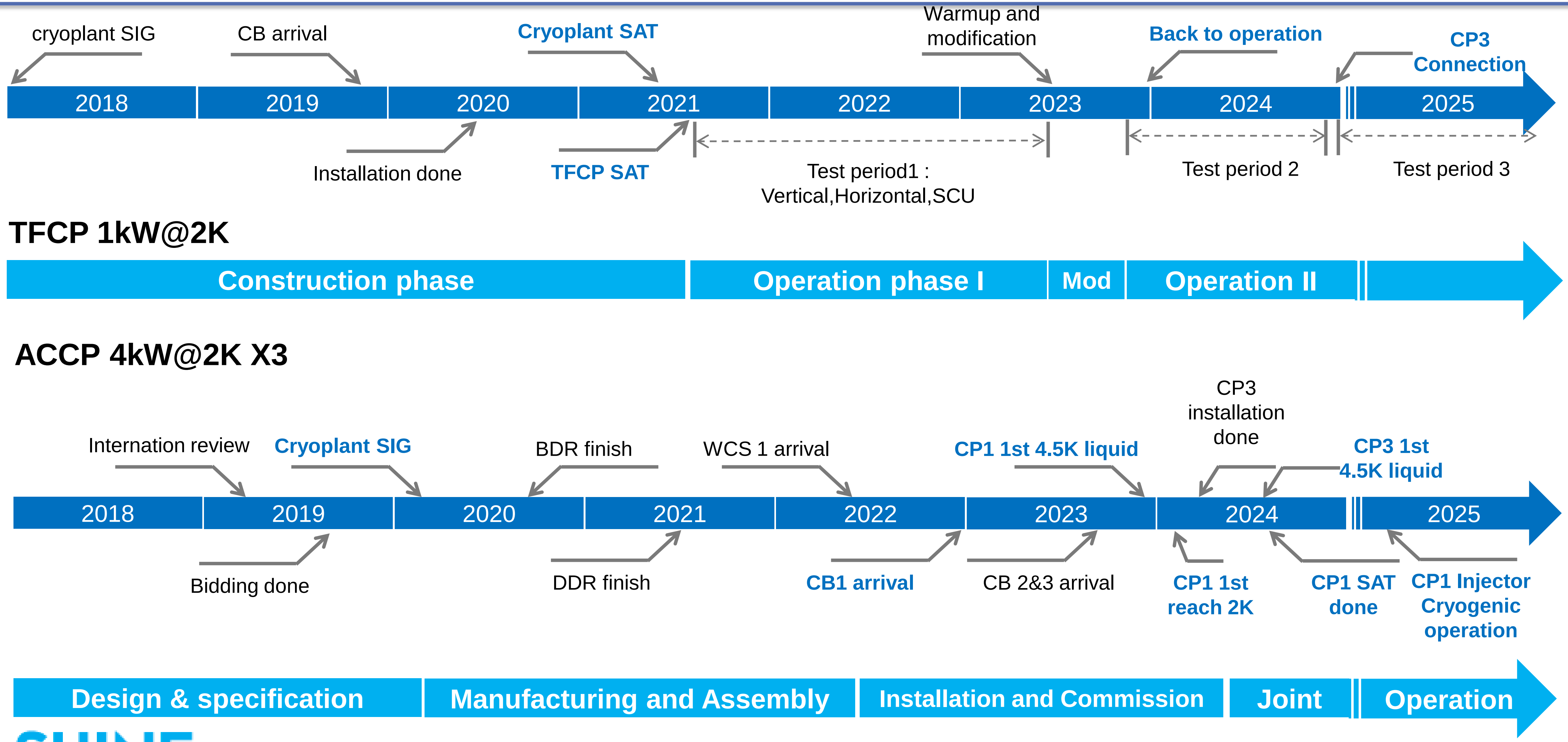
- Installation of CDS had been finished

MTL

Valve box

Cryomodule connection

SHINE Cryogenic System Timeline



SHINE Cryogenic System Status

ACCP1	ACCP2	ACCP3	TFCP
Auxiliary WCS	Auxiliary	Auxiliary WCS	Auxiliary
4.5K cold box 2K cold box Helium Dewar CDS 4.5K -2K CB	WCS 4.5K cold box 2K cold box Helium Dewar	4.5K cold box Helium Dewar	Compressor Cold box PVPS 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

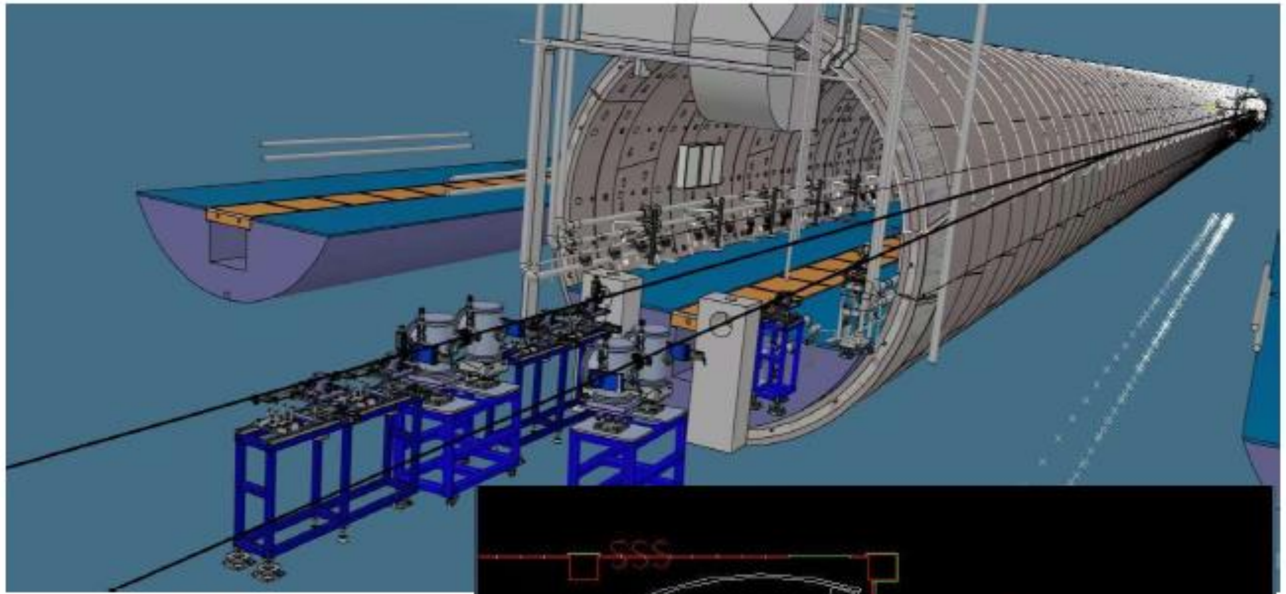
- Production
- Installation
- Commission
- Operation

- **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**

SHINE

Progress of Beamlines and Endstations

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



SHINE

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.

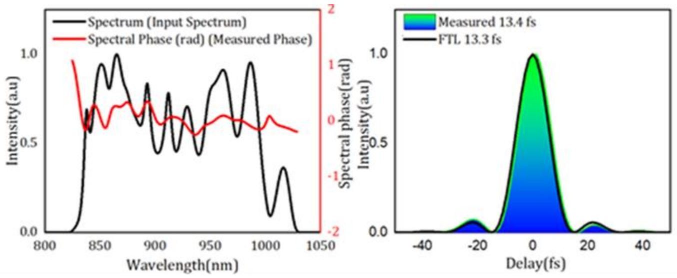
Constant temperature shed completed

The front-end DAQ computer server room

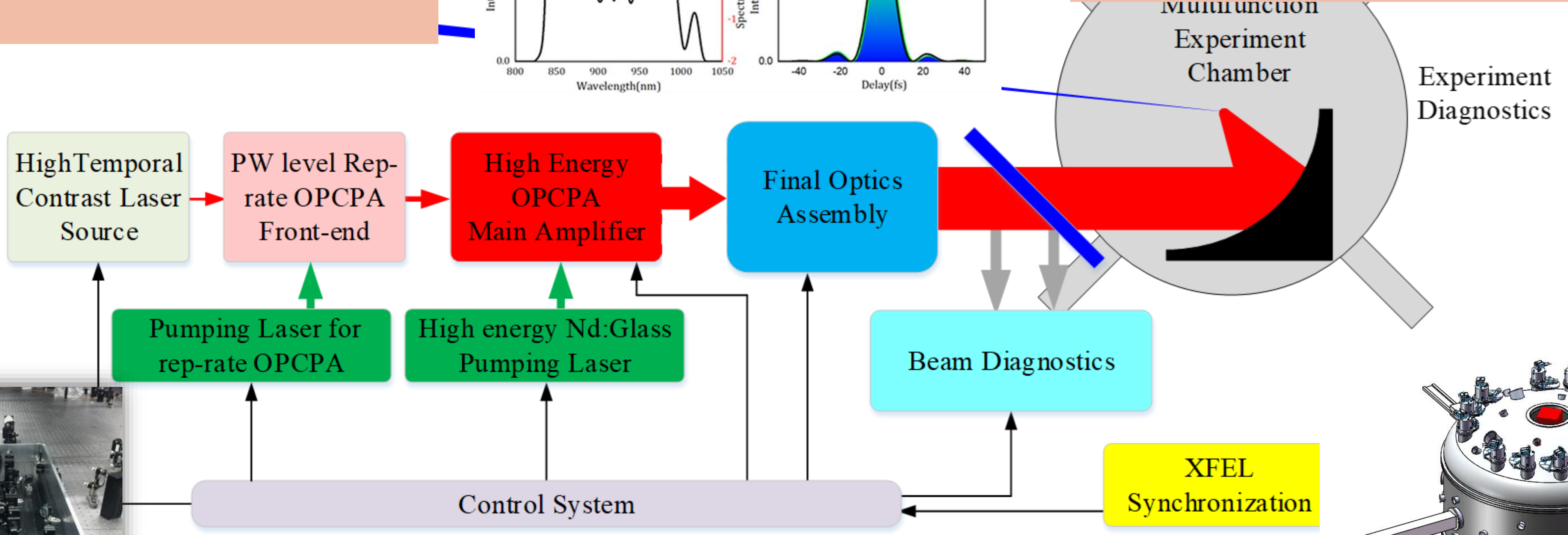
The establishment of the beamline control network

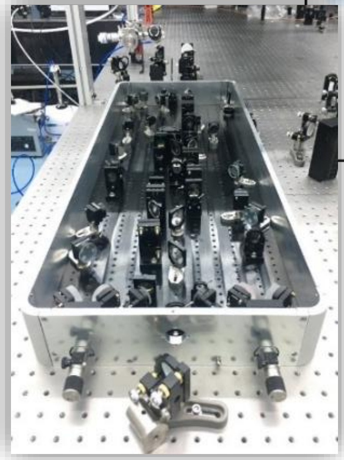
Progress of Station of Extreme Light (SEL)

<u>A prototype with peak power of 250TW has been demonstrated, which will be installed as the front-end of the 100PW laser.</u>



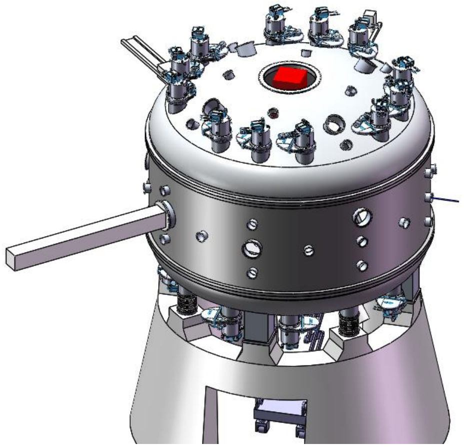
Technical and Engineering Design for high energy OPCPA main amplifier and compressor are in process optimization.





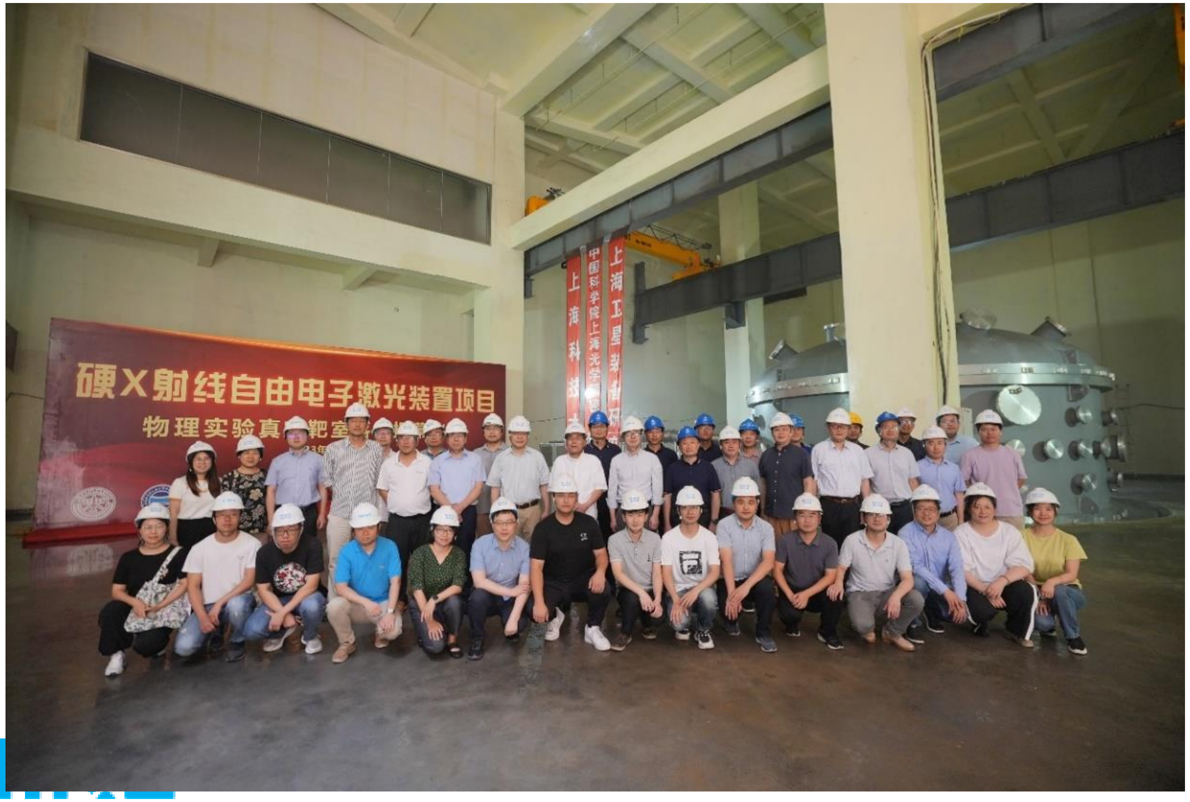
Theoretical and Technical Design for QED experiment is optimized, including experimental chamber, focusing optics and synchronization system.

The chamber has been installed underground.



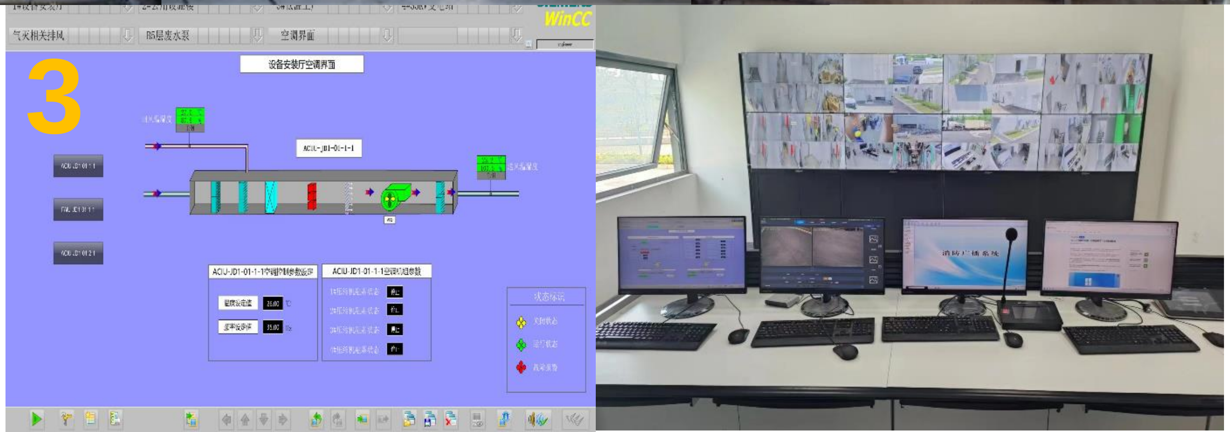
Progress of Station of Extreme Light (SEL)

- 100PW laser beam of 1000×1000 mm^2 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



SHINE

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

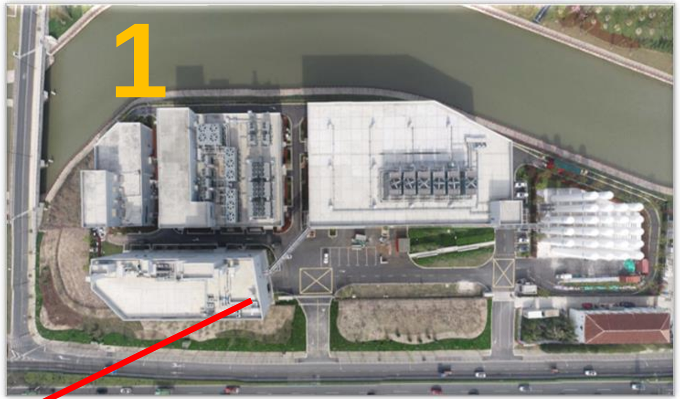
Eastern tunnel between Shaft #4 and Shaft #5

Near Experimental Hall

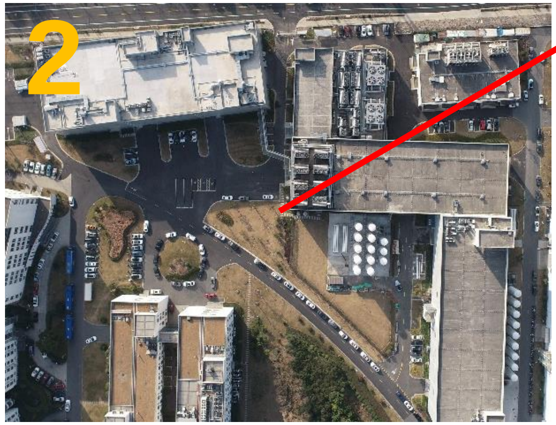
Far Experimental Hall

SHINE

Civil Engineering

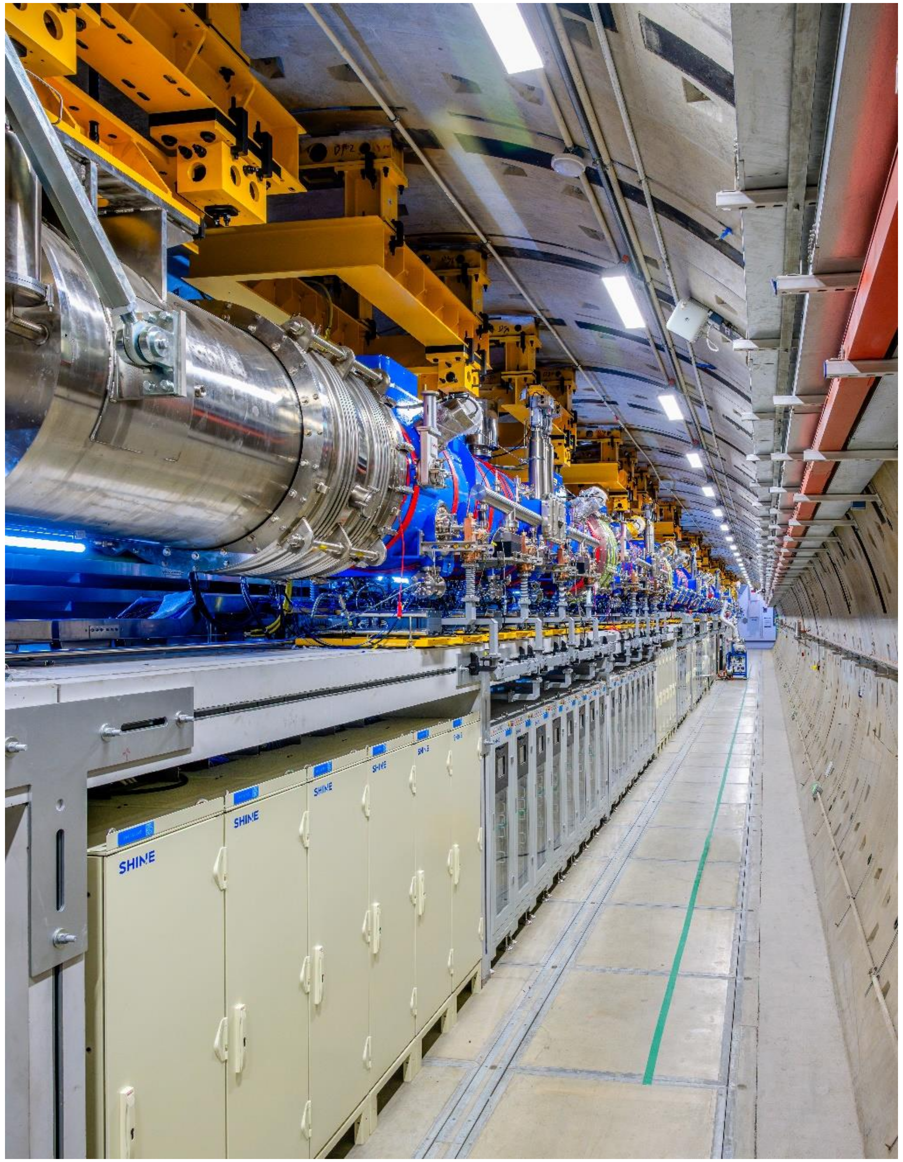


1. Shaft #1, 2. Shaft #2
3. Shaft #3, 4. Shaft #4
5. Shaft #5

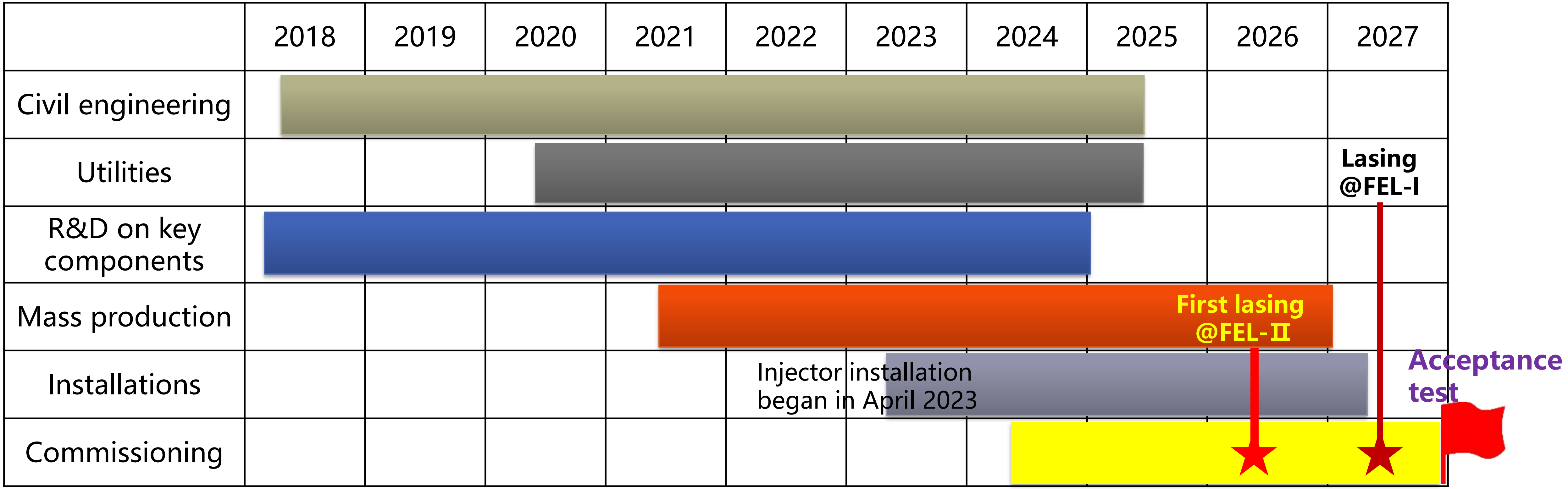


SHINE

Installation Ongoing



Construction Timeline



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

Summary

- The design and construction of the SHINE facility is in good progress, but the project is still facing challenges in key technologies, schedule and budget.
- The civil engineering and utility constructions are expected to be completed in July 2025, which can meet timely the facility requirements.
- The injector commissioning was completed with the designed performance by the end of 2024.
- The L1-BC1 section of the Linac is under installation towards starting the beam commissioning in July 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 cryomodule 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.


Thanks for Your Attention !