

Shanghai Hard X-ray FEL Progress Status

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SHINE: Shanghai Hard X-ray FEL Facility



Shanghai High repetition rate XFEL and Extreme light facility (SHINE)

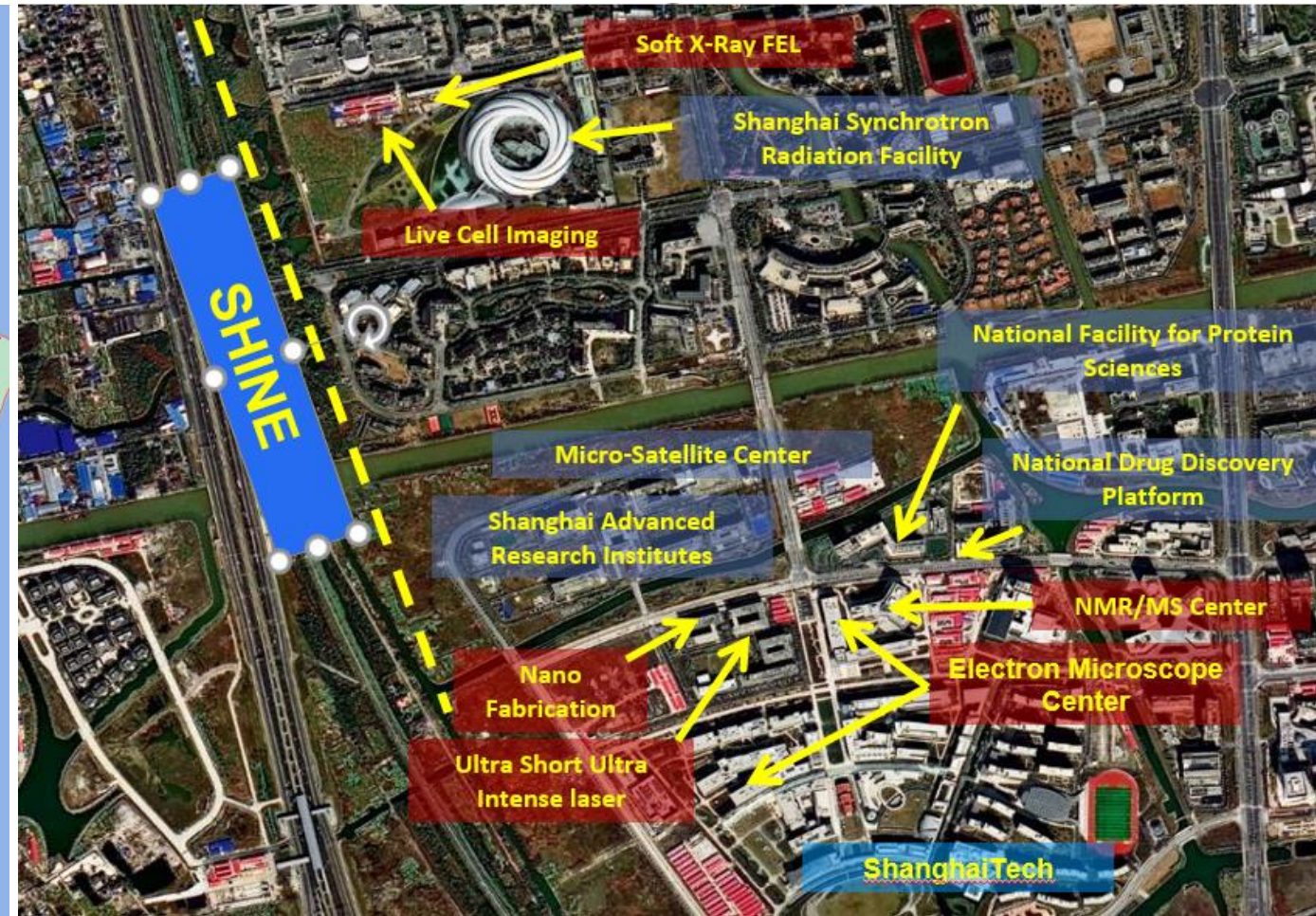
- SHINE is an 8 GeV CW SCRF linac based high rep-rate XFEL facility, it will be installed in a 3.1 km long tunnel underground at Zhangjiang High-Tech Park, across the SSRF campus to the southwest corner of ShanghaiTech University;
- This XFEL facility, assisting with a 100 PW super-intense laser facility, has 3 undulator lines, 3 beamlines and 10 experimental stations in phase-I, and it can provide the XFEL radiation in the photon energy range of 0.4 -25 keV.
- This project was launched by the central government in April 2017, and its groundbreaking was made in April 2018, aiming at the first lasing by the end of 2025.

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

SHINE

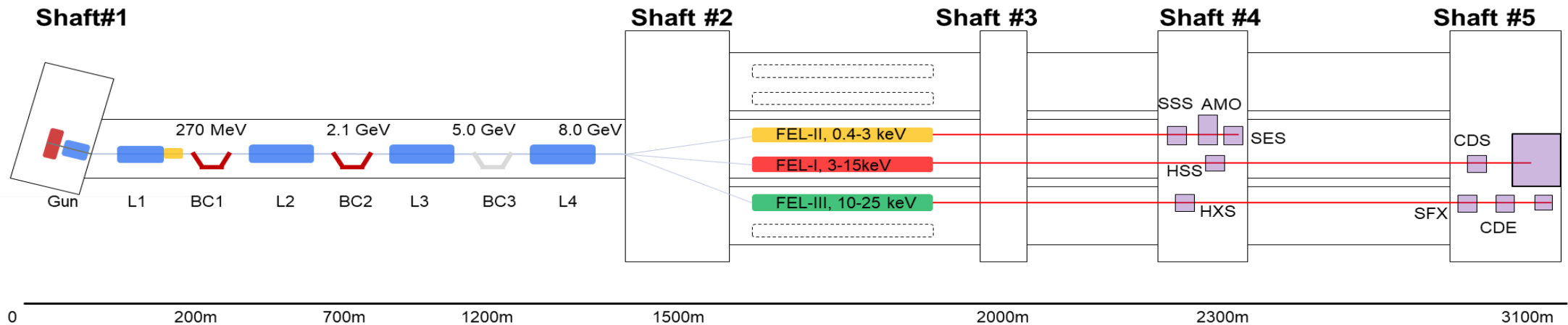
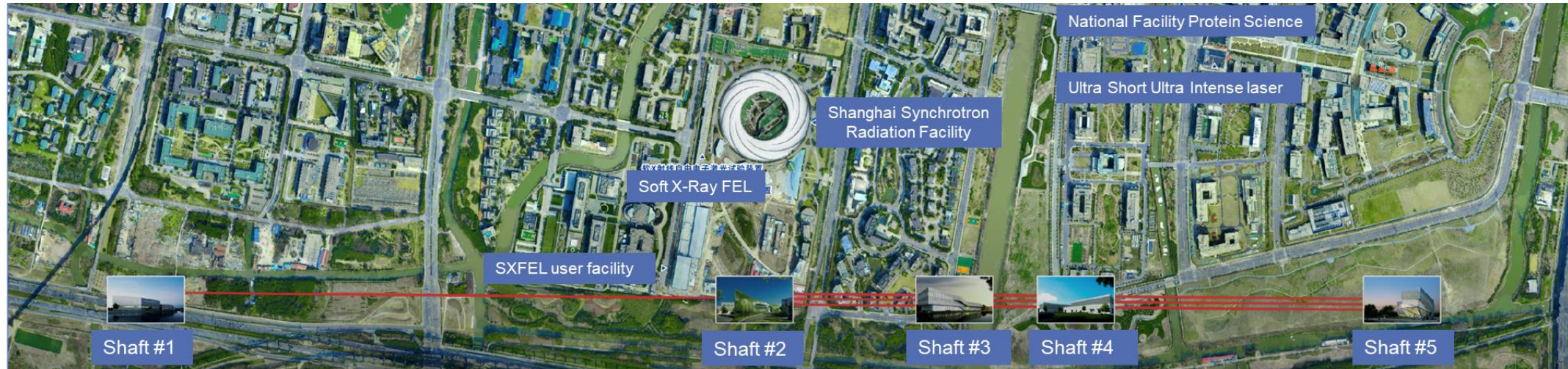


Location: Zhangjiang, Shanghai



Large research infrastructures cluster: Zhangjiang Photon Science Facilities

SHINE: Layout and Main Parameters



- An **8GeV** SCRF linac, 3 undulator lines to deliver photons from **0.4-25 keV**, up to **1 MHz** pulse train with pulse duration of 1-100 fs
- **3 X-ray beamlines and 10 End-stations**
- **100 PW** super-intense laser facility
- **Total length 3.1 km; 29.0 m underground**

Breakdown of the SHINE Construction Tasks

➤ ShanghaiTech University

- Overall project management;
- Civil engineering construction, including tunnels, shafts and buildings;
- Design and construction of the first 3 SHINE beamlines and 9 end-stations.

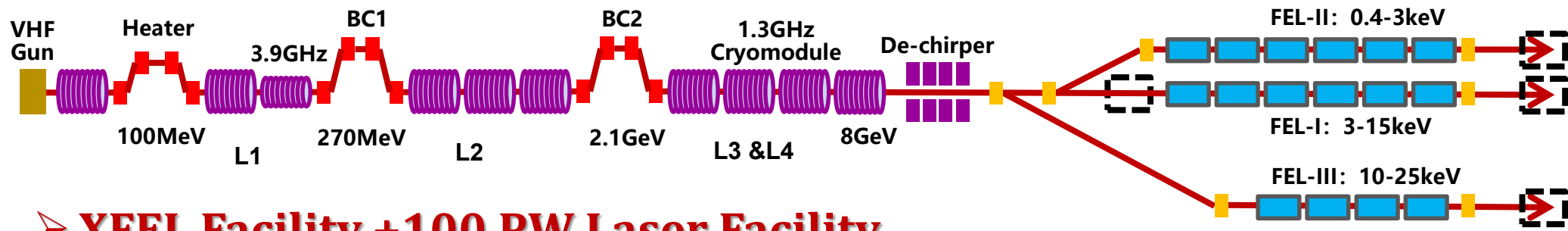
➤ SARI (from SSRF/SINAP): Shanghai Advanced Research Institute, CAS

- Design and construction of the SHINE accelerator, including an 8GeV SRF linac, a beam switchyard for 3 beamlines, and 3 undulator lines
- Utility facilities for SHINE;

➤ SIOM: Shanghai Institute of Optics and fine Mechanics, CAS

- Design and construction of a 100PW super-intense & ultrashort laser system and an end-station of extreme light.

SHINE: A High-rep Rate XFEL Based on SCRF

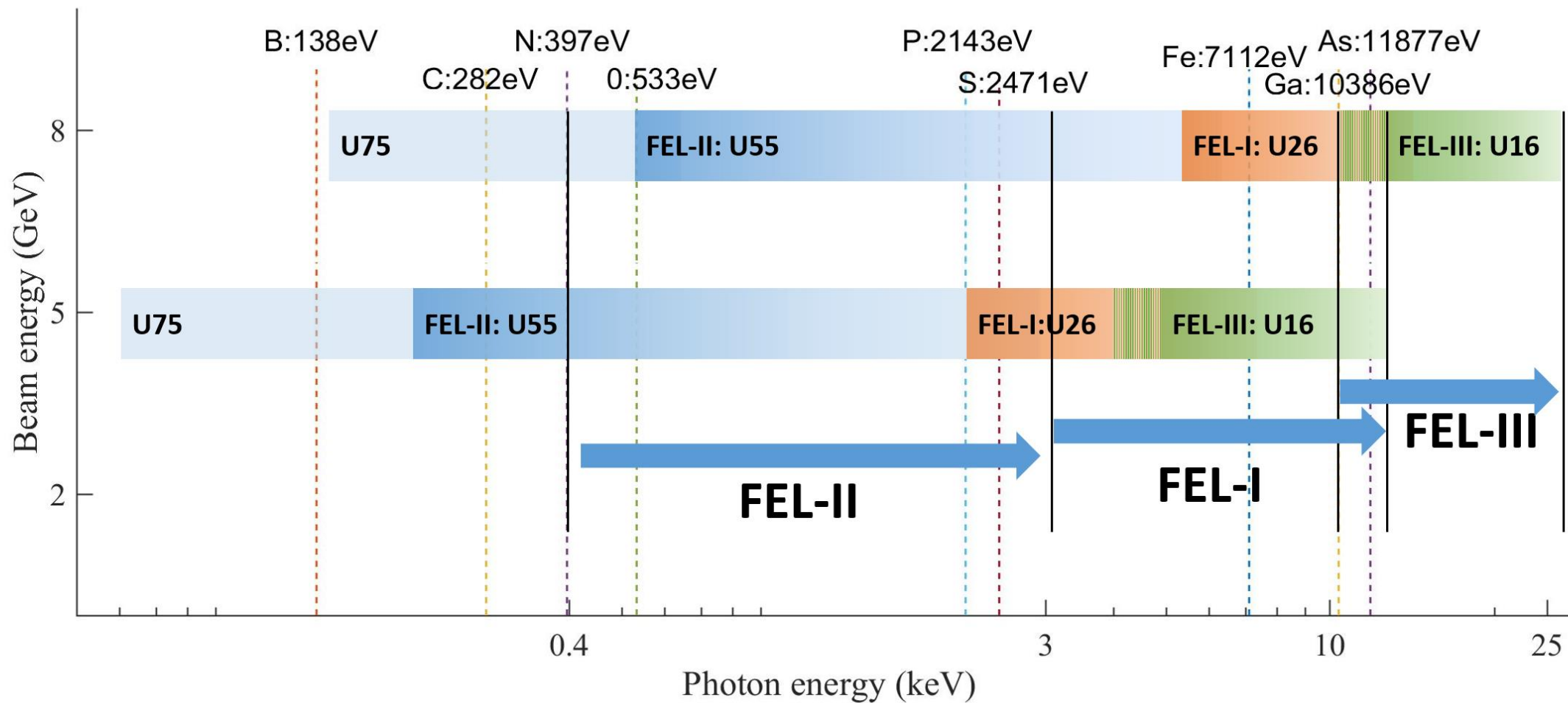


➤ XFEL Facility +100 PW Laser Facility

	Objective
Beam energy /GeV	8.0
Bunch charge /pC	100
Max rep-rate /MHz	1
Beam power /MW	0.8
Photon energy /keV	0.4-25
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	0.4-3
Photon number per pulse @1.24keV	$>10^{12}$
FEL-III	
Photon energy /keV	10-25
Photon number per pulse @15.0keV	$>10^{10}$

Photon Energy Coverage of SHINE



10 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 + 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

Progress of Overall Project Construction

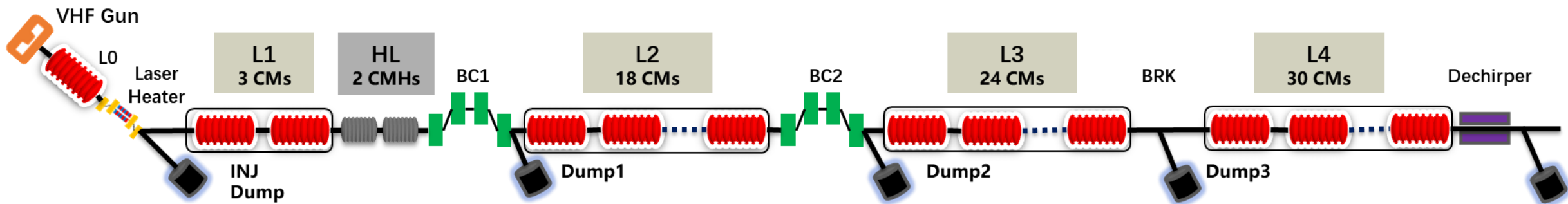


- **Accelerator development progress: R&Ds, prototypes, equipment/component manufacture, installation and commissioning**
 - Injector: VHF gun, buncher, single-cavity cryomodule, eight-cavity cryomodule
 - Linac: standard 1.3GHz SRF eight-cavity cryomodules, 3.9GHz eight-cavity cryomodules
 - Undulators: planar U26 and U55/75, APPLE-III 68, and SCU
 - Other acc. sub-systems: kicker, RF, BI, laser, control and beam dump...
 - Cryogenic systems: 1kW@2K plant, 3X4kW@2K plants
- **Beamlines and Endstations**
- **Progress of high-power laser system**
- **Civil Engineering & Utilities**

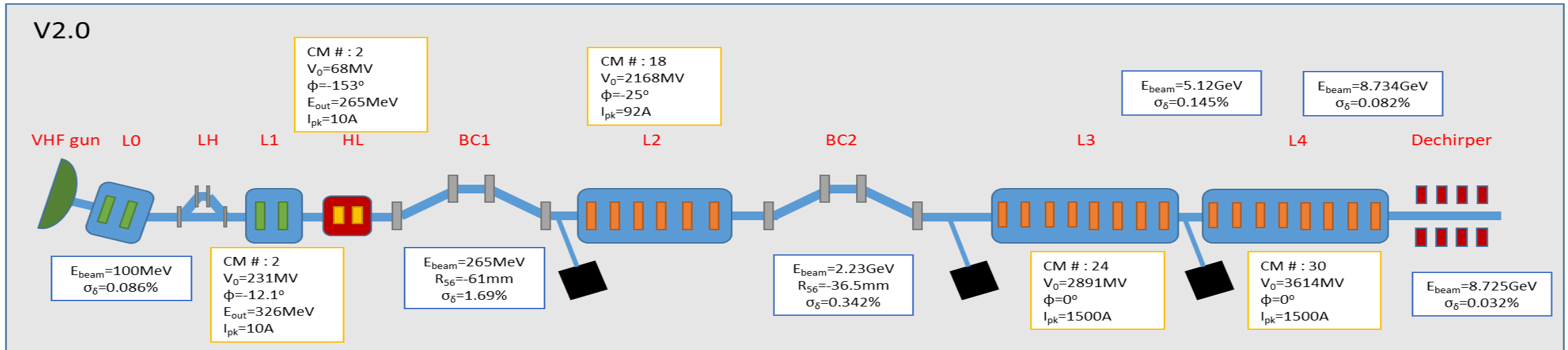
The SHINE Linear Accelerator



- **The SHINE Accelerator** consists of
 - An injector section: 750kV/217MHz photo cathode VHF gun, a two-cell buncher, a single-cavity CM and an eight-cavity CM;
 - 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.



Performance of the SHINE Accelerator



Injector Parameters	Value
Beam energy (MeV)	100
Bunch charge (pC)	100
Normalized emittance (95%, $\mu\text{m}\cdot\text{rad}$)	0.4
Slice energy spread (10^{-4})*	0.1/0.5
Bunch length, rms (mm)	1
Peak current (A)	12

	No. of CM's	Avail. Cavities	Powered. Cavities*	Gradient (MV/m)	Eout (MeV)	σ_z (mm)
L0	1	8	7	16.3	100	1.15
L1	2	16	15	14.8	326	1.15
HL	2	16	15	13.1	265	1.15
BC1	-	-	-	-	265	0.13
L2	18	144	135	15.5	2229	0.13
BC2	-	-	-	-	2229	0.006
L3	24	192	180	15.5	5120	0.006
L4	30	240	226	15.5	8734	0.006
Dcp	-	-	-	-	8725	0.006

➤ 750kV VHF gun + 1.3GHz Single 9-cell cavity CM + 1.3GHz Injector CM + 1.3GHz Standard CM:X75 + 3.9GHz CM:X2

The SHINE Accelerator Construction Progress

- Construction of three 4kW@2K helium refrigerators in two cryo-plants are going well currently, the first one is in commissioning and its 2K liquification was achieved;
- The injector started its installation in April 2023, the VHF gun commissioning started with RF in October 2023 and with beam in December 2023;
- Two prototypes of standard CMs have been developed and horizontally tested, the required total accelerating voltage over 128MV has been achieved;
- The single-cavity CM (i1CM) for injector is installed in the tunnel; the eight-cavities CM (i8CM, ABBA type) for injector has been assembled and tested, and was just sent to the tunnel for installation; the first eight-cavities standard cryomodule CM01 for the SHINE linac has been assembled and tested with qualified performance;
- Other accelerator components such as various beam instrumentation devices, magnets and power supplies, vacuum components, etc., are under batch production.

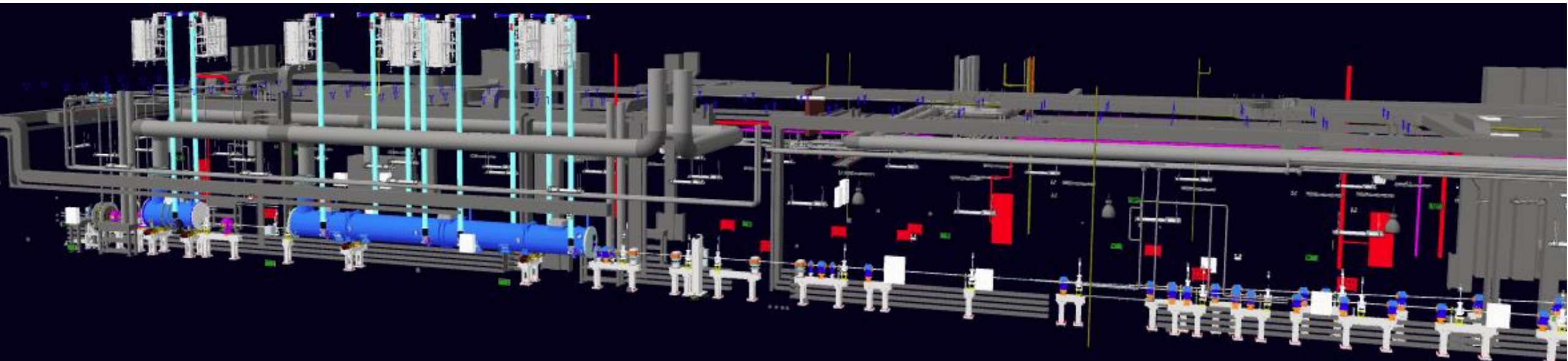
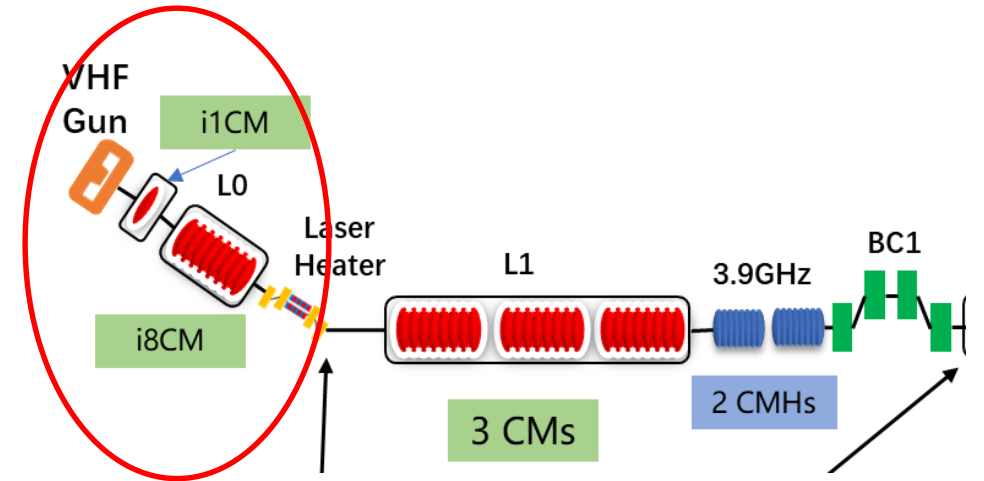
Injector: VHF gun and CMs

More details in MOPC47

Injector layout:

- 750kV VHF gun
- Single-cavity CM (i1CM)
- Eight-cavity CM (i8CM)
- DBA bending section

Parameters	Value
Bunch charge (pC)	10~300
Repetition Rate (MHz)	0~1
Beam energy (MeV)	90~120
Slice energy spread (10^{-4})*	0.1~1
Peak current (A)	5~20
Normalized emittance (95%, $\mu\text{m}\cdot\text{rad}$)	0.2~0.6



Injector: installation progress

More details in MOPC47



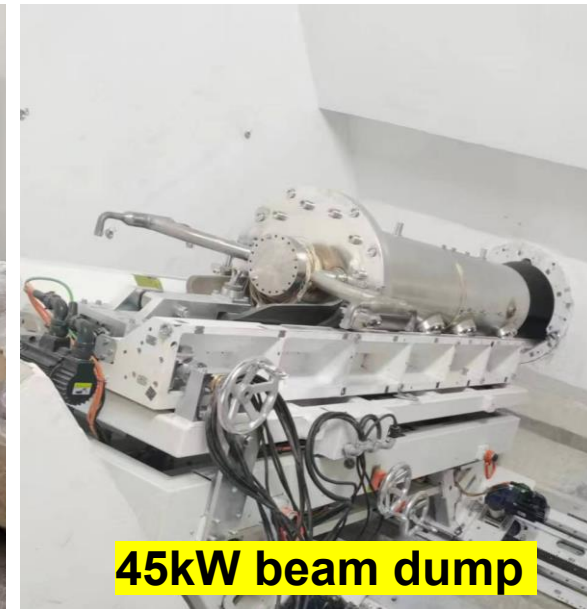
Gun section



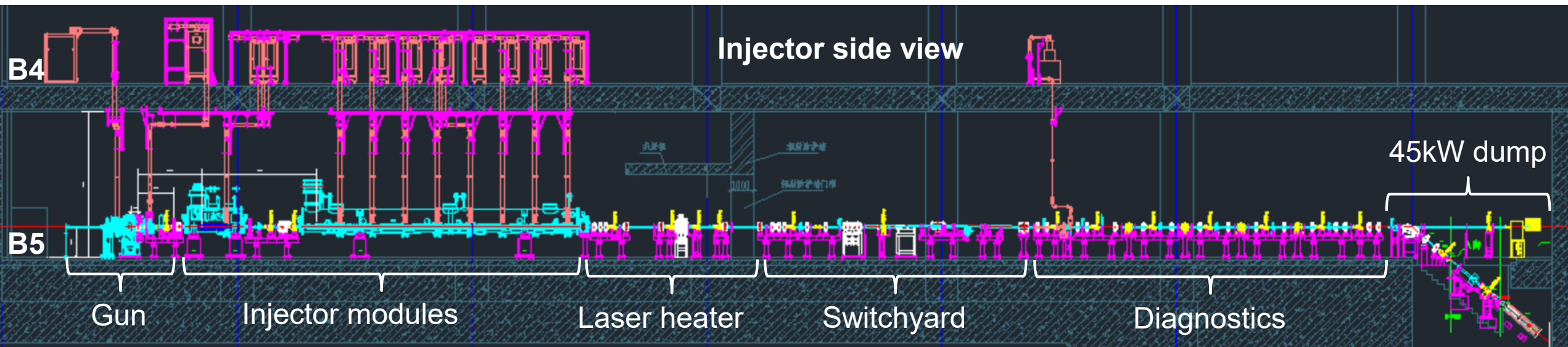
1-cav SC module



Pre-assembled beamline



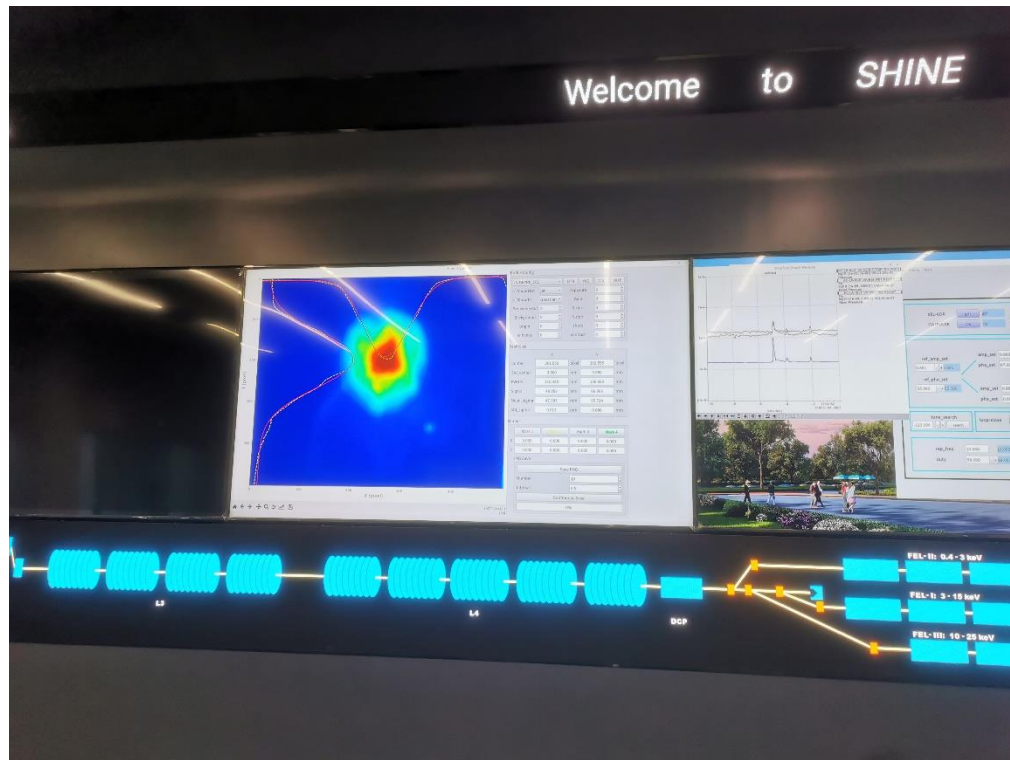
45kW beam dump



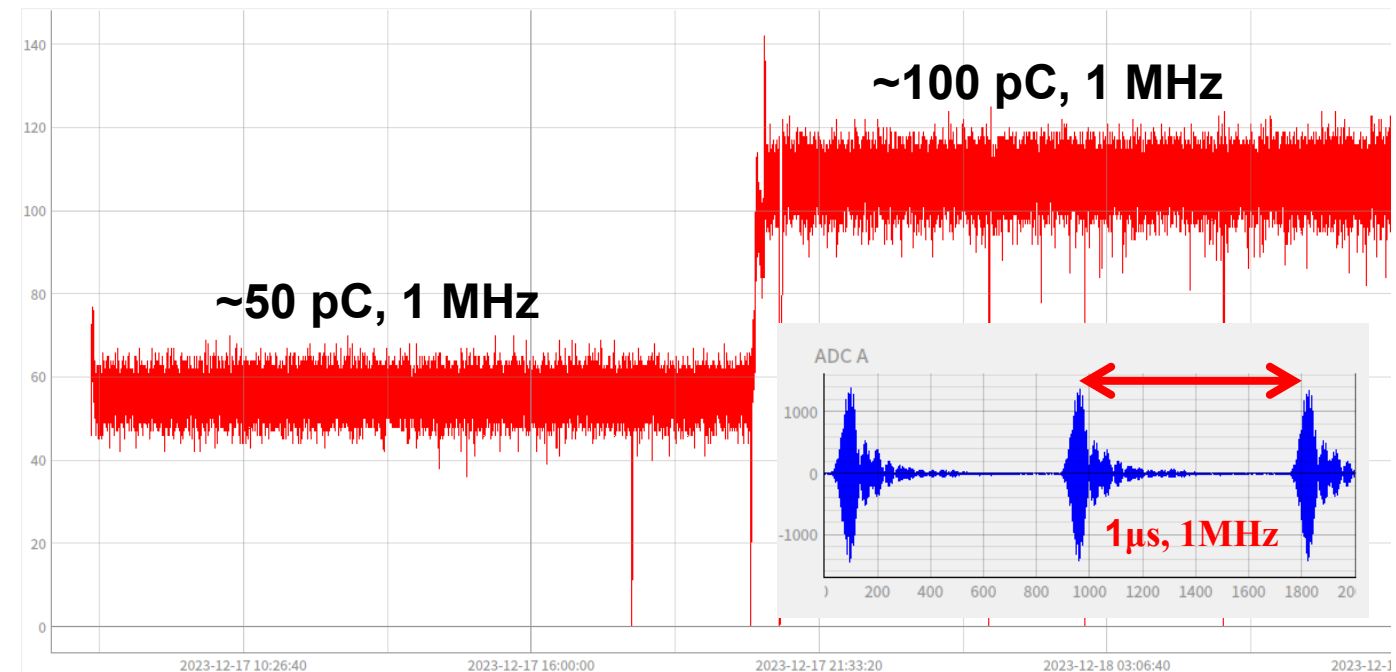
Injector: gun commissioning

More details in MOPC47

- From 10 Hz beam to 1 MHz beam



First photoelectron beam from the gun!
Dec. 03, 2023



Continuous 1 MHz beam for 24 hours!
Dec.17, 2023

Cryomodules Development

More details in WEPS42



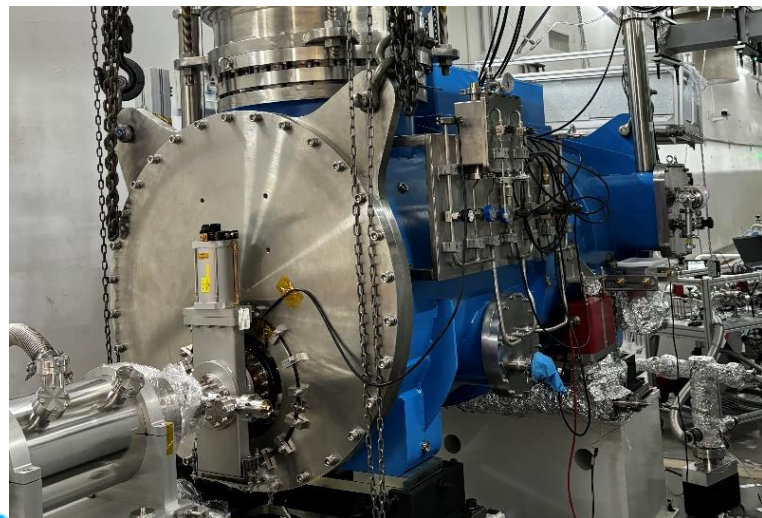
CM prototype with 8 BCPed cavities



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.)

Cryomodules: a Prototype

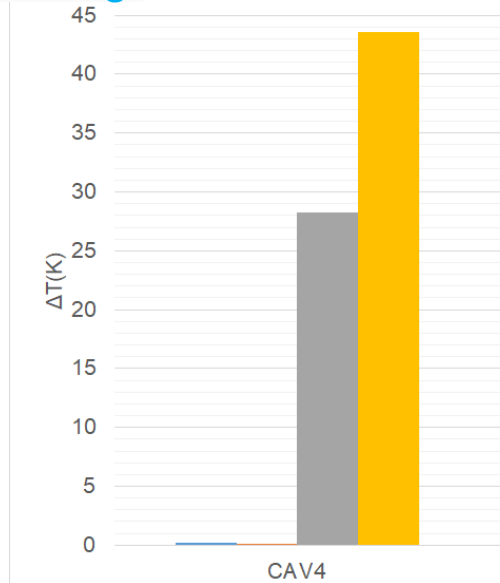
More details in WEPS42

- Recently, the high-Q Cryomodule (CM) prototype with six mid-T baked, one N-doped and one large-grain cavities, was tested and has reached an average $Q_0 = 3.0 \times 10^{10}$ at a total voltage of 135 MV, after CM degaussing and fast cooling, which meets CM specification.

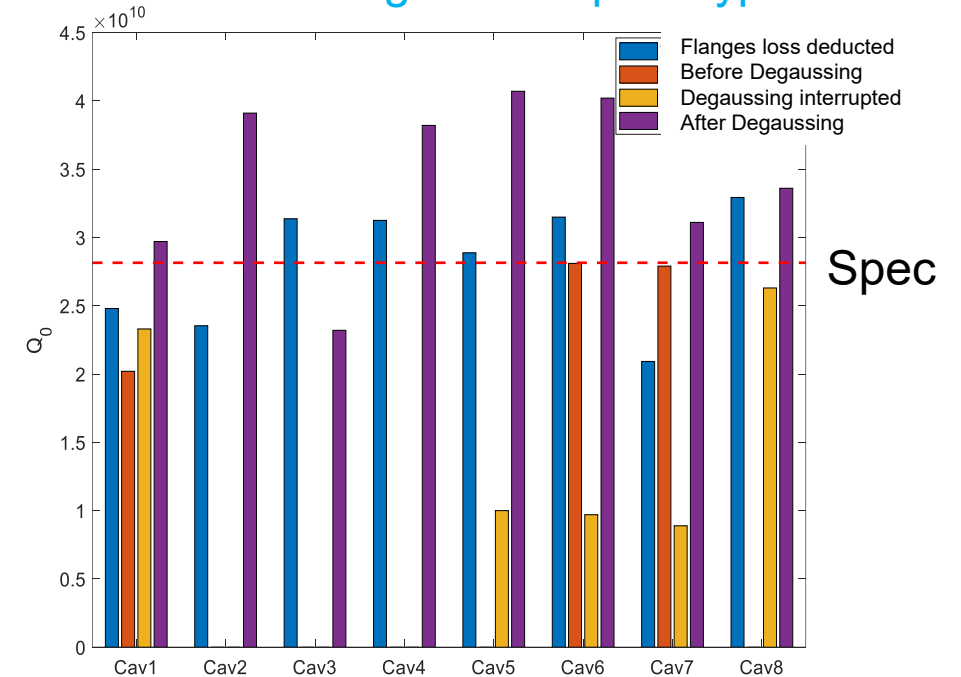
CM Degaussing



Thermal difference between cell top and bottom during cooling

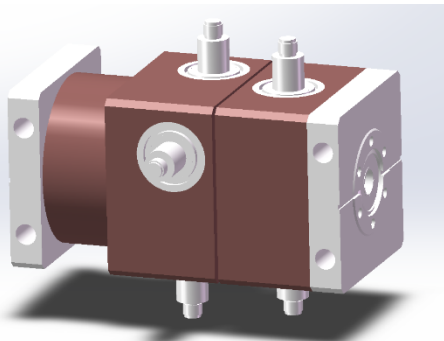


Q_0 measurement of 8 cavities at ~16 MV/m in the high-Q CM prototype

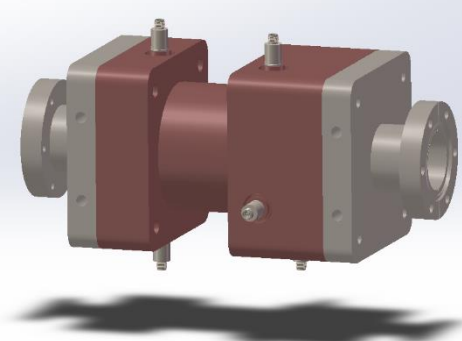
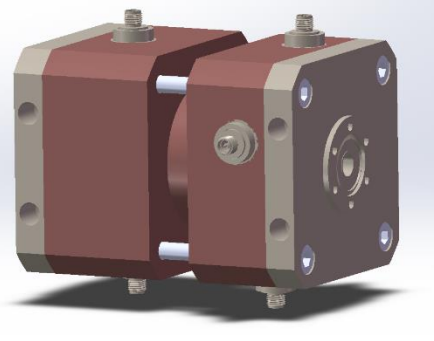


Cavity BPM

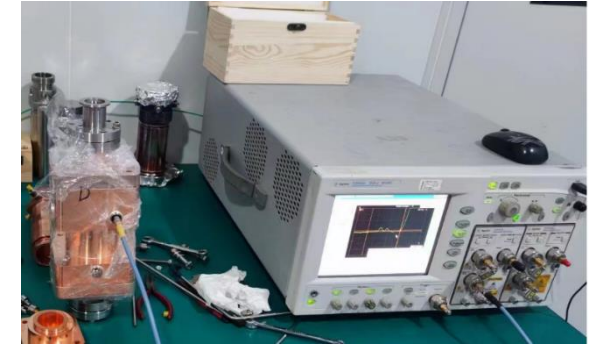
More details in WEPG79



Cavity pickup - $\Phi 8$ mm

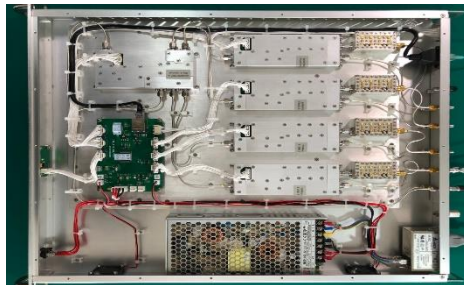


Cavity pickup – $\Phi 35$ mm

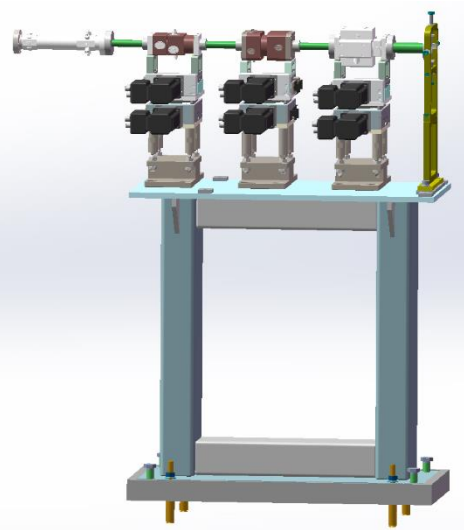


Frequency: 3520.8 MHz
Decay time: 200 ns
IF: 54.2 MHz

Frequency: 5254.2MHz
Decay time: 200 ns
IF: 54.2 MHz



SHINE RF Front-end + Digital BPM Processor

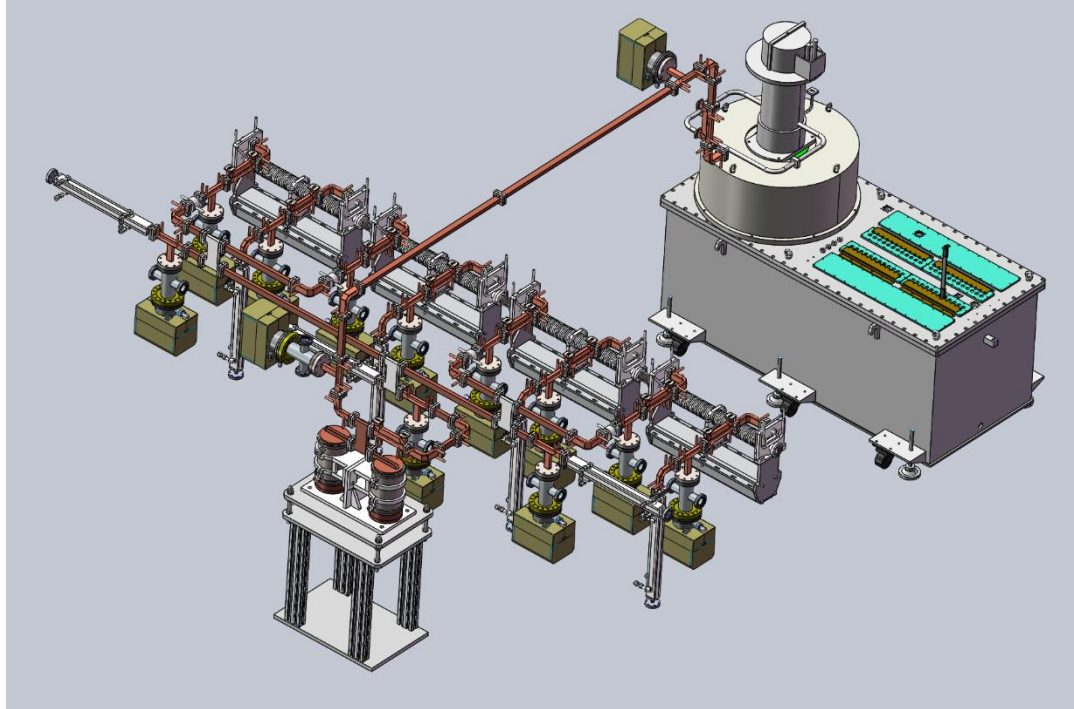


CBPM test bench @ SXFEL

- Prototypes of cavity pickups with beam pipe diameters of $\Phi 8$ and $\Phi 35$ have been designed and fabricated. The cold test results (S parameters) have met the specifications.
- The RF front-end and digital BPM processor have been completed, the relative amplitude extraction uncertainty is better than 0.3‰ during the commissioning tests.
- The beam test bench for the CBPM system has been set up at SXFEL, and the performance evaluation will be carried out.

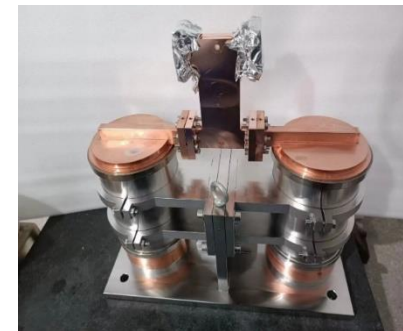
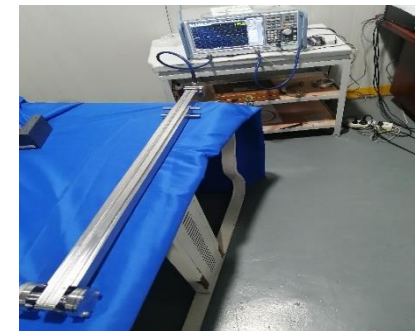
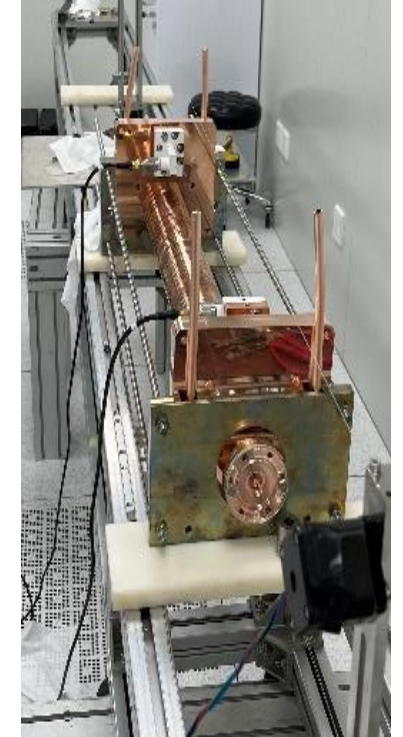
X-band Deflector

- 1 X-deflector for switchyard
- 3 X-deflectors for each FEL undulator line



X-band deflecting system
40MV deflecting voltage, 11.989GHz

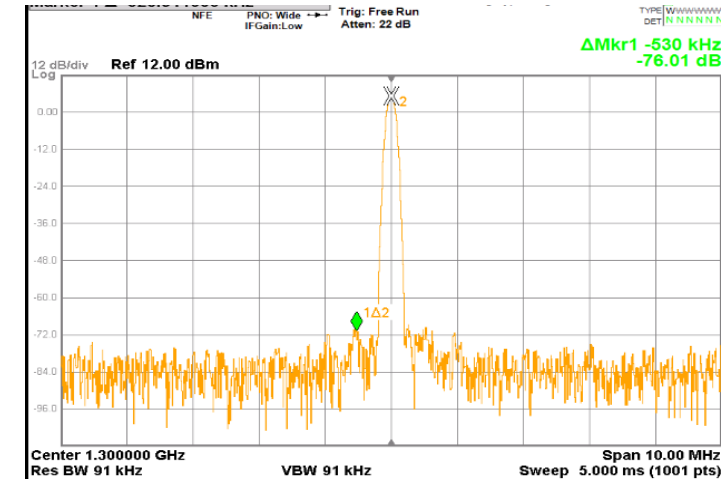
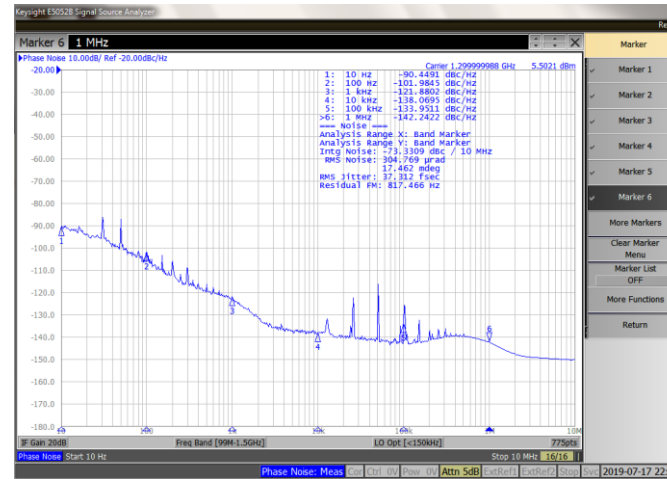
More details in MOPC49



The first X-band deflector system with full performance will be ready this year. (for Switchyard)

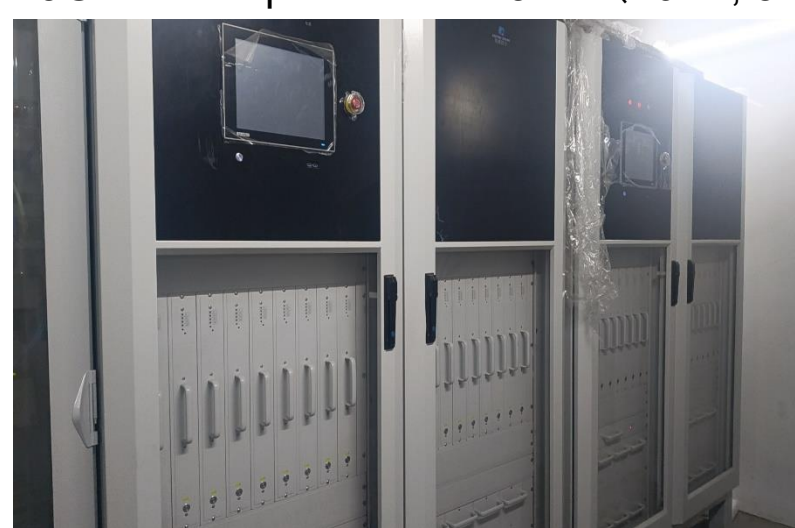
RF Power - SSAs

- **High Power SSA**
 - four 1.3GHz/5.2kW prototypes
 - **68 1.3GHz/5.2kW SSAs**
 - **1 1.3GHz/15kWSSA for Buncher**
 - **2 216MHz/60kW SSA for VHF gun**
 - 1 3.9GHz/2kW prototype
- **Other high power SSA**



1.3GHz SSA phase noise 37fs (10Hz, 5MHz)

spur : -75dBc



Injector SSA
SHINE

SSA for Beam
current test platform

VHF gun SSA

SSA for cavity horizontal test

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+Deepin Operating System+PyDM UI+White Rabbit



Server Room



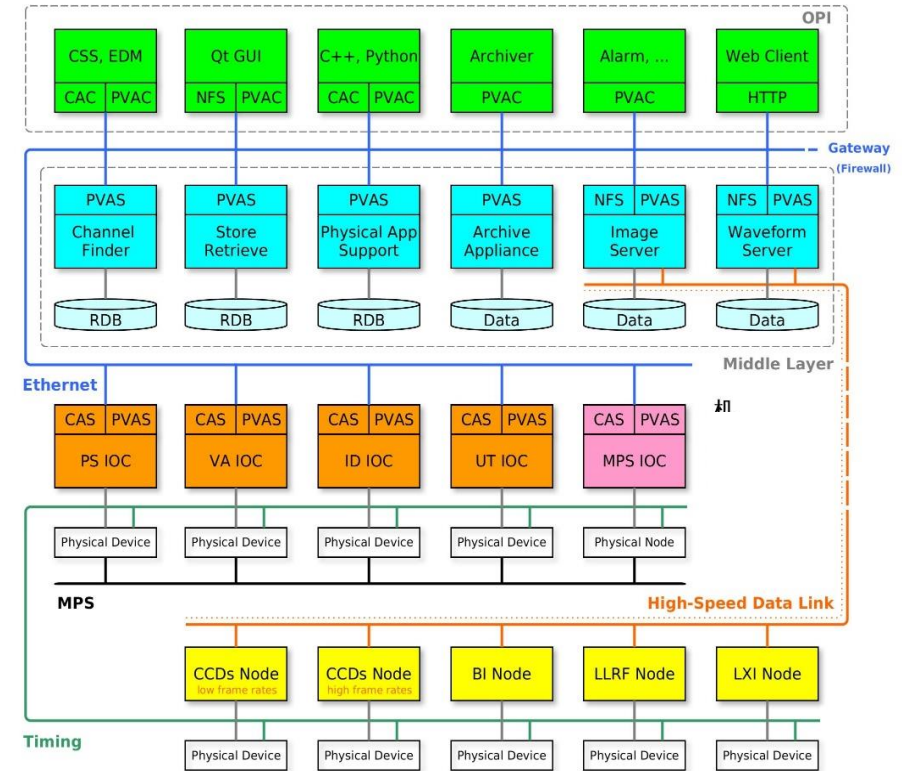
Core Switches



File Servers

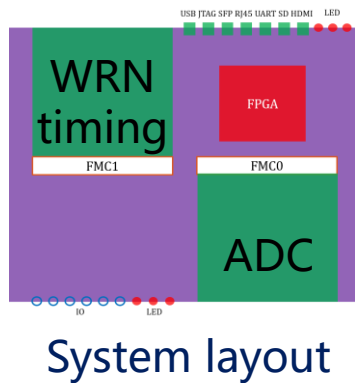


Machine Protection System



Beam Diagnostic Electronics

- Developed generic electronics for beam signal processing (more than 400 units): 1U Stand alone structure integrating SoC FPGA carrier board, high speed ADC board, White Rabbit timing board
- 4 channels input, ADC: 1GSPS sampling rate, 2GHz band width, 14bits resolution
- First batches (70) arrived, tested and installed in field in the injector



FPGA board and ADC board



Generic Electronics (front)



Generic Electronics (back)



First batches

Synchronization System

RMO (SMA100B)

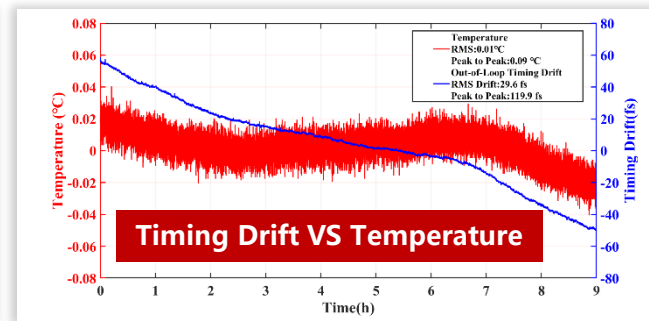
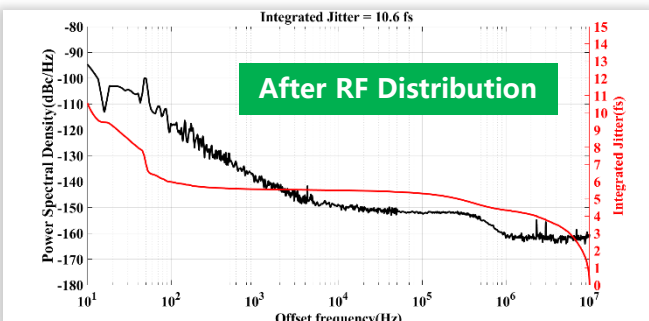
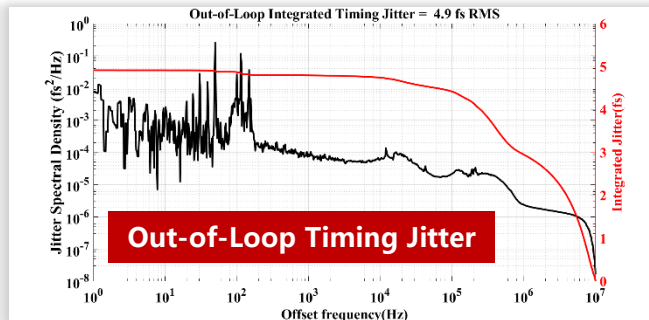
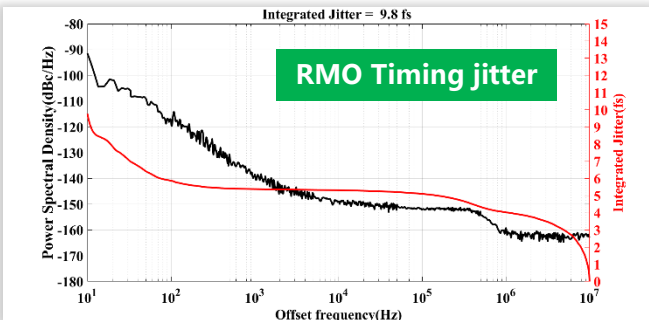
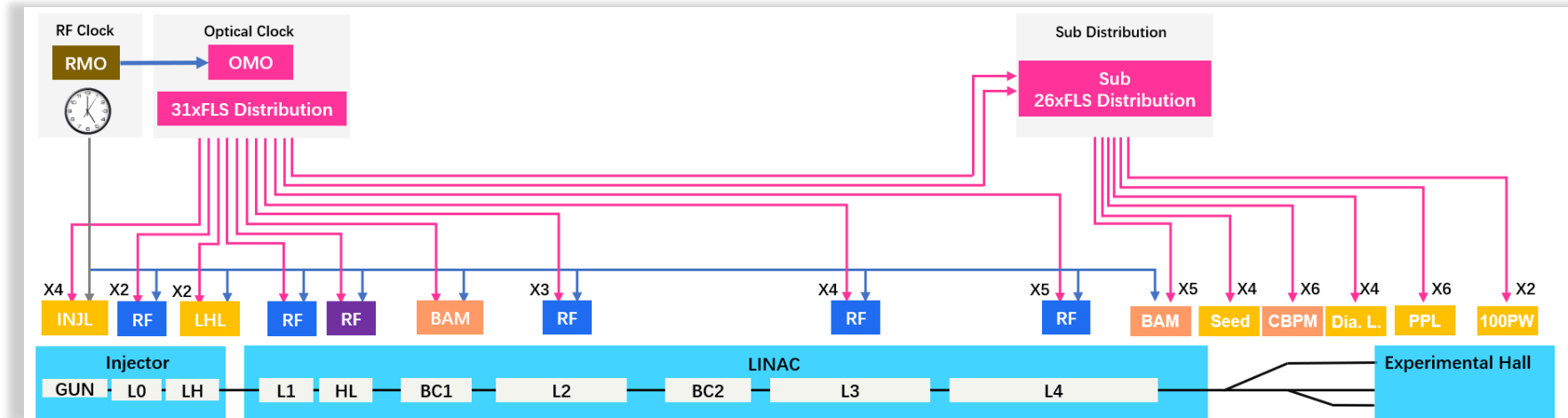
- Absolute jitter **9.8 fs**

RF-SD

- Absolute jitter **10.6 fs**

OMO locked to RMO

- Timing jitter **4.9 fs**



Electrical Installation



Cabinets (1#B4)



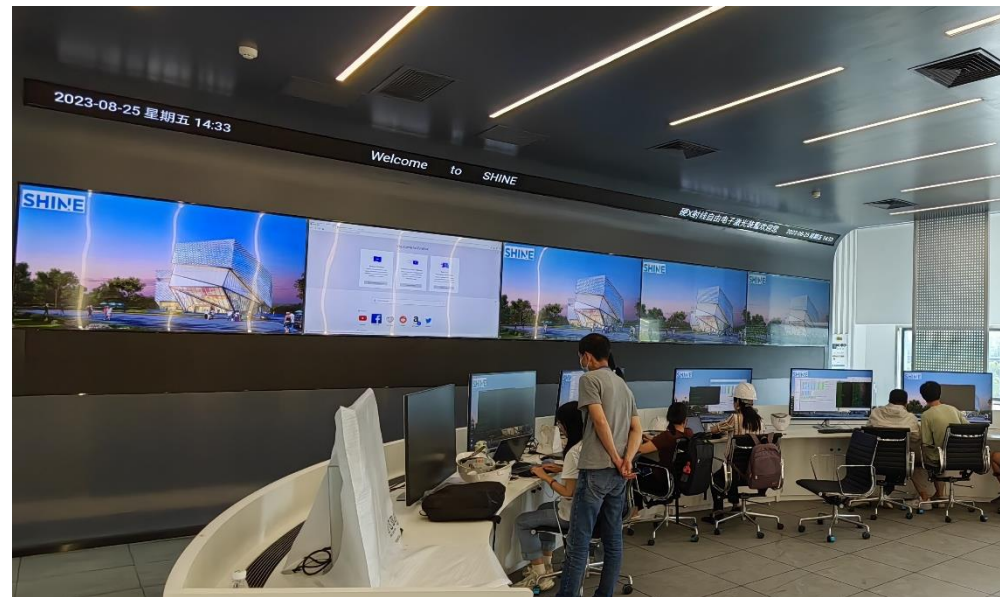
Network Cabinet



Cabling



Laser Clean Room (1#)

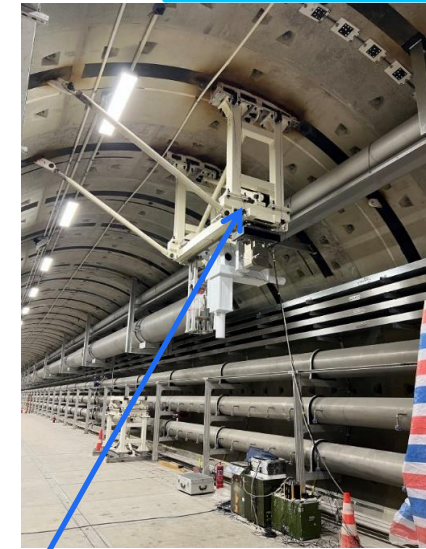


Accelerator Control Room (1#)

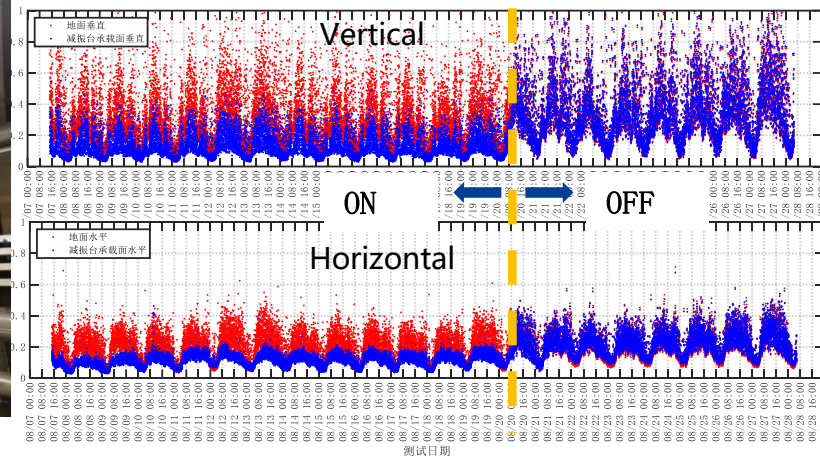
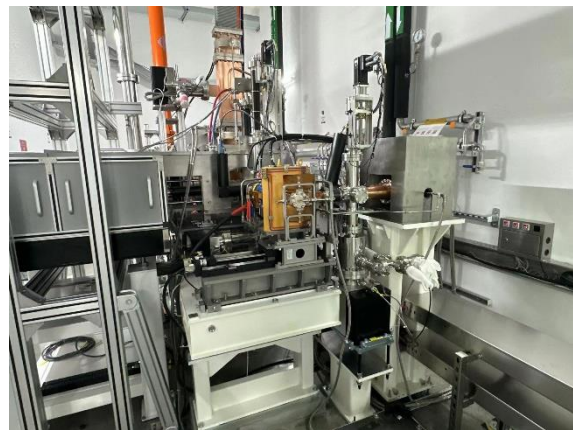
Mechanical Supports



Model of electron gun segment



Active vibration reduction support



Contrast of RMS vibration (1-100Hz) between ground(red) and dummy load(blue)

Mechanical supports in electric gun segment have been installed and aligned.

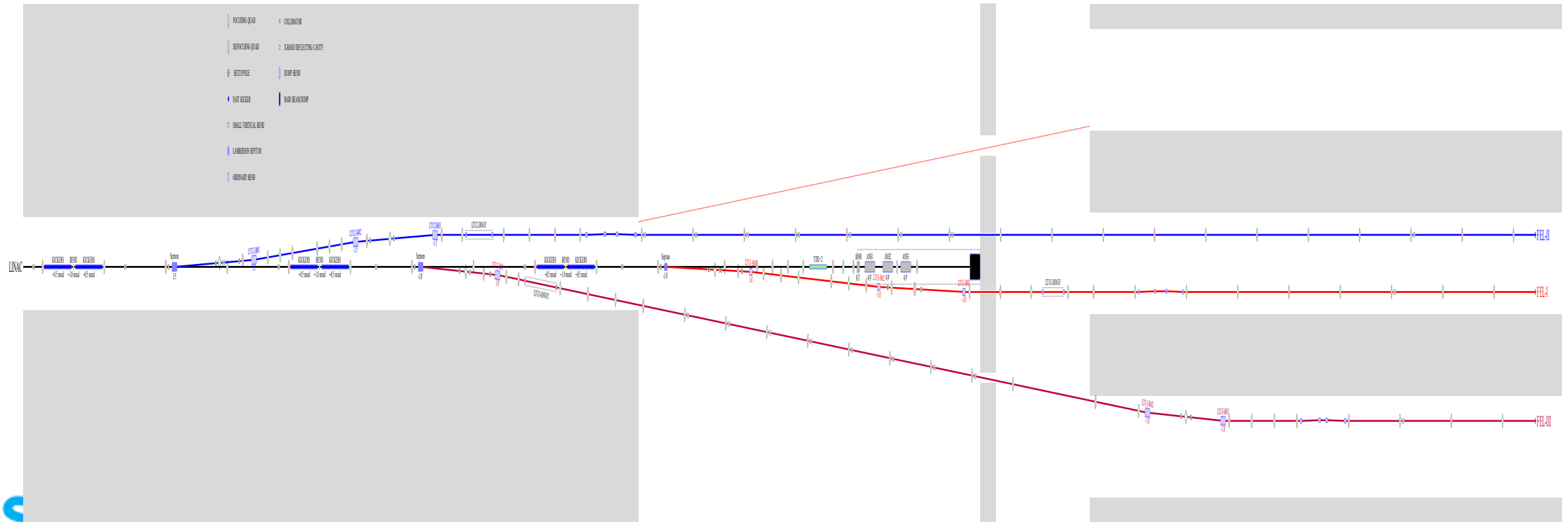
The exchange system used for 45KW dump has been assembled and accepted.

The prototype of suspension support used for cryomodule has been installed.

The SHINE Beam Switchyard

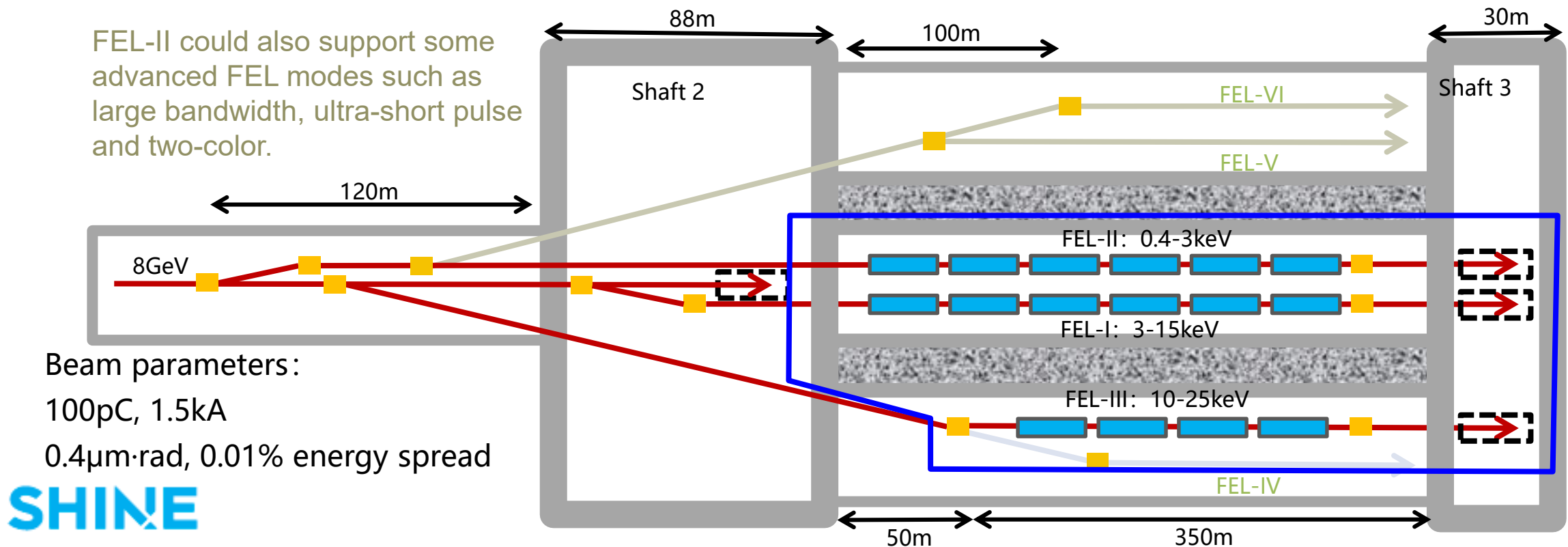


- Linear accelerator → 3 LTU branches → 3 FEL lines
- Fast kickers in vertical + DC Lambertson Septum



The SHINE Undulator Lines and FEL Schemes

- Three undulator lines to cover the photon energy range 0.4-25keV, external seeding and self-seeding schemes have been adopted for fully coherent FEL generation
 - FEL-I (3-15keV): SASE, self-seeding
 - FEL-II (0.4-3keV): SASE, EEHG/HGHG, self-seeding, polarization control
 - FEL-III (10-25keV): SASE, self-seeding



The SHINE Kicker, Septum, and Undulators

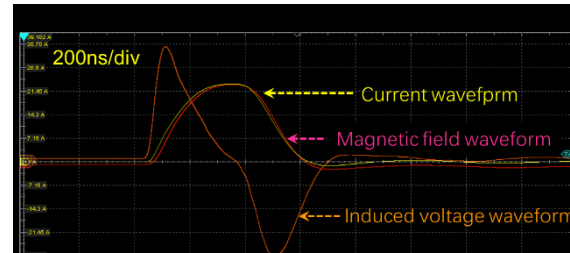
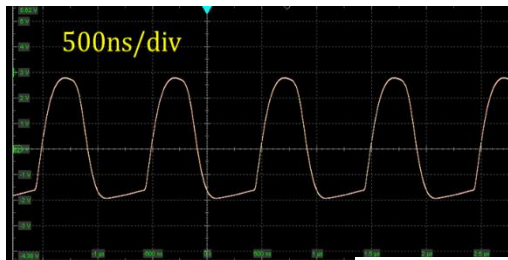
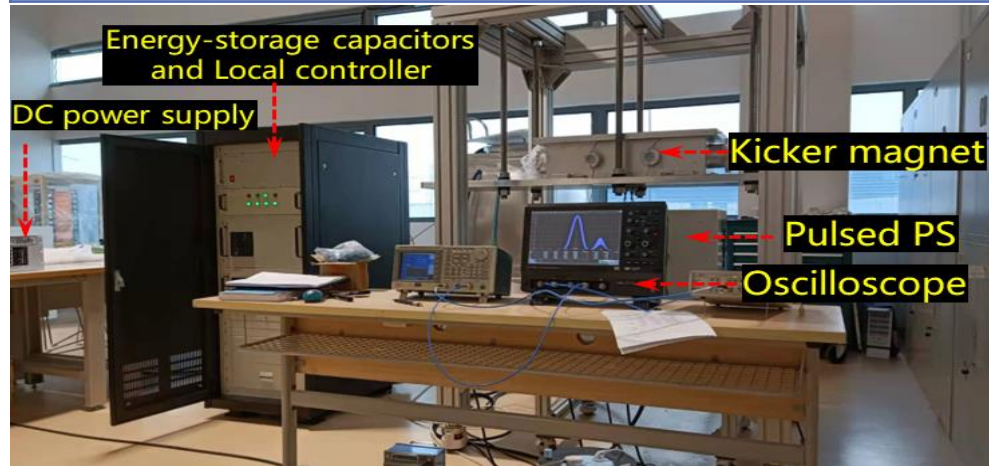


- **Prototypes of kicker and Lambertson septum have been developed, and their first pieces are in factory acceptance test;**
 - Single turn inductance type kicker and pulser;
 - DC Lambertson septum;
- **Prototypes of three kinds of warm permanent undulators and two standard intersections between undulators were developed. The mechanical structure of 4m planar undulators for FEL-I U26 and FEL-II U55 are in mass production;**
 - Two 4m planar undulators with magnetic period of 26mm and 55/75mm;
 - A 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, some promising results have been achieved.**

Fast Kicker for Beam Switchyard

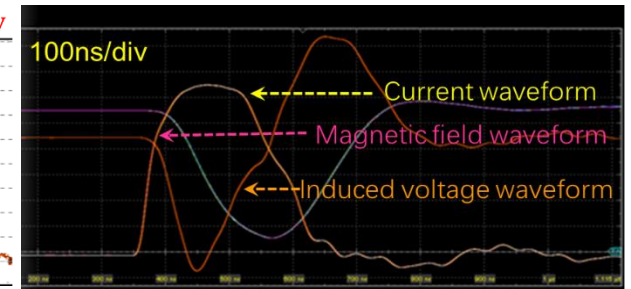
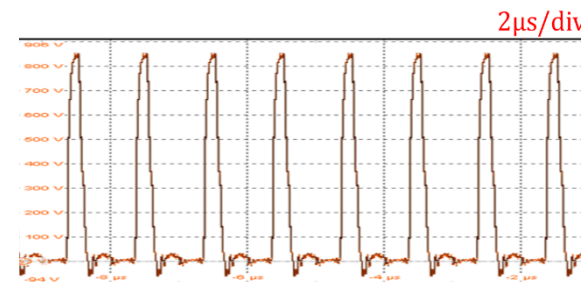
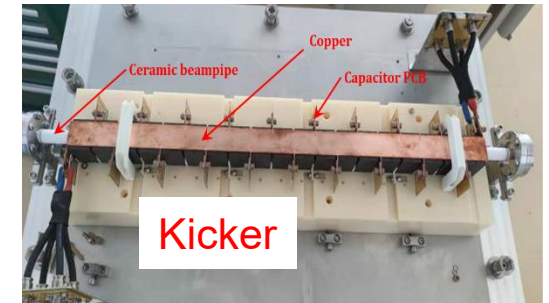
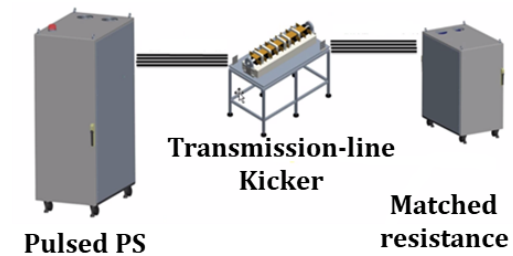
➤ Lumped-inductance Kicker

Key parameters of Lumped-inductance Kicker			
Beam energy	8 GeV	Bending angle	0.1 mrad
Effective length	0.5 m	Max. Rep. rate	1 MHz
Aperture(H)	10 mm	Field intensity	5.3 mT
Aperture(V)	16 mm	Peak current	50 A



➤ Transmission-line Kicker.

Key parameters of Transmission-line Kicker			
Beam energy	8 GeV	Bending angle	0.1 mrad
Effective length	0.8 m	Max. Rep. rate	1 MHz
Aperture(H)	25 mm	Field intensity	3.3 mT
Aperture(V)	25 mm	Peak current	67 A
Ceramic beampipe	Φ15 mm	Kicker impedance	12.5 Ω



Warm Undulators in Mass Production



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

APPLE III Undulator Prototype

- Max magnetic field 1.5T in L.P and 1.06T in C.P
- Vertical and Horizontal gap 3mm
- Full force compensation
magnetic force $\leq 12\text{kN}$ for each girder
- Phase error less than 12 degree

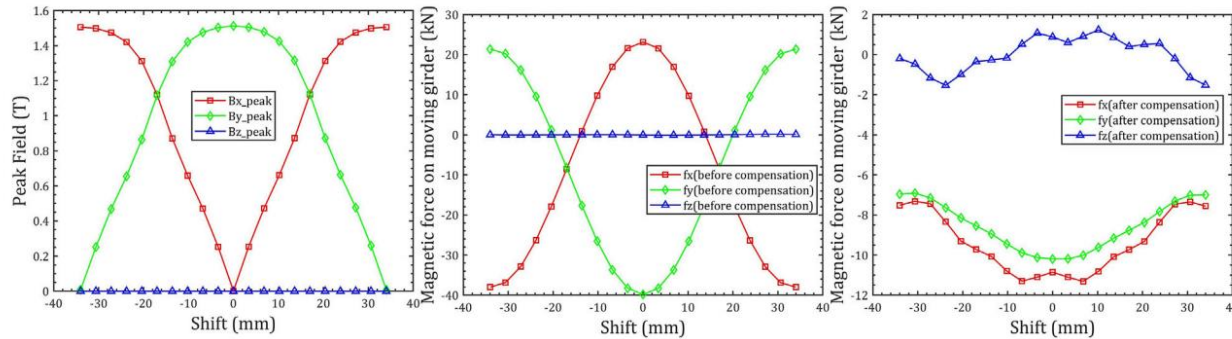
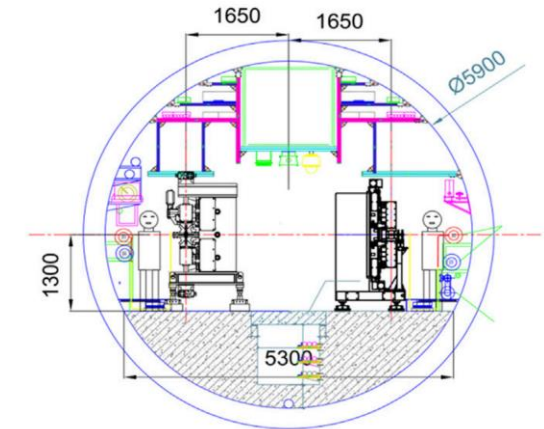
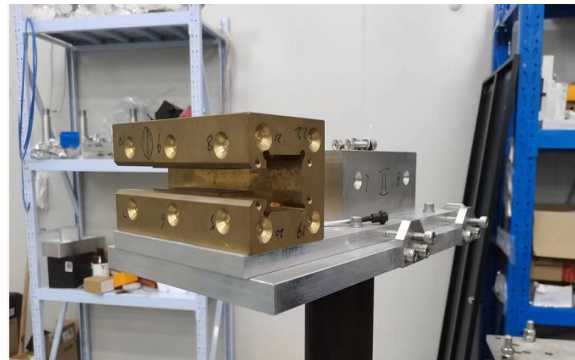
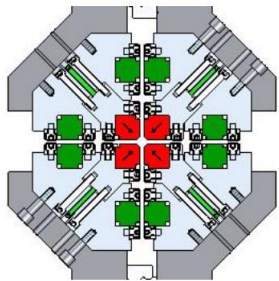


TABLE 1 Main parameters of the FEL-II EPU (EPU68 prototype).

Parameter	Value
Photon energy [keV]	0.4–3.0
Period [mm]	68
Work gap range [mm]	3–30
Max gap [mm]	150
Effective magnetic field [T]	1.5
Segment length [m]	4
RMS phase error [deg]	<12



magnet design

EPU in MMS lab

The landmark

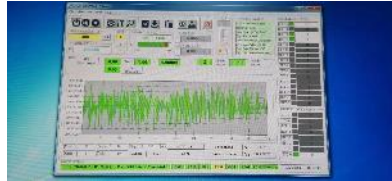
flipping coil

SHINE FEL-I&II tunnel

Superconducting Undulator: SCU16



- All components tested OK;
- SCU assembly and cooldown are OK;
- 3m SCU was tested to designed current.



Height of Half Core	18.3 mm
Length of Core	4027.5 mm
Pole Thickness	3.5 mm
Width of Active Pole	108.5 mm
Width of Neutral Pole	95 mm
Turn / Layer of Coil	60/8
SC wire (NbTi)	$\phi 0.6$ mm
Ratio Cu/NbTi	0.93
Max. Current	380 A

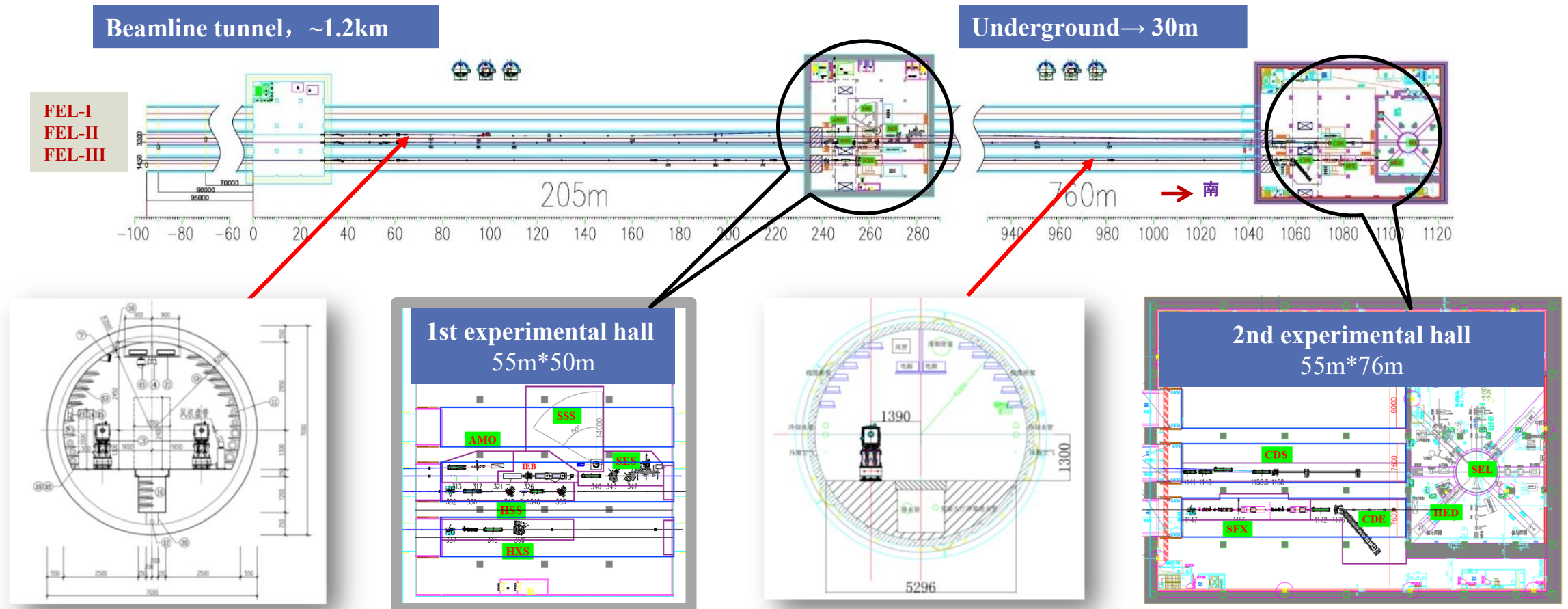


SHINE

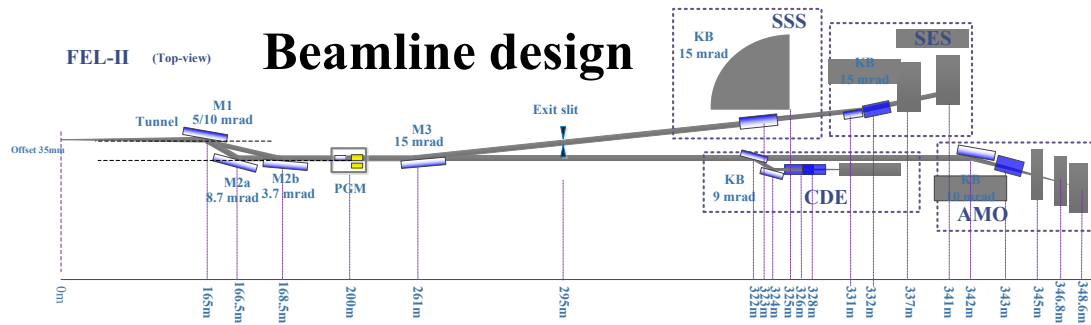
3m long, period length is 16mm, $B_{max} > 1.583T$ achieved

Progress of Beamlines and Endstations

- SHINE will build 3 beamlines, 10 endstations and experimental supporting systems.
- Currently, beamline design has been completed, and endstations design is close to freeze.



Beamline Design & Diagnostic & Metrology



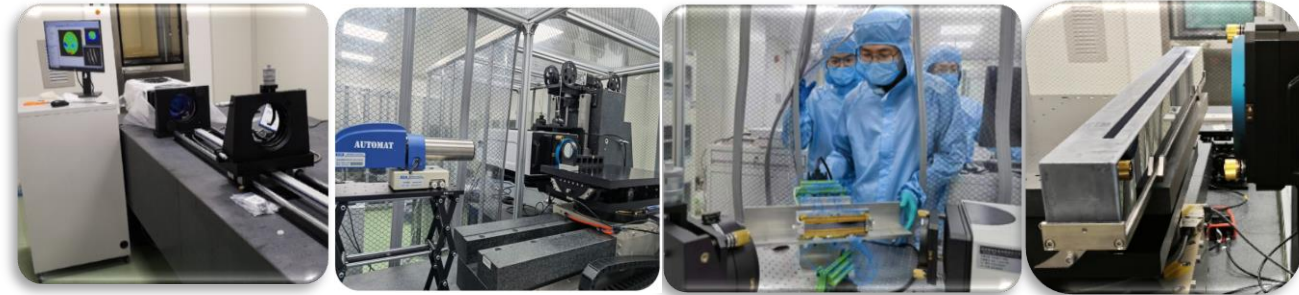
- Finished three beamlines design (TDR)
- **FEL-II** beamline in implementation
- **Thirteen** types of diagnostic instruments
- PAM, XGMD, Imager, BPIM, BLM are in manufacture, other instruments will start soon



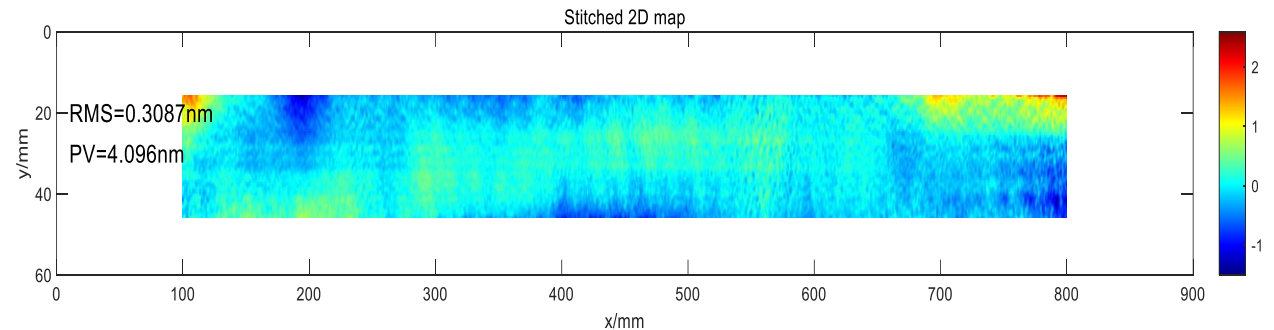
PAM



XGMD



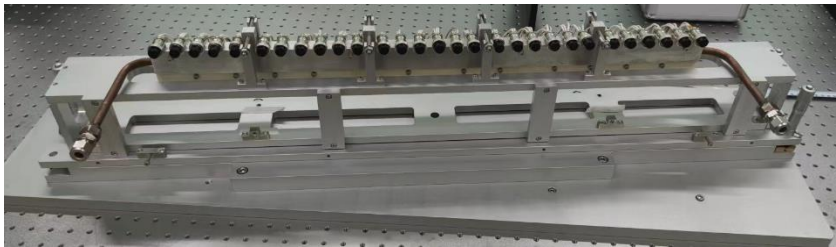
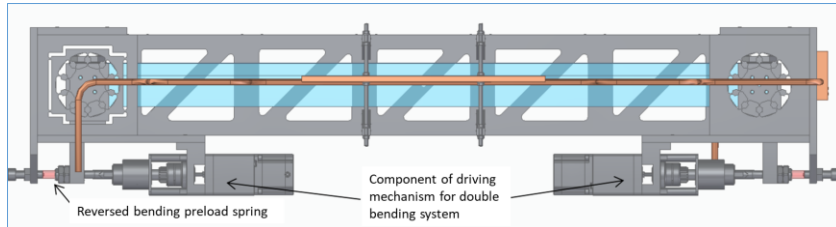
- ~30m² ISO-6 clean room metrology lab
- Fizeau stitching interferometry with 532nm, ϕ 150mm interferometer for 1000mm long mirrors



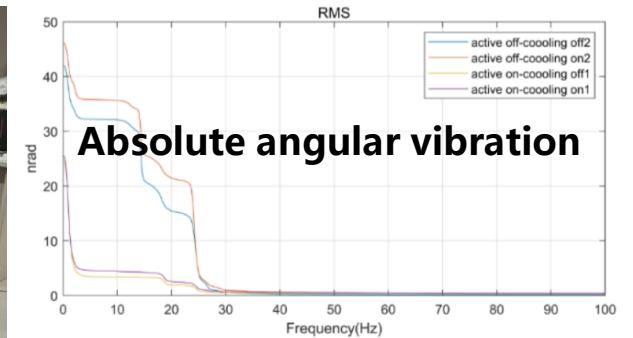
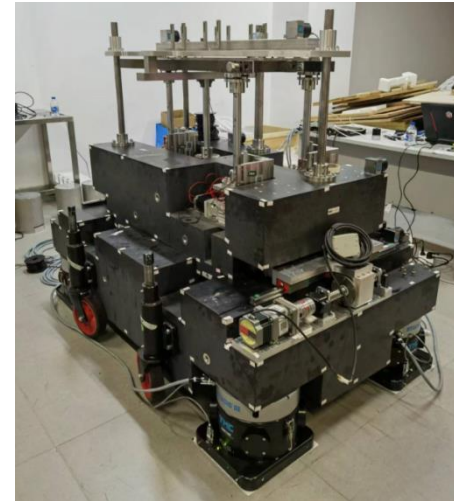
- Sub-nanometer measuring repeatability was achieved
- FEL-II M1 inspection results: 0.27nm(rms); 35nrad (rms)

FEL-II Beamline Key Components

➤ Flat mirror supporting device

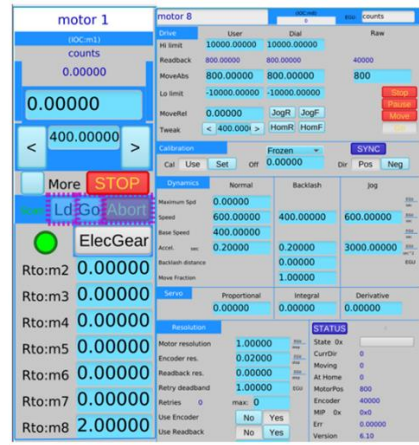
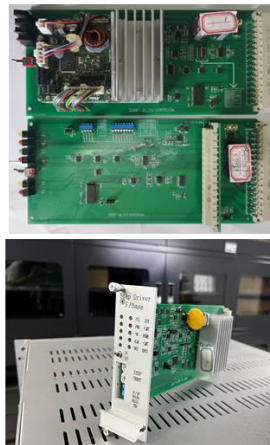


➤ Stiff active vibration isolation system



Pitch vibration achieved about ~40nrad

➤ Stepping motor motion control device

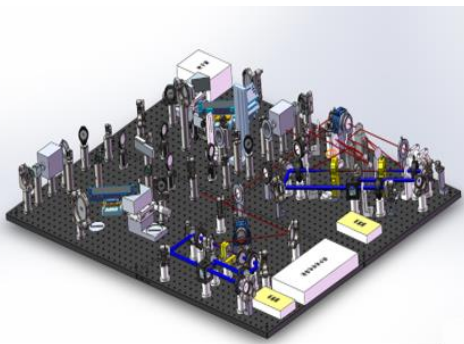


➤ Vacuum particle detection device

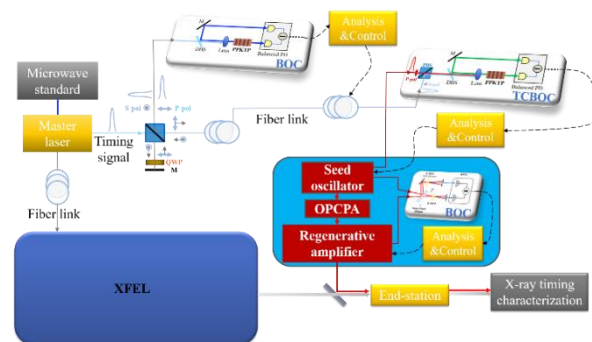


Experimental Supporting Key Technologies

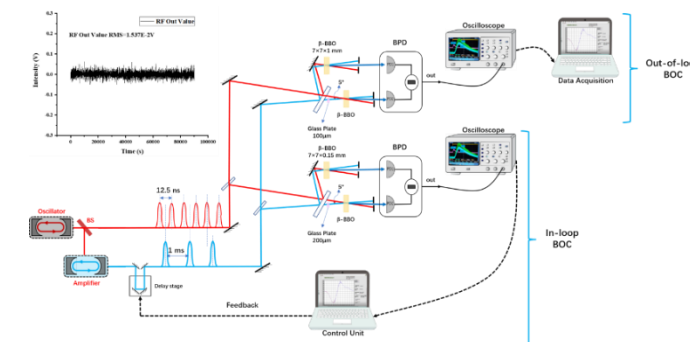
➤ Pump-probe laser system - Technical design completed



Pump-probe lasers



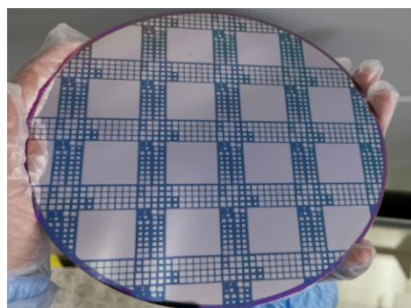
Synchronization between XFEL and PP laser



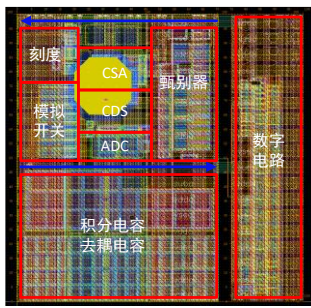
Compensation of timing drift between oscillator and amplifier based on BOC

➤ X-ray imaging detector

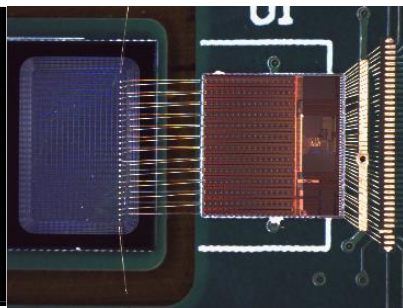
- Key technology path established
- Full system expected in 4 years



Sensor



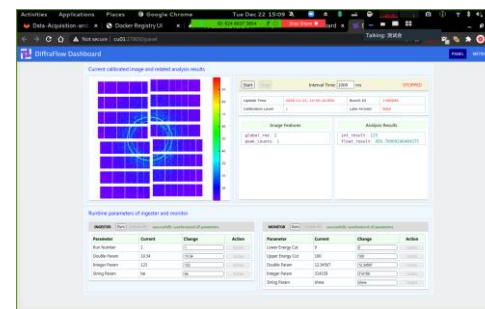
Readout chip



Light detection

➤ DAQ & Software & Data Center

- FEL-II DAQ Technical design completed
- Data Center ready to start construction



DAQ software of area detectors



Data Center Layout

SEL: Station of Extreme Light

➤ Marriage of the most two powerful lasers: 100PW + XFEL

With focused intensity 10^{23}W/cm^2 + hard XFEL, vacuum QED effect can be verified experimentally in laboratory for the first time.

In SEL, an ultra-intense laser will be used to excite QED effect (e.g. vacuum birefringence), and use hard XFEL to probe the effect.

$$\varepsilon = \left| \frac{i\Delta\phi}{2} \right|^2 = \frac{1}{4} \left(\frac{4\alpha}{15} \frac{\pi z_R}{\lambda_X} \frac{I_0}{I_S} \right)^2 G^2(z_R, \tau_R)$$

I_0 : Laser intensity

λ_X : Wavelength of XFEL

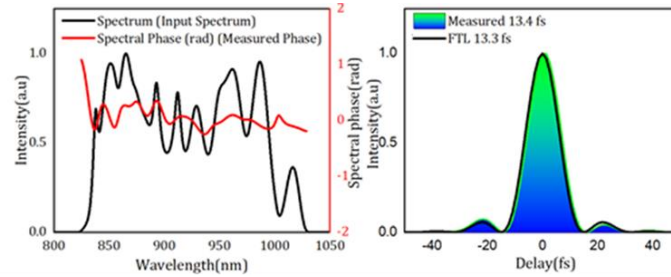
- Polarized XFEL Photon number for detection per shot can reach about 10.*
- Vacuum birefringence can be proved and observed in lab.

*Calculated with:

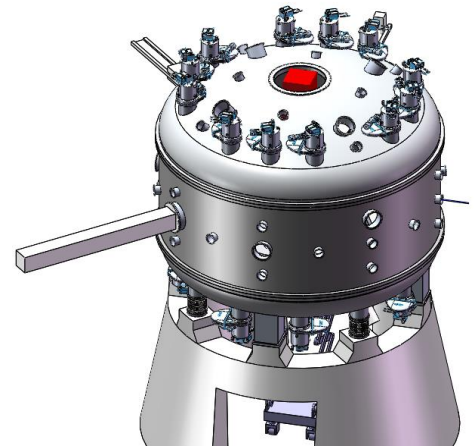
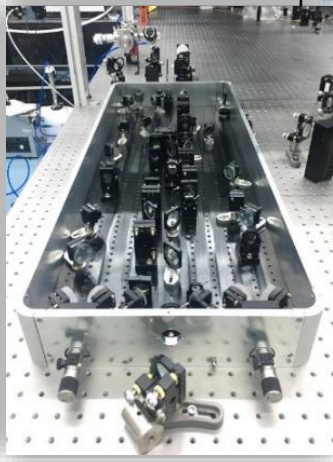
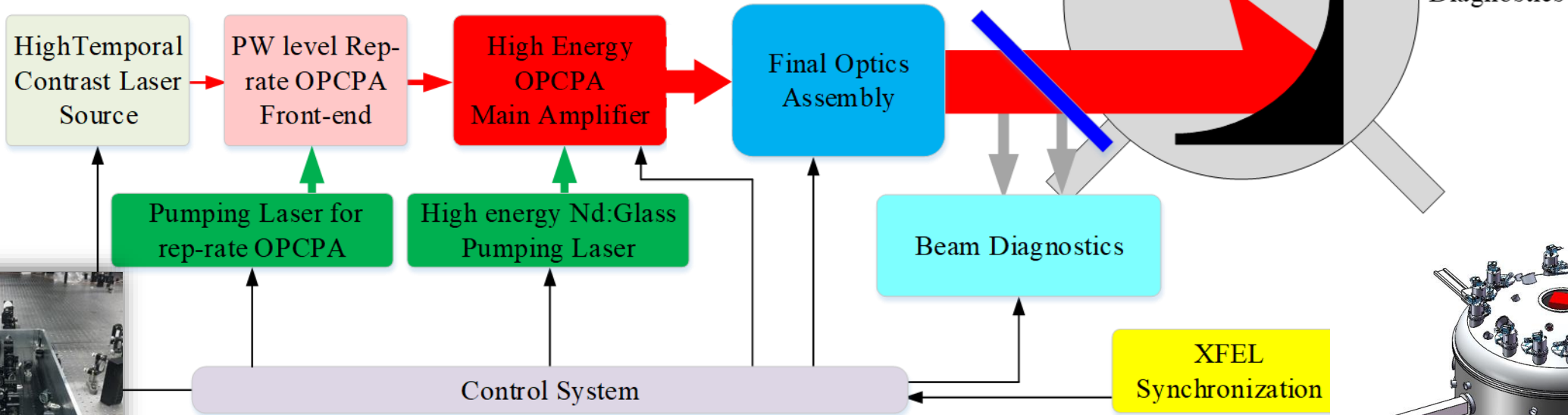
- Laser peak power - 100PW, focused spot size – 5 μm
- Injected X-ray photon – 10^{12} , X-ray photon energy – 12.9keV.

SEL: Current Progress

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

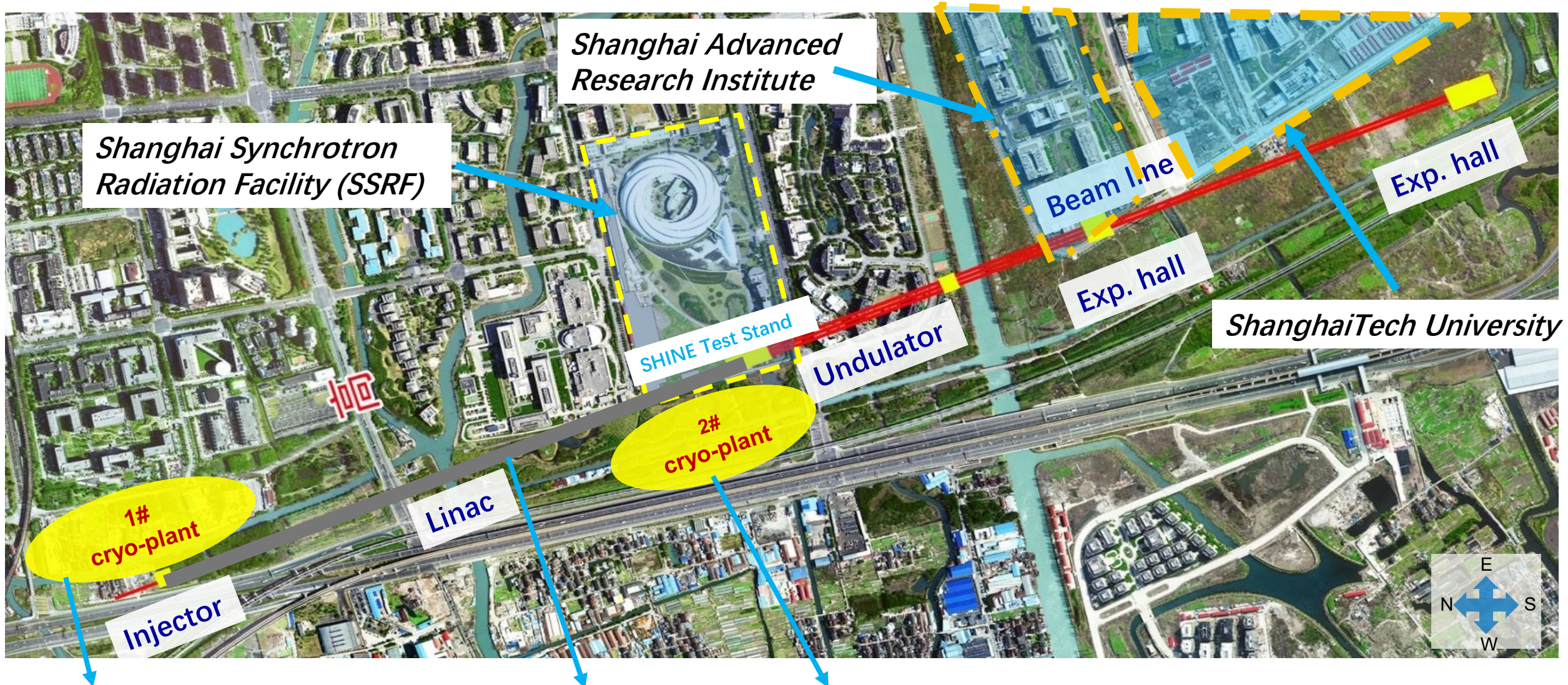


Technical and Engineering Design for high energy OPCPA main amplifier and compressor are in process optimization.



Theoretical and Technical Design for QED experiment is optimized, including experimental chamber, focusing optics and synchronization system.
The chamber has been installed underground.

SHINE Cryoplants



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

Cryogenic multi-
channel transfer lines

1 set of 4kW@2K refrigerator (for SHINE main facility)
1 set of 1kW@2K refrigerator (for SHINE test facility)

SHINE Cryogenic System Construction



No.1 refrigerator (1st of 3 4kW@2K liquid helium refrigerators) is in commissioning



2K cold boxes (X2) & Distribution box (X3) in commissioning

2nd WCS installation finished



1st 4.5K cold box commissioned

2nd 4.5K cold box installed

1st WCS commissioning finished

SHINE Cryogenic System Construction



Compressors, transfer lines



The helium buffer tank and LN2 tank

Utilities

1. High-voltage Power System
2. Cooling Water System
3. Control & Low-voltage Electric System
4. Fire Protection System

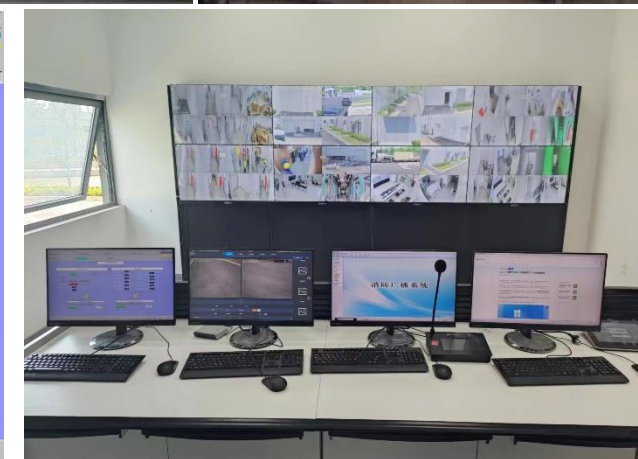
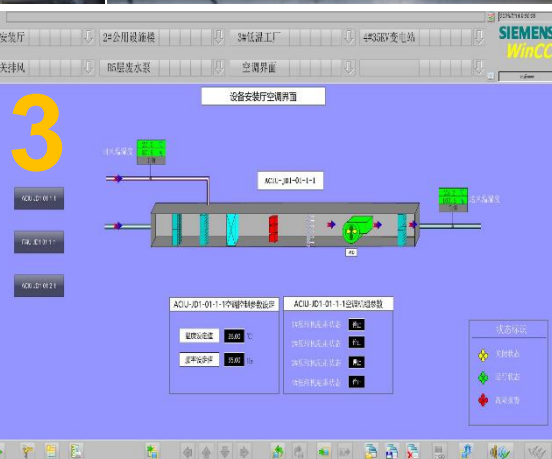
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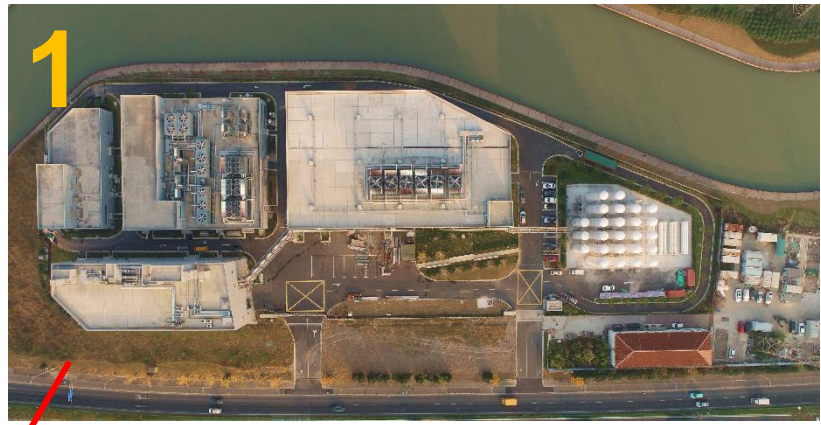


4



Civil Engineering

- 1. Shaft #1, 2. Shaft #2
- 3. Shaft #3, 4. Shaft #4
- 5. Shaft #5, 6. Linac Tunnel
- 7. HED Target Chamber installed in #5-B5



Civil Engineering

- The shield tunneling machine began tunneling in January, 2021.
- Ten tunnels have been completed in March, 2023.



Tunnel between Shaft#1 and Shaft #2



Eastern tunnel between Shaft #3 and Shaft #4

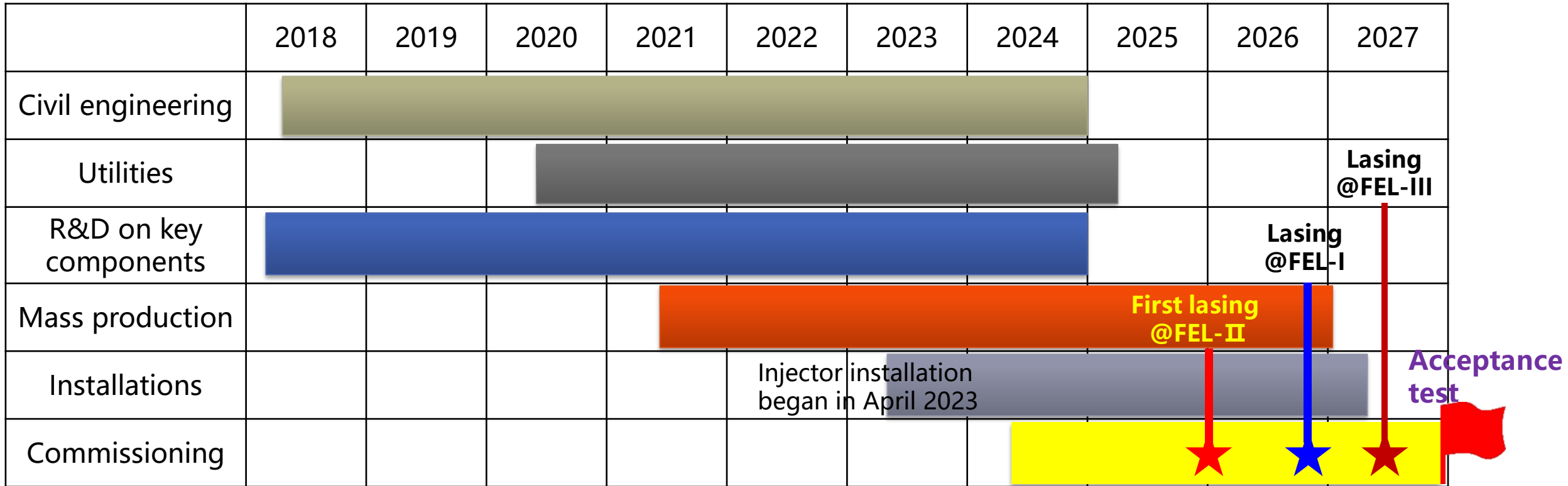


Eastern tunnel between Shaft #2 and Shaft #3



Eastern tunnel between Shaft #4 and Shaft #5

Construction Timeline



Groundbreaking was made on April 27, 2018. First lasing is expected at the end of 2025.

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;
- R&Ds of key technologies for SHINE project have been started since 2017 and are still ongoing, need to realize the full breakthrough in SRF CM and SCU;
- Mass production of components started successively according to the schedule;
- The civil engineering and utility constructions are proceeded in good shape, providing timely the conditions for facility equipment installation;
- The injector installation started in Apr. 2023, and 100pC/1MHz beam from the VHF gun was obtained in Dec. 2023; the SHINE injector beam commissioning will start in July 2024;
- The first lasing of FEL-II is anticipated to be at the end of 2025.



Thanks for Your Attention !

谢谢!