LINAC2022 LIVERPOOL

Progress of Shanghai HIgh repetitioN rate XFEL and Extreme light facility

Bo Liu, for the SHINE team
Shanghai Advanced Research Institute, CAS
2022.08.30

SHINE

Outline

- Introduction to the SHINE project
- Design and Layout
- R&D and Construction Progress
- Summary

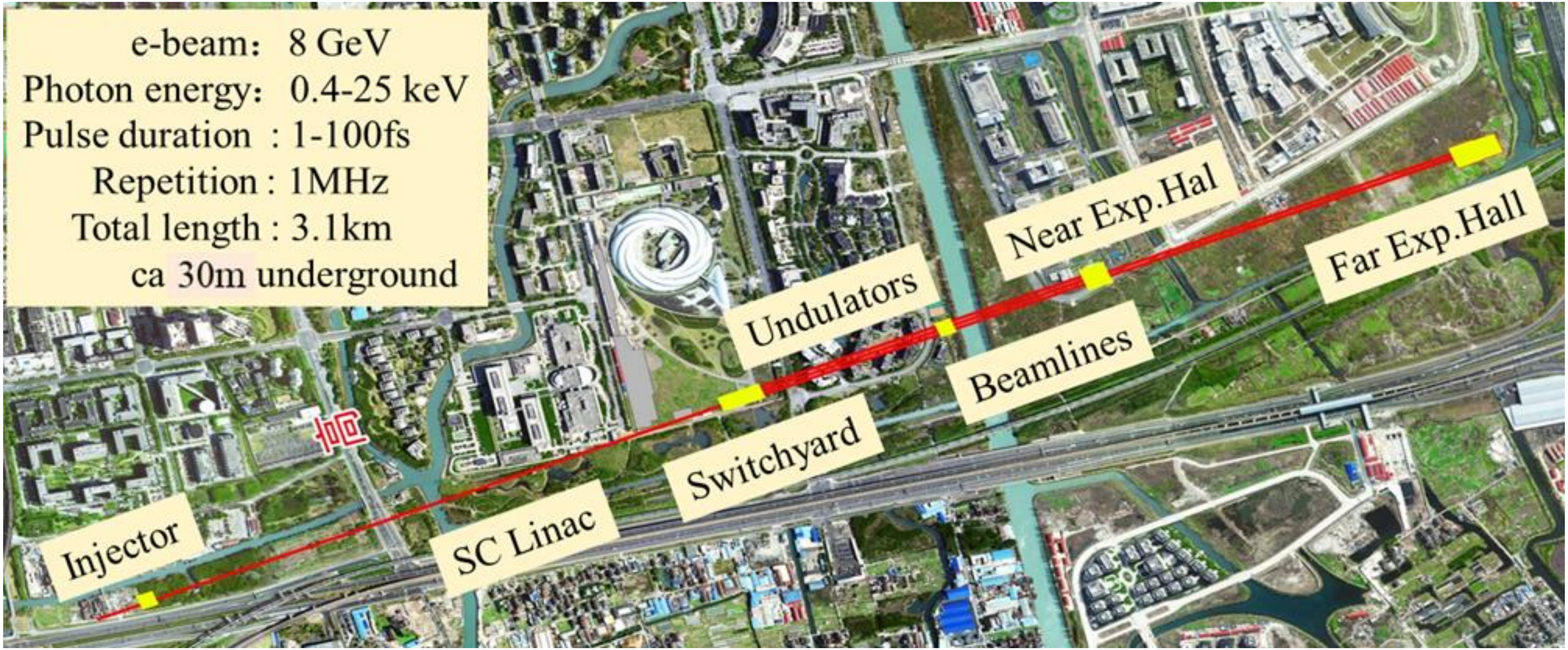
SHINE — Shanghai Hard X-ray FEL Facility

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

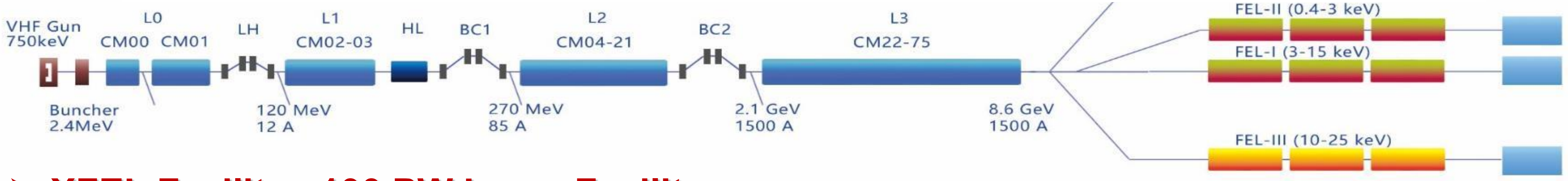
- SHINE is a high rep-rate XFEL facility, based on an 8 GeV CW SCRF linac, under development in Shanghai;
- This facility will be built in a 3.1 km long tunnel underground at Zhang-Jiang High Tech Park, across the SSRF campus;
- This XFEL facility has 3 undulator lines and 10 experimental stations in phase-I, and it can provide the XFEL radiation in the photon energy range of 0.4 -25 keV.
- This XFEL project was approved by the central government in 2017, and its groundbreaking was made in April, 2018, aiming at lasing in 2025.

This facility will be developed by Shanghai-Tech Univ., SARI and SIOM of CAS.

SHINE: General Parameters and Location



SHINE: A high rep-rate XFEL based on SCRF

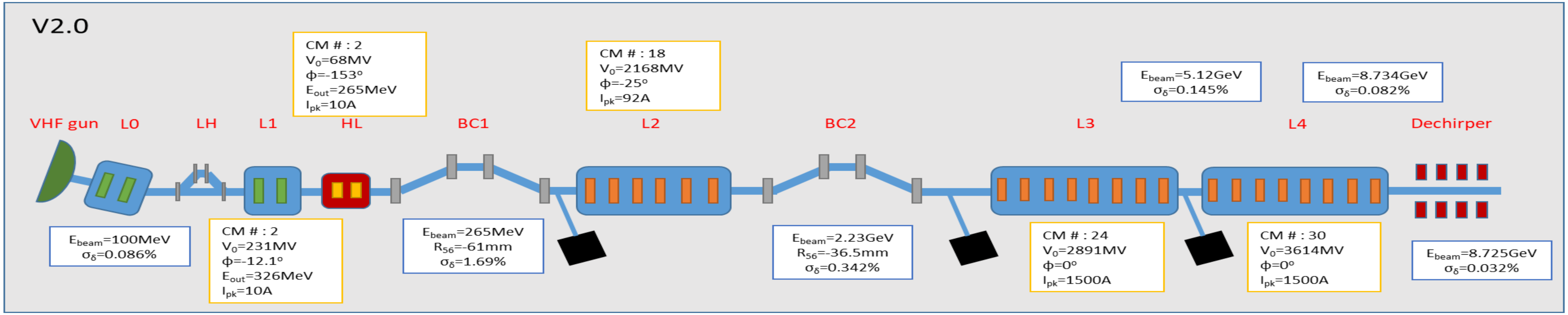


➢ **XFEL Facility +100 PW Laser Facility**

	Nominal
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}
Total facility length/km	3.1
Tunnel diameter/m	5.9
2K Cryogenic power/kW	12
RF Power/MW	2.28

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

Layout of the SHINE accelerator



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

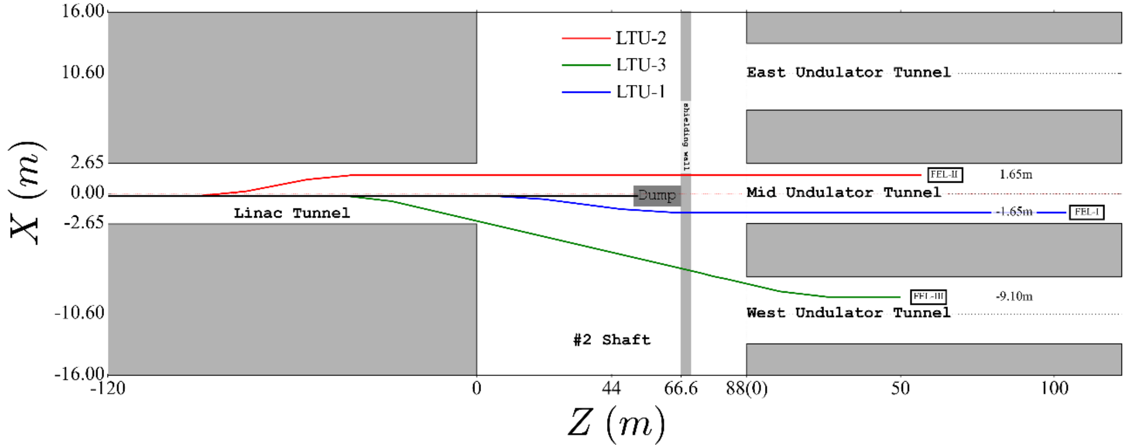
	No. of CM's	Avail. Cavities	Powered. Cavities*	Gradient (MV/m)	Eout (MeV)	σ_z (mm)
L0	1	8	7	16.3	100	1.15
L1	2	16	15	14.8	326	1.15
HL	2	16	15	13.1	265	1.15
BC1	-	-	-	-	265	0.13
L2	18	144	135	15.5	2229	0.13
BC2	-	-	-	-	2229	0.006
L3	24	192	180	15.5	5120	0.006
L4	30	240	226	15.5	8734	0.006
Dcp	-	-	-	-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

750kV VHF gun +Single cavity CM + 1.3GHz SCRF cryomodules: 75 + 3.9GHz SCRF cryomodules: 2

LINAC2022 LIVERPOOL

Beam Switchyard

One SRF Linac → Three FEL Lines

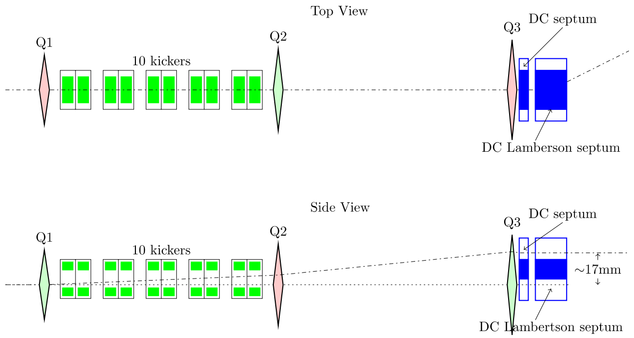


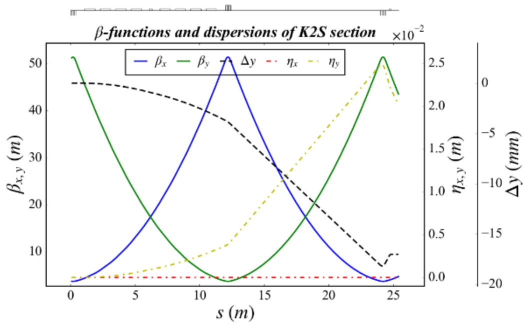
At least *3* LTU deflection branches and *1* straight dump line

- **LTU-2**： linac → FEL-II in Middle Undulator tunnel
  - *3.0°deflecting angle, +1.85m horizontal offset*
- **LTU-3**： linac → FEL-III in West Undulator tunnel
  - *3.6°deflecting angle, −8.90m horizontal offset*
- **LTU-1**： linac → FEL-I in Middle Undulator tunnel
  - *2.0°deflecting angle, −1.45m horizontal offset*
- **LTD**： linac → Dump in middle of #2 Shaft

Fast vertical kicker Set + DC Lamberson Septum

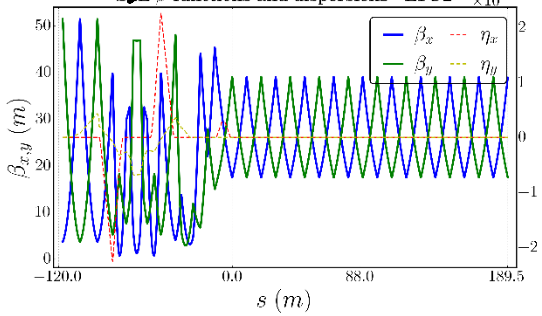
- Bunch-by-Bunch beam distribution of 1 MHz beam
- ~ 1 mrad kick angle, ~17 mm Y-offset @ Lamberson

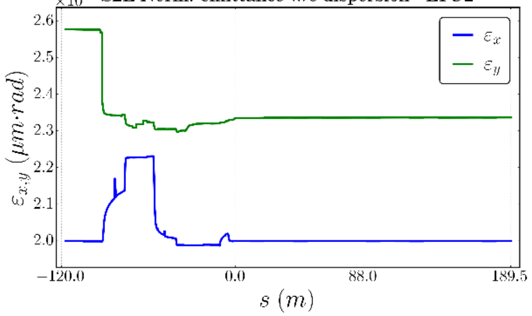




Lattice design for minimizing CSR induced emittance growth

- Symmetrical lattice with optics balance method



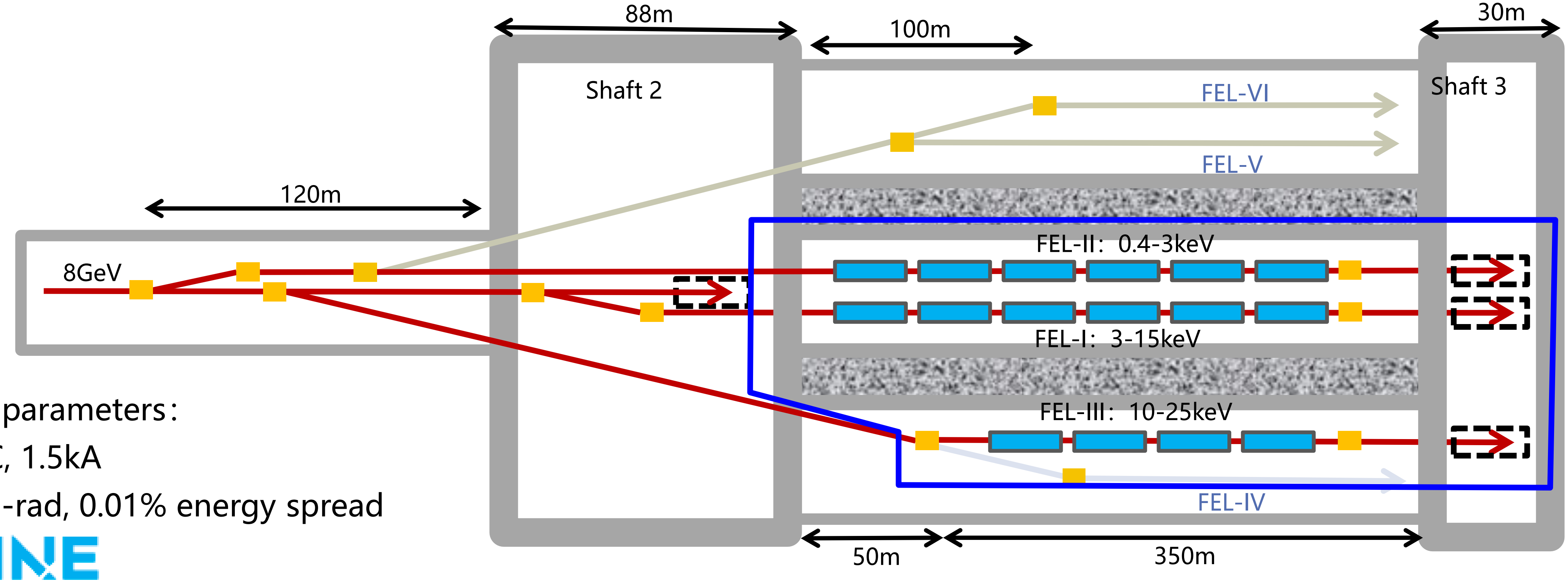


SHINE

Undulator Layout and FEL Schemes

Three undulator beamlines 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）：EEHG/HGHG、self-seeding
- FEL-III（10-25keV）：SASE、self-seeding



Beam parameters：
100pC, 1.5kA
0.4μm-rad, 0.01% energy spread

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

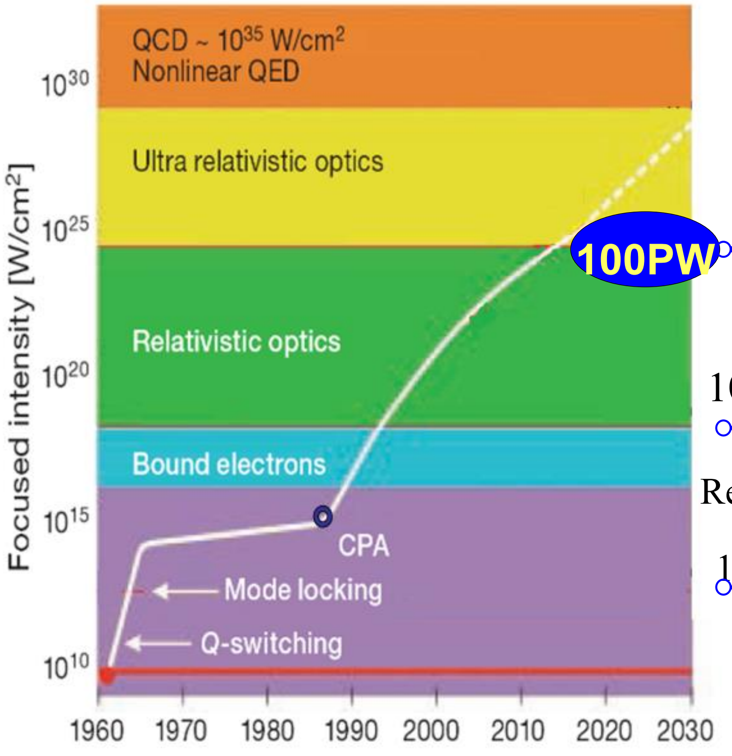
- **AMO:** Atomic, Molecular, and Optical Science
- **SES:** Spectrometer for Electronic Structure
- **SSS:** Soft X-ray Scattering and Spectroscopy

FEL-III Hard X-ray End-stations

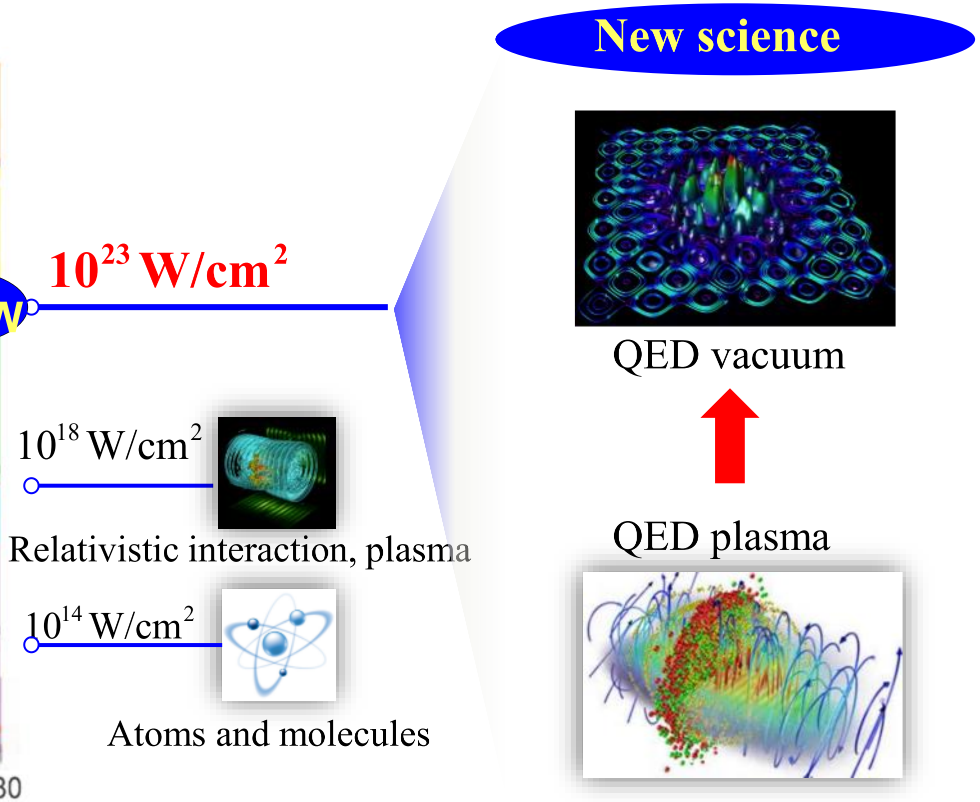
- **HXS:** Hard X-ray Spectroscopy
- **SFX:** Serial Femtosecond Crystallography
- **CDE:** Coherent Diffraction Imaging
- **HED:** High Energy Density Science

SEL: XFEL + 100 PW Laser System

The marriage of optical laser pulse with an intensity of 10^{23}W/cm^2 and intense XFEL will potentially open the gate for investigating high field vacuum QED

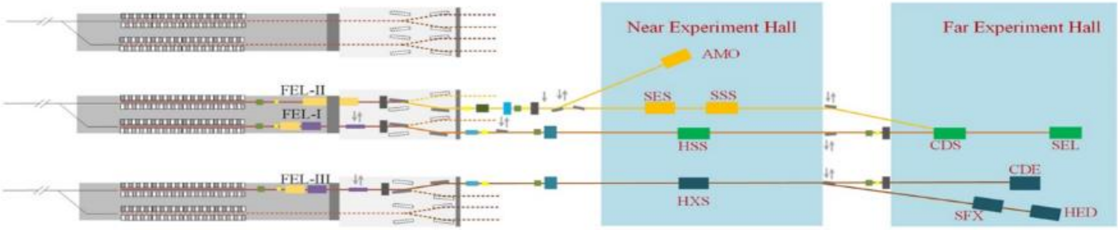


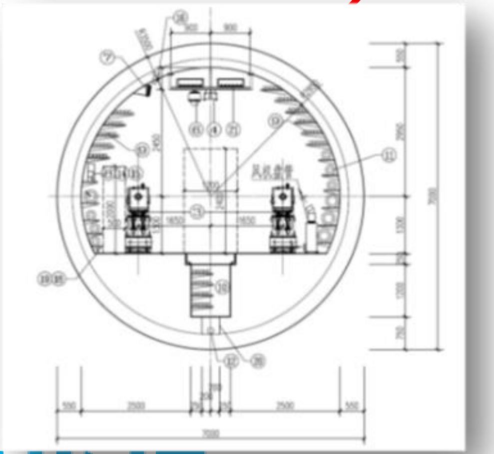
G. Mourou and T. Tajima

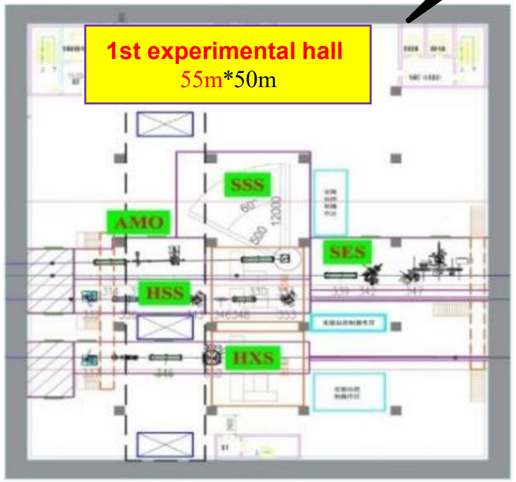


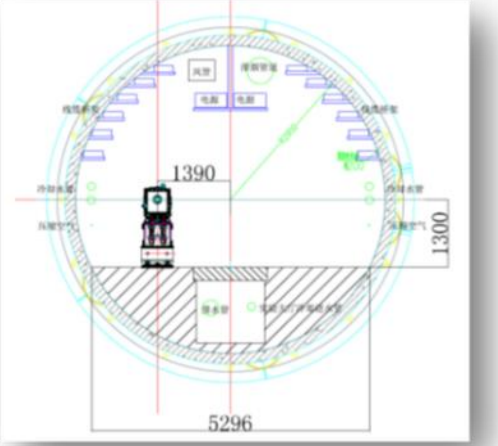
SHINE

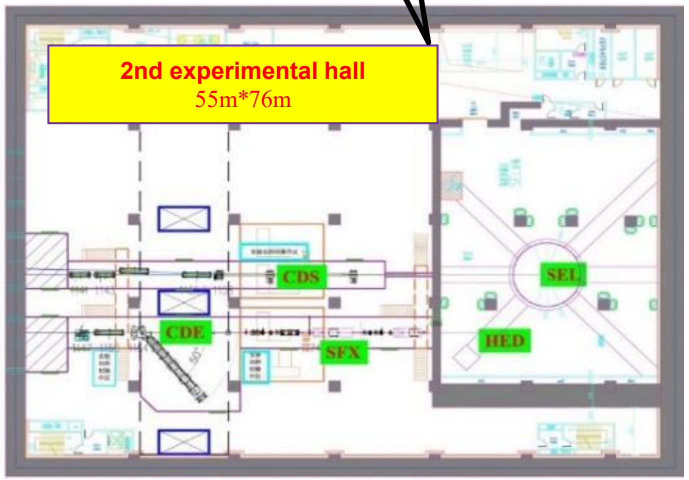
Layout of Beamlines and End-stations











SHINE

Comparison of world-wide high rep-rate XFEL

	European XFEL	LCLS-II	SHINE
Facility site	Hamburg, Germany	Stanford, USA	Shanghai, China
Facility length	~ 3.4km	~2.0km	~ 3.1km
Photon energy	0.5 ~ 24keV	0.2 ~ 5keV	0.4 ~ 25keV
E-beam energy	17.5GeV	4GeV	~ 8GeV
Rep. rate	3000×10 Hz	0.93MHz	1MHz
Beam current	~ 0.03mA	~ 0.1mA	~ 0.1mA
Budget	~1.5 billion euro	~1.045 billion USD	~ 10 billion RMB
Time schedule	2009-2018	2014-2022	2018-2025
tunnel	6-38m underground	Half-underground	30m underground
Mode	Macro Pulse	Continuous wave	Continuous wave
FEL lines	5 (3 initial)	2	6 (3 initial)

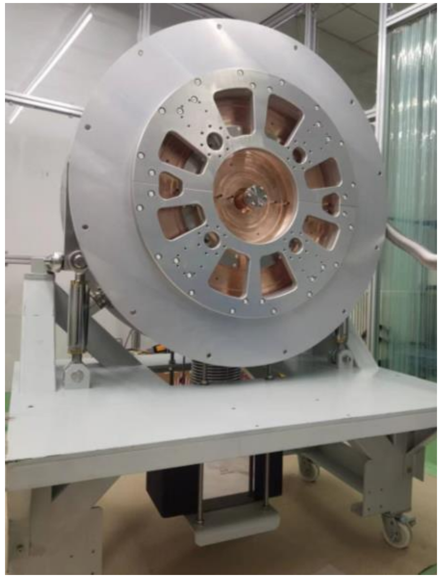
R&D and Construction Progress

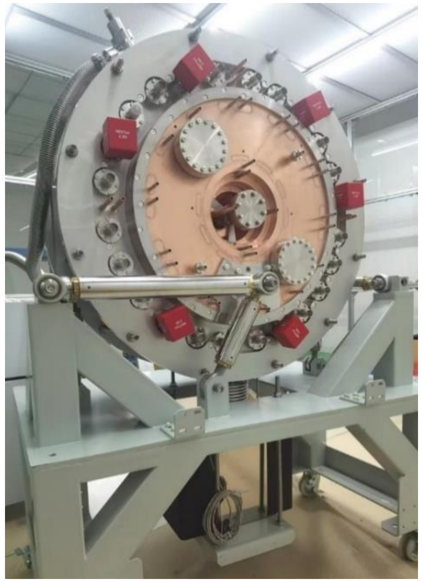
- Groundbreaking was made on April 27, 2018. Construction of shafts is in good progress;
- Accelerator engineering design, technical infrastructure development, component prototyping and long-lead equipment procurements are underway;
- Beamline design optimization are being carried out, R&D of key optics component and Pixel array detector development are in progress;
- Technical and engineering design of high energy OPCPA, R&D of key laser technologies for SEL are in progress;
- …

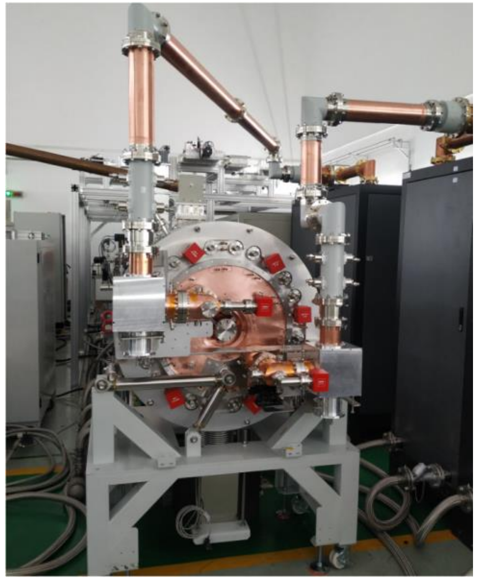
Development of the VHF Gun

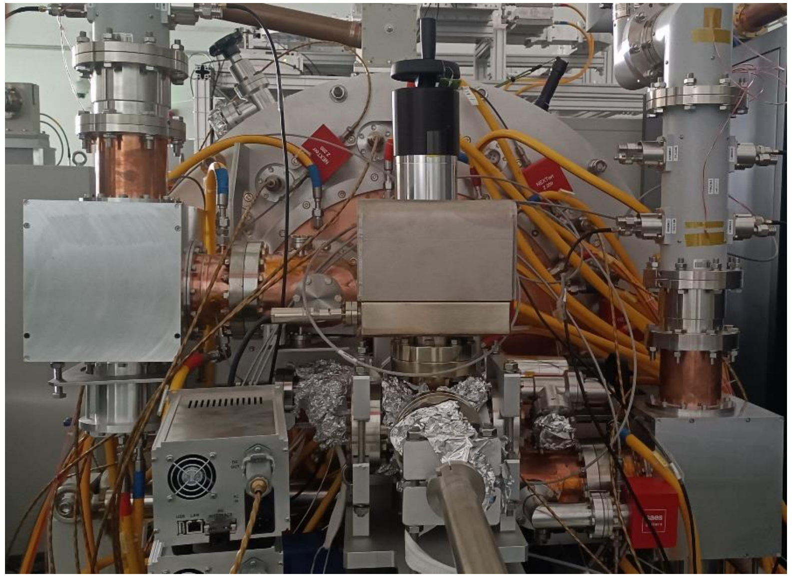
LINAC2022 LIVERPOOL

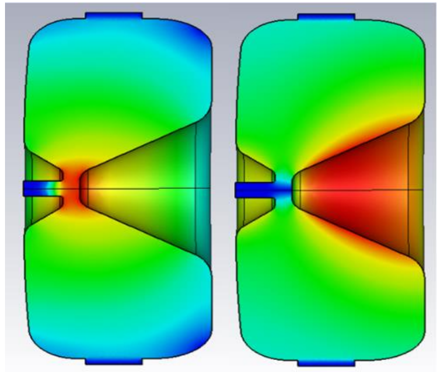
The fabrication of the VHF electron gun developed by Tsinghua University has been completed.











Frequency	216.67 MHz
Cathode gradient	30 MV/m
Input power	90.4 kW
Maximum surface electric field	36.99 MV/m (2.5kilp)
Maximum surface power density	28.45 W/cm^2
Voltage	868 keV
Stored energy	2.24 J
Quality factor Q_0	33717
Shunt impedance	8.34 MΩ

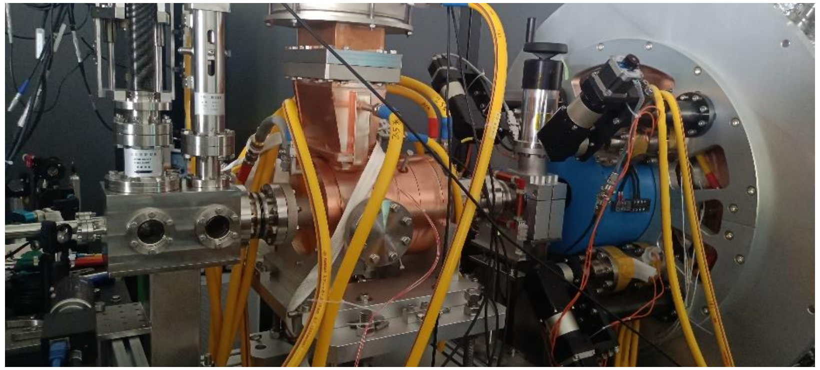
High power test has been done. CW 70kW power has been input into the gun with maximum temperature increase less than 40℃. Mechanical tuners have been successfully applied in gun detuning.

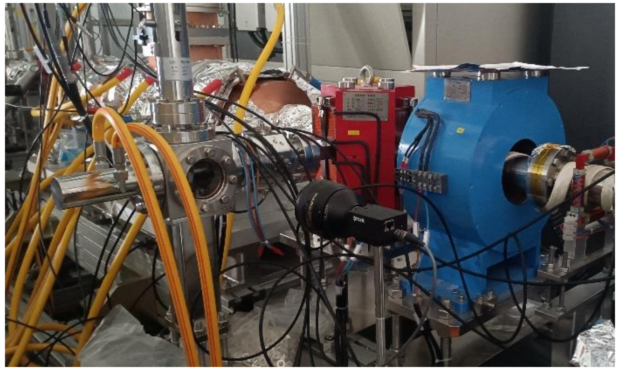
SHINE

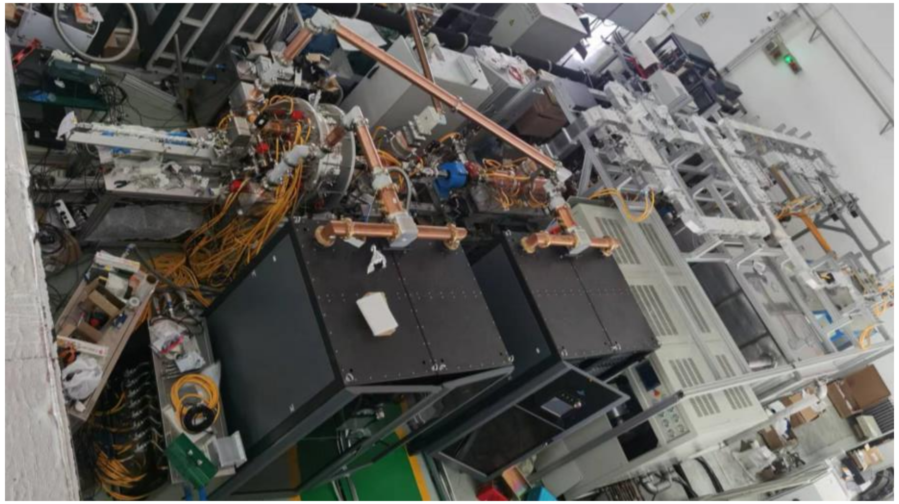
Courtesy Tsinghua University team

Development of the VHF Gun

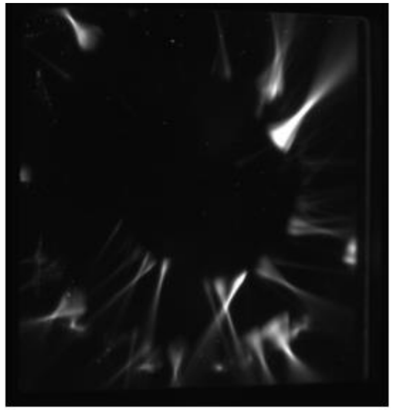
Test beamline has been constructed. The designed maximum beam energy is ~30 MeV.

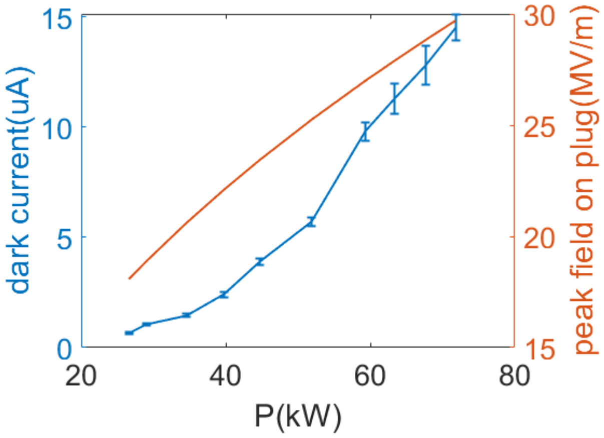






Dark current test

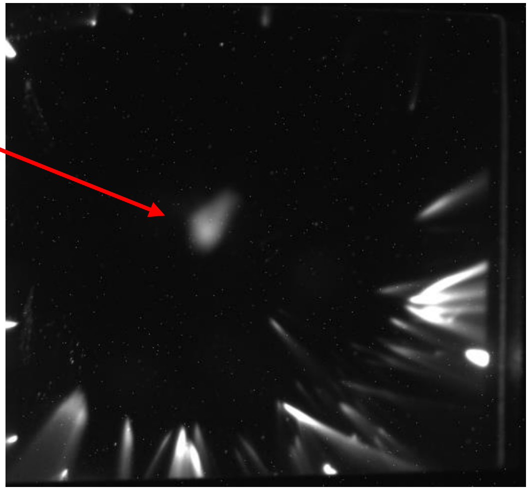




~14 uA@72 kW

Photon-induced beam
First beam

Beam energy is 788 keV measured by the dipole downstream the gun.



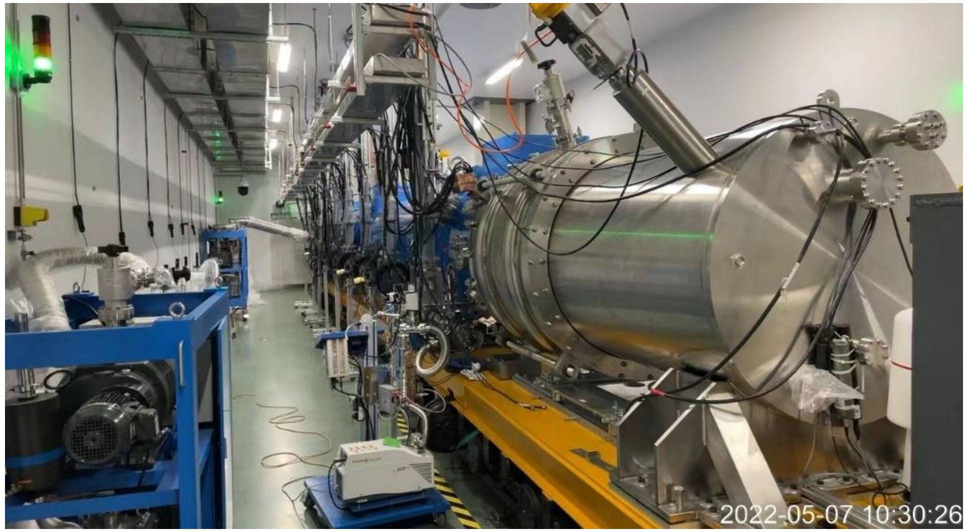
SHINE

Courtesy Tsinghua University team

Development of the SHINE Cryomodule

- **SHINE Linac consists of 75 1.3GHz cryomodules (CMs) for beam accelerating, and two 3.9GHz cryomodules for non-linear correction.**
- **The cryomodule design is based on the TESLA technology and refers to European XFEL and LCLS-II**

- **Prototypes & infrastructures built for R&D and production**
- **First standard 8-cavity (BCP refurbished) CM,** RF tested in June 2022, has reached its main goal (>128 MV, >1.0E+10, <1 nA).
- **More standard 8-cavity (High Q) CMs,** in preparation, include midT-baked and N-doped cavities.
- **High-Q technologies** (N-doping& midT-baking) have been achieved on 1.3 GHz 9-cell cavities.



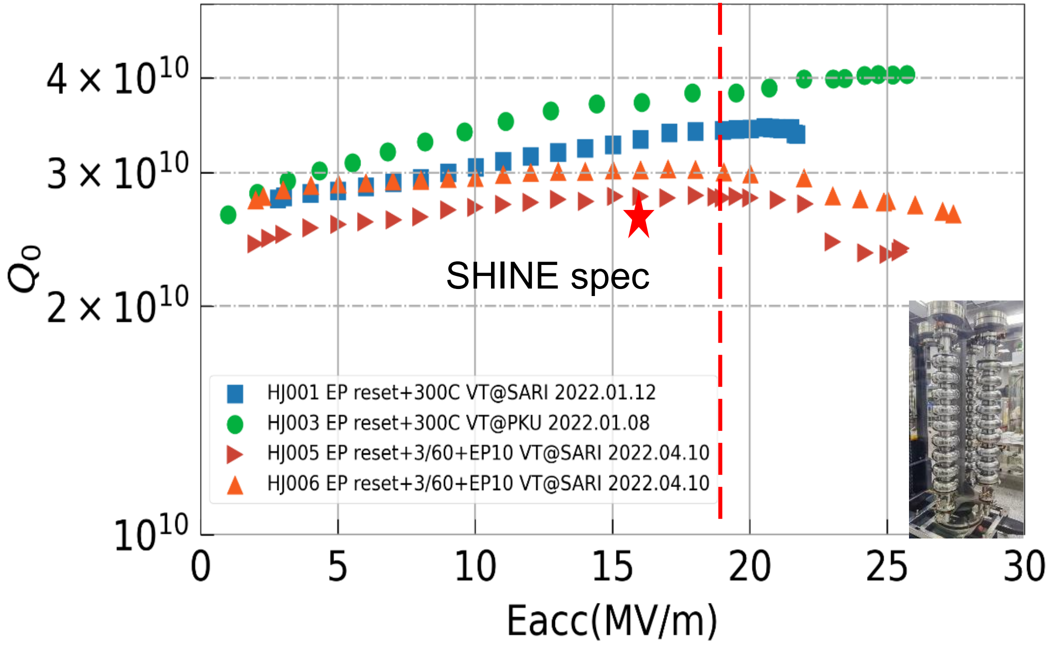
CM with 8 BCP'ed cavities under testing

More details in: TH1PA01
Dr. Yiyong Liu's talk on Thursday

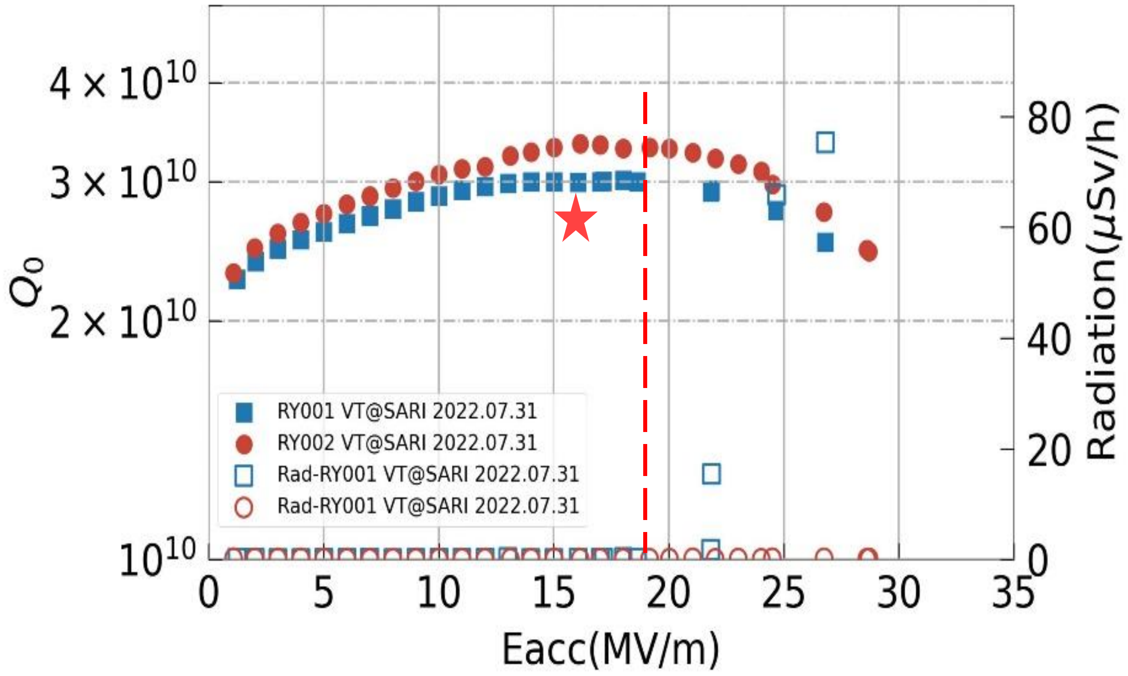
R&D on High-Q 9-cell cavities

- High-Q technologies (both N-doping& midT-baking) have been achieved on SHINE 1.3 GHz 9-cell cavities, with Q_0>2.7E+10 @16-21MV/m and max Eacc>25 MV/m in average, based on the new SHINE facilities co-built in Wuxi; and have been replicated by different companies, including RI and ZANON.

Cavities treated with SHINE facilities in Wuxi



First 2 cavities produced by RI with SHINE High-Q recipe



Permanent Magnet Undulators

	FEL-I	FEL-II	
Type	Planar	Planar	EPU
Periodic Length	26mm	Double period: 75 mm&55mm Normal period: 55mm	68 mm
Quantities	42	14/22	4
Segment Length	4.0 m	4.0 m	4.0 m
Number of Periods	152	71 for U55; 52 for U75	58
Maximum Field	1.02T	1.25T for U55 1.5T for U75	1.5 T for H.&V. Mode bx=by=1.06T @circular mode
Minimum Gap	vertical 7.2mm	vertical 10.2mm	vertical gap 3mm center area Ø7.2mm
Structure	Hybrid	Hybrid	APPLE-III

EPU Prototype

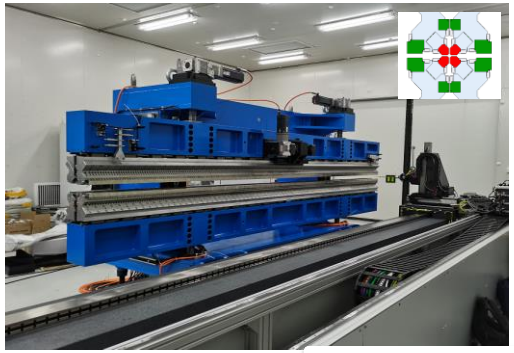
Magnetic force cancellation (cancellation for Fx,Fy,Fz)

- Max load in Fy： before -7t ~+4t after -2t~-2t
- 4 center arrays APPLE-III
- 8 arrays for magnetic force cancellation

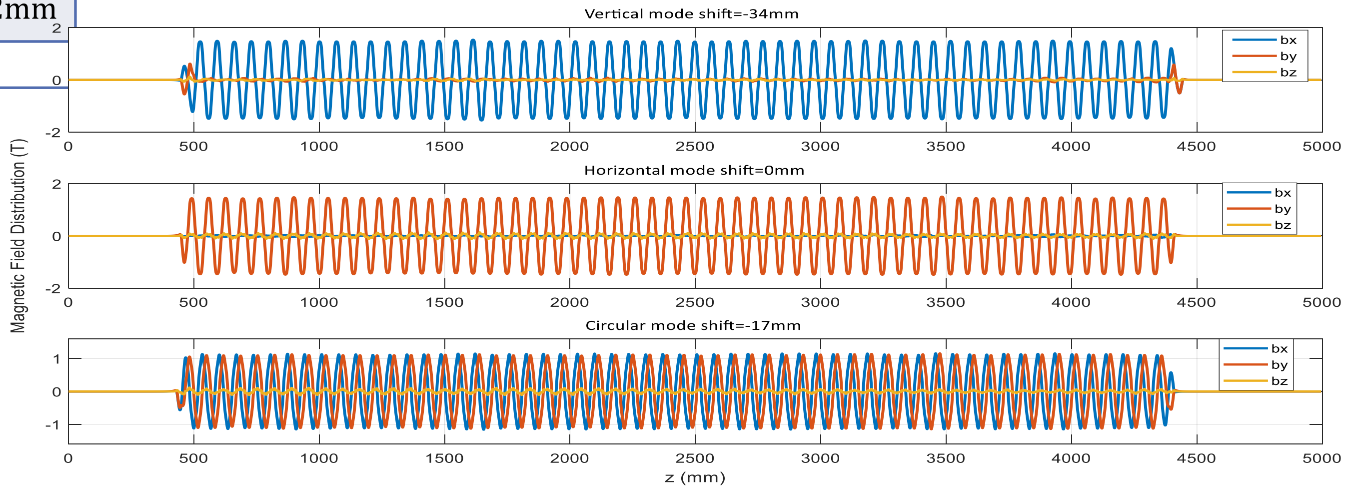
Magnetic performance

- bx/by peak field 1.5T @ plannar mode **is achieved**
- bx=by=1.06T @ circular mode **is achieved**

Prototype Plan： Start shimming, will be finished in Sep. 2022



prototype EPU is in shimming



Magnetic field distribution for different polarization

SHINE

Permanent Magnet Undulators

LINAC2022 LIVERPOOL

PU Prototype U26 and U55&75

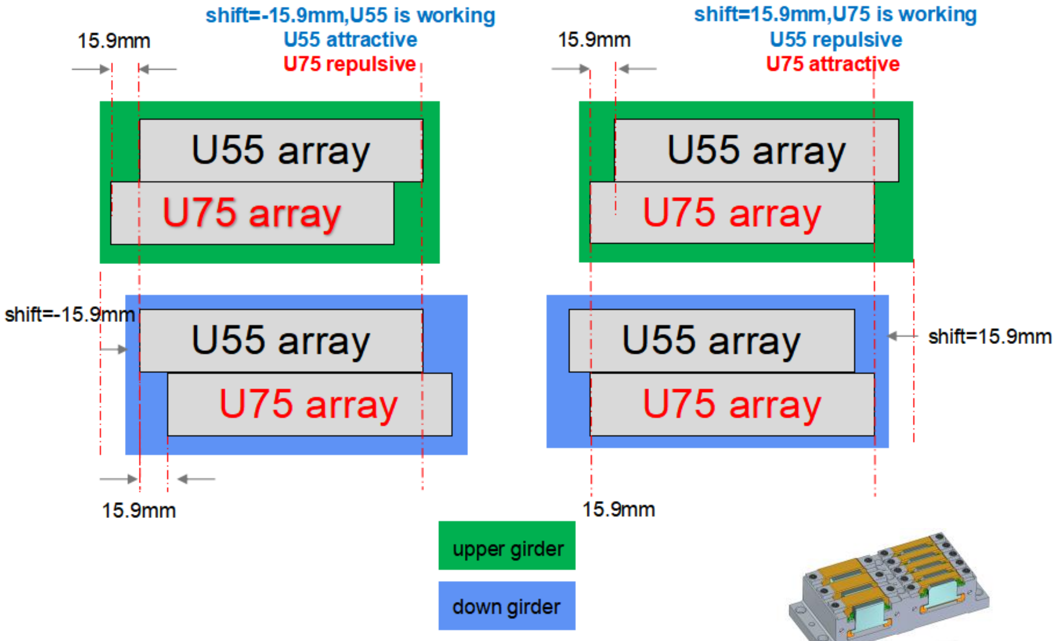
Planar Undulator U26

- 4 Four Servo Motors.
- Precision gap control with accuracy ±1μm.
- Max Taper 0.3mm for 4m undulator.
- Hybrid magnetic structure: peak field 1.02T@7.2mm

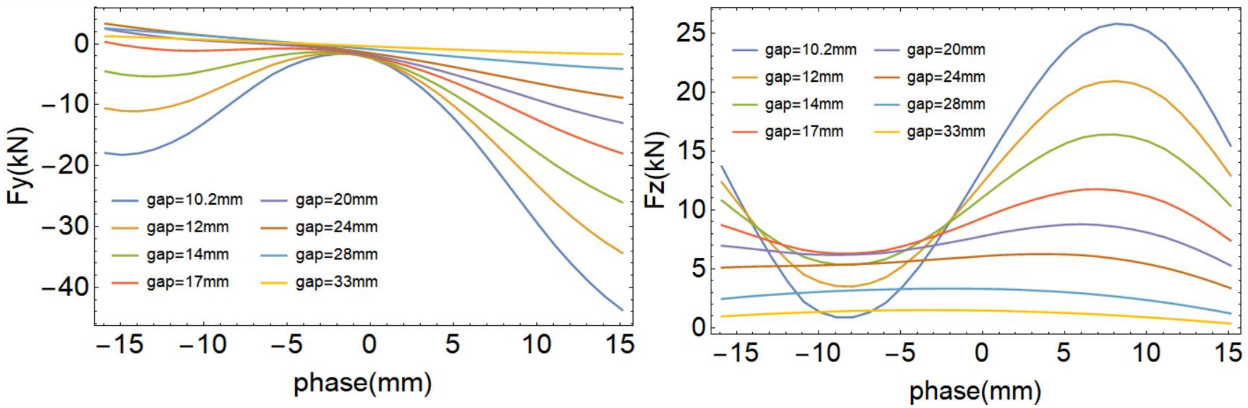
Double periods U55&75: similar design to U26

- Two periods arrays fixed on the same girder
- Switch 100mm between U55 arrays to U75 arrays in x-direction
- An optimized phase delay 15.9mm from U55 to U75 in z-direction
- working logic: U55 gap open→switch x position to U75 center→switch shift from -15.9mm to 15.9mm→U75 gap close

Prototype： Start parts processing, will be finished in May. 2023



prototype U55&75



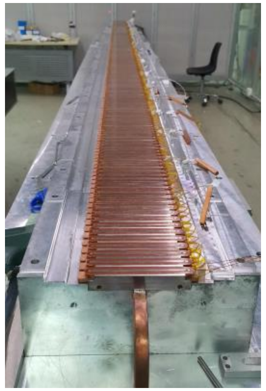
Total magnetic force in double period U55&75

SHINE

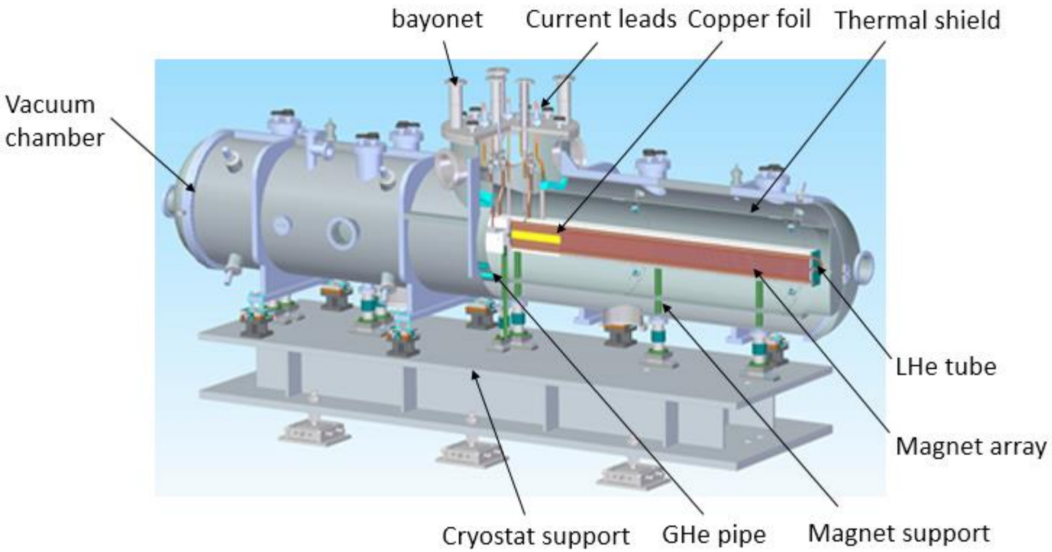
Superconducting Undulator Prototype

- There are 504 horizontal racetrack coils with NbTi wire in one undulator.
- Five power supplies will be used, two for the end coils, three for the main coils including one for the "phase shifter" in the middle.
- There is no beam vaccum chamber.
- The thermal shield and the HTS leadings are cooled by 50K GHe, and the magnet is cooled by 4K LHe.
- The prototype has been assembled and will be tested in next two months.

Undulator Length	4.5 m
Period Length	16 mm
Magnetic Length	4 m
Pole Gap	5 mm
Beam Gap	4 mm
Peak Fields	0.68-1.58 T



- The magnetic fields will be measured by a Hall probe system with three Hall sensors, one temperature sensor and an optic system used to locate the 3D positions of the Hall sensors.

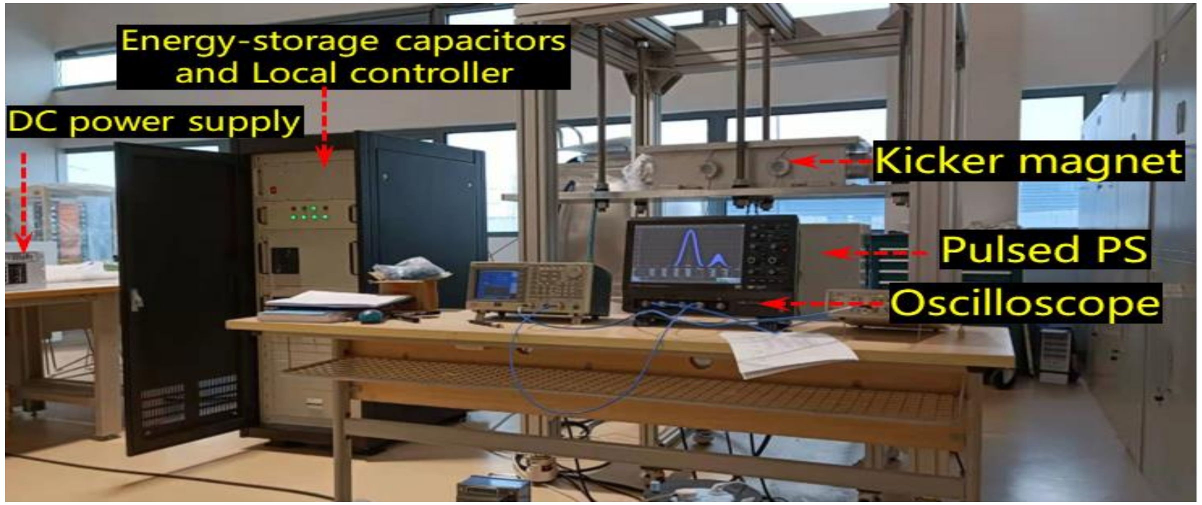


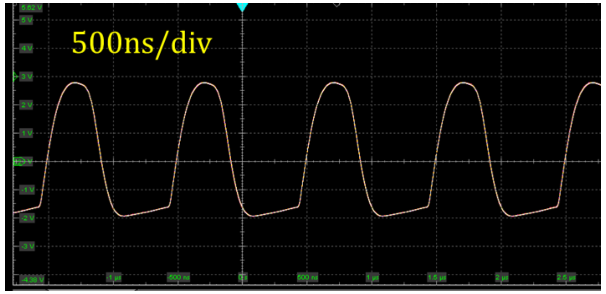
SHINE

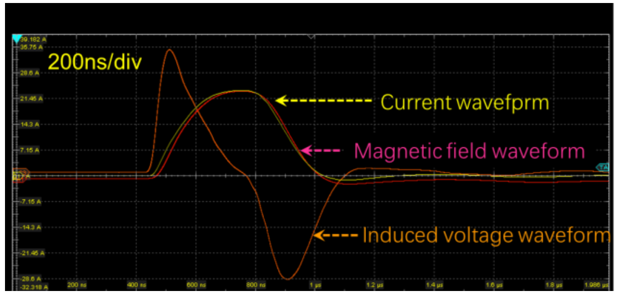
Kicker Prototypes

- 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

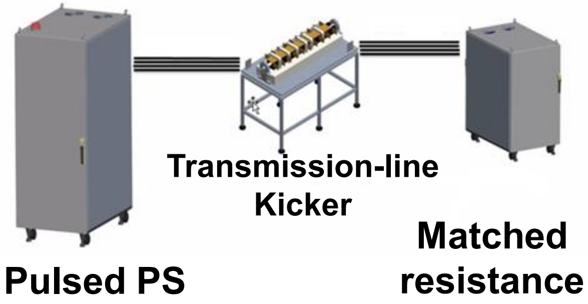


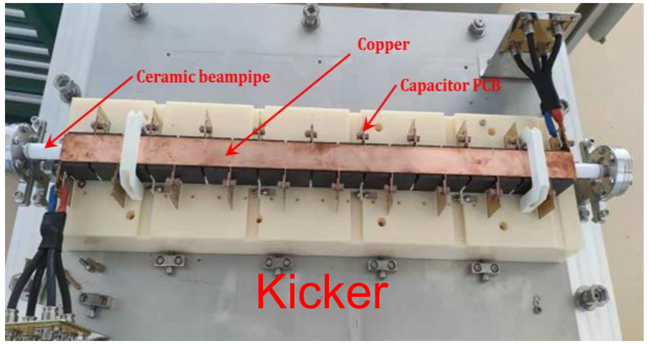


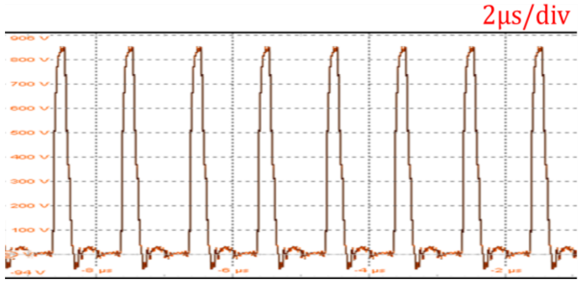


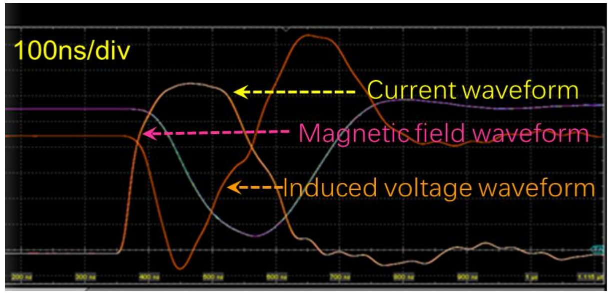
- Transmission-line Kicker.

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
LC section number	20	Kicker impedance	12.5 Ω
Ceramic beampipe	Φ15 mm	LC parameter	50nH/320pF



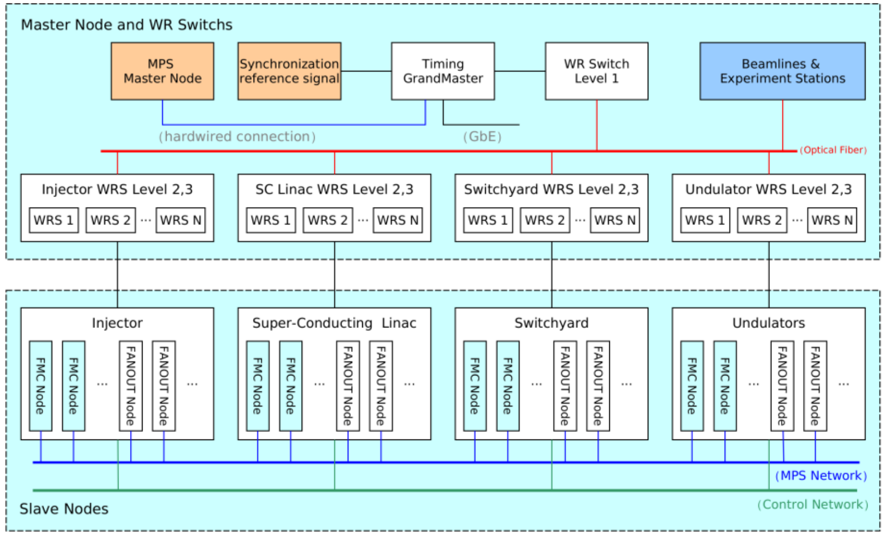


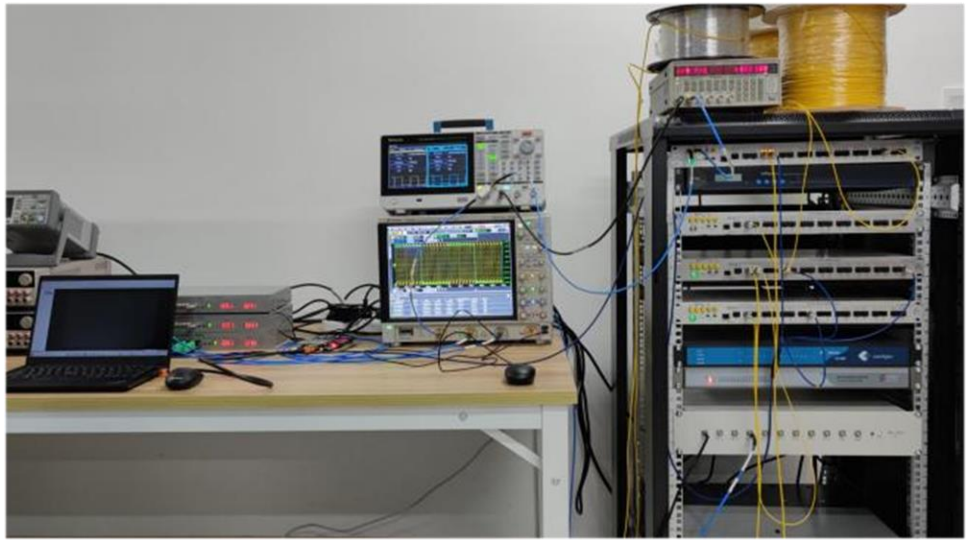


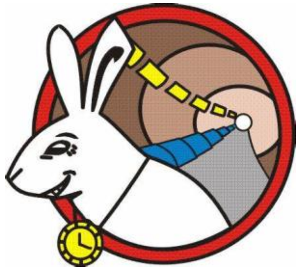


Development of the Timing System

- Precise distribution and synchronization of the 1.003086MHz timing signals over a long distance of about 3.1 km
- Two prototype systems were developed.
- The **non-standard clock transmission** was proposed and verified.
- **Beam-synchronous trigger signal distribution**
  - Jitter between the slave node output and reference signal <10ps
  - Jitter between slave nodes outputs <**5ps**
- Random-event trigger signal distribution

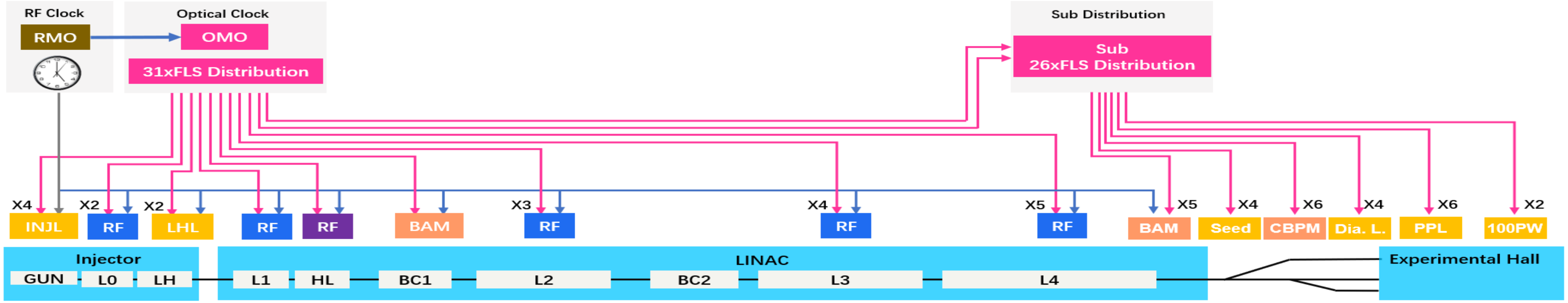






SHINE

Development of the Synchronization System



RF master oscillator (commercial, R&S)

- 8.2 fs rms jitter@[10Hz, 10MHz]

Optical master oscillator (commercial, Menhi

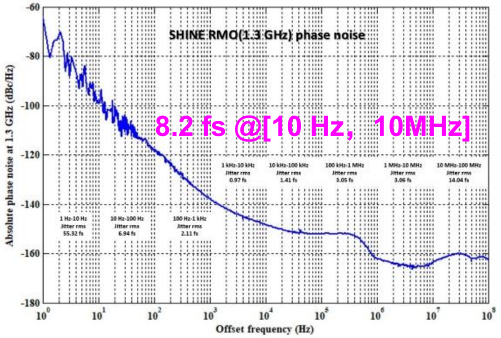
- 16.8 fs rms jitter of lock to RMO

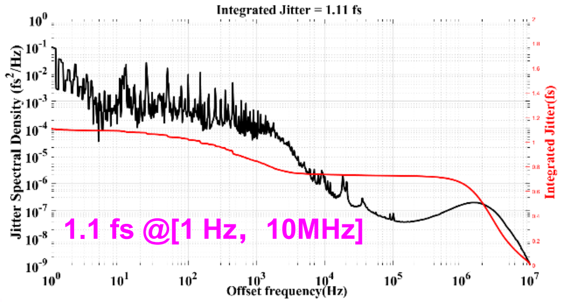
31-port PMF splitter distribution

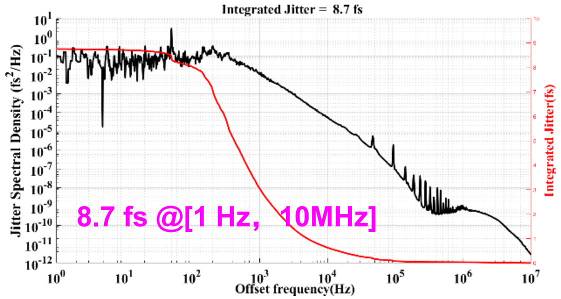
- Temperature-stabilized platform
- Fiber length stabilizer(BOC)
- 4 ns motorized optical delay Line
- 1.1 fs short-term rms jiter
- 2 fs long-term drift

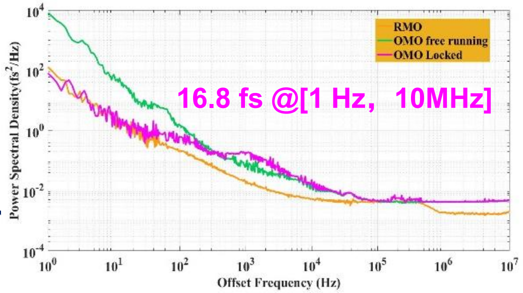
Laser oscillator locking

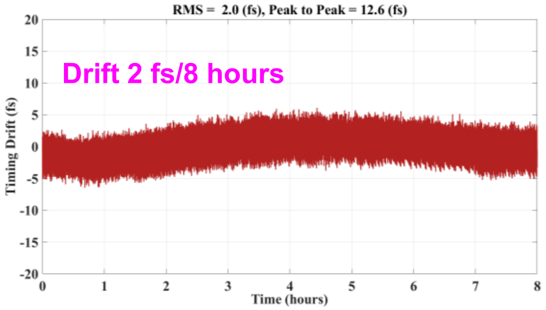
- Two-color balanced optical cross-correlatior
- 8.7 fs short-term rms jiter
- 1.2 fs long-term drift

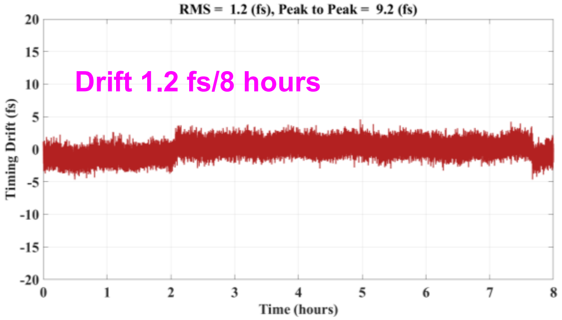








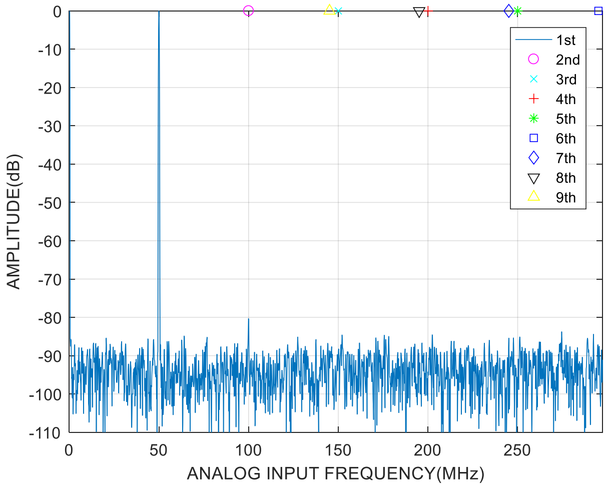


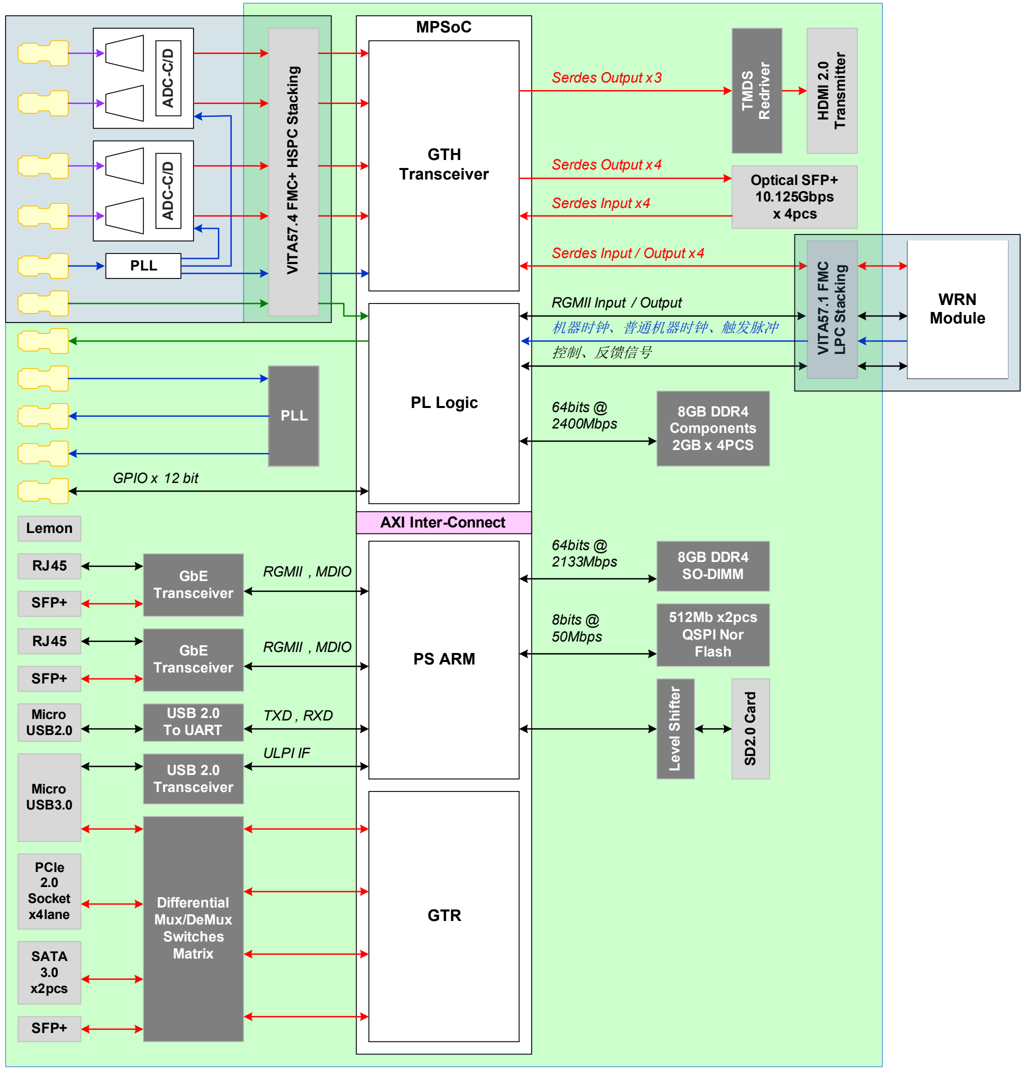


LINAC2022 LIVERPOOL

Development of the Beam Signal Processor

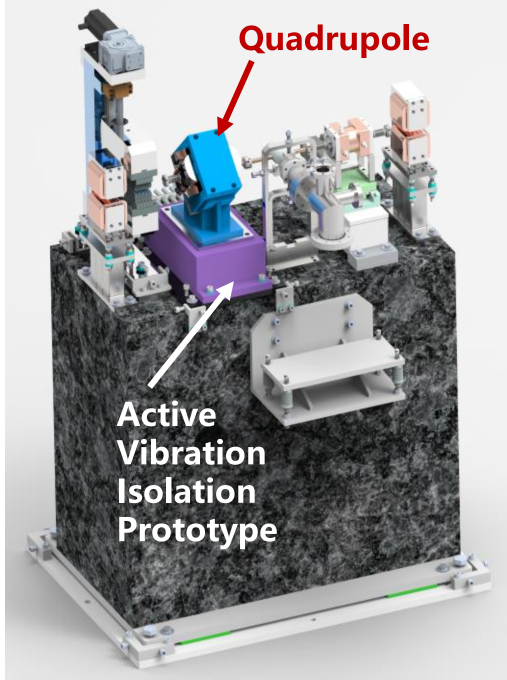
- A generic beam signal processor has been developed for SHINE, which is used for the measurement of stripline BPM, cold button BPM, cavity BPM, bunch charge, BAM, wire scanner, beam loss, and bunch length.
- 1U height stand alone structure based on an Zynq UltraScale+ MPSoC FPGA. Two FMC connectors support an four channel ADC board (14bits, 1GSPS) and a White Rabbit timing board.



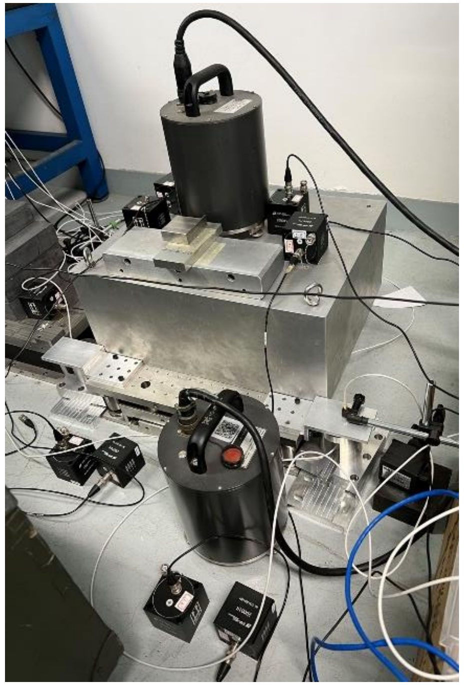


SHINE

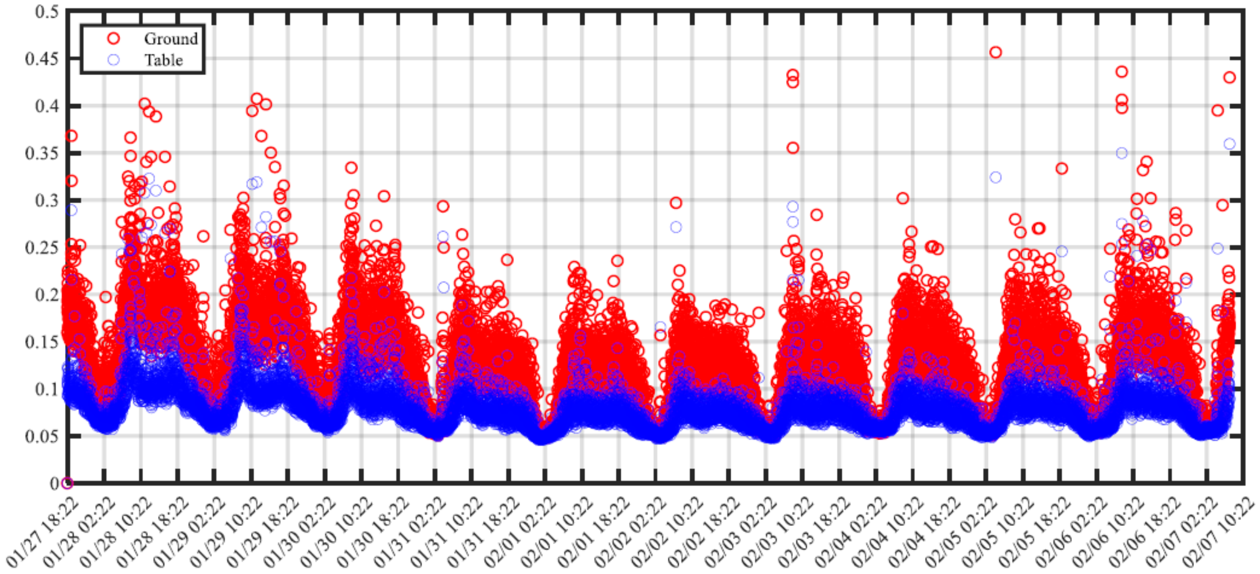
Active Vibration Isolation Prototype

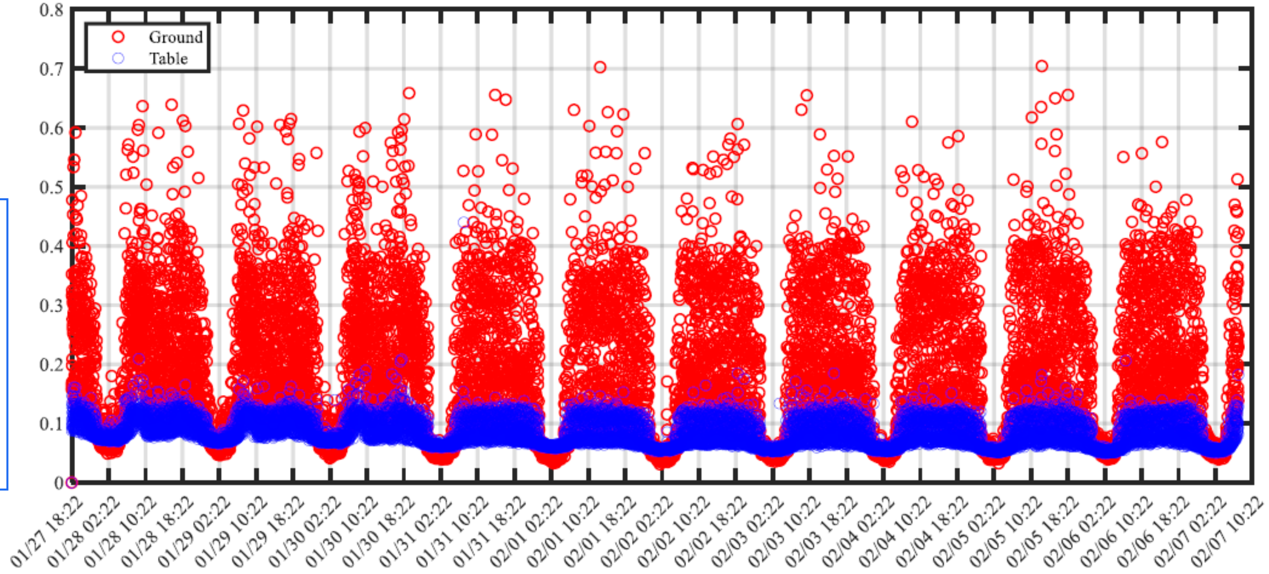


BBA model



Test of active vibration isolation prototype





- Goal: Vibration stability of quadrupole center (H/V, RMS, >1Hz) ≤0.15um
- Ground vibration is much higher than 0.15um
- Active vibration isolation prototype is tested. Vibration of dummy load is reduced by at least 30% compared with ground vibration and can reach ≤0.15um.

SHINE Cryo-plants

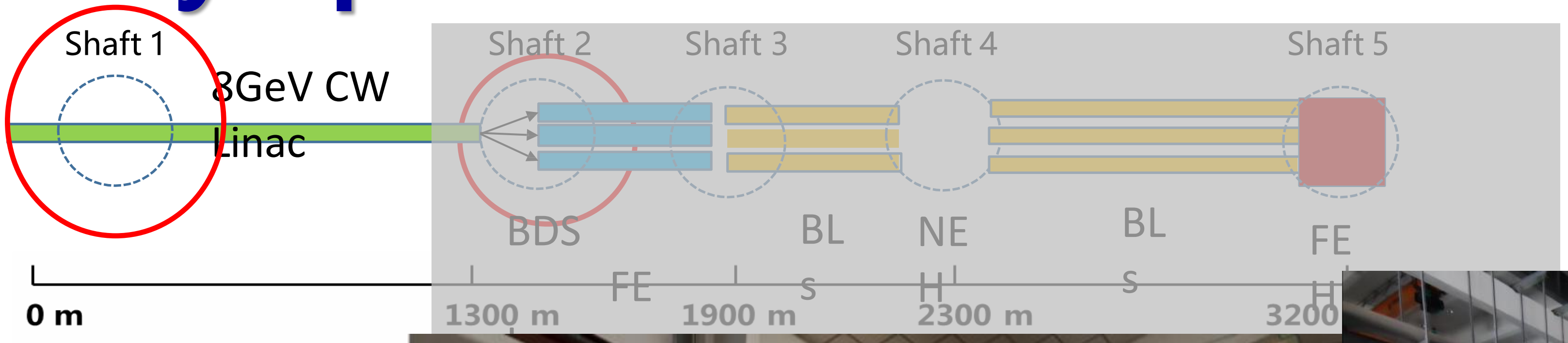
2 sets of **4kW@2K** cyroplants (for SHINE main facility)

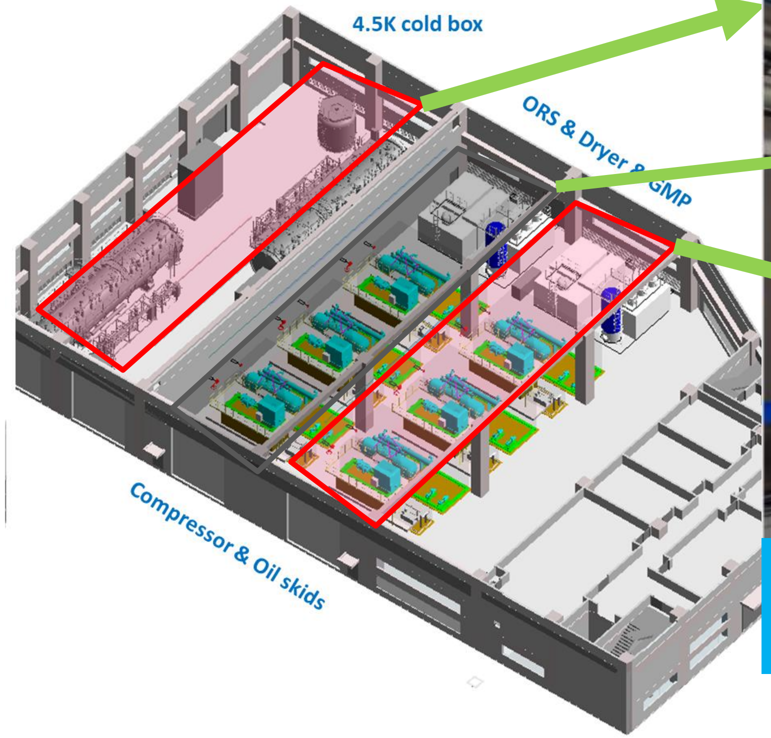
Cryogenic multi-channel transfer lines

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

LINAC2022 LIVERPOOL

SHINE Cryo-plants





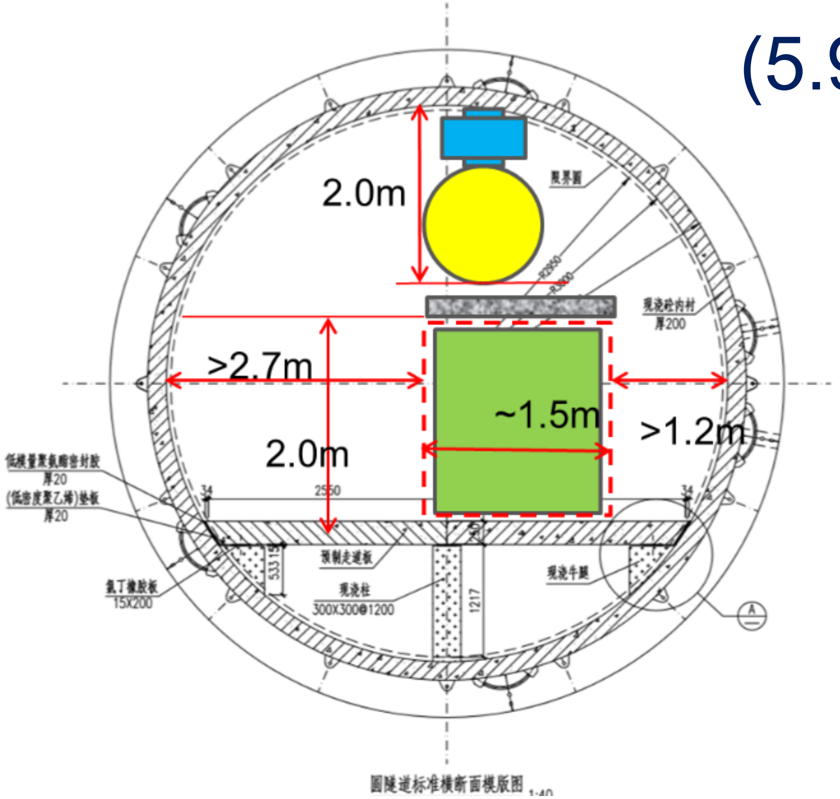
1st Cryoplant passed the FAT and will be shipped soon.

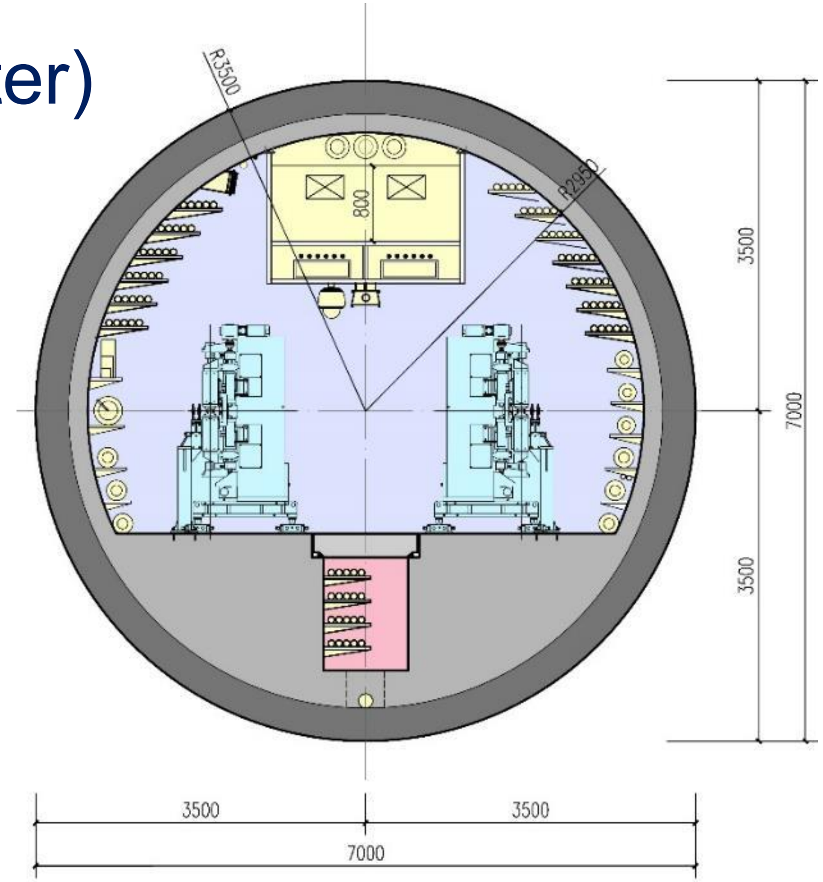
Compressor hall construction

1st Compressors arrived at site

Linac and FEL Undulator Tunnels

(5.9m diameter)





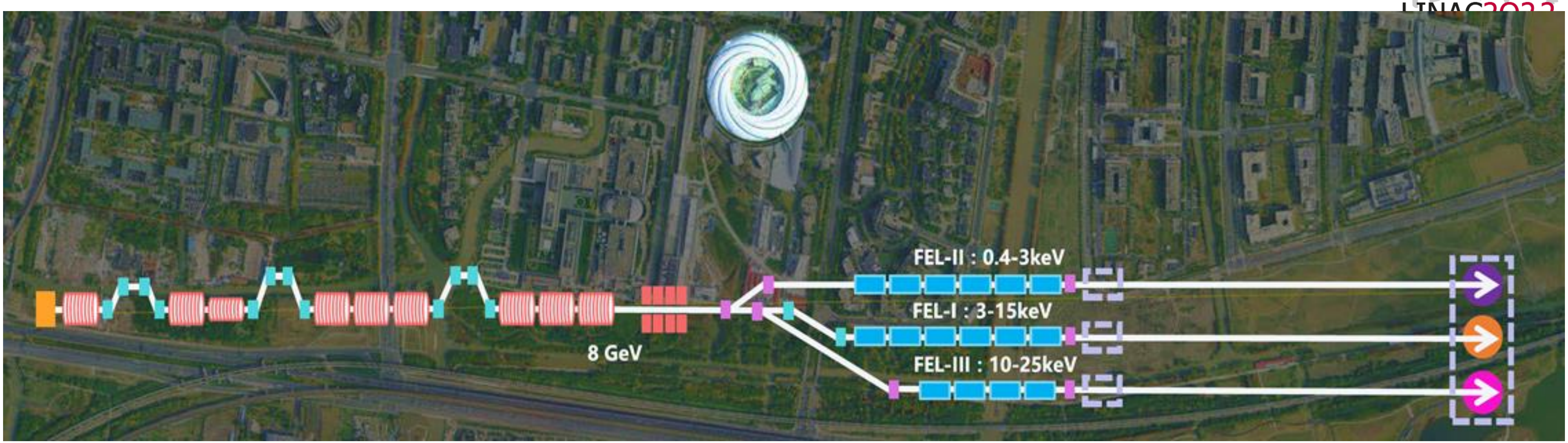
- Left： cross section of the linac tunnel
- Right： cross section of undulator tunnel

SHINE

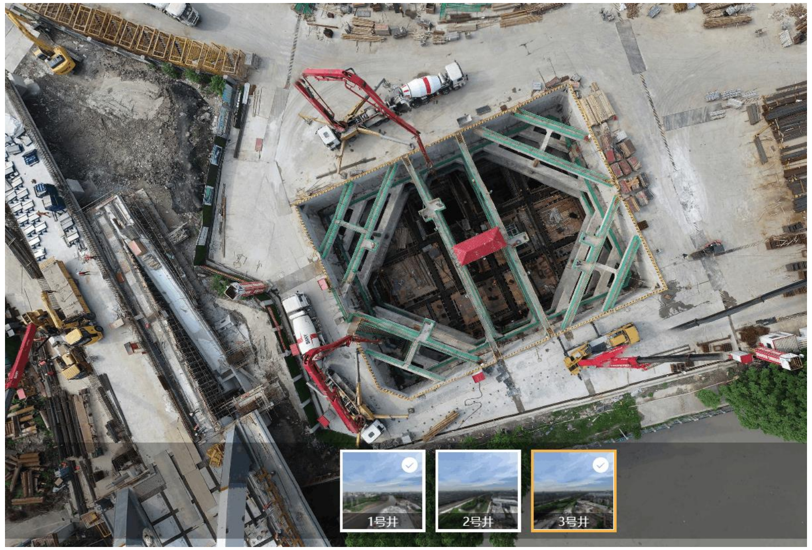
Groundbreaking on April 27, 2018

SHINE


上海光
软X射线自由电子激光实验装置
活细胞结构功能成像等线站
国家蛋白质设施（上海）
上海科技大学
号工作井
注入器
二号工作井
主加速器
三号工作井
波荡器与光束线
四号工作井
实验大厅
五号工作井
实验大厅


FEL-II : 0.4-3keV
FEL-I : 3-15keV
FEL-III : 10-25keV
8 GeV


Tunnels: ~30 m underground


1号井
2号井
3号井

Summary

- SHINE is a high rep-rate hard X-ray FEL facility being developed in Shanghai, consisting of an 8 GeV CW SCRF linac, a 100PW laser system, 3 phase-I undulator lines and 10 end-stations;
- This hard X-ray FEL project started its civil construction in April 2018, aiming to achieve the first XFEL lasing in 2025;
- R&Ds of several key technologies and key components are still ongoing.
- Technical and engineering design is almost frozen, and mass production of several key components is in progress.


Thanks for Your Attention !
谢谢！