XFEL Projects in China

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29th Linear Accelerator Conference, Beijing, 16-21 September, 2018

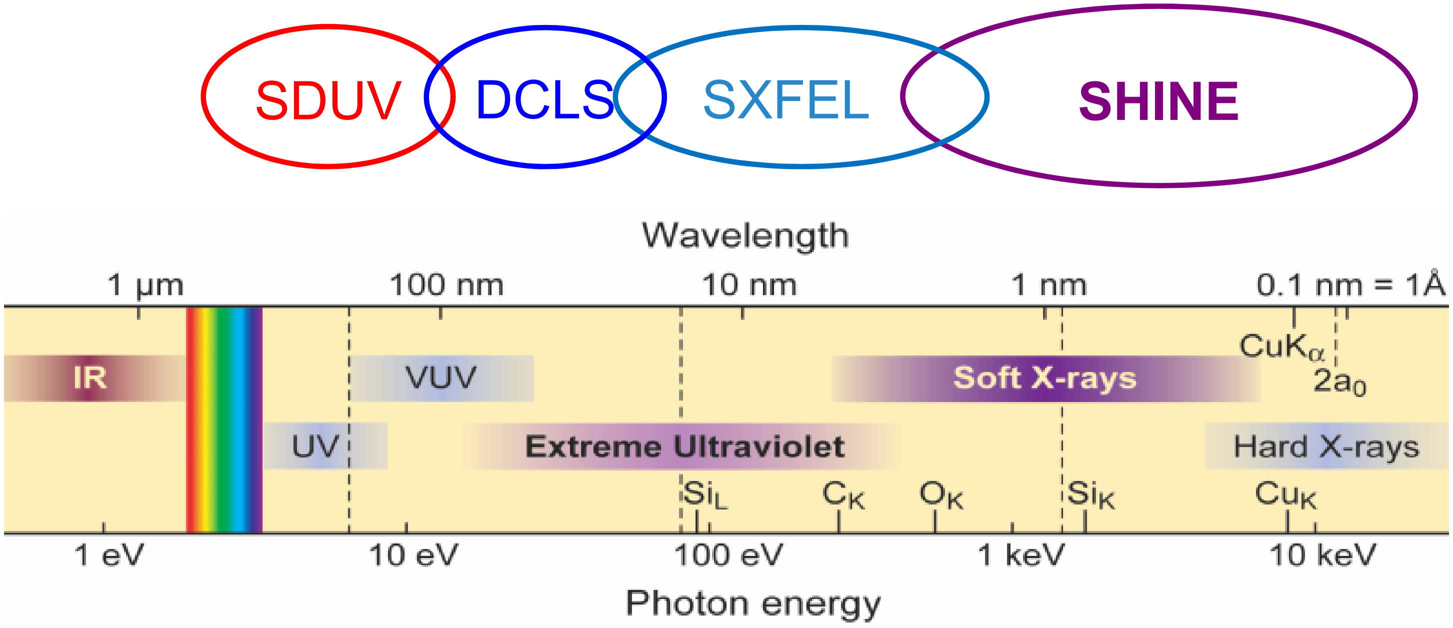
Outline

- Introduction
- Soft X-ray Free Electron Laser Project (SXFEL)
- Hard X-ray Free Electron Laser Project (SHINE)
- Summary

Introduction

- China started to develop high gain FEL in late 1990s, when a HGHG scheme based DUV-FEL was proposed;
- In the past 10 years, the SDUV-FEL test facility based a 180MeV linac and the DCLS, an EUV-FEL user facility, based on a 300MeV linac were constructed
- **SXFEL**, a soft x-ray FEL, phased in test &user facilities, has been under development, its test facility is under commissioning;
- **SHINE**, a high rep-rate hard X-ray FEL facility based on an 8GeV CW SCRF linac started its construction in April of 2018.

High-gain FEL Facilities in China



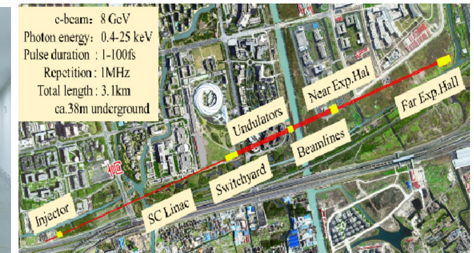
- Photon energy coverage from UV to hard X-ray

High-gain FEL Facilities in China

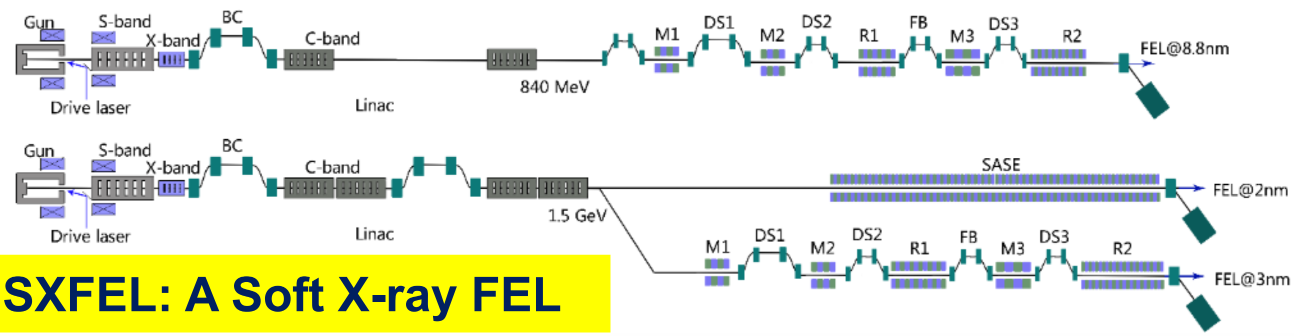
Shanghai Depp UV FEL (SDUV-FEL)
A test bench for novel FEL schemes

Dalian Coherent Light Souece (DCLS)
An EUV user facility (50 – 150 nm)

Shanghai Soft X-ray FEL (SXFEL)
A test and user facility (2 – 10 nm)

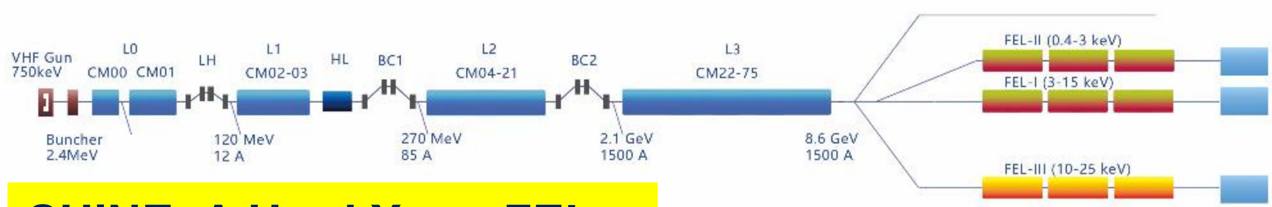


Shanghai Coherent Light Facility (SHINE)
High repe-rate XFEL based on SC linac



SXFEL: A Soft X-ray FEL

- ✓ SXFEL-TF&UF: EEHG, HGHG cascade, EEHG-HGHG cascade
- ✓ Coverage: 0.1-0.6 keV



SHINE: A Hard X-ray FEL

- ✓ SHINE FEL-II: HGHG cascade, EEHG-HGHG cascade
- ✓ Coverage: 0.4-3keV

- Various external seeding schemes have been adopted as basic operation modes for FEL facilities in China
- Photon energy using seeding schemes covers the range from VUV to tender X-ray

High-gain FELs constructed in China

	SDUV-FEL	DCLS	SXFEL-TF	SXFEL-UF	SHINE
Facility type	Test facility	User facility	**Test facility**	**User facility**	**User facility**
Status	Operating	Construction	**Commissioning**	**Construction**	**Construction**
Wavelength	150-350nm	50-150nm	**8.8nm**	**2.0nm**	**0.05-3.0nm**
Length	65m	150m	**300m**	**540m**	**3100m**
Accelerator	S band	S band	**S+C band**	**S+C band**	**L band/SRF**
Beam energy	100-200MeV	300MeV	**0.84GeV**	**1.5GeV**	**8GeV**
FEL principle	HGHG, EEHG	HGHG	**HGHG, EEHG**	**EEHG, SASE**	**SASE, EEHG**
Location	Shanghai	Dalian	**Shanghai**	**Shanghai**	**Shanghai**
First lasing	2009	2016	**2018**	**2019**	**2025**

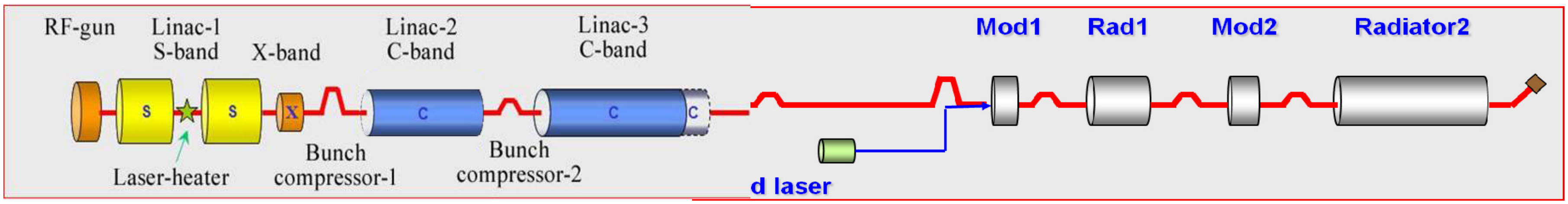
SXFEL Facility: TF +UF Projects

- **SXFEL facility** consists of two projects independently funded, **SXFEL test facility + SXFEL user facility**, with a total budget of ~155M$;
- **SXFEL test facility** was initiated in 2006 and founded in 2014, its ~300m long building was completed in April 2016. Its 0.84GeV linac and undulators are in operation now, and seeded FEL schemes are under commissioning;
- **SXFEL user facility** was founded to upgrade the test linac energy to 1.5 GeV for feeding two undulator lines with 5 experimental stations in the water window region, aiming at serving users in 2019.

SINAP, THUB and ShanghaiTech are collaborating in the design and construction of the SXFEL facility

Test Facility: SXFEL-TF

- A seeded FEL with two-stage HGHG or EEHG +HGHG based on an 0.84GeV linac and located in the campus of SSRF, closing to its synchrotron;



FEL parameters

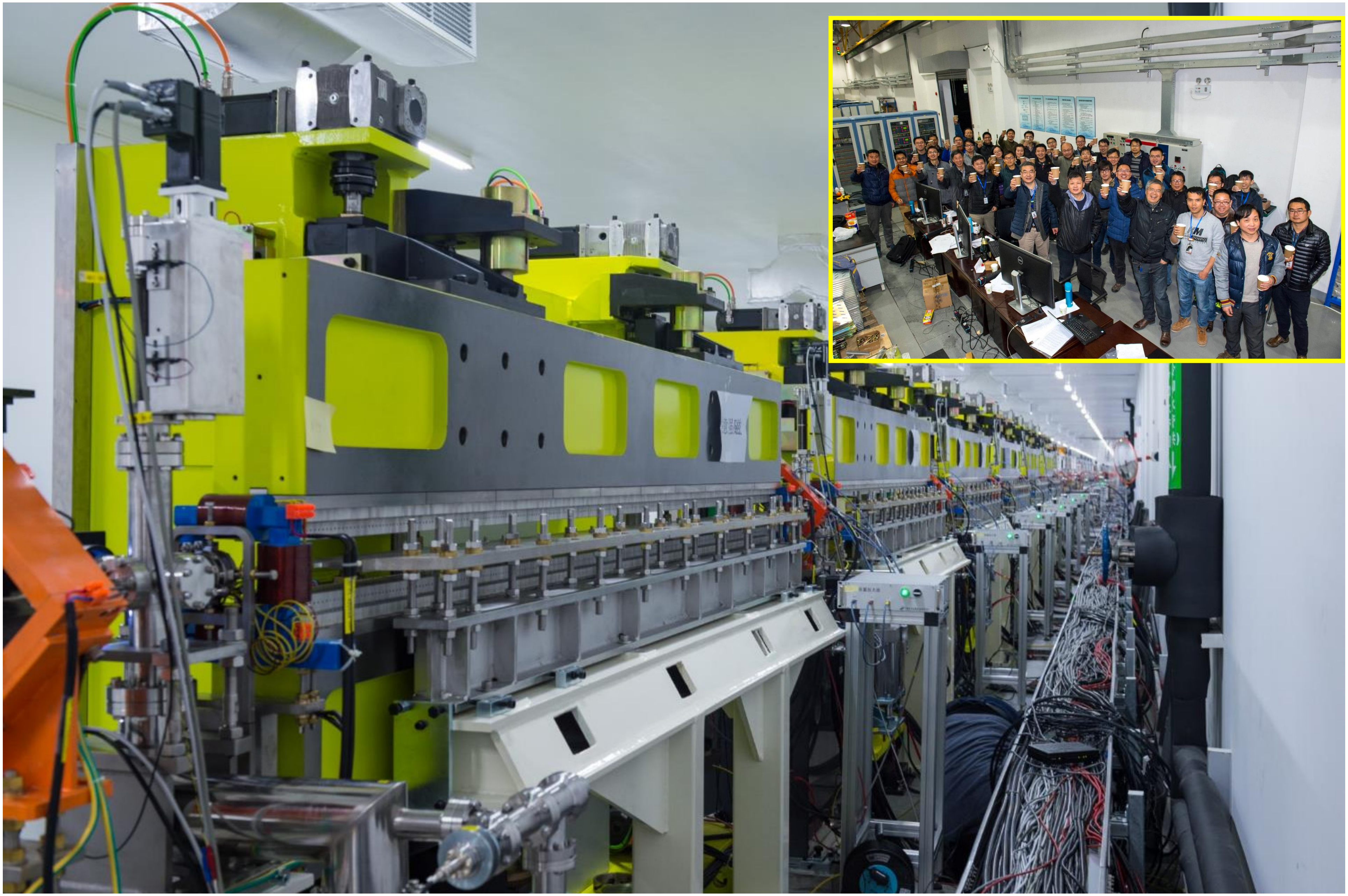
	Baseline I (8.8nm)		Baseline II (6.3nm)
Scheme	HGHG-HGHG	EEHG-HGHG	HGHG-HGHG
Harmonics	6 × 5	6 × 5	7 × 6
Beam energy	730MeV	730MeV	840MeV
FEL wavelength	8.83nm	8.83nm	6.3nm
FEL pulse	< 100fs	<100fs	< 100fs
FEL power	>100MW	>100MW	>100MW

SXFEL-TF Building

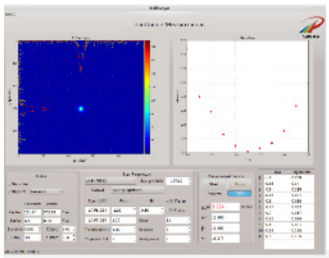
SXFEL-TF: 0.84GeV C-band linac + HGHG/EEHG Schemes

SXFEL-TF: C-band Copper Linac

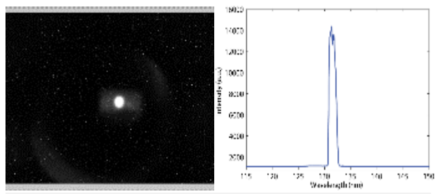
SXFEL-TF: Undulator Radiator



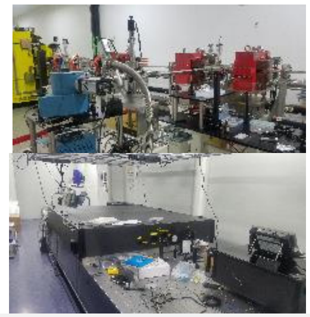
A Summary of the SXFEL Commissioning



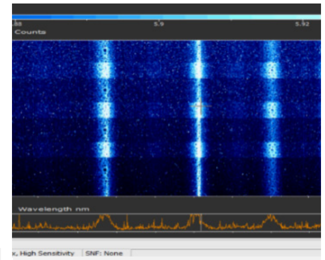
Start commissioning of the injector and main linac during the installation of undulators



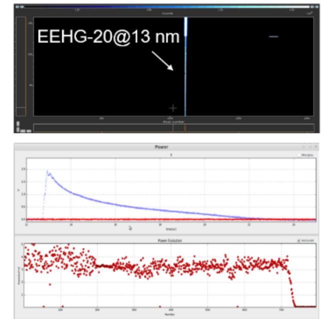
First coherent signal from the 1st stage HGHG



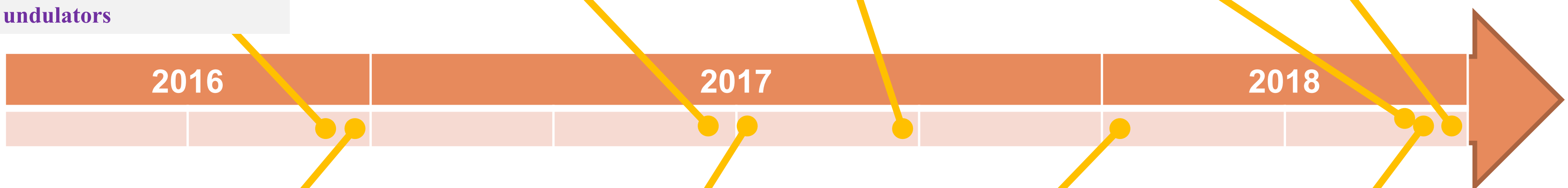
Installation of X-band linear, spectrometer and a new seed laser for the echo experiment



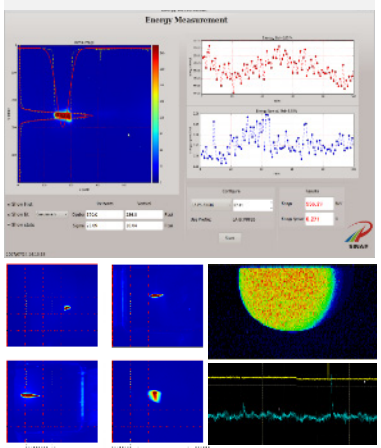
Coherent signal from EEHG-14 to EEHG-30



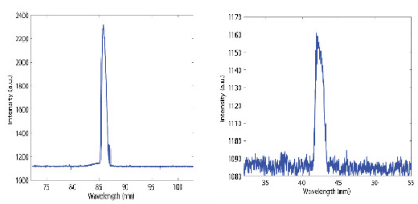
Amplification of EEHG-20



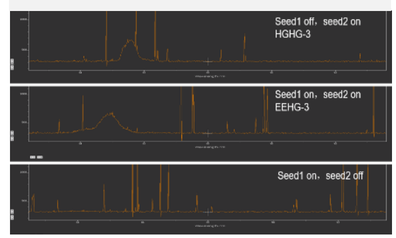
Beam energy = 700 MeV, first soft x-ray radiation from the undulator beamline



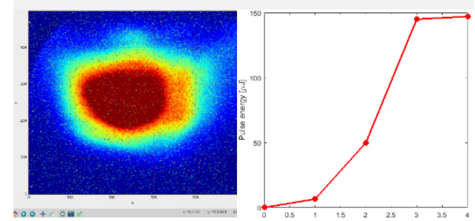
HGHG: 2nd to 6th harmonic



First coherent signal from the 1st stage EEHG. Pulse energy of the 3rd harmonic radiation exceeds 1 mJ



Lasing of HGHG-11 and EEHG-11

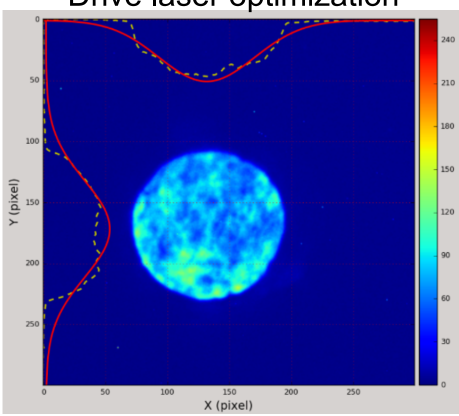


Lasing of EEHG-11 at 24nm

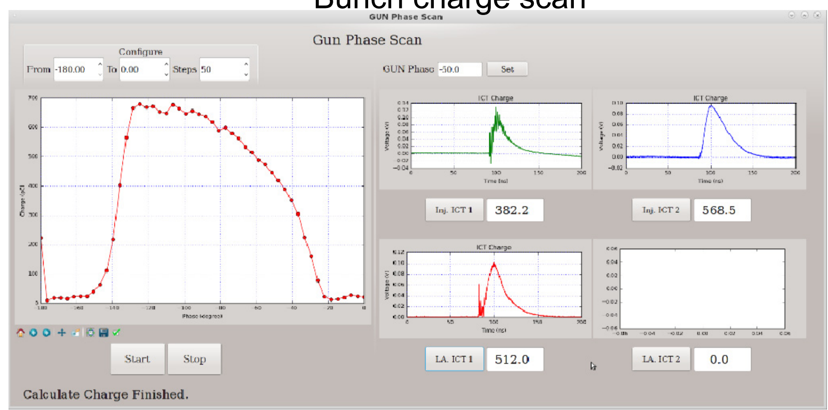
Commissioning of Injector and Linac

Bunch charge/pC	300-500
Central energy/MeV	400~890
Project energy spread（rms）	0.1%
Stability of the beam energy（rms）	0.05%
Peak current/A	~500
Full bunch length/ps	~1
Project emittance-x/mm-mrad	1.0 mm-mrad (Injector), <2 (linac)
Project emittance-y/mm-mrad	1.2 mm-mrad (Injector), <2 (linac)

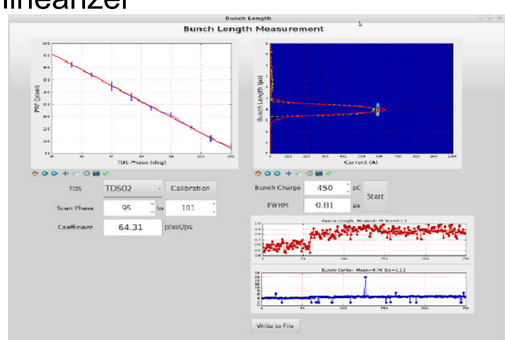
Drive laser optimization



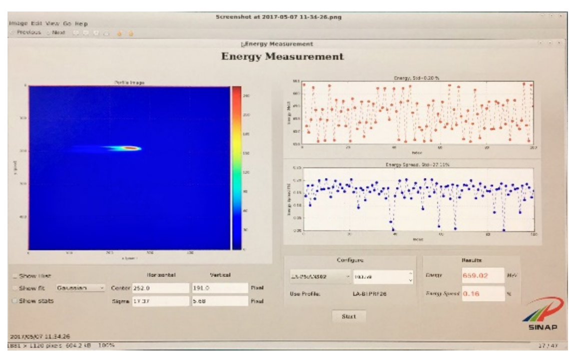
Bunch charge scan



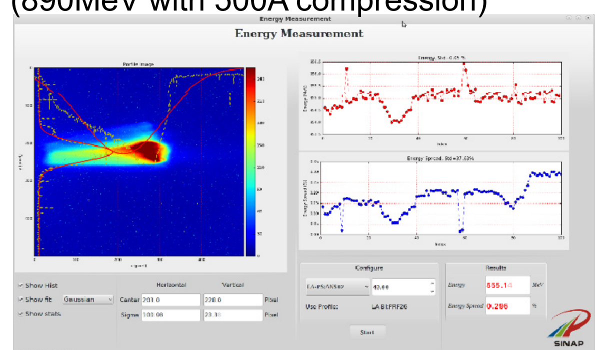
Bunch compression with x-band linearizer



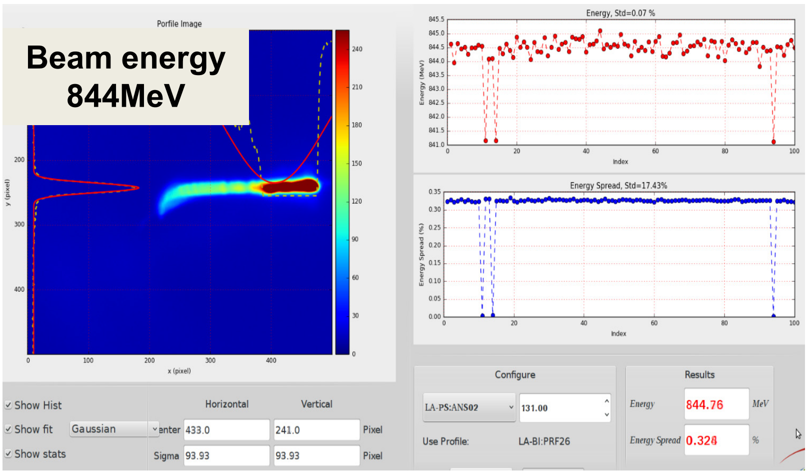
Further acceleration with C-band structures

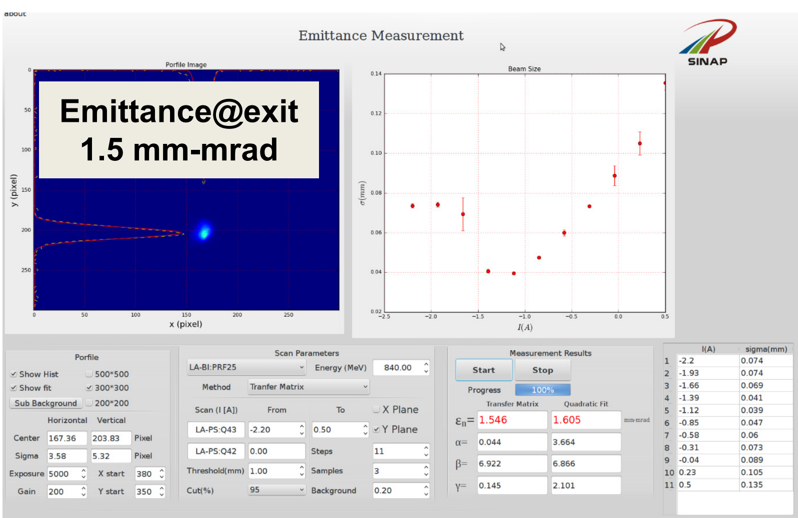


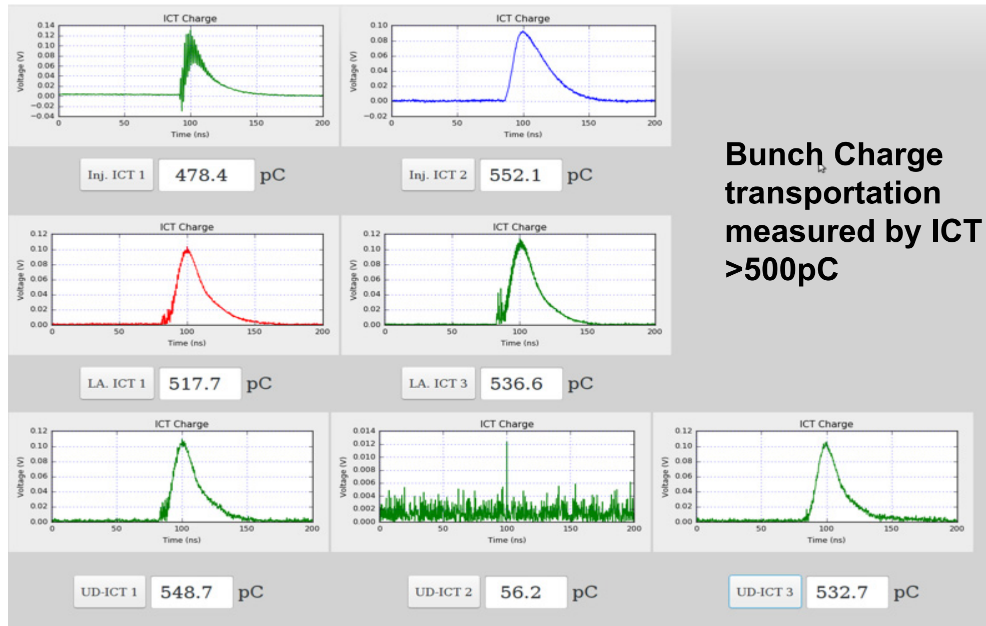
Maximal beam energy achieved (890MeV with 500A compression)



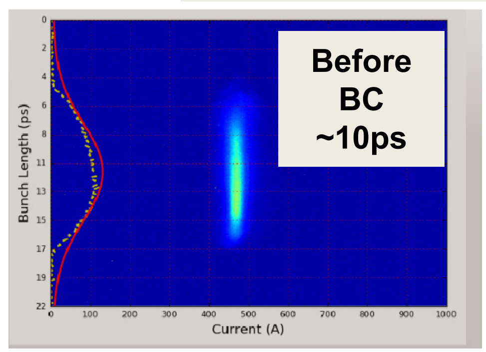
Typical Performance of the SXFEL-TF linac

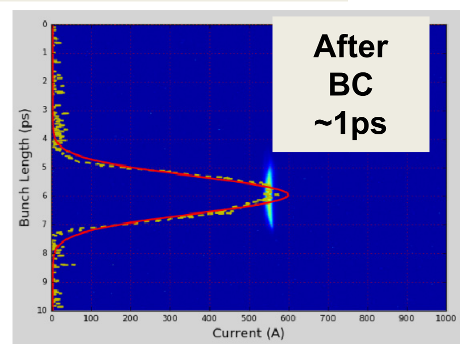






Bunch length measurement by TDS

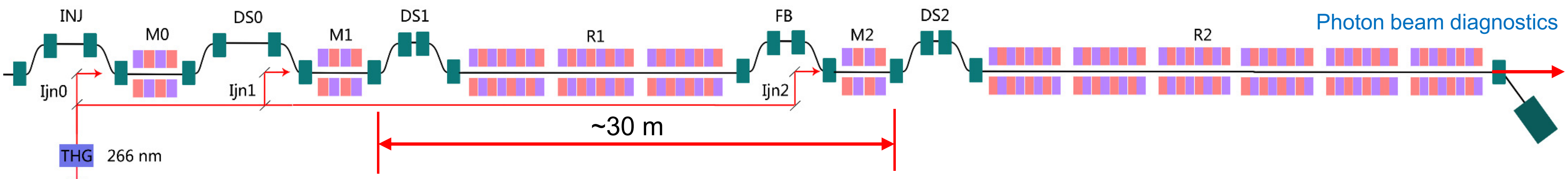




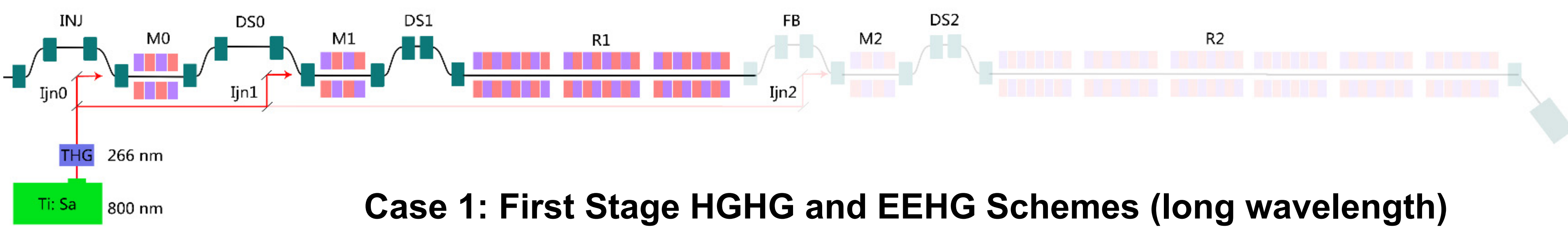
Current Performance of the SXFEL-TF linac

	Design Specification	Achieved Performance	
Repetition (Hz)	10	10	Injector
Charge (pC)	500	>500	
Normalized Emittance(μm-rad)	<1.5	~1.0	
Bunch length(FWHM, ps)	~10	~10	
Energy(MeV)	120	125	
Energy Spread(rms, %)	≤0.14	<0.1	
Energy(MeV)	840	400 ~ 890	Main linac
Energy Spread(rms, %)	≤0.15	<0.1	
Bunch length(FWHM, ps)	~1ps	~1ps	
Normalized Emittance(μm-rad)	2.5	<2.0	

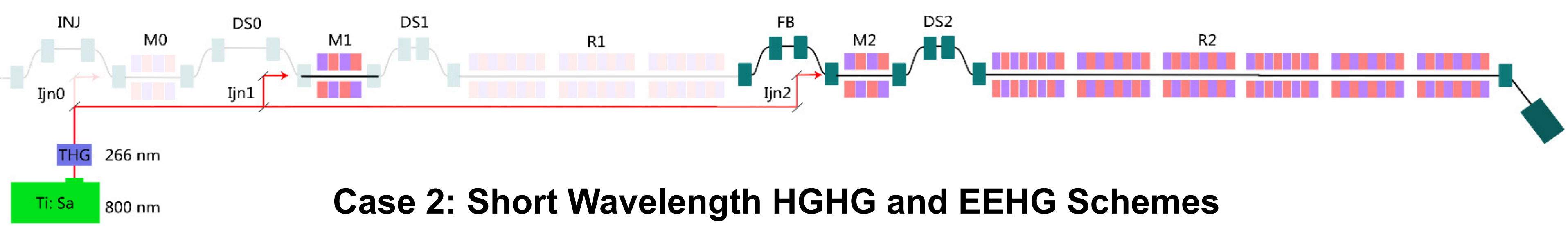
Commissioning of HGHG and EEHG Schemes at SXFEL



Layout of Undulators at SXFEL-TF

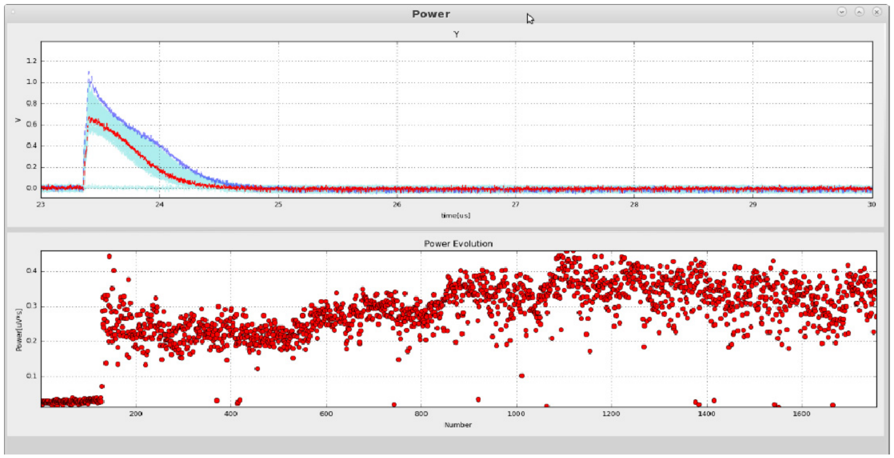


Case 1: First Stage HGHG and EEHG Schemes (long wavelength)

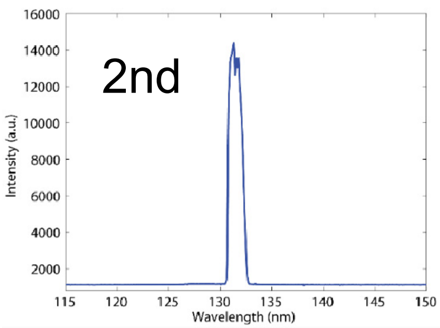


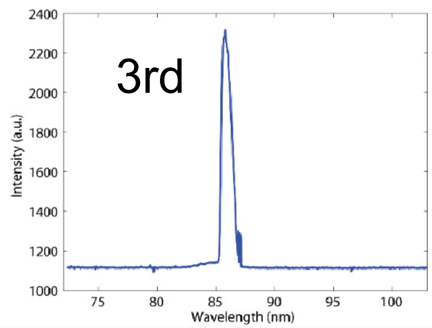
Case 2: Short Wavelength HGHG and EEHG Schemes

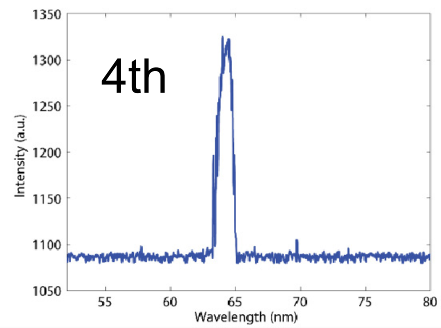
Case1: Lasing of the First Stage HGHG at Long Wavelengths

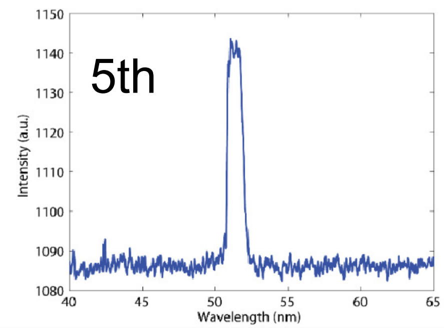


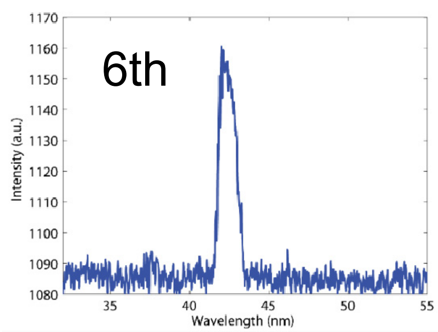
- Seed laser: 100 fs/1ps, ~100 μJ @266 nm
- Spectra of the coherent radiation at 2^{nd}-6^{th} harmonics of the seed was measured
- The output pulse energy at 88nm is larger than 100 μJ (measured with photodiode)
- The stability of the output power can be better than 10% (rms)

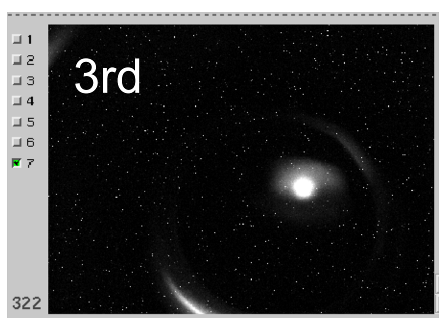


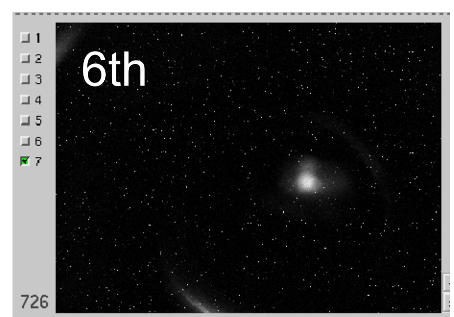




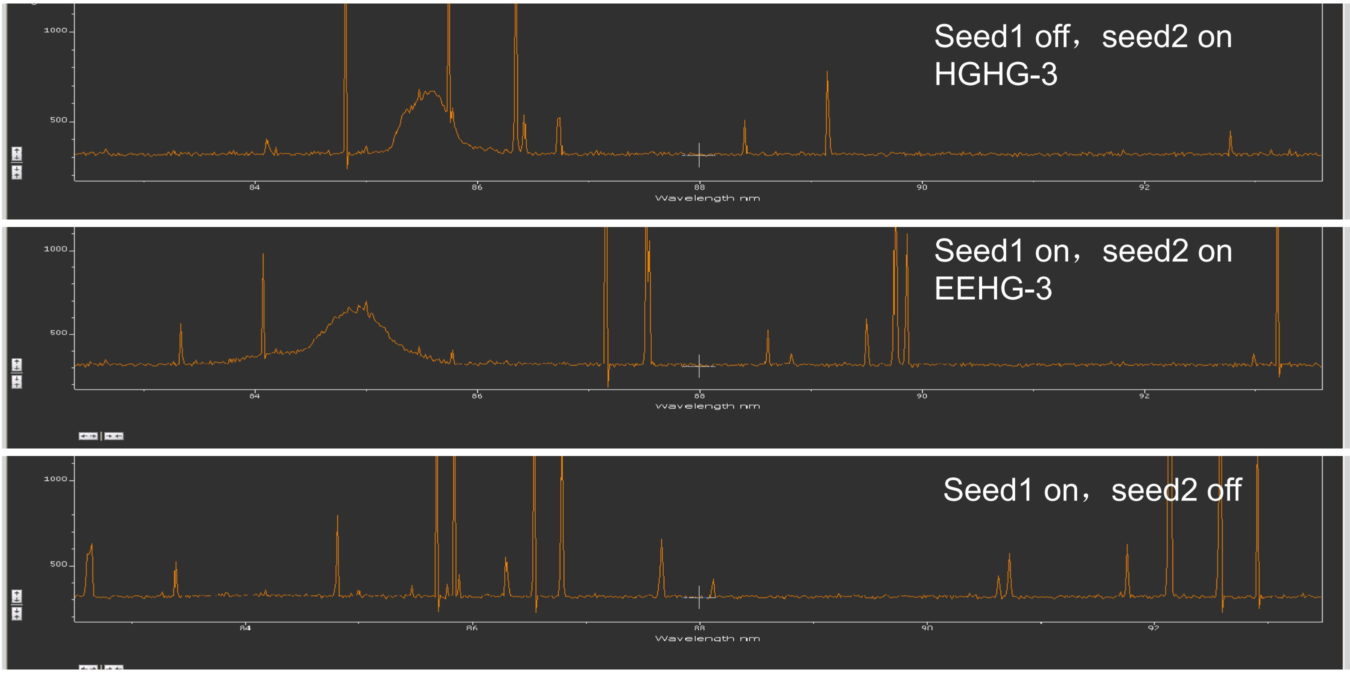


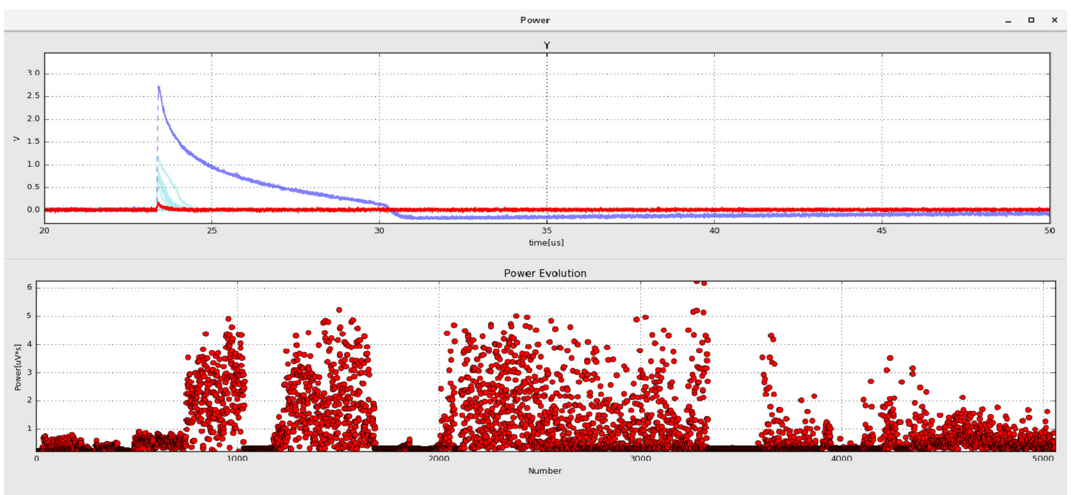






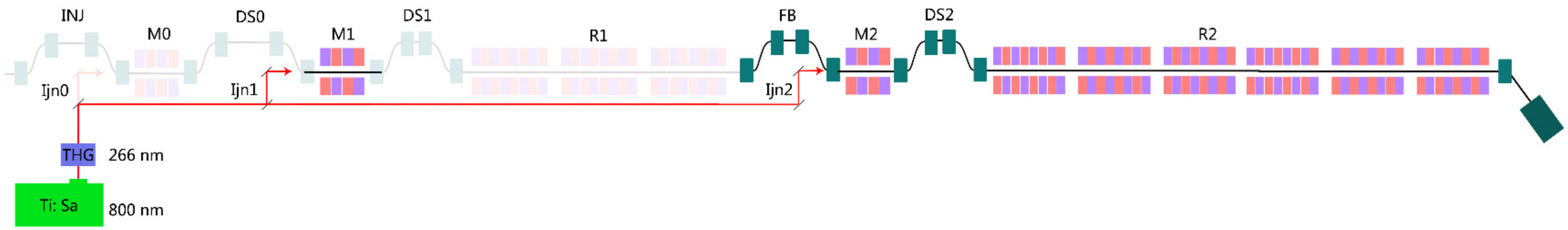
Case1: Lasing of the EEHG-3@88nm



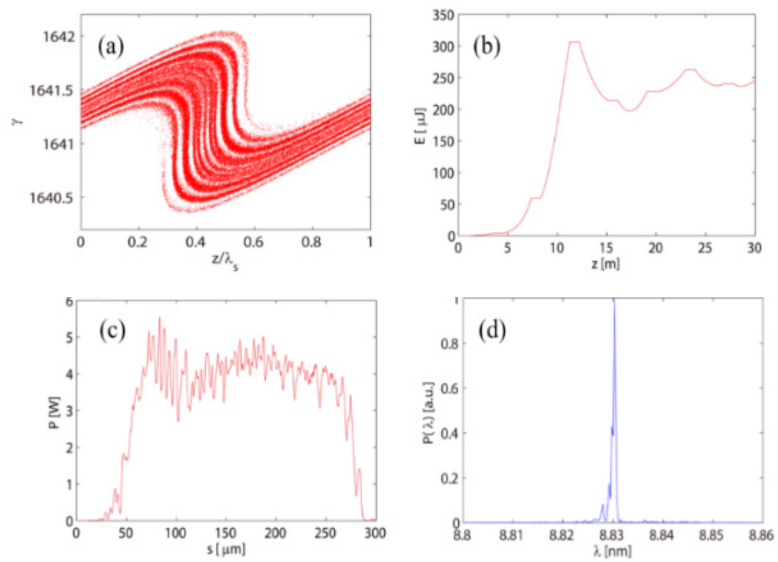


- Two seed lasers: 1ps, >100μJ @266nm
- Observing the wavelength shift for EEHG@88nm
- **Maximal output pulse energy> 1mJ@88nm**

Case 2: Echo-11, 20 and 30 Experiments at SXFEL



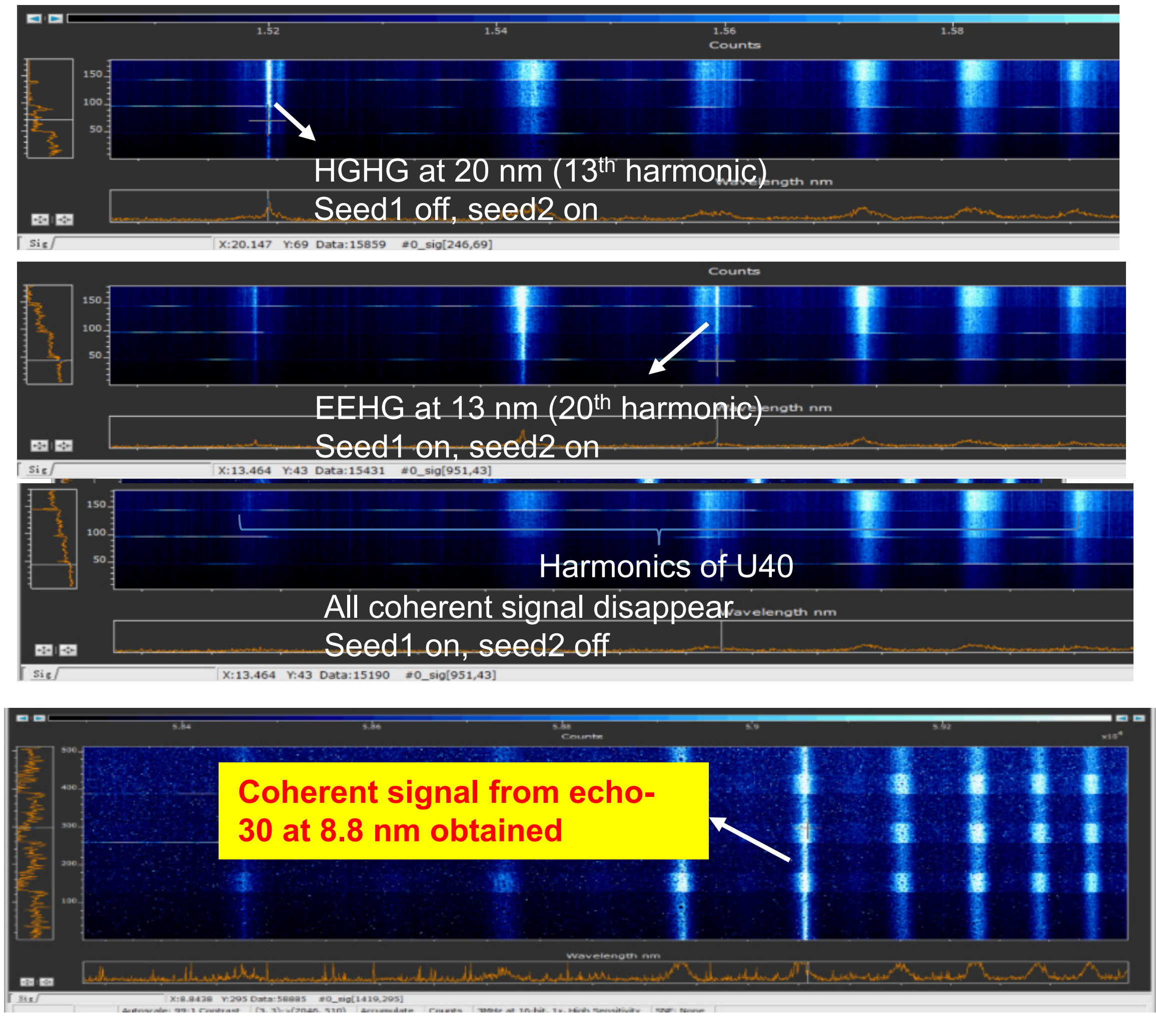
Layout for the EEHG-30 experiment at SXFEL



Results from s2e simulations

- **Coherent radiation of EEHG-30 (at 8.8 nm) has been obtained at SXFEL**
- Efforts are being made to realize the lasing and saturation of EEHG-20 and EEHG-30

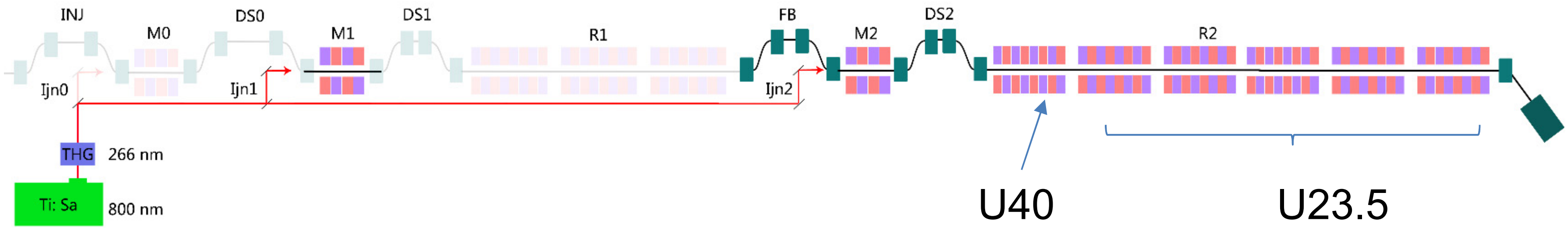
First coherent x-ray from EEHG at SXFEL



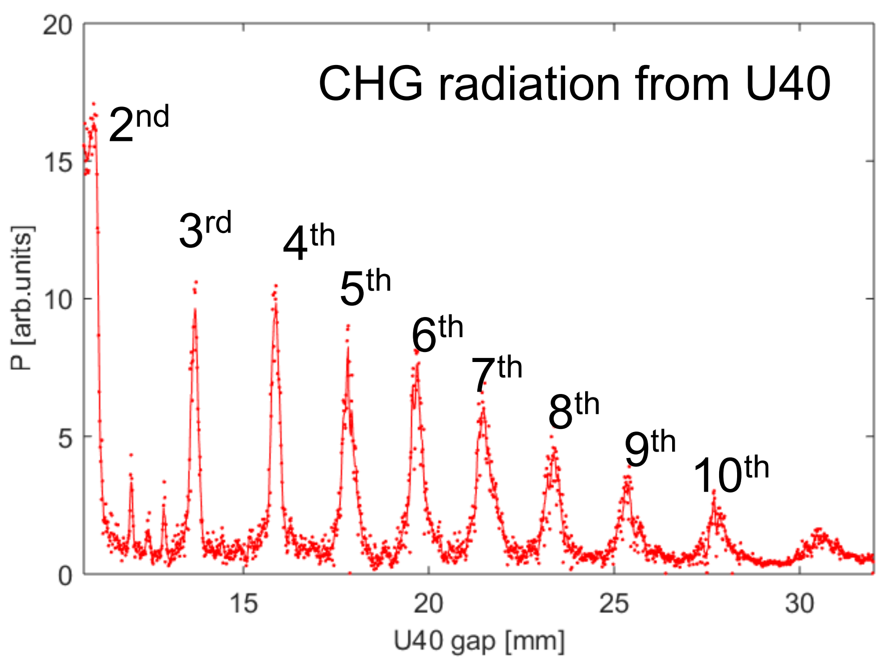
- Observed coherent signal for both HGHG and EEHG on the spectrometer
- It's hardly to see the coherent signal of HGHG for harmonic number larger than 16
- For EEHG it's easy to generate coherent signal at 20th and 30th harmonics of the seed by tuning the strength of the first chicane.

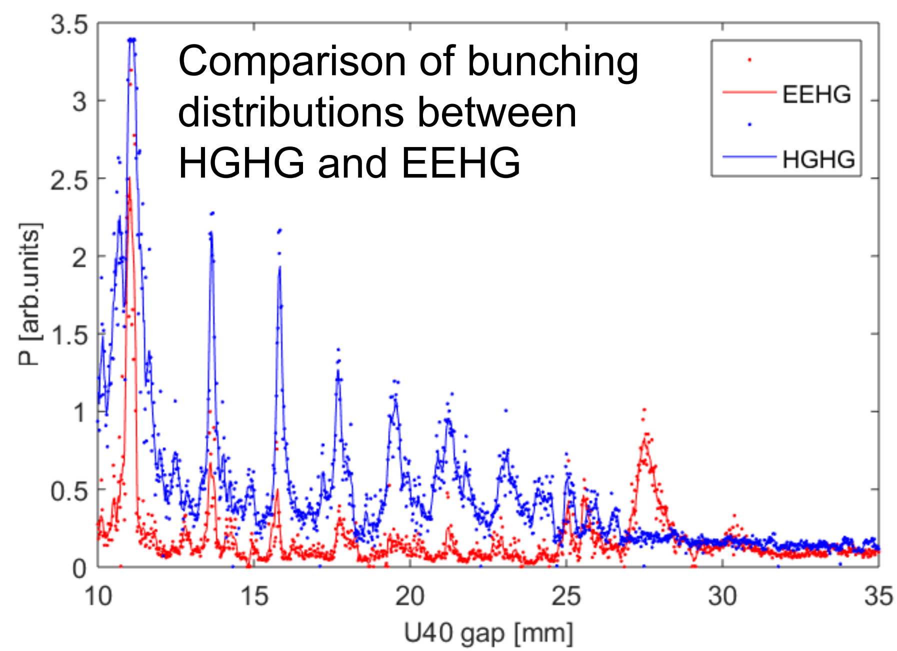
Bunching of HGHG and EEHG

(with low peak power of the 2nd seed laser)



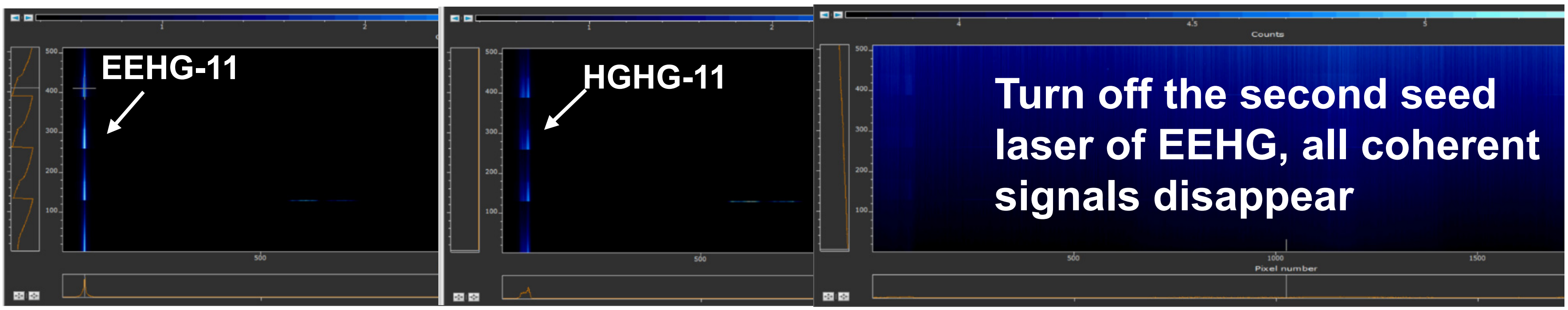
- By scanning the gap of U40, we can get coherent signals for different harmonics, which reflects the bunching factor distributions for HGHG and EEHG.
- Bunching factors for EEHG are lower than HGHG at low harmonics, but much higher than HGHG at the target harmonic.



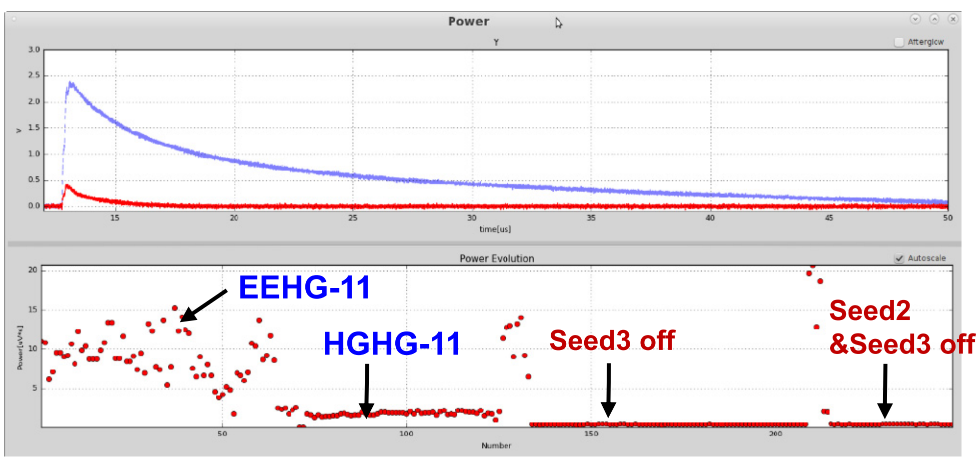


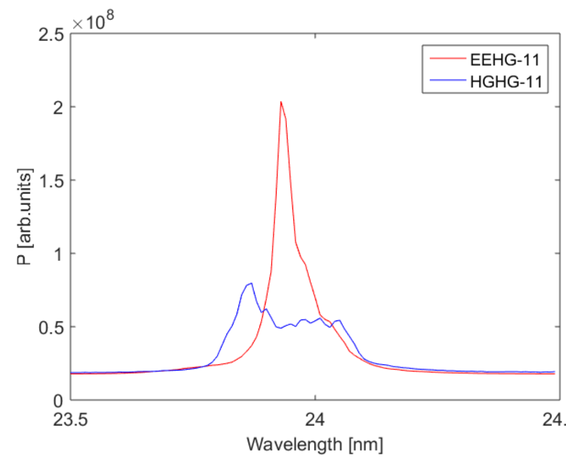
Lasing of EEHG-11@24nm at SXFEL-TF

- With high peak power of the 2nd seed laser, coherent signals for both HGHG and EEHG appear at 11th harmonic
- The bandwidth of EEHG-11 is much narrower than HGHG (due to the nonlinear chirp in the electron beam)



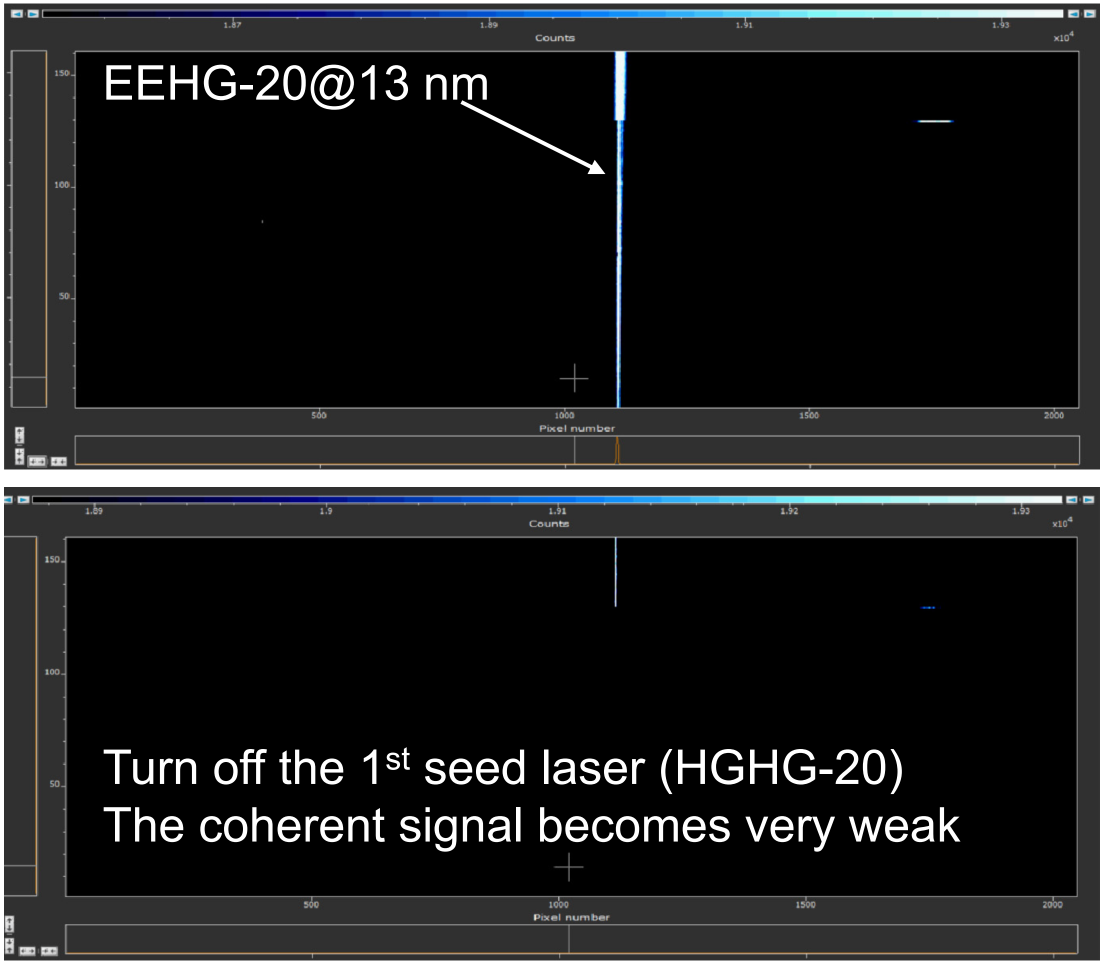
- Reducing the peak power of the 2nd seed laser, the HGHG-11 becomes very weak, while EEHG-11 is very strong, about two orders of magnitudes higher.





Accumulated by 50 shots

Radiation of EEHG-20@13nm at SXFEL-TF

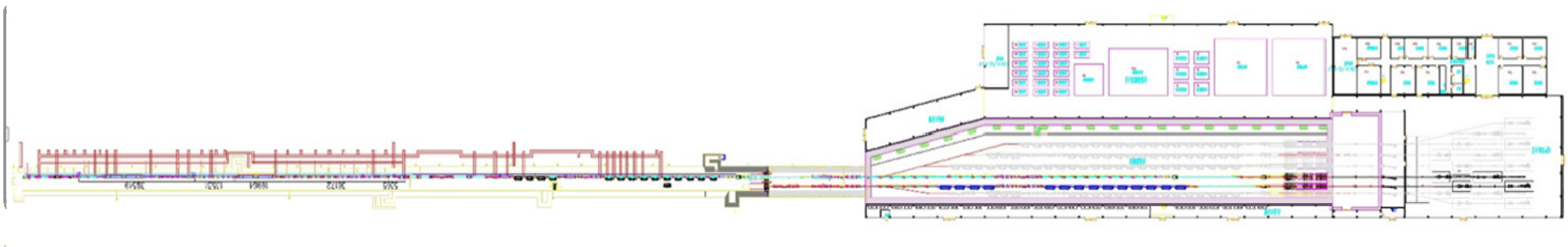


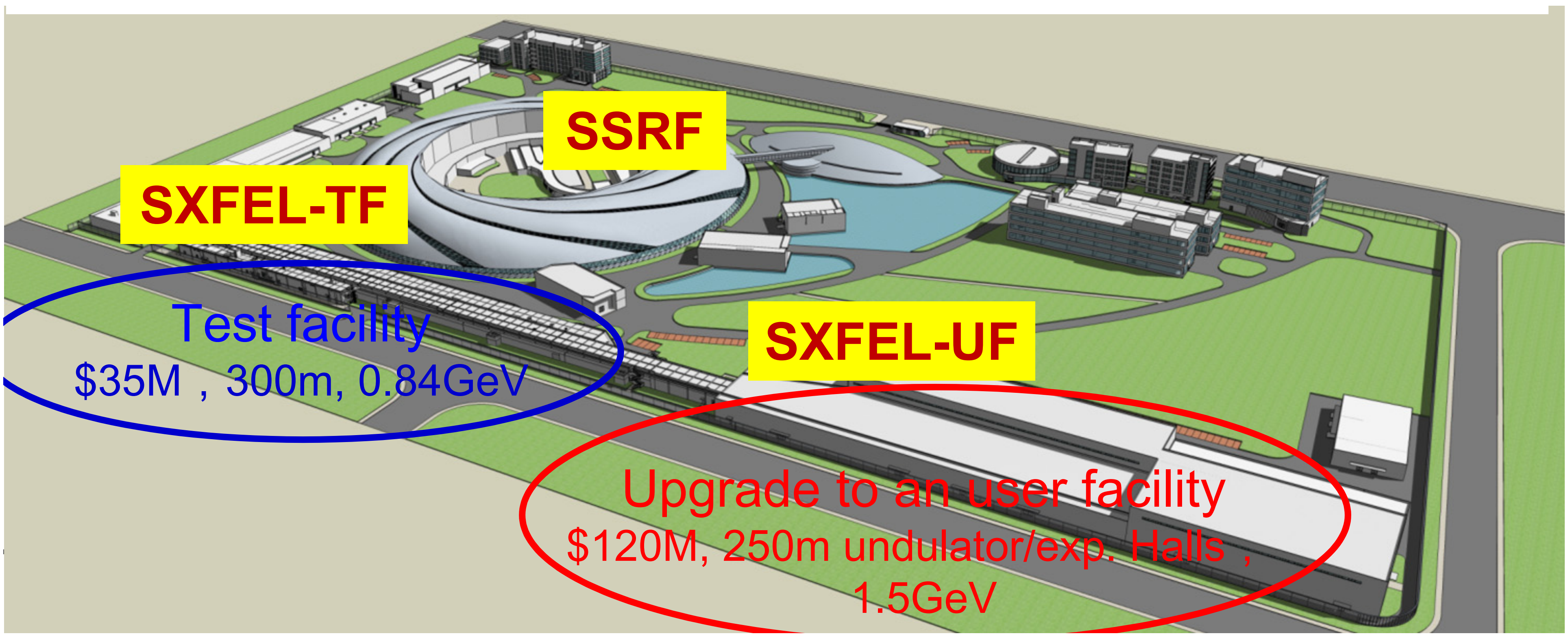
- At 20th harmonic, EEHG is much stronger than HGHG

Shanghai Institute of Applied Physics, Chinese Academy of Sciences

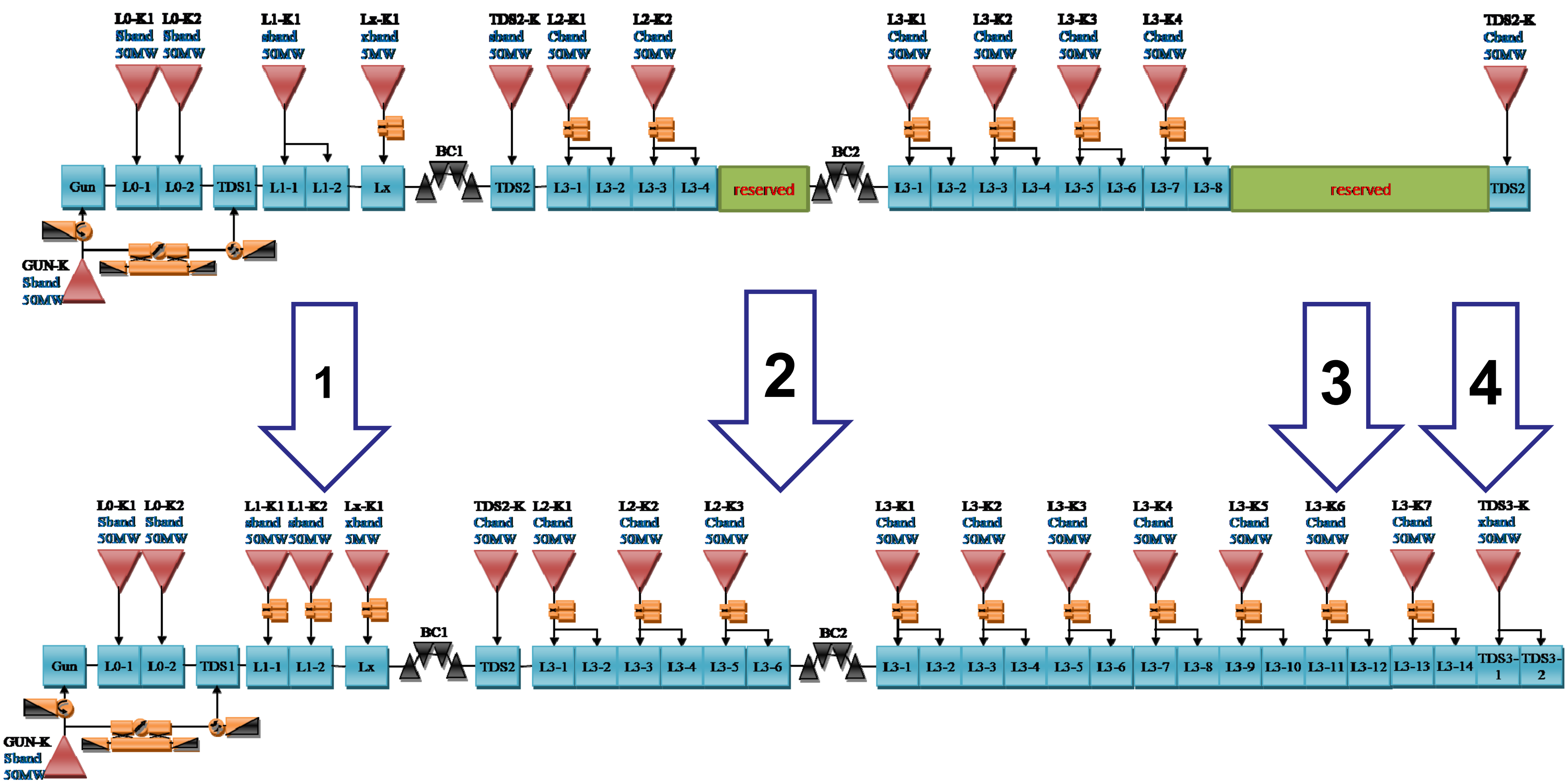
User Facility: SXFEL-UF

- A soft X-ray FEL user facility based on SXFEL-TF with two undulator line, a seeded FEL line and a SASE FEL line, is founded mainly by Shanghai local government, aiming at opening to users in 2019





Linac energy upgrade：~1.5GeV



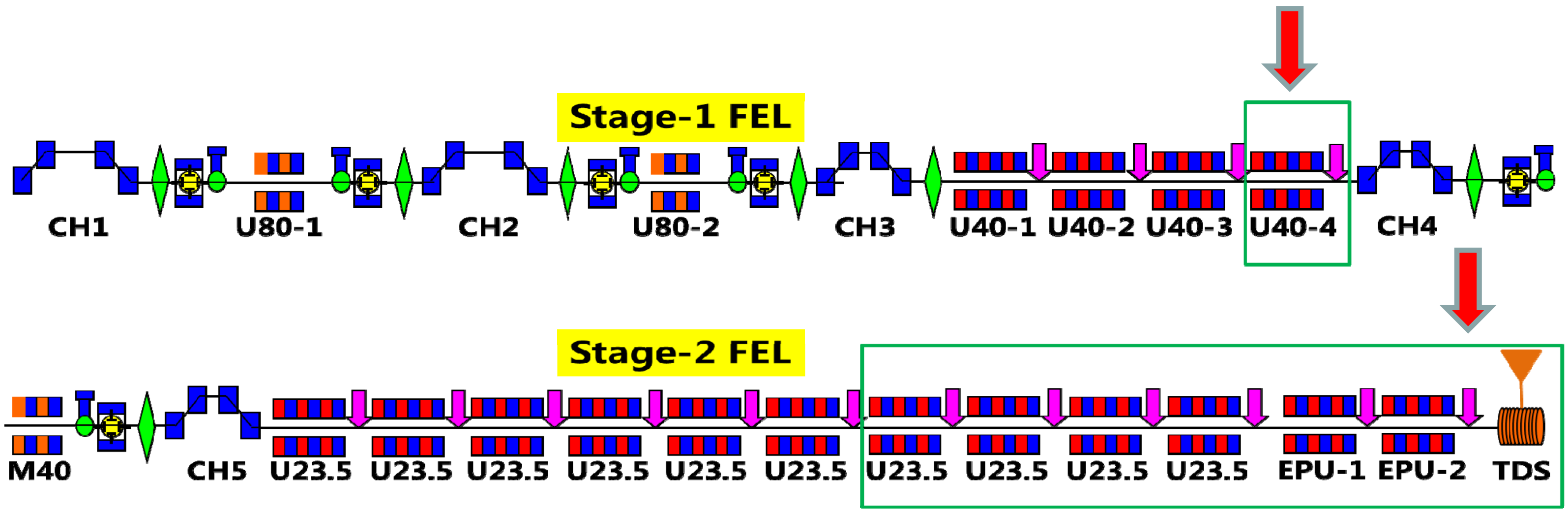
Adding:

1) 1 S-band klystron and 2 SLEDs

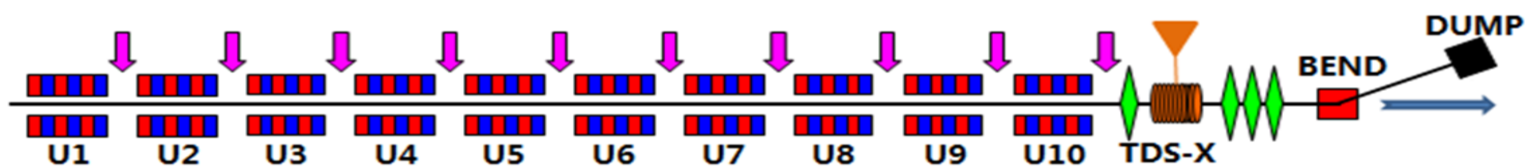
2) 1 C-band RF unit
3) 3 C-band RF units

4) 1 X-band deflecting structure

- **FEL1:** Seeded FEL line: add 7 undulator units

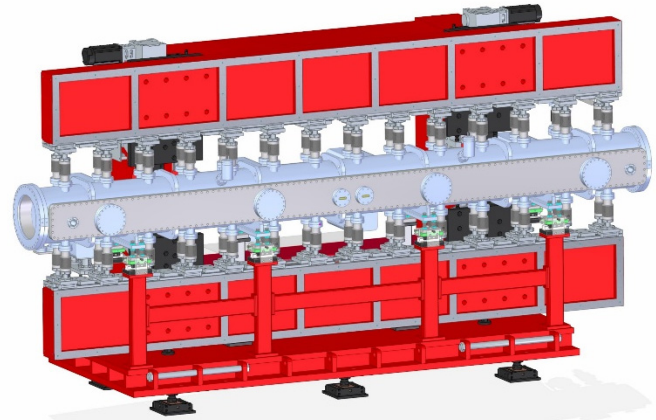


- **FEL2:** SASE FEL line: build 10 in-vacuum undulator sections



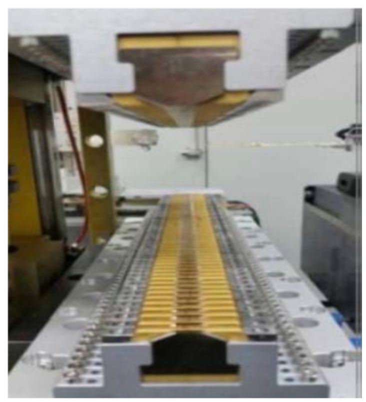
SXFEL-UF C-band Accelerating Unit and Undulators


C-band Accelerating Unit


In-vacuum Undulator


Undulator

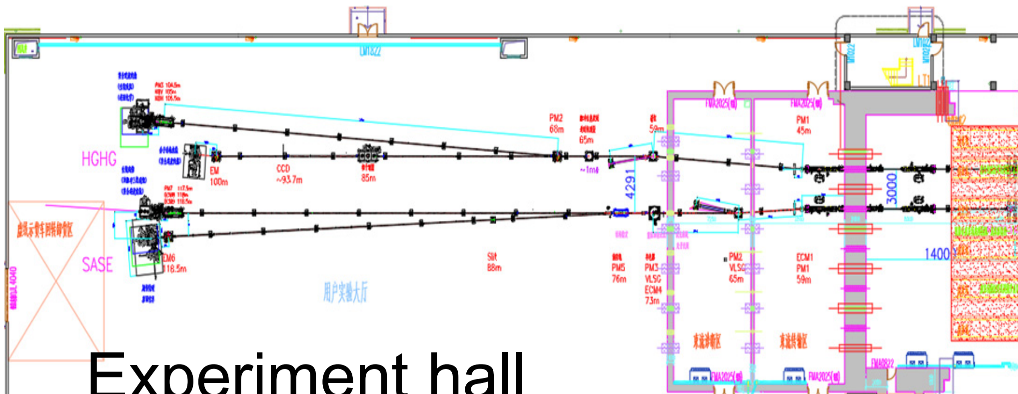

IVU16 Mechanical frame

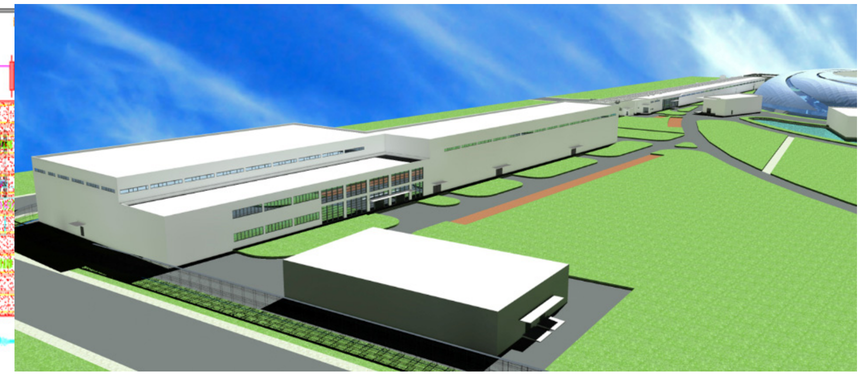

Undulator magnets


IVU16-Vacuum chamber

SXFEL-UF

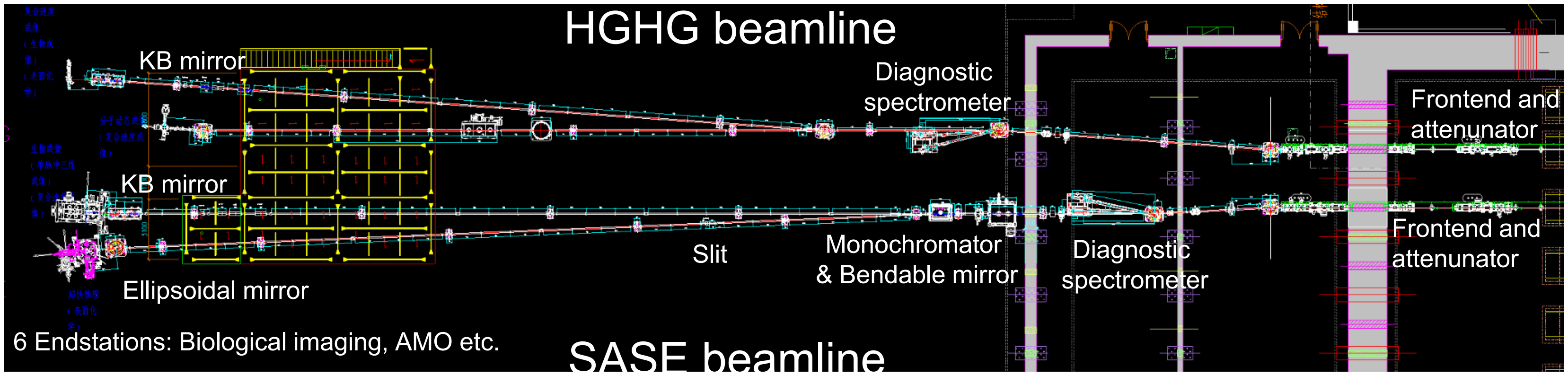
- **Endstations**: Coherent Diffraction Imaging, Atom Molecules Optics, Ultrafast Physics, Surface Chemistry, Pho.-Electr. Spectroscopy



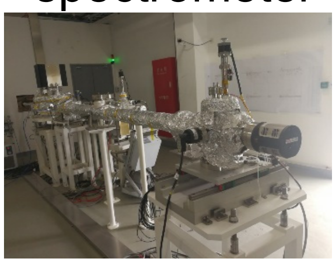


Experiment hall

HGHG & SASE Beamlines

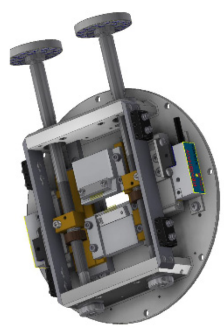


Diagnostic spectrometer

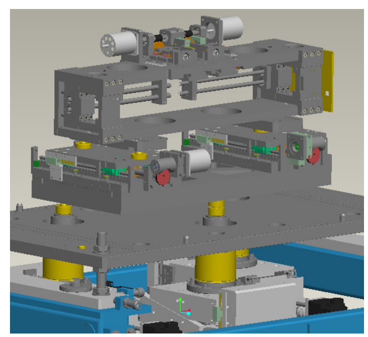


GMD

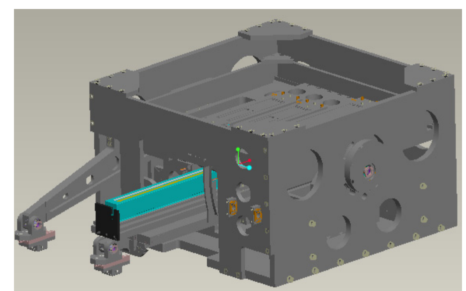
Slit



Bendable mirror



Monochromator



SXFEL-Parameters at Sample Positions

	SASE beamline	HGHG beamline
Energy range	1.2-12 nm (100-1000 eV)	2.4~24nm (50~500eV)
Pulse energy	330μJ @100eV,47μJ @620eV	64μJ @56eV , 5μJ @500eV
Photon flux /pulse	4.6×10^{11}@620eV ~1.3×10^{13}@100eV	5×10^{9}@500eV ~2.9×10^{12}@50eV
Energy resolution (ΔE/E)	0.04%~0.2%	0.008%~0.04%
Energy resolving power Of diagnostic spectrometer (E/ΔE)	~3×10^{4} @620 eV	~4×10^{3} @200eV
Spot size	~3μm	~10μm
Pulse width (fs)	117fs@620eV	50 fs@300eV
Rep-rate	1~50 Hz	1~50 Hz

SXFEL-UF Building

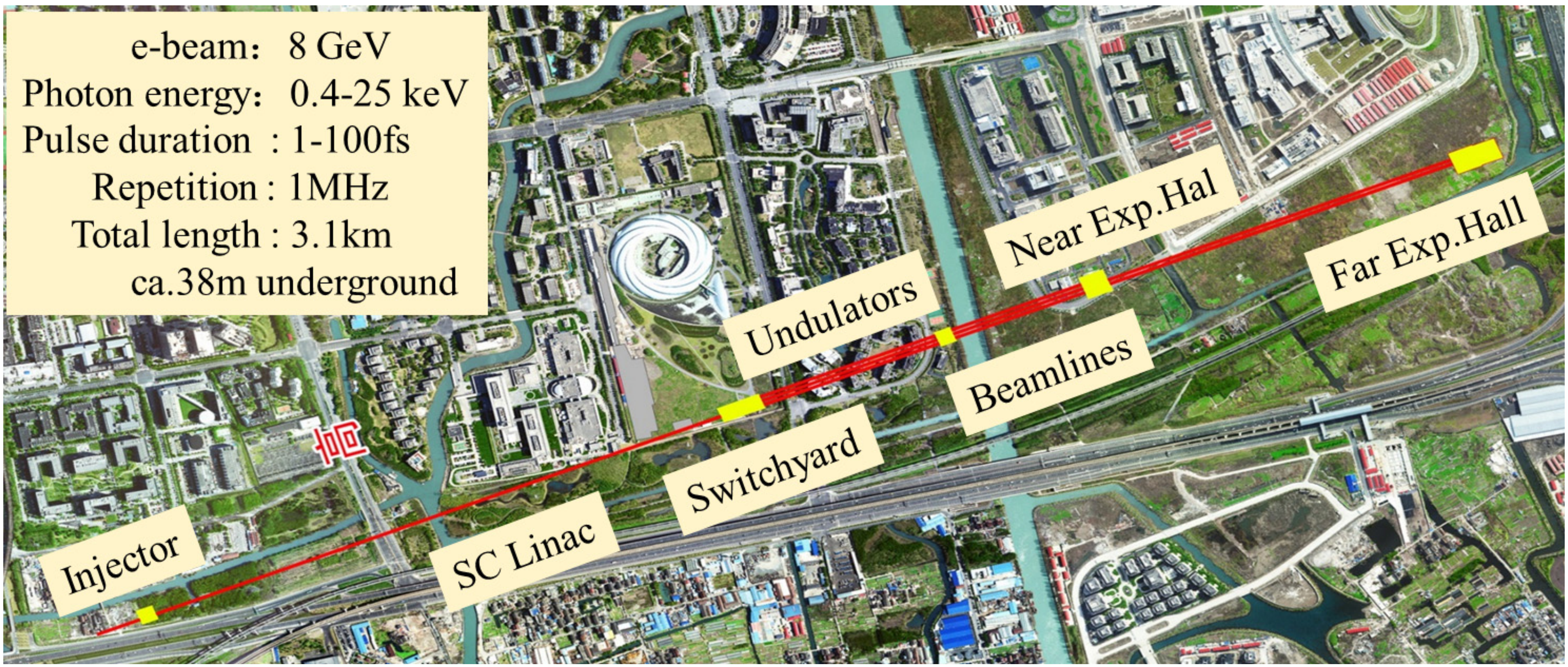
Shanghai Hard X-ray FEL Facility (SHINE)

- SHINE is a high rep-rate XFEL facility, based on an 8 GeV CW SCRF linac, under development in China;
- 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, 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 starting user experiments in 2025.

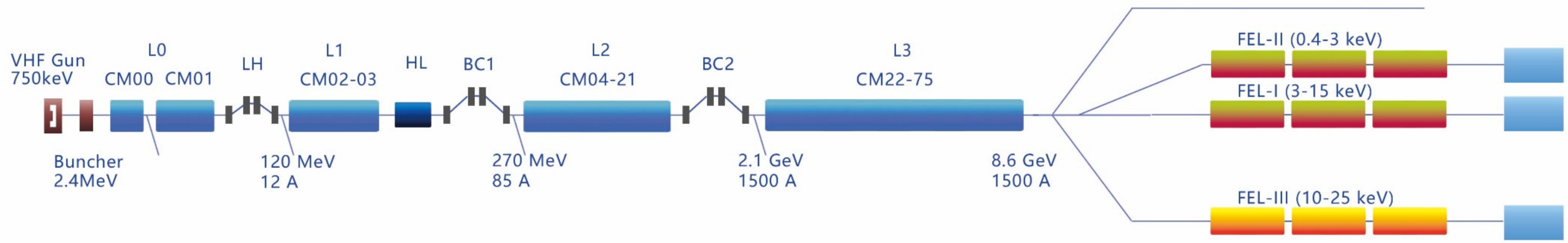
This facility will be developed by Shanghai-Tech Univ., SINAP and SIOM of Chinese Academy of Sciences.

Shanghai Hard X-ray FEL Facility (SHINE)

- **SHINE**: Shanghai HIgh repetition rate XFEL aNd Extreme light facility
- This newly launched high rep-rate hard X-ray FEL is funded with a strong support from Shanghai local government (about 80% of the total budget ~1.5B US$)



SHINE: A high-rep rate XFEL based on SCRF

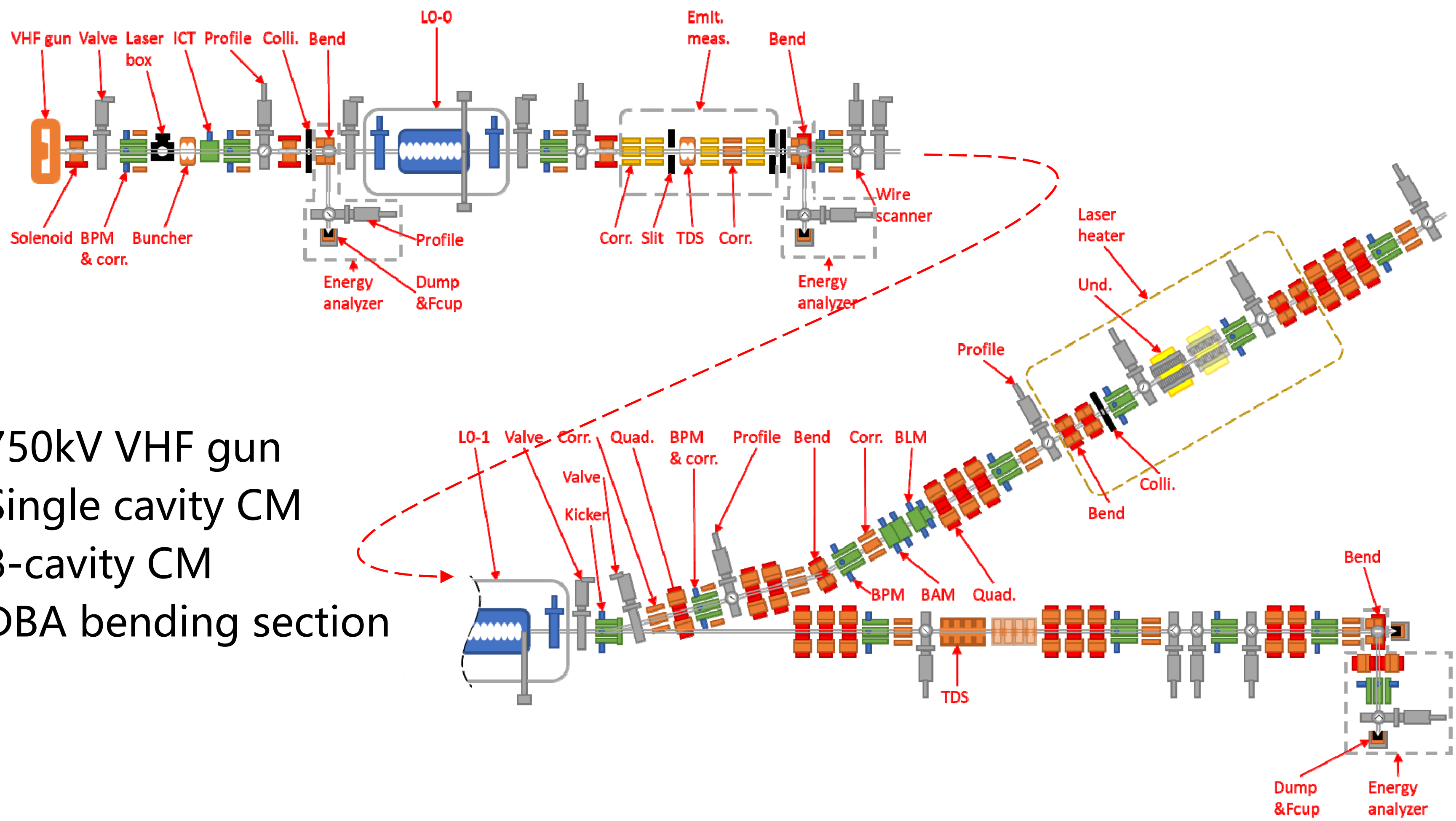


➢ **XFEL Facility +100 PW Laser Facility**

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

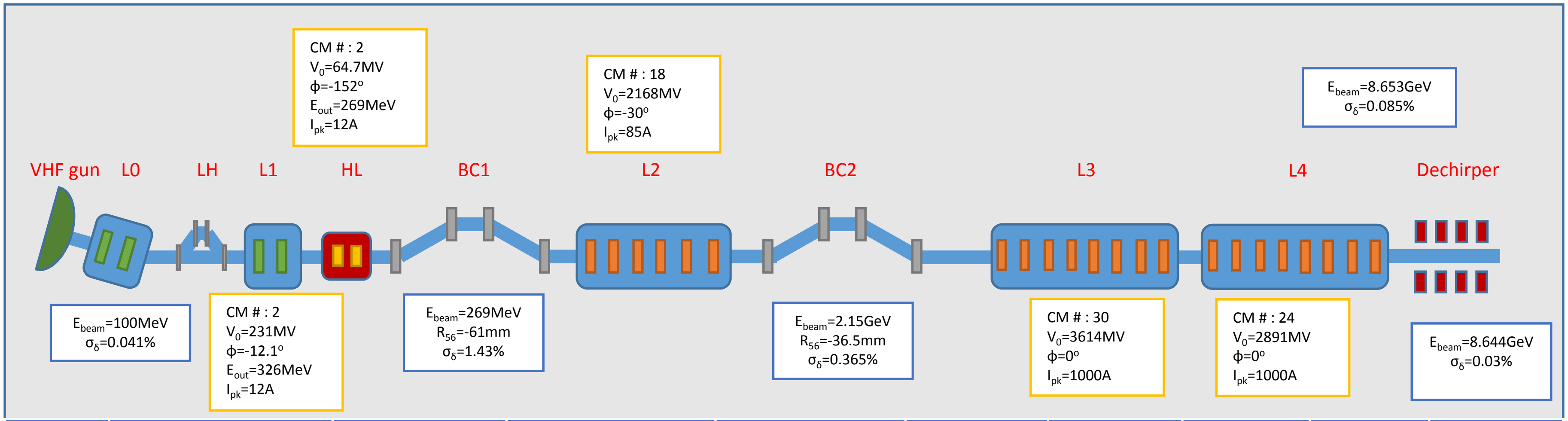
FEL Line	Objective
FEL-I	
Photon energy/keV	3-15
Photon number per pulse @12.4keV	$>10^{11}$
Max pulse repetition rate/MHz	1
FEL-II	
Photon energy/keV	0.4-3
Photon number per pulse @1.24keV	$>10^{13}$
Max pulse repetition rate/MHz	1
FEL-III	
Photon energy/keV	10-25
Photon number per pulse @15keV	$>10^{10}$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

Injector Layout



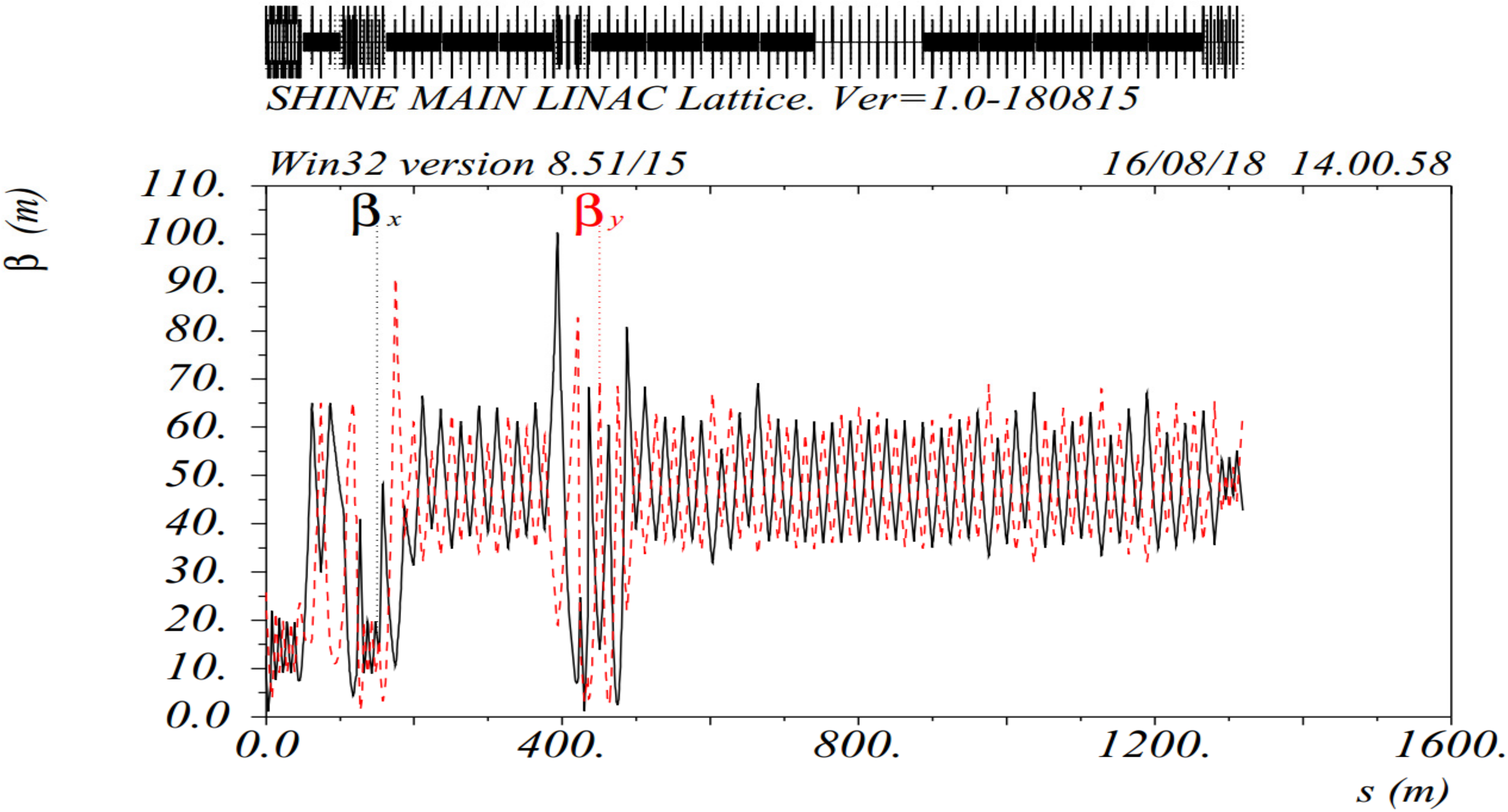
- 750kV VHF gun
- Single cavity CM
- 8-cavity CM
- DBA bending section

Linac Layout



	No. of CM's	Avail. Cavities	Powered. Cavities*	Gradient (MV/m)	Eout (MeV)	σ_z (mm)	σ_δ (%)	ϕ_{rf}	R_{56} (mm)
L0	1	8	7	16.3	100	1	0.04	0	-
L1	2	16	15	14.8	326	1	0.383	-12.1	-
HL	2	16	15	12.5	269	1	1.433	-152	-
BC1	-	-	-	-	269	0.14	1.433	-	-61
L2	18	144	135	15.5	2148	0.14	0.365	-30	-
BC2	-	-	-	-	2148	0.007	0.365	-	-36.5
L3	30	240	225	15.5	5762	0.007	0.085	0	-
L4	24	192	180	15.5	8653	0.007	0.085	0	

Lattice of the SHINE Linac

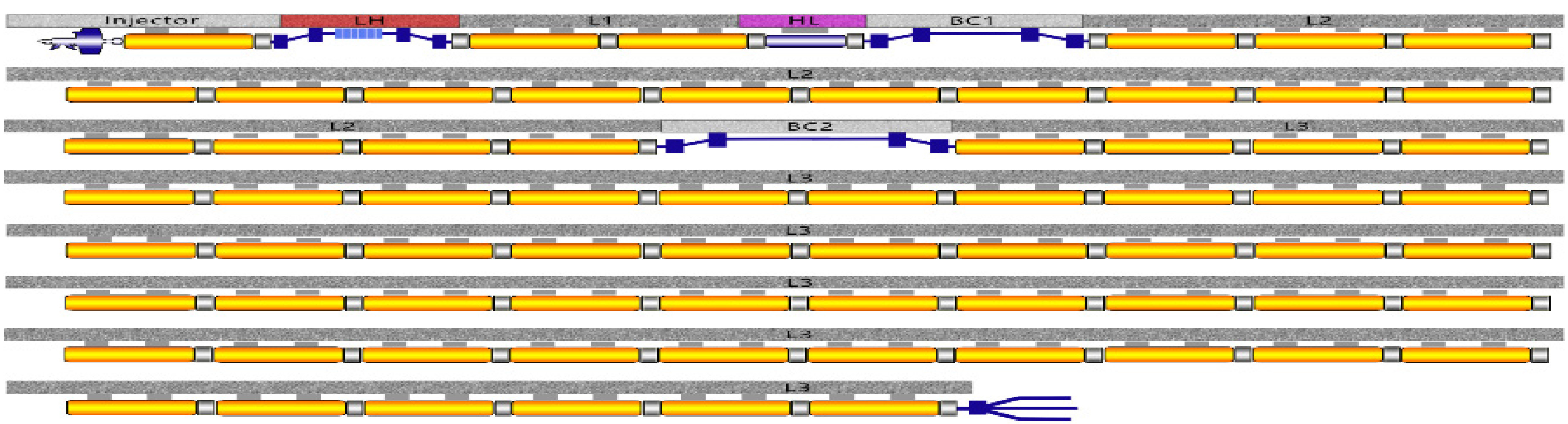


8GeV SCRF Electron Linac

Parameters	Specification
Energy (GeV)	8
Slice energy spread (rms)	≤0.01%
Slice emitt. (mm·mrad, rms)	≤0.4
Pulse Charge (pC)	100
Peak current (A)	1500
Repe-rate (kHz)	660 (100~1000)

	No. of CM's	Avail. Cavities	Powered Cavities	Gradient (MV/m)	E_{out} (MeV)
L0	1	8	7	16.3	100
L1	2	16	15	14.8	326
HL	2	16	15	12.5	269
BC1	-	-			269
L2	18	144	135	15.5	2148
BC2	-	-			2148
L3	54	432	406	15.5	8653
	75+2	600+16			

- 1.3GHz SCRF cryomodules: 75
- 3.9GHz SCRF cryomodules: 2



Cryomodule

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 shielding
- 1 - Vacuum components and valves
- 1 - Cold mass support system
- 1 – Vacuum vessel
- 1 - Cryomodule support system

Integration of many components and techniques

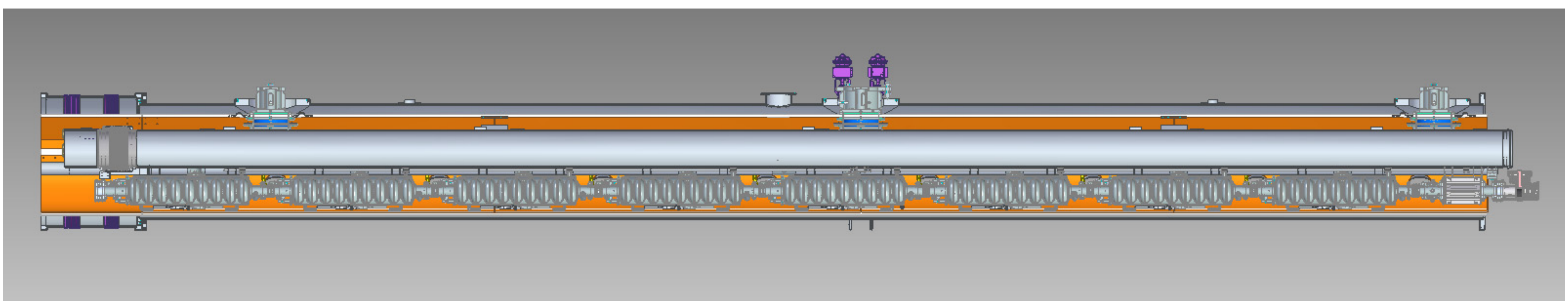
Superconducting, RF, Magnet,

Beam instrumentation, Vacuum, Particle free,

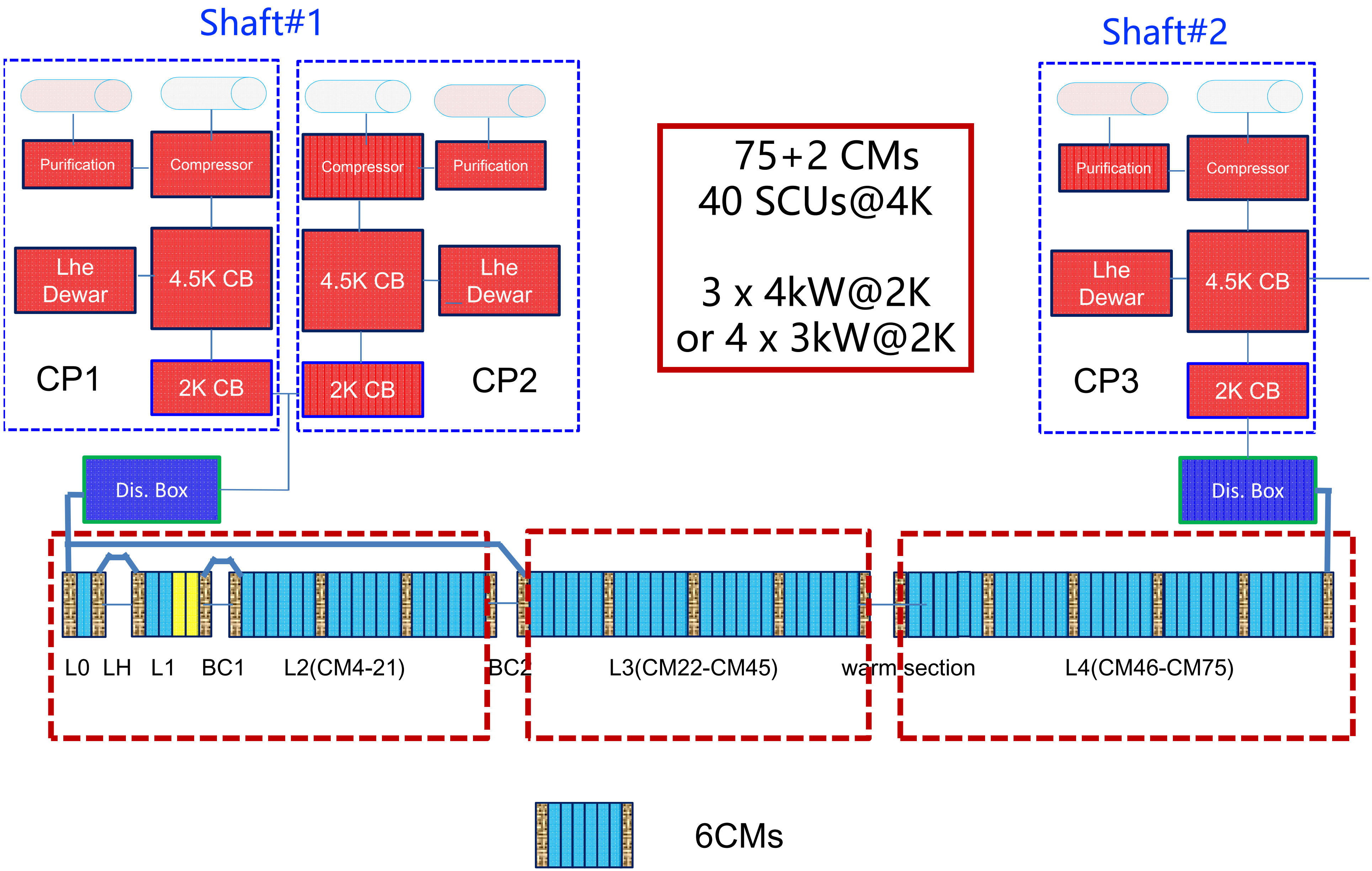
Cryogenic, Mechanics, Alignment……

Main parameters for the CM

CW accelerating voltage	**≥ 128 MV**
Dark current	**< 1 nA**
Heat load@2K @5K @45K	**< 93 W** **< 25 W** **< 215 W**



Cryomodules and Cryogenic System



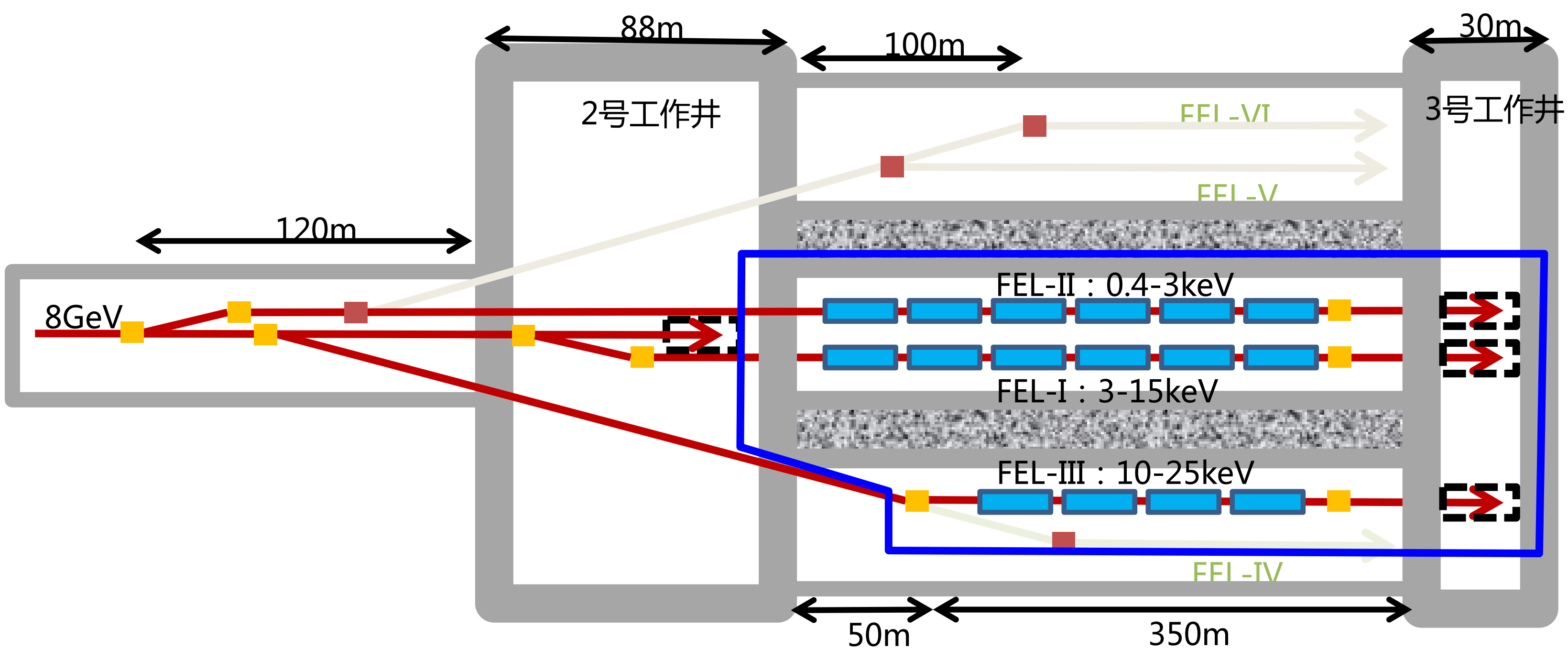
Undulator Layout and FEL Schemes

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

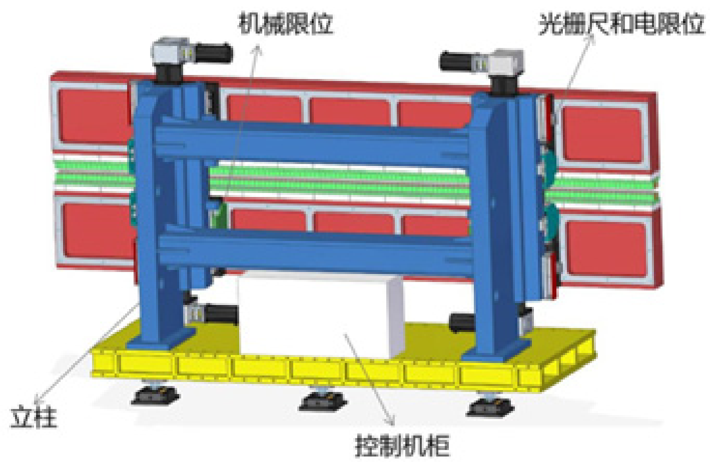


Undulators

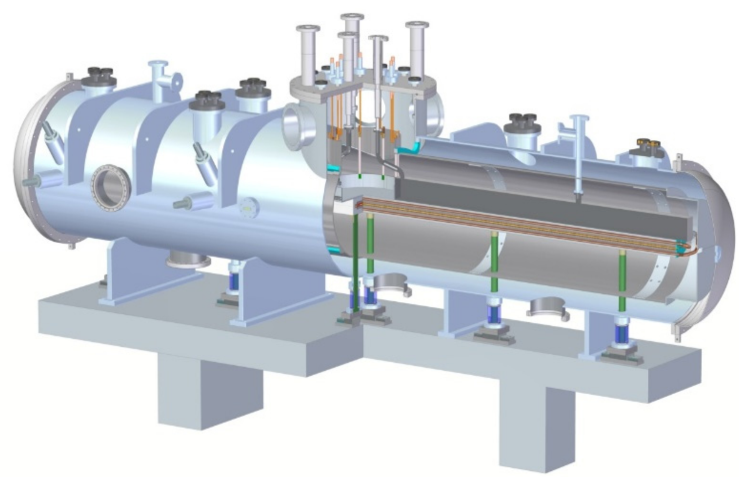
	FEL-I	FEL-II	
Type	**Planar**	**Planar**	**Elliptical**
Quantity	34	40	4
Period Length (mm)	26	68	68
Effective Length (m)	5	4	4
Minimum Gap (mm)	7	7	5
Maximum Peak Field (T)	1.0	1.5	1.5/1.5/1.06

Type	Planar
Quantity	40
Period Length (mm)	16
Effective Length (m)	4
Minimum Gap (mm)	5
Aperture (mm)	4
Maximum Peak Field (T)	1.58
Winding Material	NbTi/Cu
Cooling	LHe conduction, 4.2-4.5 K

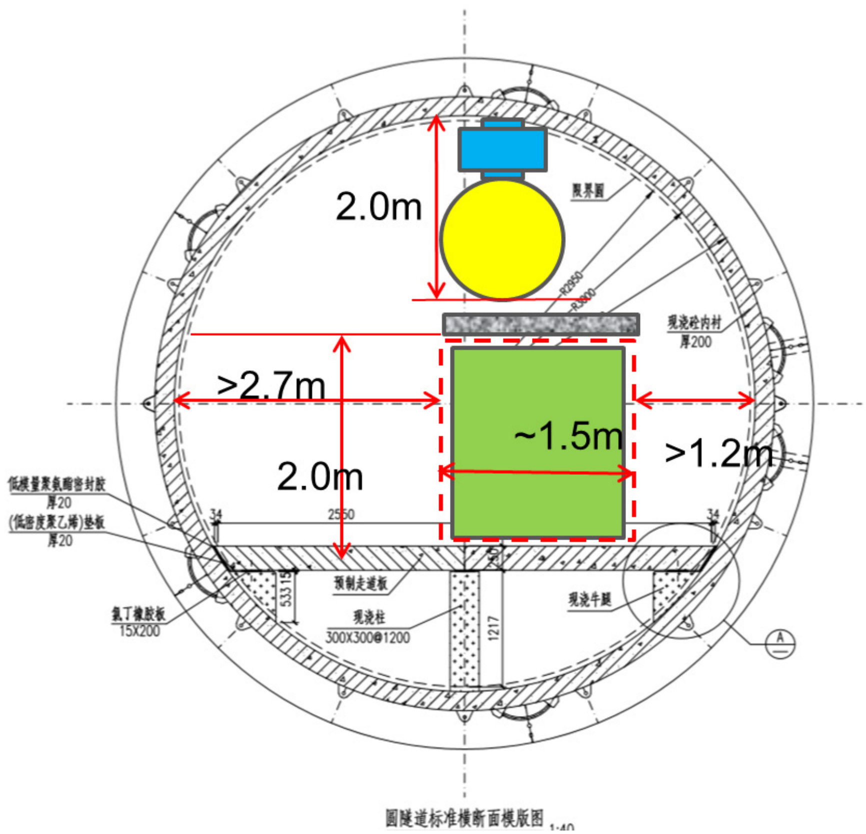
Permanent magnet undulator

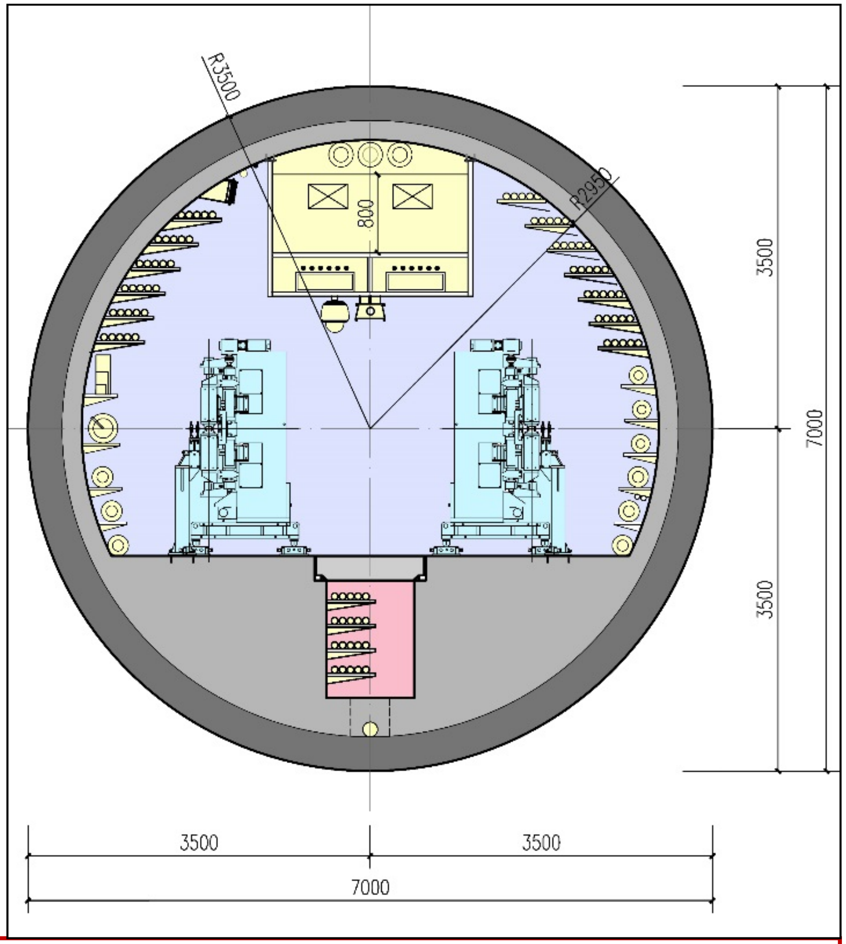


Superconducting undulator



Linac and FEL Undulator Tunnels
(5.9m diameter)

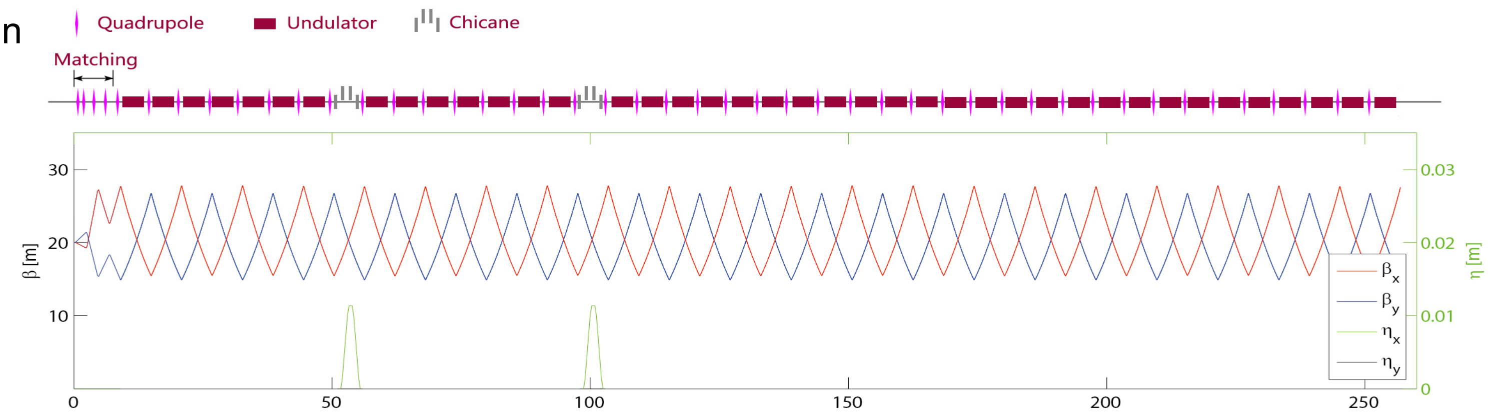




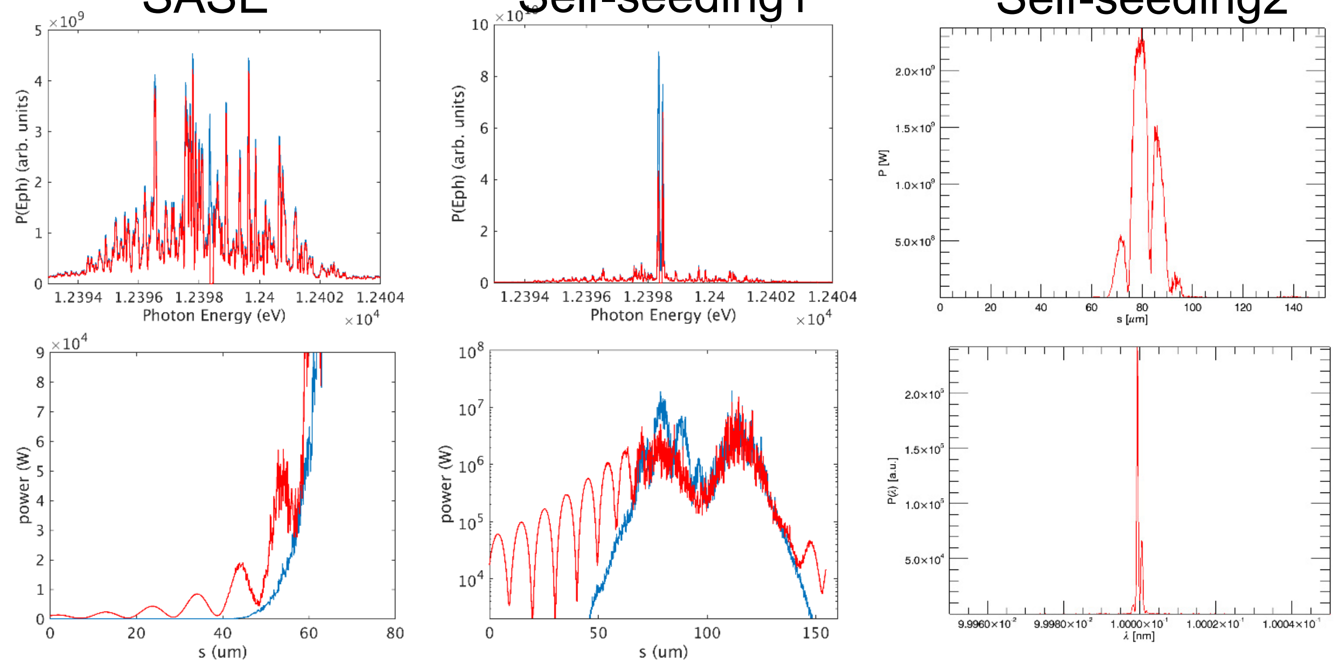
- Left：cross section of the linac tunnel
- Right：cross section of undulator tunnel

FEL-I & FEL-III (hard x-ray self-seeding)

Lattice design

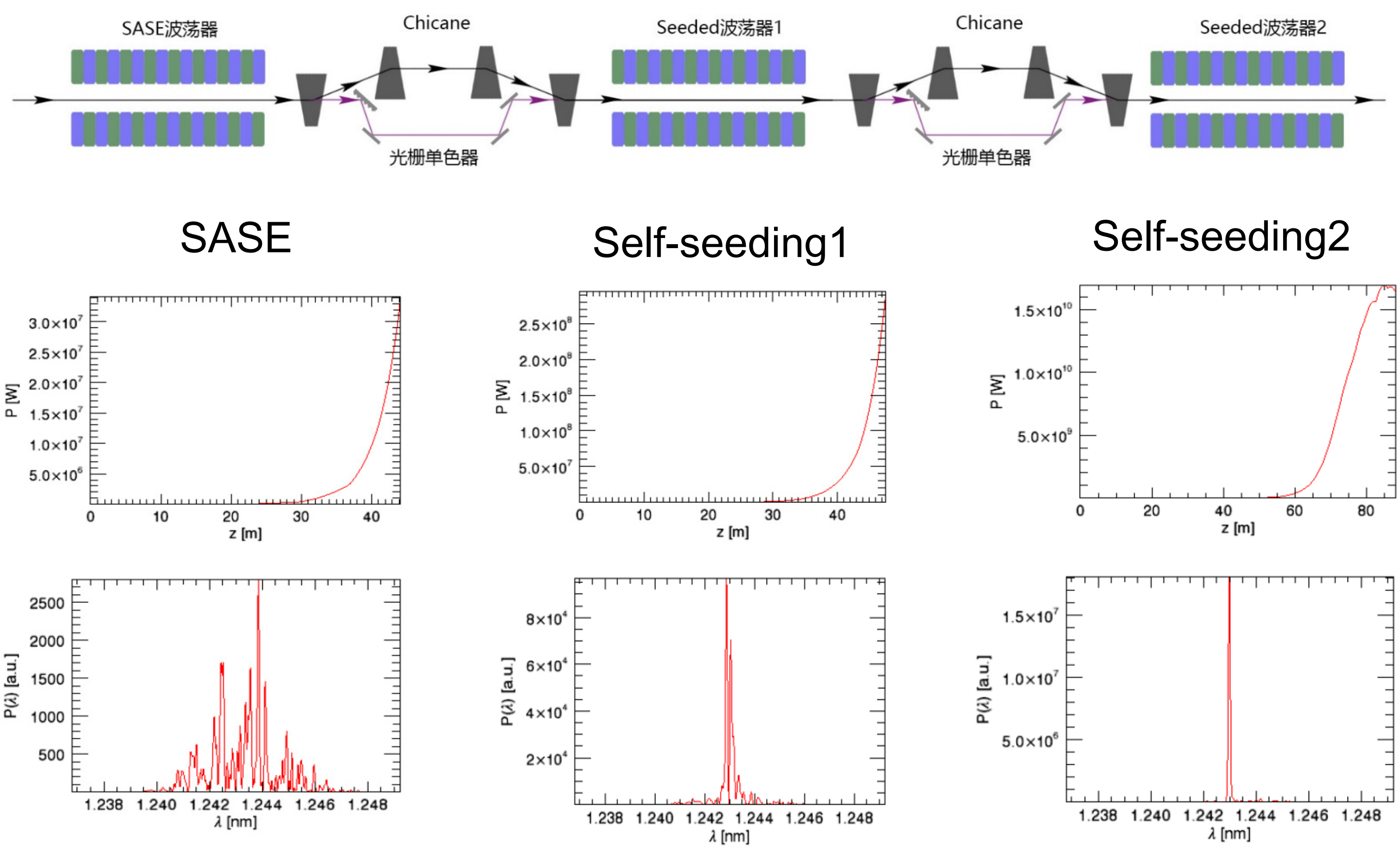


SASE | Self-seeding1 | Self-seeding2



- Adopt two-stage crystal-based monochromators
- Cover the photon energy range from 3-15 keV

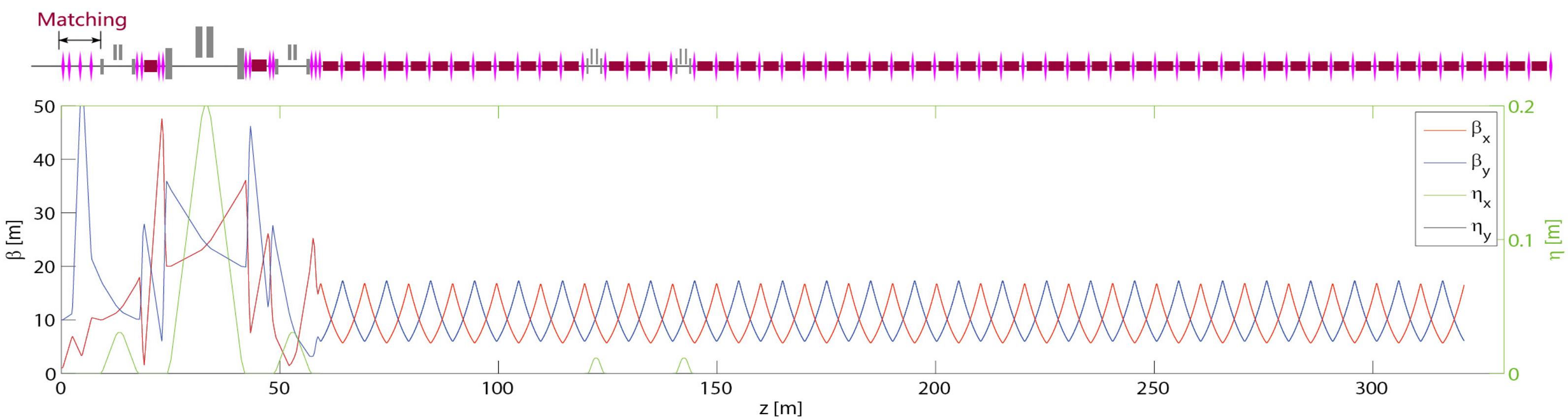
FEL-II (soft x-ray self-seeding)



- Adopt two-stage grating-based monochromators to relax the heat-loading effect for high repetition rate operation and improve the temporal coherence
- Cover the photon energy range from 0.4-1.5 keV

FEL-II (external seeding)

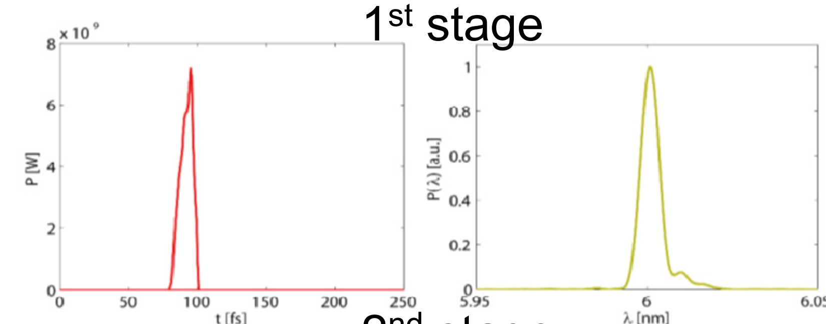
Lattice design



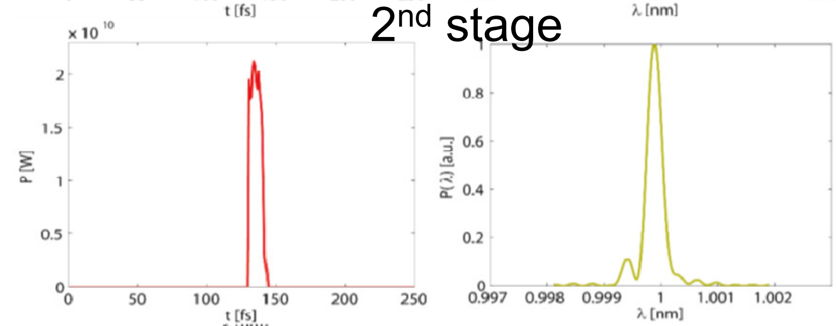
EEHG-HGHG cascade

	1st stage (EEHG)	2nd stage (HGHG)
Modulator	40cm×10	6.8cm×40×2
Seed laser wavelength	266nm	3~6nm
Seed laser power	10GW	~10GW
Seed laser pulse length	30fs、100fs	30fs、100fs
Seed laser waist（rms）	1mm	~1mm
Dispersion 1/2（R56）	0~9 mm/0~0.5mm	0~0.1mm
Radiator	6.8cm×60×12	6.8cm×60×24
FEL wavelength	3~6nm	1~3nm

1st stage

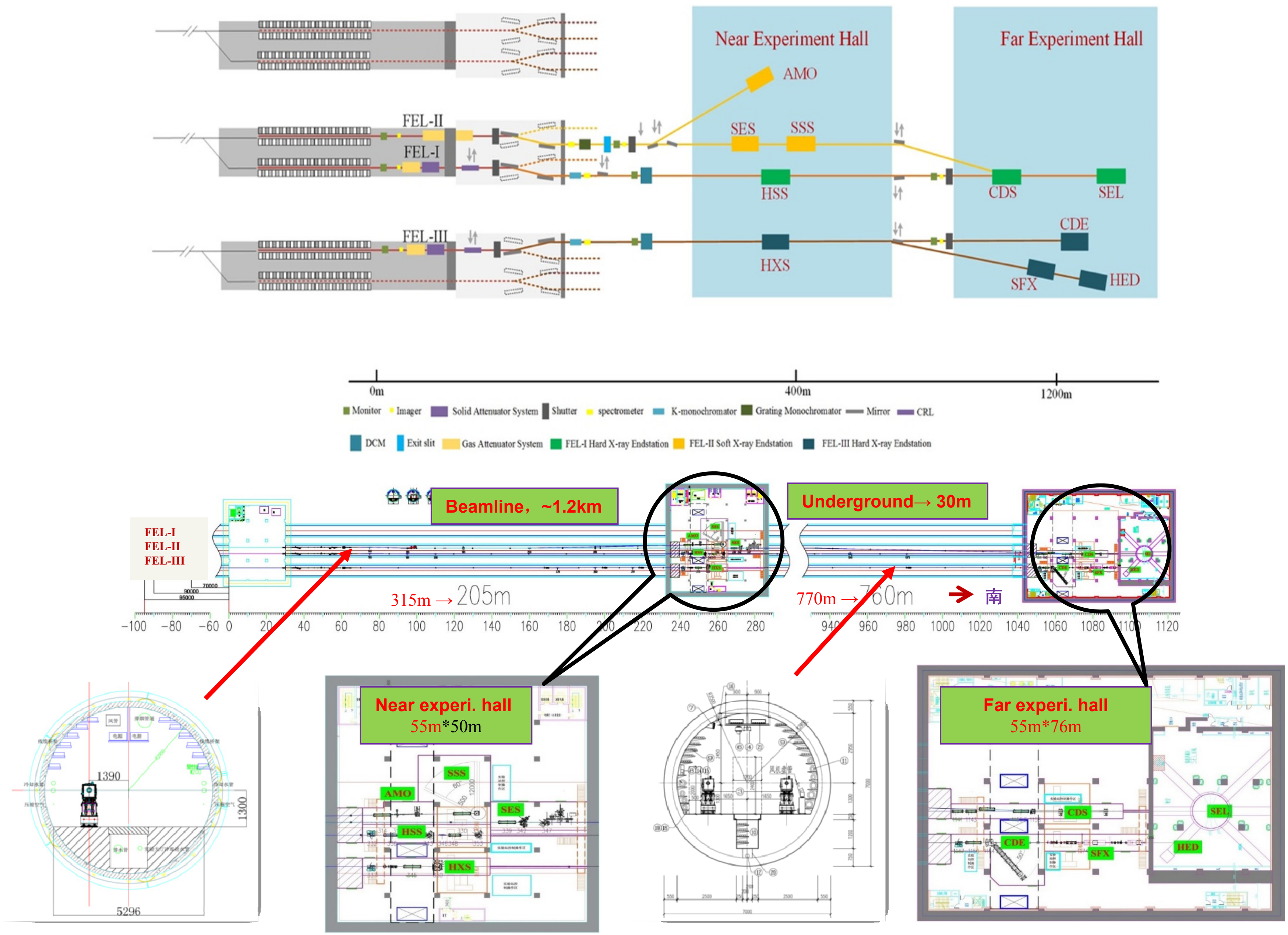


2nd stage



Fully coherent radiation at 1nm and below

Layout of Beamlines and Experimental Stations



10 Phase-I End-Stations

➢ FEL-I Hard X-ray Endstation

•**HSS:** Hard X-ray Scattering Spectrometer
•**CDS:** Coherent diffraction end-station for single particle and biomolecules
•**SEL:** Station of Extreme Light **→XFEL Facility +100 PW Laser Facility**

➢ FEL-II Soft X-ray Endstation

•**AMO:** atomic, molecular, and optical physics
•**SES:** Spectrometer for Electronic Structure
•**SSS:** Soft X-ray Scattering Spectrometer

➢ FEL-III Hard X-ray Endstation

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

FEL Parameters of SHINE

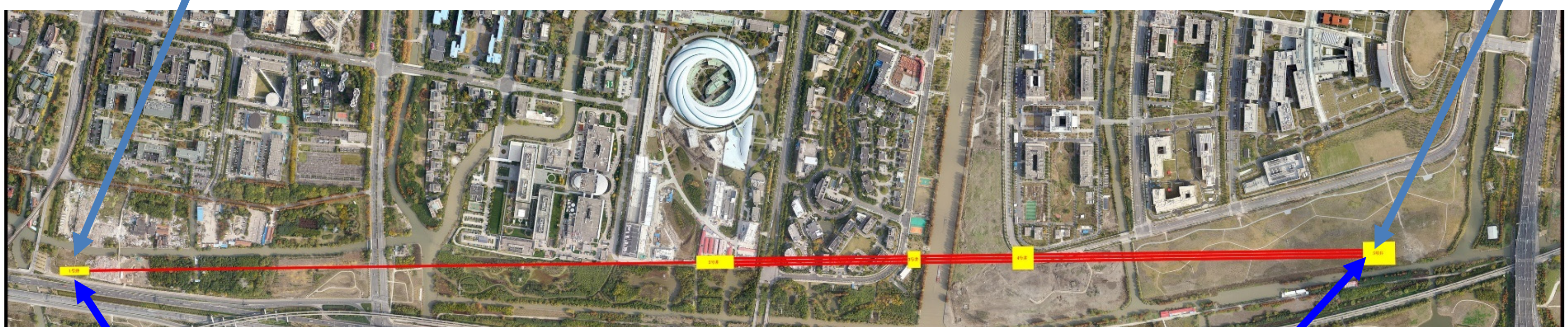
	FEL-I	FEL-II	FEL-III
Undulator type	planar	Planar + EPU	SCU
Period length	26mm	68mm	16mm
Section length	5m	4m	4m
FEL modes	HXSS/SASE	SXSS/EEHG/SASE	HXSS/SASE
FEL photon energy	3.0-15keV	0.4-3.0keV	10-25keV
FEL peak power	5-25GW	30-55GW	4-18GW
FEL pulse energy*	25-1100μJ	130-2400μJ	20-800μJ
FEL BW（RMS）	0.06%	0.1%	0.027%
FEL spot（RMS）	50μm	60μm	40μm
FEL diverge.（RMS）	3μrad	10μrad	2μrad

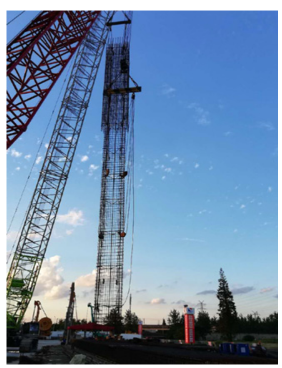
Parameters for Experiments in SEL

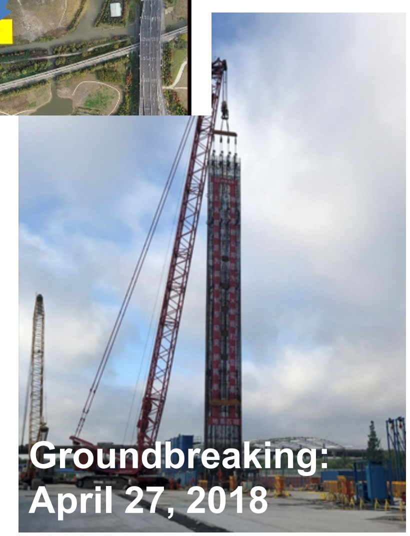
Parameters		Nominal	Objective
X-ray	Photon Energy	3 - 15 keV	3 - 15 keV
	Photons per pulse	10^{12}	10^{12}
	Polarization	45^{o}	45^{o}
	Pulse length	20- 50 fs	5 - 200 fs
	beam spot size	200nm	200nm
	Energy Resolution	0.6 eV	0.6 eV
	Optimized photon energy	12.914keV	12.914keV
Laser	Focused intensity	1×10^{23} W/cm^2	1×10^{23} W/cm^2
	Peak power	100 PW	100 PW level
	Repetition rate	1Hz@0.1-1PW Single shot@100PW	1Hz@0.1-1PW Single shot@100PW

- Pulse energy 1500J; duration 15fs; Central wavelength 900nm; Peak power 100 PW; Focused spot size 5μm; Intensity >10^{23} W/cm^2; Contrast ratio >10^{12}

Groundbreaking and the Civil Constructions of the SHINE Project



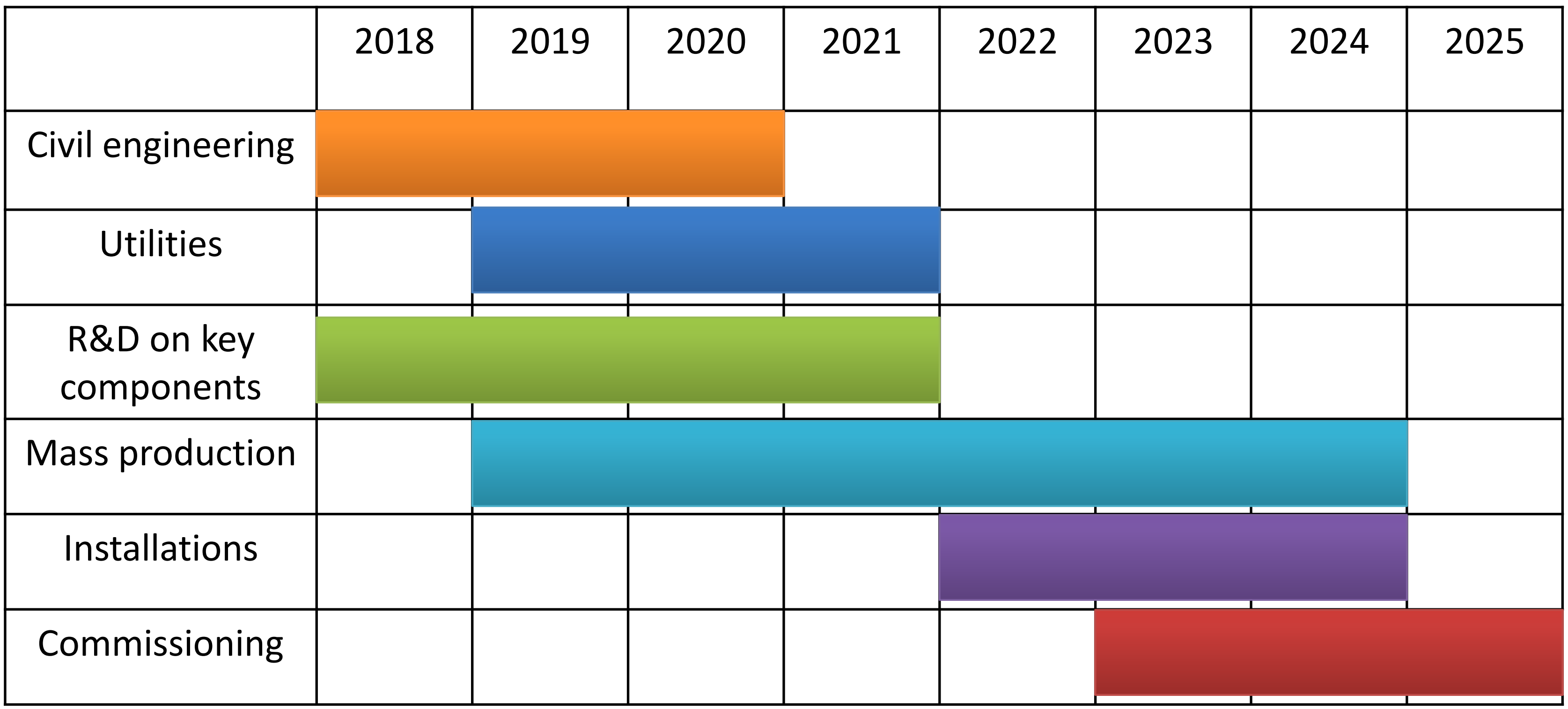




Estimated Construction Cost

Total Construction Cost	~1.5B US$
Central/Local Investment ratio	~20/80

Preliminary Construction Schedule



Groundbreaking was made in April, 2018, user experiments is expected to start in 2025.

Summary

- A soft X-ray FEL facility based on ~1.5 GeV C-band linac is under development, its first phase commissioning has been making progress, aiming at serving users in 2019;
- A high rep-rate hard X-ray FEL facility, with an 8 GeV CW SRF linac, 3 phase-I undulator lines and 10 end-stations, is going to be developed in China.
- This hard X-ray FEL project was approved by central government in 2017, its groundbreaking was made in April 2018, aiming to start user experiments in 2025.


Thank you for your attention
谢谢！
AURORA