Status of SXFEL Test and User Facilities

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Introduction

- China started to develop high gain FEL in late 1990s, when a HGHG scheme based DUV-FEL was proposed;
- In the past decade, the SDUV-FEL test facility that is based on 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 since 2014. Now the test facility is in commissioning, and the user facility is in integration;
- **SHINE**, a high repetition-rate hard X-ray FEL facility based on an 8GeV CW SCRF linac started its construction in April of 2018.

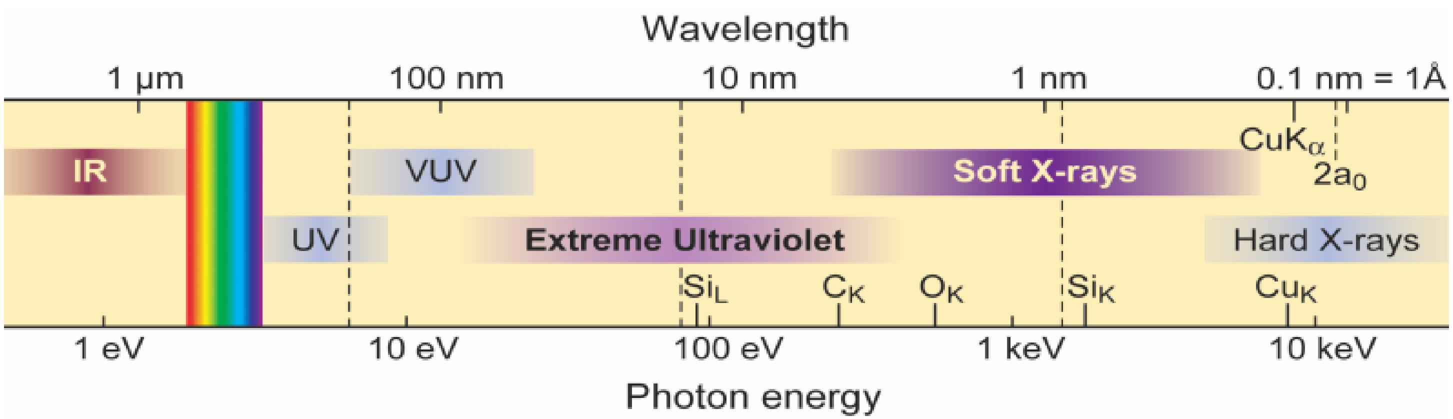
High-gain FEL Facilities in China

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



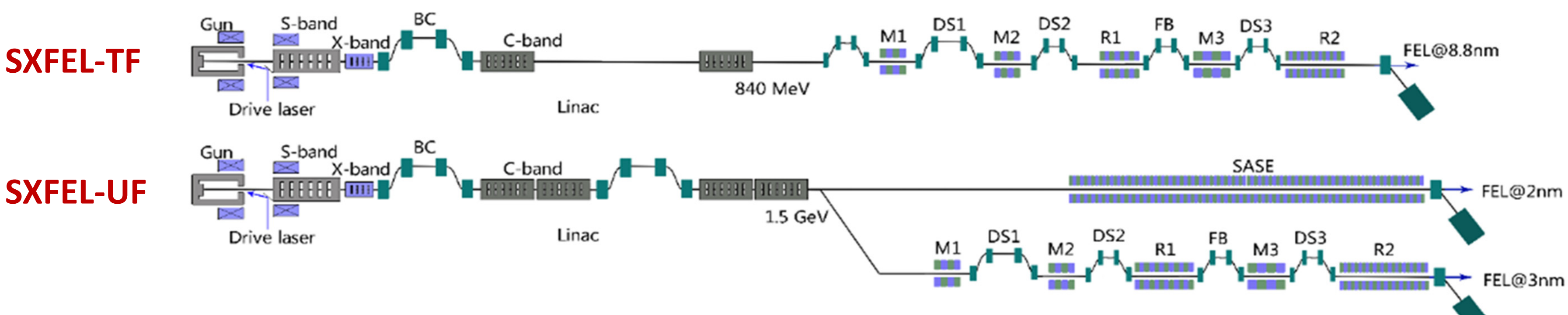
- Photon energy coverage from UV to hard X-ray

High-gain FEL Projects in China

	SDUV-FEL	DCLS	SXFEL-TF	SXFEL-UF	SHINE
Facility type	Test facility	User facility	**Test facility**	**User facility**	**User facility**
Status	Shut **down**	Operation	**Commissioning**	**Construction**	**Construction**
Wavelength	150-350nm	50-150nm	**8.8nm**	**2.0nm**	**0.05-3.0nm**
Length	65m	150m	**293m**	**532m**	**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 scheme	HGHG, EEHG	HGHG	**HGHG, EEHG**	**HGHG/EEHG, SASE**	**SASE, EEHG**
Location	Shanghai	Dalian	**Shanghai**	**Shanghai**	**Shanghai**
First lasing	2009	2016	**2018**	**2020**	**2025**

SXFEL：Shanghai Soft X-ray FEL Facility

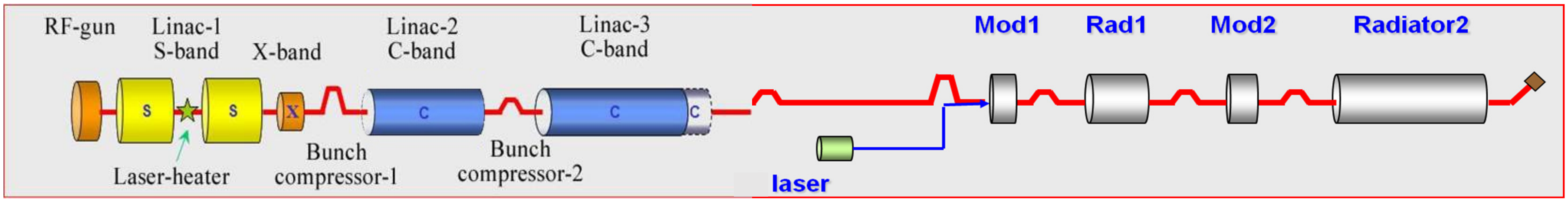
- **SXFEL Facility** consists of two projects independently funded, SXFEL test facility (SXFEL-TF) + SXFEL user facility (SXFEL-UF), located at the SSRF campus;
- **SXFEL-TF** was initiated in 2006 and founded in 2014, its 0.84GeV linac and undulators was installed through 2016 to 2018, it is for testing the cascaded seeding schemes;
- **SXFEL-UF** was founded to upgrade the linac energy to 1.5 GeV for driving 2 undulator lines (SASE+HGHG/EEHG) with 5 experimental stations in the water window region.



Total length	532m
Photon energy	0.2 – 0.6 keV
Pulse length	>10 fs
Repetition rate	10 - 50 Hz
Peak photon power	1 GW
Electron energy	0.8 - 1.5 GeV

Test Facility: SXFEL-TF

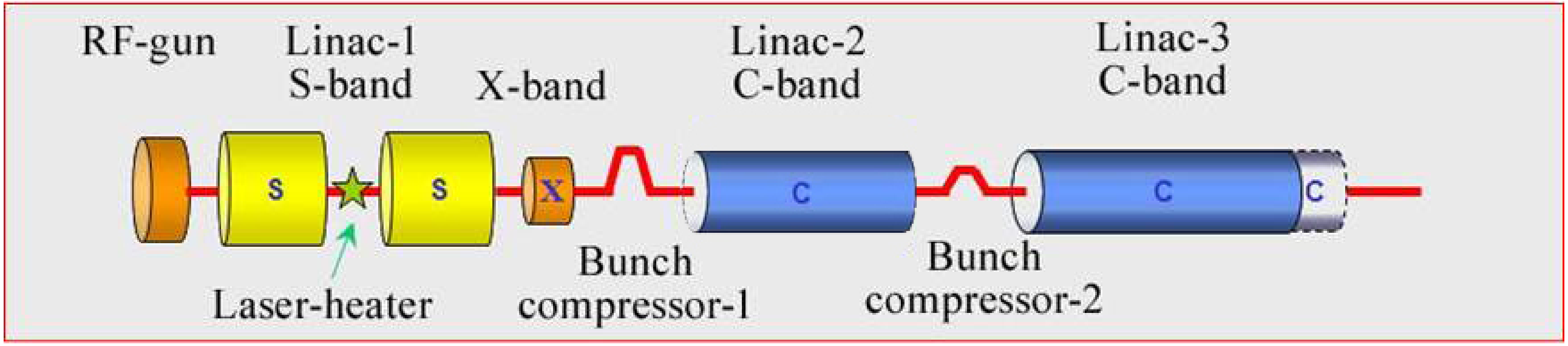
- A seeded FEL with two-stage HGHG or EEHG +HGHG based on a ~0.8GeV linac and located in the campus of SSRF, closing to its synchrotron;



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/MeV	790	790	840
FEL wavelength/nm	8.83	8.83	6.3
FEL pulse/fs	100 – 200	100 - 200	100 - 200
FEL power/MW	>100	>100	>100

SXFEL-TF Linac



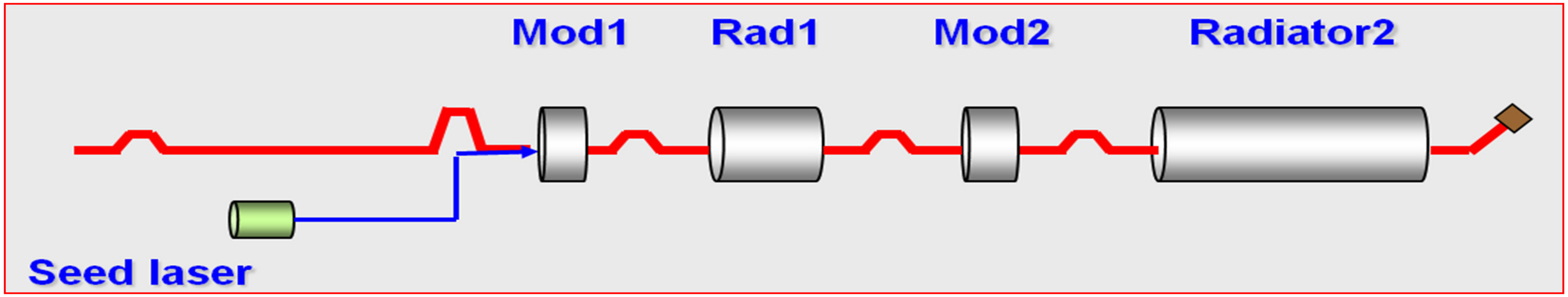
Injector beam parameters

Bunch charge (nC)	0.5
Beam energy (MeV)	129.4
Pulse length (ps, FWHM)	9
Emittance (mm.mrad, rms)	0.95
Energy spread (rms)	< 0.14%
Rep-rate (Hz)	1-10

Main linac beam parameters

Bunch charge (nC)	0.5
Beam energy (GeV)	0.79
Bunch length (ps, FWHM)	1.0
Emittance (mm.mrad, rms)	< 2.0
Energy spread (rms)	< 0.15%
Rep-rate (Hz)	1-10
Peak current (A)	≥ 500

SXFEL-TF Undulator System



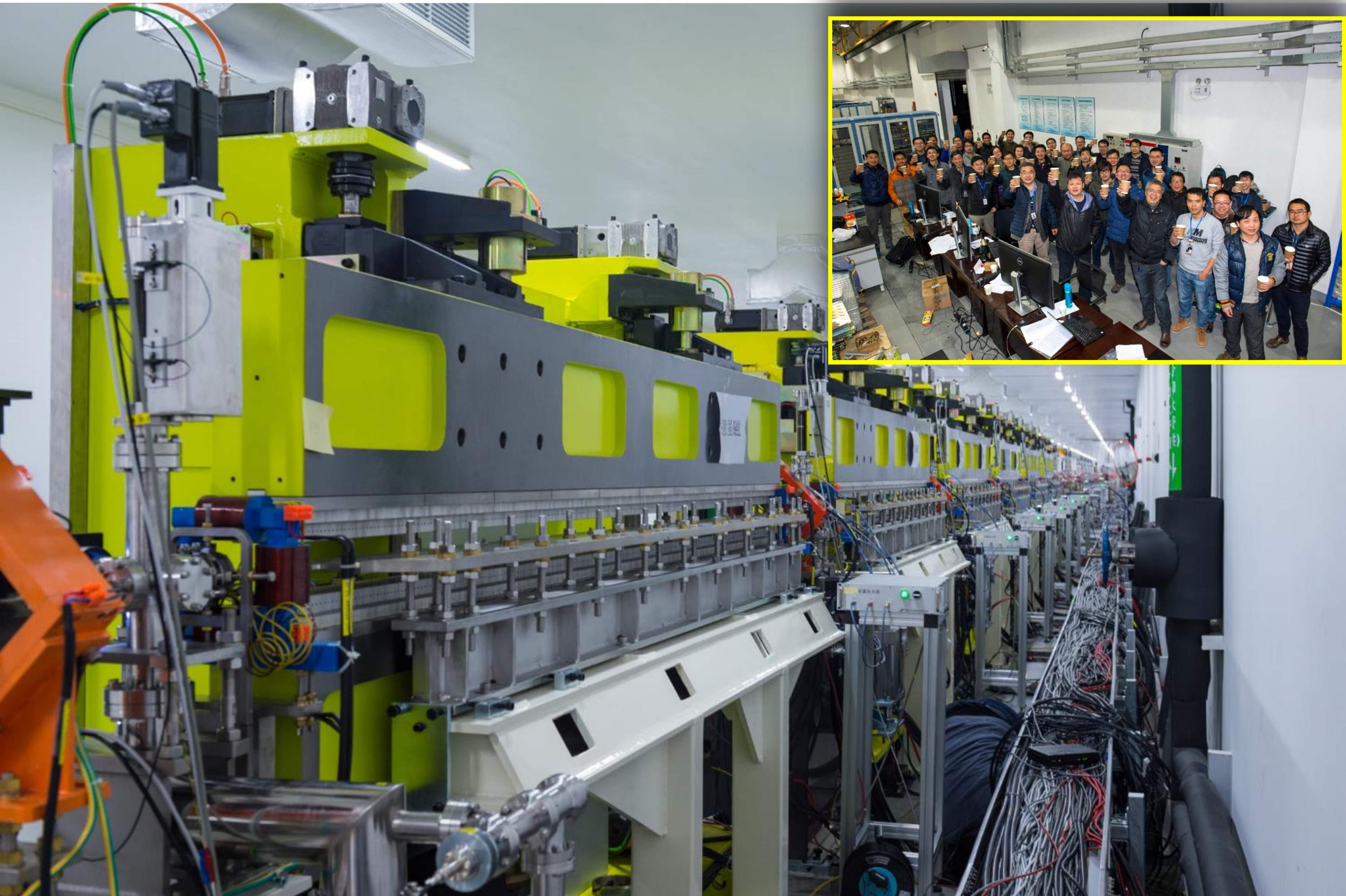
Undulators	
M1: Np×λu	20×8cm
R1: Ns×Np×λu	3×75×4cm
M2: Np×λu	30×5.5cm
R2: Ns×Np×λu	6×125×2.35cm

Chicanes	
DS1: length/θ/R56	12m/0-52mrad/0-25mm
DS2: length/θ/R56	3m/0-34mrad/0-2mm
FB: length/θ/R56	4.46 m/0-47 mrad/0-7mm
DS3: length/θ/R56	3m/0-34mrad/0-2mm

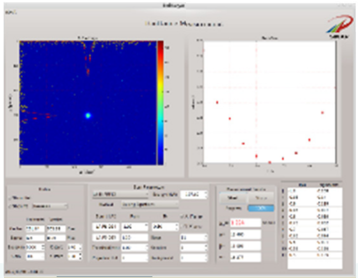
SXFEL-TF: 0.84GeV C-band linac + HGHG/EEHG Schemes

SXFEL-TF: C-band Copper Linac

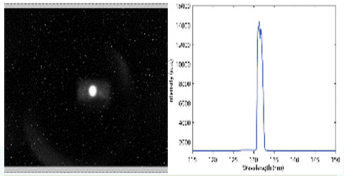
SXFEL-TF: Undulator Radiator



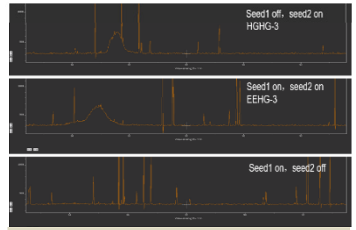
SXFEL-TF commissioning milestones



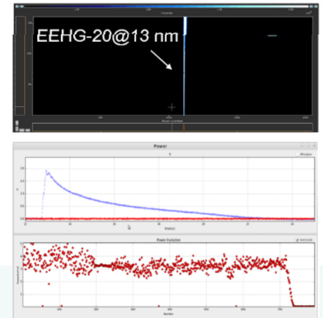
Start commissioning of the injector and main linac during the installation of undulators



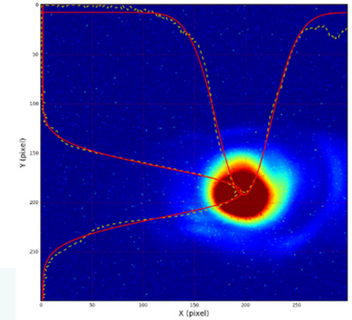
First coherent signal from the 1st stage HGHG



Amplification of the 1st stage EEHG. Pulse energy of the 3rd harmonic radiation exceeds 1 mJ



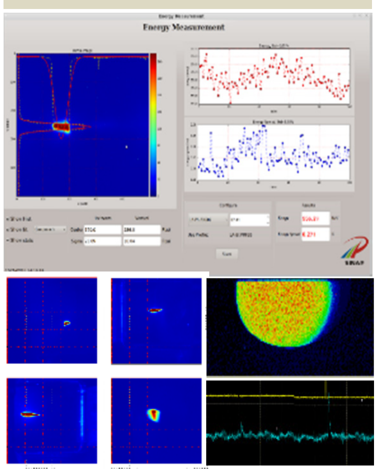
Amplification of EEHG-20



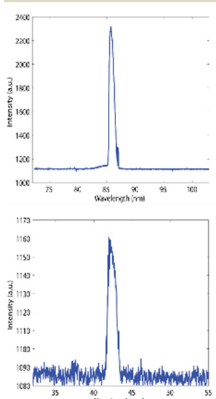
Cascaded HGHG FEL lased at 30th harmonic (8.8nm)

2016 | 2017 | 2018 | 2019

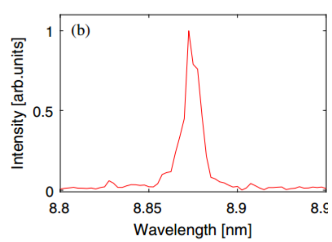
first soft x-ray radiation from the undulator beamline



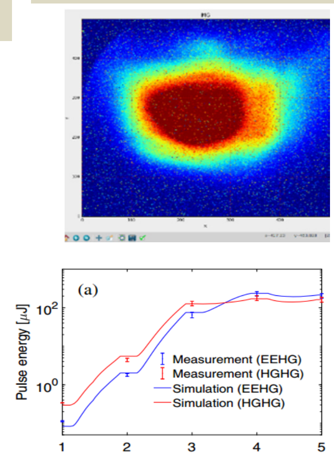
HGHG: 2nd to 6th harmonic



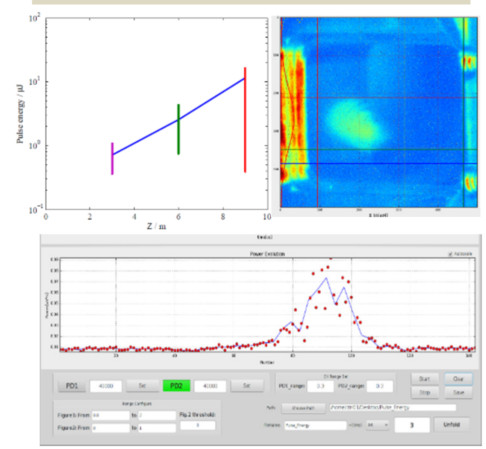
Coherent signal from EEHG-30@8.8nm



Saturation of HGHG-11 and EEHG-11



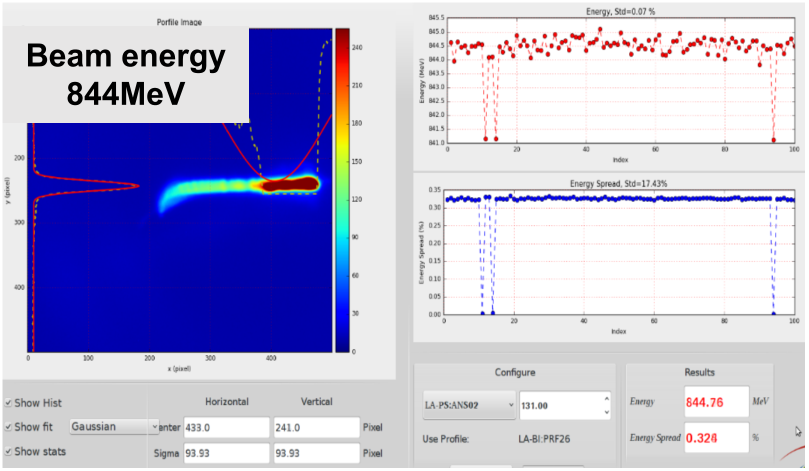
Lasing of the 1st stage HGHG at 6th harmonic and get coherent signal from the 2nd stage HGHG with "fresh bunch"

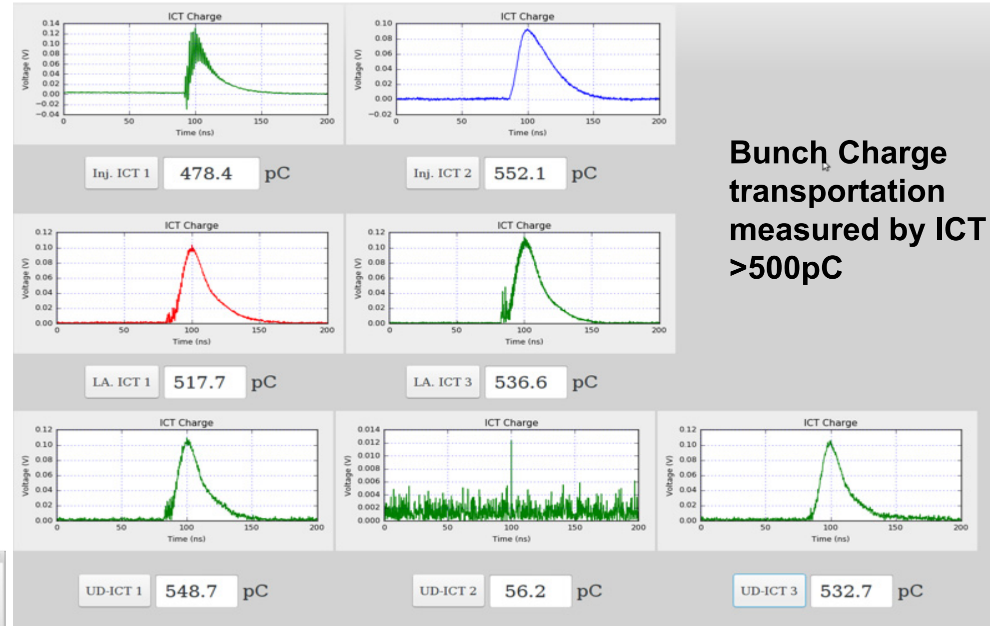


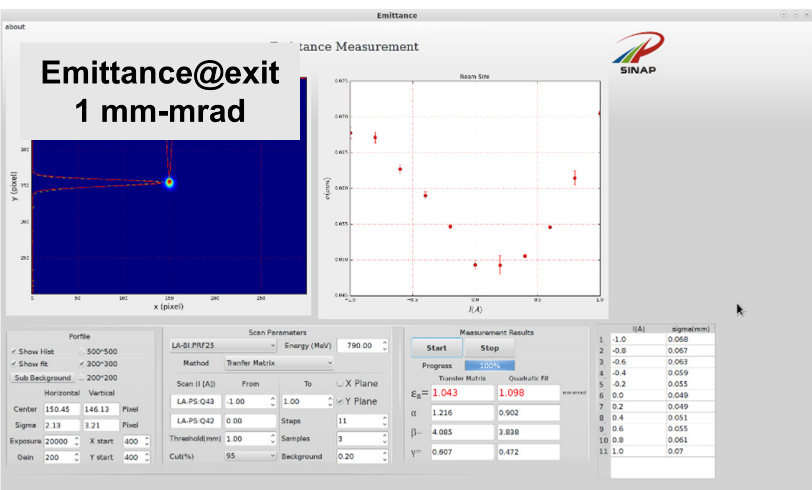
Current Performance of the SXFEL-TF linac

	Design Specification	Achieved Performance	Operating Parameters	
Repetition (Hz)	10	10	2	Injector
Charge (pC)	500	>500	~600	
Normalized Emittance(μm-rad)	<1.5	~1.0	~1.0	
Bunch Length(FWHM, ps)	~10	~10	8	
Energy(MeV)	120	125	120	
Energy Spread(rms, %)	≤0.14	<0.1	<0.1	
Energy(MeV)	840	400 ~ 890	790	Main linac
Energy Spread(rms, %)	≤0.15	<0.1	<0.1	
Bunch Length(FWHM, ps)	~1ps	~1ps	~1ps	
Normalized Emittance(μm-rad)	2.5	<2.0	~1.2	

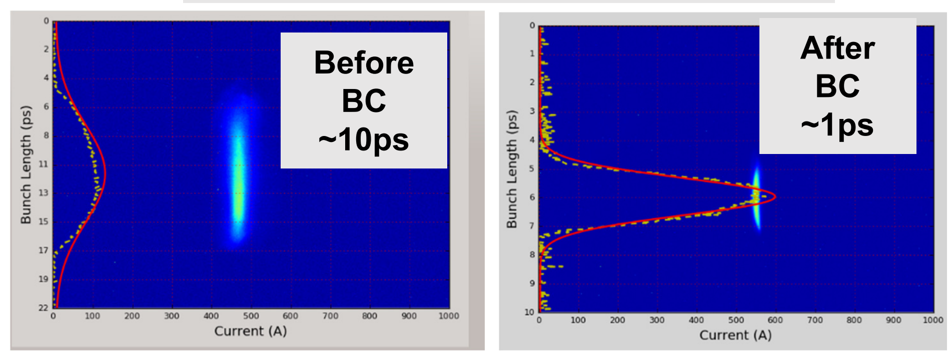
Typical Performance of the SXFEL-TF linac







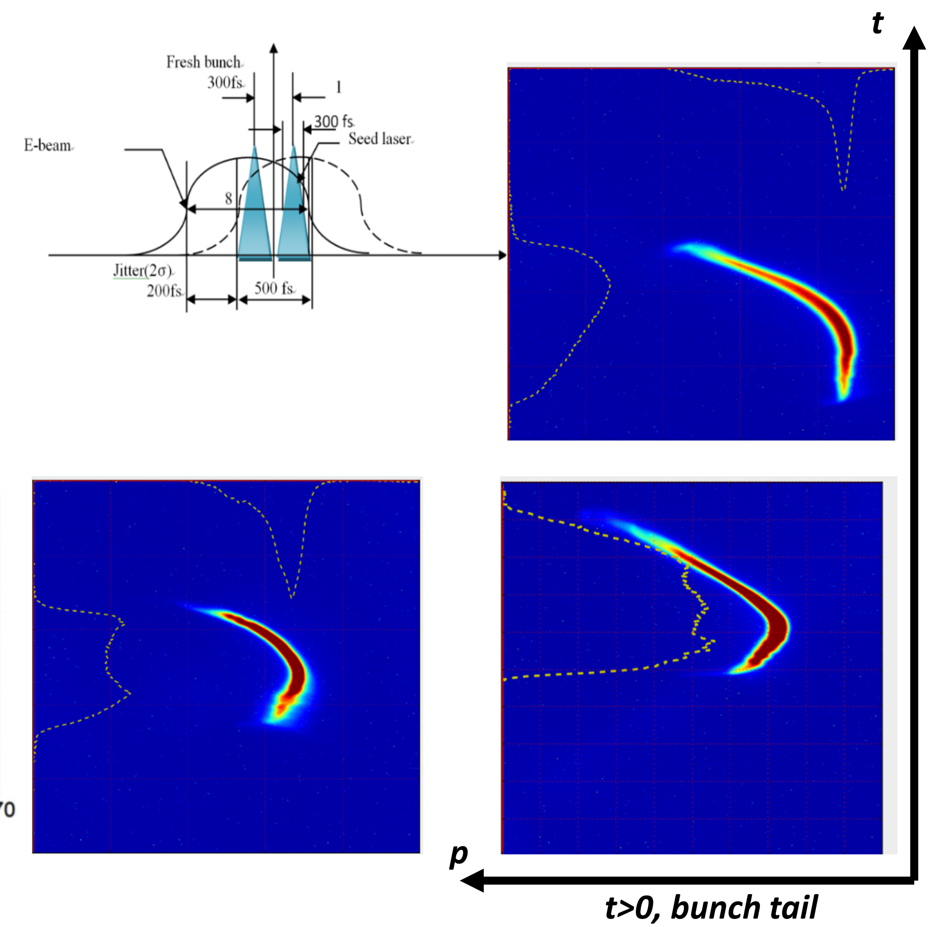
Bunch length measurement by TDS

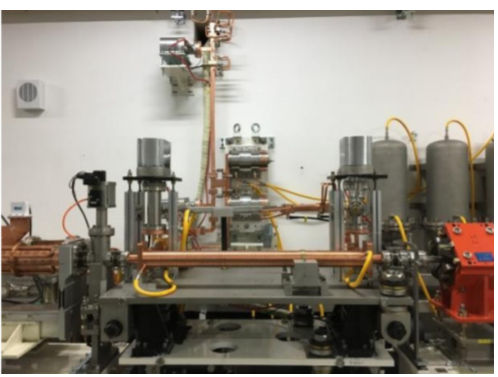


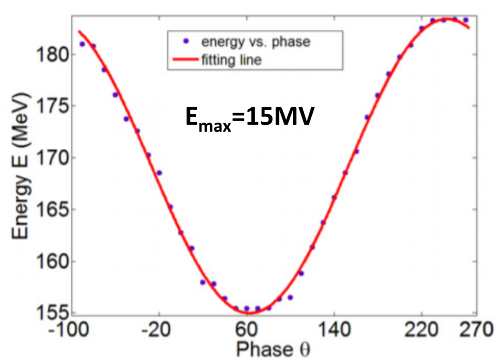
Nonlinear compensation for BC

- To maintain the initial temporal bunch profile during chicane, one 1-m X-band section is adopted to compensate the compression transformation up to second order.
- This non-linear effect during compression is also utilized for bunch profile control for cascaded HGHG lasing scheme.

Bunch Profile Control

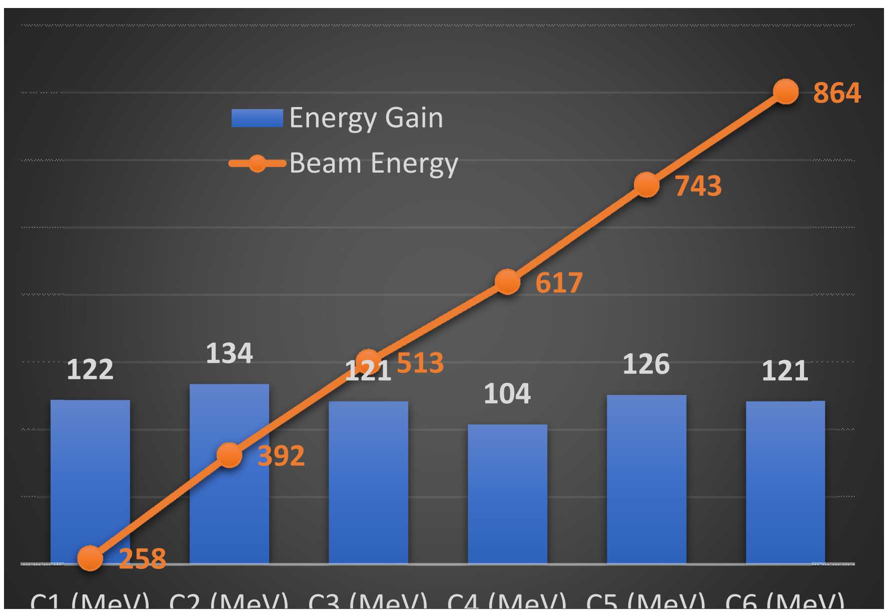


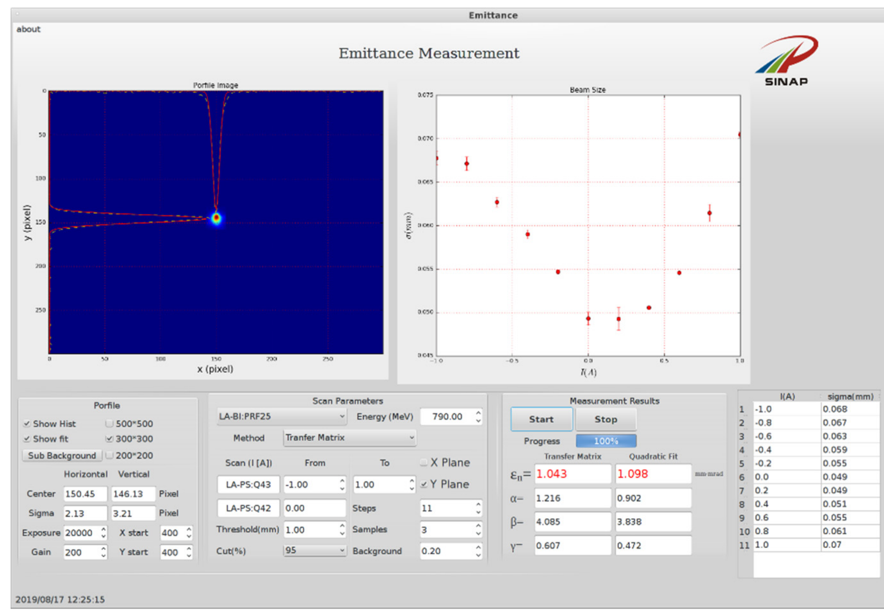




Beam emittance preservation @ linac exit

- Wakefield effect compensation for 500pC beam, especially in 1-m long X-band structure, is developed by beam-based alignment.
- This strong collective effect is also notable in ~30m main linac C-band RF structures.
- Beam optics matching is also helpful for optimized beam transportation.

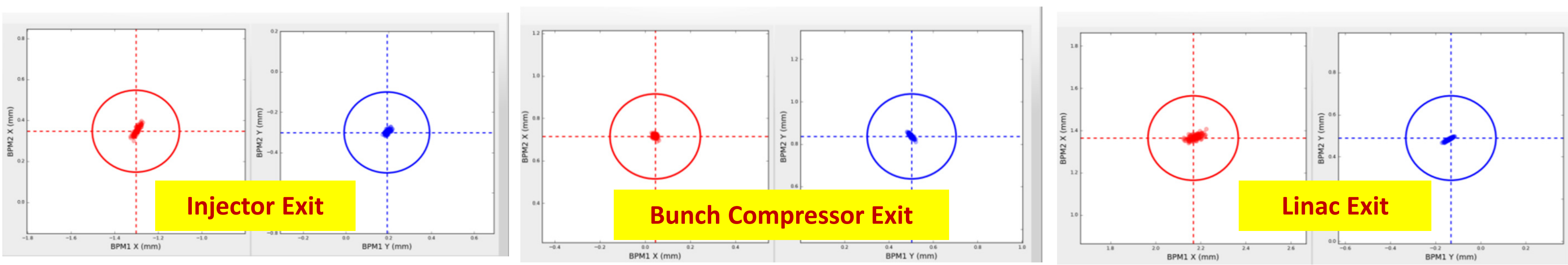


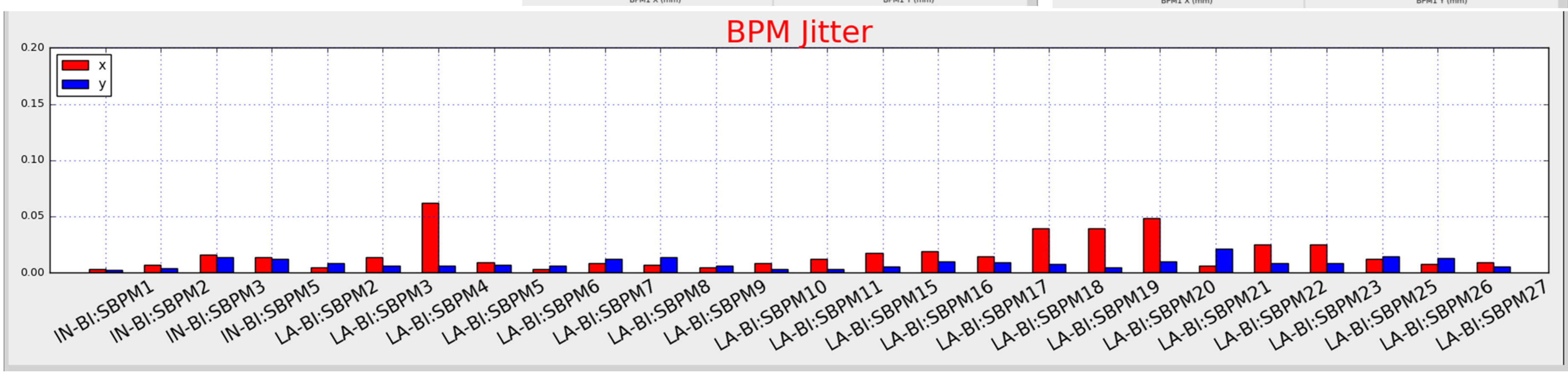


The project emittance at the 790MeV linac exit is about 1 μmrad for a peak current of ~500A

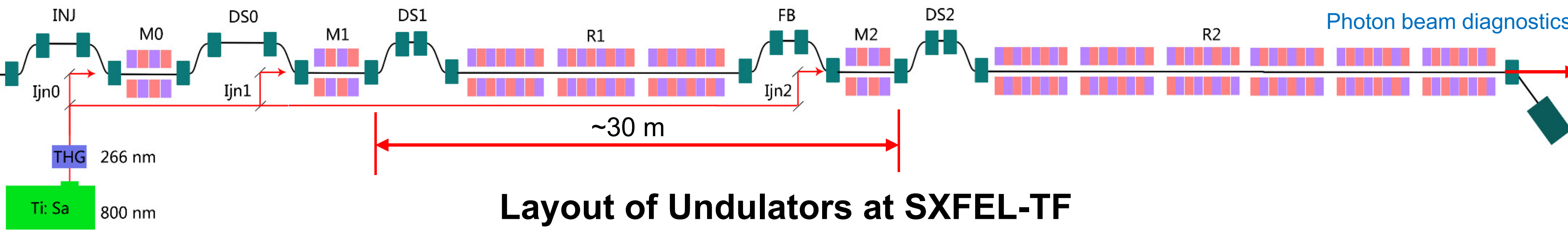
Long-term stability of the SXFEL Linac

- The requirements for tolerance budget are fulfiled and beam jitters at the linac are well controlled in SXFEL-TF, including not only RF sources for longitudinal beam jitter, but also magnet regulations for transverse beam pointing jitter.
- Long-term stability is also maintained by beam-based feedback toolkit.
- Day-night phenomenon of the beam orbit stability is observed during commissioning period and analyzing, the possible reasons are under investigations.

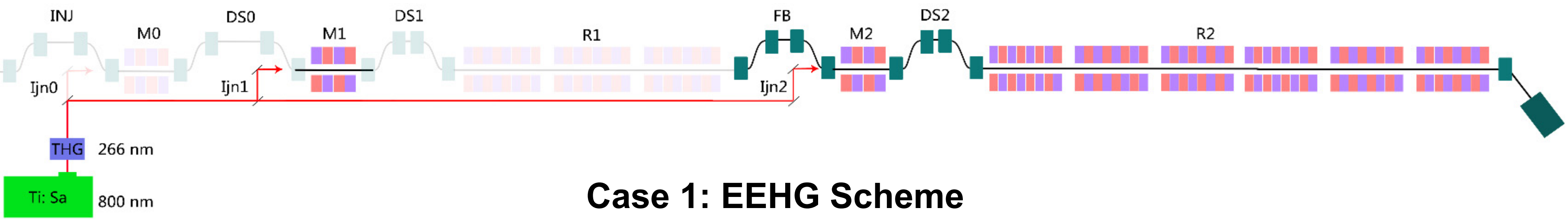




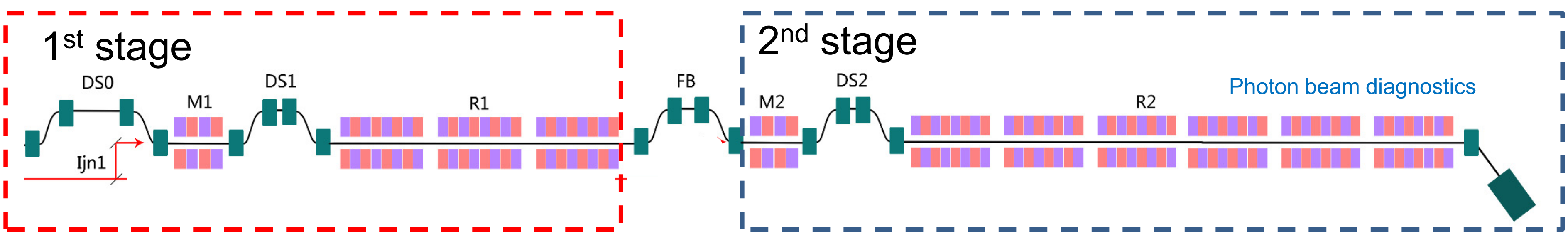
Commissioning EEHG and cascade HGHG at SXFEL-TF



Layout of Undulators at SXFEL-TF

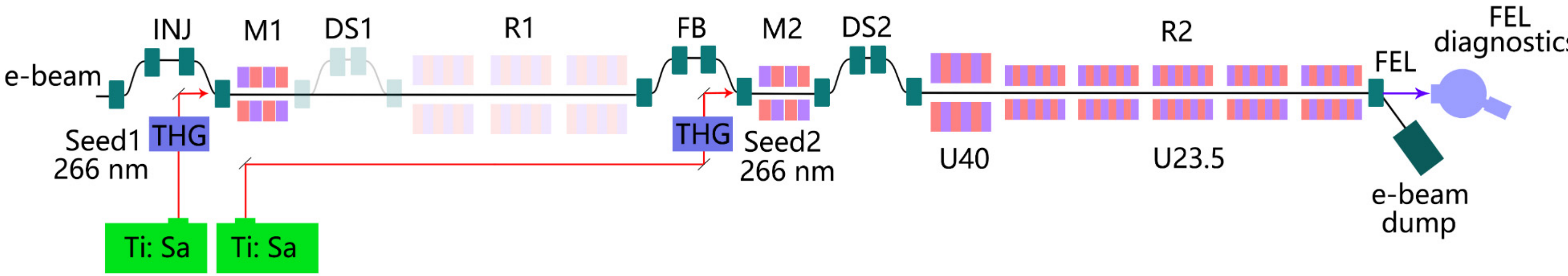


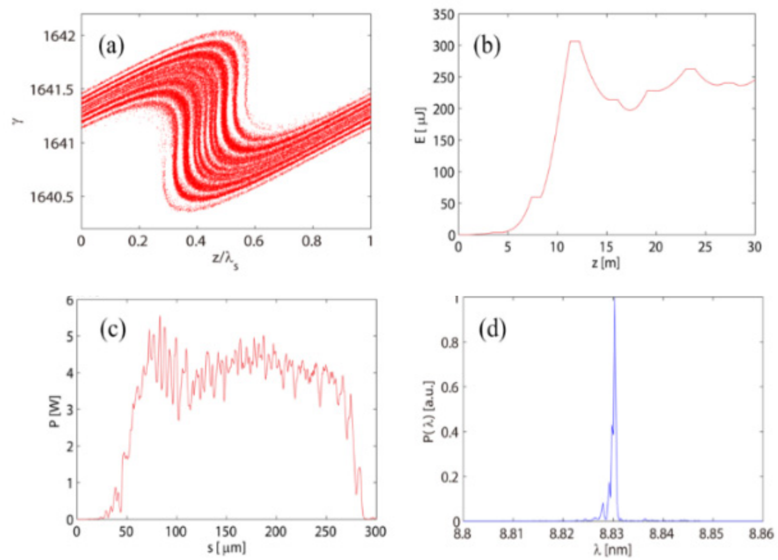
Case 1: EEHG Scheme



Case 2: cascade HGHG scheme

Case 1: Echo-11, 20 and 30 Experiments at SXFEL

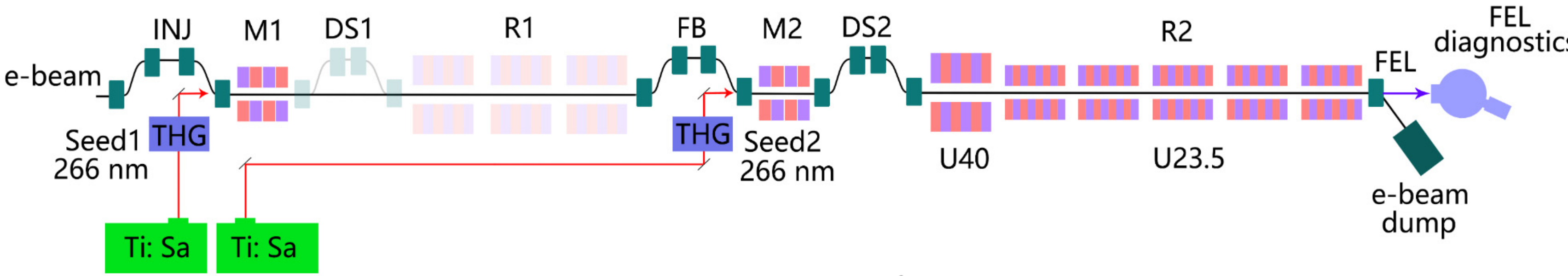




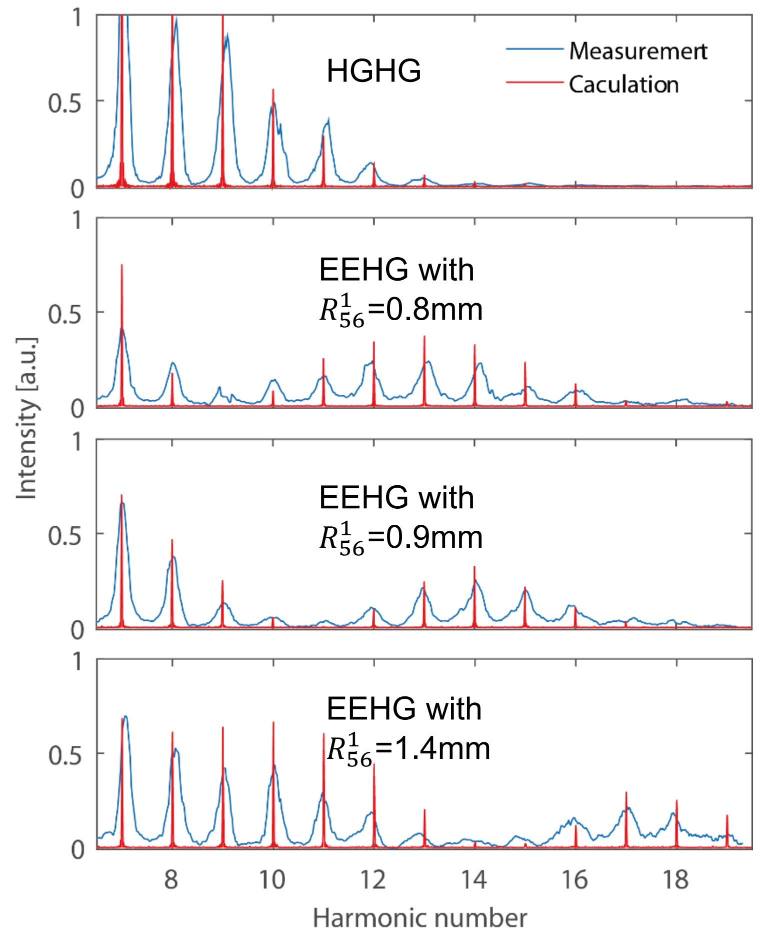
Results from s2e simulations

- **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

Comparison of HGHG and EEHG

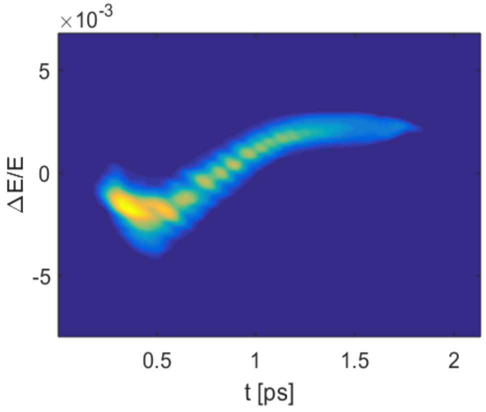


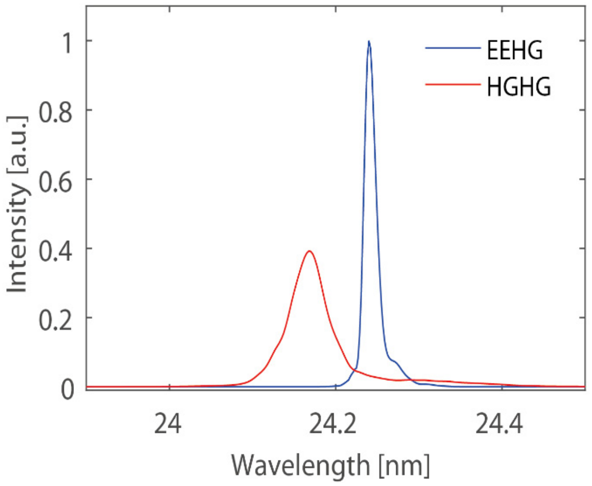
- By scanning the gap of U40, we can get coherent signals for different harmonics, which reflects the bunching factor distributions for HGHG and EEHG.
- Bunching factors for EEHG are lower than HGHG at low harmonics, but much higher than HGHG at the target harmonic.
- A cluster of bunching factor of EEHG can be continually shifted to higher harmonics by simply increasing the first dispersion strength (R_{56}^{1}).
- The bunching factor of EEHG can be maintained at a high level for high harmonics without increasing the energy modulation amplitudes.

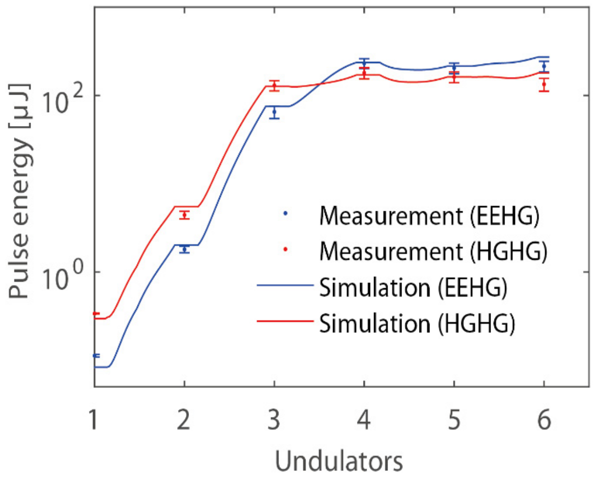


Lasing of EEHG-11@24nm at SXFEL-TF

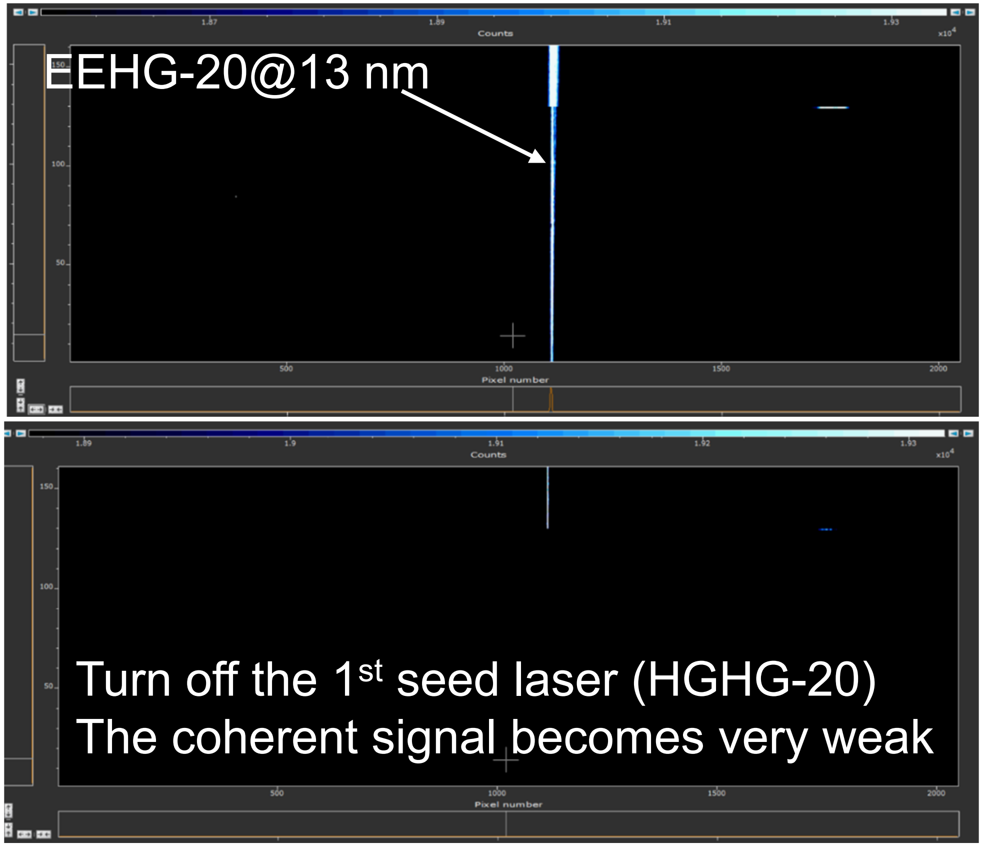
- With high peak power of the 2nd seed laser, coherent signals for both HGHG and EEHG appear at 11th harmonic
- The bandwidth of EEHG-11 is narrower than that of HGHG (due to the nonlinear chirp in the electron beam)
- Reducing the peak power of the 2nd seed laser, the HGHG-11 becomes very weak, while EEHG-11 is very strong, about two orders of magnitudes higher.

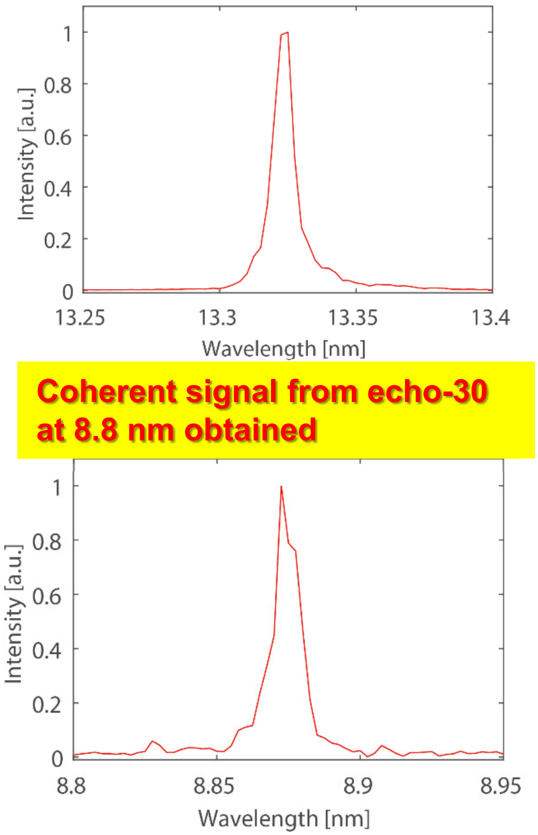






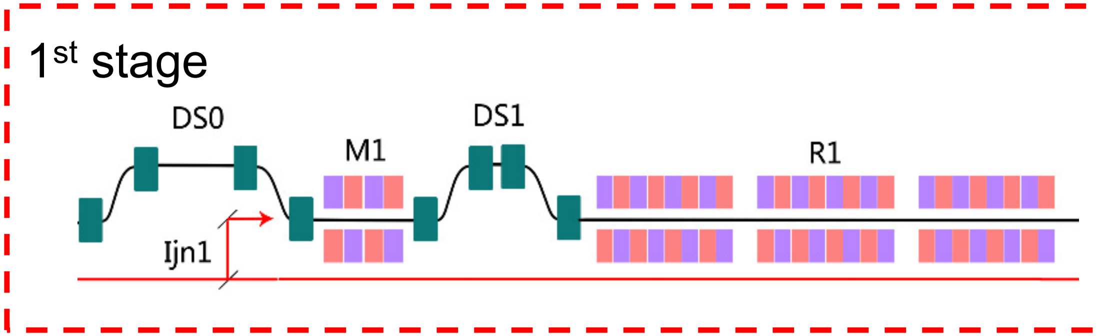
Radiation of EEHG-20 and EEHG-30 at SXFEL-TF



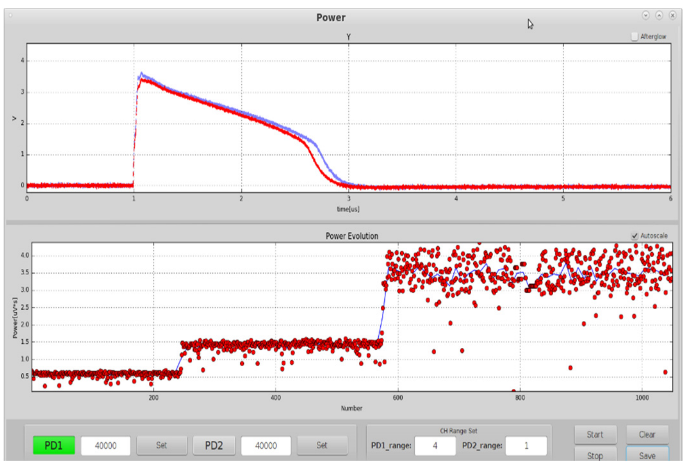


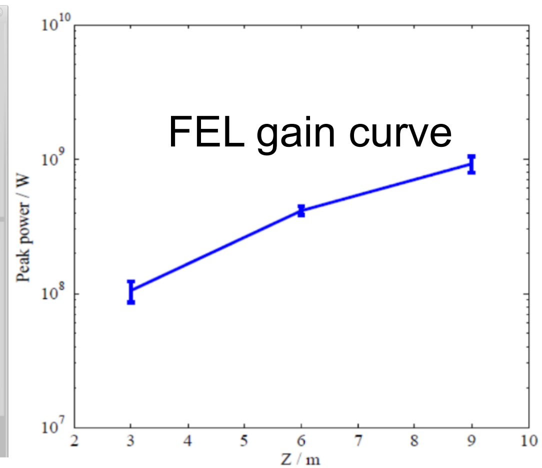
- Observed coherent signal for both HGHG and EEHG on the spectrometer
- It's hardly to see the coherent signal of HGHG for harmonic number larger than 16
- For EEHG it's easy to generate coherent signal at 20^{th} and 30^{th} harmonics of the seed by tuning the strength of the first chicane.

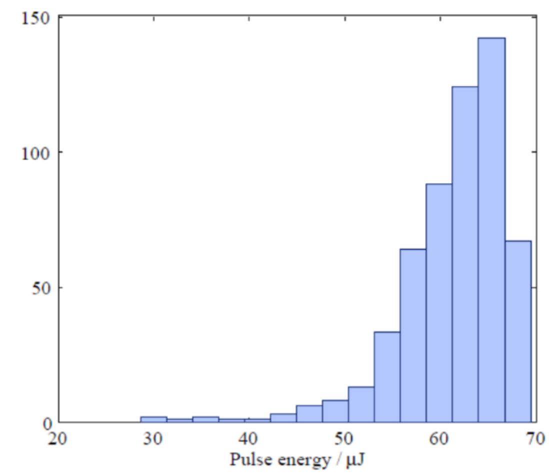
Case 2: cascade HGHG at SXFEL-TF



Amplification of the 1st stage HGHG





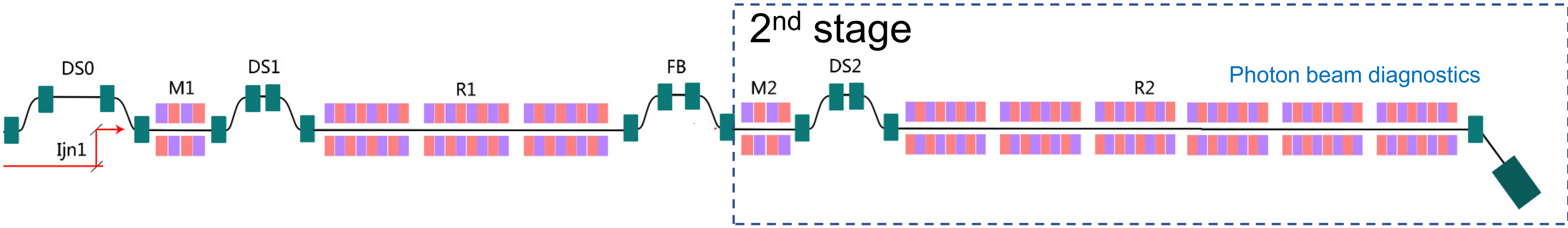


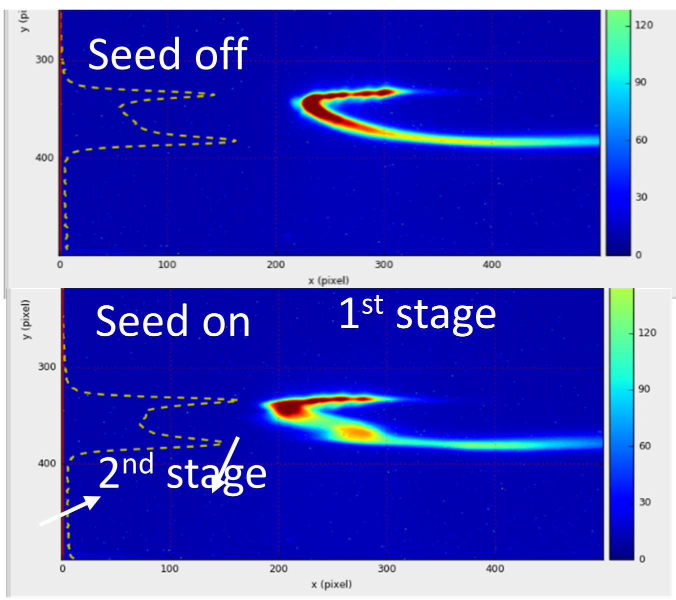
- Saturation of the first stage HGHG at 44nm has been achieved with peak power of hundreds of MWs.

Stability (550 shots)
Average pulse energy: 61μJ
Stability: 9.4% (rms)

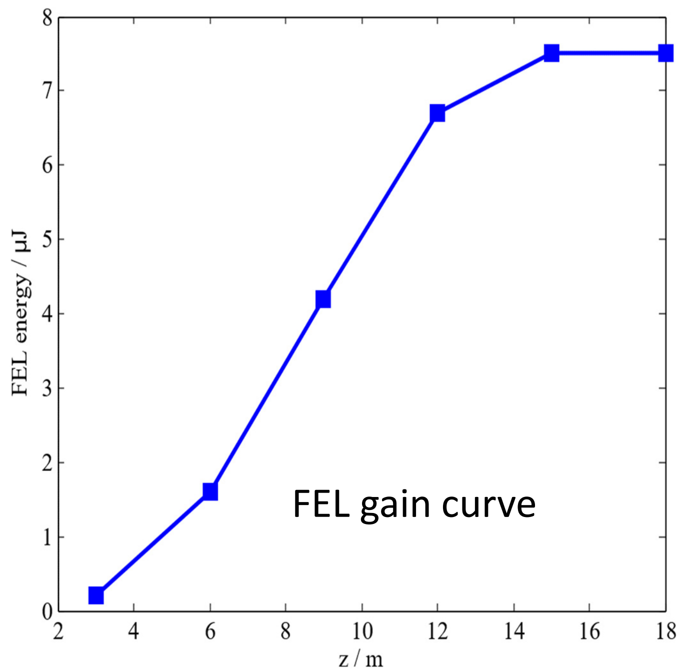
Amplification of the 2nd stage HGHG at 8.8nm

- Pulse energy >7.5 μJ, peak power > 30 MW, efforts are on going.

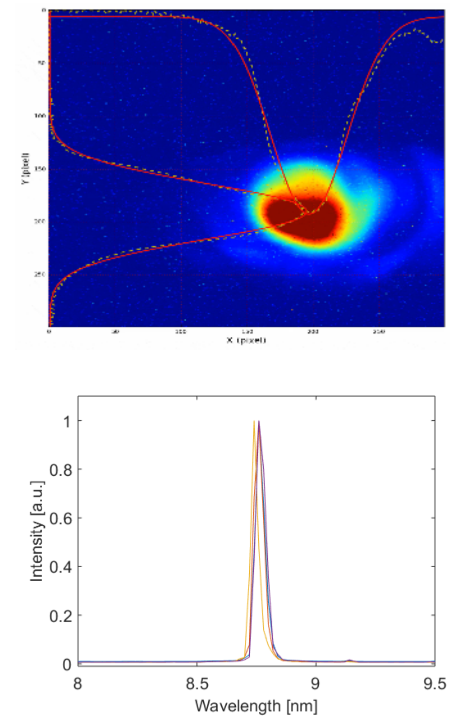




Effects of FEL lasing on the e-beam



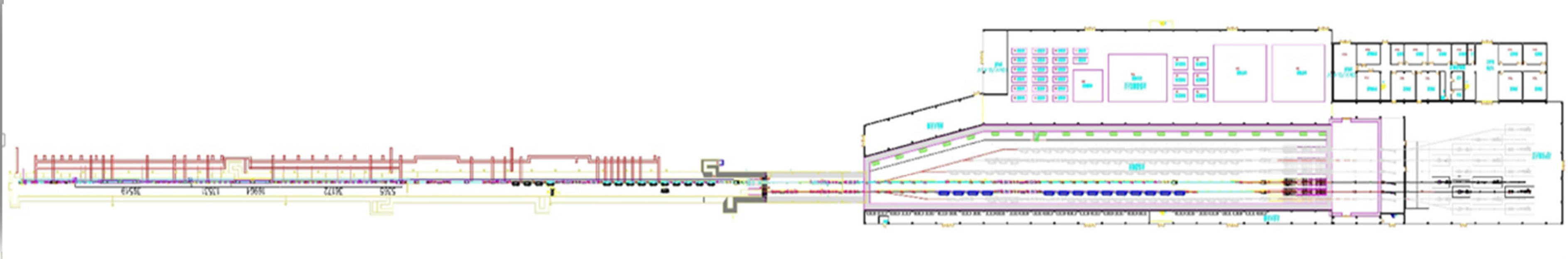
HGHG amplification at the 2nd stage

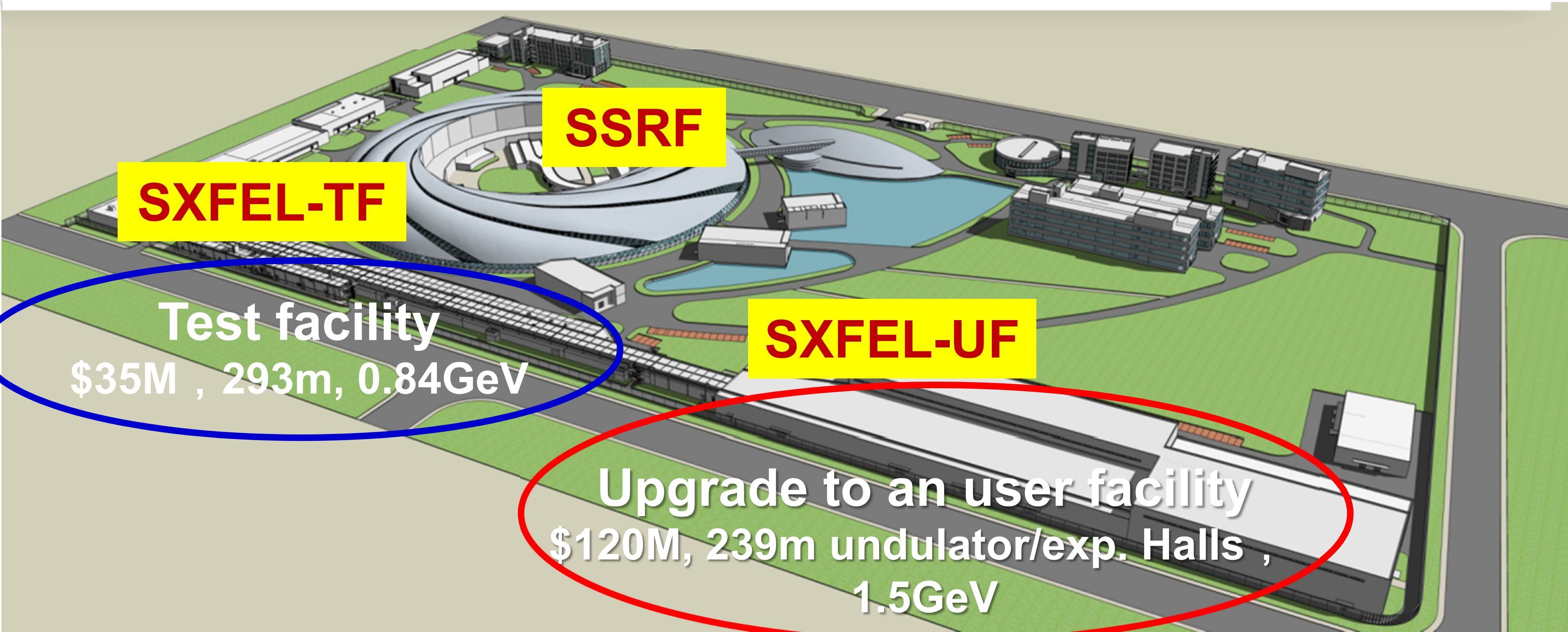


FEL spectrum
from the 2nd stage @ 8.8nm

User Facility: SXFEL-UF

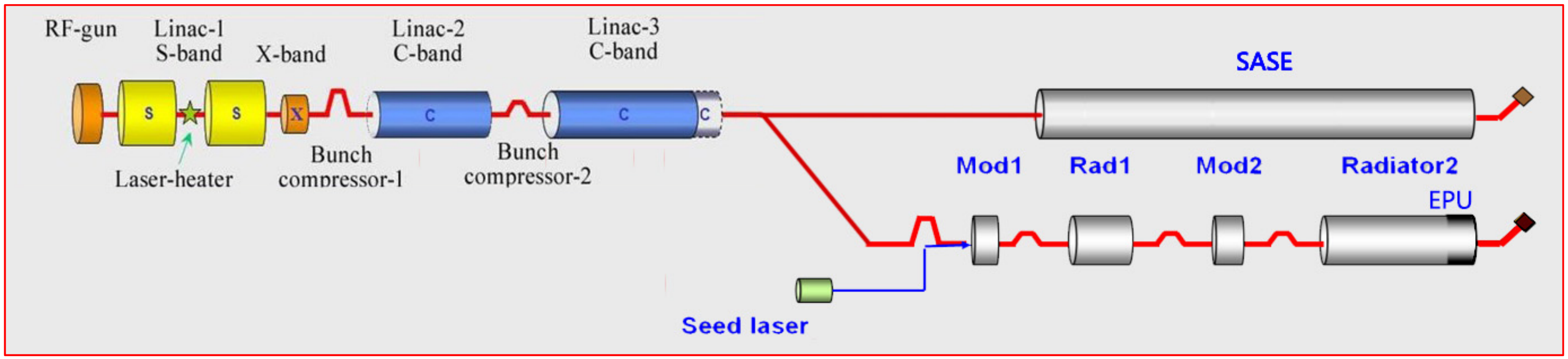
- A soft X-ray FEL user facility based on SXFEL-TF with two undulator line, a seeded FEL line and a SASE FEL line, is funded mainly by Shanghai local government, aiming at opening to users in 2020





User Facility: SXFEL-UF

- Upgrade the SXFEL-TF to a user facility, consisting of a 1.5 GeV linac and two undulator FEL lines, one is based on SASE and another based on EEHG/HGHG cascade, as well as five end-stations.



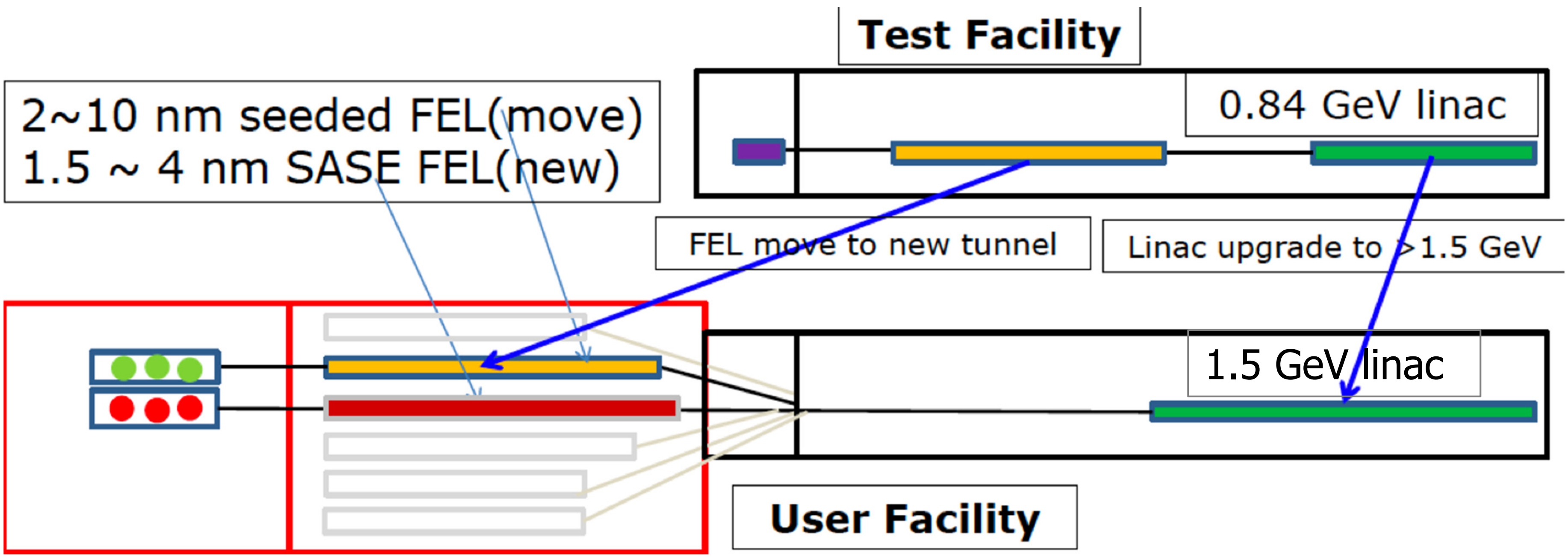
FEL Parameters

	SASE line	Seeding line
Beam energy/GeV	1.5	1.5
FEL wavelength/nm	2 nm	3 nm
FEL pulse/fs	100 - 200	100 - 200
FEL power/MW	>100	>100
Rep. rate/Hz	50	50

SXFEL-UF Building

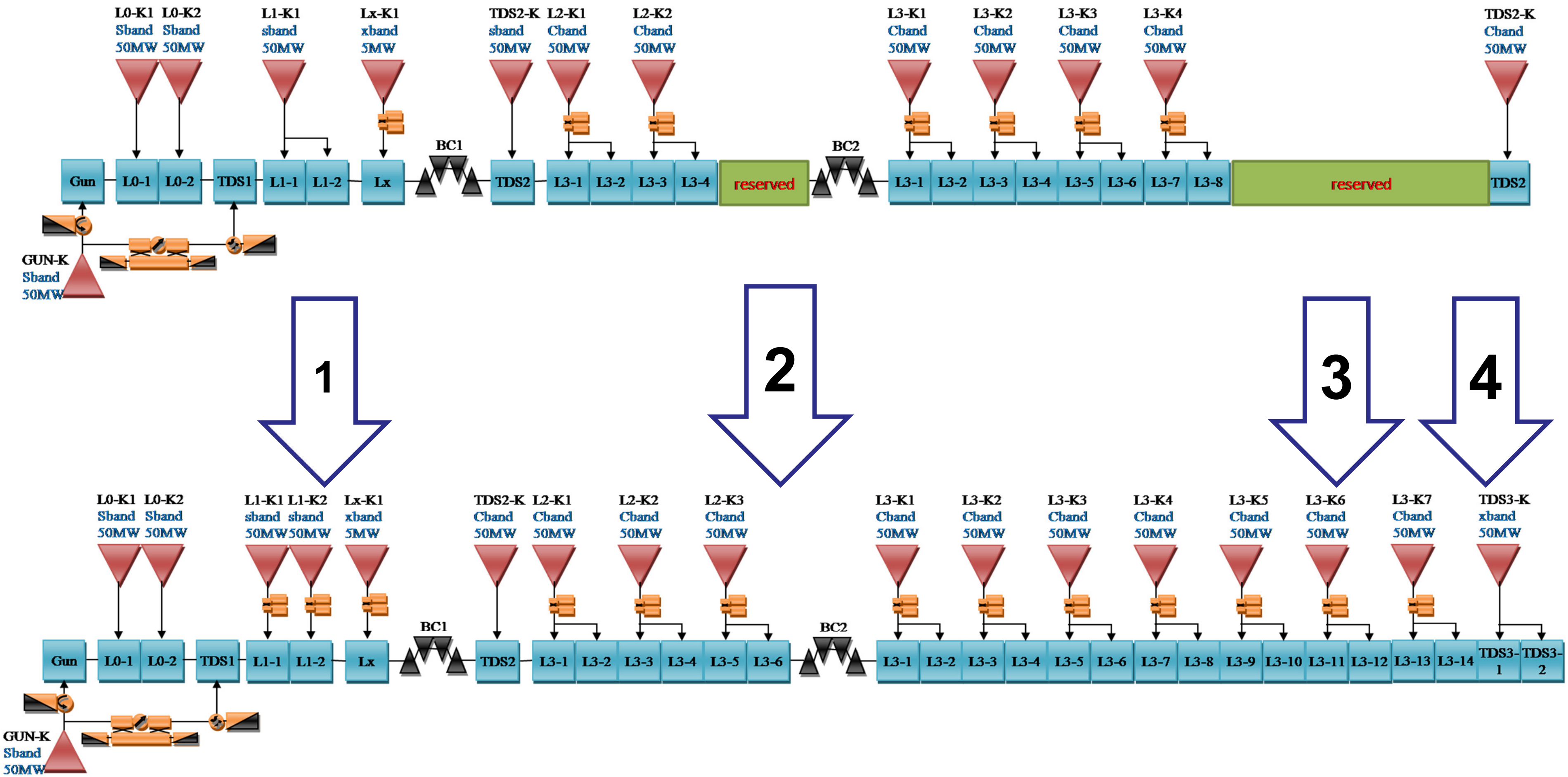
Upgrade SXFEL-TF to SXFEL-UF

- Increase the linac energy to 1.5GeV
- Upgrade the linac with laser heater and second bunch compressor
- Construct a SASE FEL line and a seeding FEL line
- Construct 5 experimental stations



SXFEL-UF Linac

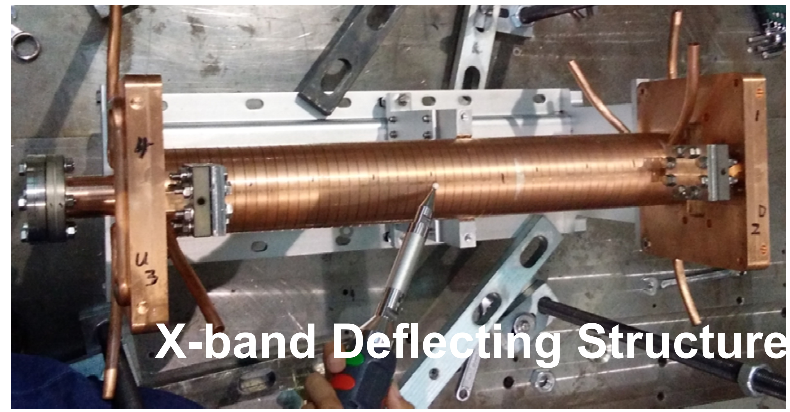
- Increase the linac energy to : ~1.5GeV

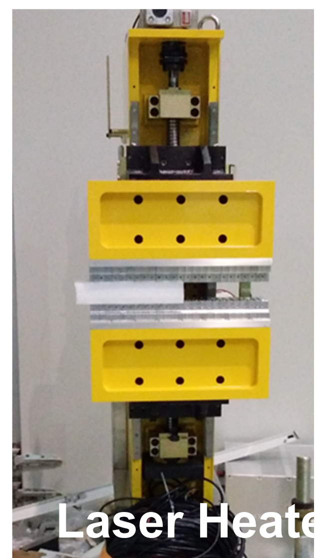


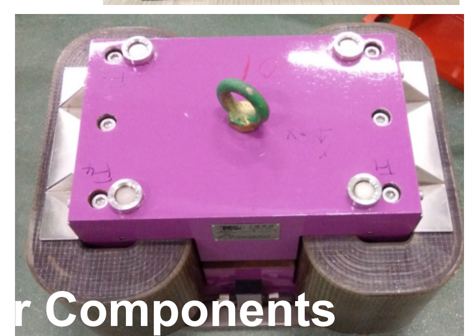
Adding:

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

C-band Accelerating Unit and Laser Heater Components





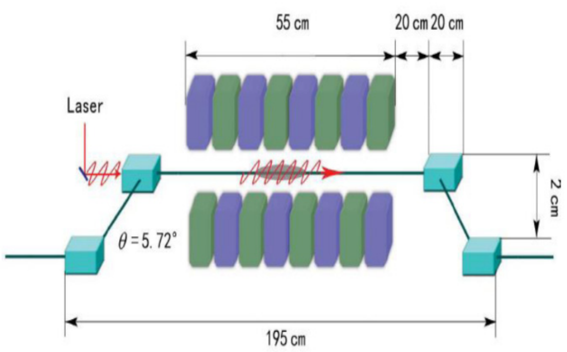


SXFEL-UF Linac

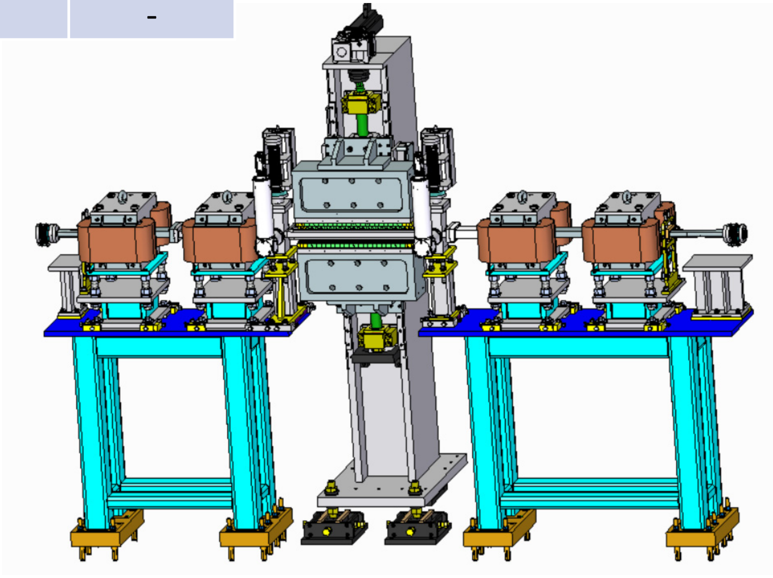
- **Upgrade the SXFEL-TF linac with :**

laser heater and 2nd magnetic bunch compressor

	E_{out} (MeV)	$\sigma_{z\text{-}out}$ (mm)	$\sigma_{\delta\text{-}out}$ (%)	E (MV/m)	ϕ_{rf}/θ_{bend} (Deg)	R_{56} (mm)
L0	130	0.86	0.14		-	-
L1	273	0.86	1.44	27	-29.2	-
X	256	0.86	1.51	19	180	-
BC1	-	0.13	-		3.968	-48
L2	640	0.13	0.42	38	4	-
BC2	-	0.07	-		2.217	-15
L3	1500	0.07	0.028	38	6	-



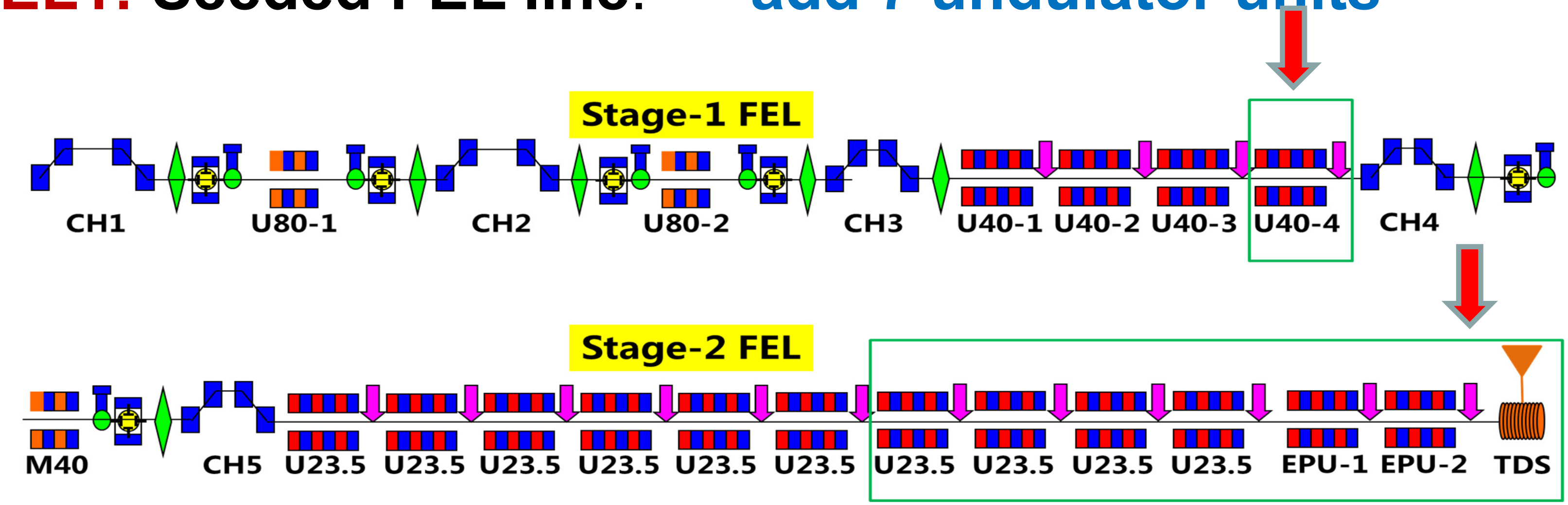
Add one more moveable chicane BC2, further increase the peak current to >700A



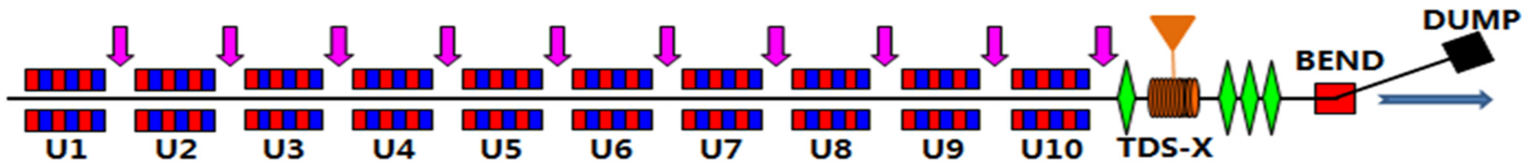
Schematic layout of SXFEL-UF laser heater

SXFEL-UF FEL lines

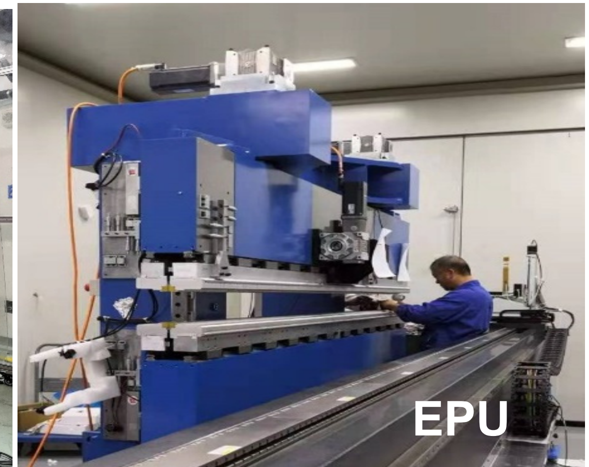
➢ **FEL1: Seeded FEL line:** add 7 undulator units



➢ **FEL2: SASE FEL line:** build 10 IVU sections



SXFEL-UF Undulators

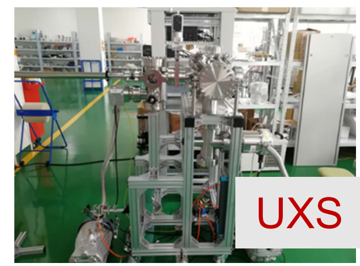


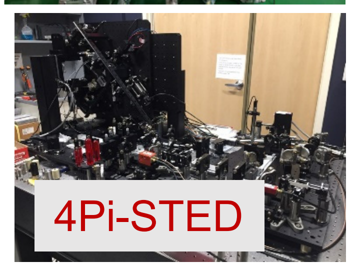
	Period（mm）	Period Number	Mini gap（mm）	Effective field (T)	Phase error (rms)	Quantity	Usage
Planar	40	73	8.75	0.97	<5°	4	Seeding, Radiator-1
Planar	23.5	125	8.75	0.64	<5°	10	Seeding, Radiator-2
EPU	30	98	4	0.8	<5°	2	Seeding, After burner
IVU	16	243	4	1.05	<5°	10	SASE, Radiator

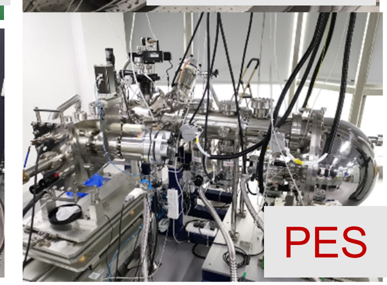
SXFEL-UF Beamline and End-stations

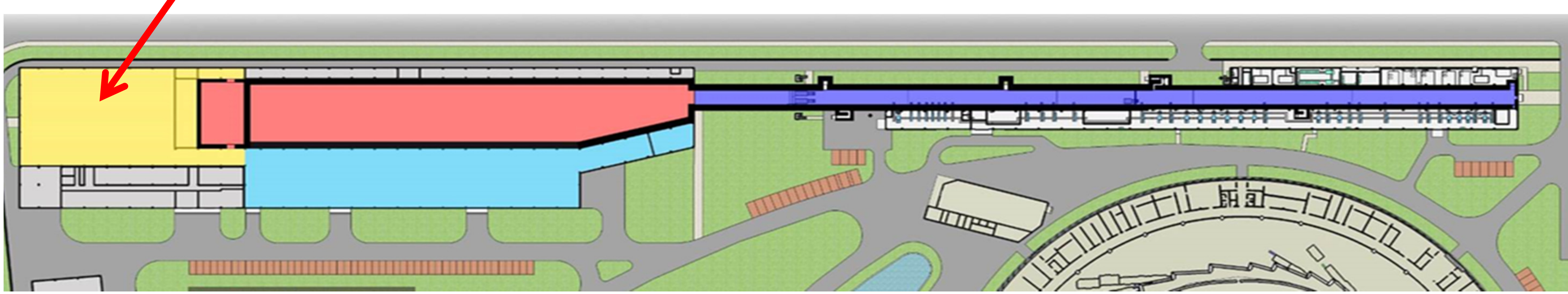
The user facility enters the installation phase and is expected to be finished by end of this year, the beamline commissioning will start March next year.

5 Endstations	
Coherent Diffraction Imaging and Fluorescence Microscope	CDI
Time-resolved X-ray Scattering	TXS
Ambient Pressure Photoelectron Spectroscopy	PES
Ultrafast X-ray Spectroscopy for Chemistry	UXS
Molecular Dynamic Imaging and Composite Velocity-map Imaging Spectrometer	AMO









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

Summary

- X-ray FEL facilities, SXFEL based on a 1.5 GeV C-band copper linac and SHINE based on an 8 GeV CW SCRF linac, are under active development in China;
- The SXFEL is a phased facility, consisting of two funded independently projects of central and local governments, aiming at serving experiments in 2020;
- The SXFEL-TF was constructed from 2015 to 2018, its linac has achieved the design performance, and its FEL commissioning is in progress with the EEHG lasing at 24nm and two stage HGHG lasing at 8.8nm;
- The SXFEL-UF construction started in 2016, now most of the equipment and components are ready for installation, its commissioning is expected to start in March 2020.

Thank You for Your Attention！

谢谢!