FUSEE

FUture of SEeded free Electron lasers

Elettra Sincrotrone Trieste

Short wavelengths seeding options at SXFEL and SHINE

Chao Feng，Kaishang Zhou, Zhentang Zhao

Shanghai Advanced Research Institute, CAS

FUSEE2019, Trieste, 10-11 Dec. 2019

Outline

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

Introduction

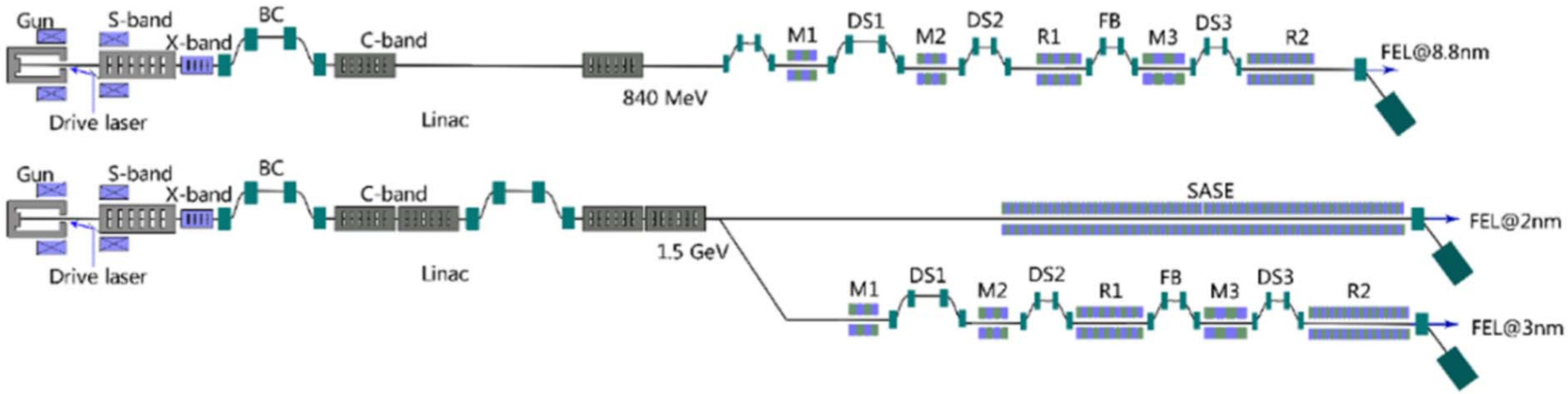
- We started to develop high gain FEL in late 1990s, when a DUV-FEL based on HGHG working mode was proposed
- In the past 10 years, the SDUV-FEL test facility based on HGHG/EEHG/cascade HGHG, and the DCLS, an EUV-FEL user facility, based on HGHG were constructed
- In the meantime, a soft x-ray FEL based on HGHG/EEHG/EEHG-HGHG cascade, has been under development, its test facility is under commissioning
- A high rep-rate hard X-ray FEL facility based on SASE/self-seeding/EEHG-HGHG cascade is under construction

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 in 2016, it's now under commissioning;
- **SXFEL-UF** was founded to upgrade the linac energy to 1.5 GeV for building two undulator lines with 5 experimental stations in the water window region.

SXFEL-TF

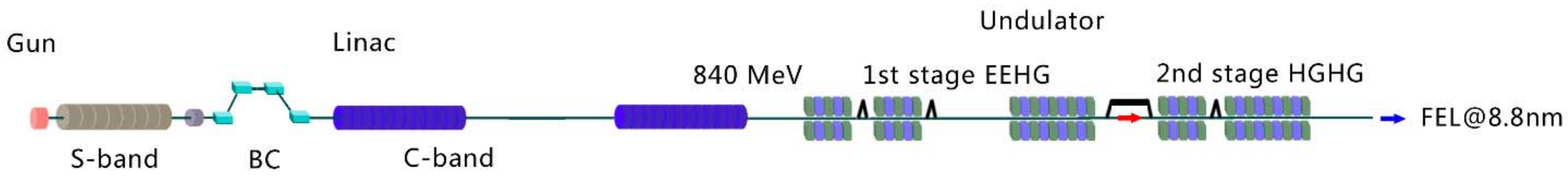
SXFEL-UF



Total length	532m
Photon energy	0.2 – 0.6 keV
Pulse length	~100 fs
Repetition rate	10 - 50 Hz
Peak photon power	1 GW
Electron energy	0.8 - 1.5 GeV

X-ray FEL test Facility: SXFEL-TF

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

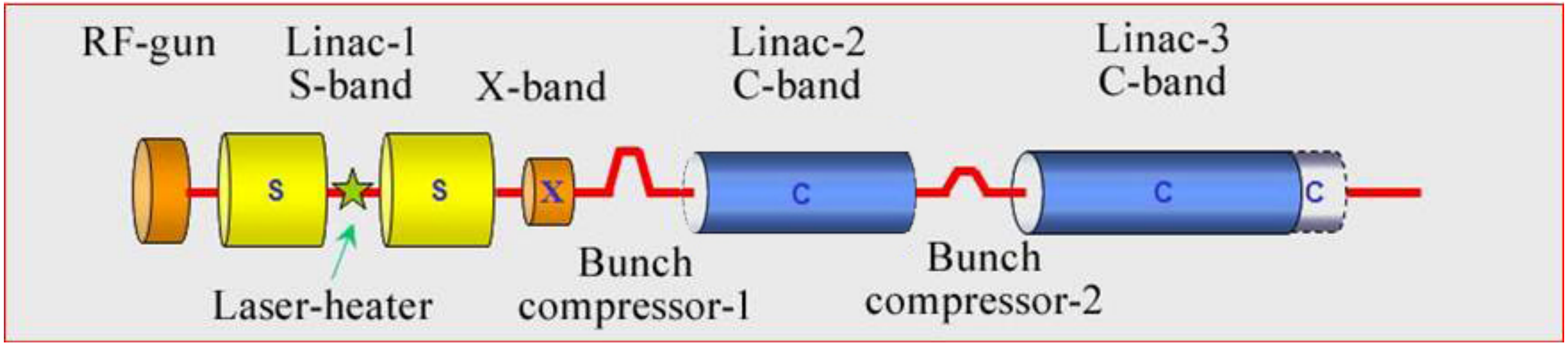


FEL parameters

	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	800	800	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: 0.8GeV C-band linac + HGHG/EEHG Schemes

Test Facility: Linac



Injector beam parameters

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

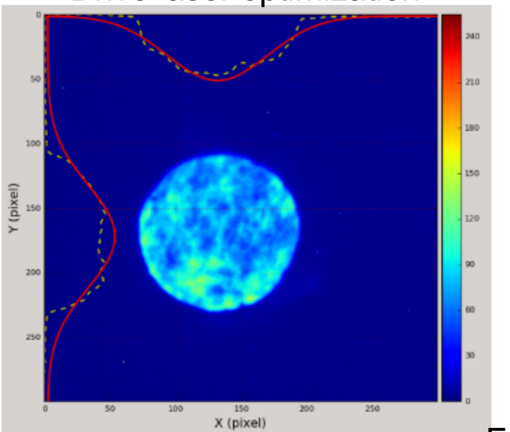
Main linac beam parameters

Bunch charge (nC)	0.5
Beam energy (GeV)	0.8
Bunch length (ps, FWHM)	1.0
Norm. emittance (mm.mrad)	< 2.0
Energy spread (rms)	< 0.15%
Rep-rate (Hz)	1-10
Peak current (A)	≥ 500

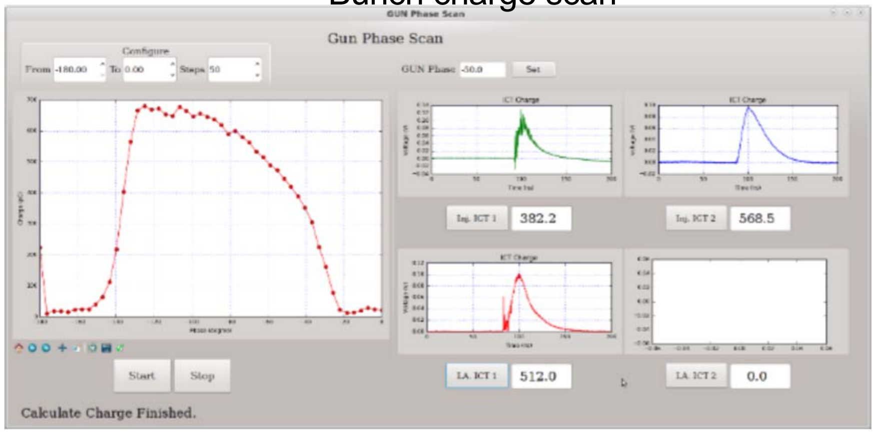
Commissioning of Injector and Linac

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	1.0 mm-mrad (Injector), <2 (linac)

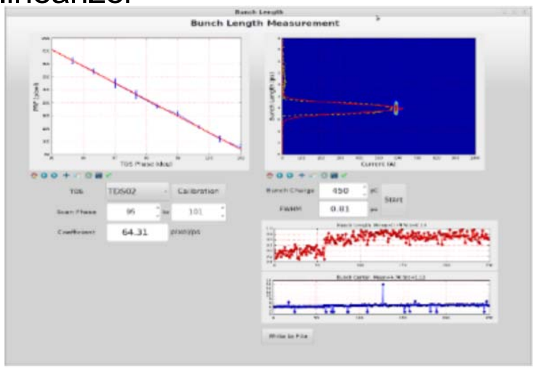
Drive laser optimization



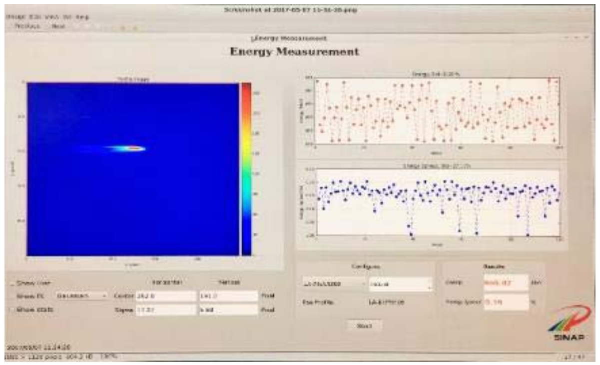
Bunch charge scan



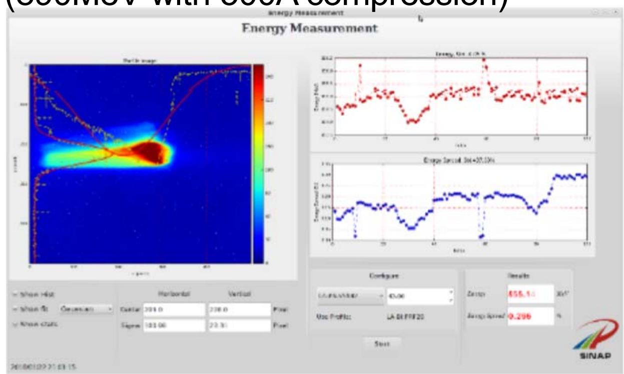
Bunch compression with x-band linearizer



Further acceleration with C-band structures



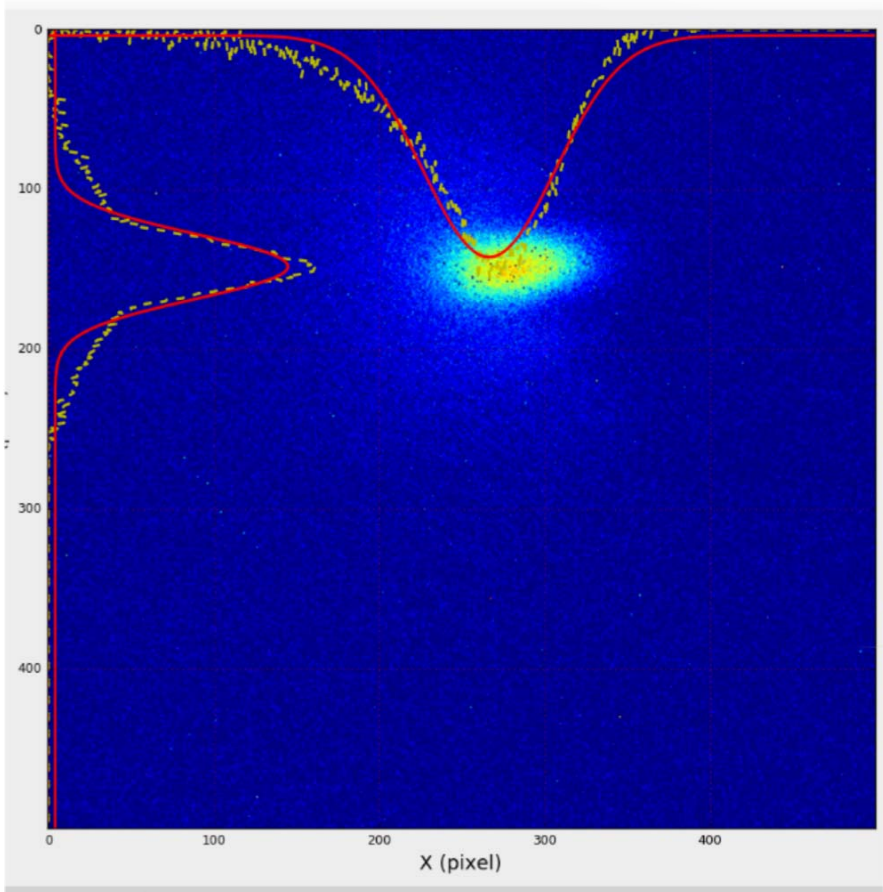
Maximal beam energy achieved (890MeV with 500A compression)



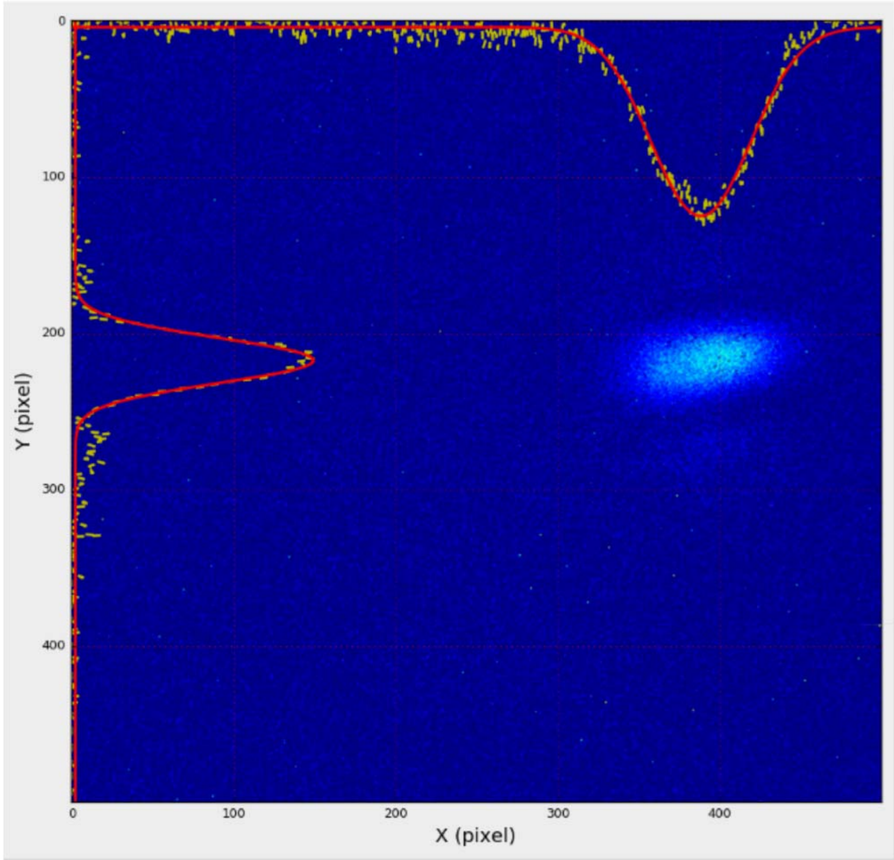
Seed laser at SXFEL

Ti:Sa laser @ 800nm —THG→ Seed laser @ 266nm

Before the 1st stage modulator

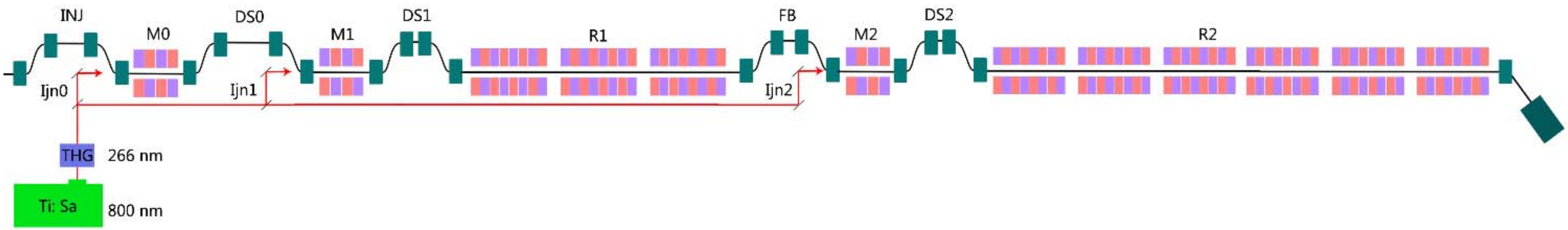


After the 1st stage modulator



The transverse laser beam size is about 1mm, which is much larger than the electron beam

Test Facility: Undulator system

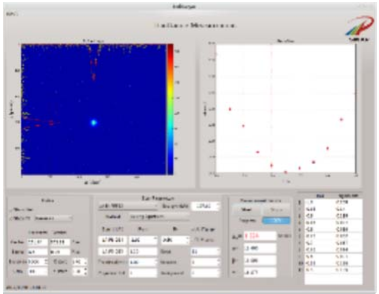


Seed laser	
Wavelength	266nm
Pulse length	~170fs
Pulse energy	~50 µJ
Transverse size in the modulator	~500µm

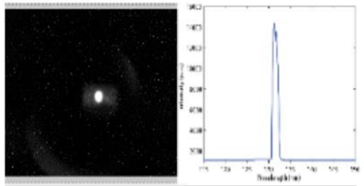
Undulators	
M1/2: Np×λu	20×8cm
R1: Ns×Np×λu	3×75×4cm
M3: Np×λu	30×5.5cm
R2: Ns×Np×λu	6×125×2.35cm

Chicanes	
DS1: length/R56	12m/0-25mm
DS2: length/R56	3m/0-2mm
FB: length/R56	4.46 m/0-7mm
DS3: length/R56	3m/0-2mm

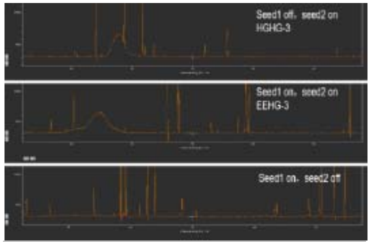
SXFEL-TF commissioning milestones



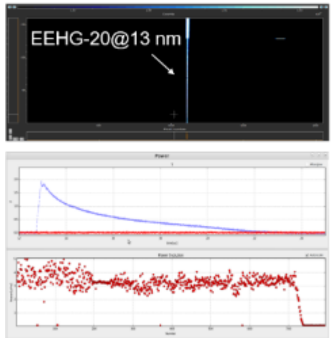
Start commissioning of the injector and main linac during the installation of undulators



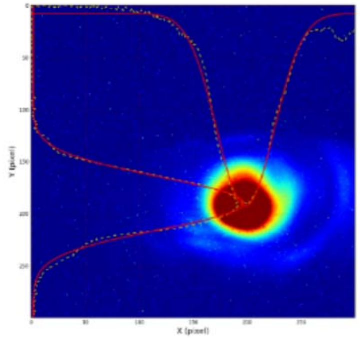
First coherent signal from the 1st stage HGHG



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



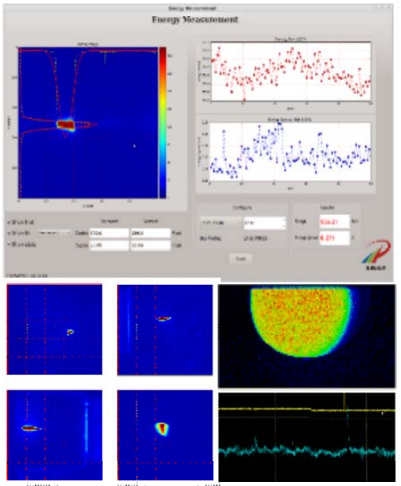
Amplification of EEHG-20



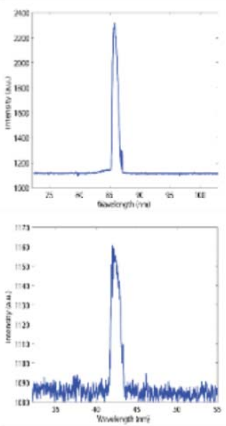
Cascaded HGHG FEL lased at 30th harmonic (8.8nm)

2016 | 2017 | 2018 | 2019

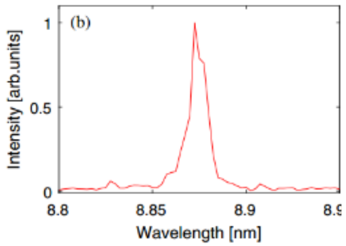
first soft x-ray radiation from the undulator beamline



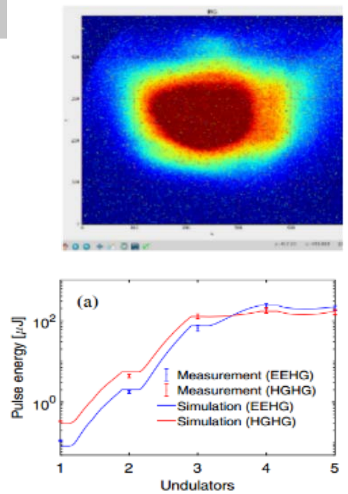
HGHG: 2nd to 6th harmonic



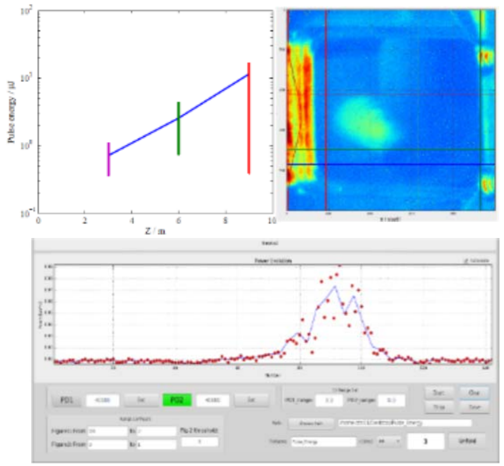
Coherent signal from EEHG-30@8.8nm



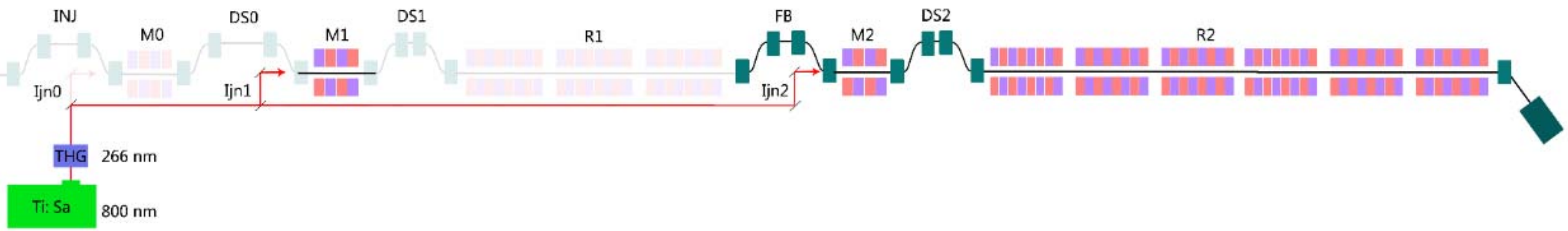
Saturation of HGHG-11 and EEHG-11



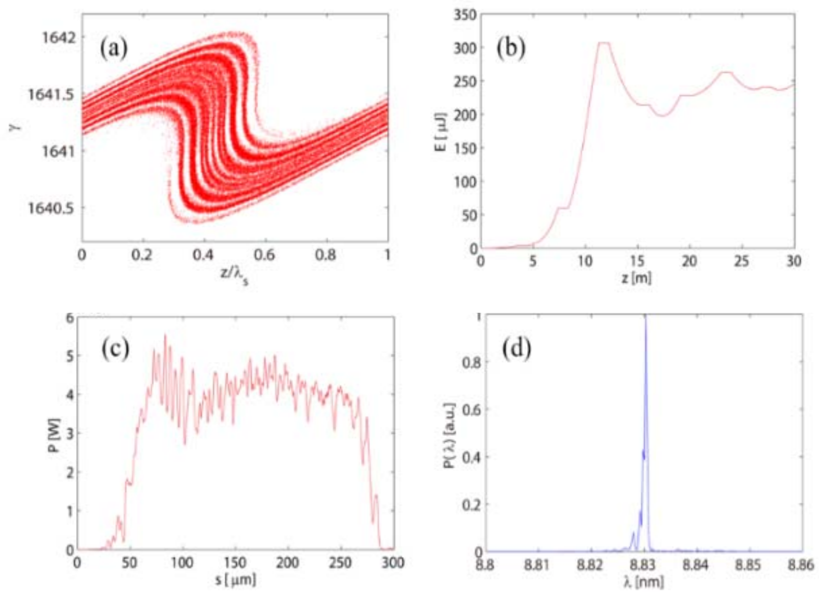
Lasing of the 1st stage HGHG at 6th harmonic and get coherent signal from the 2nd stage HGHG with "fresh bunch"



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



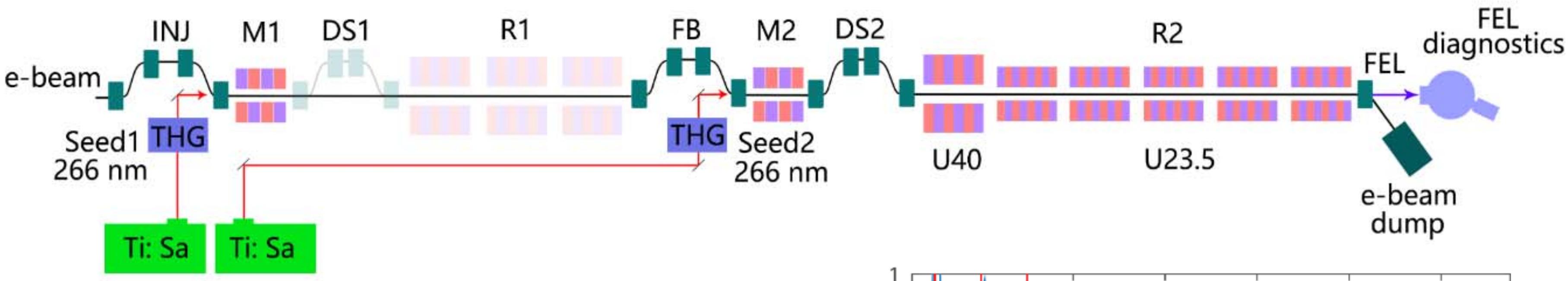
Layout for the EEHG experiment at SXFEL



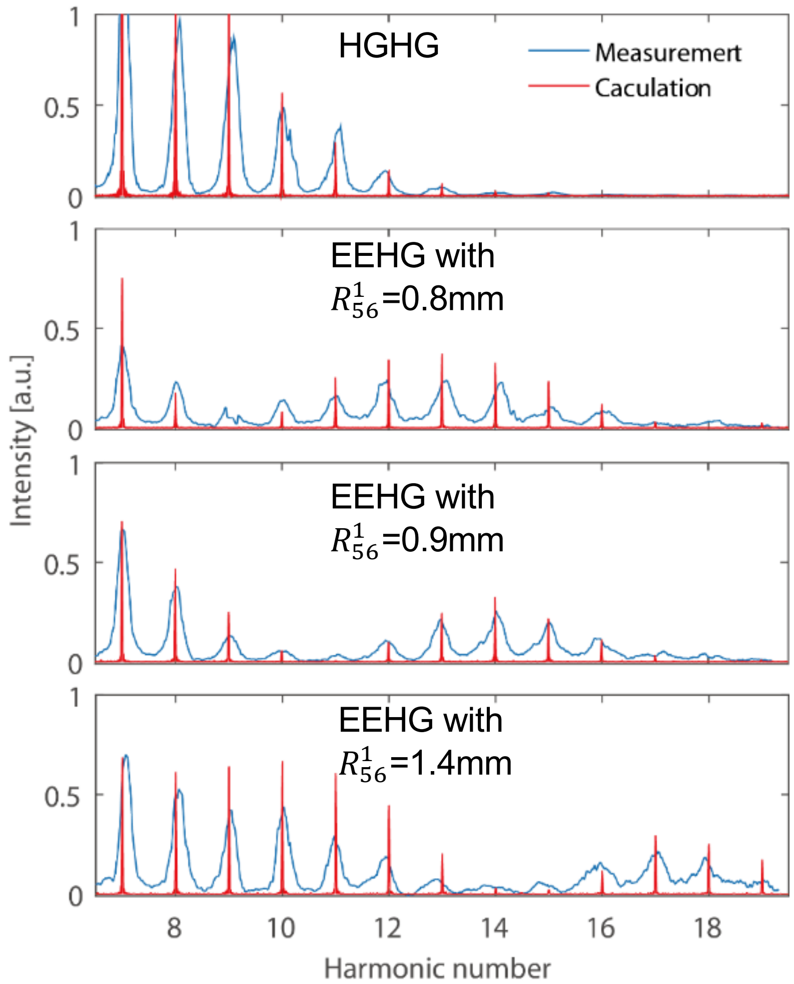
Results from s2e simulations

- **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

Comparison of HGHG and EEHG

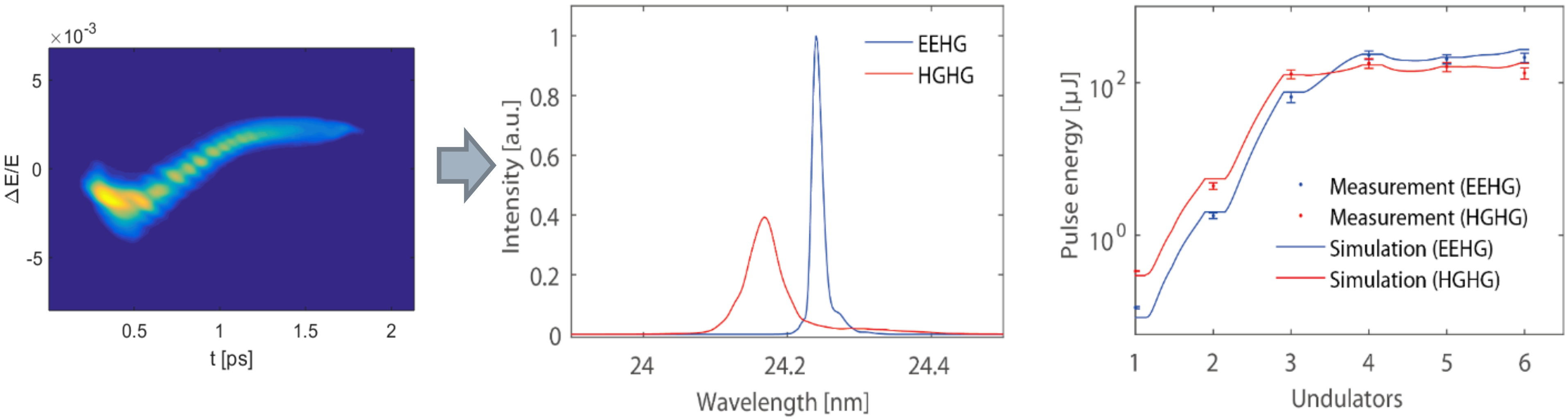


- By scanning the gap of U40, we can get coherent signals for different harmonics, which reflects the bunching factor distributions for HGHG and EEHG.
- Bunching factors for EEHG are lower than HGHG at low harmonics, but much higher than HGHG at the target harmonic.
- A cluster of bunching of EEHG can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

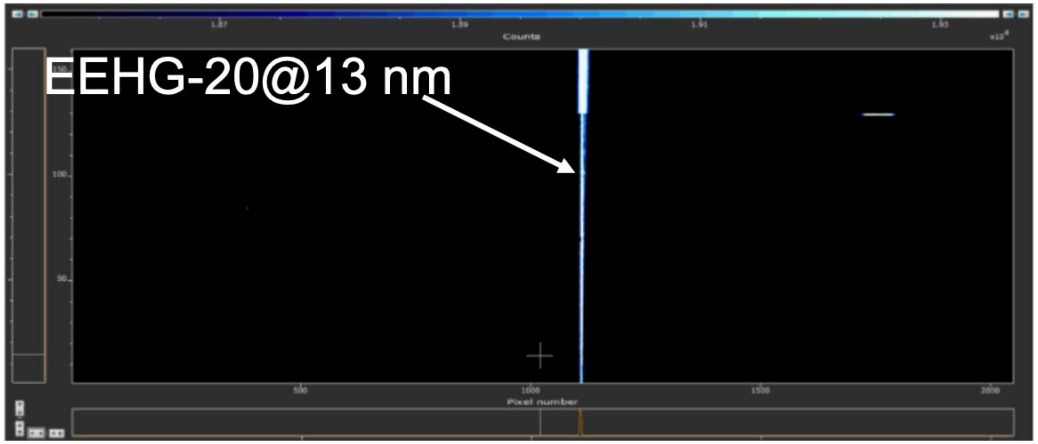


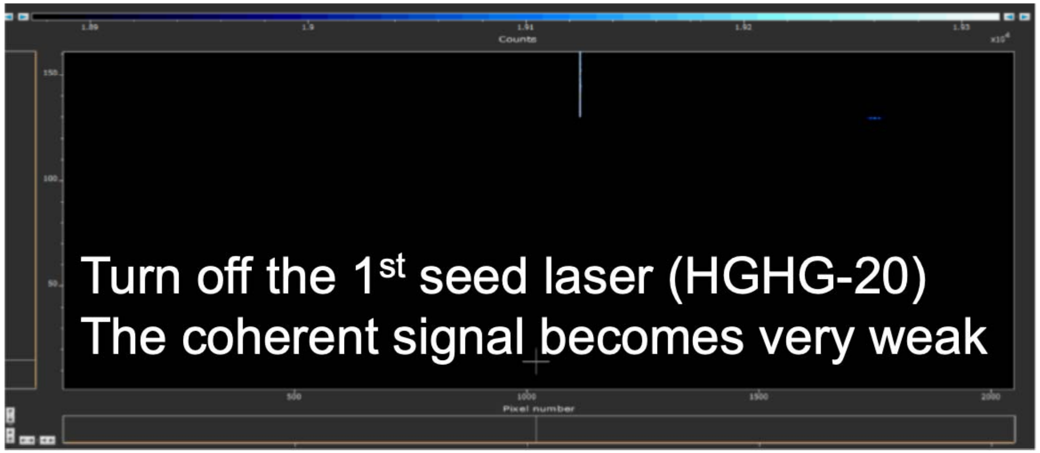
Lasing of EEHG-11@24nm at SXFEL-TF

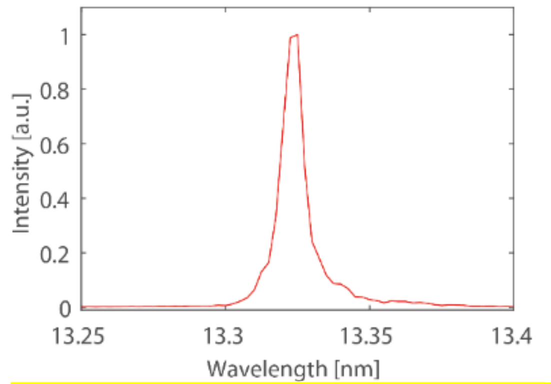
- With high peak power of the 2nd seed laser, coherent signals for both HGHG and EEHG appear at 11th harmonic
- The bandwidth of EEHG-11 is much narrower than HGHG (due to the nonlinear chirp in the electron beam)
- Reducing the peak power of the 2nd seed laser, the HGHG-11 becomes very weak, while EEHG-11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



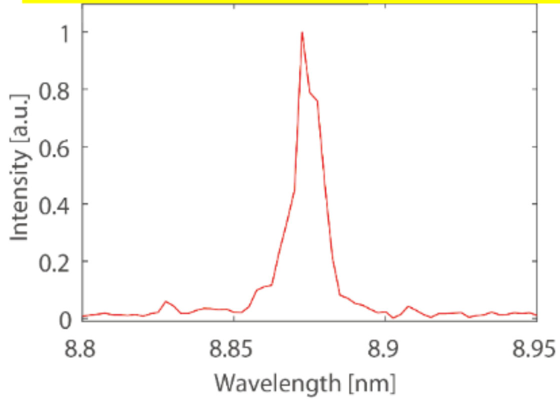
Coherent radiation from EEHG-20 and 30





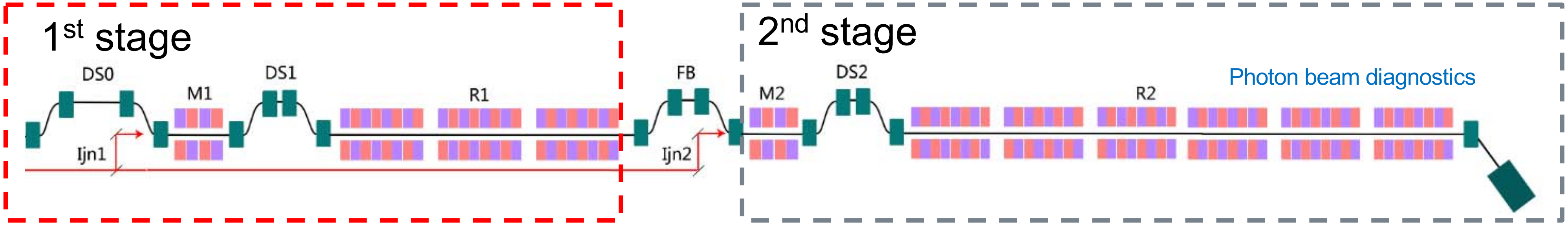


Coherent signal from echo-30 at 8.8 nm obtained



- 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.

Case 2: cascade HGHG at SXFEL

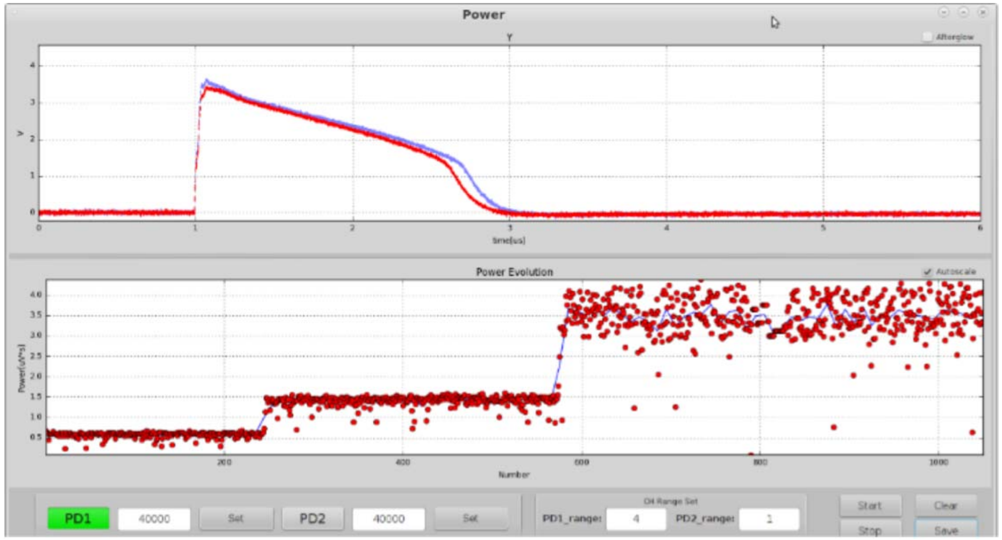


Undulators	
M1: Np×λu	20×8cm
R1: Ns×Np×λu	3×75×4cm
M3: Np×λu	30×5.5cm
R2: Ns×Np×λu	6×125×2.35cm

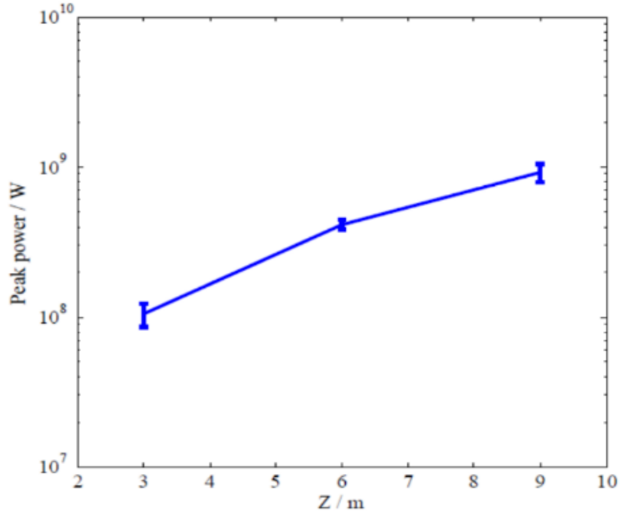
Chicanes	
DS1: length/θ/R56	12m/0-52mrad/0-25mm
DS2: length/θ/R56	3m/0-34mrad/0-2mm
FB: length/θ/R56	4.46 m/0-47 mrad/0-7mm
DS3: length/θ/R56	3m/0-34mrad/0-2mm

Case 2: cascade HGHG at SXFEL

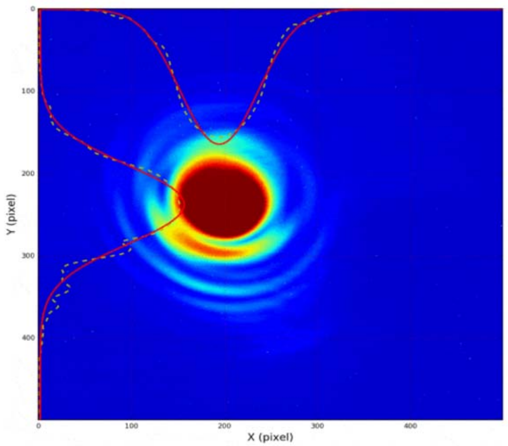
Saturation of the 1st stage HGHG

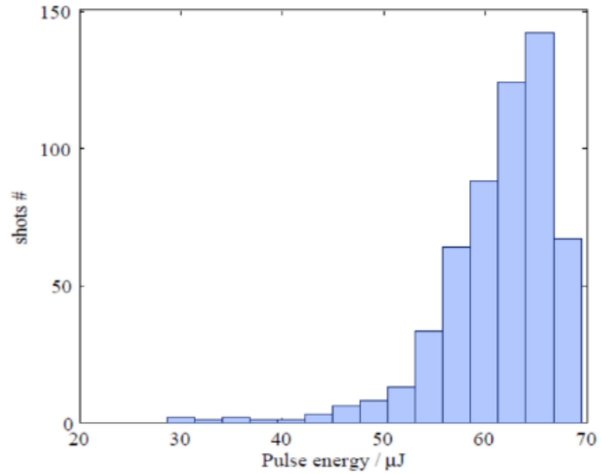


FEL gain curve



FEL spot from 1st stage @ 44nm



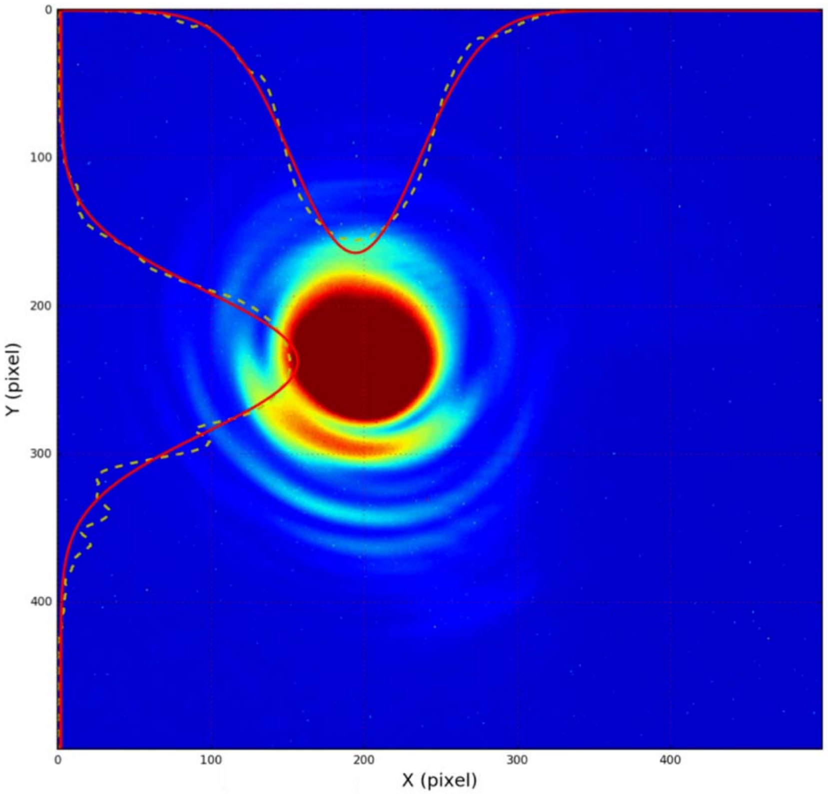


- Saturation of the 1st stage at 44nm has been achieved with peak power of several hundreds MW level.

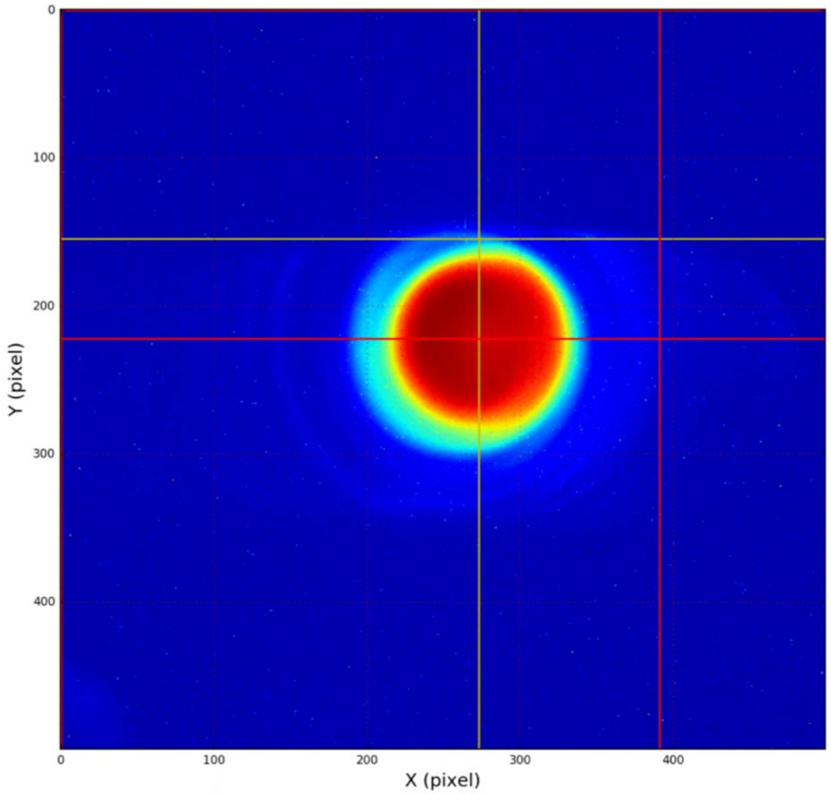
Stability (550 shots)
Average pulse energy: 61μJ
Stability: 9.4% (rms)

FEL from the 1st stage

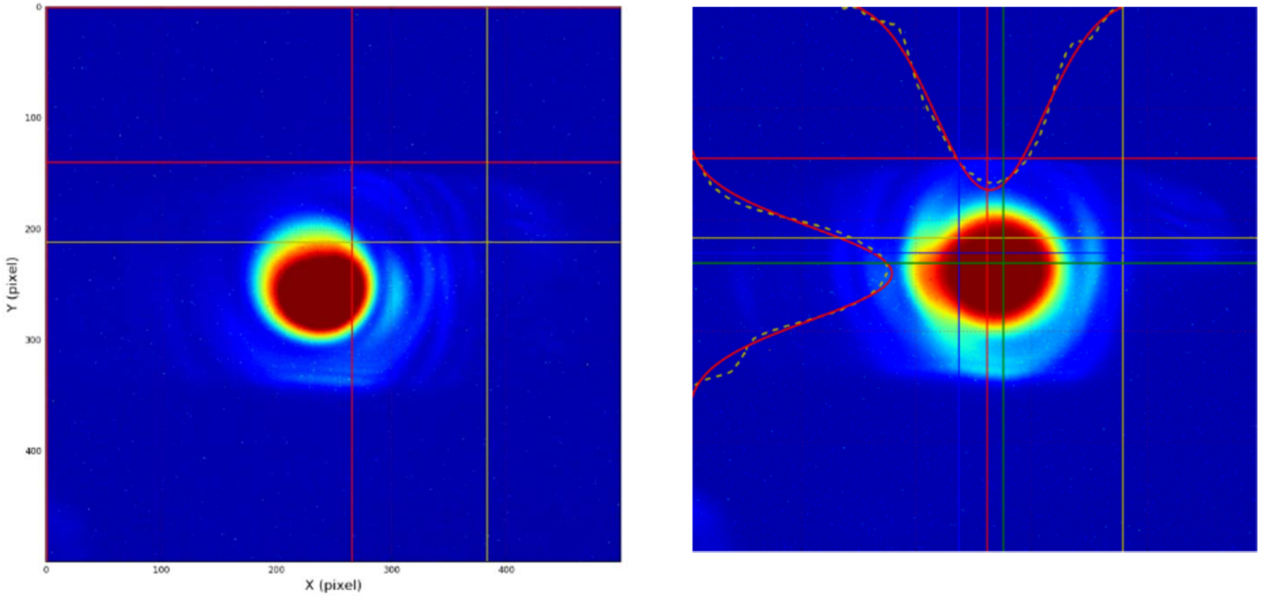
Before the 2nd stage modulator



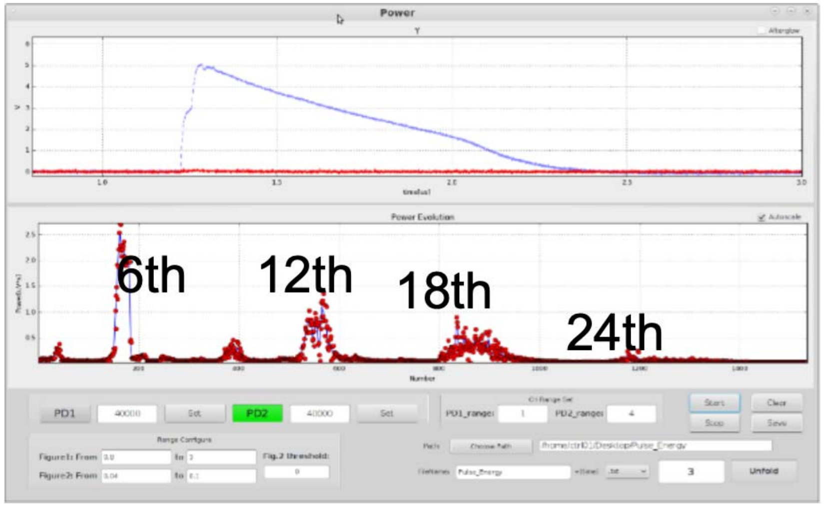
After the 2nd stage modulator



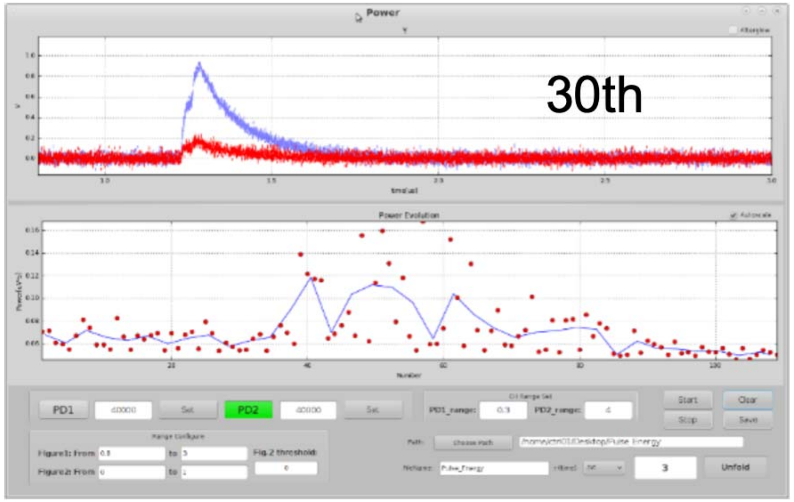
Realized the fresh bunch technique



FEL spots before and after the 2nd stage modulator

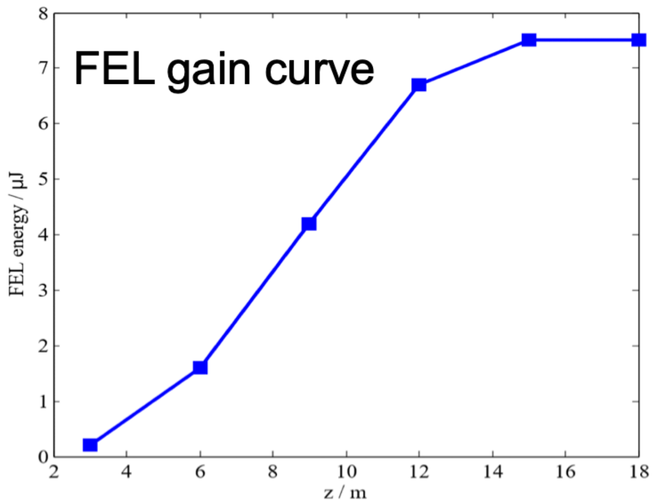


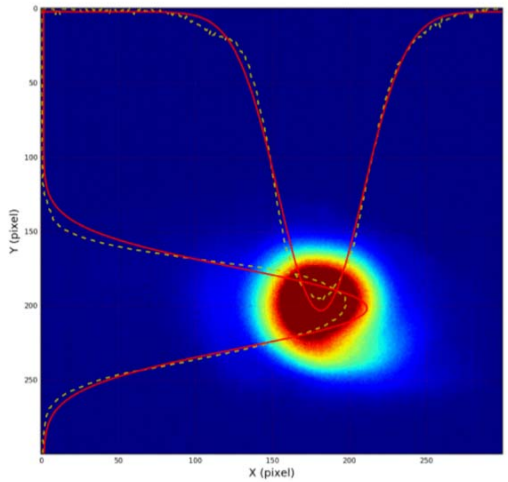
Scan the Gap of U40 and get coherent signal at various harmonics



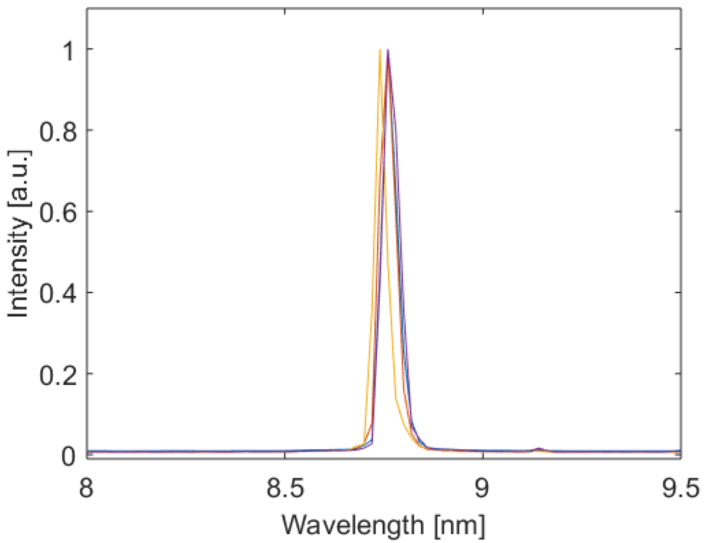
Scan the Gap of U235 and get coherent signal at 30^{th} harmonic

Amplification of the 2nd stage HGHG at 8.8nm

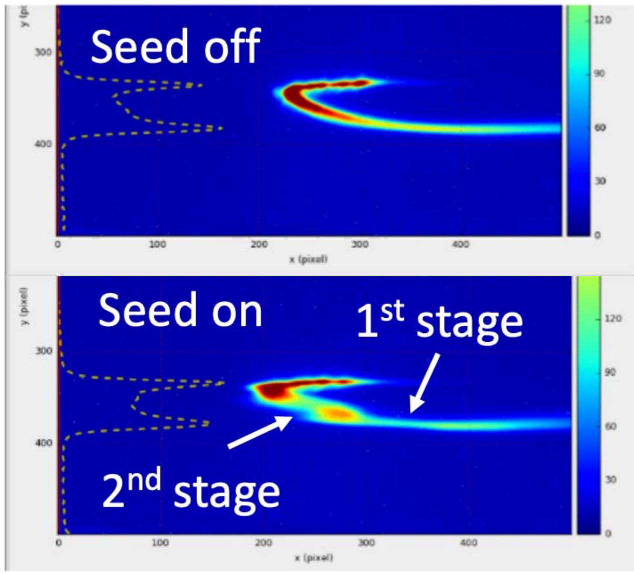




FEL spectrum from the 2nd stage @ 8.8nm



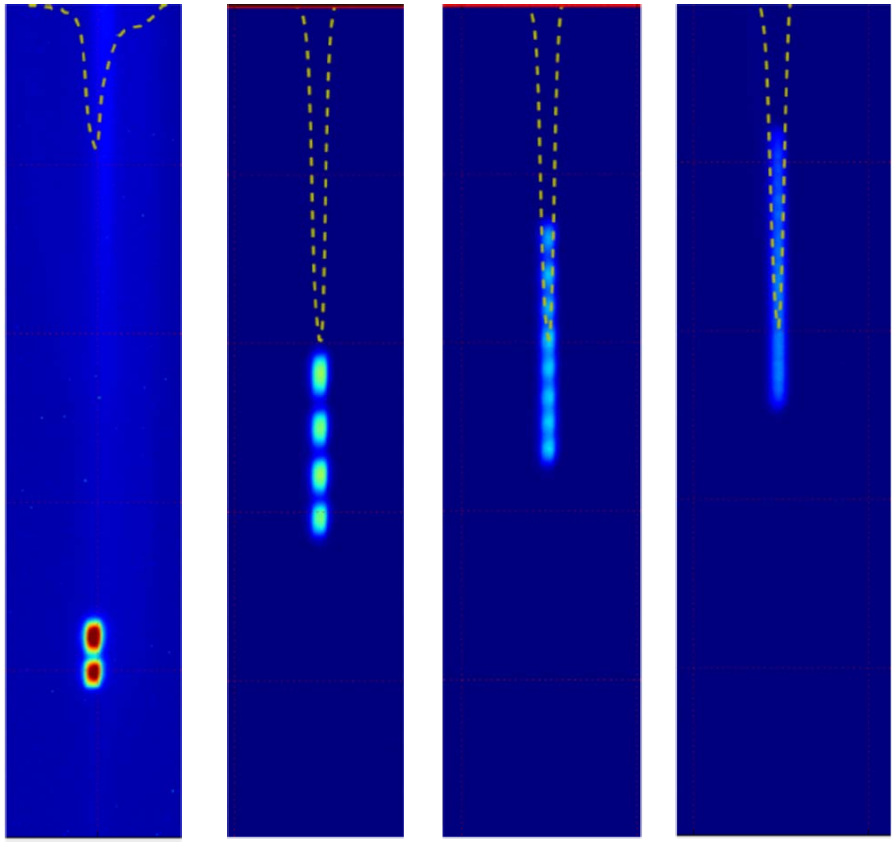
Effects of FEL lasing on the e-beam



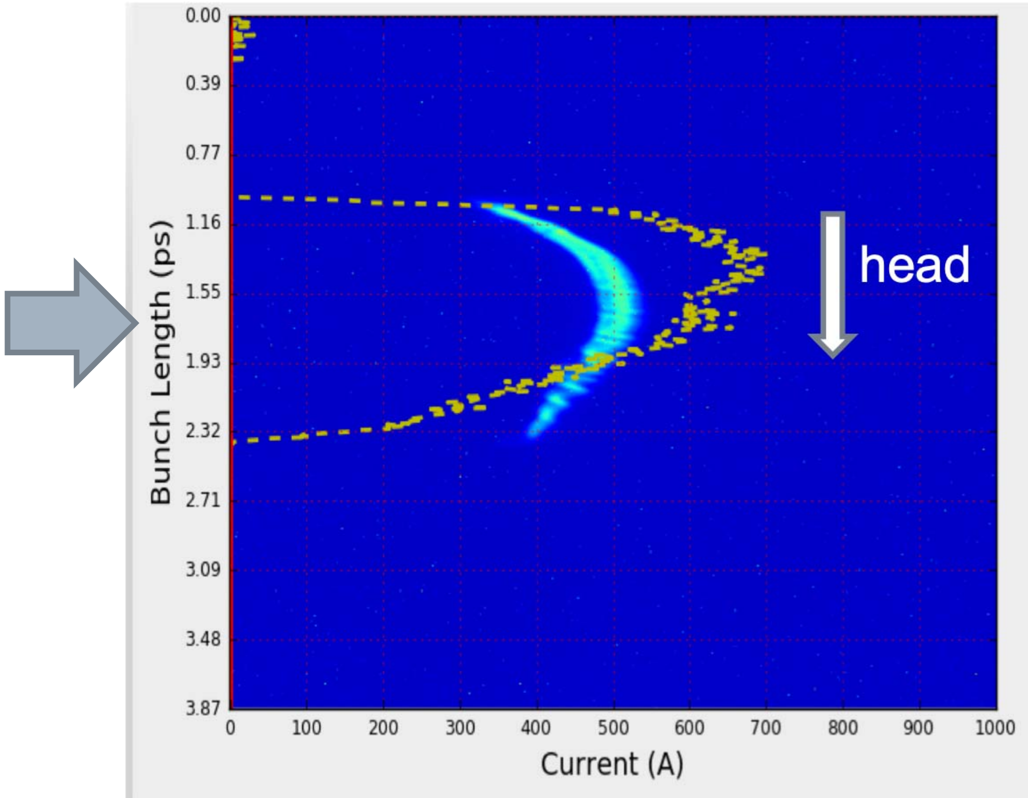
- Pulse energy >7.5 μJ, peak power > 50 MW
- Commissioning is still going on, and the final goal is not far …

Problem: strong MBI from laser pulse-stacking

Drive laser pulse stacking

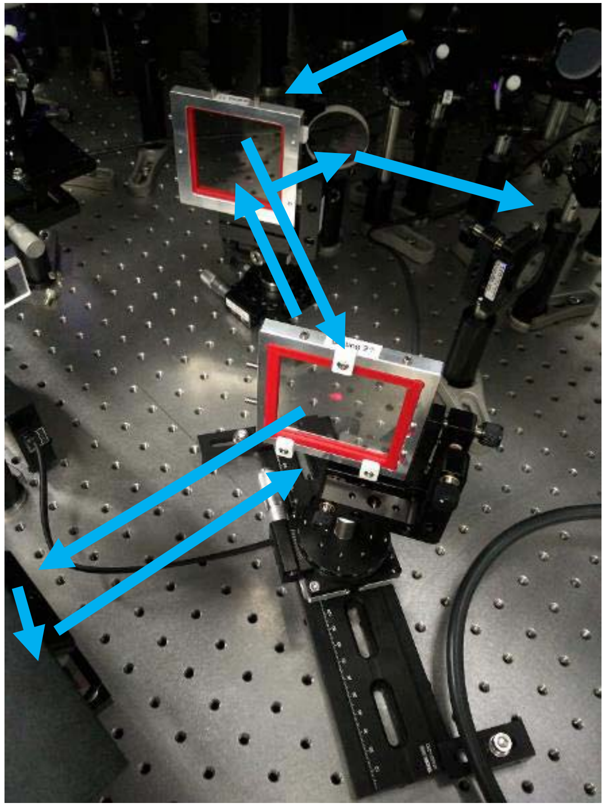


Strong microbunching @ end of linac

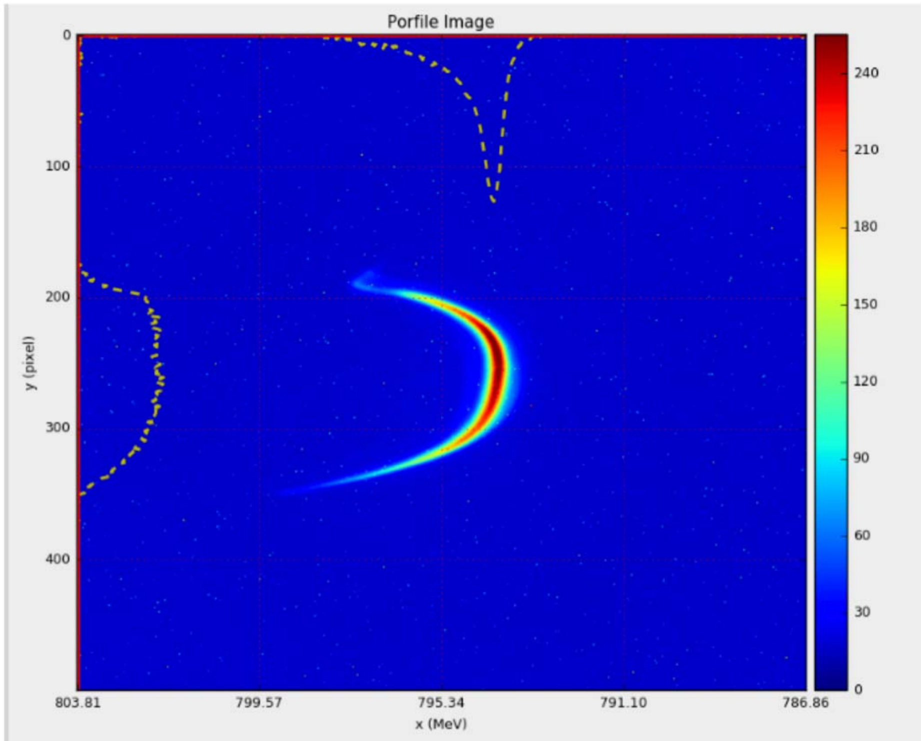


Solution: replaced the pulse stacking with UV-Grating stretcher

Pulse stretcher



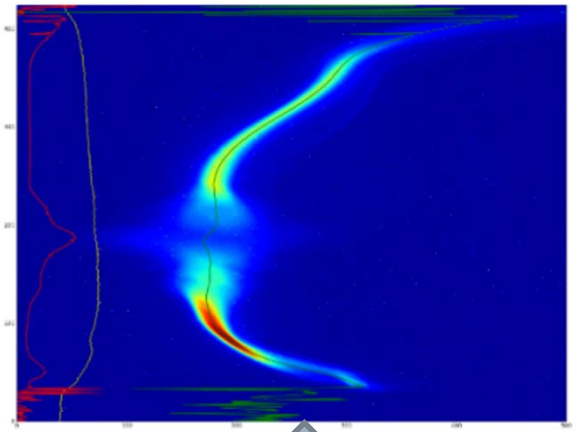
Got ‘perfect’ electron beam



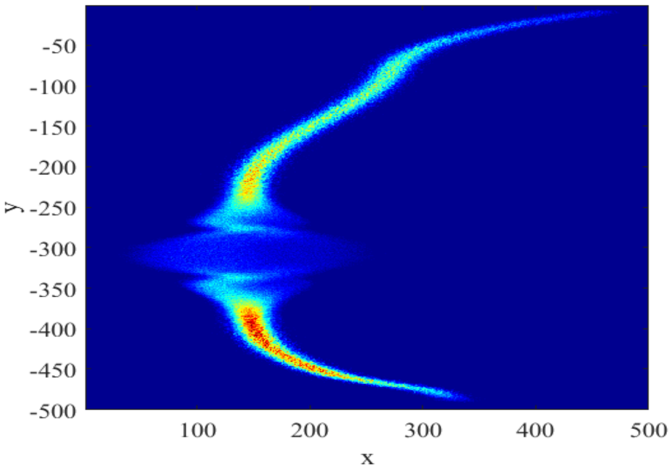
An X-band TDS had been installed after the final radiator

X-band TDS

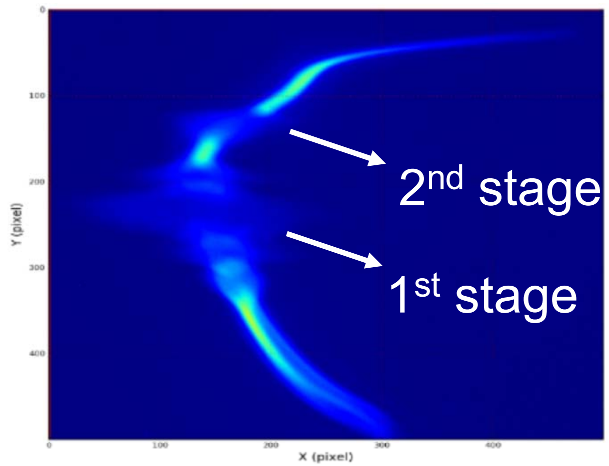
Experiment result for only 1st stage lasing



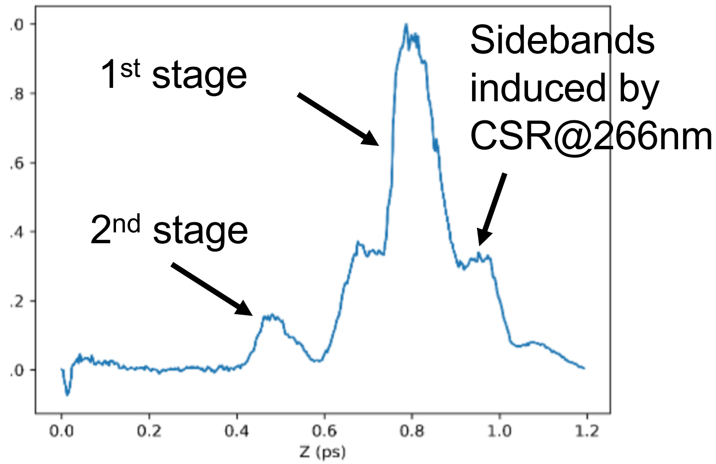
Simulation result



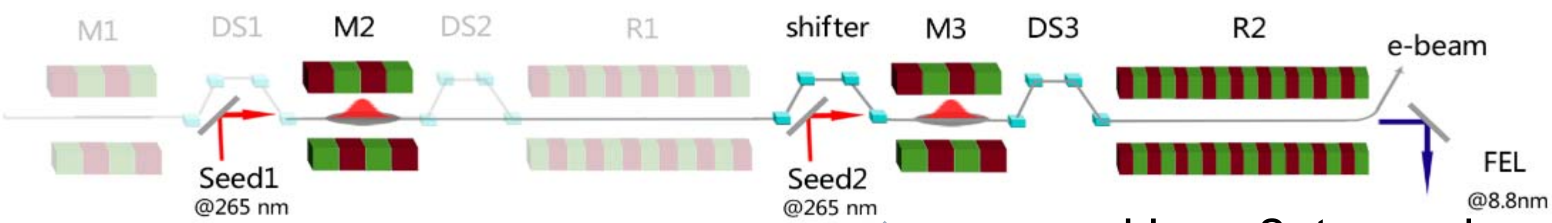
Experiment result for two stages lasing



Single pulse reconstruction

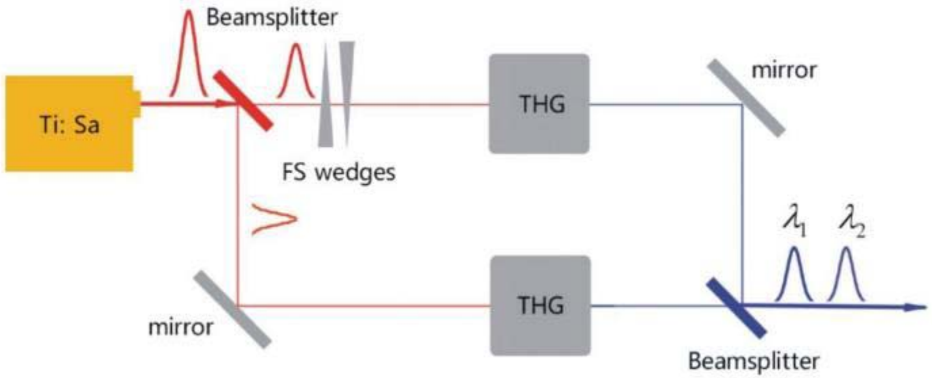


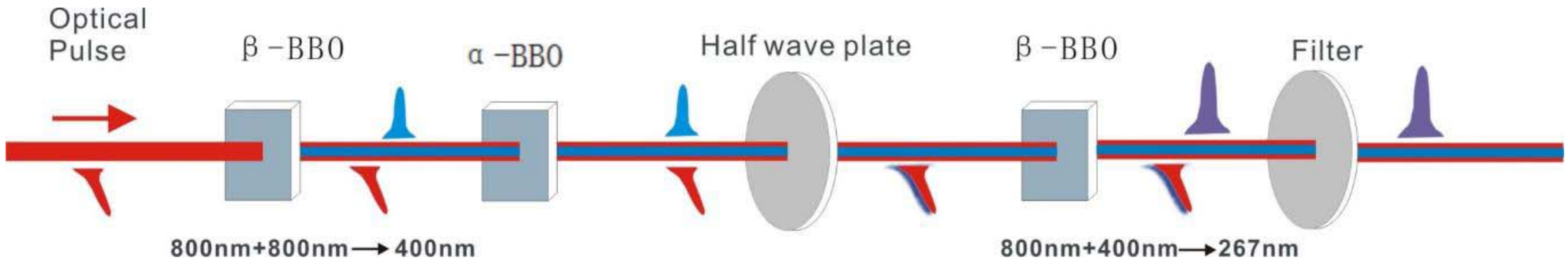
Plans: EEHG-30 and two-color EEHG



seed laser1: 1ps

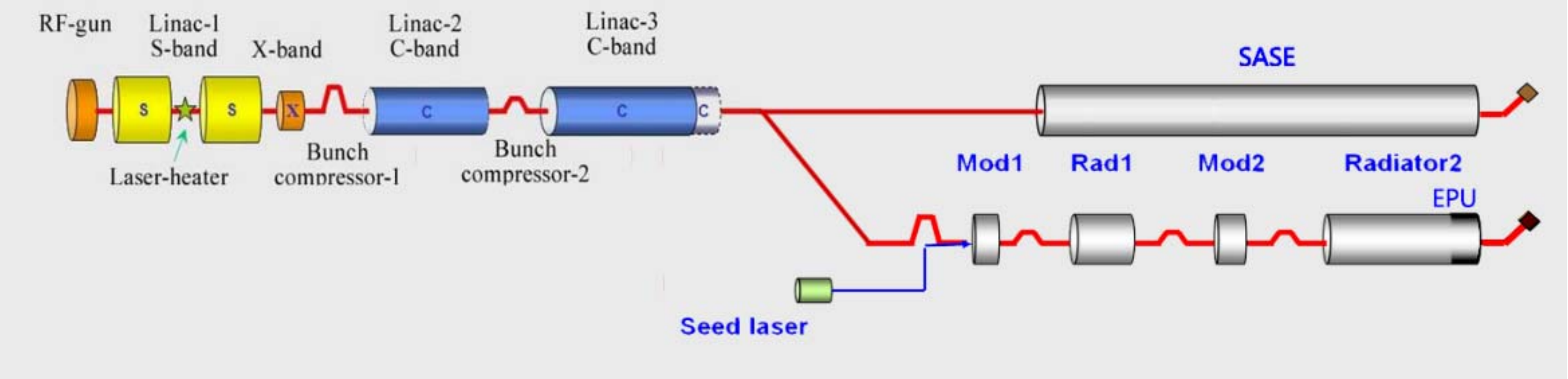
seed laser2: two-color, double pulse, 100fs





Upgrade SXFEL-TF to SXFEL-UF

- Upgrade the linac energy to 1.5GeV
- Upgrade the linac with laser heater and second bunch compressor
- Construct a SASE FEL line and a EEHG/HGHG cascade FEL line
- Construct 5 experimental stations

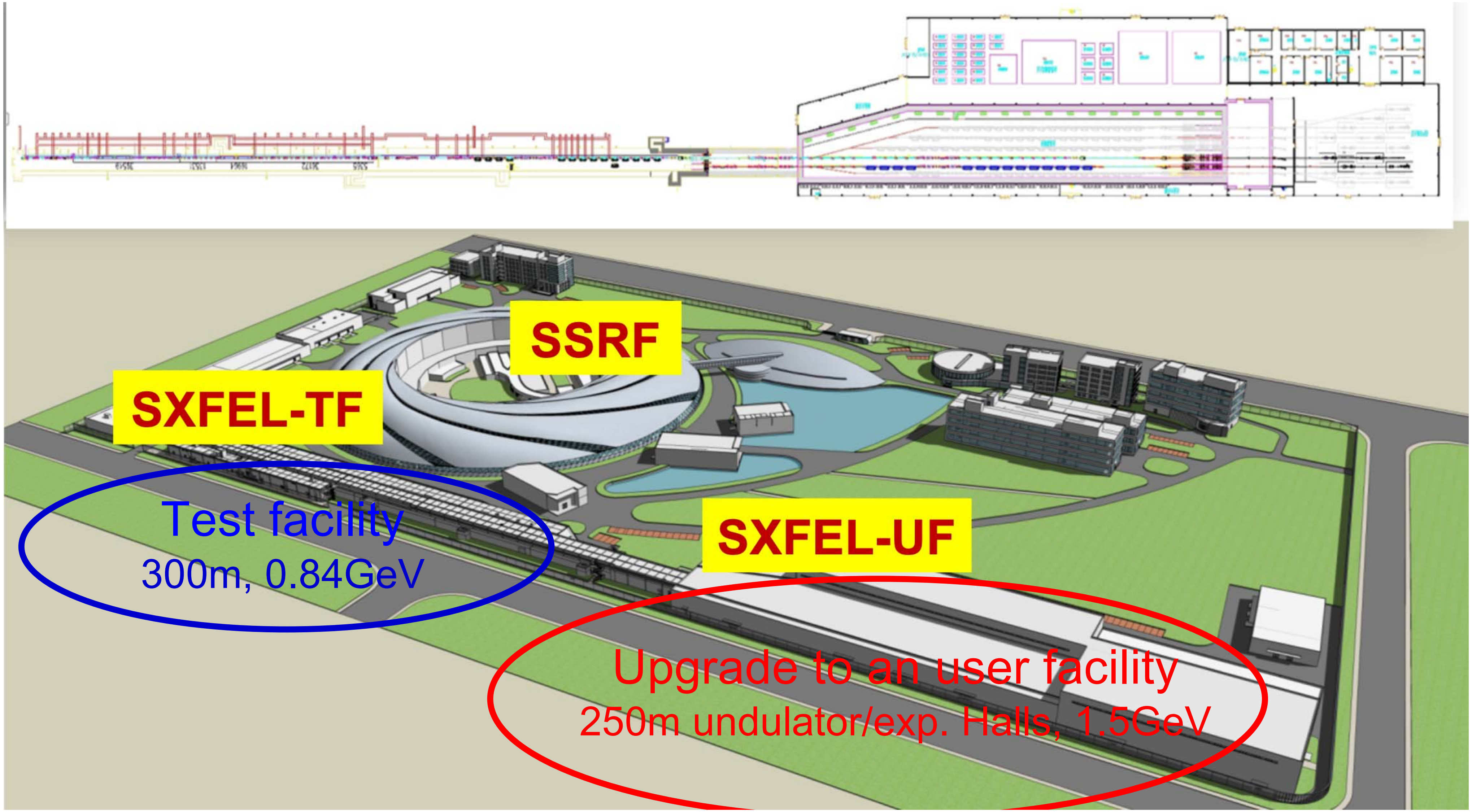


FEL parameters

	SASE line	Seeding line
Beam energy/GeV	1.5	1.5
FEL wavelength/nm	2 nm	3 nm
FEL pulse/fs	100-300	100 - 200
FEL power/MW	>100	>100
Rep. rate/Hz	50	50

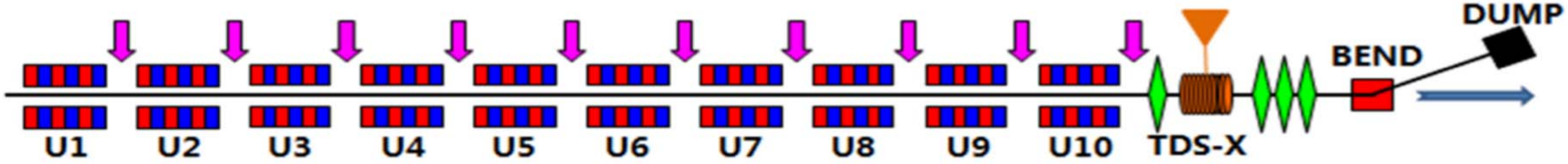
User Facility: SXFEL-UF

- 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

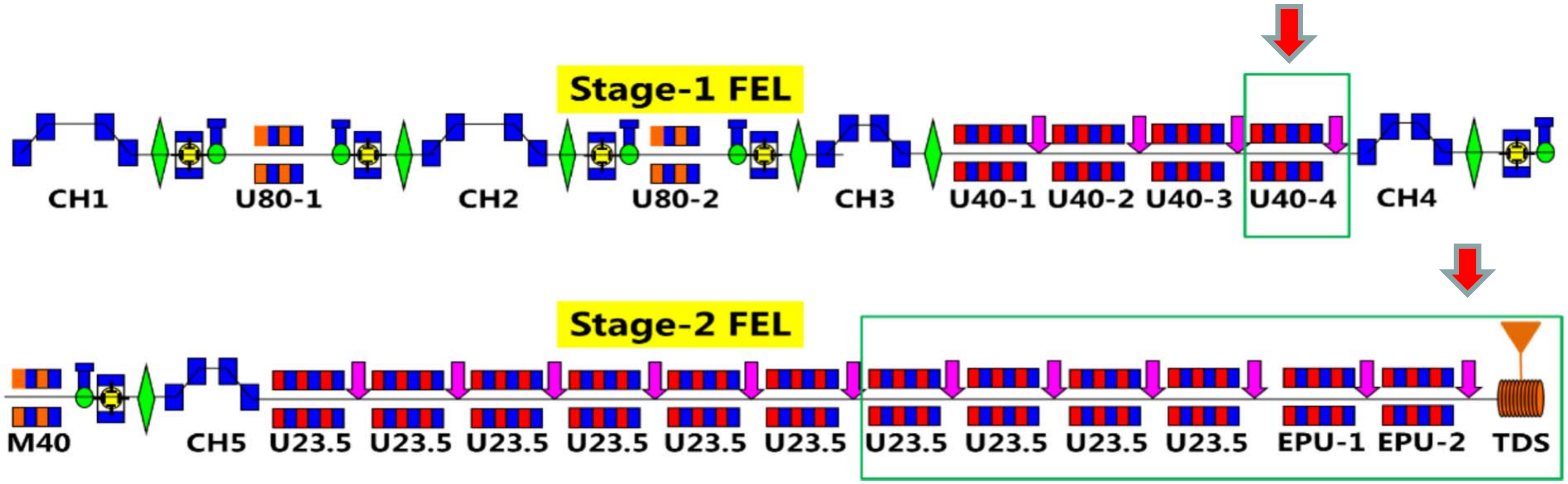


SXFEL-UF FEL lines

- **FEL1: SASE FEL line:** **build 10 IVU sections**



- **FEL2: Seeded FEL line:** **add 7 undulator units**

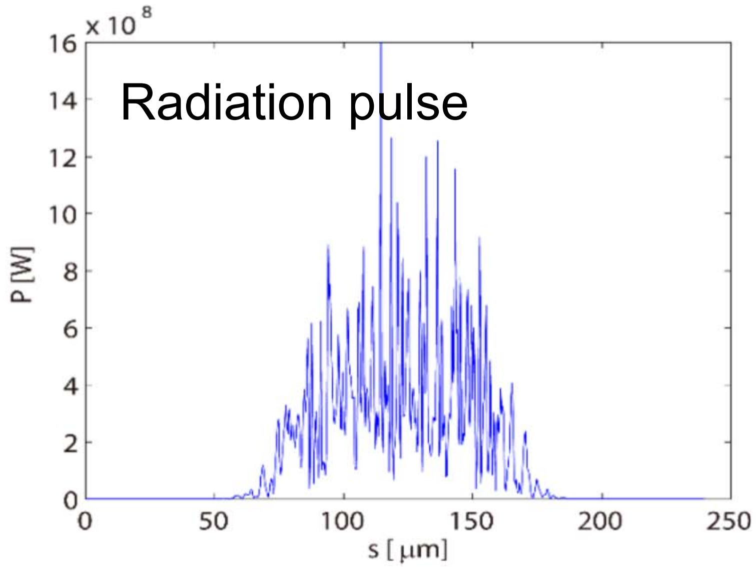


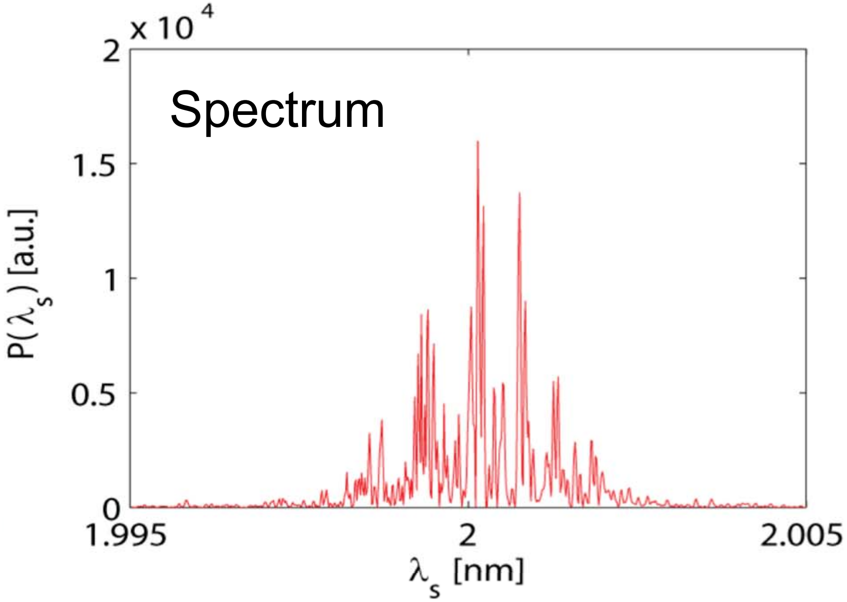
SXFEL-Parameters at Sample Positions

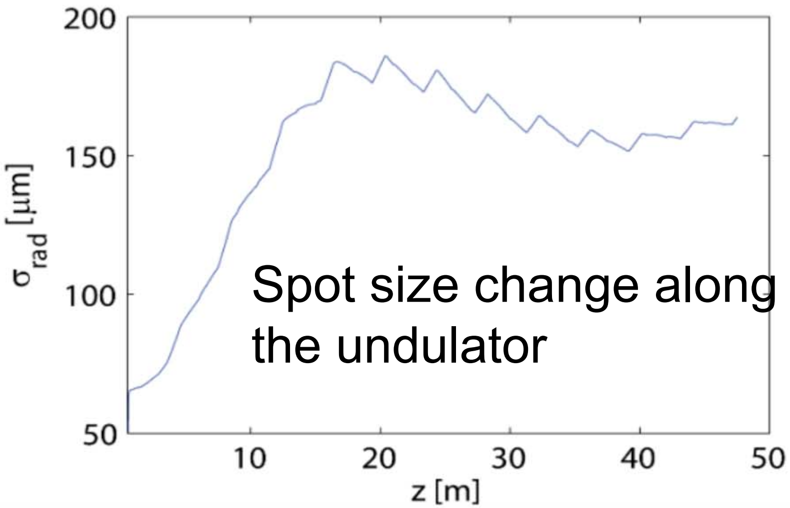
	SASE beamline	HGHG beamline
Energy range	1.2-12 nm (100-1000 eV)	2.4~24nm (50~500eV)
Pulse energy	330μJ @100eV,47μJ @620eV	64μJ @56eV , 5μJ @500eV
Photon flux /pulse	4.6×10^{11}@620eV ~1.3×10^{13}@100eV	5×10^{9}@500eV ~2.9×10^{12}@50eV
Energy resolution (ΔE/E)	0.04%~0.2%	0.008%~0.04%
Energy resolving 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

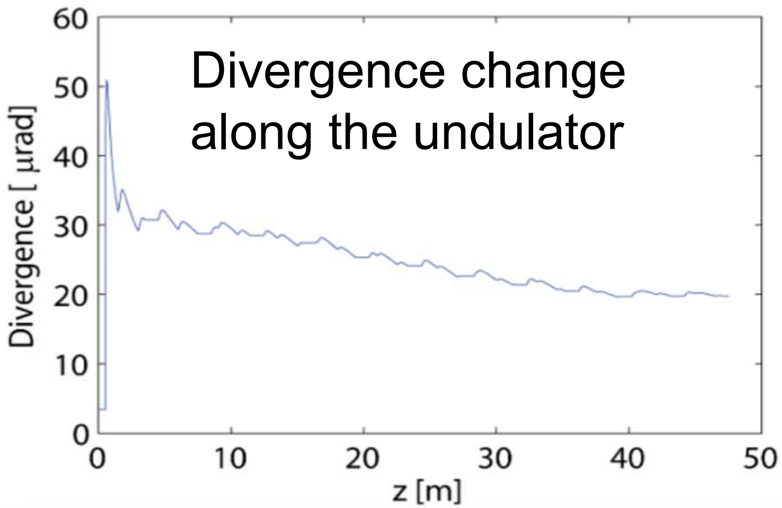
FEL1: SASE@2nm, newly built

(self-seeding and HB-SASE being considered)







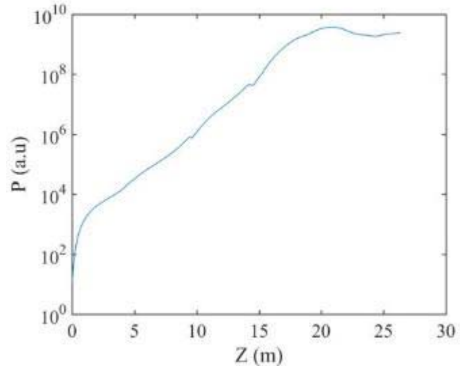


FEL1: self-seeding

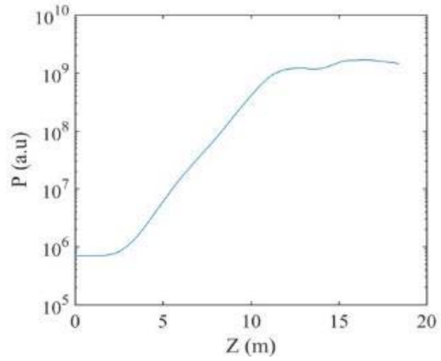
Soft x-ray self-seeding monochromator

Type	Grating-based
Coverage	300-800 eV
Efficiency	>3%
Resolution (FWHM)	~5000
Rep. rate	50Hz
Input power	~100 MW

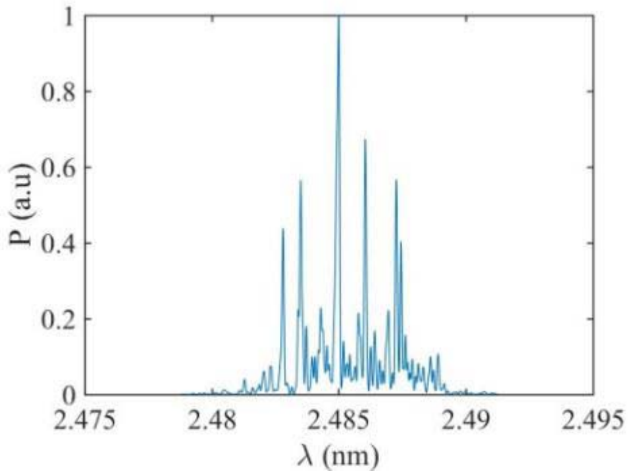
Before mono.



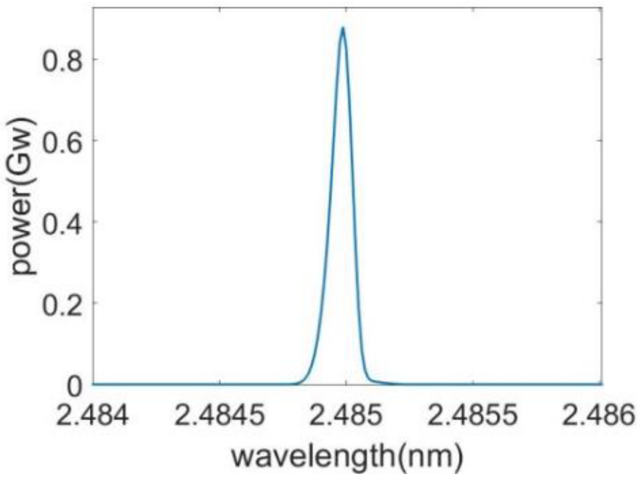
After mono.



Spectrum before mono.



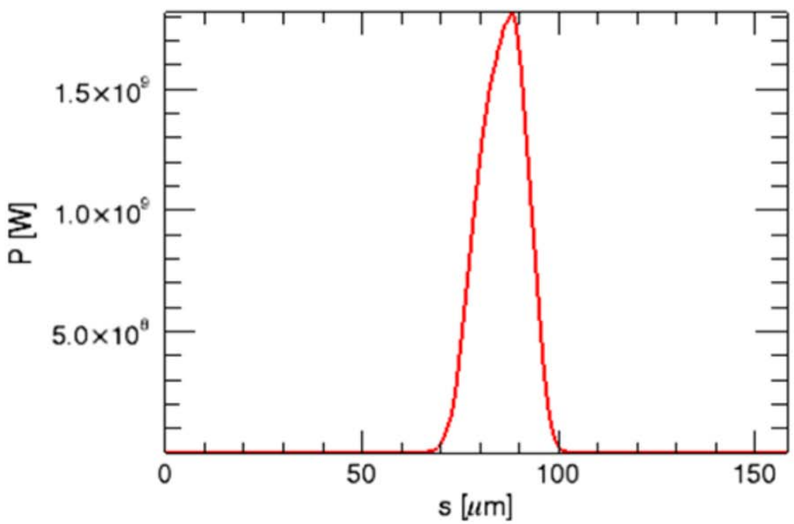
Spectrum@saturation

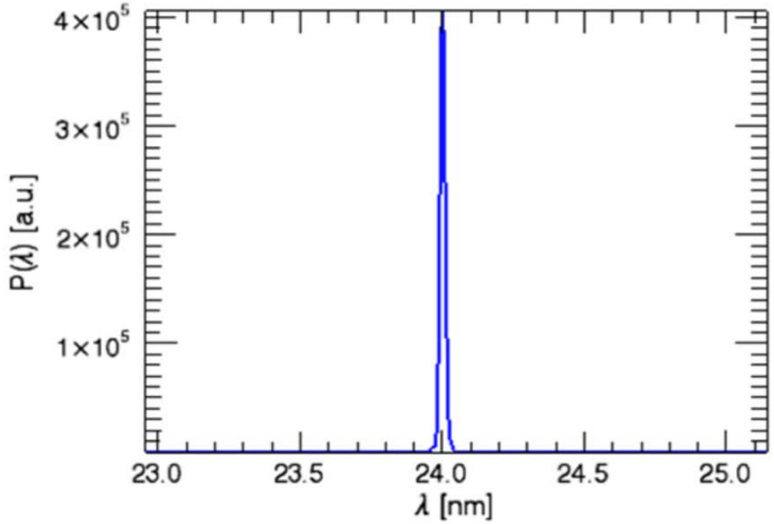


FEL2: seeding@3nm, upgrade

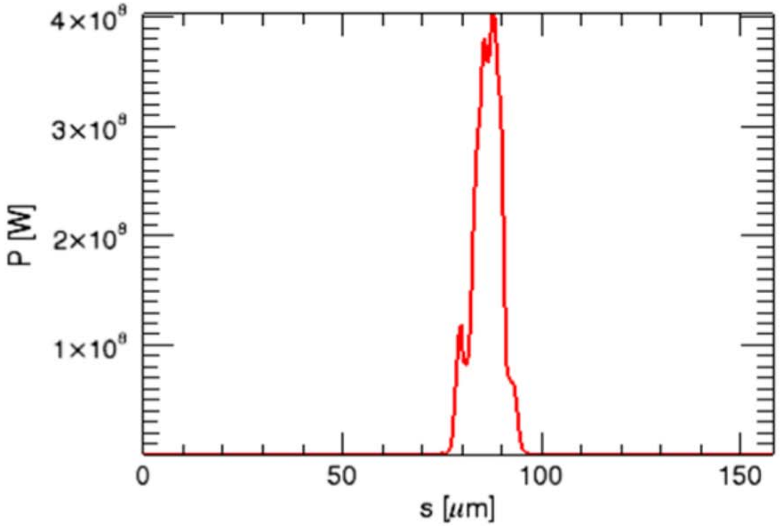
Harmonic number: 11×8

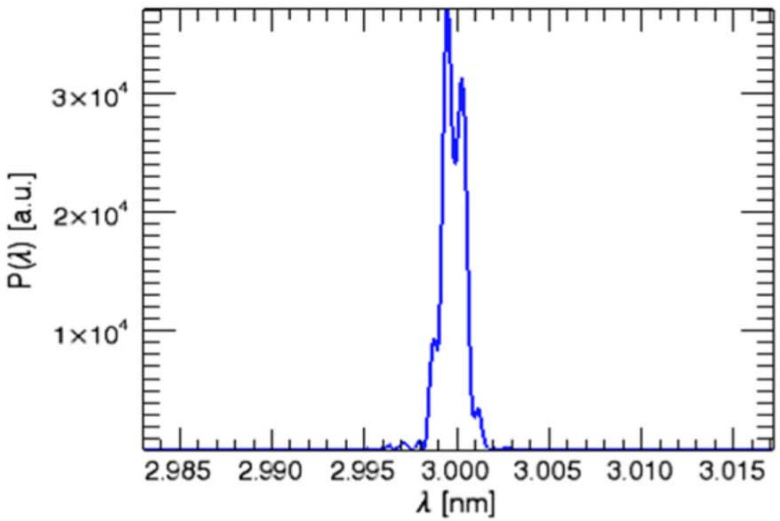
Stage-1 , EEHG:





Stage-2 , HGHG:



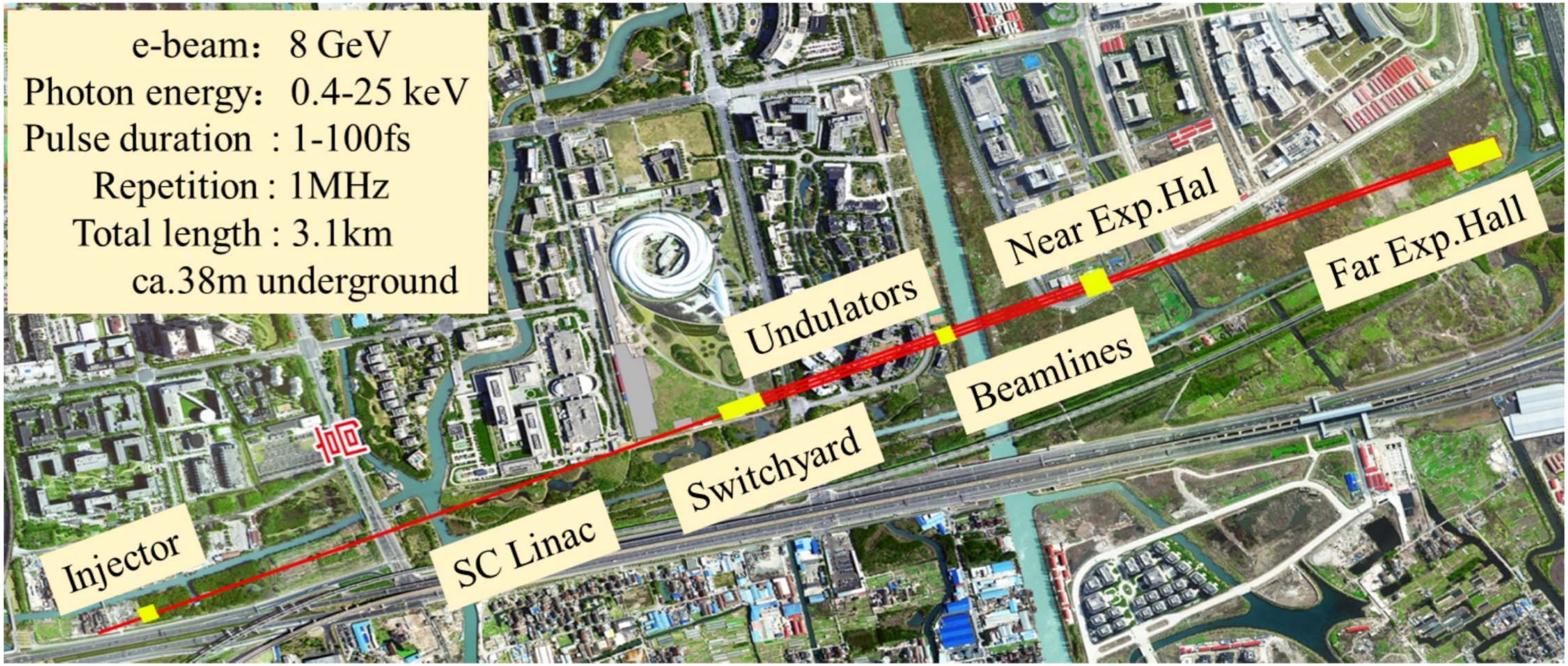


Shanghai Hard X-ray FEL Facility (SHINE)

- 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.

Shanghai Hard X-ray FEL Facility (SHINE)

- As a newly launched National Big Scientific Infrastructure

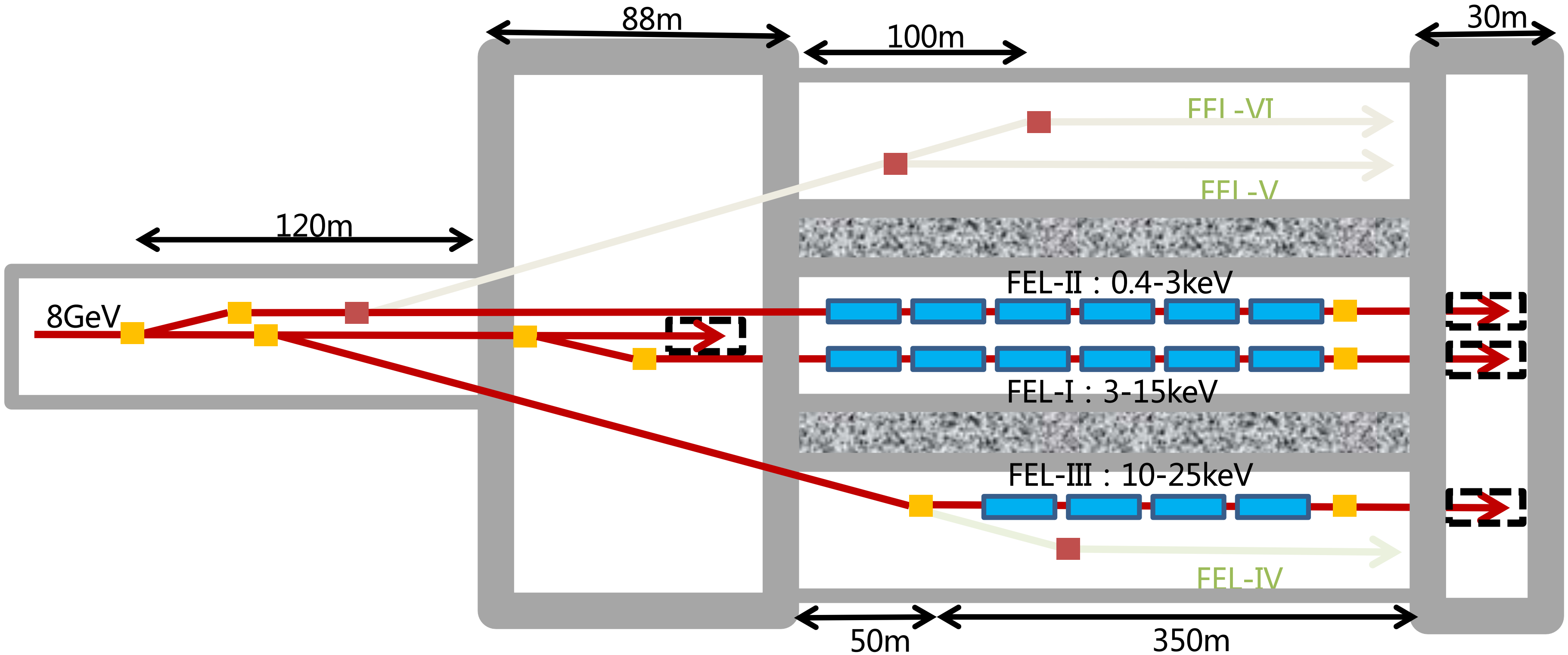


SHINE: A high-rep rate XFEL based on SCRF

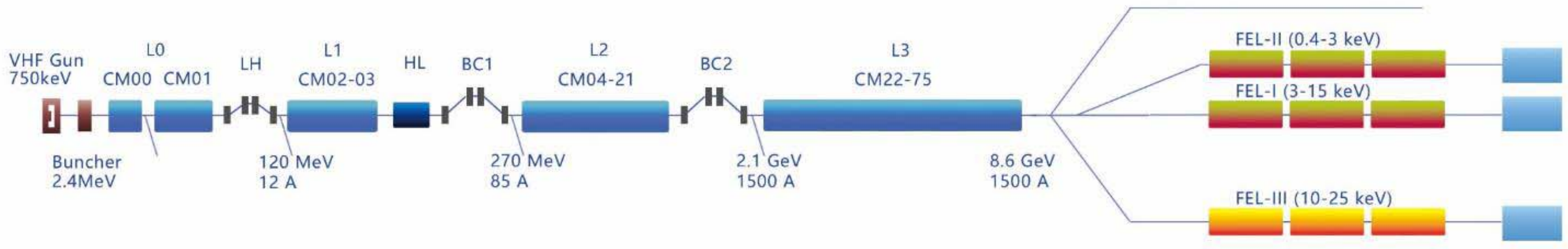
1st phase: 3 undulator beamlines to cover the photon energy range of 0.4-25keV

baseline：

- FEL-I（3-15keV）： SASE, self-seeding
- FEL-II（0.4-3keV）： EEHG-HGHG cascade, self-seeding
- FEL-III（10-25keV）： SASE, self-seeding

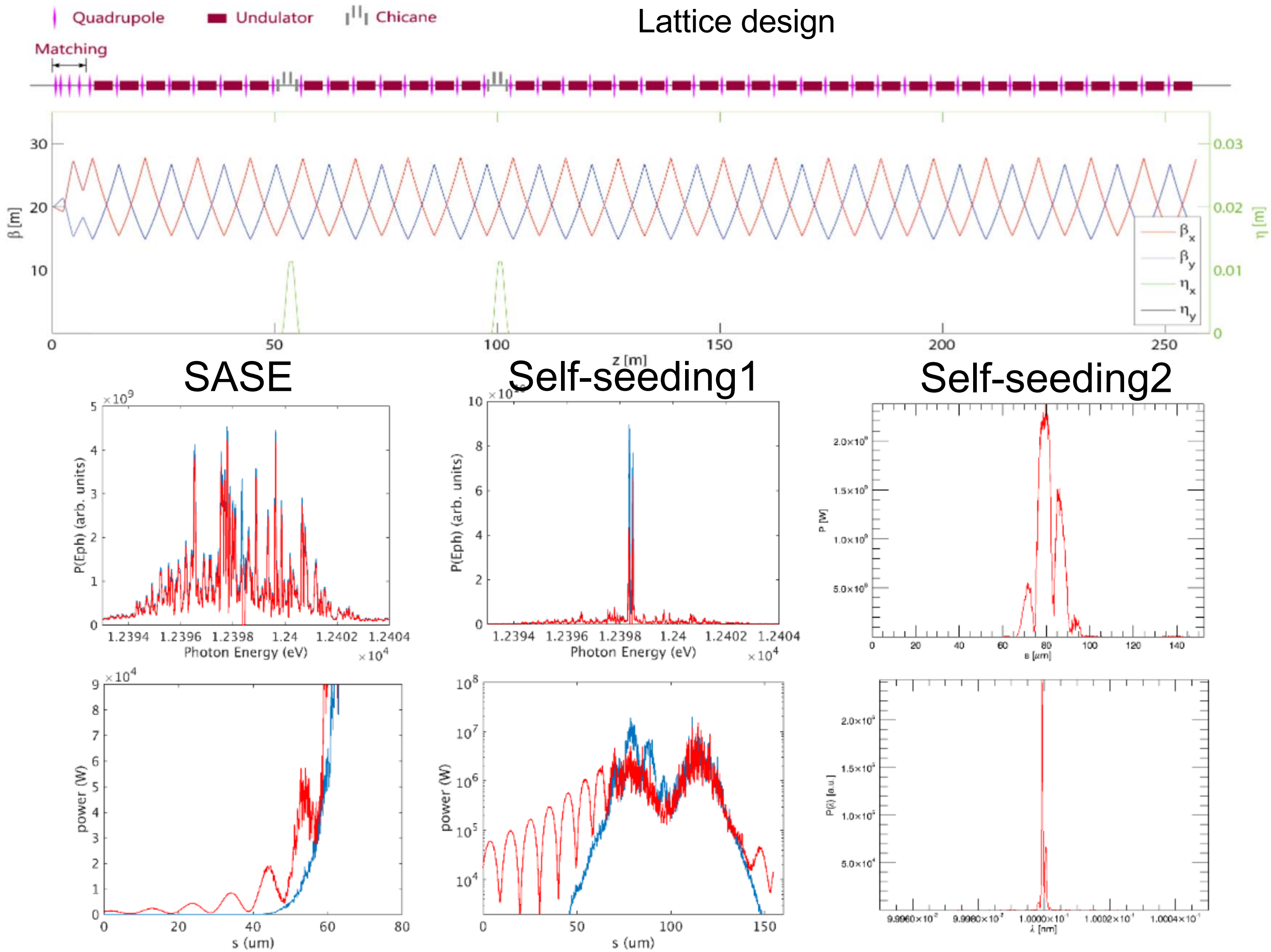


SHINE: A high-rep rate XFEL based on SCRF



	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

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

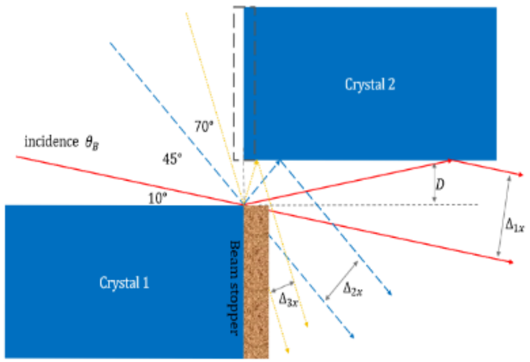


- Adopt two-stage crystal-based monochromators
- Cover the photon energy range from 3-15 keV

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

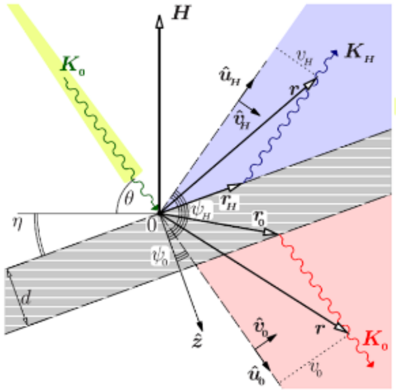
(Reflection or transmission type? To be determined)

Hard x-ray self-seeding monochromator (under design):
Type: Reflection/transmission
Photon energy coverage: 5-15keV
Resolution<10^{-4}
Efficiency>0.1%



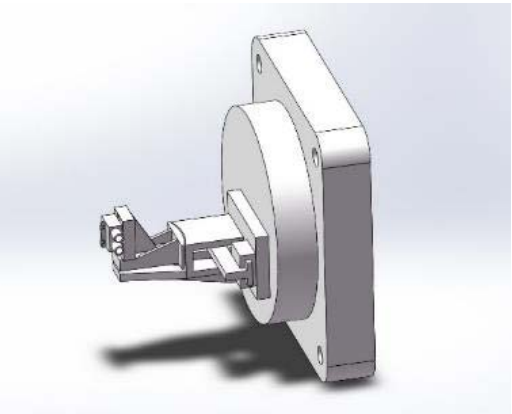
Reflection monochromator with double-crystal

Or/and



Transmission monochromator with single-crystal

Mechanical design is given and suitable for both of them

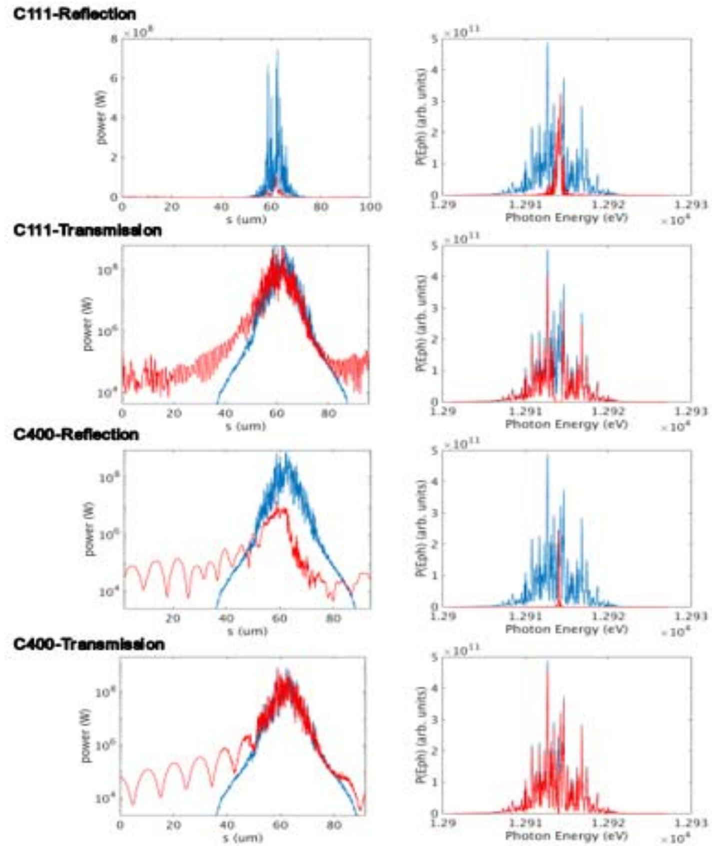


FEL-I & FEL-III (hard x-ray self-seeding)

(Reflection or transmission type? To be determined)

	Transmission		Reflection
Lattice	C111	C400	C111
Thickness/Gap	100μm	100μm	100μm
Bragg Angle	25° -90°	25° -90°	10° -40°
Photon energy (keV)	3-7.1	7-16.7	4.7-17.3
Mono-bandwidth (12.4keV)	6e-5	8e-6	6e-5
Mono-efficiency of SASE	~0.1%	~0.1%	>1%
Time delay	~20μm	~20μm	30-130μm
Transverse offset	0-50μm	0-50μm	150-200μm
Suffered FEL power	~1e7-1e9 W	~1e7-1e9 W	~1e6-1e7 W

13 keV FEL pulses and spectra before (blue) and after (red) diamond crystal monochromator with lattice C111 and C400.



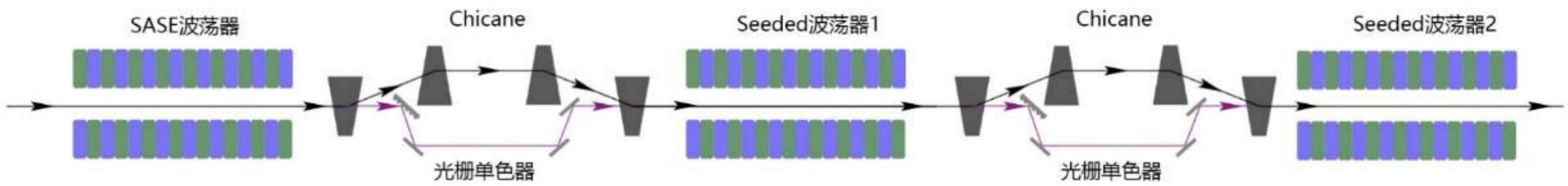
Transmission crystal monochromator:

- Demonstrated at LCLS and PAL-XFEL, in preparation at European-XFEL.
- Easy to get the transverse overlap of the mono light and e-beam.
- ~0.1% monochromatic efficiency, relative heavy heat-loading.

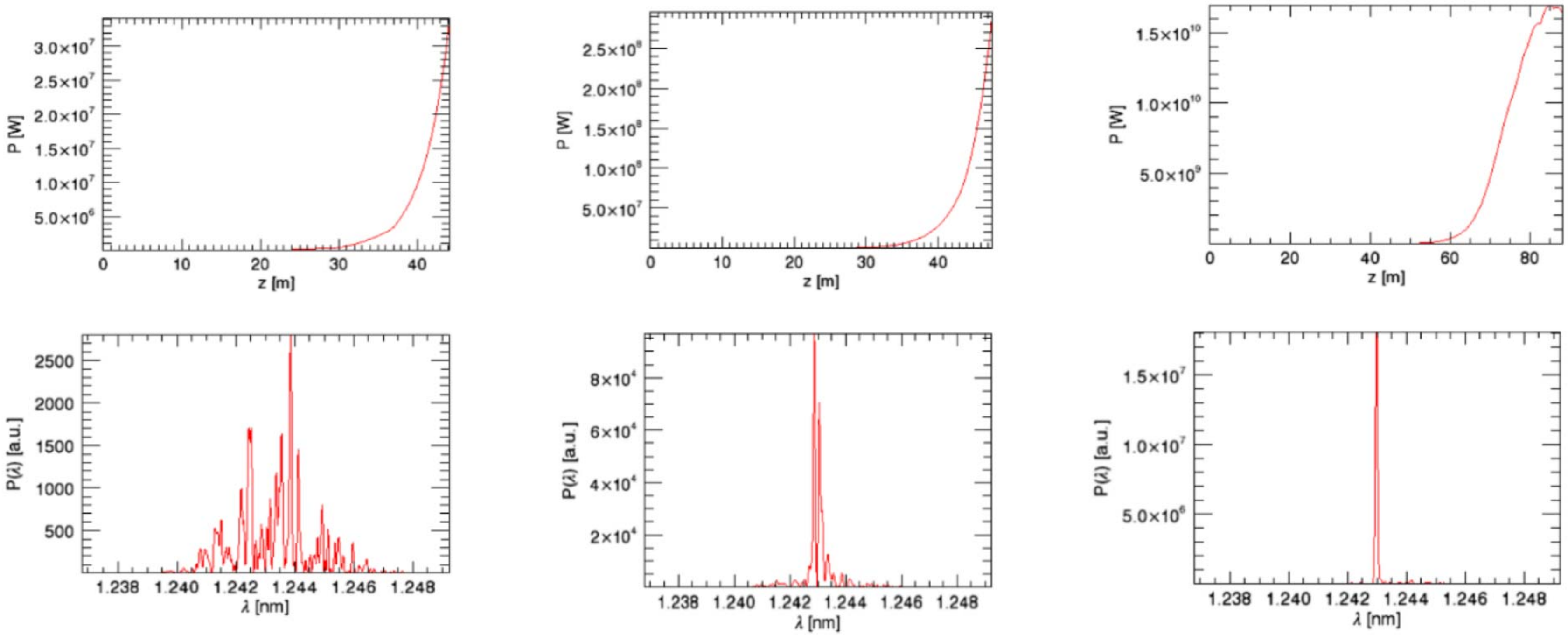
Channel-cut reflection crystal monochromator:

- Demonstrated at SACLA.
- 1 − 2 order of magnitude monochromatic efficiency higher than the transmission one.
- Smaller heat-loading, easy for the cooling system.
- Small incident angle, covering higher photon energy range.
- Large transverse offset, need to tune the central of the electron beam and also downstream undulators

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



SASE | Self-seeding1 | Self-seeding2

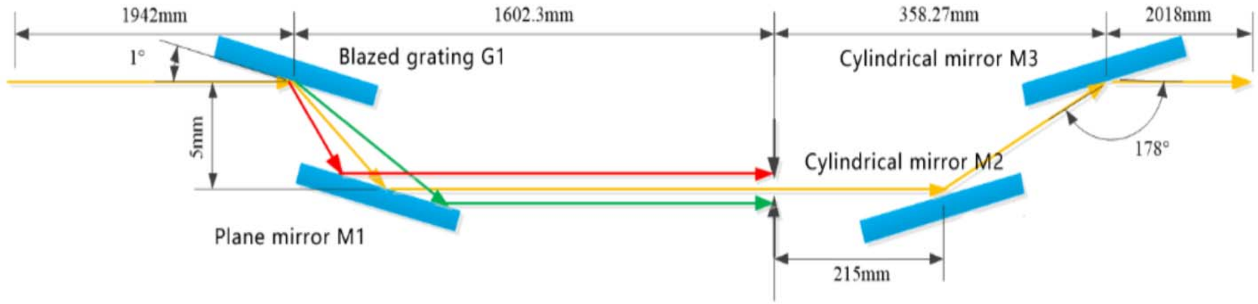


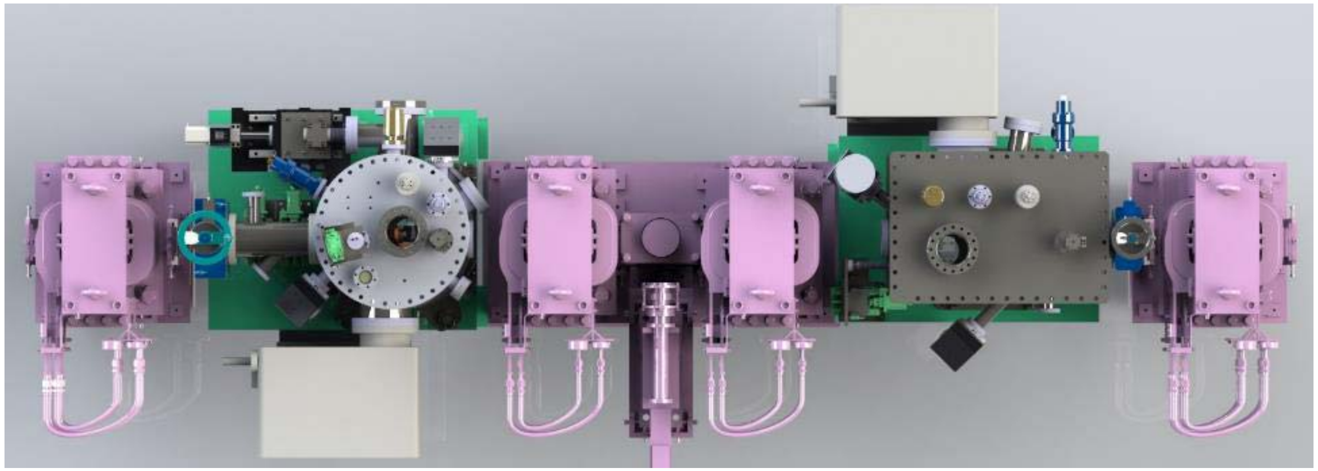
- Adopt two-stage grating-based monochromators to relax the heat-loading effect for high repetition rate operation and improve the temporal coherence
- Cover the photon energy range from 0.4-1.5 keV

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

Soft x-ray self-seeding monochromator (design finished, under fabrication):

Type: grating based
Photon energy coverage: 0.4-1.5keV
Resolution>5000
Transmission efficiency>0.5%

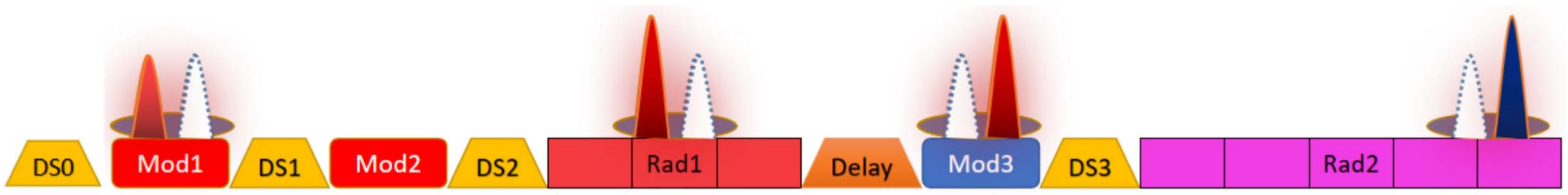




FEL-II (external seeding)

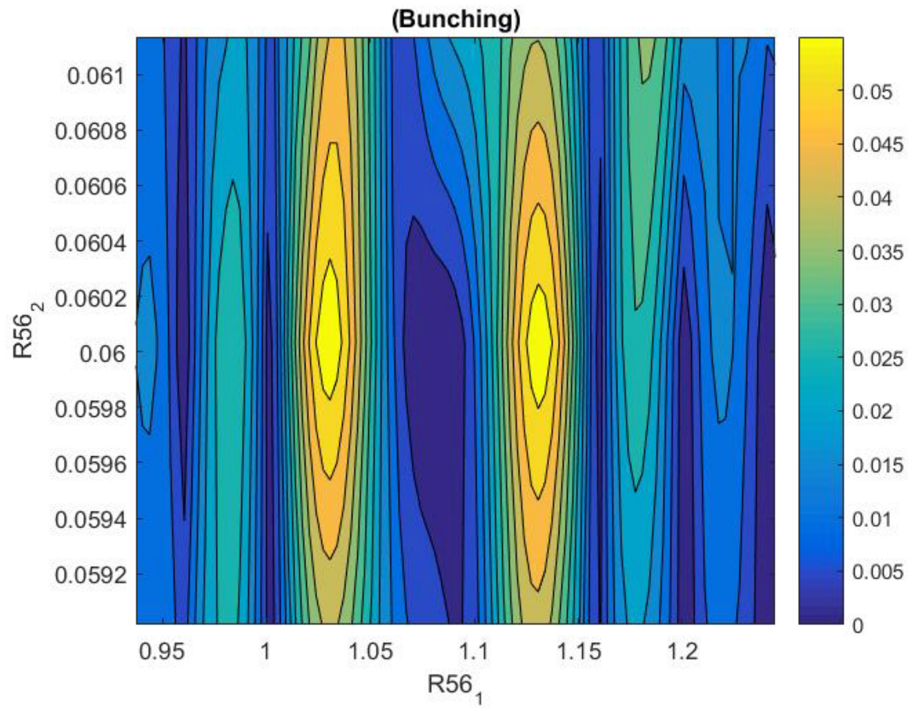
Layout and description

EEHG-HGHG cascade



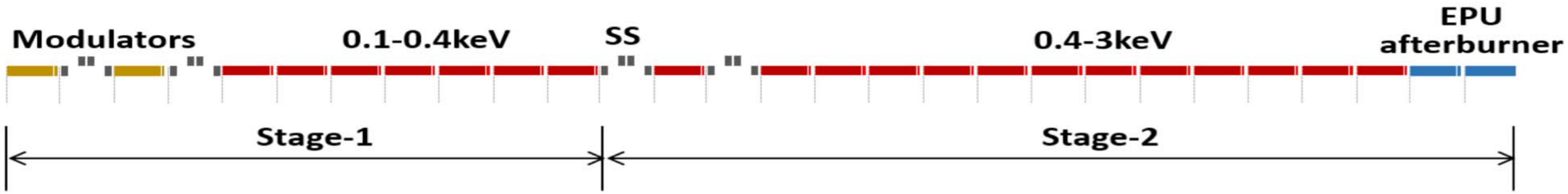
Optimized parameters

	Stage-1	Stage-2
Modulator period	240mm	68mm
Modulator length	Mod1 2.4m×1 Mod2 1.2m×1	4m×1
Seed laser wavelength	270nm	1-3nm
Seed laser duration	~30fs	
Radiator period	68mm	68mm
Radiator length	4m×10	4m×28
Radiator wavelength	9-3nm	3-0.4nm
EPU afterburner		4m×4

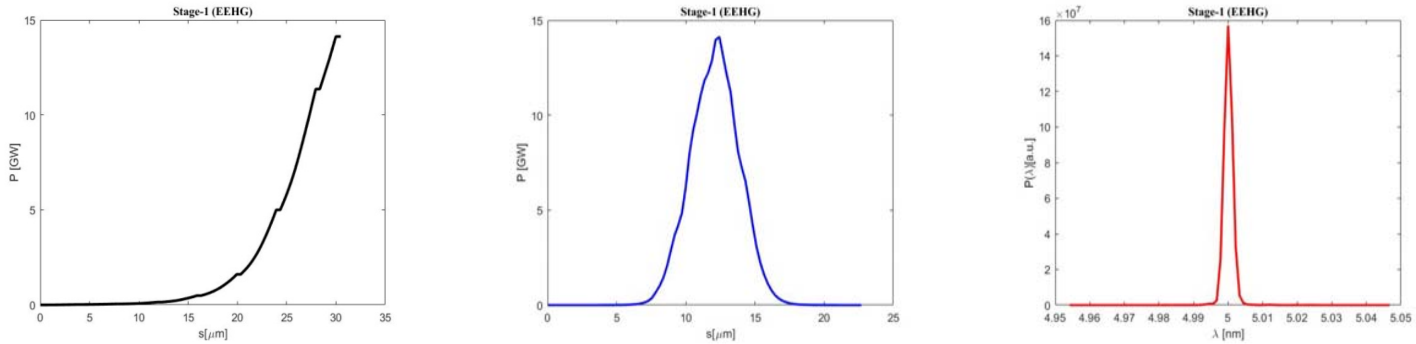


FEL-II (external seeding)

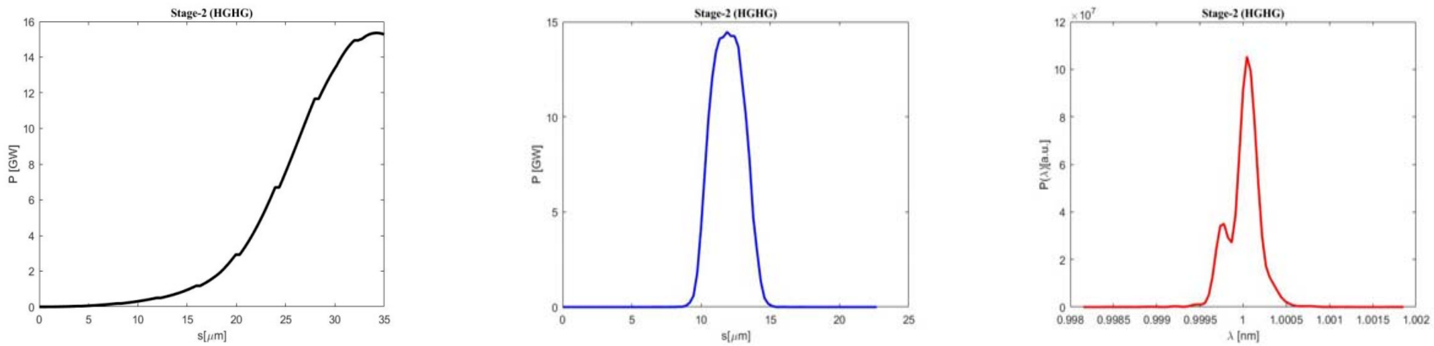
Layout and description



First-stage EEHG (54th harmonic)



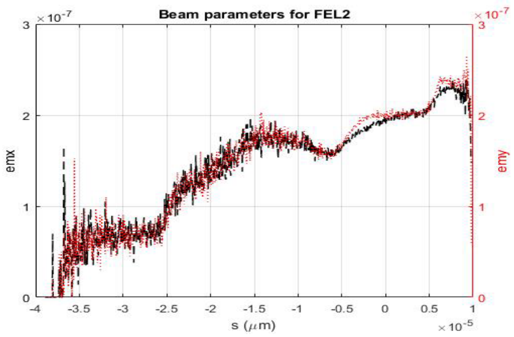
Second-stage HGHG(5th harmonic)

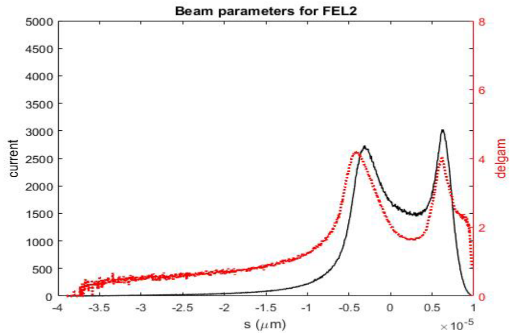


Fully coherent at 1nm

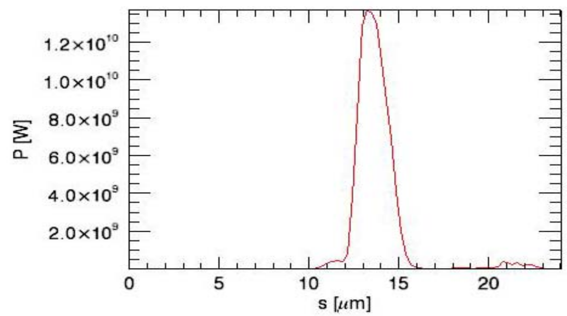
FEL-II (Start to end simulation)

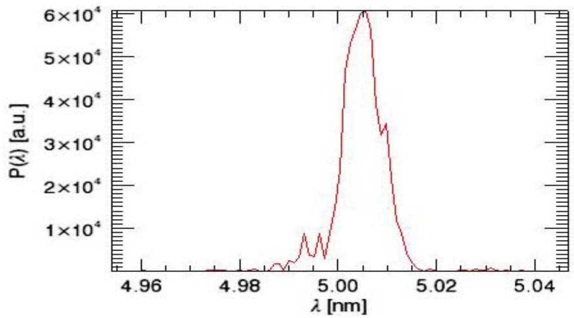
1.The emittance and current profile of the electron beam from the LINAC



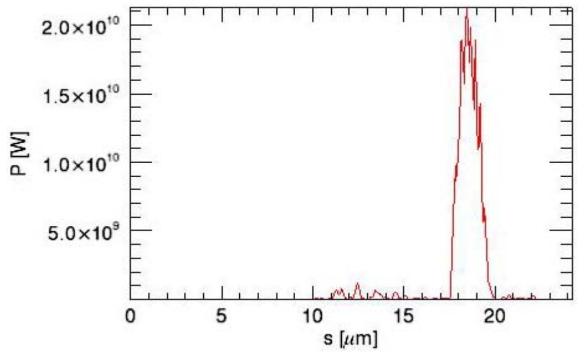


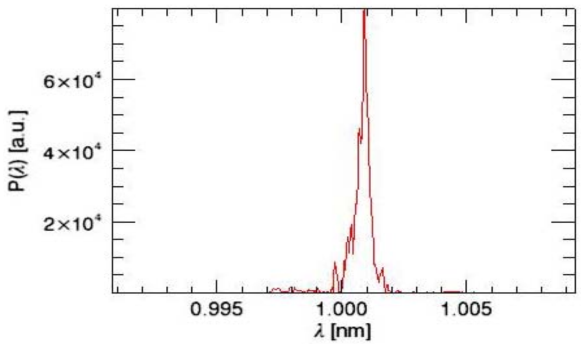
2.Radiation power and spectrum from the 1st stage EEHG





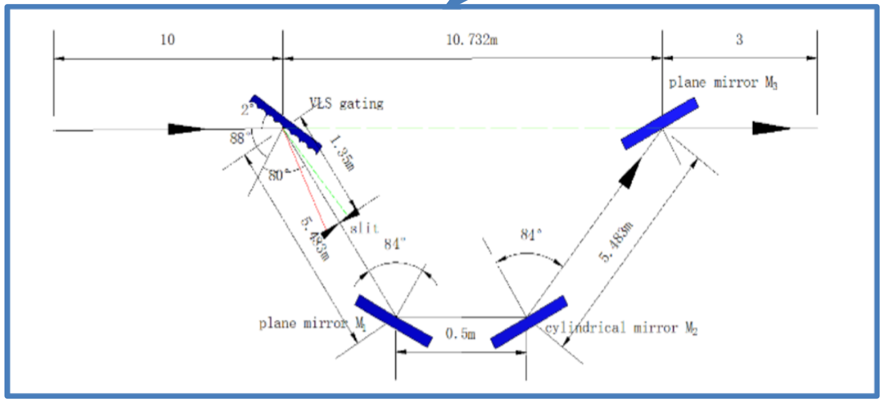
3.Radiation power and spectrum from the 2nd stage HGHG

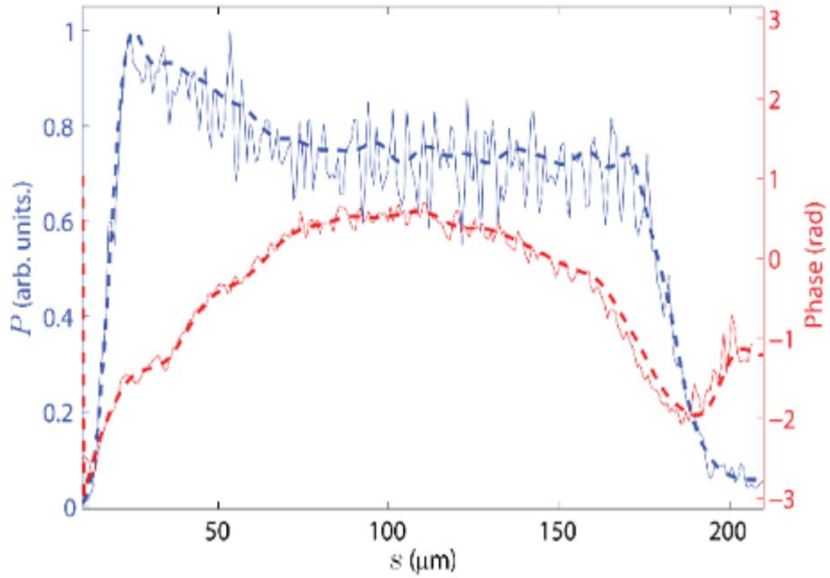




FEL-II (external seeding for 1nm and below)

Fresh bunch chicane & mono chicane





Longitudinal profile (blue) and phase (red) of the radiation pulse before (soiled line) and after (dashed line) the monochromator.

- Electron beams with quite different properties are separately used in each stage for improve the stability and peak power of the final output
- The noise amplification problem of harmonic cascading schemes may be solved by using the soft x-ray monochromator between the two stages

Summary

- A soft X-ray FEL facility is under development, its first phase commissioning has been making progress.
- 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.
- The SXFEL is aiming at serving users in 2020, and SHINE is aiming to start user experiments in 2025.
- Various external seeding and self-seeding schemes have been adopted in these facilities and we are developing new techniques for fully coherent radiation pulse at even higher photon energies.


谢
谢！
Thanks for your attention !
AURORA