Commissioning Progress and Advanced FEL Experiments at the SXFEL Facility

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Shanghai Advanced Research Institute, Chinese Academy of Sciences

67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources

Lucerne, Switzerland, from August 27 to September 1, 2023

Outline

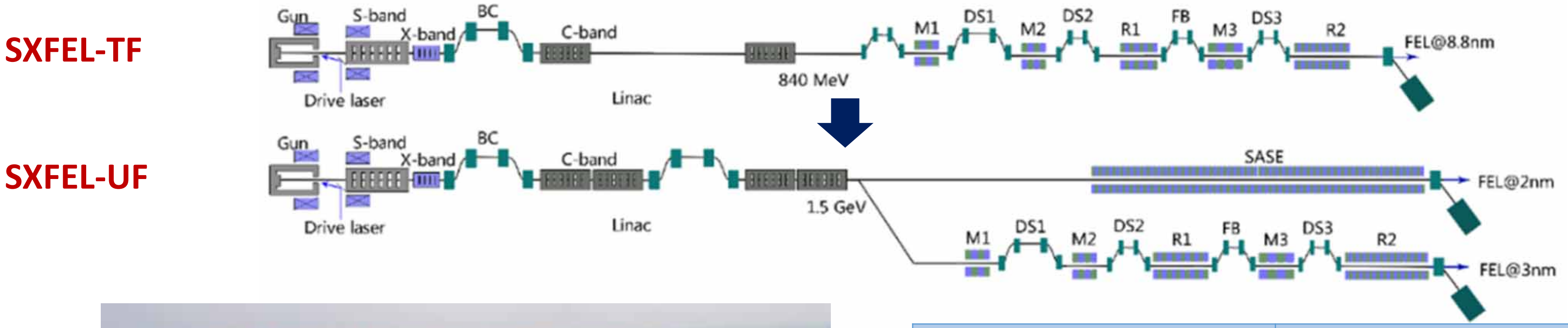
- Introduction
- SASE-FEL at SXFEL
- Seeded-FEL at SXFEL
- Plans on advanced FEL experiments

Shanghai X-ray light sources cluster

SXFEL: Shanghai Soft X-ray FEL Facility

- **Two phases of SXFEL Facility:** SXFEL test facility (SXFEL-TF) + SXFEL user facility, located at the SSRF campus;
- **SXFEL-TF** was initiated in 2006 and funded in 2014, its 0.84GeV linac and main undulators started to be installed in 2016. The commissioning of the test facility had been finished in 2020;
- **SXFEL-UF (+SBP)** was funded to upgrade the linac energy to 1.5 GeV for building two undulator lines with 5 experimental stations. The commissioning of the user facility started in 2021 and finished in 2022.

From test facility to user facility

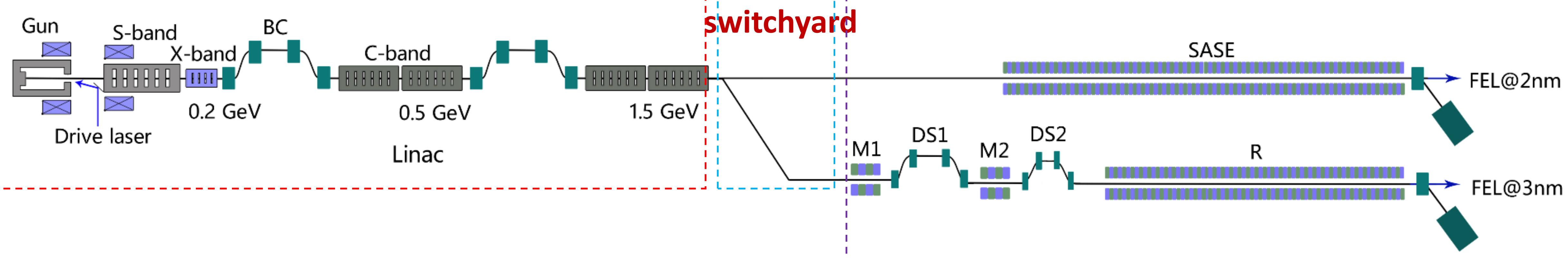


Total length	532m
Electron energy	0.8 - 1.5 GeV
Photon energy	0.2 – 0.6 keV
Pulse length	~100 fs
Repetition rate	10 - 50 Hz
Peak photon power	1 GW

Layout of the SXFEL user facility

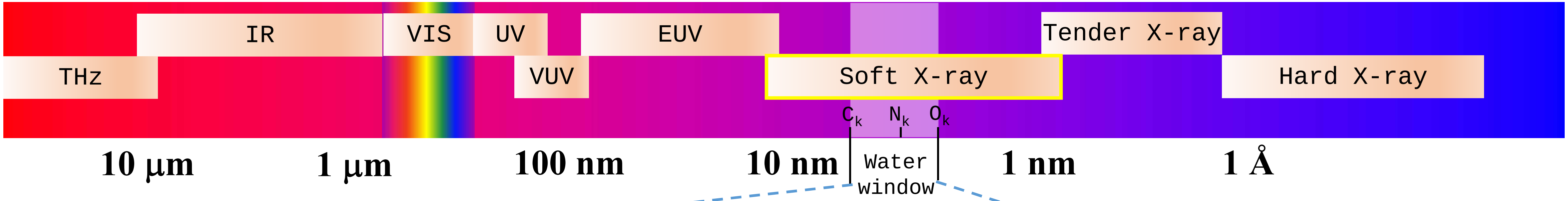
Linac: S-band injector + C-band main accelerator + X linearizer + two bunch compressors

Undulators: SASE line + Seeding line

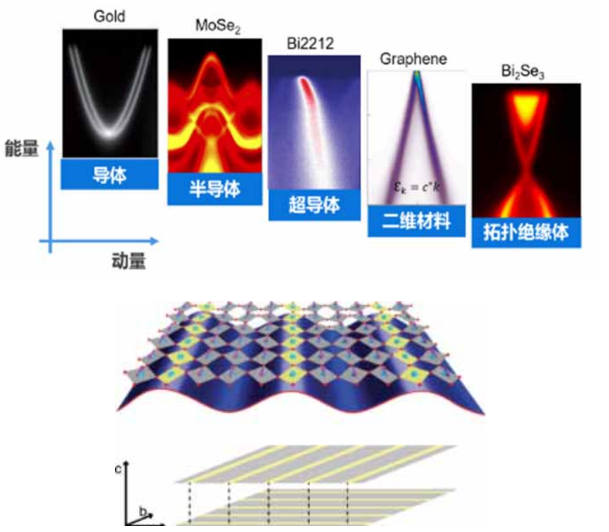


SXFEL can cover the “water-window” region

➢ **SXFEL has important application prospects in both scientific and industrial fields**

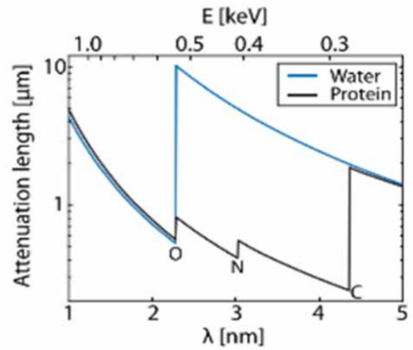


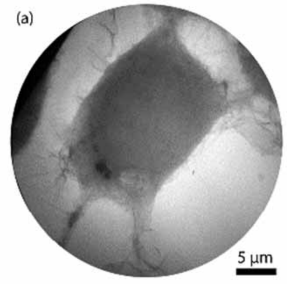
Material science



Bioscience

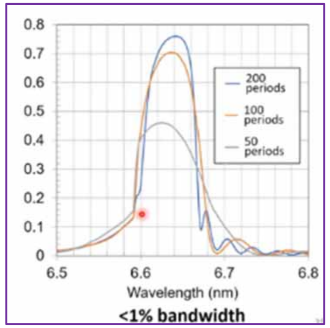
Imaging biological samples with soft X-rays in the "water window" (2.3-4.4 nm) has the best contrast



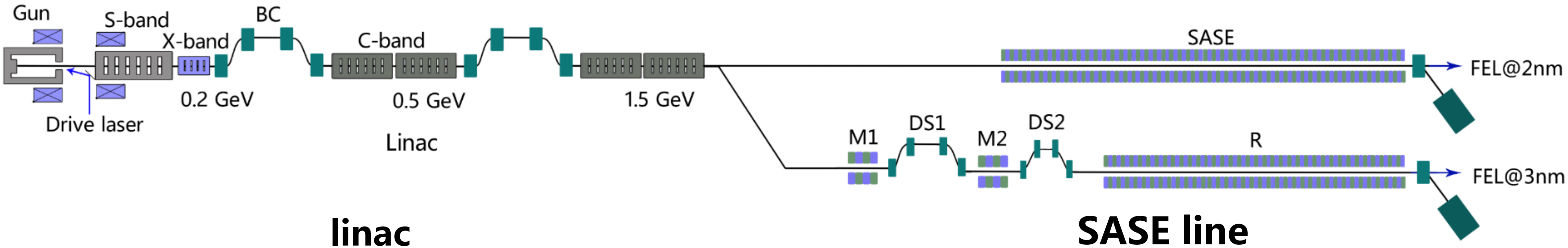


Industrial applications

EUV&BEUV



Main parameters of the SXFEL



linac

	Design	Realized
Beam energy (GeV)	1.5	**1.51**
Nor. emittance (mm.mrad, rms)	≤ 1.5	**1.2**
Bunch charge(nC)	0.5	**0.6**
Peak current (A)	≥ 700	**>1000**

SASE line

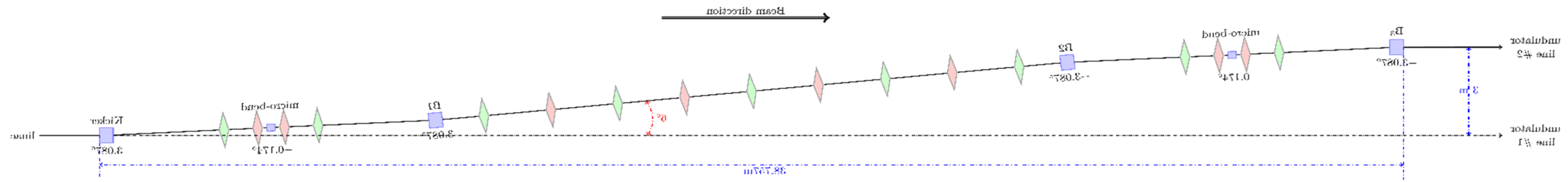
	Design	Realized
Wavelength (nm)	2.0	**1.98**
duration (fs)	~400	**<300**
Peak power (GW)	≥ 0.1	**>1**

Seeding line

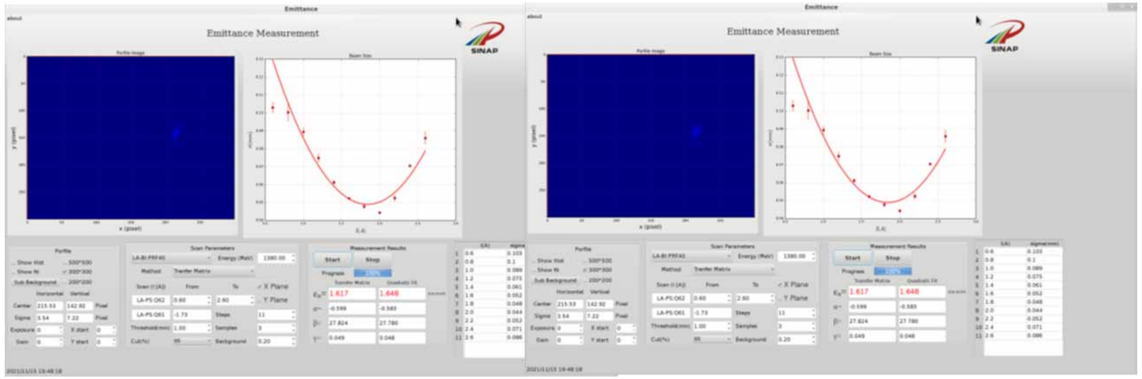
	Design	Realized
Wavelength (nm)	3.0	**2.96**
duration (fs)	~100	**~100**
Peak power (GW)	≥ 0.1	**>0.2**

The main parameters of linac and FEL have reached or exceeded the design values

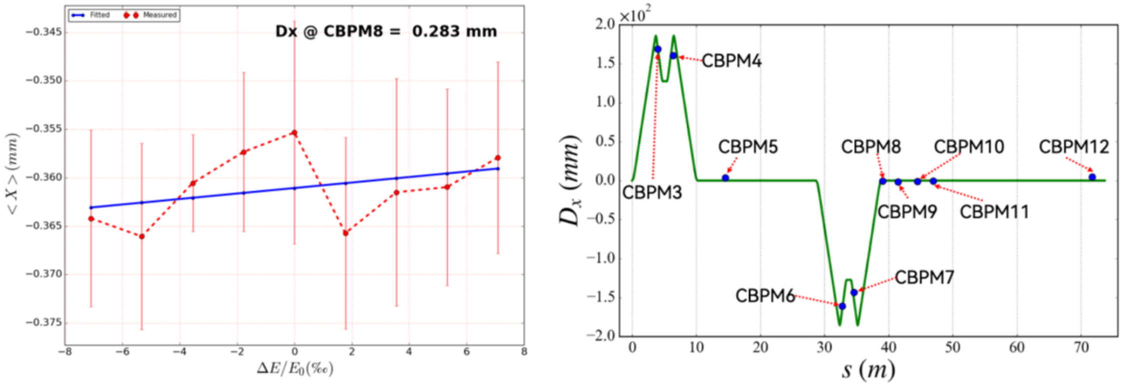
Switchyard design and performance



- SBP(SASE) line -> Seeding line ~ 3 m in horizontal
- Symmetrical lattice, total length about 39 m
- Dual-DBA dog-leg，total deflecting angle 6°
- Kicker with 3° & 25 Hz for beam separation
- Optics balance for suppressing CSR effect
- micro-bend in the middle of DBA for R56=0



Emittance growth after the switchyard: ~3%

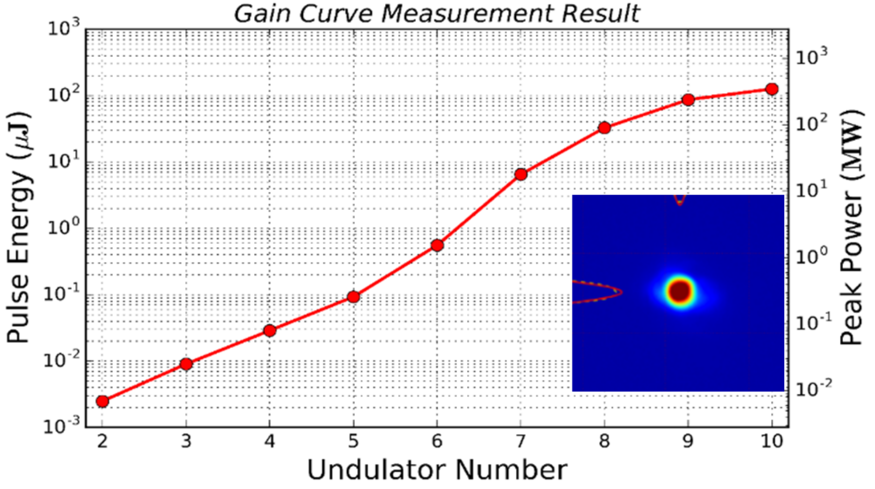


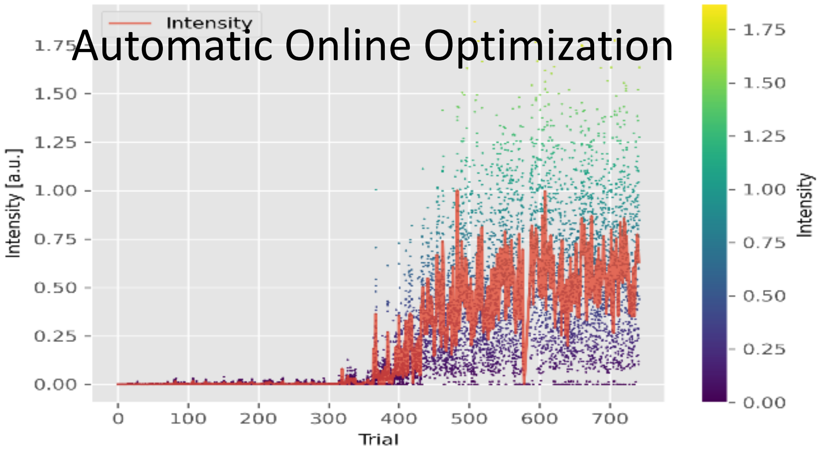
Horizontal residual dispersion <1 mm

Si Chen, et al., TU4P08

SASE-FEL performance at 2 nm

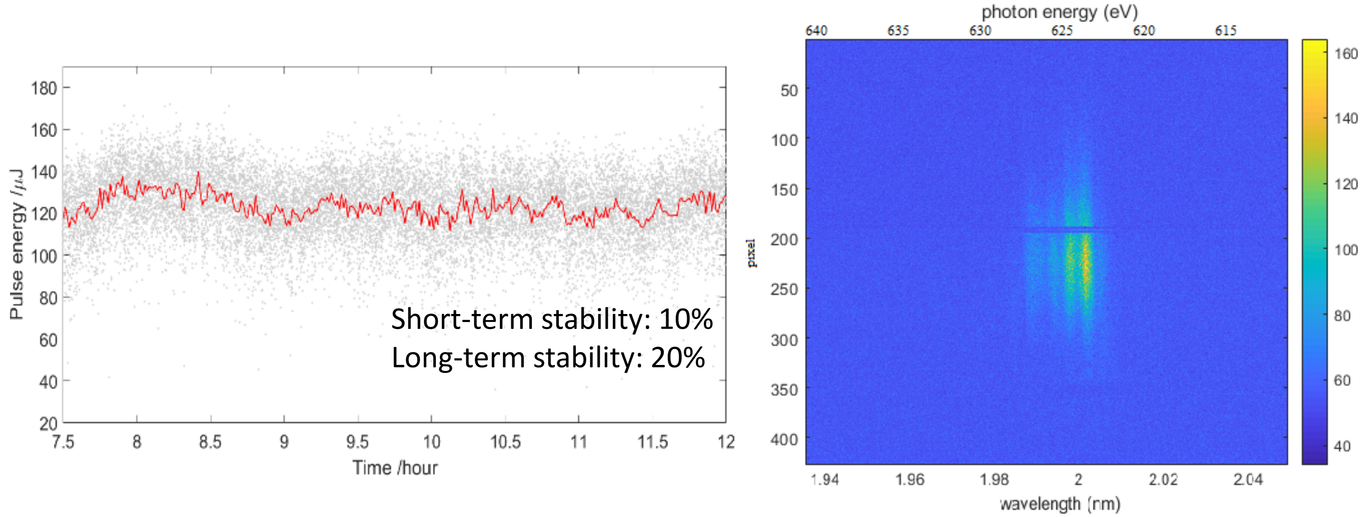
2nm SASE lasing, pulse energy > 200 μJ





Automatic Online Optimization

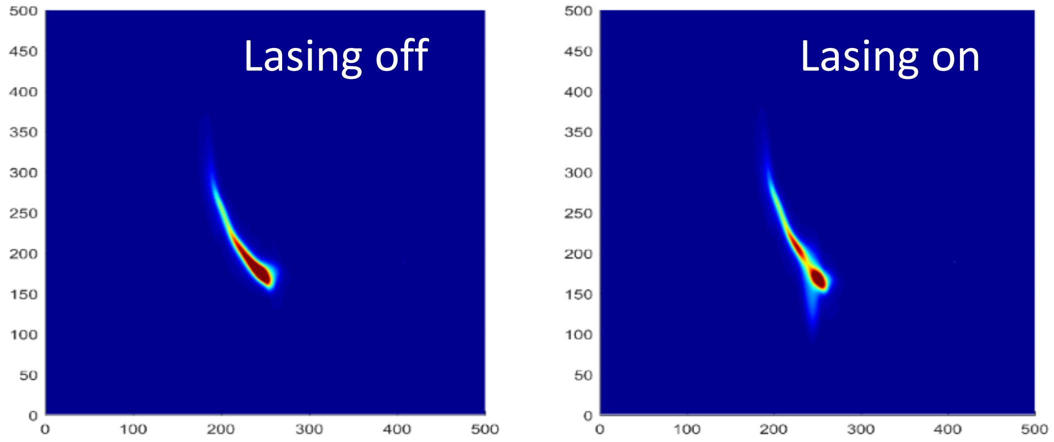
SASE pulse energy and spectrum from GMD and online spectrometer



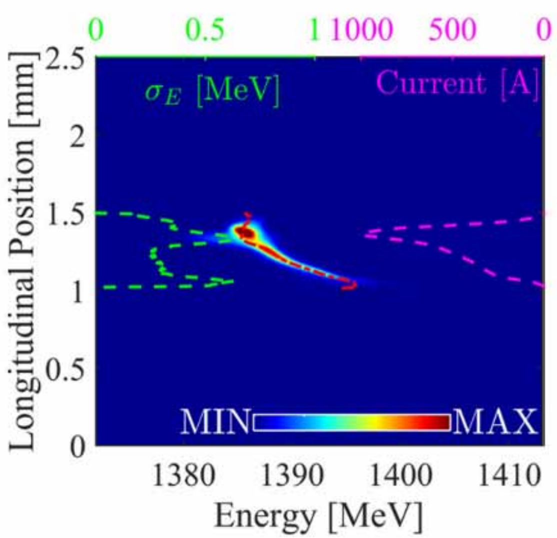
N.S. Huang, et al., WE4P11
H. Luo, et al., WE4P12

SASE-FEL performance at 2.4 nm

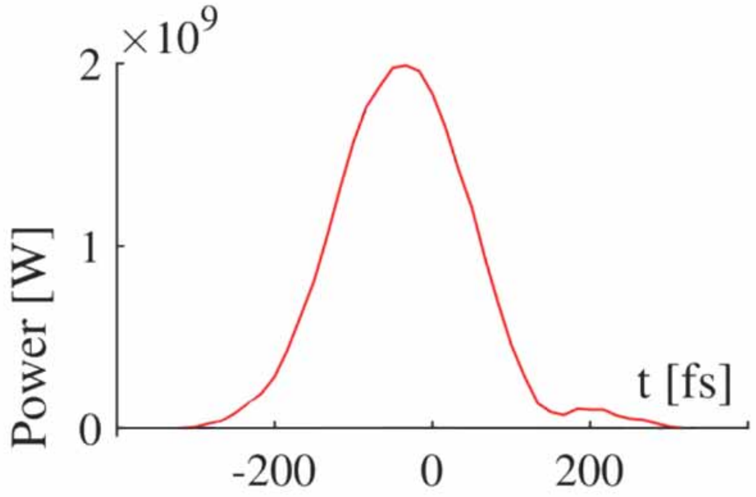
Longitudinal phase space of the e-beam after passing through undulators



- Shorter saturation length (last 3 undulators used for tapering)
- Maximal beam energy loss>2MeV
- FEL peak power~2GW (Peak current~1kA, with only BC1)
- Pulse duration (FWHM)~200fs, only a small fragment in the head lasing, may due to the strong Wakefield of the in-vacuum undulator)
- Pulse energy~400μJ



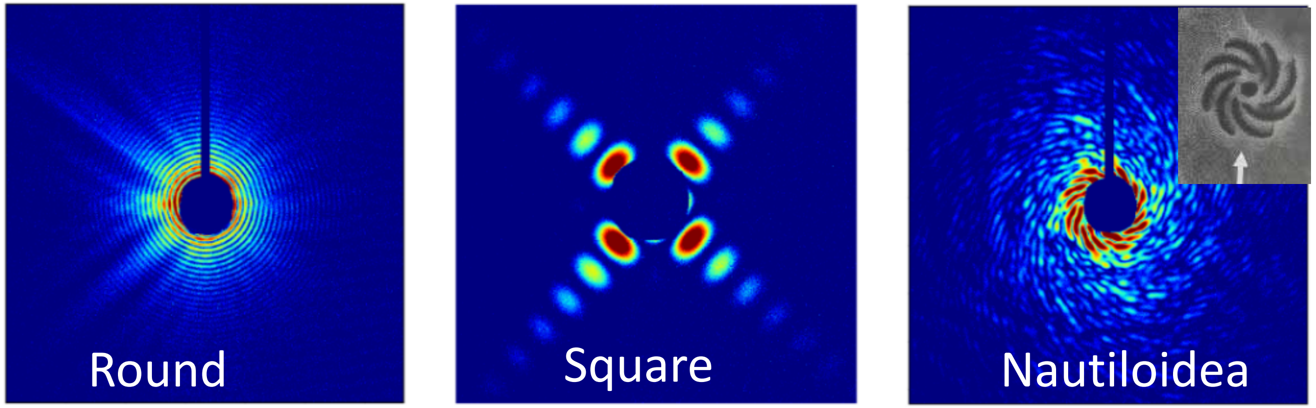
Single-shot reconstruction



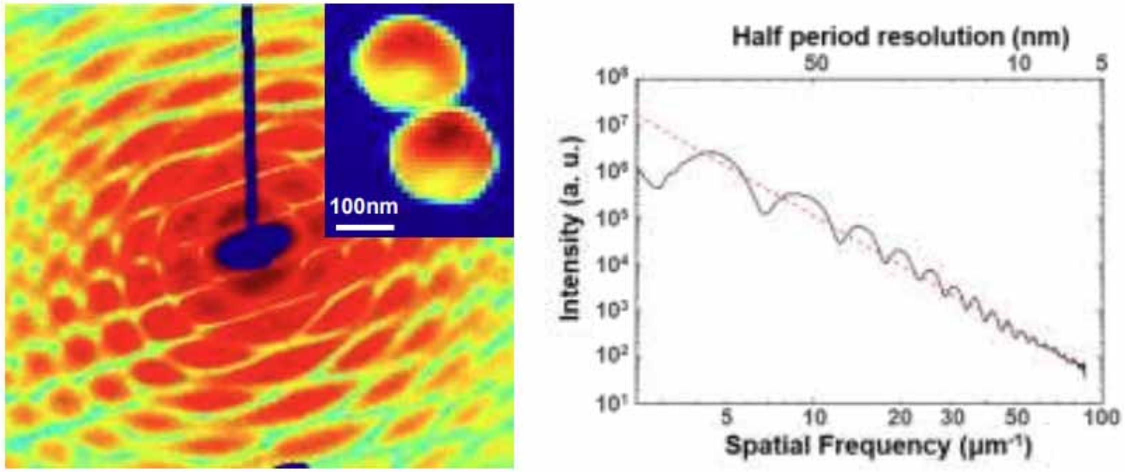
Li Zeng, et al., Fundamental Research 2, 929, 2022

CDI with the SASE beam in "water-window"

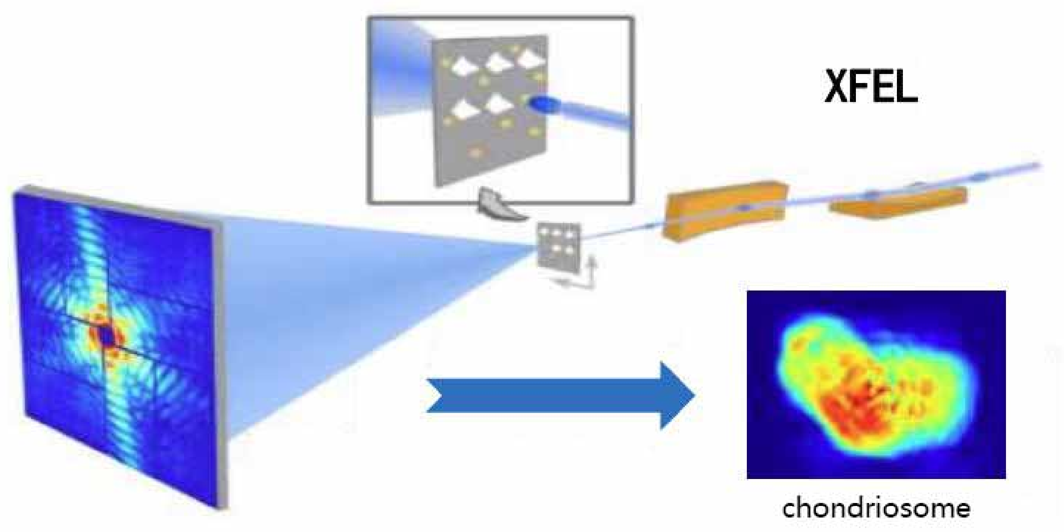
First single-shot coherent diffraction imaging experiments at SXFEL with SASE@ 2.4 nm



Diffraction and reconstruction images of double golden balls with a resolution of ~18.5 nm



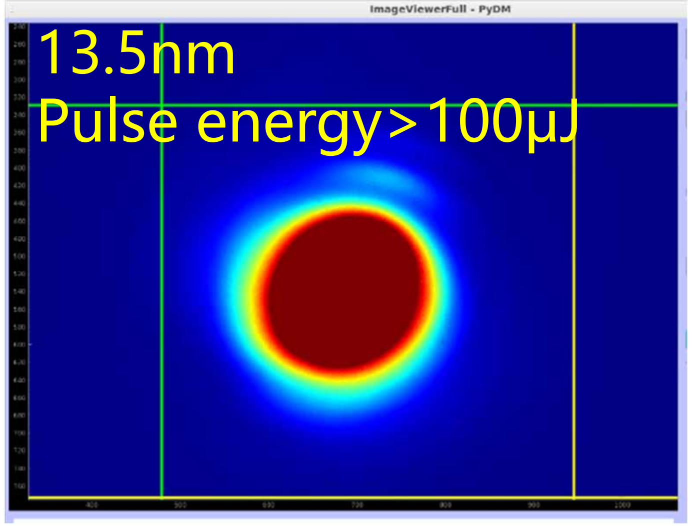
Biological sample imaging

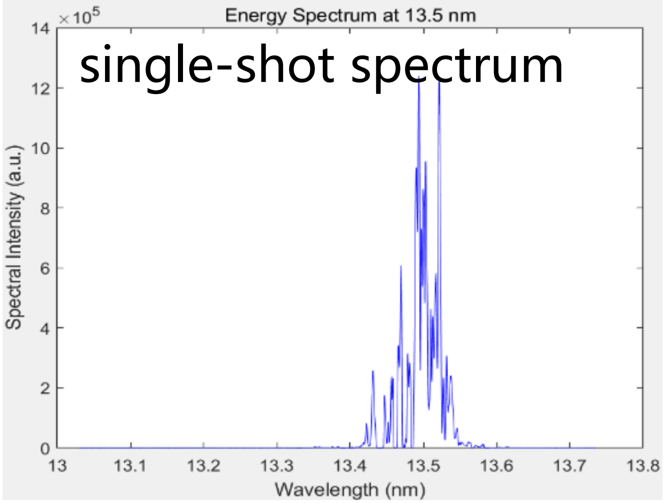


ShanghaiTech University team

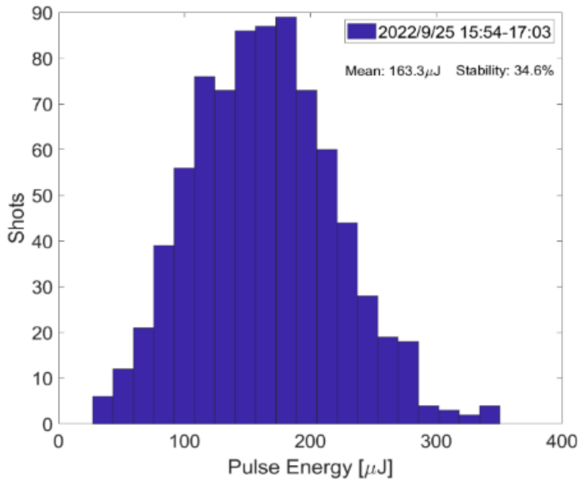
SASE-FEL performance at 13.5 and 6.75 nm

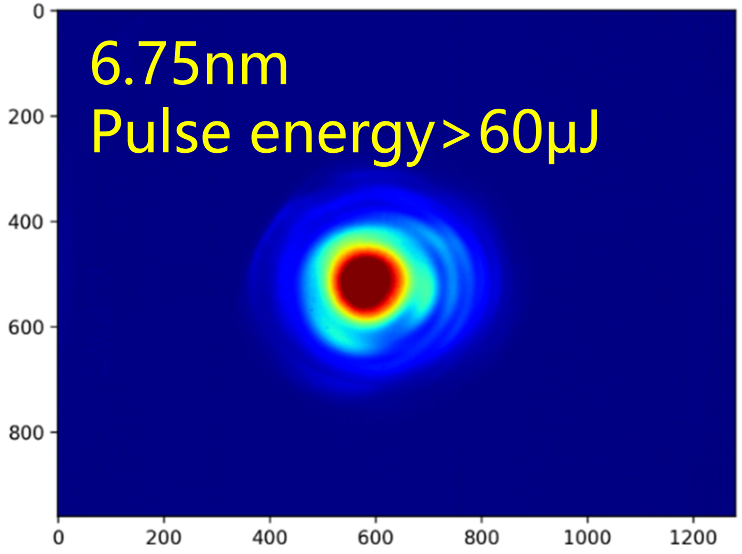
➢ **SASE-FEL for EUV and BEUV lithography research**

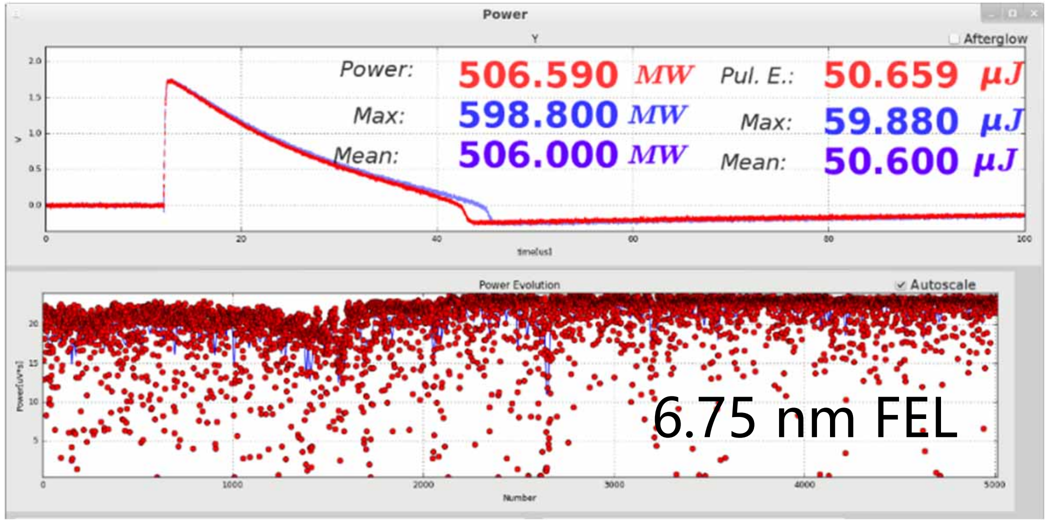




Shot-to-shot stability



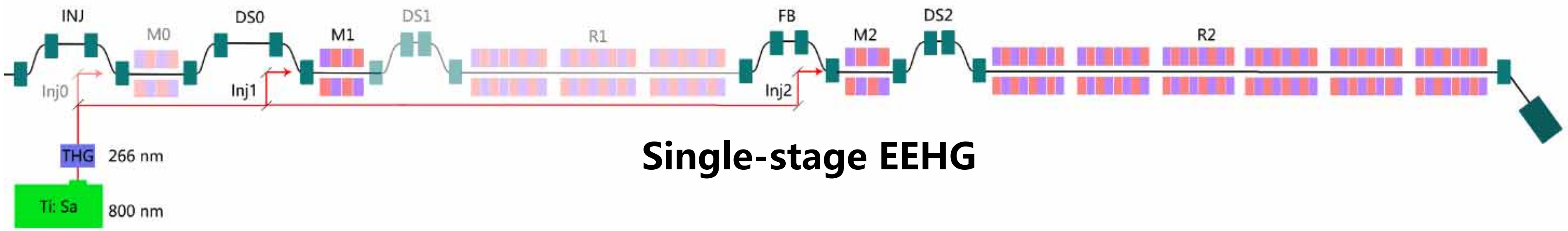




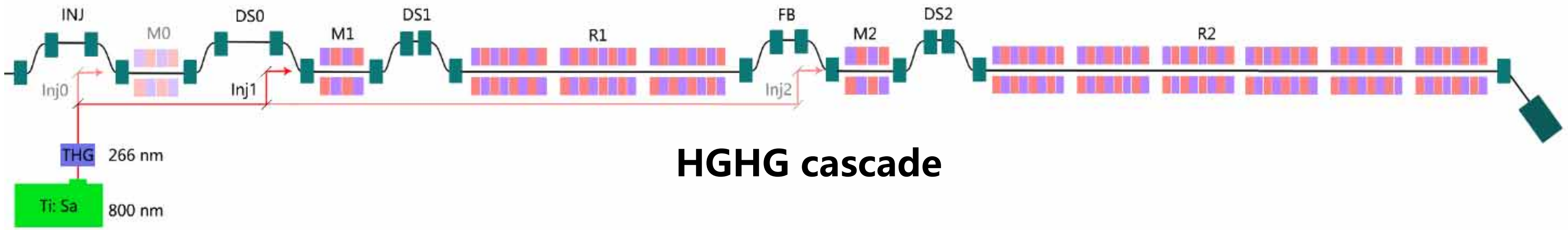
Seeded FEL experiments at SXFEL

2018

2019

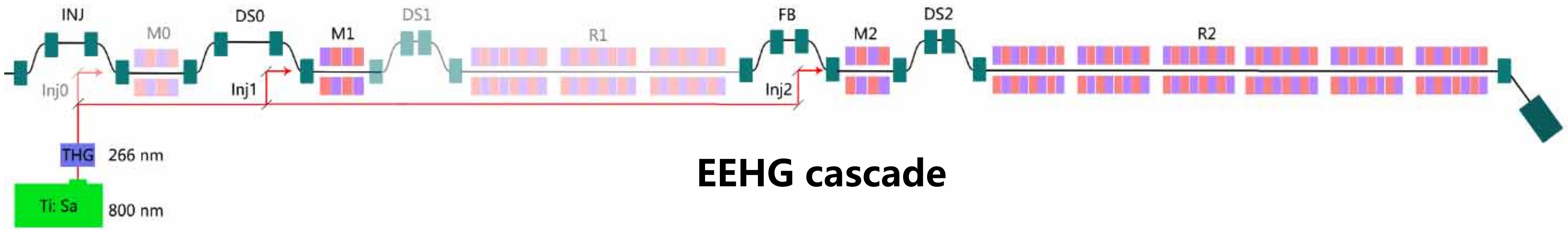


Single-stage EEHG



HGHG cascade

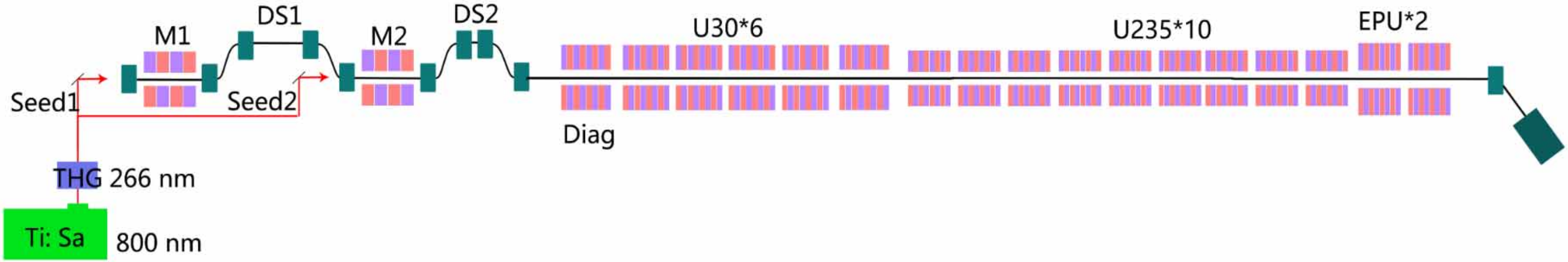
2020



EEHG cascade

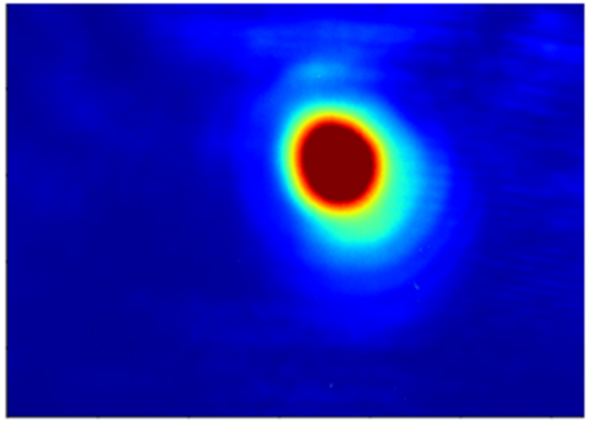
2022

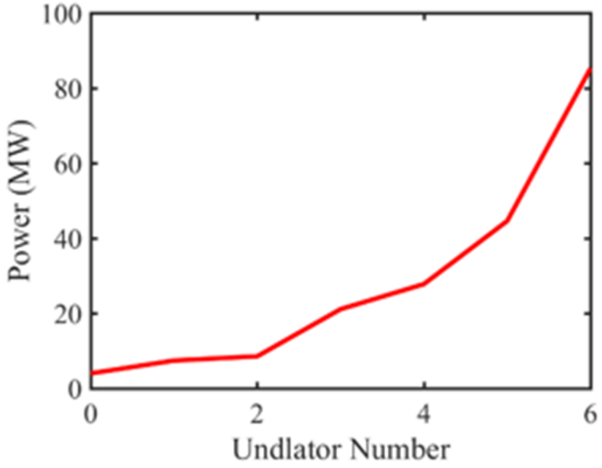
Single-stage EEHG experiments

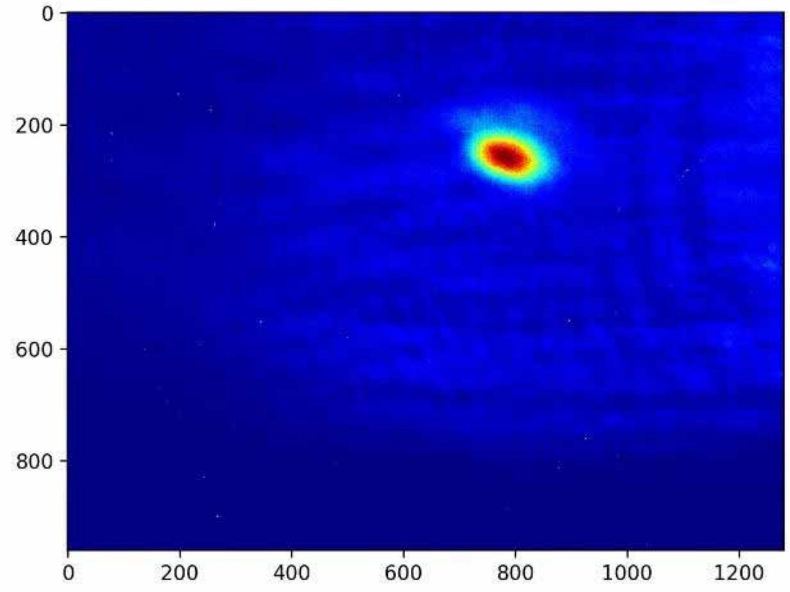


EEHG-46th (5.78 nm) lasing with U30s

Coherent radiation from EEHG-61st (4.36 nm)





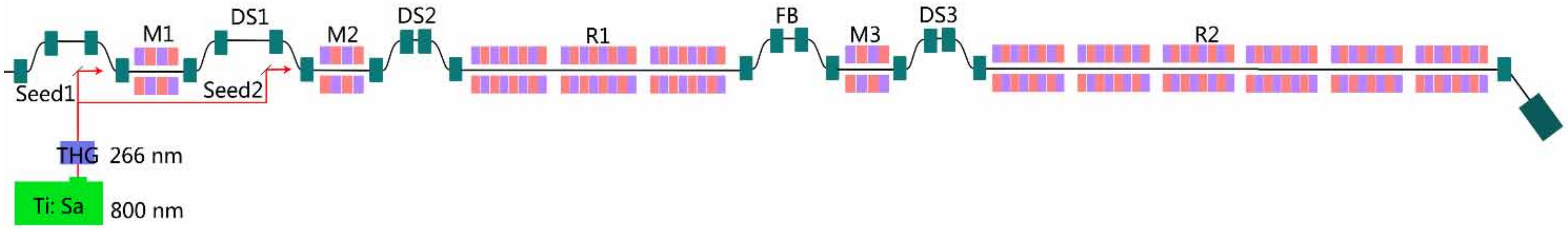


Problems:

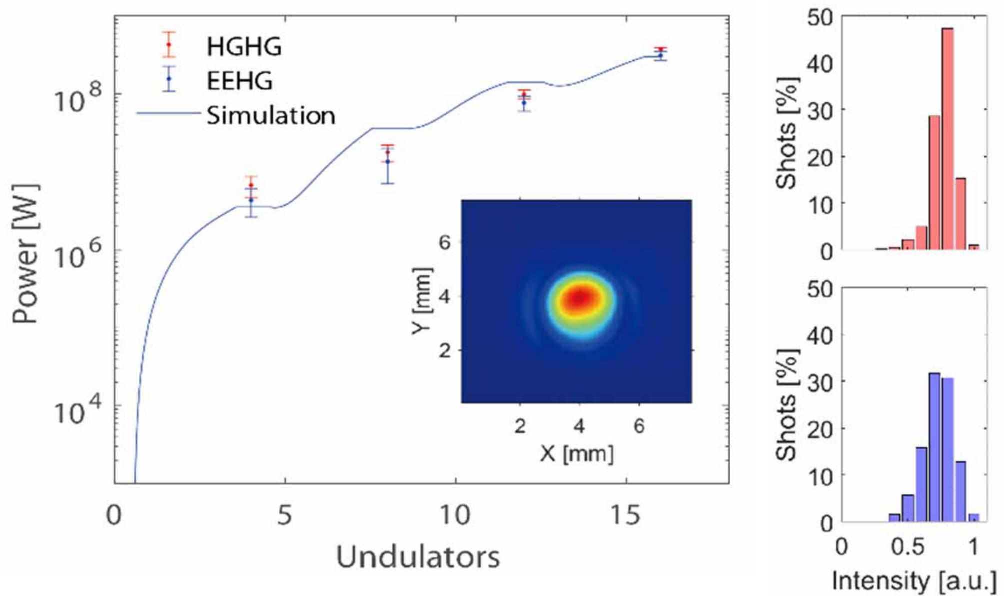
- Echo-61 is quite difficult to be amplified with U30s (may due to the relatively weak bunching and undulator field)

EEHG cascade (EEHC) experiments

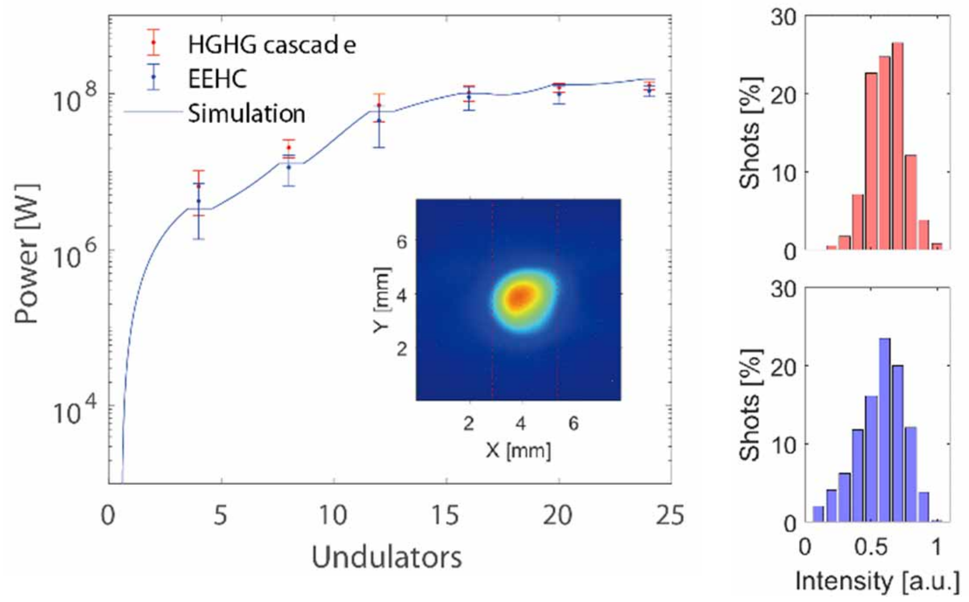
EEHC with fresh bunch technique



First stage: HGHG-6 or EEHG-6

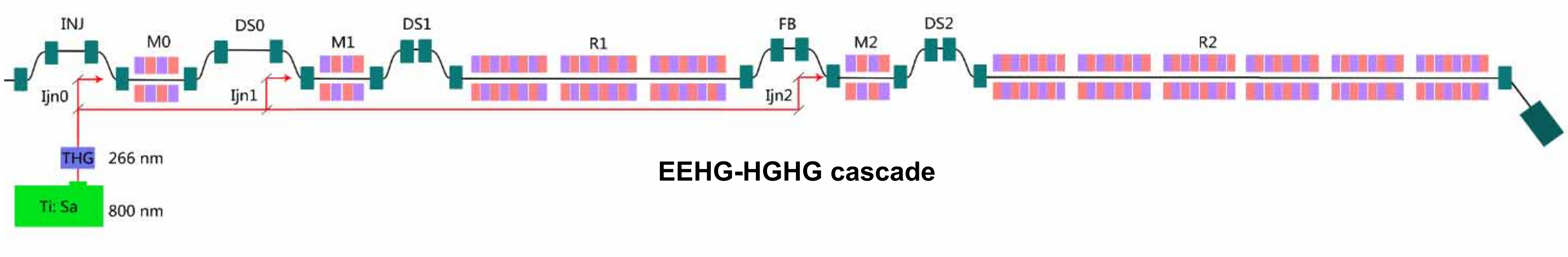


Second stage: HGHG-5



➢ The power fluctuation of EEHG-6 is larger than HGHG-6 due to the jitters of seed1.

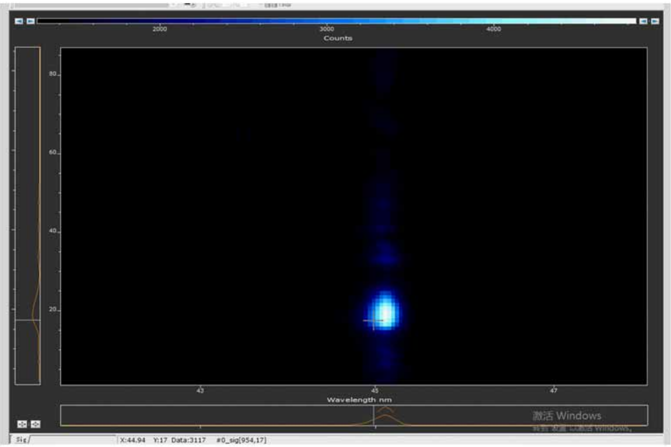
EEHG cascade (EEHC) experiments



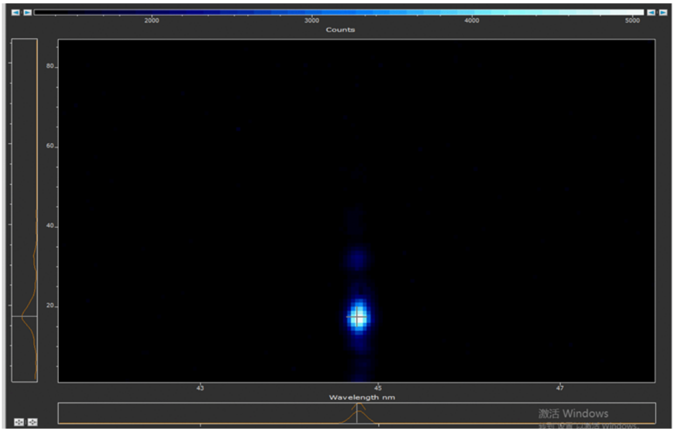
EEHG-HGHG cascade

First stage

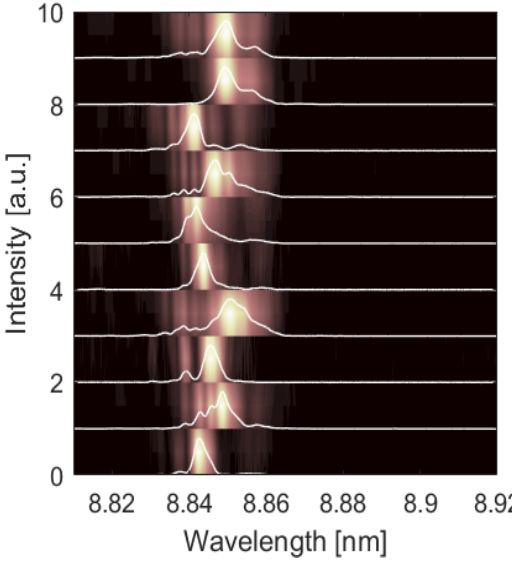
1st stage HGHG

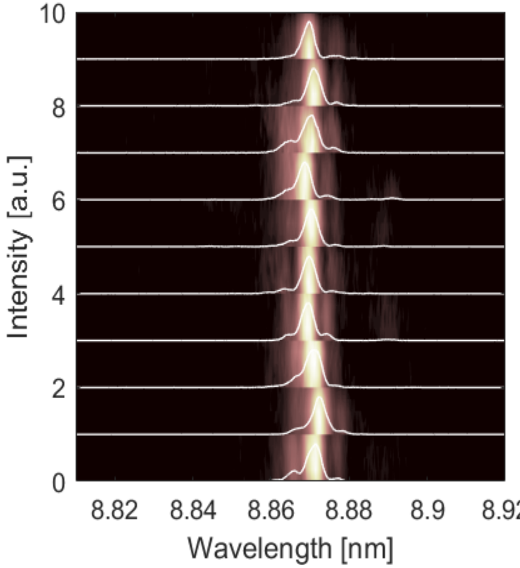


1st stage EEHG



Second stage

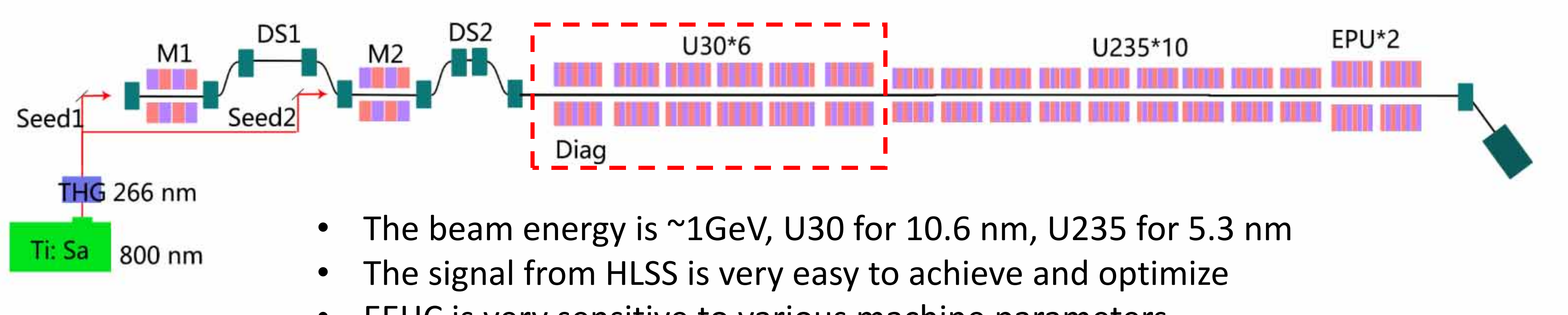




- The bandwidth of HGHG cascade@8.8 nm is large and sensitive to the laser heater
- The output central wavelength of EEHC is quite stable
- The output bandwidth of EEHC is close to the transform-limited
- The output bandwidth of EEHC is not sensitive to the laser heater, however, the LH can suppress spectral sidebands

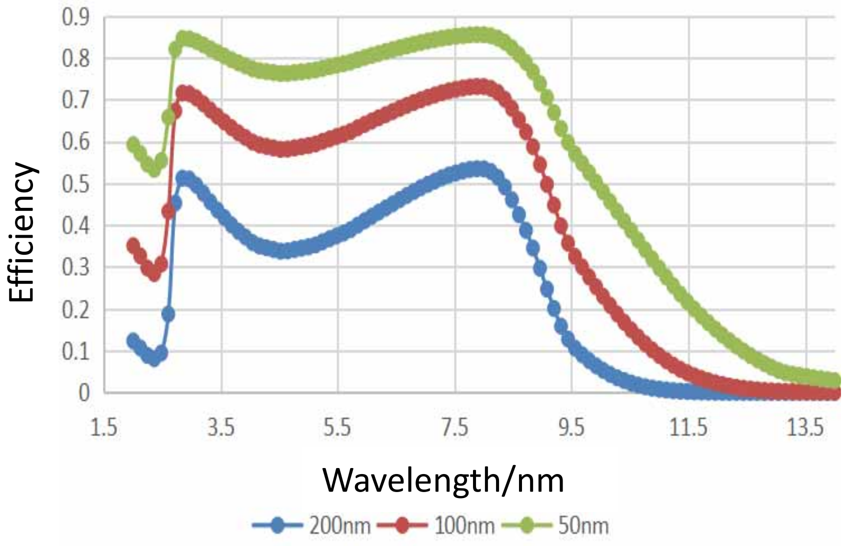
C. Feng, et al., Optica 9, 785-791 (2022)

Preliminary results: EEHC-50 (25×2, 5.32 nm)

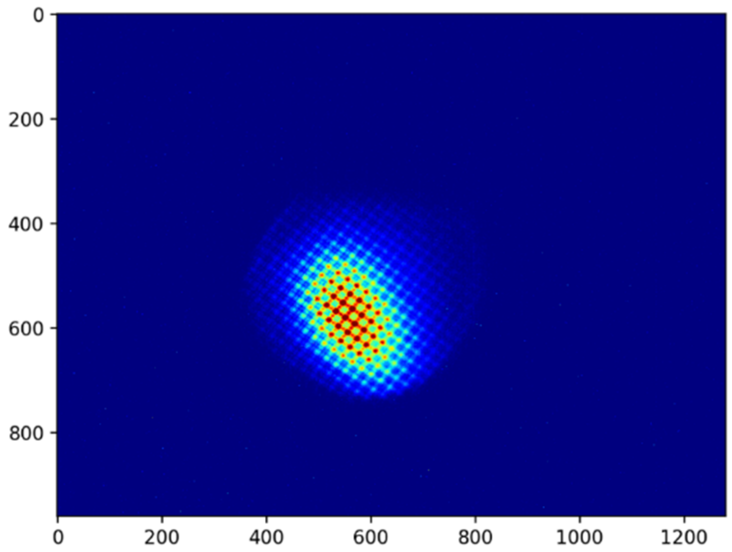


- The beam energy is ~1GeV, U30 for 10.6 nm, U235 for 5.3 nm
- The signal from HLSS is very easy to achieve and optimize
- EEHC is very sensitive to various machine parameters

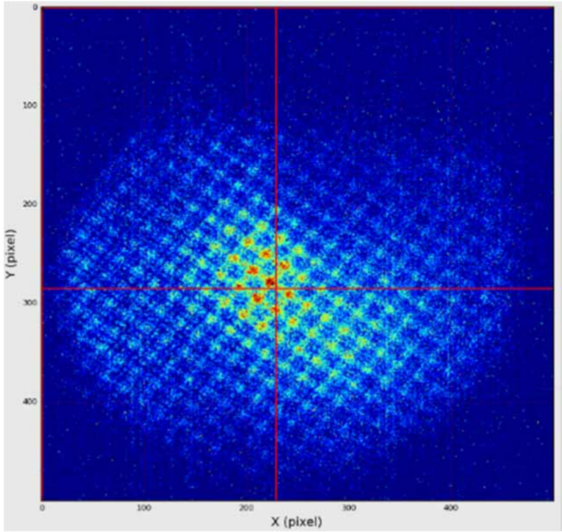
Filter (In) before the screen



HLSS (10.64nm-5.32nm)



EEHC (10.64nm-5.32nm)

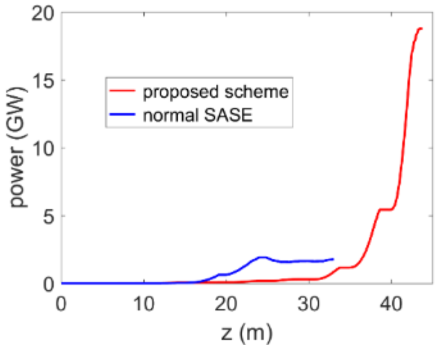


Experiments for EEHC is in progress

Plans: flexible control of the FEL properties

Ultra-short pulse generation

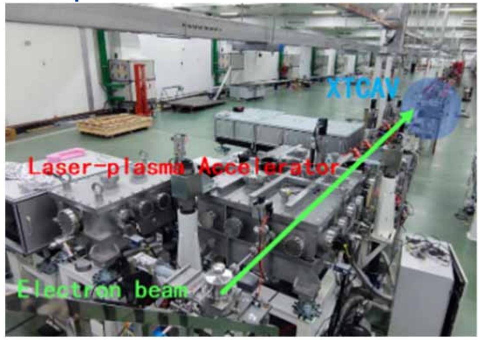
ESASE modulator

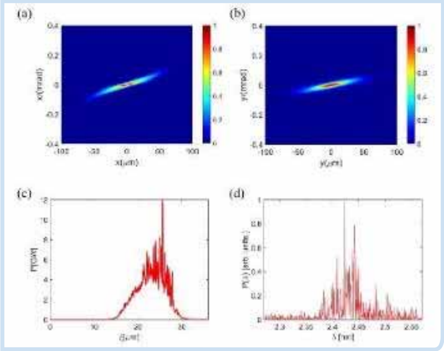


Z. Wang, C. Feng, HPL 11, 33, 2023

Spectral bandwidth control with plasma wakefield

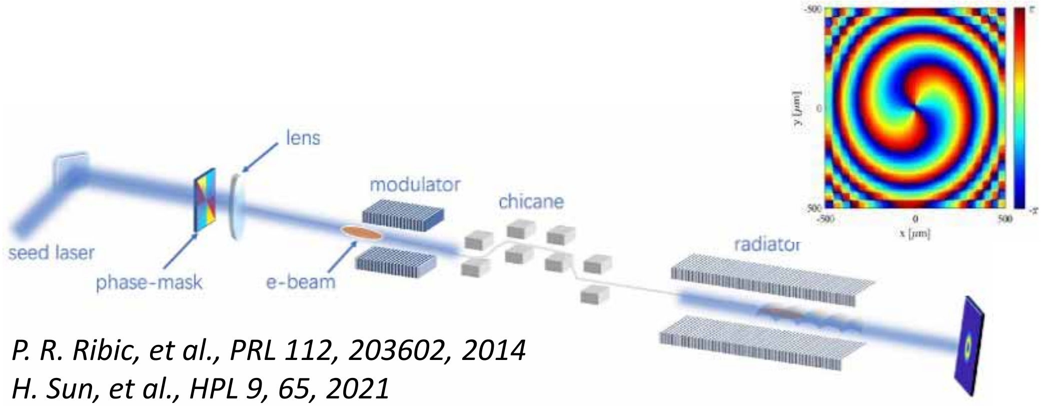
Laser-plasma cell in the SASE line





B. Peng, et al., PR Applied 19, 054066, 2023

OAM generation at Seeding line

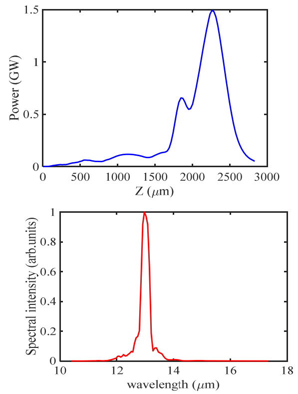


P. R. Ribic, et al., PRL 112, 203602, 2014

H. Sun, et al., HPL 9, 65, 2021

Intense THz pulse generation

THz afterburner

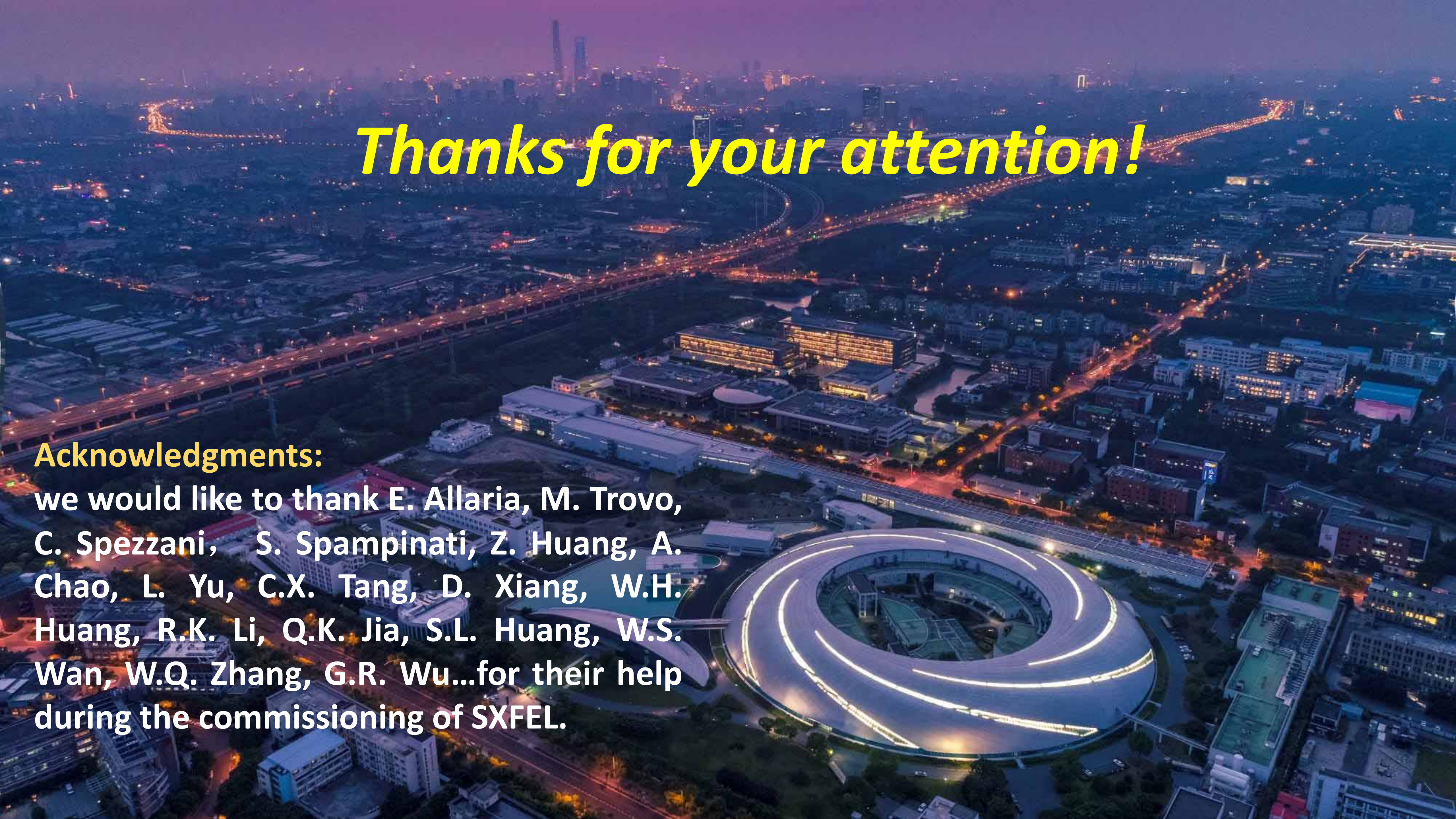


K. Yin, et al., Photonics. 10, 133, 2023

F. Li, et al., TH4A1; Z. Qi, WE4P15; K. Zhang, et al., TU4P06

Summary

- The main parameters of linac and FEL have reached or exceeded the design values.
- We have achieved the lasing of SASE with the shortest wavelength of 2 nm, lasing of EEHG at 5.6 nm (47th harmonic), and got coherent signal at 4.3 nm (61st harmonic), lasing of EEHG cascade at 8.8 nm (30^{th} harmonic) and got coherent signal at 5.3 nm (50th harmonic).
- Beam lines and end-stations are under commissioning.
- The first round of user experiments has been launched (supported 10 user teams).
- Advanced experiments for flexible control of the FEL properties are now in preparation.



Thanks for your attention!

Acknowledgments:

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