Status of the SXFEL commissioning

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CHINESE ACADEMY OF SCIENCES

Outline

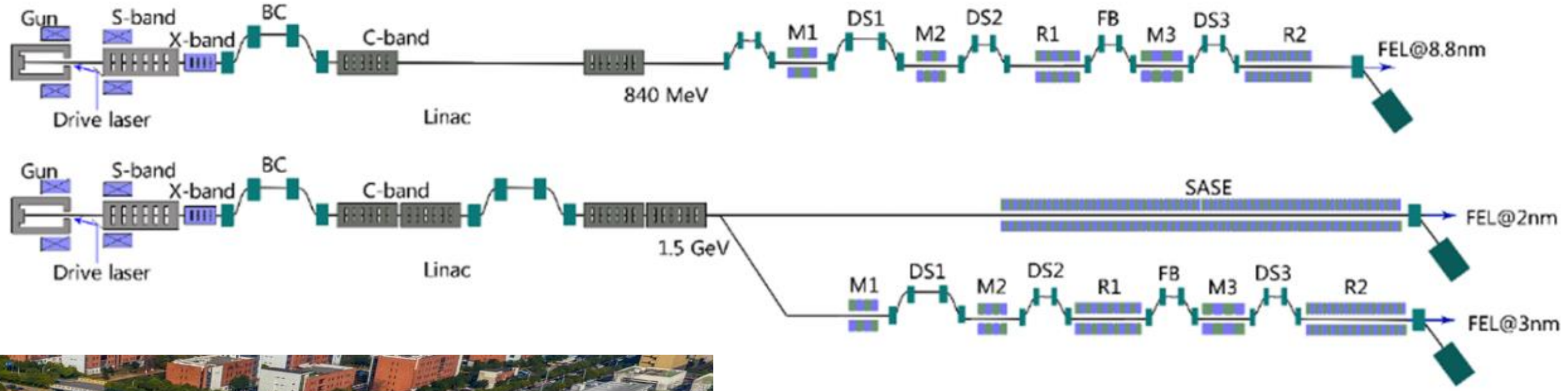
- Introduction of the SXFEL
- Construction of the SXFEL user facility
- Commissioning status
  - Linac
  - SASE line
  - Switchyard to the seeding line
- Summary

SXFEL：Shanghai Soft X-ray FEL Facility

- **SXFEL Facility**, located at the SSRF campus, is being developed in two steps:
- **SXFEL-TF** was initiated in 2006 and funded in 2014, its 840 MeV linac and main undulators started to be installed in 2016, the commissioning of SXFEL-TF was 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 in the water window region.

Test facility

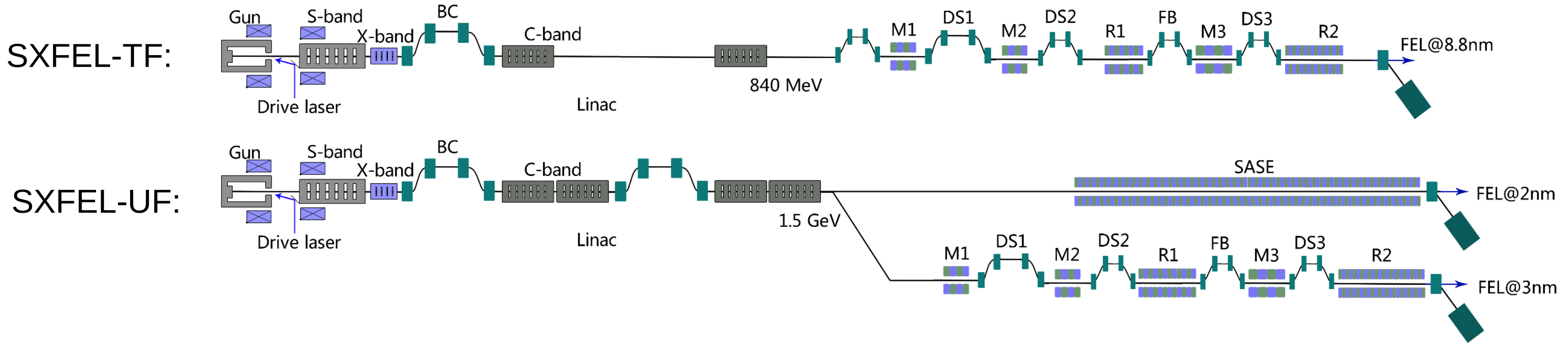
User facility



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

From test facility to user facility

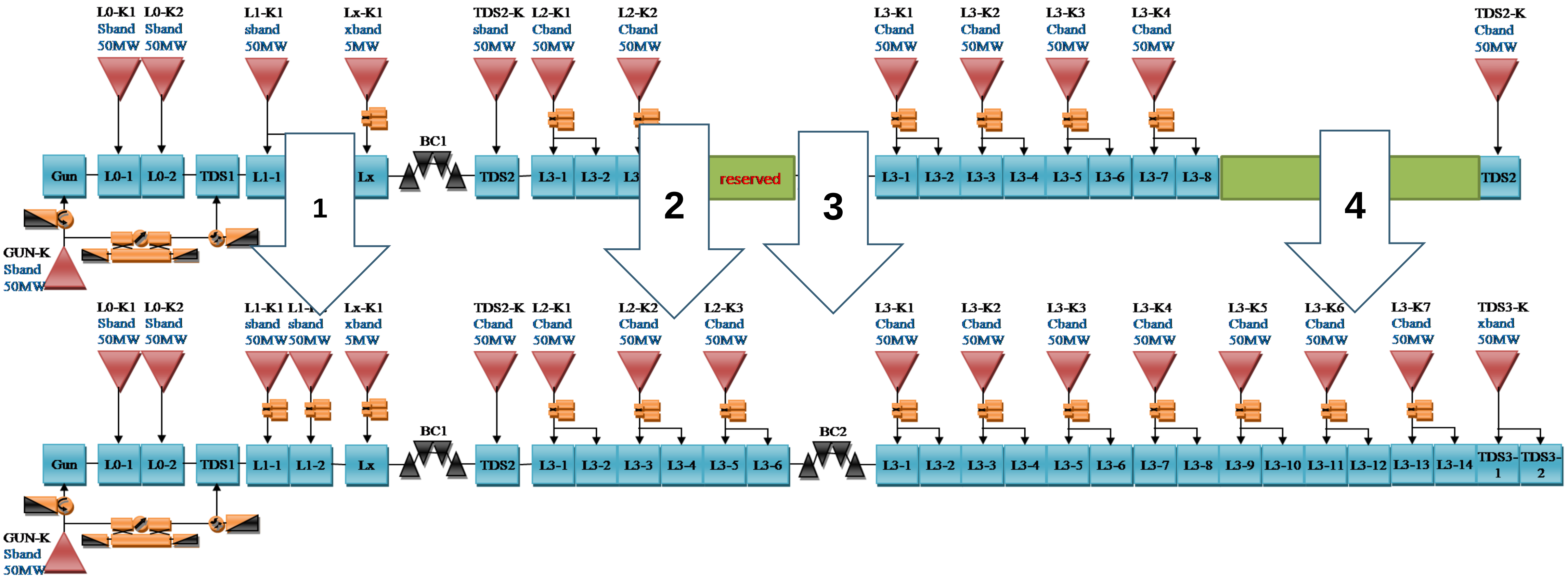
➢ Upgrade the linac energy to ~1.5 GeV, and have two undulator beamlines: one is based on SASE, another one is based on single stage EEHG or EEHG-HGHG cascade



FEL parameters

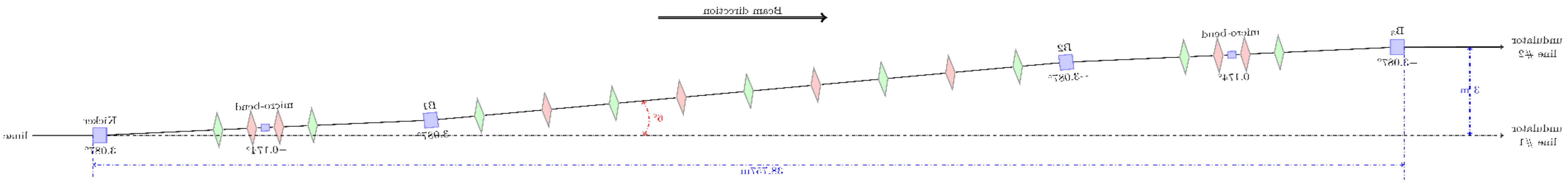
	SASE line	Seeding line
Beam energy/GeV	1.5	1.5
FEL wavelength/nm	2 nm	3 nm
FEL pulse/fs	100-300	100 - 200
FEL power/MW	>100	>100
Rep. rate/Hz	50	50

From test facility to user facility: Linac

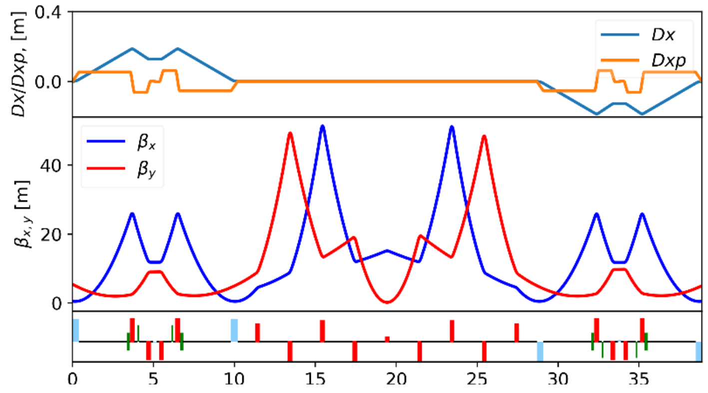


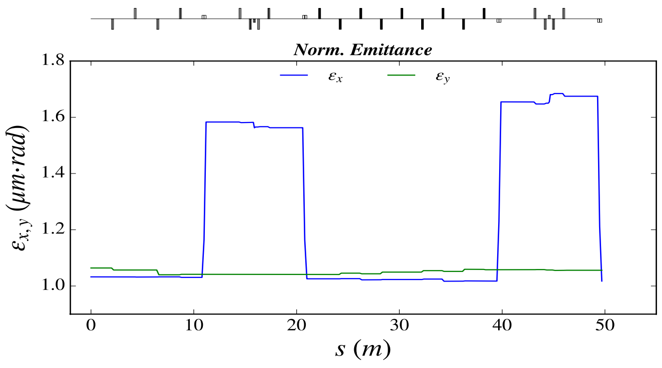
Adding:	1) 1 S-band klystron and 2 SLEDs	2) 1 C-band RF unit	3) 2nd bunch compressor	4) 3 C-band RF units

Beam distribution system : layout & main parameters



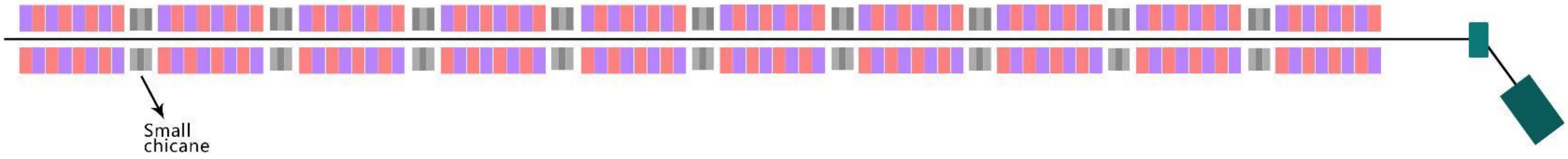
- SBP(SASE) line -> Seeding line ~ 3 m in horizontal
- Symmetrical lattice, total length about 39 m
- Dual-DBA dog-leg， total deflecting angle 6°
- Kicker with 3° & 25 Hz for beam separation
- Optics balance for suppressing CSR effect
- micro-bend in the middle of DBA for R_{56}=0



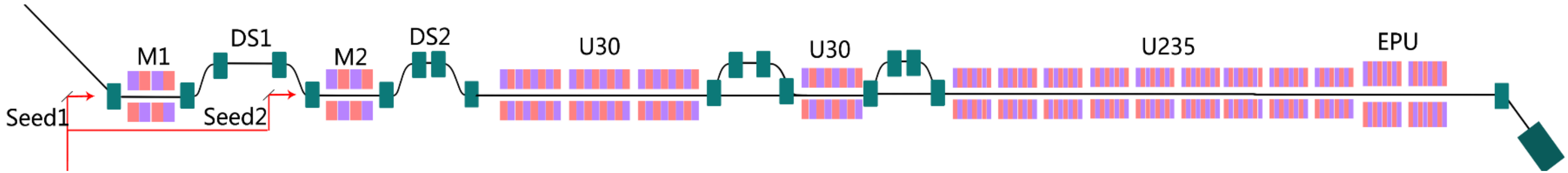


From test facility to user facility: switchyard and undulators

- **FEL1: SASE FEL line (new): build 10 IVU (16 mm) sections**

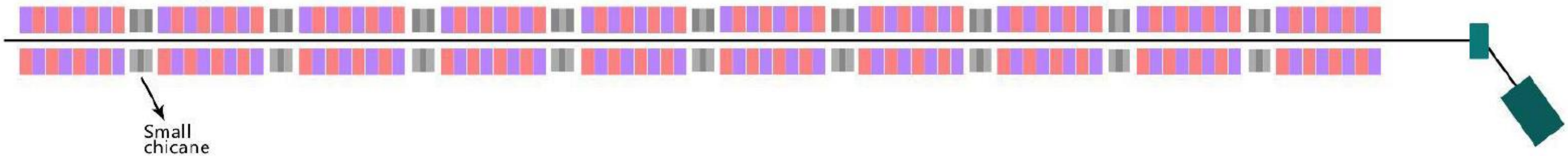


- **FEL2: Seeded FEL line: add 7 undulator units**

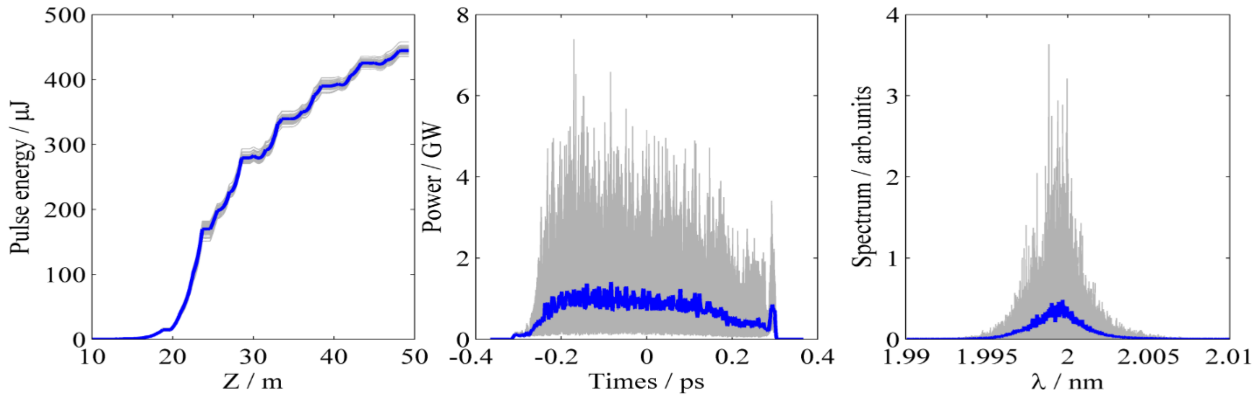


- ☐ The basic operation mode is single stage EEHG (60th to 90th)
- ☐ Can also operate with EEHG-HGHG mode (30*3th)

SASE line: layout & main parameters



Simulation results for SASE@2 nm

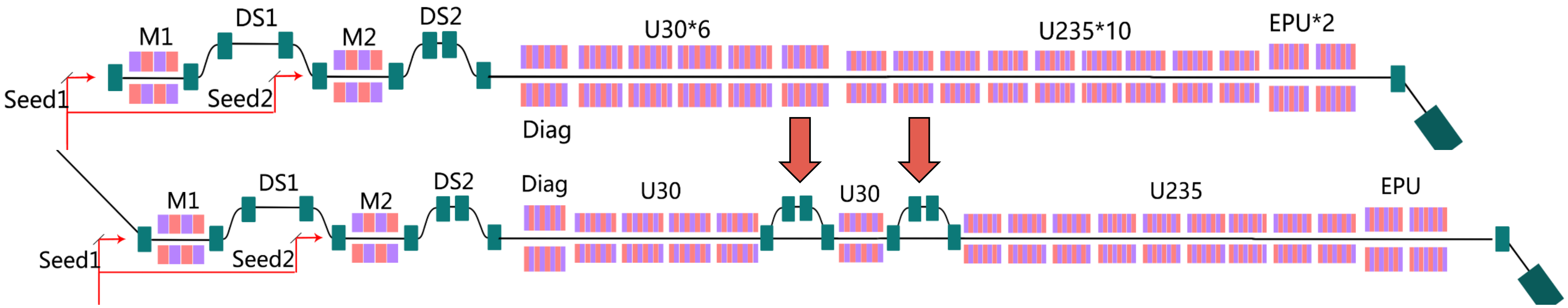


Parameters	Values
Beam energy	1.5 GeV
Peak current	0.7-1 kA
Undulator period	16 mm (in-vacuum)
Undulator length	4 m*10
FEL wavelength	2-4 nm
Peak power	> 100 MW

- Ten in-vacuum undulators (IVU16) for SASE@2nm
- Movable quadrupoles, high-resolution cavity BPMs, phase shifters, small chicanes, correctors and Profiles between undulator segments
- X-band deflecting cavity and beam dump after the undulator line

Seeding line: layout & main parameters

- EEHG @ 3-6nm (1.4 GeV, U30, Gap: 10.6 mm; 1GeV, U235, Gap: 9.2 mm)



- EEHG-HGHG @ 3nm (1.4 GeV, U30, Gap: 16.9 mm, K=1; U235, Gap: 9.4 mm, K=1.33)

- Can be operated with SASE, EEHG and EEHG-HGHG cascade
- 2 modulators (U80)+1 diagnostic undulator (U30/50)+17 radiator unds (U30*5+U235*10+EPU*2
- Movable quadrupoles, high-resolution cavity BPMs, phase shifters, correctors and Profiles between undulator segments
- X-band deflecting cavity and beam dump after the undulator line

Parameters	Values
Modulator	80 mm*2
DS1	12 m, max R56~20 mm
Other DSs	3 m, max R56~1 mm
Radiator	U30*6+U235*10+EPU*2
FEL wavelength	3-6 nm
Peak power	> 100 MW

Construction of the SXFEL user facility

Construction of the main building was finished in 2019

Construction of the SXFEL user facility

Apr. 2019
Installation of switchyard

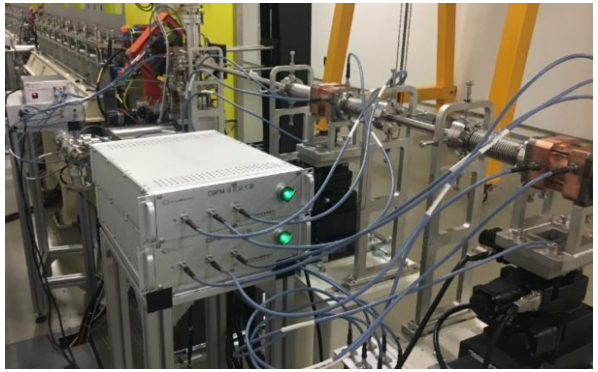
Aug. 2020
Installation of IVUs

Jan. 2021
Installation of electric equipment

Jan. 2021
SASE beamline

Feb. 2021
X-band TDS

Mar. 2021
MPS system



Mar. 2021
Diagnostic system

Construction of the SXFEL user facility

➢ **switchyard**

➢ **FEL1: SASE FEL line**

➢ **FEL2: Seeded FEL line**

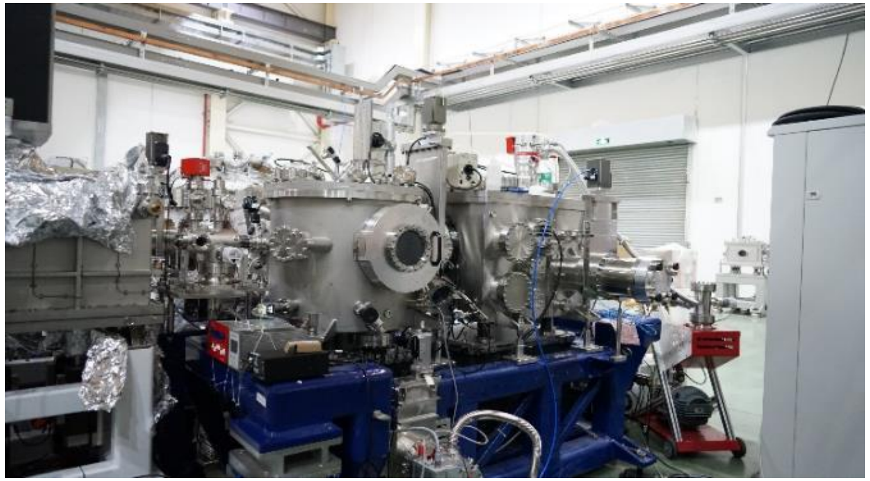
➢ **beam dump**

Construction of the SXFEL user facility

X-ray beamline and end-stations

Construction of the SXFEL user facility

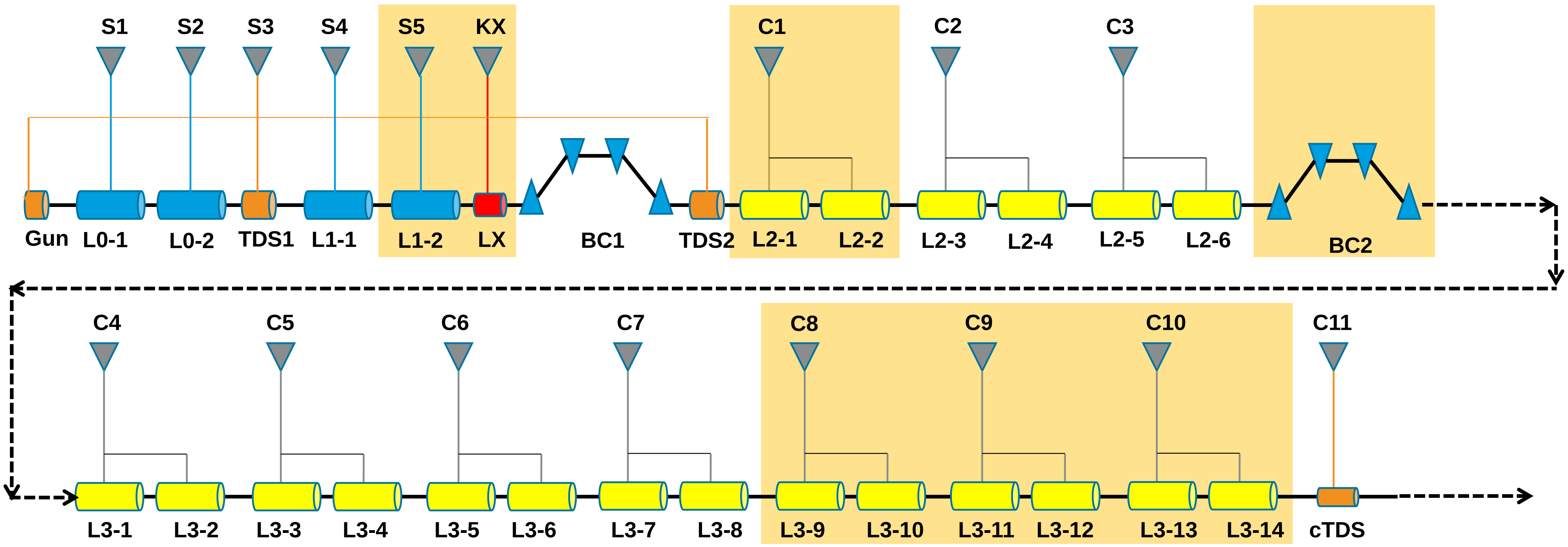
X-ray beamline and end-stations



Commissioning progress

- Jan. 25-Mar. 29 linac optimization
- Mar. 29 -Apr. 9 beam to the final dump, hardware online test
- Apr. 9-24 beam matching
- Apr. 24 first lasing @5.6 nm (890 MeV)
- May 11 3.5 nm saturation (1130 MeV)
- May 13-14 lasing at 2.4 nm and 2.0 nm successively (1357 MeV)
- May 19 first signal on the online X-ray spectrometer
- Jun. 21 first diffraction image with 2.4 nm FEL
- Oct. 27 Realized dispersion free of the switchyard
- Nov. 3 Resolution of the single particle imaging < 20 nm

Commissioning of the linac



Installation:
Nov. 2020~Jan. 2021

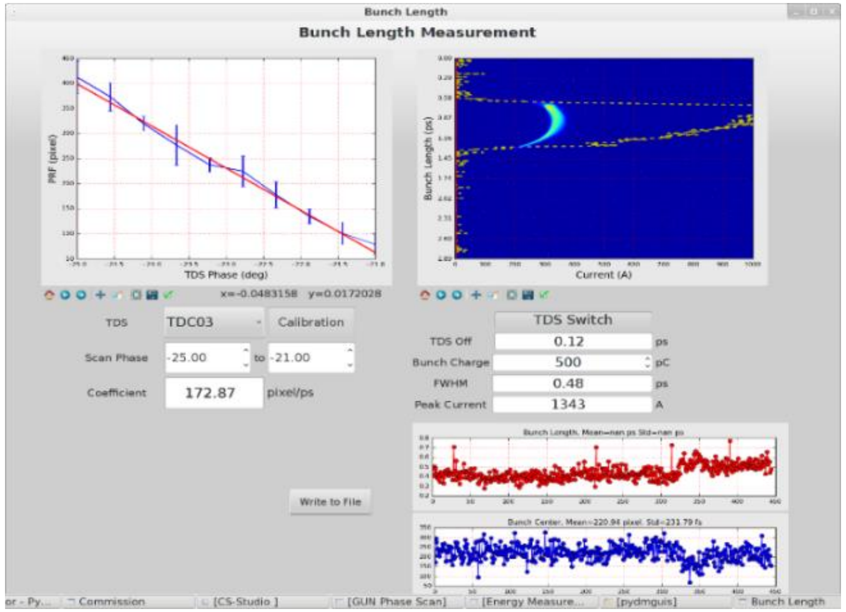
RF commissioning:
Jan. 22, 2021~Feb.10, 2021

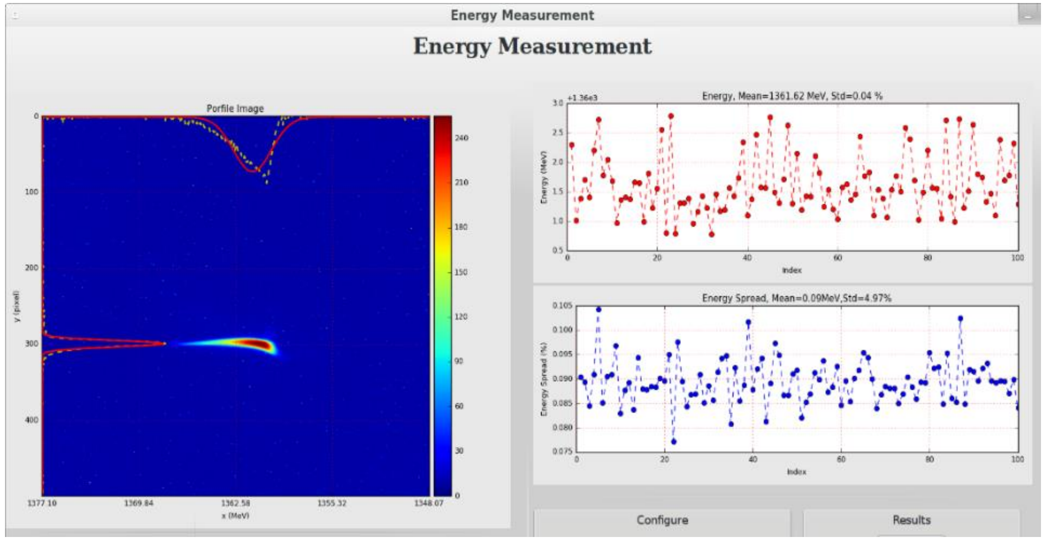
Linac optimization:
Jan. 25, 2021~Mar. 29, 2021

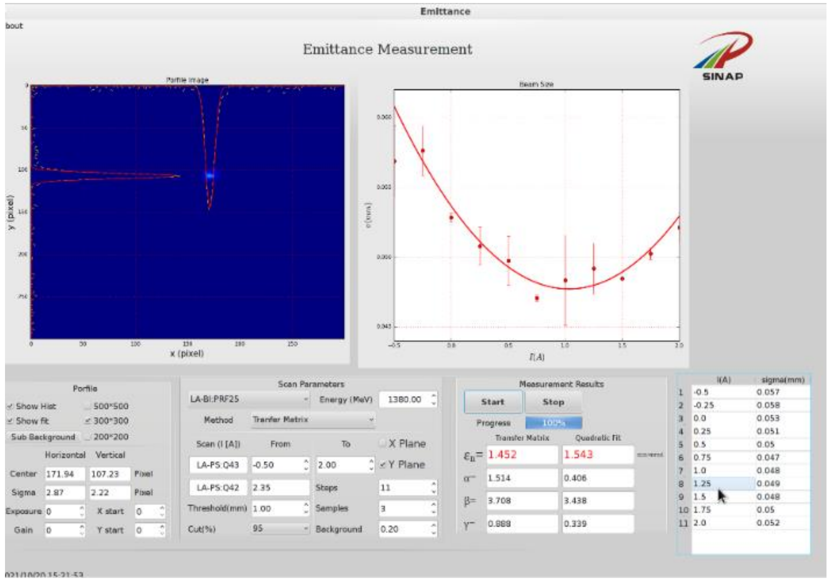
Jan. 25, gun/S1/S2 120MeV@BC2
Jan. 26 recover C2~C7 815MeV
Jan. 29 passing through130m long drift
Feb. 06 injector ~0.8mm-mrad
Apr. 15 beam energy1.35GeV

Linac performances after upgrade

Parameters	SXFEL-TF (achieved)	SXFEL-UF (design)	SXFEL-UF (achieved)
Beam energy (GeV)	0.84	1.5	~1.38
Energy spread (rms)	≤0.15%	≤0.15%	< 0.05%
Nor. emittance (mm-mrad, rms)	≤2.5	≤1.5	~1.5
Bunch length (ps, FWHM)	≤1.0	≤0.7	< 0.5
charge (nC)	0.5	0.5	> 0.5
Peak current (A)	≥500	≥700	> 1000
Rep-rate (Hz)	10	50	2

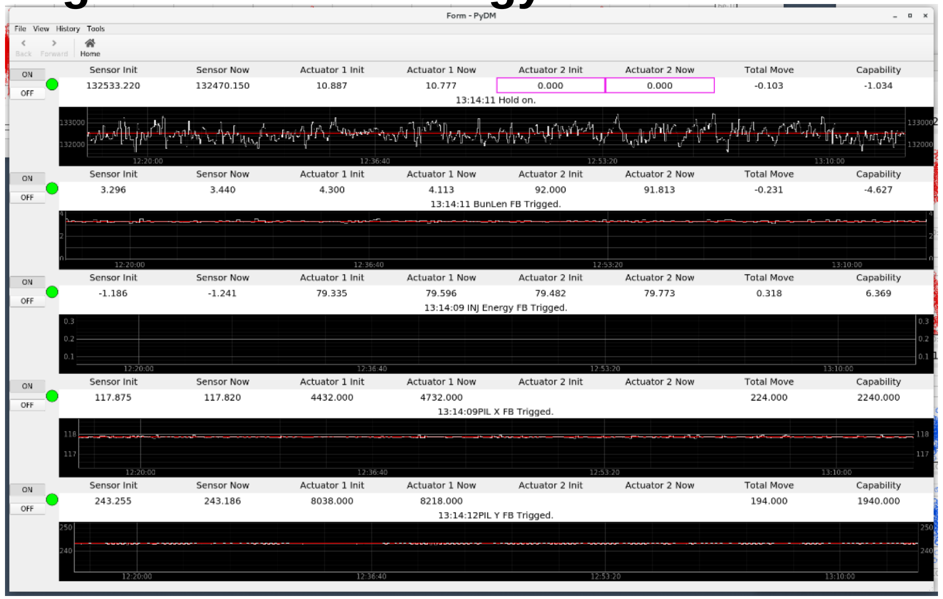




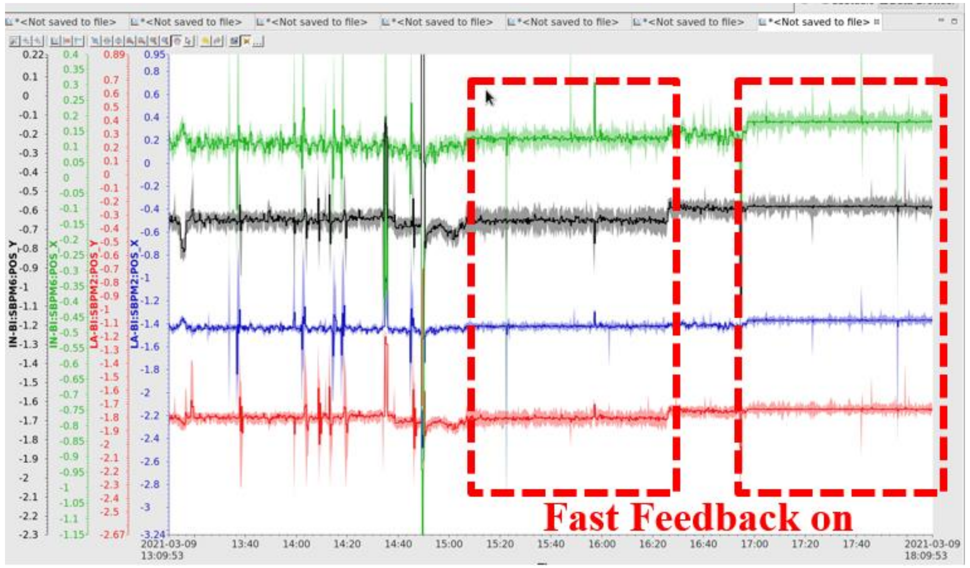


Linac performances after upgrade

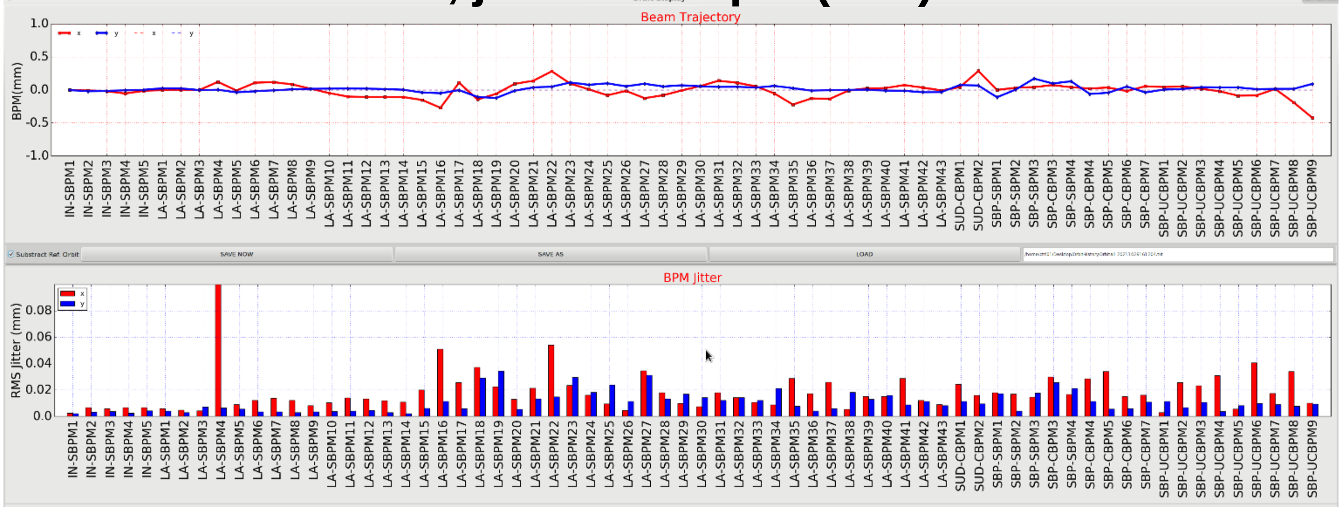
Feedback system for drive laser, bunch length and beam energy



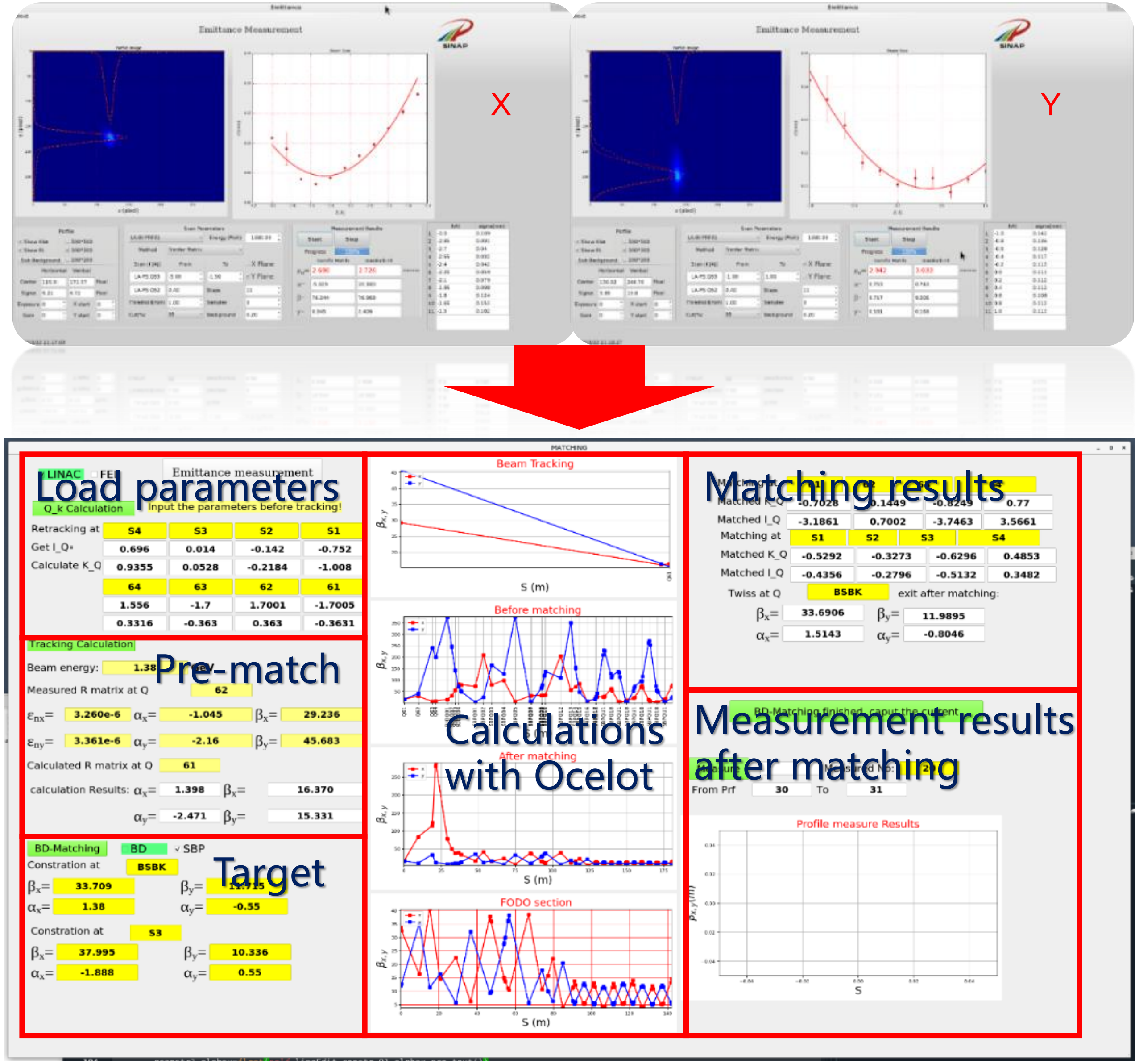
Fast orbit Feedback



Beam trajectory and jitter along the whole machine, jitter:10-20 μm (rms)



Commissioning of the SASE line: TWISS matching

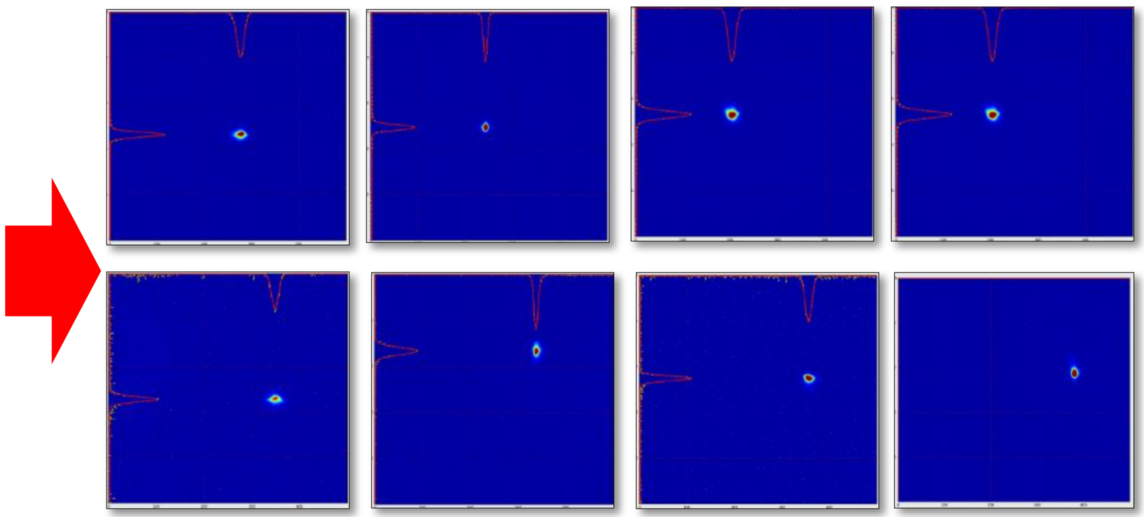


Target: FODO in the undulator with $\bar{\beta}_{x,y} \sim 10\mathrm{m}$

Procedures:

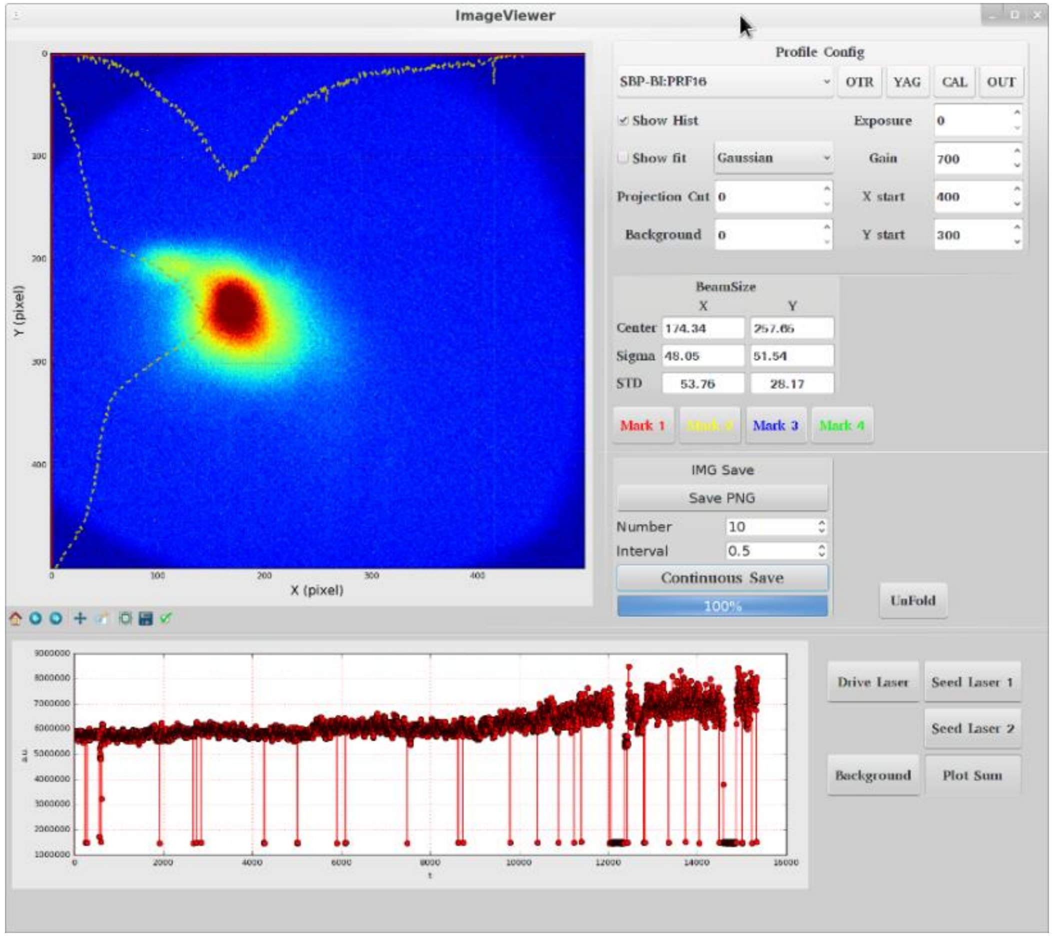
1. Emittance and Twiss parameters measurement after the linac
2. Pre-match in the long drift section
3. Emittance and Twiss parameters measurement after the long drift
4. Matching for the undulator section

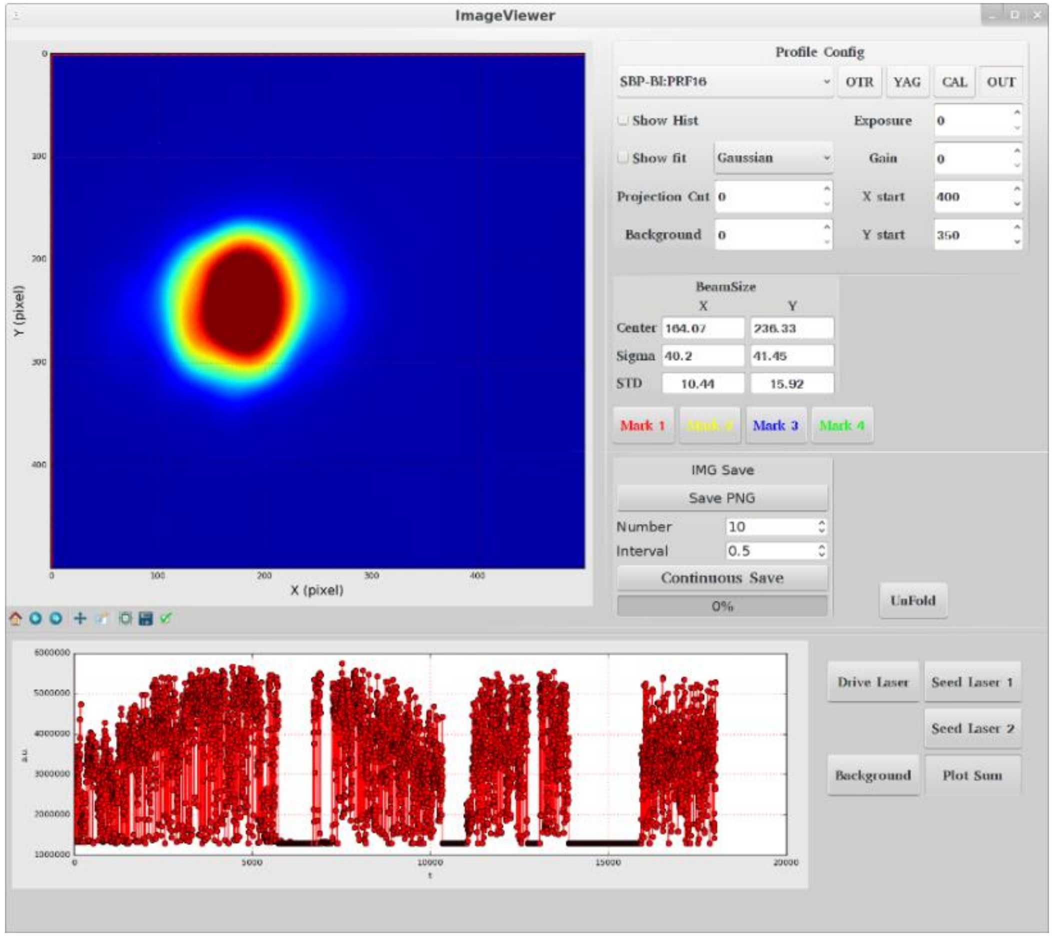
Control the beam size in the whole undulator



First lasing at 5.6 nm! (Apr. 24)

Beam energy: 890 MeV

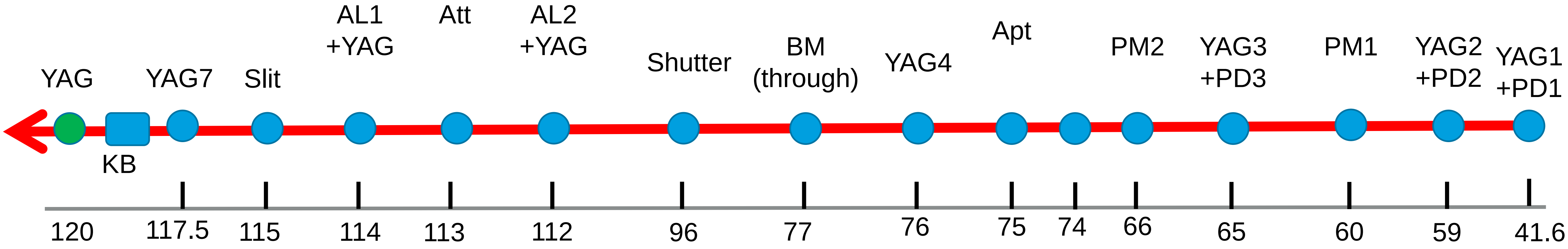




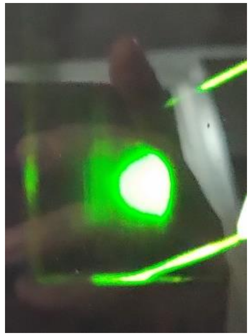
- Left: April 24, First Lasing at 5.6 nm (after one hour of SASE commissioning)
- Right: April 29, FEL @5.6 nm after optimization

X-ray beamline commissioning (Apr. 29-May. 9)

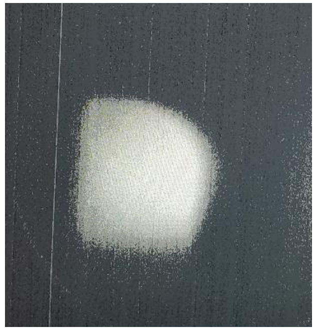
FEL passing through the whole beamline to the end-station (May. 9)



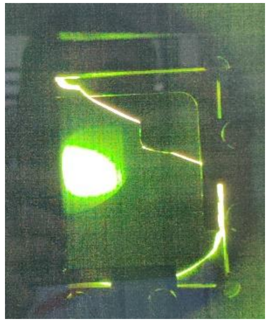
YAG just before the end-station chamber



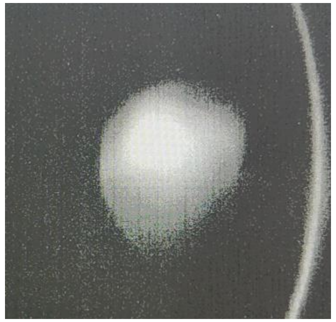
YAG7



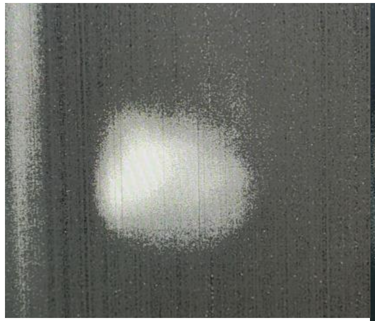
AL2
-YAG



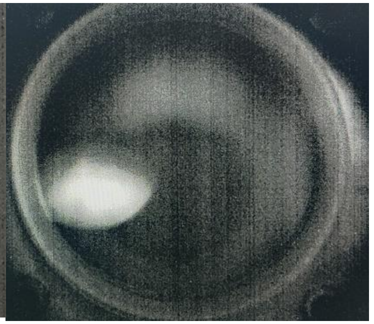
YAG4



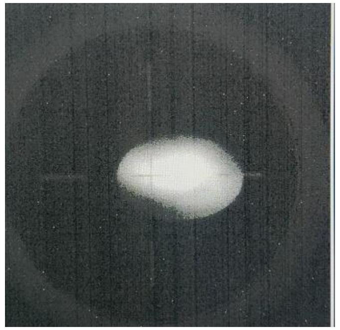
YAG3



YAG2

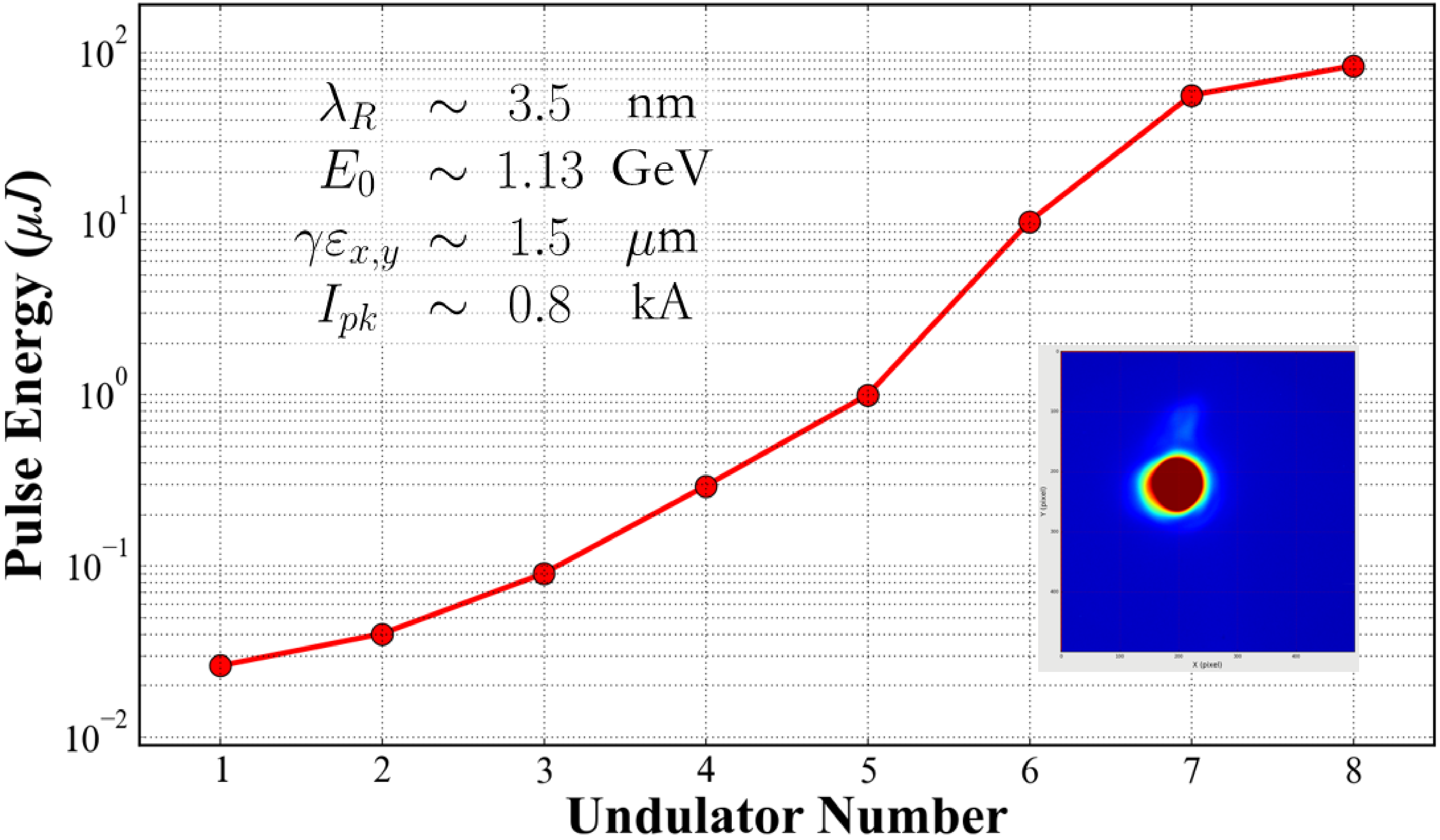


YAG1



FEL saturation at 3.5 nm (May 11)

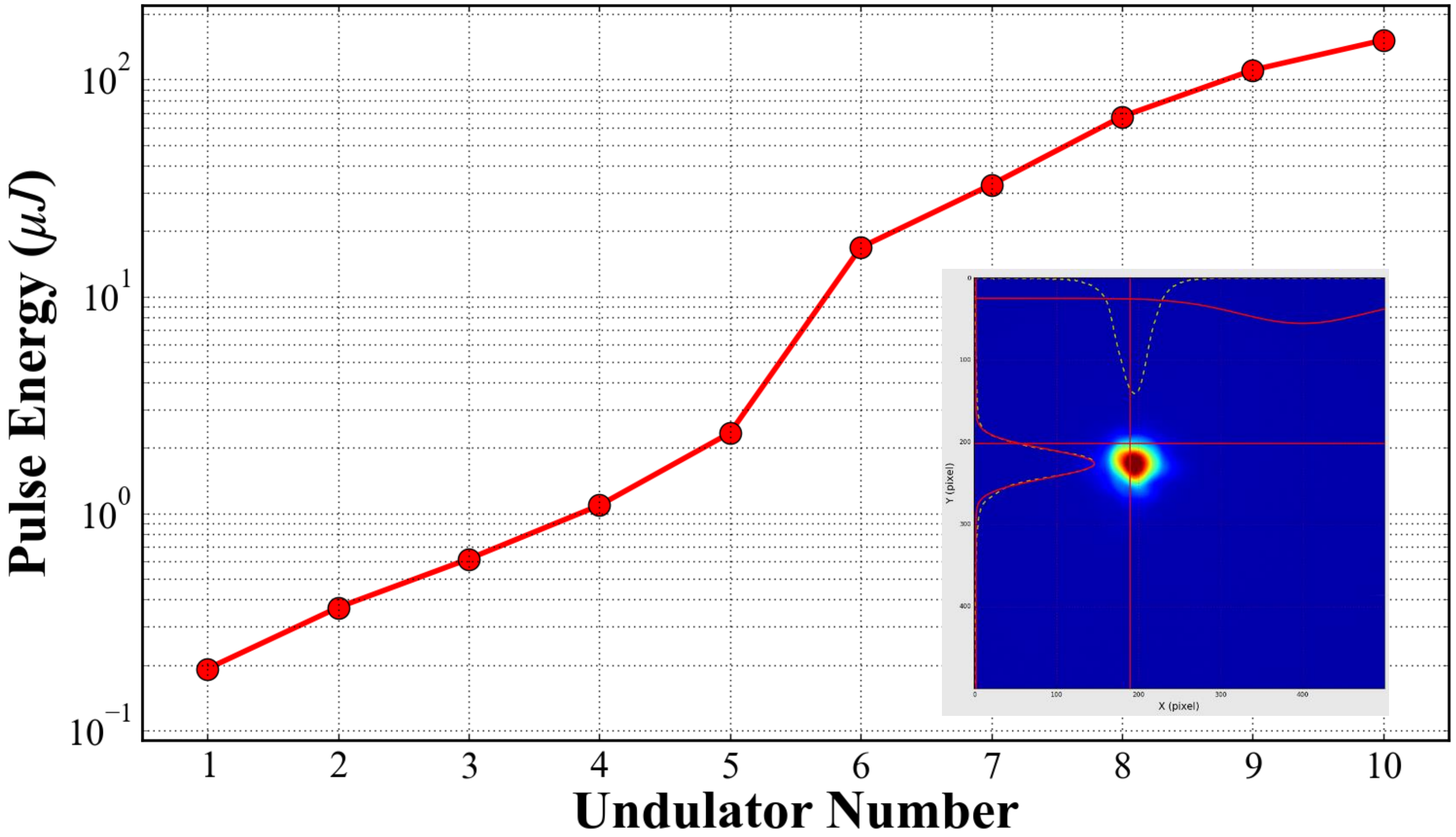
Beam energy: 1.13 GeV



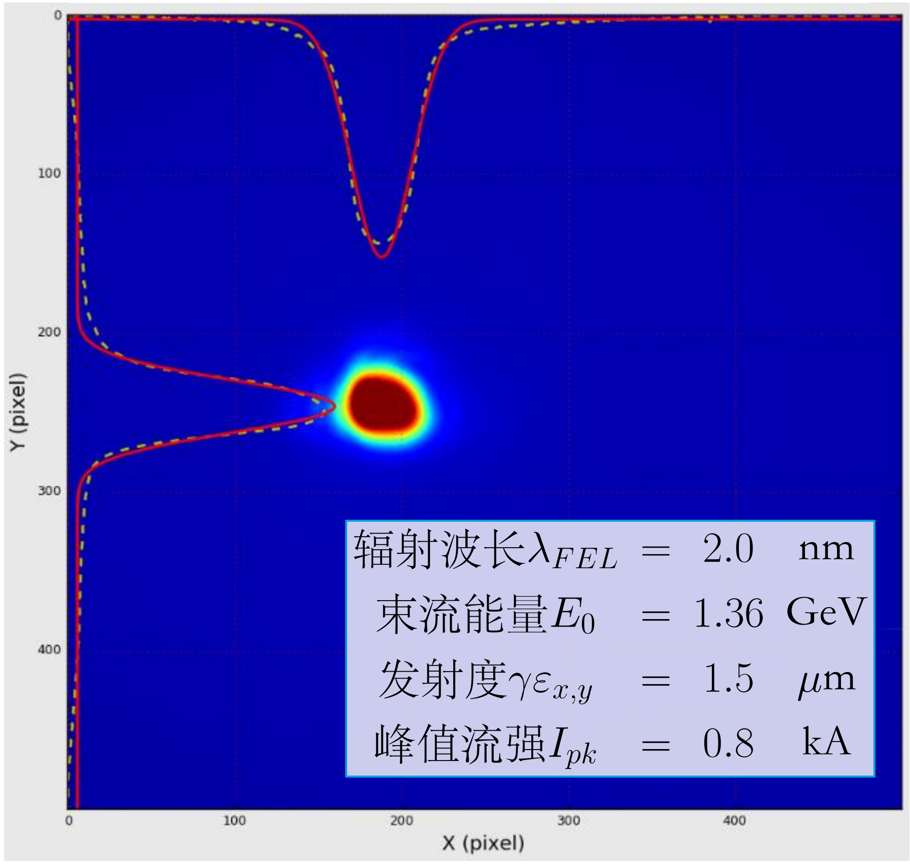
FEL lasing at 2.4 nm and 2 nm (May 13-14)

Beam energy: 1.36 GeV

Lasing @2.4 nm
—— 2021.05.13

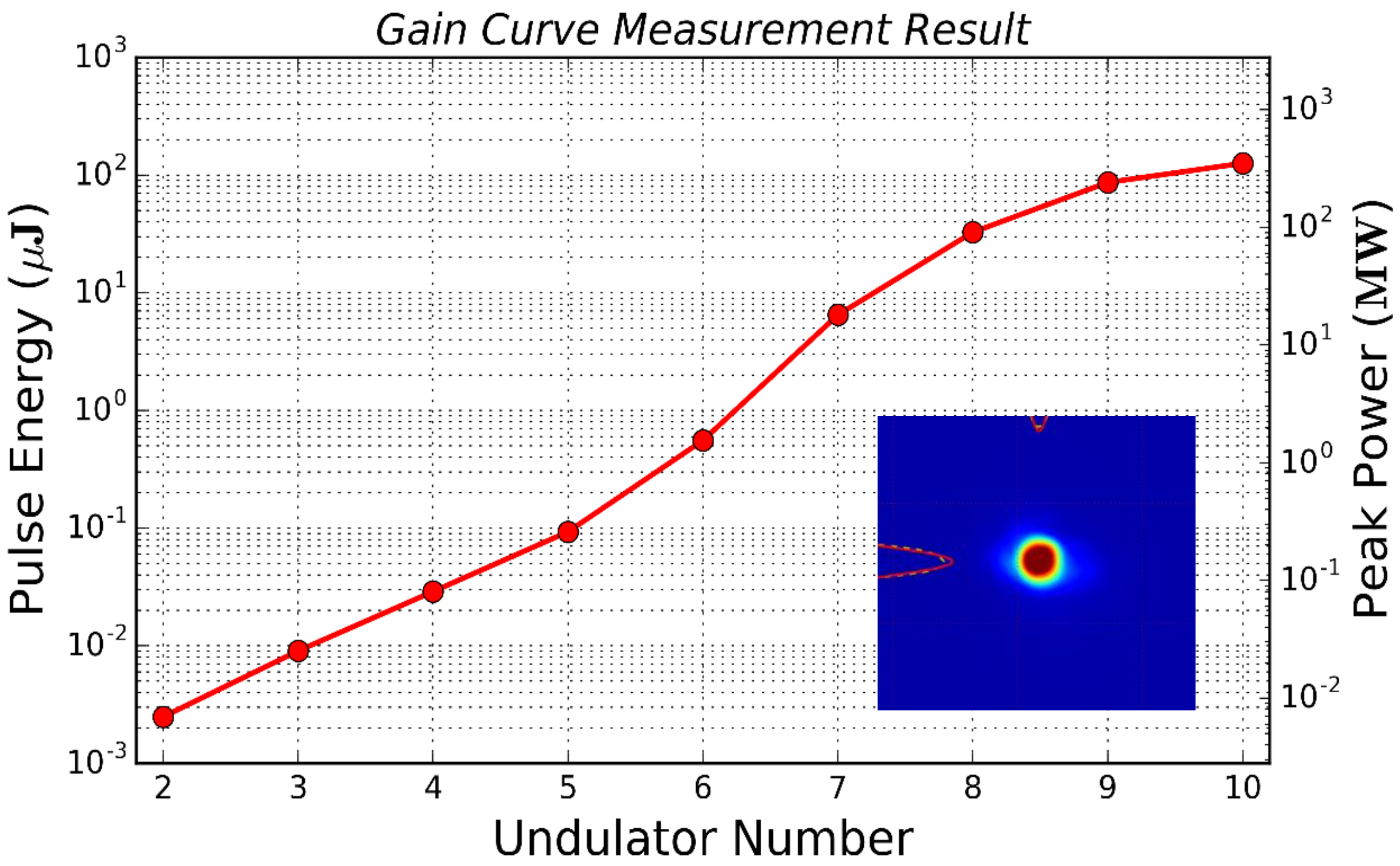


Lasing @2.0 nm
—— 2021.05.14

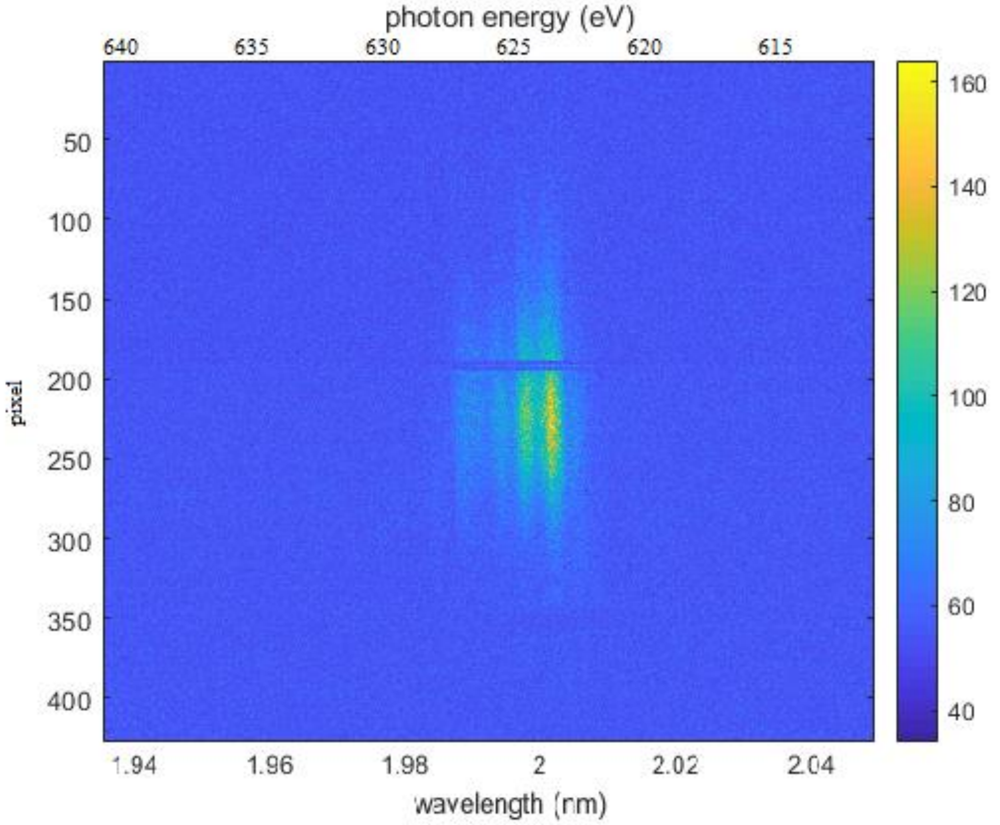


FEL saturation @ 2 nm (May 19)

Compress the bunch   (peak current > 1kA)

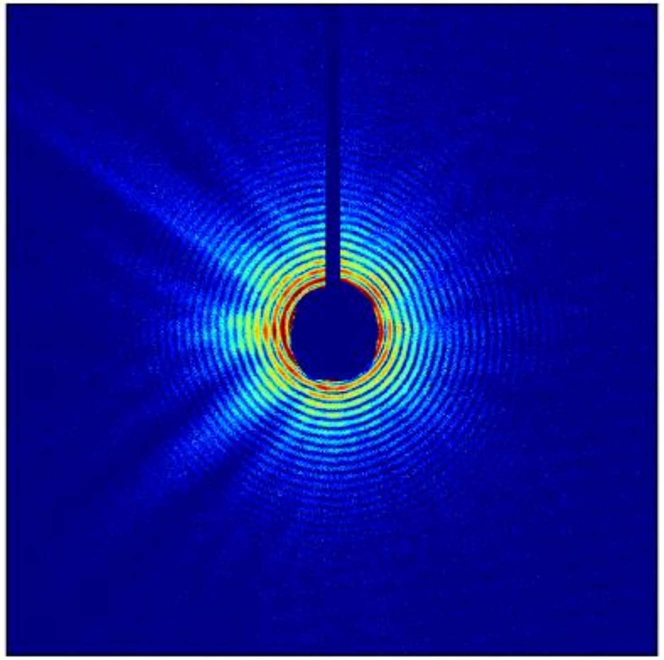


SASE spectrum from online spectrometer

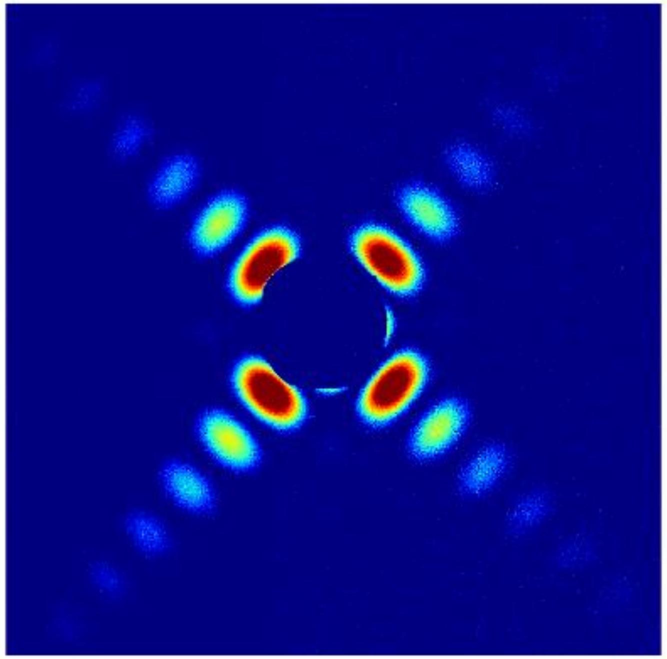


Coherent diffractive imaging with SASE beam (Jun. 21)

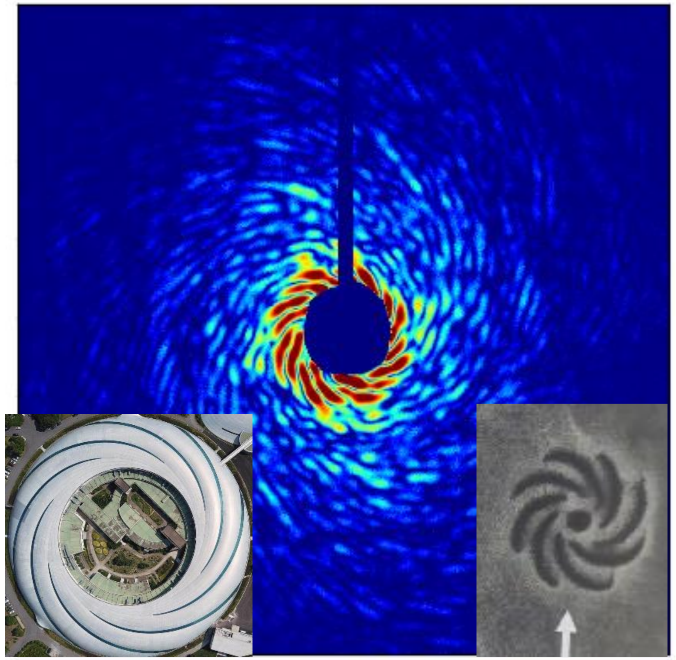
First single-shot coherent diffraction imaging experiments at SXFEL with SASE@ 2.4 nm (6.21-25)



Round



Square



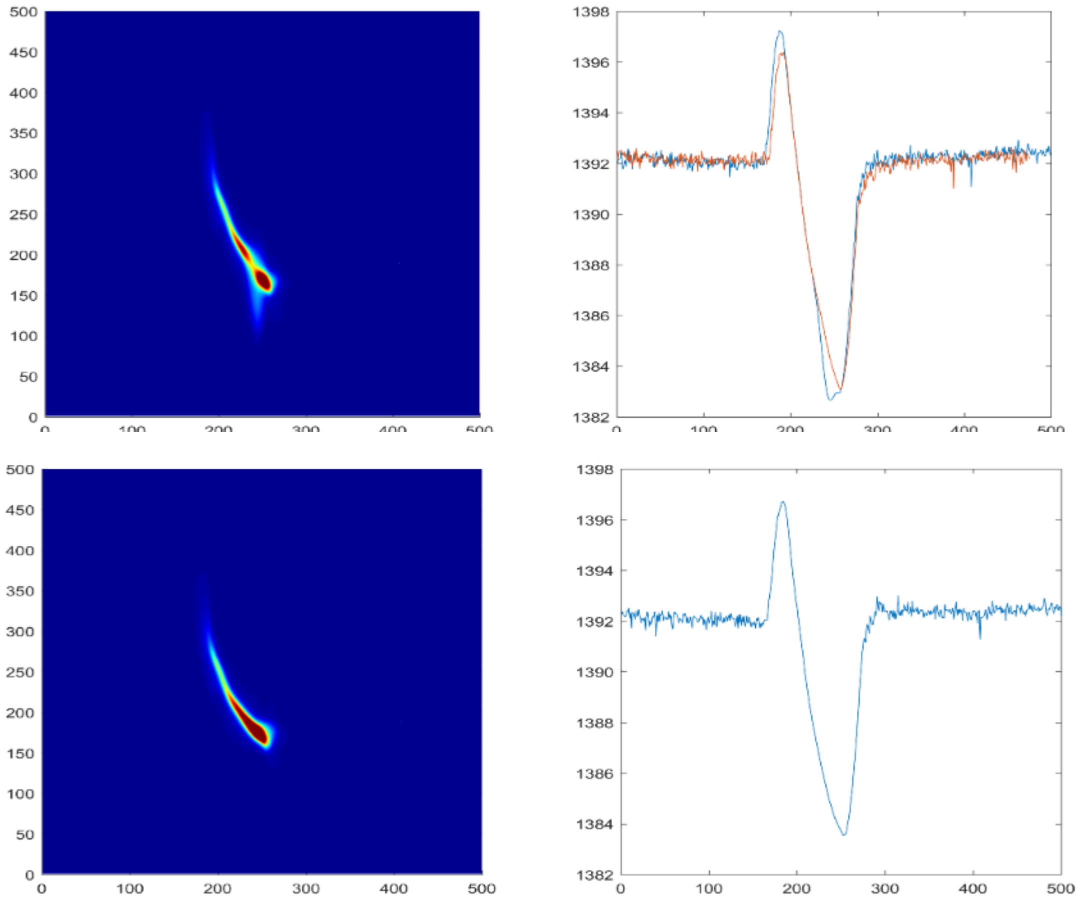
Nautiloidea

ShanghaiTech University team

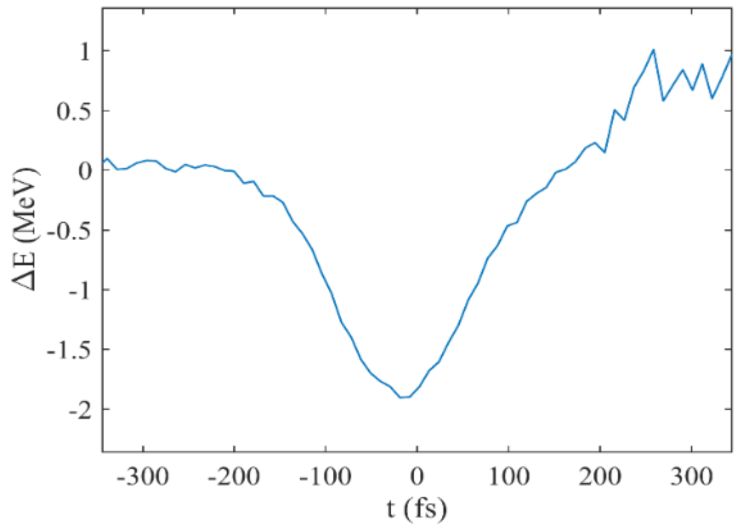
Recent results of SASE @ 2.4 nm

Further compress the electron beam for higher pulse energy and shorter pulse duration

Reconstruction of the FEL pulse

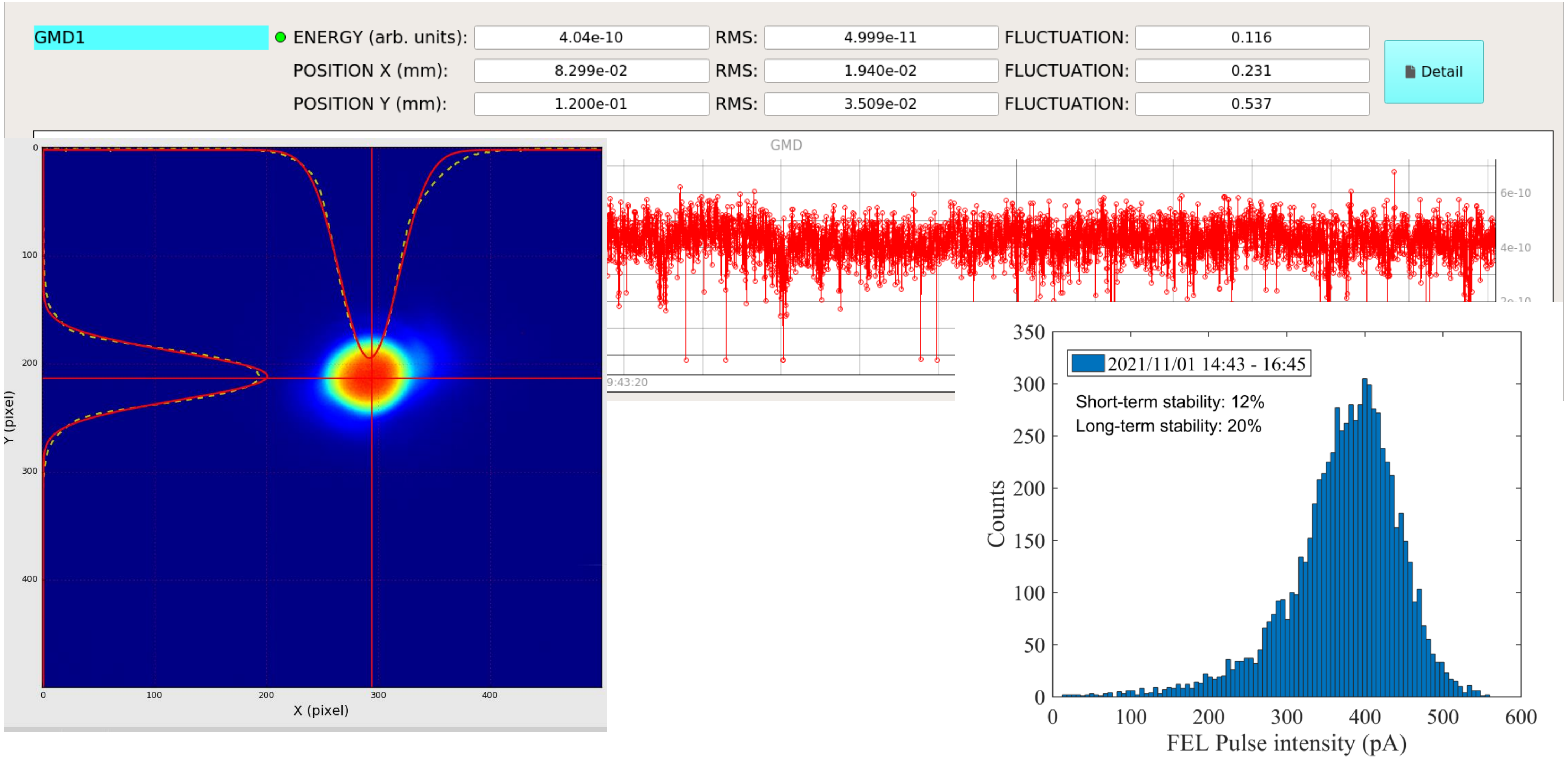


- Shorter saturation length (last 3 undulator used for tapering)
- Maximal beam energy loss>2MeV
- FEL peak power~2GW (Peak current~1kA, with only BC1)
- Pulse duration (FWHM)~200fs, only a small fragment in the head lasing, may due to the strong Wakefield of the undulator)
- Pulse energy~400μJ



Recent results of SASE @ 2.4 nm

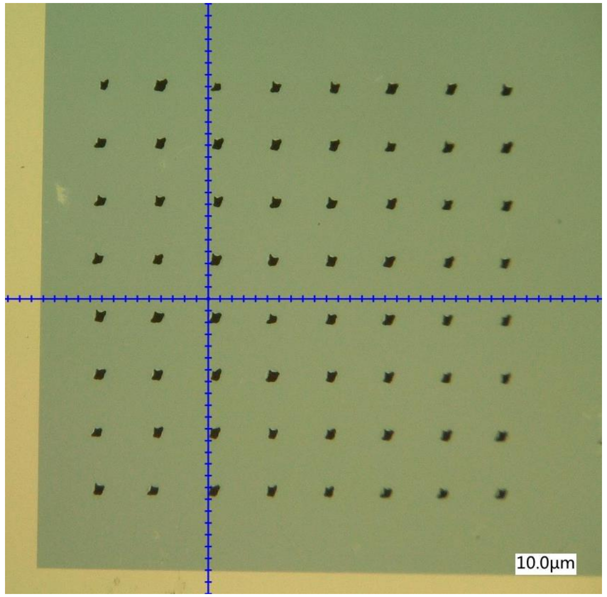
Short-term stability ~12%
Long-term stability ~20%



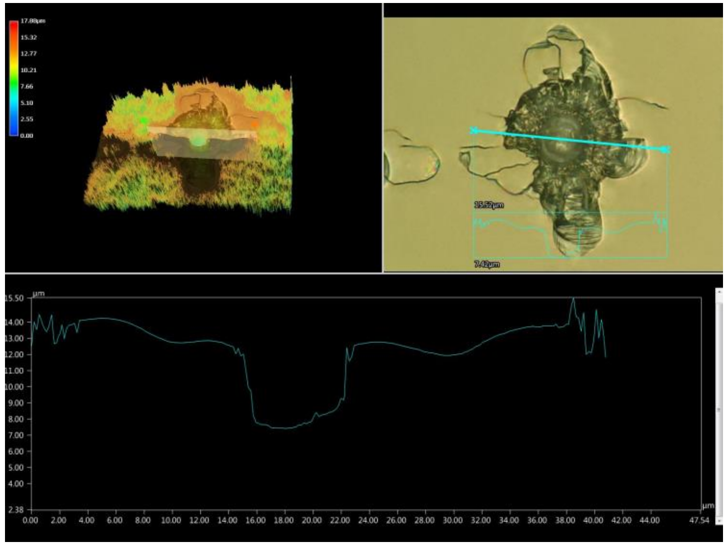
Recent results from end-station

Focusing with optical microscope

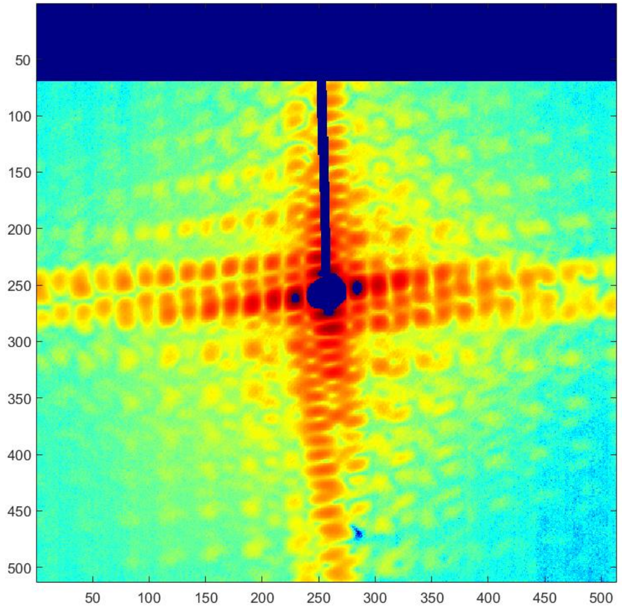
Multiple particles, single shot imaging



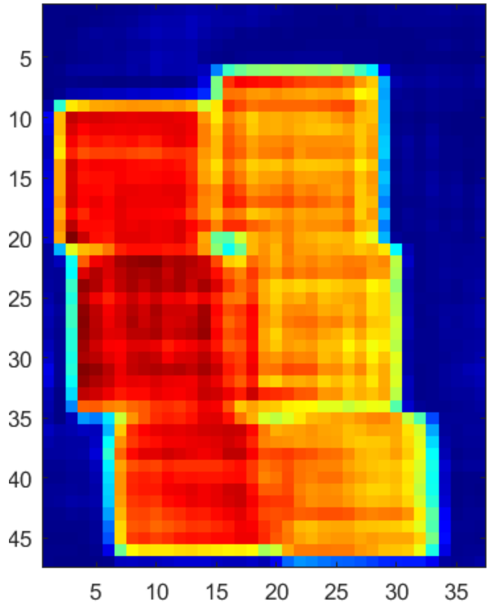
Beam shape on SiN: ~10µm



Beam shape on Si frame: ~8µm

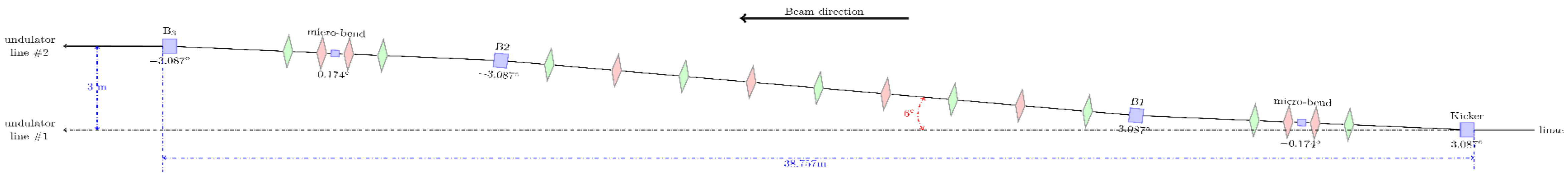


Experimental diffraction pattern

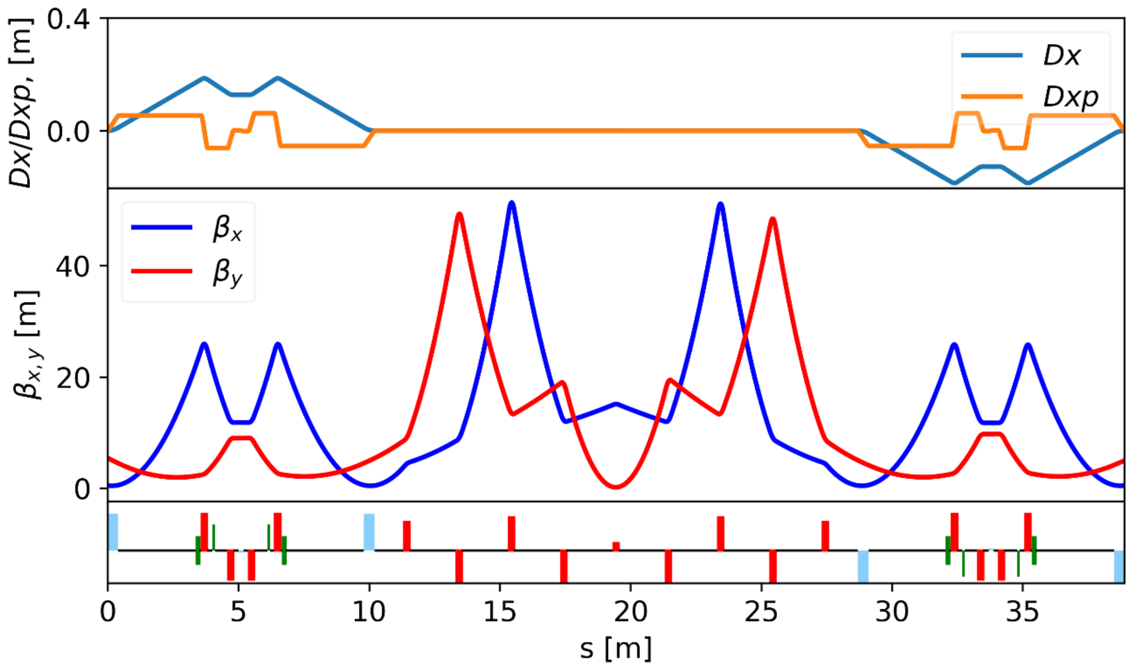


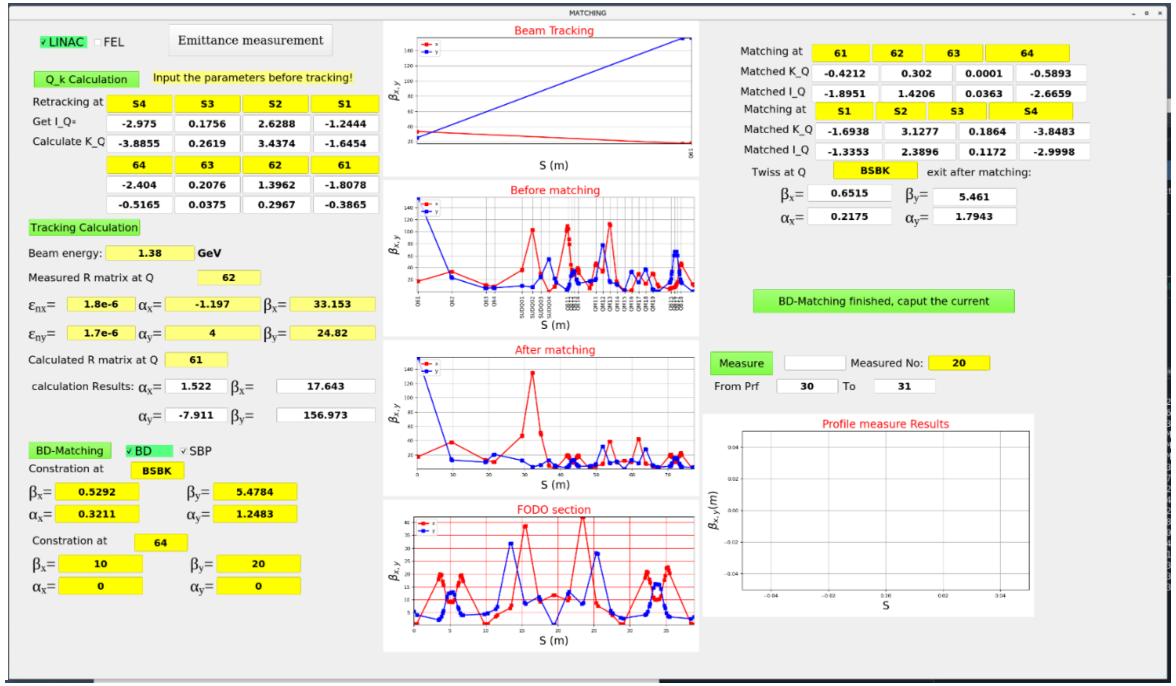
reconstruction

Commissioning of the switchyard to seeding line: matching



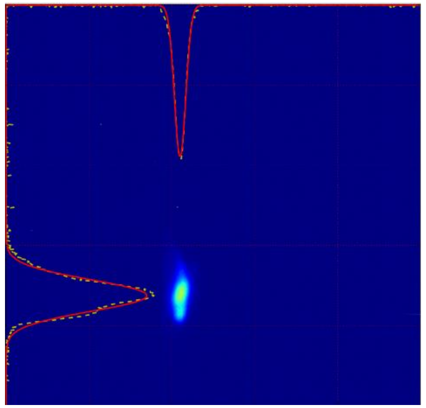
- Entrance parameter matching from the end of the linac
- Set the QUADs based on the matching results
- Slightly modified the Quads value (~0.2A) from the calculated values

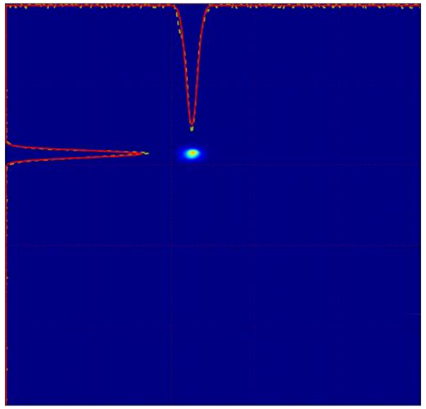


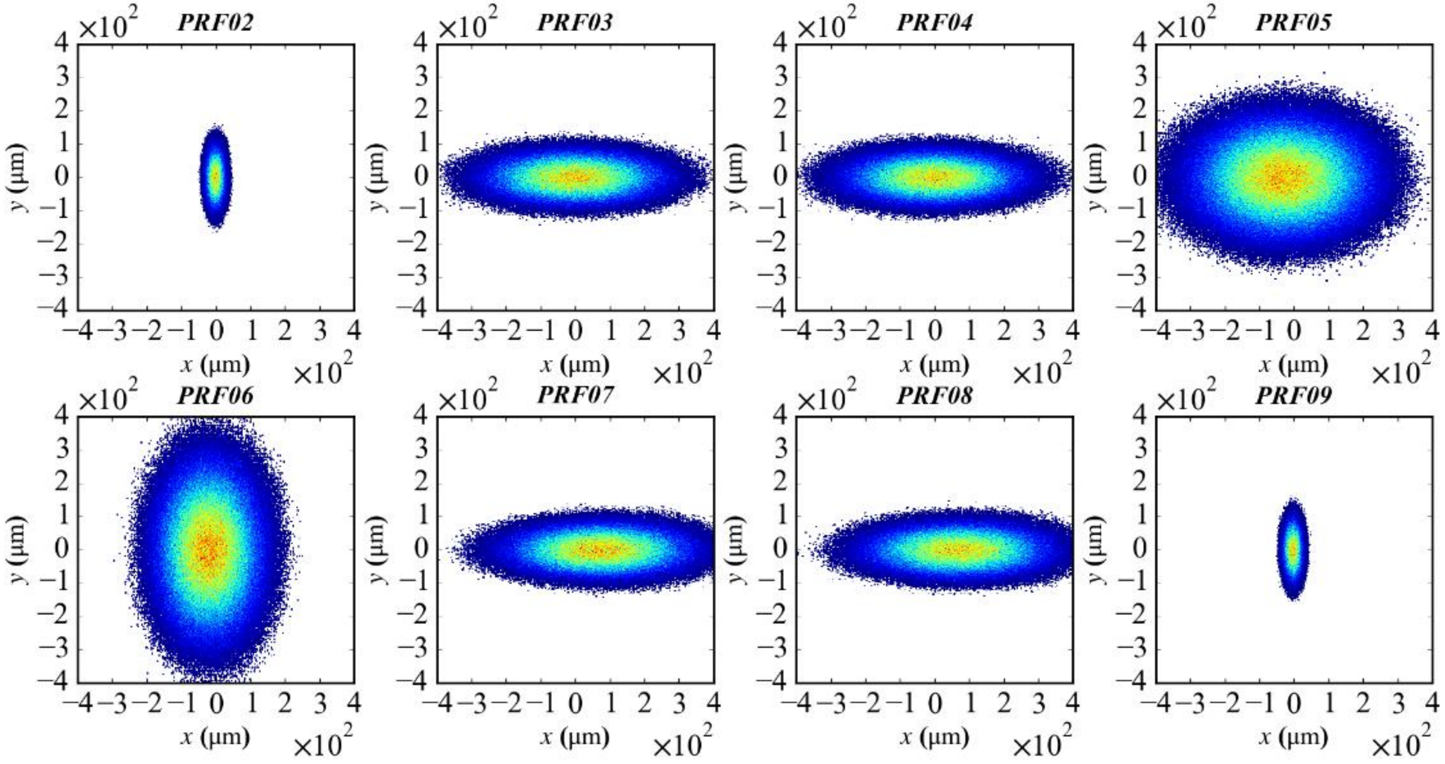


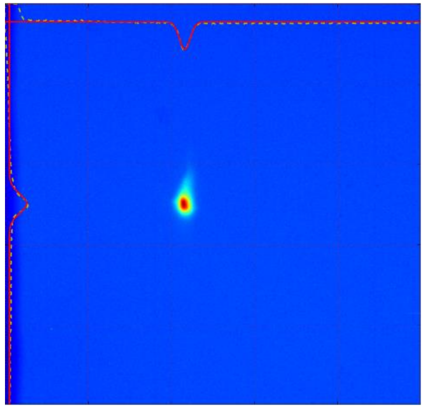
Commissioning of the switchyard to seeding line: matching

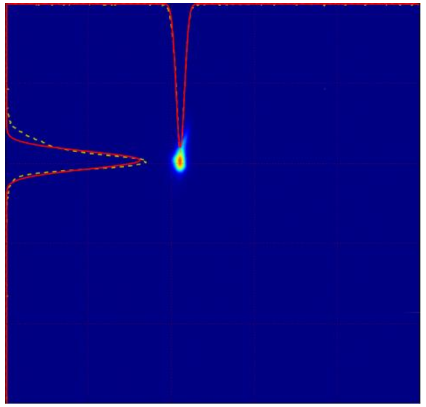
- Entrance parameter matching from the end of the linac







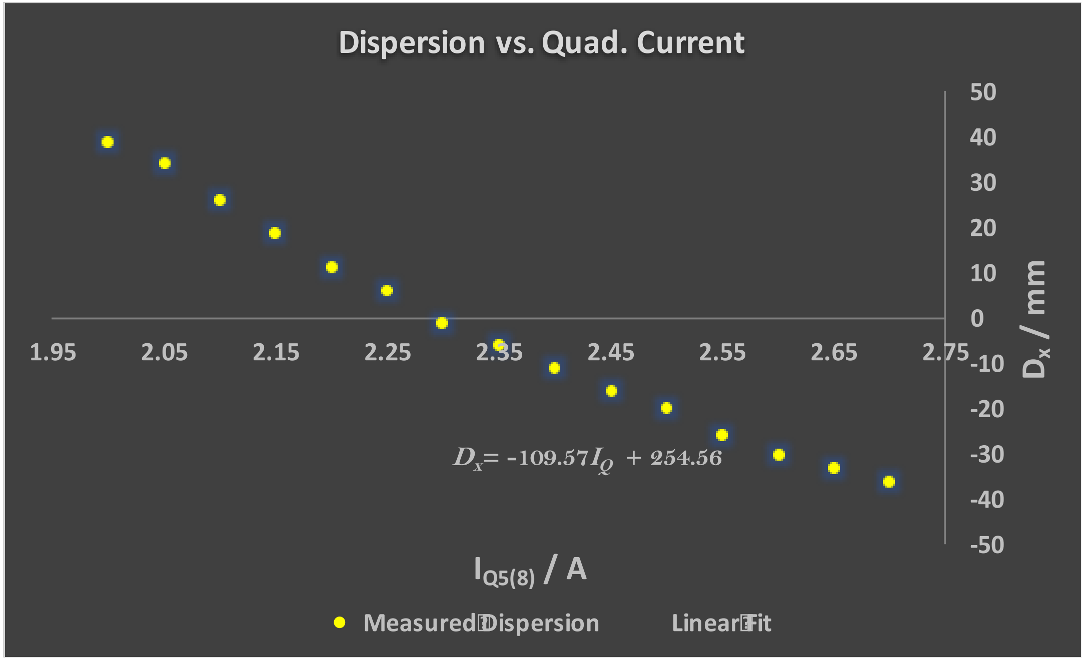




- Needs further optimization

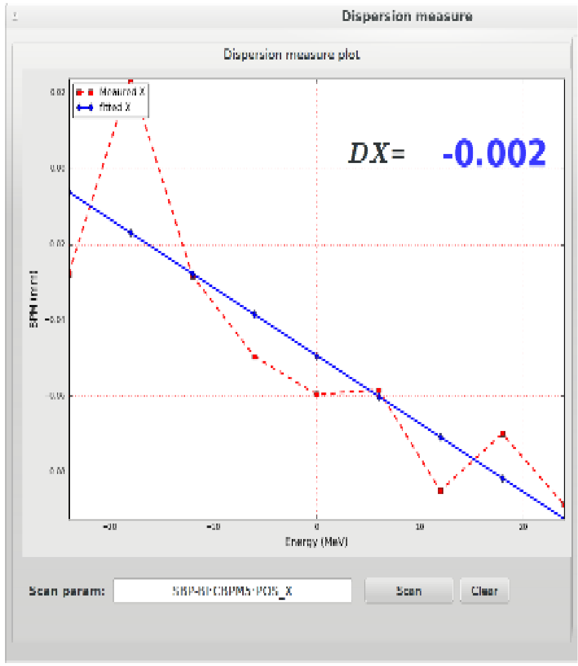
Commissioning of the switchyard to seeding line

- I_Q vs D_x response curve
- Find disp. free conditions for DBAs

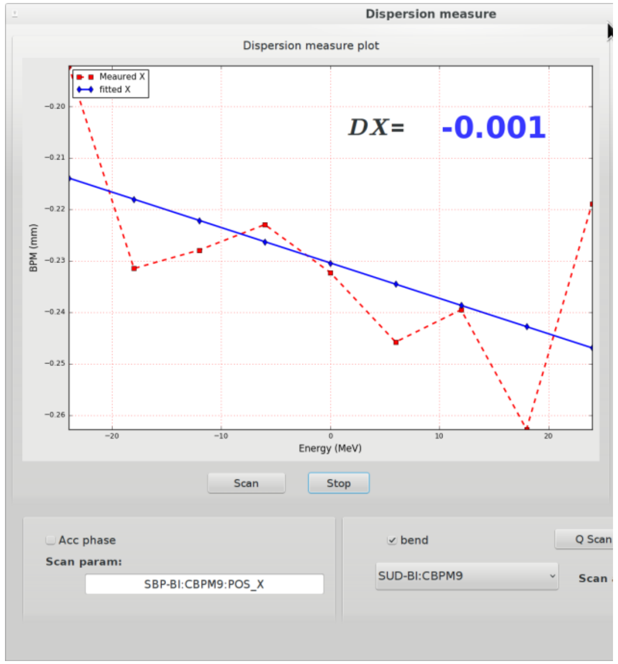


- theoretical values of DBAs were set and optimized for dispersion free. (difference between design value and optimized value < 10%)

DBA1



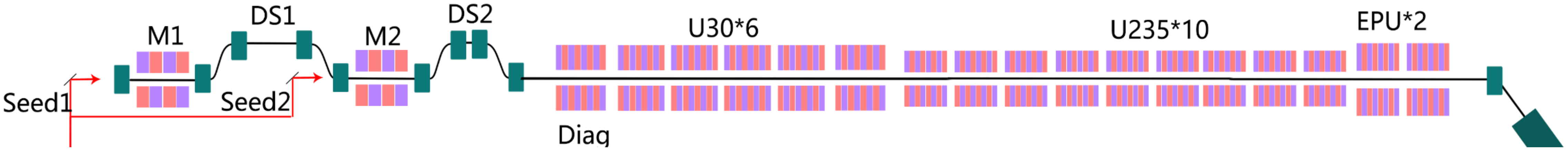
DBA2



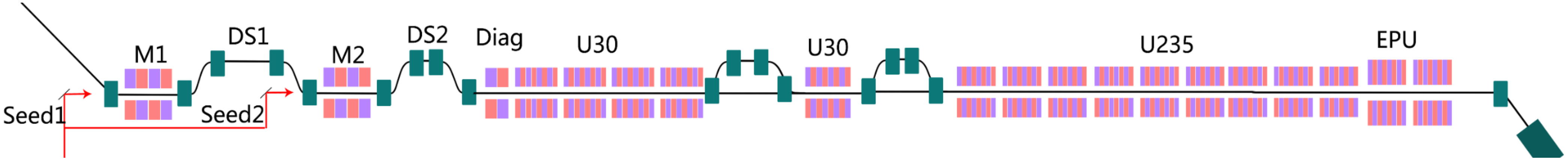
- Next step: optimization of matching for the whole beamline, reduce the CSR effects and maintain the emittance, Global matching to the seeding line

Seeding line: tasks & plan

Goal: external seeding for fully coherent radiation at 3 nm

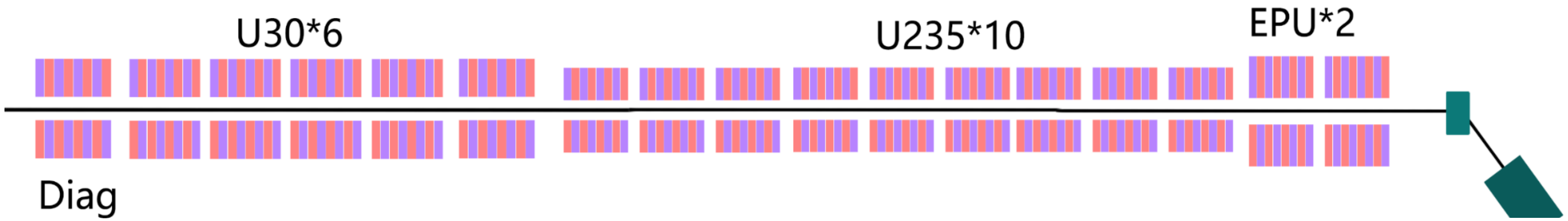


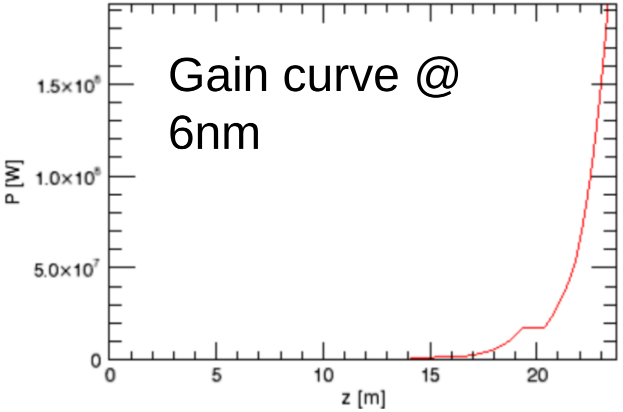
- EEHG @ 3-6nm (1.4 GeV, U30, Gap: 10.6 mm; 1GeV, U235, Gap: 9.2 mm)

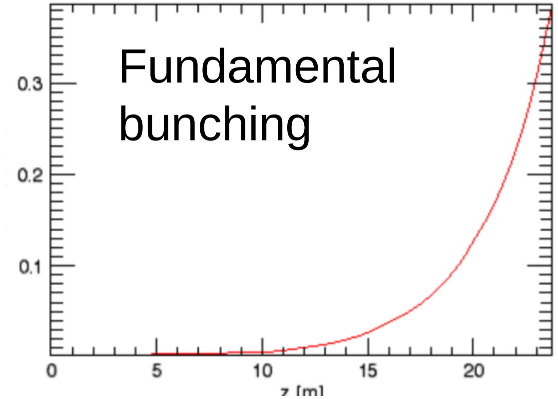


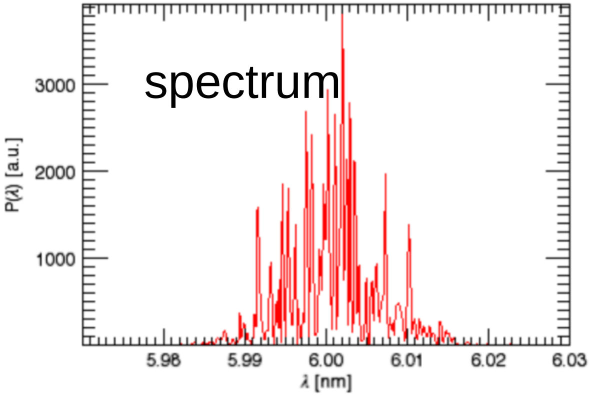
- EEHG-HGHG @ 3nm (1.4 GeV, U30, Gap: 16.9 mm, K=1; U235, Gap: 9.4 mm, K=1.33)

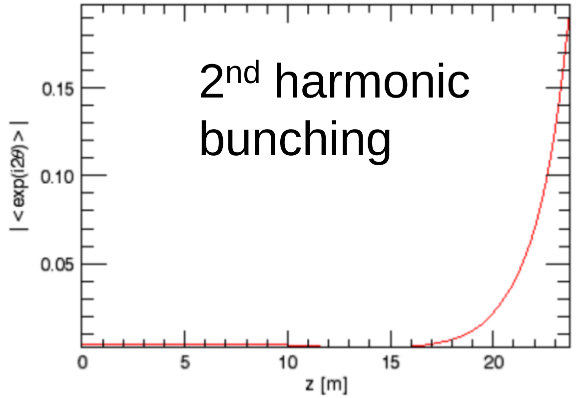
Seeding line: SASE @ 6-3 nm



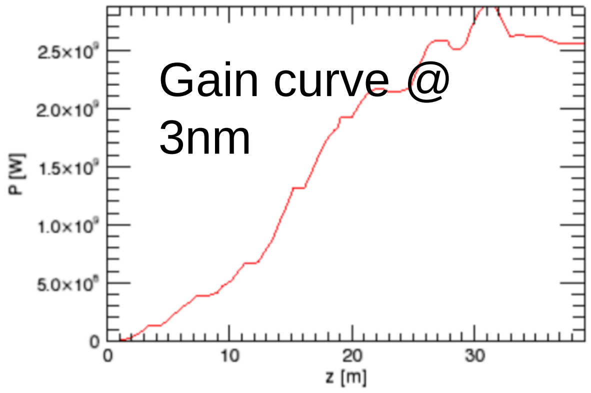


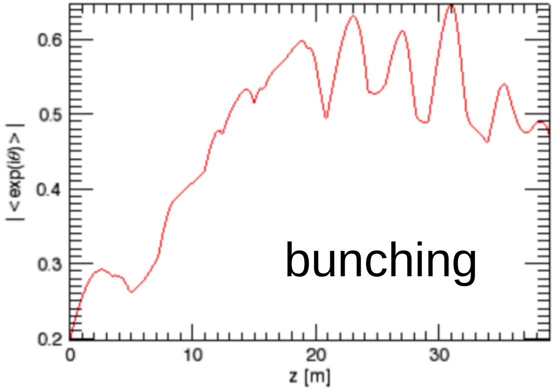


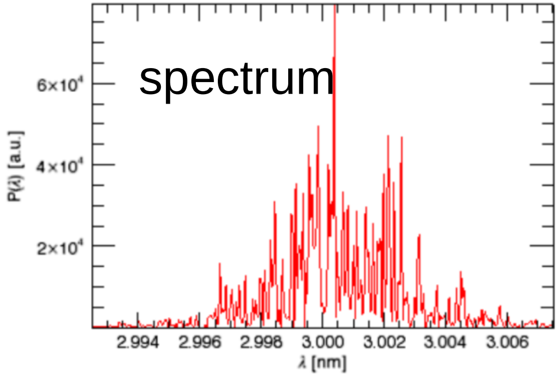




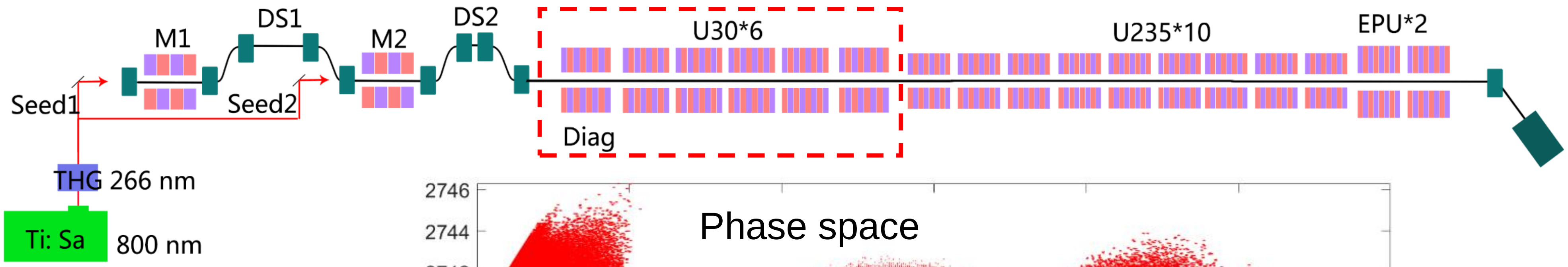
HLSS:

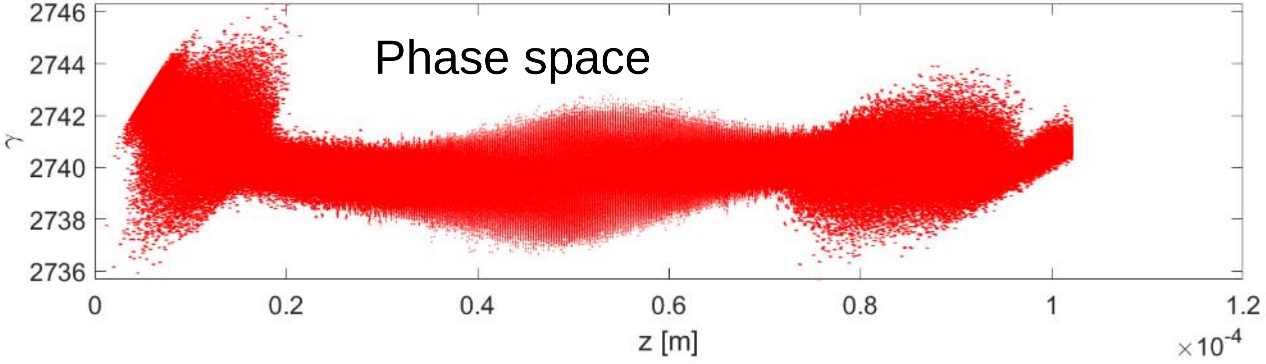


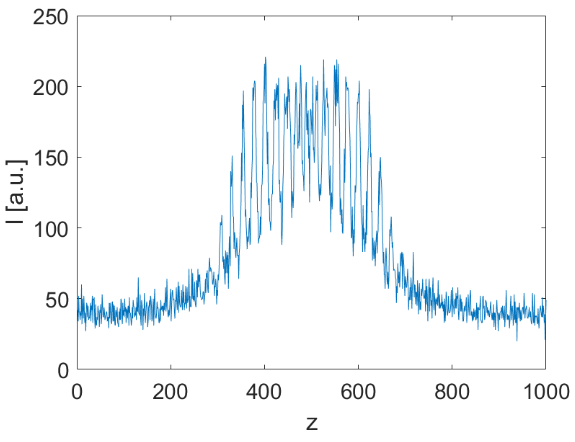


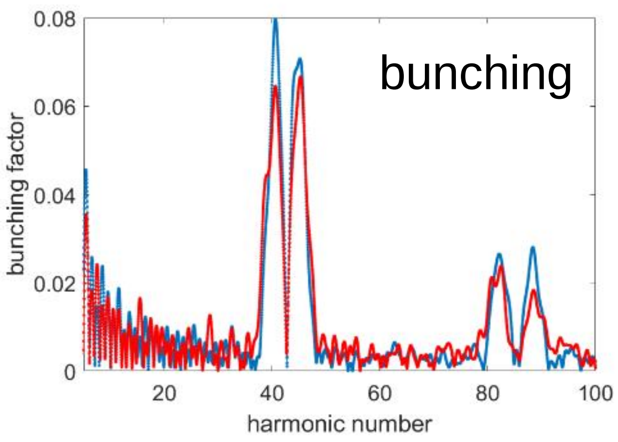


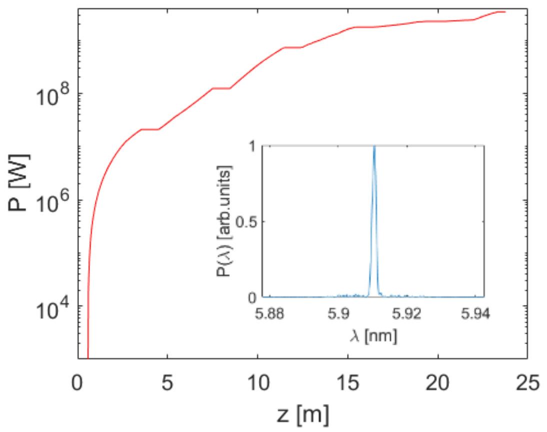
Seeding line: EEHG @ 6 nm

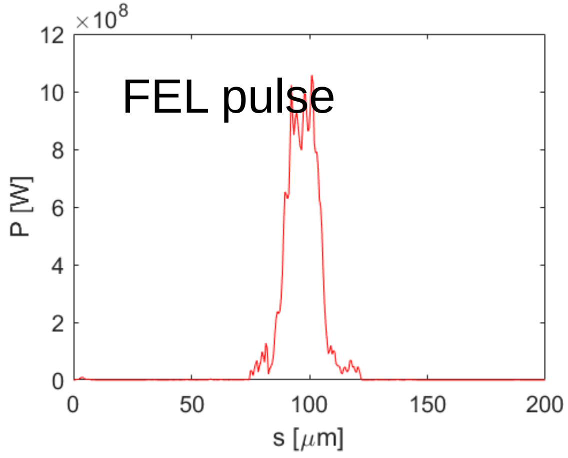




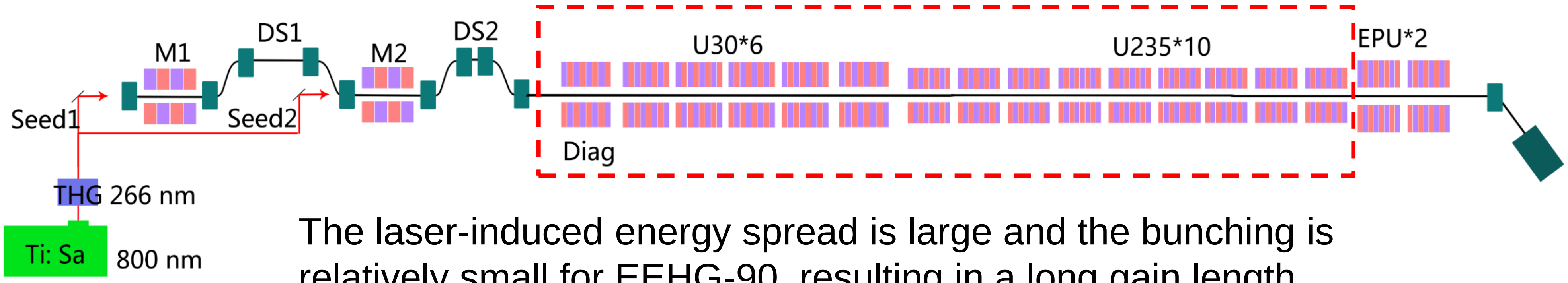




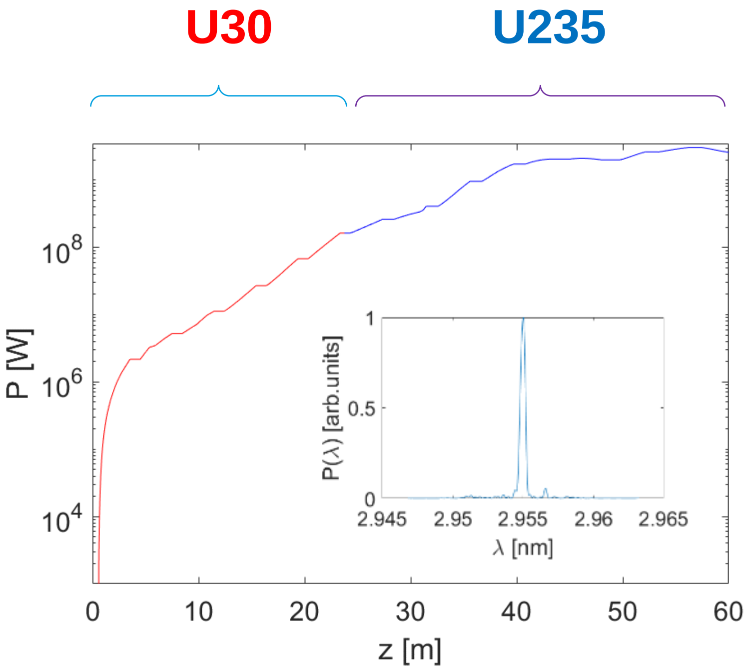




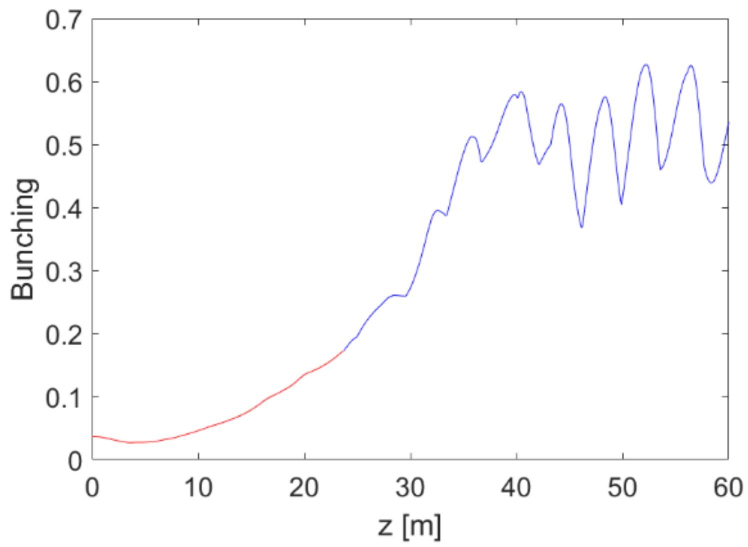
Seeding line: EEHG @ 3 nm



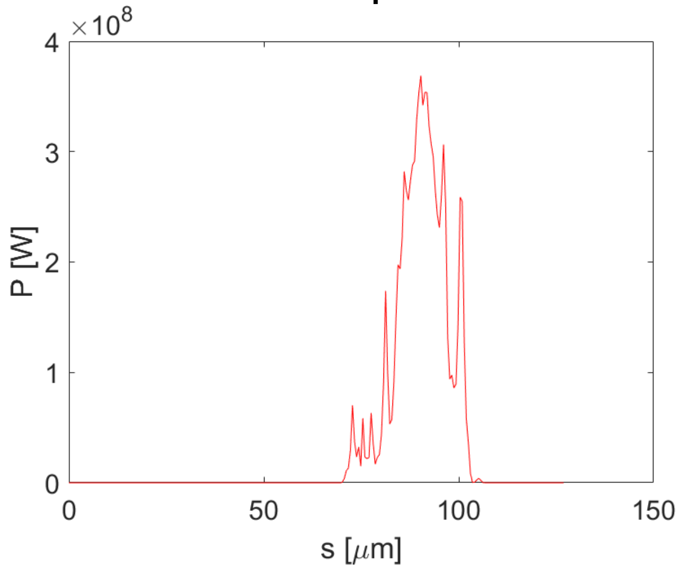
The laser-induced energy spread is large and the bunching is relatively small for EEHG-90, resulting in a long gain length



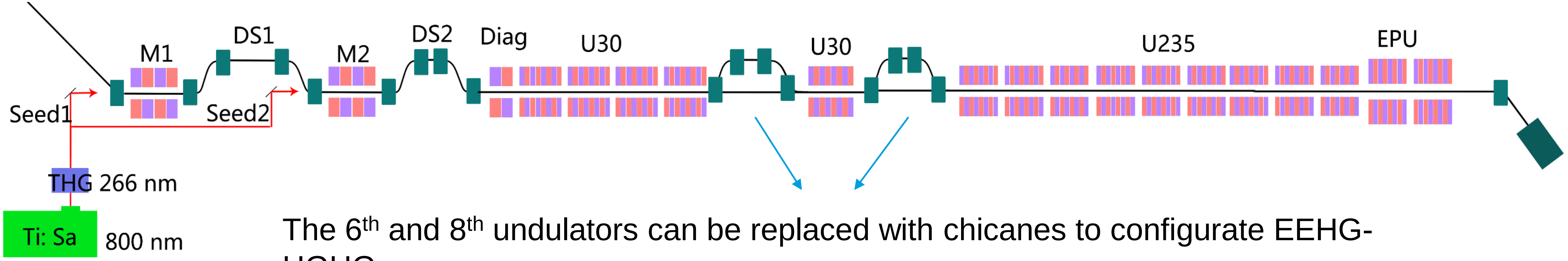
Saturation around 35m



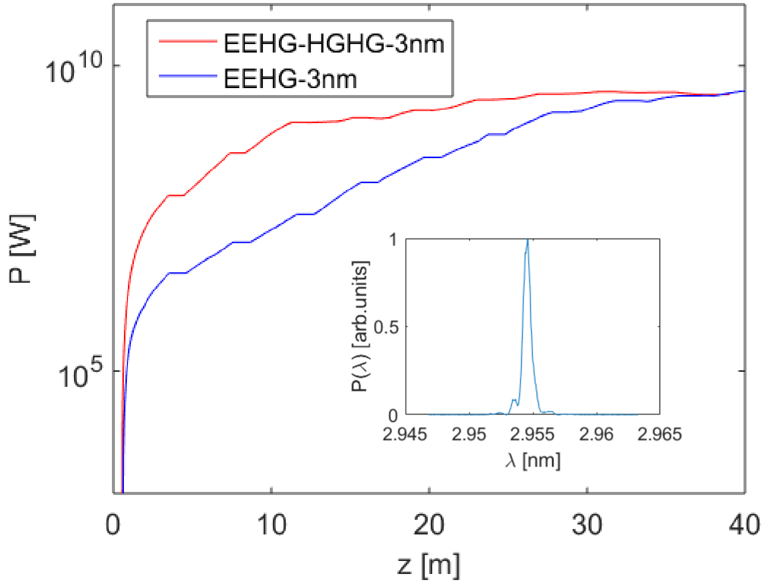
FEL pulse

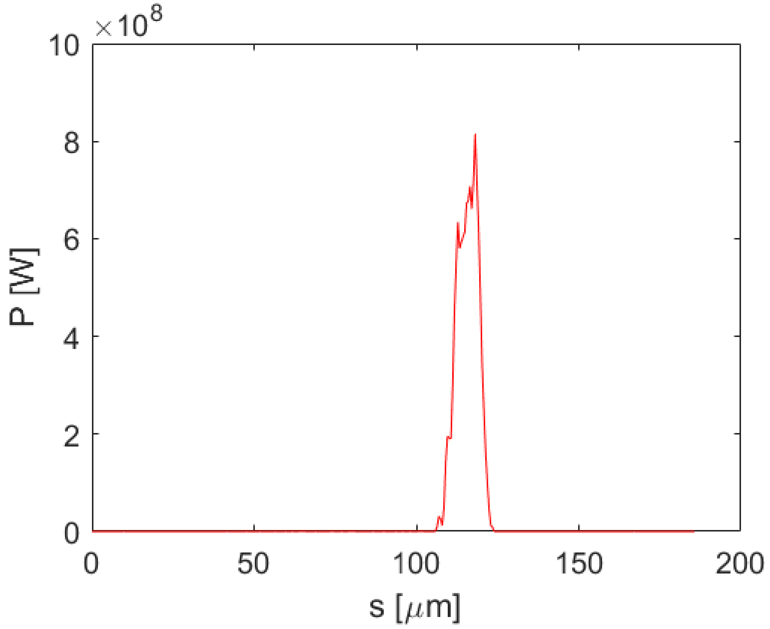


Seeding line: EEHG-HGHG@ 3 nm



The 6th and 8th undulators can be replaced with chicanes to configurate EEHG-HGHG





Lower energy spread and higher bunching significantly reduce the gain length at 3 nm

Summary

- The SXFEL user facility is under commissioning, aiming at serving users next year.

- Commissioning of SASE line has been finished. Commissioning of switchyard and seeding line was just started.

- Problems: (1) conflicts between the requirements of high peak current for SASE and uniform phase space for seeding. (2) Stability issues. （3） Only a fraction of the electron beam lasing. (4) shorter pulse length.

Thanks for your attention!