Commissioning process on HLSS and EEHG at SXFEL

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Outline

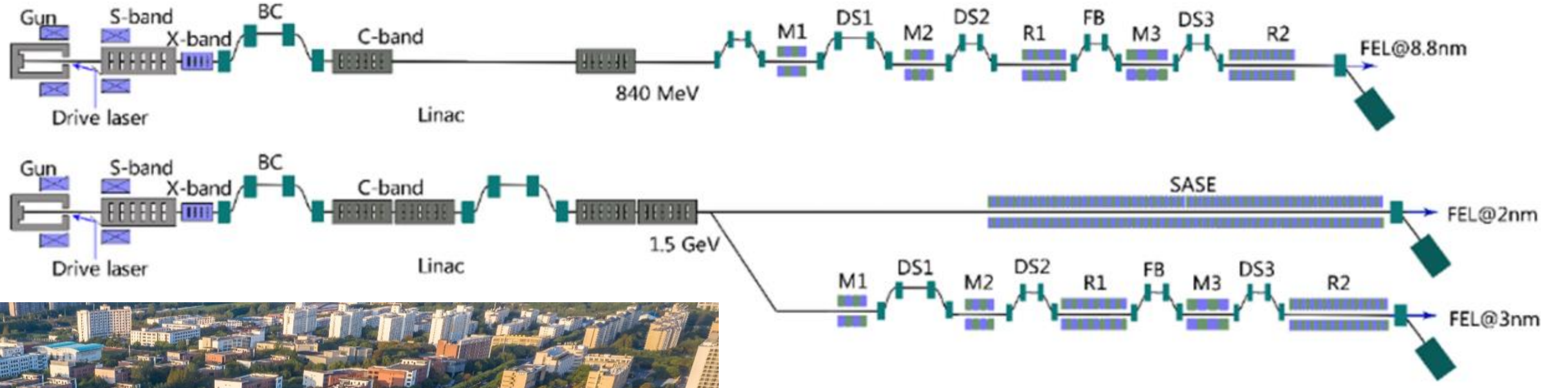
- Introduction of the SXFEL
- Commissioning process
  - EEHG
  - EEHG harmonic cascade
  - HLSS
- Summary

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 the 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

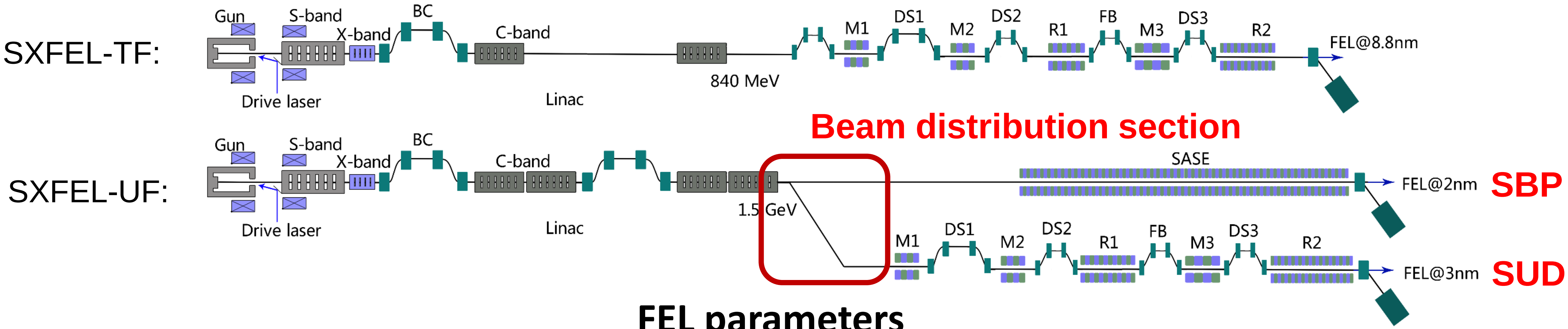
User facility



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

SXFEL：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-harmonic cascade



FEL parameters

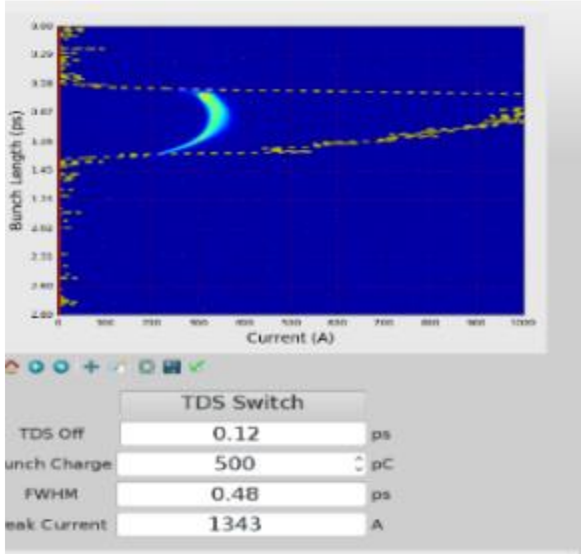
	SASE line	Seeding line (SUD)
Beam energy/GeV	1.5	1.5
FEL wavelength/nm	2 nm	3 nm
FEL pulse/fs	100-300	100 - 200
FEL power/MW	＞100	＞100
Rep. rate/Hz	50	50

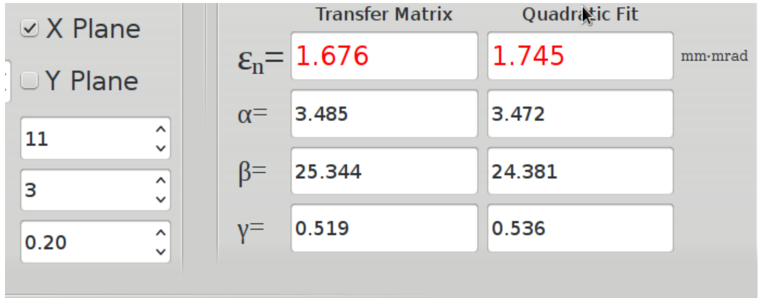
SXFEL

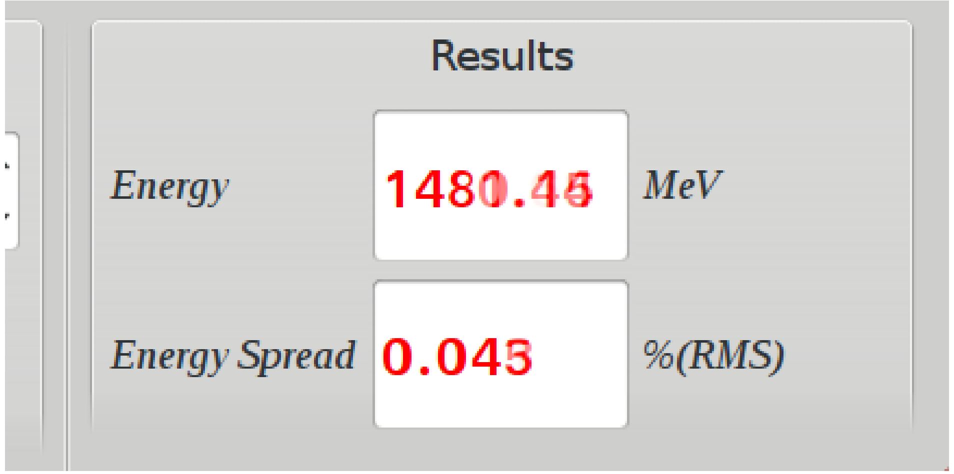
1.5GeV e- / ~1keV x-ray
532m, 2 FEL lines/5 stations

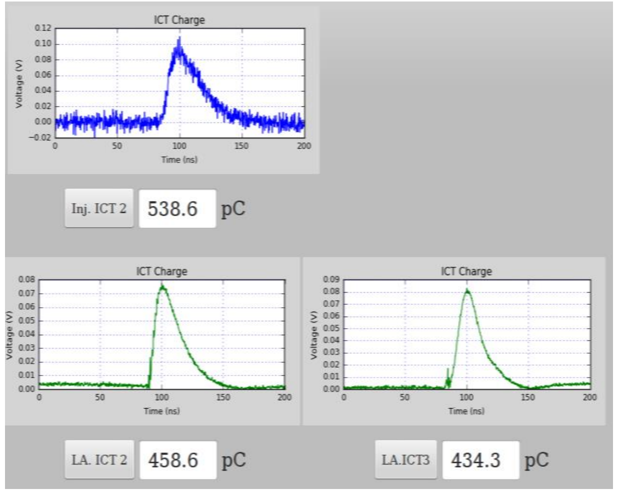
Linac performances

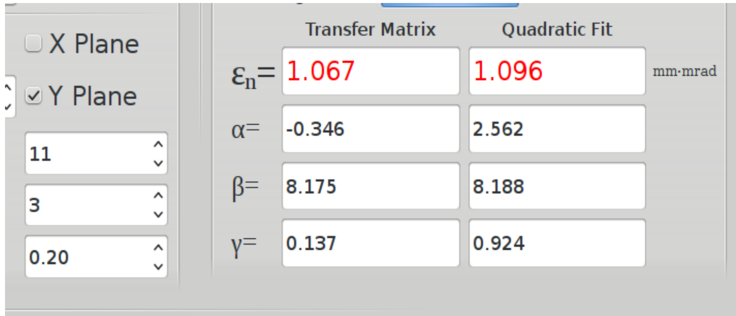
Parameters	SXFEL-TF (achieved)	SXFEL-UF (design)	SXFEL-UF (achieved)
Beam energy (GeV)	0.84	1.5	~1.5
Energy spread (rms)	≤0.15%	≤0.15%	< 0.05%
Nor. emittance (mm-mrad, rms)	≤2.5	≤1.5	~1.5
Bunch length (ps, FWHM)	≤1.0	≤0.7	< 0.5
charge (nC)	0.5	0.5	> 0.5
Peak current (A)	≥500	≥700	> 1000
Rep-rate (Hz)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



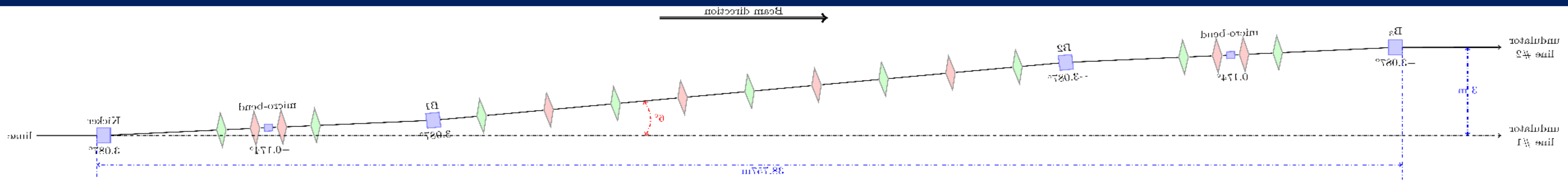


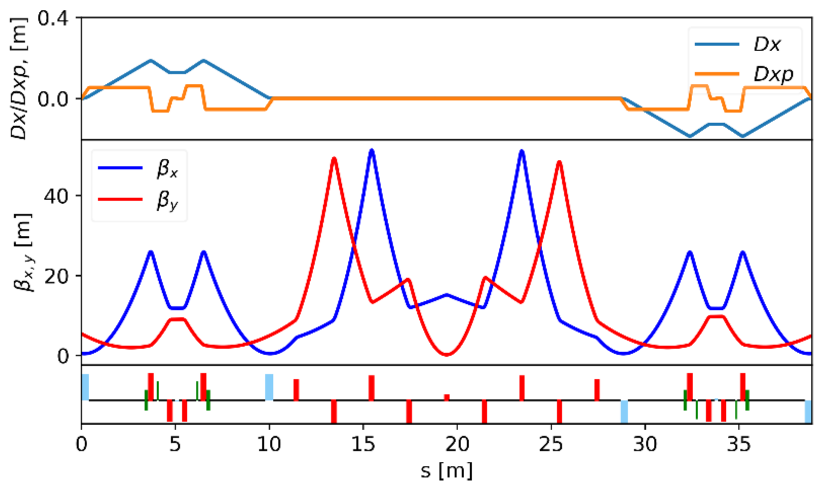


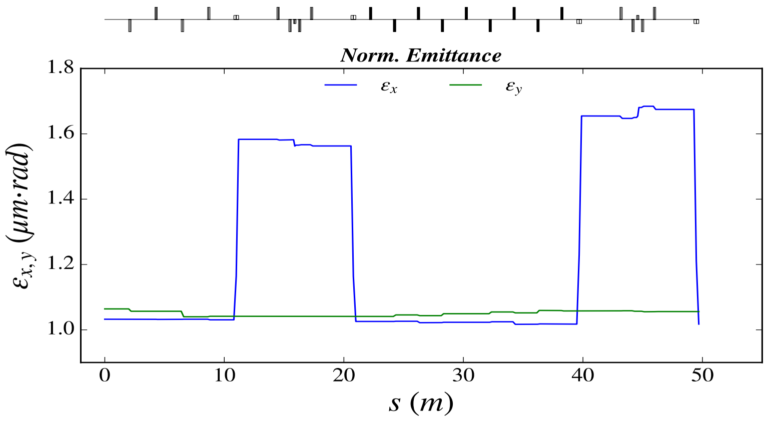




Beam distribution system : layout & main parameters





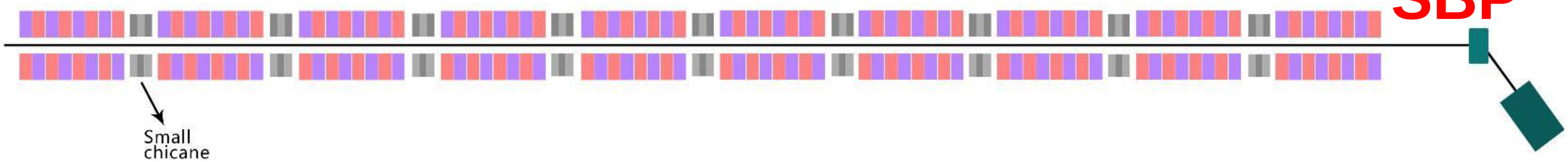


- SBP(SASE) line -> Seeding line ~ 3 m in horizontal
- Symmetrical lattice, total length about 39 m
- Dual-DBA dog-leg， total deflecting angle 6°

Undulator lines: SBP and Seeding line (SUD)

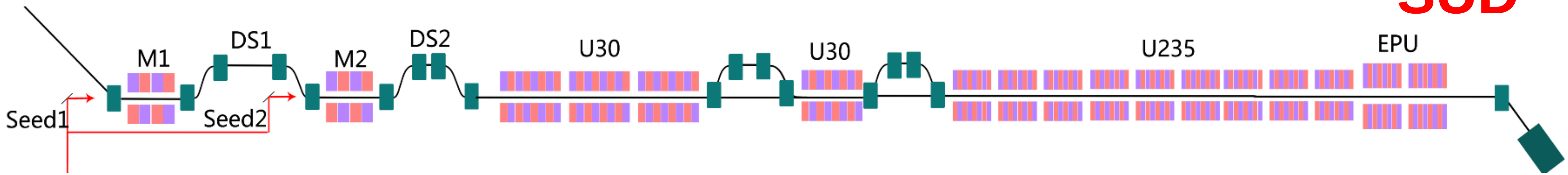
- **FEL1: SASE FEL line (new): build 10 IVU (16 mm) sections**

SBP



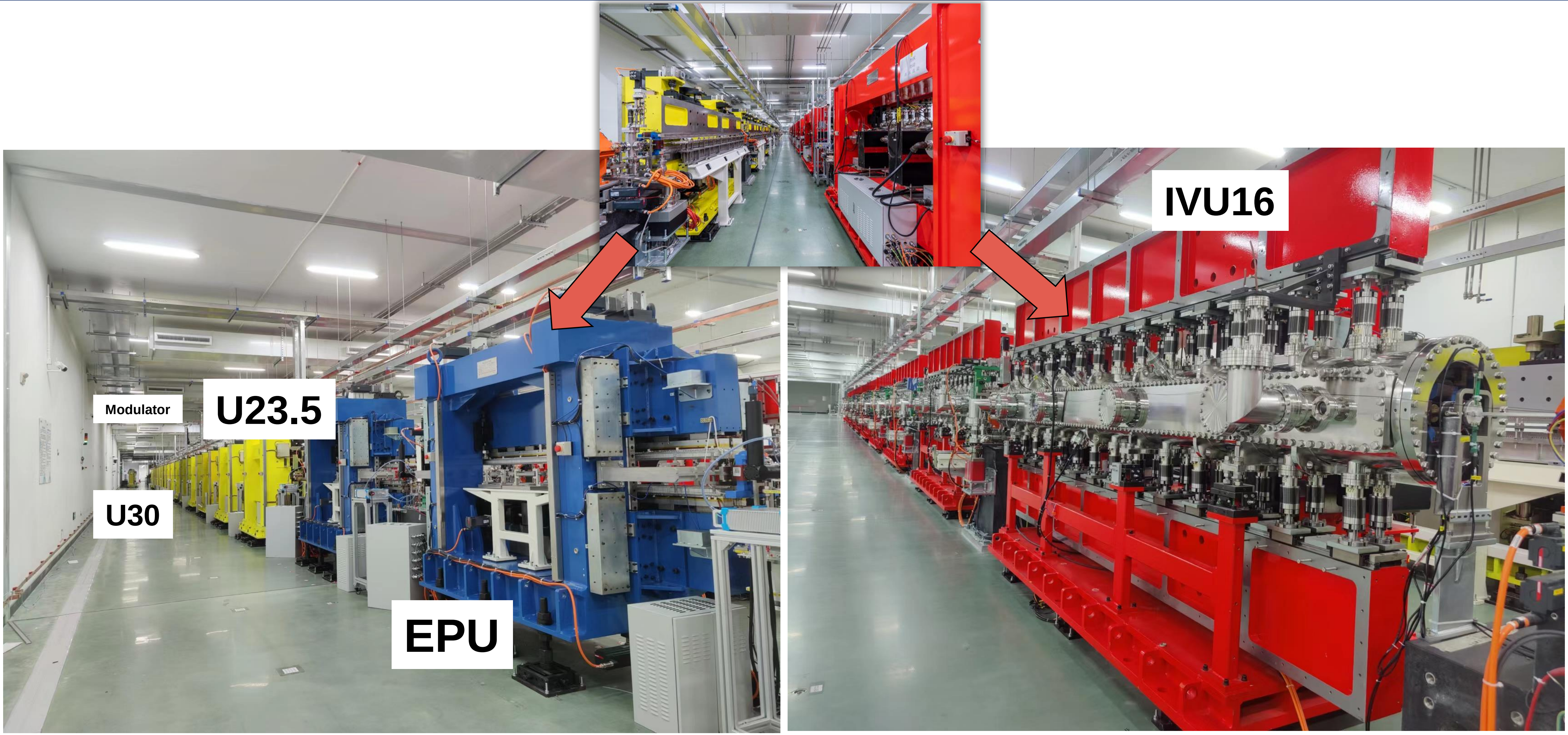
- **FEL2: Seeded FEL line: add 7 undulator units**

SUD

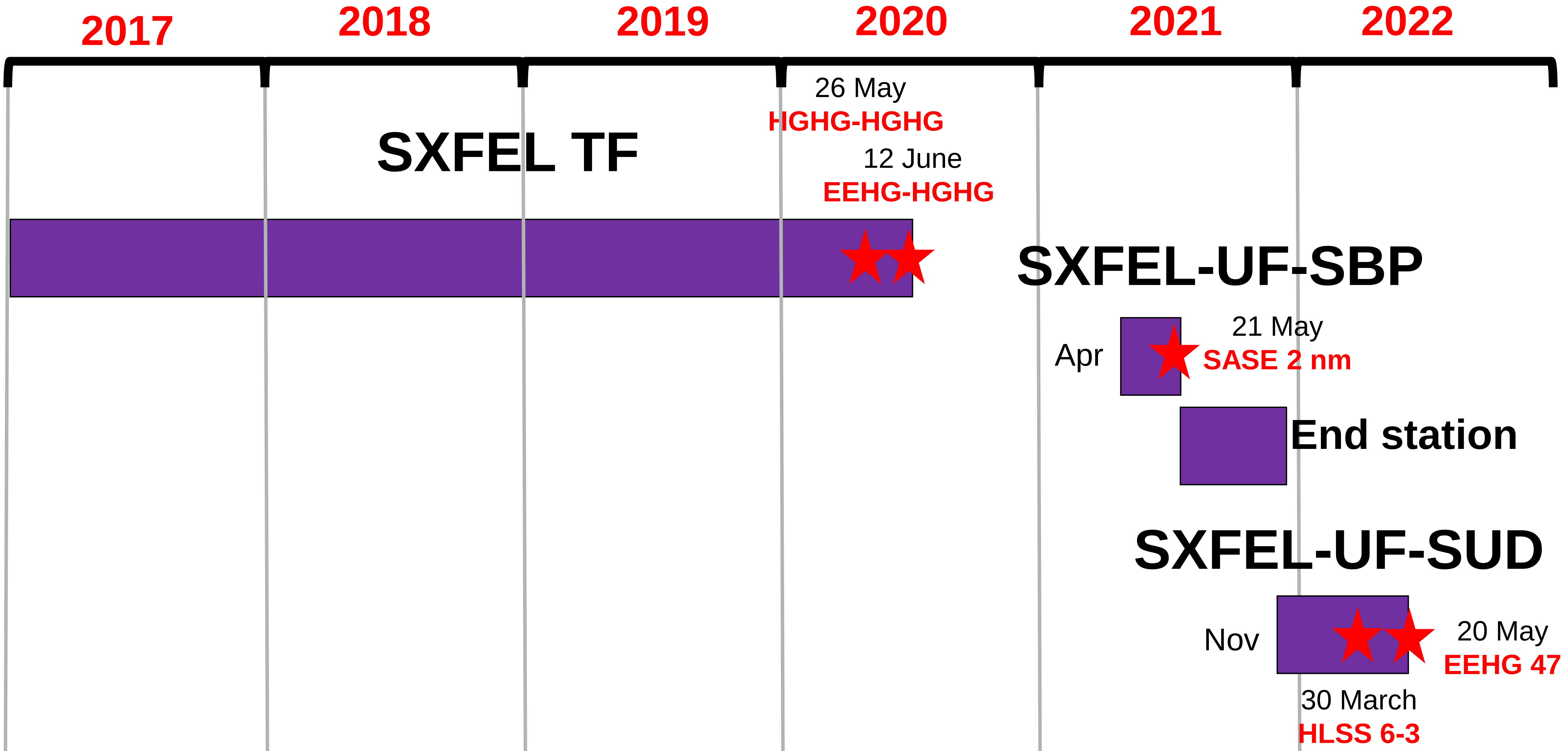


- ☐ The basic operation mode is single stage EEHG
- ☐ Can also operate with many other FEL modes

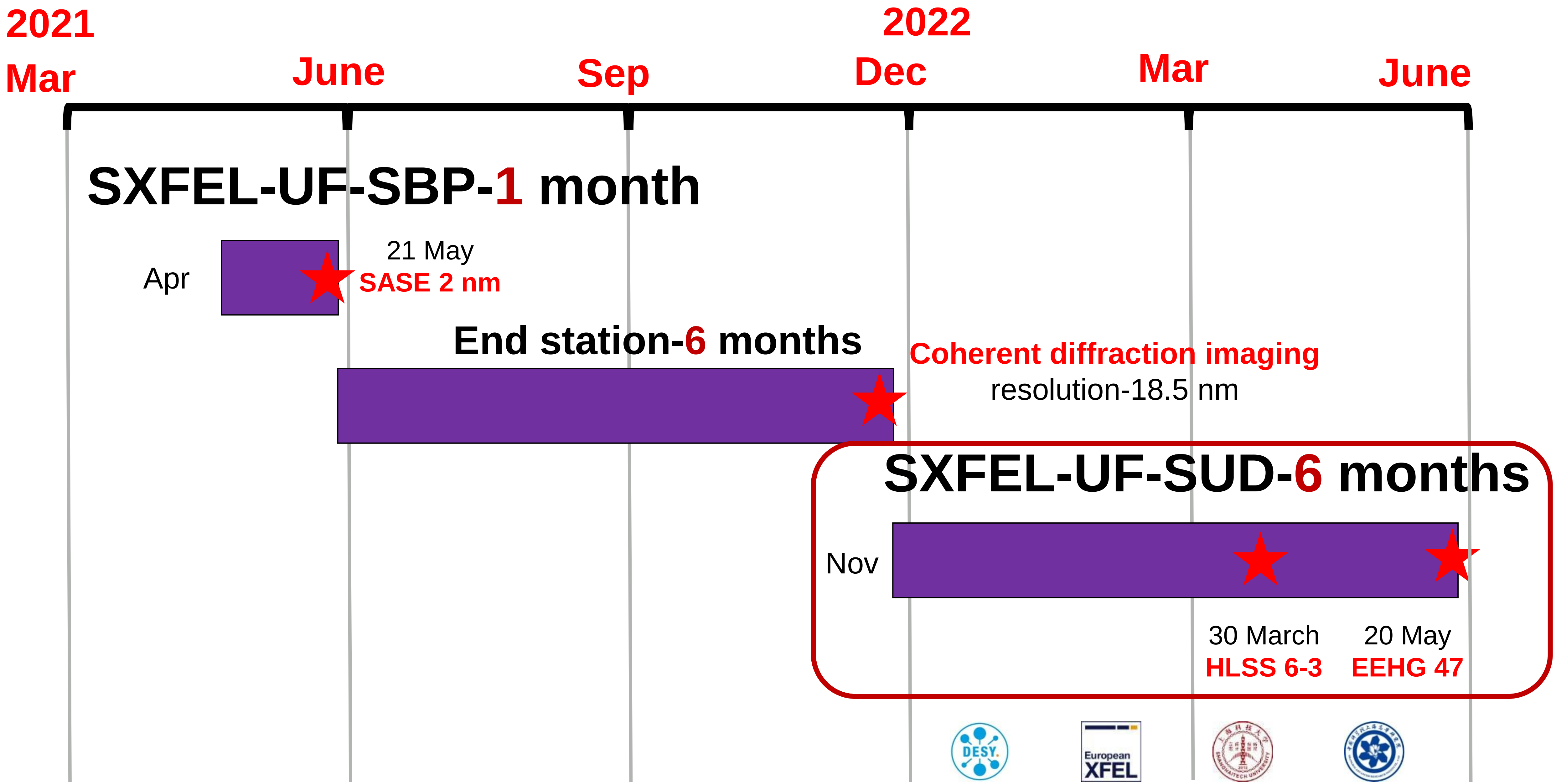
Undulator lines: SBP and Seeding line (SUD)



SXFEL FEL commissioning

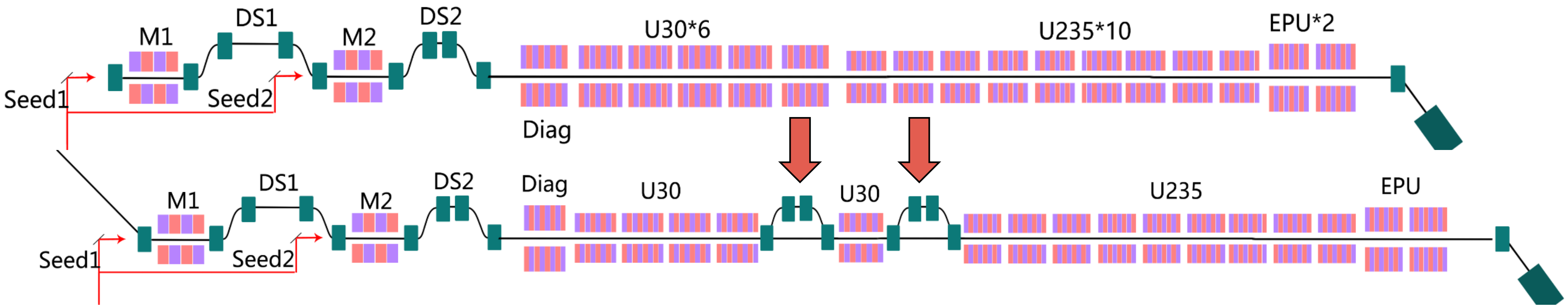


SXFEL-UF FEL commissioning



SUD (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, EEHG-HGHG cascade and EEHG-harmonic cascade
- 2 modulators (U80)+1 diagnostic undulator (U30/50)+17 radiator unds (U30*5+U235*10+EPU*2)
- Movable quadrupoles, high-resolution CBPMs, 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

Seeding line: layout & main parameters

E=1.4-1.5 GeV

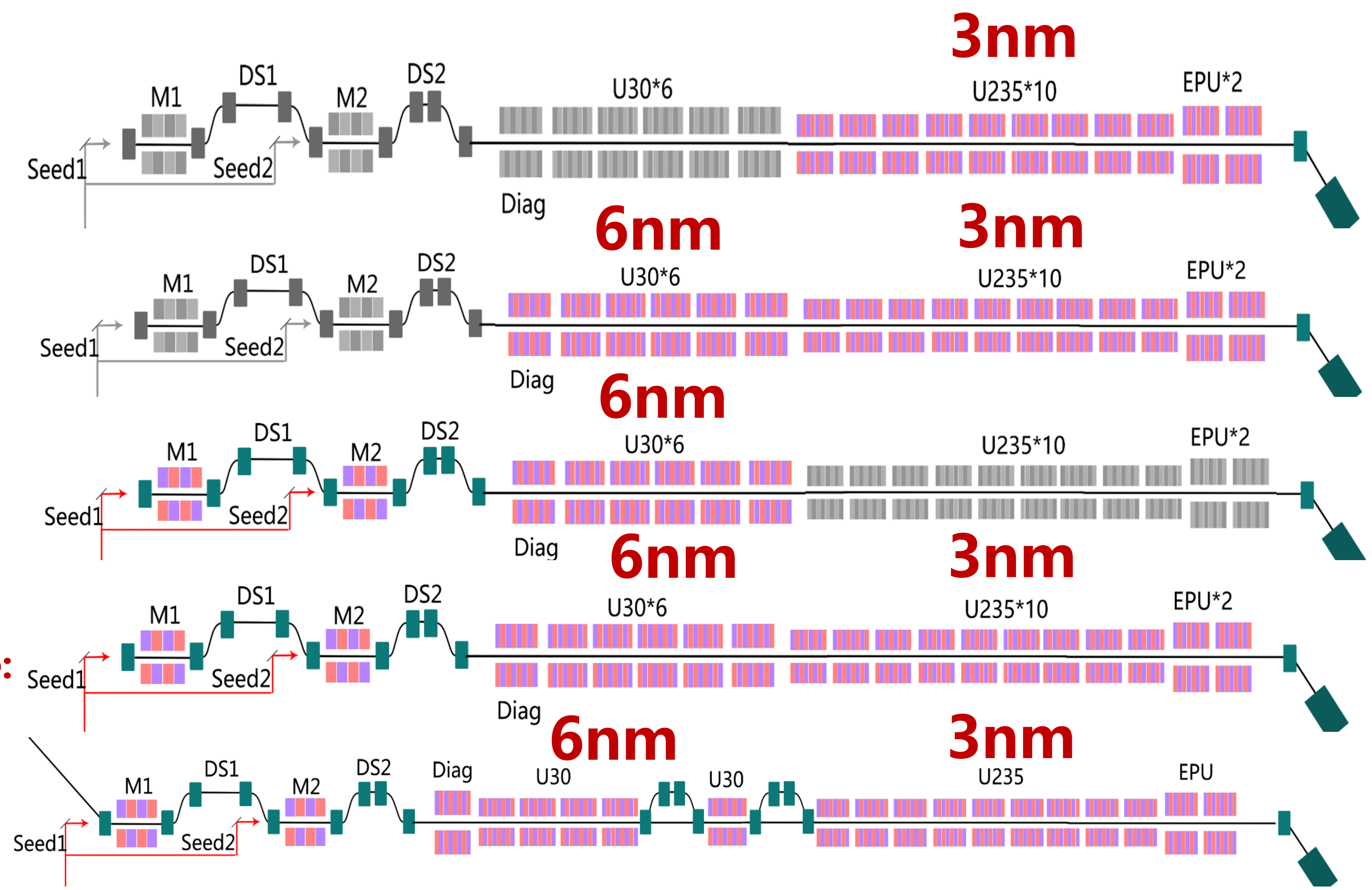
SASE:

HLSS:
6-3nm

EEHG:

EEHG Harmonic cascade:

EEHG HGHG cascade:



SUD (seeding) line FEL commissioning-timeline

2021 Nov
- 16-17日

2021 Dec

Seed Laser is not ready

- 21-22日
- 23日
- 28日

2022 Jan

EEHG signal

- 15日
- 21日
- 27日

Chinese New Year
LH, SL adjustment

2022 March

HLSS and EEHG Amplification

- 2日
- 17日
- 27日

2022 Apr
- 5日

2022 May
- 8日
- 19日

DESY.
European XFEL

SUD (seeding) line FEL commissioning-timeline

2021-11-08， starting to BD commissioning，which means the begin of SUD commissioning.

2021 Nov

- 16-17日 — 7.6-6 nm lasing

HLSS 6-3nm

Installation, LINAC-SL commissioning

2021 Dec

- 21-22日 — 13.5-11.2 nm lasing
- 23日 — HLSS FEL 11.2-5.6nm
- 28日 — 3 nm FEL

2022 Jan

- 15日 — HGHG 5-20 signal
- 21日 — EEHG 30-44 signal
- 27日 — EEHG 45 signal

Chinese New Year LH, SL adjustment

2022 March

E=1GeV

- 2日 — EEHG 32 Amplification

EEHG 32*3

E= 1.4GeV

- 17日 — EEHG 46 Amplification

EEHG 45*2

- 27日 — HLSS 6-3 nm FEL

2022 Apr

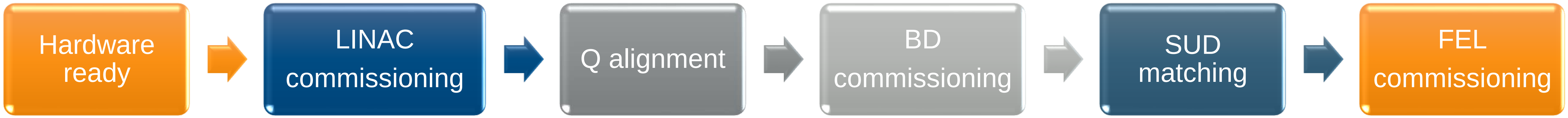
- 5日 — EEHG 61 Signal

EEHG 25*2

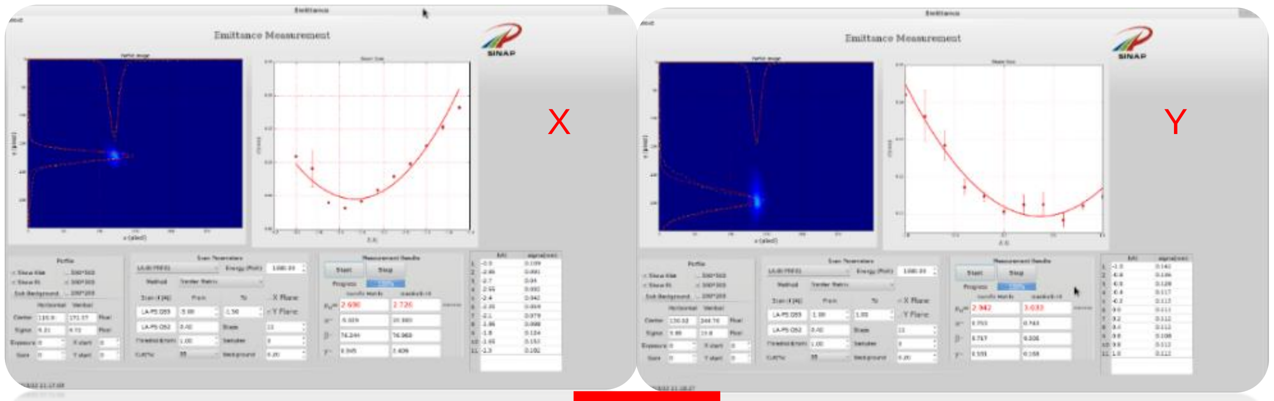
2022 May

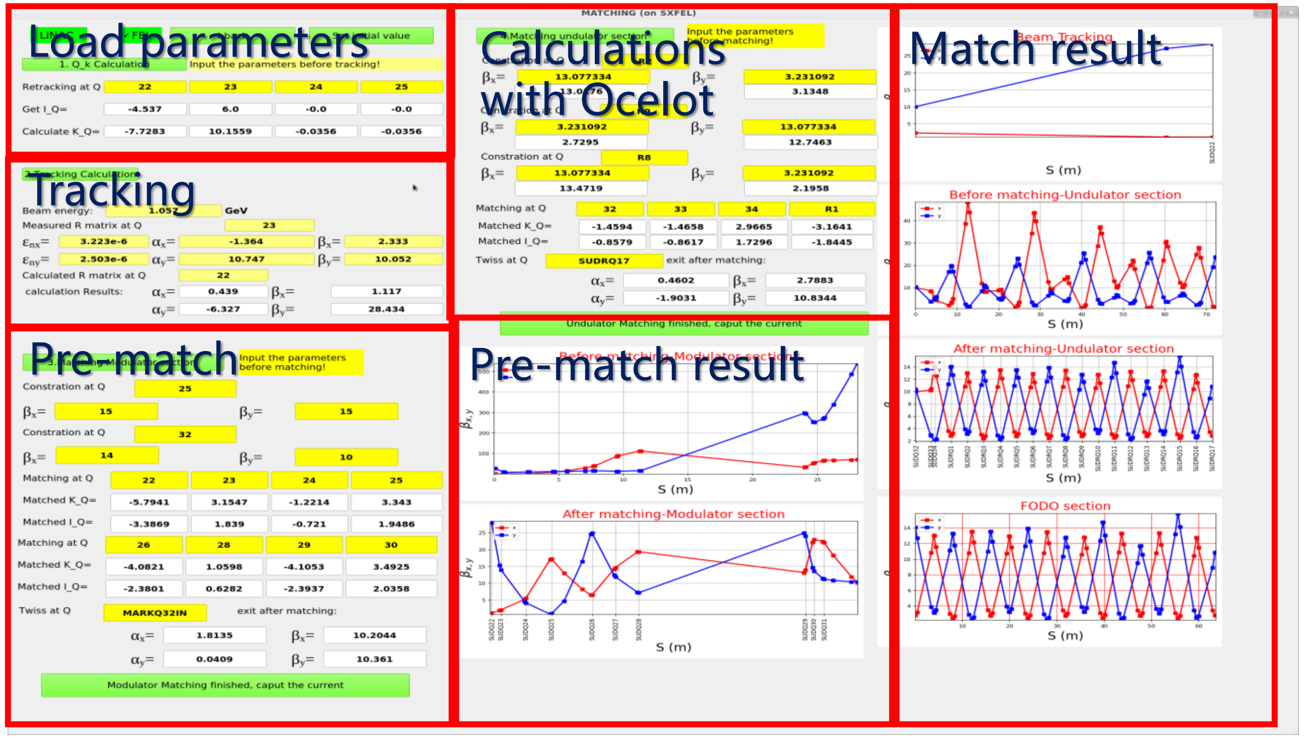
- 8日 — EEHG 50 Amplification
- 19日 — EEHG 47 Amplification

FEL Commissioning procedure



Commissioning of the SUD line: TWISS matching



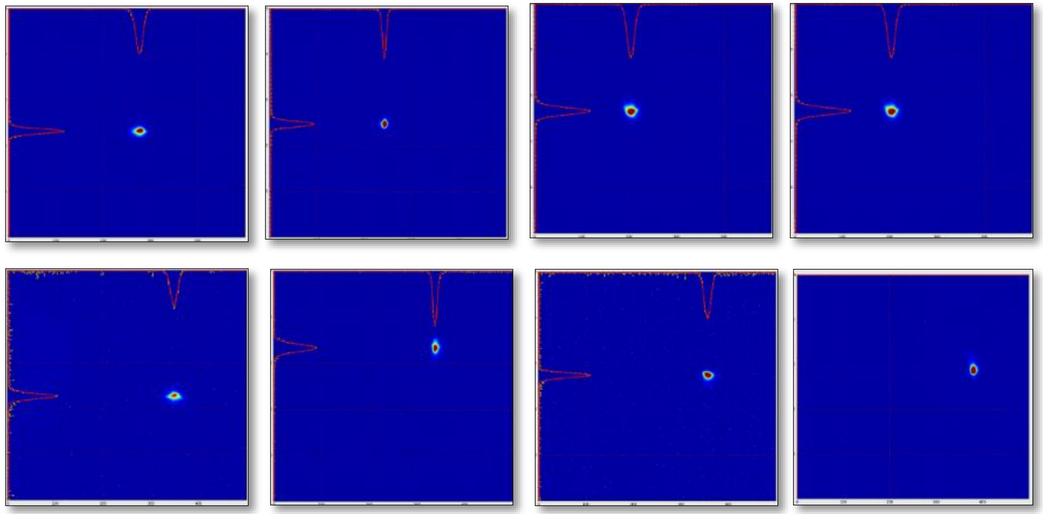


Target: FODO in the undulator with $\bar{\beta}_{x,y} \sim 10\mathrm{m}$

Procedures:

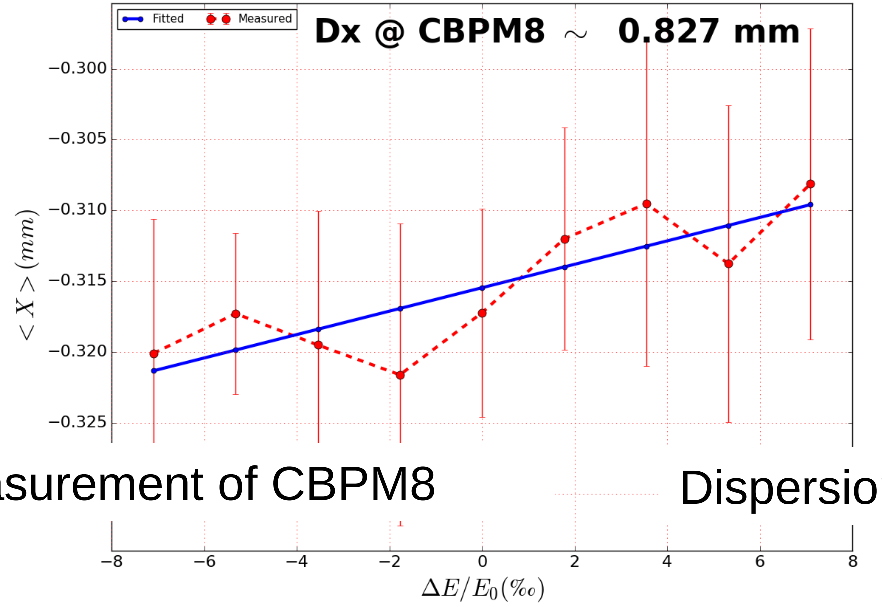
1. Emittance and Twiss parameters measurement after the linac
2. Pre-match in the long drift section of LINAC
3. Emittance and Twiss parameters measurement after BD section
4. Matching for the undulator section

Control the beam size in the whole undulator

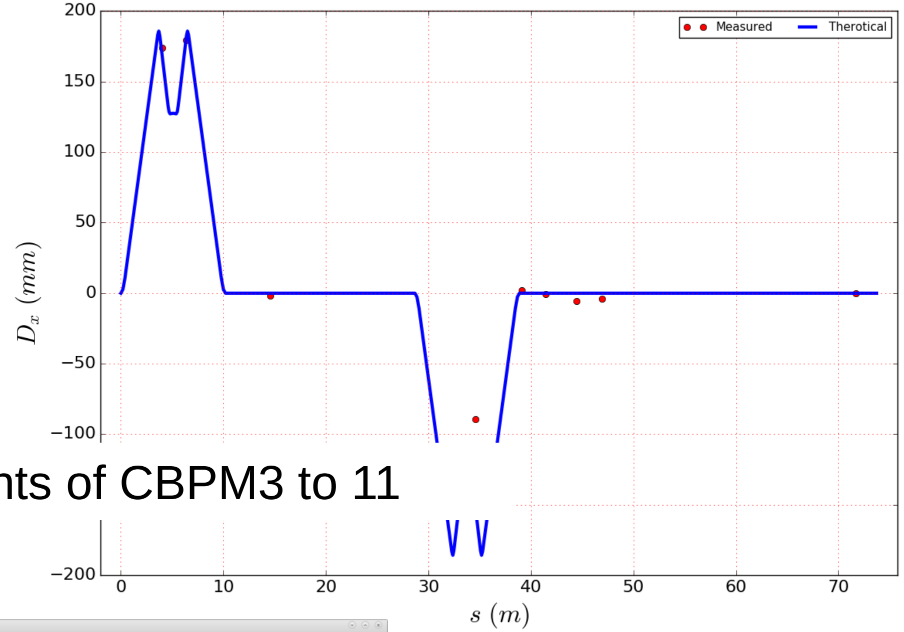


Commissioning of the BD section

Dispersion is little enough and good agree with theory

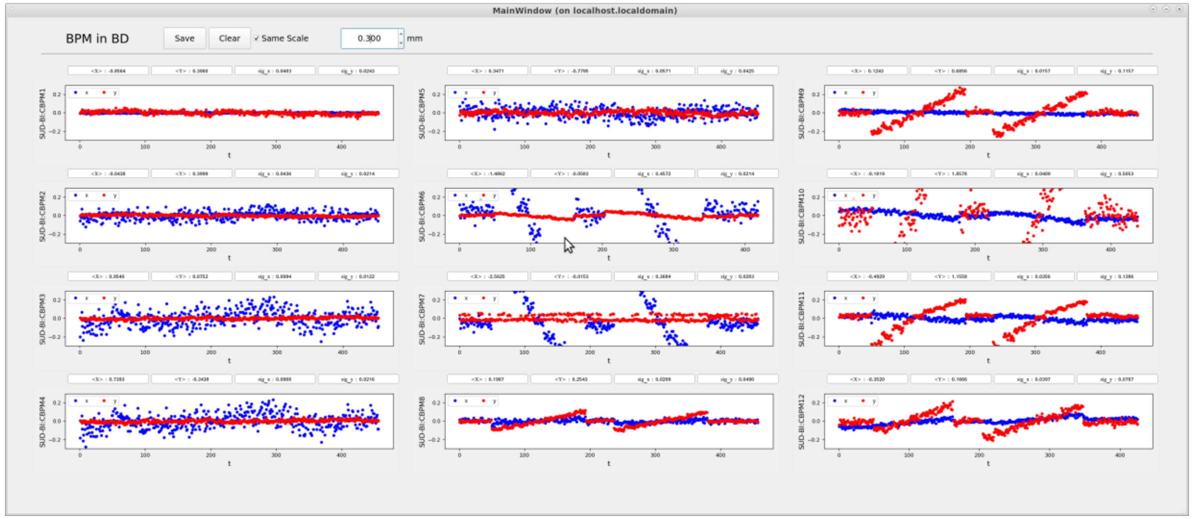


Dispersion measurement of CBPM8



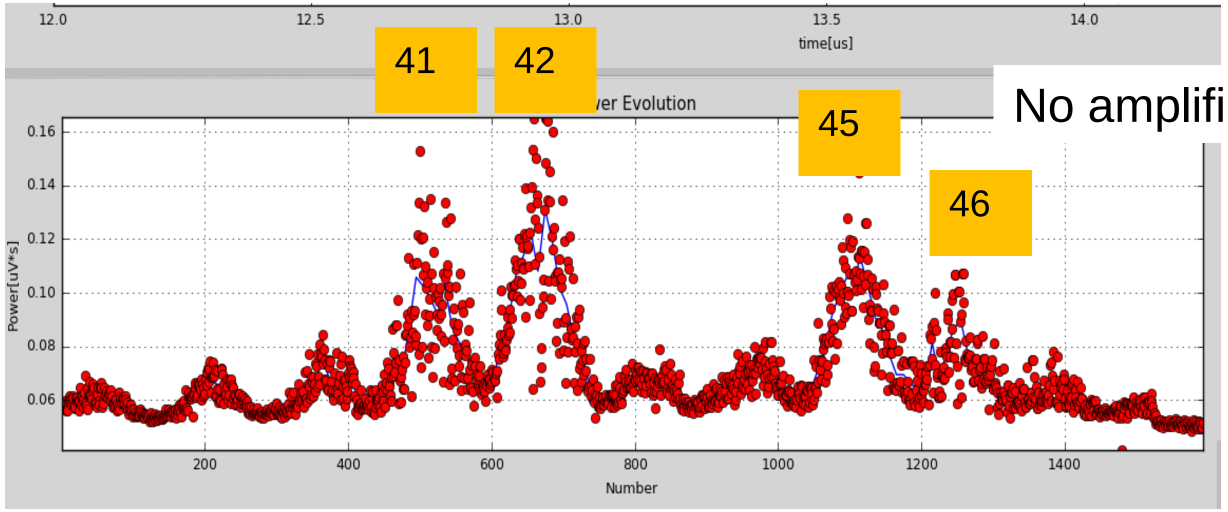
Dispersion measurements of CBPM3 to 11

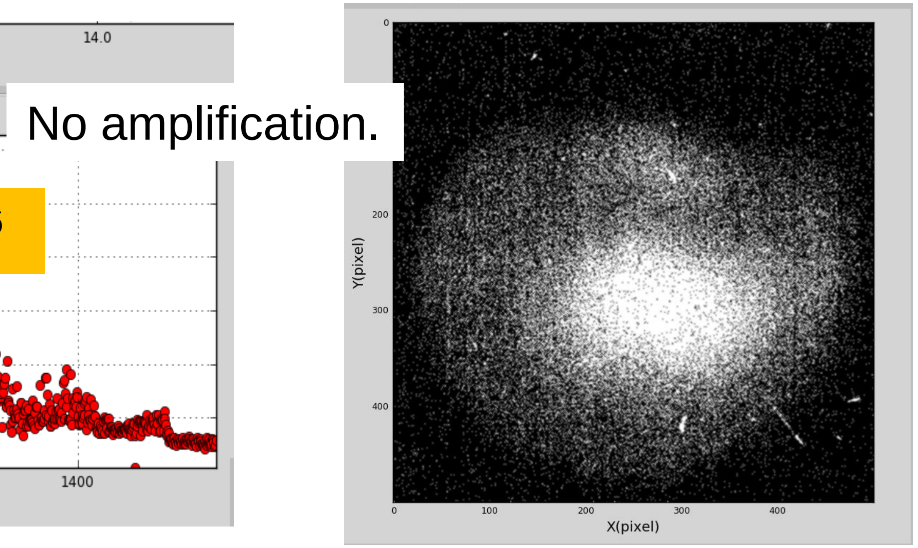
CBPM monitor



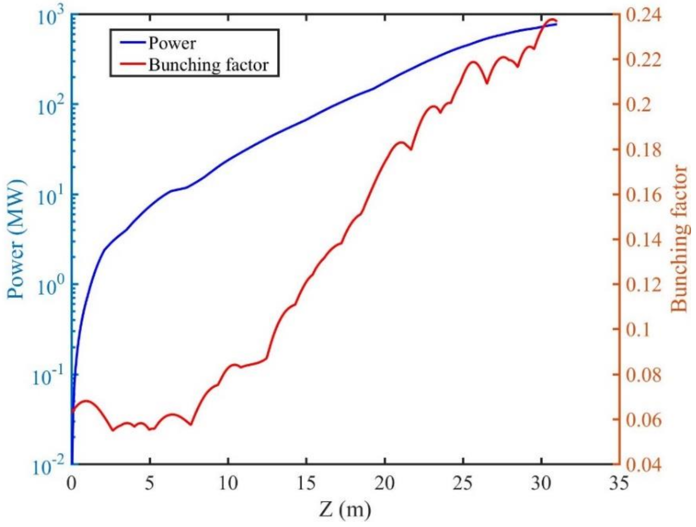
EEHG process presented by Tao

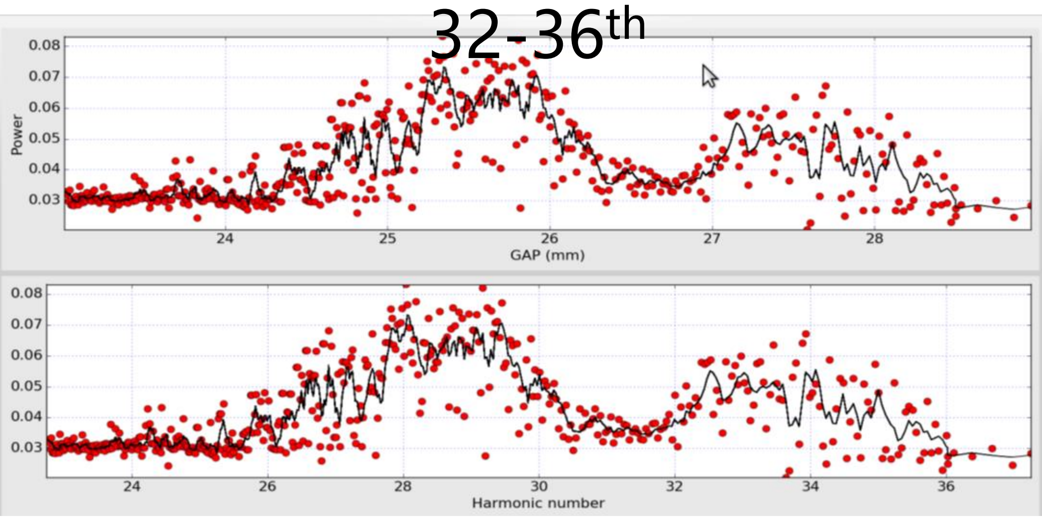
EEHG 46
27 Jan





EEHG30*3
E=1.3GeV
Feb 20

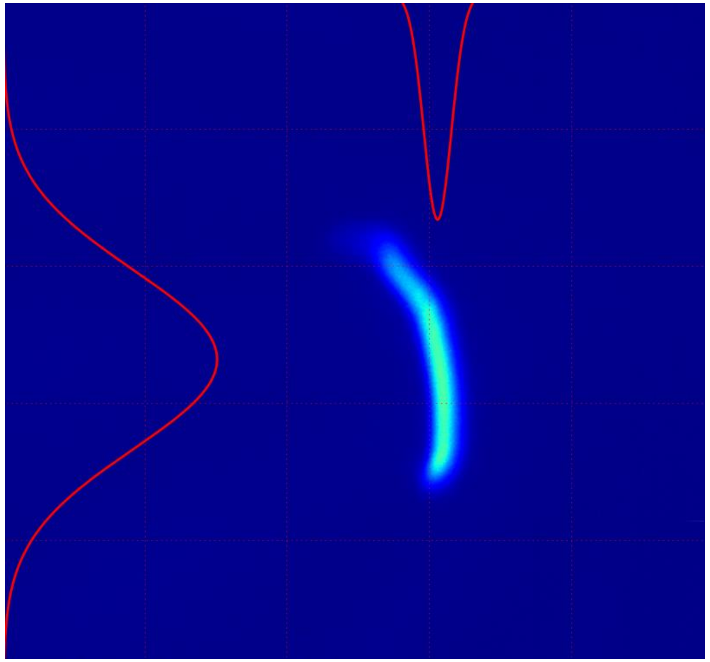




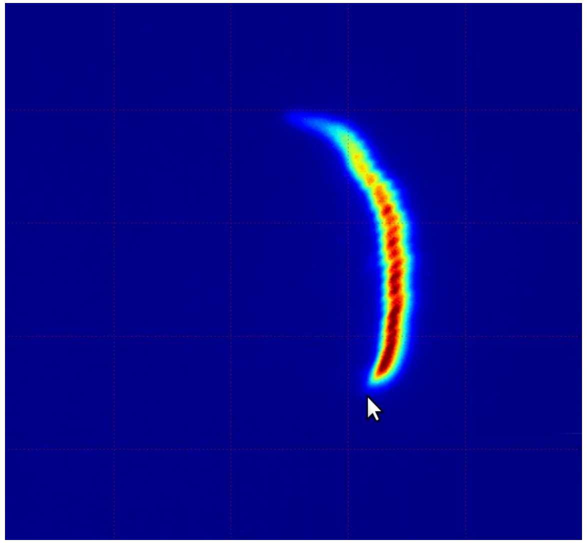
Can not distinguish the harmonic number due to the continuous EEHG signal.

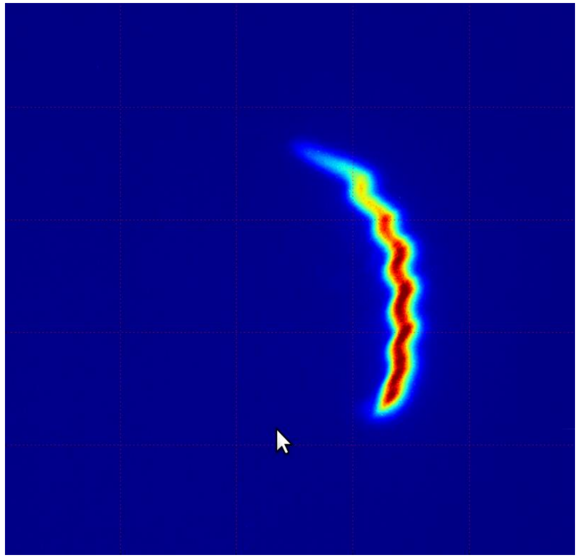
Laser heater commissioning-2.22-2.30

LH off



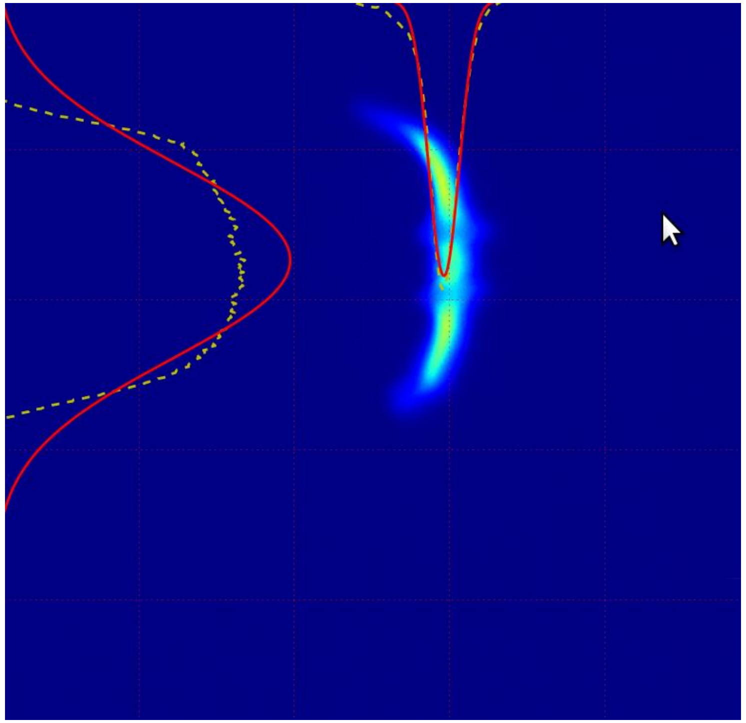
LH on

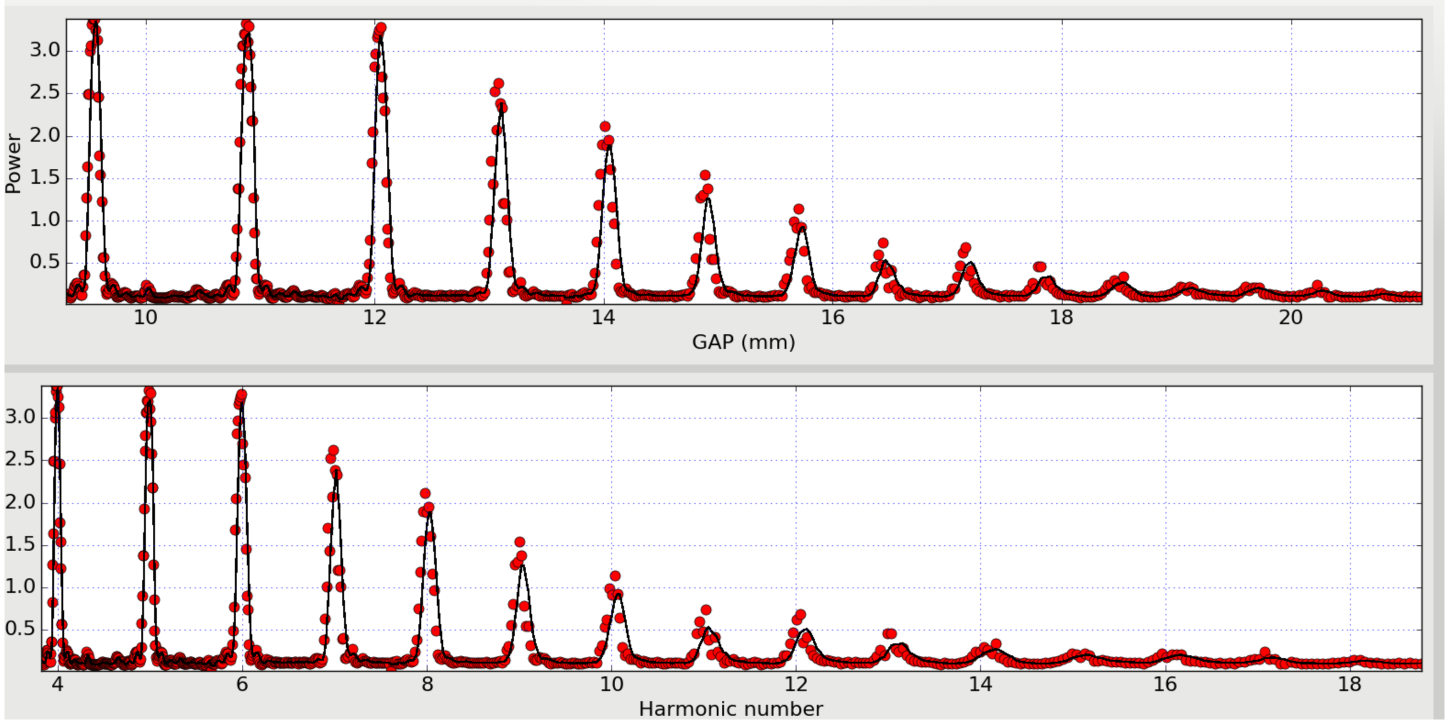




1. Beating frequency exits at phase space of beam
2. Reason: The layers of mirror have height
3. Can smooth the MB structure with a correct Gap

Seed Laser synchronization and HGHG scan-3.1





EEHG commissioning procedures:

-SL synchronization

-SL2 HGHG optimization (better interaction between beam and SL2);

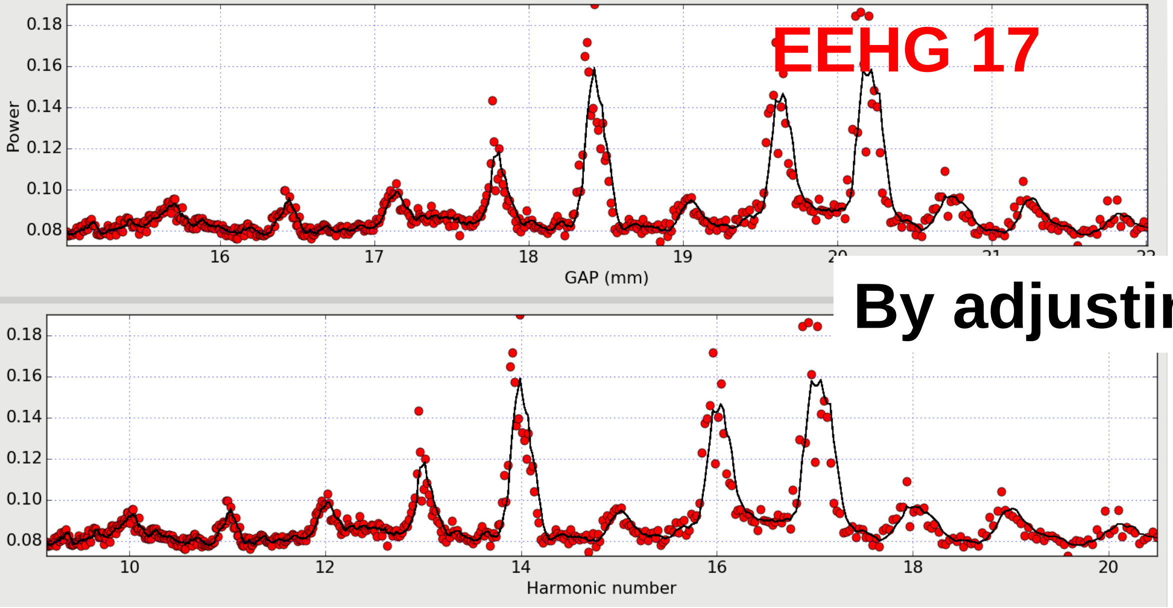
-SL1 optimization (better interaction between beam and SL1);

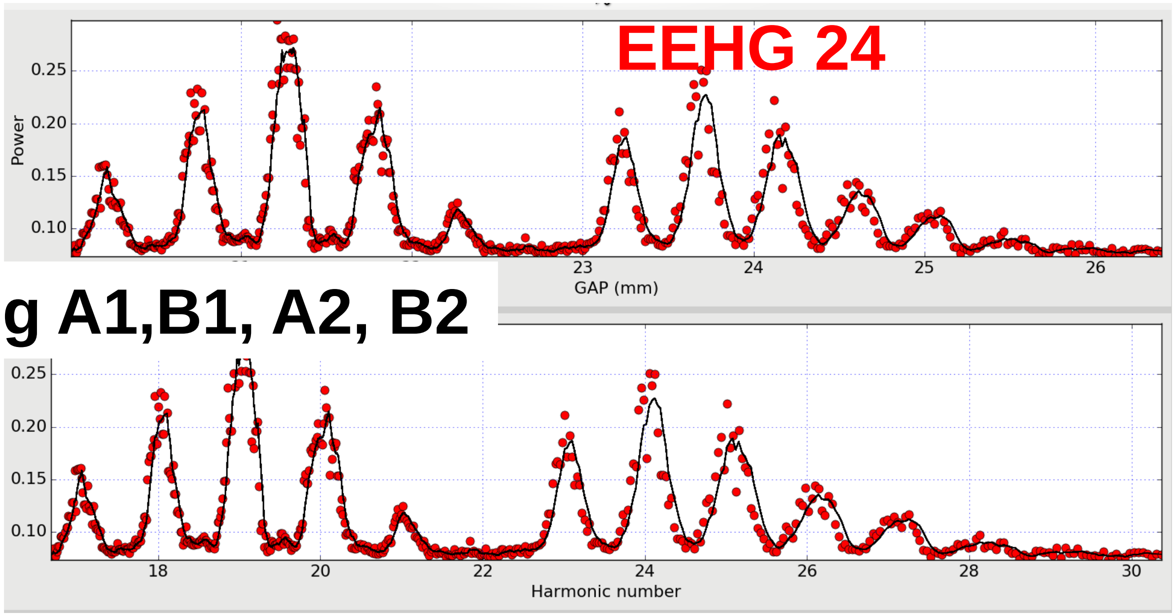
-EEHG scan ;

-EEHG optimization at a certain harmonic;

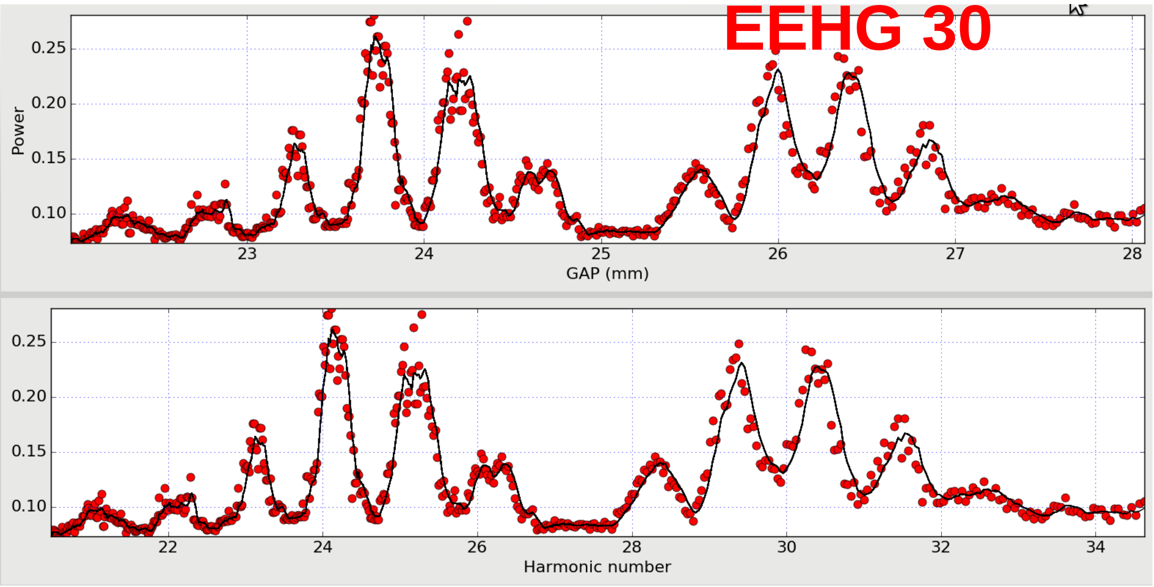
-Increase the harmonic number;

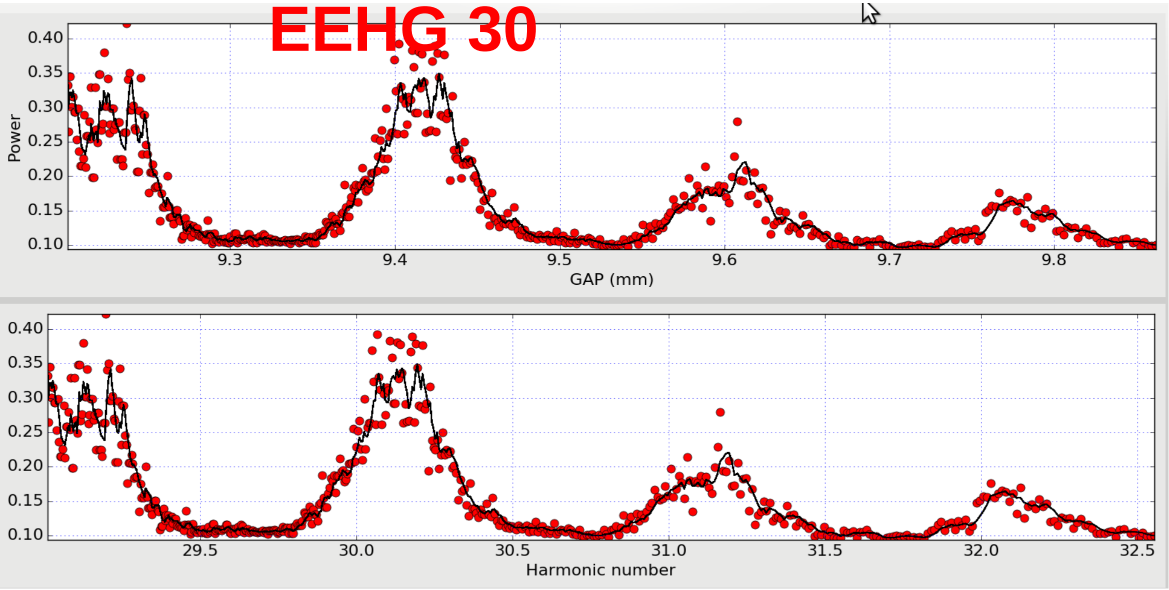
EEHG scan-3.1



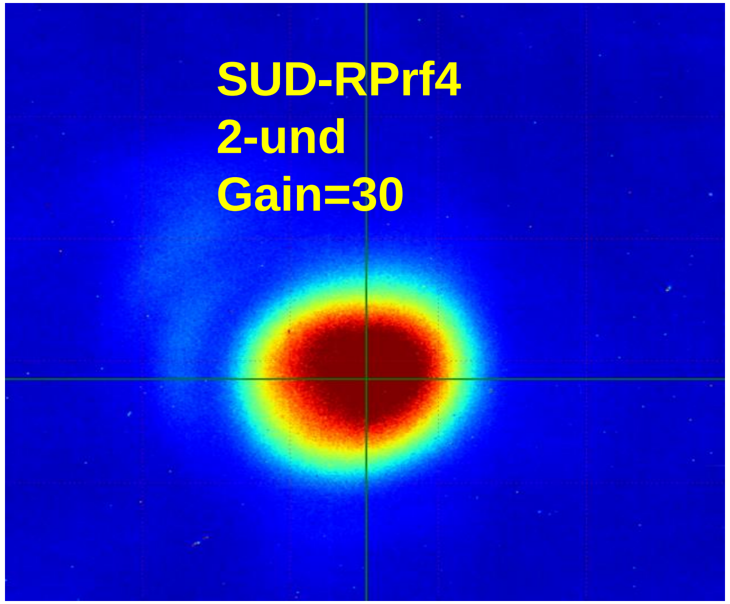


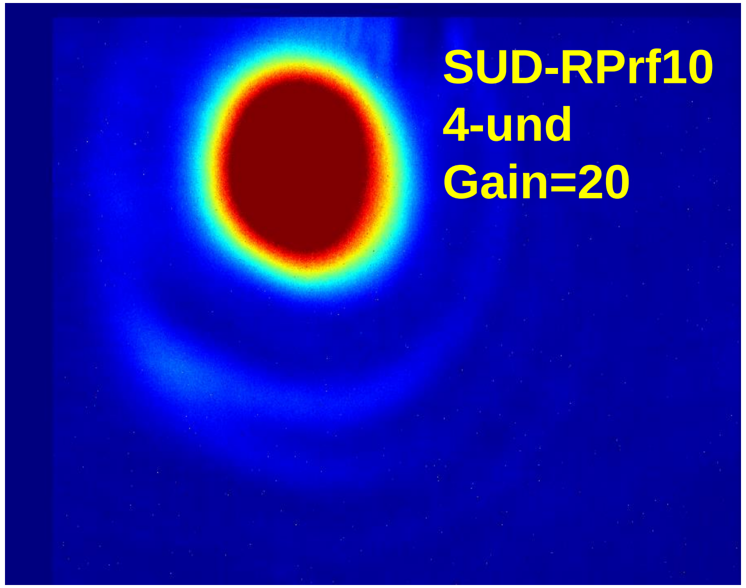
By adjusting A1,B1, A2, B2

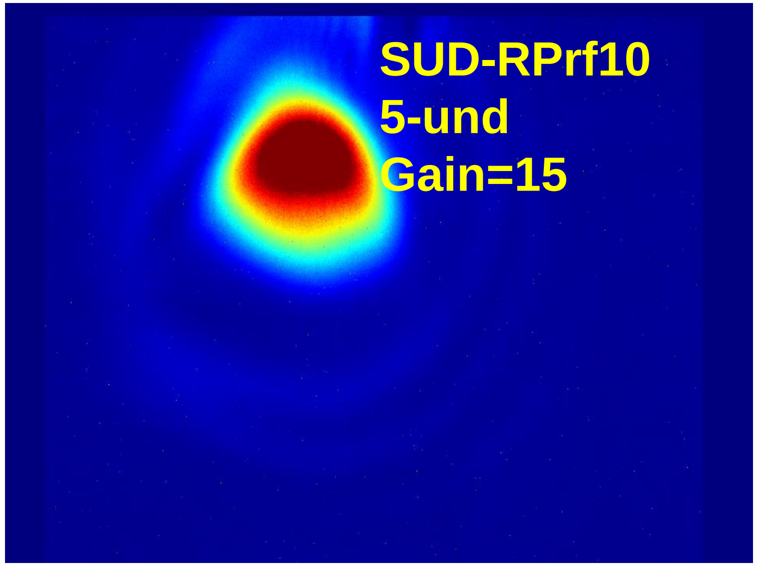


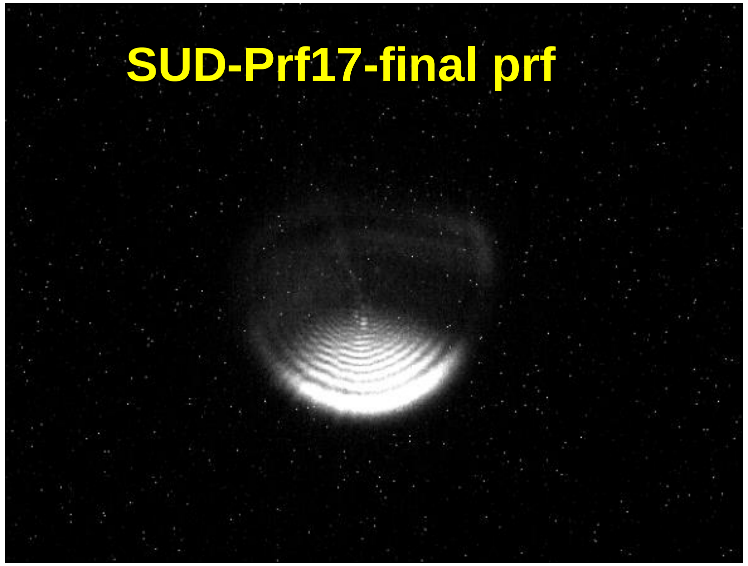


EEHG 32 amplification -3.4

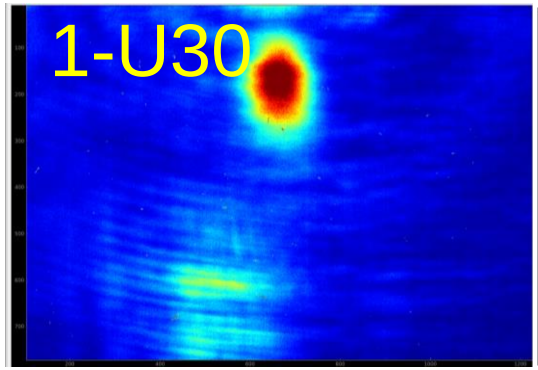


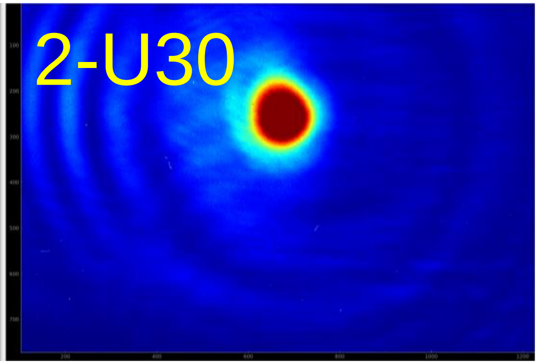


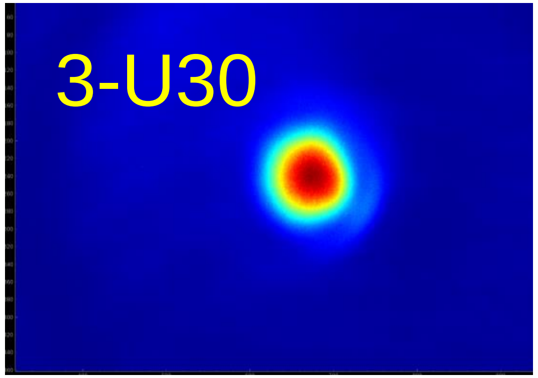


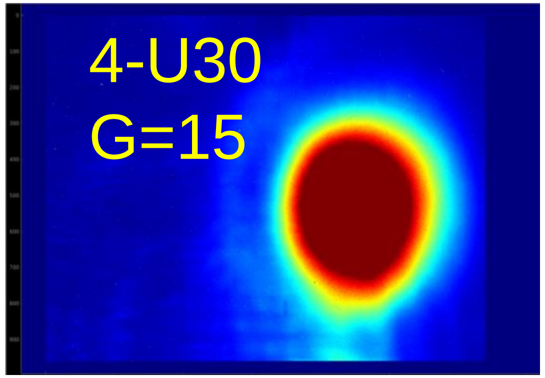


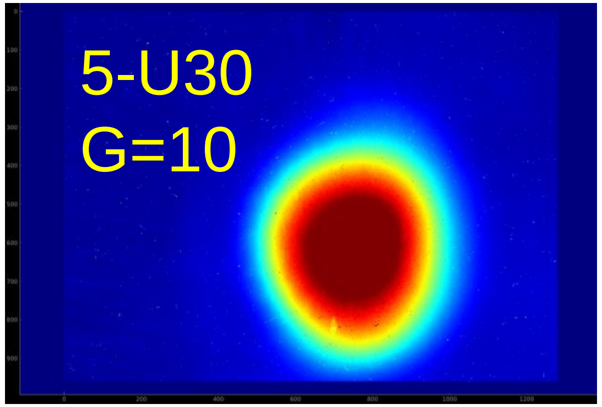
EEHG-32 amplification-3.12、13

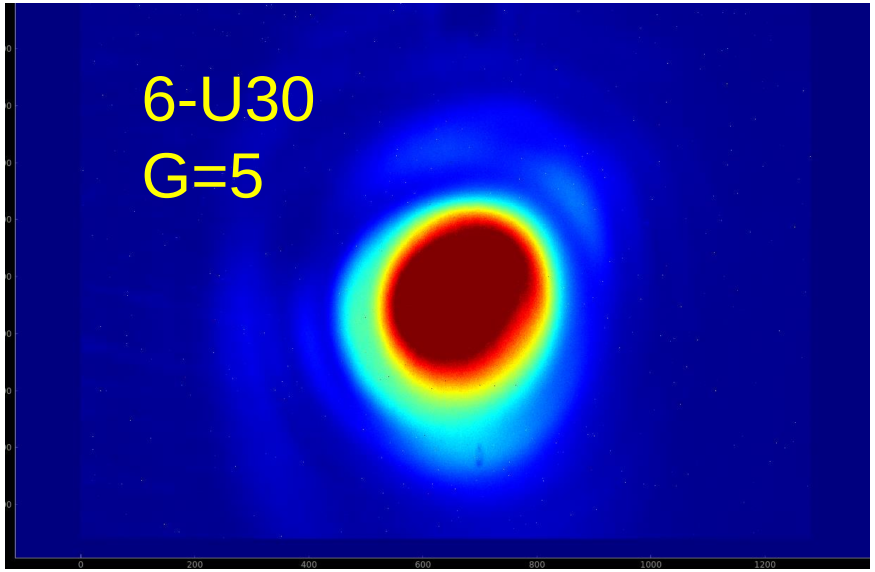


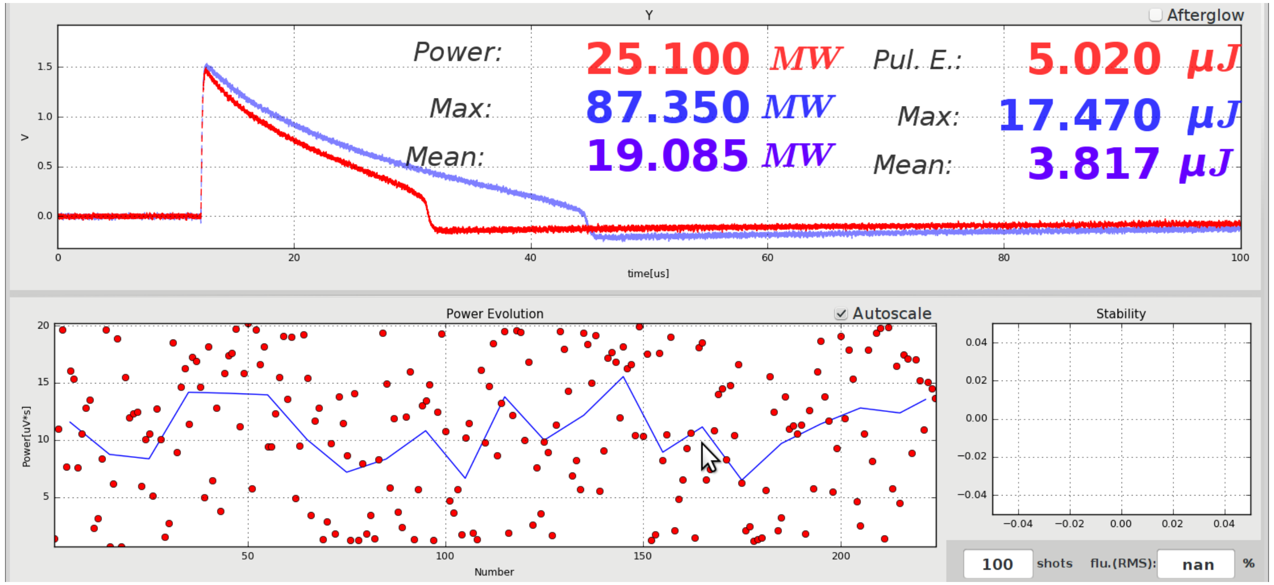




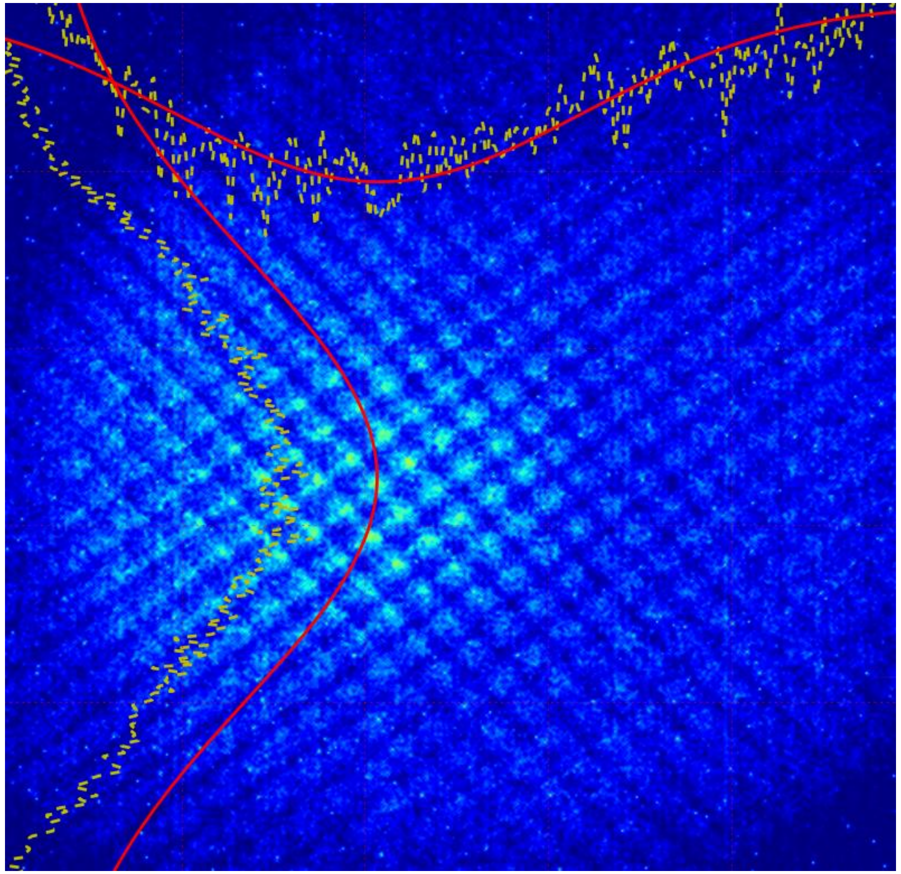


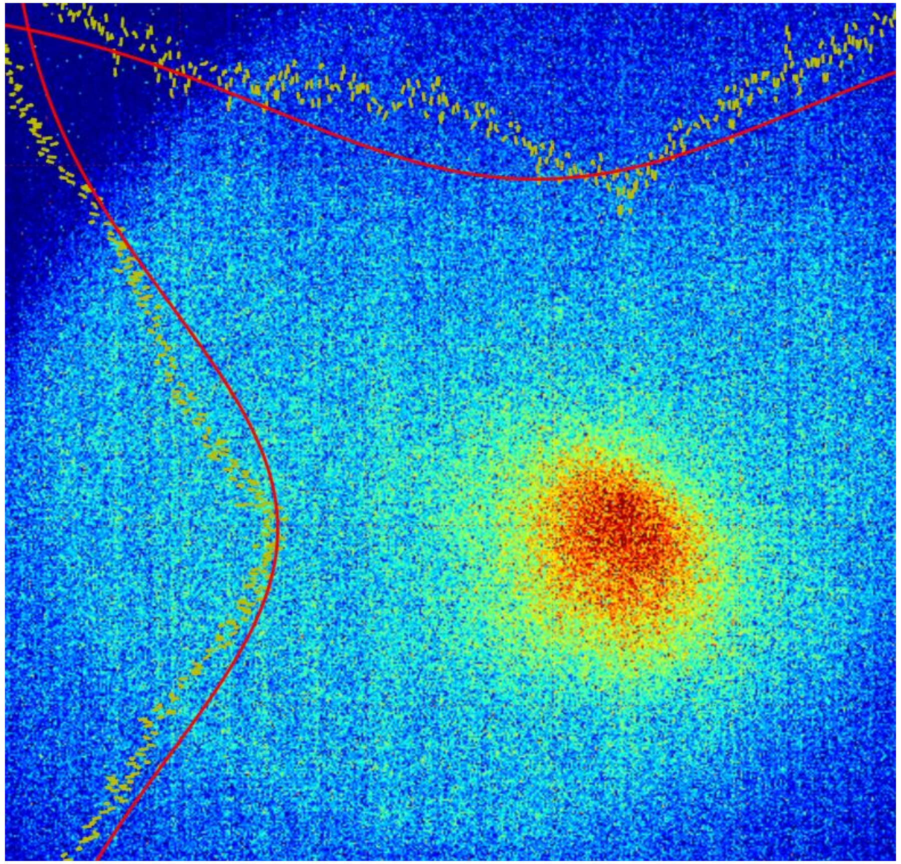






EEHG-32*3 attempt-3.13



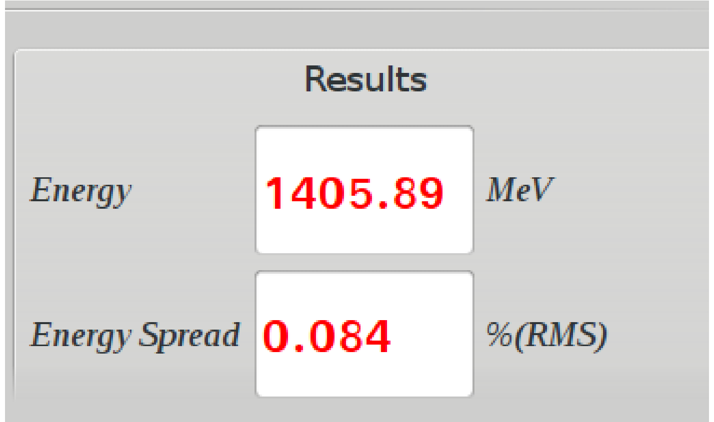


No 3rd harmonic signal of EEHG 32 wavelength

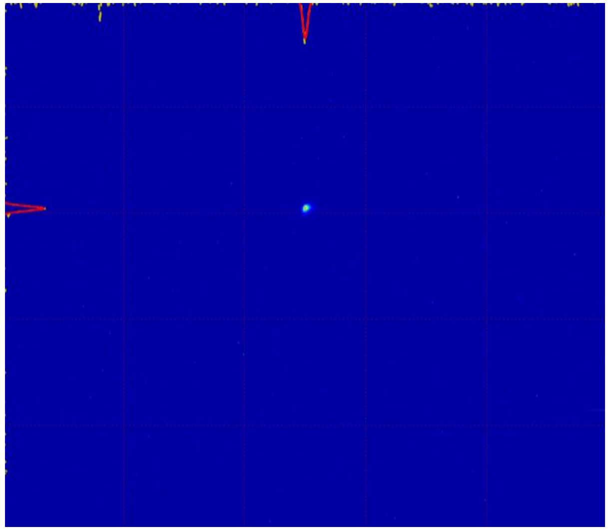
- SASE 2.94 nm
- Add the EEHG 32 signal
- Still have no EEHG 32*3 signal

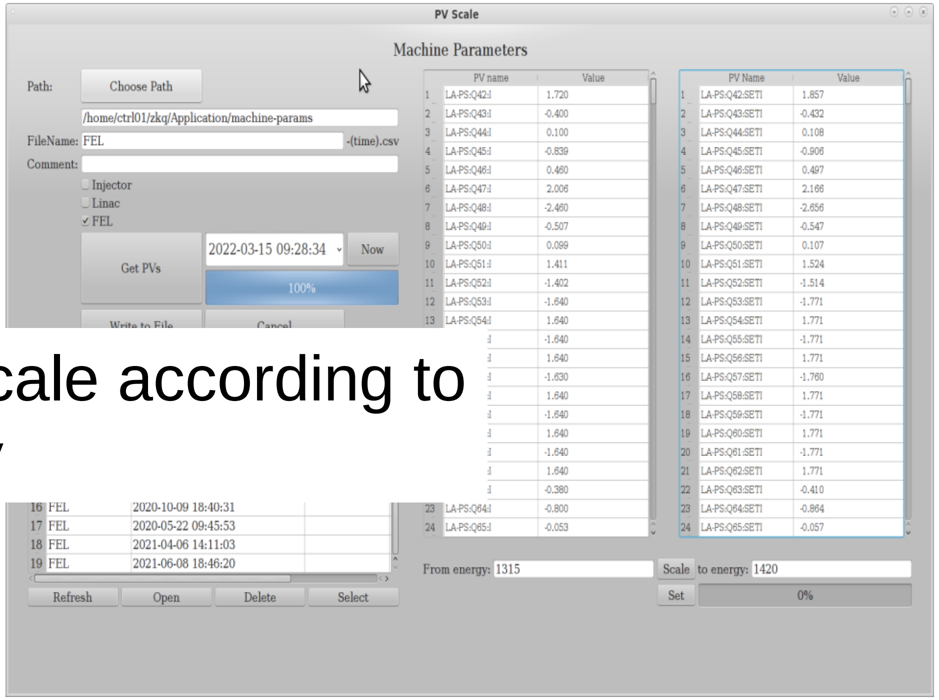
Increase beam energy to 1.4GeV-3.15

E=1.4GeV



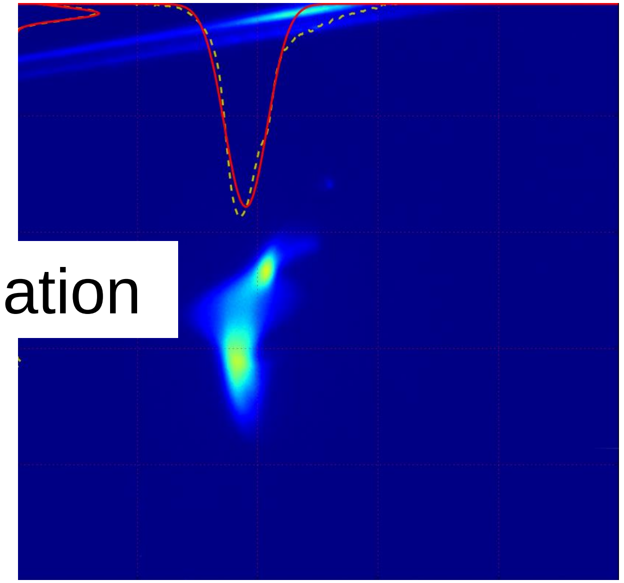
Matching



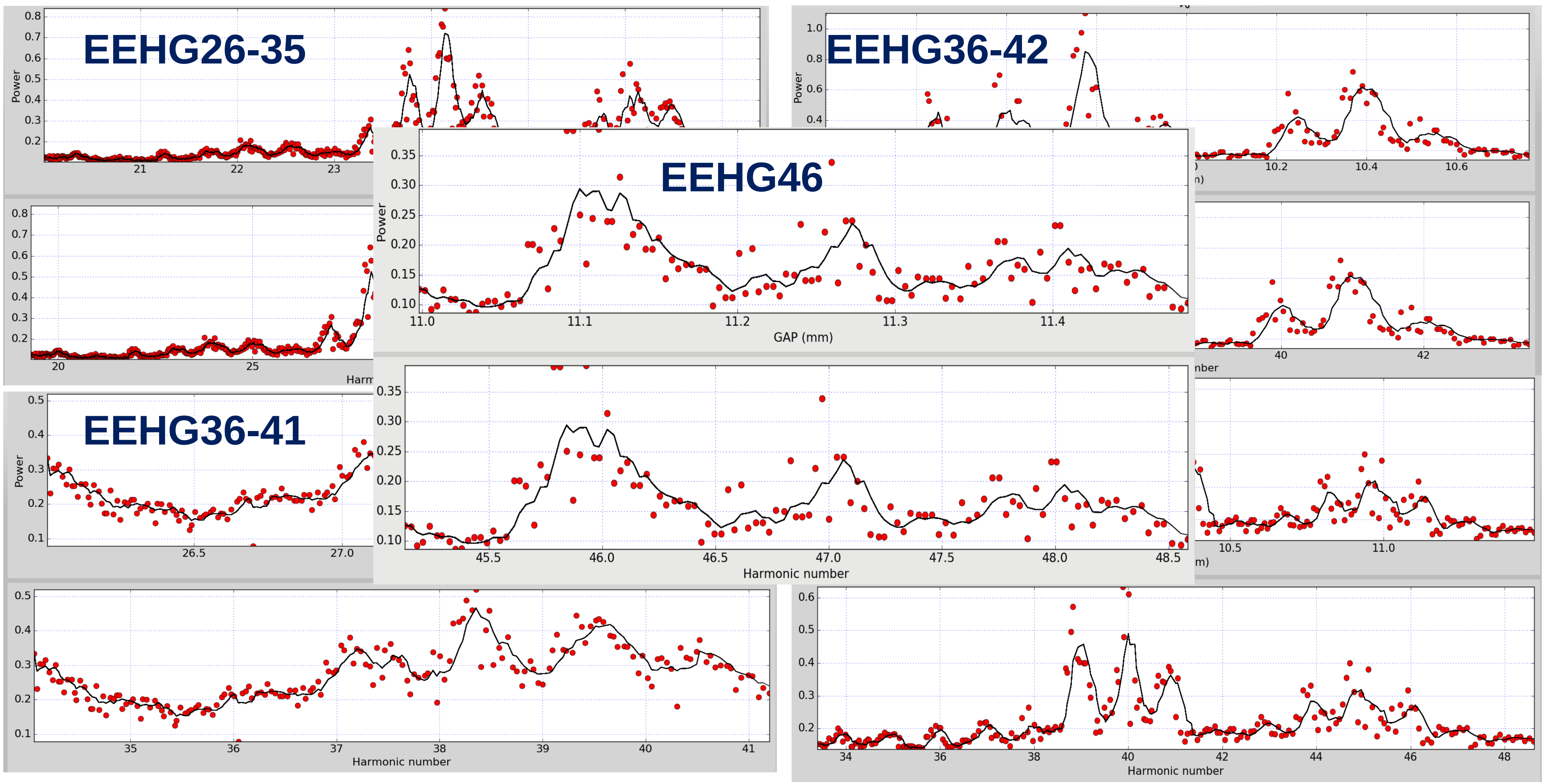


PV current scale according to beam energy

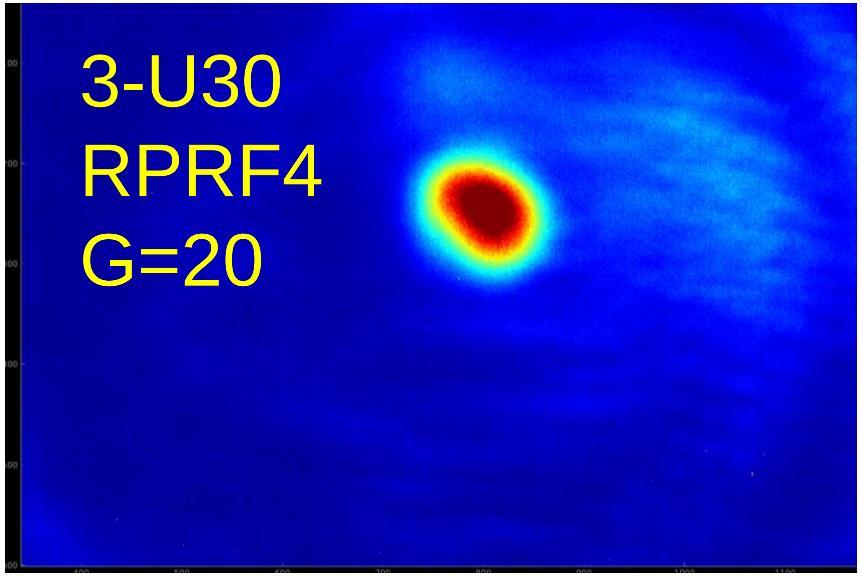
SL synchronization

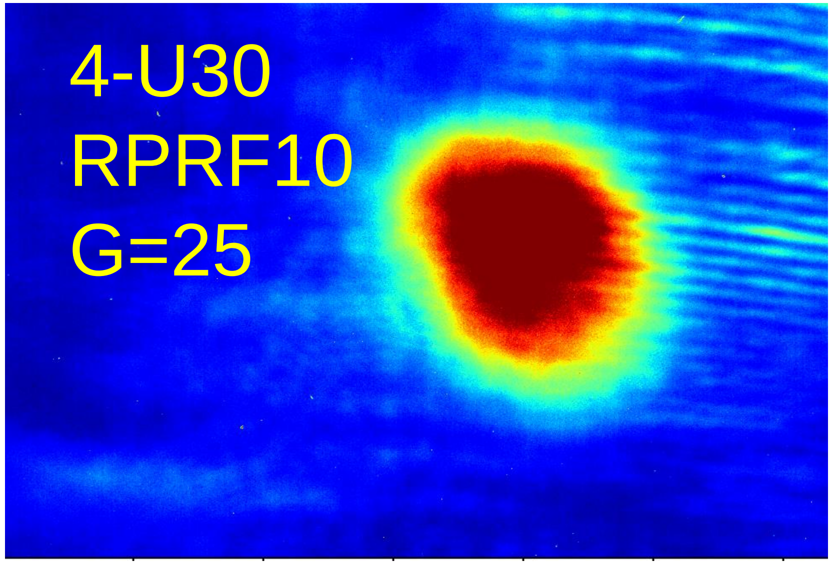


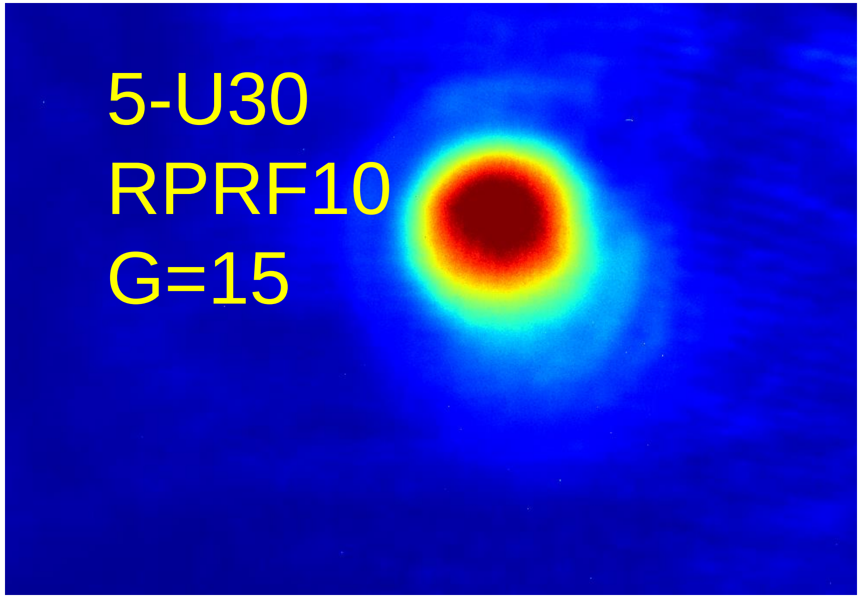
EEHG 26-46 optimization 3.17

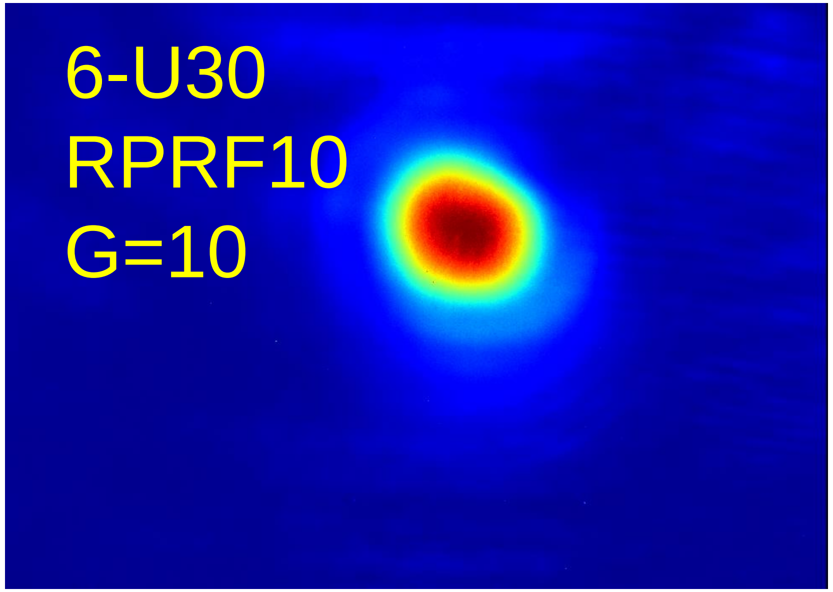


EEHG 46 amplification 3.17-3.18



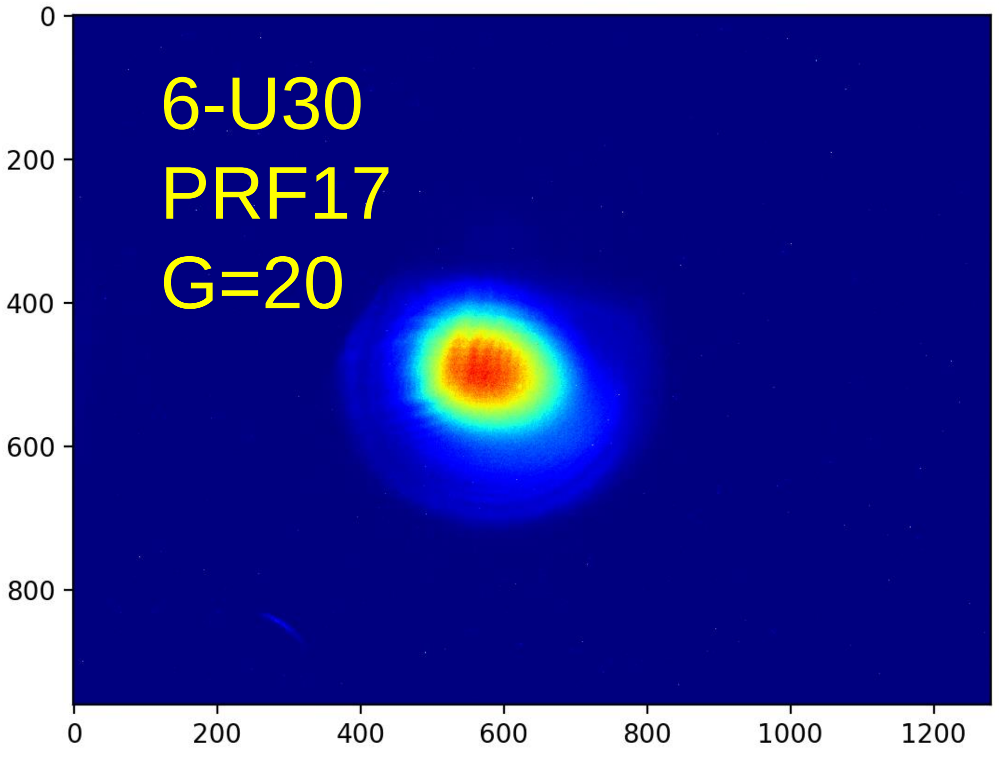


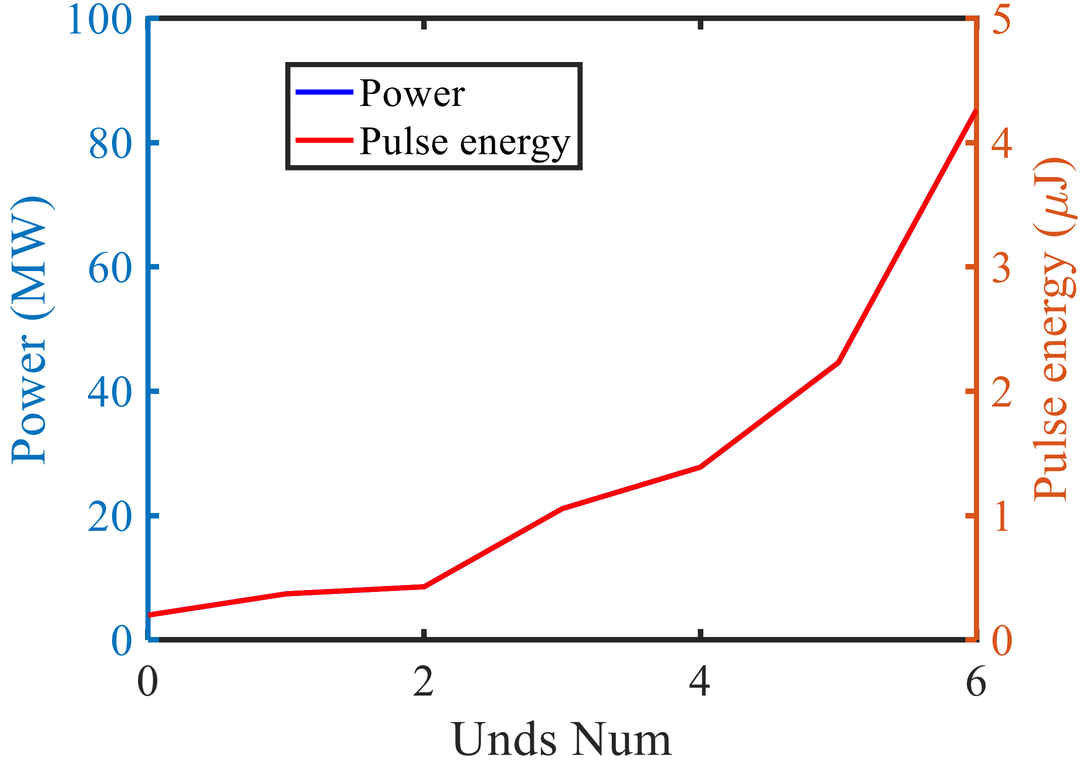




EEHG 46 amplification 3.18

- Harmonic number： h=46
- Wavelength： 5.78 nm
- Coherent X-ray FEL amplification with Shortest wavelength and largest harmonic number based on EEHG mode。

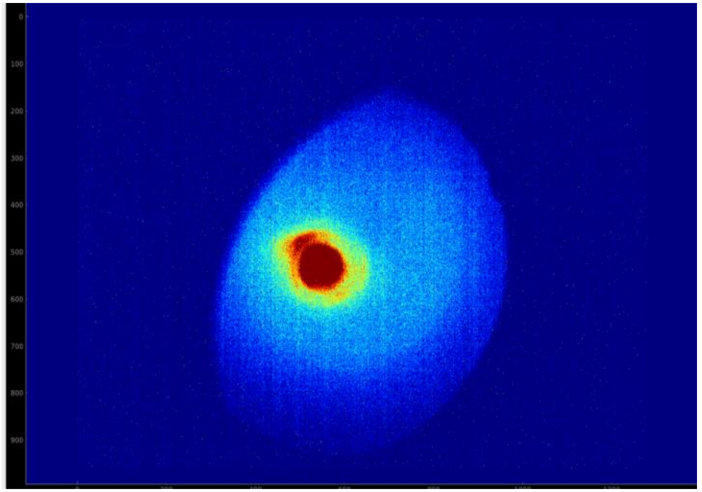


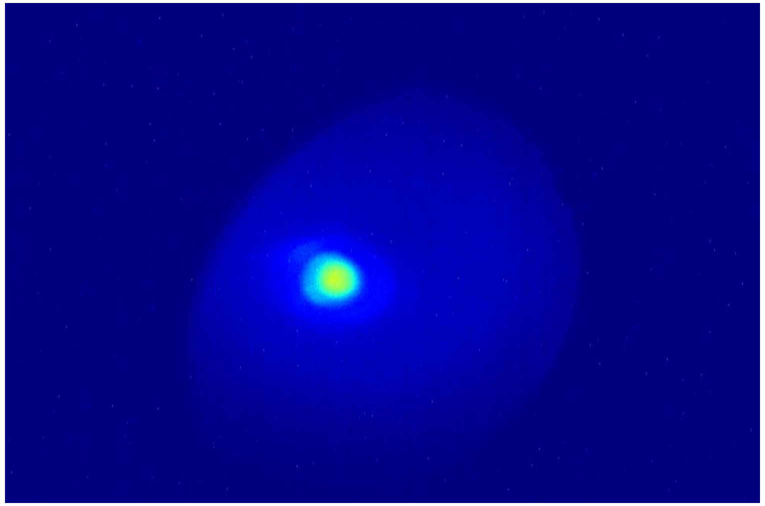


EEHG 46*2 attempt and Beam Line commissioning

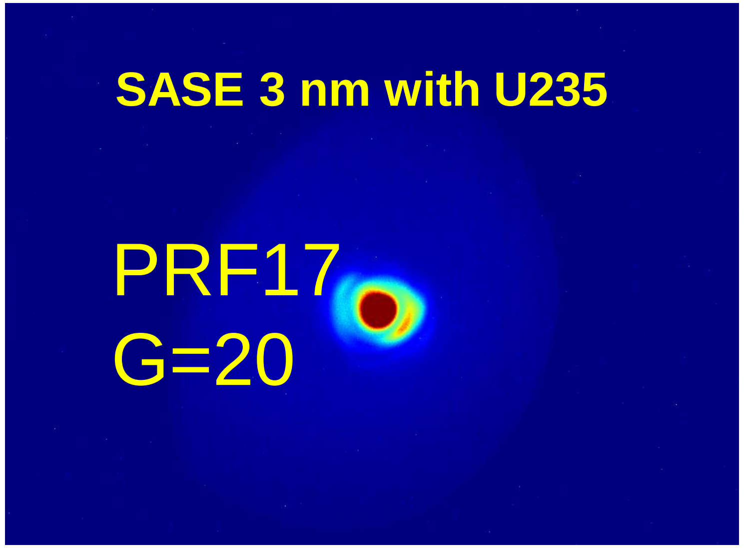
- Using simulated chicane with 4 correctors to block EEHG 46 radiation. No EEHG 46*2 signal, but with CSR signal;
- Do not use chicane， add Zr filter to find EEHG 46*2 signal –No result， but with EEHG 46 signal， low SNR;
- SASE 3nm commissioning， add EEHG signal-no result.

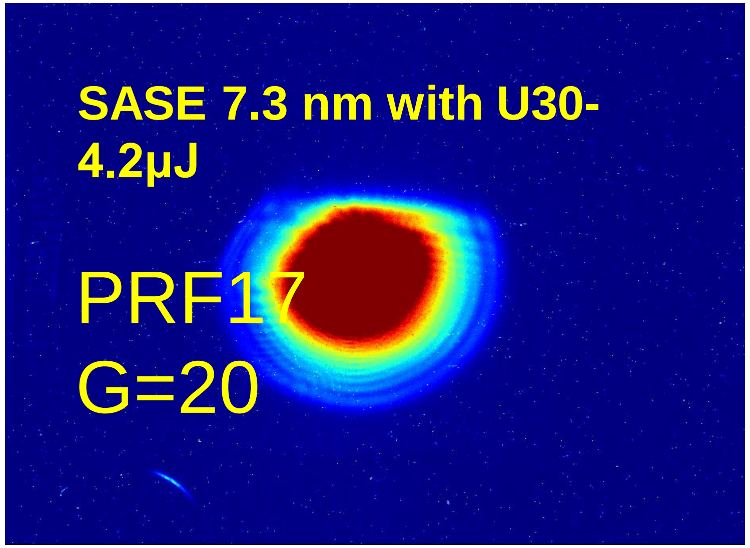
Transmit EEHG 46 radiation to beam Line

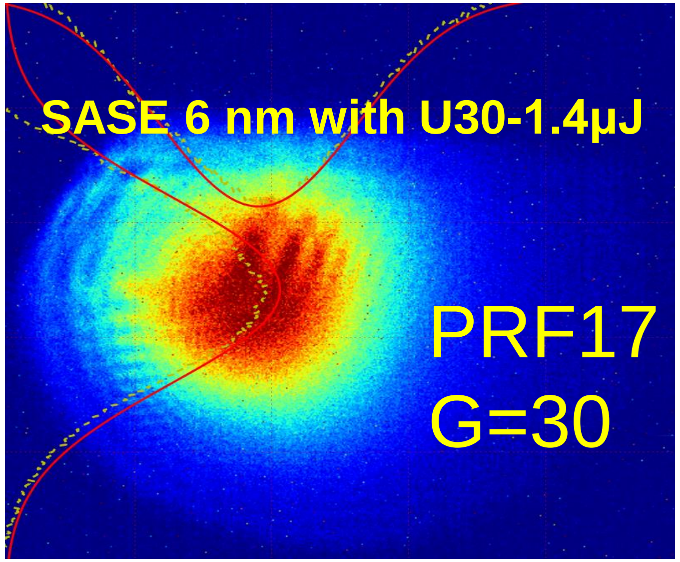




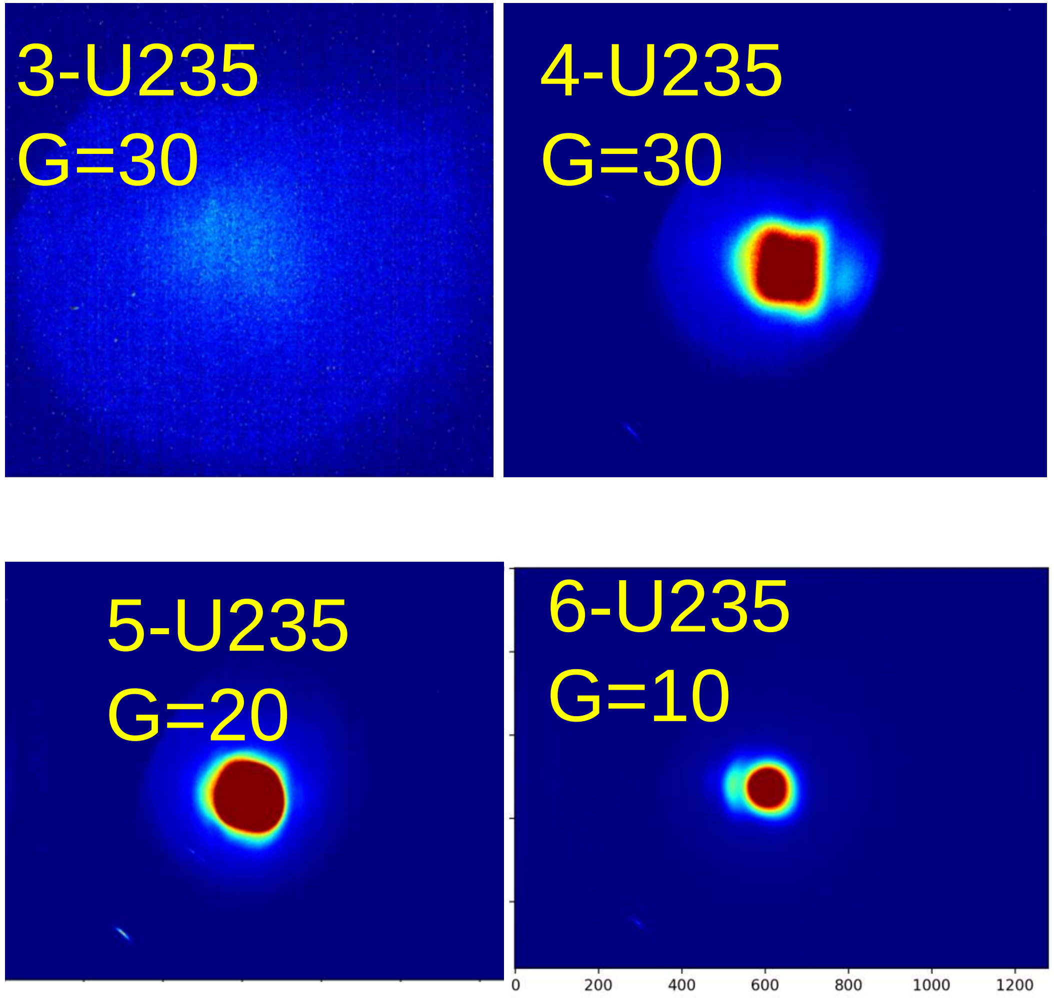
SASE commissioning 3.21-24



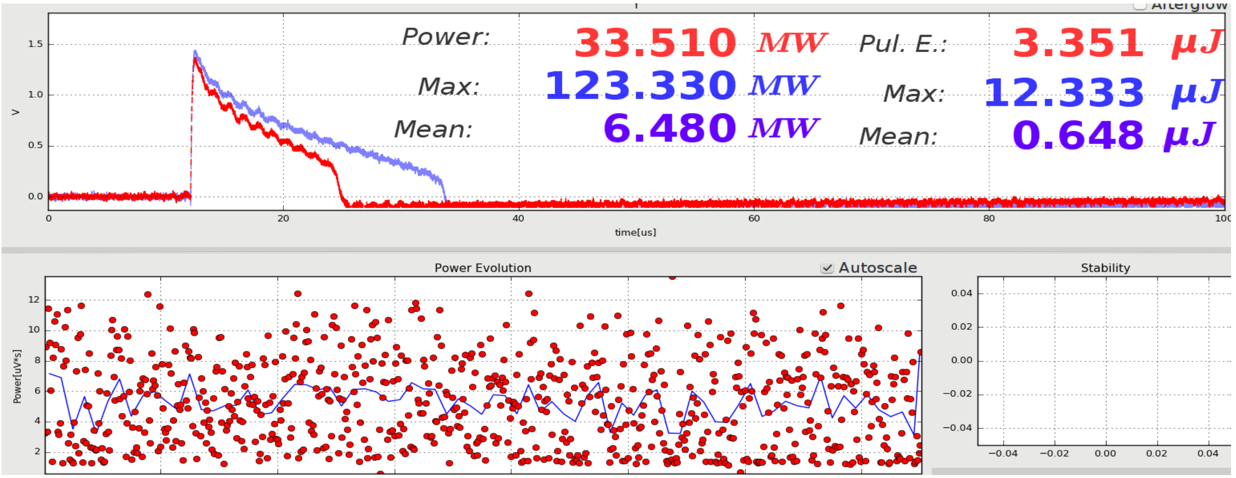




HLSS 6-3 nm + reverse taper



- Achieve HLSS 6-3nm FEL amplification;
- Reverse taper can suppress the power of SASE 6 nm (radiation induced energy spread) significantly;
- Enhance the power of harmonic radiation-3nm with reverse taper;
- The radiation pulse energy is above10 μJ with 6-U235;



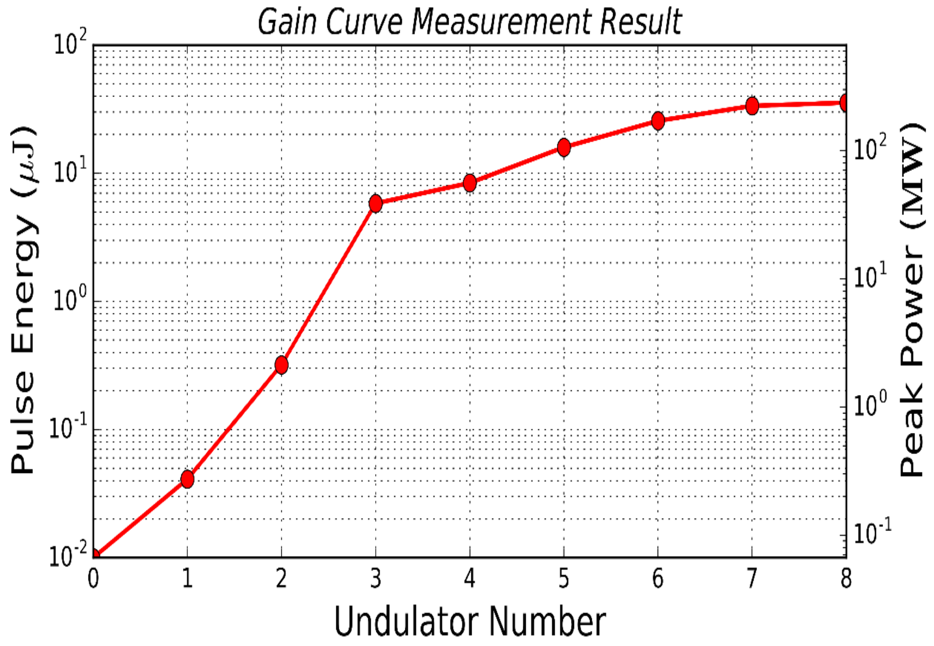
HLSS 6-3 nm acceptance test 3.30

Pulse energy measurement result

	Target	Measurement result
Pulse energy(μJ)	/	**34.0**
Peak power (MW)	≥50	**227**

Gain curve measurement result

	U235-1	U235-2	U235-3	U235-4
Pulse energy (μJ)	0.04	0.32	5.82	8.4
	U235-5	U235-6	U235-7	U235-8
Pulse energy (μJ)	15.94	25.62	33.56	35.50



HLSS 6-3 nm acceptance test 3.30

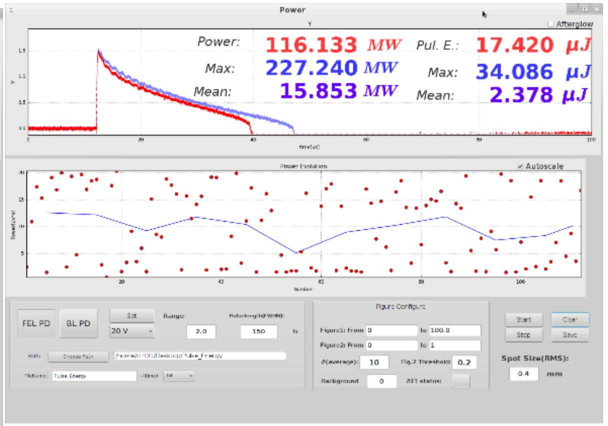
6nm pulse energy (μJ， without reverse taper)	1. 5	3nm pulse energy (μJ， without reverse taper)	4. 9
6nm pulse energy (μJ， with reverse taper)	0. 4	3nm pulse energy (μJ， with reverse taper)	33. 7

- **Reverse taper can suppress the pulse energy of SASE FEL at 6nm significantly (from 1.5 to 0.4 μJ)**
- **Reverse taper can enhance the pulse energy of HLSS FEL at 3 nm from 4.9 μJ to 33.7 μJ (6.8 times) .**

6nm **pulse energy (without reverse taper)**

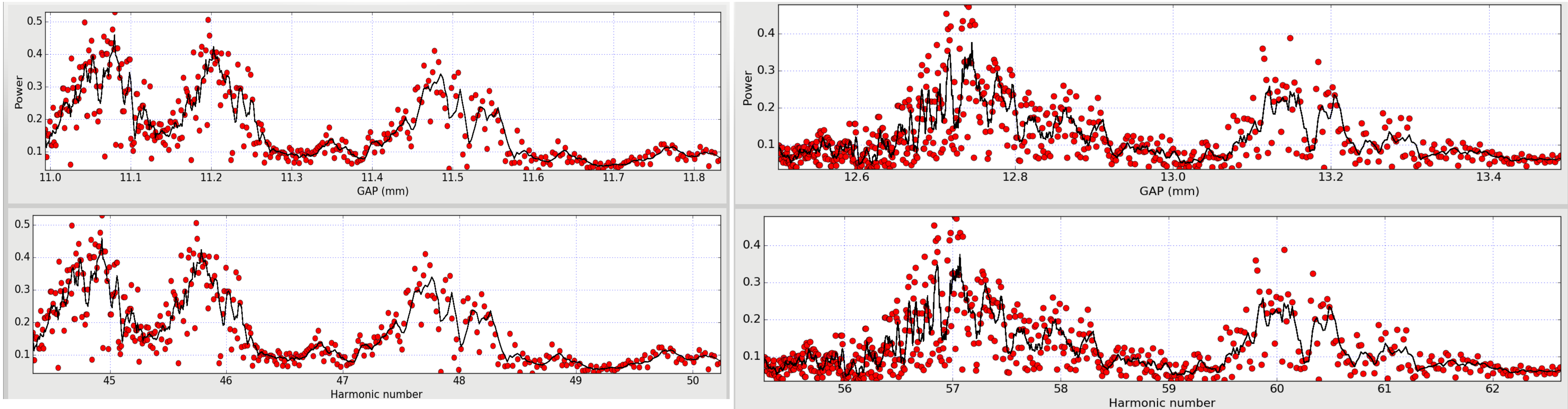
6nm **pulse energy (with reverse taper)**

3nm **pulse energy (without reverse taper)**



3nm **pulse energy (with reverse taper)**

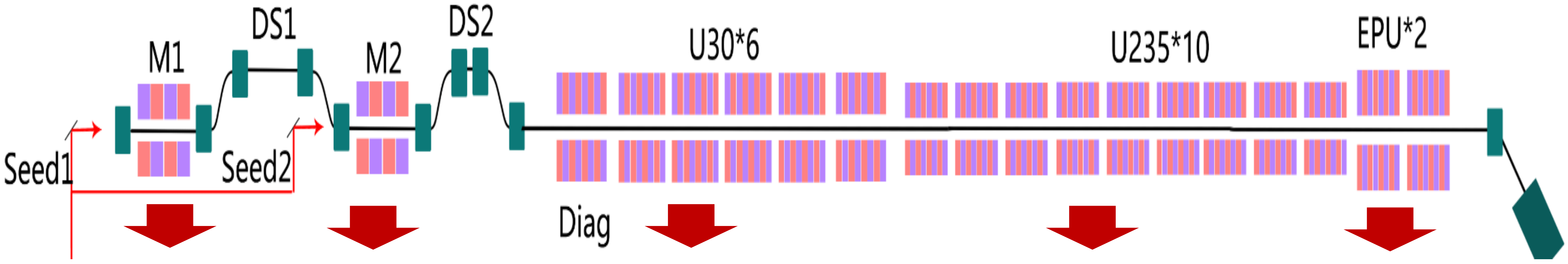
EEHG 61 signal 4.05



- **We obtain EEHG signal at maximum harmonic of 61.**

- **The EEHG 61 signal is relative weak, can not be distinguished easily.**
- **A light spot with a good transverse mode is obtained, but the signal was not be amplified successfully.**

SXFEL SUD Line

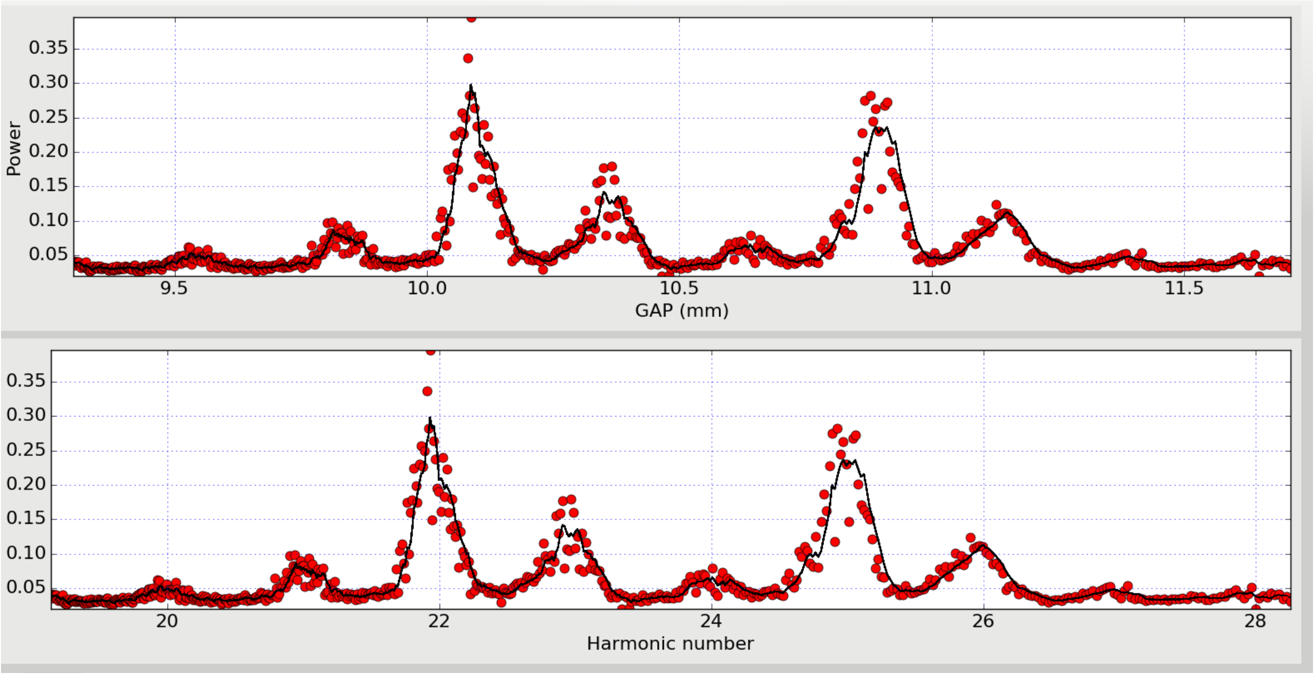


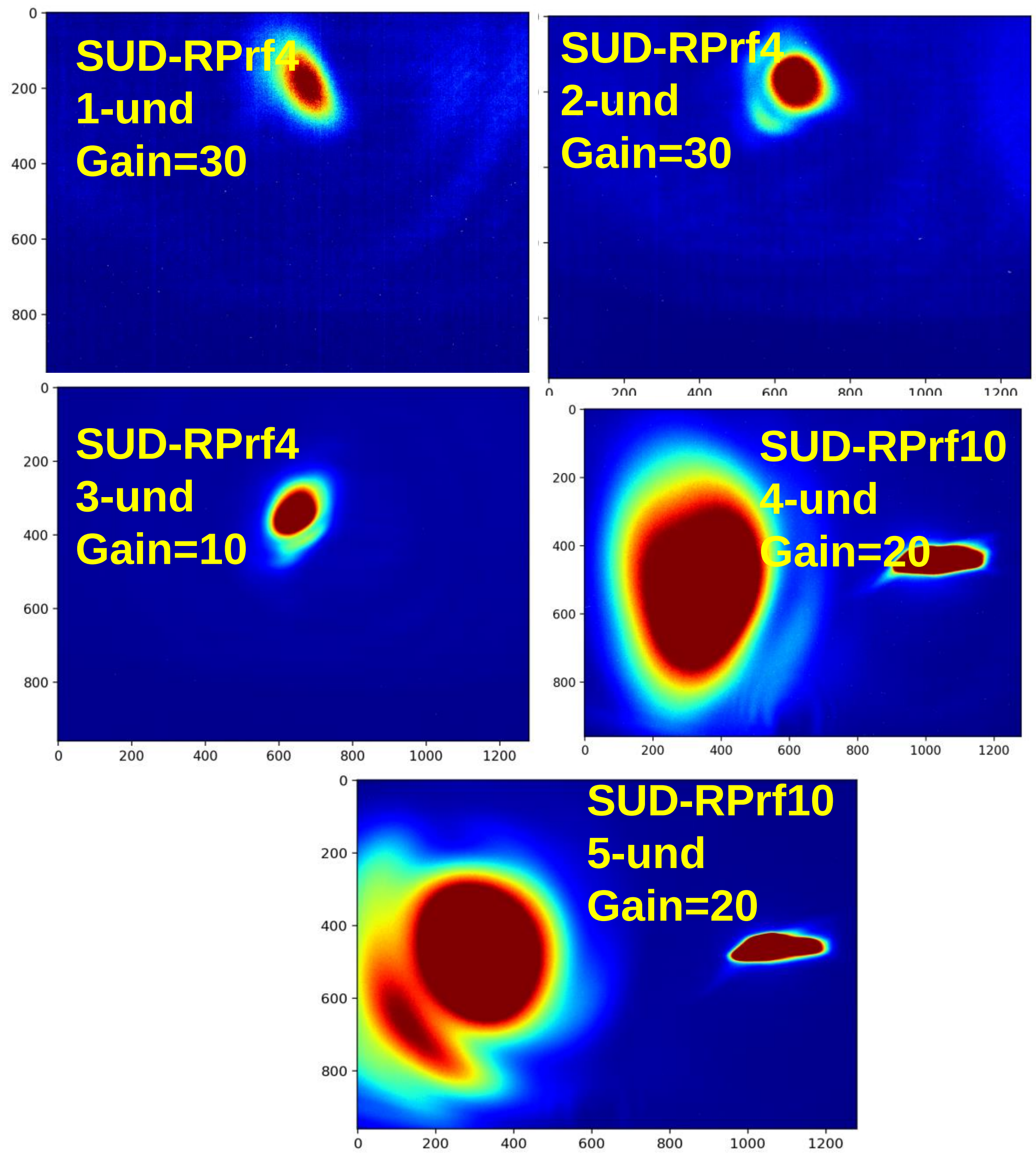
1-U80 **1-U80** **6-U30** **10-U235** **2-UEPU**

FEL commissioning target:

- **EEHG 25*2, E=1 GeV**
- **EEHG 50, E=1.48 GeV**

EEHG 25 amplification 4.16

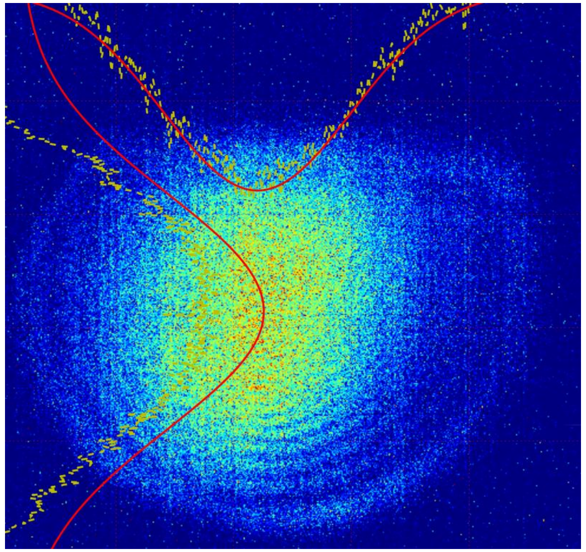


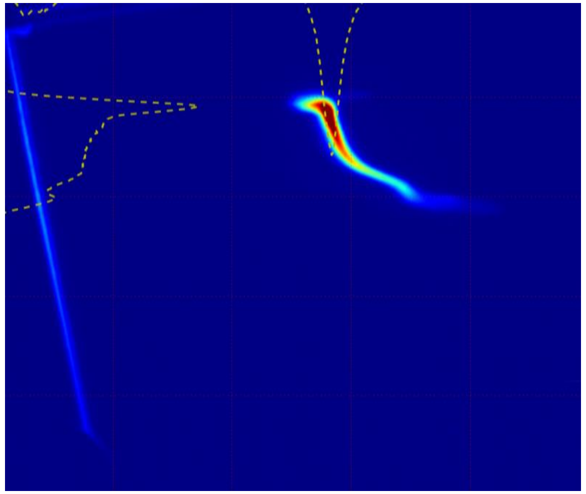


- **E=1 GeV, target is EEHG 25*2.**
- **The EEHG amplification at 25 harmonic can be easily achieved.**

SASE 10.6 and EEHG 25 -4.17

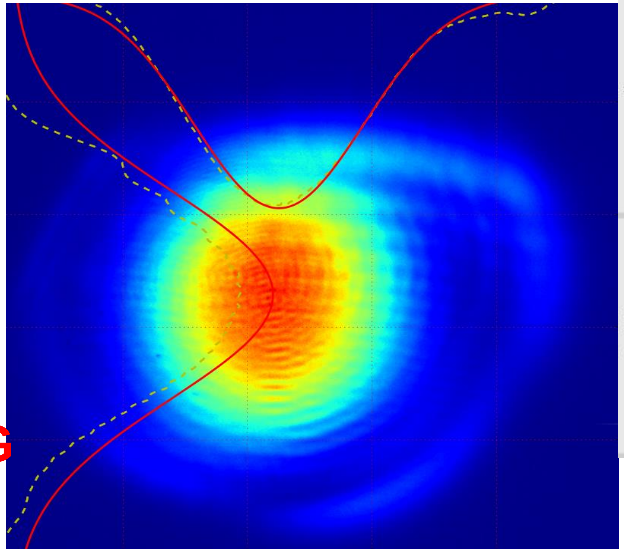
SASE 10.6 nm

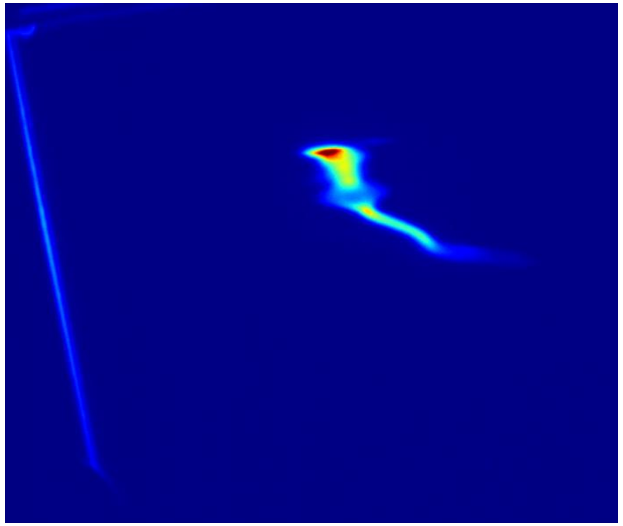


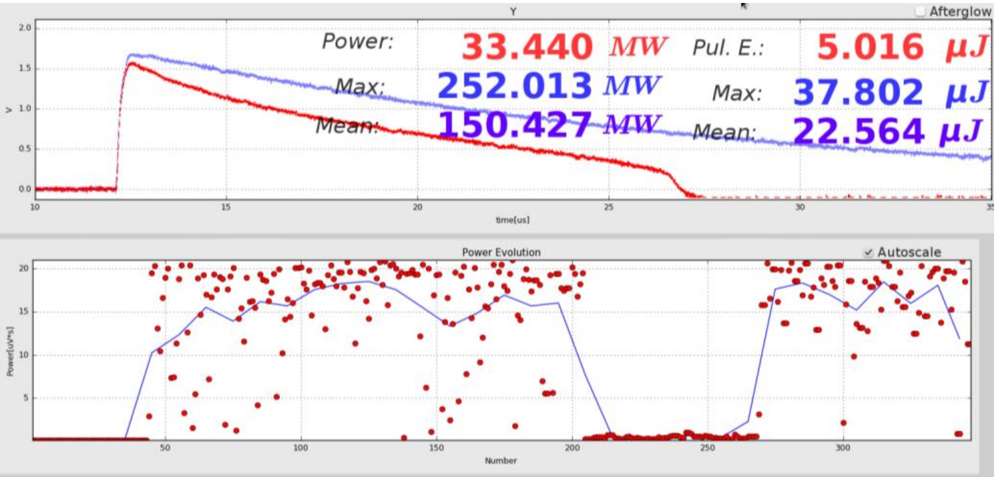


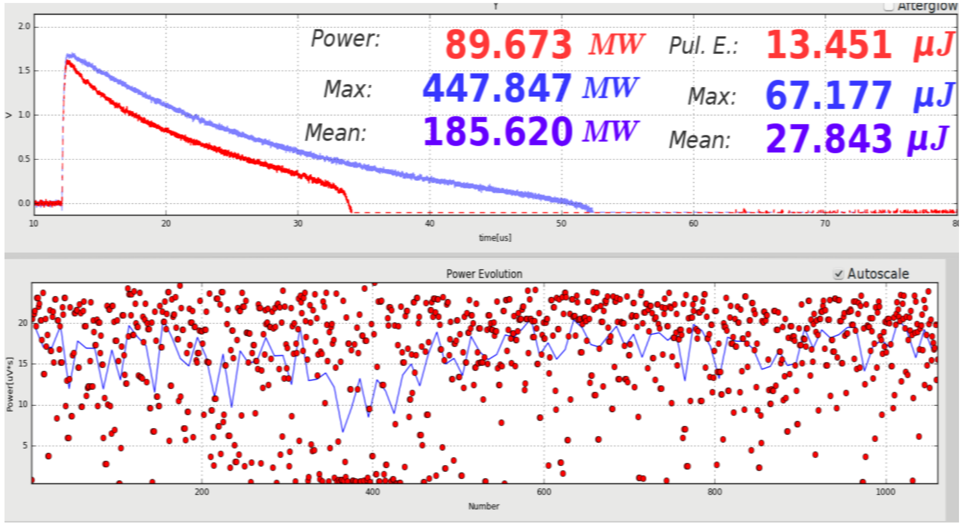
Add EEHG 25 signal

EEHG 25-10.6 nm



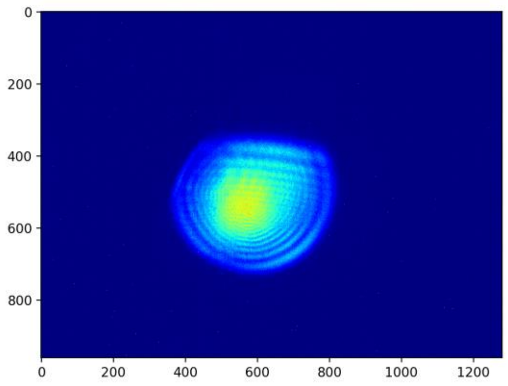


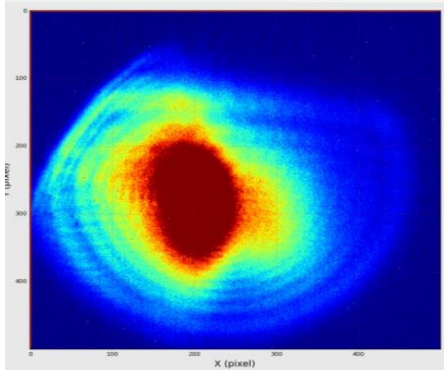




EEHG 25*2 attempt amplification 4.17

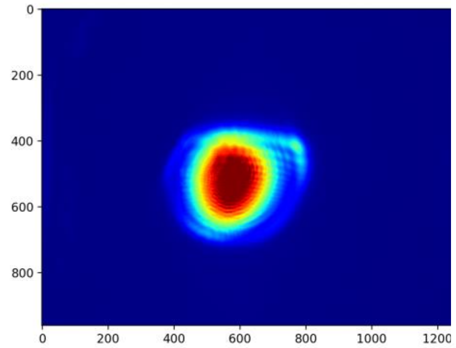
Step 1:
HLSS 10.6-5.3 nm

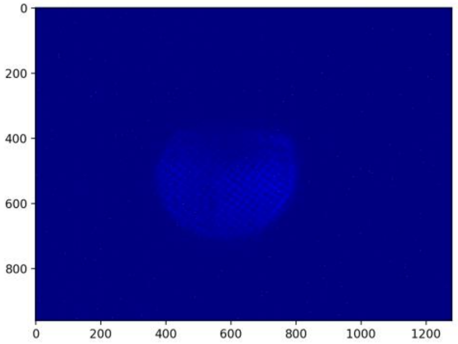




Step 2:

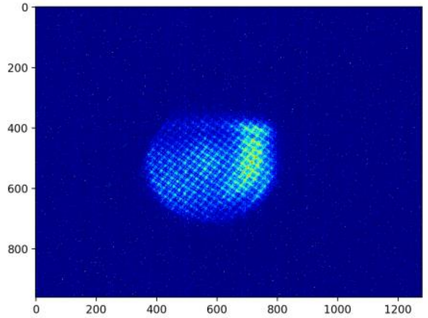
Add EEHG signal and suppress EEHG radiation with reverse taper





Step 3:

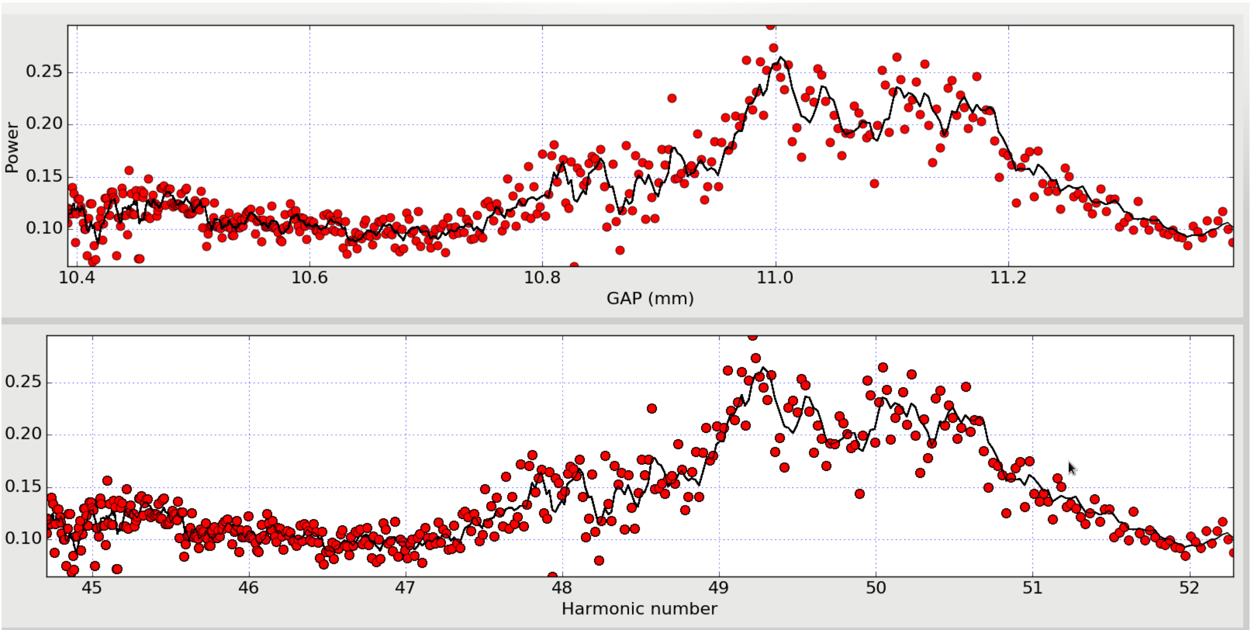
Try to find EEHG 25*2, No result

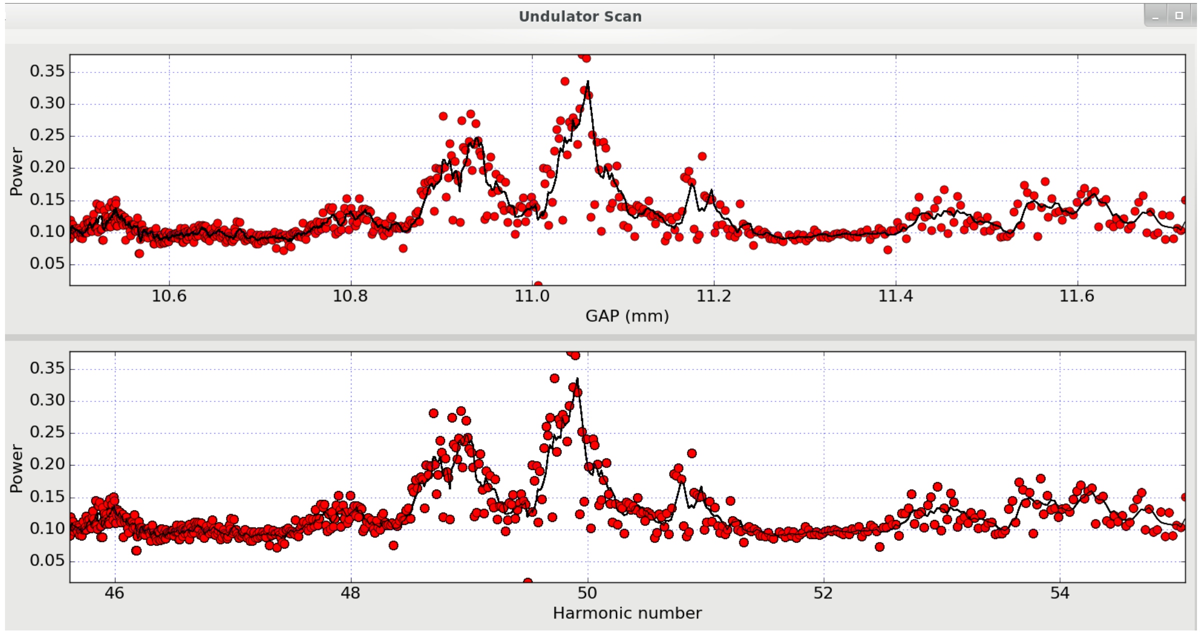


Conclusion:

- **Reverse taper can suppress the radiation of EEHG 25 significantly;**
- **Filter can filter parts of EEHG 25 radiation;**
- **HLSS 10.6-5.3nm, add EEHG signal, light spot of 5.3nm vanishes;**
- **Add reverse taper, still no EEHG 25*2 signal;**
- **EEHG25 amplification with 3, 4, 5 U30, still no EEHG 25*2 signal .**

EEHG 50 Commissioning 5.07

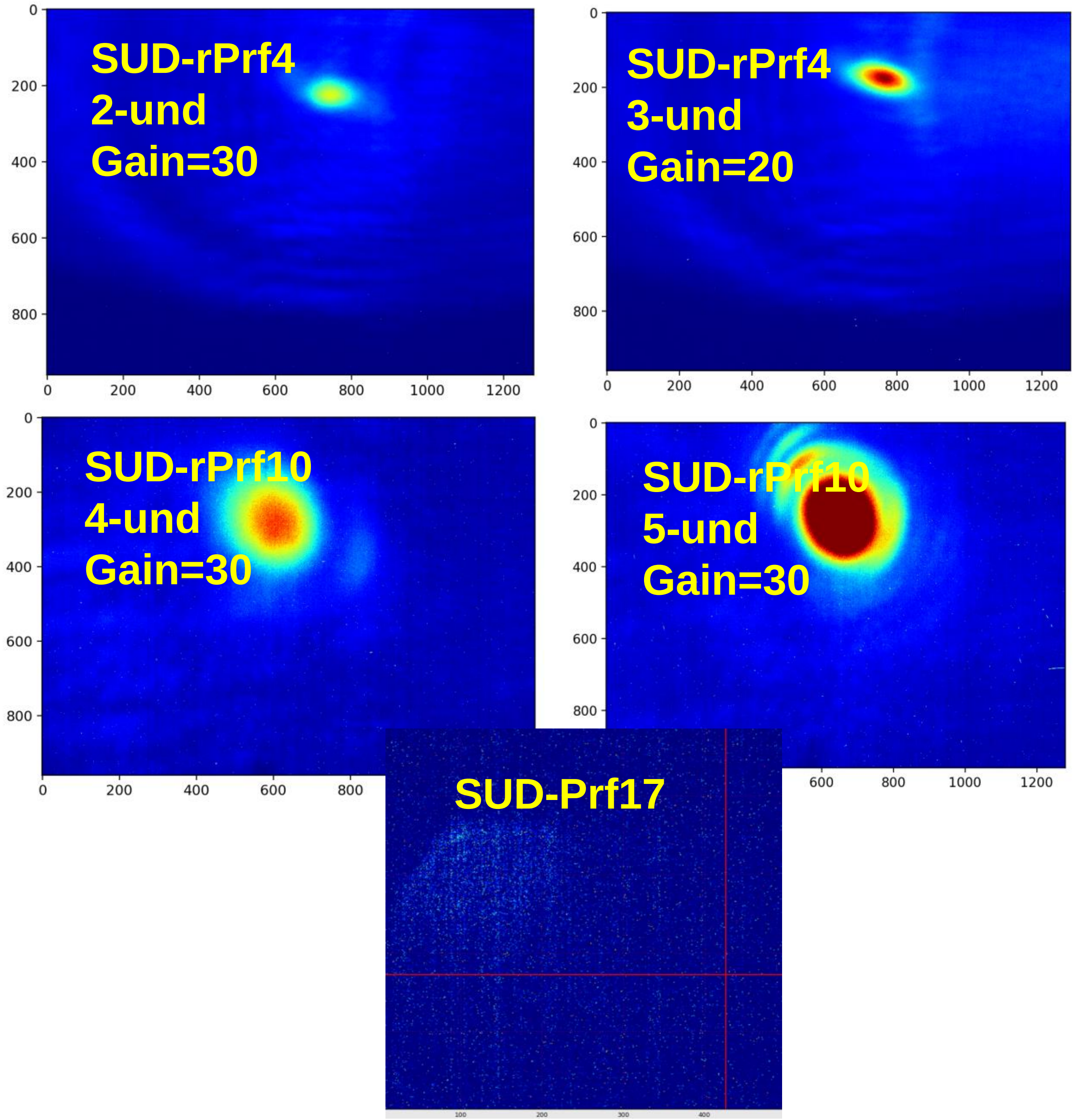




EEHG signal of 48-51 can not be distinguished

EEHG signal of 48-51 can be distinguished after EEHG condition optimization (A, B)

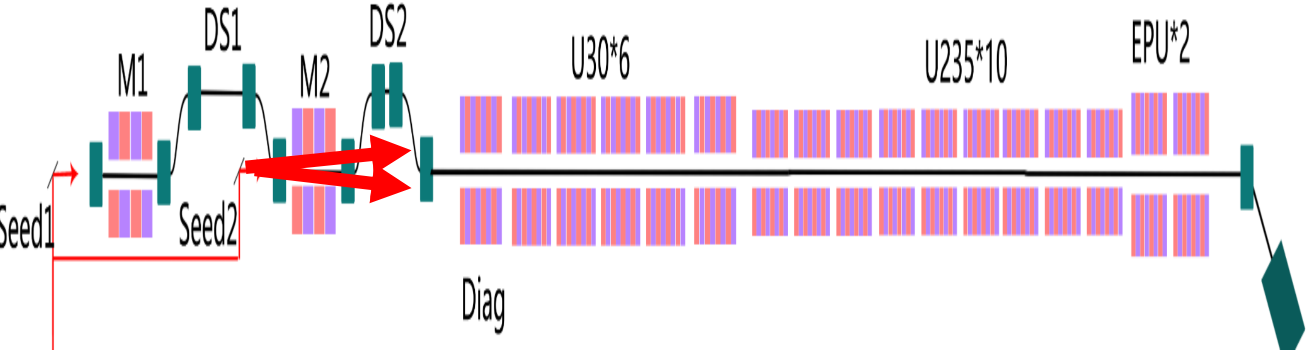
EEHG 50 amplification 5.08



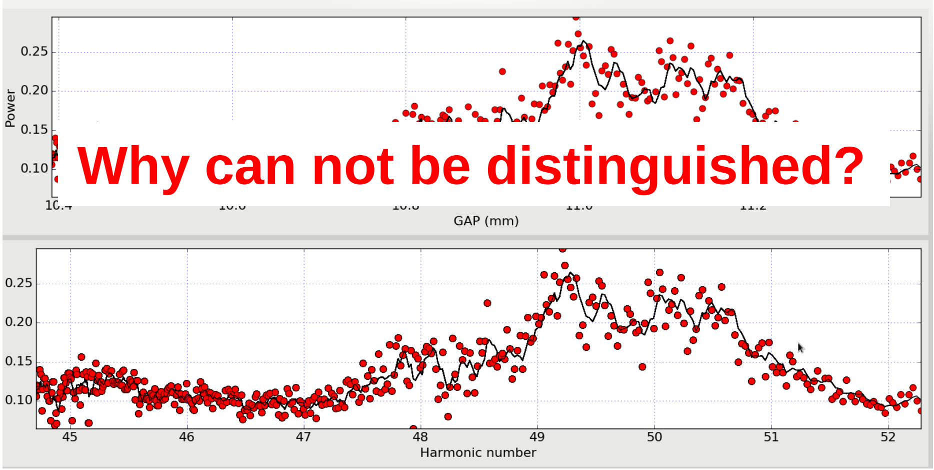
EEHG 50:

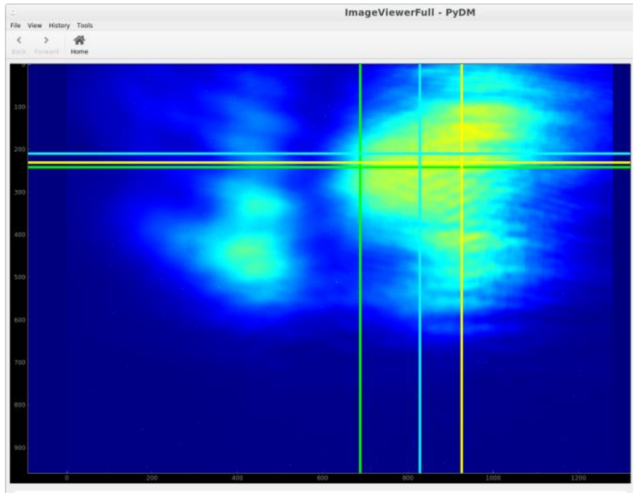
- **Harmonic number: h=50**
- **Wavelength: 5.32 nm**
- **The harmonic number is larger than our previous result.**
- **The pulse energy is far lower than that of EEHG 46.**

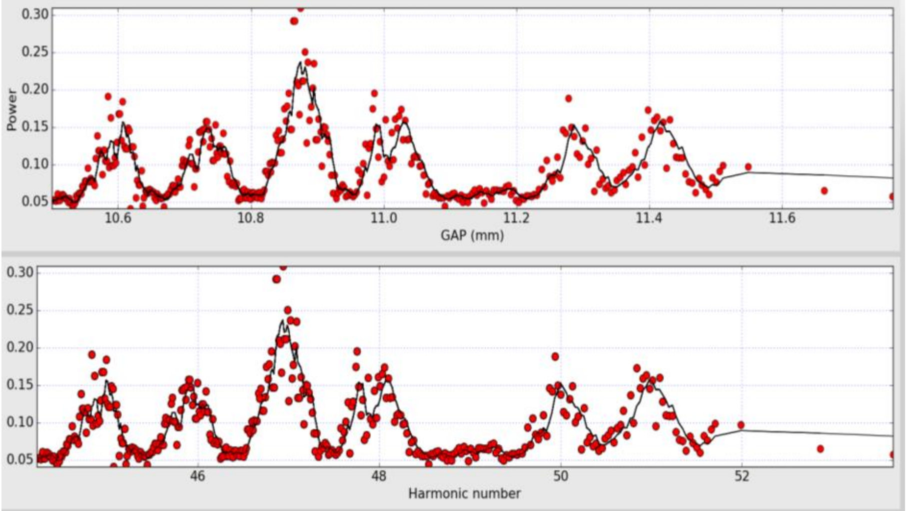
Seed laser angle optimization for EEHG 5.16



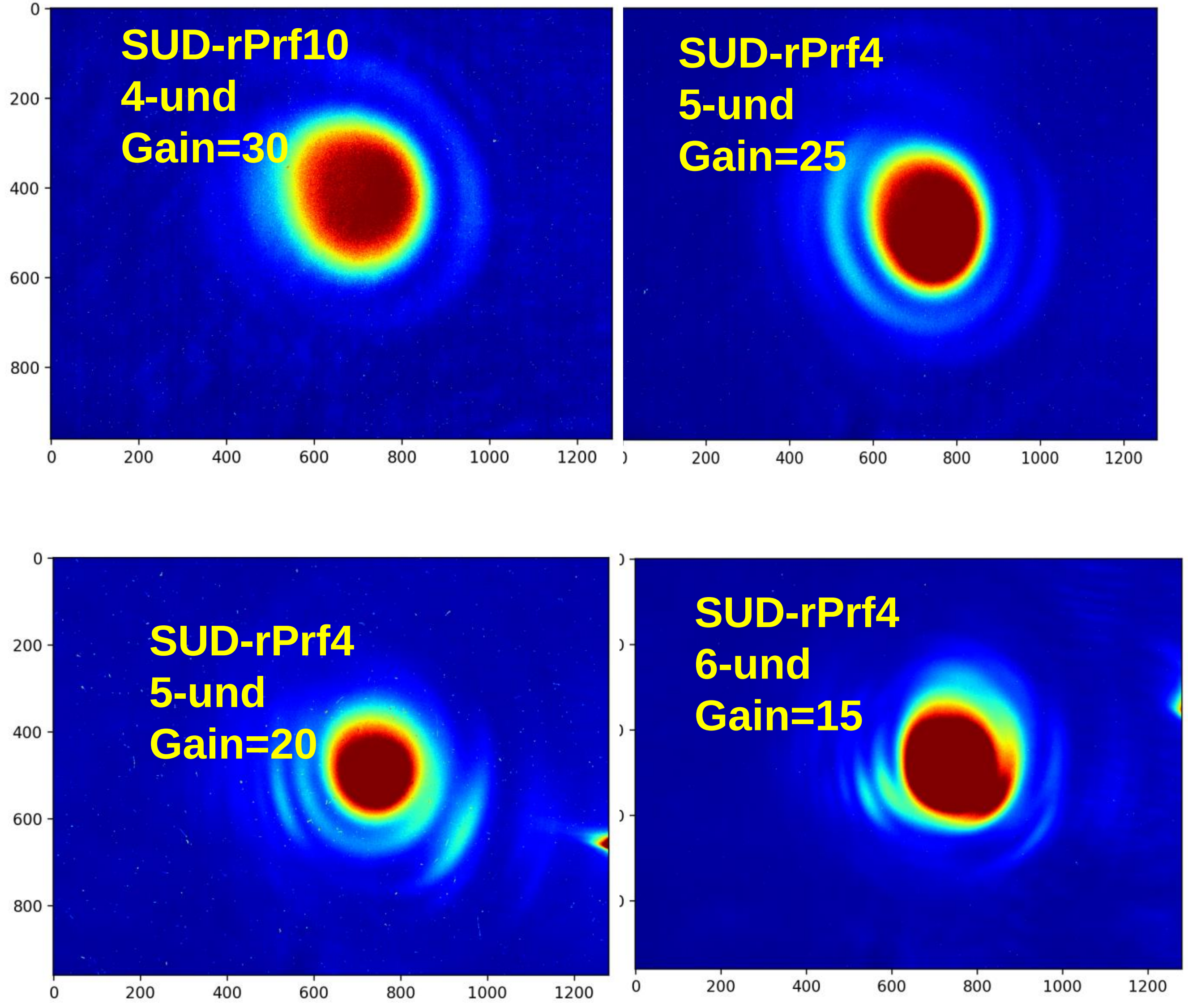
- The angle of seed laser can also be optimized;
- We use not only PD but Profile to optimize EEHG bunching.
- Amplify EEHG 47 to obtain a peak power of 50 MW.



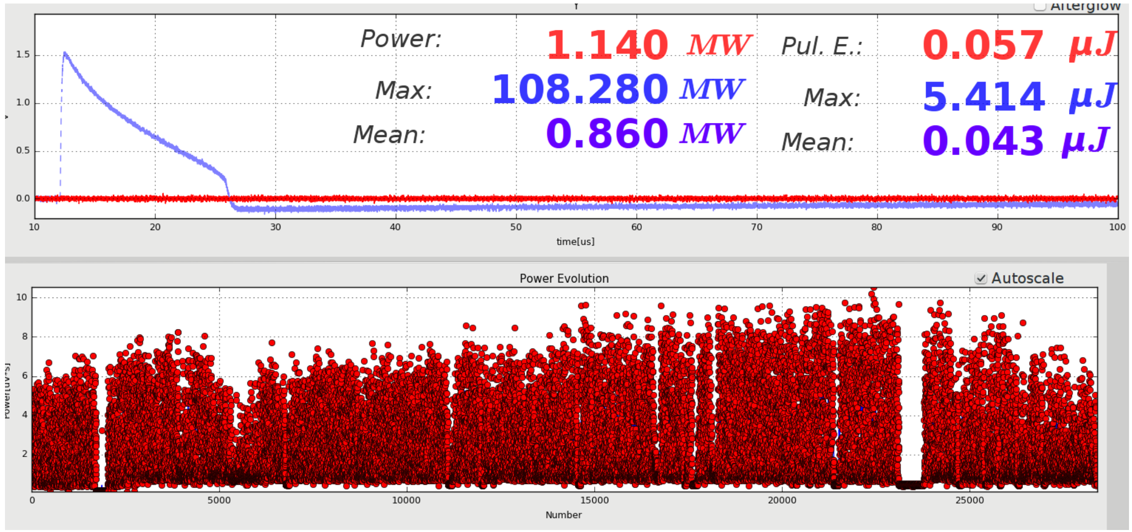




EEHG 47 amplification 5.19



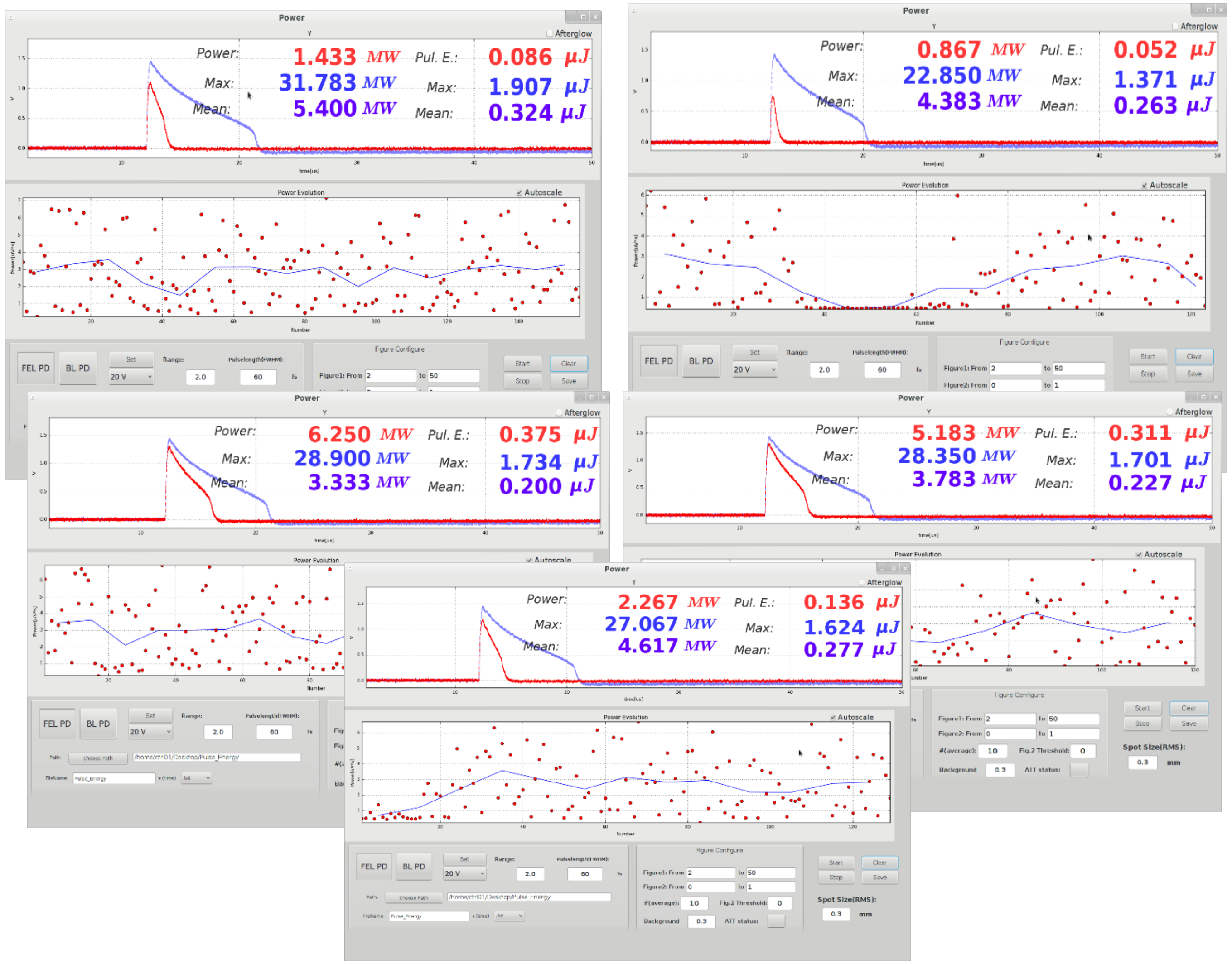
- EEHG 47 is amplified with 6 U30 successfully;
- The light can arrive the beam Line;
- The peak power is above 100 MW.



EEHG 47 Acceptance test 5.20

	Measurement result
Pulse energy (μJ)	1.7
Peak power (MW)	27.8

	1	2	3	4	5	Mean value
Pulse energy (μJ)	1.37	1.91	1.73	1.70	1.62	1.7

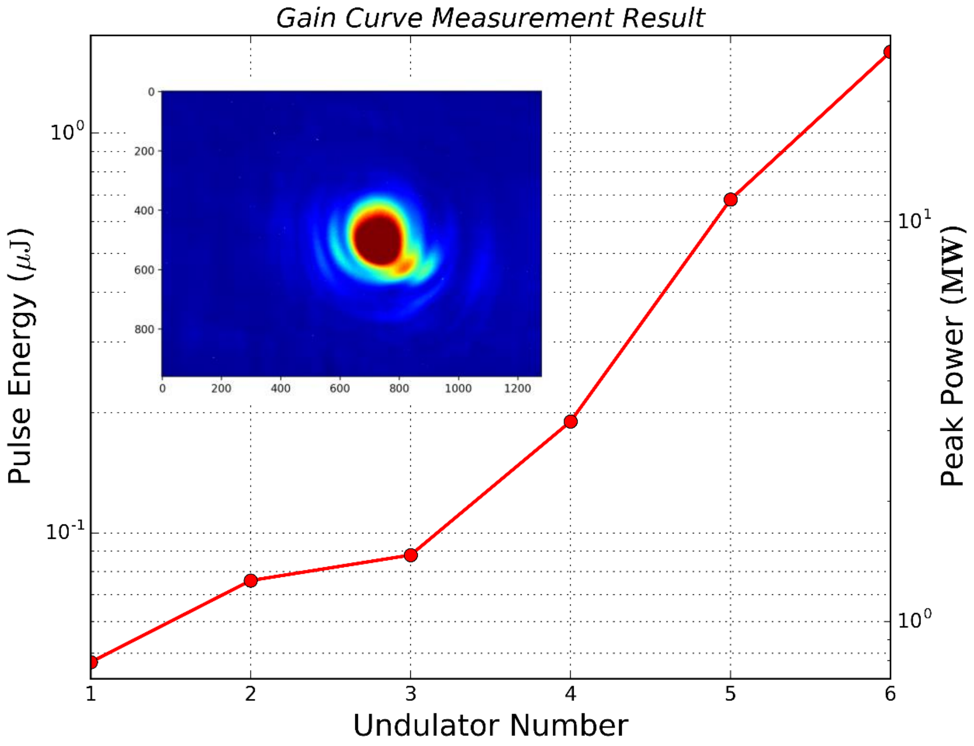


- **A stable beam status is necessary for the commissioning, amplification and radiation of EEHG at this harmonic number**

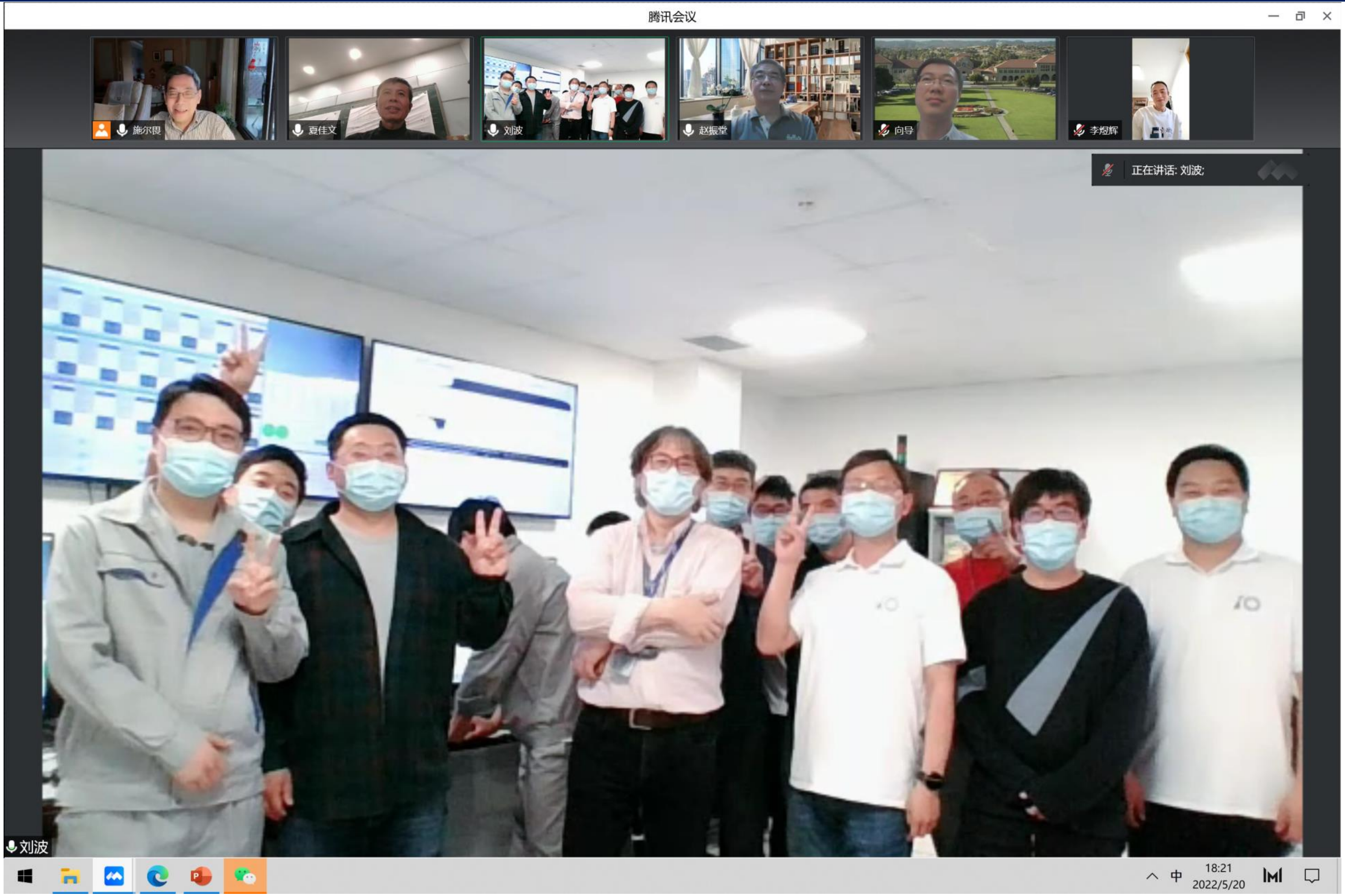
EEHG 47 Acceptance test 5.20

Measurement summary

	Parameters	**Measurement result**
FEL	Wavelength（nm）	5. 7
	Peak power（MW）	27. 8
	Pulse energy（μJ）	1. 7



EEHG 47 Acceptance test 5.20



Summary

- SXFEL SUD line FEL commissioning has been carried out for 6 months.
- Harmonic lasing self-seeding (HLSS) from 6 nm to 3nm has been successfully achieved and finished the acceptance test at March 30.
- EEHG at maximum harmonic of 61st harmonic has been achieved at April. 05.
- EEHG amplification at maximum harmonic of 50th has been achieved at May. 08, but the pulse energy is not as good as expected.
- EEHG amplifications at the harmonics of 25th, 32nd, 46th, 47th were also achieved, EEHG 47 amplification has finished the acceptance test at May 30.
- The EEHG harmonic cascade experiment is still on going.

Thanks for your attention!