The 13th International Particle Accelerator Conference (IPAC'22)

Self-amplification of laser-induced energy modulation in FELs

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THAILAND June 14th, 2022

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Outline

- External-seeded FELs & Motivations
- Self-amplification of coherent energy modulation
- Experimental demonstration
- Amplification of laser-induced modulation in a dipole
- Summary and Outlook

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- **External-seeded FELs & Motivations**
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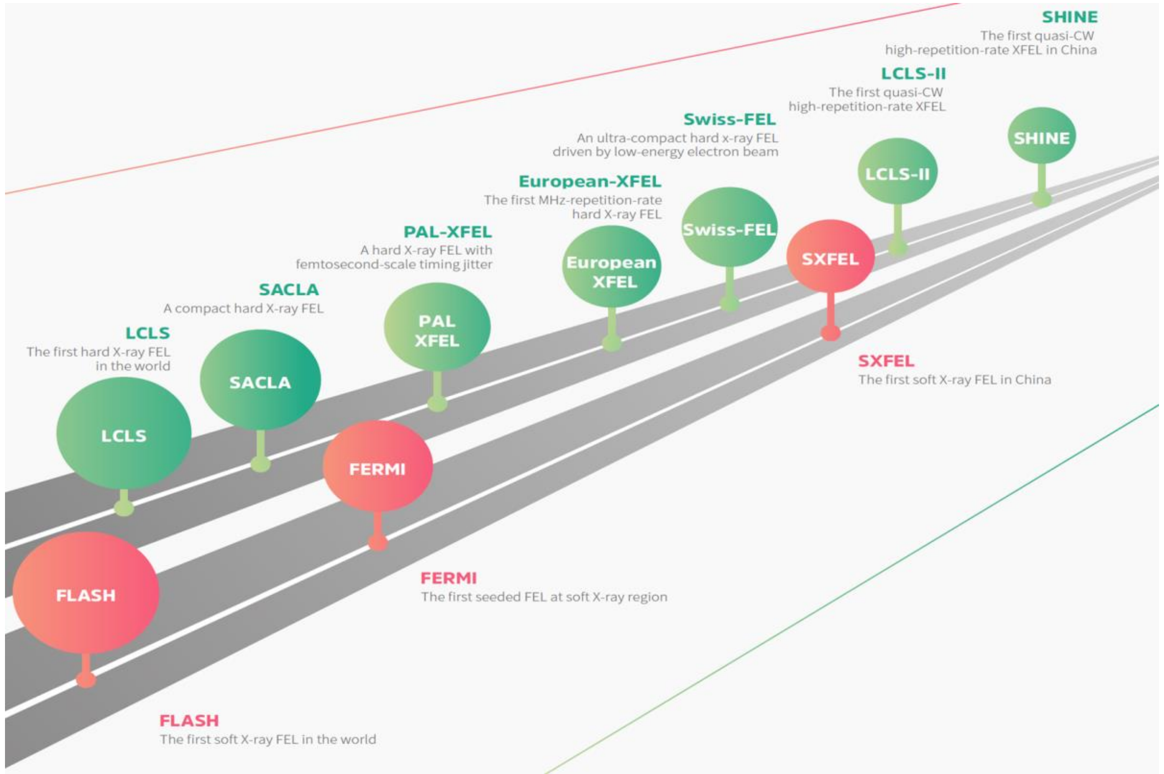
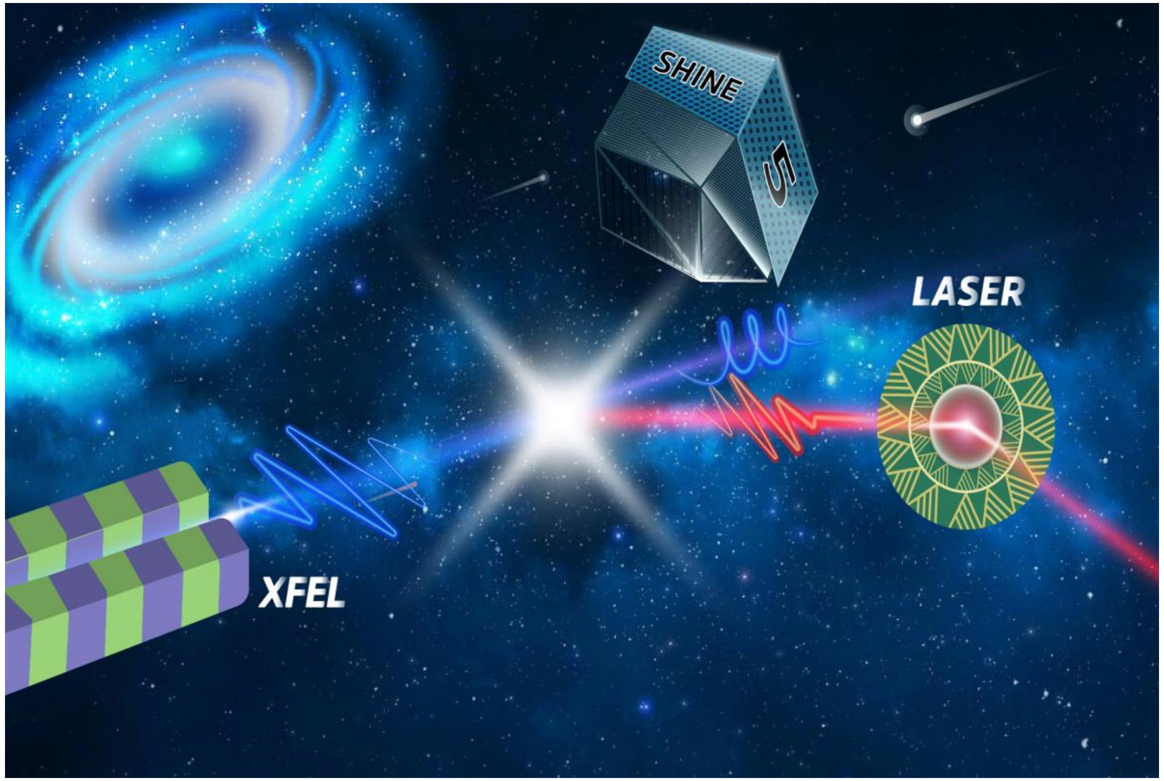
Features and futures of X-ray free electron lasers

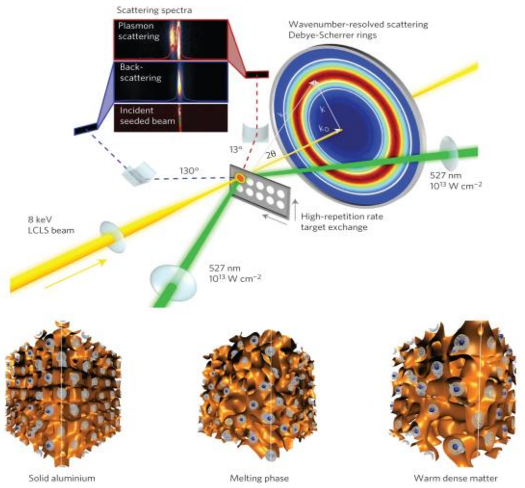




N. Huang, H. Deng*, B. Liu, D. Wang, Z. Zhao*,
Features and futures of X-ray free-electron laser. The Innovation 2 (2021) 100097.

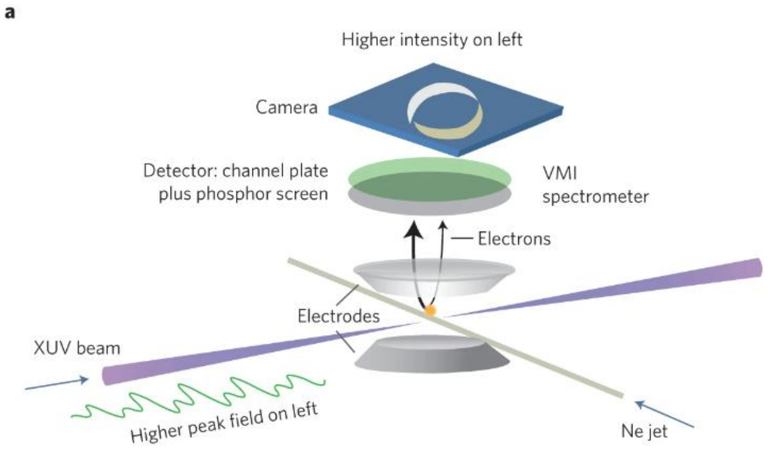
In pursuit of fully coherent X-ray FELs

- User requirements for fully coherent, phase locked radiation promote the development of fully coherent XFEL
- **Self-seeded、External seeded、X-ray oscillator**
- see, *Review of fully coherent free-electron lasers, Nuclear Science and Techniques (2018) 29: 160.*



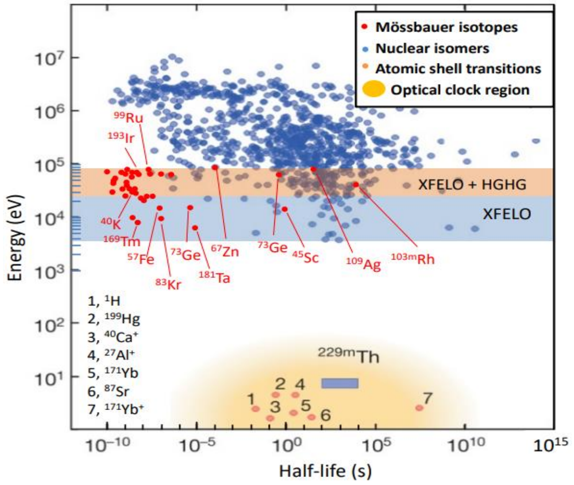
Ultrabright X-ray laser scattering for dynamic warm dense matter physics.

***Nature Photonics*, 2015, 9(4): 274-279.**



Coherent control with a short-wavelength free-electron laser.

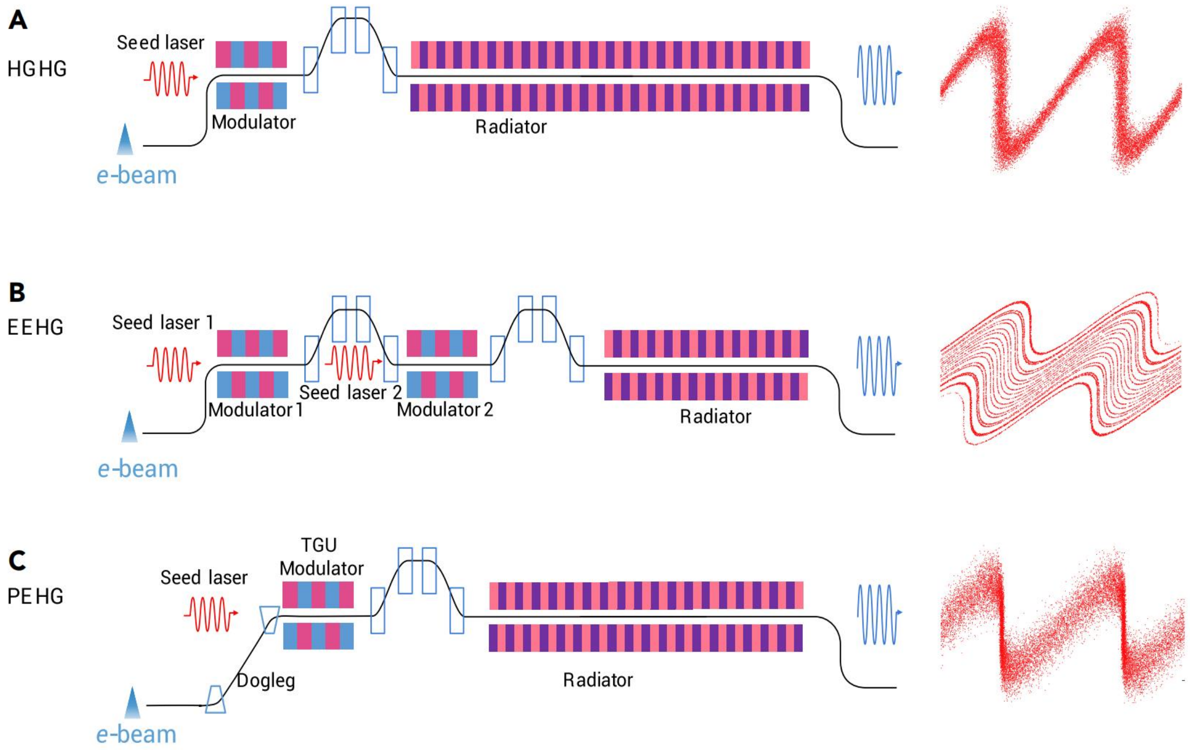
***Nature Photonics*, 2016, 10(3): 176-179.**



Scientific Opportunities with an X-ray Free-Electron Laser Oscillator.

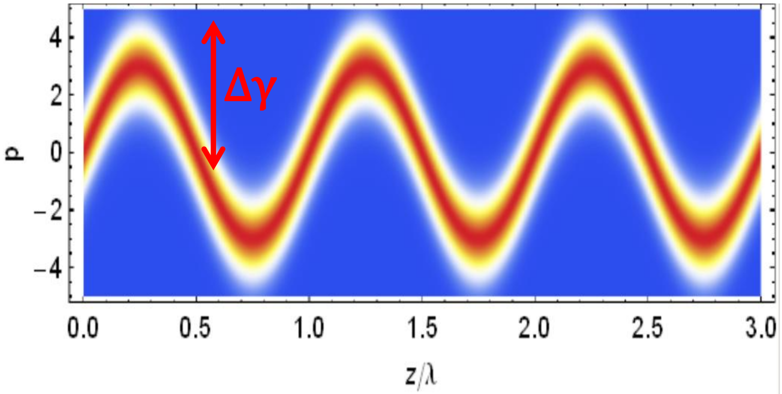
***arXiv:1903.09317*, 2019.**

External seeded FEL for EUV and soft x-ray



L. H. Yu, PRA (1991)
G. Stupakov, PRL (2009)
H. Deng, PRL (2013)

- An external seed laser introduces coherent energy modulation at longer wavelength.
- Coherent energy modulation is converted to density bunching with fruitful harmonic contents after compression with a chicane.
- Then a selected harmonic is picked up and amplified with a succeeding undulator.



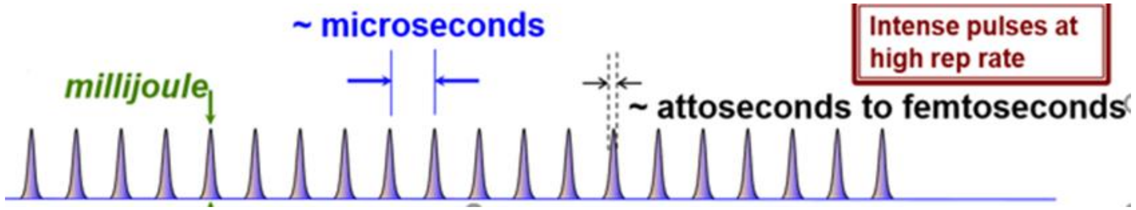
$$A = \Delta\gamma / \sigma_\gamma$$

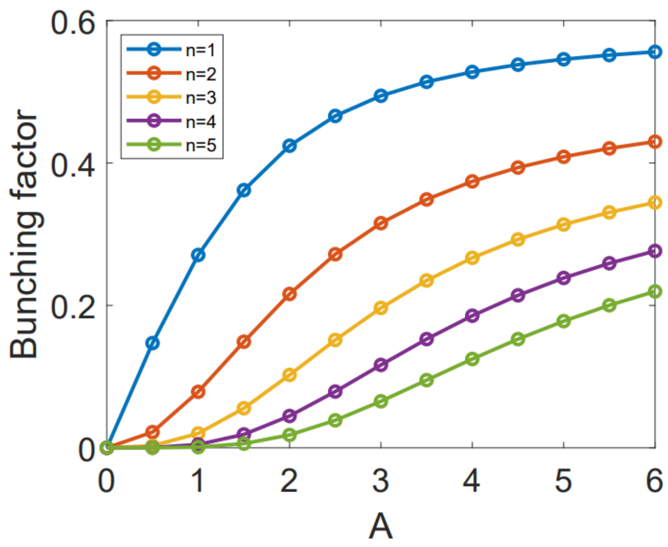
Normalized energy modulation amplitude

- In typical HGHG, **A > n** is required, where n is the interested harmonic number.

High-repetition-rate seeded FELs

- European XFEL, LCLS-II, SHINE
- How to realize a 1MHz seeded FEL?





Bunching factor .vs. energy modulation amplitude

- It is an Opportunity & Challenge for Advanced laser system, e.g., OPCPA

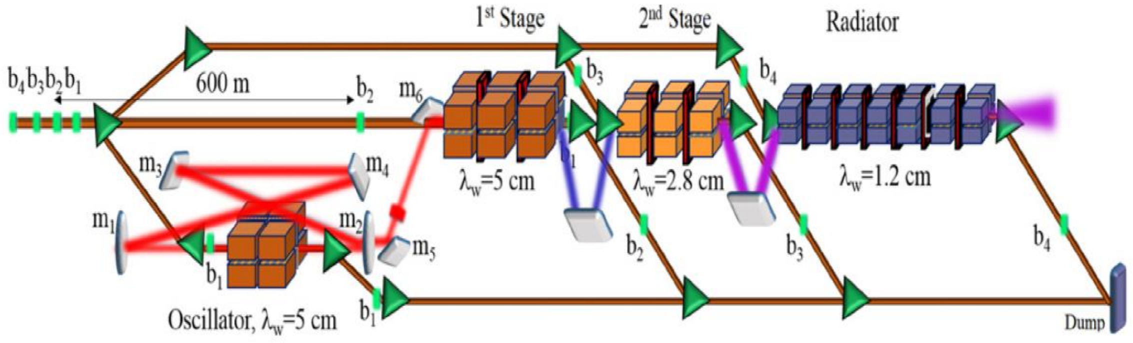
	specification	target
wavelength	240-260nm	
rep. rate	≥10kHz	×100
Pulse energy	10μJ	×10-100
Pulse duration (FWHM)	25fs	
Energy jitter (rms)	≤2%	
Pointing stability (rms)	≤5μrad	
Timing jitter (rms)	≤10fs	÷10
Laser spot (FWHM)	0.2mm	

Seed laser specification for FEL-II of SHINE

It is currently impossible for state-of-the-art laser systems to obtain laser pulses with sufficient peak power and high repetition rate at the same time

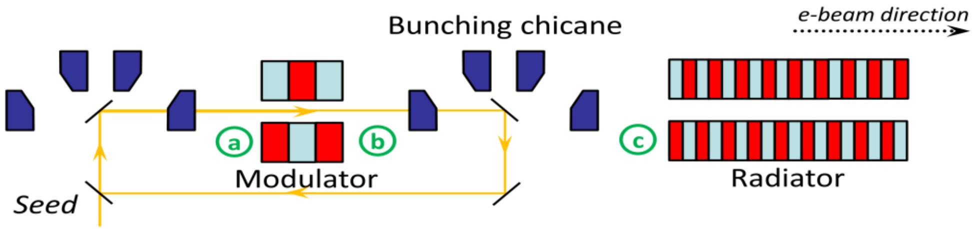
High-repetition-rate seeded FELs

□ EUV Oscillator as a seed source



V Petrillo, et al., NJP (2020)

□ Optical resonator scheme



Sven Ackermann, et al., PRAB (2020)

□ Is there any other solution? Still in collaboration with the external laser.

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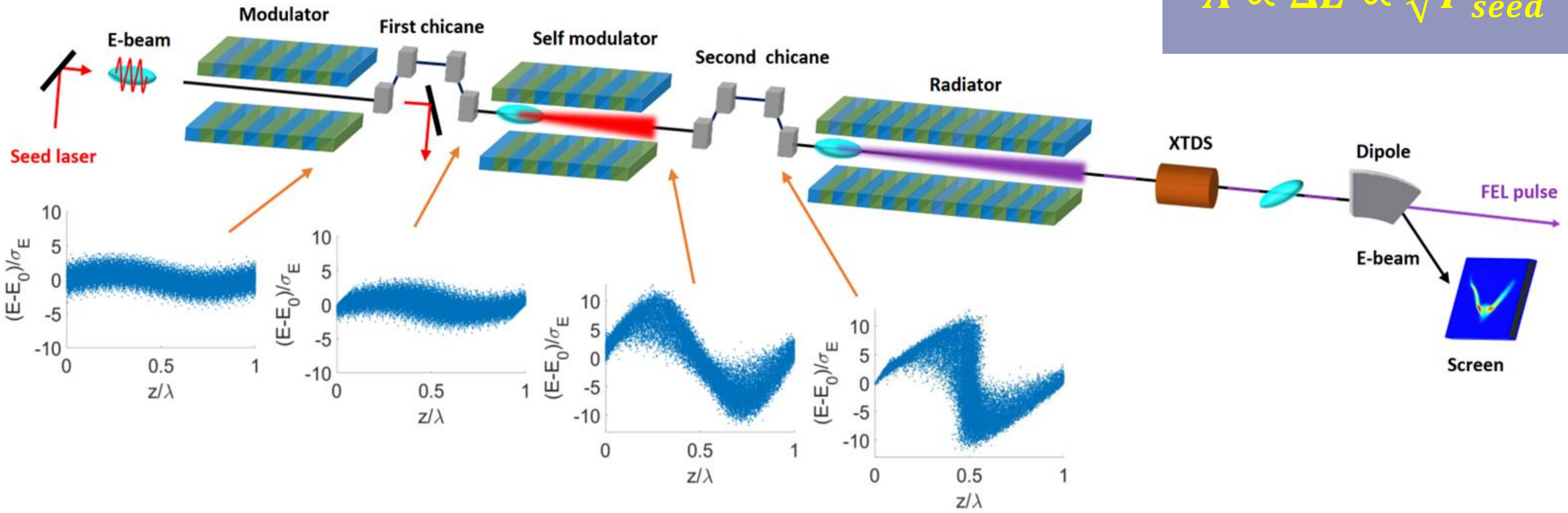
Self-amplification of laser-induced energy modulation

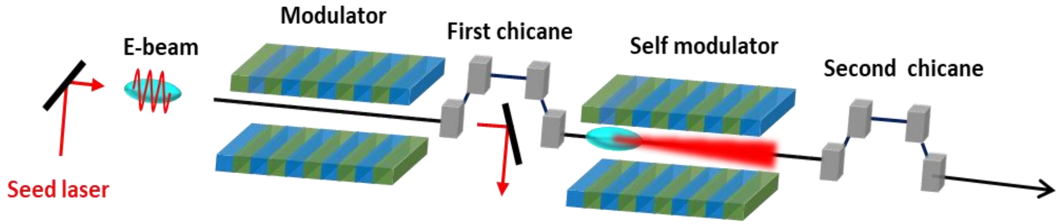
$$A \propto \Delta E \propto \sqrt{P_{seed}}$$



A ~ 1 ➡ **A ~ 10 The external seed power can be relaxed more than two orders of magnitude**

Phys. Rev. Lett. ***126*** *(2021) 084801*

Self-modulation scheme - numerical simulation



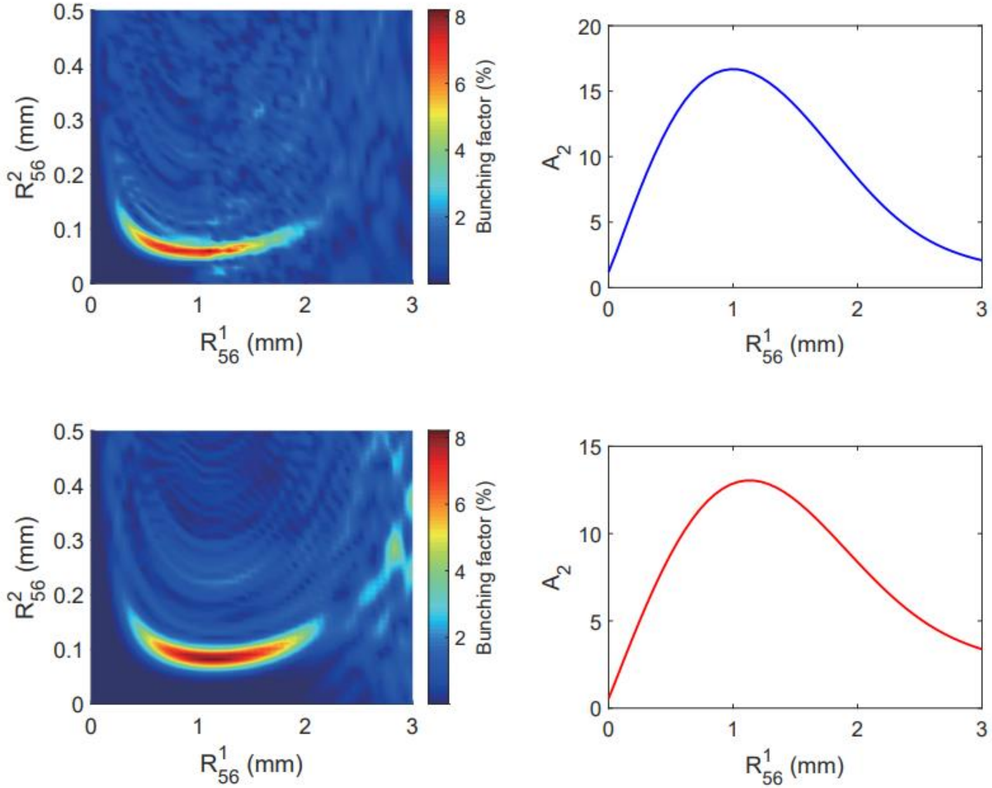
Parameters of SXFEL user facility

Beam Energy	1400 MeV
Peak current	~ 700 A
Bunch length	~ 0.8 ps
Emittance	1 mm-mrad
Slice energy spread	~ 50 keV
(Self-) Modulator	1.6 m/80 mm
Seed laser	266 nm
Seed laser power (HGHG)	17-75 MW
Seed laser power (self-modulation HGHG)	0.019 - 1.6 MW

$$P_{coh} = \frac{Z_0(K[JJ]_1 L_u I b_n)^2}{32\pi\sigma^2\gamma^2}$$

Beam size

8% bunching factor at 13-th harmonic



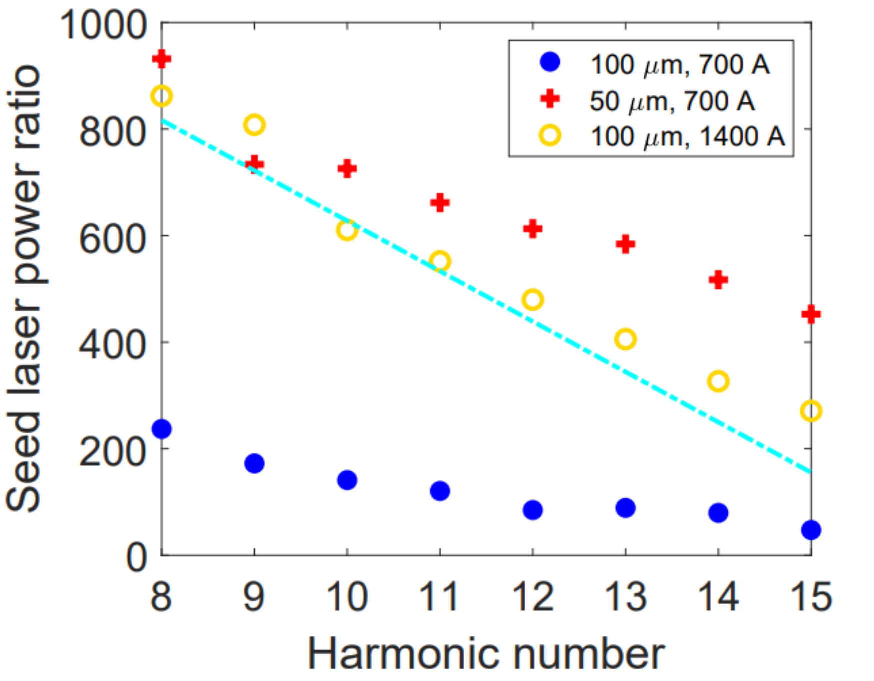
100 μm size

0.62 MW (vs. 55 MW)

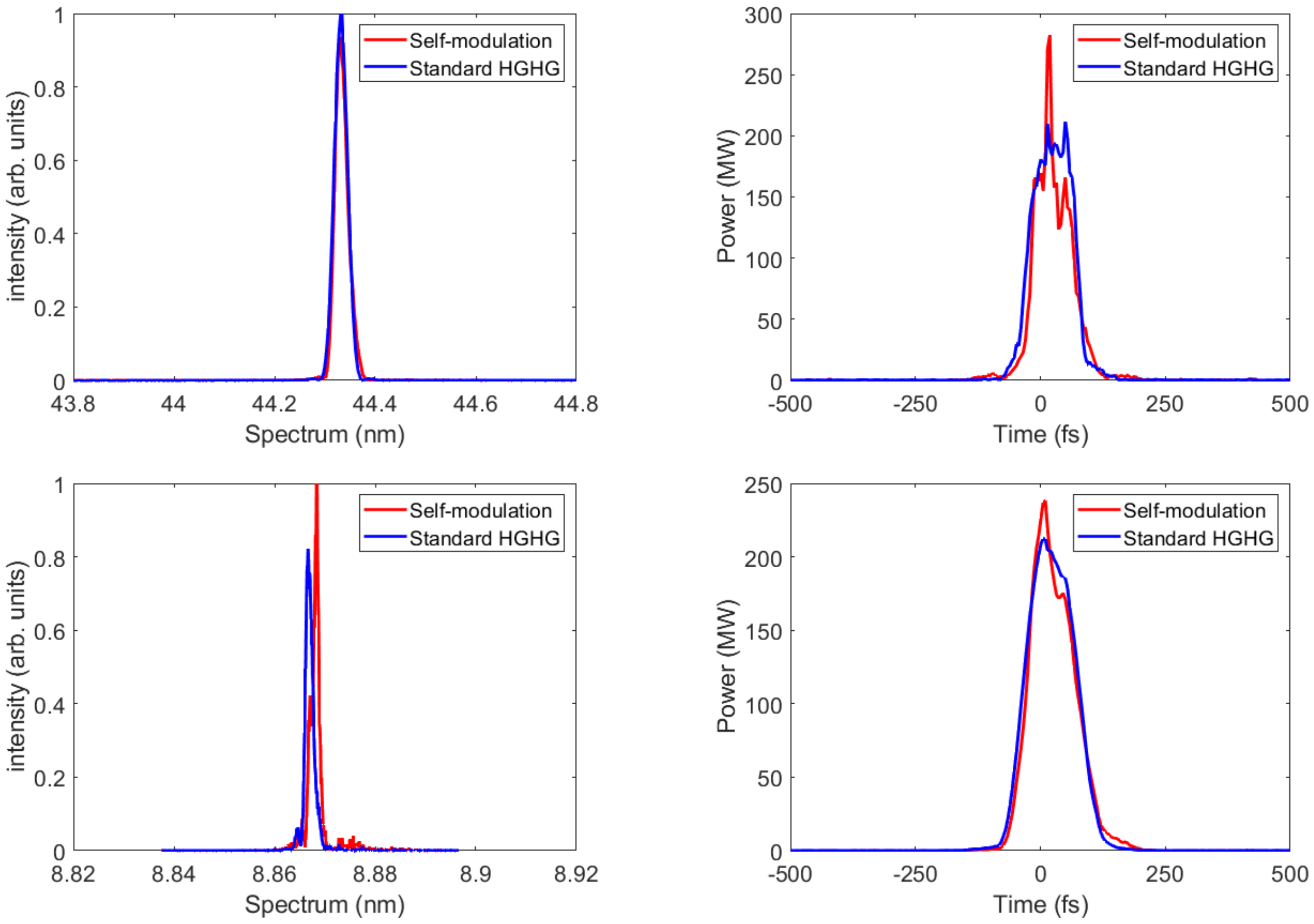
50 μm size

0.085 MW (vs. 50 MW)

Self-modulation scheme - numerical simulation



To reach the same bunching factor of 8%, the seed laser power can be reduced by up to 950 folds



Similar FEL performance compared with the standard HGHG

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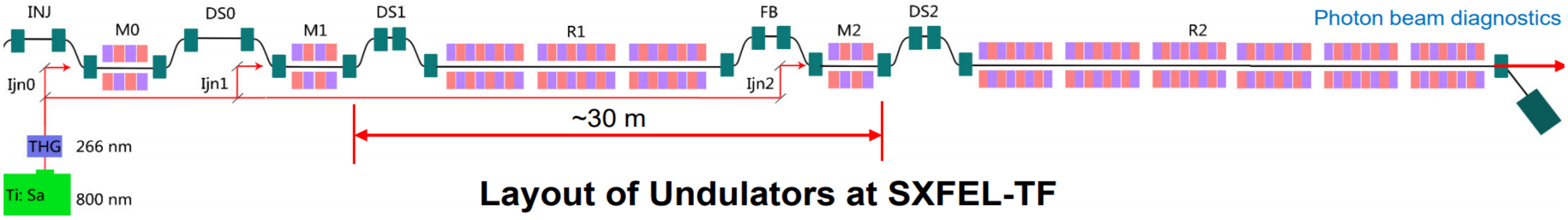
Experimental demonstration at SXFEL test facility



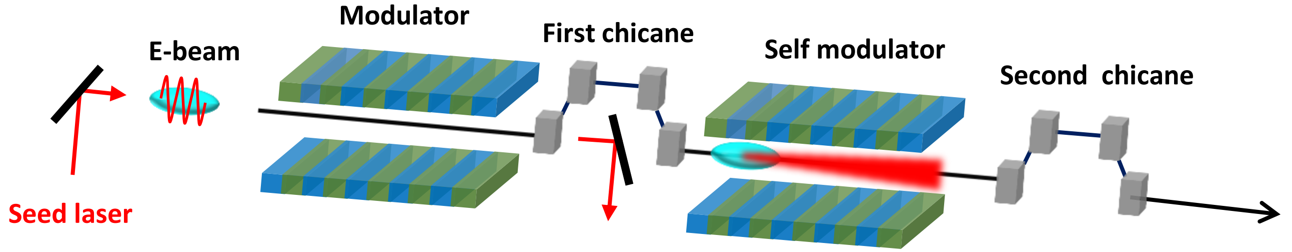
Layout of Undulators at SXFEL-TF

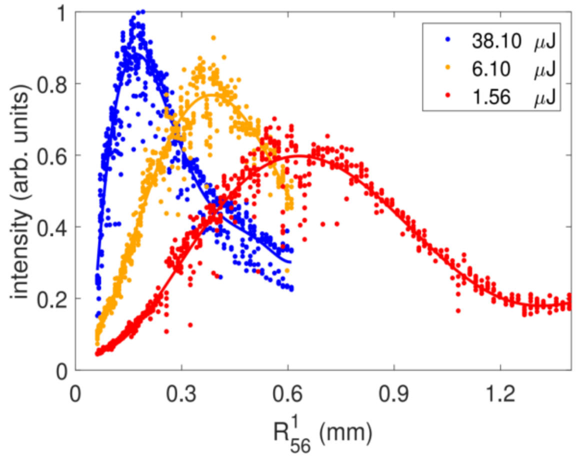
- Shanghai soft x-ray test facility (2014-2020), now at user facility phase.
- two-stage seeded FEL: HGHG-HGHG, and EEHG-HGHG
- a perfect platform for self-amplification of laser-induced modulation
- the second modulator in EEHG serves as the self-modulator
- the experiments were conducted at 12th-17th June, 2020.

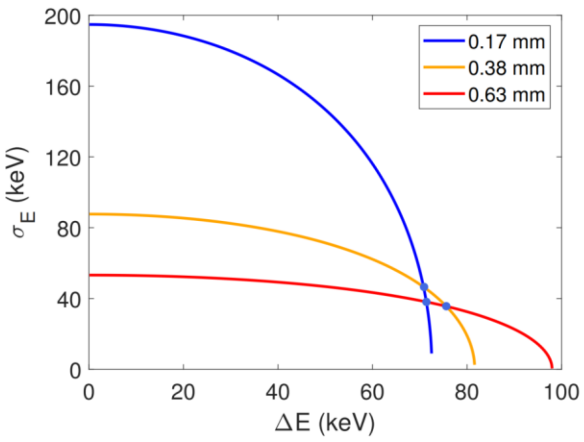
Self-modulation scheme – experimental demonstration

Parameters of SXFEL-TF

Parameters	Values
Energy	800 MeV
Peak current	~ 600 A
Bunch length	~ 1 ps
Emittance	1.5 mm mrad
Slice energy spread	~ 40 keV
Seed laser	266 nm
(Self-) Modulator	1.5 m/80 mm

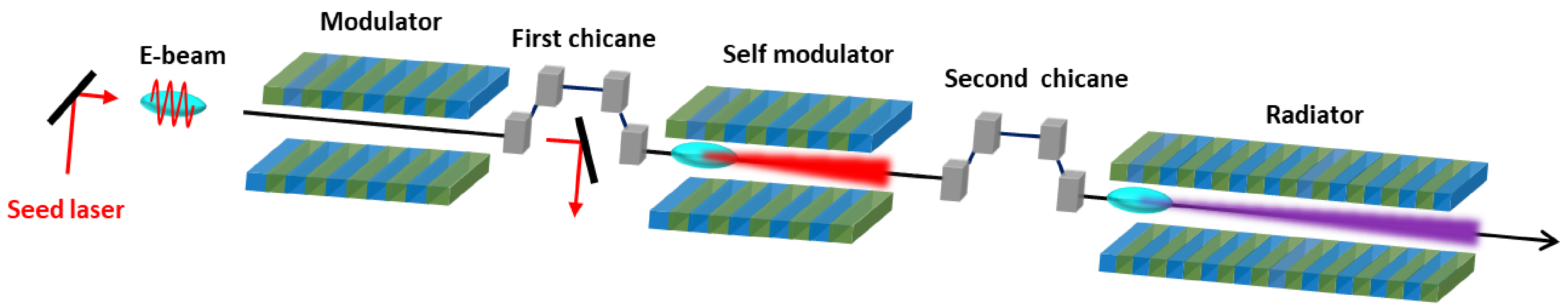


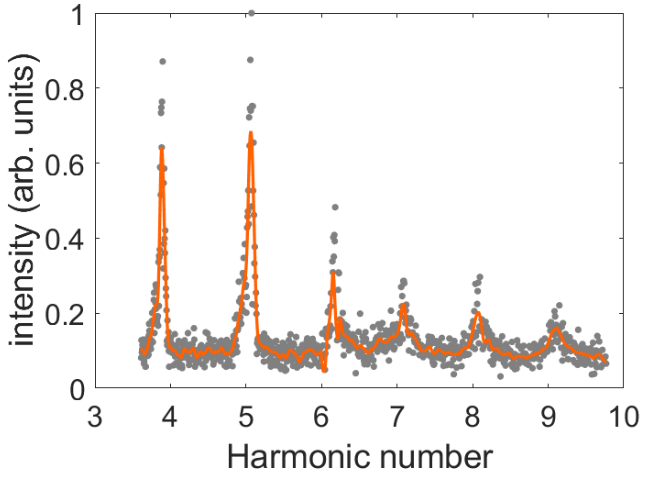




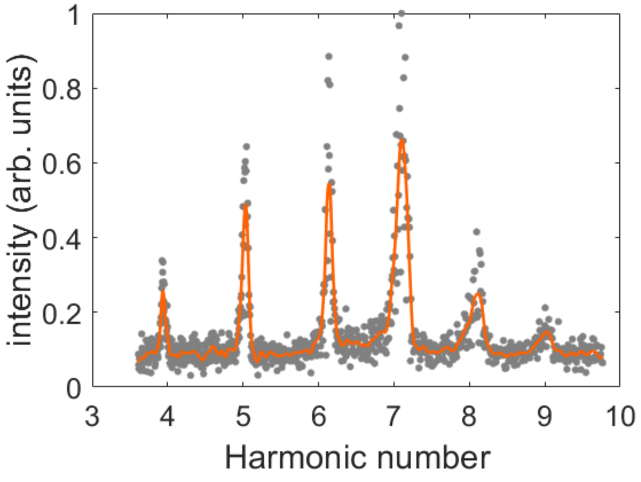
Initial slice energy spread: 40 keV
Energy modulation amplitude: 73 keV
P_{seed} = 1.56 μJ; A = 1.8

Self-modulation scheme – experimental demonstration





R^2_{56} = 0.23 mm



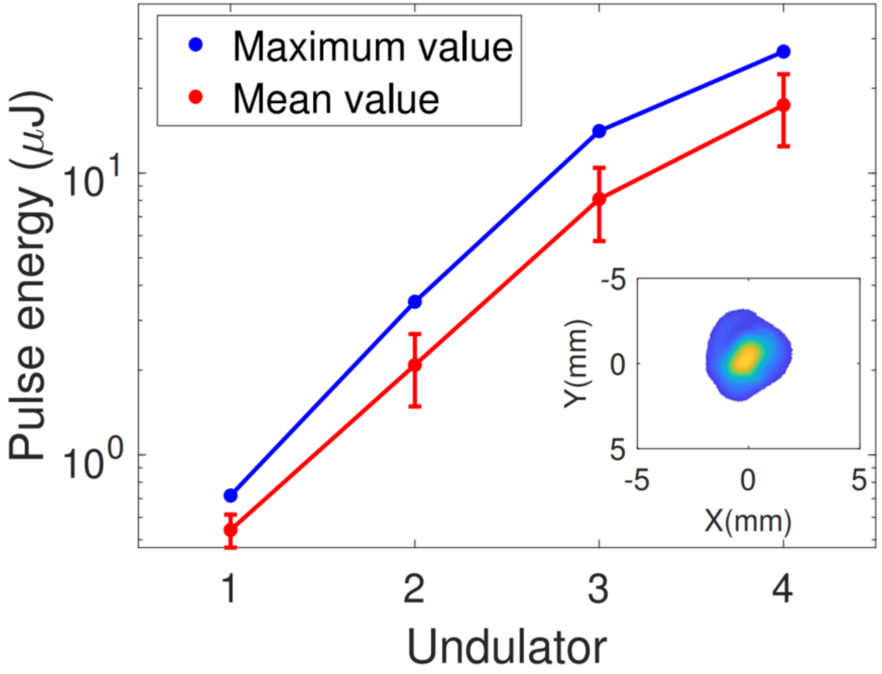
R^2_{56} = 0.16 mm

Optimial R^2_{56}: 0.17 mm (7-th harmonic)

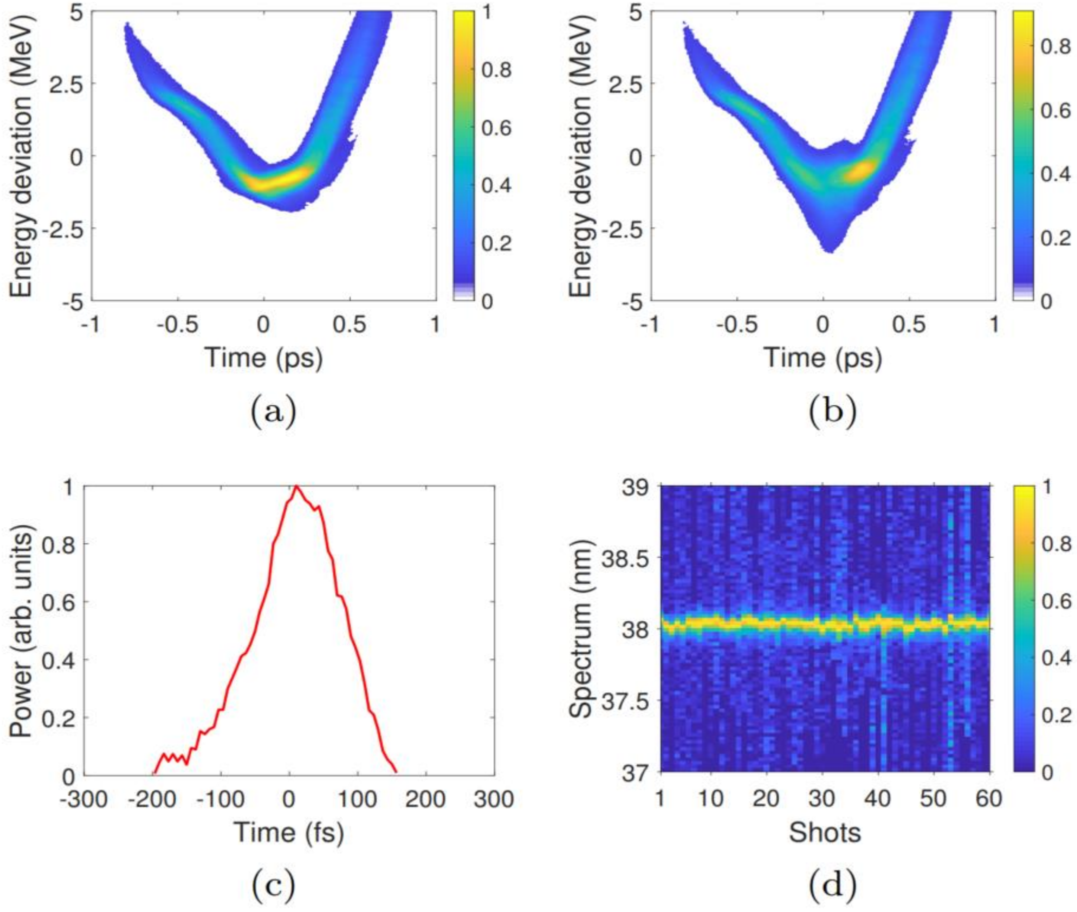
Energy modulation amplitude: 218 keV

Enhanced ~ 3-fold

Self-modulation scheme – experimental demonstration

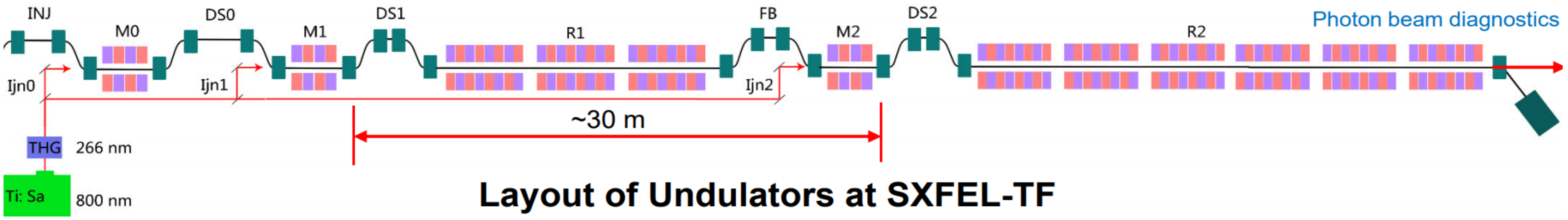


Average pulse energy ~ 17 μJ



Pulse length: 153 fs
Relative bandwidth ~ 2×10^{-3}

Self-modulation scheme – experimental demonstration

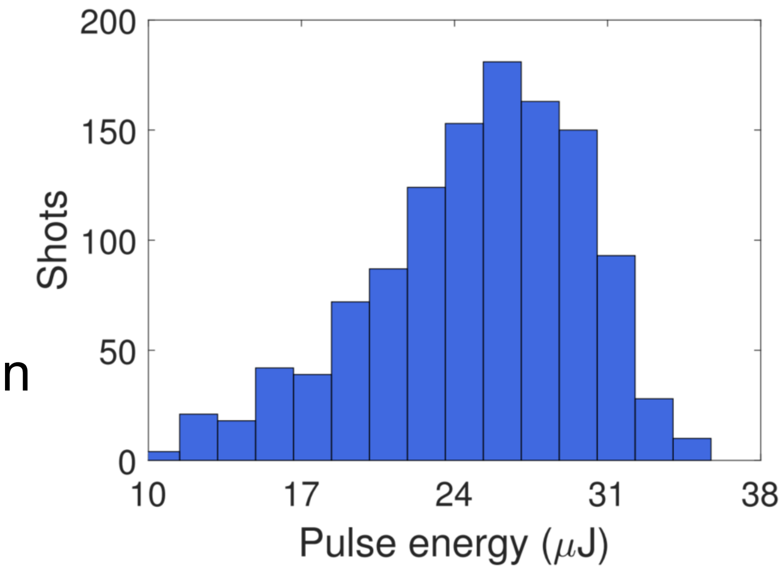


Layout of Undulators at SXFEL-TF

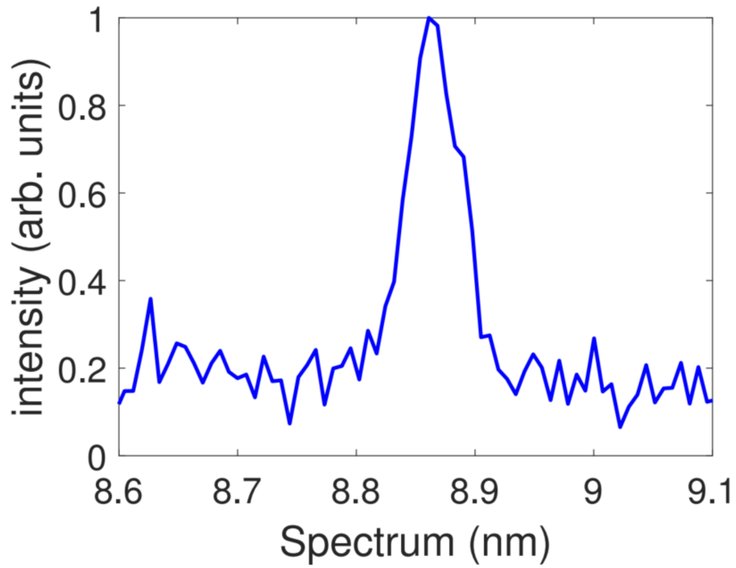
Two stage HGHG：6×5

Proof-of-principle demonstration

~0.5 μJ, Not well optimized



The 6th harmonic lasing
Single-stage



The 30th harmonic lasing
Two-stage

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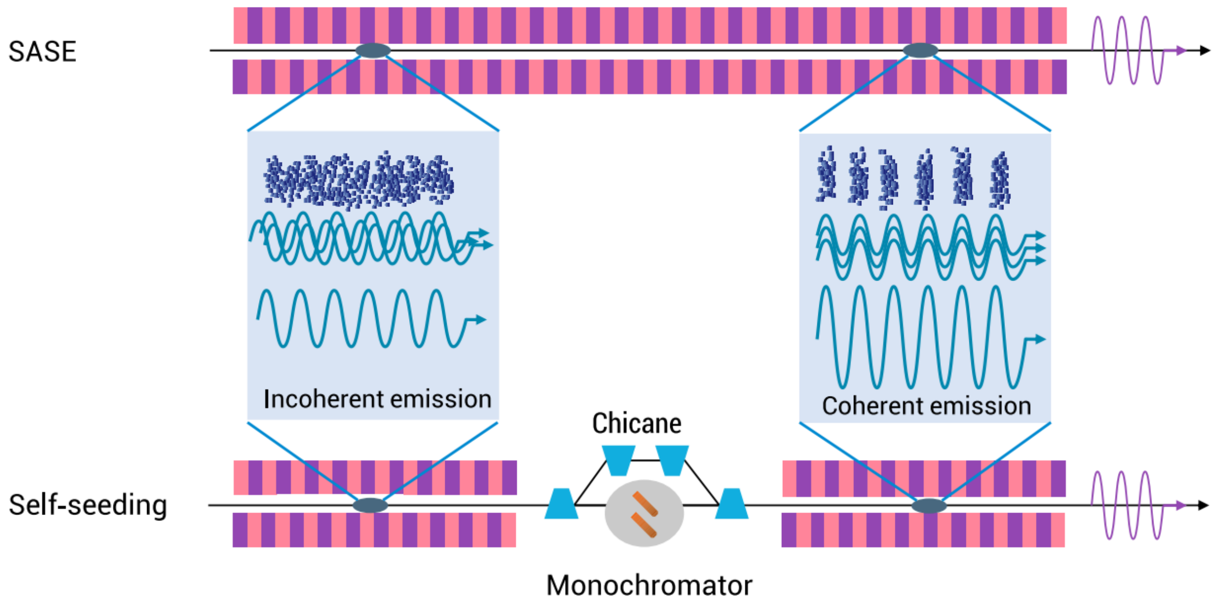
Fundamental interaction behind FEL physics



Density bunching

Energy Modulation

FEL Lasing

FEL physics: continuous interaction

FEL equation: an undulation period average

Fundamental FEL process:

electromagnetic wave & electrons interaction in a pure dipole magnetic field.

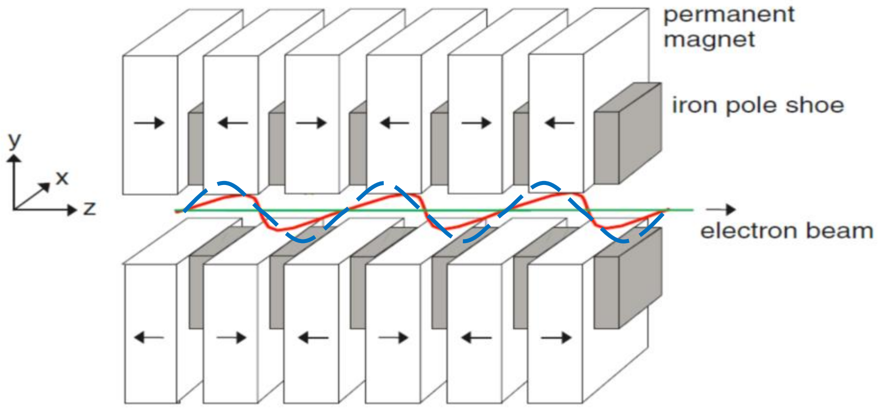
$$mc^2 \frac{d\gamma}{dt} = e v_x E_x$$

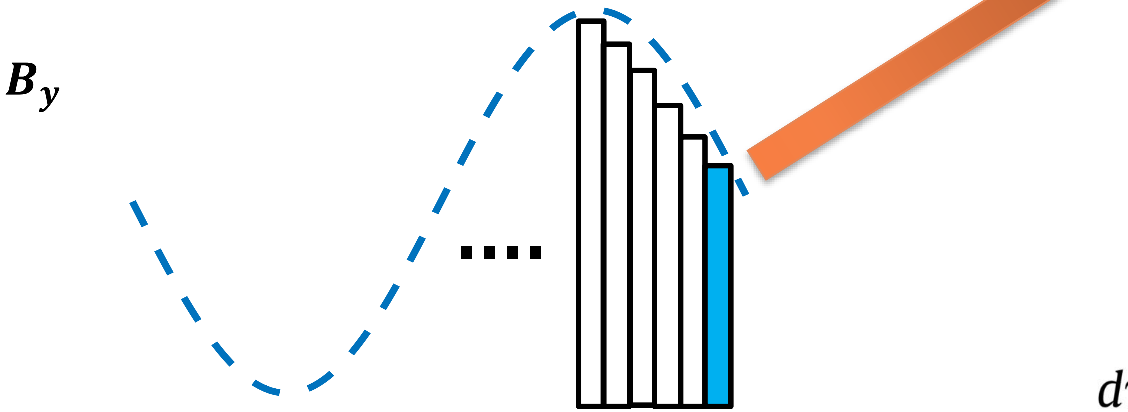
$$B_y(z) = B_0 \sin(k_u z)$$

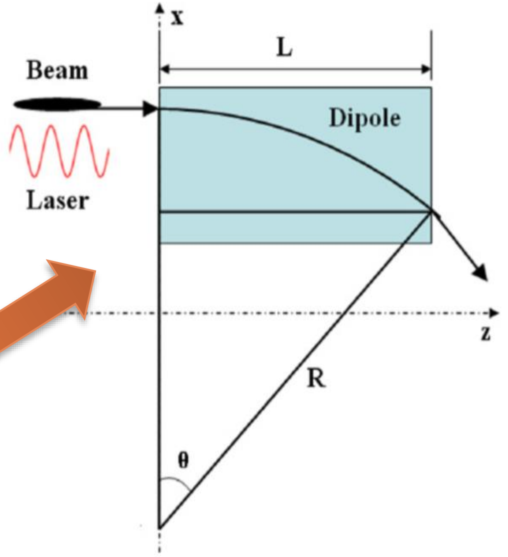
Laser-beam interaction in a dipole magnet?

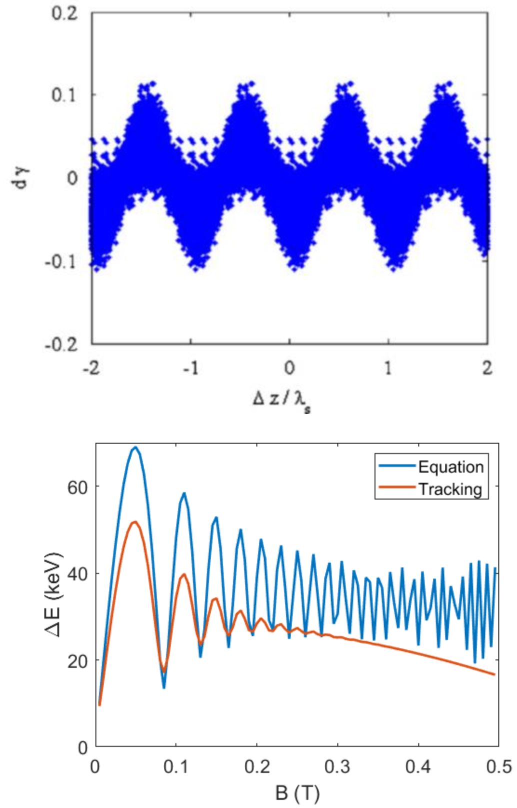
Yes, think about CSR effect in chicane.

laser-beam interaction in a dipole magnet ?







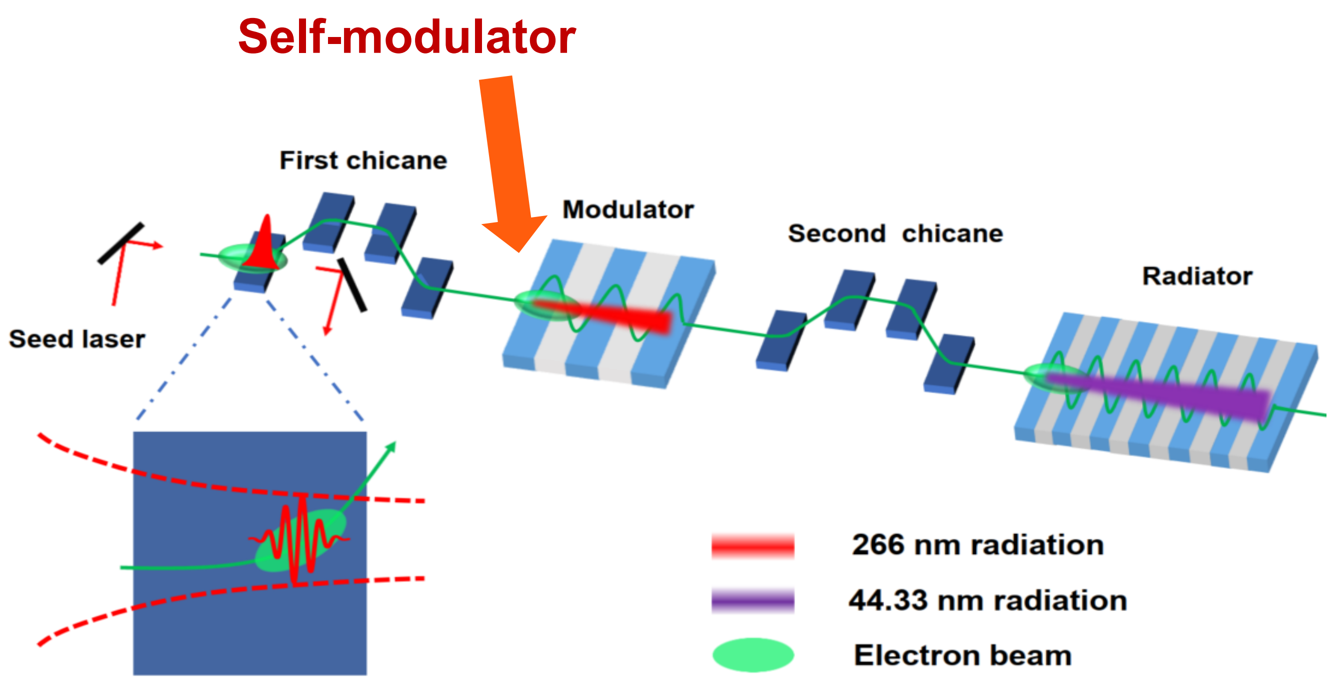


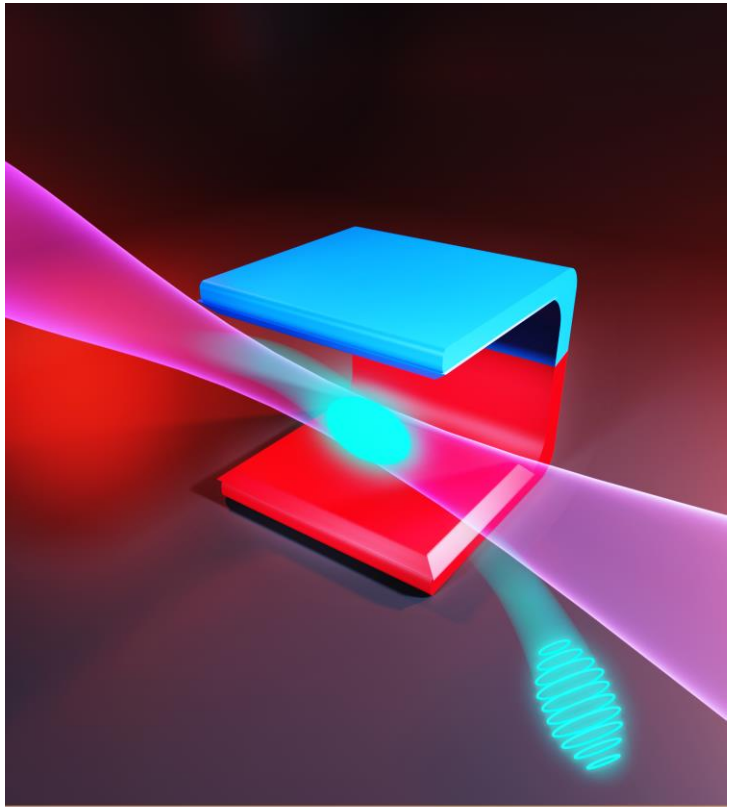
$$d\gamma(\psi_0) = \int_0^{-\theta} \frac{eE_0}{mc^2} \varphi \sin\left[k_s \Delta s(\varphi) + \psi_0\right] R\cos\varphi \, d\varphi.$$

One undulator period can be treated as a series of dipole magnets

Haixiao Deng, et al, NIMA ***622*** *(2010) 508*

Experimental setup at SXFEL test facility





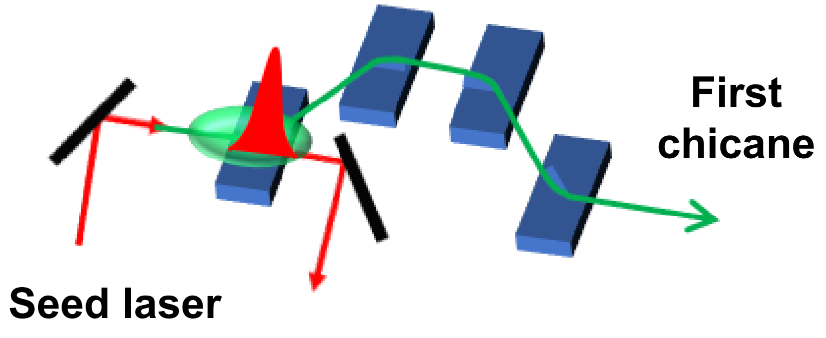
- Laser-beam interaction in the 1st dipole magnet of the 1st chicane
- Energy modulation & density modulation in one chicane
- Feasibility for launching a seeded FEL
- Switch on the 1st laser of EEHG, and switch off the 2nd laser

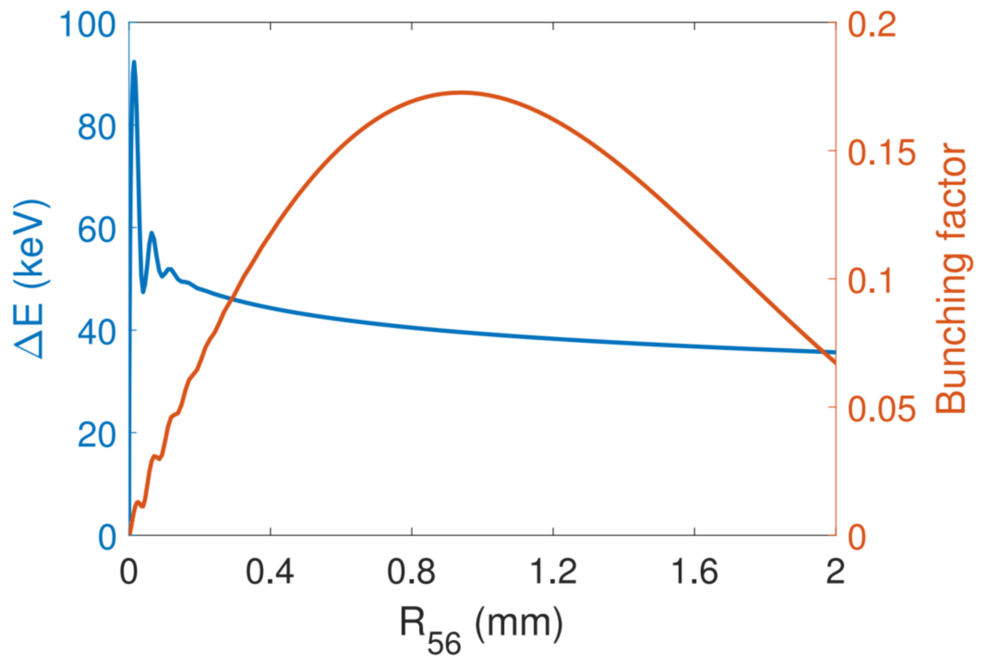
Advanced Photonics **3** *(2021) 045003*

Laser-beam interaction in a dipole: simulations

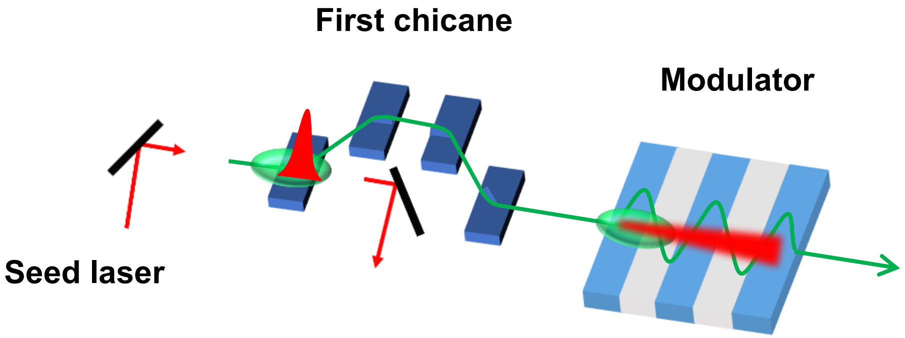
Parameters of the experiment

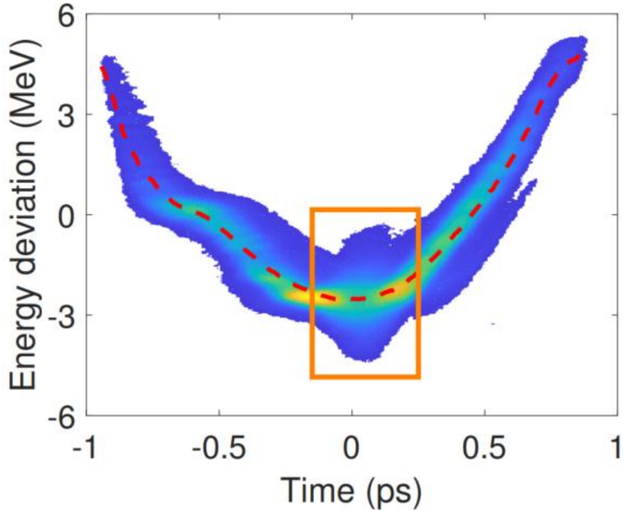
Parameters	Values
Energy	800 MeV
Peak current	600 A
Beam envelope	200 μm
Slice energy spread	30 keV
Seed laser wavelength	266 nm
Peak power	220 MW
Dipole length	0.3 m
Magnetic strength	0.03 – 0.12 T
R_{56}^{1}	0.11 – 1.7 mm



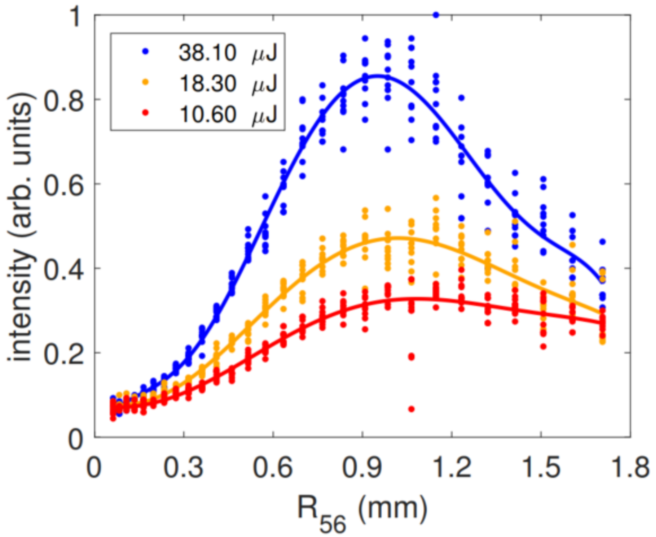


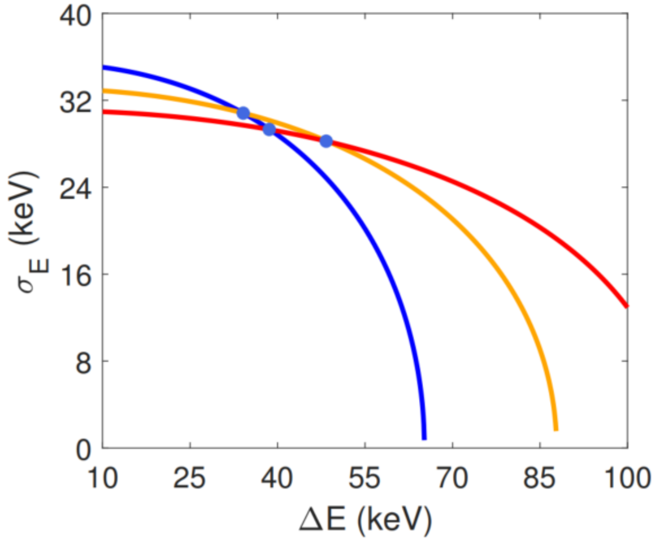
laser-beam interaction in a dipole: first observation





Just interact in the dipole , from XTCAV





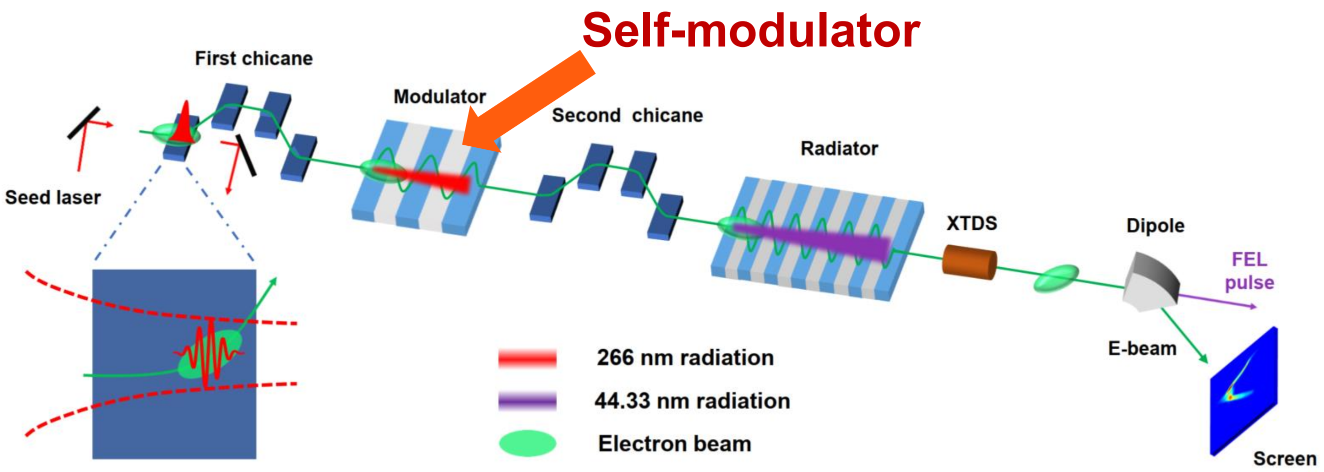
Energy modulation amplitude measurement

Initial slice energy spread: 28 keV

Energy modulation amplitude: 40 keV

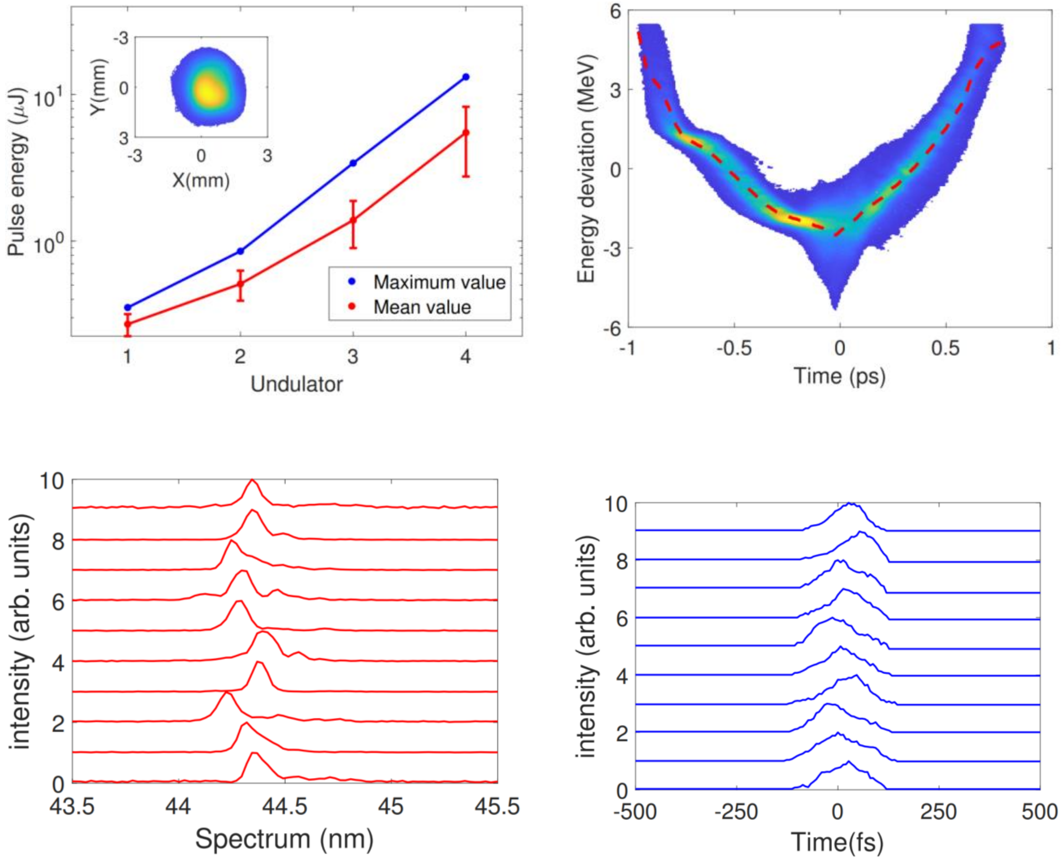
P_{seed} = 38.1 μJ; A = 1.4

Laser-beam interaction in a dipole: FEL lasing



With self-modulation amplification

A′= 253 keV, 6-fold enhancement
Average 44nm FEL pulse energy ~5.5uJ
Relative bandwidth ~ 1.7×10^{-3}
Pulse length: 113 fs



Measurement results

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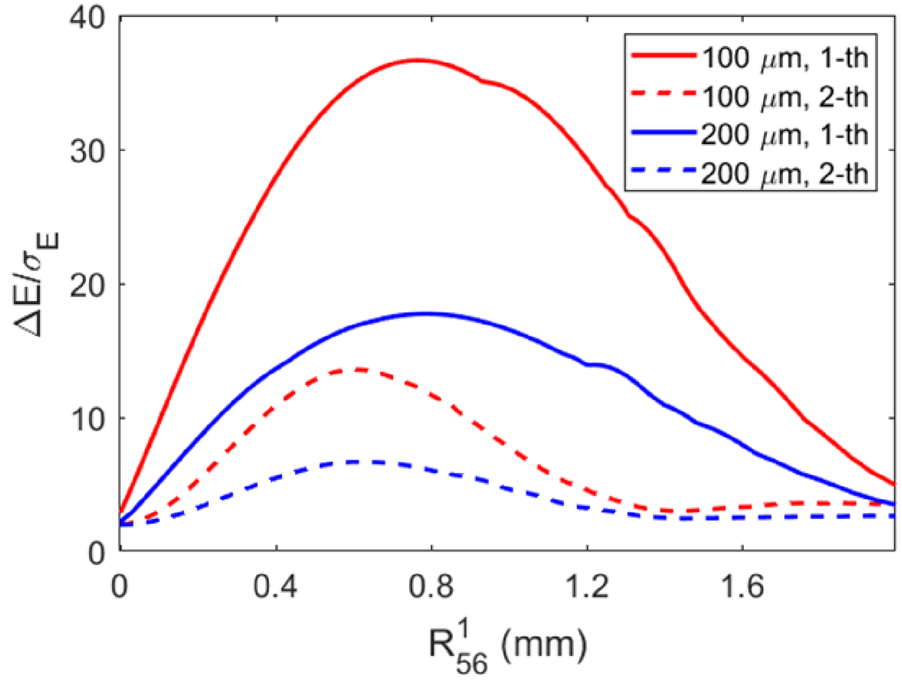
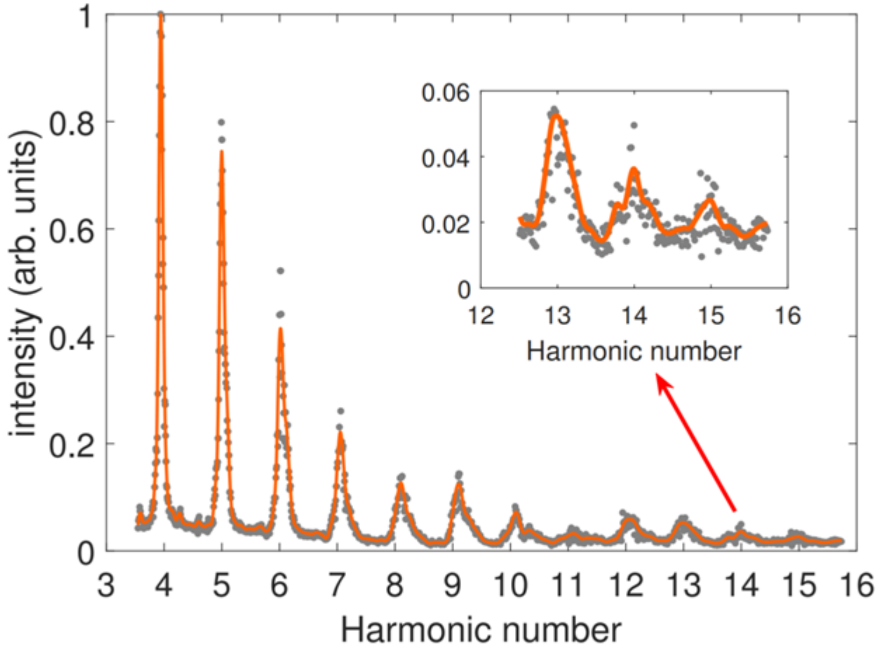
Self-modulation scheme – further exploration





A=2 ⇨ A > 35

Ultra-large energy modulation enhancement

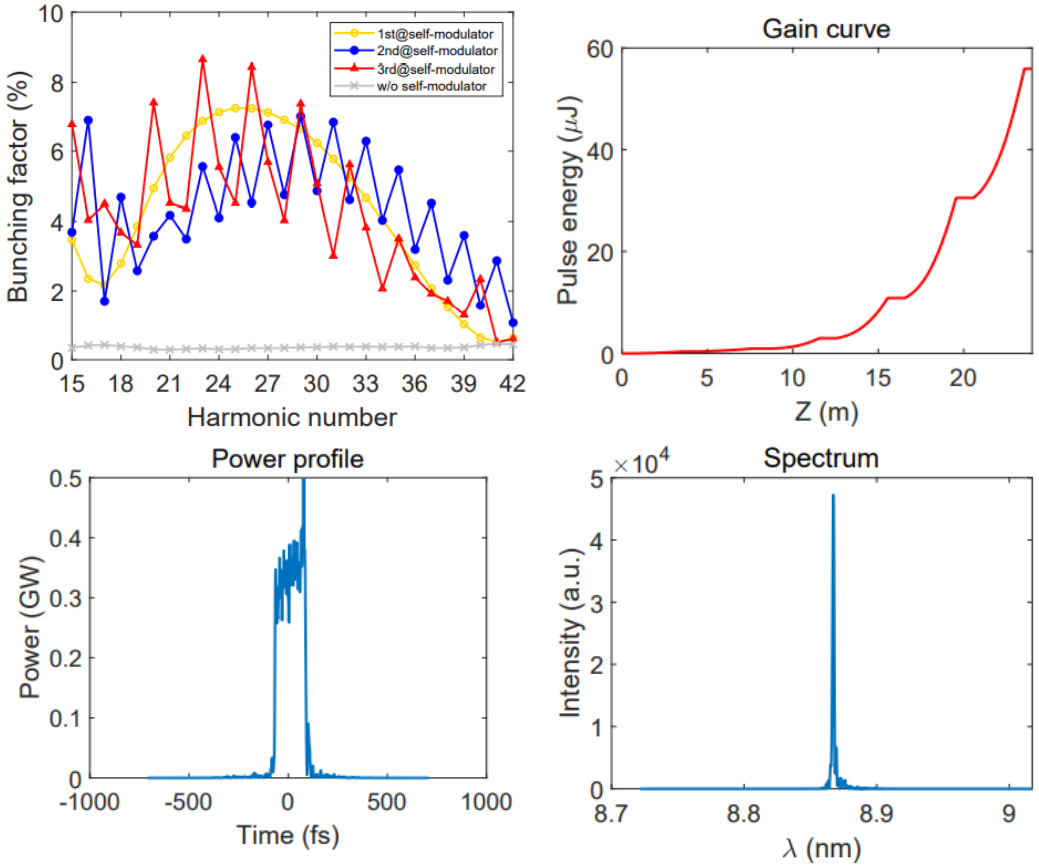
Optimized self-modulation experiment，
CHG@15th harmonic,
energy modulation ~1MeV & A~20

Paper in preparation

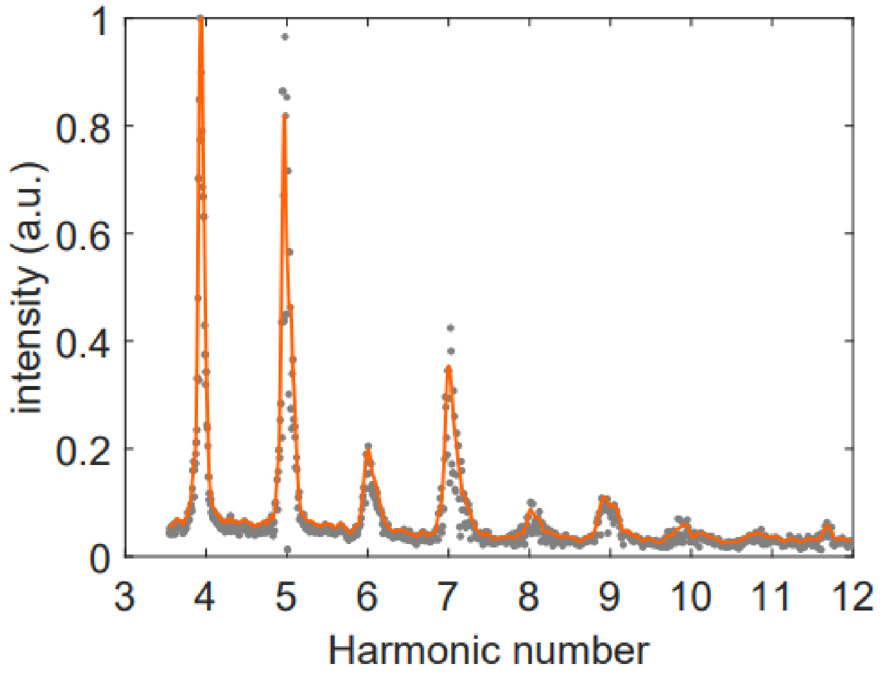
Self-modulation scheme – further exploration

Harmonic self-modulation

Large bunching factor & energy spread control



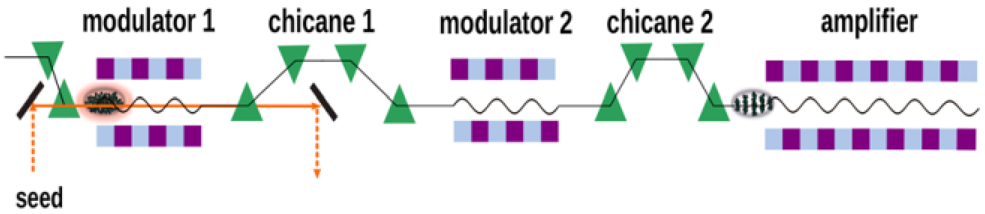
The output FEL performance at the 30th harmonic of the seed laser in the third-harmonic self-modulation



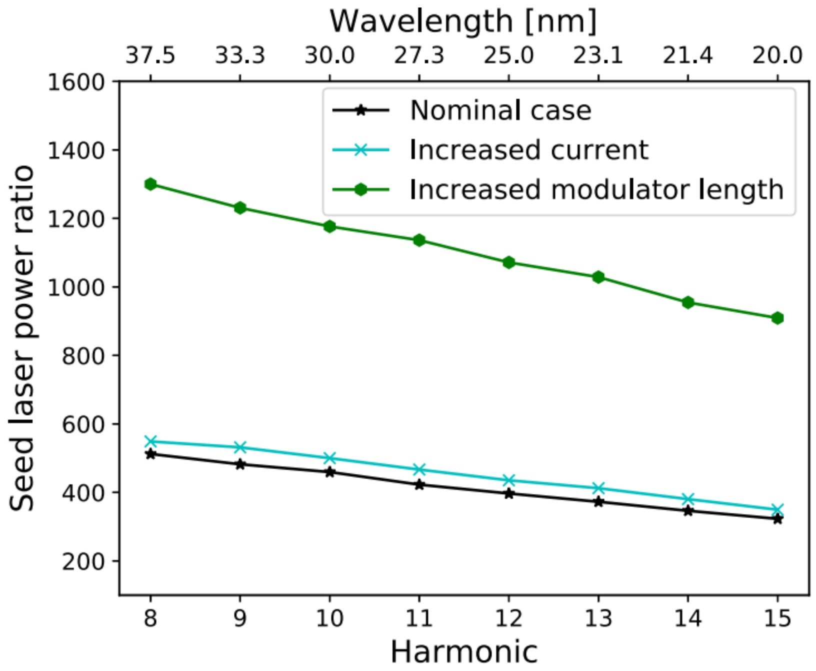
Experimental demonstration of the 2nd harmonic self-modulation

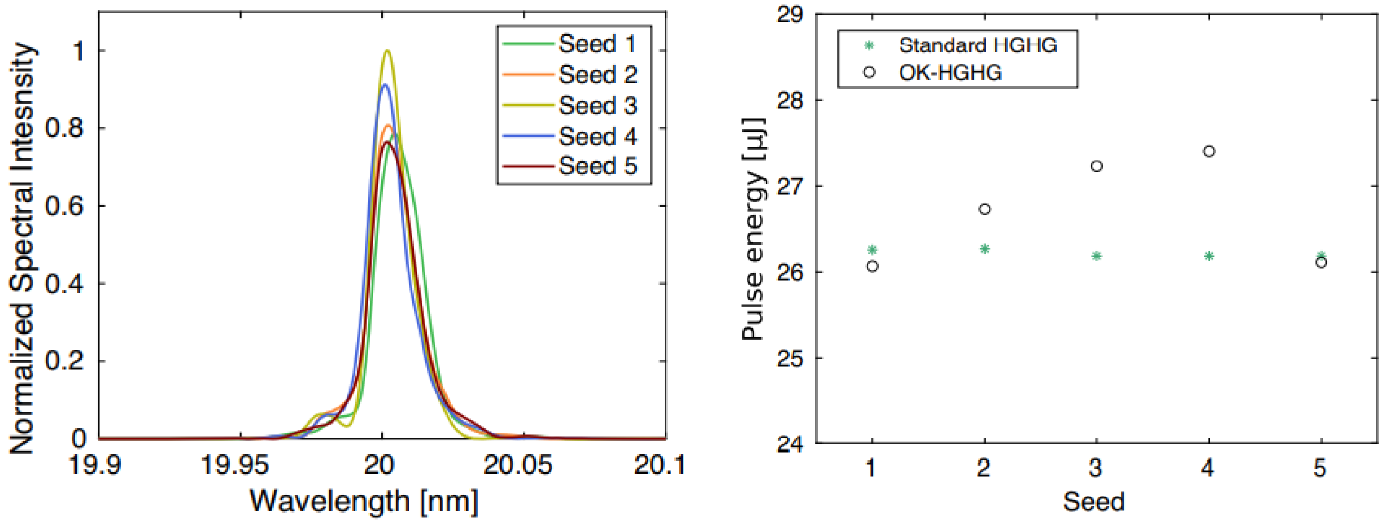
Paper in preparation

Self-modulation scheme – FLASH2020+ studies



See THOXSP3, IPAC2022
Paraskaki's talk, on Thursday.





Low signal to noise ratio does not deteriorate the coherence properties of the output FEL from shot to shot.

Reduction of the seed laser power by a factor of up to 1300.

Paraskaki G, Allaria E, Schneidmiller E, et al. PRAB, 2021, 24(12): 120701.

Summary and Outlook

Summary

- ✓ We proposed and experimentally demonstrated the self-modulation mechanism in seeded FEL
- ✓ More than 5-fold energy modulation enhancement, several tens of seed laser power relaxation achieved
- ✓ A = 1.8 for lasing at 7th harmonic in single-stage HGHG & 30th harmonic in two-stage HGHG
- ✓ Demonstration & measurement of the laser-beam interaction in a dipole magnet

Outlook

- ✓ Relax the seed laser power by three orders of magnitude
- ✓ Ultra-large energy modulation, coherent harmonic generation at >60th harmonic ?
- ✓ Ultra-high harmonic generation, single-stage HGHG at 30th harmonic ?
- ✓ Improving timing jitter（longer seed laser pulse）and transverse overlap jitter（larger seed laser size)
- ✓ HHG-seeded FELs

Thanks for your attention!