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

# Self-amplification of laser-induced energy modulation in FELs


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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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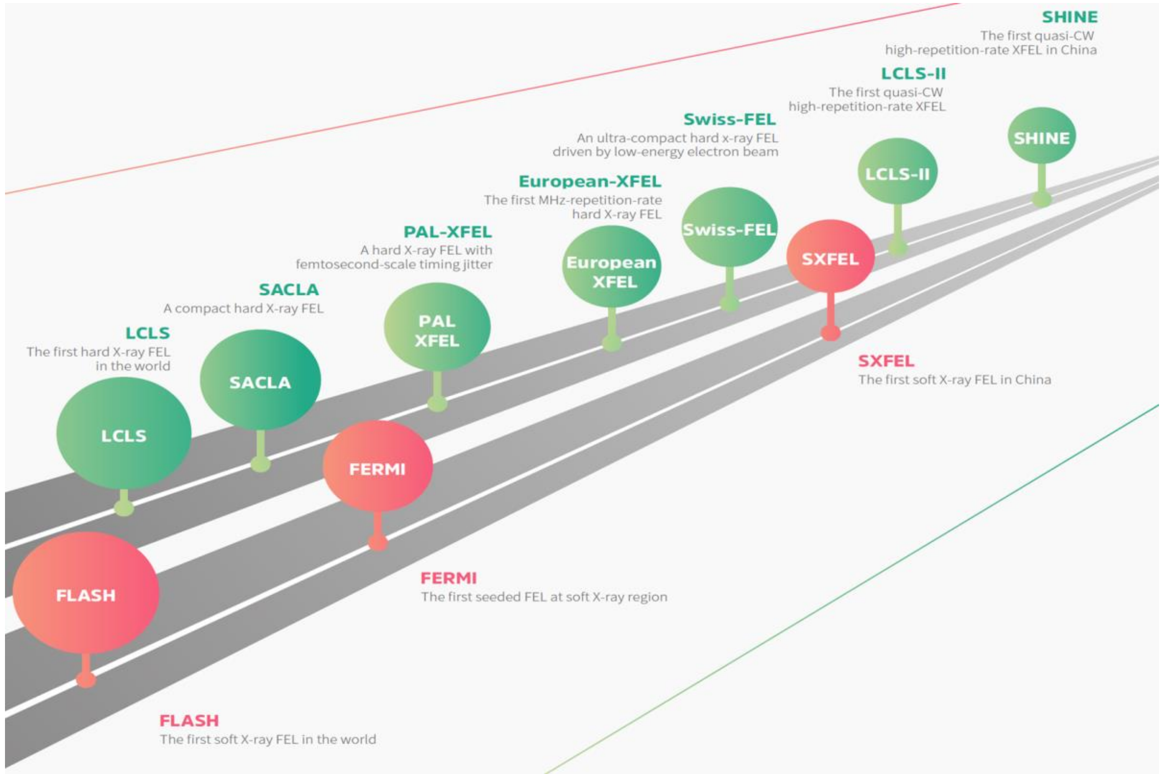
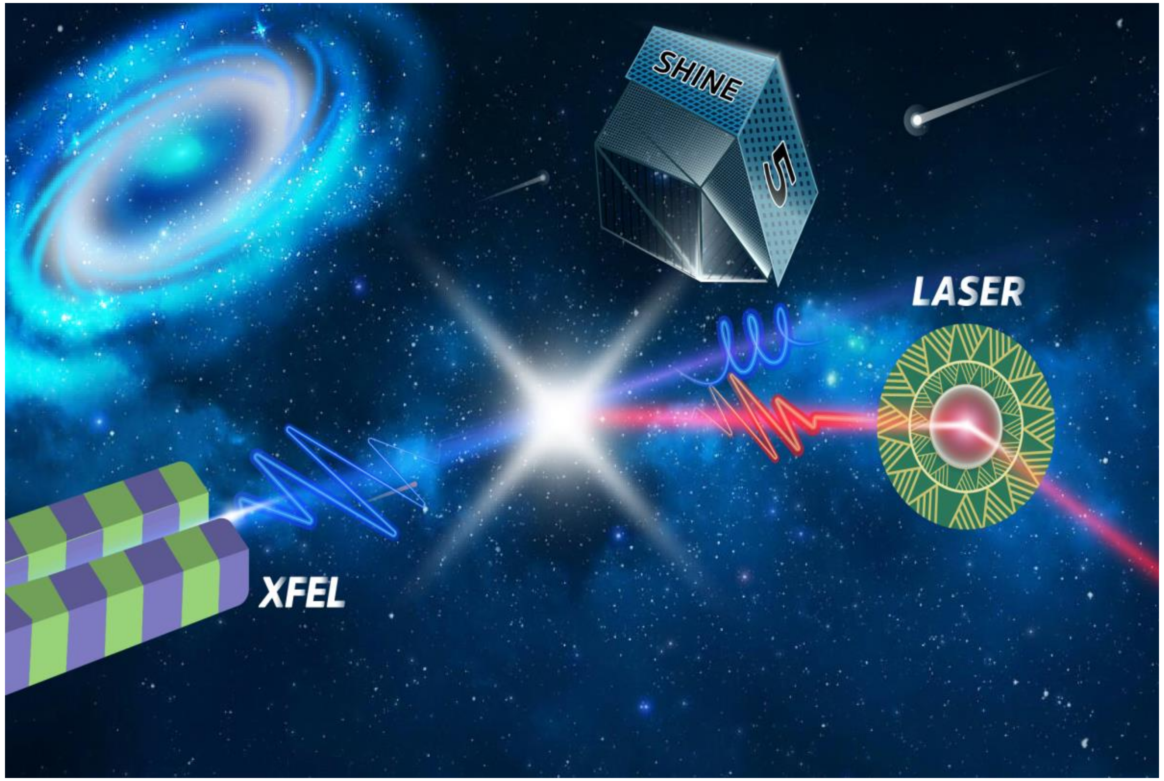
# Features and futures of X-ray free electron lasers

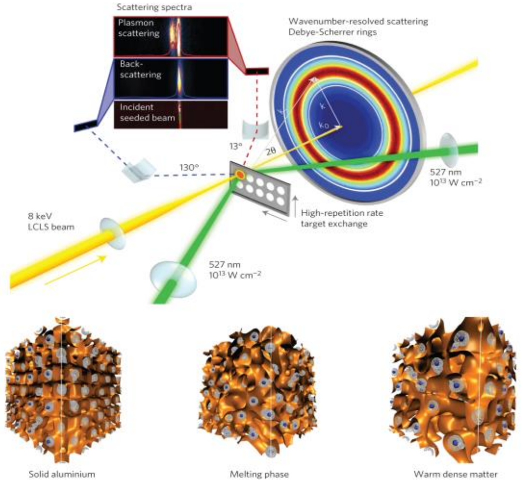



N. Huang, H. Deng*, B. Liu, D. Wang, Z. Zhao*,
Features and futures of X-ray free-electron laser. The Innovation 2 (2021) 100097.

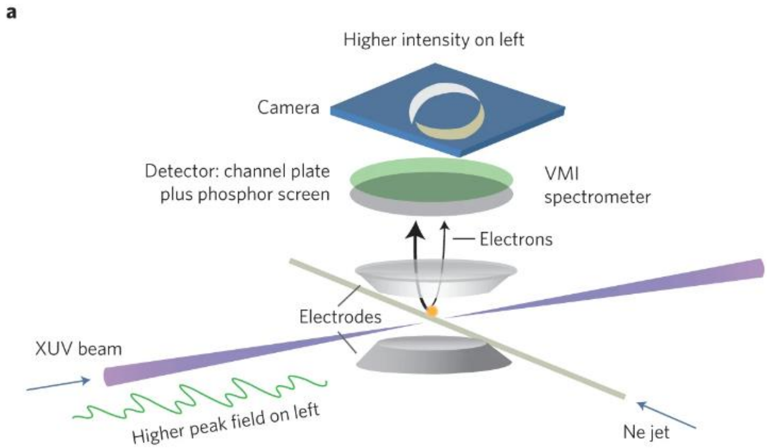
# In pursuit of fully coherent X-ray FELs

- 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.*



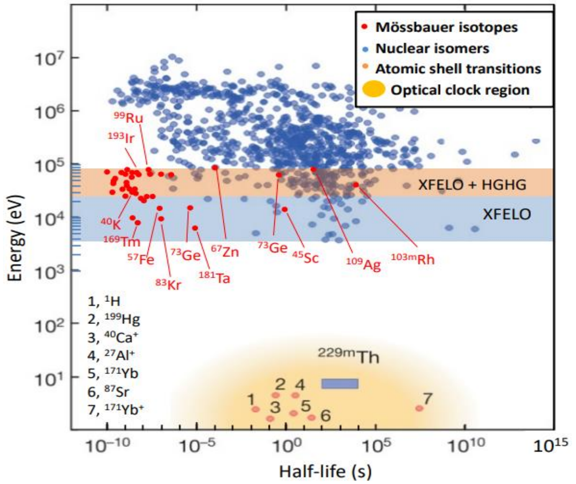

Ultrabright X-ray laser scattering for dynamic warm dense matter physics.

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




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

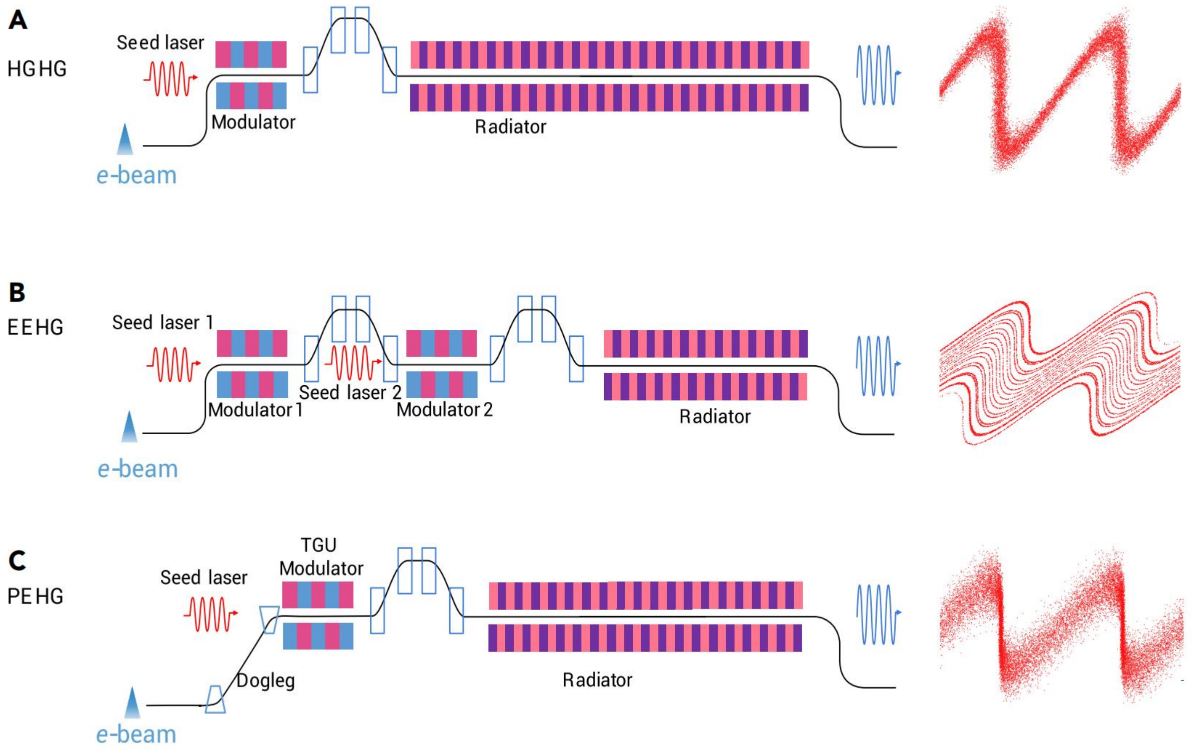
***Nature Photonics*, 2016, 10(3): 176-179.**




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

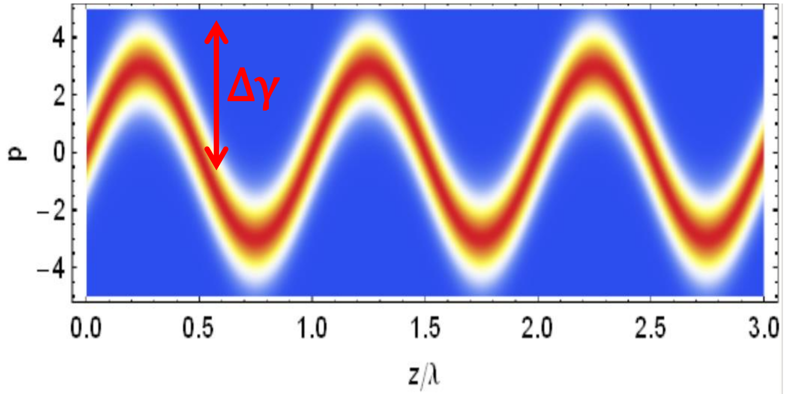
***arXiv:1903.09317, 2019.***

# 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.



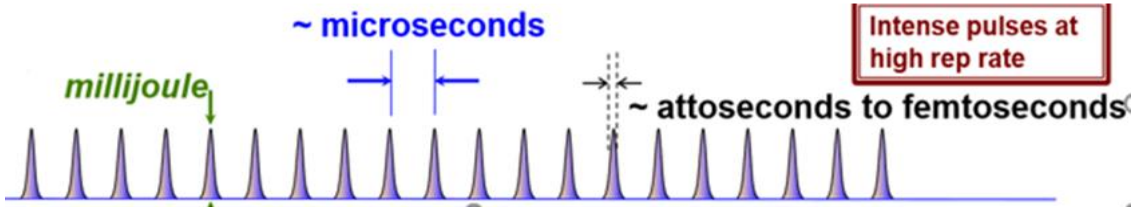

$$A = \Delta\gamma / \sigma_\gamma$$

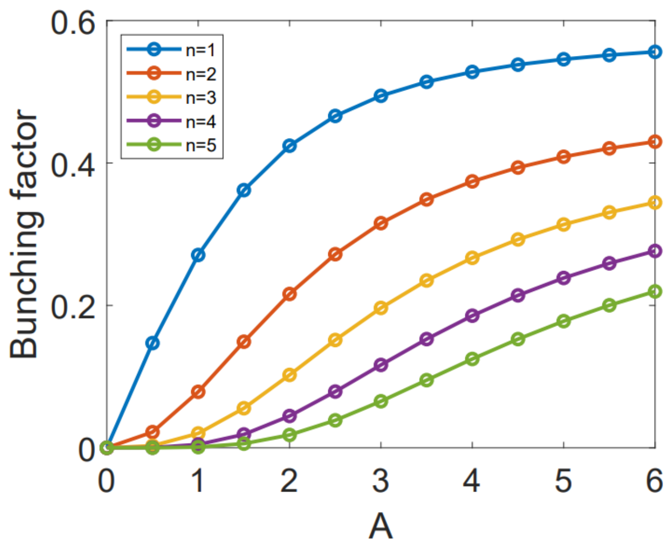
Normalized energy modulation amplitude

- 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

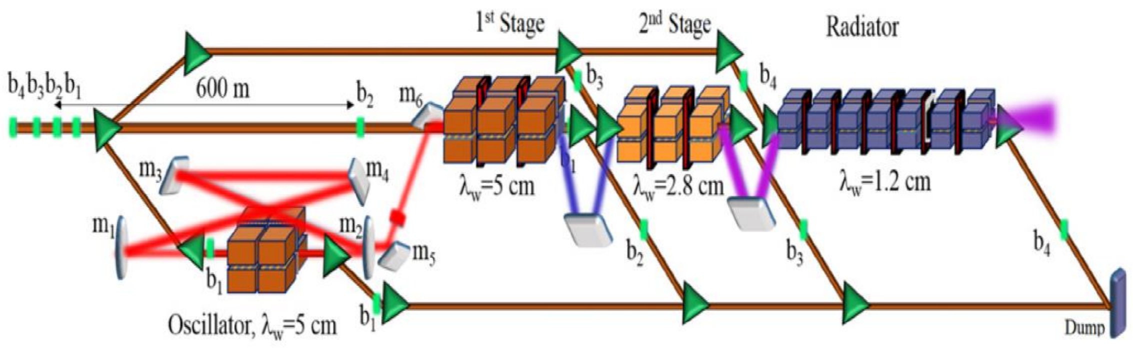
| | specification | target |
|---|---|---|
| wavelength | 240-260nm | |
| rep. rate | ≥10kHz | ×100 |
| Pulse energy | 10μJ | ×10-100 |
| Pulse duration (FWHM) | 25fs | |
| Energy jitter (rms) | ≤2% | |
| Pointing stability (rms) | ≤5μrad | |
| Timing jitter (rms) | ≤10fs | ÷10 |
| Laser spot (FWHM)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

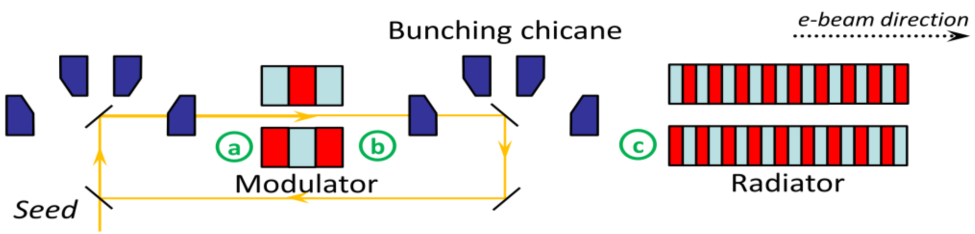
# High-repetition-rate seeded FELs

## ◻ 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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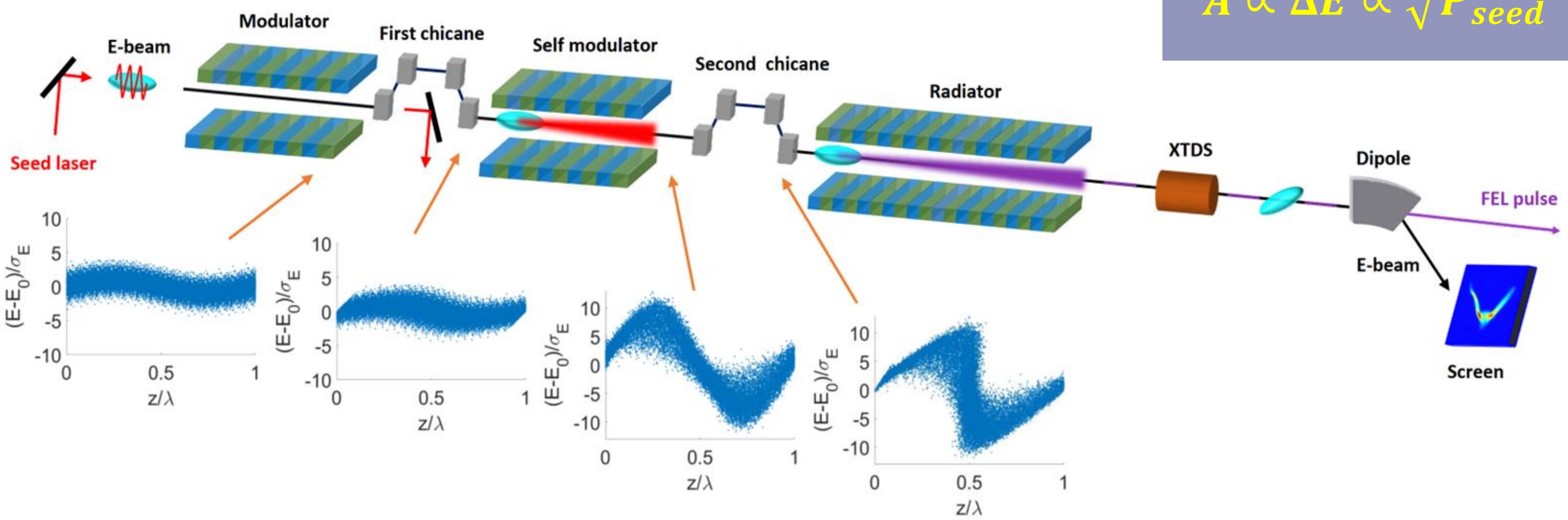
# Self-amplification of laser-induced energy modulation

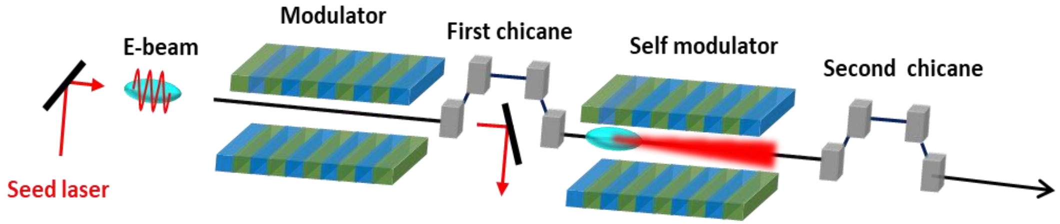
$$A \propto \Delta E \propto \sqrt{P_{seed}}$$




**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



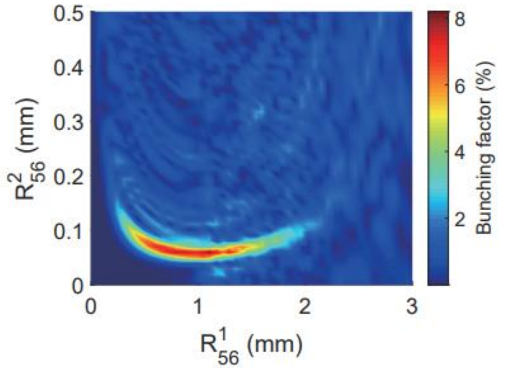

Parameters of SXFEL user facility

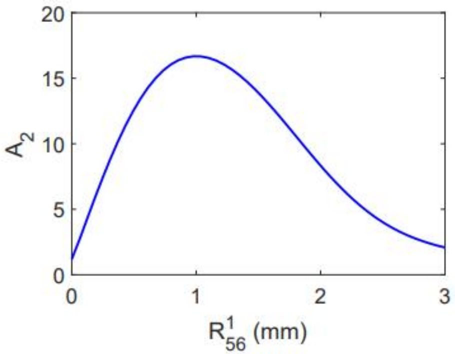
| | |
|---|---|
| Beam Energy | 1400 MeV |
| Peak current | ~ 700 A |
| Bunch length | ~ 0.8 ps |
| Emittance | 1 mm-mrad |
| Slice energy spread | ~ 50 keV |
| (Self-) Modulator | 1.6 m/80 mm |
| Seed laser | 266 nm |
| Seed laser power (HGHG) | 17-75 MW |
| Seed laser power (self-modulation HGHG) |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

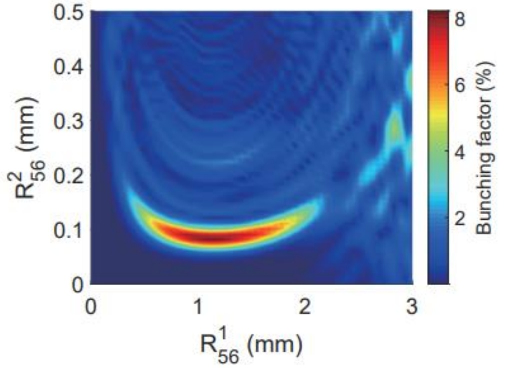
**8% bunching factor at 13-th harmonic**

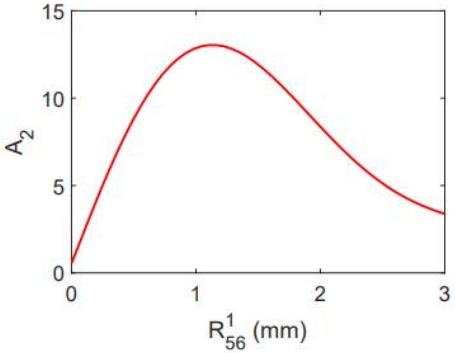



100 $\mu m$ size

0.62 MW (vs. 55 MW)

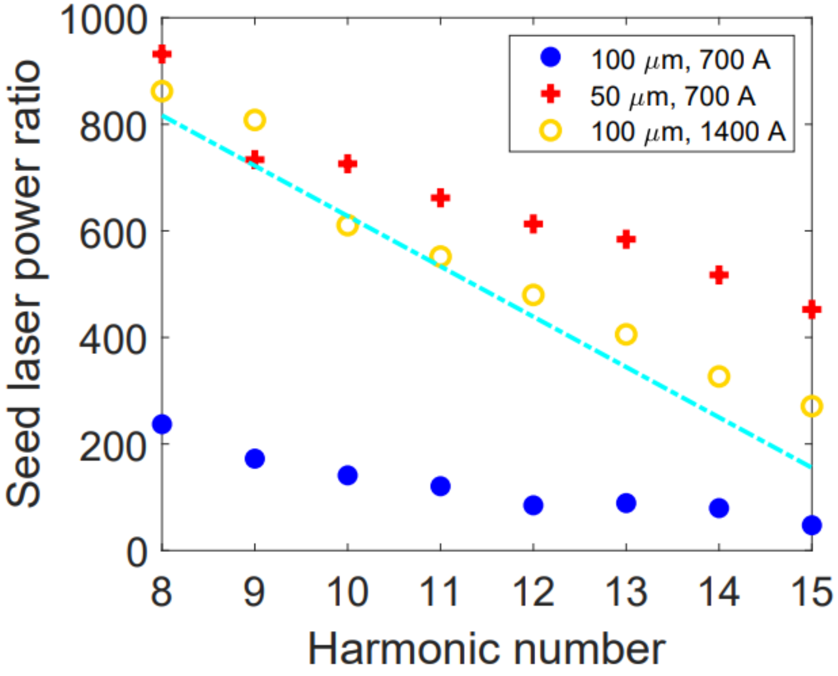


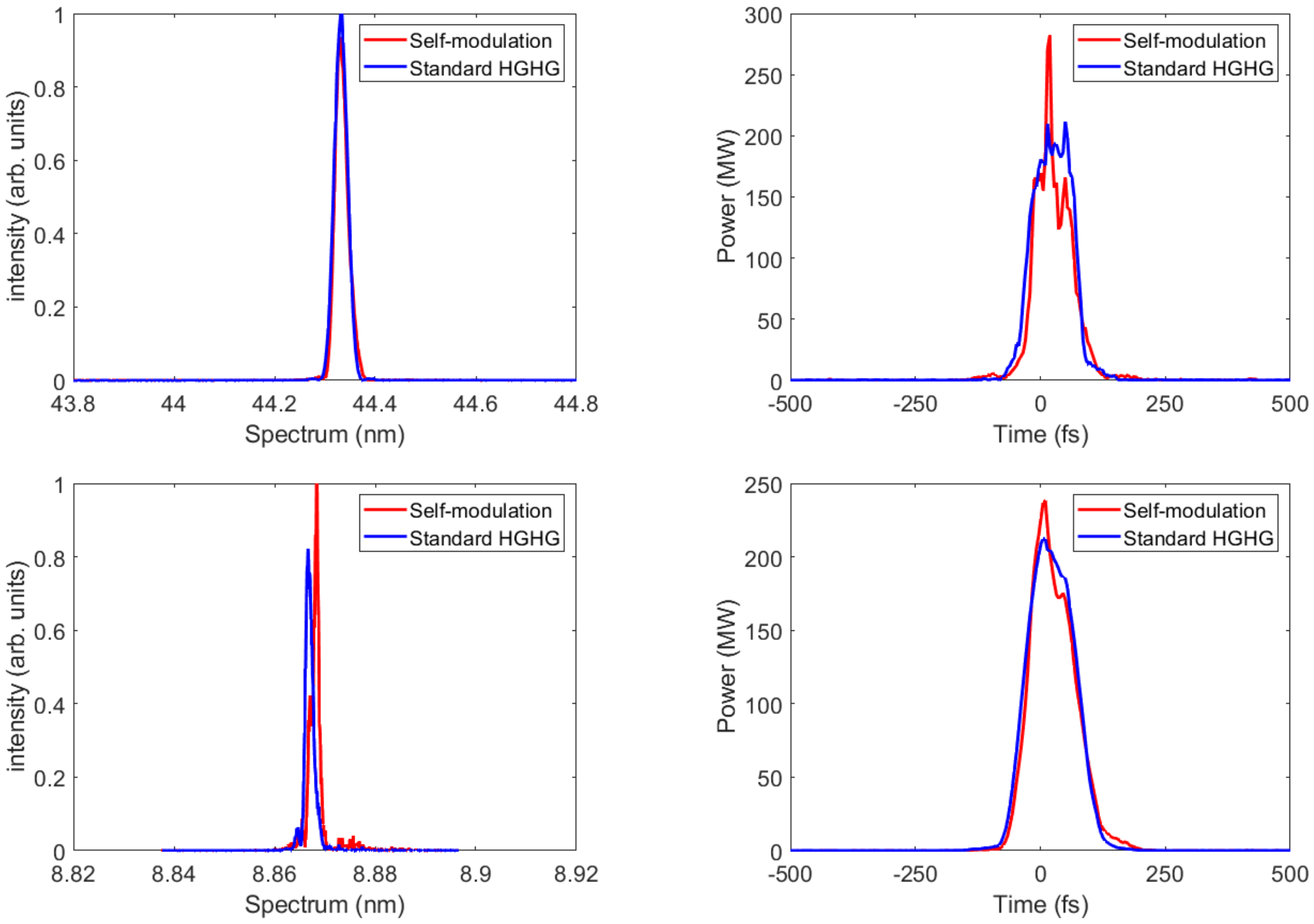

50 $\mu m$ size

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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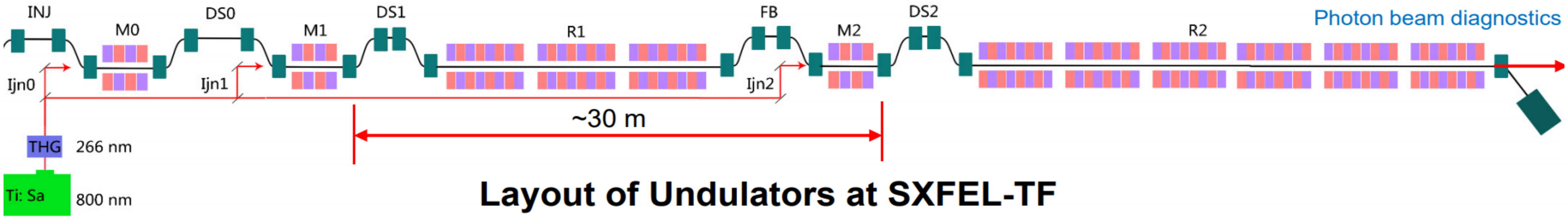
# Experimental demonstration at SXFEL test facility



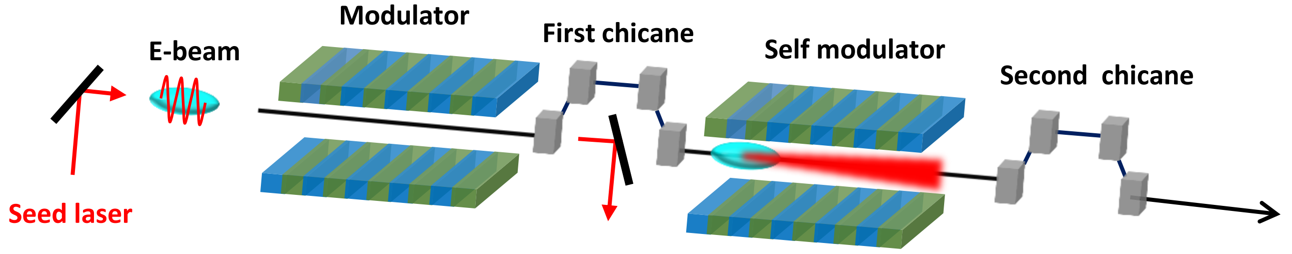

Layout of Undulators at SXFEL-TF

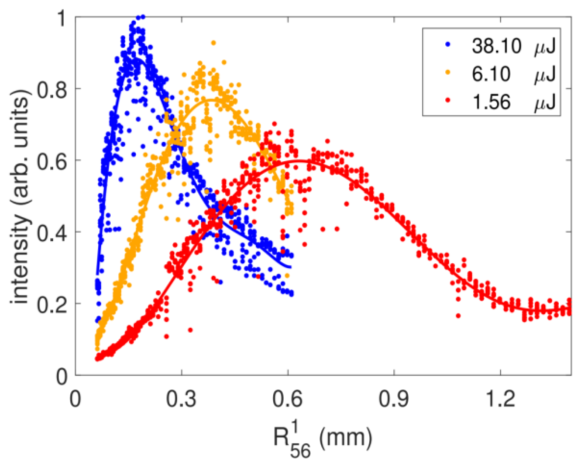
- Shanghai soft x-ray test facility (2014-2020), now at user facility phase.
- two-stage seeded FEL: HGHG-HGHG, and EEHG-HGHG
- a perfect platform for self-amplification of laser-induced modulation
- the second modulator in EEHG serves as the self-modulator
- the experiments were conducted at $12^{th}$-$17^{th}$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

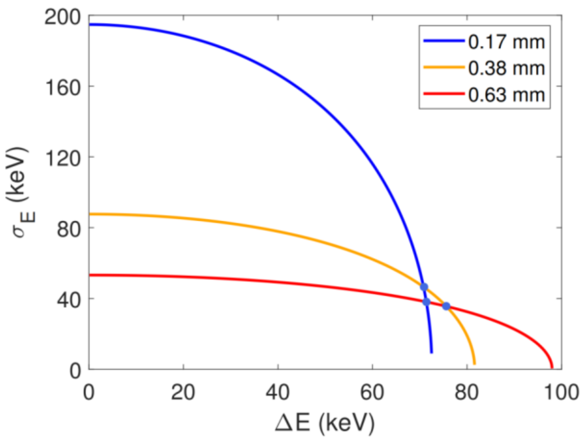
# Self-modulation scheme – experimental demonstration

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 |

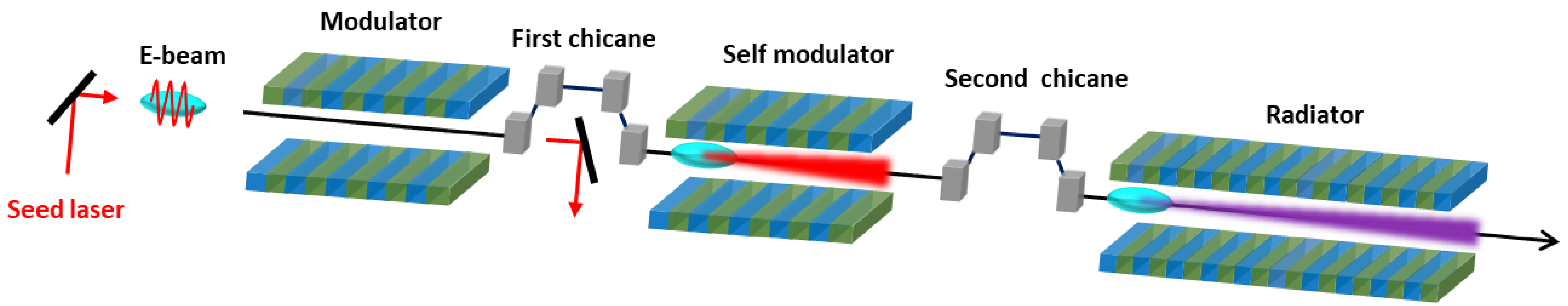


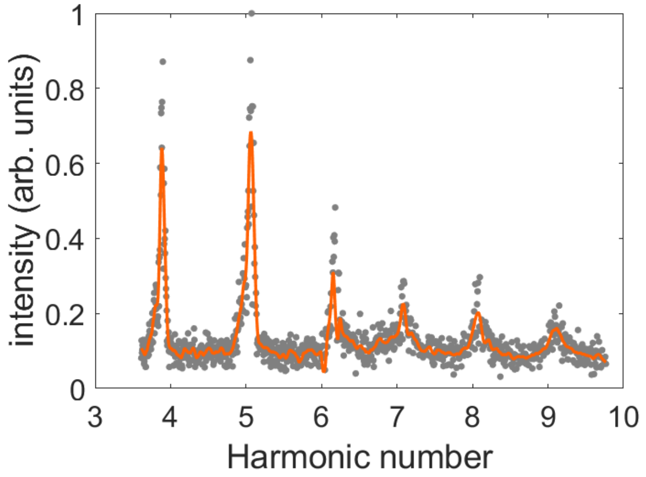



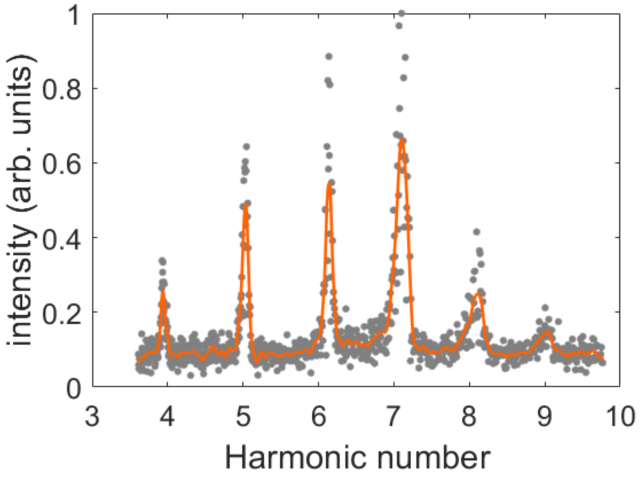

**Initial slice energy spread: 40 keV**
**Energy modulation amplitude: 73 keV**
**$P_{seed}$ = 1.56 μJ; A = 1.8**

# Self-modulation scheme – experimental demonstration




$R_{56}^2$ = 0.23 mm



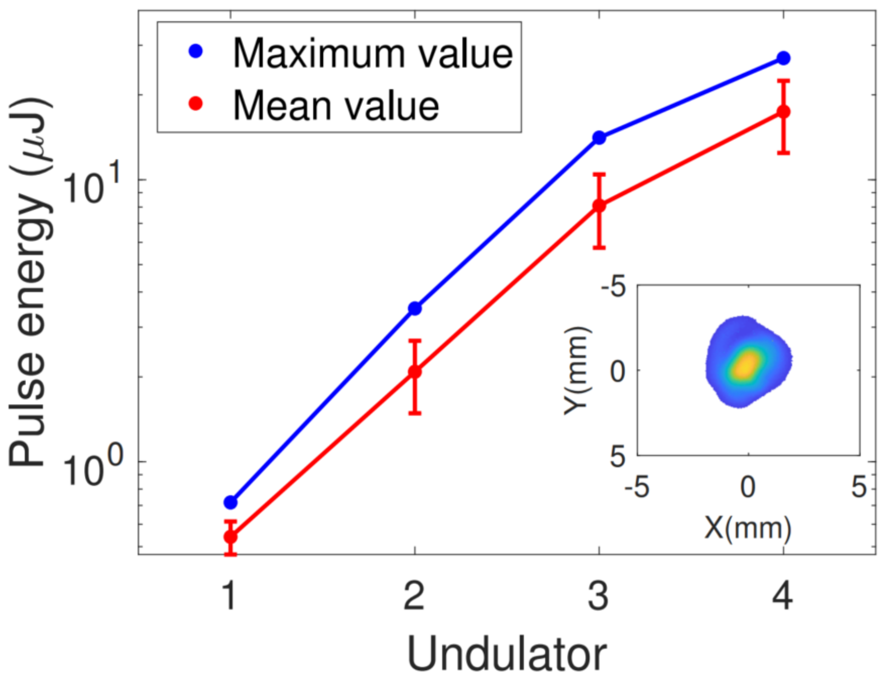

$R_{56}^2$ = 0.16 mm

**Optimial $R_{56}^2$: 0.17 mm (7-th harmonic)**

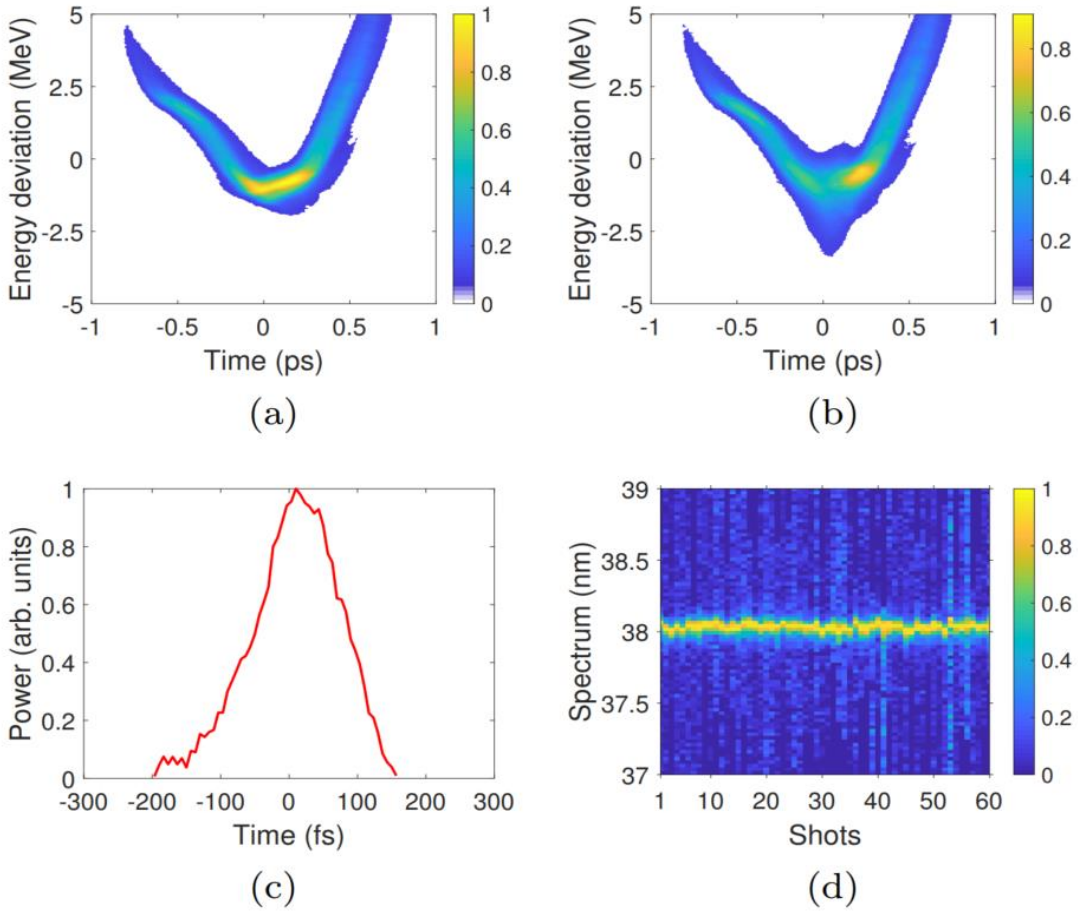
**Energy modulation amplitude: 218 keV**

**Enhanced ~ 3-fold**

# Self-modulation scheme – experimental demonstration



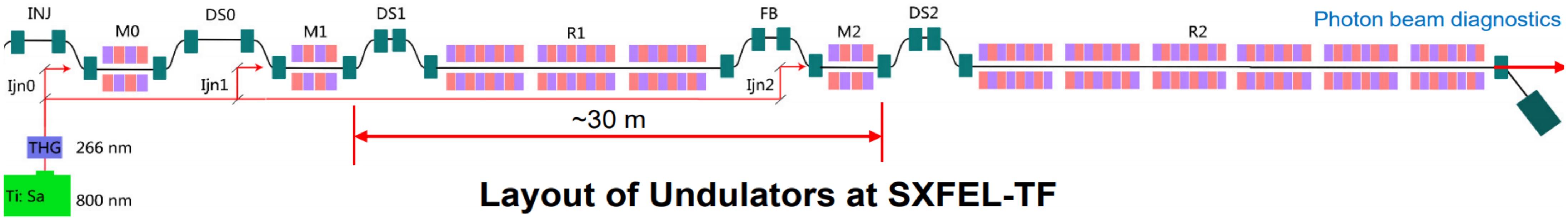

**Average pulse energy ~ 17 μJ**




**Pulse length: 153 fs**

**Relative bandwidth ~ $2 \times 10^{-3}$**

# Self-modulation scheme – experimental demonstration

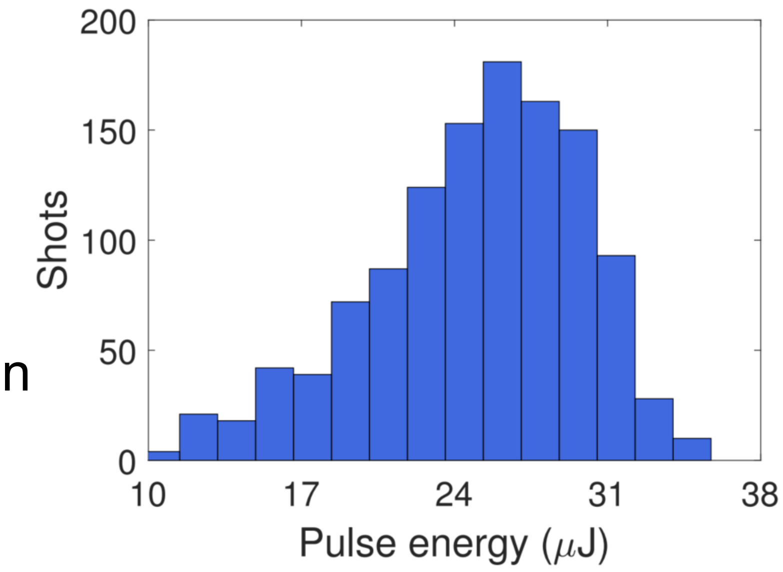



Layout of Undulators at SXFEL-TF

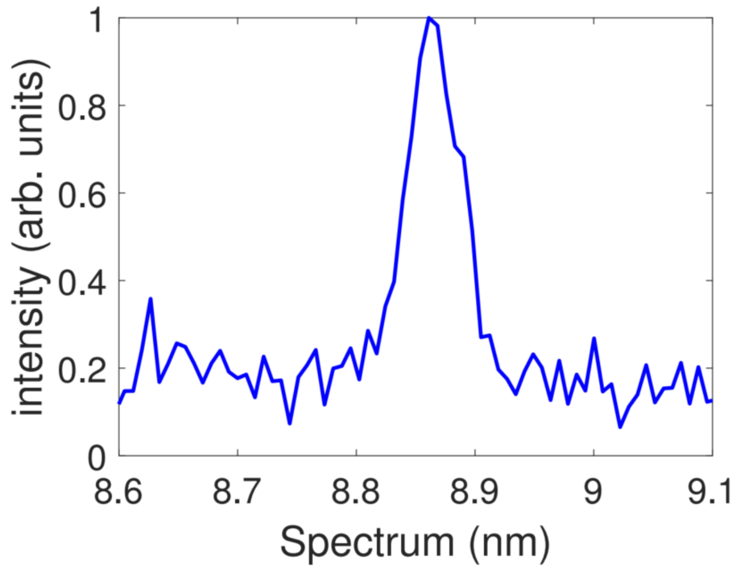
**Two stage HGHG：6×5**

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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- **Amplification of laser-induced modulation in a dipole**
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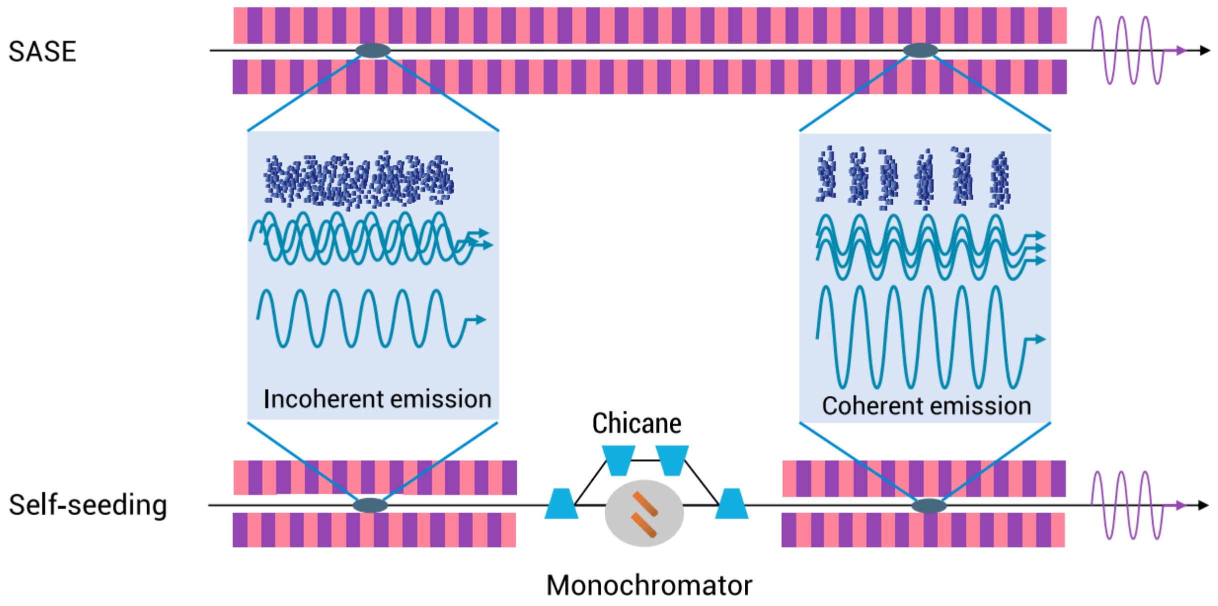
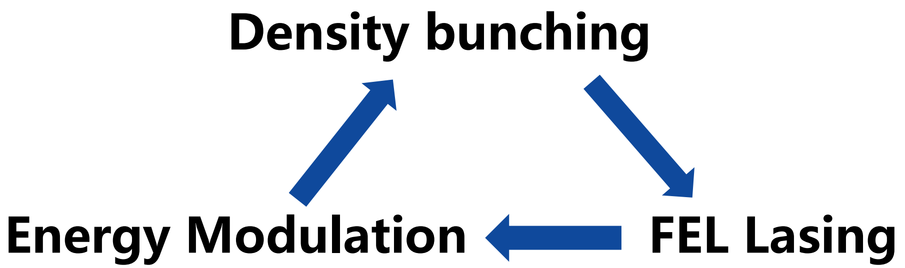
# Fundamental interaction behind FEL physics




**FEL physics: continuous interaction**

**FEL equation: an undulation period average**

**Fundamental FEL process:**

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

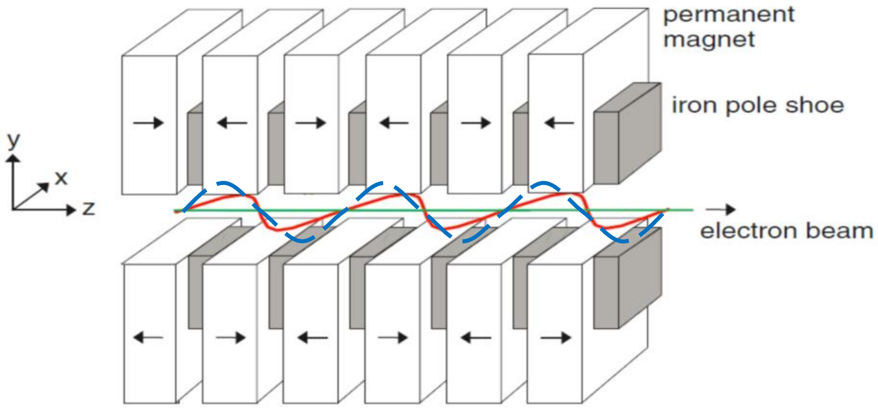
$$mc^2 \frac{d\gamma}{dt} = ev_x E_x$$

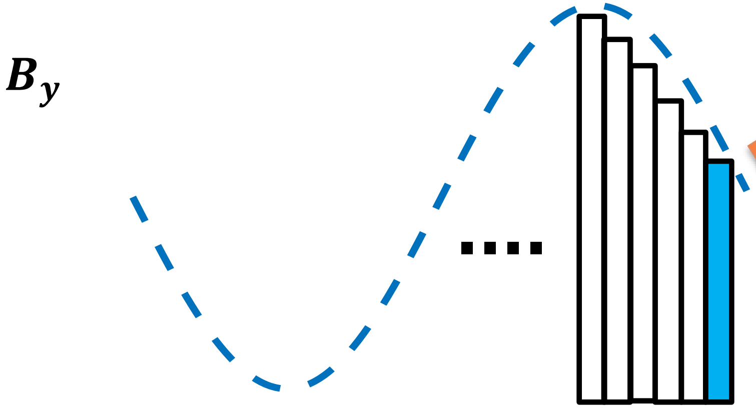
$$B_y(z) = B_0 \sin(k_u z)$$

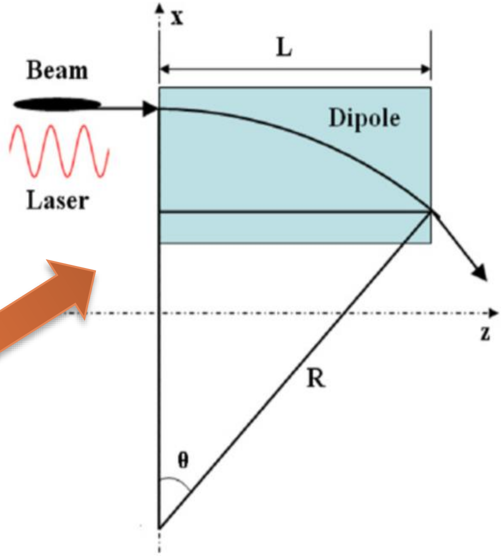
**Laser-beam interaction in a dipole magnet?**

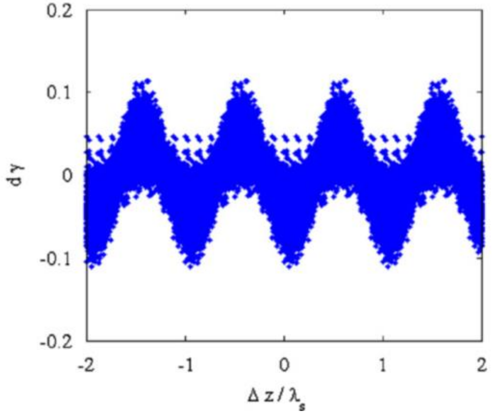
**Yes, think about CSR effect in chicane.**

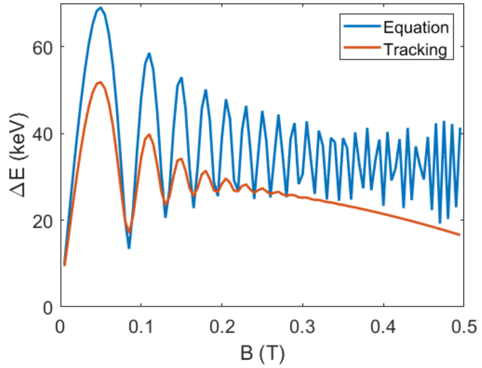
# laser-beam interaction in a dipole magnet ?



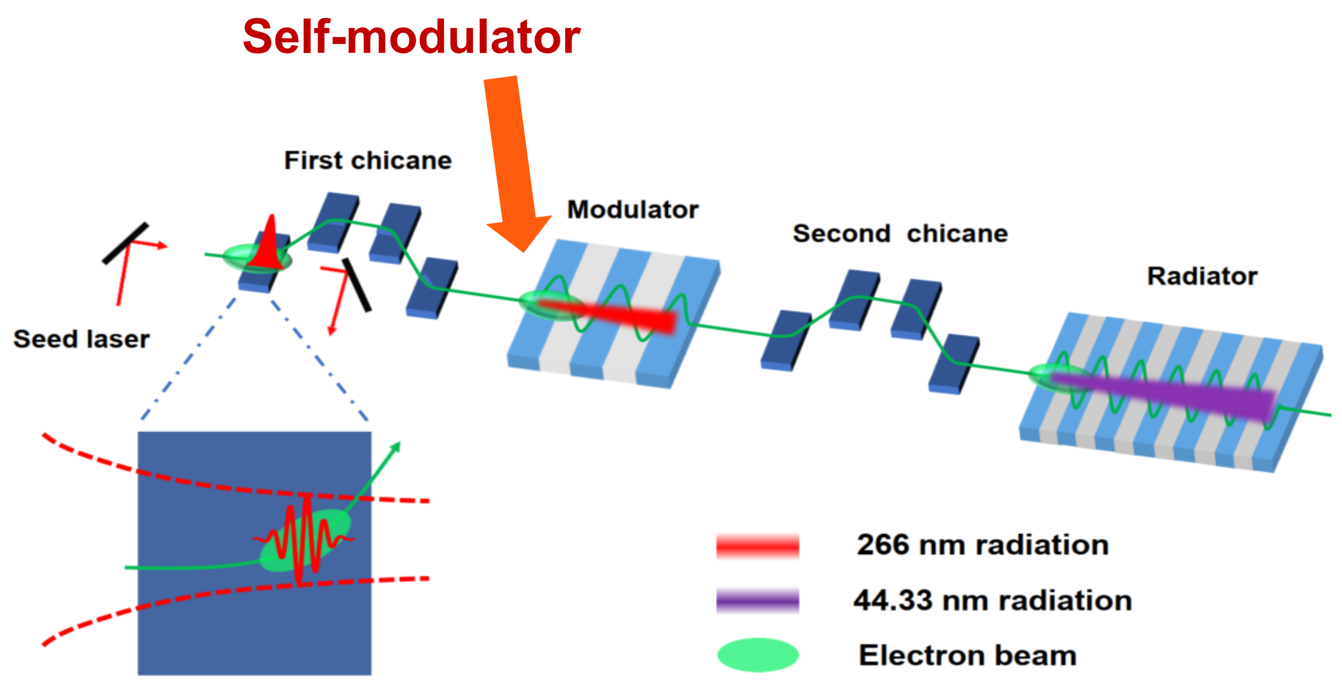



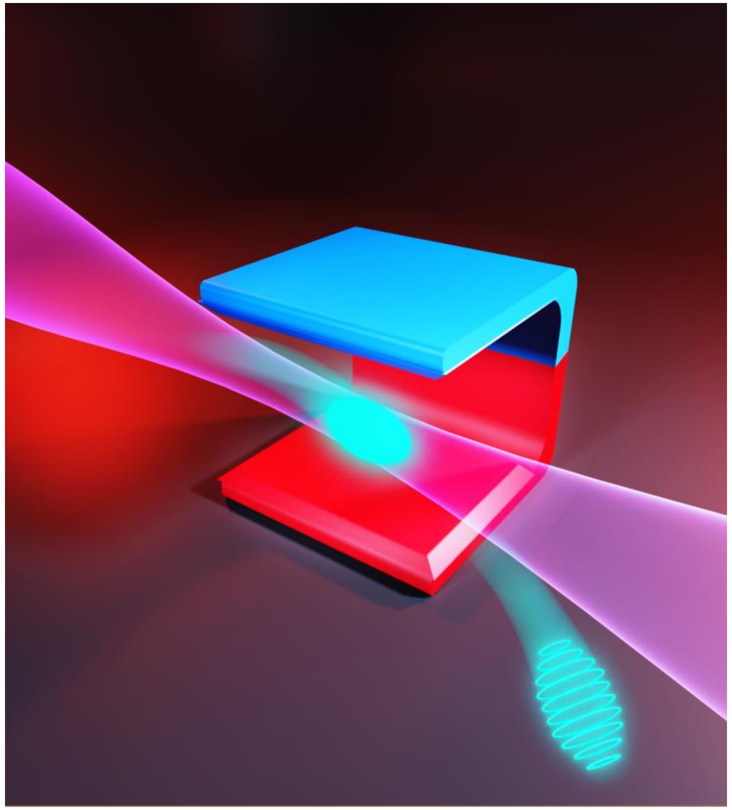

$$d\gamma(\psi_0) = \int_0^{-\theta} \frac{eE_0}{mc^2} \varphi \sin\left[k_s \Delta s(\varphi) + \psi_0\right] R\cos\varphi \, d\varphi.$$

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



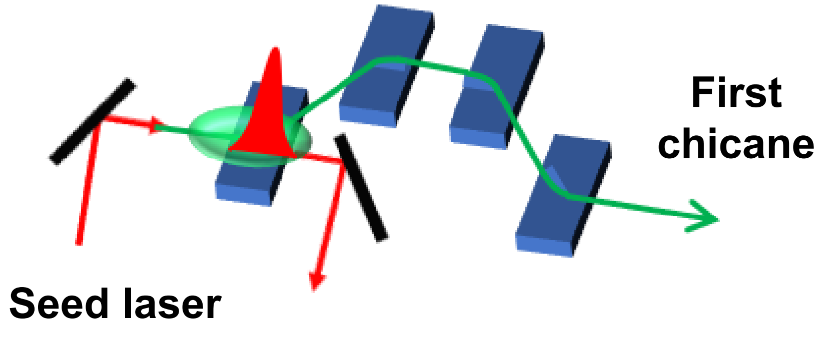
- Laser-beam interaction in the 1st dipole magnet of the 1st chicane
- Energy modulation & density modulation in one chicane
- Feasibility for launching a seeded FEL
- Switch on the 1st laser of EEHG, and switch off the 2nd laser

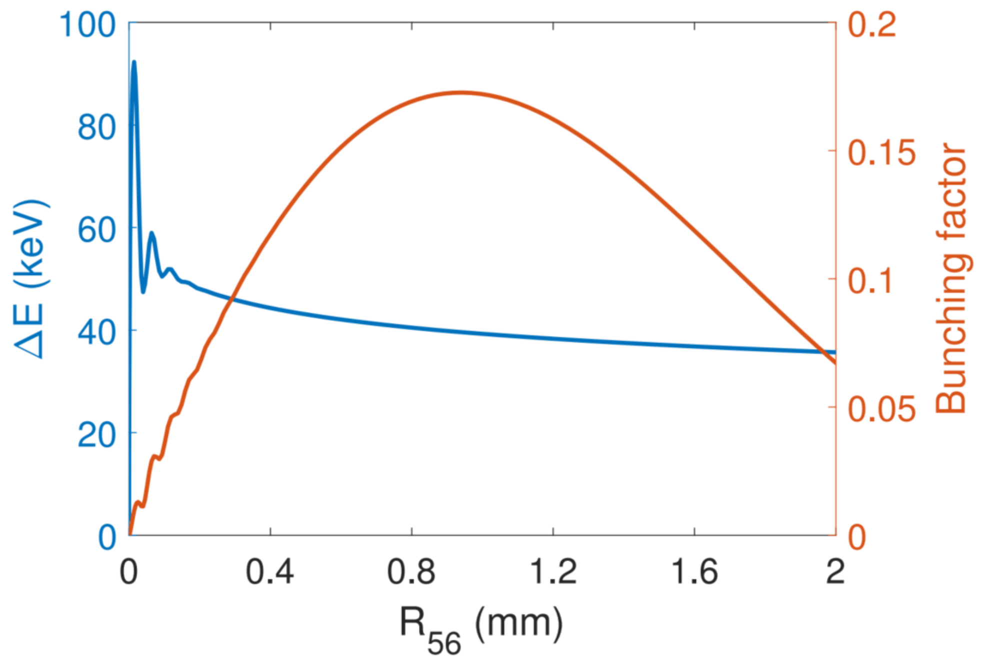
*Advanced Photonics* **3** *(2021) 045003*

# Laser-beam interaction in a dipole: simulations

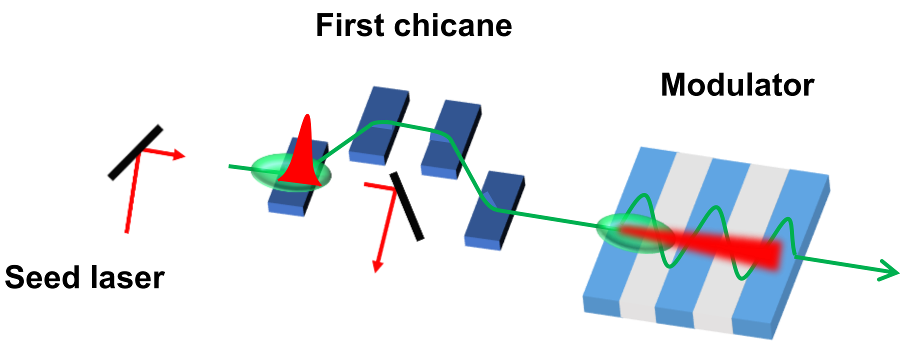
**Parameters of the experiment**

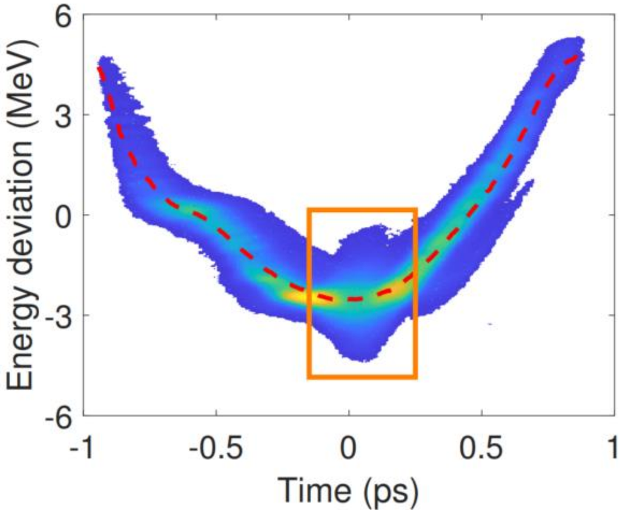
| Parameters | Values |
|---|---|
| Energy | 800 MeV |
| Peak current | 600 A |
| Beam envelope | 200 $\mu m$ |
| Slice energy spread | 30 keV |
| Seed laser wavelength | 266 nm |
| Peak power | 220 MW |
| Dipole length | 0.3 m |
| Magnetic strength | 0.03 – 0.12 T |
| $R_{56}^{1}$ | 0.11 – 1.7 mm |



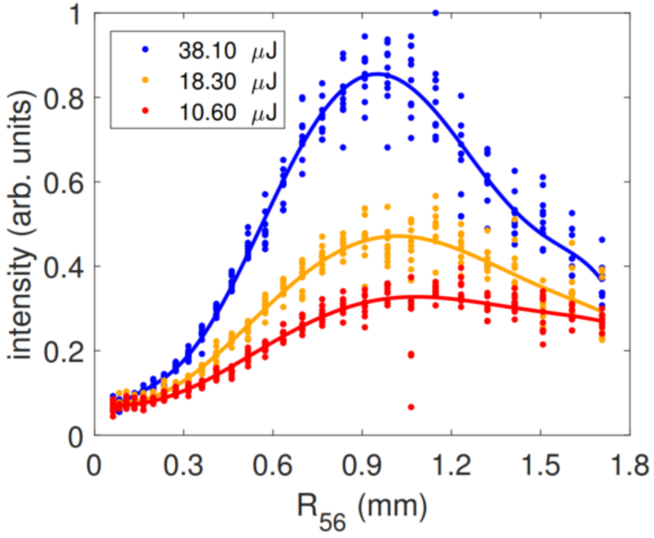



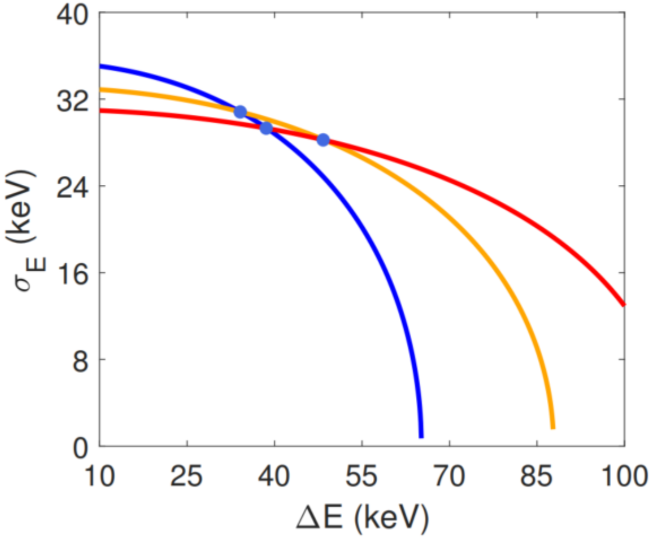
# laser-beam interaction in a dipole: first observation




**Just interact in the dipole , from XTCAV**



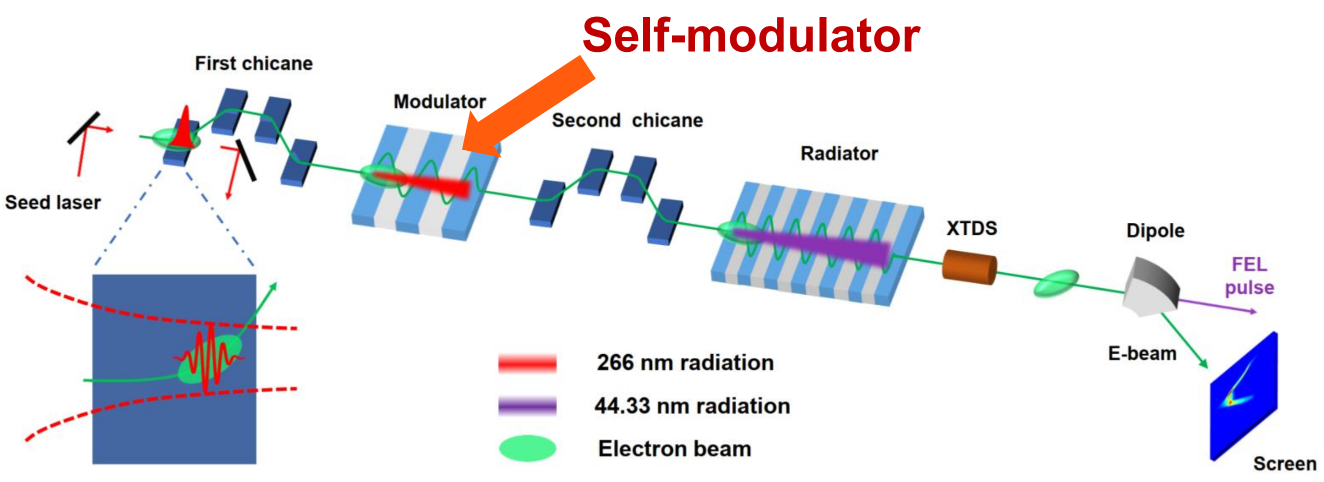

**Energy modulation amplitude measurement**

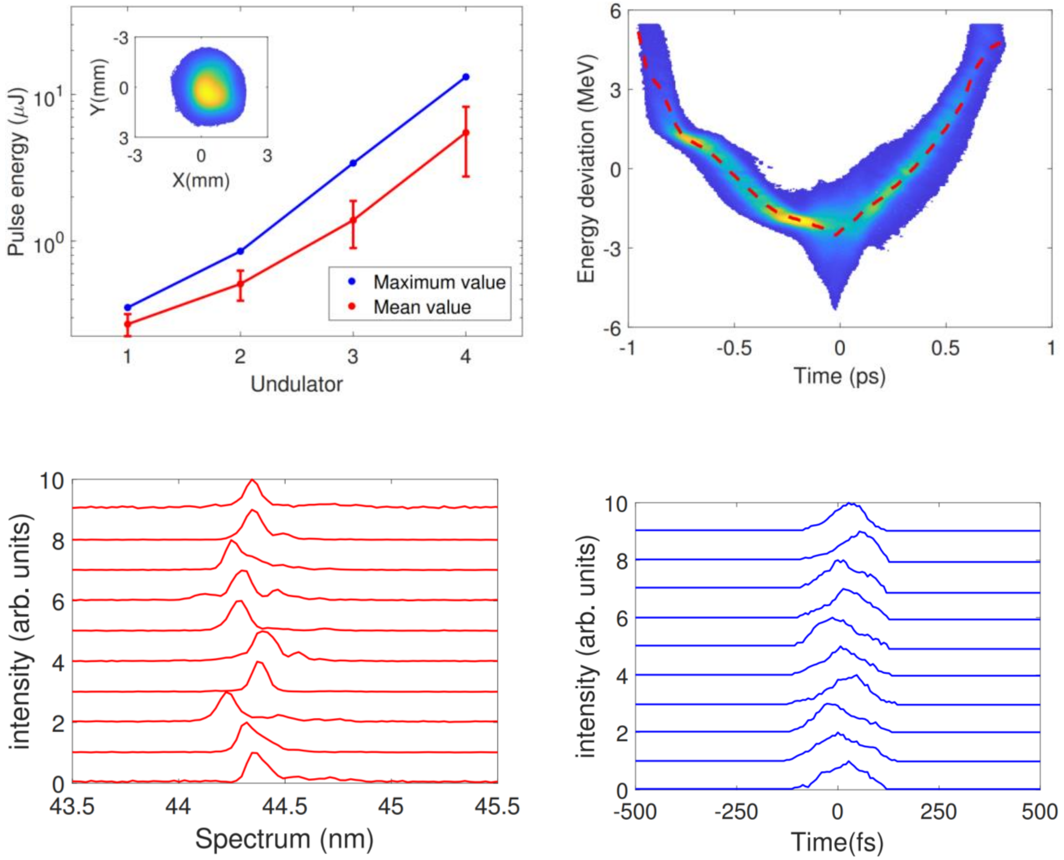
**Initial slice energy spread: 28 keV**

**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 ~ $1.7 \times 10^{-3}$**
**Pulse length: 113 fs**

**Measurement results**

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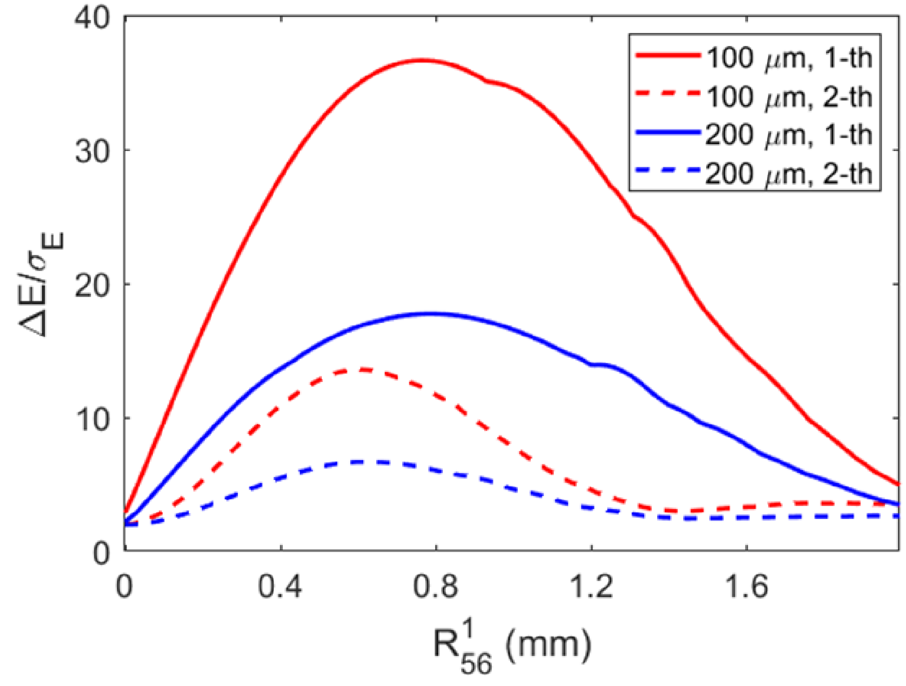
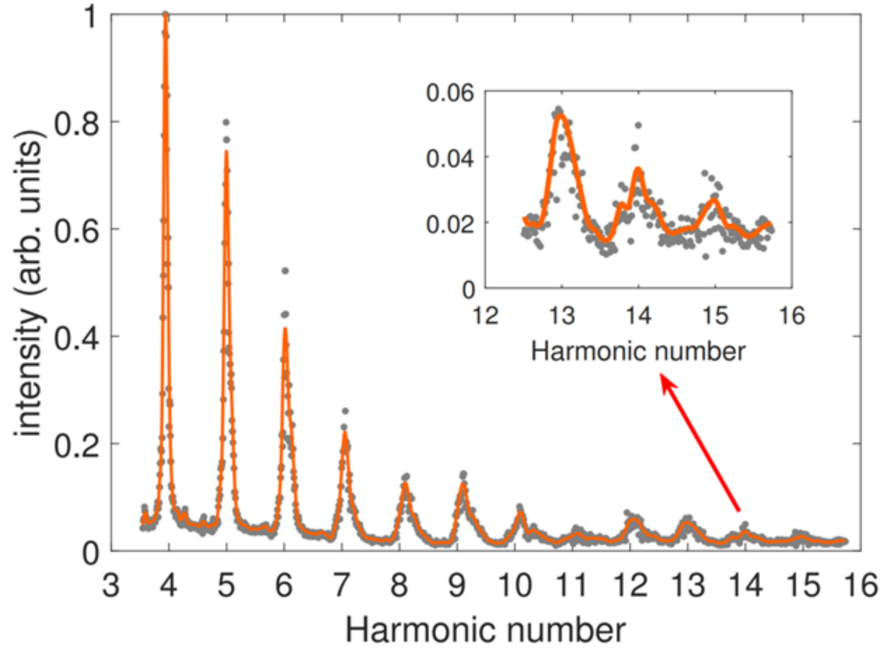
# Self-modulation scheme – further exploration




A=2 ⇨ A > 35

Ultra-large energy modulation enhancement



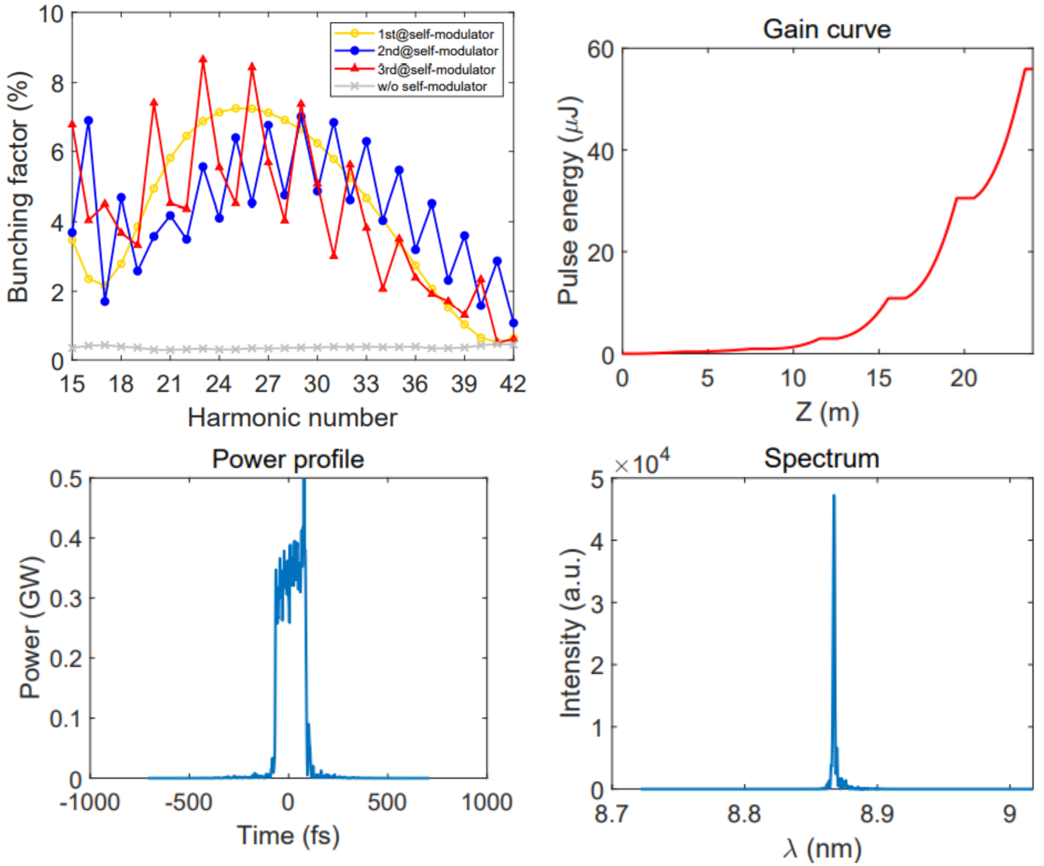

**Optimized self-modulation experiment，**
**CHG@15th harmonic,**
**energy modulation ~1MeV & A~20**

***Paper in preparation***

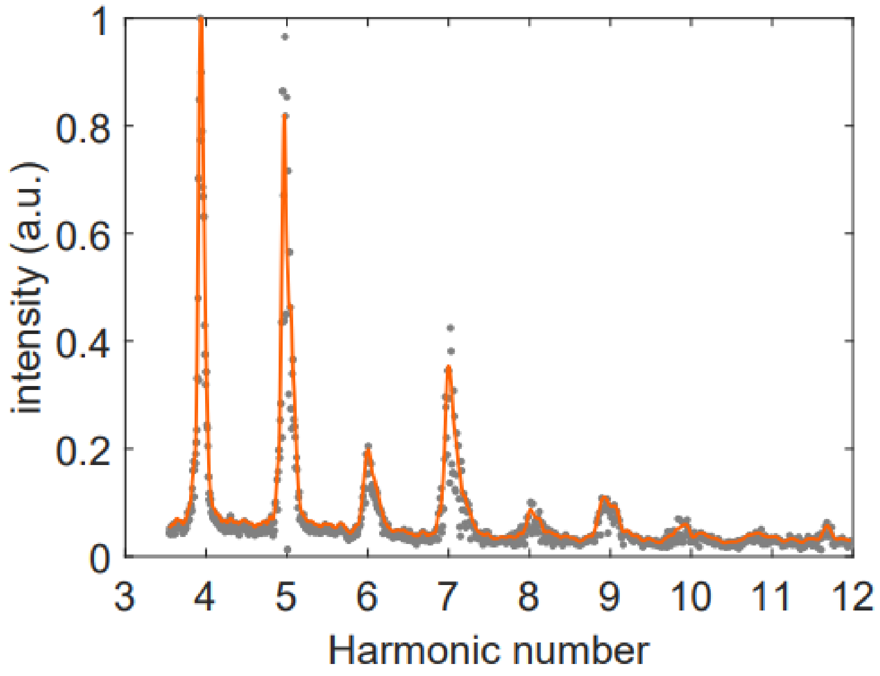
# Self-modulation scheme – further exploration

**Harmonic self-modulation**

Large bunching factor & energy spread control



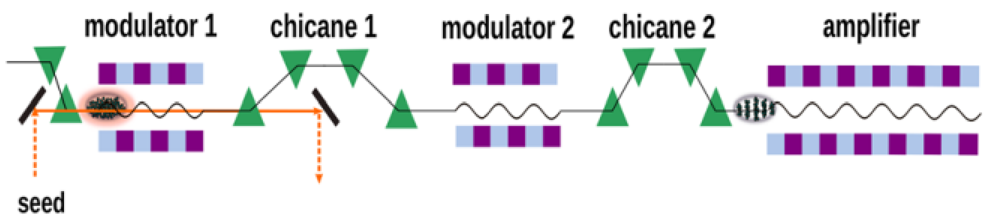

The output FEL performance at the 30th harmonic of the seed laser in the third-harmonic self-modulation



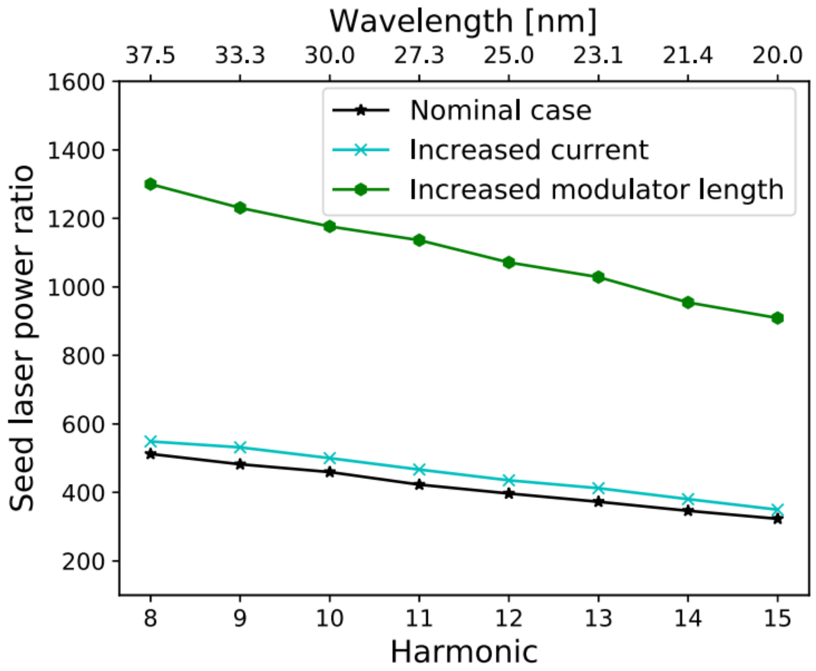

**Experimental demonstration of the 2nd harmonic self-modulation**

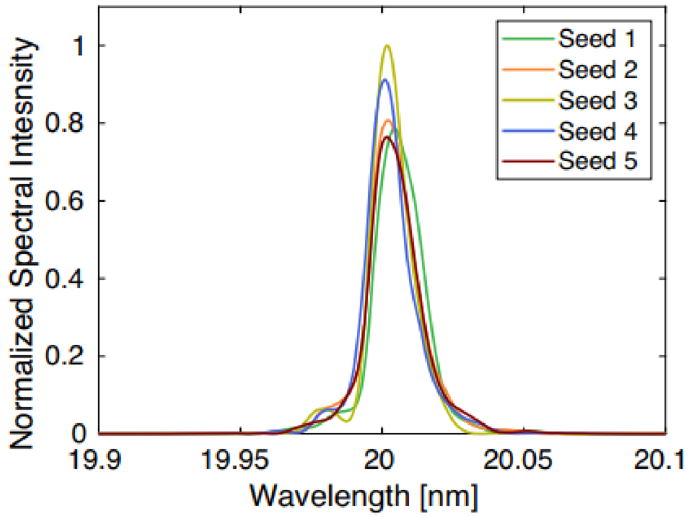
***Paper in preparation***

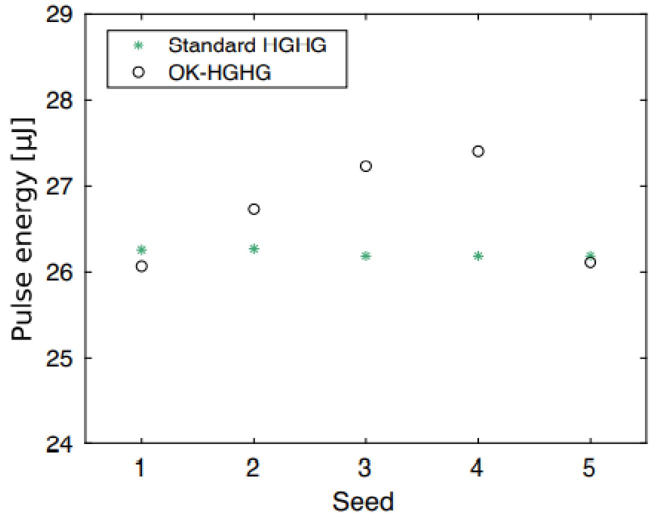
# Self-modulation scheme – FLASH2020+ studies




***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!***