Physics & Applications of High Efficiency FELs Workshop

High brightness FEL amplifier using chirped beam and XFELO seeding

Haixiao Deng

Shanghai Institute of Applied Physics, CAS

California, USA 2018.04.12

SINAP 中国科学院上海应用物理研究所

Shanghai Institute of Applied Physics, Chinese Academy of Sciences

Outline

- Motivation
- Background
  - Tapering technique
  - XFELO development
  - Motivation
  - Oscillator + Amplifier (OA)
- XFELO using a chirped beam
- X-ray amplifier seeded by XFELO
- Summary & Prospect

Tapering technique

Free-Electron Lasers with Variable Parameter Wigglers

NORMAN M. KROLL, PHILIP L. MORTON, AND MARSHALL N. ROSENBLUTH

IEEE J . Quantum Electron, 17, 8 (1981).

VOLUME 57, NUMBER 17 PHYSICAL REVIEW LETTERS 27 OCTOBER 1986

High-Efficiency Extraction of Microwave Radiation from a Tapered-Wiggler Free-Electron Laser

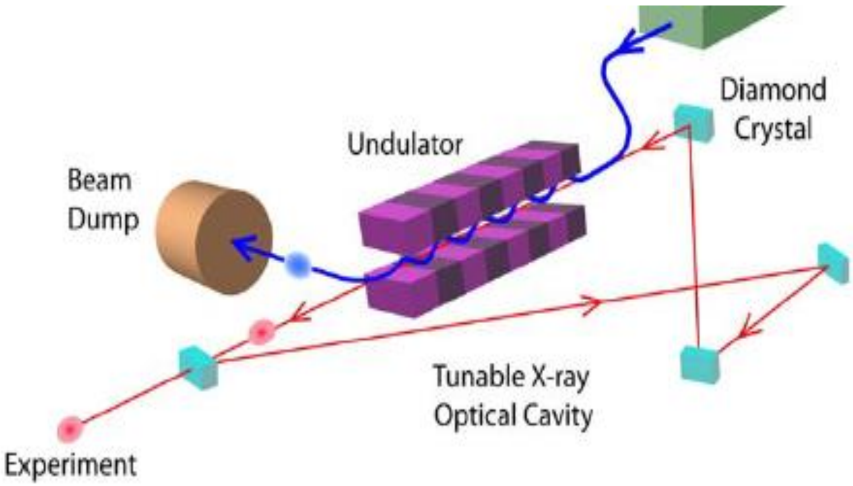
Results:

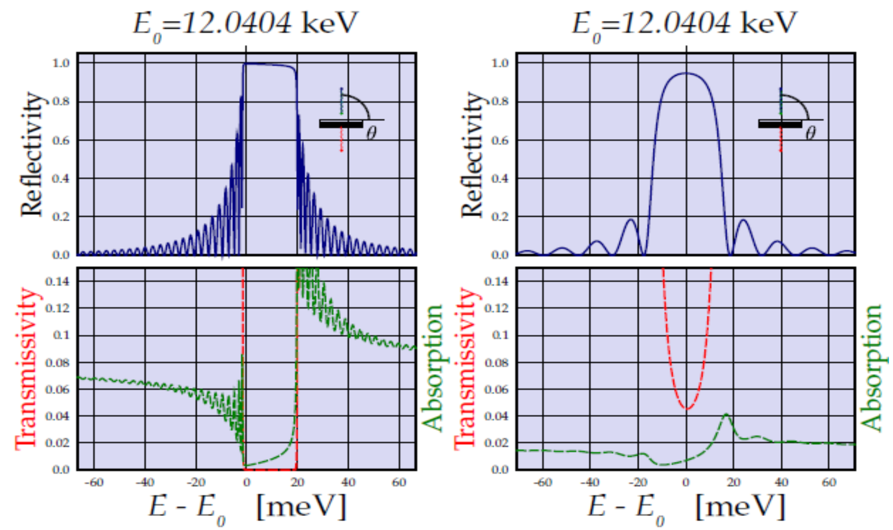
- ✓ 1.3m 45% tapering wiggler
- ✓ 180MW --> 1GW
- ✓ Energy extraction efficiency 34%

Further development:

- ➢ Go to shorter wavelength
- ➢ Taper optimization strategy
- ➢ Various new schemes

XFELO development





C(4 4 4); L = 0.2 mm; T = 300 K   C(4 4 4); L = 0.042 mm; T = 300 K

XFELO History:

- In 1984, proposed by Collela & Luccio
- In 2008, resurrected by Kwang-Je Kim
- In 2010, tunable wavelength X-ray cavity

- New ideas and proposals is coming out.

XFELO Proposal:

- XFELO driven by 7GeV ERL
- Storage ring based XFELO
- XFELO options at European XFEL

- XFELO at LCLS-II and LCLS-II (HE)
- XFELO proposal at 8GeV SCLF

Motivation

High power (TW) X-ray

Electron beam
- Trans. emittance
- Long. phase space
- Pre-bunched

FEL quality

Seed laser
- High intensity
- Quite stable
- Fully coherent

XFELO

Undulator
- Fine taper
- Phase shifter
- FODO lattice

FEL amplifier

Oscillator + Amplifier (OA) in X-ray regime

Shanghai Institute of Applied Physics, Chinese Academy of Sciences

中国科学院上海应用物理研究所

SINAP

OA @ laser community

COHERENT.

Vitara

Automated, Hands-Free Ultrashort Pulse Ti:Sapphire Oscillator Family

Vitara is the new industry standard for hands-free, integrated, ultra-broadband, flexible ultrafast lasers. Representing the culmination of 20 years of in-house expertise with Kerr Lens mode-locking and thousands of clean-room manufactured, industrial-grade ultrafast lasers, the Vitara family satisfies the most sophisticated requirements for amplifier seeding, terahertz generation, attosecond studies, quantum control experiments, non-linear imaging and spectroscopy applications.

Models within the Vitara family range from an ultrabroadband version generating pulses shorter than 8 fs, a tunable version with user-adjustable bandwidth and sub-12 fs compressed output, a high power version providing 1 Watt-class average power and a version tailored for seeding ultrafast amplifiers. All models of the Vitara platform provide hands-free operation ensured by Coherent's proprietary clean manufacturing practices, our unique Optically Pumped Semiconductor (OPS) pump lasers and a suite of automated controls.

In addition to its exquisite flexibility, Vitara satisfies the most sophisticated requirement in Carrier to Envelope Phase (CEP) stabilization and external source synchronization thanks to its broad range of accessories.

Designed as a long-lasting and expandable ultrafast laser platform, Vitara provides reliable hands-free operation even in the most demanding applications and environments.

Superior Reliability & Performance

Vitara Features:

- Automated for hands-free, reliable operation
- Computer controlled bandwidth
- Computer tunable center wavelength
- PowerTrack™ active optimization
- <8 fs to >30 fs pulsewidth capability
- Low noise
- Integrated Verdi™ G pump laser
- Compact footprint

Vitara Options and Accessories:

- Carrier-Envelope Phase (CEP) Stabilizer
- Pulse synchronization – Synchrolock-AP
- Integrated, calibrated spectrometer
- Compact Pulse Compressor – CPC-II
- Second Harmonic Generator
- Factory configurable for use with internal or external pump laser

www.Coherent.com/Vitara

COHERENT.

Legend Elite HE+

Ultrafast Ti:Sapphire Amplifier

The Legend Elite series of ultrafast amplifiers offers a market-leading combination of performance, stability and reliability. The Legend Elite HE+ delivers output power up to 8W from a single regenerative amplifier stage, with pulse widths available at <25 fs, <35 fs, <130 fs and 1 ps.

The Legend Elite series utilizes technology unique to Coherent, e.g. slab Ti:Sapphire rod design for enhanced cooling and optimal beam quality, temperature stabilized baseplate and CEP-grade hardware for superior stability.

Powered by an integrated Revolution pump laser, the Legend Elite HE+ is very compact and when seeded by a Vitara ultrafast oscillator the small foot print of this 2-box, high-performance amplifier system allows sophisticated experimental setups on a single optical table. These subsystems are built to Coherent's exacting manufacturing standards using our advanced HASS verification to ensure the highest level of quality and reliability.

The Legend Elite design enables numerous upgrade pathways, for example to higher energy or CEP stabilization, making it the most flexible, high-performance amplifier on the market.

Superior Reliability & Performance

Legend Elite HE+ Features:

- High energy, high efficiency design (up to >7.0 mJ)
- Integrated Revolution pump laser
- Thermally stabilized E-2 Engine regenerative amplifier platform
- Unsurpassed stability – energy, pointing, pulse width
- Pulse widths from <25 fs to 1 ps
- Multiple upgrade pathways up to >20 mJ, >25W

Legend Elite HE+ Applications:

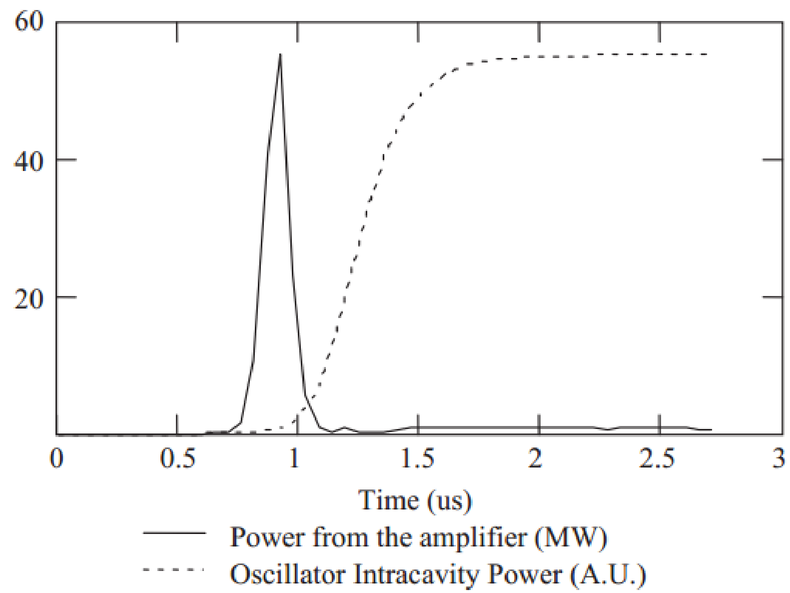
- Time-resolved Spectroscopy
- Multidimensional Spectroscopy
- THz Spectroscopy
- fs Micromachining
- Surface SFG/SHG
- Stimulated Raman Scattering
- High Harmonic Generation

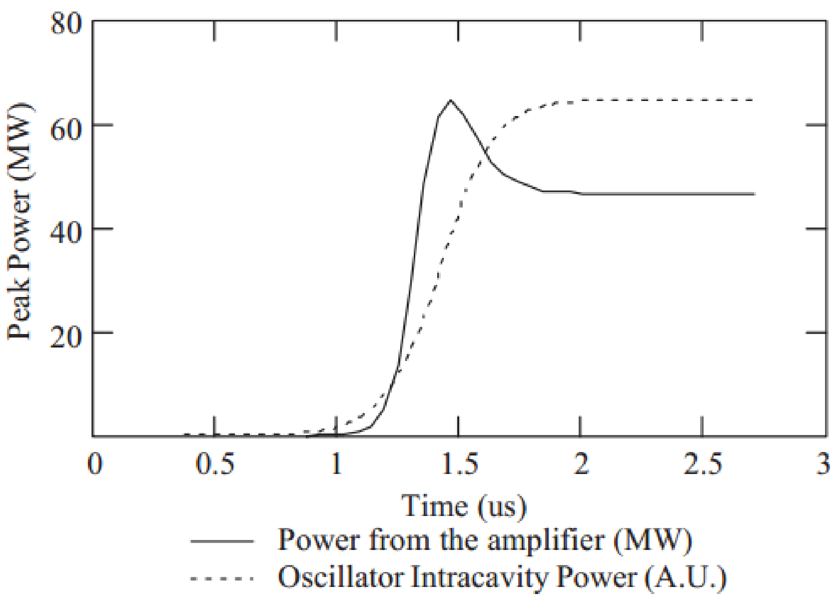
www.Coherent.com/LegendEliteHE+

800nm/80MHz/500mW/6nJ

800nm/1kHz/25W/25mJ

OA @ long wavelength FEL





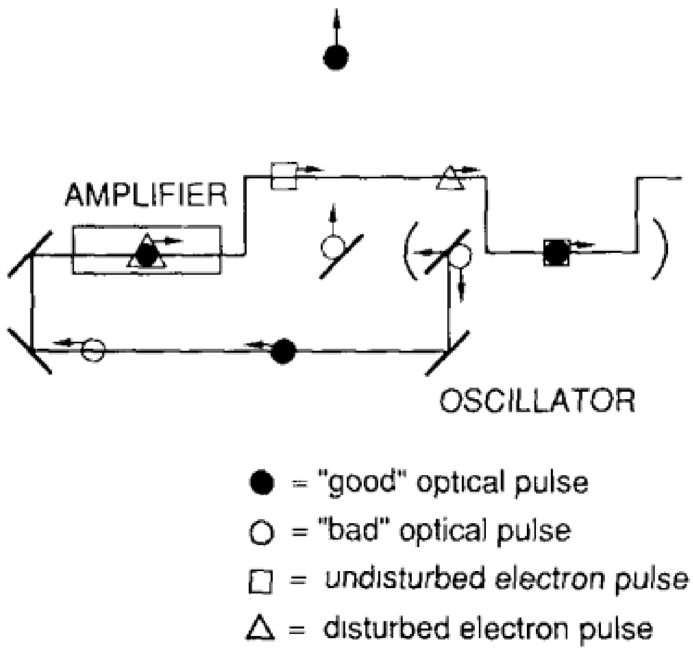
Optical-klystron:

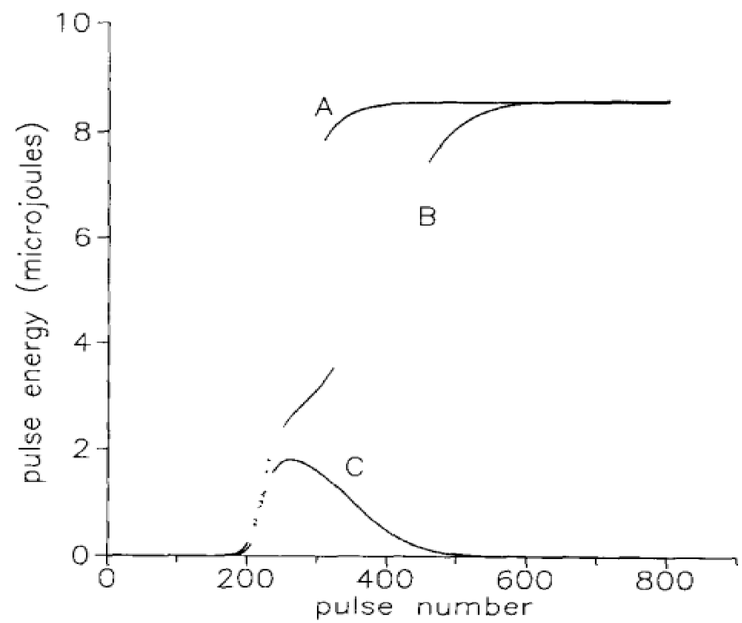
- Energy modulation to density modulation
- Pre-bunched electron beam
- Energy spread compatible with the harmonic amplifier

NIMA 507, 26 (2003)

OA @ long wavelength FEL

NIMA 304, 667 (1991)

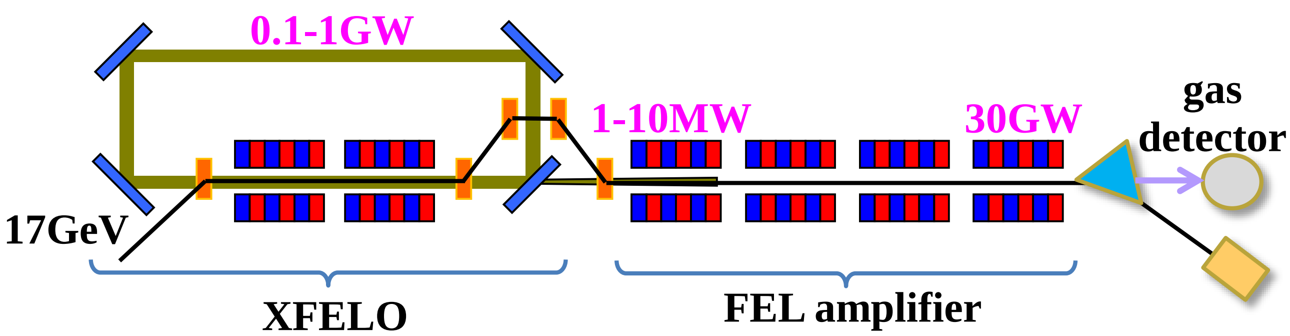




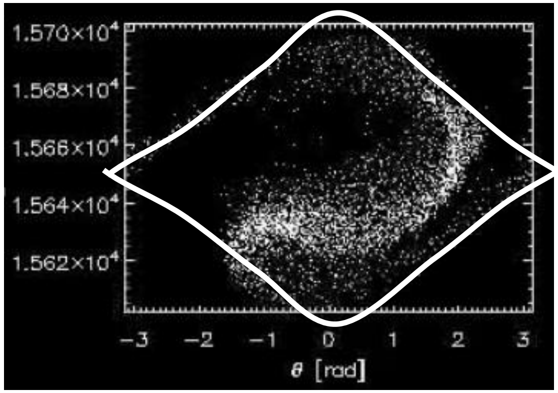
- Fancy and attractive, but reliability need examined experimentally.
- Might need some X-ray optical elements which are not available.

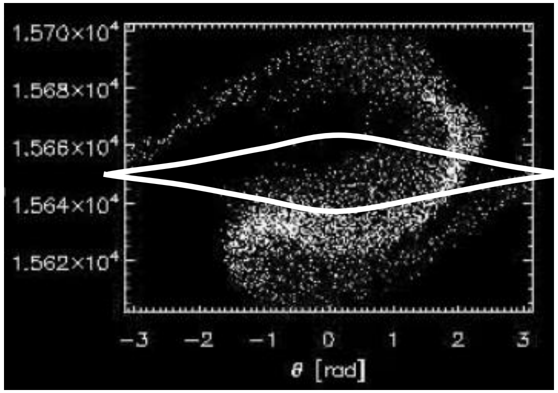
XFELO + Amplifier

- high-brightness, fully coherent, stable X-ray FEL.
- XFELO + Amplifier configuration.



H. Deng, C. Feng, IPAC13, p1214



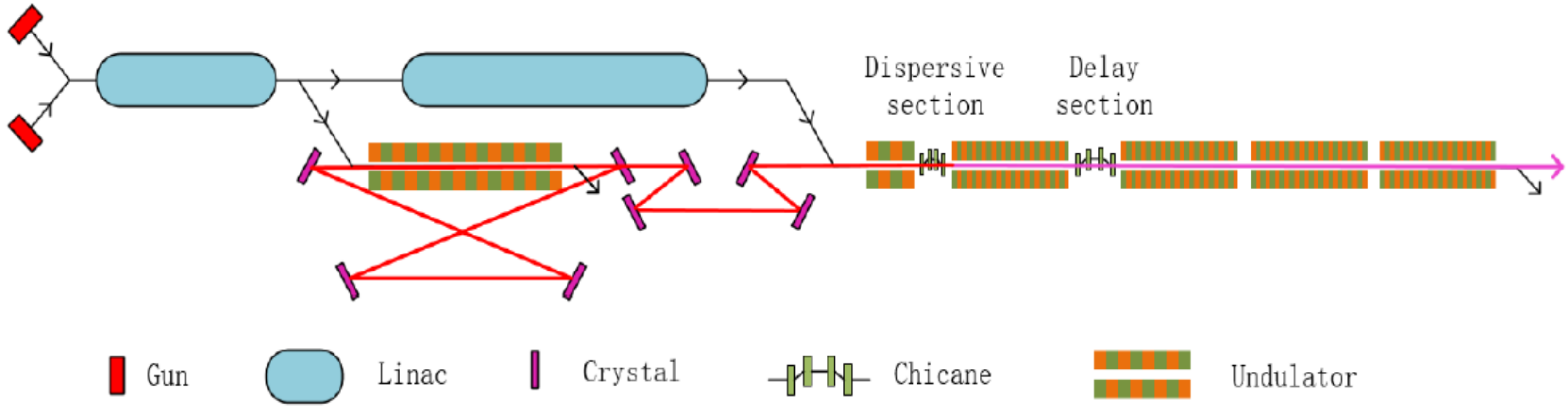


Problem:

The energy spread due to over-modulation inside XFELO induces gain degradation in following FEL amplifier.

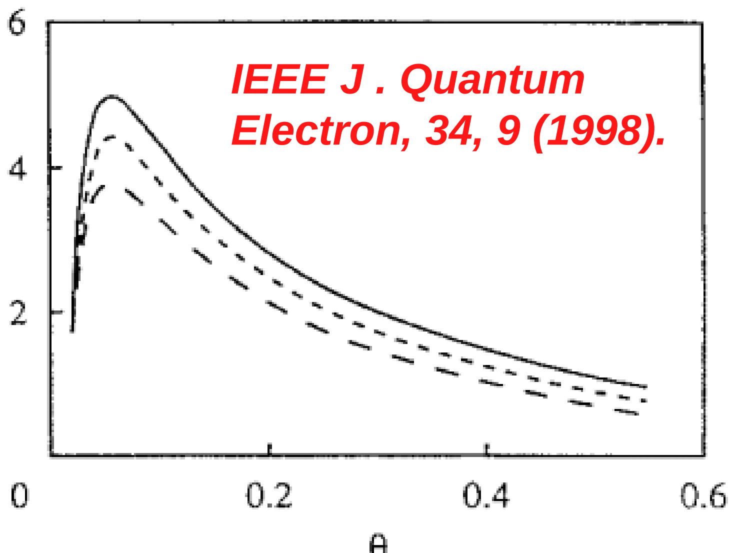
XFELO + Amplifier

- XFELO +(harmonic generation) +high gain amplifier
- Ultrashort X-ray pulses, higher photon energy up t0 60 keV (MaRIE)

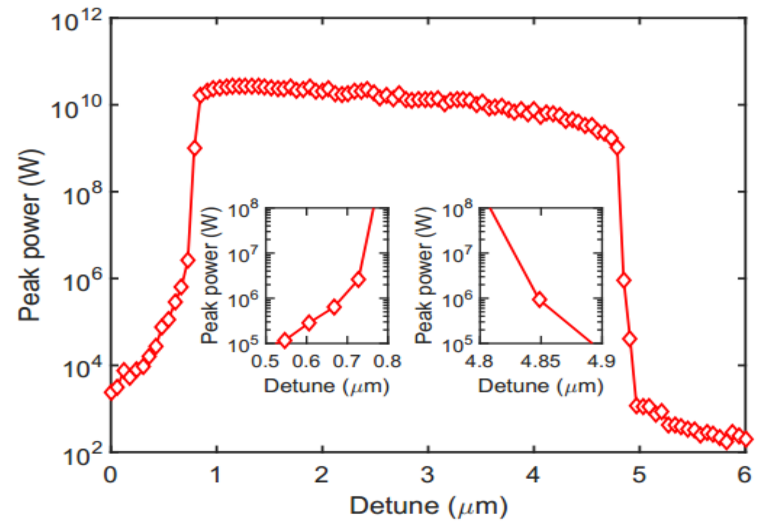


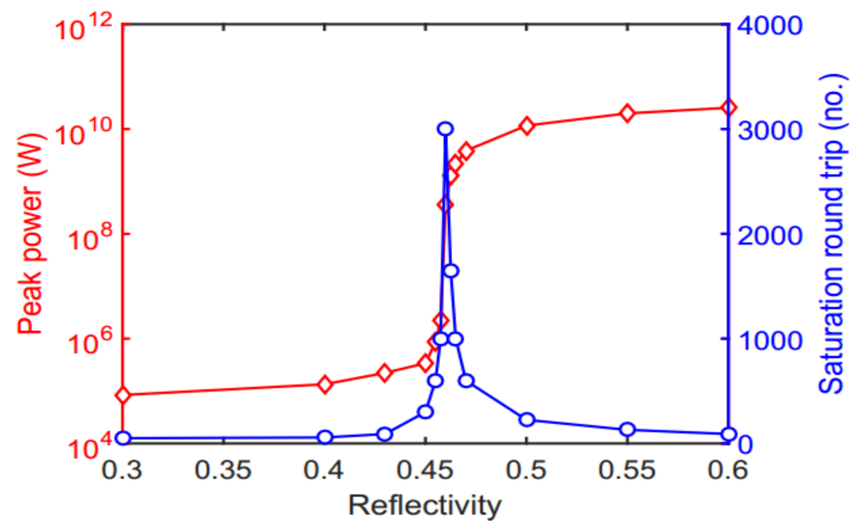
Kwang-Je. Kim, see in FEL2017, FLS2018

XFELO + Amplifier



FELO power .vs. cavity detuning

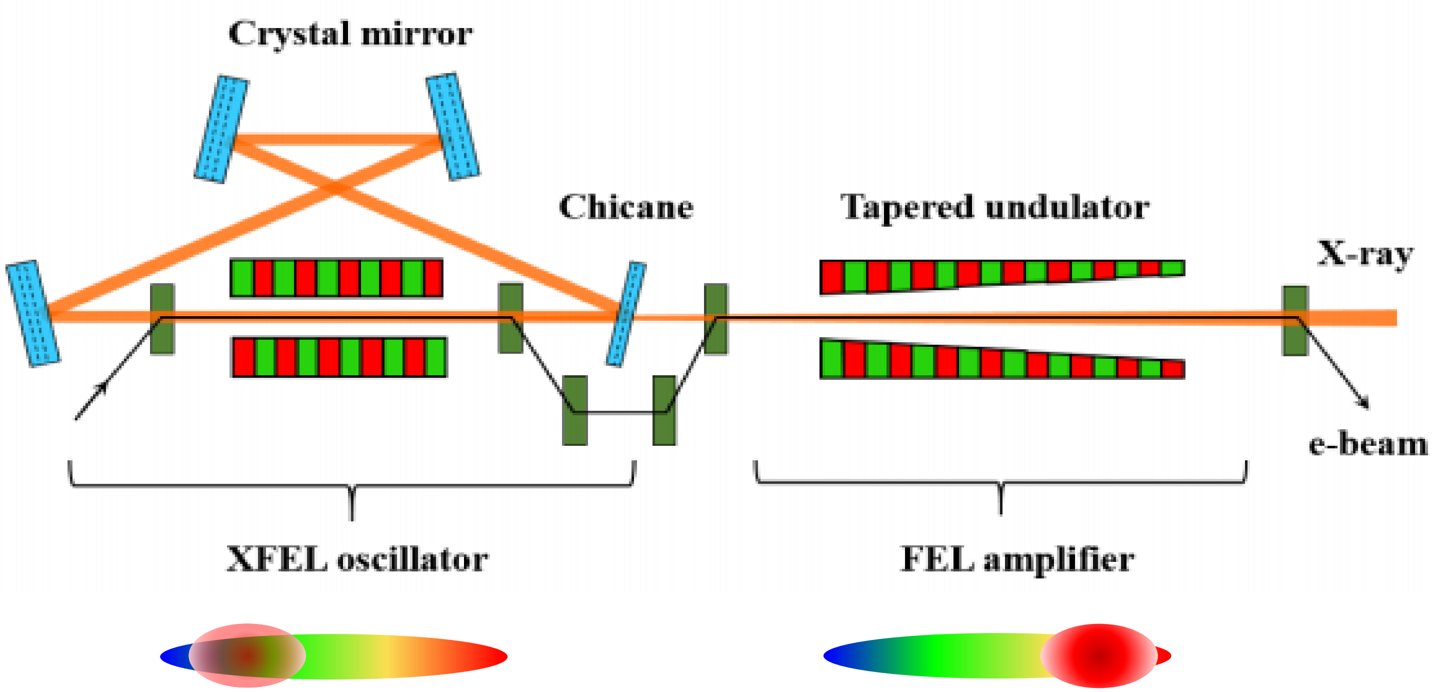




Cavity tuning:

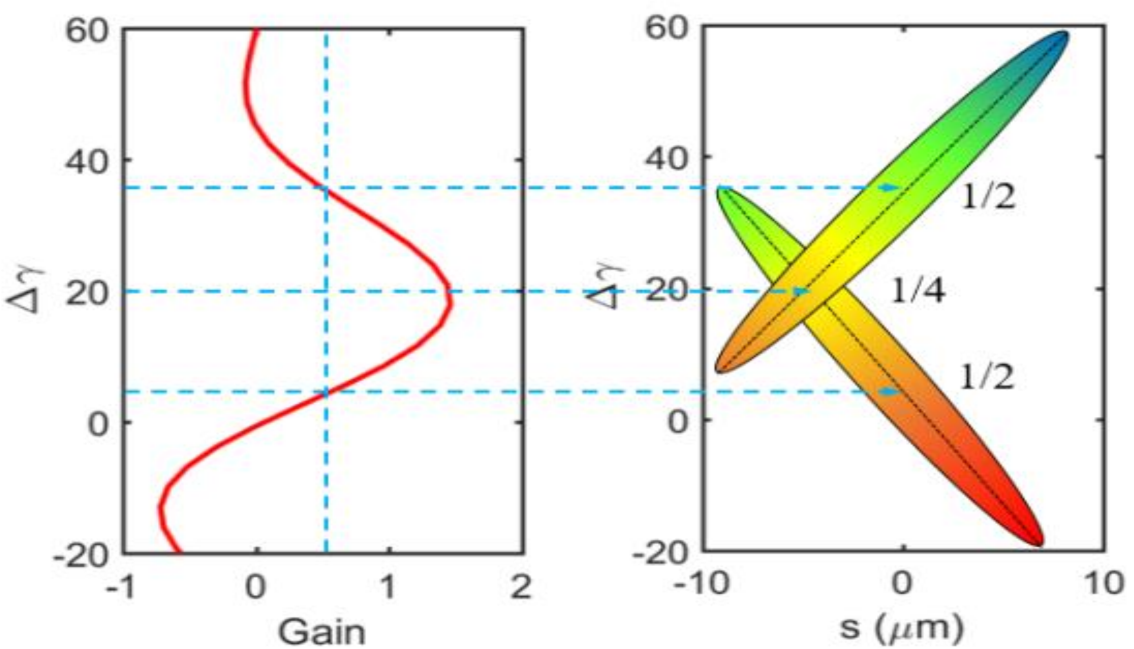
- Cavity detuning seems to be not feasible for XFELO.
- Cavity reflectivity is not feasible both practical and theoretical.

XFELO using chirped beam



- Chirped beam is used to let electron beam lasing at tail inside XFELO, while preserve the head electron beam for the following FEL amplifier.

XFELO using chirped beam



$$R(1+G) > 1,$$

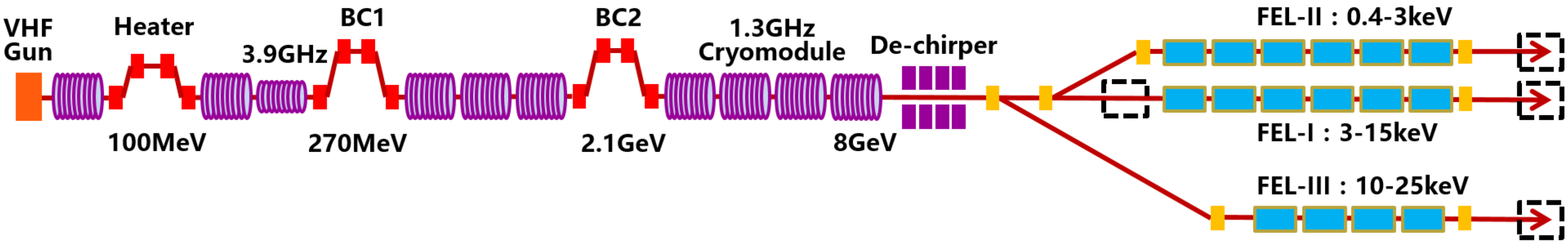
$$\alpha = \frac{\Delta\gamma/\gamma_0}{\Delta l/L_b} = 4\,\frac{\gamma_{1/2}-\gamma_{1/4}}{\gamma_0},$$

For: 100pC, 3kA, flat-top current electron beam.

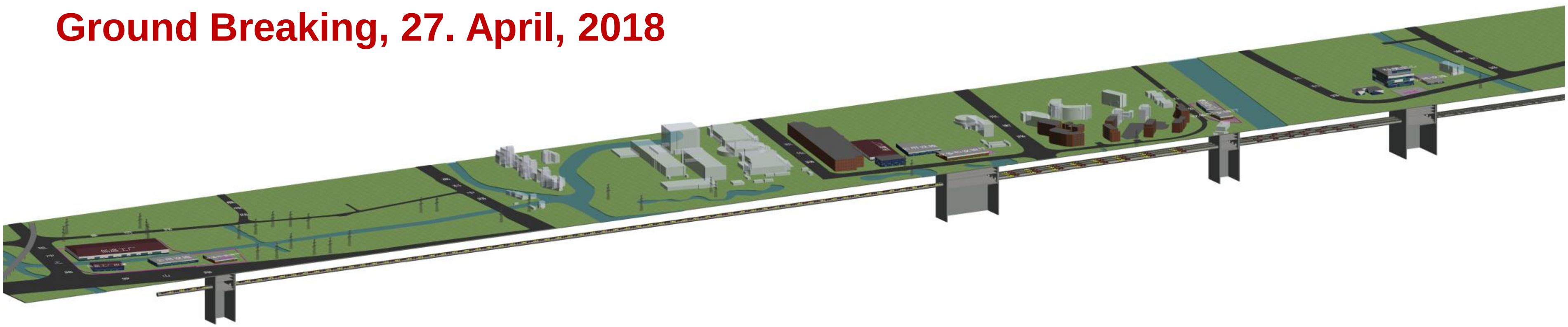
$$\alpha = 6.1\times10^{-3}$$

- **Assuming that 50% gain is necessary, and the 1/4 bunch tail point corresponds to the maximum single pass gain, while the central point relates to 50% single pass gain.**
- **Bunch tail gets enough gain to compensate the round trip net loss, while bunch head does not lase significantly inside the XFELO.**

Shanghai Coherent Light Facility (SCLF)



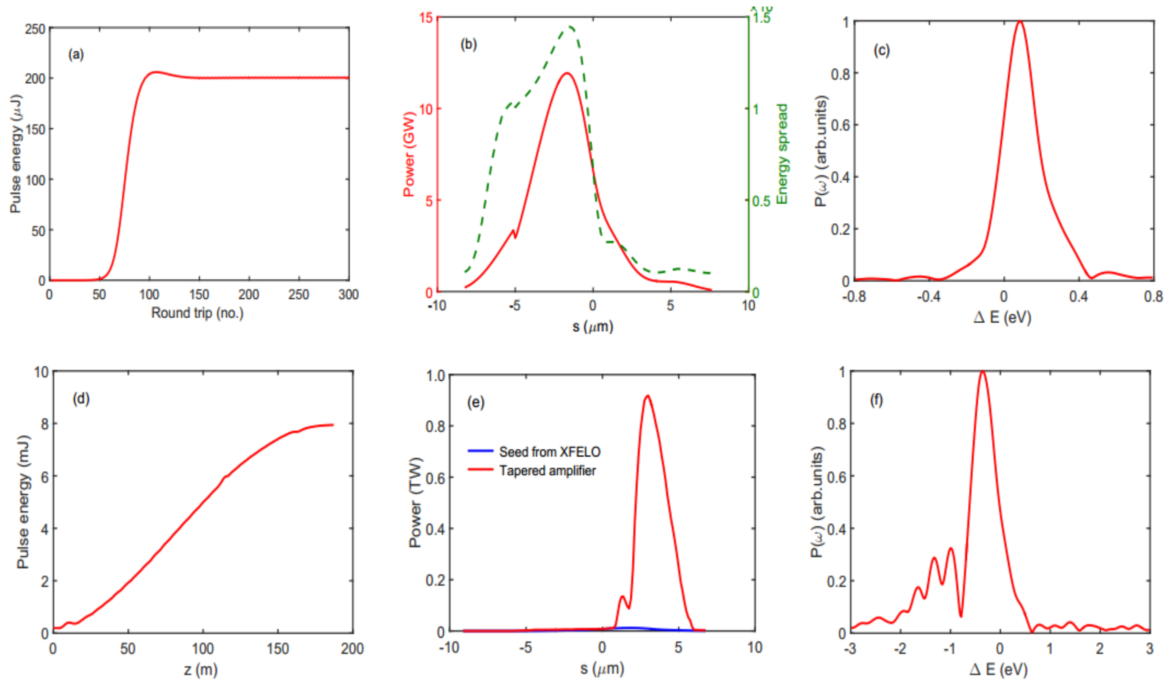
Ground Breaking, 27. April, 2018



X-ray amplifier seeded by XFELO

TABLE I. The main parameters of SCLF.

Parameter	Value	Unit
Beam energy	8	GeV
Slice relative energy spread	0.01	%
Normalized emittance	0.4	μm-rad
Repetition rate	1	MHz
Peak current	3	kA
Bunch charge	100	pC
Undulator period	26	mm
Undulator mean beta function	13	m
XFELO single pass gain	1.5	
Total undulator length	200	m

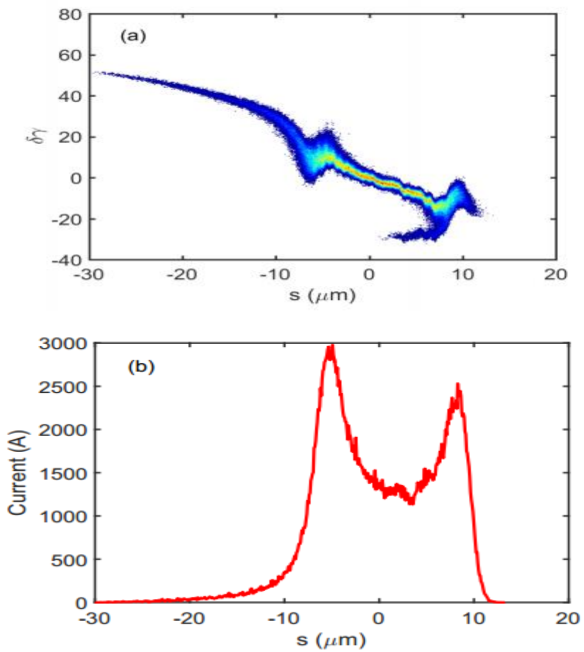


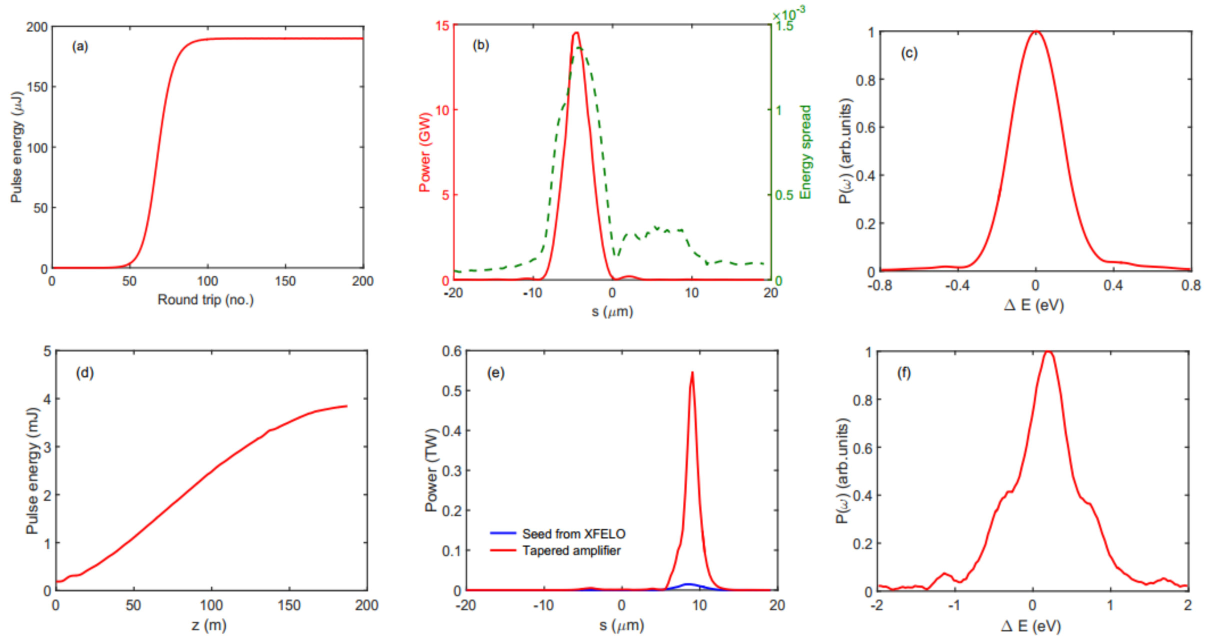
XFELO power & Amplifier output

- **Numerical simulation:**
  - ✓ GENESIS + OPC + BRIGHT
  - ✓ 5 keV, diamond crystal (1 1 1)
  - ✓ XFELO N_u=200
  - ✓ Amplifier without break sections

- **Results:**
  - ✓ ~ 1 TW, 7.9 mJ
  - ✓ ~ 14 fs, bandwidth<2×10^{-4}
  - ✓ Fully coherent

X-ray amplifier seeded by XFELO





XFELO power & Amplifier output

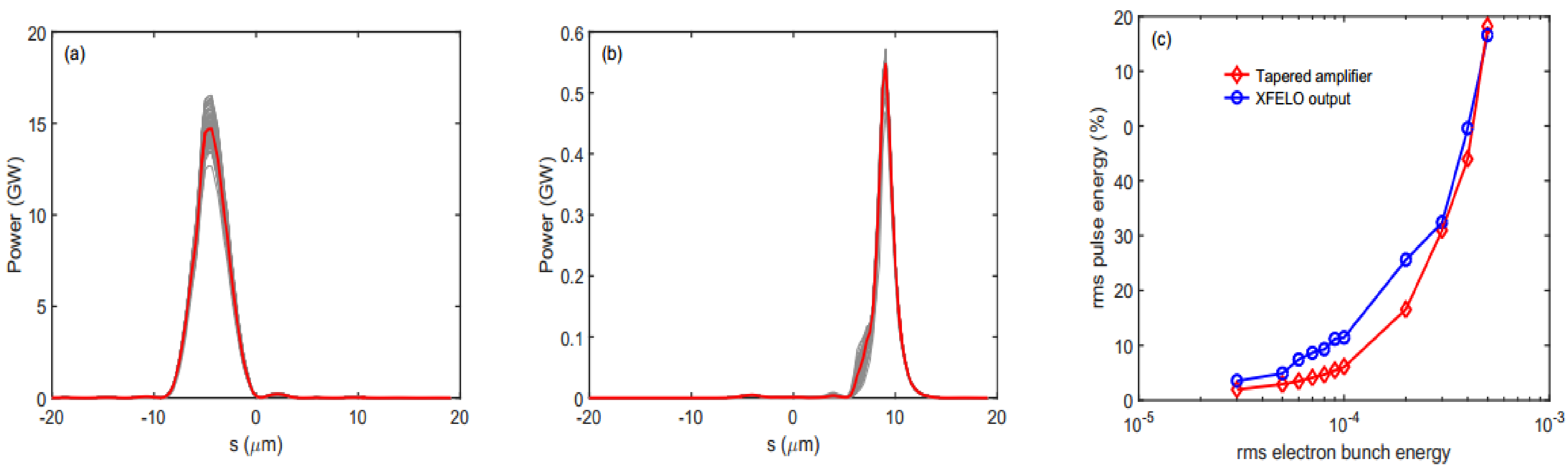
Numerical simulation:

- ✓ ASTRA + ELEGANT
- ✓ Without 12 m corrugated de-chirper
- ✓ Adjust output coupling $\alpha=-1.3\times10^{-3}$

Results:

- ✓ ~ 0.55 TW, 3.8 mJ
- ✓ ~ 5.5 fs, bandwidth $<1.3\times10^{-4}$
- ✓ Fully coherent

X-ray amplifier seeded by XFELO



XFELO power & Amplifier power & output pulse energy .vs. beam energy jitter

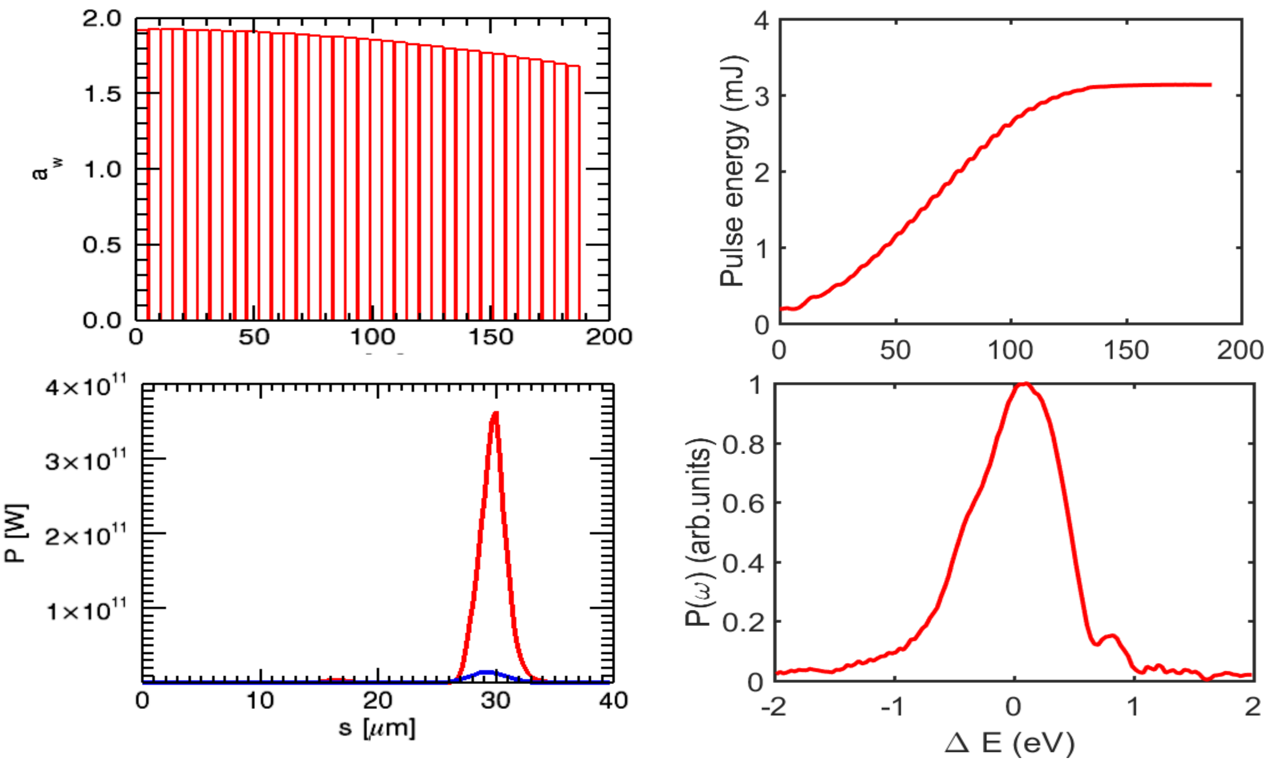
Numerical simulation:

- ✓ For XFELO + amplifier configuration
- ✓ RMS beam energy jitter $0.2\sim5\times10^{-4}$
- ✓ 100 s2e simulation for each jitter

Results:

For typical 1×10^{-4} RMS beam energy jitter, output FEL pulse energy jitter as low as 3% RMS

X-ray amplifier seeded by XFELO



- **Amplifier taper configuration & output**
- **Undulators and phase shifter are optimized by Genetic Algorithm**
- **Results: ~ 0.36 TW, 3.1 mJ**

Amplifier undulator & Output pulse energy & Pulse power & Spectrum

K. Li, H. Deng, arXiv: 1711.01028
In press at PRAB

What is next ?

High power (TW) X-ray

Electron beam
- Trans. emittance
- Long. phase space
- Pre-bunched

Seed laser
- High intensity
- Quite stable
- Fully coherent

Undulator
- Fine taper
- Phase shifter
- FODO lattice

? How to use pre-bunched electron beam to further improve peak power ?

? May fresh-slice technique be helpful in this issue?

? Further taper optimization， but be careful.

Summary & Prospect

- High brightness FEL amplifier using chirped beam and XFELO seeding is possible theoretically.
- The MOPA configuration is examined thoroughly in optical lasers.
- Using chirped beam is a simple scheme overcomes the problem of electron beam over-modulation inside XFELO.
- It is capable of generating TW level, fully coherent X-ray.
- Thanks to the stable XFELO seeds, the final output is quite stable.
- In this discussion, taper is not fully optimized. There might be some methods for peak power further enhancement.

Thanks!!!