International FEL2017 Conference

Harmonic lasing & gain-cascading More efficient X-Ray free-electron laser oscillators

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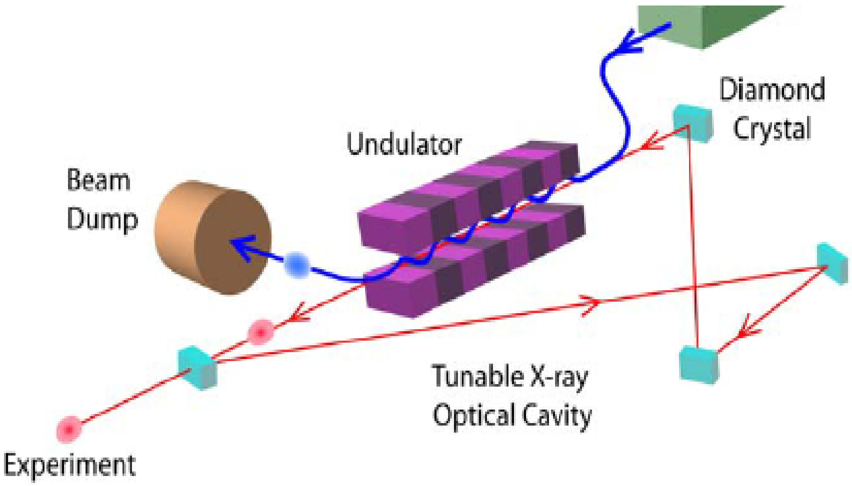
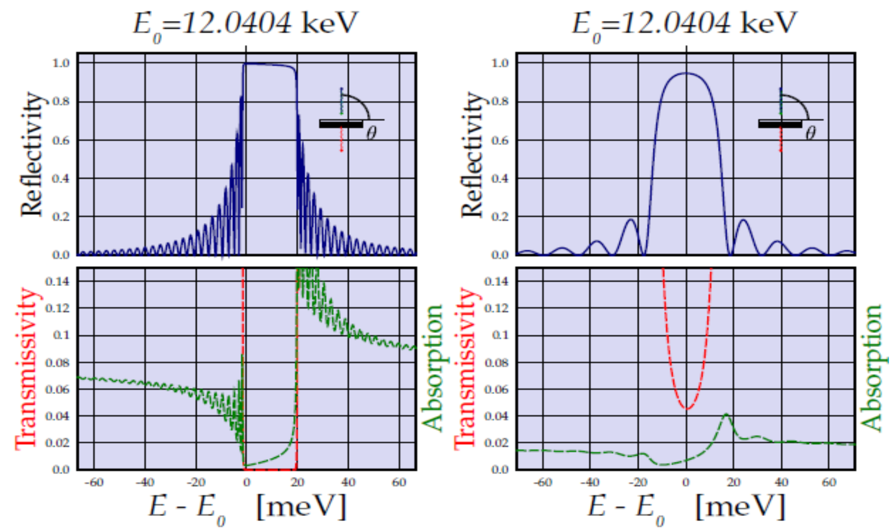
Outline

- **Background & Motivation**
- **Harmonic lasing scheme of XFELO**
- **Gain-cascading scheme of XFELO**
- **Other XFELO issues**
  - ✓ Simplified model for fast optimization
  - ✓ XFELO options for SCLF
- **Summary & Outlook**

Background & Motivation





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

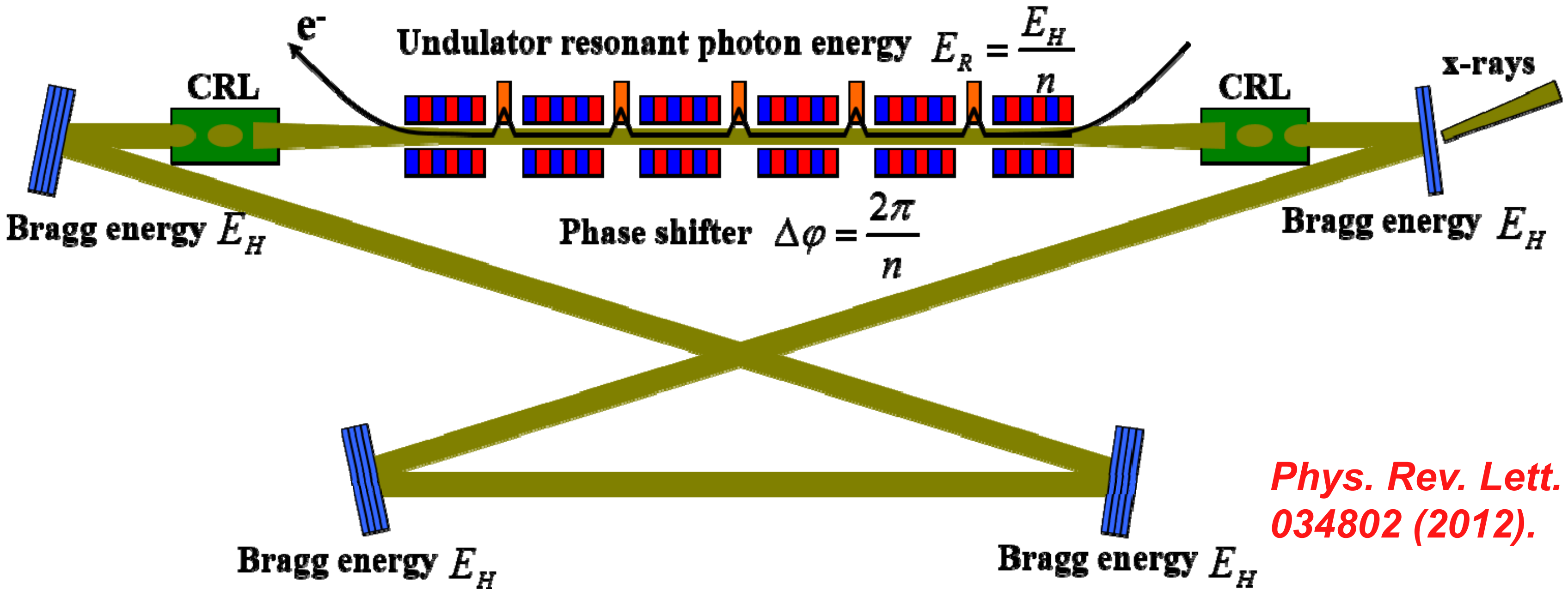
- XFELO driven by 7GeV ERL
- Storage ring based XFELO
- XFELO options at European XFEL

- XFELO proposal at 4GeV LCLS-II
- XFELO proposal at 8GeV SCLF

Harmonic lasing scheme of XFELO

- **Goal: achieving shorter wavelength with a lower beam energy**
- **For high-gain FEL, various harmonic lasing schemes were proposed.**
  - ✓ Harmonic amplifier (Latham 1991)
  - ✓ Harmonic lasing of SASE (McNeil 2006, Schneidmiller 2012)
  - ✓ Super-radiant harmonic lasing of HGHG (Giannessi 2006)
  - ✓ Linear harmonic lasing of HGHG (Dai & Deng, 2004-2009)
- **However for low-gain FEL , harmonic lasing already demonstrated**
  - ✓ Harmonic lasing of FEL oscillator proposed (Colson 1980)
  - ✓ Harmonic lasing of FEL oscillator demonstrated at Stanford (1989)
  - ✓ 2^{nd}, 3^{rd}, 5^{th} harmonic lasing at JLAB (2000)
  - ✓ 3^{rd} harmonic lasing at Novo-FEL (2011)

Harmonic lasing scheme of XFELO

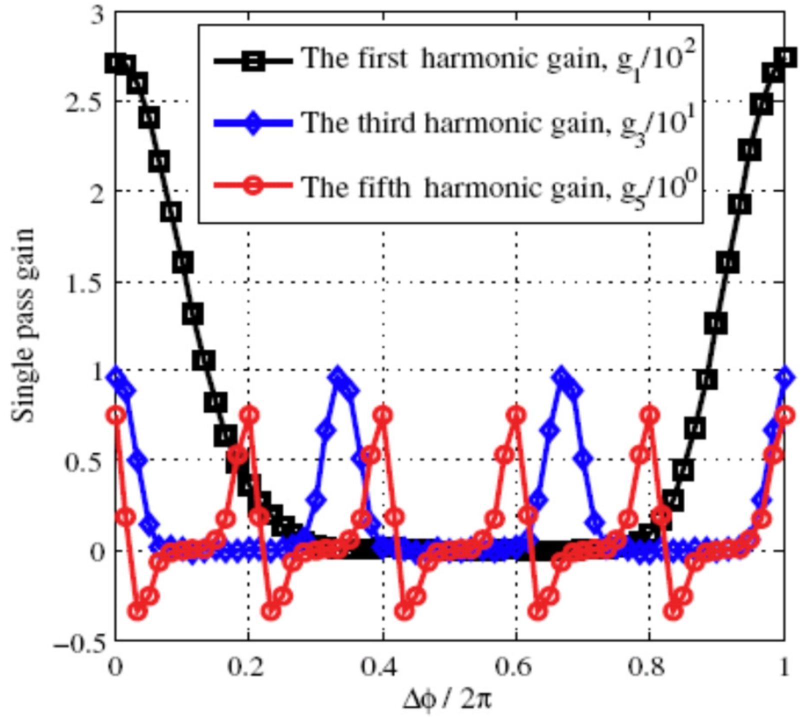


Phys. Rev. Lett. 108, 034802 (2012).

- **Cavity crystals with Bragg energy equals to the interested harmonic, instead of the fundamental.**
- **Phase-shifters are tuned to the interested harmonics, while suppressing the fundamental and other harmonics.**

Harmonic lasing scheme of XFELO

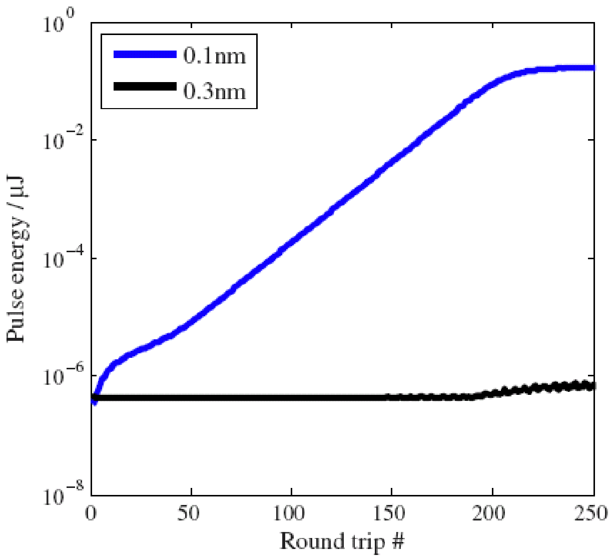
Parameters	Third harmonic	Fifth harmonic
Crystal Bragg energy E_H	12.42 keV	20.71 keV
Phase jump $\Delta\varphi$	$4\pi/3$	$6\pi/5$
Undulator period λ_u	15 mm	15 mm
Undulator number N_u	1200	1200
Undulator parameter K	1.3244	1.3244
Beam energy E	3.5 GeV	3.5 GeV
Slice energy spread σ	100 keV	100 keV
Beam peak current I	20 A	100 A
Slice emittance ε_n	0.083 μm-rad	0.083 μm-rad
Single-pass gain g_h	65%	72%
Total cavity reflection r	80%	80%
Cavity length L_c	150 m	150 m
Bragg crystal	C(4,4,4)	C(5,5,9)
FWHM spectral width	5.5 meV	24.6 meV
FWHM temporal width	463 fs	107 fs
Photons/pulse	0.86×10^8	0.24×10^8
Output peak power	0.35 MW	0.74 MW



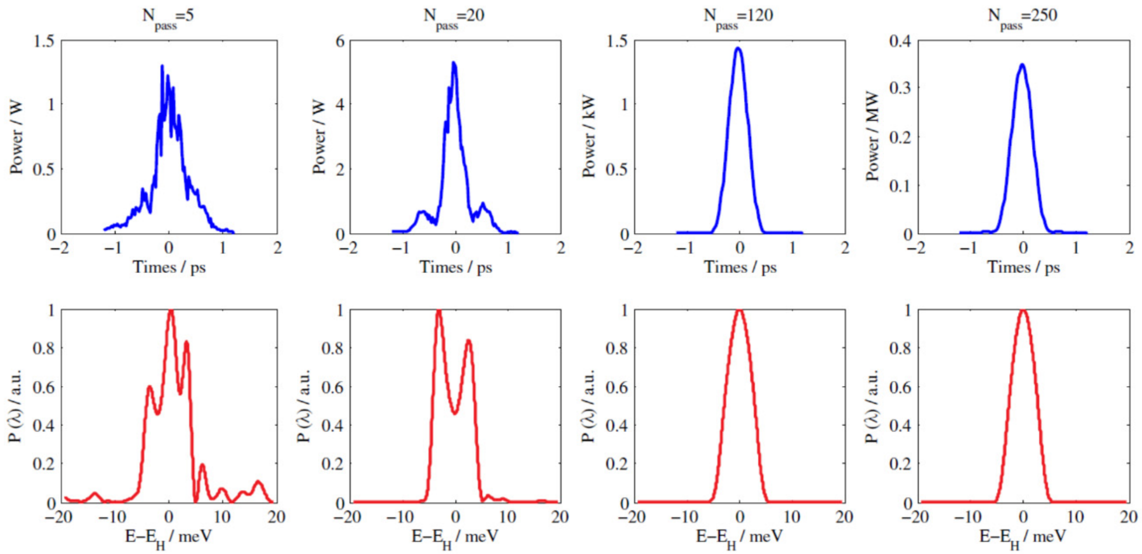
Single-pass gain .vs. phase-shifter

$g_1=270$, $g_3=10$, $g_5=0.8$ ($\Delta\varphi=0$)
$g_1=2.2$, $g_3=0.1$, $g_5=0.8$ ($\Delta\varphi=6\pi/5$)

Harmonic lasing scheme of XFELO



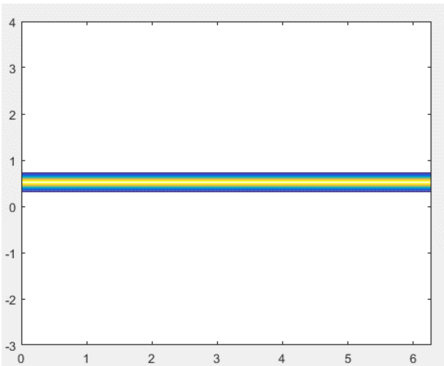
FEL growth .vs. roundtrip

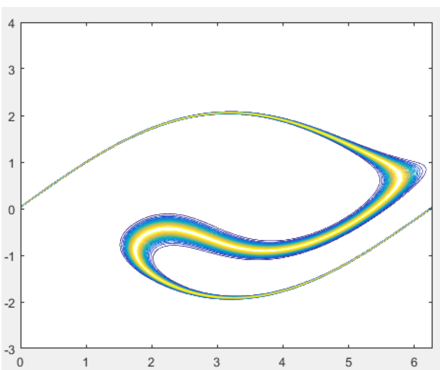


FEL evolution in time and spectral domain

- Numerical simulation
  - ✓ GENESIS + OPC
  - ✓ harmonic field import
  - ✓ Proper noise loading
- Sensitivity anlysis on X-ray cavities
  - ✓ ~μm offset
  - ✓ ~10nrad tilt
  - ✓ <1×10^{-7} /K thermal expansion coefficient

Gain-cascading scheme of XFELO





Pendulum equation

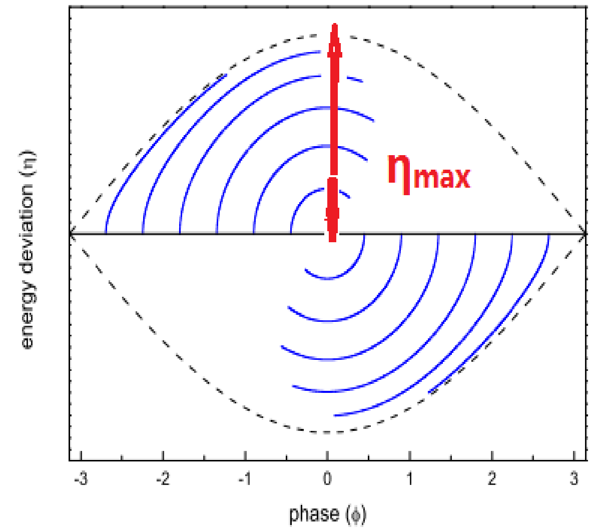
$$k_s = \frac{\sqrt{\varepsilon}}{L_u}; \qquad \eta_{\max} = \frac{\sqrt{\varepsilon}}{k_u L_u}$$

Expected saturation

$$L_u = \frac{1}{4}\frac{2\pi}{k_s} = \frac{\pi/2}{\sqrt{\varepsilon}} L_u$$

Efficiency

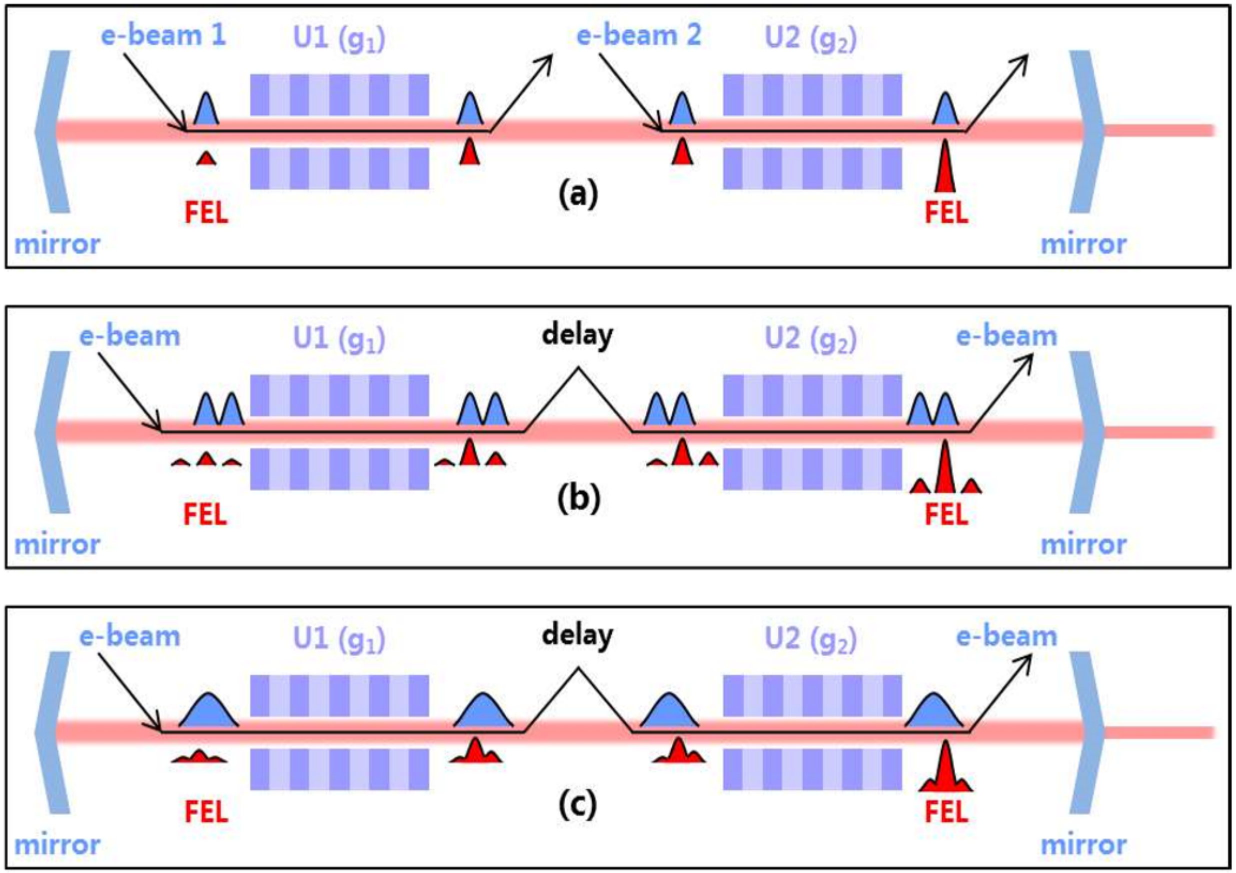
$$\eta = \frac{P_{out}}{P_{beam}} = \frac{1}{4N_u}$$



IR FELO : N=25 , η=1%
XFELO : N=1000 , η=0.02%

- **Problem:** Is it possible to extract more FEL power from the electrons? if one decrease the undulator period number Nu.
- **Solution:** In the following undulators, replace the used electron beam with a fresh one and continue to gain.

Gain-cascading scheme of XFELO



Condition

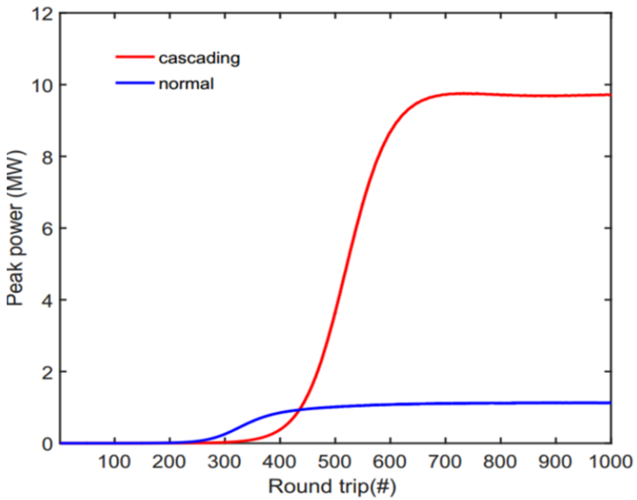
$$r\prod_{1}^{n}(1+g_i) > 1$$

$$r\prod_{1}^{n-1}(1+g_i) < 1$$

arXiv:1605.00872 (2016).

Electron beams act as in a RELAY race

Gain-cascading scheme of XFELO



12.4keV X-ray FELO simulation

Normal XFELO:

- 7GeV, 0.2μm-rad,10A, 20pC
- 18.8mm×2000, g=15%

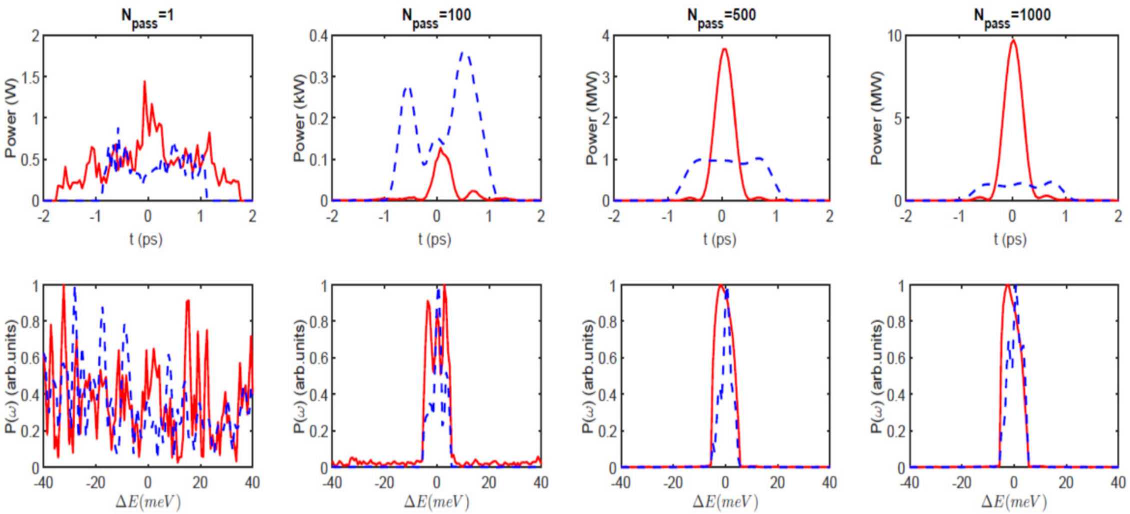
Gain-cascading XFELO:

- 7GeV, 0.2μm-rad,10A, 20pC
- 18.8mm×900×4, $g_1+g_2+g_3+g_4=15\%$
- 0.5ps delay for each chicane

Peak power:
1.1MW → 9.7MW

Pulse length:
1.7ps → 0.46ps

Pulse energy:
1.67μJ → 4.23μJ



Simplified XFELO model

Motivation: the traditional way of tracking each macro-particle is time-consuming.

Solution:

- Solving the electron density partial differential equation to get single-pass gain.
- Calculating the light evolution using the initial noise, gain and cavity reflectivity.

Electron density distribution equation

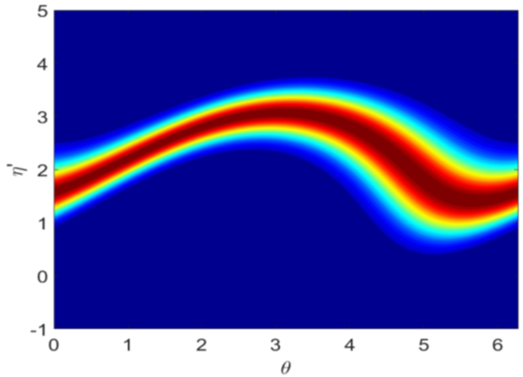
$$\frac{\partial \rho}{\partial z'} + \eta' \frac{\partial \rho}{\partial \theta} + \sin\theta \frac{\partial \rho}{\partial \eta'} = 0$$

Light power profile evolution equation

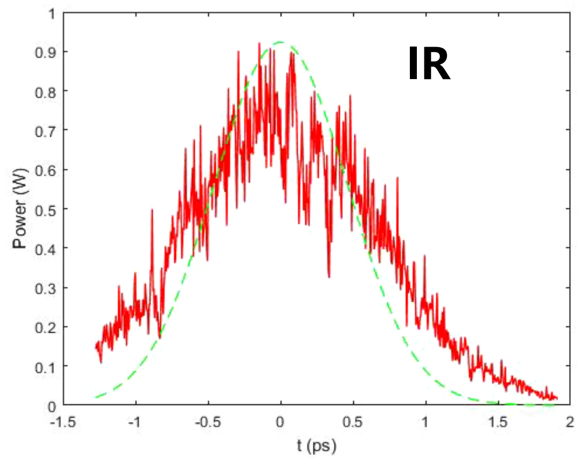
$$P_{n+1} = P_n \left(1 + g(P)\right) R(\omega)$$

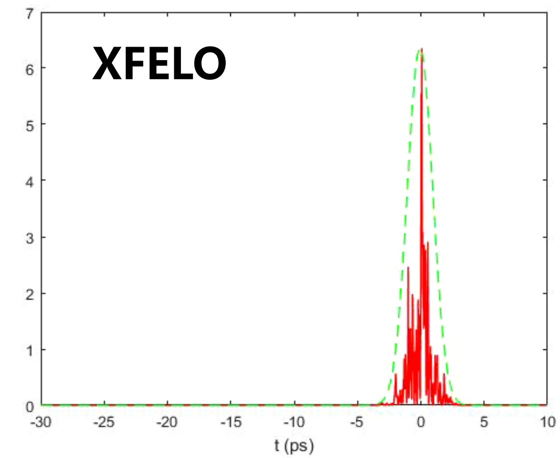
- ☐ **Theoretical model**
- ☐ **Fast optimization (~minute)**
- ☐ **Cavity detuning analysis**

Phys. Rev. AB 20, 030702 (2017).



Electron density distribution





XFELO options for SCLF

- Shanghai Coherent Light Facility (SCLF) : 8GeV CW-FEL

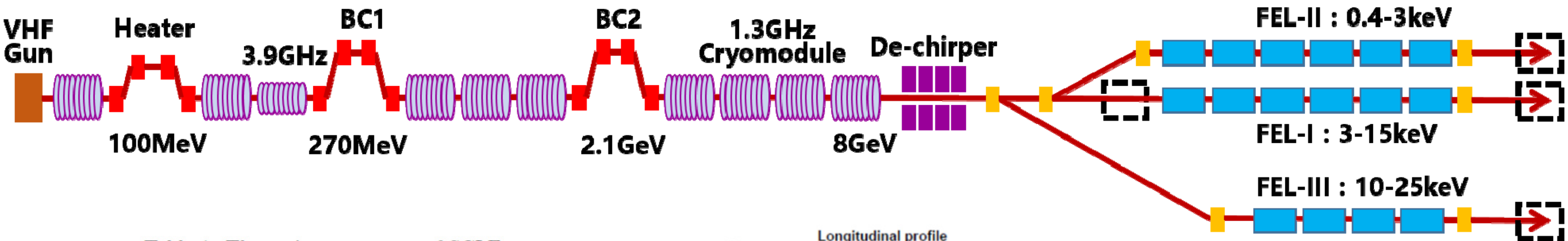
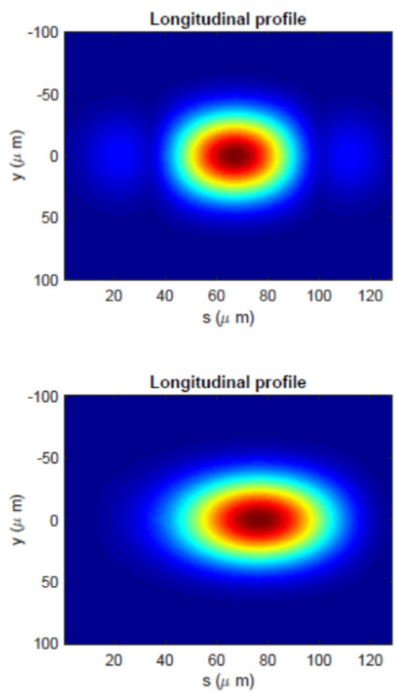
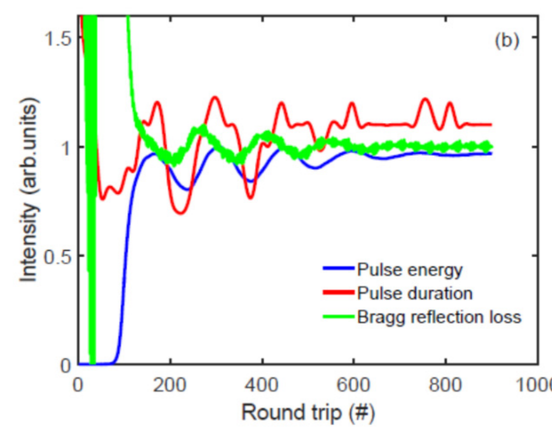


Table 1: The main parameters of SCLF.

Parameter	Value
Beam energy	8 GeV
Relative energy spread	0.01 %
Repetition rate	1 MHz
Peak current (low mode)	10, 20, 30 A
Bunch charge (low mode)	20 pC
Normalized emittance (low mode)	0.2 mm·mrad
Peak current (high mode)	0.5, 1, 1.5 kA
Bunch charge (high mode)	100 pC
Normalized emittance (high mode)	0.4 mm·mrad
Undulator period length	26 mm
Undulator module length	5 m
Radiation wavelength	0.1 nm





arXiv :1706.06338 (2017).
MOP063, FEL2017

X-ray pulse oscillation

Summary & Outlook

- **Full scientific potentials of X-ray FEL will be realized if both the amplifiers and oscillators are available.**
- **Harmonic lasing scheme for XFELO allows for hard X-ray generation with a low beam energy, e.g., 3-4GeV electron beam.**
- **Gain-cascading scheme for XFELO delivers fully coherent x-ray pulse with higher peak power (×10), shorter pulse length (×1/4), and higher pulse energy (×2.5) in the mean time. On other hand, for an Oscillator which is suffered from large cavity loss, gain cascading scheme may make it lase.**
- **There are still many new ideas and proposals for XFELO. With the constructions of high-repetition rate / CW machines, i.e., European XFEL, LCLS-II, and SCLF, there exists an opportunity for XFELO.**

Acknowledgment

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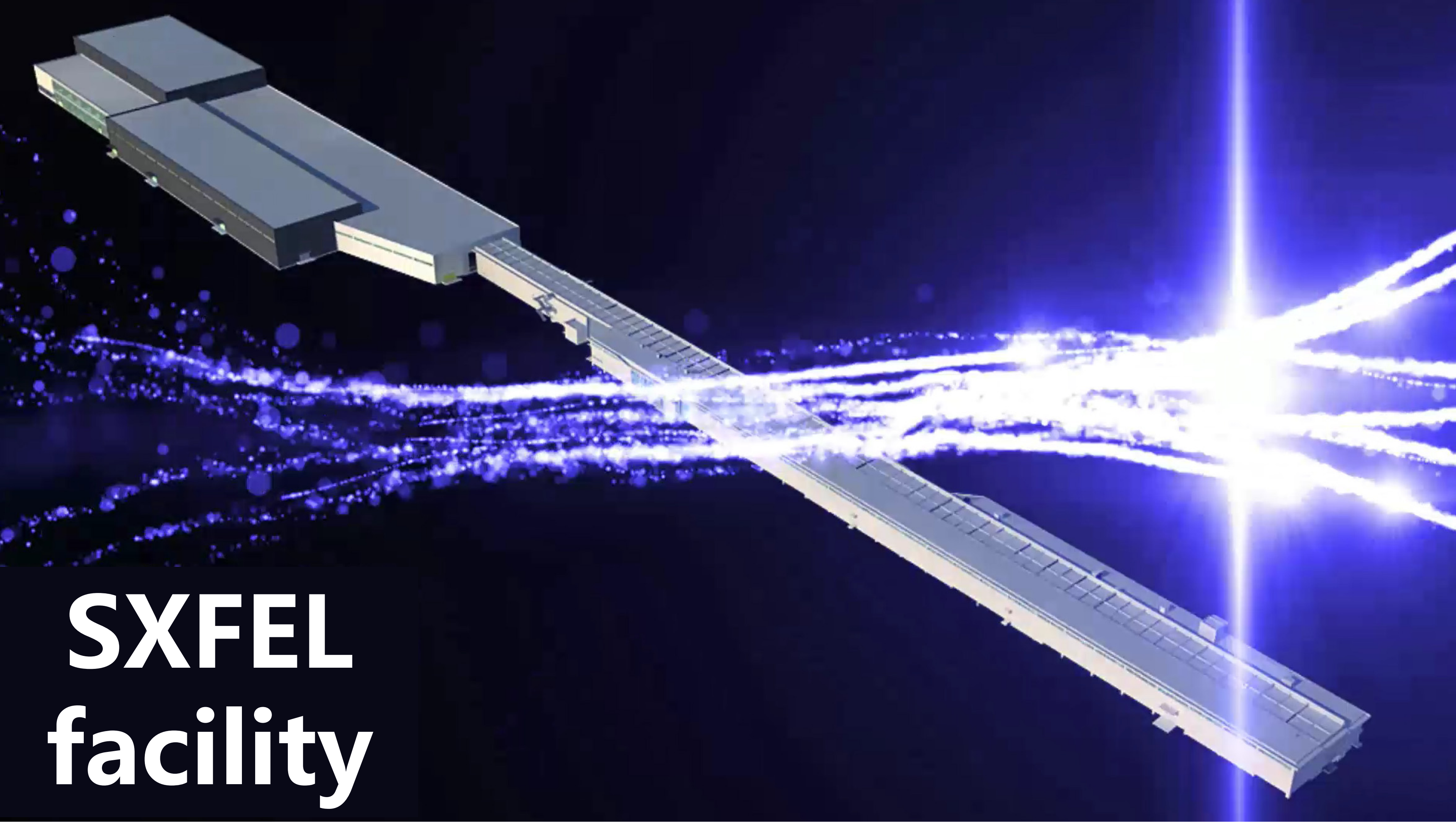
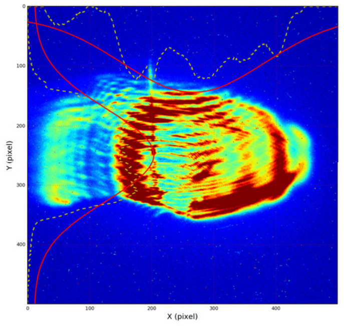
- Special thanks to my collaborator, Qingmin Zhang, Kai Li.
- And many others.





Thanks for attention !