High Extraction Efficiency Operation of Oscillator-type Free Electron Laser Driven by a Normal Conducting Linac

Heishun Zen[1)], Ryoichi Hajima[2)], and Hideaki Ohgaki[1)]

1. IAE, Kyoto University,   2. QST

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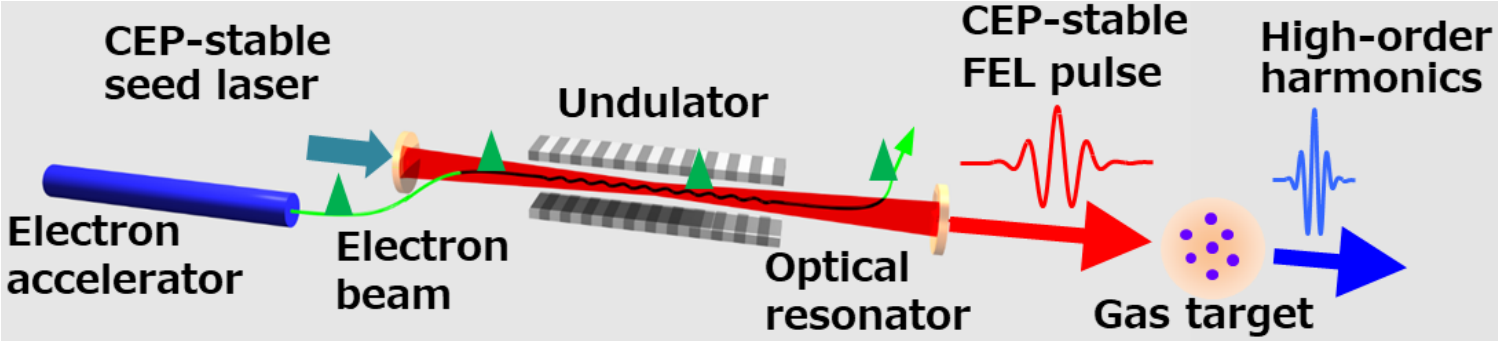
Outline

- Introduction
- Experimental Condition & Results
- Summary

Motivation

Project under MEXT Q-LEAP

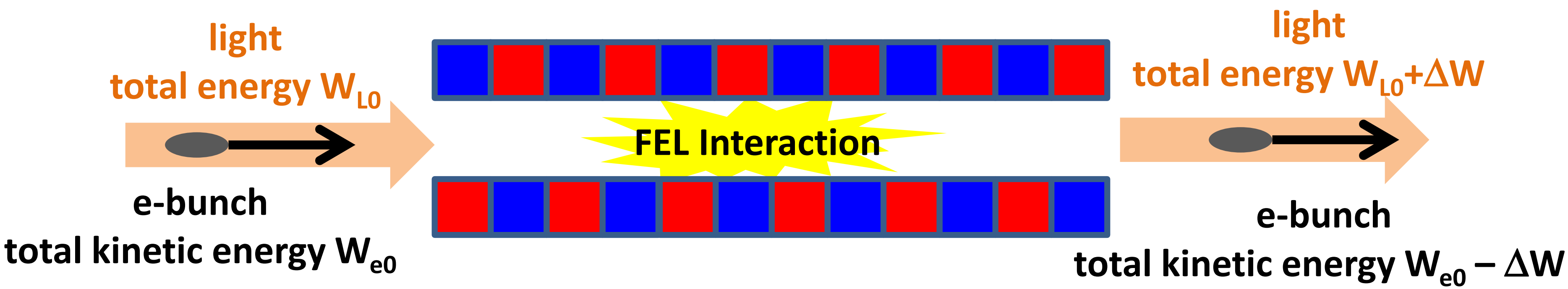


- Our ongoing project: LWIR-FEL driven HHG for hard X-ray attosecond pulse generation.
  ➔Need 1-mJ class few-cycle LWIR (8–14 μm)-FEL pulses
- In this project, KU-FEL is used to study the way to generate such high intensity and ultrashort pulse by an oscillator FEL.
- Increase efficiency of oscillator FEL is key issue to generate few-cycle and high energy pulses from an oscillator FEL.

Pulse energy ∝ Efficiency **Pulse duration ∝ 1/Efficiency**

Extraction Efficiency of FEL

FEL converts the kinetic energy of e-bunch to the energy of EM wave.

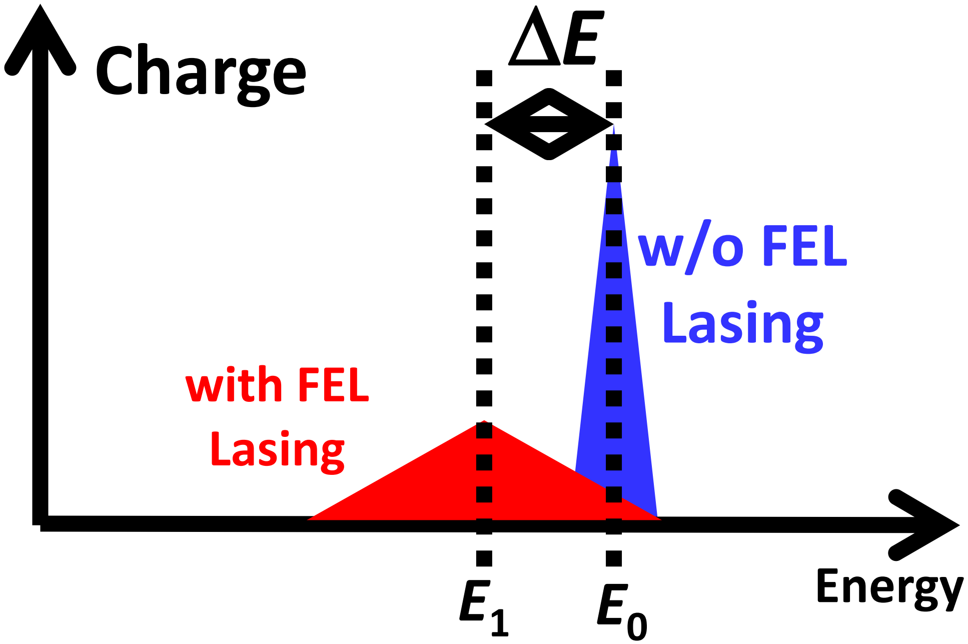


When light is amplified, e-bunch lose kinetic energy ($\Delta W > 0$)

Extraction Efficiency $\eta = \Delta W / W_{e0}$

How large fraction of kinetic energy of e-bunch transferred to EM energy.

How to Measure the Extraction Efficiency



E_0 : Average w/o FEL lasing
E_1 : Average with FEL lasing

$\Delta E = E_0 - E_1$: **Extracted Energy**

$$\eta = \frac{\Delta E}{E_0}$$: **Extraction Efficiency**

- FEL oscillator normally has a bending magnet after the undulator.
- The dispersive section can be used for measuring the extraction efficiency.
- By using a charge detector having high temporal resolution, evolution of the efficiency in a macro-pulse can be measured.

Limit of Extraction Efficiency of FEL Oscillator

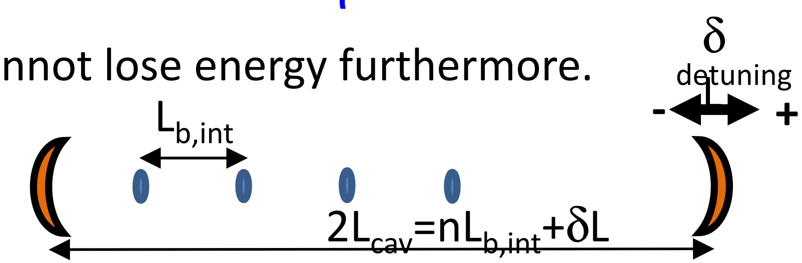
Bunch Length L_b >> Slippage length L_S (= λ_r x N_u)

FEL efficiency is limited by gain bandwidth of FEL system determined by number of periods of undulator N_u.

$$\eta \sim \frac{1}{2N_u}$$

typical undulator for oscillator FEL N_u > 30
➔ η < 1.7%

Electron has larger energy loss than gain bandwidth cannot lose energy furthermore.



Bunch Length L_b < Slippage length L_S

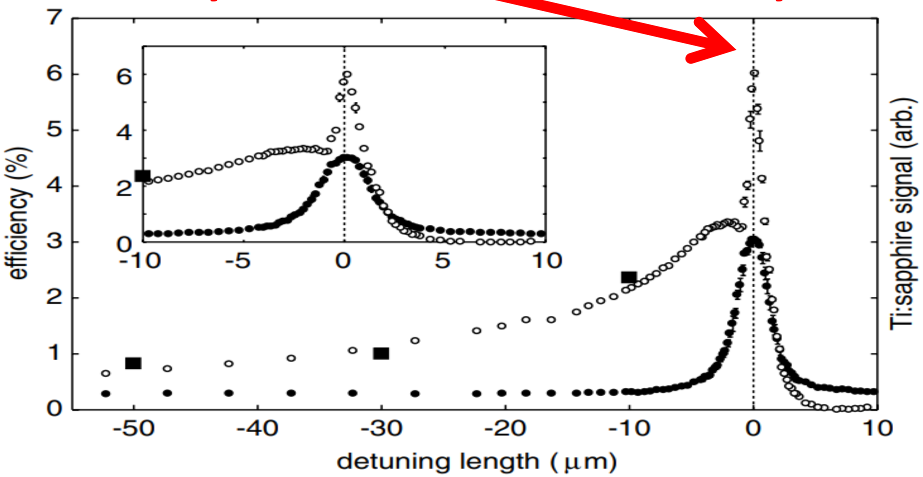
- The extraction efficiency strongly depends on the detuning of the optical cavity since the FEL micro-pulse width also strongly depends on that.

- At the perfect synchronization condition of e-bunch repetition rate and fundamental or harmonic roundtrip frequency of the optical cavity, the shortest FEL micro-pulse width and the highest extraction efficiency can be obtained.

Lasing of FEL at the perfect synchronization condition

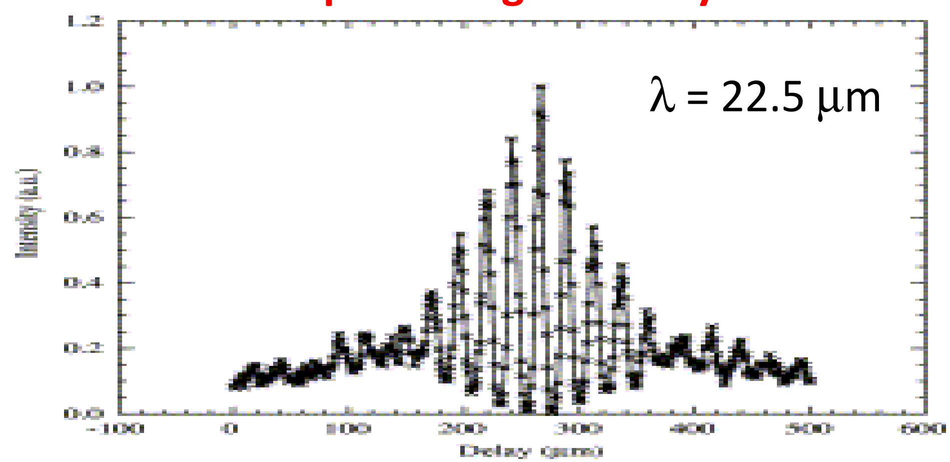
FEL lasing at the perfect synchronization condition has been achieved at JAERI-FEL which was reported in 2001.

Perfect synchronization!! ➔ Efficiency ~ 6%.



N. Nishimori et al., Phys. Rev. Lett. 86, 5707 (2001)

Micro-pulse length ~3.4 cycle



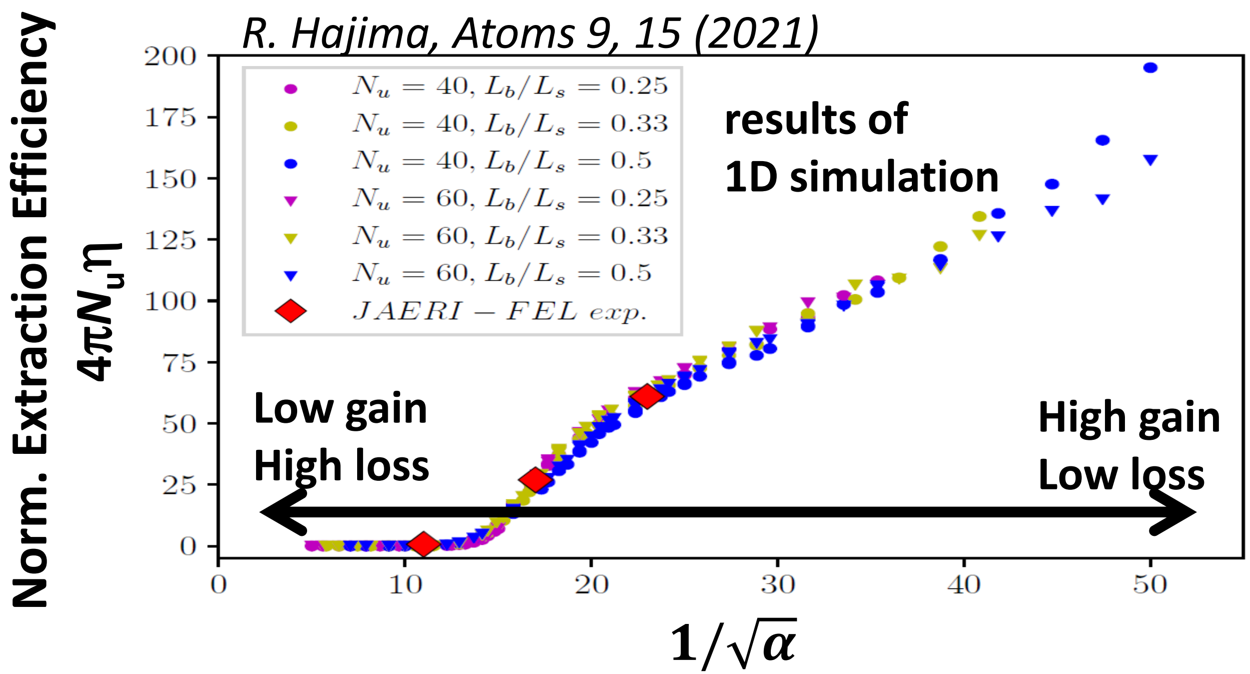
R. Nagai et al., NIM A 483, p.129-133 (2002)

- At the perfect synchronization condition, the FEL micro-pulse length L_p get much shorter than the slippage length L_S. (in JAERI-FEL, L_S ~ 1.2 mm, L_p ~ 0.08 mm ➔ L_S / L_p = 15).
- Only in 3.5 undulator periods, FEL overlaps with same electrons in the e-bunch.

➔ Widen effective gain bandwidth ➔ Higher extraction efficiency

Extraction Efficiency Scaling

At the perfect synchronization condition, the extraction efficiency scales with normalized cavity loss.



$\alpha = \alpha_0/j_0$ **α_0: optical cavity loss**

j_0: Colson's dimensionless current = $2(4\pi N_u \rho)^3$

Pros and Cons of Perfect Synchronization Condition

Under the perfect synchronization condition, the e-bunch and light pulse in an oscillator have small temporal overlap.

↓

Pros

- Ultrashort micro-pulse duration
- High extraction efficiency

Cons

- Strong detuning dependence
- Suppressed gain ➔ <u>slow startup</u>

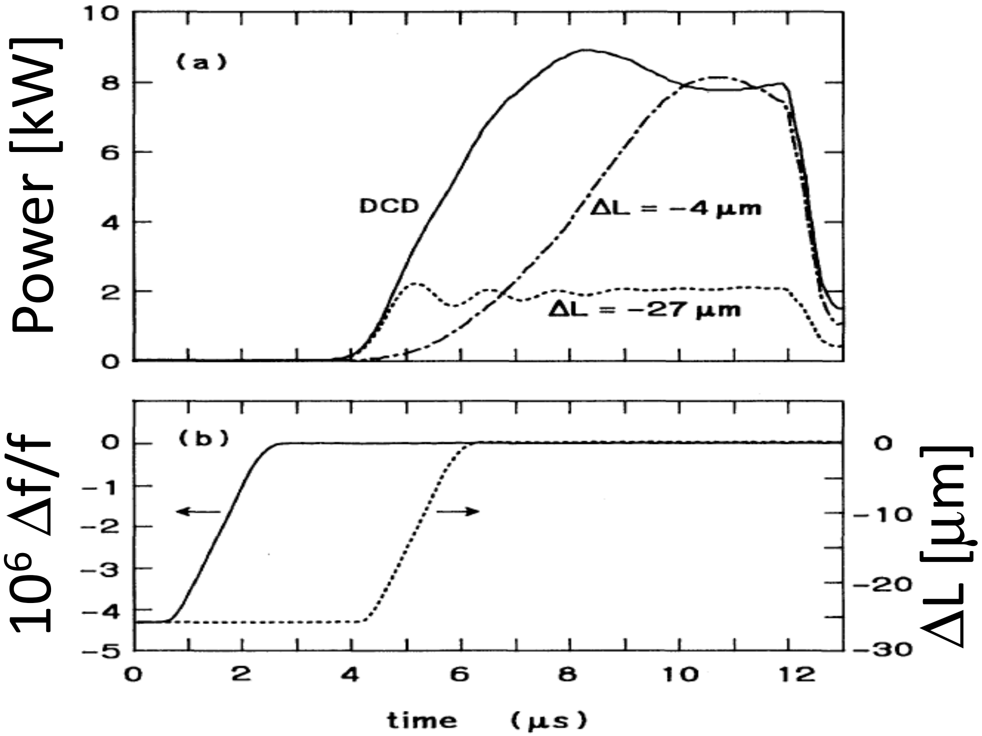
Due to the slow startup feature of this condition, lasing at the perfect synchronization condition has only been observed in JAERI-FEL which driven by a superconducting linac capable to supply e-beam with quite long macro-pulse duration (~400 μs).

How can we realize this lasing in normal conducting linac with short macro-pulse e-beams?

Dynamic Cavity Desynchronization (DCD)

Invented by FELIX group

R.J. Bakker et al., PRE 48, R3256 (1993)



The speed of startup strongly depends on the detuning condition.

- Large negative detuning
  ➔ fast startup but low efficiency
- Small negative detuning
  ➔ slow startup but high efficiency

<< Idea >>
Switch detuning condition in a macro-pulse from large detuning to small detuning by modulating e-bunch repetition rate.

Fast startup and higher efficiency can be realized at the same time!!!

Recent Development of KU-FEL

- Introduction of Dynamic Cavity Desynchronization
  - Faster startup & higher saturation power were achieved.
  - Extraction Efficiency of 5.5% was recorded with the e-bunch charge about 55 pC.
  - We confirmed that DCD enables us to have lasing under the equivalent condition with the perfect synchronization.

This work was reported in H. Zen et al., Phys. Rev. Accel. Beams 23, 070701 (2020).

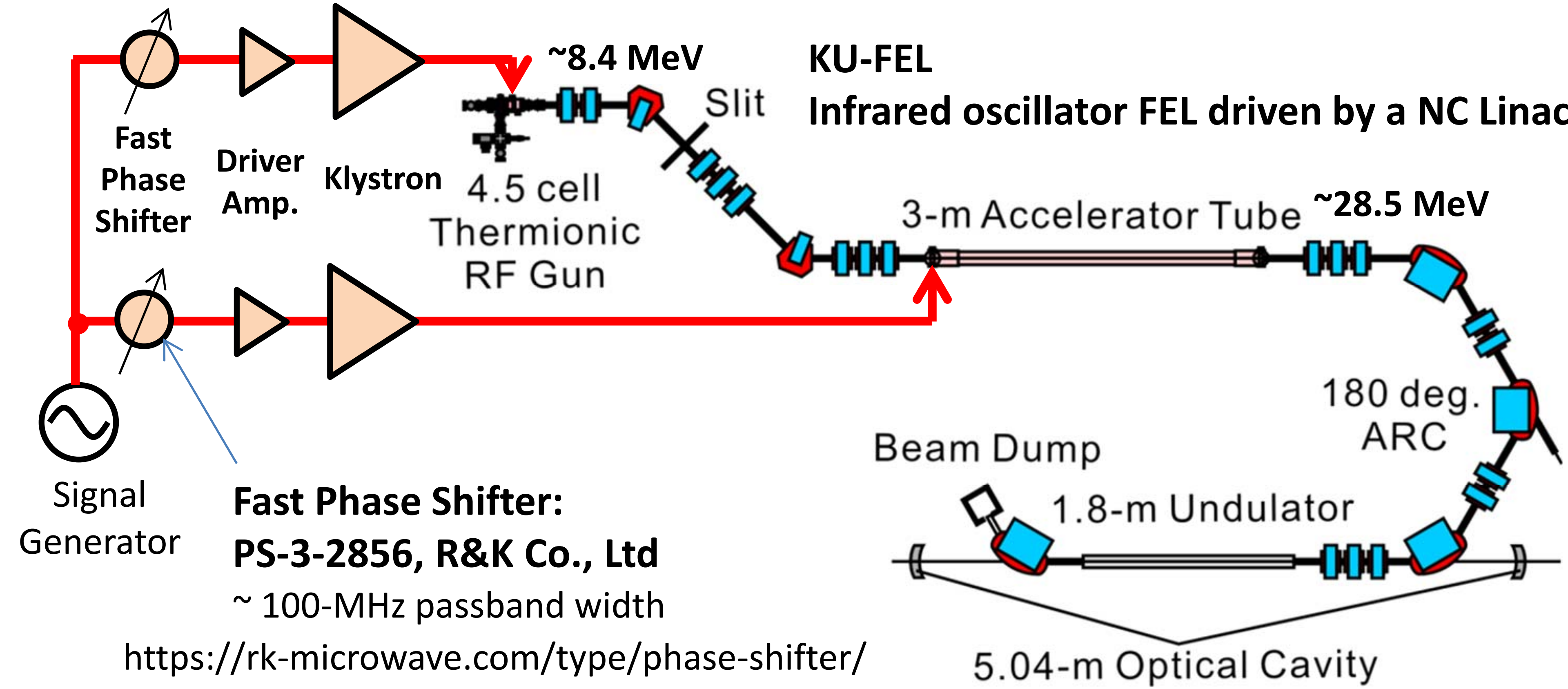
- Photocathode operation of thermionic RF gun
  - LaB_6 cathode was illuminated with DUV ps multi-bunch laser.
  - Extraction Efficiency of 9.4% was recorded with the e-bunch charge around 190 pC & DCD technique.

This work was reported in H. Zen et al., Appl. Phys. Express 13, 102007 (2020)

+ recent results on pulse shape measurement

Experimental Condition

RF gun and Acc. tube are driven by different Klystrons. ➔ Bunch frequency modulation can be optimized.



Experimental condition

Electron Beam

Macro-pulse Rep. Rate	2 Hz
Bunch Rep. Rate	29.75 MHz
Bunch Length	**< 300 μm (< 1 ps)**
Energy	28.5 MeV
Bunch Charge	**~190 pC**

Undulator

Number of Periods	52
Period Length	33 mm
K-Value	1.34
Structure	Hybrid
Taper	No

Optical Cavity

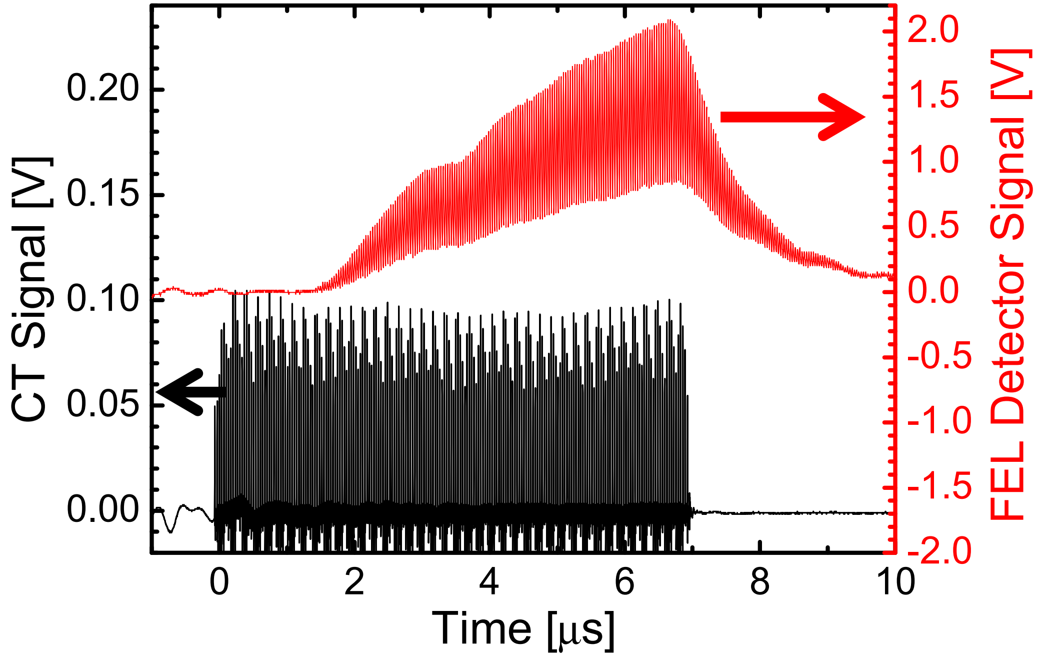
Total Length	5.0385 m
Loss per roundtrip	**~3.4%**

FEL

Peak Wavelength	**10.7 μm**
Slippage Length	**~556.4 μm**

Experimental Result

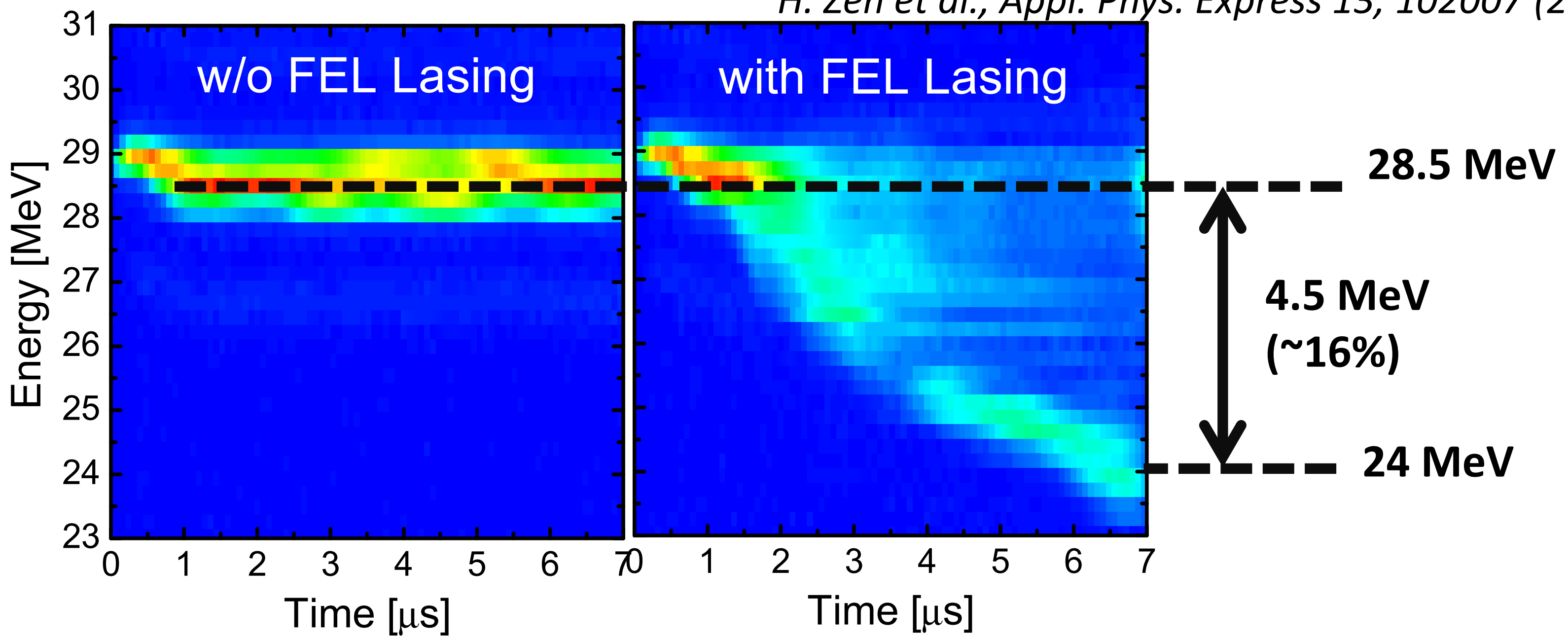
H. Zen et al., Appl. Phys. Express 13, 102007 (2020)



- e-beam macro-pulse duration : 7μs ➔ FEL macro-pulse duration : 3.7μs in FWHM
- The micro-pulse energy at the end of macro-pulse was estimated to be **100 μJ/ micro-pulse**

Energy distribution with and w/o FEL lasing

H. Zen et al., Appl. Phys. Express 13, 102007 (2020)

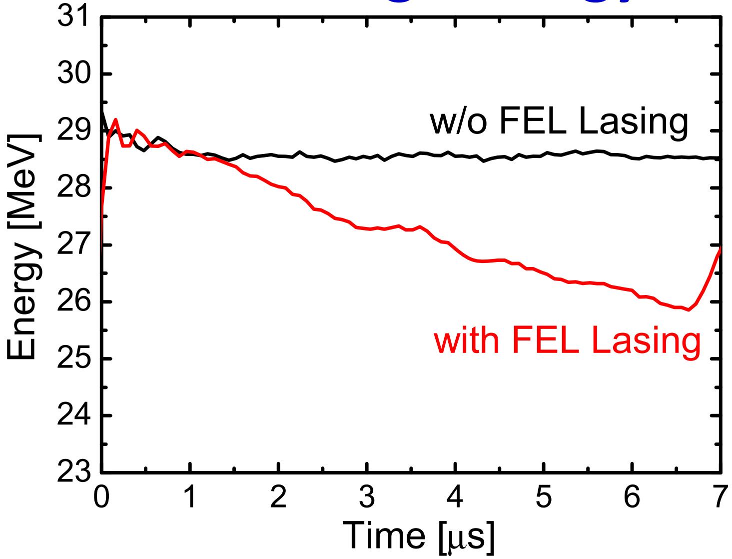


- Measured by energy analyzer after undulator section
- Large energy decrease was observed when FEL lased.
- The max. energy drop of electron was 16%.
- Large fraction of electron in the beam is efficiently decelerated and efficient energy conversion from kinetic energy of electron beam to laser EM field occurred.

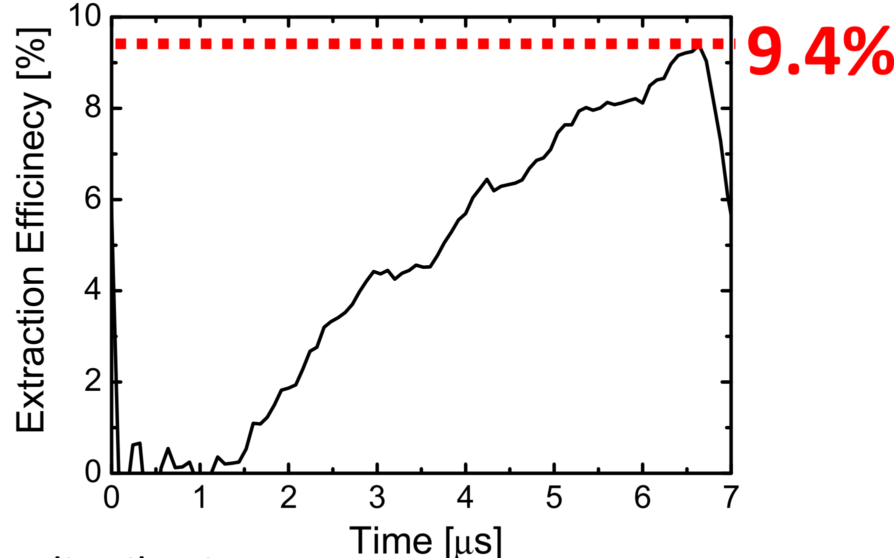
Variation of Average Energy and Extraction Efficiency

H. Zen et al., Appl. Phys. Express 13, 102007 (2020)

Variation of average energy



Extraction Efficiency



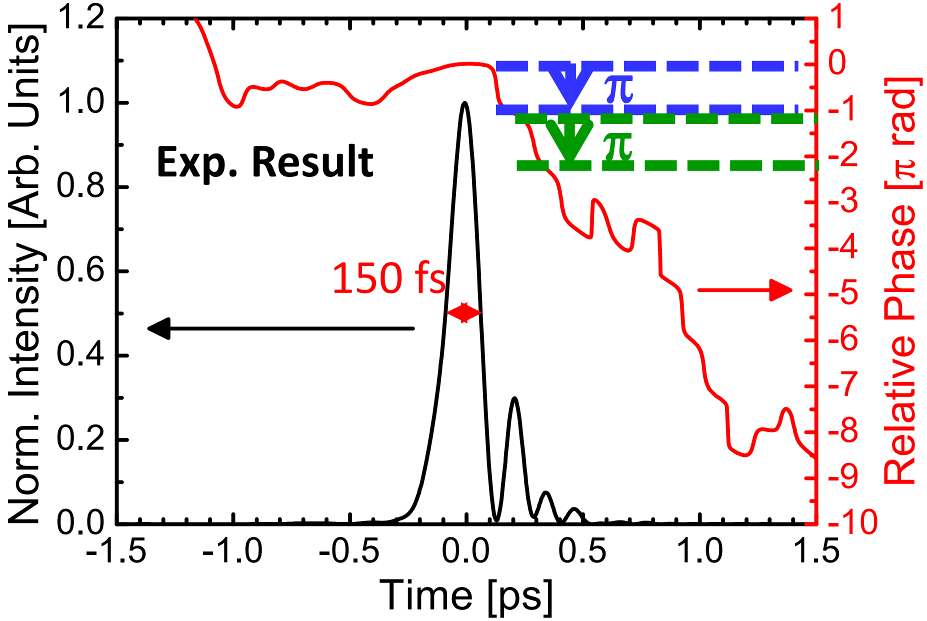
- Evaluate the average energy from measured energy distribution.
- Relative energy variation for FEL ON and OFF corresponds to the extraction efficiency
- Max extraction efficiency : 9.4%
- **Record high efficiency comparable to the JAERI-FEL even with a NC accelerator.**

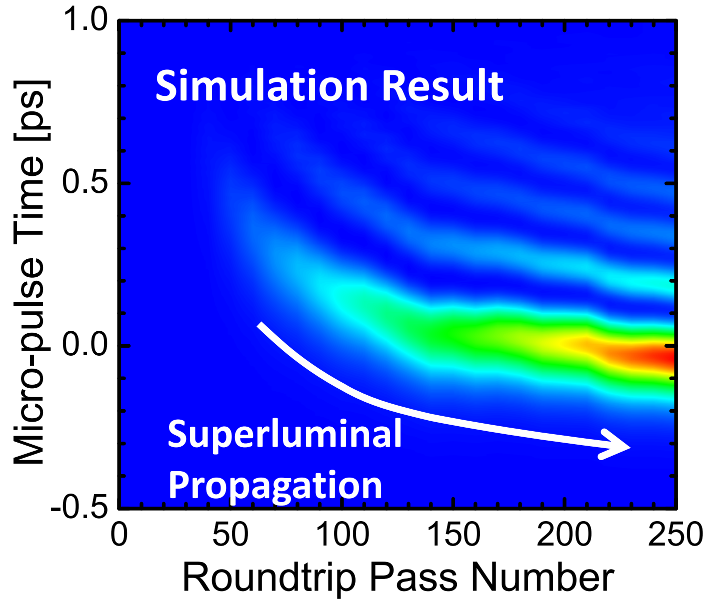
(The highest efficiency before this work was 9%@2002 JAERI-FEL w/SC accelerator)

N. Nishimori et al., NIM-A 483, 134 (2002).

Micro-pulse structure

The micro-pulse structure of KU-FEL has been determined by phase retrieval with **EPRIAC** algorithm using linear and Fringe Resolved Autocorrelation results. Opt. Comm. 271, 169 (2007)



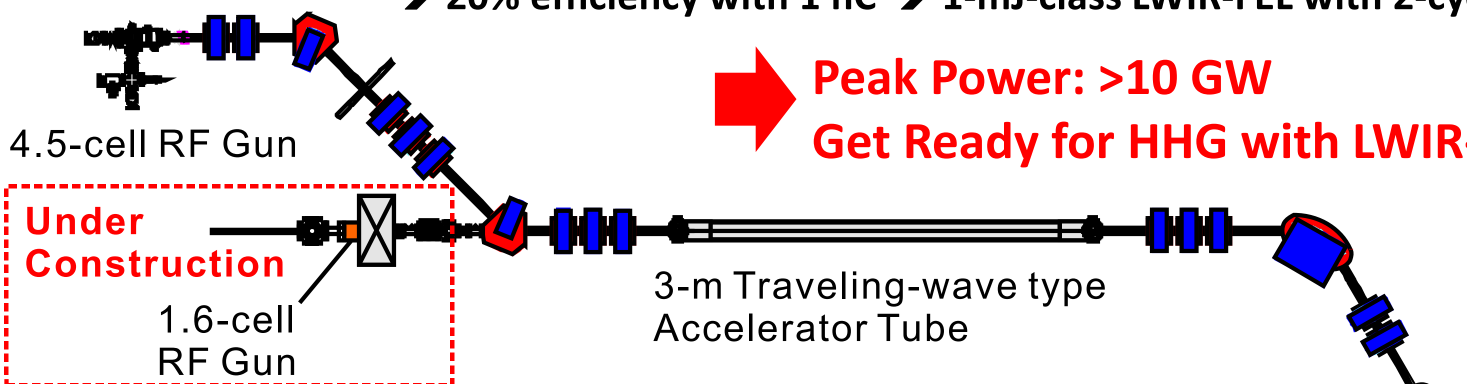


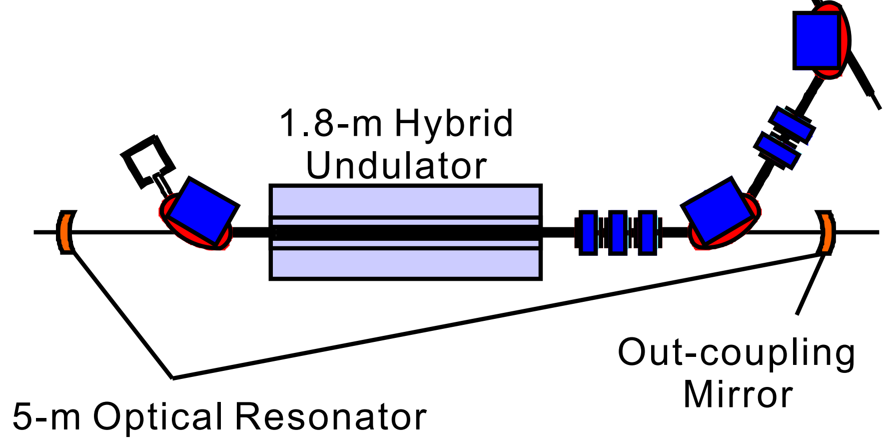
- 150-fs micro-pulse duration (4.2 optical cycles @10.7 μm). ➔ ~670 MW (~50 GW @intracavity)
- Sub-pulse formation and π-phase jumps ➔ Burnham-Chiao Ringing, well agree with simulation.
- Superluminal propagation of main and sub pulses are expected.

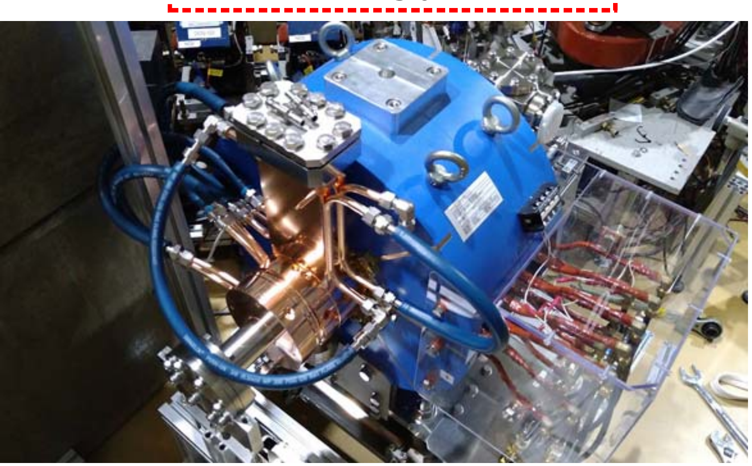
Further Upgrade in Progress

Installation of a dedicated photocathode RF gun with the CsTe cathode
➔ 20% efficiency with 1 nC ➔ 1-mJ-class LWIR-FEL with 2-cycle pulse length

Peak Power: >10 GW
Get Ready for HHG with LWIR-FEL in 2023.







Summary

- Project on demonstration of FEL-HHG is ongoing.
- Require 1-mJ class pulse energy with few-cycle duration.
  ➔High efficiency operation is required.
- Perfect synchronized cavity and e-bunch rep. rate is required high efficiency FEL oscillator.
- Dynamic cavity desynchronization enabled lasing at perfect synchronized condition with short macro-pulse e-beam.
- Dynamic cavity desynchronization + photocathode operation of RF gun
  ➔ 9.4% extraction efficiency at the end of macro-pulse.
- Micro-pulse energy of 100 μJ & 150-fs (4.2 cycle) micro-pulse duration ➔ 670 MW.
- Ringing structure and π-phase jumps observed. ➔ Burnham-Chiao Ringing.
- Superluminal propagation of FEL pulse is expected under the condition.
- Further upgrade is in progress.

Thank you for the kind attention.