Application of infrared FEL oscillators for producing isolated attosecond X-ray pulses via high-harmonic generation in rare gases

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Contents

- Introduction of HHG and possible combination with FELs
- Few-cycle pulse generation in FEL oscillators
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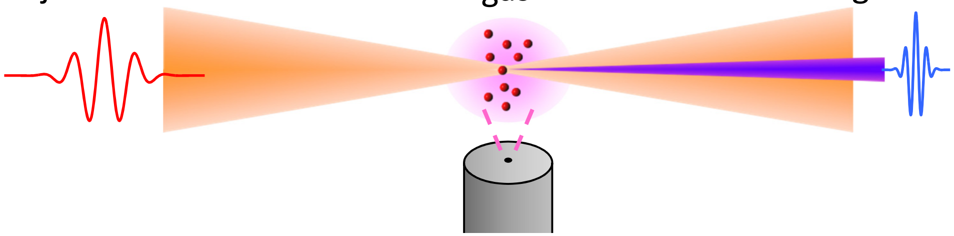
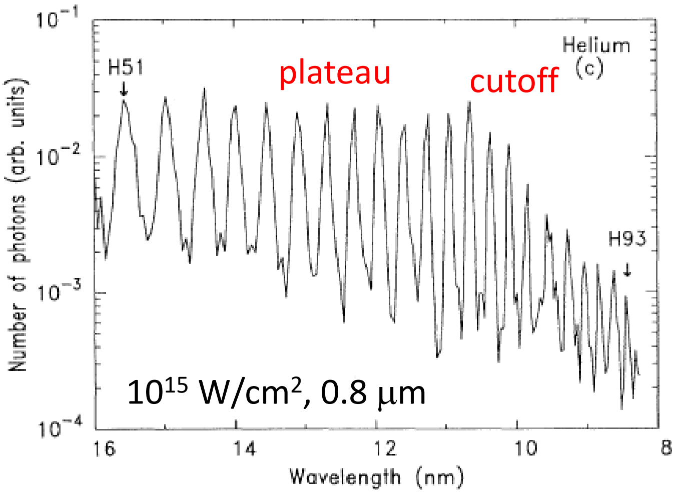
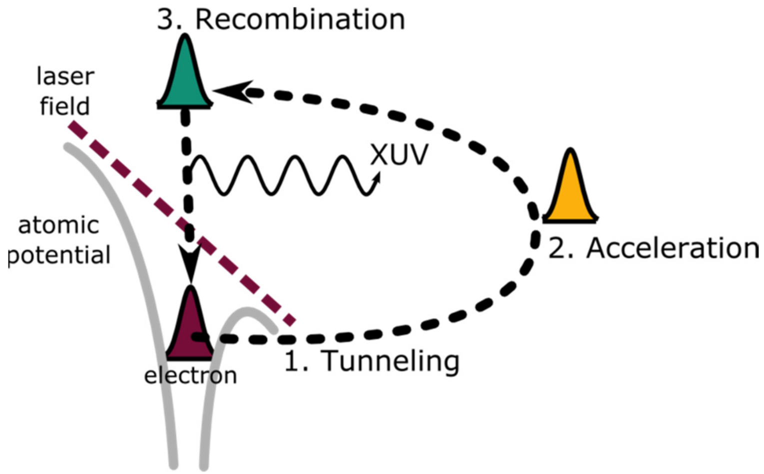
High Harmonic Generation; HHG





odd-harmonics with time and spatial coherence

Wahlström et al., Phys. Rev. A 48, 4709 (1993)



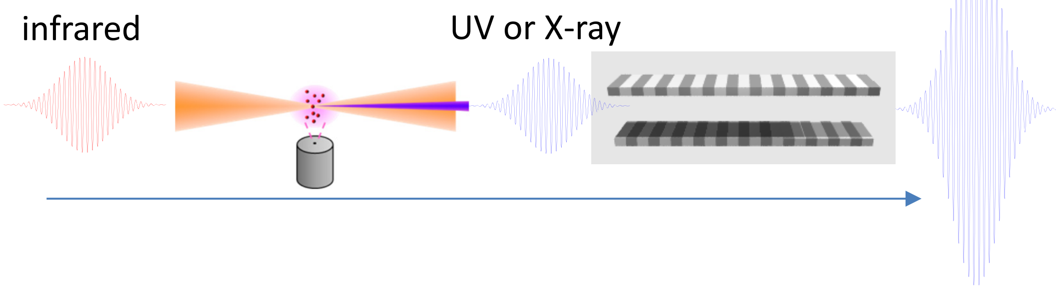
Wikipedia

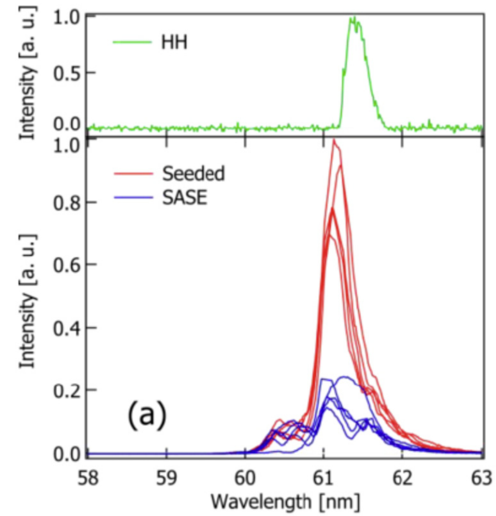
3-step model

1. tunneling ionization by E_{laser}
2. acceleration of the electron by E_{laser}
3. recombination with the parent atom

Combination of HHG and FEL

HHG → FEL

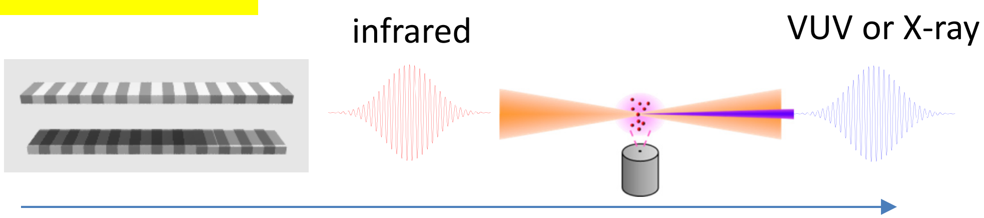




✓ By injecting HHG as a seed laser, we can control FEL spectral and temporal shapes to suppress SASE-induced fluctuation.

T. Togashi et al., Opt. Exp. 19, 317 (2011).

FEL → HHG



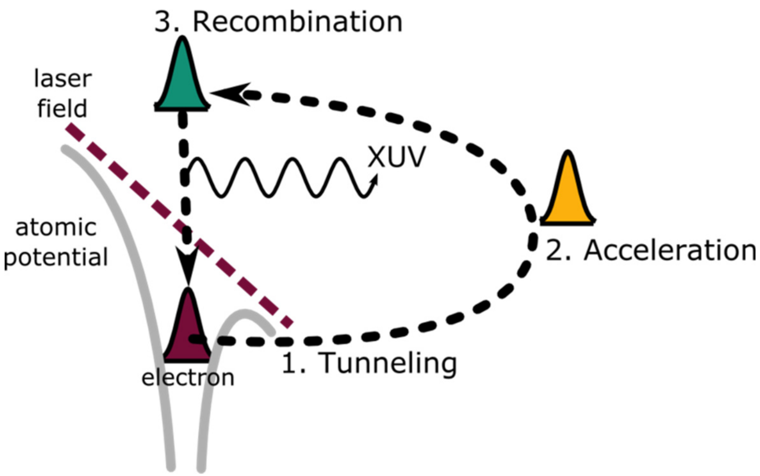
M. Tecimer, PRST-AB 15, 020703 (2012).

✓ generating VUV and X-ray with a small-size FEL
✓ attosecond pulses available

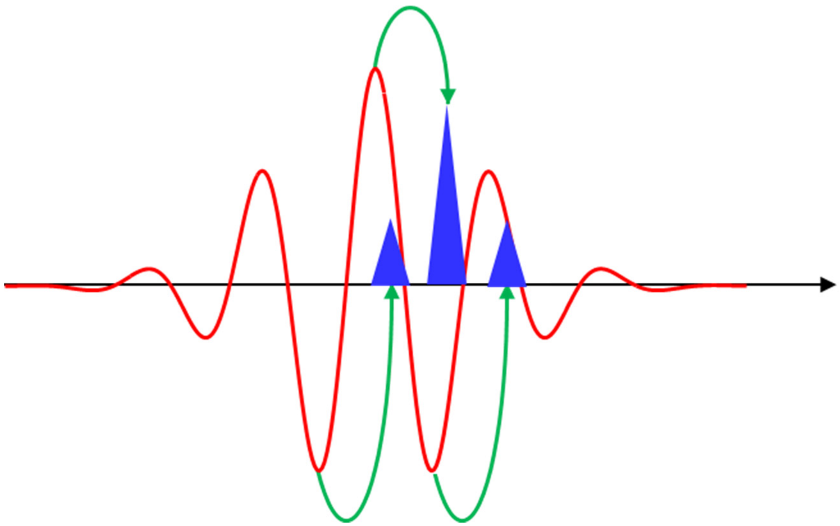
Not demonstrated yet !

Keys to the attosecond pulse generation in HHG

High Intensity



Few-cycle pulse



Typical laser intensity for HHG

~10^{14} W/cm^2 ⟺ 0.3-1 mJ, 3-cycle, λ = 2-6 μm, w = 100 μm

Can a FEL generate such pulses?

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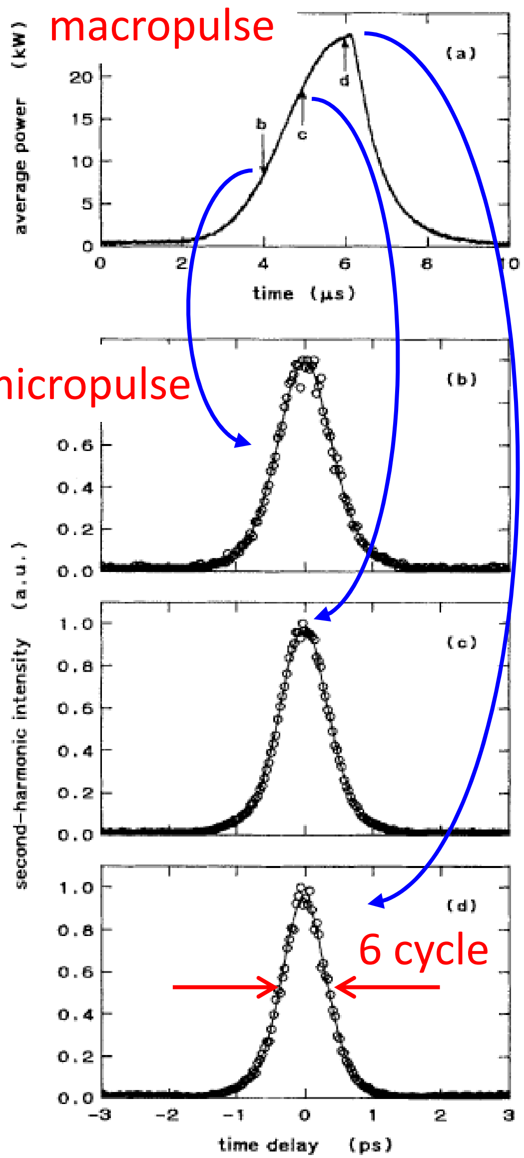
Few-cycle FEL pulses (transient regime)



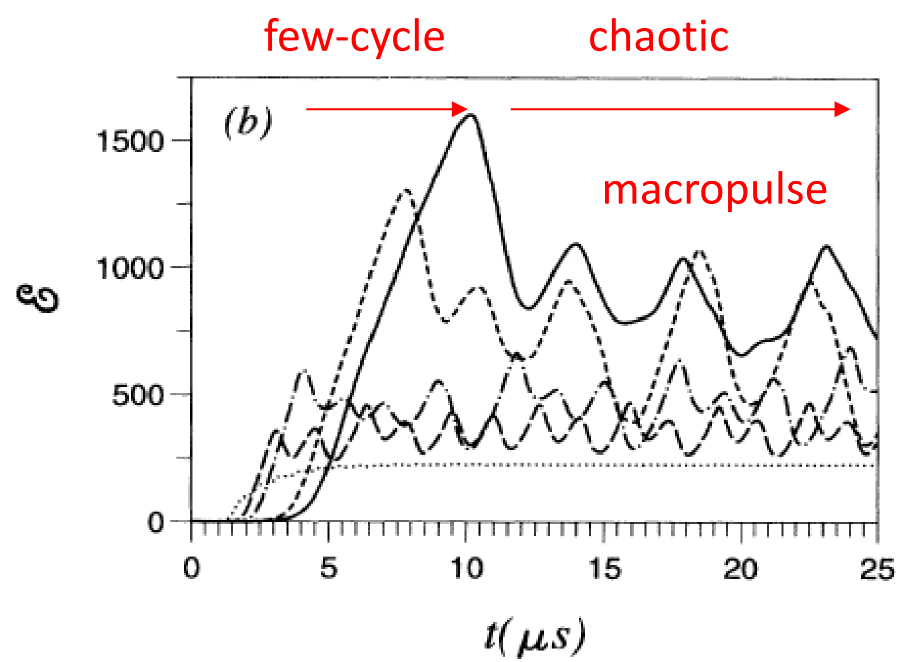
6-cycle pulses were demonstrated at a FEL oscillator, FELIX.

10 μJ, 6 cycle, 10.4 and 24.5 μm

G.M.H. Knippels et al., Phys. Rev. Lett. 75, 1755 (1995)

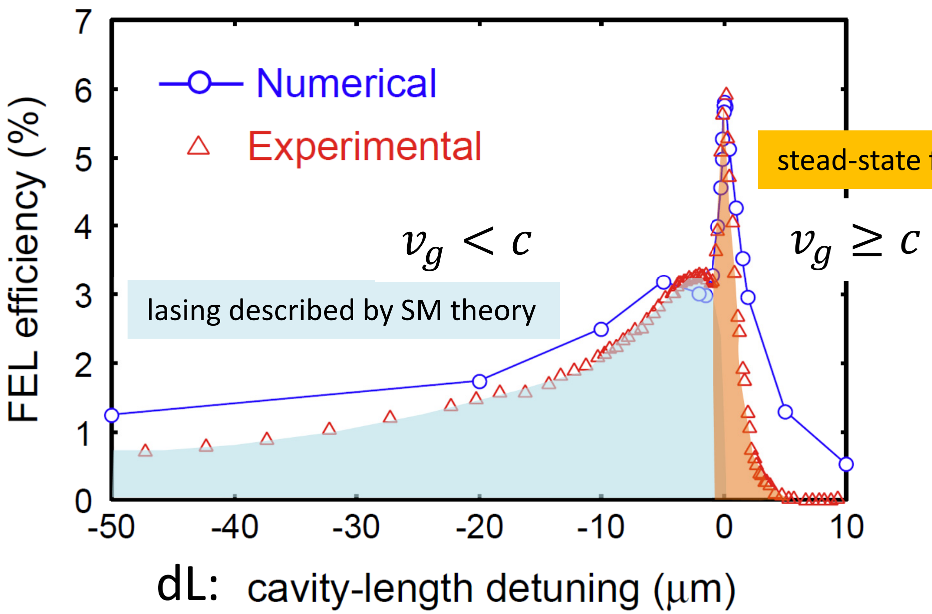
Few-cycle pulses are only available at the transient regime.
Chaotic lasing appears after the saturation.

N. Piovella et al., Phys. Rev. E 52, 5470 (1995)

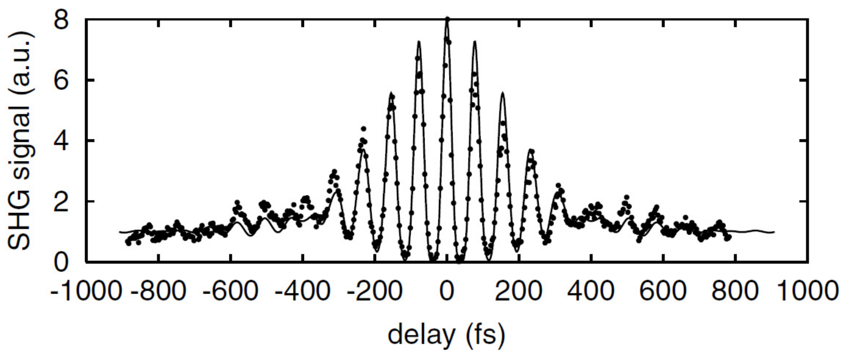


Few-cycle FEL pulses (steady state)

High-efficiency lasing at dL=0 was found at JAERI FEL.
A few-cycle FEL pulse was confirmed by autocorrelation measurement.



N. Nishimori et al., PRL 86, 5707 (2001)
R. Hajima et al., NIM-A 475, 270 (2001)



1.55 cycle after chirp compensation

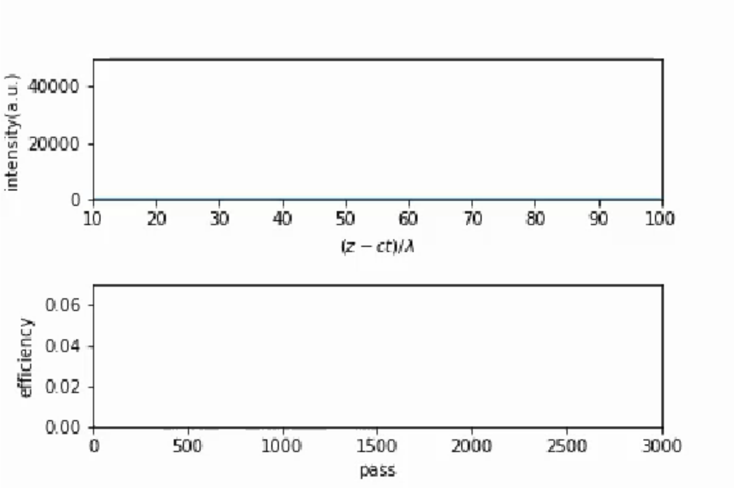
pulse energy ~ 0.2 mJ

R. Hajima and R. Nagai, PRL 91, 024801 (2003)
R. Nagai et al., NIM-A 483, 129 (2002)

Few-cycle pulse evolution in FEL Oscillators

dL<0

dL=0



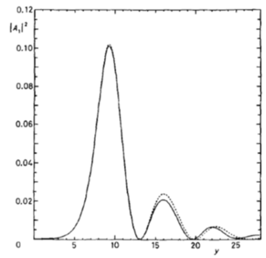
Transient regime
Chaotic lasing

Steady state regime
Solitary pulse

Principle of few-cycle pulse generation at dL=0

Single-pass FEL

weak* superradiance
in short-pulse limit



(*) Peak is lower than the steady-state lasing

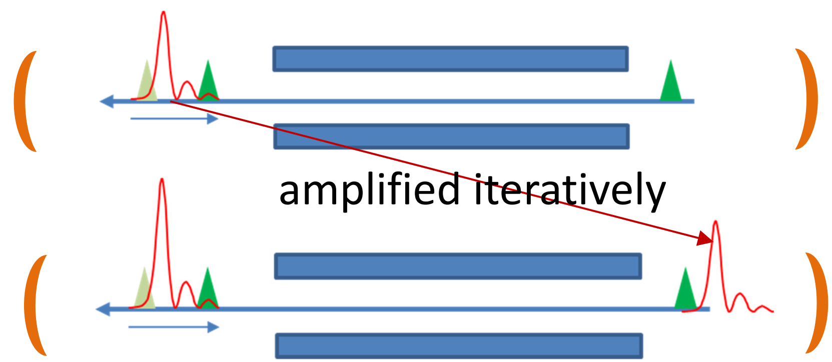
R. Bonifacio et al., Riv. Nuovo Cimento (1990)

Radiation emitted in the slippage region.

Short pule FEL Oscillator at dL=0

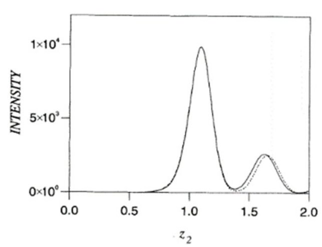
Evolution of a solitary pulse

N. Piovella, Opt. Comm. (1991)
R. Bonifacio, N. Piovella, B.W.J. McNeil, PRA (1991)

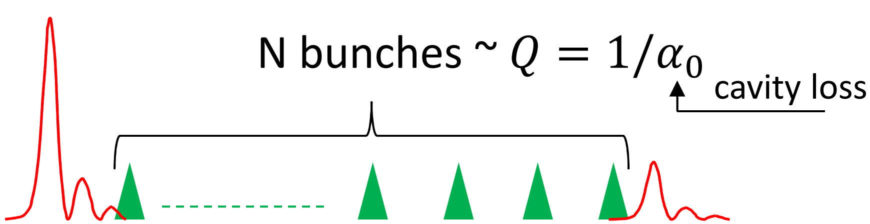


Superradiant pulse evolution
at a loss-less cavity

N. Piovella,
Phys. Rev. E 51, 5147 (1995)



Peak exceeds the steady-state lasing

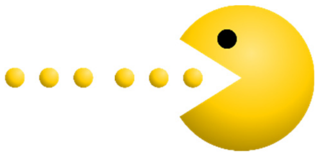


Superradiant pulse evolution
at a lossy cavity (with shot noise)

R. Hajima et al., NIM-A 475, 270 (2001).

$peak \propto N_e^2 \propto (qQ)^2$

$width \propto N_e^{-1/2}$



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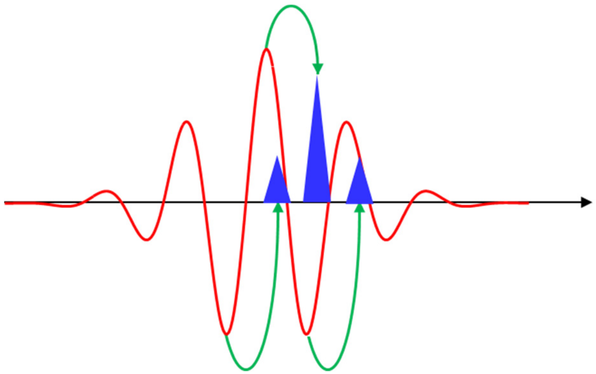
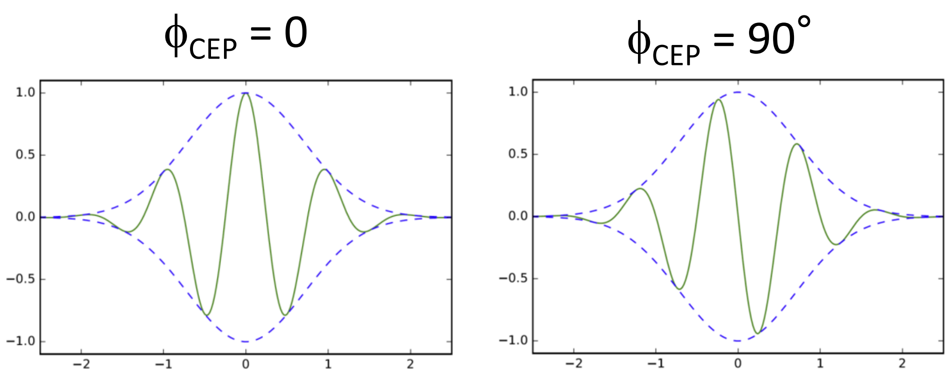
Carrier-Envelope Phase (CEP)



HHG is governed by laser oscillating electric field.

Carrier-envelope phase (CEP) affects
the properties of HHG, cut-off energy, spectrum and yield.

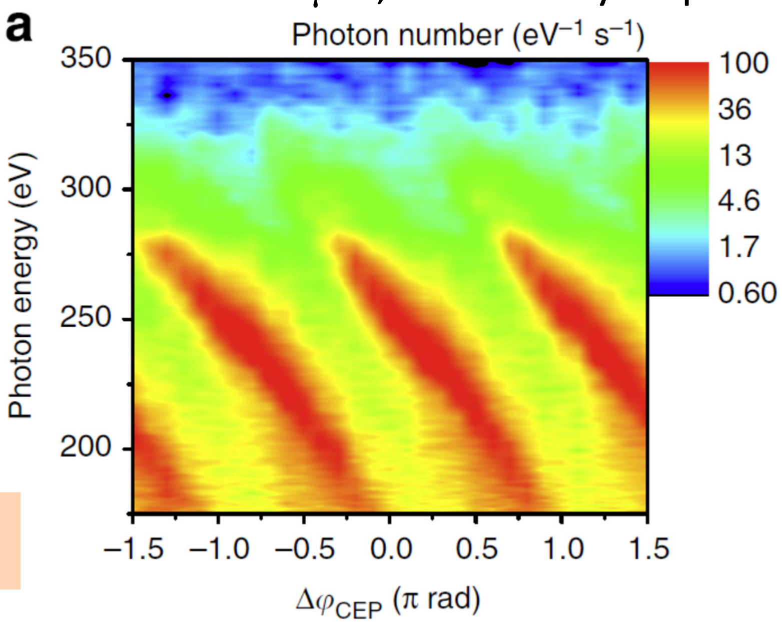
CEP must be stabilized for a practical use of HHG.



Carrier-Envelope Phase (CEP)

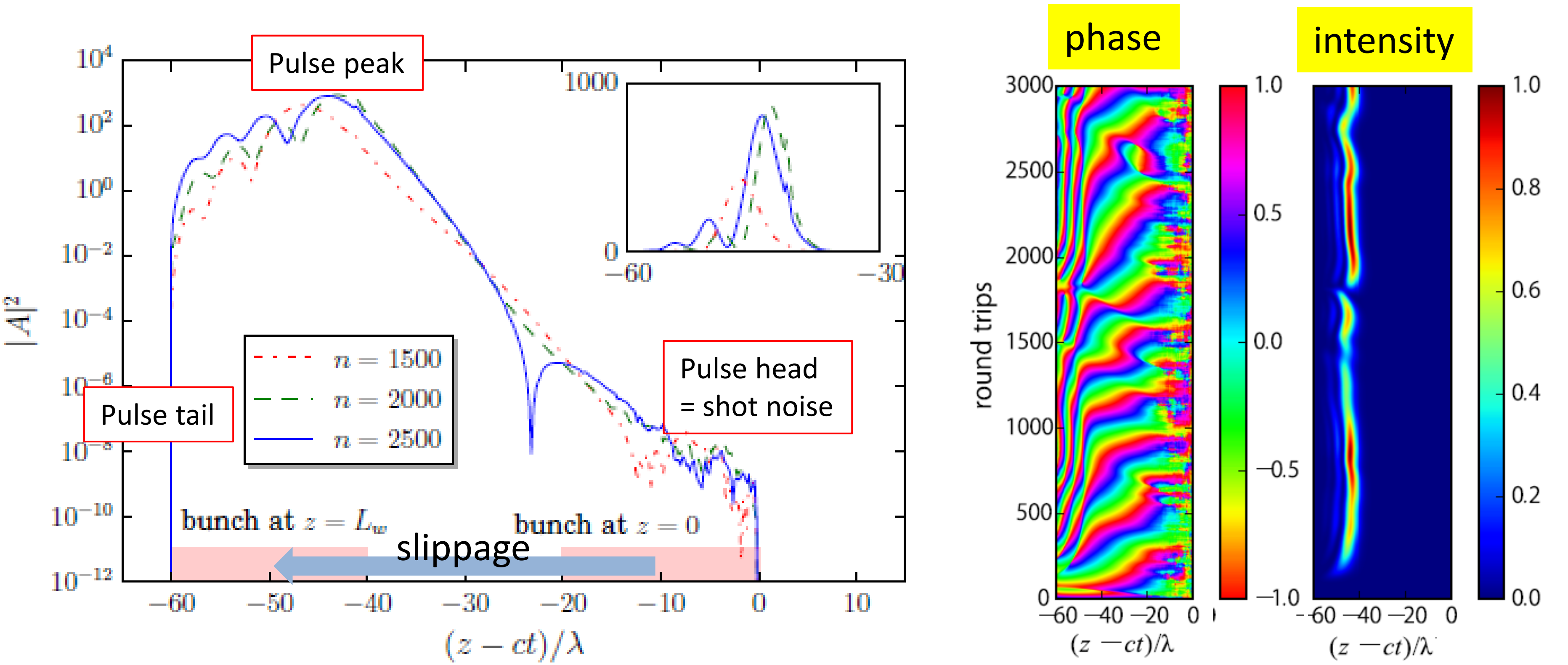
Can a FEL generate CEP-stable pulses?

HHG with 1.6 μm, sub-two-cycle pulses



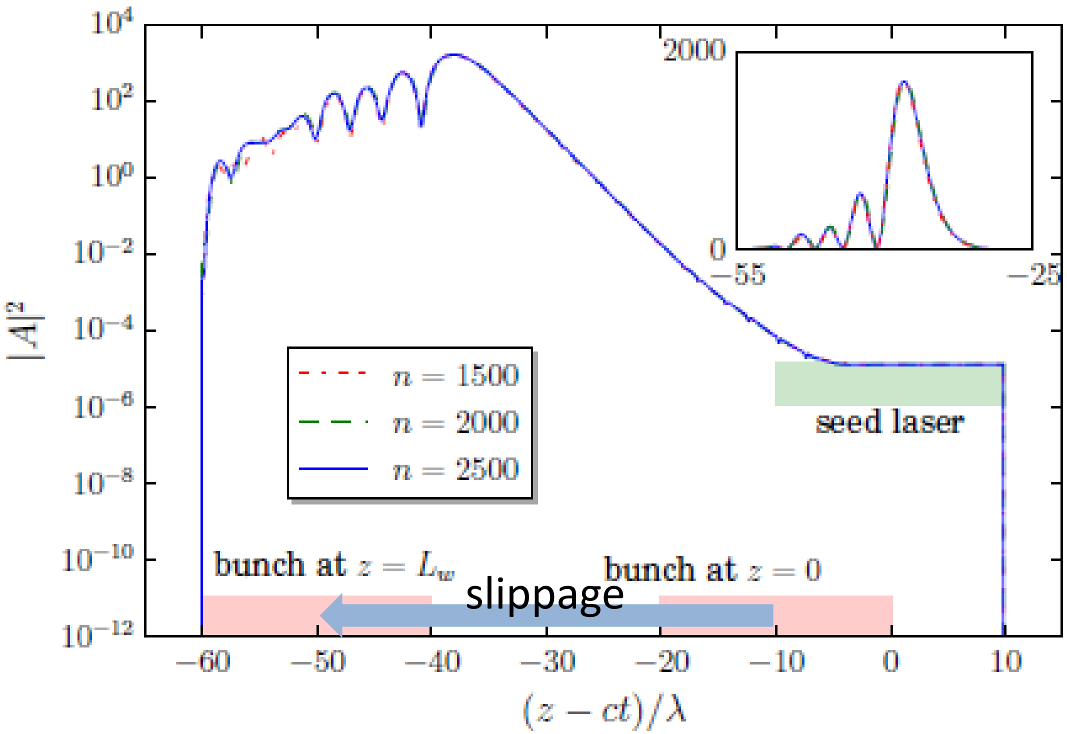
N. Ishii et al., Nature Comm. 5, 3311 (2014).

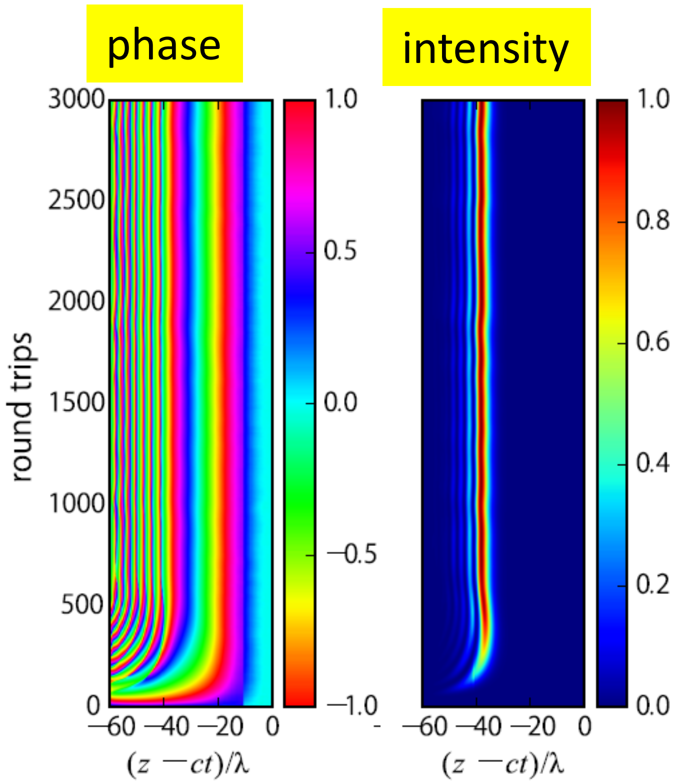
FEL simulation for dL=0 lasing



- The electron bunch slips back in the optical pulse during the FEL interaction.
- Intensity of the optical pulse spans over 11 orders from shot noise in the head to the pulse peak.
- No intra-pulse feedback from the tail to the head because dL=0.
- The optical pulse has fluctuation both in its phase and intensity.

CEP stabilization by an external seed laser



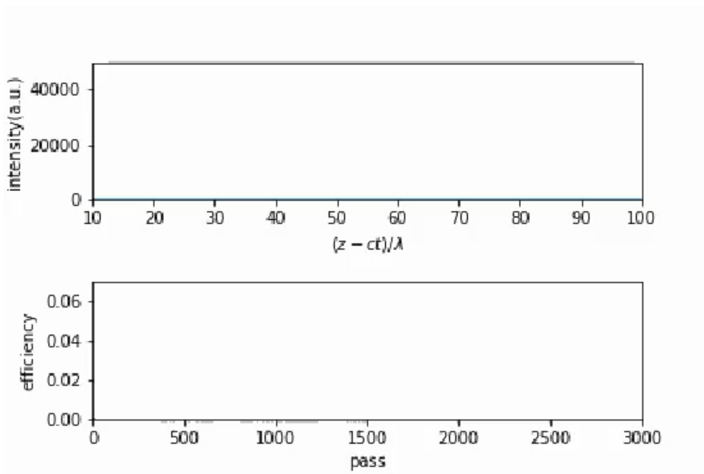


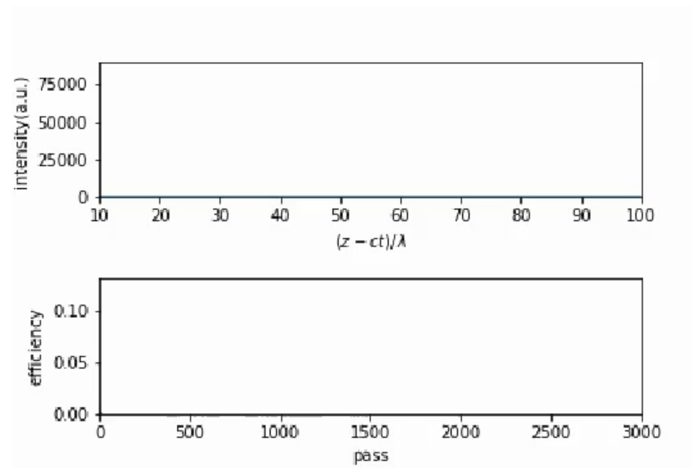
- Introducing a CEP-stabilized seed pulse to overlap the shot-noise part
- The leading edge of FEL pulse has a fixed amplitude and phase.
- The FEL interaction starts with a well-defined optical field.
- Over-all lasing dynamics is stabilized.
- CEP-stabilized few-cycle FEL pulses

R. Hajima and R. Nagai, PRL 119, 204802 (2017)

Stabilization by an external seed laser

Lasing at dL=0





Without a seed laser

Fluctuation due to the shot noise

With a seed laser

Stabilization by the seed laser

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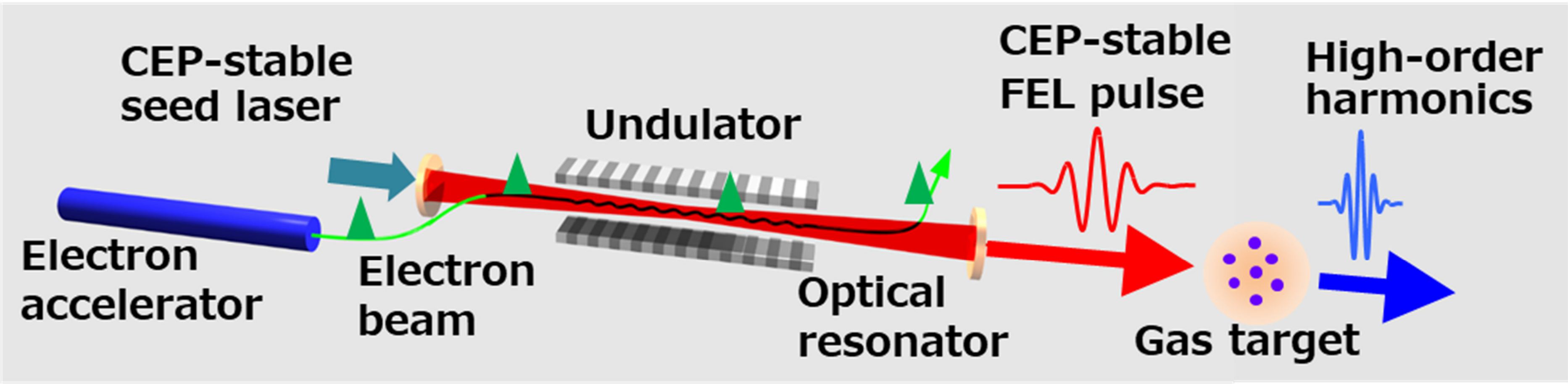
Proposal of FEL-HHG



Infrared FEL Oscillator

+

Lasing at zero-detuning length → Few-cycle pulse

+

Seed laser → CEP stabilization

+

High-harmonic generation → Attosecond VUV/X-ray pulses

Design Parameters

To obtain 0.5-mJ, few-cycle pulses

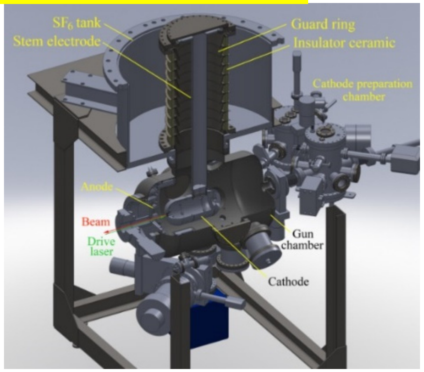
λ = 2 μm   85 MeV x 60 pC x 10% = 0.5 mJ

λ = 6 μm   50 MeV x 100 pC x 10% = 0.5 mJ

	(A)	(B)
Electron beam		
energy (MeV)	85	50
bunch charge (pC)	60	100
norm. emittance (x/y) (mm-mrad)	12/12	12/12
bunch length (ps)	0.27	0.4
peak current (A)	220	250
bunch repetition (MHz)	10	10
undulator		
undulator parameter (rms)	1.34	1.25
pitch (cm)	4.0	4.5
number of periods	80	40
FEL		
wavelength (μm)	2	6
Rayleigh length (m)	0.92	0.52
FEL parameter, ρ	0.0030	0.0052
cavity loss	6%	4%

These parameters are within the existing technologies of SCA linacs.

JAEA-KEK Gun



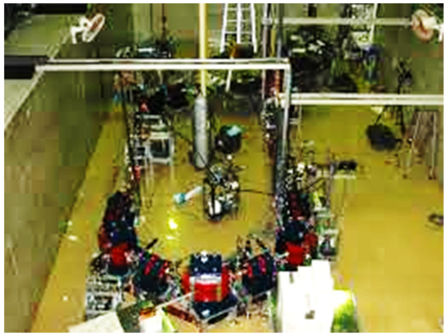
Photocathode gun

KEK ERL

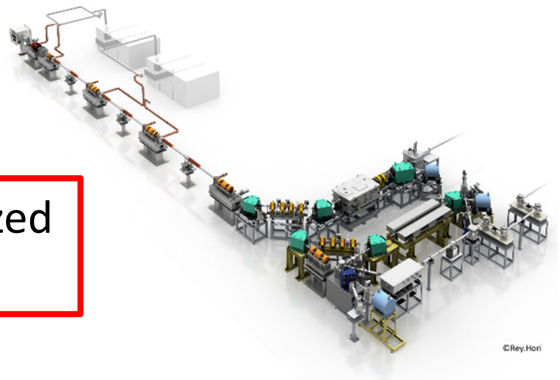
L-band SCA

A research program has been launched for the FEL-HHG

Kyoto University KU-FEL (3.4-26 μm)

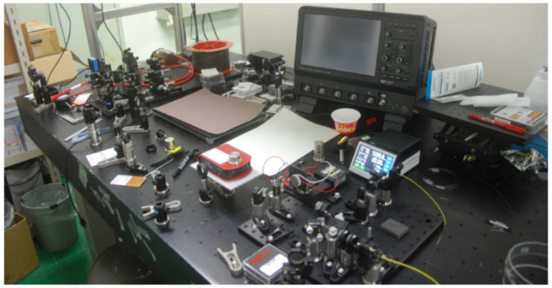


Nihon University LEBRA-FEL (0.827-6.1 μm)

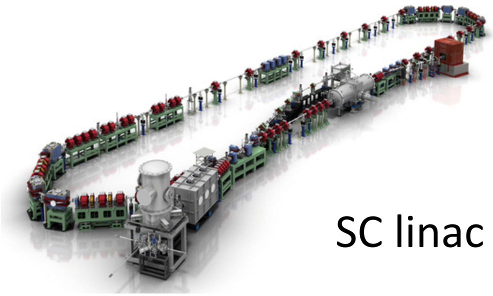


Normal conducting linacs are utilized for R&D and a PoC experiment.

QST Laser laboratory



KEK Compact ERL



SC linac technologies

MEXT Q-LEAP

<u>2018-2023</u>
Development of basic technologies

<u>2024-2027</u>
Proof-of-Concept experiment of FEL-HHG

User facility of attosecond VUV/X-ray

Challenge the efficiency, pulse duration limit

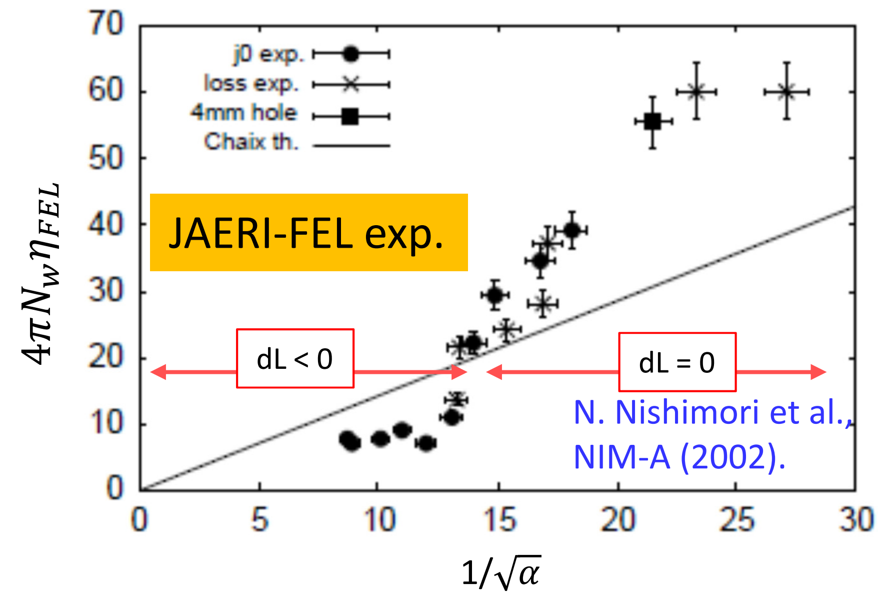
Analytical studies suggest

In short-pulse FELs,
efficiency and optical cycles scale as

$$4\pi N_w \eta \approx 1.43/\sqrt{\alpha}$$
$$N_s \approx 0.56 N_w \sqrt{\alpha}$$
for small dL

α: cavity loss normalized by gain parameter

N. Piovella, P. Chaix, G. Shvets, D.A. Jaroszynski, PRE (1995)
P. Chaix, N. Piovella, G. Grégoire, PRE (1999)



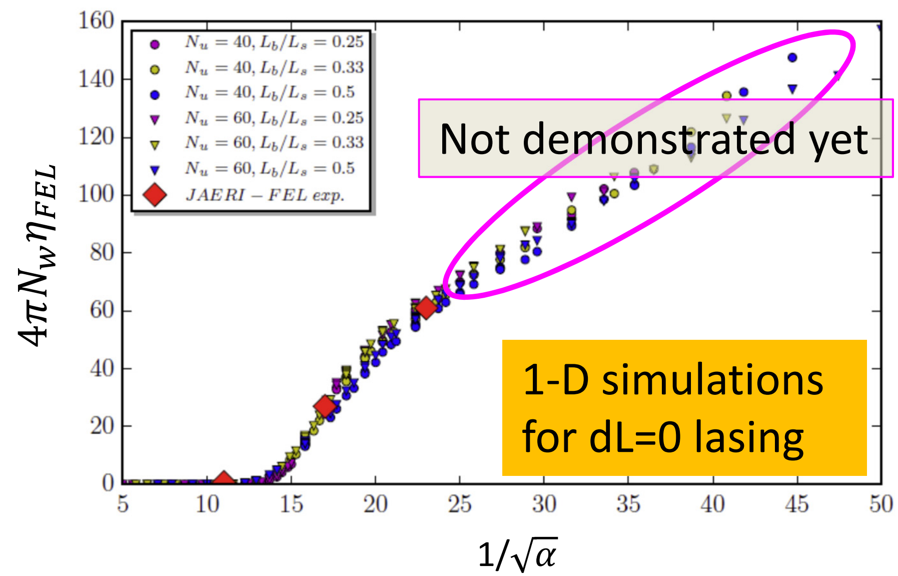
"solitary FEL pulse" in FEL oscillator of dL=0

N. Piovella, Opt. Comm. (1991)
R. Bonifacio, N. Piovella, B.W.J. McNeil, PRA (1991)

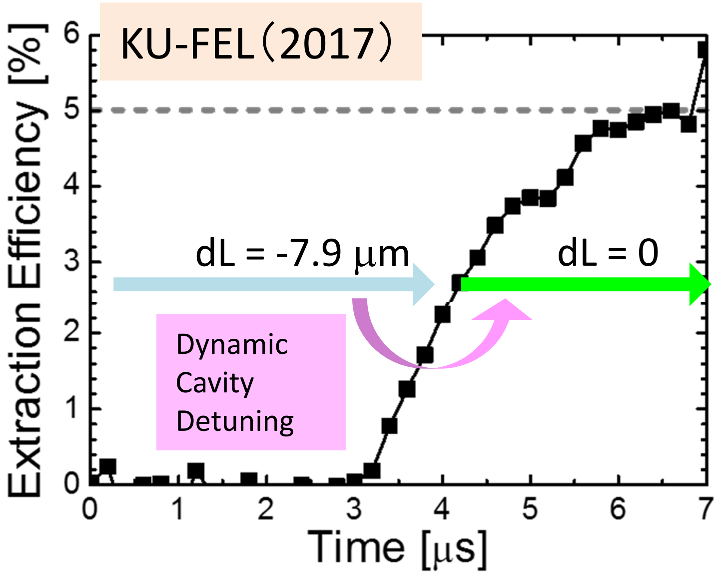
threshold exists for "solitary FEL pulse"

$$S \geq 1 + 2K^{3/2}\left[1 - \left(2\sqrt{3/9}\right)\log|b_0|\right]^{3/2}$$

N. Piovella, Opt. Comm. (1991)



High-efficiency lasing at KU-FEL



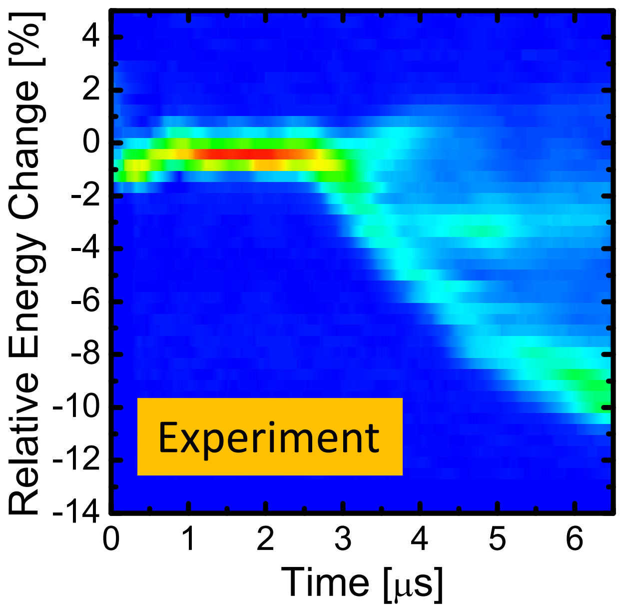
We follow the technique of
dynamic cavity desynchronization (DCD).

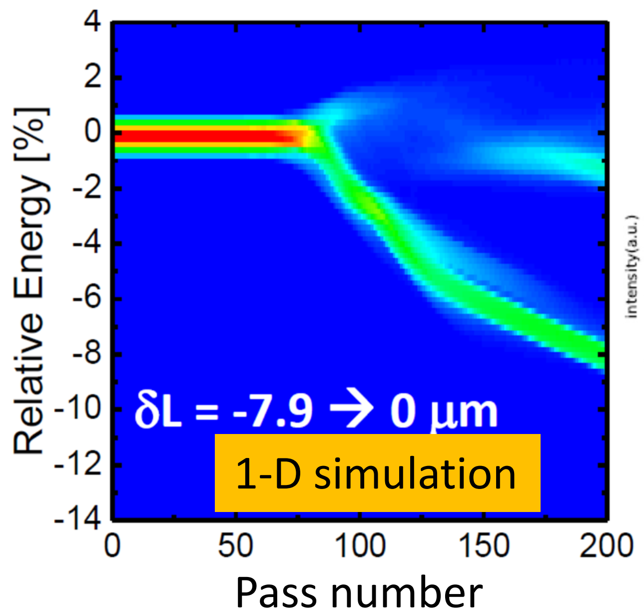
D.A. Jaroszynski et al., NIMA (1990),
R.J. Bakker et al., PRE (1993).

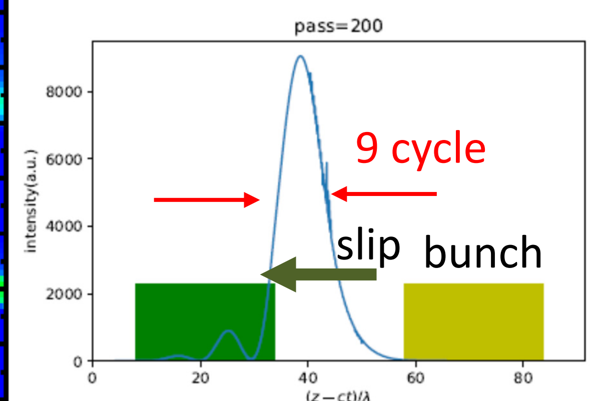
Bunch repetition is modulated to introduce effective cavity-length variation in a macro pulse.

"dL=0 lasing" is obtained at a normal conducting FEL.

H. Zen et al., Poster TUP013



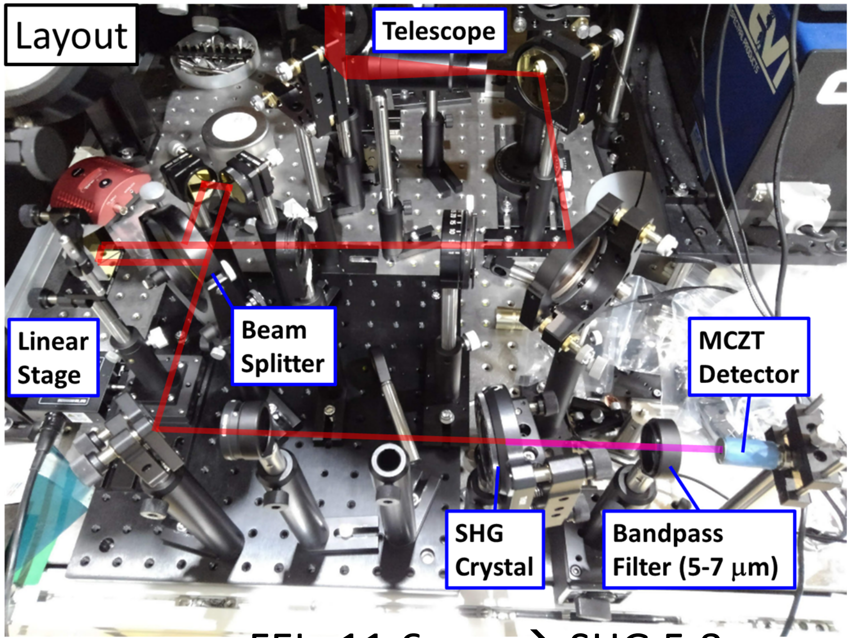




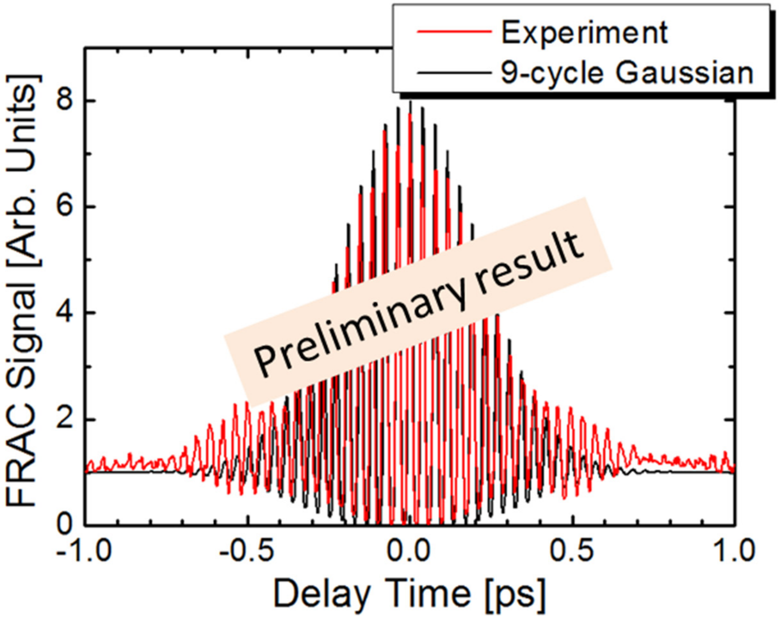
Simulation suggests
a 9-cycle pulse

FEL pulse measurement at KU-FEL

Fringe-resolved auto correlation (FRAC)



FEL: 11.6 μm → SHG 5.8 μm

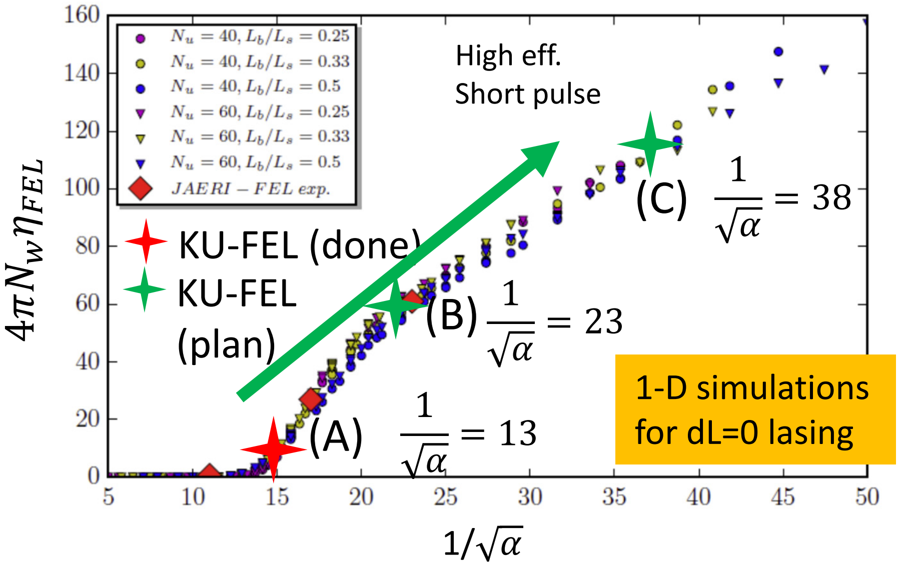


Pulse duration is evaluated by FRAC.

Measured FRAC signal is examined with Gaussian pulses and numerical results.

Further measurements and analysis are in progress.

Challenge the efficiency, pulse duration limit at KU-FEL



Normalized cavity loss is the key parameter.

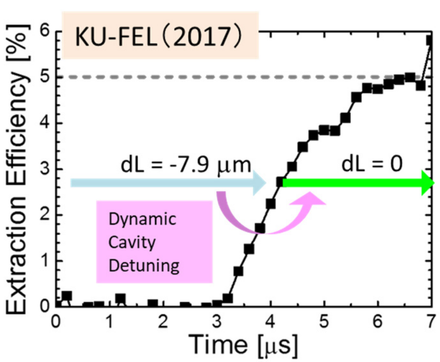
$$\alpha = \alpha_0/\Gamma$$

α_0 cavity round-trip loss

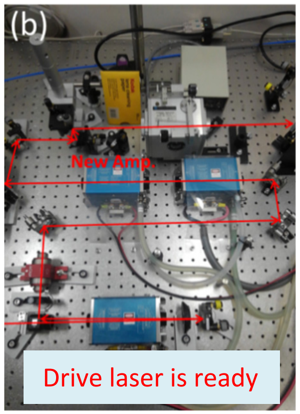
$\Gamma = (L_b/L_s)(j_0/2)$ gain integrated over the slippage length

$N_s \propto 1/\eta$ optical cycle

N. Piovella et al., PRE (1995); P. Chaix et al., PRE (1999)



(A) 4.5-cell RF gun with thermionic-cathode mode (40 pC, λ=11 μm)



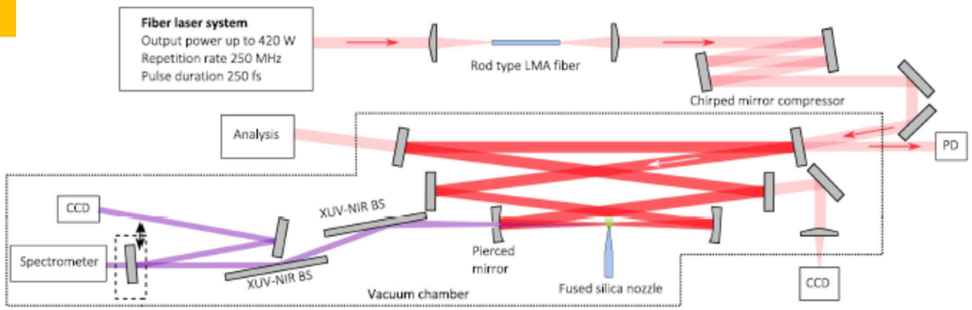
(B) 4.5-cell RF gun with photo-cathode mode (120 pC)

(C) Replace a hole-coupled mirror by a low-loss dielectric mirror (loss = 3% → 1%)

(D) Install a new 1.6-cell RF gun (1-nC bunch train)

Pulse stacking in an external enhancement cavity

HHG



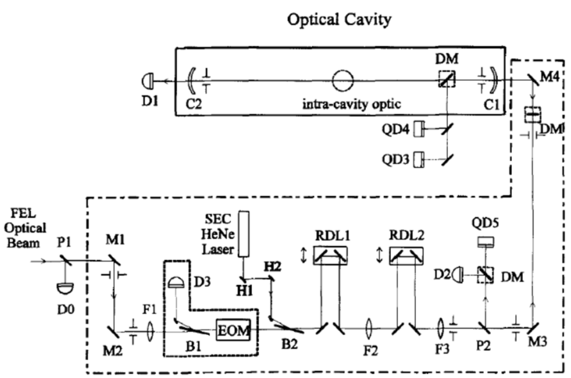
MPQ

Enhancement is 170 W → 10 kW

H. Carstens et al., Optica (2016).

External enhancement cavities in FELs

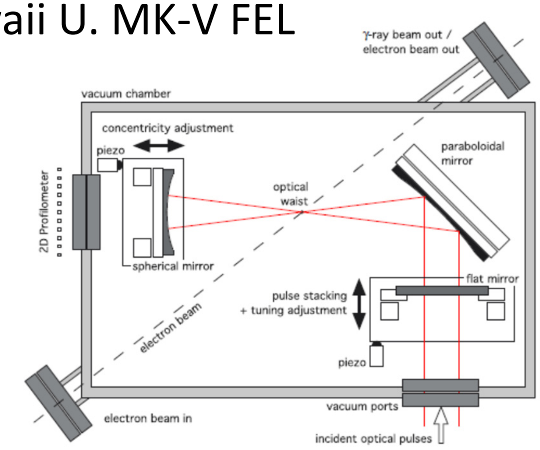
Stanford SCA FEL



75-times enhancement
in the steady-state regime (quasi-CW)

T.I. Smith et al., NIMA (1997).

Hawaii U. MK-V FEL



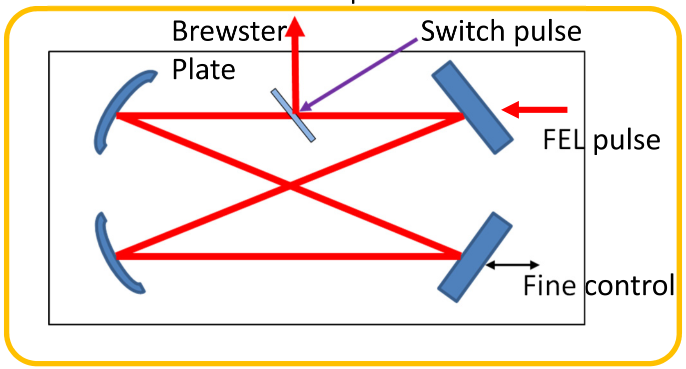
GHz repetition with phase-locked FEL
in the transient regime (4.5 μs)

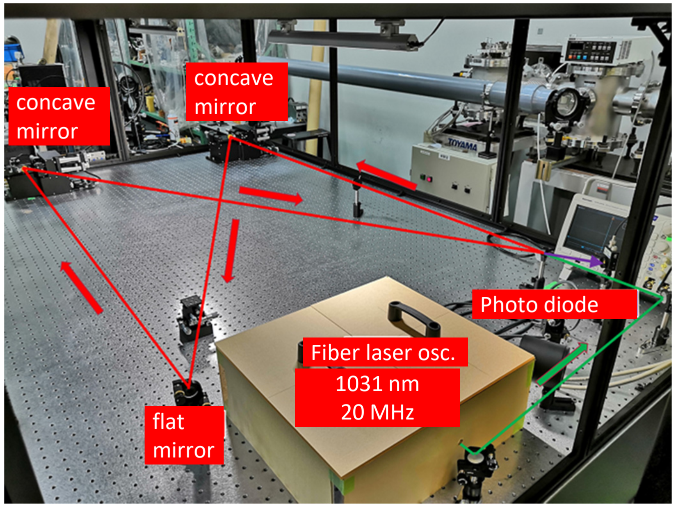
P. Niknejadi et al., PR-AB (2019).

Pulse stacking cavity at LEBRA FEL

LEBRA FEL has a relatively long macro pulse (20 μs)

→ Suitable for pulse stacking experiment.

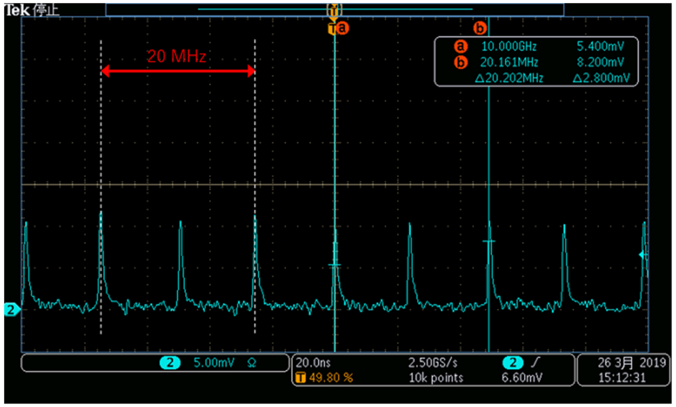




External cavity is under development.
Recirculation was confirmed with a fiber laser.

We continue the experiment to demonstrate pulse enhancement, first with the mode-locked fiber laser, and then real FEL pulses.

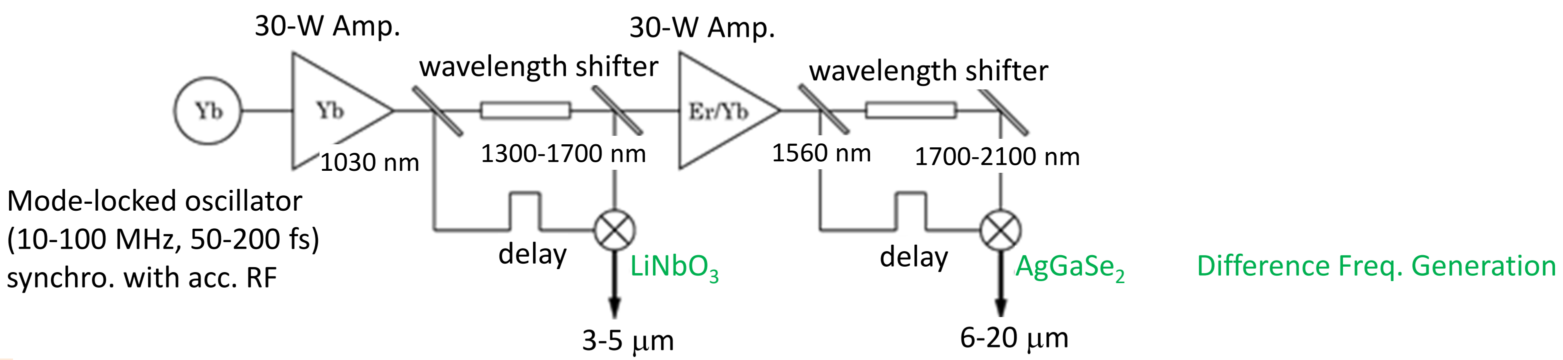
Intracavity exp. and cavity dumping are planned for HHG.



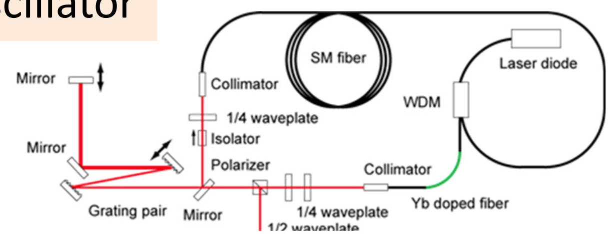
Mid-IR laser for seeding FEL

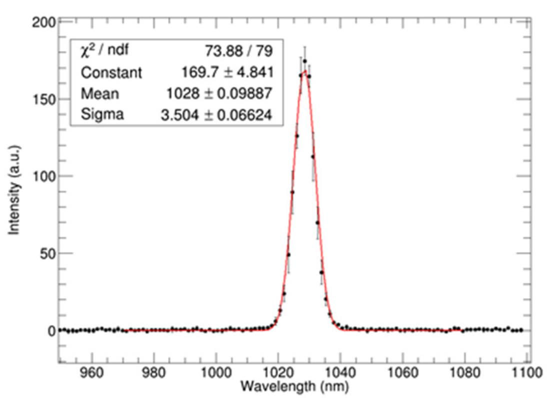
Laser system

CEP-stable Mid-IR pulses synchronized to the acc. RF.

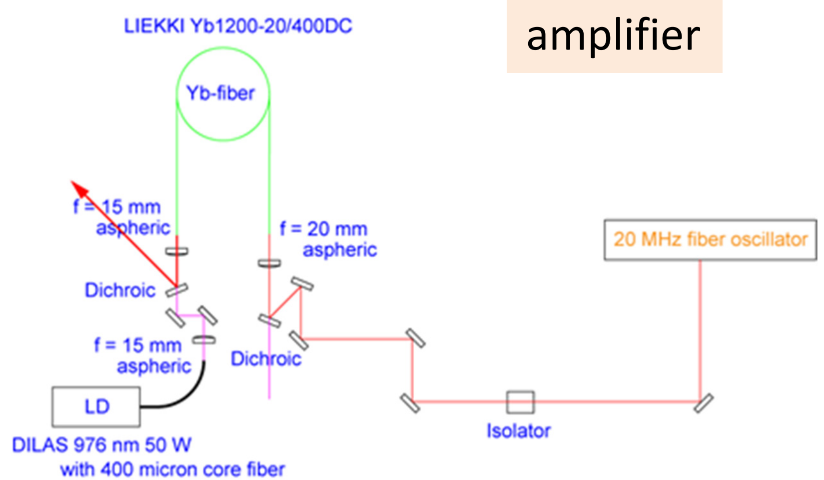


oscillator

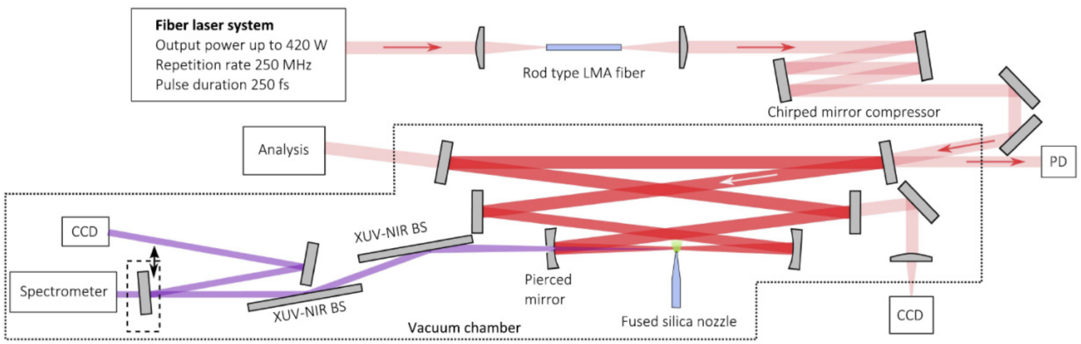




amplifier

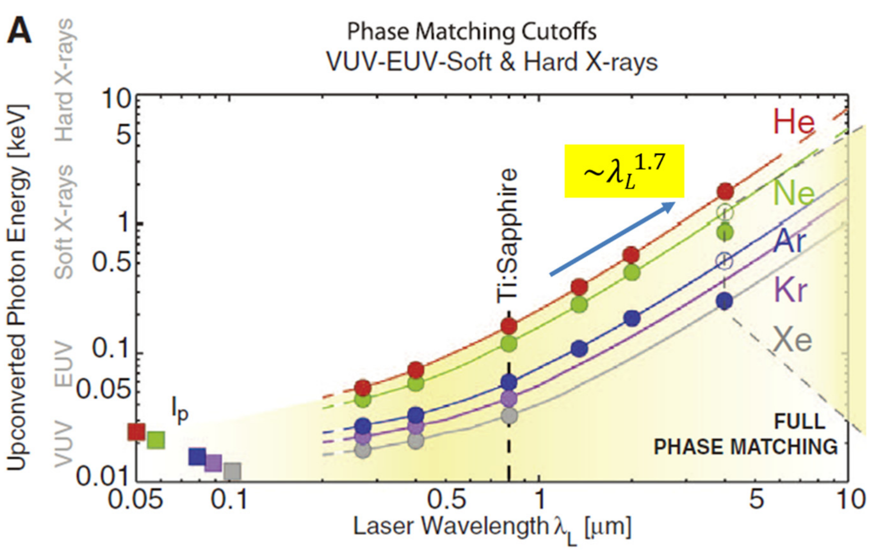


What are Impacts of FEL-HHG ?



HHG in a laser enhancement cavity for UV/X-ray frequency combs, and pump-probe photoelectron microscopy and spectroscopy
-- 250 MHz, 10 kW, 30 fs

H. Carstens et al., Optica 3, 366 (2016).



T. Popmintchev et al., Science 336, 1287-1291 (2012).

1. Higher flux

Average power of FEL can exceed 100 kW with an external cavity of a modest Q ~25.

2. Higher photon energy

Mid-infrared FEL (4-10 μm) is suitable for generating 1-10 keV in HHG.

Summary

- Few-cycle pulses are available in a FEL oscillator at dL=0.
- CEP-stabilization is possible with injection seeding.
- Operated at mid-infrared wavelengths, the FEL is an efficient driver of HHG to produce high-flux and high-energy photon pulses with attosecond duration.
- A research program has been launched for technology development and a proof-of-concept experiment of FEL-HHG.
  - Challenge the limit of efficiency and pulse duration (KU-FEL)
  - FEL pulse stacking at an external cavity (LEBRA-FEL)
  - Seed laser (QST)
  - PoC experiment (KU-FEL and/or LEBRA-FEL)
- After the PoC, a full-scale FEL-HHG can be constructed with a SC linac FEL.