CEP-stabilized few-cycle MIR-FELs for Driving High-Repetition-Rate (>10 MHz) attosecond X-ray Sources based on HHG

Ryoichi Hajima

National Inst. for Quantum and Radiological Sci. and Tech. (QST)

March 7, 2018

FLS 2018, The 60th ICFA Advanced Beam Dynamics Workshop

Work supported by:

- The Research Foundation for Opto-Science and Technology.

Collaborators

Ryoji Nagai (QST)

Tsukasa Miyajima (KEK)

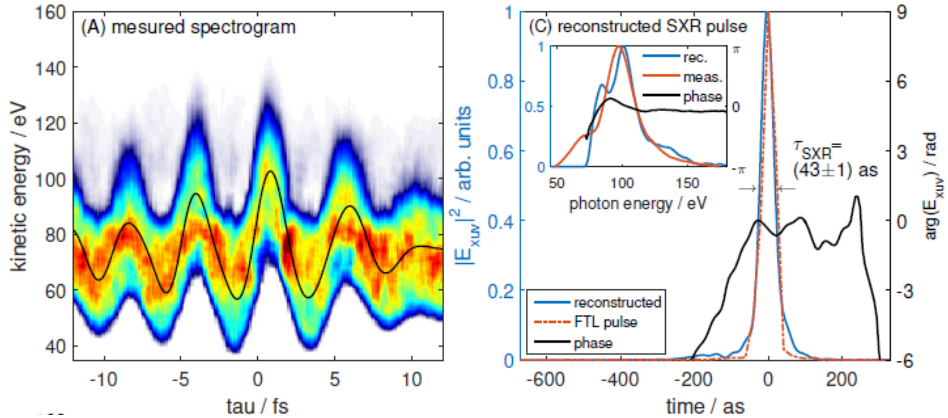
Jiro Itatani and Nobuhisa Ishii (ISSP, U. Tokyo)

Xiao-Min Tong (Tsukuba U.)

Two Papers Published in October, 2017

High Harmonic Generation (HHG)

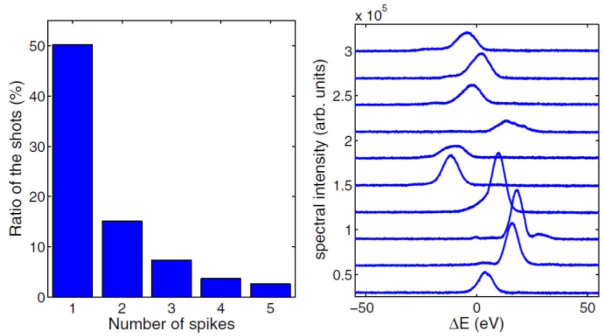
"Streaking of 43-attosecond soft-X-ray pulses generated by a passively CEP-stable mid-infrared driver
T. Gaumnitz et al.,
Opt. Exp. 25, 17506 (2017)



43-attosecond SXR → new world record

Free Electron Laser (FEL)

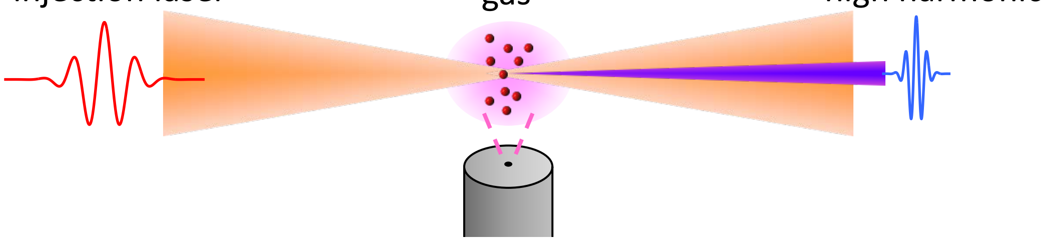
Generating single-spike hard X-ray pulses with nonlinear bunch compression in free-electron lasers
S. Huang et al.
PRL 119, 154801 (2017)



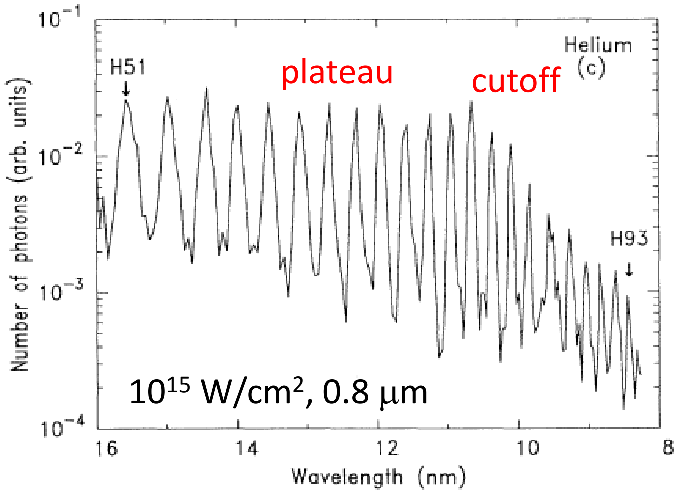
suggested 200-attosecond pulses from XFEL

HHG and FEL are both cutting-edge photon sources to explore ultrafast science.

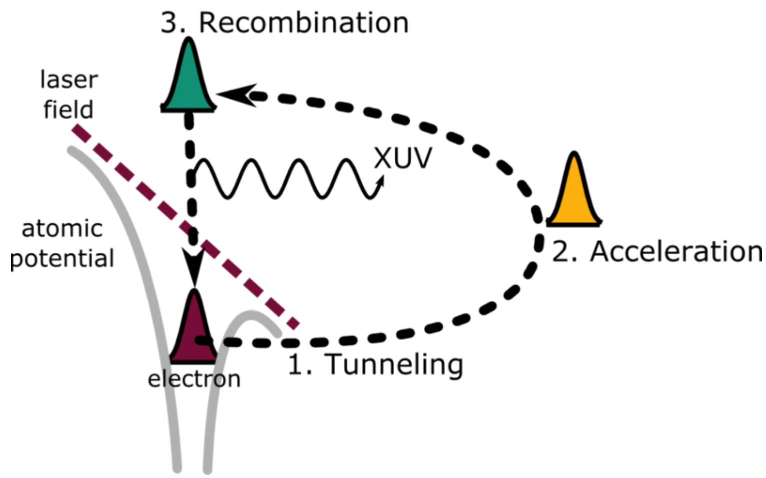
High Harmonic Generation; HHG



odd-harmonics with time and spatial coherence



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



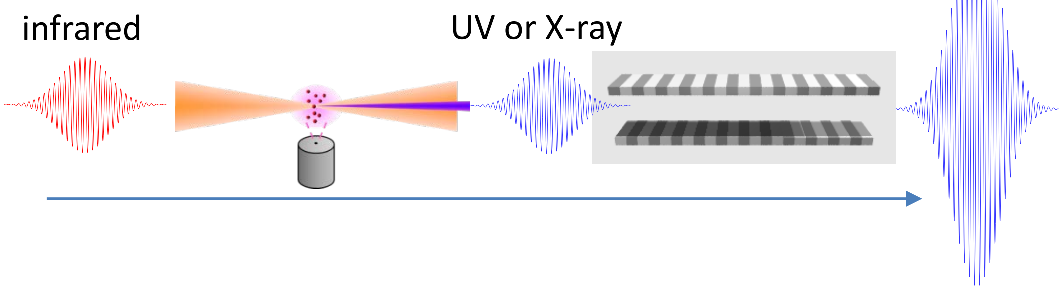
Wikipedia

3-step model

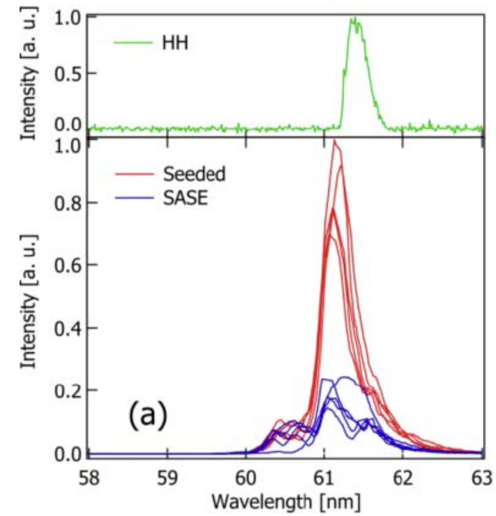
1. tunneling ionization by E_{laser}
2. acceleration of the electron by E_{laser}
3. recombination with the parent atom

Combination of HHG and FEL

HHG → FEL

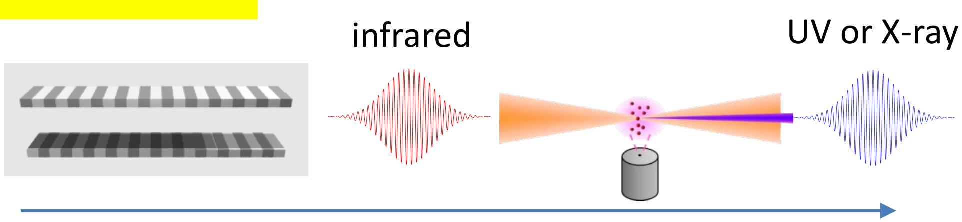


- ✓ controlling FEL spectral and temporal shapes
- ✓ avoiding SASE-induced fluctuations



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

FEL → HHG

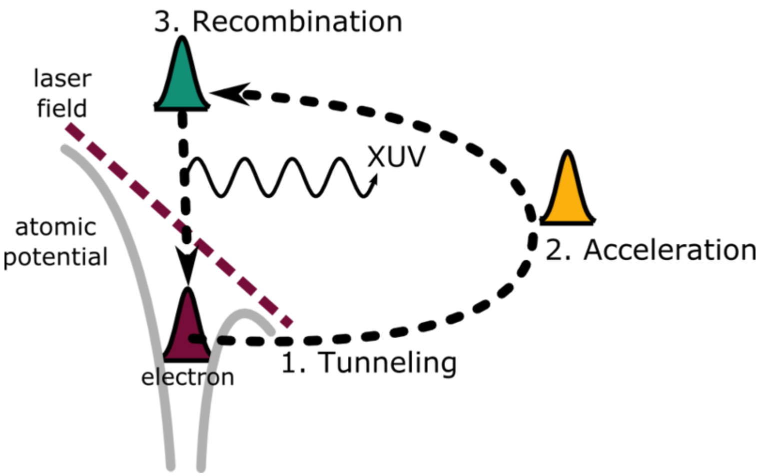


- ✓ generating UV and X-ray with a small-size FEL
- ✓ attosecond pulses available

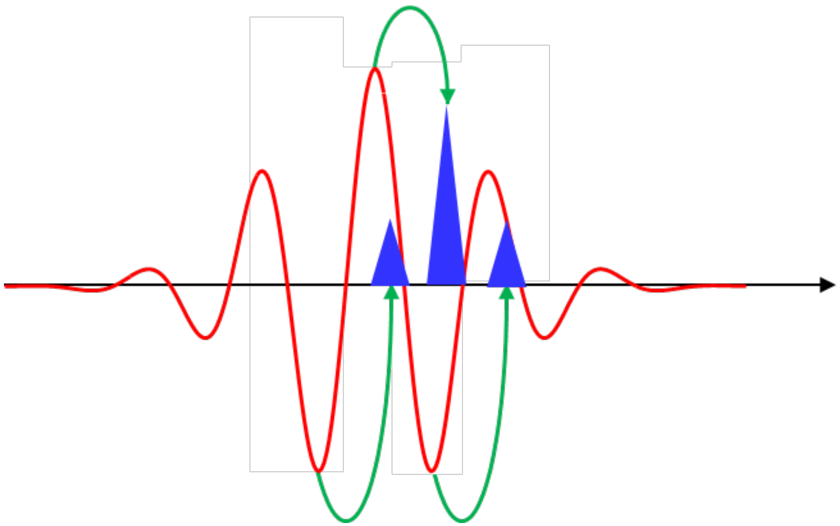
Not demonstrated yet !

Keys to the attosecond pulse generation in HHG

High Intensity



Few-cycle pulse

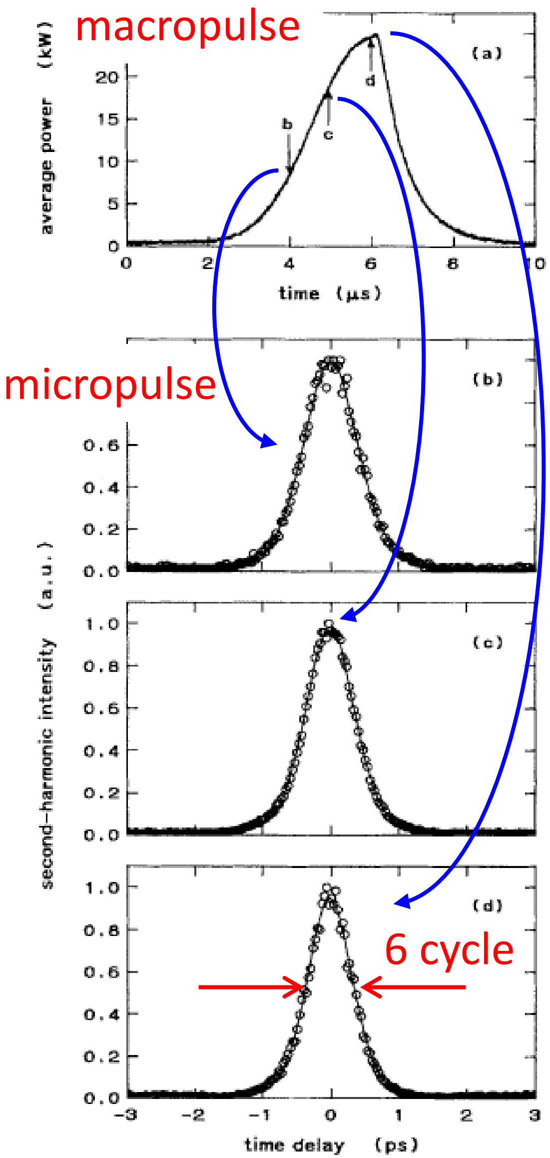


Typical laser intensity for HHG

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

Can a FEL generate such pulses?

Few-cycle FEL pulses (transient regime)



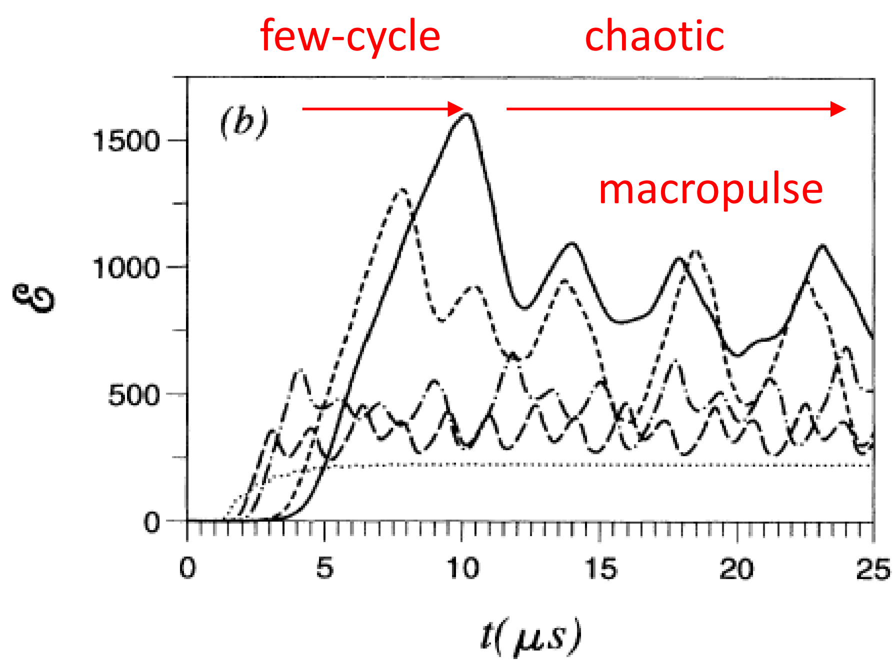
6-cycle pulses were demonstrated at a FEL oscillator, FELIX.

10 μJ, 6 cycle, 10.4 and 24.5 μm

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

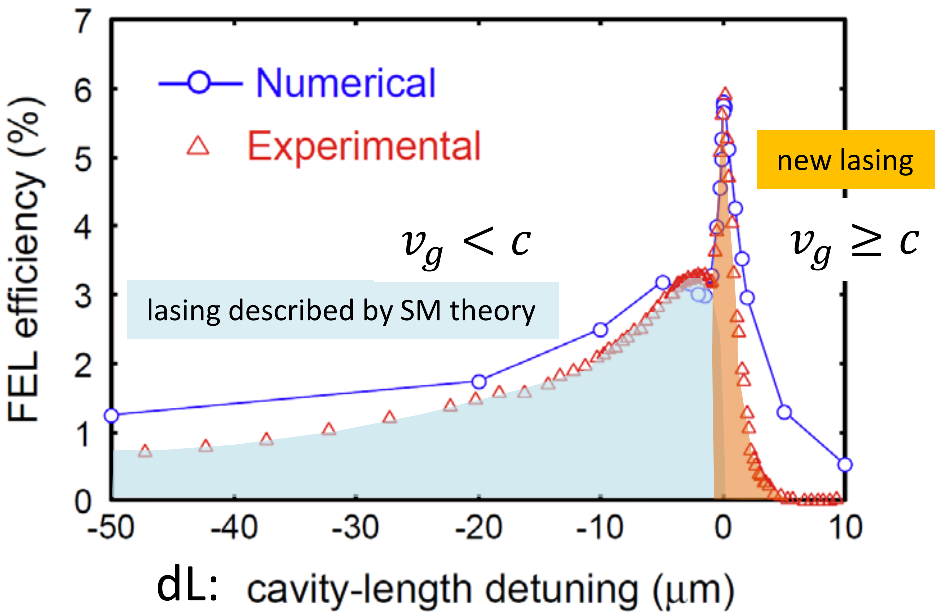
The pulses are only available at the transient regime .
Chaotic lasing appears after the saturation.

N. Piovella et al., Phys. Rev. E 52, 5474 (1995)



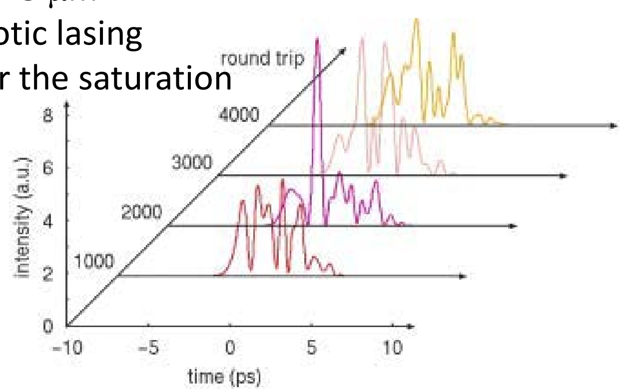
Few-cycle FEL pulses (steady state)

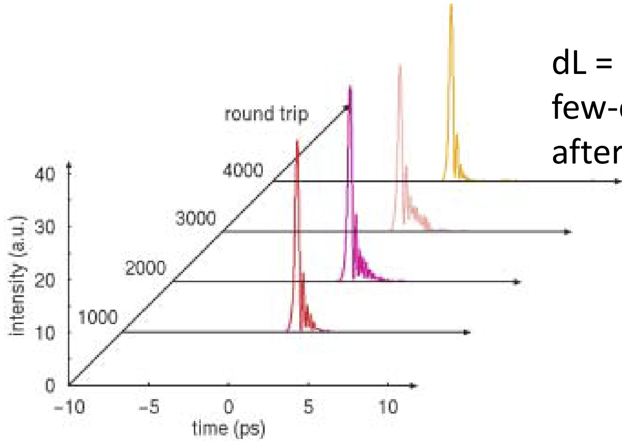
High-efficiency lasing at dL=0 was found at JAERI FEL.
Numerical study suggested few-cycle lasing at the saturated regime.



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

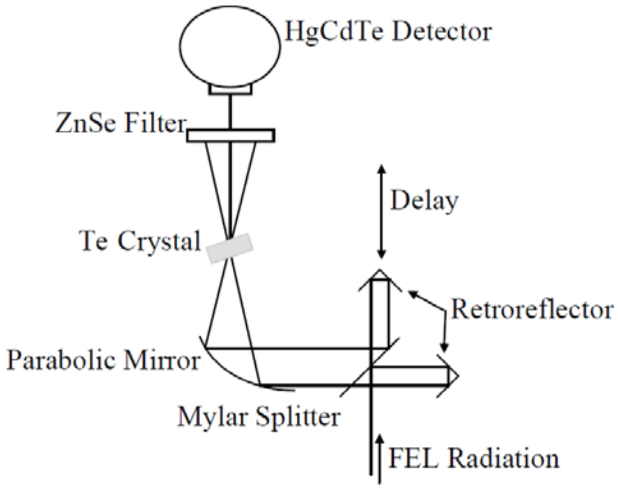
dL = -3 μm
chaotic lasing
after the saturation





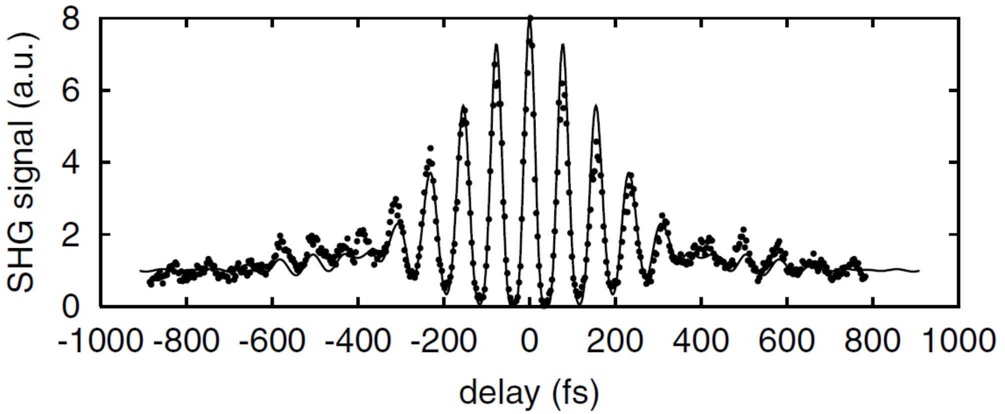
dL = 0
few-cycle lasing
after the saturation

FEL pulse measurement at JAERI FEL



energy	16.5 MeV
ave. current	5.3 mA
bunch charge	0.51 nC
bunch length (FWHM)	$<$5 ps
peak current	$>$100 A
rms energy spread	1.2%
nor. emittance (x/y)	40 / 22 mm-mrad
bunch reptititon	10.4125 MHz
und. period	3.3 cm
number of und. period	52
und. parameter (rms)	0.7
cavity length	14.4 m
Rayleight range	1.00 m
mirror radii	6 cm
FEL wavelength	22 μm

fringe-resolved autocorrelation



2.32 cycle (FWHM) with a chirped-sech fitting
1.55 cycle after numerical 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)

High-efficiency few-cycle pulses generation at FEL oscillators

Proposal of FEL-HHG

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 020703 (2012)

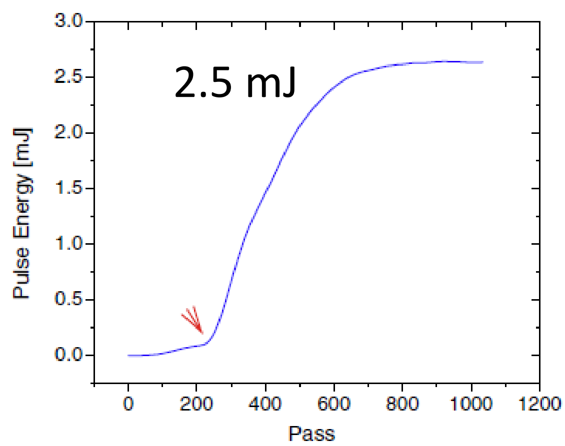
High power coupled midinfrared free-electron-laser oscillator scheme as a driver for up-frequency conversion processes in the x-ray region

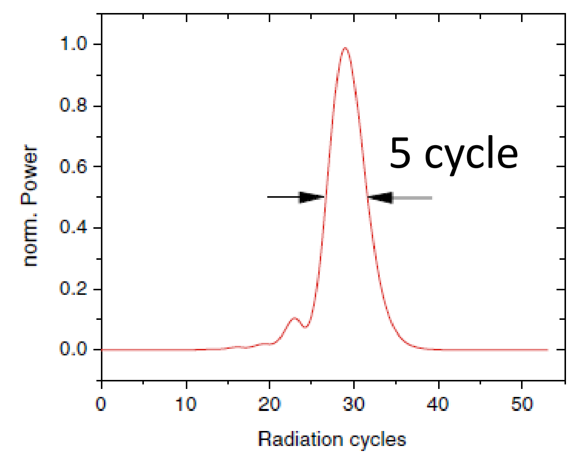
M. Tecimer

THz-FEL Group, University of Hawaii at Manoã, Honolulu, Hawaii 96822, USA

(Received 19 June 2011; published 27 February 2012)

Electron beam
= 100 MeV, 80 pC
FEL
= 6 μm, ~5 cycle, ~2.5 mJ
HHG
= 1-10 keV,
10^5-10^6 ph/1%BW/pulse

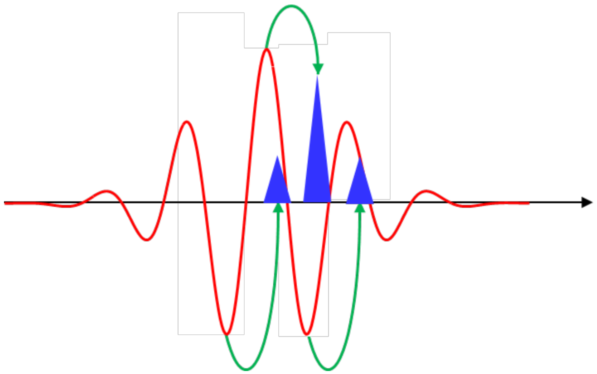




FEL oscillator at dL =0
→ An efficient driver of HHG to generate attosecond X-ray pulses

One thing missing was CEP stabilization.

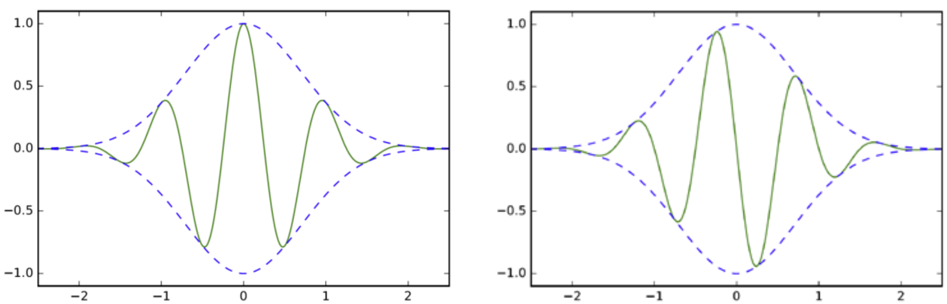
Carrier-Envelope Phase (CEP)



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

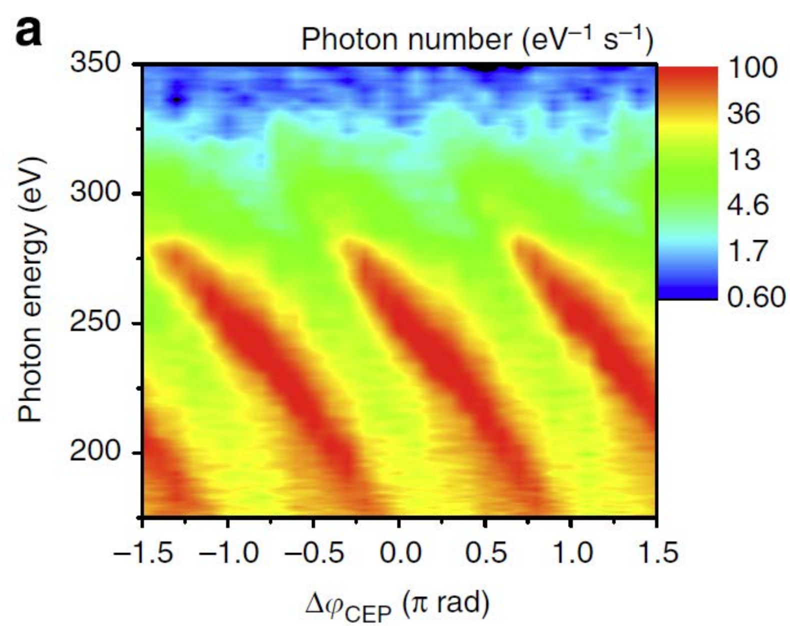
CEP stabilization has been established in solid-state lasers.

ϕ_{CEP} = 0 ϕ_{CEP} = 90°



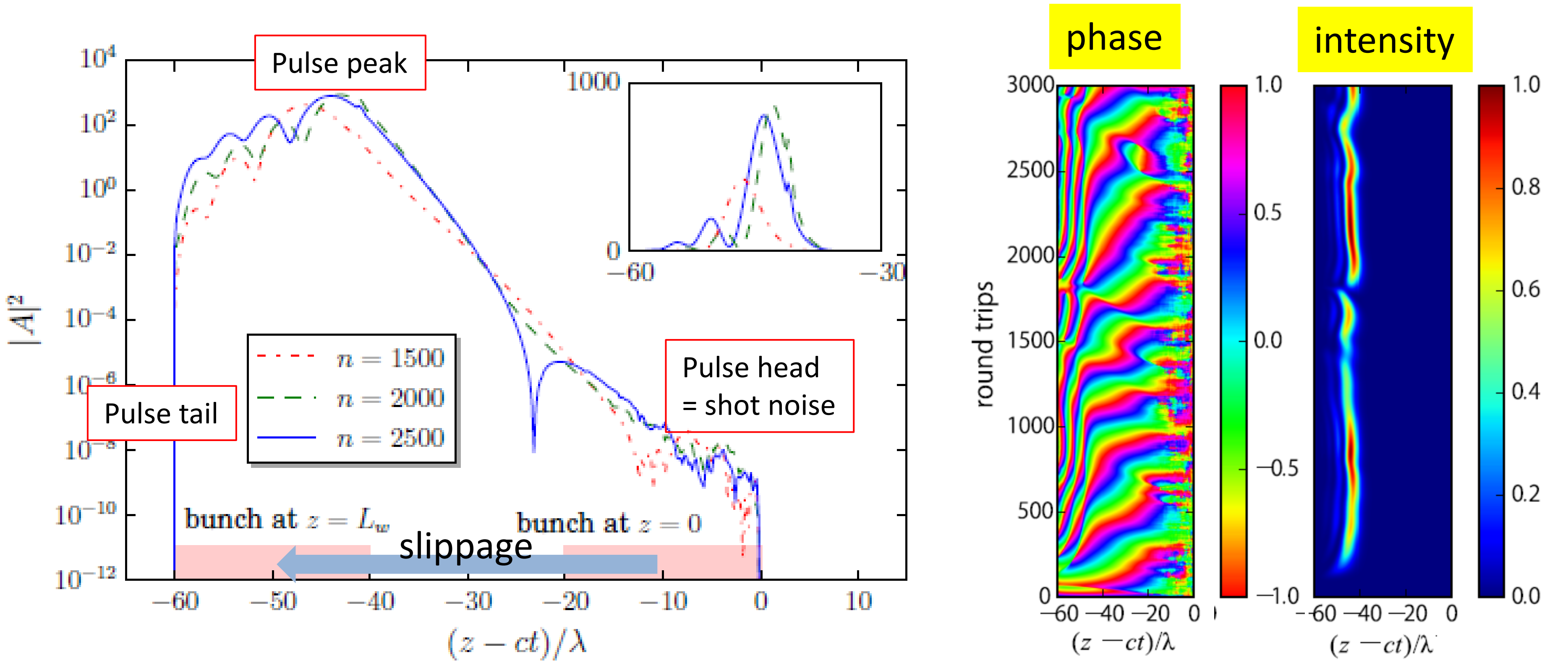
Carrier-Envelope Phase (CEP)

HHG with 1.6 μm, sub-two-cycle pulses



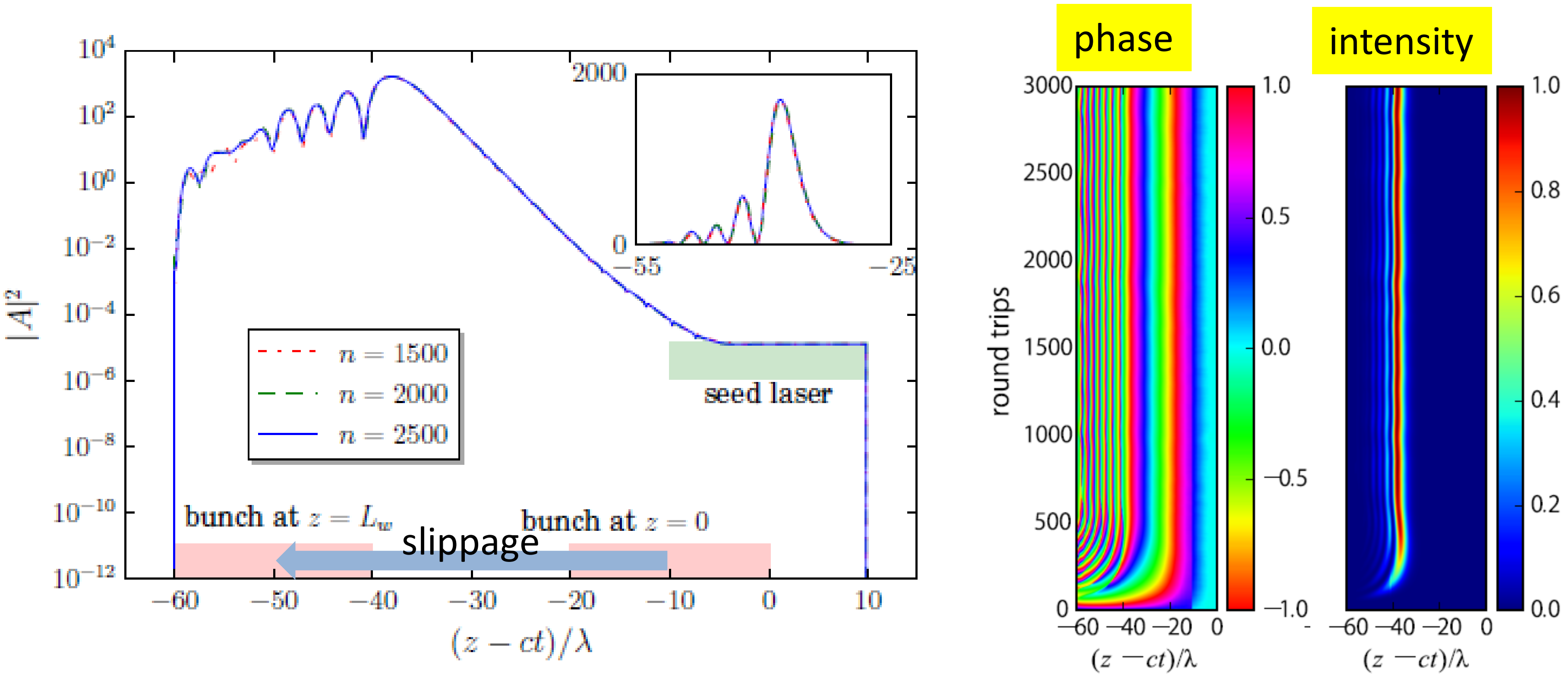
N. Ishii et al., Nature Comm. 5, 3311 (2014).

FEL simulation for dL=0 lasing



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

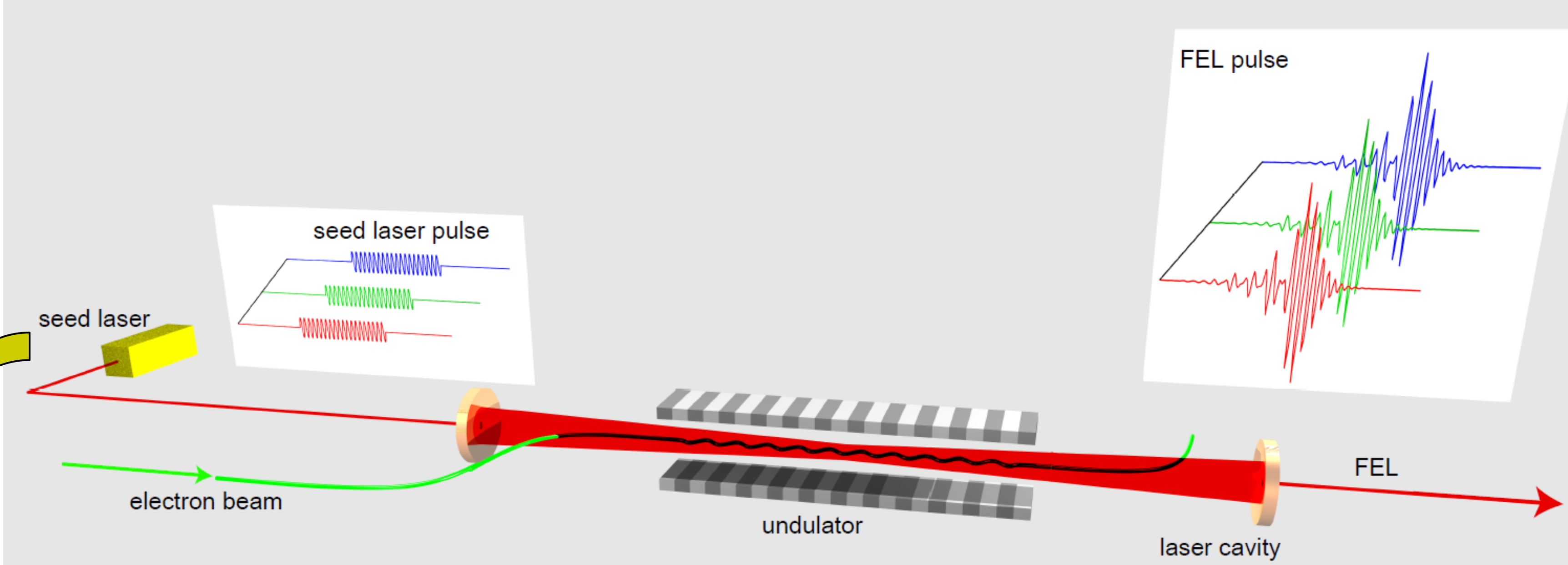
CEP stabilization by an external seed laser



- Overlapping a CEP-stabilized seed pulse with a FEL pulse
- 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)

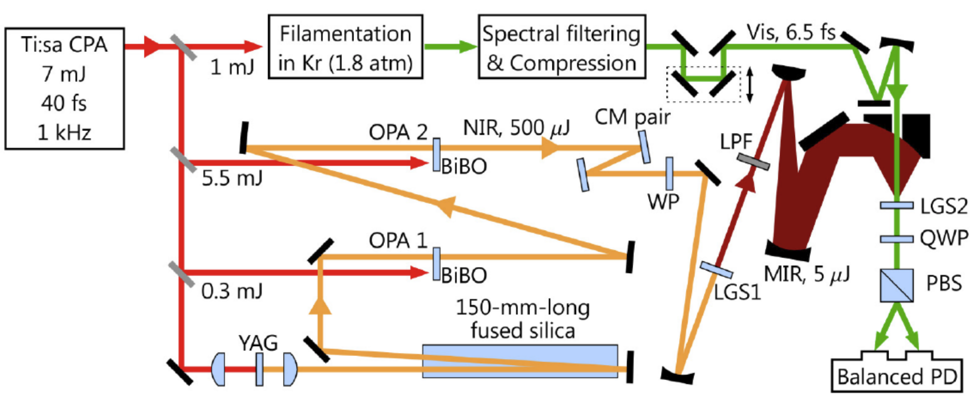
Generating CEP-stabilized few-cycle FEL pulses



Seed laser can be realized by OPA + DFG

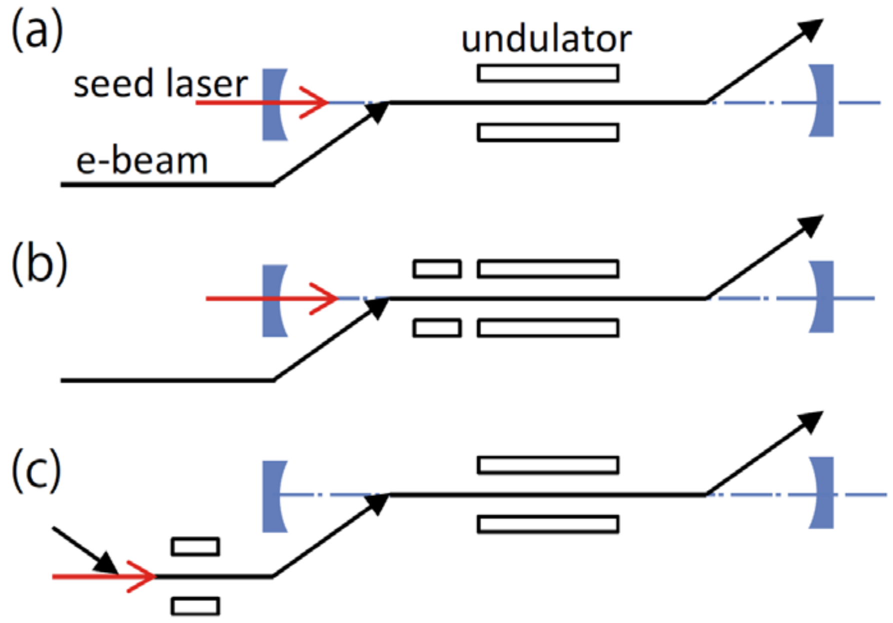
OPA: optical parametric amplification
DFG: difference frequency generation

Laser system for CEP stabilized 5-11 μm pulses



K. Kaneshima et al., Opt. Exp. 24, 8660 (2016)

Possible seeding configuration



(a) FEL and seed laser share a single undulator
(b) seed undulator (Nu < 10) before the FEL undulator
(c) seed undulator upstream

Seed laser and FEL may have different polarization in (b) and (c).

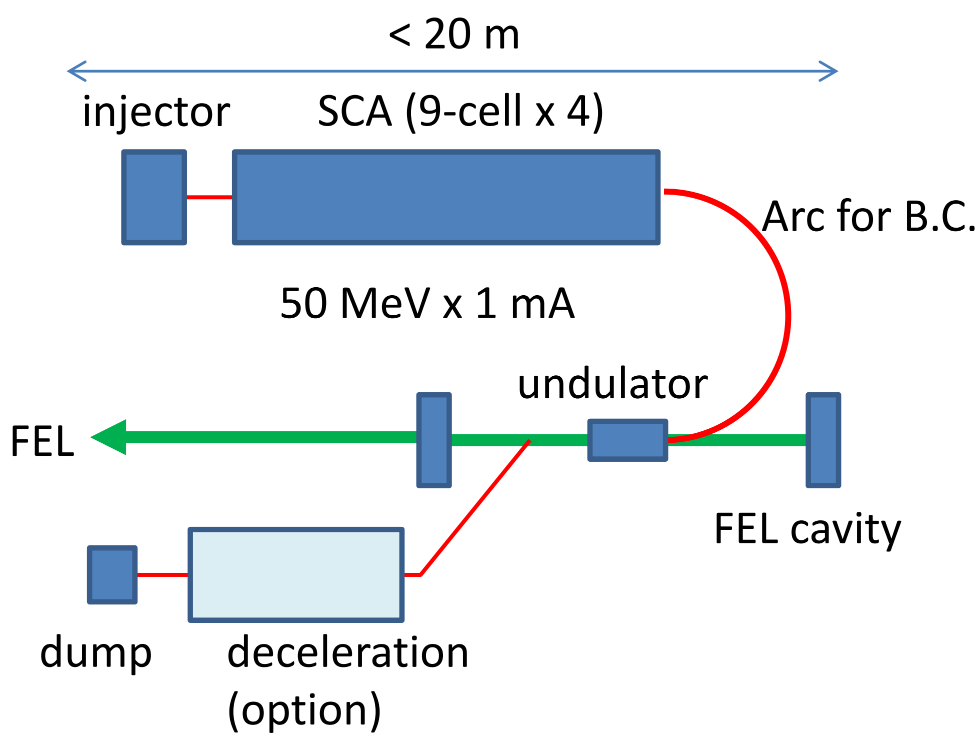
Design Example

Design example: 50 MeV x 100 pC x 10% = 0.5 mJ – FEL pulse energy
100 pC x 10 MHz = 1 mA – beam current

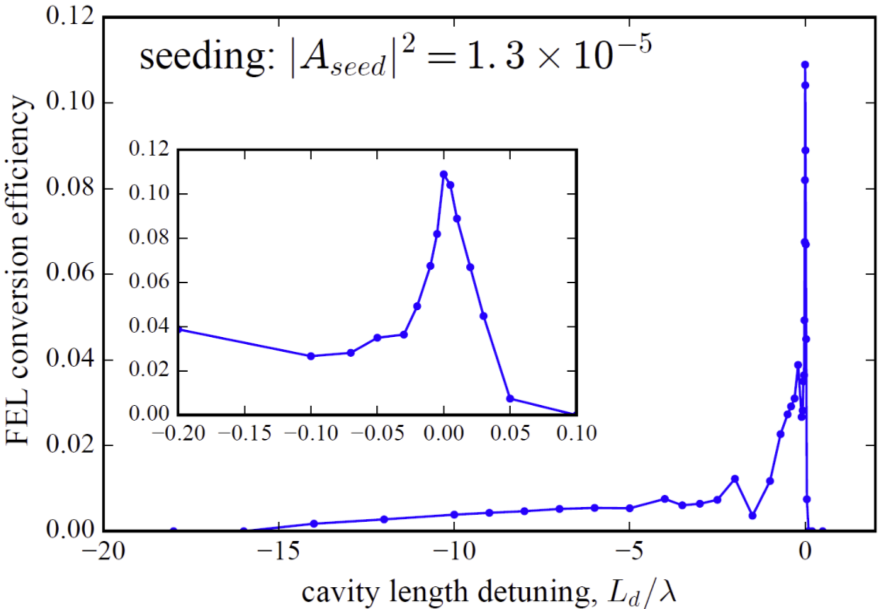
TABLE I. Parameters of the FEL oscillators.

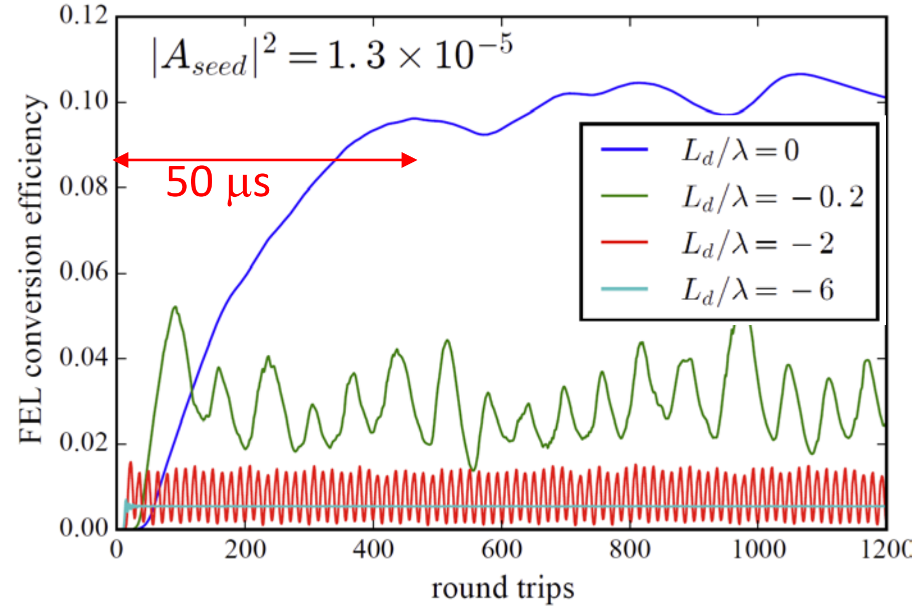
	JAERI FEL	This work
Electron beam		
Energy (MeV)	16.5	50
Bunch charge (pC)	510	100
Normalized emittance (x/y) (mm mrad)	40/22	12/12
Bunch length[a] (ps)	5	0.4
Peak current (A)	200	250
Bunch repetition (MHz)	10	10
Undulator		
Undulator parameter (rms)	0.7	1.25
Pitch (cm)	3.3	4.5
Number of periods	52	40
FEL		
Wavelength (μm)	22.3	6
Rayleigh length (m)	1.0	0.52
FEL parameter, ρ	0.0044	0.0052
Cavity loss	6%	4%

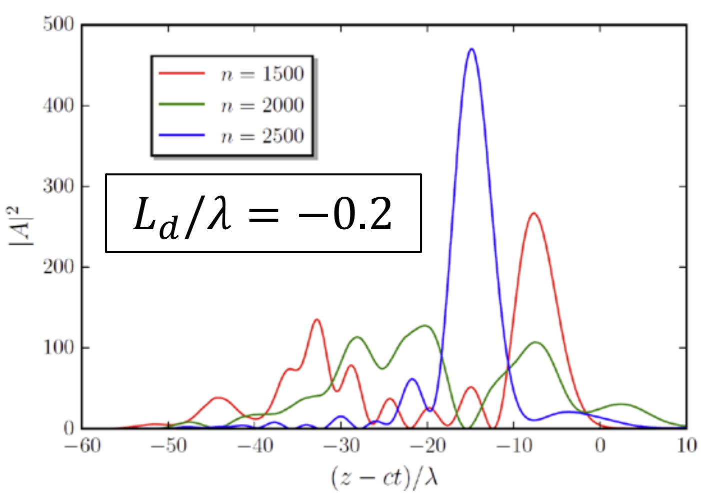
[a]The bunch length is the FWHM of a triangular bunch for the JAERI FEL and the full width of a rectangular bunch for the simulations in this work.

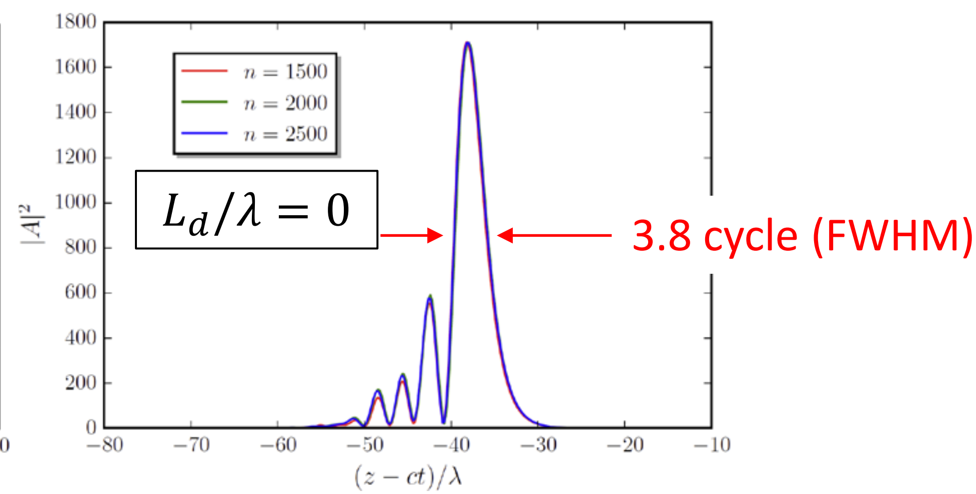


1-D time-dependent simulation results



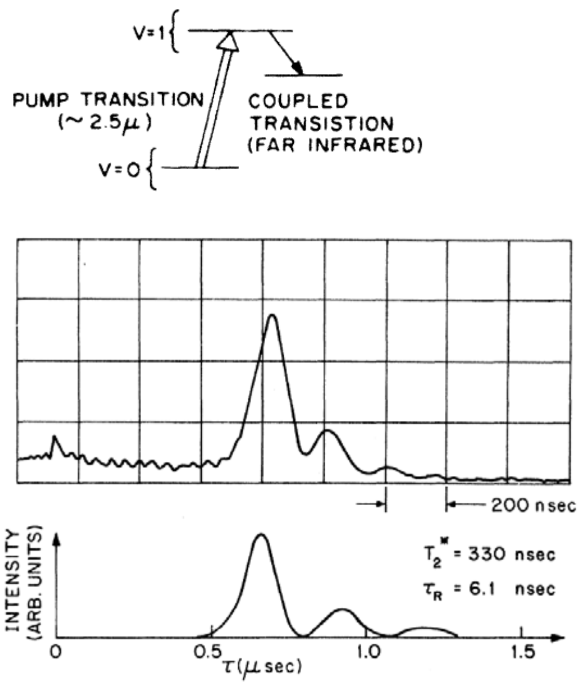






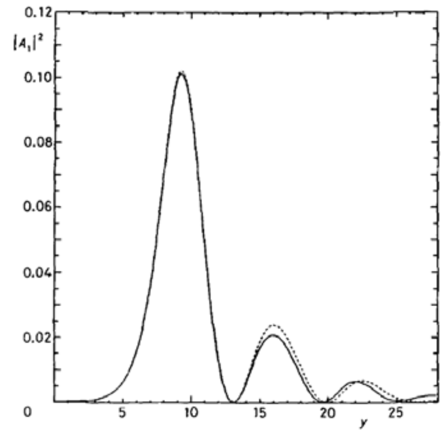
All Superradiance

Two-level system (Dicke's SR)



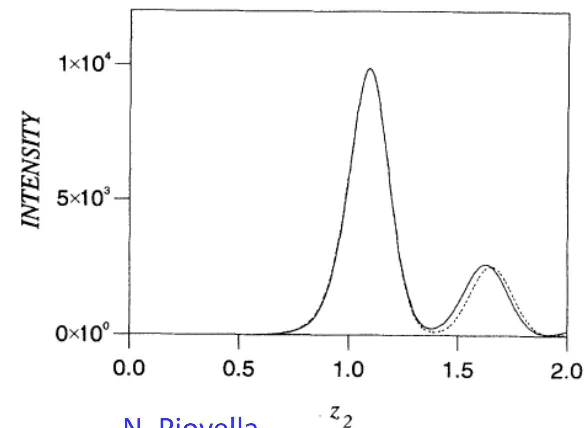
N. Skribanowitz et al., PRL 30, 309 (1973)

FEL amplifier
(weak SR)

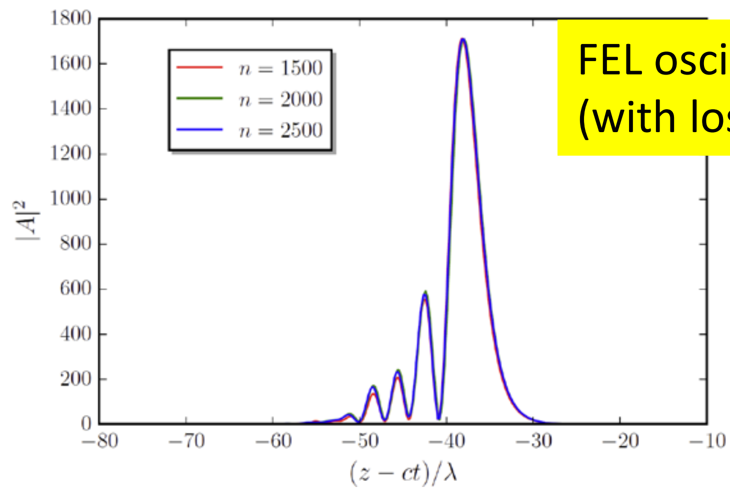


R. Bonifacio et al.,
Rivista Del Nuovo Ciment, 13, 1 (1990)

FEL oscillator of dL=0
(without loss & shot noise)

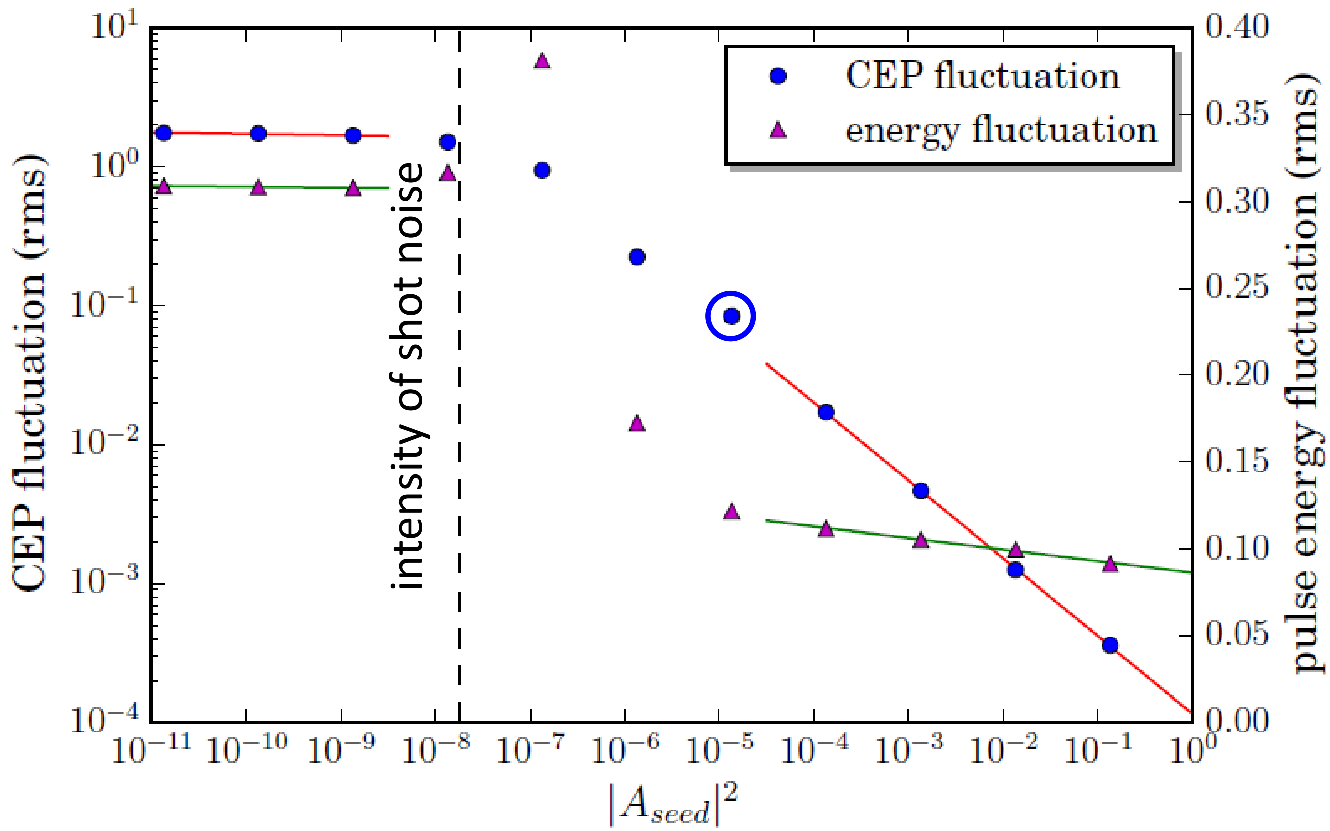


N. Piovella,
Phys. Rev. E 51, 5147 (1995)



FEL oscillator of dL=0
(with loss & shot noise)

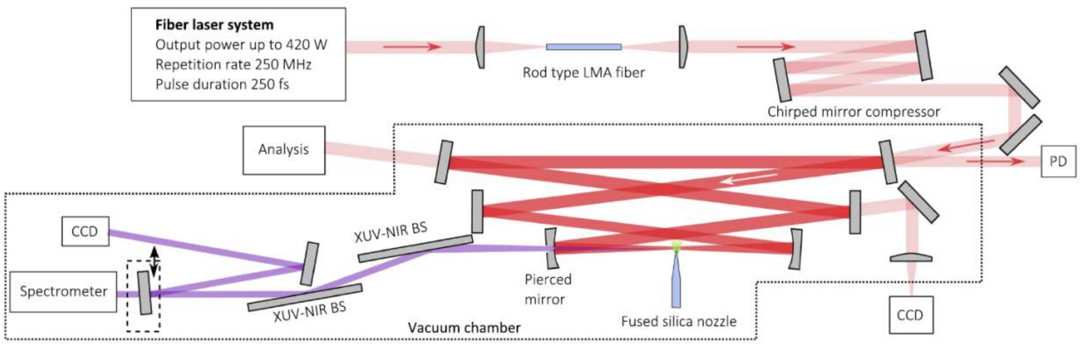
Pulse fluctuation VS seed laser intensity



Both CEP and pulse energy are stabilized for seed laser above shot noise intensity.

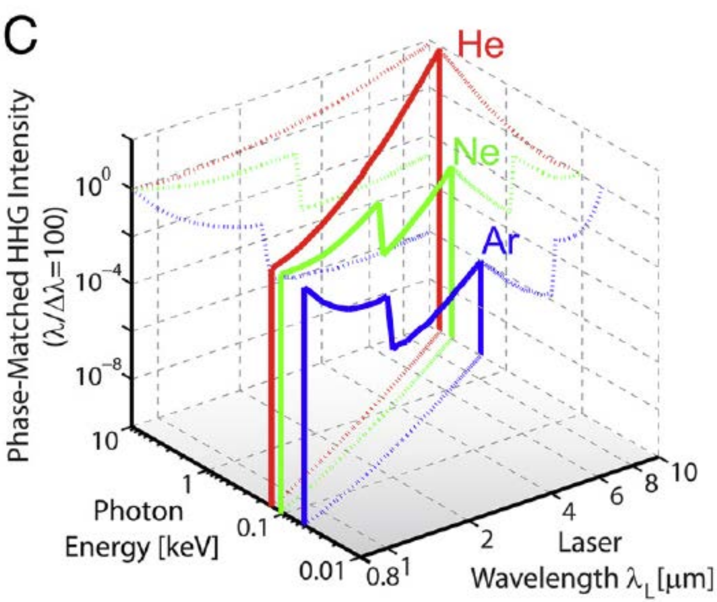
○ Seed pulse : 0.34 nJ x 10 MHz = 3.4 mW

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).



1. Higher flux

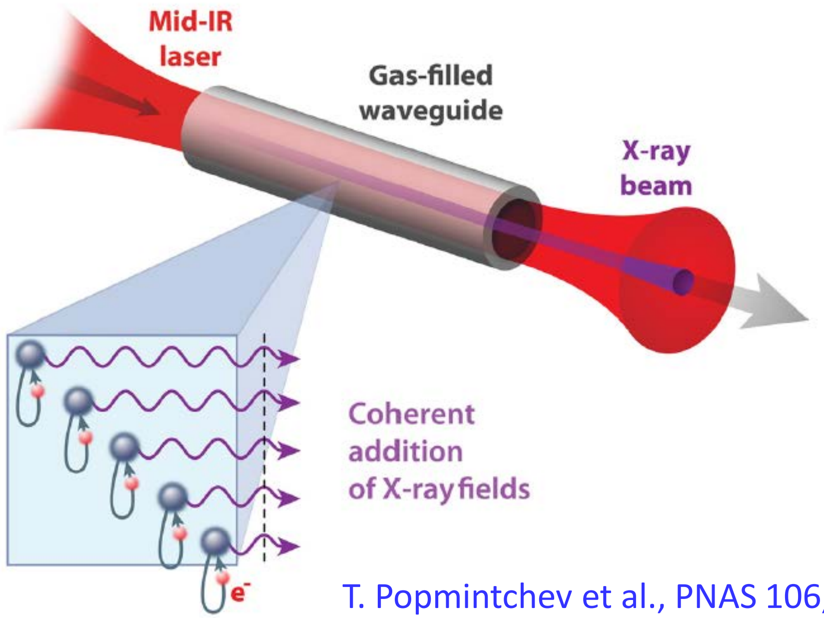
Average power of FEL can exceed 100 kW with an external cavity of a modest Q ~25.

2. Higher photon energy

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

T. Popmintchev et al., PNAS 106, 10516 (2009)

Phase Matching in HHG



T. Popmintchev et al., PNAS 106, 10516 (2009)

Phase matching must be satisfied for efficient HHG.

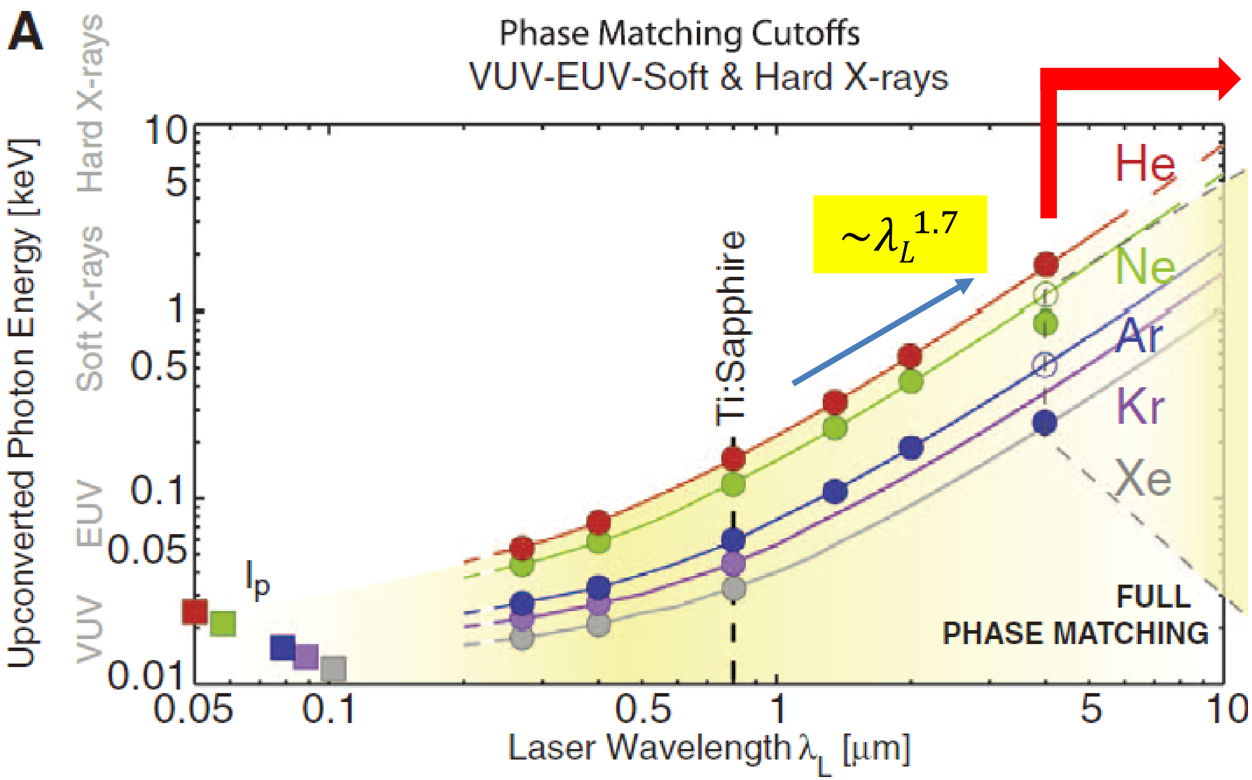
Phase slips between injection laser and HHG

$$\Delta k = q\left[\left(\frac{u_{11}^2\lambda_0}{4\pi a^2}\right) - P\left\{(1-\eta)\frac{2\pi}{\lambda_0}\Delta\delta - \eta(N_{atom} r_e \lambda_0)\right\}\right] + \Delta k_{quantum}$$

waveguide Neutrals Plasma Quantum

Δk << 1 is necessary for the phase matching

Phase Matching Cutoff Energy at HHG



1.6 keV HHG
with 3.9 μm laser
~10^5 ph/pulse/1%BW

From T. Popmintchev et al., Science 336, 1287-1291 (2012).
Reprinted with permission from AAAS.

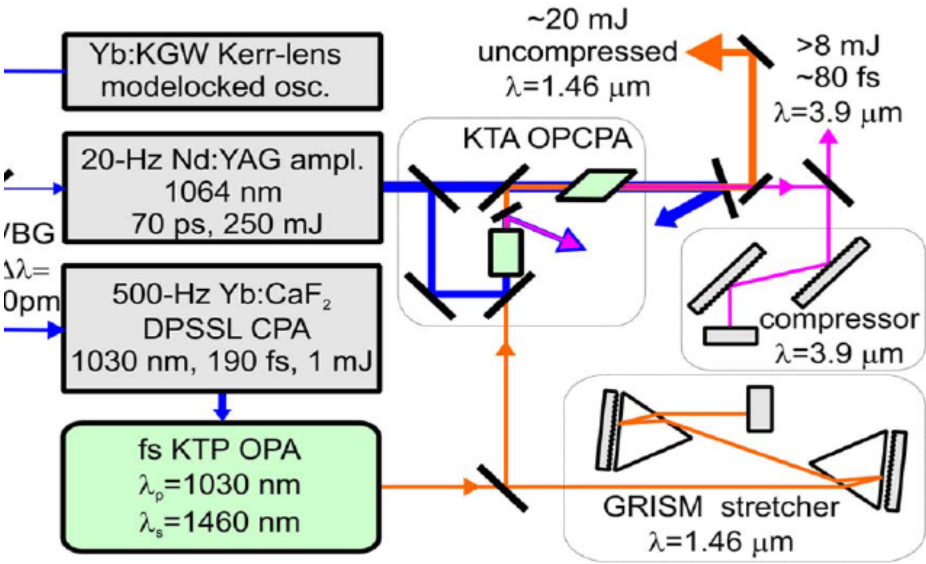
$E_{PM} \propto \lambda_L^{1.7}$ scaling has been confirmed by experimental and theoretical studies.

Generation of mid-IR pulses is one of the key technologies in HHG.

Mid-IR pulses from a solid-state laser

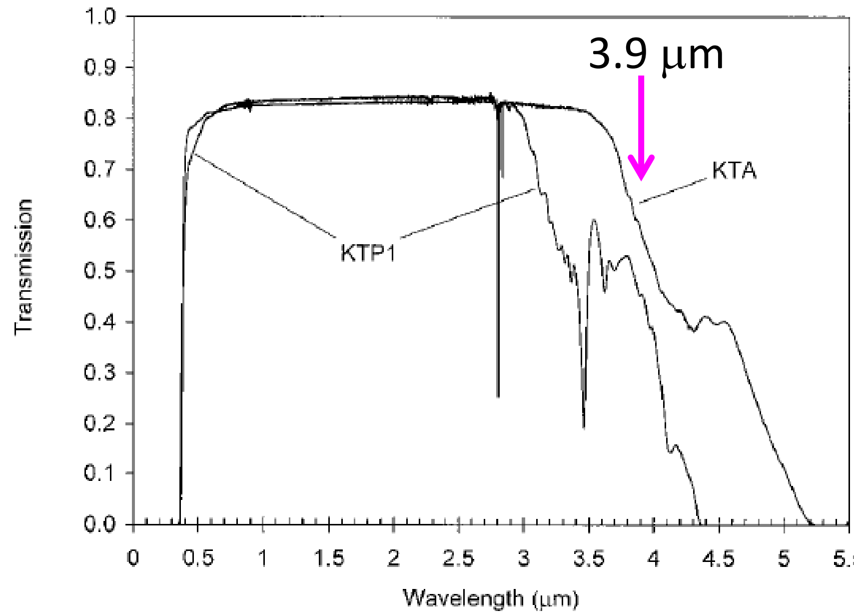
Laser system for the 1.6 keV HHG

8 mJ, 80 fs, 3.9 μm, 20 Hz



G. Andriukaitis et al., Opt. Lett. 36, 2755 (2011)

Transmission of KTA crystal



G. Hansson et al., Appl. Opt. 39m 5058 (2000)

Pulse energy and repetition are limited by thermal load.

Mid-IR wavelength is limited by nonlinear crystal.
2-step conversion is necessary for wavelength > 4 μm.

Effects of FEL gain jitter on the CEP stabilization

CEP stabilization is affected by FEL gain jitter

High-gain FEL theory → $E(z) = E(0)exp\left(\left(\sqrt{3} + i\right)k_u\rho z\right)$

FEL amplification is accompanied by phase rotation.

There are many sources of FEL gain jitter in a linac FEL.

In a single-pass SASE-FEL, CEP stabilization is practically impossible even with a seeding.

The effect is relaxed in a FEL oscillator operated at dL=0

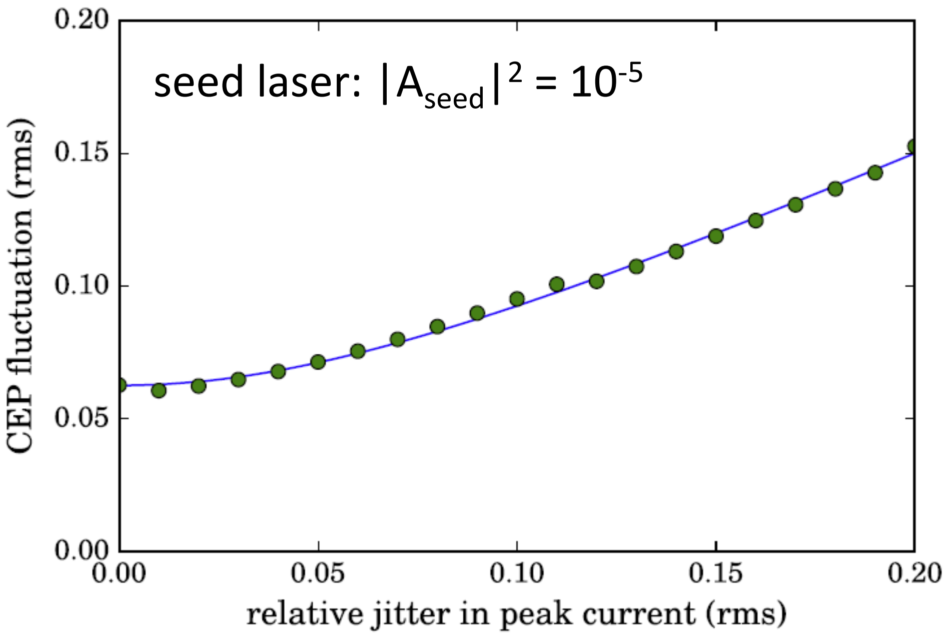
because

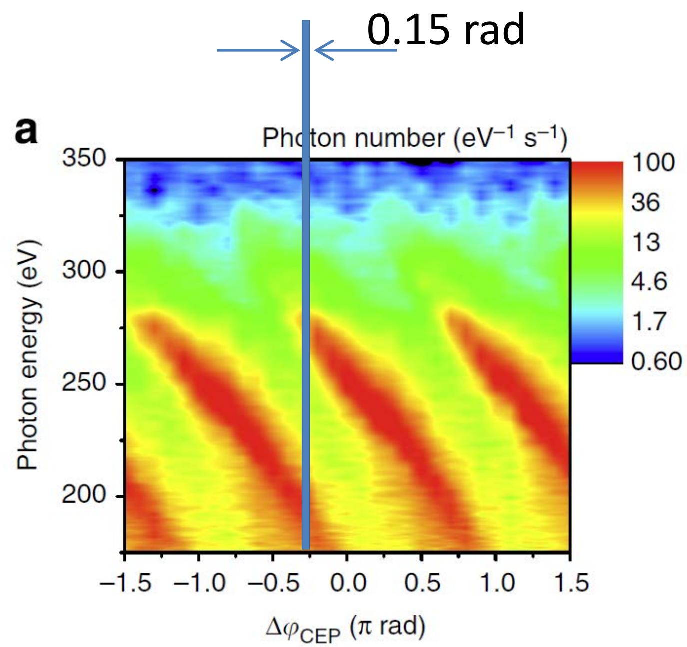
FEL evolution is governed by “integral gain” not “local gain”

The effect of jitter is averaged over round trips – oscillator cavity Q

integral gain $\Gamma = \dfrac{\int_0^{L_b} G(s)ds}{L_s}$

Simulation with a FEL gain jitter





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

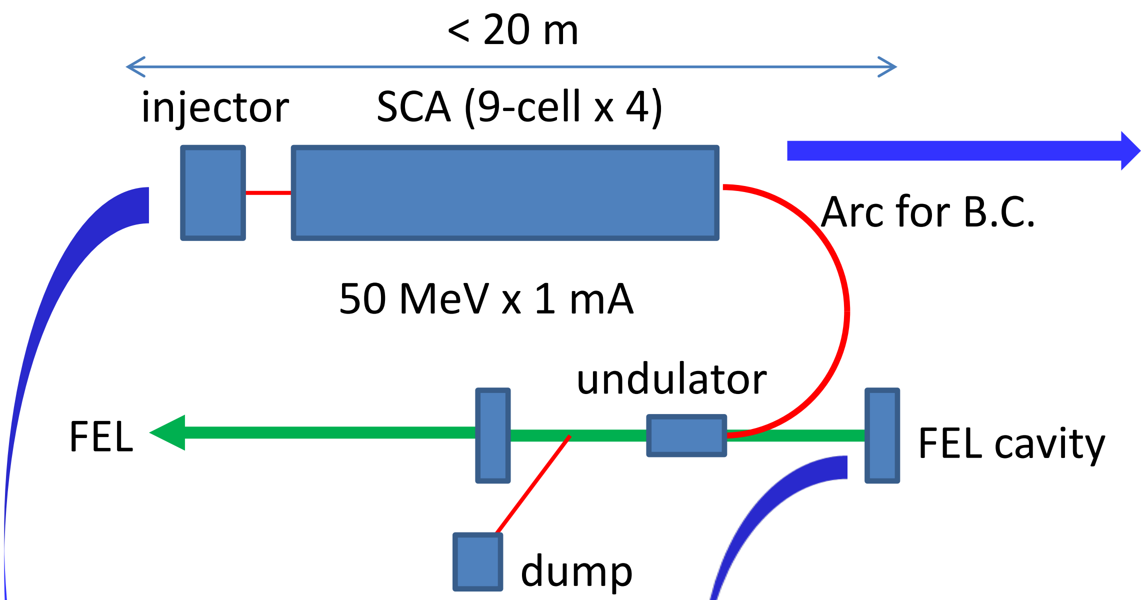
20 % jitter in the peak current (or the integral gain)
→ CEP jitter of 0.15 rad

Further studies are necessary for a practical design.

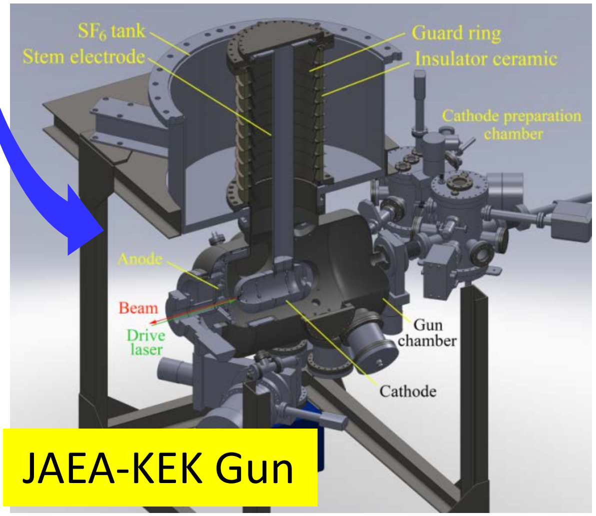
c.f. MOGA optimization for minimizing jitters in LCLS-II.

L. Wang and T. O. Raubenheimer, J. Mech. Eng, Autom. 4, 632 (2014).

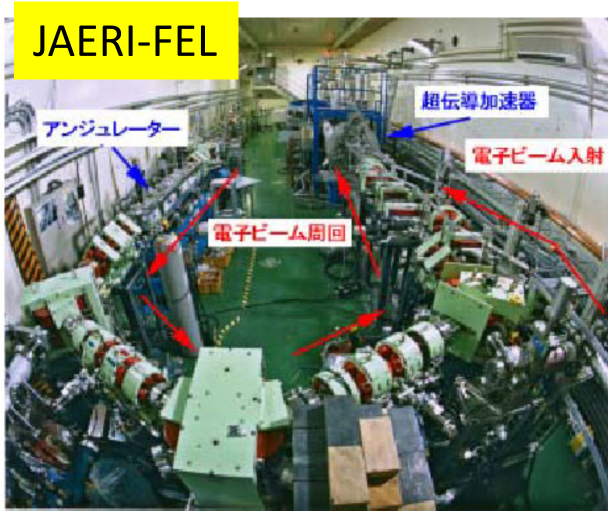
Technologies for the mid-IR FEL are ready



L-band SCA for a CW beam



Photocathode gun for a CW beam

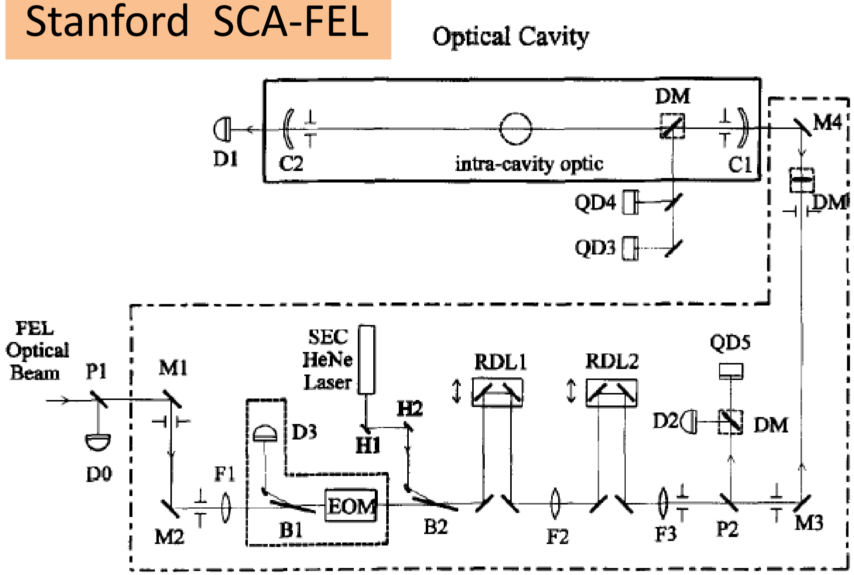


FEL oscillator operated at dL=0

FEL pulse stacking in an external cavity

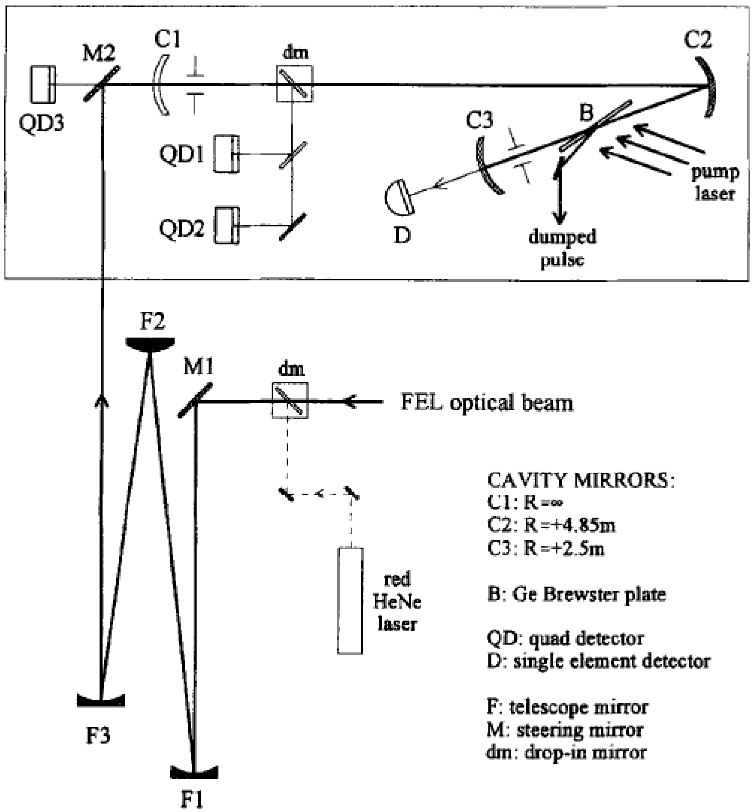
Pulses from an FEL oscillator can be stacked in an external cavity
for intra-cavity experiments or cavity dumping with higher pulse energy at lower rep rate.

Stanford SCA-FEL



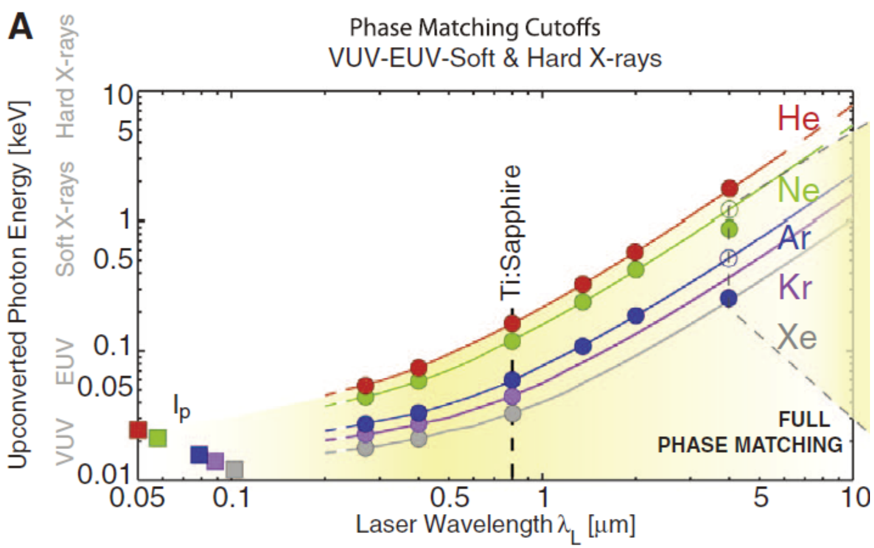
λ = 5 μm
Cavity length = 12.68 m
Q (meas.) = 25
Enhancement = 73

Design of cavity dump

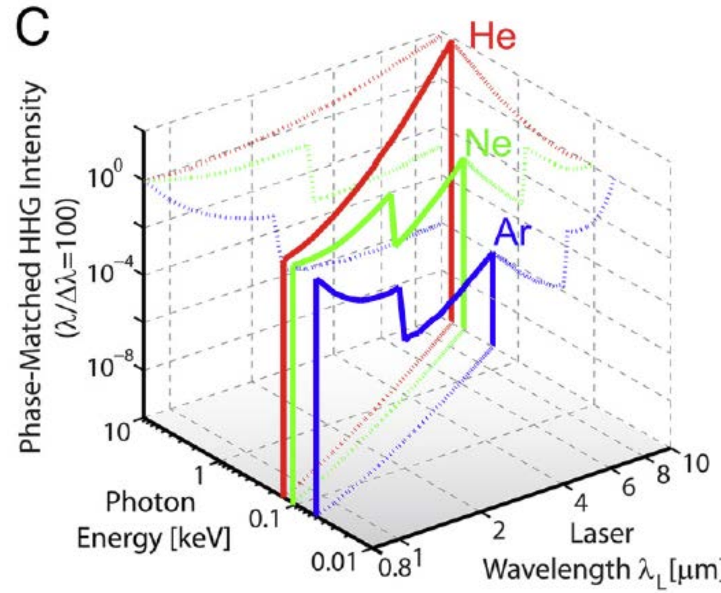


T.I. Smith et al., Nucl. Instr. Meth. A393, 245 (1997).

Estimation of HHG photon yield



From T. Popmintchev et al., Science 336, 1287-1291 (2012).
Reprinted with permission from AAAS.



T. Popmintchev et al., PNAS 106, 10516 (2009)

1.6 keV HHG
with 3.9 μm, 6-cycle, 10 mJ, 20 Hz laser
~10^5 ph/pulse/1%BW

HHG photon yield and cut-off energy
Increases as the laser wavelength

Assuming a FEL with mid-IR pulses, 4-10 μm, ~2-cycle, ~2-mJ and 10 MHz,
the HHG yield will be

10^5-10^6 ph/pulse/1%BW, 10^{12}-10^{13} ph/s/1%BW at 1-10 keV

Summary and Outlook

- 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.
- The HHG photon covers energies up to 1-10 keV with isolated attosecond and zeptosecond pulses.
- FEL-HHG will open a door to full-scale experiments of attosecond x-ray pulses and push ultrafast laser science to the zeptosecond regime.
- And more
  - -X-ray frequency comb for precision spectroscopy
  - -CEP-stable pulses for coherent control of chemical reaction
  - -seeding the HHG pulse to another XFEL (FEL-HHG-FEL)