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

Ryoichi Hajima A), Ryoji Nagai A), Keigo Kawase A), Hideaki Ohgaki B), Heishun Zen B), Yasushi Hayakawa C), Takeshi Sakai C), Yoske Sumitomo C), Miho Shimada D), Tsukasa Miyajima D)

A) National Institutes for Quantum and Radiological Science and Technology
B) Kyoto University, C) Nihon University, D) High Energy Accelerator Research Organization

This work was supported by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant Number JPMXS0118070271.
Contents

• Introduction of HHG and possible combination with FELs
  • Few-cycle pulse generation in FEL oscillators
  • Stabilization of carrier-envelope phase (CEP)
  • Research Program for FEL-HHG
High Harmonic Generation; HHG

odd-harmonics with time and spatial coherence

3-step model

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


R. Hajima et al. FEL 2019
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.

**FEL → HHG**

- Generating VUV and X-ray with a small-size FEL
- Attosecond pulses available

---


R. Hajima et al., FEL 2019
Keys to the attosecond pulse generation in HHG

Typical laser intensity for HHG

$\sim 10^{14} \text{ W/cm}^2$

0.3-1 mJ, 3-cycle,
$\lambda = 2-6 \mu\text{m}, w = 100 \mu\text{m}$

Can a FEL generate such pulses?

R. Hajima et al.  FEL 2019
Introduction of HHG and possible combination with FELs

Few-cycle pulse generation in FEL oscillators

Stabilization of carrier-envelope phase (CEP)

Research Program for FEL-HHG
Few-cycle FEL pulses (transient regime)

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

10 \mu J, 6 cycle, 10.4 and 24.5 \mu m


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


R. Hajima et al. FEL 2019
High-efficiency lasing at $dL=0$ was found at JAERI FEL. A few-cycle FEL pulse was confirmed by autocorrelation measurement.

1.55 cycle after chirp compensation
pulse energy ~ 0.2 mJ
Few-cycle pulse evolution in FEL Oscillators

\[ dL < 0 \]

**Transient regime**
- Chaotic lasing

\[ dL = 0 \]

**Steady state regime**
- Solitary pulse

R. Hajima et al.  FEL 2019
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

Short pulse FEL Oscillator at dL=0

Evolution of a solitary pulse


Superradiant pulse evolution at a loss-less cavity

N. Piovella,

Peak exceeds the steady-state lasing

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


\[ \text{peak} \propto N_e^2 \propto (qQ)^2 \]
\[ \text{width} \propto N_e^{-1/2} \]
Contents

• Introduction of HHG and possible combination with FELs
• Few-cycle pulse generation in FEL oscillators
• Stabilization of carrier-envelope phase (CEP)
• Research Program for FEL-HHG
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.

Can a FEL generate CEP-stable pulses?

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.
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 et al.  FEL 2019
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
Contents

- Introduction of HHG and possible combination with FELs
- Few-cycle pulse generation in FEL oscillators
- Stabilization of carrier-envelope phase (CEP)
- Research Program for FEL-HHG
Proposal of FEL-HHG

Infrared FEL Oscillator

- Lasing at zero-detuning length
- Seed laser
- High-harmonic generation

→ Few-cycle pulse
→ CEP stabilization
→ Attosecond VUV/X-ray pulses

R. Hajima et al.  FEL 2019
Design Parameters

To obtain 0.5-mJ, few-cycle pulses

\[
\lambda = 2 \, \mu m \quad 85 \text{ MeV} \times 60 \text{ pC} \times 10\% = 0.5 \text{ mJ}
\]

\[
\lambda = 6 \, \mu m \quad 50 \text{ MeV} \times 100 \text{ pC} \times 10\% = 0.5 \text{ mJ}
\]

These parameters are within the existing technologies of SCA linacs.

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

JAEA-KEK Gun

KEK ERL

Photocathode gun

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

MEXT Q-LEAP

2018-2023 Development of basic technologies

2024-2027 Proof-of-Concept experiment of FEL-HHG

User facility of attosecond VUV/X-ray

SC linac technologies
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 \( dL \)

\( \alpha \): cavity loss normalized by gain parameter

P. Chaix, N. Piovella, G. Grégoire, PRE (1999)

“solitary FEL pulse” in FEL oscillator of \( dL=0 \)


Threshold exists for “solitary FEL pulse”

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

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
Fringe-resolved auto correlation (FRAC)

Pulse duration is evaluated by FRAC.

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

Further measurements and analysis are in progress.

FEL: 11.6 μm → SHG 5.8 μm
Challenge the efficiency, pulse duration limit at KU-FEL

- (A) 4.5-cell RF gun with thermionic-cathode mode (40 pC, \( \lambda = 11 \mu m \))
- (B) 4.5-cell RF gun with photocathode mode (120 pC)
- (C) Replace a hole-coupled mirror by a low-loss dielectric mirror (loss = 3% \( \rightarrow \) 1%)
- (D) Install a new 1.6-cell RF gun (1-nC bunch train)

Normalized cavity loss is the key parameter.

\[
\alpha = \alpha_0 / \Gamma
\]

\( \alpha_0 \) cavity round-trip loss
\( \Gamma = (L_B/L_S)(j_0/2) \) gain integrated over the slippage length

\[
N_s \propto 1/\eta \quad \text{optical cycle}
\]

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

\[
\alpha \triangleq \alpha / \Gamma
\]

\[
\Gamma = \frac{L_B}{L_S}(j_0/2)
\]

\[
\alpha = \frac{1}{\sqrt{\alpha}} = 38
\]

1-D simulations for dL=0 lasing

R. Hajima et al. FEL 2019
Pulse stacking in an external enhancement cavity

**HHG**

*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).

R. Hajima et al.  FEL 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.

Mode-locked oscillator (10-100 MHz, 50-200 fs) synchro. with acc. RF

 Oscillator

Amplifier

Difference Freq. Generation
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

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.

---


R. Hajima et al.  FEL 2019
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.