Numerical Simulation of High Harmonic Generation Using Liquid Flat-Jet Targets

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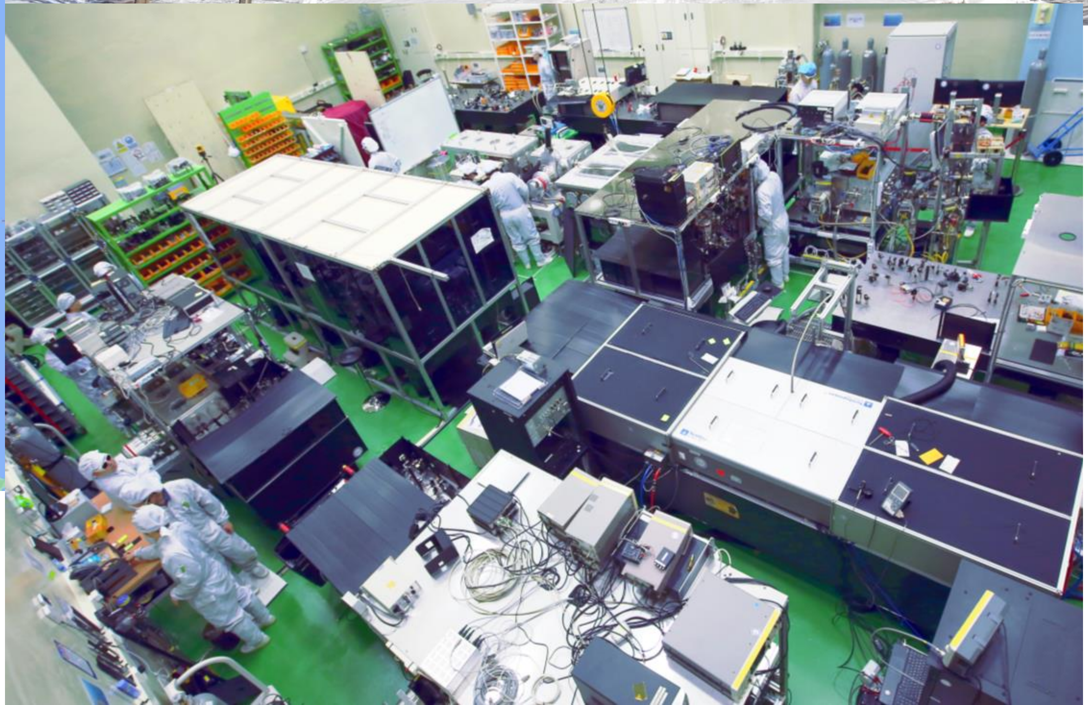

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High-harmonic generation from a flat liquid-sheet plasma mirror

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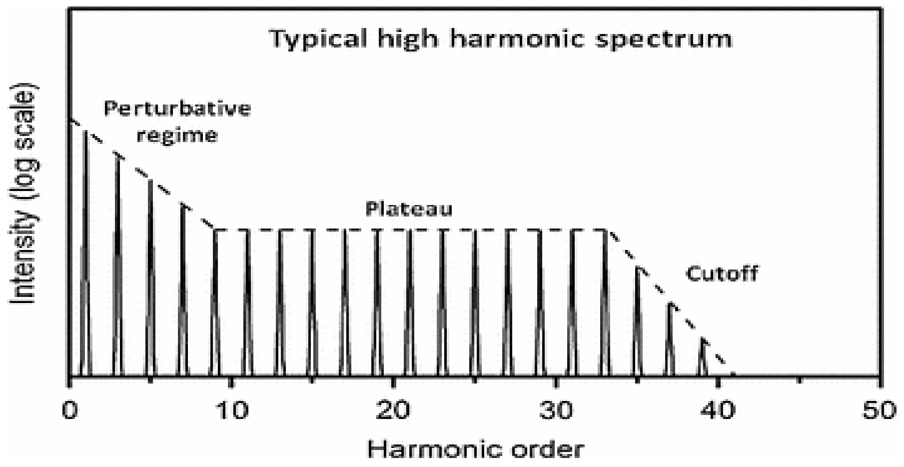
What is High-harmonic Generation (HHG)?

- High-harmonic Generation?
  - ➔ Phenomenon where high frequency photons are generated when intense laser light interacts with a medium.

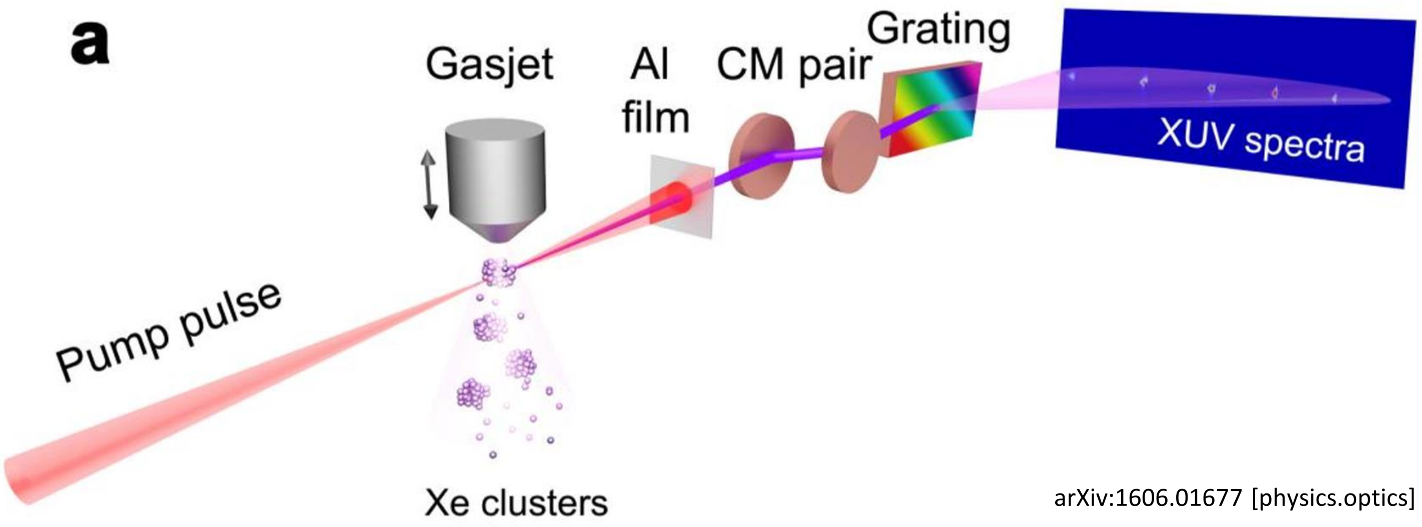
➔ Why we need High-harmonic generation?

- ➔ High-harmonic generation is a pulse with X-ray wavelengths in the spectral domain and an attosecond duration pulse($\sim 10^{-18} sec$) in the temporal domain
  - ➔ Useful for the time resolution of ultrafast(attosecond) dynamics of electrons in the matter
  - ➔ Industrially, it can be used as a table-top coherent X-ray source in fields such as semiconductor fabrication.



Research on high-harmonic generation in gases has been conducted.

- Limitation on driving laser intensity (Saturation of ionization rate.~10^{14}W/cm2)
- Low conversion efficiency $\sim 10^{-8}$
- High harmonic from gas is too weak!

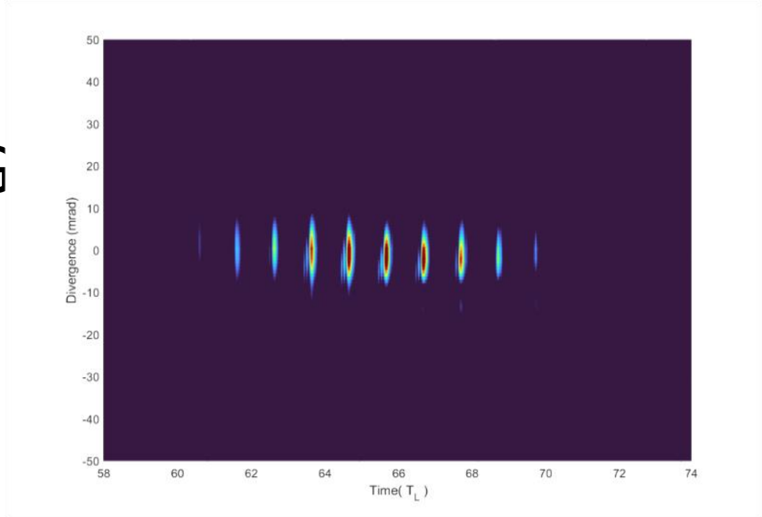


arXiv:1606.01677 [physics.optics]

High-harmonic generation (HHG) in plasma

- No limitation on driving laser intensity
- Higher conversion efficiency ($> 10^{-6}$) than gas HHG

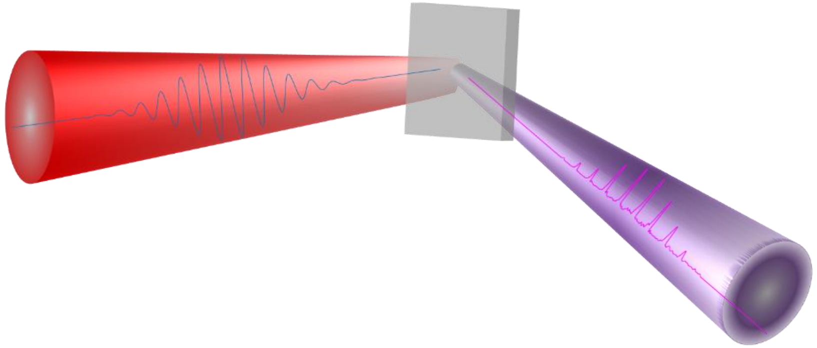
- There are two types of mechanism in plasma HHG
  - Coherent Wake Emission (CWE)
  - Relativistic Oscillating Mirror (ROM)



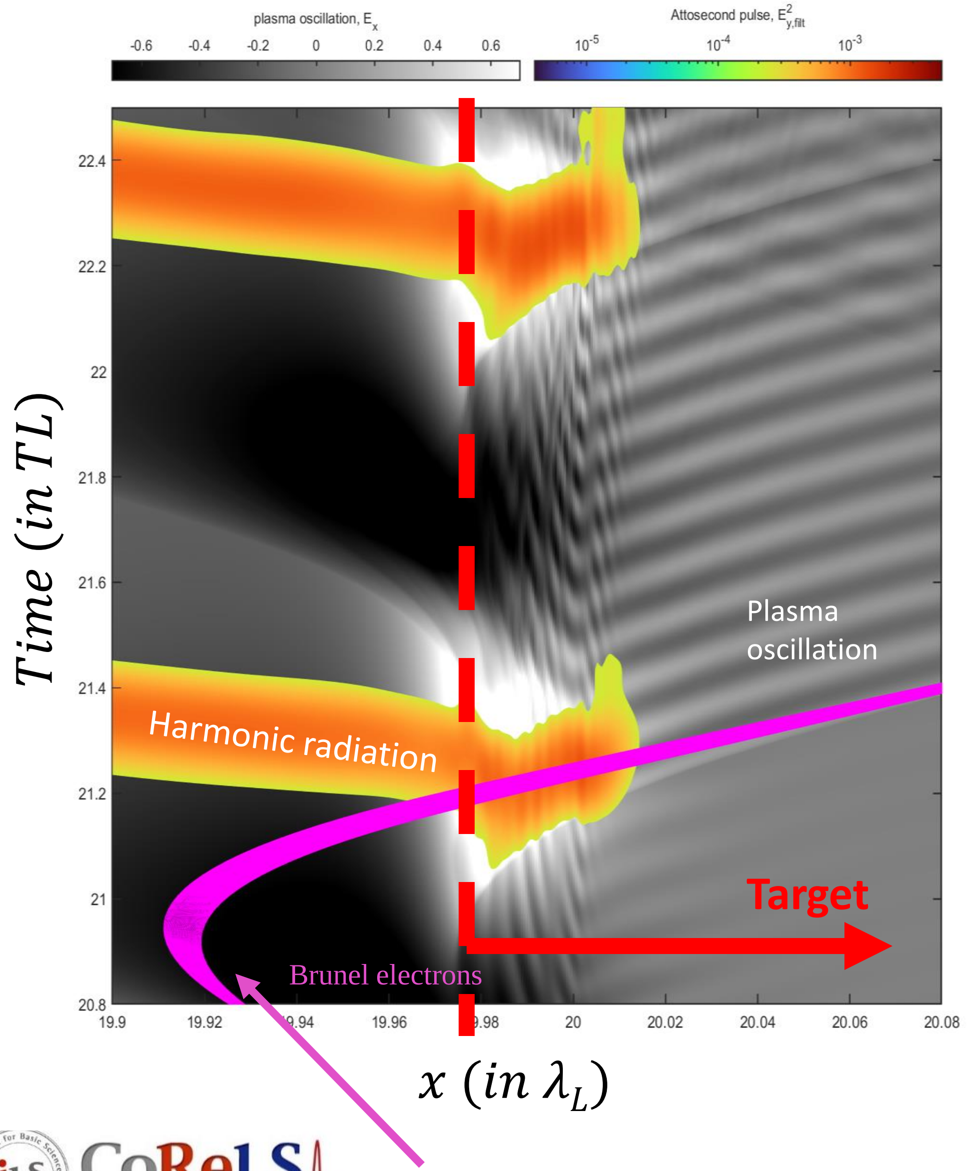
- Normalized vector potential a_0,

  a_0<1 ➔ CWE dominant

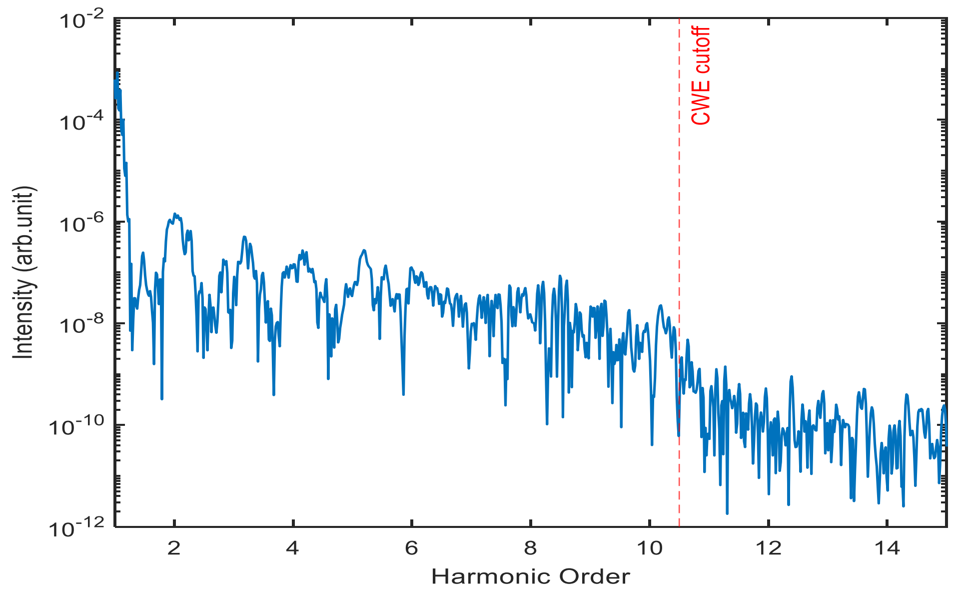
  a_0>1 ➔ ROM dominant



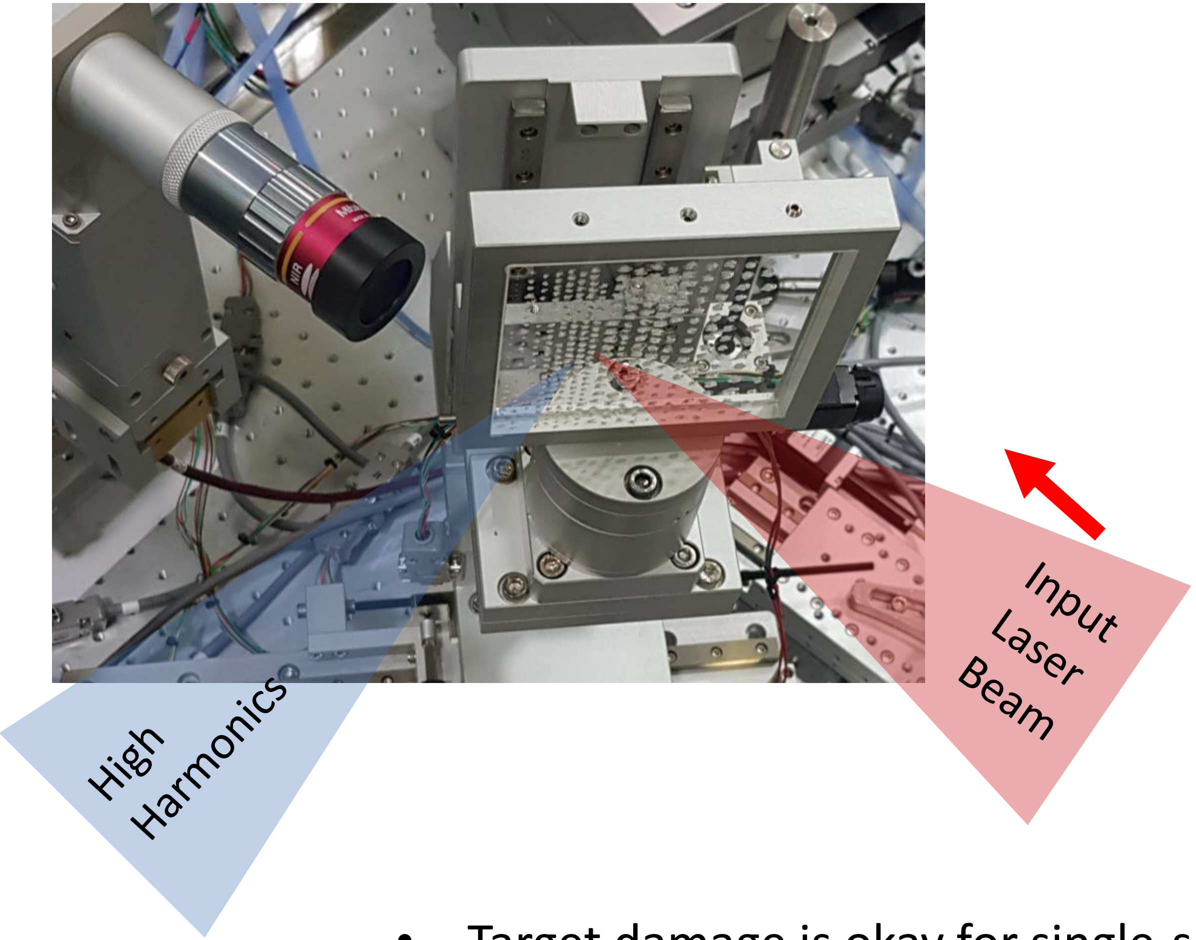
Plasma HHG - Coherent wake emission (CWE)



- Plasma oscillation is driven by Brunel electrons which is responsible for CWE emission.
- Driving laser intensity: $\sim 10^{16}\ W/cm^2$
- Efficiency: pretty high ($\sim 10^{-6\sim-4}$)
- Cutoff freq: $< w_p$



For kHz-repetition-rate lasers, damage issue becomes very critical.



- Target damage is okay for single-shot based experiment.
- But for 1-kHz lasers, further solutions for the damage issue is required.

A liquid jet would be a good solution for kHz-lasers.

- Tape targets

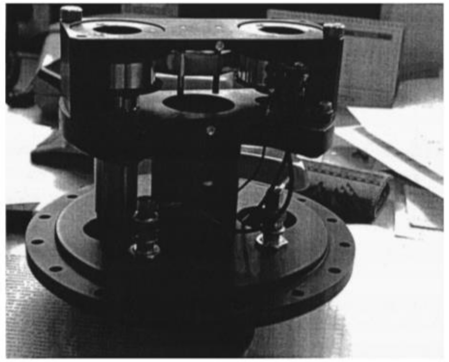


Image from E. Fill et al., RSI **73** (2002).

- Rotating wheel

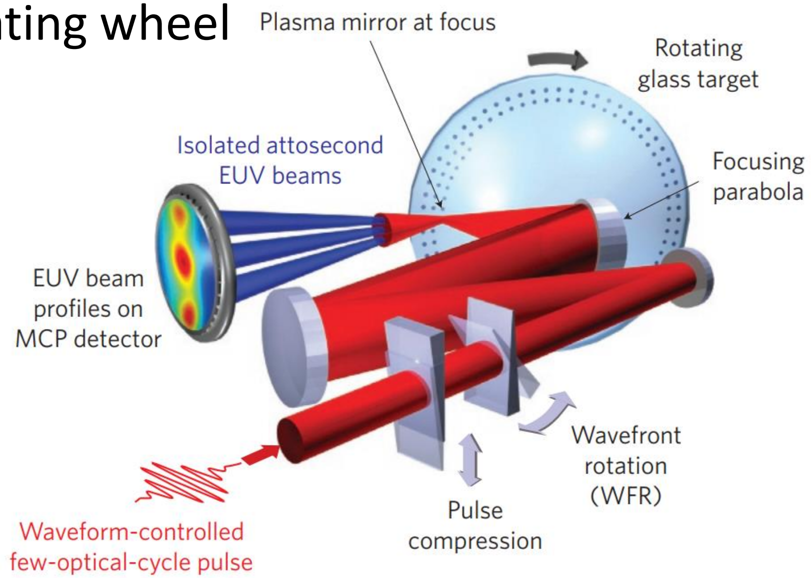
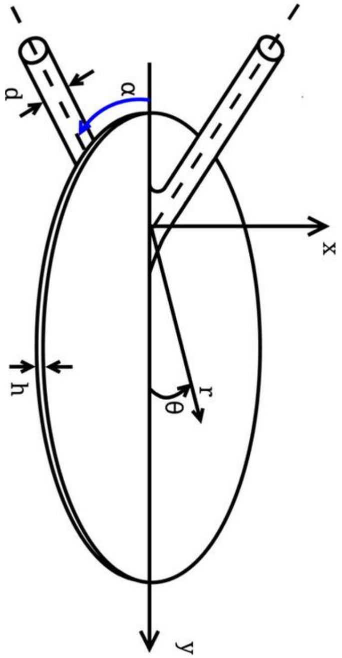
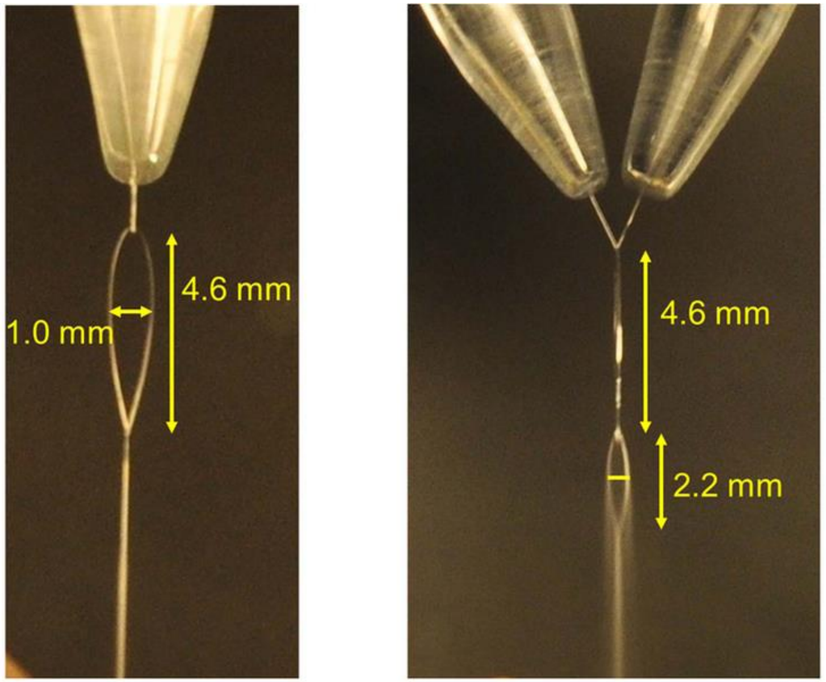


Image from Jonathan A. Wheeler et al., Nat. Photonics **6** (2002)

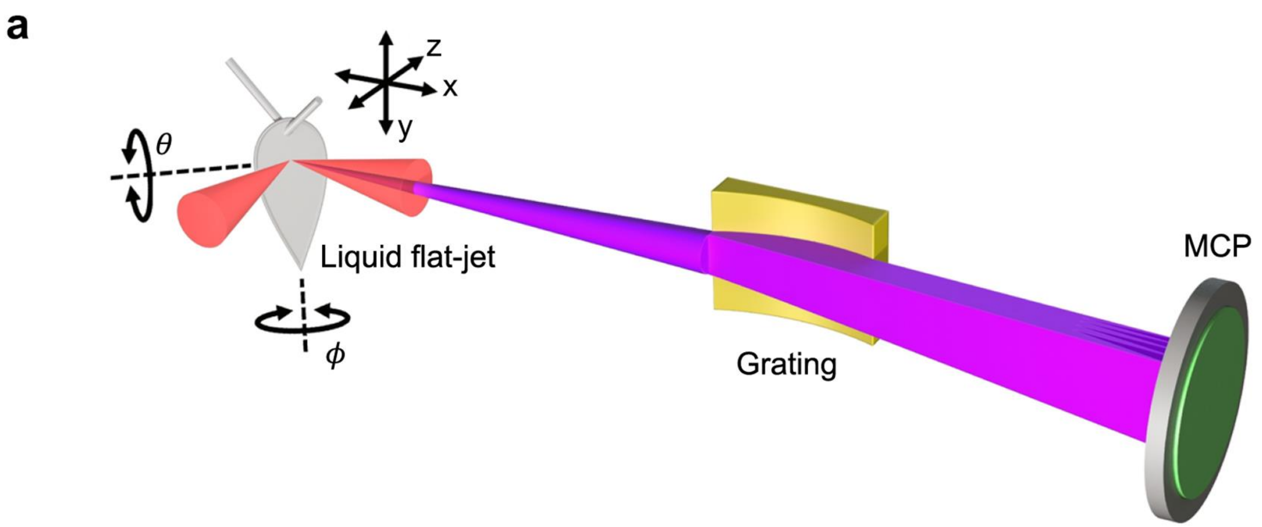
- Liquid flat jet target





Images from Maria Ekimova et al., Structural Dynamics **2** (2015).

We tried to reproduce experimental results.



Experimental conditions

- ➢ Target = propylene glycol
- ➢ Pulse duration = 30 fs
- ➢ Focal spot size = 2.5 μm

Simulation parameters

- ➢Electron number density of PG = 198n_c
- ➢Pulse duration = 11.2 T_L (= 30 fs @ 800 nm)
- ➢Focal spot size = 3.2 λ_L (= 2.5 um @ 800 nm)
- ➢Numerical parameters

Scale length =$0.006\lambda_L$ (optimal for CWE HHG)

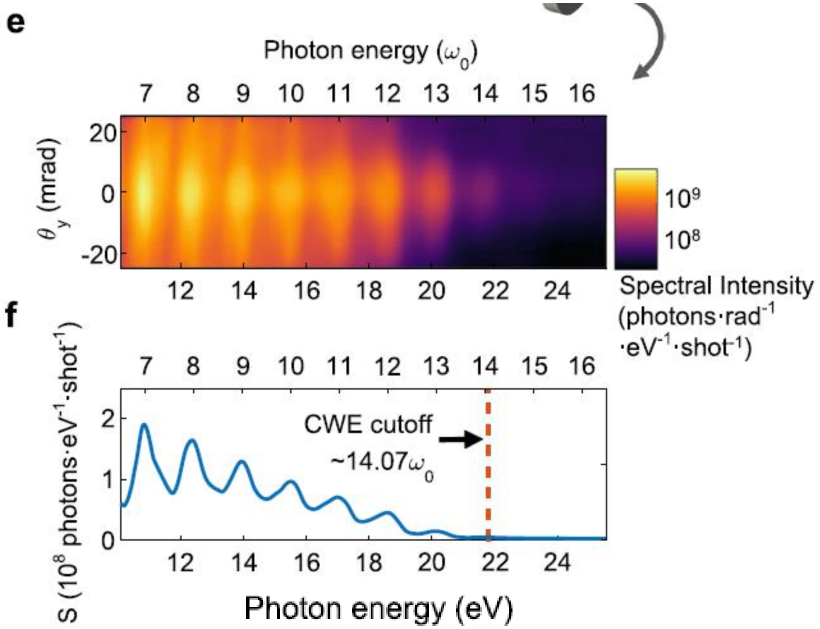
dx= dy =λ_L/256

dt = T_L/370 (0.98 CFL condition)

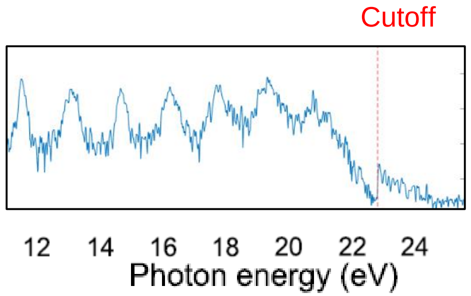
We successfully reproduced experimental results.

Main result: High-harmonic spectra

Experimental results

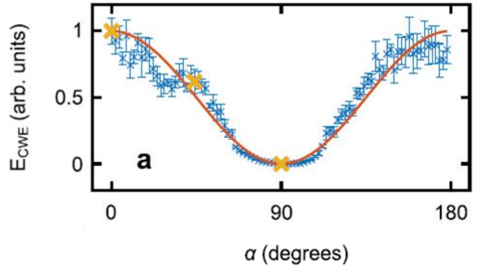


Simulation results

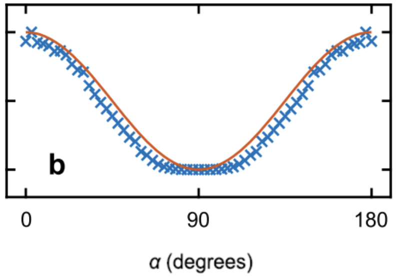


Polarization dependence

Experiment

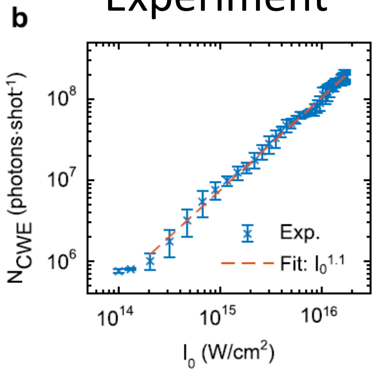


Simulation

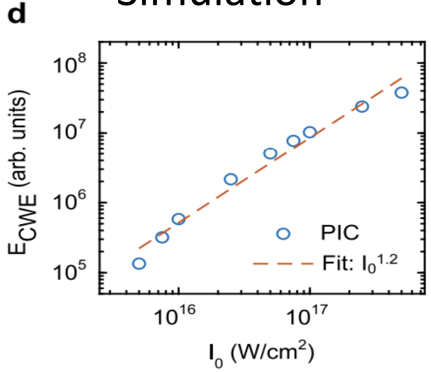


Intensity dependence

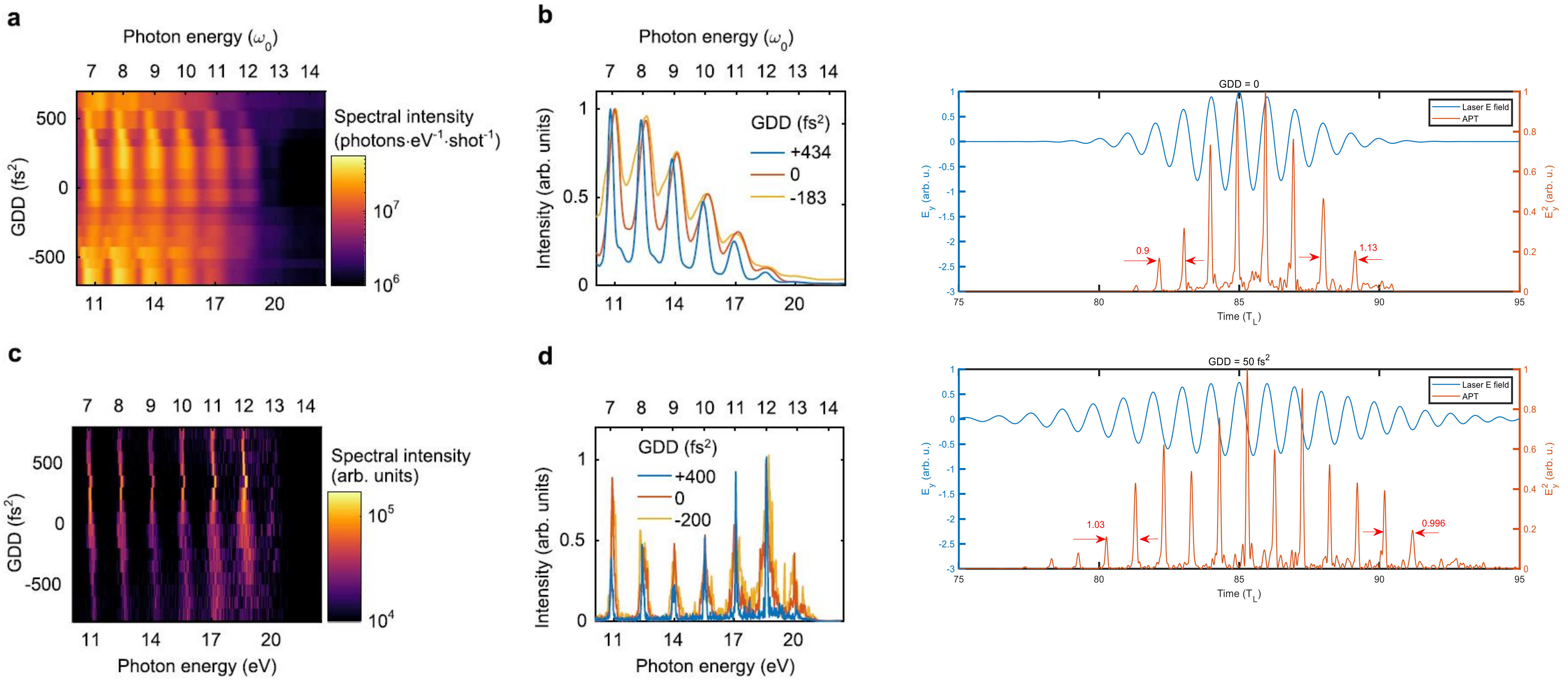
Experiment



Simulation

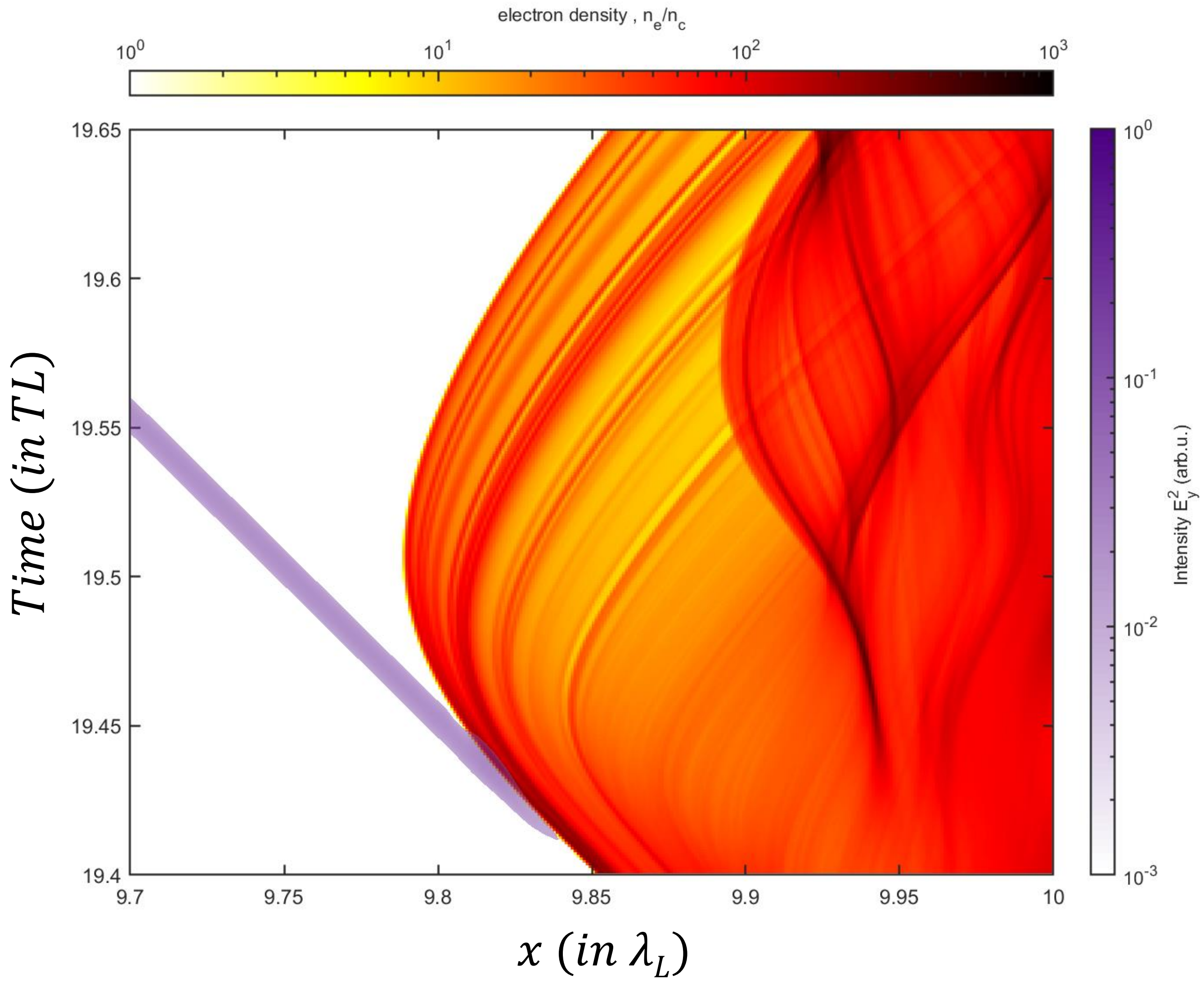


We successfully reproduced experimental results.



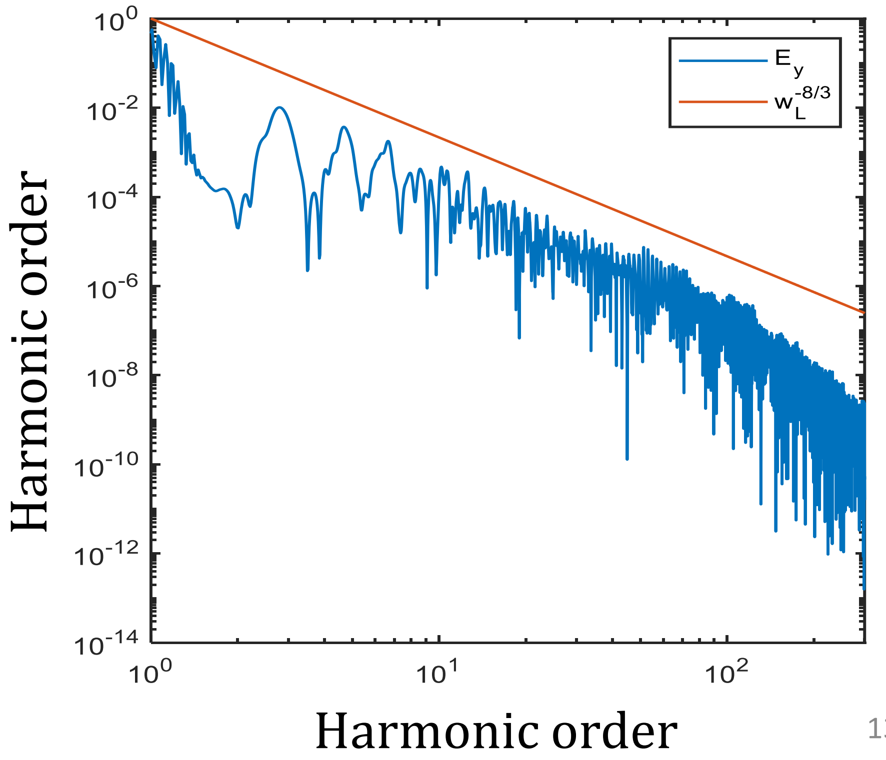
Experimental result & Numerical simulation well-matched!

Plasma HHG – Relativstic Oscillating Mirror (ROM)



- Driving laser intensity: $I > \sim 10^{18} W/cm^2$
- Periodic Doppler effect induced by relativistic oscillation of the plasma surface
- Efficiency : **VERY HIGH!** $(\sim \mathbf{10^{-8/3}})$

➔ Promising EUV source !



Recent working- Isolated attosecond pulse gating -Motivation

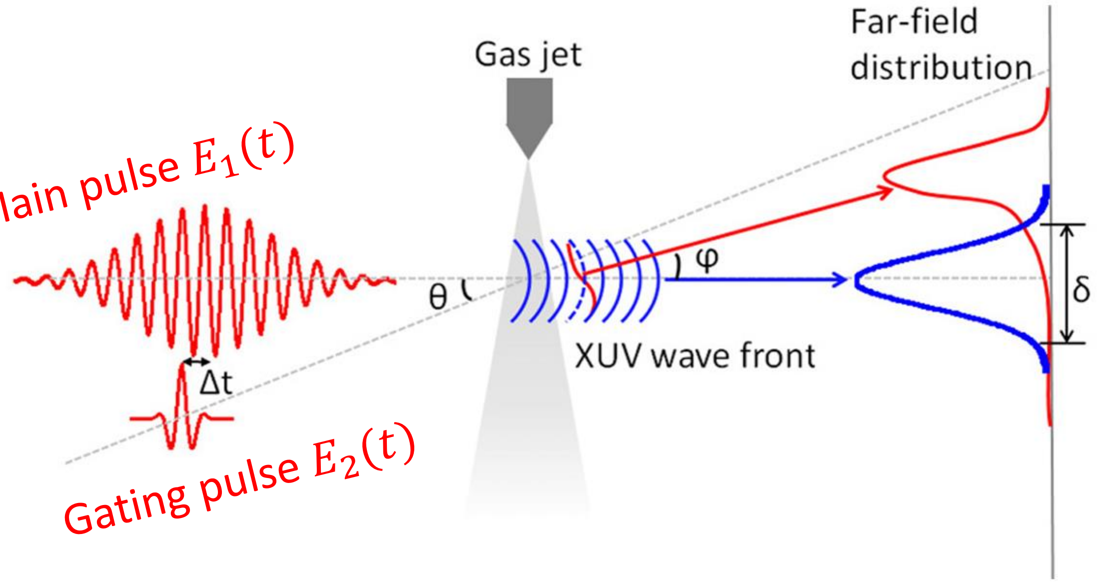


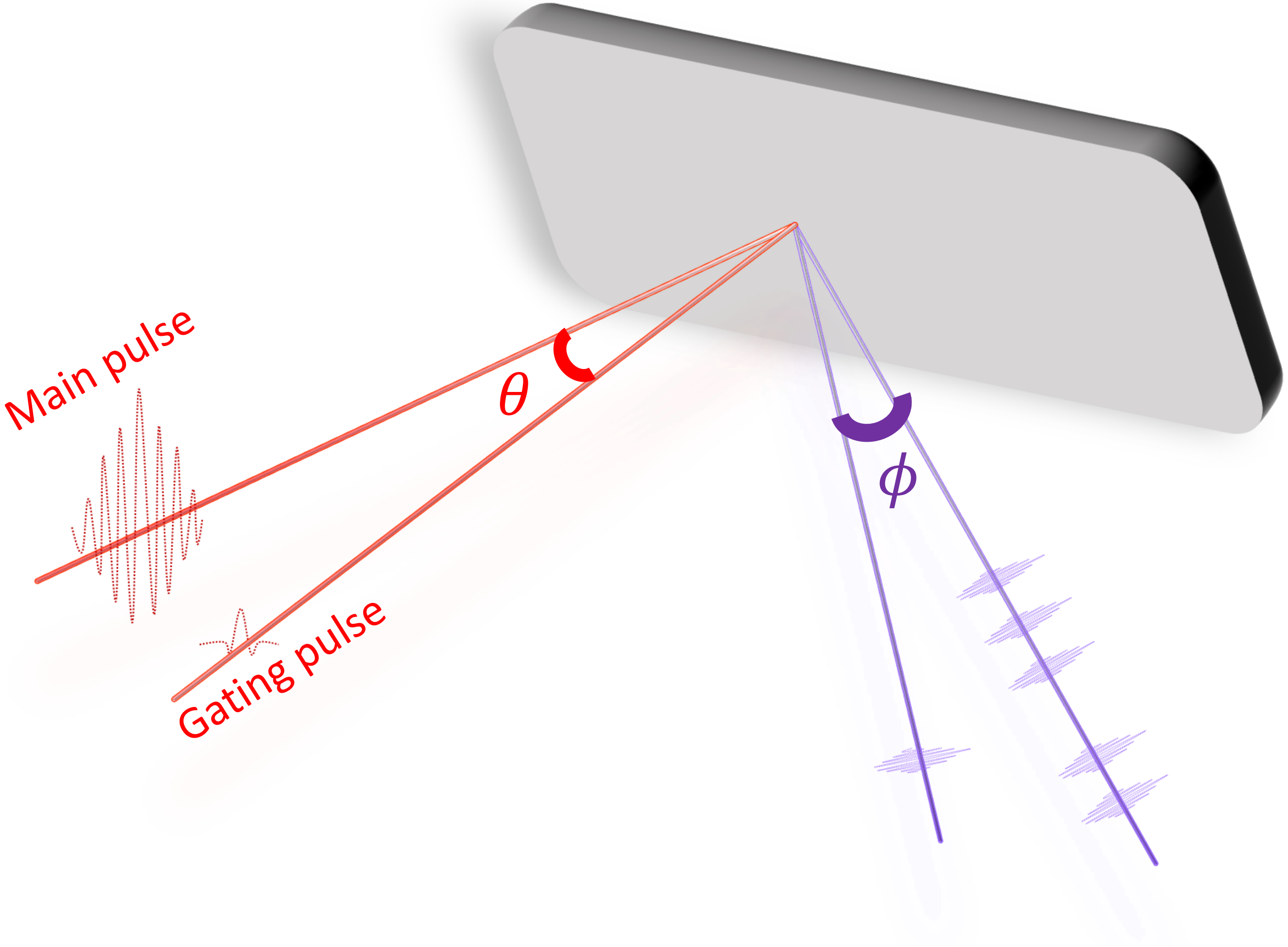
Image from Zhong, Shiyang, et al. *Physical Review A* 93.3 (2016): 033854.

$$\phi \propto \theta \frac{\frac{E_2}{E_1}}{1+\frac{E_2}{E_1}}$$

Isolated attosecond pulse gating from gas high harmonic

How about on plasma high harmonic?

Recent working- Isolated attosecond pulse gating



Simulation Parameter

Geometry = 2D cartesian
Simulation box size = 20 λ_L X 40 λ_L
Maxwell solver = Bouchard solver
dx = $\lambda_L/256$
dy = $\lambda_L/256$
dt = $T_L/512$

Main Pulse

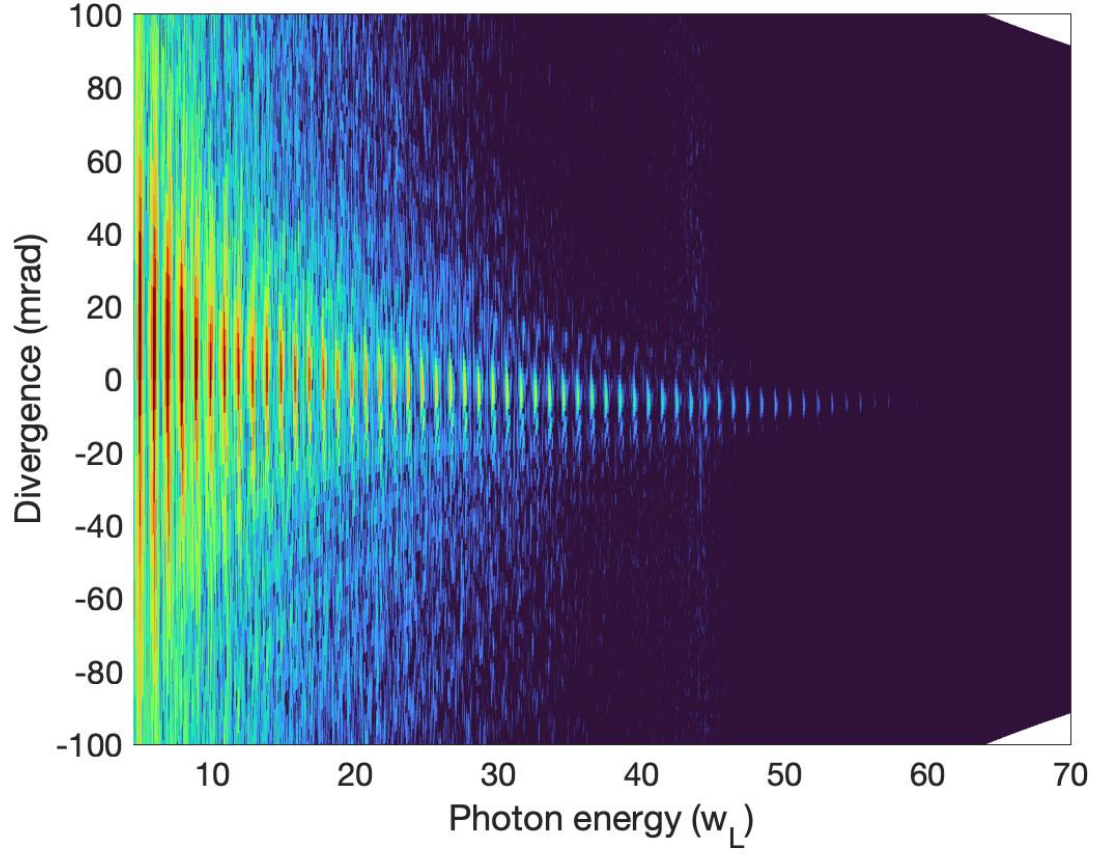
Intensity(a_0) $= 21\ (10^{21}W/cm^2)$
FWHM = 8 T_L
Focal spot size = 1 λ_L
Incidence angle = 45°

Gating Pulse

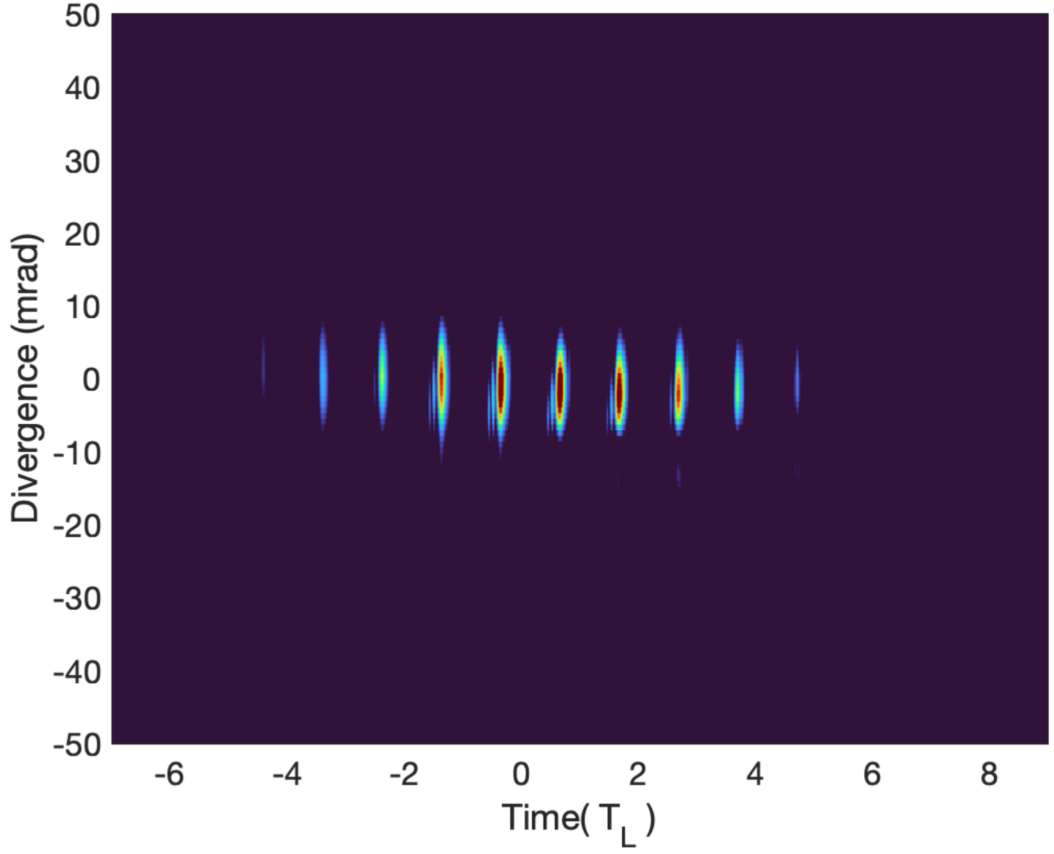
Intensity(a_0) $= 3\ (\ 1.9 \times 10^{19}W/cm^2)$
FWHM = 1 T_L
Focal spot size = 1 λ_L

Recent working- Isolated attosecond pulse gating

Angle-resolved Spectrum



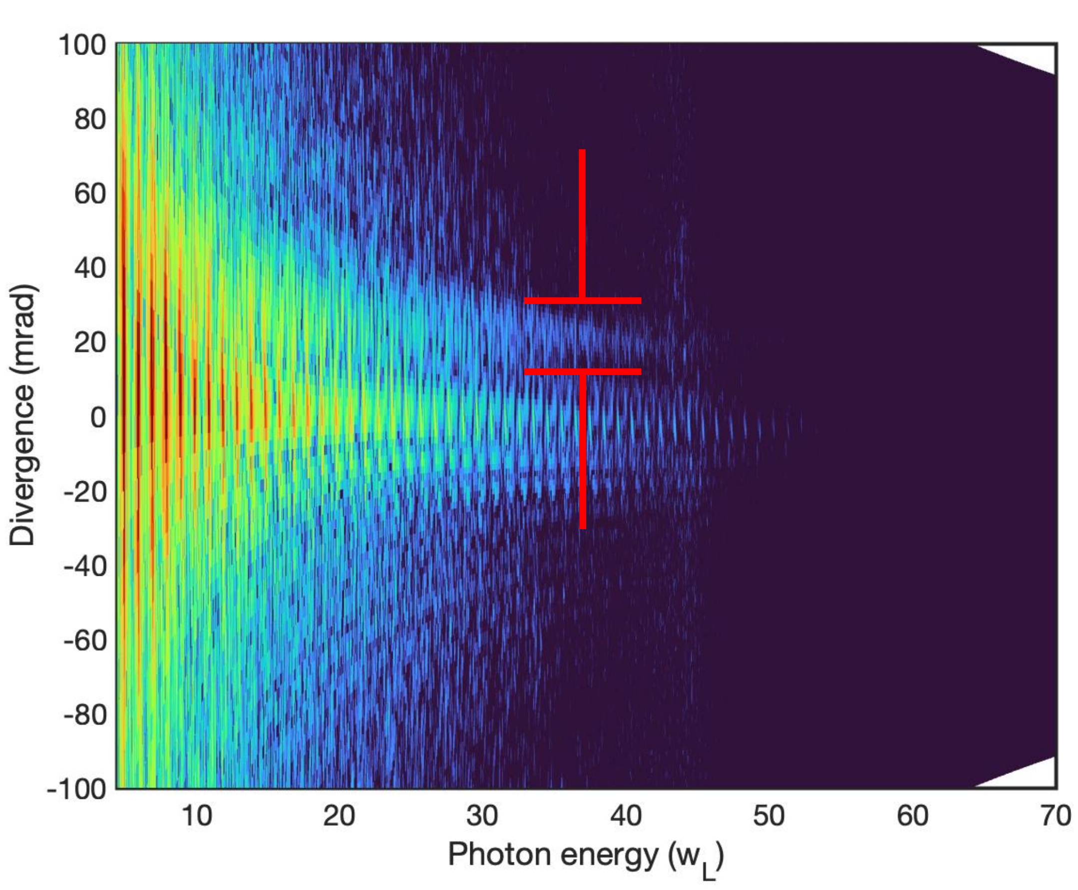
Angle-resolved Temporal profile



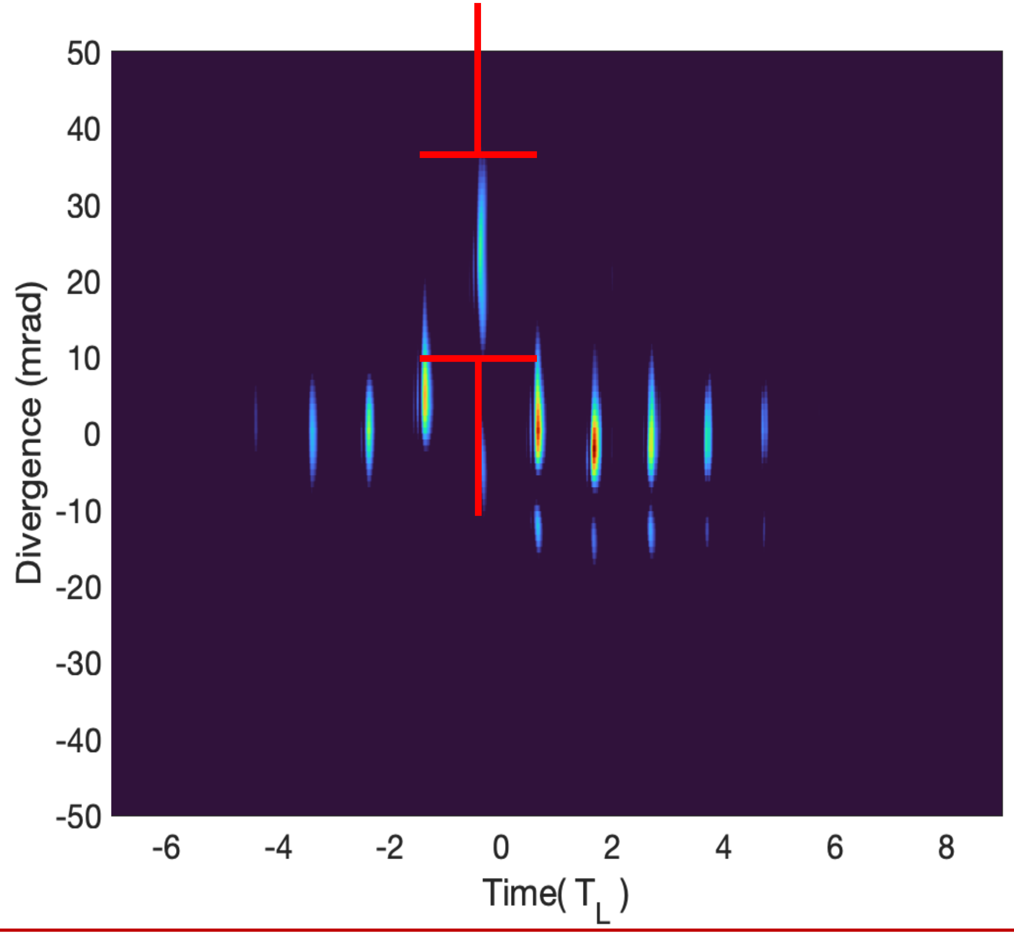
Attosecond Pulse Train by Relativistic Oscillating Mirror(ROM)

Recent working- Isolated attosecond pulse gating

Angle-resolved Spectrum

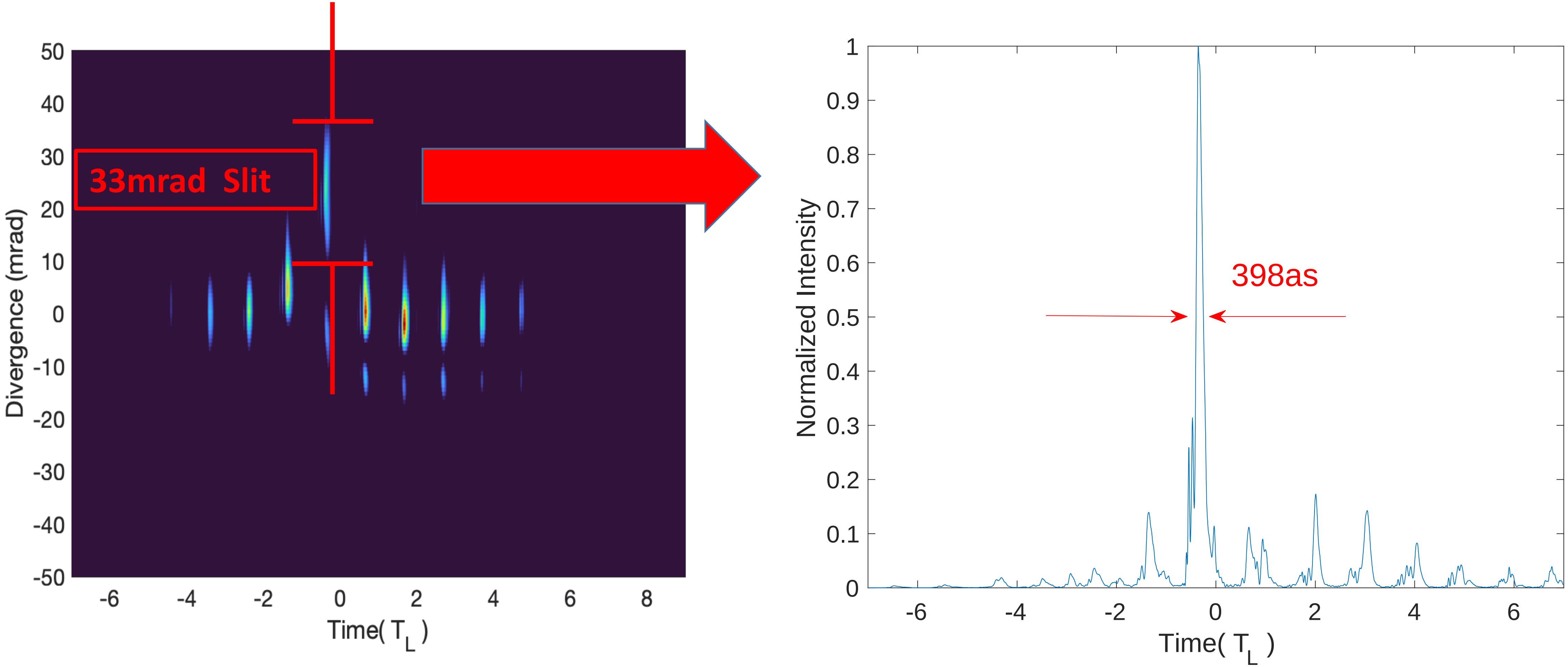


Angle-resolved Temporal profile



Separation of attosecond pulse when using gating pulse !

Recent working- Isolated attosecond pulse gating



This single attosecond pulse can be employed in pump-probe experiment!

Conclusion

- We demonstrated that CWE harmonics successfully reproduced by PIC simulation .

- We demonstrated that single attosecond pulse can be separated via noncollinear gating of long pulse and short pulse.

- The single attosecond pulse obtained through noncollinear gating can be utilized in attosecond streaking experiment for
  - Temporal characterization of atto pulses generated through CWE and ROM
  - Ultrafast plasma dynamics

Yang Hwan Kim and Kyung Taec Kim et al., Nat. Com. **14** (2023).
Hyeon Kim, To be sumitted (2024).

CoReLS Center for Relativistic Laser Science

Attosecond science group at GIST / IBS

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Prof. Tran Trung Luu, Hong Kong Univ.

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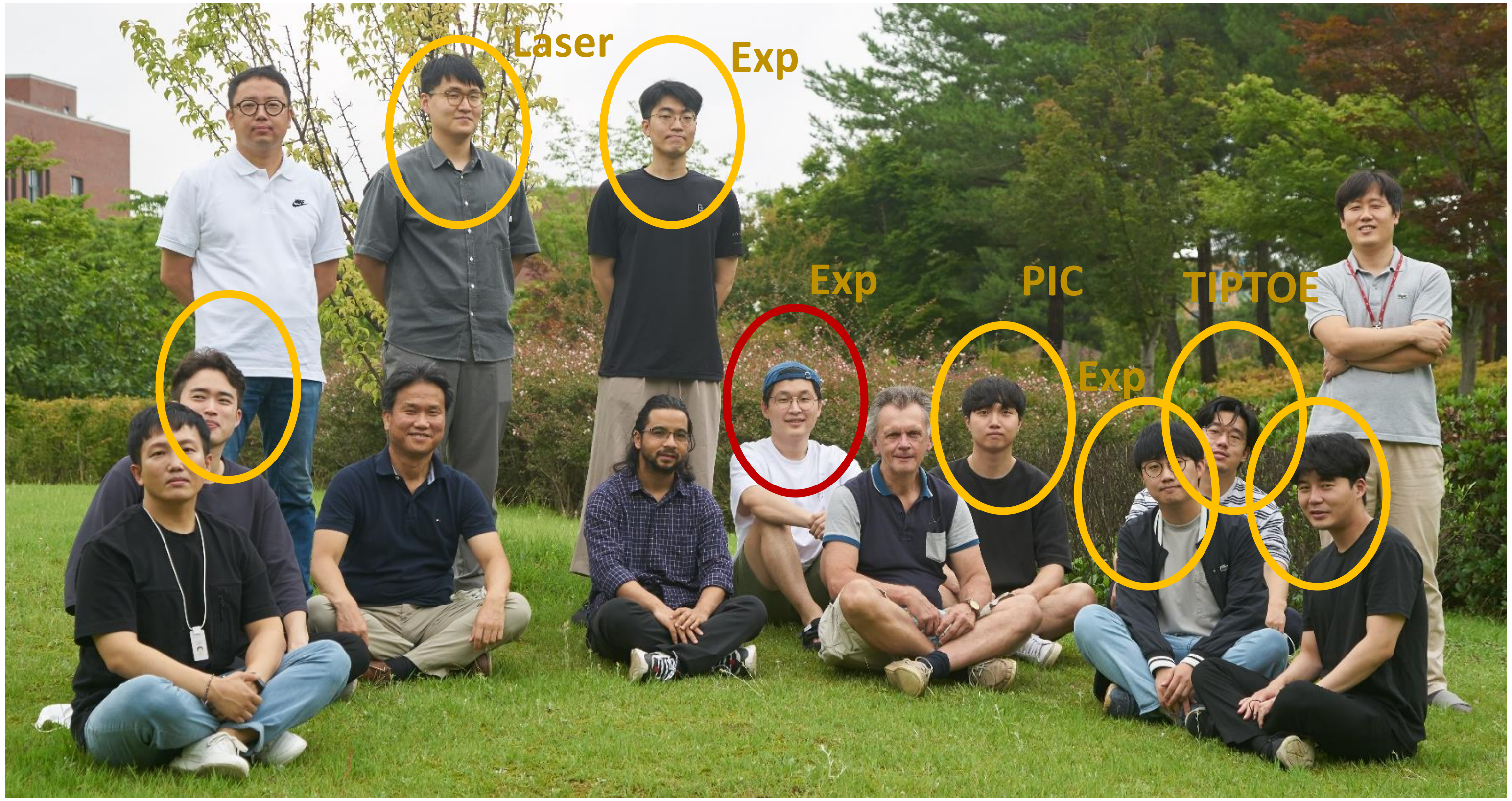
Post doc. Researchers: **Yang Hwan Kim,** Wosik Cho, Jeong-uk Shin
Ph. D. Candidates: Rajaram Shrestha (ELI ALPS), Kyung Hoon Yeom, Tae Yong Kwon, Hyeon Kim, Bin Kim, Sung Chul Park, Jeong Ho Ha
Technical support: Wontae Ra



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