

Mini Review

# About Efficiency of High-order Harmonic Generation in Attosecond Physics

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## Abstract

For the first time, the interaction between Hydrogen atom and Free-Electron Lasers (FEL) is simulated. The conversion efficiency of High-order Harmonic Generation (HHG) can be enhanced by utilizing a two-color free electron laser with frequency multiplication. It is found that the conversion efficiency of HHG is improved to the largest extent when fourth-fold frequency multiplication is introduced into two-color FEL. The microscopic mechanism of improving the efficiency of HHG is analyzed and discussed.

## Introduction

Attosecond physics belongs to one of the areas in ultrafast science since it provides the feasibility to observe the motion of electronic wave packets inside atoms, molecules, and solids [1,2]. Currently, it is established as a mature research field, which offers effective methods for the investigation of fundamental electronic processes [3]. The field of attosecond physics was justly awarded the Nobel Prize for physics in the year 2023.

The appearance of attosecond pulses results from High-order Harmonic Generation (HHG) in gases, which occurs as a strong nonlinear process when an intense and short-light pulse is concentrated onto a gas medium. Subsequently, coherent Extreme Ultraviolet (XUV) radiation with pulse duration down to the attosecond range is obtained in this HHG process [4]. The physical processes causing HHG can be explained utilizing a quasi-classical three-step model [5]. This model is rather useful and interesting, because it gives a clear physical picture regarding the production of very short radiation bursts, with duration in the attosecond regime. Additionally, it has already been confirmed by a previous experiment [6]. Although HHG is believed to have broad applicable prospects, there are certain discrepancies for practical applications of HHG, which is mainly due to the low conversion efficiencies of HHG. Hence, how to improve the efficiency of HHG has become one of the most important topics in the investigations of HHG. In this work, numerical simulations have been conducted to improve the efficiency of HHG. It is demonstrated that the efficiency of HHG can be enhanced by using a two-color Free Electron Laser (FEL).

## More Information

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Submitted: October 15, 2024

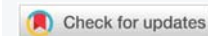
Approved: October 28, 2024

Published: October 29, 2024

How to cite this article: Yu AY. About Efficiency of High-order Harmonic Generation in Attosecond Physics. Int J Clin Virol. 2024; 8(2): 045-047. Available from: <https://dx.doi.org/10.29328/journal.ijcv.1001061>

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Keywords: Free-electron lasers; High-order harmonic generation; Ionization probability; Wavepacket; Attosecond



## Methodology

In this article, a hydrogen atom is chosen to delve into enhancing the efficiency of HHG induced by a two-color free electron laser. FREE-ELECTRON LASERS (FEL) can give rise to coherent light by accelerating a beam of relativistic electrons injected into an undulator magnet [7]. Similar to synchrotron radiation, FEL is a device that is capable of generating coherent radiation due to stimulated bremsstrahlung. Free-electron lasers have many advantages, including useful radiation with wavelengths ranging from 50 nm and 150 nm [8,9] and operating in an ultrafast pulse mode [10,11]. Therefore, FEL will be regarded as an important machine for applications in many subjects, including physics and chemistry [12-14].

## Results and discussion

We solve the time-dependent Schrödinger equation numerically to investigate the interaction between free electron laser and hydrogen atom. One-dimensional model is adopted because of its simplicity and high efficiency, as well as the convenience for treating problems in atomic physics. The one-dimensional time-dependent Schrödinger equation for the interaction between Free Electron Laser (FEL) and hydrogen atom can be expressed as:

$$i \frac{\partial}{\partial t} \Psi(x, t) = \left[ -\frac{1}{2} \frac{\partial^2}{\partial x^2} + V_a(x) + E(t)x \right] \Psi(x, t)$$

Where  $V_a(x)$  is atomic potential, which has the functional form  $V_a(x) = -\frac{1}{\sqrt{x^2 + 2}}$ .

$E(t)x$  is the interaction potential between electron and FEL.  $\Psi(x,t)$  Denotes the wave function of the investigated system at time  $t$ . For the purpose of calculating the HHG subjected to free-electron laser, the form of two-color FEL is set as  $E(t) = E_0 f(t) [\sin(\omega_0 t) + r \sin(n\omega_0 t)]$ , where one-color free electron laser corresponds to  $r = 0$  and two-color free electron laser has  $r = 0.2$ .  $\omega_0$  and  $n$  denote the fundamental frequency and frequency multiplication number, respectively.  $f(t)$  refers to pulse envelope [15]. The split-operator method [16] is adopted to execute the wavepacket propagation. Additionally, it is necessary to employ the absorption potential so that the time-dependent wave function can eschew boundary reflections [17].

The harmonic spectrum can be expressed as  $P(\omega) = |a(\omega)|^2$ , where  $a(\omega)$  is the Fourier transformation of the time-dependent acceleration  $a(t)$ , which is obtained from the time-dependent wavefunction  $\Psi(x,t)$ ,

$$a(t) = \left\langle \Psi(x,t) \left| -\frac{dV(x)}{dx} - E(t) \right| \Psi(x,t) \right\rangle$$

The ionization probability  $I(t)$  means the total electron population minus the population in certain bound states.

$$I(t) = 1 - \sum_{k=0}^n \left| \left\langle \phi_k(x) \left| \Psi(x,t) \right\rangle \right|^2$$

Although there are some experimental quests for better conversion efficiency of HHG [18-20], very little theoretical work has been performed regarding this topic. The emphasis of this work is to test whether the efficiency of HHG can be enhanced by two-color FEL with frequency multiplication. Figure 1 demonstrates the harmonic spectrum under the influence of one-color ( $r = 0$ ) and two-color ( $r = 0.2, n = 4$ ) free electron lasers. It is shown that the plateau region is enhanced by 10 to 100 times although the amplitude of frequency-multiplied FEL is only one-fifth ( $r = 0.2$ ), compared with that in one-color FEL. Additionally, even-order harmonics appear, which is attributed to the interference of two-color free electron lasers. These mean that the efficiency of HHG can be enhanced because the paths of electronic transition have increased with the addition of two-color FEL with frequency multiplication.

Figure 2 illustrates the ionization probability under the influence of one-color and two-color FELs. It can be seen that the Ionization Probability (IP) caused by two-color FEL is larger than the IP of one-color FEL, which means that the population of continuum states increases. There is more prominent ionization with the addition of frequency-multiple two-color FEL. Subsequently, the number of electrons that return to the ground state and combine with nuclei increases, compared with the number under the radiation of one-color

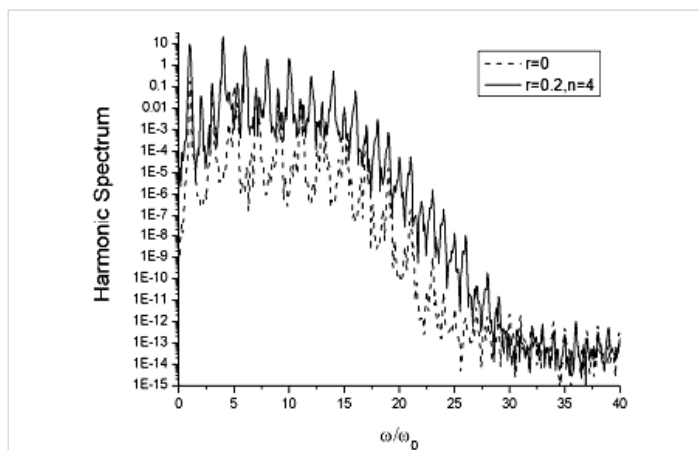


Figure 1: Harmonic spectrum induced by one-color ( $r = 0$ ) and two-color ( $r = 0.2, n = 4$ ) free electron lasers.

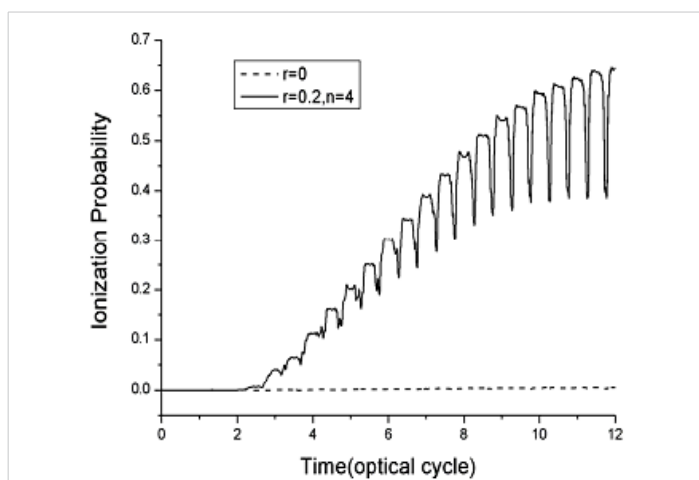


Figure 2: Ionization probability under the influence of one-color and two-color FEL.

FEL. As a result, the number of photons emitted is enlarged correspondingly. Therefore, the number of HHG photons increases dramatically, which has enhanced the efficiency of HHG greatly.

It is necessary to compare the numbers of harmonic, which can impact the efficiency of HHG more or less. Figure 3 exhibits the harmonic spectrum under the radiation of different two-color FELs. It is demonstrated that the efficiency of HHG is enhanced to the most extent with the addition of fourth-fold frequency two-color FEL. Figure 4 exhibits the ionization probability under the radiation of different two-color FELs. It is shown that the ionization probability under the radiation of fourth-fold frequency two-color FEL is much larger than those under the radiation of twice and sixth-fold frequency two-color FELs. Since the energy of the fourth-fold frequency is very adjacent to the ionization energy of the first excited state, which makes the ionization probability of the first excited state quite large after absorbing one photon from the fourth-fold frequency FEL, thus, the population of the first excited state is little with the addition of fourth-fold frequency two-color FEL. Concomitantly, the transition probabilities from the continuum state to the ground state and each excited state are increased, which can help enhance the efficiency of HHG.

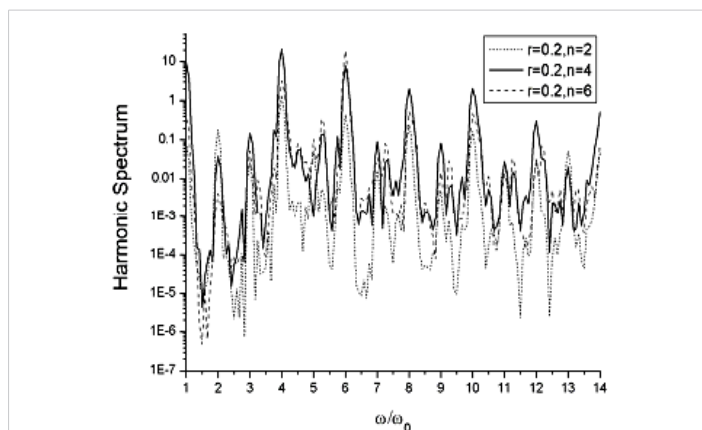


Figure 3: Harmonic spectrum under the radiation of different two-color FELs.

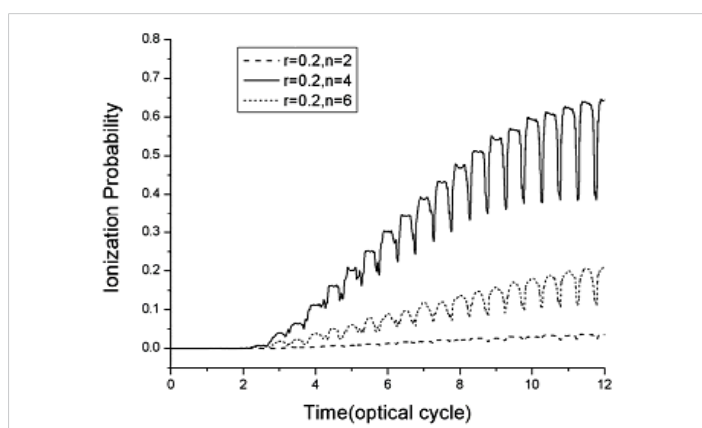


Figure 4: Ionization probability under the radiation of different two-color FELs.

## Conclusion

To summarize, the ionization probability is increased with the addition of a fourth-fold frequency two-color FEL. Meanwhile, the number of emitted HHG photons rises greatly, which thus enhances the efficiency of HHG. Therefore, we can conclude that the application of two-color FEL with proper frequency multiplication is an effective method of increasing the efficiency of HHG. It should be mentioned that there are some other factors, which can have some impact on improving the efficiency of HHG. For instance, the phase of the frequency-multiple FEL can influence the efficiency of HHG, which deserves further study in the future. Overall, it is expected that more feasible methods will be found to enhance the efficiency of HHG, which can make HHG serve as a benefit for humankind.

## Acknowledgment

Support of this work by the National Natural Science Foundation of China is gratefully acknowledged.

## Data statement

Original data are available from the corresponding author upon request.

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