Carrier-Envelope-Phase-Controlled Acceleration of Multicolored Attosecond Electron Bunches in a Millijoule-Laser-Driven Wakefield

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Electron bunches with tens of MeV energy and attosecond pulse duration are powerful tools to explore matter structures and the related ultrafast dynamics[1]. It is still a great challenge to obtain such electron bunches with traditional radio-frequency (RF) accelerators due to the longitudinal beam expansion when the acceleration gradient is relatively low. Although many compression schemes have been proposed and femtosecond electron beams have been successfully demonstrated[2], attosecond electron beams have not yet been reported.

In recent years, due to its tremendous acceleration gradient, laser wakefield acceleration (LWFA) has attracted worldwide attention and has been developed very rapidly. LWFA shows a great potential for the next generation of compact radiation sources. The wide applications of such LWFA electrons are currently being developed. However, one of the obstacles for these applications is the average flux, which is limited by the repetition rates of drive laser pulses. Currently, LWFA is mainly driven by Joule-class Ti:sapphire laser systems, which operates with a repetition rate of a few hertz. They are appropriate for radiation sources with high peak brightness requirement and future collider applications requiring high electron energy. To increase the average flux, high repetition rates such as kilohertz (kHz) and above should be used, which are still difficult for Joule-class and tens-of-terawatt (TW) laser systems.

In recent years, along with the fast development of high repetition-rate, few-cycle laser systems and ultra-short gas nozzles, there is an increasing interest in LWFA driven by few-millijoule and TW-level kHz lasers. In this regime, many unique characteristics appear. On the one hand, the few-cycle laser has a large bandwidth, leading to strong group velocity dispersion. On the other hand, the pondermotive force is not the only dominant effect for wake generation and the carrier-envelope phase (CEP) becomes particularly important. These characteristics change the structure of the wake. Both the electron injection and acceleration processes are different. Meanwhile, high-quality attosecond electron beams with multiple energy peaks provide a way to generate multicolor attosecond x-rays, which may have similar applications with multicolor x-ray sources based on free electron lasers, such as time-resolved multidimensional x-ray spectroscopy[3]. Although the multi-energy femtosecond electron beam has already been demonstrated by optically assisted shock-front injection [4], to obtain multicolor electron bunches with attosecond duration and even low-energy spread remains a challenge.

In this paper, we propose a scheme to generate multicolor attosecond electron bunches by a mJ-level few-cycle laser-driven wakefield, as shown in FIG.1[5]. Due to the laser pulse dispersion in plasma and the Gouy phase shift, it is shown that the CEP of the drive pulse shifts rapidly, which periodically varies the maximum electric field of the laser pulse, leading to transient electron ionization injection in the wakefield. Finally, attosecond electron bunches with multicolor peaks in spectrum and central energy about tens of MeV can be generated. Such laser systems with kHz or higher repletion rates are available right now in laboratories.

References

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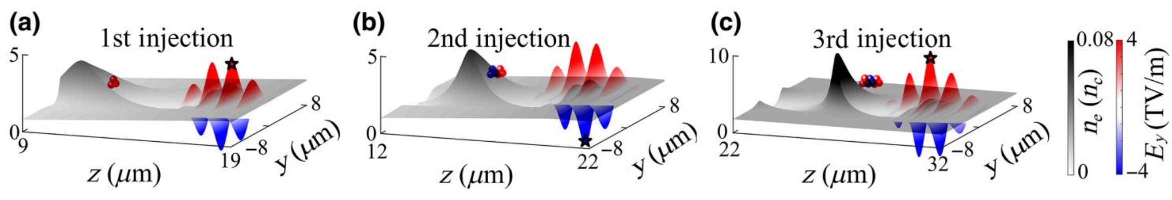

FIG. 1. Schematic view of the periodically shifted CEP-controlled ionization injection and electron acceleration. Electrons ionized at the positions (labeled by the black stars) where the laser fields exceed the ionization threshold of the inner shell electrons of the high-Z gas can be periodically injected into the wake (labeled by the gray background). Electrons injected during different CEP shift periods are alternatively marked by the red and blue points.