Particle-in-cell simulations of high-density electron bunch formation during relativistic laser plasma interactions

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The reflection of relativistic, few-cycle laser pulses from solid targets offers a route toward the generation of intense high-order harmonics of the laser fundamental with photon energies reaching the extreme ultraviolet and soft x-ray regime [1-6]. This radiation is coherent and contains a broad bandwidth such that, upon filtering out the lower harmonics, it manifests itself as a train of attosecond pulses in the time domain. This technique offers a distinct advantage over attosecond pulse generation from gaseous media. High harmonic generation (HHG) from gas targets has matured to the point where sub-hundred-attosecond pulses can be generated routinely [7, 8]. However, the resulting attosecond pulse intensities have suffered from low conversion efficiencies and are ultimately limited by the ionization threshold of the target. Therefore, HHG from gas targets cannot take advantage of new and near-future high-power laser systems. On the other hand, since a plasma is already ionized and can support many orders of magnitude higher electric field strengths than gas targets, solid targets are well suited for new petawatt-class laser systems.

Current table-top laser systems can output few-cycle pulses with enough energy that when probably focused can reach laser intensities exceeding the relativistic threshold ($I > 2.14*10^{18}$ W/cm^2 for an 800nm driving wavelength) [9, 10]. This intensity is strong enough that the solid target is rapidly ionized and an overdense, highly reflective plasma is created. It has been uncovered using one-dimensional particle-in-cell (PIC) simulations that during this interaction electrons at the plasma surface are coherently bunched together and subsequently accelerated in the specular direction. During this acceleration the electrons undergo synchrotron-like trajectories and emit intense bursts of radiation [11-13]. A comparison of the electron dynamics observed from self-consistent PIC simulations to that of a single charged particle in vacuum yields similar electron dynamics [11, 14]. Under certain laser-plasma conditions, the dense electron bunches formed are seen to reach many thousands of critical densities in a spatial width of just a few nanometers. The dynamical control of these electron bunches is important for achieving the highest conversion efficiencies of the interaction. For the most intense attosecond pulses, one would like this bunch of electrons to contain a large number of particles travelling at high longitudinal velocities and transverse accelerations with little spatial spread.

Particle-in-cell (PIC) simulations have been the workhorse for modeling and predicting the behavior of laser-plasma interactions in this relativistic regime [15, 16]. Like most theoretical and computational works in plasma physics, PIC simulations rely on several assumptions and approximations to the governing equations. Previous work has indicated the effects of numerical resolution (grid spacing) on the properties of the electron bunch formation [17]. Most previous computational and theoretical works have been performed in a 1D geometry that is valid in the regime where the spot size of the beam is much larger than its wavelength. This assumption fails for the tightly focused laser beams presently used to achieve relativistic intensities. Furthermore, as opposed to the physically correct 3D space charge force between particles which varies proportional to the inverse square of the separation distance, in a reduced geometry the force between charges is constant (1D) or varies inversely with distance (2D). Thus, the demand for higher dimensional PIC simulations is needed to account for the intense transverse laser forces and variation of the space charge force that are not considered in a reduced 1D geometry. In this work, 2D simulations will be performed using the fully relativistic EPOCH particle-in-cell code [16]. Initial results show that a tightly focused beam will enhance HHG conversion efficiency and approach the 1D results in the high spot size limit [18]. In addition to this work, by adjusting the driving laser characteristics and the target material and geometry, a study of the ability to enhance the properties of the electron bunches will be performed with the intent to produce stable radiation with the best possible conversion efficiency to the highest photon energies.

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