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**Generation of Superponderomotive Electrons in Multipicosecond Interactions of Kilojoule Laser Beams with Solid-Density Plasmas**

A. Sorokovikova, A. V. Arefiev, C. McGuffey, B. Qiao, A. P. L. Robinson, M. S. Wei, H. S. McLean, and F. N. Beg


Generation of superponderomotive electrons in multi-picosecond interactions of kilo-Joule laser beams with solid-density plasmas

A. Sorokovikova,1 A. V. Arefiev,2 C. McGuffey,1,* B. Qiao,1 A. P. L. Robinson,1 M. S. Wei,4 H. S. McLean,4 and F. N. Beg1,†

1 Center for Energy Research, University of California, San Diego, California 92093, USA
2Institute for Fusion Studies, The University of Texas, Austin, Texas, 78712, USA
3Central Laser Facility, STFC Rutherford-Appleton Laboratory, Didcot, OX11 0QX, UK
4General Atomics, San Diego, California, 92186, USA
5Lawrence Livermore National Laboratory, Livermore, California, 94551, USA

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Interaction of a multi-picosecond (ps), kilo-Joule laser pulse with a surface of a solid target has been shown to produce electrons with energies far beyond the free-electron ponderomotive limit, $me^2a_0^2/2$. Particle-in-cell simulations indicate that increase in the pulse duration from 1 to 10 ps leads to formation of a low-density shelf (about 10% of the critical density). The shelf extends over 100 μm toward the vacuum side, with a non-stationary potential barrier forming in that area. Electrons reflected from the barrier gain super-ponderomotive energy from the potential. Some electrons experience even greater energy gain due to ponderomotive acceleration when their “dephasing rate”, $R = γ - p/m_e$, drops well below unity, thus increasing acceleration by a factor 1/$R$. Both 1D and 2D simulations indicate that these mechanisms are responsible for generation of extensive thermal distributions with $T_e > 10$ MeV and a high-energy cutoff of hundreds of MeVs.

Laser-plasma interaction (LPI) at relativistic intensities ($> 10^{18}$W/cm$^2$) offers an efficient source of fast electrons with energy above 10’s of MeV, which is of fundamental interest for a range of applications including accelerator science [1], laboratory astrophysics, and inertial fusion energy [2]. Relativistic LPIs in low-density plasmas have a notable ability to produce high-energy electrons through several known mechanisms such as wake-field [3-5] and direct laser acceleration [6].

However, solid target interaction with such a laser is complex, spanning several orders of magnitude difference in the characteristic temporal and spatial scales between solids and low-density preplasma [7-9]. On sub-picosecond timescales, if the preplasma scale length is steep (or zero), fast electrons are produced predominantly by relativistic $j \times B$ heating [10], resulting in a Boltzmann-like energy distribution [11-13] with a slope temperature close to the ponderomotive scaling $T_e = [(1 + a_0^2)/4 - 1]mc^2$ [14] and maximum energy near the free electron ponderomotive limit $E_p = me^2a_0^2/2$. When a long-scale preplasma [15-17] is created by intrinsic laser prepsulses, electrons of energy $> E_p$ can be produced due to stochastic acceleration [18, 19]. However, so far, most studies have focused only on subpicosecond laser cases.

High-intensity petawatt laser facilities that deliver multi-picosecond (ps) kilojoule (kJ) laser pulses have become available, such as OMEGA-EP [20], LFEX [21], PHELIX [22], PETAL [23], and NIF-ARC will become available soon [24]. In this new multi-ps kJ regime, the nature of preplasma [15-17] is created by intrinsic laser prepulses, which represent different numbers of real particles. All four sides of the domain allow us to correctly resolve the dynamics of accelerated electrons [29].

Considerable preplasma is expected to build up even for a high contrast laser due to the thermal expansion of electrons, and on multi-ps timescales the ions also move collectively. Recent particle-in-cell (PIC) simulations [25] demonstrated 5ps evolution of solid target interaction with lasers, but their scope is limited to a steep preplasma density gradient and a low-Z deuterium plasma. The underlying physics of multi-ps, kJ LPIs are unexplored.

In this Letter, we report theoretical and numerical studies on plasma dynamics and fast electron generation inherent to multi-ps LPIs, yet previously unexplored. Our one- and two-dimensional (1D, 2D) PIC simulations reveal that electrons with energy far exceeding the free electron ponderomotive limit are produced, and temperature and maximum energy of these superhigh energy electrons significantly increase as laser pulse duration increases from 1 to 10ps. We find that on multi-ps timescales the electron density distribution self-evolves into a step-like profile jumping from critical density $n_c = n_0$ [26, 27]. Since the duration and volume in which the antidephasing occurs increase with pulse duration, the number and energy of super-ponderomotive electrons increase. We show that the antidephasing acceleration occurs even when multi-dimensional effects are included.

1D simulations have been carried out using the PIC code, EPOCH [28]. We choose a simulation domain spanning [-600, 200] μm in x with 64000 cells. The corresponding time-step allows us to correctly resolve the dynamics of the accelerated electrons [29]. All four sides of the domain have an open boundary condition which allow particles and fields to leave the domain freely. 1000 electrons and 100 A$^/$ions per cell are loaded for a solid (2.7g/cm$^3$) aluminum target, which represent different numbers of real particles. The initial electron density is $n(x) = Zn_{atom}[(1 + \exp(-x-x_0/L)]]$, shown in Fig. 1(a), where $L = 10\mu$m, $Z = 13$ and $x_0 = 150\mu$m. The preplasma extends to $x = 0$, reaching $2.4 \times 10^5$cm$^{-3}$. The space $x < 0$ is vacuum, allowing room for thermal expansion of plasma electrons throughout multi-ps. Initial electron and ion temperatures are both chosen to be 100eV. A 1μm wavelength laser with peak intensity $10^{20}$W/cm$^2$ ($a_0 = 8.54$) is injected at $x = -600\mu$m, and reaches the plasma at $x = 0$ at $t \equiv t_0$ which is 2.0ps for all 1D simulations here. The laser field $E_l$ has temporal profile sin($\pi t/t_0$), where $t$ is the laser pulse duration.
The electron is initially at rest, we get a key integral of electron motion in the transverse and longitudinal directions respectively as
\[ dp_x/dt = -eE_x v_x - e(E_x v_y + E_y v_x)/mc, \]

\[ dp_z/dt = -eE_z v_z - e(E_z v_x + E_x v_z)/mc. \]

The potential energy of the electron,\( E_p = mc^2\alpha_0^2/2 \), can directly accelerate electrons. Note that the left-most side of the potential barrier in Fig. 1 is much wider and deeper than the right. So electrons dominates on the vacuum side, the left half of the potential profile develops. The effect of the induced electrostatic potential barrier is not only directly awarding additional energy \( E_p \) to electrons, but also linked with the laser ponderomotive acceleration through the dephasing rate \( R \).

Eqs. (1) and (2) together describe the dynamics of super-high energy electron production in the near-critical shelf region during multi-ps LPI, where a deep electrostatic potential profile develops. The effect of the induced electrostatic potential barrier is not only directly awarding additional energy \( E_p \) to electrons, but also linked with the laser ponderomotive acceleration through the dephasing rate \( R \).

As seen in Fig. 1(c), because the plasma expansion dominates on the vacuum side, the left half of the potential barrier is much wider and deeper than the right. So electrons always experience longer and larger antidephasing than dephasing. From the viewpoint of a non-stationary Hamiltonian theory [31-34], antidephasing (resulting in a high-energy electron acceleration) may be interpreted as a reduction of the “moving-frame” Hamiltonian, \( H(\tau, x) = m_c c^2 \gamma_e - cp_x - e\phi \), where \( \gamma = (1 + p^2/m_e^2c^2)^{1/2} \).

Note that the profile of the potential evolves during the multi-ps LPI. A broader, deeper left wall and a sharper right wall potential should produce more superhigh energy electrons, because it creates a large volume for antidephasing. Note that the left-most side of the potential barrier in Fig. 1 can directly accelerate electrons.
Figure 2 displays information from recorded trajectories of individual particles. Fig. 2(a) shows the time histories of work done by electric field components on two particles exemplifying superhigh acceleration ('H', top) and \( \mathbf{j} \times \mathbf{B} \) heating ('L', bottom). Their dephasing rate and momentum time histories are shown in Figs. 2(b) and 2(c), respectively. Both electrons experienced large antidephasing (\( R \) decreases to \( \ll 1 \)) from the left of the potential barrier, which began forming by \( t - t_0 \approx 0.6 \) ps [Fig. 1(c)]. However, particle H first moved toward the vacuum side then experienced rapid acceleration and antidephasing throughout its transit from \( x=10 \) μm until it reached maximum energy at \( x=70 \) μm. As a result, it achieved final \( p_x/m_c \) of 180, 4.5 times greater than particle L and 3.5 times the free-electron ponderomotive limit. Particle L was accelerated with minimal work done by the electrostatic potential, and antidephasing coincided with acceleration only briefly between \( x=35-55 \) μm, resulting in much lower final \( p_x/m_c \) of 40.

Fig. 2(d) displays the work done by the different field components averaged over all test particles binned by their final energy. The lowest energy particles gain energy predominantly by the perpendicular (laser) field, and intermediate energies (10<E<80 MeV) gain nearly the same quantity (10-20 MeV) from the laser field. The highest energy electrons (>80 MeV) gain significant energy from the longitudinal field (electrostatic potential) and notably experience work greatly exceeding the free-electron ponderomotive limit by the laser field. Figure 2(e) plots the average original positions and left-most extents of eventual fast electrons. The electrons reaching low and modest energies originate from the steep critical surface, and energy correlates with long travel into the shelf region. The superhighenergy ones (E>80 MeV) come from shelf region far from the critical surface. From Fig. 2(f) - the final dephasing rate \( R \) of fast electrons binned by their final energy - we can also see that superhigh energy electrons do come from the antidephasing mechanism with final \( R \ll 1 \).

The evolution of the electrostatic potential profile plays a key role in the antidephasing mechanism. Therefore, electron acceleration in multi-ps LPIs heavily depends on the laser pulse durations \( \tau \). Figures 3(a)-3(d) plot electron density profiles late in the interactions for \( \tau = 1, 3, 5 \) and 10ps respectively. The longer pulse durations significantly enhance both the density steepening and the extension of the long shelf profile. Correspondingly, a much wider and deeper potential barrier is self-formed for longer \( \tau \) [Fig. 3(f)], leading to longer and greater antidephasing electron acceleration. The temperature and maximum energy of electrons are increased by extension of the laser pulse, see Fig. 3(e). On the other hand, the low-energy spectrum shapes are similar, due to the fixed intensity.

To check if the antidephasing mechanism is extant in a multi-dimensional case, 2D simulations were conducted in a system domain spanning \( x = [-170, 130] \)μm in the longitu-
dinal direction (18000 cells) resulting in $t_0 = 567 fs$ and $y = [-30, 30] \mu m$ in the transverse direction (1200 cells). The density profiles were the same as those in the 1D simulations with 20 electrons and 5 ions per cell. The laser had transverse Gaussian profile with 10.6 μm FWHM and durations $r = 1$ and 5ps. Figures 4(a) and 4(b) plot electron density distributions and their longitudinal profiles [4(c)] for both durations. The intense laser propagates deeply into the plasma, reaching the relativistic critical density of $10^{22} cm^{-3}$, and a quasistatic lower-density ($10^{20} - 10^{21} cm^{-3}$) channel is created near the x-axis. Inside the channel, the radial charge separation electric field balances the radial expelling ponderomotive force, allowing fast electrons to be accelerated longitudinally via dynamics similar to the 1D cases. Both the critical density steepening and the self-formation of the near-critical shelf can still be observed inside the channel [4(c)], inducing a broad electrostatic potential profile [4(d)]. The previously discussed acceleration mechanisms still occur in 2D geometry.

Figure 4(e) shows the time-integrated electron energy spectra in 2D simulations. The results are consistent with the 1D results: a large number of super-high energy electrons are produced and their temperature and maximum energy increase for longer pulse duration. The difference between 1D and 2D results at the highest energies can be attributed to weaker potential barrier [compare Fig. 4(d) to 3(f)] due to an additional degree of freedom allowed for plasma expansion, and the strong potential is restricted to the axis, affecting fewer particles.

In summary, we have studied intense LPI and fast electron generation in the multi-ps kJ scale regime. It is found that a substantial number of superponderomotive electrons are produced and their temperature and maximum energy significantly increase with the laser pulse duration (1-10ps). The electrostatic potential barrier, which builds up on the subcritical side throughout the multi-ps interaction, increases electron energy through electrostatic acceleration and enhances the ponderomotive acceleration via the anti-dephasing mechanism. Both effects contribute to generation of numerous super-ponderomotive electrons with temperature >10 MeV, and energy cutoff of hundreds of MeVs.

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* Corresponding author: emmcguffey@ucsd.edu
  * fbeg@ucsd.edu