Underdense Relativistically Thermal Plasma Produced by Magnetically Assisted Direct Laser Acceleration

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The discovery of special relativity in 1905 transformed the fields of electromagnetism and charged-particle kinetics that, some 20 years later, would coalesce into the field of plasma physics. Predictions have continually emphasized the importance of special relativity in plasmas where the majority of electrons are relativistic regardless of reference frame, but, even today, experimental verifications of these predictions remain relatively rare. The laboratory generation of these relativistically thermal plasmas is needed to address open questions in astrophysics regarding shock acceleration and the origin of cosmic rays,[1] fast radio bursts,[2,3] and γ-ray bursts.[4] Relativistically thermal plasmas also feature a substantially modified response to electromagnetic radiation relative to the nonrelativistic or nonthermal cases, which is of significant interest in basic plasma physics,[5] laboratory astrophysics,[6,7] and laser-plasma physics.[8–11]

It is challenging, however, to produce relativistically thermal plasma in the laboratory with sufficient volume and duration for subsequent probing. Pulsed-power and microwave sources, while capable of igniting thermal plasma over large volumes, are incapable of reaching relativistic electron temperatures. Laser pulses with relativistic intensity ($I_0 \gtrsim 10^{18}$ W/cm^2 for λ_0 = 1-μm wavelength) are capable of imparting substantial energy to electrons, but they are conventionally unable to create persistent, large-volume plasma where the majority of electrons are relativistic. Configurations involving opaque plasma ($n_\mathrm{e} > n_\mathrm{c}$, where $n_\mathrm{c} \approx 10^{21}$ cm^{-3} is the critical density for $\lambda_0 = 1$ μm),[12,13] near-critical density plasma,[14] or acceleration by the plasma (wakefield) electric field[15,16] typically leave the majority of electrons cold in either momentum or configuration space. In the underdense regime ($n_\mathrm{e} < n_\mathrm{c}$), laser pulses can volumetrically accelerate electrons to high energy,[17,18] but the plasma does not remain hot after the laser pulse passes due to the reversibility of the acceleration process. This reversibility is disrupted, however, by the addition of a uniform static magnetic field, enabling dramatic plasma heating.

We propose the first method to volumetrically generate relativistically thermal, underdense plasma. Our approach leverages two regimes of magnetically assisted direct laser acceleration, as illustrated in Figs. 1(a)–1(c). First, a +x-propagating, y-polarized relativistic short (20-fs) laser pulse interacts with electrons in an underdense (10^{-3} n_c) plasma with an embedded transverse magnetic field $B_0\hat{z}$ = 500 T, imparting net energy as electrons slip through the full pulse duration [Fig. 1(b)]. Second, a longer (0.8-ps) laser pulse with the same propagation and polarization directions interacts with these preheated electrons, delivering half-laser-cycle energy kicks that promote the electron to higher-energy cyclotron orbits [Fig. 1(c)]. The short (subscript "s") and long (subscript "ℓ") laser pulses have peak normalized electric-field amplitude ($a_0 = \left|e\right|E_0 / mc\omega_0$, where ω_0 is the laser frequency) of a_s = 5 and a_ℓ = 1. Simulations were conducted in 2-D using the particle-in-cell code *EPOCH*.[19]

The interaction of the two laser pulses with the target creates multi-MeV average electron energy over a large volume (e.g., $r < w/2 = 25$ μm, where w is the HWHM laser spot size), which persists for picoseconds following the interaction [Fig. 1(d)]. The corresponding momentum spectrum is 2-D isotropic (in p_x and p_y) with a flat energy spectrum. While the plasma can be heated somewhat by the short laser pulse and magnetic field alone, significant relativistic heating requires all three elements of

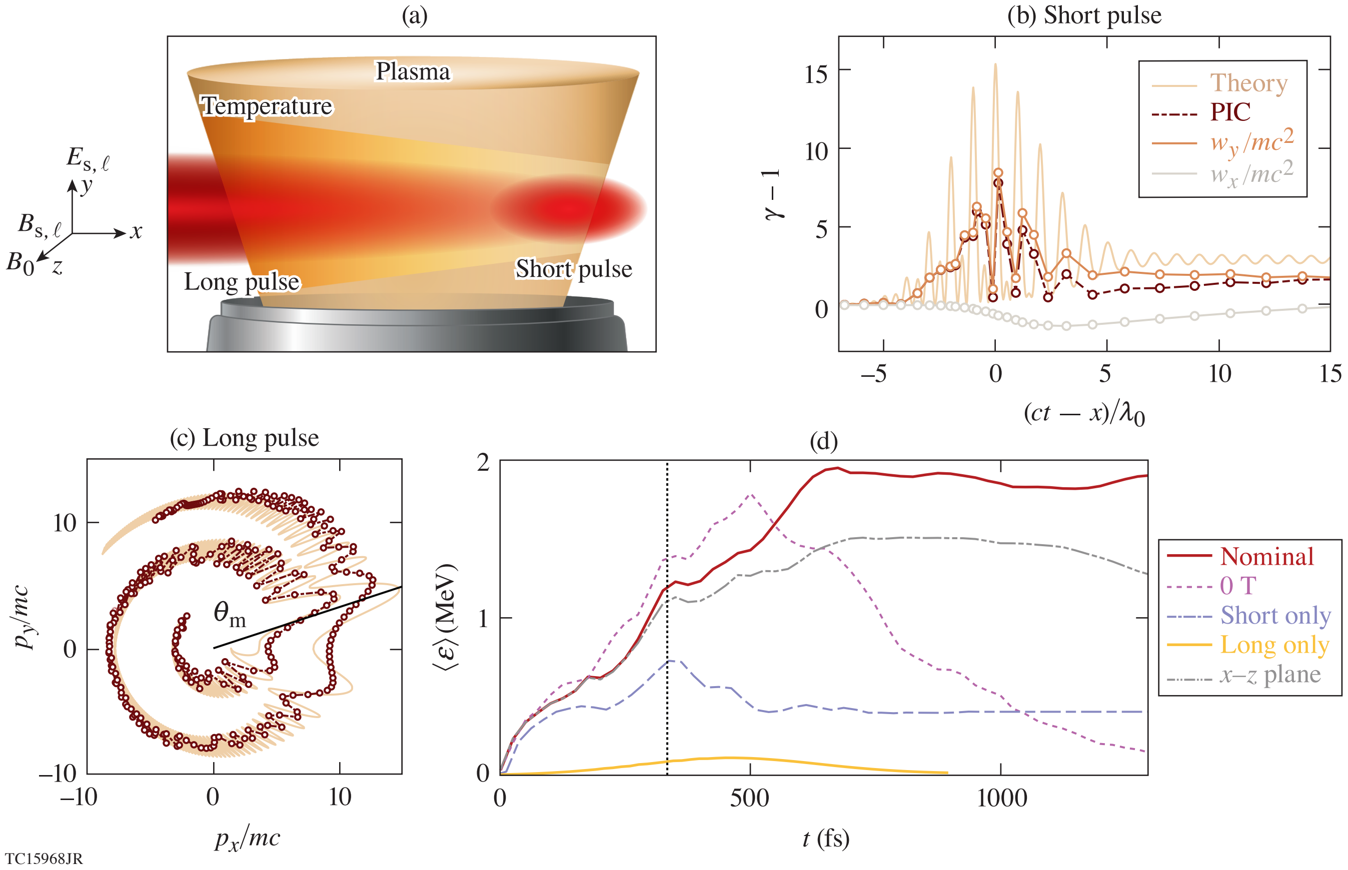

Figure 1
Generation of relativistic underdense plasma via magnetically assisted direct laser acceleration. (a) Illustration of laser and magnetic-field configuration. [(b),(c)] Example of the energy-gain process for a representative electron interacting with (b) the short pulse, and (c) the long pulse. w_y (w_x) is the work done by the transverse (longitudinal) electric field. (d) Average energy of all electrons in $r < 25$ μm. Vertical black dotted line: the time the peak of the short pulse leaves the plasma slab. The long-pulse intensity has dropped to a_ℓ/e at the right edge of the slab at the final time shown. The nominal case corresponds to both laser pulses and $B_{z0} = 500$ T, simulated in the x–y plane.

the short laser pulse, long laser pulse, and applied magnetic field [c.f., cases in Fig. 1(d)]. Unlike conventional laser-based heating methods, more than half of the electron population is heated to $\gamma \geqslant 2$, i.e., the plasma is relativistically thermal.

These observations are explainable as volumetric heating by magnetically assisted direct laser acceleration in the two distinct regimes covered by the short pulse and the long pulse. The energy retained following electron interaction with the short laser pulse through multicycle magnetically assisted direct laser acceleration[20] is used to catalyze subsequent heating by a long (picosecond) laser pulse via half-cycle magnetically assisted direct laser acceleration.[21] The latter process is capable of imparting higher net energy than the former; however it requires preheating of electrons, which in our case is provided by the short pulse.

The generation of relativistically thermal plasma is robust to increased electron density (up to 10^{-2} n_c), finite laser spot size in the magnetic-field direction, and lower applied magnetic-field strength (e.g., 200 T). The average electron energy can additionally be increased by increasing the plasma size and the laser pulse duration, as shown in Fig. 2.

Our results demonstrate that the generation of underdense, relativisitically thermal plasma can be realized with currently available laser and magnetic-field–generation capabilities. With a 200-T magnetic field, we anticipate multi-MeV average electron energy under gas-jet–relevant conditions ($n_e \sim 10^{18}$ cm^{-3}, few-millimeter plasma size) using kilojoule-class laser pulses with a

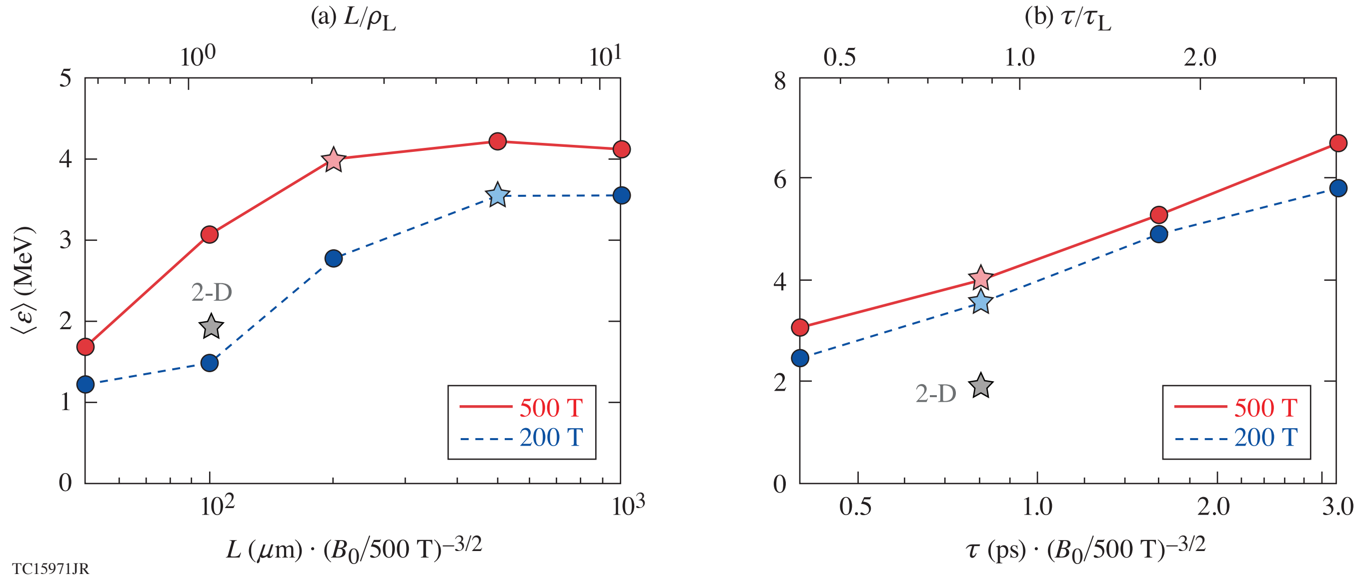

Figure 2
Strategies for improving average electron energy in 1-D particle-in-cell simulations. (a) Scan over plasma size near $L/\rho_L \sim 1$ with fixed duration. (b) Scan over long-pulse duration near $\tau_\ell/\tau_L \sim 1$ with fixed plasma size. ρ_L and τ_L are the Larmor radius and cyclotron period associated with the maximum energy that can be delivered in a half-cycle energy kick $\Delta\gamma \sim 2^{3/2} a^{3/2}_\ell (\omega_0/\omega_{c0})^{1/2}$. The starred points are shared between (a) and (b). The peak of the short pulse is kept coincident with a_ℓ/e on the rising edge of the long pulse. $\tau_s = 50$ fs for the 200-T cases.

few-hundred-micron spot size and 50-fs/multipicosecond duration. Our approach is thereby anticipated to offer the first practical access to the relativistically thermal plasma regime, enabling experimental verification of longstanding, foundational predictions in basic plasma physics, laboratory astrophysics, and laser-plasma physics.

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