

Optical Imaging of Laser-Driven Fast Electron Weibel-like Filamentation in Overcritical Density Plasma

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We report on the measurement of filamented transport of laser-generated fast electron beams in near-critical density plasma. A relativistic intensity long-wave-infrared laser irradiated a hydrodynamically shaped helium gas flow at an electron density $n_e \simeq 10^{25} \text{ m}^{-3}$, generating a large flux of fast electrons that propagated beyond the critical surface. The beam-to-background electron density ratio was sufficiently high to drive growth of Weibel-like filamentation, which was measured by optical probing to extend up to 800 μm with radii $\sim 10 \mu\text{m}$. Particle-in-cell simulations reproduce the main features of the filamentation generation, suggesting that collisionless processes are dominant in these interactions. Expansion of the filaments after formation infers a fast electron heated plasma temperature $\sim 400 \text{ eV}$ in the overcritical density plasma.

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High-intensity laser-plasma interactions with opaque targets can accelerate large numbers of electrons. These “fast” electron beams are generated by a number of mechanisms depending on the plasma density profile [1,2] and normalized vector potential a_0 [3,4]. The energetic electron current can exceed the Alfvén limit [5] by orders of magnitude, necessitating a balancing return current [6]. The resultant beam-plasma system is subject to collisionless instabilities which develop over all k space, including the transverse Weibel-like current-filamentation instability [7–9]. In this instability, magnetic field perturbations grow perpendicular to the flow, breaking up the electron beam into filamentary structures. This instability is thought to be an important mechanism in generating seed magnetic fields for the galactic dynamo [10] and a source of fields in relativistic collisionless astrophysical shocks such as gamma-ray bursts [11–13].

There is concerted activity in developing laboratory schemes investigating these processes [14–16]. The instability has been observed in the laboratory in nonrelativistic

colliding flows [17–19] and by exploiting natural anisotropies following optical field ionisation [20]. It is important for fast ignition of inertial confinement fusion [9,21], where it increases the angular distribution of the laser-generated electron beam and contributes to collisionless stopping. It leads to large-scale filamentation in low-density blowoff plasma in intense laser-solid interactions [22,23] and can impact laser ion sources, deteriorating the spatial uniformity of the accelerated beams [24–26]. Highly relativistic particle beams propagating in plasma can also filament for sufficiently large beam size and propagation length [27,28].

For low beam-to-background density ratio $\alpha \equiv n_b/n_e \ll 1$, the current filamentation instability has a cold growth rate $\delta = \beta_b [\alpha/\gamma_b]^{1/2} \omega_p$ [8,29], where ω_p is the plasma frequency and γ_b and β_b are the relativistic factors of the beam. The instability is particularly important near the critical density of the laser-plasma interaction (LPI) ($n_e \gtrsim n_{cr} \equiv \epsilon_0 m_e \omega_0^2 / e^2$), where laser energy is converted into a dense relativistic electron beam, leading to a high growth rate. The growth rate and spatial scale, though, are strongly affected by time-varying beam distribution functions, interplay with parallel and oblique modes, and ion motion [8,9,30,31], motivating further studies.

It is extremely challenging to directly observe Weibel-like instabilities of electron beams propagating into overcritical density plasma when driven by near-infrared lasers. This is due to the small transverse filament size, typically $r_f \lesssim 2\pi c/\omega_p \ll 1 \mu\text{m}$ [15,32], at a high plasma density

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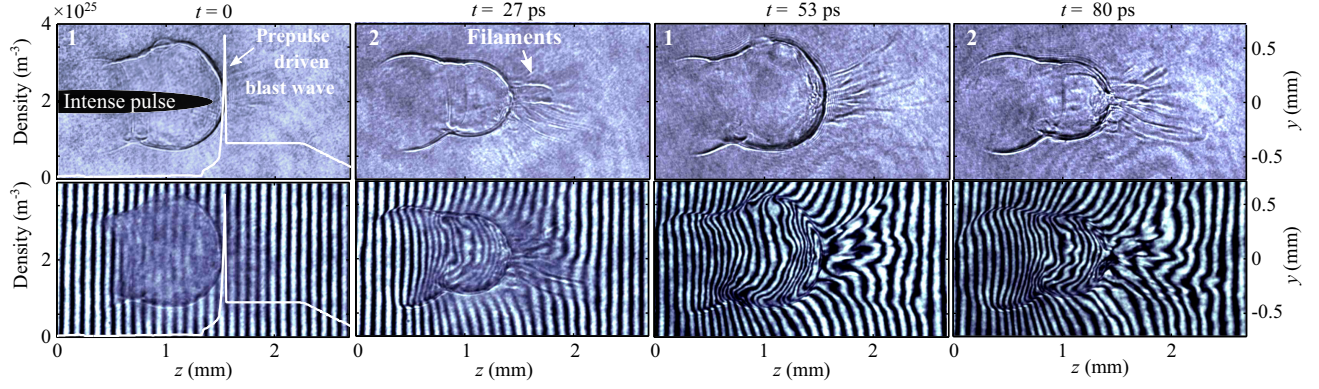


FIG. 1. Evolution of filaments observed by shadowgraphy (top) and interferometry (bottom) for $n_i = 1.1n_{cr}$ at four different times ($t = 0$ is when probe and drive pulse overlap) from two different shots, 1 and 2, with $E_L = 8.3$ and 9.0 J. The images at $t = 0$ show the estimated axial density profile overlaid (white line).

$n_e > n_{cr} \approx 10^{27} \text{ m}^{-3}$. The presence of the Weibel instability has been inferred from filamented particle beam profiles from solid targets with long plasma blowoff regions [24,25,33], optical transition radiation [34,35], and particle probing [22,23,36]. The filamentation of electrons generated from a laser-solid interaction passing into a low-density ambient gas has been observed [37]. But all of these studies were done far from the region where the fast electrons are generated without fine control or measurement of the background density, highlighting the difficulty of quantitative studies.

In this Letter, we present a first parametric study of Weibel-like filamentation of laser-heated electron beams. The electrons were generated in the interaction of an intense long-wave infrared ($\lambda_L = 10.3 \text{ }\mu\text{m}$) laser with a near-critical density helium plasma. For this wavelength, $n_{cr} \approx 10^{25} \text{ m}^{-3}$. By using an optical probe pulse ($\lambda_p = 532 \text{ nm}$), for which these densities are strongly underdense, it was possible to directly probe the density variations due to the filamentation which are on the scale $\approx \lambda_L$. We observe filaments of radius $\sim 10 \text{ }\mu\text{m}$ penetrating up to $800 \text{ }\mu\text{m}$ into the plasma. The radius and propagation distance were observed to decrease with increasing target density. The filaments expand radially after the end of the LPI, implying that the background plasma has been strongly heated by beam electrons. Numerical simulations elucidate the role of the current filamentation instability in filament formation, heating, and evolution.

The experiment was performed using the CO_2 laser at the Accelerator Test Facility, Brookhaven National Laboratory. The $\tau \approx 5 \text{ ps}$, $E_L = 7.5 \pm 1.0 \text{ J}$ linearly polarized laser beam was focused to a spot $w_0 \approx 65 \text{ }\mu\text{m}$ ($1/e^2$) 1 mm above a 2 mm exit diameter supersonic helium gas jet, providing a focal intensity $I_L \approx 2 \times 10^{20} \text{ W m}^{-2}$. This gives a normalized vector potential $a_0 = (I_L \lambda_L^2 / 1.37 \times 10^{22} \text{ W m}^{-2} \mu\text{m}^2)^{1/2} \approx 1.3$. The gas jet profile is well approximated to a $850 \text{ }\mu\text{m}$ flat density region with $1200 \text{ }\mu\text{m}$ linear ramps at the jet edge with variable

maximum atomic density n_i , characterized by *in situ* interferometry. A prepulse with $E_{pp} \approx 200 \text{ mJ}$, $\tau_{pp} \approx 5 \text{ ps}$ was introduced 25 ns before the drive pulse, driving a blast wave and shaping the gas prior to the high-intensity LPI [38,39]. This provided a shortened density ramp $\approx 200 \text{ }\mu\text{m}$ from 0 to a peak fully ionized electron density of $2\text{--}15n_{cr}$, controlled by varying the gas pressure. The interaction was diagnosed using a transverse optical probe ($\lambda_p = 532 \text{ nm}$, $\tau_p \approx 10 \text{ ps}$) at two times for each shot.

Figure 1 presents probe images showing the evolution of filamentary structures formed after the interaction of the intense pulse with He gas of maximum unshocked atomic density $n_i = 1.1n_{cr}$ from two shots labeled 1 and 2. The shadowgraphy allows visualization of the number and size of the filaments, while interferometry provides line-integrated density measurements. The prepulse and drive laser enter from the left. At $t = 0$, the prepulse-induced blast wave cavity is clearly visible. The axial density profile of this cavity predicted by hydrodynamic simulation is overlaid [39]. As the intense pulse arrives, it ionizes the blast wave. The resulting rapid change in density occurs over a timescale shorter than the probe pulse length, resulting in blurring of the interferogram fringes.

The peak atomic density in the blast wave is given by the strong shock limit $n_{ip} = (\gamma + 1)n_i / (\gamma - 1) = 4n_i$, where $\gamma = \frac{5}{3}$ is the adiabatic index [40]. For $n_i = 1.1n_{cr}$, $n_{ip} \approx 4.4n_{cr}$, and as the main pulse peak laser intensity exceeds the threshold to double field ionize helium ($I \gtrsim 9 \times 10^{19} \text{ W m}^{-2}$), the peak electron density $n_{ep} \approx 9n_{cr}$. At such high densities, the laser is strongly absorbed and partially reflected from the blast wave. Strong absorption is also evidenced by the detection of $> \text{MeV}$ ions accelerated from radiation pressure-driven collisionless shocks under similar conditions [38,41].

By $t = 27 \text{ ps}$, filaments are visible extending up to $800 \text{ }\mu\text{m}$ into the constant density region beyond the blast wave shell. These filaments have an initial radii $r_{f0} = 8\text{--}15 \text{ }\mu\text{m}$, taken as the FWHM of the feature on

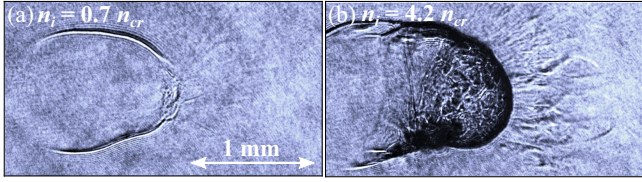


FIG. 2. Shadowgraphy at $t = 60$ ps for (a) $n_i = 0.7n_{cr}$ and (b) $n_i = 4.2n_{cr}$.

shadowgraphy. The filaments appear to be initiated from a region that extends ≈ 250 μm transversely from the LPI, several times the laser focal spot size. By $t = 53$ ps, the plasma evolution has slowed sufficiently that interferometry becomes well defined, showing density modulation around the filaments.

The structure of the filaments varies with initial target density. Figure 2 shows shadowgraphy for lower and higher initial densities, $n_i = (0.7, 4.2)n_{cr}$, at $t = 60$ ps. For $n_i = 0.7n_{cr}$, no filaments are observed. Instead, a “hole” is seen in the blast wave, indicating the laser has penetrated the cavity wall instead of being absorbed. This prevents efficient hot electron generation, stopping the occurrence of filamentation. Although the peak electron density should exceed n_{cr} for this density, relativistic self-focusing can occur in both the rarefied remnant plasma in the blast wave cavity and the blast wave density ramp. This would enhance the laser intensity over the nominal value, and, hence, a modest relativistic increase in the critical density, $n_{cr,rel} \approx a_0 n_{cr}$ is expected [42].

Filamentation is observed only when the unperturbed density exceeds $n_i \approx n_{cr}$ as in Fig. 1. At higher density, for example at $n_i = 4.2n_{cr}$ in Fig. 2(b), numerous filaments are observed, penetrating less deeply (≈ 400 μm) compared to $n_i = 1.1n_{cr}$ and over a larger transverse region. The filaments are typically narrower, with a minimum observed radius $r_{f0} \approx 5$ μm , close to the resolution of the imaging system. The initial filament size, thus, closely follows the collisionless skin depth, $r_f \approx 2\pi c/\omega_p \propto 1/n_e^{1/2}$, which is the expected spatial scale of the Weibel-like current filamentation instability.

To determine the feasibility of the observations being due to the Weibel instability, we can estimate its growth time. From energy conservation, the fast electron density $n_b = \chi I_L / m_e c^3 \bar{\beta}_b (\bar{\gamma}_b - 1)$, where χ is the conversion efficiency of laser energy into energetic electrons. The ponderomotive scaling gives $\bar{\gamma}_b = (1 + a_0^2)^{1/2}$ [3]. For our parameters, $\bar{\gamma}_b \approx 1.7$ and $\bar{\beta}_b \approx 0.8$. Taking $\chi \sim 0.4$ [43,44] gives $n_b \approx 6 \times 10^{24} \text{ m}^{-3}$, corresponding to $\alpha \sim 0.3$ for $n_i = n_{cr}$. The time for one e -folding of the instability $\tau_\delta \approx 10$ fs is much shorter than the electron beam duration $\tau_e \approx \tau_L = 5$ ps, and the instability is, therefore, expected to grow strongly during the LPI.

2D particle-in-cell simulations of the interaction were performed using the code EPOCH [45]. A $\lambda_L = 10.3$ μm ,

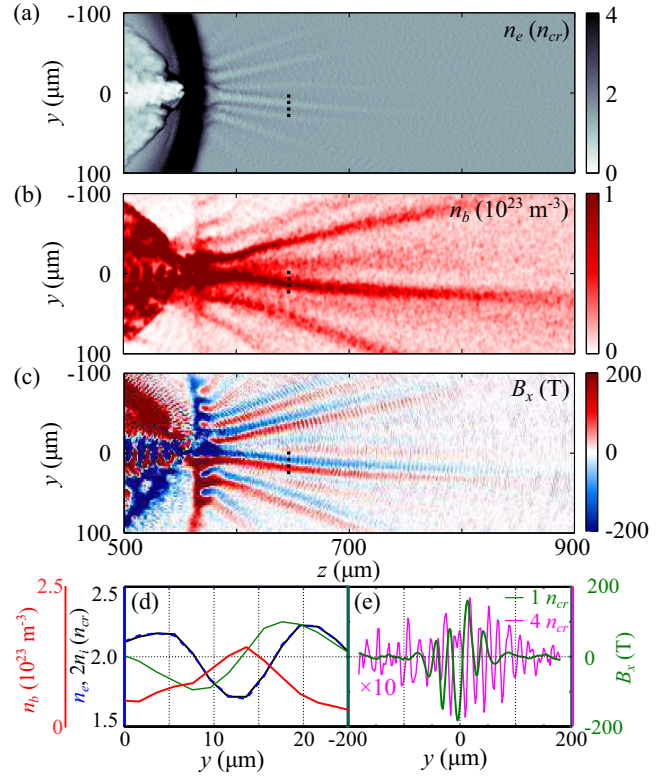


FIG. 3. Region ahead of LPI at $t = 10$ ps, just after the peak of the pulse, for $n_i = 1.0n_{cr}$: (a) n_e , (b) n_b , (c) B_x , and (d) transverse lineout along single filament [dotted line in (a)–(c)], showing n_e (blue), n_i (black), B_x (green), and n_b (red), and (e) transverse B_x from $n_i = (1, 4)n_{cr}$.

$a_0 = 1.25$, $\tau_L = 5$ ps linearly polarized laser was focused to $w_0 = 65$ μm in a box 2000×400 μm with cell size 200×400 μm . The peak of the pulse entered the box at $t = 6.4$ ps, and the simulation ran until $t = 15$ ps. The target was preionized He with $T_e = 1$ eV and ten particles per cell for electrons and He. The density profile was taken from a hydrodynamic simulation of the prepulse shaping of the gas [39]. The electron density distribution just after the peak of the pulse is shown in Fig. 3(a) for $n_i = 1.0n_{cr}$. The laser is incident from the left and bores through the density ramp up to the critical surface. The laser intensity and subsequent ponderomotive force are enhanced via self-focusing, and low-density plasma is expelled from the focal region during the rising pulse. Along the density ramp, a large number of electrons are accelerated to high energy and propagate into the undisturbed plasma ahead of the LPI. The distribution of fast electrons, n_b , is shown in Fig. 3(b). n_b is calculated from electrons with momentum along the laser axis $p_e > 0.5m_e c$, chosen to be significantly higher than the bulk temperature. This electron current generates a strong azimuthal magnetic field ahead of the blast wave along the laser axis [46], while a return current at the channel edge generates an outer magnetic field of opposite sign [47], as shown in Fig. 3(c). These fields trap

and scatter the electrons and increase the effective electron source volume. The experimental probe images (Fig. 1) also showed filamentation over a transverse region exceeding the focal spot size. The simulations determine that it is this magnetic field scattering that is responsible for the large effective source size of fast electrons.

These electrons travel into the unperturbed plasma, reaching a maximum beam-to-background ratio of $\alpha \approx 0.1$ just ahead of the critical surface. α decreases further into the target due to transverse diffusion. The background electrons comprising the return current are pulled toward the LPI region with velocity $v_e \approx \alpha \bar{v}_b \sim c/10$. The system is unstable. By the peak of the pulse, transverse cavities form in the total electron density [Fig. 3(a)], which are correlated with the increased beam density [Fig. 3(b)]. The initial transverse filament diameter, determined by the fastest growing mode, is $\approx 10 \mu\text{m}$, similar to the skin depth $2\pi c/\omega_p \approx 8 \mu\text{m}$, as was seen experimentally. The filaments continue to grow transversely, reaching between 12 and 20 μm by the end of the LPI [32,48].

The filament azimuthal field is $B_x \approx 300 \text{ T}$ [Fig. 3(c)], consistent with predictions from the magnetic-trapping model at instability saturation [15]. Lineouts of the beam, background, and ion densities and the magnetic field perpendicular to the filament direction are shown in Fig. 3(d). The magnetic field has collimated the beam electrons and cavitated the higher density returning background of electrons. The radial imbalance of fast and return electron densities results in a net reduction of electron density inside the filament, generating a positive space charge. The resultant electric field grows until it constrains the cavitation of the background electrons $E \approx v_e B \sim 10^9 \text{ V m}^{-1}$ and leads to cavitation of the ions. Such coupling of electrostatic modes to the initially electromagnetic instability has been shown to impact the instability growth rate [30,31].

The effect of varying plasma density was also simulated. Transverse lineouts of the azimuthal magnetic field at the end of the LPI are shown in Fig. 3(e) for $n_i = (1, 4)n_{\text{cr}}$. The density of the remnant gas in the cavity is greater for $n_i = 4n_{\text{cr}}$. Fast electrons are generated along a longer length, reducing n_b and resulting in a larger number of filaments over a greater transverse extent. The smaller α , due to higher n_e and reduced n_b , results in slower instability growth and, therefore, a smaller B_x . r_f is smaller and the filaments do not expand significantly during the LPI. This also replicates the density dependence determined experimentally.

Simulating over longer timescales is challenging due to reduced dimensionality and artificial numerical heating, affecting the plasma sound speed. However, the filament size evolution could be measured experimentally over timescales significantly exceeding the laser pulse length. Figure 4(a) shows optical probe images taken at $t = 260 \text{ ps}$ for $n_i = 1.1n_{\text{cr}}$, demonstrating an increase in the filament

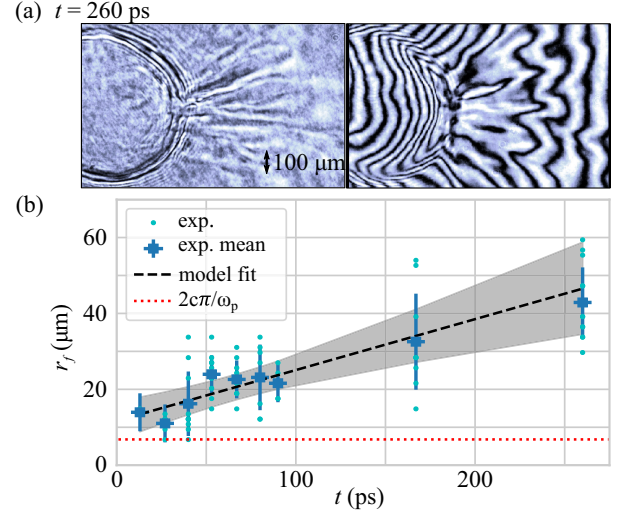


FIG. 4. (a) Shadowgraphy (left) and interferometry (right) at $t = 260 \text{ ps}$. (b) Filament radius r_f as a function of time including individual measurements (cyan); resultant mean and standard deviation (blue); and best fit (dashed) and 2σ uncertainty (shaded) of the fitted thermal expansion model.

radius. In some cases, filaments overlap in the out-of-plane direction of the image, making it difficult to identify individual filaments. Considering only filaments that are clearly visible and isolated, the filament radius has increased to $r_f \sim 50 \mu\text{m}$. This is much larger than the filament radius $r_{f0} \sim 2\pi c/\omega_p \approx 10 \mu\text{m}$ observed just after the LPI. The increase in filament radius, measured from shadowgraphy at a fixed plane $200 \mu\text{m}$ into the target from the LPI, with time is shown in Fig. 4(b) for $n_i = 1.1n_{\text{cr}}$. Under these conditions, the expansion of the ion cavity is acoustic and increases as $r_f(t) = r_{f0} + c_s t$, where $c_s = \sqrt{Zk_B T_e/m_i}$ is the plasma sound speed for a background plasma temperature T_e . This assumes that the plasma electrons are preferentially heated and the electron-ion equilibration is slow over this timescale. Hence, the expansion of the filaments is primarily determined by the background plasma temperature. Fitting of the multivariate thermal expansion model was performed using a Markov chain Monte Carlo method, resulting in $c_s \approx 1.5 \times 10^5 \text{ ms}^{-1}$ and $r_{f0} = 12 \pm 2 \mu\text{m}$, which implies $T_e = 400 \pm 200 \text{ eV}$. The obtained $r_f(t)$ model fit is overlaid on the experimental data in Fig. 4(b). The estimated collisional Ohmic heating rate $dT/dt \approx \eta j_b^2 \sim 10 \text{ eV/ps}$, where j_b is the beam current density and η is the background plasma resistivity, both obtained from simulations, is much smaller than the heating observed. This implies the filament formation and heating is driven by collisionless processes.

Such collisionless heating is key for interpretations of collisionless shock-wave acceleration (CSA) [49]. Helium acceleration to $\sim \text{MeV}$ energies consistent with CSA was observed in very similar conditions to this experiment [38]. Given the values of c_s measured here, this would imply

very high Mach numbers ($M = v_s/c_s$, where v_s is the shock speed). This rules out acceleration by isothermal shocks for which $M \lesssim 2$. Furthermore, the measured temperature is 2 orders of magnitude lower than the prediction used in the widely adopted thermal shock-wave acceleration scaling [49]. Therefore, our plasma dynamic measurements provide strong evidence that ion generation from just-over-critical-density targets irradiated by high-power CO₂ pulses [38,41] was from radiation pressure-driven, rather than thermally driven, CSA.

In conclusion, by using an intense long-wave-IR drive laser with low-density targets, we have made parametric studies of the Weibel-like beam driven filamentation of fast electrons penetrating into an overcritical density plasma. The observed strong collisionless background heating in these studies could have important implications for electron beam heating in novel laser-driven fusion schemes. By relaxing the length and timescales through the use of a long-wave-IR driver, it is possible to investigate this and many other aspects of intense laser plasma interaction and energetic electron transport in near-critical-density plasma.

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Data availability—The data that support the findings of this article are available from the authors upon reasonable request.

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