

From filamentation to stratification: Instability dynamics in scissors-shaped relativistic beam-plasma system

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Counter-streaming systems are a canonical model for beam-plasma instabilities, such as the filamentation instability, which is critical in high-energy density physics. However, scenarios involving intersecting fast electron beams break the cylindrical symmetry inherent to such systems. Here, we introduce the scissors-shaped configuration, a fundamental multivelocity-component system that captures this broken symmetry. Through theoretical analysis and particle-in-cell simulations, we reveal a dramatic shift in the instability dynamics: the system undergoes a stratification mode instead of filamentation. This mode is rapidly quenched by magnetic reconnection, leading to a quasistable state with magnetic energy two orders of magnitude lower than in the counter-streaming case. This discovery establishes a principle of passive instability control via geometric configuration, offering a perspective on beam-plasma interactions in astrophysics and inertial confinement fusion. The underlying physics is verifiable in upcoming multilaser experiments.

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Introduction. The interaction of relativistic electron beams with dense plasmas is a fundamental process in high-energy-density physics (HEDP), underpinning phenomena in inertial confinement fusion (ICF) schemes like fast ignition (FI) [1–12] and laboratory astrophysics [13–17]. In many of these scenarios, electromagnetic instabilities, such as filamentation instability, critically limit the transport efficiency and quality of fast electron beams [18–22].

The study of beam-plasma instabilities has a rich history, advancing through theoretical, computational, and experimental efforts. Theoretically, since Weibel’s seminal work [18], analytical models have successfully described the linear phase of these instabilities. Key developments include the relativistic formulation of the Weibel instability by Yoon and Davidson [23], explorations of the purely transverse Weibel instability relative to fast ignition by Silva *et al.* [24], and systematic investigations by Bret that clarified the role of oblique modes and compared the dominant parameter ranges of various instabilities [15,25,26]. These foundational theories have been extended to include collisional effects [27,28] and have been complemented by a fully kinetic Vlasov model [29–31]. Computationally, particle-in-cell (PIC) simulations have provided crucial insights into the nonlinear dynamics, revealing

filament merging as a primary mechanism driving fast electron beam deceleration and dissipation [32], demonstrating that instabilities can be actively mitigated by applying external oscillating drivers [33], and elucidating the impact of various plasma parameters [20,34,35]. Theoretical and computational predictions have been corroborated by experimental observations, which have directly imaged beam filamentation and confirmed the presence of Weibel-generated magnetic fields [36–38]. However, the vast majority of these seminal studies have focused on the counter-streaming system with cylindrical symmetry, in which two symmetric plasmas counterpropagate, or a single fast electron beam propagates opposite to a background return current.

A crucial and largely unexplored question is how the system evolves when cylindrical symmetry is broken. Such scenarios are not merely theoretical curiosities but are becoming increasingly relevant. For instance, in the overlapping relativistic electron jets in astrophysics, and in the double-cone ignition campaign [39], which is upgrading the laser facility to employ two or more ultraintense picosecond lasers to generate multiple fast electron beams for fast ignition as illustrated in Fig. 1. The transport of these nonparallel electron beams leads to an inevitable overlapping region inside the cone, where their mutual interaction inherently breaks the system’s cylindrical symmetry. Furthermore, in scenarios like proton fast ignition [40,41], the finite opening angle of the guiding cone introduces a natural beam divergence, which also constitutes a clear departure from cylindrical symmetry. In all these cases, the intersection or divergence of multiple fast beams forms a multiple-velocity-component system (composed of the fast electron beams and the background return current) that cannot be transformed into a conventional

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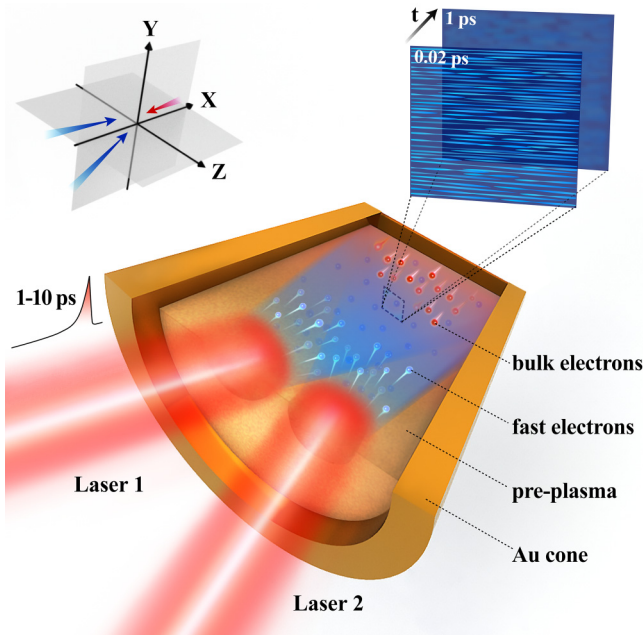


FIG. 1. Schematic diagram of the scissors-shaped configuration.

counter-streaming system through a simple reference frame transformation.

In this Letter, we address this question by introducing a canonical noncounter-streaming system: A scissors-shaped configuration formed by two intersecting fast electron beams and a background electron return current (with the electrical neutrality ensured by ions). Using theoretical analysis and PIC simulations, we demonstrate that breaking the cylindrical symmetry fundamentally alters the pattern of instability and the evolutionary behavior of the system. Instead of filamenting, the beams undergo a stratification mode, which is rapidly suppressed. We find that this configuration maintains excellent transverse beam uniformity for a duration of several picoseconds. In the nonlinear stage, we observe a secondary growth of magnetic field energy. This stage is termed the bulk cavitation stage, which ultimately terminates the transverse uniformity of the system. Our work reveals a mechanism for passively controlling beam-plasma instabilities and provides a framework for understanding the interaction of multiple fast electron beams.

Simulation setups. Three sets of the most representative high-precision two-dimensional simulations were selected to investigate the evolution behavior of scissors-shaped configuration. First, simulation with a single fast electron beam injecting into the background (referred to as one-beam system) was conducted to offer a benchmark as the traditional counter-streaming system, in which the fast electron beam velocity is $\vec{v}_{b,1} = v_0 \hat{e}_x$. The second set is the scissors-shaped fast electron beams simulation (referred to as two-beam system), in which the velocities of the two symmetric fast electron beams are $\vec{v}_{b,2} = v_0 \cos 15^\circ \hat{e}_x \pm (v_0 \sin 15^\circ \cos 40^\circ \hat{e}_z + v_0 \sin 15^\circ \sin 40^\circ \hat{e}_y)$. The half-angle of 15° represents the initial direction of the fast electron beams relative to the x axis. To represent the extreme case of further increasing the number of fast electron beams, an infinite-beam simulation (referred

to as infinite-beam system) was selected as the third set. In this simulation, the fast electron beam velocity is isotropic in the z - y plane, given by $\vec{v}_{b,\text{inf}} = v_0 \cos 15^\circ \hat{e}_x + v_0 \sin 15^\circ \hat{e}_\perp$. The x direction is referred to as the longitudinal direction, while the z - y plane is designated as the transverse plane. Our two-dimensional simulations are performed in the z - y plane, capturing the evolution at a cross section of the propagating fast electron beams.

In each set of simulations, the fast electron energy is 10 MeV ($\gamma = 20$) to make the relativistic effects more pronounced, and the total density of the fast electron beams is $n_b = 2n_c = 2.4 \times 10^{21} \text{ cm}^{-3}$. The background electron density is $n_p = 500n_c$, which is a typical value around Au cone tip in fast ignition. The background electron velocity is $\vec{v}_p = -(n_b/n_p)v_0 \hat{e}_x$ for the one-beam system and $\vec{v}_p = -(n_b/n_p)v_0 \cos 15^\circ \hat{e}_x$ for the two-beam and infinite-beam systems to ensure current neutralization. (For clarity, all particle number densities presented in this Letter are observed in the background frame, rather than the proper densities in the electron rest frame. Our current neutralization condition is thus consistent with the requirements of relativistic electrodynamics.) Au ions, which lack directed velocity, have an ionization degree $Z = 10$, a mass $m_i = 361\,682m_e$, and a number density $n_i = 50.2n_c$. Both ions and electrons have an initial temperature of 500 eV, and each particle is uniformly distributed within the simulation box. For the fast electrons, this uniform distribution models a prefilled state where they have already reached the cross section from all directions. The simulation employs a uniform grid spanning the z - y plane, with $N_z \times N_y = 200 \times 200$ cells. Each grid cell has edge lengths $\Delta z = \Delta y = 0.01 \mu\text{m}$, and contains 400 background electrons, 200 fast electrons, and 100 background ions. The high number of particles per cell ensures that the transverse velocity of fast electrons is nearly isotropic in each cell of the infinite-beam system. While fully three-dimensional simulations are computationally extremely challenging, our two-dimensional simulations with periodic boundary conditions focus on a small transverse cross section of the system, which captures the essential physics. In the Supplemental Material, we present a convergence analysis using larger simulation sizes, demonstrating that doubling the side length in the z - y plane yields consistent results with those reported here [42]. Both collisionless and collisional scenarios were investigated, and our main focus is on the collisionless scenario, with the collisional scenario detailed in the Supplemental Material [42].

Linear stage. Figure 2(a) illustrates the temporal evolution of the total magnetic field energy for the three sets of simulations. The evolution of magnetic field energy in the two-beam system initially approximates that of the one-beam system, but after a short period, it declines sharply and becomes essentially consistent with the infinite-beam system. Both two-beam and infinite-beam systems exhibit significantly lower magnetic field energy compared to the one-beam system, indicating a substantial suppression of electromagnetic instability. Then around $t = 8 \text{ ps}$, an unusual secondary growth occurs in these two systems.

During the linear phase, the dispersion relations for the three systems can be derived using linear theory [14,25,26,42]. The maximum instability growth rates for the one-beam, two-beam, and infinite-beam systems, denoted as

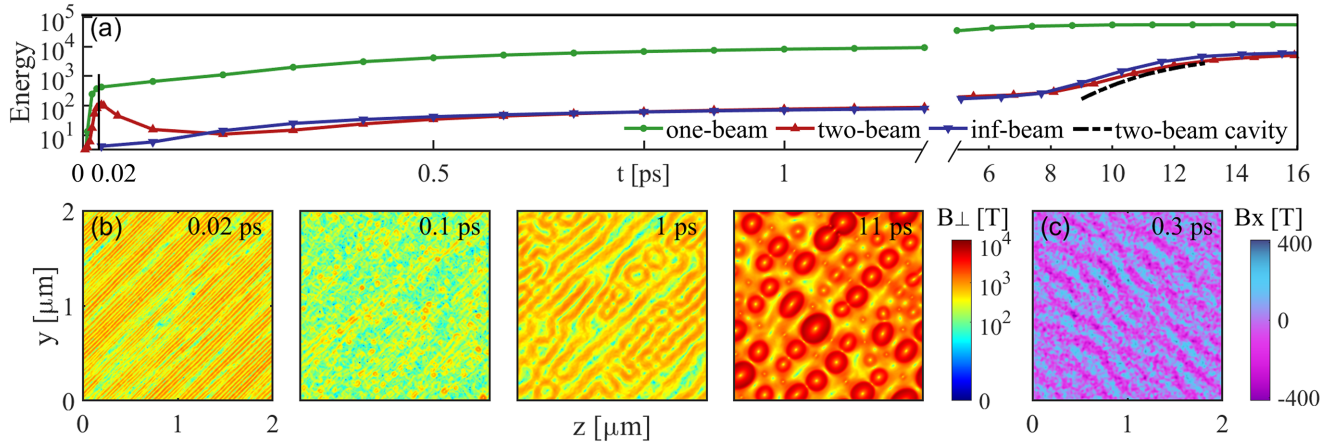


FIG. 2. (a) Temporal evolution of magnetic field energy in three cases, with black dashed line indicating the magnetic field energy inside the cavities during the bulk cavitation stage of the two-beam system. The time axis includes a break to emphasize the initial and late time evolution. (b) The magnetic field in the z - y plane $B_\perp$ of the two-beam system at $t = 0.02, 0.1, 1$, and 11 ps. (c) The magnetic field in the x direction B_x of the two-beam system at $t = 0.3$ ps.

Γ_1 , Γ_2 , and Γ_{inf} respectively, exhibit a trend of $\Gamma_1 > \Gamma_2 \gg \Gamma_{\text{inf}}$. This trend matches the simulation results well, as shown in Figs. 2(a) and 3(a). The two-dimensional Fourier analysis results of $(B_z + iB_y)$ for the three systems at $t = 0.02$ ps are presented in Figs. 3(b)–3(d). In contrast to the other two systems, the broken symmetry in the two-beam system dictates a selective excitation of modes, whose wave vectors are concentrated along the symmetry axis of the system (perpendicular

to the plane of the fast electron beams' initial velocities), corresponding to a stratification mode. The excited magnetic field structure is not the traditional toroidal shape but a series of parallel straight lines with alternating directions, as shown in Fig. 2(b), causing the current density of the fast electron beams and background electrons to form a similar layered structure. The small window in Fig. 3(a) shows that as the incident angle decreases, the theoretical growth rate in the two-beam system converges to that in the one-beam system, providing a crucial self-consistency check for the theory. However, for infinite-beam system, due to the different topologies of the initial distribution function, the mathematical derivation results cannot converge with small incident angles, which is discussed in the Supplemental Material [42].

Although the growth rate Γ_2 of the stratification mode is close to Γ_1 of the filamentation instability, within a mere 0.03 ps, the stratification mode is suppressed due to collisionless magnetic reconnection, leading to a sharp decline in magnetic field energy. The layered structures of the magnetic field and fast electron beams quickly disintegrate, resulting in a disordered state at $t = 0.1$ ps [42].

Additionally, at $t \sim 0.3$ ps, due to the anisotropy of the fast electron beams' velocity in the z - y plane, Weibel-like instability and the magnetic field in the x direction are excited, as shown in Fig. 2(c). Although this instability exists for a very short time, the residual magnetic field in the x direction continues to drive the two-beam system toward the infinite-beam system, which reaches transverse velocity isotropy around $t = 8$ ps [42].

The magnetic field structure in the two-beam system is similar to the infinite-beam system for several picoseconds after the suppression of the stratification mode, forming an interconnected mazelike structure. At $t = 6$ ps, the magnetic field energies of all three systems temporarily reach a quasissteady state, with the magnetic field energy of the two-beam and infinite-beam systems being about two orders of magnitude lower than that of the one-beam system, demonstrating a significant suppression effect on electromagnetic instabilities.

Nonlinear stage. For both the two-beam and infinite-beam systems, around $t = 8$ ps, the magnetic field energy

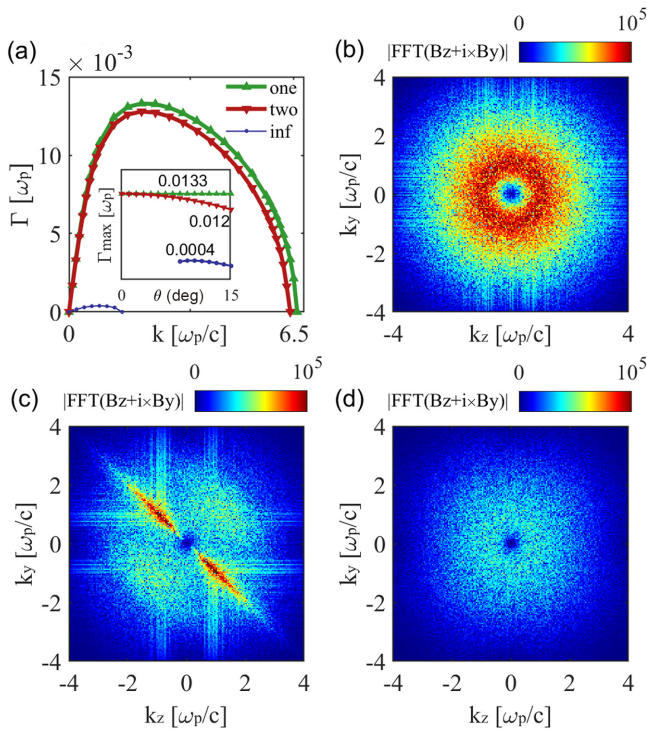


FIG. 3. (a) Dispersion relation curves for the three systems. The inset shows the variation of the maximum growth rate with the initial incident angle of the fast electron beams for the three systems. (b)–(d) Two-dimensional Fourier analysis results of $(B_z + iB_y)$ for one-beam, two-beam, and infinite-beam systems at the linear stage ($t = 0.02$ ps), respectively.

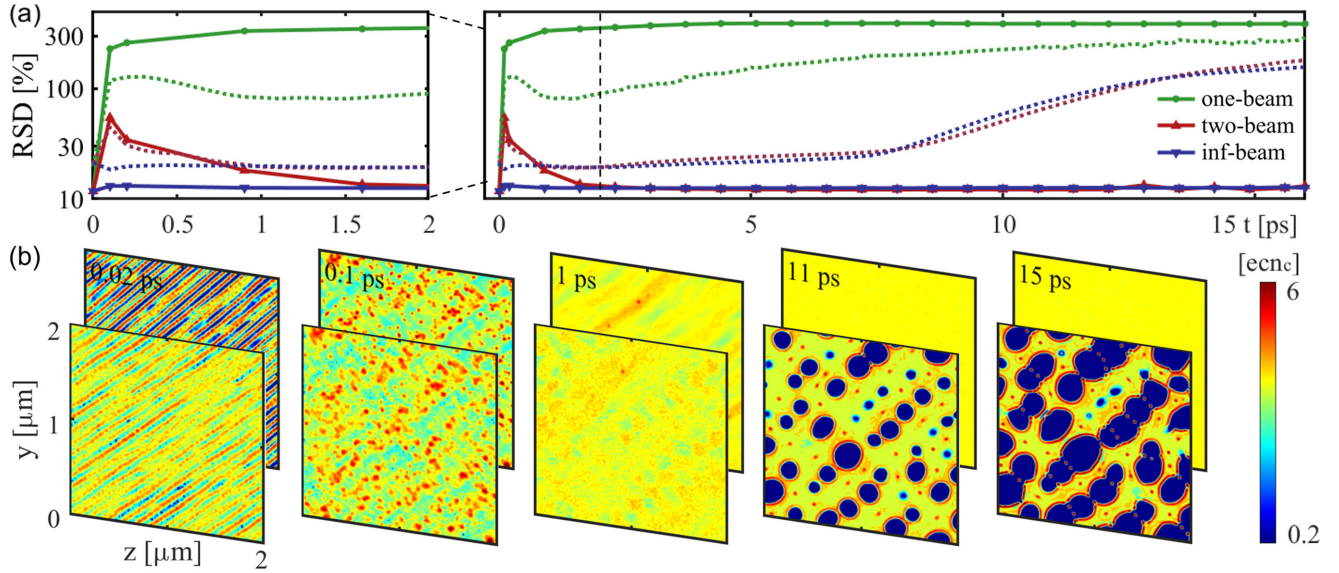


FIG. 4. (a) Transverse inhomogeneity (RSD) of the fast electron (solid lines) and background electron (dashed lines) current densities for the three systems. (b) The transverse distribution of the background current density $j_{p,x}$ (front) and the beam current density $-j_{b,x}$ (behind). Each column corresponds to $t = 0.02, 0.1, 1, 11$, and 15 ps, respectively.

underwent a secondary growth. In this stage, the systems' behavior could no longer be described by the linear theory of electromagnetic instability. Due to the isotropy of the fast electrons transverse velocity in the two-beam system around $t = 8$ ps, the two-beam and infinite-beam systems behave similarly and are hereafter discussed collectively.

Around $t = 8$ ps, the connected magnetic field structure is likely disrupted by a process akin to collisionless magnetic reconnection, forming closed magnetic field vortices. The Lorentz force within counterclockwise magnetic vortices expels background plasma (electrons and ions), carving out a series of low-density cavities and leading us to designate this phase as the bulk cavitation stage.

Simulations revealed that during the bulk cavitation stage, the density of background electrons and ions within the cavities decreased to the level of the beam electron density ($\sim 1n_c$), causing the background electron current density in the cavities to nearly vanish. However, due to the high transverse momentum, the net Lorentz force integrated along a fast electron's trajectory through a cavity is nearly zero, leaving their transverse momentum largely unperturbed. Thus, the fast electron beams maintained a nearly uniform distribution in the z - y plane, as illustrated in Fig. 4(b). The complete evolution of the fast electron beam and the background electron current density is visualized in Movie S1 in the Supplemental Material [42].

It is found that the magnetic field strength inside a cavity is roughly proportional to the distance from its center, while the equivalent cavity radius grows approximately linearly with time [42]. The evolution of the total magnetic field energy within the cavities E_{in} for the two-beam system is plotted in Fig. 2(a) (black dashed line). To explain this behavior, we developed a simplified hydrodynamic model, which predicts that the magnetic energy should grow as the fourth power of time, i.e., $E_{in} \sim A(t - t_0)^4$. To verify this prediction, we performed a power-law fit to the simulation data during the

bulk cavitation stage. The resulting exponent consistently falls within the range of 3.95–4.05, in excellent agreement with our theoretical model. This correspondence suggests that the secondary growth of magnetic energy is well captured by our cavitation model, rather than being driven by other potential instabilities.

Transverse uniformity. The degree of transverse spatial inhomogeneity of the fast electron beams and background electrons can be represented by the relative standard deviation (RSD) of the current density,

$$\text{RSD} = \sqrt{\frac{1}{S} \iint \frac{(j_x(z, y) - \langle j_x \rangle)^2}{\langle j_x \rangle^2} dz dy}. \quad (1)$$

Figure 4(a) illustrates that as the stratification mode of the two-beam system is suppressed, the fast electron beam current density returns to a state closely resembling the initial uniform state. The RSD of the fast electron beams in both the two-beam and infinite-beam systems remains around 10%, and the uniformity of the background electrons is significantly improved compared to the one-beam system before $t = 8$ ps. In contrast, due to filamentation instability, the RSD of the fast electron beam in the one-beam system rapidly exceeds 300%, and the RSD of the background electrons surpasses 100%.

During the bulk cavitation stage, the background RSD in the two-beam and infinite-beam systems rapidly increases, resembling a filamentationlike instability driven solely by the background return current. This stage signifies the end of the system's transverse uniformity, indicating that our method for enhancing the transverse uniformity of the fast electron beam is effective for approximately 8 ps, which is sufficient for typical picosecond laser pulses in fast ignition. While the fast electron beams remain transversely uniform in our two-dimensional simulations, a crucial consideration in a realistic three-dimensional scenario is their longitudinal transport. As the initial electron population propagates out of the system

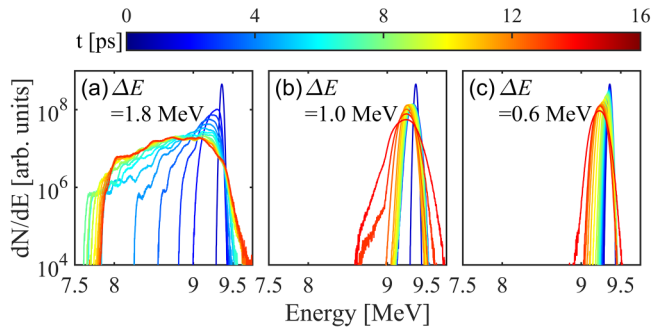


FIG. 5. Fast electron energy spectrum of (a) one-beam, (b) two-beam, and (c) infinite-beam systems. The displayed energy values are the kinetic energy of the fast electrons, calculated by subtracting their rest energy. ΔE is the final full width at half maximum.

along the x direction, it is replaced by a continuous influx of electrons. These newly introduced beams will encounter the preformed background cavities and strong magnetic fields, making them highly susceptible to filamentation, particularly for electrons with lower energy.

Energy spectrum. By comparing the evolution of fast electron beam energy spectrum in the three systems depicted in Fig. 5, we observed that both the two-beam and infinite-beam systems effectively mitigate the thermalization and energy loss of fast electron beams caused by filamentation instability. Filamentation instability leads to a gradual broadening and leftward shift of the fast electron beam energy spectrum in the one-beam system, with the broadening reaching approximately 2 MeV. Conversely, in the two-beam and infinite-beam systems, the fast electron energy remains relatively stable, with only a minimal broadening of the energy spectrum over the picosecond timescales relevant to fast ignition. This indicates that the instabilities in multivelocity-component systems have less impact on the deceleration and heating of fast electrons.

Discussion and conclusion. In conclusion, we have demonstrated that breaking the cylindrical symmetry in a relativistic beam-plasma system fundamentally alters its instability dynamics. By employing a scissors-shaped configuration, the dominant instability shifts from filamentation to a stratification mode, which is rapidly quenched by magnetic reconnection. This yields a state of strong magnetic field suppression and remarkably high-beam uniformity persisting for several picoseconds. The mechanism remains effective even in collisional cases [42]. This study establishes a principle:

Geometric configuration can serve as a powerful passive tool for controlling beam-plasma instabilities, enriching our understanding of multivelocity-component plasma systems. While our two-dimensional simulations provide a proof of principle, the evolutionary behavior of multivelocity-component systems in three dimensions remains a critical open question for future investigation. Nevertheless, our work offers a perspective for interpreting phenomena in overlapping astrophysical jets and for designing future multilaser HEDP experiments, with key predictions on the initial instability evolution being testable at upcoming dual-beam laser facilities.

In this Letter, the instability growth was initiated under simplified density assumptions. The plasma density was assumed uniform in the transverse (z - y) plane, an approximation valid for the small cross-section considered, while periodic boundary conditions enforced effective uniformity in the longitudinal direction. In realistic ICF scenarios, especially involving gold cones or similar structures, the plasma density often exhibits significant gradients along both transverse and, particularly, the longitudinal direction. Such nonuniformities, especially the longitudinal density gradients, may fundamentally alter the growth rates, modify the dominant instability modes, or even bypass the early temporal phase of instability development by providing preexisting structures. This could have important implications for the overall evolution of instabilities and laser-plasma coupling. Future work involving full 3D simulations with multidimensional density profiles will be essential to quantify these effects and further validate the models presented here, thereby enhancing the relevance of our findings to practical ICF applications.

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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- [42] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/tv85-lk5j> for the derivations of dispersion relations of instabilities, the additional PIC simulation results, the effect of ions on linear and the bulk cavitation stage, the theoretical model and analysis of the bulk cavitation stage, the simulation

results of collisional cases, and the numerical convergence analysis of large-scale PIC simulations, which includes Refs. [6,15–18,28,32–34,43–45]. The material also includes one movie. Movie S1: Evolution of the magnetic field in the z - y plane (top row), fast electron beam current density (middle row), and background electron current density (bottom row). The movie compares the dynamics for the one-beam (left column), two-beam (middle column), and infinite-beam (right column) systems.

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