Laboratory observation of magnetic field decay in nonlinear Weibel instability

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Collisionless shocks are ubiquitous in a great variety of explosive events, such as supernova remnants and gamma-ray bursts. Generally, these phenomena with the same physical characteristic is collisionless interpenetration process, meaning that the necessary dissipation of shock is mediated by micro-instabilities instead of particle collisions. The Weibel instability (WI)[1-3], arising from anisotropic/interpenetrating plasmas, is regarded as a promising mechanism responsible for astrophysical collisionless shock formation. The local self-generated magnetic fields via WI providing Lorenz force ($\boldsymbol{q} \times \boldsymbol{B}$) traps the ions to create a shock.

Recently, laboratory experiments[4-6] have showed the capacity of achieving collisionless regime, shedding light on the microphysics underlying astrophysical collisionless shocks. Pioneering experiments[7,8], utilizing proton radiography, demonstrate that the WI can be performed with laser-produced interpenetrating flows. However, current experiments demonstration of the Weibel-mediated-shock remain elusive, since the characteristics of nonlinear WI are not well-understood. More experiments are needed to verify the characteristics of nonlinear WI for the forthcoming laboratory study of astrophysical collisionless shocks formation and particles acceleration.

Here we create a laboratory version of collisionless laser-produced interpenetrating system to study the nonlinear WI. Shown in Fig. 1, the WI fast evolving into nonlinear stage in counter-streaming supersonic flows. Filamentary structures and associated magnetic fields are simultaneously identified with optical diagnostics. The spatiotemporal evolution of filamentation spacing is consistent with Ruyer's analysis model[9], but the magnetic field strength drops quickly in the later stage. Following particle-in-cell simulations well-reproduce the experimental observed WI features. Highly consistent evolutionary trends between current and magnetic field indicate that the dropping behavior of magnetic field is mainly caused by the declining current density. These important findings not only benefit the future study of Weibel-mediated-shock formation in laboratory, but also advance the understanding of many other phenomena relative to WI such as cosmic rays and radiation properties from astrophysical objects.

References
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Figure

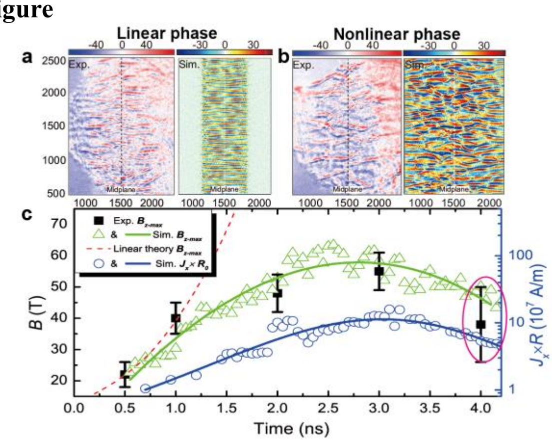

Fig.1 **a-b**, Typical magnetic fields (transverse component $\boldsymbol{B_Z}$) distribution in X-Y plane at different phases obtained from the experiments and simulations. **c**, The evolution of $B_{z\text{-}max}$ associated with Weibel instability in experiments (black squares) and simulations (green triangle & solid line). The similarity between magnetic fields (green solid line) and associated current density (blue solid line) in simulation indicates that the observed magnetic fields features are caused by the current density. The plotted red dash-line is the theoretical linear growth curve with $\boldsymbol{B_0}$ = 13 T and $\boldsymbol{\Gamma}$ = 1.0×10^9 s^{-1}. A large deviation appearing between 1-2 ns, indicating that the WI has stepped into the nonlinear phase.