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Overcoming the forest-effect in probing the Weibel-instability-generated electric and magnetic fields from proton radiography

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The Weibel instability (WI) is a subject of relevance from many physics fields ranging from ICF to astrophysical scenarios. In two counterstreaming plasma flows, WI can be unstable and lead to stochastically distributed current filaments. The self-generated magnetic field ***B*** and electric field ***E*** are the major media by which WI has an impact on the plasma energy transportation, the collisionless shock formation and the gamma ray bursts. Experimentally, WI is usually probed with the side-on proton radiography. The proton density perturbation striations on the detection plane are used to indicate the emergence of WI. However, observations conflict with the assumption that the deflection from ***E*** is ignorable in the proton radiography [1]. The nature of the radiographed fields has never been carefully examined. Meanwhile, because of the "forest-effect", deflection from these fields would be compensated by itself, both for ***E*** and ***B***. The proton flux density perturbation $\delta n/n_0$ can only deliver a qualitative characteristic of the 2D isotropic and stochastic self-generated fields. The strength and spatial wavelength of these fields, which are the most important parameters for WI, remain undetectable. The quantitative diagnostics of ***E*** and ***B*** relay on the inversion algorithms, which are still awaiting for developing.

With the new diagnosing methods demonstrated in our work, the compensation of the stochastic fields in the proton radiography of WI is overcame. It allows to overcome the forest-effect extract the strengths and wavelengths of the ***E*** and ***B*** from the proton radiography for the first time.

With 3D PIC simulations, ***E*** and ***B*** are generated in two counterstreaming plasmas ($1.1\times10^{23}/\mathrm{m}^3$, $\pm0.5c$) [2]. The distributions at about saturation show typical 2D isotropic and stochastic distributions. The proton radiography is calculated with the ray tracing method.

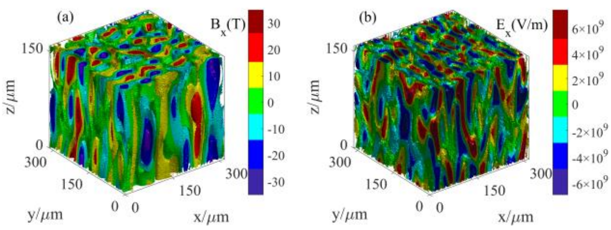

Fig. 1. 3D structures of WI generated ***E*** and ***B***.

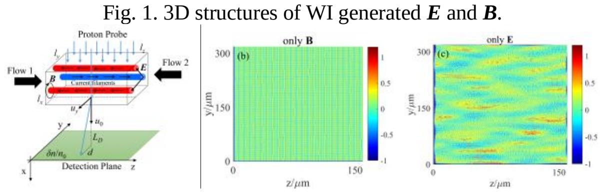

Fig. 2. Proton radiography of the WI. $\delta n/n_0$ from ***B*** is much smaller than ***E***. L_D is the detector distance, u_0 is the initial speed of the probe proton beam, d is the deflection distance.

Country to the traditional assumptions [2], Fig. 2 indicates that the deflection velocity u_y introduced from ***B*** is ignorable because of the tube-like structure of ***B***. ***E*** dominates over ***B*** in deflecting the probe beam in the proton radiography of WI.

By theoretically analyzing the autocorrelation of the 2D isotropic and stochastic ***E***, it is found that the energy spectrum of ***E*** is linked with the spatial spectrum of u_y,

$$\varepsilon_E(k_y) = (4\pi / l_x l_y)(\gamma m_p u_0 / q)^2 k_y \hat{u}_y^2(k_y) \qquad (1)$$

After reconstructing u_y by $u_y = -(u_0 / L_D)\int_{y_0}^{y} \delta n / n_0 dy$, the strength of ***E*** is deduced with $E_{rms}^2 = \int_0^\infty dk \varepsilon_E(k_y)$, whereas the wavelength $\lambda_{|\boldsymbol{E}|}$ can be read from $\varepsilon_E(k)$. At the same time, after the linear growth stage of WI, ***E*** is balanced by the magnetic pressure, i.e., $\boldsymbol{E} = -\nabla B^2 / e\mu_0 n_e$ [3]. This allows us to extract the strength and wavelength of ***B*** from the proton radiography by $B_{rms} \approx \sqrt{4e\mu_0 n_e E_{rms} \lambda_{|\boldsymbol{E}|} / \pi^2}$ and $\lambda_{|\boldsymbol{B}|} = 2\lambda_{|\boldsymbol{E}|}$.

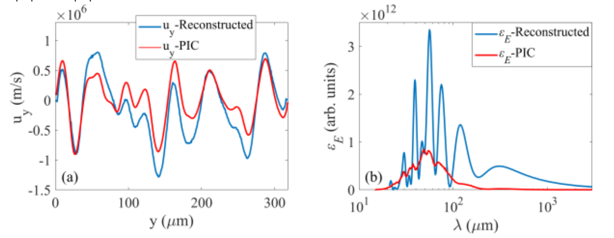

Fig. 3. Comparisons between the reconstructed and simulated u_y, ε_E.

For ***E***, the reconstructed and simulated average strengths E_{rms} are 4.1×10^9 V/m and 3.1×10^9 V/m, whereas the wavelengths $\lambda_{|\boldsymbol{E}|}$ are 28 μm and 24 μm, respectively. For ***B***, the reconstructed and simulated average strengths B_{rms} are 32 T and 18 T, whereas the wavelengths $\lambda_{|\boldsymbol{B}|}$ are 56 μm and 32 μm, respectively. The consistence between the reconstructed and simulated values validates that the "forest-effect" is overcame with our diagnosing method.

As a comparison, when reconstructed through the traditional $E_y = \gamma m_p u_0^2 d_s / q L_D l_x$ [4] by reading the striations distances, it gives $E_{rms}=4.2\times10^{10}$ V/m, which is over one amplitude larger than the PIC simulation. When using the reconstructed u_y in Fig. 3(a), it gives an average strength of ***E*** about 0.7×10^9 V/m, which is also too small because of the forest-effect. This highlights the advantages of our methods.

References:

[1] *Nat. Phys.* **11**, 173 (2015);
[2] *Phys. Plasmas* **10**, 1979 (2003);
[3] *Plasma Phys. Control. Fusion* **51**, 124042 (2009);
[4] *Phys. Rev. Lett.* **97**, 135003 (2006).