Density filament and helical field line structures in three dimensional Weibel-mediated collisionless shocks

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Abstract. Collisionless shocks mediated by Weibel instability are attracting attention for their relevance to experimental demonstrations of astrophysical shocks in high-intensity laser facilities. The three dimensional structure of Weibel-mediated shocks is investigated through a fully kinetic particle-in-cell simulation. The structures obtained are characterized by the following features: (i) helical magnetic field lines elongated in the direction upstream of the shock region, (ii) high and low density filaments inside the helical field lines. These structures originate from the interaction between counter-streaming plasma flow and magnetic vortexes caused by Weibel instability, and potentially affect the shock formation mechanism.

1. Introduction
Collisionless shocks are fundamental process in space and astrophysical plasmas and are present in various phenomena, such as supernova remnants and magnetospheric bow shocks[1]. Observations of supernova remnants suggest that collisionless shocks could be a major source of the energetic components of cosmic rays[2]. Experimental demonstrations of collisionless shocks have been also performed by using high-intensity lasers[3,4,5]. In the primary design of experiments, collisionless shocks are generated in unmagnetized plasmas counter-streaming at a high Mach number ejected from an opposing pair of thin films.

Weibel instability[6] is considered to play an important role in collisionless shock formation in unmagnetized plasmas. The unstable modes have wavenumber perpendicular to the streaming direction and resulting density filament structures extend along the streaming direction. Previous two dimensional particle-in-cell simulations[7,8] showed that the filament coalescence causes ion-scale turbulence and dominant shock dissipation. Fluctuations of electron current density initiate this coalescence process and the scale length of shock transition is much larger than the ion inertial length. High-resolution kinetic simulation is required to capture this multi-scale process. Three dimensional feature of Weibel-mediated shock formation has not been fully investigated because of the vast computational costs.

In this paper, we investigate the three dimensional structure of unmagnetized collisionless shocks through a fully kinetic particle-in-cell code highly optimized for massive parallel computers. The simulation demonstrates high and low density cylindrical structures enclosed...
with helical magnetic field lines. This paper is organized as follows. The simulation model is presented in section 2. The simulation results are shown in section 3. Finally, the present study is summarized in section 4.

2. Simulation model
A fully kinetic plasma simulation is performed to investigate the three dimensional structure of unmagnetized collisionless shocks. The simulation scheme is the standard relativistic particle-in-cell method. Newton-Lorentz and Maxwell equations are solved by Buneman-Boris and leap-flog schemes, respectively. Second order interpolation and charge conservation scheme[9] are employed to estimate Lorentz force acting on the computational particle and current density profile on the spatial grid.

Figure 1 shows the schematic diagram of the simulation domain. The simulation domain is set in a three dimensional Cartesian coordinate system \((x, y, z)\) and implemented on a \(8000 \times 512 \times 512\) point grid. A reflection boundary condition is employed for the +\(x\)-boundary while a periodic condition is employed for the other boundaries. The origin of the \(x\)-axis is set at the reflection boundary. We consider a uniform plasma flowing in the +\(x\)-direction as the initial state of the system. The counter-streaming plasma flow is generated by the initial plasma flow and the reflected plasma flow.

The physical conditions are set as follows: The ion-to-electron mass ratio is 20. The initial electron and ion temperatures are the same. The Mach number of the initial flow is 10.7. The physical domain size is \((L_x, L_y, L_z) = (2000S_e, 128S_e, 128S_e)\), where \(S_e\) denotes electron inertia length. The domain size, \(L_x\), corresponds to hundreds of ion inertial length, \(S_i\), i.e., several times as much as the shock transition length expected from the previous simulation[8]. For the recent laser experiment on Weibel instability in counter-streaming plasmas \((n \sim 10^{25}[1/m^3])[5]\), this scale \((O(100)S_i \sim O(1)[cm])\) is comparable to or slightly larger than the measurement scale. Initially, 45 computational particles are employed for each particle species per spatial grid.

3. Simulation results
Figure 2 shows a birds-eye view of the electron density profiles at (A) \(t\omega_{pe} = 824.4\) and (B) \(t\omega_{pe} = 1331.8\), where \(\omega_{pe}\) is the electron plasma frequency. The high density region expands from the reflection boundary as the reflected plasma flows over the incoming plasma. Density profiles in the \(x\)-\(y\) and \(x\)-\(z\) planes, namely, the in-plane density profiles, are predominantly formed of filament structures elongated in the \(x\)-direction. The density filaments become thick near the reflection boundary. These features are the same as those seen in the results of previous two dimensional simulations[6,7], and originate from Weibel instability.

Figure 3 shows electron density profiles in the \(y\)-\(z\) plane, namely, the out-of-plane density profiles, at \(t\omega_{pe} = 1331.8\). Their positions on the \(x\)-axis are (A)\(-400S_e\), (B)\(-330S_e\) and (C)\(-165S_e\) (see Fig.2). The profiles obtained correspond to the sectional structures of the density filament. The clustered regions of low density in panel (A) indicate the presence of low

![Figure 1. Schematic diagram of simulation domain.](image-url)
Figure 2. Birds-eye view of the electron density profile described by color contour plots for the x-y and x-z planes at (A) $t\omega_{pe} = 824.4$ and (B) $t\omega_{pe} = 1331.8$.

Figure 3. Color contour plots of electron density profiles in the y-z planes at (A) $x = -400S_e$, (B) $x = -330S_e$ and (C) $x = -165S_e$.

density cylindrical structures away from the reflection boundary (hereinafter referred to as the upstream side). On the other hand, the clustered regions of high density in panel (C) suggest high density filaments near the reflection boundary (hereinafter referred to as the downstream side). As shown in panel (B), intermediate structures with two-layered filaments are formed around the boundary between the upstream and downstream sides.

Figure 4 shows the extracted magnetic field lines (yellow lines) superposed on the electron density profiles (color contour) on the (A) upstream ($x = -550S_e \sim -300S_e$) and (B) downstream ($x = -300S_e \sim -50S_e$) sides. The magnetic field lines form helical structures in both regions. These structures derive from magnetic vortices due to Weibel instability elongated in the streaming plasmas. The difference in these structures is the relative density level inside the helical field lines. On the upstream side, the helical magnetic field lines is twisting around
Figure 4. Birds-eye views of extracted magnetic field lines (yellow lines) and electron density profiles (color contour plots) for (A) the upstream and (B) the downstream side. Boxed thumbnails show the electron density profiles without the magnetic field lines.

...the low density regions. These field lines would be generated from the high energy component of plasma flow from the downstream side. In contrast, the magnetic field lines on the downstream side twist around the high density filaments, such that the helical field lines are filled with plasma. This difference likely originates from two contrastive interaction processes: the plasma diversion away from the thin helical field lines on the upstream side and plasma convergence into the thick helical field lines on the downstream side.

4. Conclusion
The three dimensional structure of Weibel-mediated shocks was investigated through a large-scale particle-in-cell simulation. The simulation demonstrated two types of cylindrical density structures enclosed by helical magnetic field lines. The first type is thin cylindrical low density regions on the upstream side and the other is high density thick filaments on the downstream side. These structures could originate from the interaction between in-plane plasma flow and out-of-plane magnetic vortices due to Weibel instability. In the future, we will consider the impact of these structures on the efficiency of shock dissipation and particle acceleration.

Acknowledgments
The calculations were performed using the Plasma Simulator at the National Institute for Fusion Science (NIFS13KNSS039) and the K-computer at the RIKEN Advanced Institute for Computational Science (hp120267).

References
[1] Treuman R A 2009 *Astron. Astrophys. Rev* **17** 409
[2] Nikolic S, van de Ven G, Heng K *et al* 2013 *Science* **340** 45
[3] Kuramitsu Y, Sakawa Y, Morita T *et al* 2011 *Phys. Rev. Lett* **106** 175002
[4] Morita T, Sakawa Y, Tomita K *et al* 2013 *Phys. Plasmas* **20** 092115
[5] Fox F, Fiksel G, Bhattacharjee A, *et al* 2013 *Phys. Rev. Lett* **111** 225002
[6] Weibel E S 1959 *Phys. Rev. Lett* **2** 83
[7] Spitkovsky A 2008 *Astrophys. J* **673** L39
[8] Kato T N and Takabe H 2008 *Astrophys. J* **681** L93
[9] Esirkepov T Zh 2001 *Comp. Phys. Comm* **135** 144