Magnetic Field Amplification Through Magnetic Dipole Vortices Merging in the Upstream of Relativistic Electron/Ion Collisionless Shocks

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Abstract. Relativistic collisionless shocks generate magnetic fields and accelerate particles in high-energy astrophysical environments. Using fully 2D kinetic particle-in-cell simulations, we investigate the physical mechanisms responsible for magnetic field amplification due to magnetic dipole vortices (MDVs) merging in the upstream region of the relativistic collisionless electron/ion shocks. We demonstrate that magnetic growth continues even after the nonlinear stage of MDVs. We show that the merging of MDVs increases magnetic field amplitude by 50% and enhances transverse size. This process provides a mechanism for large-scale magnetic field amplification in relativistic electron/ion collisionless shocks, relevant for understanding particle acceleration in astrophysical systems.

INTRODUCTION

Understanding the origin and energization mechanisms of cosmic rays remains a central problem in high-energy astrophysics. Observations indicate that cosmic rays are strongly associated with collisionless shocks in astrophysical environments such as supernova remnants, relativistic jets, and gamma-ray bursts [1]. In these plasma environments, particle–particle collisions are negligible, and energy dissipation is instead mediated through collective electromagnetic interactions. Studying collisionless shock formation and evolution is therefore essential for understanding how particles are accelerated to high energies in astrophysical systems.

A key mechanism mediating relativistic collisionless shocks is the Weibel instability [2, 3]. This instability produces transverse current filaments and rapidly amplifies small magnetic perturbations. As these filaments evolve nonlinearly, they merge and reorganize, forming larger magnetic structures (magnetic dipole vortices, MDVs) and enhancing field strength. Numerical and theoretical studies have shown that the Weibel instability process is crucial for shock formation, particle isotropization, and magnetic field amplification in relativistic plasmas [2, 4].

Particle-in-cell simulations of relativistic collisionless shocks reveal that the nonlinear evolution of filamentary structures can generate magnetic structures upstream of the shock [5]. In particular, localized MDVs develop from the merging and pinching of current filaments produced after the nonlinear stage of the ion Weibel instability [5]. These MDVs appear after the nonlinear stage of filament evolution and propagate opposite to the shock propagation direction, creating transient regions of intense magnetic fields.

Although previous studies have demonstrated the formation of MDVs [5], their merging remains less explored. Despite their potential impact on the large-scale magnetic structure of collisionless shocks, the dynamics of MDVs merging and the resulting amplification of magnetic fields have not been studied [5, 6, 7]. The present work investigates the behavior of MDVs merging in the upstream region of the relativistic collisionless electron/ion shocks and analyzes the evolution of their merging processes and associated magnetic field amplification.

NUMERICAL METHOD

To investigate these processes, we analyzed data obtained from kinetic plasma simulations based on the particle-in-cell (PIC) method [5].

The simulations analyzed in this work were performed using the Virtual Laser Plasma Lab (VLPL) code [8, 9], a fully electromagnetic relativistic PIC framework. The code was modified to minimize noise properties of numerical instabilities by using third-order shaped particles and current smoothing [5, 8]. The code solves the relativistic equations of motion for charged particles together with Maxwell's equations. Parallel computational techniques allow large-scale simulations of relativistic collisionless shock dynamics [5, 9]. The simulations used a rectangular

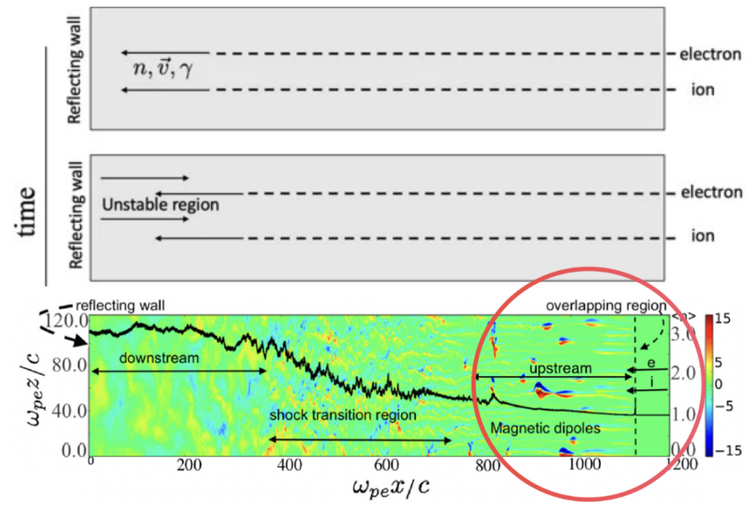

FIGURE 1. Schematic of the particle-in-cell simulation setup used to model relativistic collisionless shock formation. Top panel: Plasma streams propagate toward a reflecting boundary, producing counterstreaming electron and ion populations. The interaction between these streams triggers the Weibel instability, generating current filaments and magnetic field structures that mediate the formation of the collisionless shock. Bottom panel: Color plot of the out-of-plane magnetic field B_y in $x-z$ plane at $\omega_{pe}t = 1140$. The solid black curve (axis on right) shows transversely averaged density normalized to upstream unperturbed density. The dashed line is where the incoming e/i beams meet the counterstreams. All quantities are in normalized units [5].

simulation box in the x–z plane with dimensions $L_x = 1300\,\lambda_{pe}$ in the longitudinal direction and $L_z = 130\,\lambda_{pe}$ in the transverse direction and using the grid size $\Delta x = \Delta z = \lambda_{pe}/10$. Each computational cell contained 16 macroparticles (eight electrons and eight ions).

Electron/ion plasma flows with the mass ratio $m_i/m_e = 32$ and equal densities n_0 reflecting from the left boundary produce counterstreaming electron and ion populations. After reflection, the incoming and reflected plasmas interpenetrated and interacted, triggering the Weibel instability. This instability generates current filaments and magnetic field structures that mediated the formation of a collisionless shock [5]. The shock forms at $t \sim 420\ 1/\omega_{pe}$, where the density close to the wall reaches $3.1n_0$, in agreement with the jump condition $n = (1 + \frac{\gamma+1}{\gamma(\Gamma-1)})n_0$, where Γ is the adiabatic index in 2D geometry [4, 5]. A schematic representation of shock formation is shown in Fig. 1.

Physical quantities were expressed in dimensionless units normalized to characteristic plasma parameters. Time was normalized to the inverse electron plasma frequency ω_{pe}. Spatial scales were normalized to the electron skin depth $\lambda_e = c/\omega_{pe}$. Electromagnetic fields were expressed in normalized form as $\tilde{B}_y = \frac{eB_y}{m_e c\omega_{pe}}$, $\tilde{E}_{x,z} = \frac{eE_{x,z}}{m_e c\omega_{pe}}$ so that all quantities are dimensionless and consistent with relativistic PIC conventions. Current densities were also normalized as $\tilde{J} = J/n_e ec$. The incoming plasma flows are relativistic, characterized by the Lorentz factor $\gamma = 1/\sqrt{1-\frac{v^2}{c^2}} = 15$, where v is the plasma flow velocity. Previous simulations have shown that the nonlinear evolution of Weibel-generated current filaments can produce MDVs in the upstream region of the developing shock [5]. In this work, we analyzed magnetic-field data extracted from these simulations to identify MDVs merging and study magnetic field amplification due to merging process. By tracking these structures over time, we characterized the dynamics of MDVs merging and evaluated its role in amplifying magnetic fields in upstream regions of collisionless shocks.

SIMULATION RESULTS

Magnetic Vortex Formation

As the filamentary structures evolve, MDVs appear in the upstream region as discussed in [5]. Figure 1 shows a schematic of the interaction of two interpenetrating electron/ion beams. The bottom panel shows the color plot of the out-of-plane magnetic field B_y in the $x-z$ plane at $t\omega_{pe} = 1140$, as well as the MDVs in the upstream region (as marked) in the simulation. The dashed line is where the incoming e/i beams meet the counterstreams. Transversely averaged plasma density normalized to unperturbed upstream density (black) is overlaid on the color plot of the magnetic field. MDVs propagate opposite to the shock propagation direction (+x) and interact with neighboring MDVs over time, as can be seen in successive B_y snapshots (Fig. 2).

MDV Merging and Magnetic Field Amplification

Figure 2 shows the merging process of the MDVs in the upstream region. The three columns display the charge density, the longitudinal current density J_x, and the transverse magnetic field B_y, respectively. Each row corresponds to a simulation time.

At early times, filamentary structures are visible in both the charge density and current density distributions. These filaments become increasingly pronounced as the merging occurs, and the magnetic field grows by the merging process. At later times, neighboring MDVs approach each other and merge. This behavior is visible in both the current density and magnetic field distributions. Figure 3 shows cross-sectional profiles of $B_y(z)$ extracted across the vortex structures before and after merging. The plots of charge density and longitudinal current density show that MDV merging happens due to the incoming stream's ion flow. Plots of charge density show ion currents in the middle of MDVs with electrons in the periphery. The plots of longitudinal current density show the direction of flow, which is in the $-x$ direction, opposite to the shock propagation direction.

In Fig. 3, we notice that before merging, localized peaks in B_y are observed at around 10 in normalized units. Similar behavior is observed by the transverse induced electric field ($E_z \approx v_x B_y / c$), as can be seen in Fig. 3. After merging, the peaks increase to approximately 15, and the spatial extent of the resulting MDVs expands. Multiple merging events follow a similar pattern, with consistent amplification of the peak B_y and growth of larger coherent magnetic structures.

DISCUSSION

The simulation results indicate that magnetic field amplification in the upstream region of relativistic collisionless shocks is primarily driven by the interplay of ion dynamics, filament interactions, and MDVs merging. Initially, the Weibel instability generates transverse current filaments accompanied by small-scale magnetic fields, as observed in Fig. 1. These filaments are subsequently reinforced by the motion of incoming ions, which sustain and strengthen the longitudinal current channels. This ion-driven reinforcement increases the stability and amplitude of the filaments, allowing magnetic structures to persist and grow beyond the electron-scale saturation.

Parallel current filaments attract one another due to Ampère's force law, leading to the coalescence of neighboring filaments. This attraction drives the merging of MDVs, as evident in the magnetic field evolution shown in Fig. 3. During merging events, the resulting MDV is transferred from smaller-scale filaments to larger, more coherent MDV structures, producing an increase in both the peak magnetic field amplitude and the spatial extent of the magnetic structures. In our simulations, the peak magnetic field increases from approximately 10 to 15 in normalized PIC units during vortex merging events, corresponding to an amplification of roughly 50%. This behavior is analogous to an inverse cascade in turbulent plasma, where chaotic, small-scale motions can generate massive, long-lived magnetic fields. Compared with previous studies [2, 4, 5], our work emphasizes the role of MDVs merging as a distinct mechanism for magnetic amplification of the MDVs. While earlier research highlighted MDVs generation and growth, we explicitly show that successive MDV coalescence contributes to amplifying the magnetic field and spatial coherence. The consistent amplification observed across multiple merging events suggests that this process may play a significant role in shaping the large-scale magnetic structure upstream of relativistic shocks. MDVs in the upstream region of relativistic electron/ion collisionless shocks play an important role in the preacceleration of both electrons and ions which then participate in the Fermi mechanism [8]. The energy gain of particles in the upstream region happens during the interaction of particles with evolving fields of MDVs. As MDVs evolve, their electromagnetic fields increase. Particles can gain a significant amount of energy during a short interaction with MDVs. The preaccelerated particles moving toward a shock can participate in the Fermi acceleration process in the shock transition region.

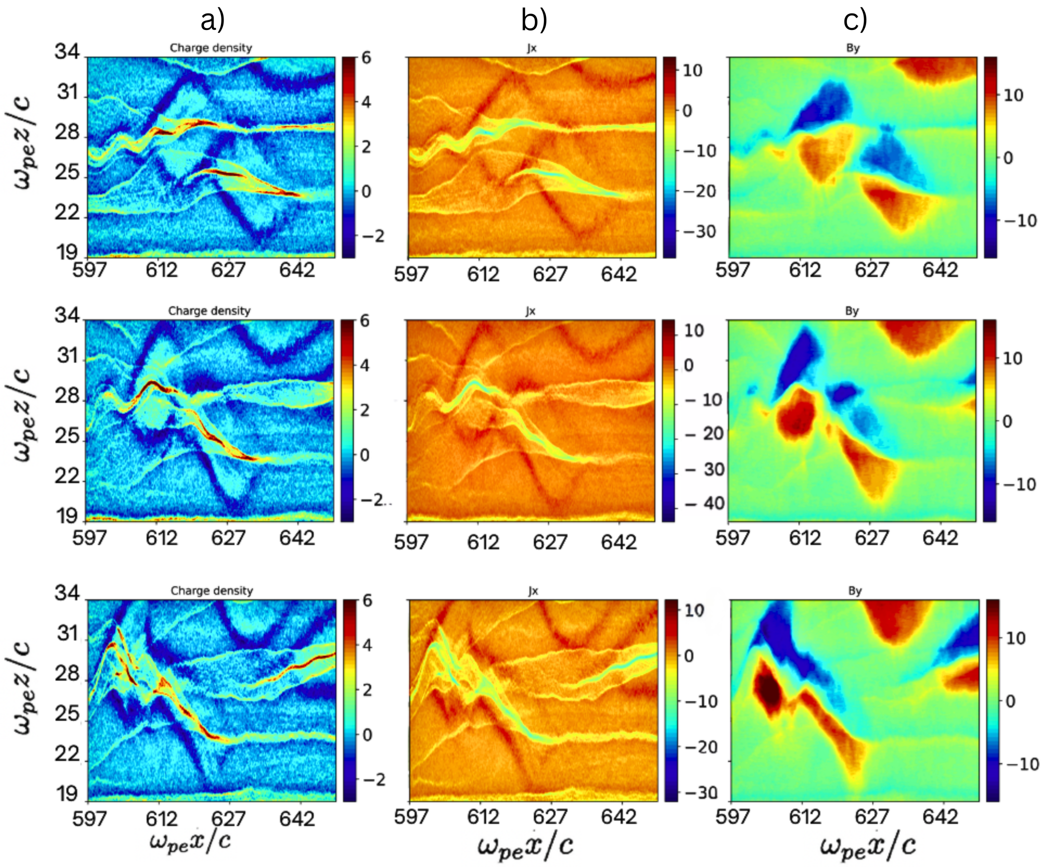

FIGURE 2. Temporal evolution of plasma structures showing the development of current filaments and early dipole-like magnetic structures at at $\omega_{pe}t = 726,\ 745,\ 760$, respectively. Columns correspond to (a) charge density, (b) longitudinal current density J_x, and (c) transverse magnetic field B_y. Rows show successive times from early to intermediate stages of the simulation. All quantities are in normalized PIC units.

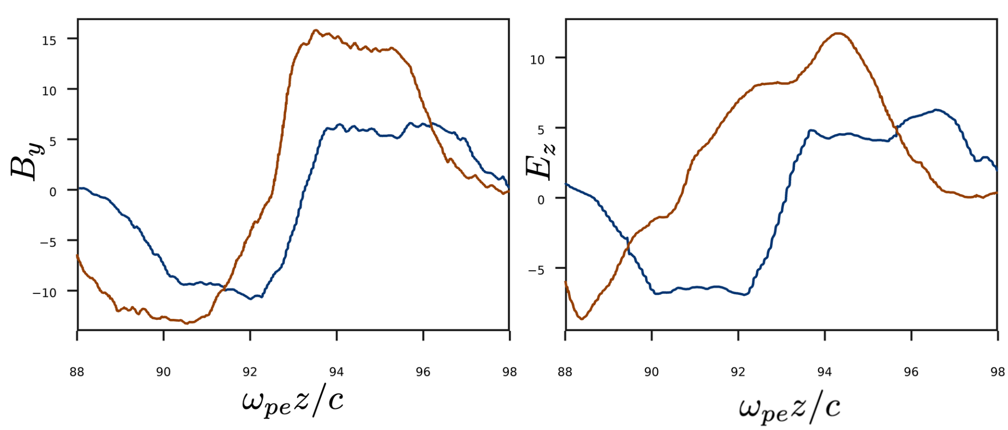

FIGURE 3. Evolution of the out-of-plane magnetic field B_y and transverse electric field E_z during MDV merging event at $\omega_{pe}t = 726,\ 760$. The panels compare profiles before (blue) and after (orange) the merging event. Following the interaction, the peak B_y increases from approximately 10 to about 15 in normalized units, and the transverse spatial extent of the magnetic structure broadens. E_z follows the same behavior.

CONCLUSION

In this paper, we analyzed particle-in-cell simulation data to investigate the merging of MDVs in the upstream of relativistic collisionless shocks. The simulations show that counter-streaming plasma flows generate current filaments through the Weibel instability, which subsequently evolve into MDVs propagating toward the shock transition region. These MDVs interact and undergo a merging process during the nonlinear stage. Merging leads to both an increase in peak magnetic field amplitude and an expansion of the magnetic structure size. Extracted magnetic field profiles indicate that peak strength of the magnetic (and transverse electric) fields increases by approximately a factor of 1.5 during these events, demonstrating that merging provides additional amplification beyond MDV generation and growth. MDV merging thus contributes to the nonlinear evolution of magnetic turbulence, transferring energy from smaller filamentary structures to larger coherent MDVs and increasing both the amplitude and spatial scale of upstream magnetic fields. This amplification is relevant for astrophysical environments where strong magnetic turbulence is necessary for particle heating and acceleration. These findings provide further insight into mechanisms of magnetic field amplification in relativistic plasma flows and suggest that MDVs merging may influence the efficiency of particle acceleration in high-energy astrophysical systems such as supernova remnants, relativistic jets, and gamma-ray bursts. Future studies will extend this work to investigate the Kelvin Helmholtz instability observed in the simulations, analyzing their impact on heating and magnetic structure dynamics.

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