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ABSTRACT

Collisionless shocks with low Alfvénic Mach numbers are expected to accelerate electrons, but the underlying physics are still unsolved. Two-dimensional particle-in-cell simulation of low-Mach-number quasi-perpendicular shock in low- β is performed to study the physics of formation of beam-like components with respect to background magnetic fields. The incoming electrons can be trapped and scattered to have velocities along the shock surface by the electrostatic wave in the foot region owing to the free energy in the relative drift between shock reflected ions and upstream electrons. Then fractional electrons can be reflected by the mirror force at the shock overshoot when escaping from the loss cone. The reflection by the mirror force makes the electrons gain quasi-parallel velocities, and the electrons are accelerated in the quasi-parallel direction during trapping in the immediate downstream, forming a beam-like component with respect to magnetic fields. Our results shown in this paper explain the physics of beam formation and could be helpful for accounting for type II radio bursts.

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I. INTRODUCTION

Collisionless shocks with a low-Mach-number [Alfvénic Mach number $M_A = 5-10$ (Winske and Quest, 1988)] are ubiquitous in solar and interplanetary environments. An interesting phenomenon related to such shocks is the type II radio burst (Bale *et al.*, 1999), which requires electrons to be reflected and accelerated by the shocks. Many works focusing the study of the electron acceleration mechanism have been reported (Matsukiyo and Matsumoto, 2015; Kobzar *et al.*, 2021; Ha *et al.*, 2021; Kim *et al.*, 2021; and Morris *et al.*, 2022).

In low-Mach-number shocks, electron acceleration via shock surfing acceleration (SSA) could function within the shock transition

region of perpendicular shocks (Umeda *et al.*, 2009). This occurs as reflected ions excite localized current-driven instability, generating large-amplitude electrostatic waves that can capture electrons. In Lembege's two-dimensional (2D) particle-in-cell (PIC) simulations (Lembège and Savoini, 2002), electrons could experience magnetic mirror-type reflection when interacting with the precursor or reflection when interacting with the shock ramp where trapping conditions are met, constraining the electrons within the shock front. Riquelme and Spitkovsky (2011), Guo *et al.* (2014a; 2014b), and Hull *et al.* (2020) used 2D PIC simulations and showed that electrons could be energized near the shocks by the scattering of whistler waves in the shock transition regions and could undergo shock drift acceleration when the electrons are reflected by the

compressed magnetic field at the shock surface. The electrostatic wave, driven by electron cyclotron drift instability (ECDI) caused by shock reflected ion beams and the incoming electrons, was studied in both the observations and simulations, and it was found that the electrostatic wave could strongly heat core and halo electrons and that accelerated electrons had a flat-top distribution in the parallel direction with respect to the magnetic field and a non-thermal, power-law part in the perpendicular direction (Wilson *et al.*, 2010; 2014; 2021; Matsukiyo and Scholer, 2006; and Muschietti and Lembedge, 2013). The electrostatic wave that appeared in the shock transition region, found both in observations and simulations (Wilson *et al.*, 2010; 2014; 2021; Matsukiyo and Scholer, 2006; Muschietti and Lembedge, 2013; and Yang *et al.*, 2018; 2020) can also trap electrons, leading to strong electron heating.

In the earth's bow shocks, Wu (1984) and Leroy and Mangeney (1984) studied energization of solar wind electrons and proposed that electrons can be reflected and accelerated by quasi-perpendicular shocks through the magnetic mirror when the electrons have sufficiently large pitch angles, and Yang *et al.* (2018) performed 2D PIC simulations, revealing nonuniform electron trapping and reflection attributable to shock rippling along the surface of quasi-perpendicular shocks. During the trapping process, electrons were accelerated, forming a non-thermal tail in their energy spectrum.

It is generally thought that electron beams exist in quasi-parallel shocks. However, some observations (Anderson, 1968) and simulations (Savoini and Lembedge, 1994; 2001) have shown that electron beams exist in front of quasi-perpendicular shocks. They find that mirror reflected electrons can form electron rings and these high parallel energy populations may contribute to the upstream wave turbulence. However, more detailed analysis of the acceleration process of the beam still needs to be carried out. Hence, in our present work, using the PIC method, we study the physics of formation of beam-like components with respect to the magnetic field in low-Mach-number quasi-perpendicular shock.

We describe our simulation settings in Sec. II. The main results including the shock structure and the physics of electron acceleration are given in Sec. III, and we give the conclusion and discussion in Sec. IV.

II. NUMERICAL METHOD

Simulation is performed using the PIC code EPOCH (Arber *et al.*, 2015; Yang *et al.*, 2015; and Yu *et al.*, 2022). We set the mass ratio $m_i/m_e = 100$, where m_i and m_e denote the ion's and electron's mass, respectively. When the mass ratio reaches tens (Shimada and Hoshino, 2000; Schmitz *et al.*, 2002; Hoshino and Shimada, 2002; and Matsumoto *et al.*, 2017), the kinetic behavior of electrons and ions can be clearly distinguished. When the electron ion mass ratio is 100, the cyclotron period of the two particles differs by two orders of magnitude. In an ion motion cycle, the electron has undergone 100 rotations, and the change in the electron is large enough, so the motion of the two particles can be clearly distinguished. Limited by the computational resources, the ratio ω_{pe}/ω_{ce} is chosen to be 2.5, which gives the speed of light $c = 25v_A$. $\omega_{pe} = \sqrt{ne^2/\epsilon_0 m_e}$, $\omega_{ce} = eB/m_e$, and $v_A = B/\sqrt{\mu_0 n m_i}$ denote the upstream plasma frequency, electron cyclotron frequency, and

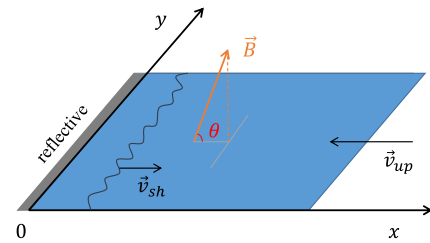


FIG. 1. Illustration of the simulation setup. The upstream flows from the right open boundary with velocity $\vec{v}_{up}$ and is reflected by the left reflective boundary, resulting in a shock propagating to the right, $\vec{v}_{sh}$. The magnetic field $\vec{B}$ lies in the x - z plane, and together with the shock normal direction, it forms an angle θ .

Alfvénic velocity with the plasma number density n , respectively. The present simulation showed here lies in the x - y plane, whereas the magnetic field lies in the x - z plane. The angle θ between the magnetic field and x axis is 75° , as shown in Fig. 1. Simulation has the grids $[n_x, n_y] = [10\,000, 1200]$, with the grid resolution $\Delta x = \Delta y = 0.007c/\omega_{pi}$. Here, $\omega_{pi} = \sqrt{ne^2/\epsilon_0 m_i}$, c represent the ion plasma frequency and light speed, respectively. Each grid has 50 particles per species, which is capable of resolving the acceleration physics of electrons (Guo *et al.*, 2014a). The left boundary of the x direction is set to be reflective at $x = 0$, while the right boundary is open. Both y boundaries are periodic. Initially, the upstream plasma has a bulk velocity $v_{up} = -4v_A$, so the quasi-perpendicular shock is formed by the interaction of the reflected plasma at the left boundary and incoming upstream and propagates to the $+x$ direction with velocity $v_{sh} \sim 2v_A$ in the downstream rest frame. The electron plasma $\beta_e = 0.3$ while the ion plasma $\beta_i = 0.1$ (Yang *et al.*, 2020; Maksimovic *et al.*, 2020; and Liu *et al.*, 2005).

III. SIMULATION RESULTS

Figures 2(a)–2(c) present the snapshots of magnetic fields B_x and B_y and the electric field E_x at time $t = 4.6/\omega_{ci}$. Here, $\omega_{ci} = eB/m_i$ denotes the upstream ion cyclotron frequency. The ion density, derived by averaging along the y direction, is superimposed on panel (c), indicated by the solid line. At this time, the shock ramp is located at about $x = 10c/\omega_{pi}$, as indicated by the maximal density. The foot, formed by accumulation of reflected ions, extends to about $x = 14c/\omega_{pi}$. Both electrostatic and electromagnetic structures are produced within the foot. The electrostatic wave, as shown in E_x in Fig. 2(c), is generated because of the free energy in the relative drift between shock reflected ions and incoming electrons. The electrostatic wave is likely produced by ECDI, as analyzed by Yang *et al.* (2020) in their PIC simulation.

Electrons are scattered by the electrostatic wave in the foot, resulting in movement along the y axis, as also shown in the study by Yang *et al.* (2018). Figure 3(a) shows the part of space distribution of electrons' parallel momenta $p_{||}$, normalized by the electron's momentum with Alfvénic velocity $p_0 = m_e v_A$. To get this panel shown in Fig. 3(a), we interpolate the particle-based parallel momenta to the computational grids in a first order scheme. The parallel momentum of each electron is scattered to the four nodes that make up the cell containing the electron in our 2D simulation,

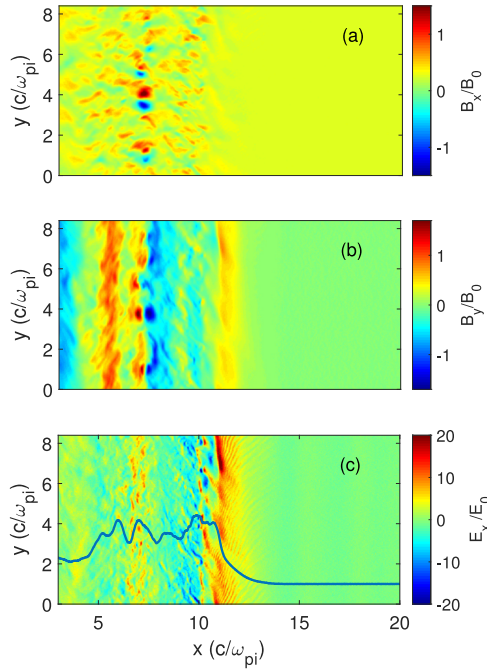


FIG. 2. Snapshots of magnetic and electric fields at $t = 4.6/\omega_{ci}$. The horizontal axis is space x normalized with the ion's inertial length c/ω_{pi} , while the vertical axis is space y . The x and y components of magnetic fields B_x and B_y are shown in (a) and (b), respectively, and magnetic fields are normalized by the upstream magnetic field strength B_0 . The x component electric field E_x is shown in panel (c), and it is normalized by $E_0 = v_A B_0$. The fields contain an electromagnetic structure and electrostatic waves. The solid line in panel (c) is the y -averaged ion density profile, indicating that the shock is located at about $x \sim 10c/\omega_{pi}$ and the foot, formed by accumulating reflected ions, extends to about $x \sim 14c/\omega_{pi}$ at that time.

and then the median value of the interpolated array is imaged. Electrons that accelerated in parallel contribute to the higher energy part, resulting in a color range from yellow to red. In these regions, beam-like components can locally form near the shock. For example, panel (a) presents two local areas marked by colored rectangles whose coordinates (x, y) correspond to $\sim(7.2, 3)c/\omega_{pi}$ and $\sim(7, 4.8)c/\omega_{pi}$, respectively. The arrow in each area indicates the plane projected magnetic fields, whose arrow and length mean the direction and strength, respectively. It shows that magnetic fields near the shock can be distorted and not uniform. Figure 3(b) gives the electron spectra of the two areas. The blue rectangle in Fig. 3(a), centered around the point $[x, y] \sim [7.2, 3]c/\omega_{pi}$, corresponds to the electron spectrum, represented by the blue line in panel (b). The brown line illustrates the electron spectrum derived from the area enclosed by the brown rectangle at $\sim(7, 4.8)c/\omega_{pi}$. The beam component can be distinguished in each spectrum, especially in the momentum range $p \sim (20-40)p_0$ at the high energy tail of the blue spectrum. This demonstrates that field-aligned beams are generated in diverse magnetic fields in the quasi-perpendicular rippling shock, and this result, required theoretically, is consistent with the observed fact (Knock *et al.*, 2001; Puluja and Bale, 2008).

To study the physics of the electron acceleration process, we analyze the evolution of typical non-thermal electrons of the blue spectrum shown in Fig. 3(b). Figure 4(a) gives the temporal evolution of kinetic energy W_k , normalized by the value $m_e v_A^2$, and contributions of electric fields, represented by the work $W_k = \int -eE_k v_k dt$. Here, E_k and v_k correspond to the electric field along the k -axis and electron velocity, respectively. Figure 4(b) gives the history of the trajectory of $p_{\parallel} - p_{\perp}$ momentum. Figure 4(a) shows that the increase in kinetic energy almost comes from the work carried out by E_z , where the black line has the same tendency as the blue line at interval $t \sim (3.5-4.6)/\omega_{ci}$, during which the electron is captured in the immediate shock region.

Three acceleration phases are selected for showing the details of the acceleration process, as shown in Fig. 5. The shock propagates from $x = 6c/\omega_{pi}$ at $t = 3.2/\omega_{ci}$ [Fig. 5(a)] to $x = 10c/\omega_{pi}$ at $t = 4.6/\omega_{ci}$ [Fig. 5(c)]. After crossing the shock overshoot at $t = 3.2/\omega_{ci}$, the electron encounters a monopole electric field, indicated by the reversed arrows in Fig. 5(a). The electric component pointing toward the foot at the shock overshoot $x = 6c/\omega_{ci}$ and the newly formed shock overshoot at $x = 8c/\omega_{ci}$ are associated with the shock potential, while the electric field pointing downstream in the immediate downstream region is produced according to $\vec{E} = -\vec{v} \times \vec{B}$ as the plasma flow has the y direction velocity. Trapped by the monopole electric field, the electron begins moving with the shock, as indicated by Fig. 5(a), where the trajectory is refracted at the shock overshoot and then moves in the x direction.

Besides the trapping process resulting in moving with the shock, the electron is reflected by the compressed magnetic field when crossing the shock at $t = 3.2/\omega_{ci}$. This process is the same as the “mirror reflection” that electrons undergo, and the adiabatic process can be reflected by the magnetic variation if it is out of the loss cone (Wu, 1984; Leroy and Mangeney, 1984; and Guo *et al.*, 2014a). As shown in Fig. 4(a), the magnetic moment μ of the electron remains almost a constant, which means the adiabatic process is not broken. The electron gets the quasi-parallel velocity v_z after experiencing reflection and gains energy from the motional electric field E_z as the increase in the kinetic energy is coincident with the work performed by the electric field. This process accounts for the increase in $p_{\parallel}$, shown in Fig. 4(b). When scattered at the shock at $t = 3.2/\omega_{ci}$ and residing in the immediate shock in the interval $t \sim (3.2-4.6)/\omega_{ci}$, the electron gyrates in the x - y plane, moving in the z direction and resulting in a slightly parallel energy pickup in every period.

In order to investigate the efficiency of the “mirror reflection” and the conditions under which the upstream electrons can participate in the reflection, it is convenient to analyze the electrons in the Hoffman–Teller (HT) frame (Wu, 1984; Leroy and Mangeney, 1984; and De Hoffmann and Teller, 1950) and upstream rest frame. In the HT frame, motional electric fields vanish on both sides of the shock, and the mirror model can be applied. The HT frame can be derived by boosting the upstream rest frame along the magnetic field with velocity

$$v_t = v_{sh-up} / \cos \theta. \quad (1)$$

Here, v_{sh-up} represents the shock velocity in the upstream rest frame. As the motional electric fields are vanishing in the HT frame,

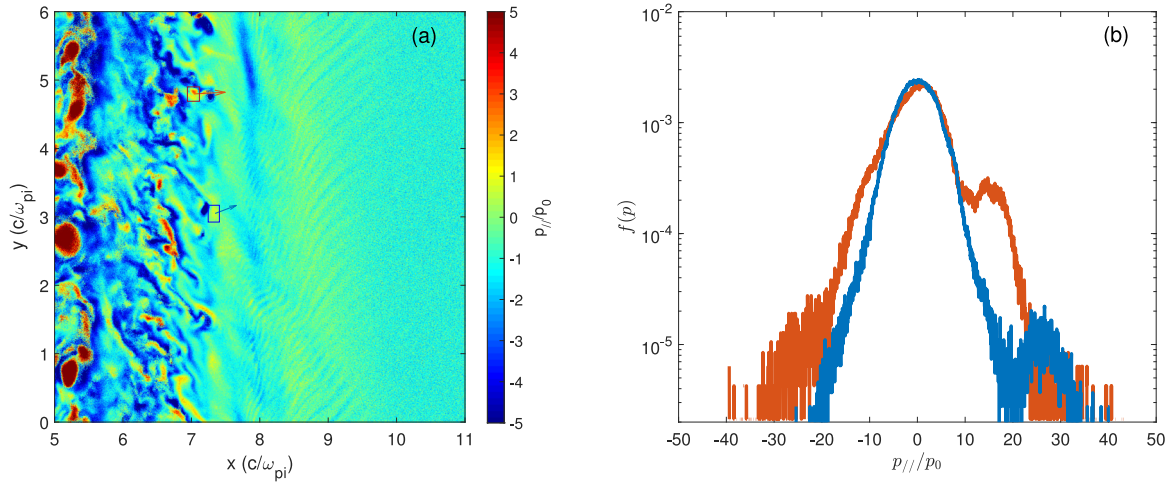


FIG. 3. (a) Spatial snapshot of electrons' parallel momenta $p_{\parallel}$ at $t = 4.6/\omega_{ci}$. The momenta are normalized by the value $p_0 = m_e v_A$. We choose the median of the array of interpolated parallel momenta by depositing the particles' parallel momenta to the meshes. Relatively narrow momentum scales are chosen for showing the enhancement near the shock clearly. The arrows indicate the plane projected magnetic fields. Arrows and their length represent the direction and strength of the projected field. The field in each local rectangle area (B_x, B_y, B_z) is $(0.4572, 0.0242, 4.0040)B_0$ for the rectangle area $y \sim 4.8c/\omega_{pi}$ and $(0.3086, 0.1170, 3.7515)B_0$ for the rectangle area $y \sim 3c/\omega_{pi}$. Fields are represented by the mean values of the small local regions. (b) Normalized electron spectra with respect to $p_{\parallel}$ of the local regions, as depicted in the colored rectangles in (a) that are located at $y \sim 3c/\omega_{pi}$ and $y \sim 4.8c/\omega_{pi}$. The blue spectrum corresponds to the region in the blue rectangle $x = [2.925, 3.125]c/\omega_{pi}$, $y = [7.250, 7.445]c/\omega_{pi}$ whereas the brown spectrum corresponds to the region in the brown rectangle $x = [4.695, 4.9]c/\omega_{pi}$, $y = [6.95, 7.125]c/\omega_{pi}$.

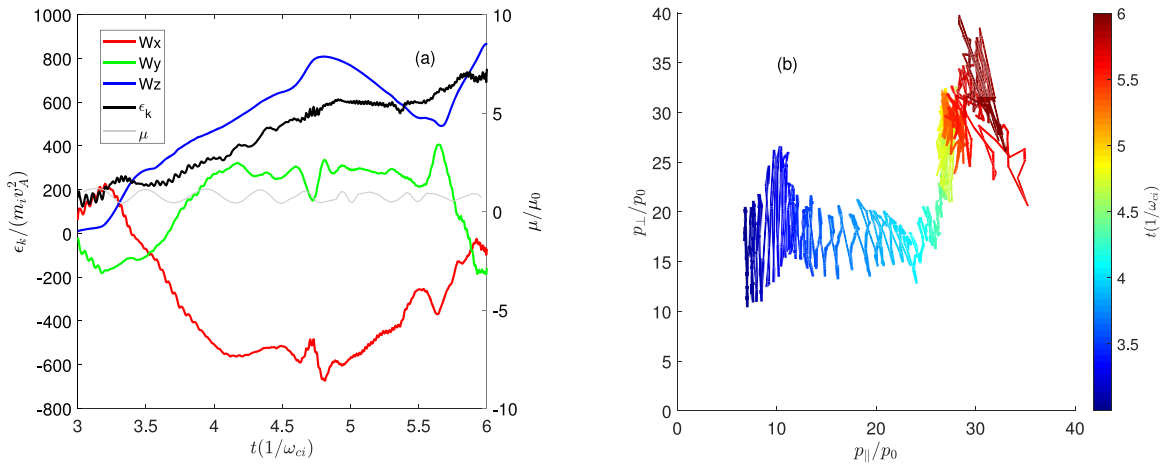


FIG. 4. (a) Temporal evolution of energy W_k of the accelerated electron is depicted by the black line, and each energy gain due to the work carried out by electric fields E_x , E_y , or E_z is depicted by red, green, and blue lines, respectively. The gray line represents the magnetic moment μ normalized by the electron's magnetic moment $\mu_0 = p_0^2/(2m_e B_0)$ at the trace start time $t = 3/\omega_{ci}$. The horizontal axis that denotes time is normalized with the inverse ion's frequency. (b) The electron's orbit in $p_{\parallel} - p_{\perp}$ momentum space with color-coded timescale. Both are normalized with the value $p_0 = m_e v_A$.

electrons' energy and magnetic moment μ can be assumed to be conserved,

$$\gamma^{HT}(x)m_e c^2 - e\phi^{HT}(x) = \text{const}, \quad (2)$$

$$\mu^{HT}(x) \equiv \frac{[p_{\perp}^{HT}(x)]^2}{2m_e B^{HT}(x)} = \text{const}. \quad (3)$$

Here, quantities with superscript HT are measured in the HT frame. Parallel velocities in the HT frame $v_{\parallel}^{HT}$ can be obtained by combining Eqs. (2) and (3),

$$v_{\parallel}^{HT}(x) = c \sqrt{1 - \frac{E_e'^2 + E_k'^2 (v_{\perp}/c)^2 r_B(x)}{[\Delta\phi(x) + E_k']^2}}, \quad (4)$$

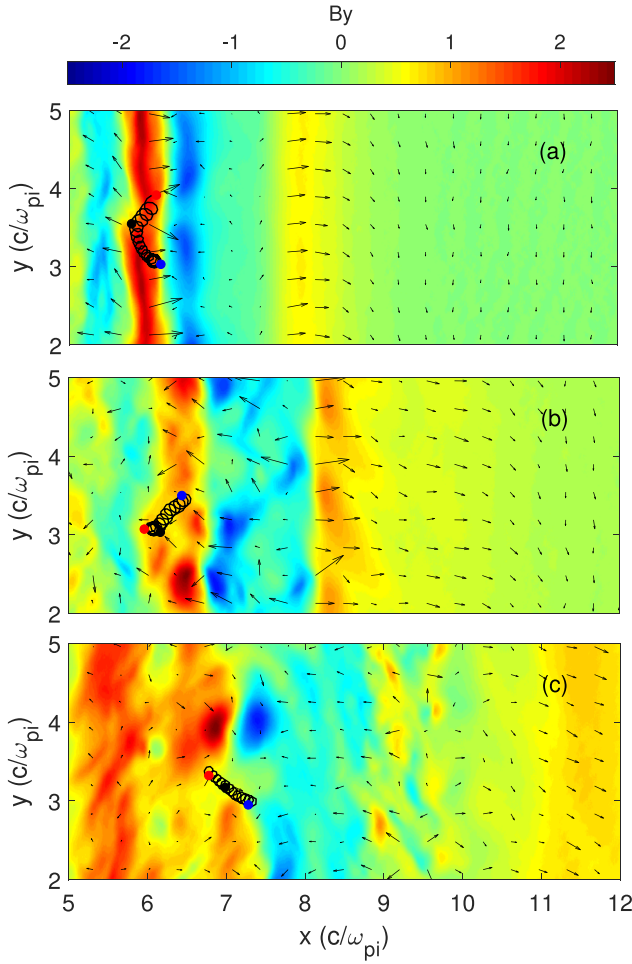


FIG. 5. Three different field snapshots of B_y with parts of trajectories. (a) Snapshot at $t = 3.2/\omega_{ci}$. The trajectory starts from $t = 3/\omega_{ci}$ to $t = 3.6/\omega_{ci}$. (b) Snapshot at $t = 3.6/\omega_{ci}$. The trajectory starts from $t = 3.4/\omega_{ci}$ to $t = 4/\omega_{ci}$. (c) Snapshot at $t = 4.4/\omega_{ci}$. The trajectory starts from $t = 4.2/\omega_{ci}$ to $t = 4.6/\omega_{ci}$. The start time in each panel is marked by a red dot while the end time is marked by a blue dot. The position of the electron at the time of the field snapshot is marked by a black dot. Arrows in the figure represent the strength and orientation of electric field in the simulation plane, with the vector (E_x, E_y) .

where $r_B = B^{HT}(x)/B_0^{HT}$ and $E'_e = m_e c^2 / (m_e v_{up}^2 / 2)$. $E'_k = \gamma^{HT} m_e c^2 / (m_e v_{up}^2 / 2)$ and $\Delta\phi(x) = e[\phi^{HT}(x) - \phi_0^{HT}] / (m_e v_{up}^2 / 2)$ represent the electron energy and electric potential change scaled with the upstream electron kinetic energy $E_{e-up} = m_e v_{up}^2 / 2$, respectively. In this frame, the electron that undergoes mirror reflection should satisfy the condition that it moves toward the shock, which gives a limit to the parallel velocity,

$$v_{\parallel}^{HT} < 0, \quad (5)$$

which naturally gives the result

$$v_{\perp}^{HT} \geq c \sqrt{\frac{1}{r_B(x)} \frac{[\Delta\phi(x) + E'_k]^2 - E_e'^2}{E_k'^2}}. \quad (6)$$

However, it is more convenient to illustrate the reflection in the upstream rest frame. The reflection conditions can be obtained in upstream parallel and perpendicular velocities $u_{\parallel-up}, v_{\perp-up}$ by the relationship of transformation,

$$v_{\parallel}^{HT} = \frac{v_{\parallel-up} - u_t}{1 - v_{\parallel-up} v_t / c^2}, \quad (7)$$

$$v_{\perp}^{HT} = \frac{v_{\perp-up}}{\gamma_t (1 - v_{\parallel-up} v_t / c^2)}, \quad (8)$$

where $\gamma_t = 1/\sqrt{1 - u_t^2/c^2}$ is the Lorentz factor of the boosted velocity.

It is thought that electric and magnetic fields are time-varying in PIC simulations. However, this so called fast Fermi reflection (Wu, 1984; Leroy and Mangeney, 1984) is still taken into consideration for electron acceleration around the shocks, as can be found in plenty of observations (Anderson, 1968), even though there are large amplitude fluctuating electric fields in the events.

Figure 6 displays the phase space distribution of electrons in the upstream rest frame. Most electrons are centered around $v_{\parallel-up} = 0$, but with a slight shift opposite to the magnetic field, as the shock potential ahead of the shock attracts the electrons to the shock. There is an obvious component with large parallel and perpendicular velocities at the top right corner. However, the velocities of the electrons cannot exceed the speed of light ($c = 25v_A$) since the electrons are distributed within the region enclosed by the white circle. The green line indicates the boosting velocity v_t from the HT to upstream rest frame. The dashed red line represents the limit of Eq. (6) with $\Delta\phi = 0$, an ideal situation when the shock potential vanishes, while the solid red line represents the limit with $\Delta\phi = 40$, the typical value of the shock potential (Amano and Hoshino, 2007). Only the electrons with parallel velocities $v_{\parallel-up} \leq v_t$, as required by condition Eq. (5), and perpendicular velocities that are larger than the limits of red lines [Eq. (6)] can be reflected. Note that the reflection efficiency of electrons when shock potential exists is lower than the situation when the potential vanishes. This is also the effect of the shock potential, which prefers attracting electrons to the shock surface and results in the number of electrons out of the loss cone to decrease.

After encountering the shock overshoot, a percentage of the reflected electrons still move like beams with respect to the magnetic fields. Figure 7 shows the trajectories of 120 electrons in the area marked by the blue rectangle in Fig. 3(a) at $t = 4.6/\omega_{ci}$. In our simulation, at time $t = 4.6/\omega_{ci}$, there are 10761 traced electrons in the black rectangle area, and 120 traced electrons form the beam-like component whose parallel momenta lie in the range $20 < p_{\parallel} < 35$. By gathering the trajectories of these beam-like component electrons, we can visualize their collective motion, as depicted in Fig. 7. The beam-like component electrons move upstream initially and are scattered by the electrostatic wave in the foot when encountering the shock transition region, resulting in energy gain in the y direction. This is further evidenced by the bends of trajectories around $x \sim 8c/\omega_{pi}$ in Fig. 7. The electrons are reflected by the shock overshoot at $x = 6c/\omega_{pi}$ when approaching the shock ramp and then trapped in the immediate downstream region and moves with the shock, as also indicated by Fig. 5(b). As can be seen in Fig. 7, the

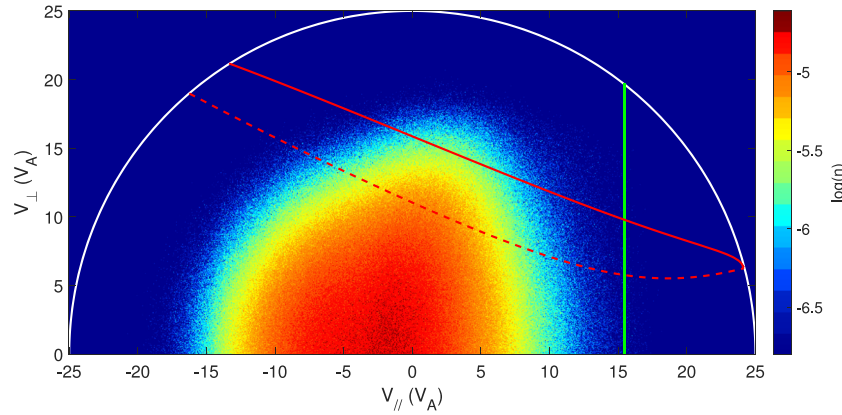


FIG. 6. Phase space distribution ($v_{\parallel-up} - v_{\perp-up}$) of electrons located at $10c/\omega_{pi} \leq x \leq 14c/\omega_{pi}$ at $t = 4.6/\omega_{ci}$, calculated in the upstream rest frame. The white curve represents the speed of light $c = 25v_A$ used in the simulation. The green vertical line represents the boosting velocity v_t that transforms the coordinates between HT and upstream frames. The dashed and solid red lines represent reflection thresholds with shock potential $\Delta\phi = 0$ and $\Delta\phi = 40E_{e-up}$, respectively. The shock potential is normalized by the upstream electron kinetic energy $E_{e-up} = m_e v_{up}^2/2$. The distribution is normalized by the total number of sampled electrons.

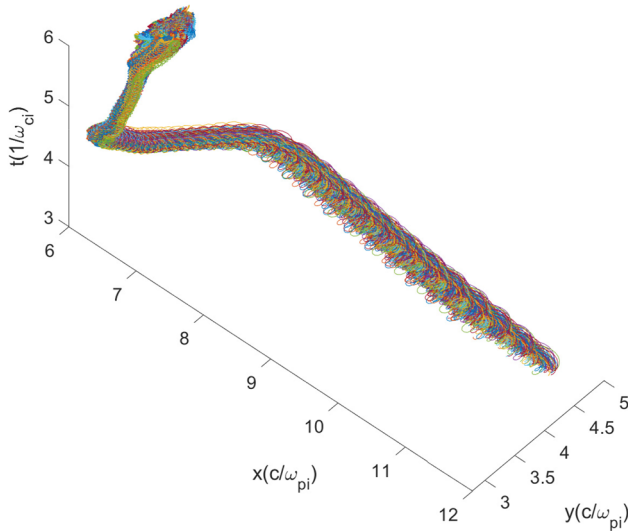


FIG. 7. Trajectories of 120 electrons that reside in the blue rectangle in Fig. 3(a) at $t = 4.6/\omega_{ci}$ with parallel momenta $0.2 < p_{\parallel} < 0.35$. Traces of the 120 electrons start from upstream at $t = 3/\omega_{ci}$ and terminate at $t = 6/\omega_{ci}$. Note that there are 10 761 traced electrons in the blue rectangle area in Fig. 3(a) at $t = 4.6/\omega_{ci}$ and that the number of electrons that trajectories show here is 1.1% of the number of electrons that has been traced in the blue rectangle in Fig. 3(a) at $t = 4.6/\omega_{ci}$.

electrons keep the beam with respect to magnetic fields during the whole acceleration process.

IV. CONCLUSION AND DISCUSSION

Most of the earlier works (Guo *et al.*, 2014; Riquelme and Spitkovsky, 2011; Kobzar *et al.*, 2021; and Ha *et al.*, 2021) have focused on the “electron injection problem” required by the shock diffusive acceleration theory, which could not be directly invoked to

account for the acceleration of electrons for the initial small gyro-radii of the electrons. Some other PIC simulations have investigated the reflection of electrons by shocks (Yang *et al.*, 2018; Lembège and Savoini, 2002). However, the detailed physics of acceleration of electron beam-like components with respect to magnetic fields and characteristics of beam behavior have not been analyzed, which is our interest in the present work.

We have performed 2D PIC simulation to analyze the physics of electron beam formation in the low-Mach-number quasi-perpendicular shock. By focusing on the details of acceleration of selected electrons, we find that

1. upstream electrons can be trapped and scattered to gain velocities along the shock surface by the electrostatic fluctuations appearing in the foot region. Then fractional electrons can be reflected, and by magnetic mirror force at the shock overshoot, they can gain quasi-parallel velocity v_z . After crossing the shock, the electrons are trapped in the immediate downstream, moving with the shock. Meanwhile, the electrons gain energy from motional electric field E_z , forming a beam-like component in the parallel direction with respect to the magnetic field.
2. compared to the results that were derived by Savoini and Lembège (1994), we calculate the phase distribution with *in situ* magnetic fields. We reproduce the bump-on-tail parallel distribution in different local regions near the shock surface, even though the local magnetic fields have diverse orientations resulting from shock rippling. We provide direct evidence that electrons forming the bump-on-tail components behave like a beam, which can be clearly seen by the non-diffusion of the cluster of electrons.

It is necessary to note that the value of ω_{pe}/ω_{ce} varies in different astrophysical backgrounds. In space physics, $\omega_{pe}/\omega_{ce} \sim 10-100$, while in the galaxy cluster, $\omega_{pe}/\omega_{ce} \sim 2$. We have also performed test simulation with $\omega_{pe}/\omega_{ce} = 5$ while other parameters are kept the same, which gives the same physics. Furthermore, we have also

performed two other simulations with larger and smaller θ angles: $\theta = 70^\circ$ and $\theta = 80^\circ$. The beam components can be observed in all simulations and they commonly result in low-Mach-number quasi-perpendicular shocks. The beam, by theory, accounted for type II radio bursts. The trapping process allows the electrons to accelerate locally, and this character presented in our work may also account for the frequency shift of type II solar radio bursts.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Chunkai Yu: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Resources (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Jian Zheng:** Conceptualization (equal); Funding acquisition (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal). **Quanming Lu:** Supervision (equal); Validation (equal); Writing – review & editing (equal). **Zhongwei Yang:** Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Project administration (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **Xinliang Gao:** Validation (equal); Writing – original draft (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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