Abstract. Shock acceleration is an ubiquitous phenomenon in astrophysical plasmas. Plasma waves and their associated instabilities (e.g., Buneman, Weibel and other two-stream instabilities) created in collisionless shocks are responsible for particle (electron, positron, and ion) acceleration. Using a 3-D relativistic electromagnetic particle (REMP) code, we have investigated particle acceleration associated with a relativistic jet front propagating into an ambient plasma with and without initial magnetic fields. We find small differences in the results for no ambient and modest ambient magnetic fields. Simulations show that the Weibel instability created in the collisionless shock front accelerates jet and ambient particles both perpendicular and parallel to the jet propagation direction. The non-linear fluctuation amplitudes of densities, currents, electric, and magnetic fields in the electron-positron shock are larger than those found in the electron-ion shock at the same simulation time. This comes from the fact that both electrons and positrons contribute to generation of the Weibel instability. While some Fermi acceleration may occur at the jet front, the majority of electron and positron acceleration takes place behind the jet front and cannot be characterized as Fermi acceleration. The simulation results show that the Weibel instability is responsible for generating and amplifying nonuniform, small-scale (mainly transverse) magnetic fields which contribute to the electron’s (positron’s) transverse deflection behind the jet head. This small scale magnetic field structure is appropriate to the generation of “jitter” radiation from deflected electrons (positrons) as opposed to synchrotron radiation. The jitter radiation has different properties than synchrotron radiation calculated assuming a uniform magnetic field. The jitter radiation resulting from small scale magnetic field structures may be important for understanding the complex time structure and spectral evolution observed in gamma-ray bursts and other astrophysical sources containing relativistic jets and relativistic collisionless shocks.

INTRODUCTION

Nonthermal radiation observed from astrophysical systems containing relativistic jets and shocks, e.g., active galactic nuclei (AGNs), gamma-ray bursts (GRBs), and Galactic microquasar systems usually has power-law emission spectra. In most of these systems,
the emission is thought to be generated by accelerated electrons through the synchrotron and/or inverse Compton mechanisms. Radiation from these systems is observed from the radio through the gamma-ray region. Radiation in optical and higher frequencies typically requires particle acceleration in order to counter radiative losses. It has been proposed that the needed particle acceleration occurs in shocks produced by differences in flow speed.

Particle-in-cell (PIC) simulations can shed light on the physical mechanism of particle acceleration that occurs in the complicated dynamics within relativistic shocks. Recent PIC simulations using injected relativistic electron-ion jets show that acceleration occurs within the downstream jet, rather than by the scattering of particles back and forth across the shock as in Fermi acceleration [2, 3, 8, 9]. Silva et al. [10] have presented simulations of the collision of two inter-penetrating electron-positron plasma shells as a model of an astrophysical collisionless shock. In the electron-positron simulations performed with counter-streaming jets [10], shock dynamics involving the propagating jet head (where Fermi acceleration may take place) was not investigated. In general, these independent simulations have confirmed that relativistic jets excite the Weibel instability [11]. The Weibel instability generates current filaments and associated magnetic fields [7], and accelerates electrons [10, 2, 5, 8, 4].

In this paper we present new simulation results of particle acceleration and magnetic field generation for relativistic electron-positron and electron-ion shocks using 3-D relativistic electromagnetic particle-in-cell (REMP) simulations. In our new simulations, electron-positron and electron-ion relativistic jets with Lorentz factor, \( \gamma = 5 \) (corresponds to 2.5 MeV) is injected into electron-positron and electron-ion plasmas in order to study the dynamics of a relativistic collisionless shock both with and without an initial ambient magnetic field.

**SIMULATION SETUP AND RESULTS**

Four simulations were performed using an \( 85 \times 85 \times 320 \) grid with a total of 180 million particles (27 particles/cell/species for the ambient plasma) and an electron skin depth, \( \lambda_{ce} = c/\omega_{pe} = 9.6\Delta \), where \( \omega_{pe} = (4\pi e^2 n_e/m_e)^{1/2} \) is the electron plasma frequency and \( \Delta \) is the grid size. In all simulations jets are injected at \( z = 25\Delta \) in the positive \( z \) direction. In all simulations radiating boundary conditions were used on the planes at \( z = 0, z_{\text{max}} \). Periodic boundary conditions were used on all other boundaries [1].

In two simulations an electron-positron jet is injected into a magnetized and unmagnetized electron-positron ambient plasma and in two simulations an electron-ion jet is injected into a magnetized and unmagnetized electron-ion ambient plasma. The choice of parameters and simulations allows comparison with previous simulations [10, 2, 3, 8, 9].

The electron number density of the jet is \( 0.741n_b \), where \( n_b \) is the density of ambient (background) electrons. The average jet velocity is \( v_j = 0.9798c \), and the corresponding Lorentz factor is 5. The jet is cold (\( v_{j,\text{th}}^e = v_{j,\text{th}}^p = 0.01c \) and \( v_{j,\text{th}}^i = 0.0022c \) in the laboratory frame). The ambient and jet electron-positron plasma has mass ratio \( m_p/m_e \equiv m_{e^+/e^-} = 1 \) (\( m_i/m_e = 20 \)). The electron and ion thermal velocities in the ambient
plasma are $v_{\text{th}}^e = 0.1c$ and $v_{\text{th}}^i = 0.022$, respectively, where $c$ is the speed of light. The time step $t = 0.013/\omega_{\text{pe}}$, the ratio $\omega_{\text{pe}}/\Omega_e = 11.5$, and the Alfvén speed (for electrons) $v_{\text{Ae}} \equiv (\Omega_e/\omega_{\text{pe}})c = 8.66 \times 10^{-2}c$. With the speed of an Alfvén wave given by $v_{\text{A}} = [V_{\text{A}}^2/(1 + V_{\text{A}}^2/c^2)]^{1/2} = 6.10 \times 10^{-2}c$ where $V_{\text{A}} \equiv [B^2/4\pi(n_em_e + n_pm_p)]^{1/2} = 6.12 \times 10^{-2}c$, the Alfvén Mach number $M_{\text{A}} \equiv v_j/v_{\text{A}} = 16.0$. With a magnetosonic speed $v_{\text{ms}} \equiv (v_{\text{th}}^e + v_{\text{A}})^{1/2} = 0.132c$ the magnetosonic Mach number $M_{\text{ms}} \equiv v_j/v_{\text{ms}} = 7.406$. At least approximately the appropriate relativistic Mach numbers multiply these values by the Lorentz factor. Thus, in an MHD approximation we are dealing with a high Mach number shock with $\gamma M >> 1$. The gyroradius of ambient electrons and positrons with $v_{\perp} = v_{\text{th}} = 0.1c$ is $11.1\Delta = 1.154\lambda_{ce}$ (for ambient ions: $49.6\Delta = 5.16\lambda_{ce}$). All the Mach numbers with electron-ion jets are approximately increased by $\sqrt{m_i/m_e} = \sqrt{20} = 4.47$.

**FIGURE 1.** 2D images in the $x-y$ plane at $z = 230\Delta$ for a flat jet injected into a unmagnetized ((a) and (b)) and magnetized ((c) and (d)) ambient medium shown at $t = 28.8/\omega_{\text{pe}}$. Colors indicate the $z$-component of the current density ($J_z$) ((a) and (c): electron-positron, (b) and (d): electron-ion) (peaks: (a) $\pm 54.7$, (b) $-123.6$, (c) $\pm 58.0$, (d) $-135.5$ with $B_x, B_y$ indicated by the arrows.
Current filaments resulting from development of the Weibel instability behind the jet front (at $z = 230 \Delta$) are shown in Figure 1 at time $t = 28.8/\omega_{pe}$ for four different cases. The upper two panels (a and b) show for unmagnetized ambient plasmas and the lower two panels (c and d) are for magnetized ambient plasmas. In cases (a and c) an electron-positron jet is injected in an electron-positron ambient plasma. An electron-ion jet is injected in an electron-ion ambient plasma (b and d). The maximum values of $J_z$ are (a) $\pm 54.7$, (b) $-123.6$, (c) $\pm 58.0$, and (d) $-135.5$. The electro-positron jets show electron (negative) and positron (positive) current filamentations, since both species contribute to the Weibel instability. On the other hind, at this simulation time mainly electron jets generate (negative) current filamentations as shown in Figs. 1 b and 1d. The effect of weak ambient magnetic fields increase the maximum values of current filamentations.
slightly.

The electrons are deflected by the transverse magnetic fields \( (B_x, B_y) \) via the Lorentz force: \(-e(v \times B)\), generated by current filaments \( (J_z) \), which in turn enhance the transverse magnetic fields \([11, 7]\). The complicated filamented structures resulting from the Weibel instability have diameters on the order of the electron skin depth \( (\lambda_{ce} = 9.6\Delta) \). This is in good agreement with the prediction of \( \lambda \approx 2^{1/4}c\gamma_{th}^{1/2}/\omega_{pe} \approx 1.188\lambda_{ce} = 11.4\Delta \) \([7]\). Here, \( \gamma_{th} \sim 1 \) is a thermal Lorentz factor. However, in the electron-positron jets the current filaments are coalesced in the transverse direction, and this shows the nonlinear evolution. The longitudinal current \( (J_z) \) in the electron-positron jets \( (a \text{ and } c) \) shows significantly more transverse variation than in the electron-ion jets \( (b \text{ and } d) \).

The acceleration of electrons has been reported in previous work \([10, 2, 3, 8, 9, 4]\). Figure 2 shows that the cold jet electrons are accelerated and decelerated. As expected, at this time jet electrons in the electron-positron jets are thermalized more strongly than in the electron-ion jets. The blue curves in Figs. 2b and 2d is close to the initial distribution of injected jet electrons. We also see that the kinetic energy \( (parallel \text{ velocity } v_\parallel \approx v_j) \) of the jet electrons is transferred to the perpendicular velocity via the electric and magnetic fields generated by the Weibel instability \([9]\). The strongest transverse acceleration of jet electrons accompanies the strongest deceleration of electron flow and occurs between \( z/\Delta = 210 - 240 \). The transverse acceleration in the electron-positron jets is over four times that in the electron-ion simulations. The strongest acceleration takes place around the maximum amplitude of perturbations due to the Weibel instability at \( z/\Delta \sim 220 \) as seen in Figs 1a and 1c.

**SUMMARY AND DISCUSSION**

We have performed self-consistent, three-dimensional relativistic particle simulations of relativistic electron-positron and electron-ion jets propagating into magnetized and unmagnetized electron-positron and electron-ion ambient plasmas. The main acceleration of electrons takes place in the downstream region. Processes in the relativistic collisionless shock are dominated by structures produced by the Weibel instability. This instability is excited in the downstream region behind the jet head, where electron density perturbations lead to the formation of current filaments \([9]\). The nonuniform electric field and magnetic field structures associated with these current filaments thermalize the jet electrons and positrons, while accelerating the ambient electrons and positrons, and accelerating (heating) the jet and ambient electrons and positrons in the transverse direction.

Other simulations with different skin depths and plasma frequencies show that the growth and structure of current filaments generated by the Weibel instability scale with the plasma frequency and the skin depth \([9]\). An additional simulation in which an electron-ion jet is injected into a ambient plasma with perpendicular magnetic field shows magnetic reconnection due to the generation of an antiparallel magnetic field generated by bending of jet electron trajectories \([5]\).

This small scale magnetic field structure generated by the Weibel instability is appropriate to the generation of “jitter” radiation from deflected electrons (positrons) \([4]\).
The jitter radiation resulting from small scale magnetic field structures needs to be calculated from the trajectories of electrons and positrons (ions) which requires extensive computational resources. This investigation will provide an idea for understanding the complex time structure and spectral evolution observed in gamma-ray bursts and other astrophysical sources containing relativistic jets and relativistic collisionless shocks.

The fundamental characteristics of relativistic shocks are essential for a proper understanding of the prompt gamma-ray and afterglow emission in gamma-ray bursts, and also to an understanding of the particle reacceleration processes and emission from the shocked regions in relativistic AGN jets. Since the shock dynamics is complex and subtle, more comprehensive studies using larger systems are required to better understand the acceleration of electrons, the generation of magnetic fields and the associated emission. This further study will provide the insight into basic relativistic collisionless shock characteristics needed to provide a firm physical basis for modeling the emission from shocks in relativistic flows.

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