# Particle Acceleration and Radiation associated with Magnetic Field Generation from Relativistic Collisionless Shocks

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**Abstract.** Shock acceleration is an ubiquitous phenomenon in astrophysical plasmas. Plasma waves and their associated instabilities (e.g., the Buneman instability, two-streaming instability, and the Weibel instability) created in the 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 through an ambient plasma with and without initial magnetic fields. We find only small differences in the results between no ambient and weak ambient magnetic fields. Simulations show that the Weibel instability created in the collisionless shock front accelerates particles perpendicular and parallel to the jet propagation direction. The simulation results show that this instability is responsible for generating and amplifying highly nonuniform, small-scale magnetic fields, which contribute to the electron's transverse deflection behind the jet head. The "jitter" radiation from deflected electrons has different properties than synchrotron radiation which is calculated in a uniform magnetic field. This jitter radiation may be important to understanding the complex time evolution and/or spectral structure in gamma-ray bursts, relativistic jets, and supernova remnants.

## INTRODUCTION

The most widely known mechanism for the acceleration of particles in astrophysical environments usually with a power-law spectrum is Fermi acceleration. This mechanism for particle acceleration relies on the shock jump conditions at relativistic shocks (e.g., Gallant 2002). Most astrophysical shocks are collisionless since dissipation is dominated by wave-particle interactions rather than particle-particle collisions. Diffusive shock acceleration (DSA) relies on repeated scattering of charged particles by magnetic irregularities (Alfvén waves) to confine the particles near the shocks. However, particle acceleration near relativistic shocks is not due to DSA because the propagation of accelerated particles near shocks, in particular ahead of the shock, cannot be described as spatial diffusion. Anisotropies in the angular distribution of the accelerated particles are large, and the diffusion approximation for spatial transport do not apply (Achterberg et al. 2001). Particle-in-cell (PIC) simulations may shed light on the physical mechanism of particle acceleration that involves the complicated dynamics of particles in relativistic shocks (Nishikawa et al. 2003, Silva et al. 2003; Frederiksen et al. 2003a,b).

## SIMULATION MODEL

The simulations were performed using a $85 \times 85 \times 160$ grid with range of 55 to 85 million particles (27 particles/cell/species for the ambient plasma). Both periodic and radiating boundary conditions are used (Buneman 1993). The ambient electron and ion plasma has a mass ratio $m_i/m_e = 20$. The electron thermal velocity $v_e$ is $0.1c$, where $c$ is the speed of light. The electron skin depth, $\lambda_{ce} = c/\omega_{pe}$, is $4.8\Delta$, where $\omega_{pe} = (4\pi e^2 n_e/m_e)^{1/2}$ is the electron plasma frequency ($\Delta$ is the grid size).

## SIMULATION RESULTS

### Flat Magnetized jets

The jet density of the flat jet is nearly $0.741 n_b$. The average jet velocity $v_j = 0.9798c$, and the Lorentz factor is 5 (corresponds to 5 MeV). The time step $\omega_{pe} t = 0.026$, the ratio $\omega_{pe}/\Omega_e = 2.89$, the Alfvén speed $v_A = 0.0775c$, and the Alfvén Mach number $M_A = v_j/v_A = 12.65$. The gyroradii of ambient electrons and ions are $1.389\Delta$, and $6.211\Delta$, respectively. In this case, the jet makes contact with the ambient plasma at a 2D interface spanning the computational domain. Therefore, the dynamics of the jet head and the propagation of a shock in the downstream region are studied. The Weibel instability is excited and the electron density is perturbed as shown in Fig. 1a. The electrons are deflected by the perturbed (small) transverse magnetic fields ($B_x, B_y$) via the Lorentz force: $-e(\mathbf{v} \times \mathbf{B})$, generating filamented current perturbations ($J_z$), which enhance the transverse magnetic fields (Weibel 1959; Medvedev and Loeb 1999). The complicated current structures due to the Weibel instability are shown in Fig. 1b. The sizes of these structures are nearly the electron skin depth ($4.8\Delta$). This is in good agreement with $\lambda \approx 2^{1/4} c \gamma_{th}^{1/2}/\omega_{pe} \approx 1.188\lambda_{ce} = 5.7\Delta$ (Medvedev & Loeb 1999). Here, $\gamma_{th}$ is a thermal Lorentz factor, and $\omega_{pe}$ is the electron plasma frequency. The shapes are elongated along the direction of the jet (the $z$-direction, horizontal in Fig. 1).

The growth rate of the Weibel instability is calculated to be, $\tau \approx \gamma_{sh}^{1/2}/\omega_{pe} \approx 21.4$ ($\gamma_{sh} = 5$) (Medvedev & Loeb 1999). This is in good agreement with the simulation results with the jet head located at $z = 136\Delta$. Figure 1 suggests that the “shock" has a thickness from about $z/\Delta = 80 - 130$. Possibly, the “turbulence" assumed for diffusive shock acceleration corresponds to this shock region. The width of the jet head is nearly the electron skin depth ($4.8\Delta$). The size of perturbations along the jet around $z = 120\Delta$ is nearly twice the electron skin depth. This result is consistent with the previous simulations by Silva et al. (2003). The Weibel instability creates elongated shell-type structures which are also shown in counter-streaming jet simulations (Nishikawa et al. 2003; Silva et al. 2003; Frederiksen et al. 2003a,b). The size of these structures transverse to the jet propagation is nearly the electron skin depth ($4.8\Delta$). Note that the

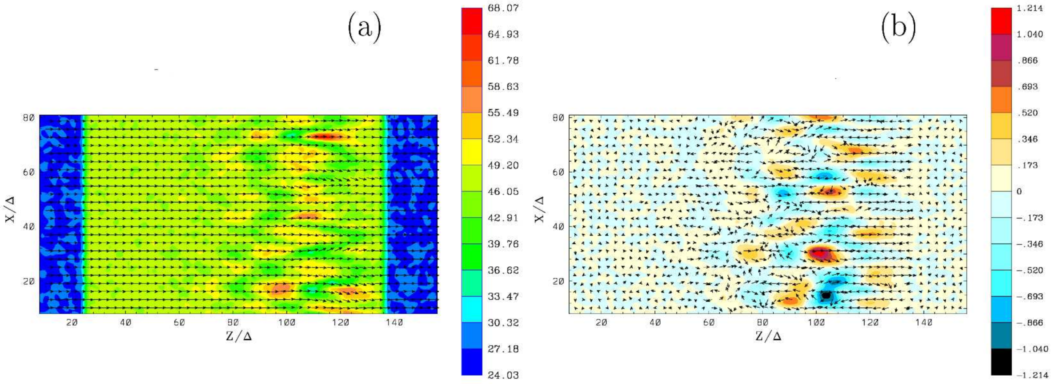

**FIGURE 1.** The Weibel instability for the flat jet is illustrated in 2D images in the $x-z$ plane ($y = 43\Delta$) in the center of the jet. In (a) the colors indicate the electron density with magnetic fields represented by arrows and in (b) the colors indicate the $y$-component of the current density ($J_y$) with $J_z, J_x$ indicated by the arrows. The Weibel instability perturbs the electron density, leading to nonuniform currents and highly structured magnetic fields.

size of the perturbations grows larger (see Fig. 1) behind the jet front as smaller scale perturbations merge to larger sizes in the nonlinear stage at the maximum amplitudes (Silva et al. 2003).

## SUMMARY AND DISCUSSIONS

We have performed the first self-consistent, three-dimensional relativistic particle simulations of electron-ion relativistic jets propagating through magnetized and unmagnetized electron-ion ambient plasmas. The Weibel instability is excited in the downstream region behind the jet head, where electron density perturbations and filamented currents are generated. The nonuniform electric field and magnetic field structures slightly decelerate the jet electrons and ions, while accelerating (heating) the jet electrons and ions in the transverse direction, in addition to accelerating the ambient material. The Weibel instability results from the fact that the electrons are deflected by the perturbed (small) transverse magnetic fields ($B_x, B_y$), and subsequently enhancement of the filamented current is seen (Weibel 1959; Medvedev and Loeb 1999; Brainerd 2000; Gruzinov 2001).

The simulation results show that the initial jet kinetic energy goes to the magnetic fields and transverse acceleration of the jet particles through the Weibel instability. The properties of the synchrotron or “jitter" emission from relativistic shocks are determined by the magnetic field strength, **B** and the electron energy distribution behind the shock. The following dimensionless parameters are used to estimate these values; $\varepsilon_B = U_B/e_{th}$ and $\varepsilon_e = U_e/e_{th}$ (Medvedev & Loeb 1999). Here $U_B = B^2/8\pi$, $U_e$ are the magnetic and electron energy densities, and $e_{th} = nm_i c^2(\gamma_{th} - 1)$ is the total thermal energy density behind the shock, where $m_i$ is the ion mass, $n$ is the ion number density, and $\gamma_{th}$ is the mean thermal Lorenz factor of ions. Based on the available diagnostics the following values are estimated; $\varepsilon_{\rm B} \approx 0.02$ and $\varepsilon_{\rm e} \approx 0.3$. These estimates are made at the maximum amplitude ($z \approx 112\Delta$).

Our present simulation study has provided the framework of the fundamental dynamics of a relativistic shock generated within a relativistic jet. While some Fermi acceleration may occur at the jet front, the majority of electron acceleration takes place behind the jet front and cannot be characterized as Fermi acceleration. Since the shock dynamics is complex and subtle, further comprehensive study is required for better understanding of the acceleration of electrons and the associated emission as compared with current theory (e.g., Rossi & Rees 2002). This further study will provide more insight into basic relativistic collisionless shock characteristics. The fundamental characteristics of such 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.

## ACKNOWLEDGMENTS

K.N. is a NRC Senior Research Fellow at NASA Marshall Space Flight Center. This research (K.N.) is partially supported by NSF ATM 9730230, ATM-9870072, ATM-0100997, and INT-9981508. The simulations have been performed on ORIGIN 2000 and IBM p690 (Copper) at NCSA which is supported by NSF.

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