# Particle Acceleration and Emission in Relativistic Jets

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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 (Medvedev 2000) 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.

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## 1. Introduction

In this paper we present new simulation results of particle acceleration and magnetic field generation in relativistic jets using 3-D relativistic electromagnetic particle-in-cell (REMP) simulations with and without initial ambient magnetic fields [7]. In our simulations, an electron-ion relativistic jet with Lorentz factor, $\gamma = 5$ (corresponds to 5 MeV) is injected into an electron-ion plasma in order to study the dynamics of a relativistic collisionless shock. We illustrate the features of the collisionless shock generated at the head of the relativistic jet injected into magnetized and unmagnetized ambient plasma. The Weibel instability is excited in the downstream region and accelerates electrons and ions. In section 2 the simulation model and initial conditions are described. The simulation results are presented in the section 3, and in section 4 we summarize and discuss the results.

## 2. Simulation model

The simulations were performed using $85 \times 85 \times 160$ grids with a total of 55 to 85 million particles (27 particles/cell/species for the ambient plasma) [7]. Both periodic and radiating boundary conditions are used [2]. The ambient electron and ion plasma has mass ratio $m_{\rm i}/m_{\rm e} = 20$. The electron thermal velocity $v_{\rm e}$ is $0.1c$, where $c$ is the speed of light. The electron skin depth, $\lambda_{\rm ce} = c/\omega_{\rm pe}$, is $4.8\Delta$, where $\omega_{\rm pe} = (4\pi e^2 n_{\rm e}/m_{\rm e})^{1/2}$ is the electron plasma frequency ($\Delta$ is the grid size). In this study three different cases were simulated to investigate the fundamental characteristics of the spatial development of the Weibel instability in electron-ion plasmas. One simulation was performed injecting a thin jet into a magnetized ambient plasma. The other two simulations consider flat jets (infinite width) injected into a magnetized ambient plasma and then into an unmagnetized ambient plasma. We show results from the unmagnetized flat jet simulation below that can be compared to previous simulations involving counter- steaming plasmas [3, 10].

## 3. Simulation results

### *3.1. Injection into Unmagnetized Ambient Plasma (Flat Jet)*

In the previous simulations of Silva et al. [10] and Frederiksen et al. [3] without ambient magnetic fields, counter-streaming plasmas allowed investigation of the temporal growth of the Weibel instability. Our simulations address the spatial growth of the Weibel instability behind a jet front. The structure of perturbations to the electron density and $z$-component of the current density are shown in Figure 1. The structures shown here are very similar to those found in the presence of a weak ambient magnetic field [7].

The unmagnetized jet generates magnetic fields due to the Weibel insta-

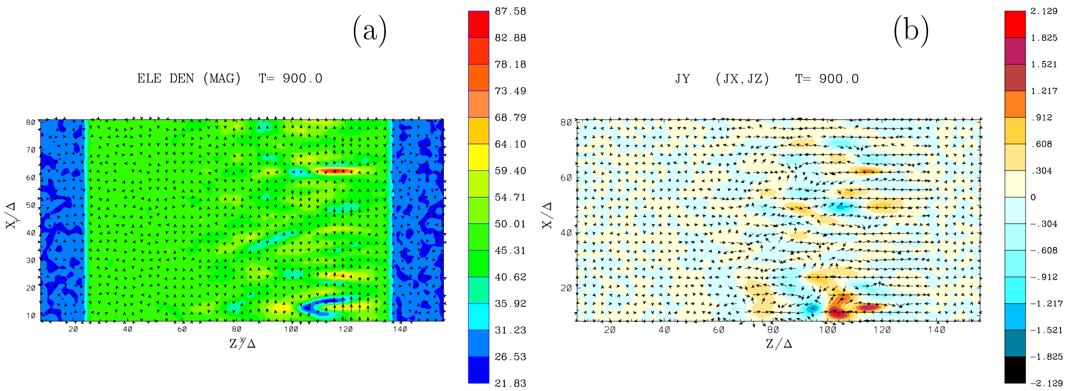


**Fig. 1.** For the simulation with an unmagnetized ambient plasma, the Weibel instability is illustrated in 2D images in the $x-z$ plane in the center of the jet ($y = 43\Delta$ at $\omega_{\rm pe}t = 23.4$). In (a) the colors indicate the electron density with magnetic fields represented by arrows and in (b) the colors indicate the $y$-component of the current density $J_{\rm y}$, with $J_{\rm z}, J_{\rm x}$ indicated by the arrows. The Weibel instability perturbs the electron density, leading to nonuniform currents and highly structured magnetic fields.

bility generated current structures as shown in Figs. 1b. The peak values of perturbations due to the Weibel instability for an unmagnetized ambient plasma is larger that those for a magnetized ambient plasma. However, the amplitude of perturbations is similar, therefore the effects of initial ambient magnetic fields are not apparent in these cases. Further investigation is required for a systematic analysis of the effects of magnetic fields. The generation of magnetic fields both with and without an initial magnetic field suggests that the synchrotron emission or jitter radiation is relevant in GRB afterglows and Crab-like pulsar winds [5, 6, 7].

## 4. 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 [7]. 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 ($B_{\rm x}, B_{\rm y}$), and subsequently enhancement of the filamented current

[11, 6, 1, 4]. The deflection of particle orbits due to the Lorentz force increases as the magnetic field perturbation grows in amplitude. The amplified magnetic field is random in the direction perpendicular to the particle motion, since it is generated from a random seed field. The perturbed electron density and filamented currents have a complicated three-dimensional structure. The transverse size of these structures is nearly equal to the electron skin depth but is larger if there are no ambient magnetic fields. However, the size along the direction of jets is larger than the transverse scales. At the termination of our simulation, the thickness of the unstable region along the jet direction ranges from $z/\Delta = 80$ to 130. The perturbation size in the transverse direction become largest around $z/\Delta = 120$, where nonlinear effects lead to the merging of the smaller scale filaments that first appear behind the jet front. This result is similar to previous counter-streaming simulation results [10] in which smaller scale filaments first appear and then merge into larger scale filaments at a later time. Now we see the temporal development appear as a spatial development.

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 [7, 8, 9].

## 5. References


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