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# Particle acceleration, magnetic field generation, and emission in relativistic pair jets(*)

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**Summary.** — Shock acceleration is a 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. We find that the growth times of Weibel instability are proportional to the Lorentz factors of jets. 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 small-scale magnetic field structure generated by the Weibel instability is appropriate to the generation of "jitter" radiation from deflected electrons (positrons) as opposed to synchrotron radiation. 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 or other astrophysical sources containing relativistic jets and relativistic collisionless shocks.

PACS 98.54.Cm – Active and peculiar galaxies and related systems.
PACS 98.62.Nx – Jets and bursts; galactic winds and fountains.
PACS 98.70.Qy – X-ray sources; X-ray bursts.
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## 1. – 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 in the radio through the gamma-ray region. Radiation in optical and higher frequencies typically requires particle re-acceleration in order to counter radiative losses.

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 [1-7]. In general, these independent simulations have confirmed that relativistic jets excite the Weibel instability [8]. The Weibel instability generates current filaments with associated magnetic fields [9], and accelerates electrons [1-7].

In this paper we present new simulation results of particle acceleration and magnetic

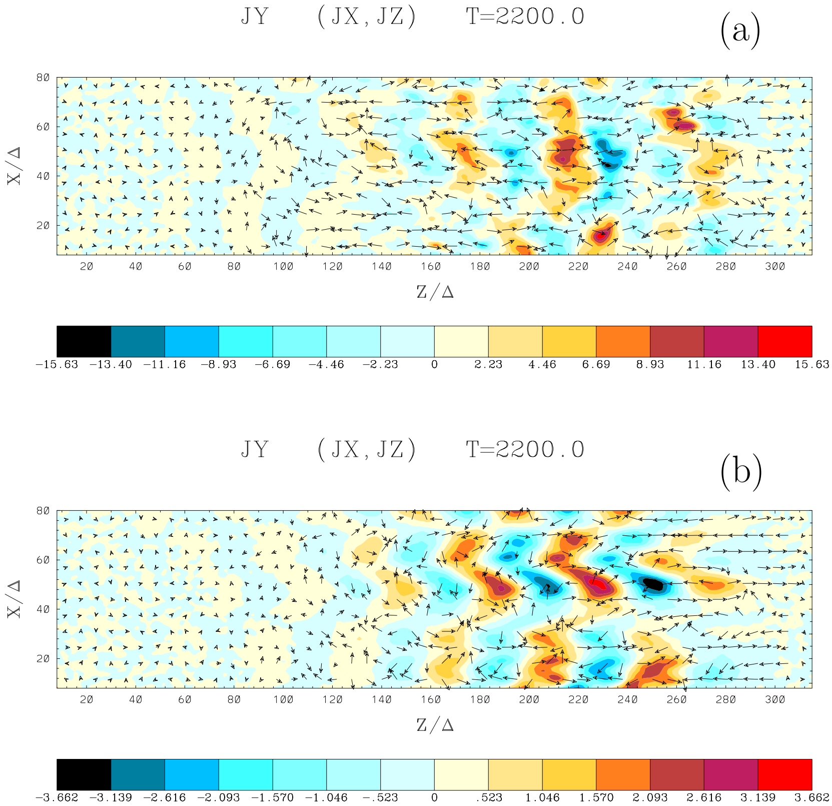


Fig. 1. – 2D images show the current density ($J_y$) at $t = 28.8/\omega_{\rm pe}$ (a) $\gamma = 5$ and (b) $\gamma = 15$. Grey scales indicate the $y$-component of the current density, $J_y$ [peak: (a) 15.63 and (b) 3.86], and the arrows indicate $J_z$ and $J_x$.

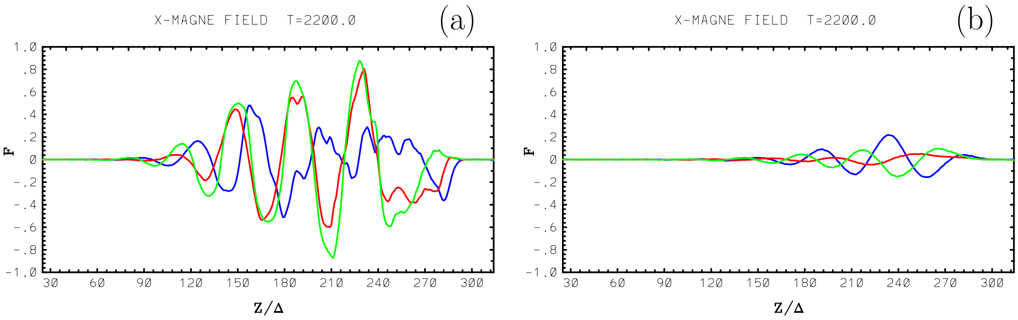


Fig. 2. – One-dimensional cuts along the $z$-direction ($25 \leq z/\Delta \leq 314$) of a flat jet (a) $\gamma = 5$ and (b) $\gamma = 15$. Shown are the $x$-component of the magnetic field shown at $t = 28.8/\omega_{\rm pe}$. Cuts are taken at $x/\Delta = 38$ and $y/\Delta = 33$ (blue-dotted), 43 (red-solid), 53 (green-dashed) and separated by about one electron skin depth.

field generation for relativistic electron-positron shocks using 3-D relativistic electromagnetic particle-in-cell (REMP) simulations. In our new simulations, the growthrates with different Lorentz factors of jets have been studied without an initial ambient magnetic field.

## 2. – Simulation setup and results

Two 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, $\lambda_{\rm ce} = c/\omega_{\rm pe} = 9.6\Delta$, where $\omega_{\rm pe} = (4\pi e^2 n_{\rm e}/m_{\rm e})^{1/2}$ is the electron plasma frequency and $\Delta$ is the grid size [6].

The electron number density of the jet is $0.741 n_{\rm b}$, where $n_{\rm b}$ is the density of ambient (background) electrons. The average jet velocities for the two simulations are $v_{\rm j} = 0.9798c, 0.9977c$ corresponding to Lorentz factors are 5 (2.5 MeV) and 15 (7.5 MeV), respectively. The jets are cold ($v^{\rm e}_{\rm j,th} = v^{\rm p}_{\rm j,th} = 0.01c$ and $v^{\rm i}_{\rm j,th} = 0.0022c$) in the rest frame of the ambient plasma. Electron-positron plasmas have mass ratio $m_{\rm p}/m_{\rm e} = 1$. The thermal velocity in the ambient plasmas is $v^{\rm e,p}_{\rm th} = 0.1c$ where $c$ is the speed of light. The time step $\Delta t = 0.013/\omega_{\rm pe}$.

Current filaments resulting from development of the Weibel instability behind the jet front are shown in figs. 1a and 1b at time $t = 28.8/\omega_{\rm pe}$ for unmagnetized ambient plasmas (a) $\gamma = 5$ and (b) $\gamma = 15$. The maximum values of $J_y$ are (a) 15.63 and (b) 3.86, respectively. The slower jet shows larger amplitudes than the faster jet at the same simulation time. The effect of Lorentz factors of jets affects the growth rates of Weibel instability as expected by the theory [8].

The differences in the growthrates between the differerent Lorentz factors are seen more clearly in the $x$-component of the generated magnetic fields as shown in fig. 2. The amplitudes of $B_x$ in the slower jet (a) are much larger than those in the faster jet (b). The comparisons in the saturated magnetic fields need much longer simulations, which are in progress at the present time.

## 3. – Summary and discussion

We have performed self-consistent, three-dimensional relativistic particle simulations of relativistic electron-positron jets propagating into magnetized and unmagnetized electron-positron ambient plasmas. The main acceleration of electrons takes place in the region behind the shock front [5]. 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. The nonuniform electric field and magnetic field structures associated with these current filaments decelerate 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.

The growthrates depend on the Lorentz factors of jet as expected by the theory [9]. The $e$-fold time is written as $\tau \simeq \sqrt{\gamma_{\rm sh}}/\omega_{\rm pe}$, where $\gamma_{\rm sh}$ is the Lorentz factor of the shock. The simulation results show that $\tau \propto \gamma_{\rm sh}$.

Other simulations with different skin depths and plasma frequencies confirm that both simulations have enough resolutions and the electron Weibel instability is characterized by the electron skin depth [5].

These simulation studies have provided new insights for particle acceleration and magnetic field generation. Further research is required to develop radiation models based on these microscopic processes.

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