Rapid Particle Acceleration due to Re-collimation in Injected Jets with Helical Magnetic Fields

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ABSTRACT

One of the key open questions in the study of relativistic jets is how magnetic reconnection occurs and whether it can effectively accelerate the jet’s electrons. We investigate the evolution of an electron-proton relativistic jet containing helical magnetic fields, focusing on the interaction with the ambient plasma. We have performed 3D particle-in-cell (PIC) simulations of a jet containing a relatively large radius with embedded helical magnetic fields, in order to examine how the helical magnetic field excites kinetic instabilities such as the Weibel instability (WI), the kinetic Kelvin-Helmholtz instability (kKHI) and the mushroom instability (MI). In our simulations these kinetic instabilities are indeed excited and particles are accelerated. We observe a recollimation-like instability near the center of the jet at the linear stage. As the electron-proton jet evolves, the helical magnetic field becomes untangled due to a reconnection-like phenomena at the end of nonlinear stage, and electrons are further accelerated by multiple magnetic reconnection events/sites within the turbulent magnetic field.

Keywords: methods: numerical — ISM: jets and outflows — relativistic processes — magnetic reconnection — turbulence — acceleration of particles

1. INTRODUCTION

Magnetic reconnection is ubiquitous in solar and magnetospheric plasmas, and it has been proposed that it is also an important mechanism for particle acceleration in Active Galactic Nuclei (AGN) and gamma-ray burst jets (Uzdensky 2011; Granot et al. 2011; Granot 2012; McKinney & Uzdensky 2012; Zhang & Yan 2011; Giannios et al. 2009; Giannios 2010, 2011; Komissarov et al. 2009; Komissarov 2012; Sironi et al. 2015). In order to study the fundamental physics of magnetic reconnection, numerous particle-in-cell (PIC) simulations have been performed that have used the Harris model in a slab geometry (e.g., Daughton 2011; Wendel et al. 2013; Karimabadi et al. 2014; Zenitani & Hoshino 2005, 2008; Zenitani et al. 2011, 2013; Oka et al. 2008; Fujimoto 2011; Kagan et al. 2013; Sironi & Spitkovsky 2011, 2014; Guo et al. 2015, 2016a,b). Studies in the slab configuration have shown significant particle acceleration. However, the slab configuration cannot be applied to astrophysical jets, since helical magnetic fields are thought to be the dominant magnetic field morphology close to the jet collimation/launching point (e.g., Tchekhovskoy 2015), as evidenced by observations (e.g., Hawley et al. 2015; Gabuzda 2019).

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The interaction of relativistic jets with the plasma environment generates relativistic shocks that are mediated by the Weibel instability (WI) and accelerate particles. At the same time magnetic turbulence is generated by the kinetic Kelvin-Helmholtz (kKHI) and the mushroom (MI) instabilities in the velocity shear boundary between the jet and the ambient medium. To achieve a complete understanding of the physics within the jet requires a global three-dimensional (3D) modeling that enables investigation of the combined shock/shear processes and includes kinetic effects. Our first PIC simulations of global jets were performed for unmagnetized plasmas. With this work we extend these studies to jets containing helical magnetic fields.

One of the key questions we want to answer is how the helical magnetic fields affect the growth of the kKHI, MI, and WI, and how and where in the jet structure particles are accelerated. In the latter respect, of special interest is the role of magnetic reconnection, that has been proposed as a process responsible for the rapid merging and breaking of the helical magnetic fields carried by relativistic jets. Relativistic magnetohydrodynamic (RMHD) simulations demonstrated that jets with helical fields develop kink instabilities (KI) (e.g., Mizuno et al. 2014; Singh et al. 2015; Barniol Duran et al. 2017), and similar structures were found in PIC simulations (see, e.g., Nishikawa et al. 2019). PIC simulations of a single flux rope modeling the jet that undergoes internal KI showed signatures of secondary shocks at the head of jet and their propagation through the jet, has not been simultaneously investigated.

In this letter, we present results of our new study of relativistic jets containing helical magnetic fields, which exhibit nonlinear evolution of kinetic instabilities, magnetic reconnection, and associated particle acceleration.

2. PIC SIMULATION SETUP OF A JET WITH HELICAL MAGNETIC FIELD STRUCTURE

In our simulations a cylindrical jet containing helical magnetic field is injected into an ambient plasma and propagates in the \( x \)-direction, as is shown schematically in Figure 1a. The structure of the helical magnetic field is implemented in the same way as in RMHD simulations by Mizuno et al. (2014), where a force-free expression of the field at the jet orifice is used. The magnetic field is thus not generated self-consistently by a rotating black hole, as in RMHD simulations of jet formation. The poloidal, \( B_z \), and toroidal, \( B_\phi \), magnetic field components in the laboratory frame are:

\[
B_z = \frac{B_0}{1 + (r/a)^2}^{\alpha}, \quad B_\phi = \frac{B_0}{(r/a)[1 + (r/a)^2]^{\alpha}} \sqrt{\left[\frac{1 + (r/a)^2}{2\alpha - 1}\right]^{2\alpha - 1} - \frac{2\alpha(r/a)^2}{2\alpha - 1}},
\]

where \( r \) is the radial coordinate in cylindrical geometry, \( B_0 \) parametrizes the magnetic-field strength, \( a \) is the characteristic radius of the magnetic field, and \( \alpha \) is the pitch profile parameter (compare Eq. 1 and 2 in Mizuno et al. 2014). Note that for a constant magnetic pitch, \( \alpha = 1 \), the toroidal field component has a maximum value at \( a \). As in Mizuno et al. (2014), here we choose \( \alpha = 1 \), which gives constant magnetic pitch and magnetic helicity. Equation 1 then takes the form:

\[
B_z = \frac{B_0}{1 + (r/a)^2}, \quad B_\phi = \frac{(r/a)B_0}{1 + (r/a)^2},
\]

The toroidal component of the magnetic field in the jet is created by an electric current \( +J_x(y, z) \) in the positive \( x \)-direction. In Cartesian coordinates used in our simulations the corresponding \( B_y \) and \( B_z \) field components are defined as:

\[
B_y(y, z) = \frac{((z - z_{jc})/a)B_0}{1 + (r/a)^2}, \quad B_z(y, z) = -\frac{(y - y_{jc})/a)B_0}{1 + (r/a)^2}.
\]

Here, the center of the jet is located at \( (y_{jc}, z_{jc}) \) and \( r = \sqrt{(y - y_{jc})^2 + (z - z_{jc})^2} \). Equation 3 defines the helicity of the magnetic field that has a left-handed polarity for positive \( B_0 \). At the jet orifice, the helical magnetic field is computed without motional electric fields. This corresponds to a toroidal magnetic field generated by jet particles moving along the \( +x \)-direction.

The simulated jet has a radius \( r_{jet} \) and is assumed to propagate in initially unmagnetized medium. For the fields external to the jet we use a damping function, \( \exp \left[-(r - r_{jet})^2/b\right] (r \geq r_{jet}) \), that multiplies expressions in Equation 3.
with the tapering parameter $b = 200$. We further assume the characteristic radius $a = 0.25 \times r_{\text{jet}}$. The profiles of the resulting helical magnetic field components are shown in Figure 1b. The toroidal magnetic field becomes zero at the center of the jet (red line in Fig. 1b). Note, that the simulation setup adopted in this work has been used in our preliminary studies of helical jets (Nishikawa et al. 2016b, 2017, 2019).

The jet head profile assumed here is that of a flat-density top-hat shape. We note that it should be noted here that the structure of the jet formation region is far more complex than what we currently simulate with our PIC simulations (e.g., Broderick & Loeb 2009; Moscibrodzka et al. 2017). A more realistic jet structure (with, e.g., a Gaussian-shaped head) will be implemented in future studies.

Figure 1. Panel (a) shows a schematic simulation setup for the entire jet. The jet is injected at $x = 100\Delta$ with the jet radius $r_{\text{jet}}$ at the center of the $y-z$ plane (not scaled). Panel (b) shows the helical magnetic fields, $B_x$ (black), $B_\varphi$ (red) with $B_0 = 0.1$ for the pitch profile $\alpha = 1.0$ with damping functions outside the jet with $b = 200.0$. The jet boundary is located at $r_{\text{jet}} = 100\Delta$.

The numerical code we use is a modified version of the relativistic electromagnetic PIC code TRISTAN (Buneman 1993) with MPI-based parallelization (Niemiec et al. 2008). The simulations are performed in Cartesian coordinates on a numerical grid of size $(L_x, L_y, L_z) = (1285\Delta, 789\Delta, 789\Delta)$, where $\Delta$ is the size of the grid cells. We use open boundaries on $x/\Delta = 0$ and $x/\Delta = 1285$ surfaces and impose periodic boundary conditions in the transverse directions. The jet radius is $r_{\text{jet}} = 100\Delta$. The jet is injected at $x = 100\Delta$ in the center of the $y-z$ plane. A large computational box allows us to follow the jet evolution over long computing times, enabling investigation of a strongly nonlinear stage. The longitudinal box size, $L_x$, and the simulation time, $t_{\text{max}} = 1000\omega_{\text{pe}}^{-1}$ are a factor of two larger than in our previous simulation studies (Nishikawa et al. 2016b, 2017, 2019), in which jets with radii $r_{\text{jet}} = 20, 40, 80, 120\Delta$ have been investigated using a short system length ($L_x = 645\Delta$).

We know that jets with different plasma compositions exhibit distinct dynamical behaviors, which will manifest as distinct morphologies in the jet evolution and its emission (Nishikawa et al. 2016a,b, 2017, 2019). In this letter only the case of the electron-proton plasma is discussed for both the jet and the ambient medium. The initial electron and proton number densities measured in the simulation frame are $n_{\text{jet}} = 8$ and $n_{\text{am}} = 12$, respectively for the jet and ambient plasma. The electron skin depth $\lambda_{\varphi e} = c/\omega_{\text{pe}} = 10.0\Delta$, where $c$ is the speed of light, $\omega_{\text{pe}} = (e^2n_{\text{am}}/\epsilon_0m_e)^{1/2}$ is the electron plasma frequency, and the electron Debye length for ambient electrons is $\lambda_D = 0.5\Delta$. The jet-electron thermal velocity is $v_{\text{jet,th,e}} = 0.014c$ in the jet reference frame. The electron thermal velocity in the ambient plasma is $v_{\text{am,th,e}} = 0.03c$, and the ion thermal velocities are smaller by $(m_p/m_e)^{1/2}$, where we use a realistic proton-to-electron mass ratio $m_p/m_e = 1836$. The jet plasma is initially weakly magnetized, and the magnetic field amplitude parameter assumed, $B_0 = 0.1c$, corresponds to plasma magnetization $\sigma = B^2/n_e m_e c^2 = 2.8 \times 10^{-3}$. The jet Lorentz factor $\gamma_{\text{jet}} = 15$.

3. STRUCTURE OF HELICALLY MAGNETIZED JETS

Figure 2 shows cross-sections through the center of the jet at time $t = 1000\omega_{\text{pe}}^{-1}$ with (a), the $y$-component of the magnetic field, $B_y$, with the $x-z$ electric field as arrows, and (b), the $x$-component of the electron current density, $J_x$, with the $x-z$ magnetic field depicted as arrows. The jet propagates from the left to right and reaches $x/\Delta \approx 1100$. One
Figure 2. Upper panels: (a) the $y$-component of the magnetic field, $B_y$, with $x$-$z$ electric field depicted by arrows, and (b), the $x$-component of the electron current density, $J_x$, with the $x$-$z$ magnetic field as arrows, both in the $x$−$z$ plane at $t = 1000\omega_{pe}$. The lower panels show the total magnetic field strength in the $y$−$z$ plane at $x/\Delta = 700$ (c), and $x/\Delta = 835$ (d). The arrows indicate the magnetic field ($B_y, B_z$).
can see that strong helical magnetic field is generated in the jet for $400 \lesssim x/\Delta \lesssim 830$, reaching intensities $B/B_0 \sim 40$ (Fig. 2a). As in the unmagnetized case (Nishikawa et al. 2016a), this field results from MI and kKHI. However, in the presence of the helical magnetized field the growth of the transverse MI modes is reduced and the field structure is strongly modulated by longitudinal kKHI wave modes. This causes multiple collimations along the jet formed by jet electrons pinched toward the center of the jet, as visible in the electron current density (Fig. 2b). It should be noted that the minimum values of $J_x$ are truncated at $J_x = -50$ in order to show the weak positive (return) current in Fig. 2b. Subsequent collimations weaken along the jet and eventually relax at $x/\Delta \gtrsim 830$. At this point $B_y$ becomes considerably weak. This demonstrates that the nonlinear saturation of the MI is accompanied by dissipation of the helical magnetic field. The magnetic field structure at possible reconnection sites at $x/\Delta = 700$ and $x/\Delta = 835$, indicated by two red lines in Figures 2a-b, are shown in the $y-z$ plane in Figures 2c and 2d, respectively. It should be noted that at $x/\Delta = 700$ clockwise-circular magnetic field is split near the jet into a number of magnetic structures. They are surrounded by the field rotating in the opposite direction due to proton currents framing the jet boundary (see Nishikawa et al. 2016a). Magnetic fields at $x = 835\Delta$ are strongly turbulent, their helical structure is distorted and split out from the center of the jet into multiple magnetic islands. The split magnetic islands interact with each other providing conditions for magnetic reconnection. In our 3D geometry reconnection does not occur at a simple X-point as in 2D slab geometry, but reconnection sites can be identified with regions of low magnetic field strength surrounded by oppositely directed magnetic field lines. An example of a possible location of reconnection can be found at $(y/\Delta, z/\Delta) = (380, 340)$, where the total magnetic field becomes minimum (the null point, Fig. 2d). The evolution of the magnetic field at the different locations in the jet ($600 < x/\Delta < 1100$) is shown in the supplemental movie. Note that the filamentary structure at the jet head (Fig. 2a-b) is formed by the electron WI. One can see in the movie that nonlinear evolution of the filaments also leads to the appearance of the magnetic structures that are prone to reconnection.

The three-dimensional morphology of the jet’s magnetic field is shown in Figure 3 where we plot magnetic-field vectors at $t = 900\omega_{pe}^{-1}$ (Fig. 3a) and $t = 1000\omega_{pe}^{-1}$ (Fig. 3b). The regions displayed ($720 < x/\Delta < 1020; 231 < y/\Delta, z/\Delta < 531$) are indicated by red dashed rectangle in Figure 2b. The plot is clipped at the center of the jet at $y/\Delta = 381$. One can see that the edge of the helical magnetic field in the jet moves from $x/\Delta = 780$ at $t = 900\omega_{pe}^{-1}$ to $x/\Delta = 830$ at $t = 1000\omega_{pe}^{-1}$, which is much slower than the jet speed. This seems to indicate that the front edge of the helical magnetic field is peeled off as the jet propagates. This may indicate that the helical magnetic field is braided by kinetic instabilities and subsequently becomes untangled as discussed in Blandford et al. (2017). Magnetic untangling results from magnetic reconnection-like phenomena that split the forward position of the helical magnetic fields. Two split smaller magnetic islands can be identified in the jet shown in Figure 3. At the same time, based on the evolution of magnetic field structure, the helical magnetic fields become untangled (unwound) within this region.

Figure 4 shows the phase-space distribution of the jet (red) and ambient (blue) electrons at $t = 900\omega_{pe}^{-1}$ (a) and $t = 1000\omega_{pe}^{-1}$ (b). The jet and ambient electrons are accelerated at several locations that coincide with the jet recollimation regions (compare Fig. 2a-b). In particular, in Figure 4a the electrons are accelerated at $x/\Delta = 780$, which corresponds to the location where the helical magnetic fields disappear as shown in Figure 3a. The disappearance of helical magnetic field near $x = 830\Delta$ coincides with the acceleration of some electrons. Note that the ambient electrons are entrained in the relativistic jet plasma and are also strongly accelerated.

A group of accelerated jet electrons around $x/\Delta = 900$ at $t = 900\omega_{pe}^{-1}$ in Figure 4a moves to around $x/\Delta = 1000$ at $t = 1000\omega_{pe}^{-1}$ (Fig. 4b). These electrons were accelerated at an earlier time. To investigate the acceleration process operating when the instabilities grow and act to energize electrons, in Figure 5 we show the correlation between electron acceleration and structures of the electromagnetic fields excited by instabilities at $t = 500\omega_{pe}^{-1}$. The MI excitation with kKHI generates a strong toroidal magnetic field, $B_T$, as shown in Figure 5a. Consequently, a large $E_x$ is visible in Figure 5b. Jet electrons are accelerated by the negative $E_x$ and decelerated where a strong positive $E_x$ exists. Note that these electrons can be further accelerated to higher Lorentz factors on account of turbulent acceleration, as in kinetic simulations of driven magnetized turbulence (e.g., Comisso & Sironi 2018; Zhdankin et al. 2018). In these simulations turbulent magnetic fluctuations are forced in the simulation system, and so the energy source for turbulence is not self-consistent. In contrast to the driven turbulence, in our simulations turbulent magnetic fields (multiple magnetic field islands) are self-consistently generated in the relativistic jets due to the untangling of the helical magnetic field. Particles can be accelerated directly in the reconnection regions and also through interactions with the magnetic islands.
4. SUMMARY

We have performed large-scale three-dimensional PIC simulations of an electron-proton jet containing helical magnetic fields in order to investigate in a systematic way how the helical magnetic field in jets evolves and accelerates electrons. The electron-proton jet undergoes kinetic instabilities which are dominated by the MI. As a result, the helical magnetic fields are periodically pinched, which in turn generate quasi-steady positive and negative parallel electric fields near the center of jet. Due to the electric fields, the jet’s electrons are accelerated with the negative electric fields, while in contrast, the positive electric field acts to decelerate the jet electrons. Ambient electrons are entrained in the relativistic jet plasma and also accelerated.

Alves et al. (2018) showed effective acceleration via an inductive electric field which requires particles to cross magnetic field lines. This implies that magnetic field inhomogeneities are crucial in the acceleration process. We have confirmed this in our present work. In our simulations we indeed find highly tangled magnetic fields which develop into structures which show that a reconnection mechanism is at play. It should be noted that this simulation does not show a kink-like instability as seen in the simulations of Alves et al. (2018). Since their simulations use a much larger magnetization factor $\sigma > 1$ the toroidal magnetic field is dominant and a kink instability grows which tangles the helical magnetic field and consequently results in reconnection. Furthermore, comparing with the jet density $n = n_0 + (n_e - n_0)/\cosh^2(2r/R_c)$ used in Alves et al. (2018), with that used in our this simulation namely; a top hat profile $(n = n_{am} + n_{jt}(r)$, here $n_{jt}(r) = n_{jt}$, $r \leq r_{jet}$), where kKHI, MI, and the Weibel instabilities dominate.

In this letter one of the possible mechanisms of electron acceleration in relativistic jets containing helical magnetic fields has been investigated in a self-consistent fashion. We have demonstrated that as the electron-proton jet evolves, the helical magnetic fields are untangled and electrons are accelerated within the ensuing turbulent magnetic fields (i.e. multiple magnetic reconnections). More simulations with larger jet radii are required where different helical magnetic field structures will vary the characteristic magnetic length $a$ and the pitch profile parameter $\alpha$. Moreover, further studies in which we vary the top hat jet profile and the jet magnetization parameter are required and will be the subject of future studies.
Figure 4. Phase-space $x - \gamma V_x$ distribution of jet (red) and ambient (blue) electrons at $t = 900 \omega^{-1}$ (a) and $t = 1000 \omega^{-1}$ (b). The two vertical lines show the regions where the 3D magnetic field vectors are plotted in Fig. 3.
Figure 5. Contours of (a) $B_y$ and (b) $E_x$ with arrows of (a) $B_{y,z}$ and (b) $E_{y,z}$. Phase-space $x - \gamma V_x$ distribution of jet (red) electrons at $t = 500 \omega_{pe}^{-1}$ (a) are overlaid. The initial $v_x \gamma = 15$ is indicated in the phase space.

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