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Particle-in-cell simulations of shear boundary layers in relativistic jets

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The supermassive black holes in the centres of active galaxies (AGN) eject powerful relativistic jets which propagate over kpc scales, showing no significant momentum loss. Both observational evidence as well as theoretical considerations from MHD simulations of jets suggest that they are radially stratified, with a fast inner spine surrounded by a slower-moving outer sheath. The resulting relativistic shear layers are a prime candidate for the site of relativistic particle acceleration in the jets of AGN and gamma-ray bursts (GRBs). We present results of particle-in-cell simulations of magnetic-field generation in the relativistic shear boundary layers of jets in AGN and GRBs. We outline future plans to include a self-consistent calculation of radiation produced by the particles accelerated at these shear boundary layers.

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1. Introduction

Relativistic jets are collimated outflows of matter from the accreting black holes residing at centres of active galaxies, which travel over kpc scales without significant loss of energy and momentum. Our current understanding of the formation of powerful jets in systems such as blazars and radio galaxies is that there is a supermassive black hole at the centre of active galaxy that is being fed with magnetised gas through an accretion disc. However, physical phenomena like jet composition, collimation, particle acceleration, stabilisation, mass loading mechanism and radiative mechanism still remain puzzling.

Both observational evidence as well as theoretical considerations from Magneto-Hydrodynamics (MHD) simulations of relativistic jets of active galactic nuclei (AGN) and gamma ray bursts (GRBs) suggest that they are radially stratified with a fast inner spine surrounded by a slower outer sheath (Ghisellini et al. 2005). As the jet penetrates ambient plasma, sharp boundary layers are formed with large velocity difference between jet and surrounding medium. The resulting shear boundary layers (SBLs) are likely to be promising avenues for the self-generation of magnetic fields and relativistic particle acceleration (Liang et al. 2013a).

The broadband non-thermal continuum emission from AGN jets consists of two components, produced by synchrotron emission and (in the framework of leptonic models) inverse-Compton scattering. Synchrotron emission from the relativistic particles is observed in the radio through optical / UV bands and in some cases in X-rays. Leptonic models proposed for the high energy emission of blazars assume that the X-rays and gamma-rays from blazars are the consequence of Compton upscattering of soft photons by the same population of relativistic electrons (e.g. Boettcher 2007).

How particles in relativistic jets are accelerated, is one of the key questions to understand the physics behind the loading mechanism of jets. Relativistic magnetic reconnection becomes significant when the magnetic energy density becomes dominant over plasma rest mass energy density with the rearrangement of the magnetic topology. It has been studied as a non-thermal particle acceleration mechanism in relativistic jets employing the particle-in-cell (PIC) method (Sironi et al. 2014, Warner et al. 2016). Substantial theoretical as well as computational efforts have been made to study the acceleration of energetic particles in relativistic astrophysical jets by Fermi processes (i.e., diffusive shock acceleration [DSA] or first-order Fermi acceleration, second order Fermi acceleration or stochastic acceleration, and shear acceleration). The first order Fermi acceleration mechanism seems to be one of the most probable mechanisms as knotty features have been detected in extragalactic jets which are likely to be identified with sites of strong shock formation. However, recent high-resolution studies of extragalactic jets reveal that first order Fermi acceleration alone cannot fully account for the detection of extended high energy emission (Rieger et al. 2006). In the case of quasar 3C 279, the strong synchrotron cooling process, which is expected in the DSA scenario has not been observed (Jester et al. 2001). This suggests the need for a continuous re-acceleration mechanism in the relativistic jets to address those issues, showing that shear acceleration is likely to be important at high energies. Thus, there is growing evidence for the presence of SBLs in relativistic jets with a fast inner spine surrounded by the slow outer sheath.

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The self-generated electromagnetic fields in SBLs create turbulence in the spine-sheath interface which eventually leads to the particle acceleration up to TeV energy in jets.

2. Model setup & self-generated E & B fields in SBLs

We present the PIC simulation results of relativistic SBLs considering initially unmagnetised plasma, using the 2.5D (2D space, 3D momenta) code-ACRONYM (Kilian et al. 2012). The initial conditions of our simulations are shown in figure 2.1. The simulations are carried out in equal Lorentz factor frame (ELF) with initial bulk Lorentz factor (p_0)=15, in which right-moving plasma, called spine, occupying the central 50% of the y-grid, moves with equal but opposite velocity to that of left-moving plasma, called sheath, occupying the top 25% and bottom 25% of the y-grid. In our setup, the simulation boxes have dimension of 1024×2048, where number of cells along y-axis $(L_y) = 2\times$number of cells along x-axis (L_x). The positron-electron mass ratio (m_i/m_e) is 1, where as the proton-electron mass ratio (m_p/m_e) is used to be 1836. The shear interfaces are located at y=512 and y=1536 respectively. The time is taken in units of $1/\omega_{p,e}$, where $\omega_{p,e}$=electron plasma frequency, and all spatial distances are in units of skin depth ($c/\omega_{p,e}$). The 2D instabilities in the x-y plane are referred to as P modes, and those in y-z plane as T-modes. The longitudinal P-mode is completely dominant in electromagnetic energy in the SBLs, while the transverse T-mode saturates at very low level, and contributes little to particle acceleration (Liang et al. 2017).

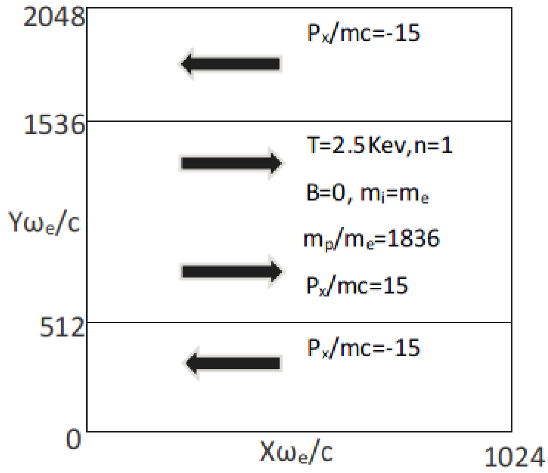


Figure 2.1: Model setup for simulations of shear boundary layers in radially stratified jets.

Recent PIC simulation results have demonstrated that the self-generated magnetic field, which may develop due to some plasma instabilities like the Weibel instability (Weibel 1959) and two-stream instability (Boyd & Sanderson 2003), develops turbulence in SBLs of jets from initially unmagnetized shear flows, which leads to particle energization (Liang et al. 2013b, Alves et al. 2012). Strongly angle-dependent lepton spectra are expected to be produced due to shear layer acceleration, which leads to significantly stronger forward boosting of the emission than in the case of the regular Doppler boosting effect (Liang et al. 2018). This may resolve the problem of the Lorentz factor crisis in AGN jets (Liang et al. 2017).

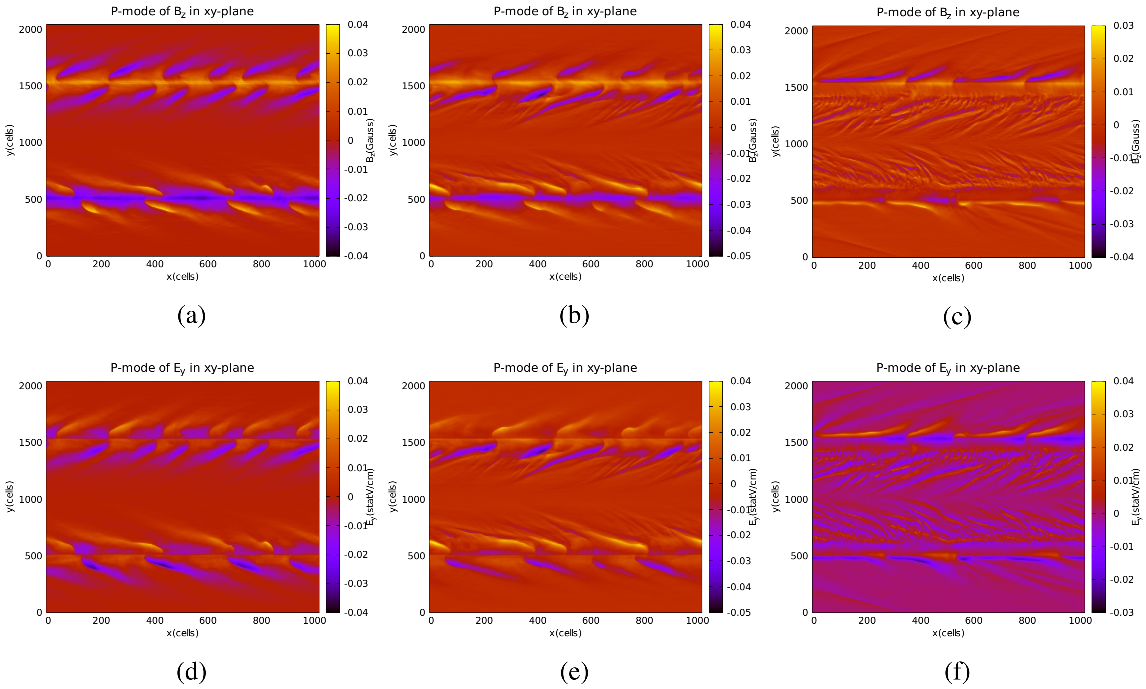


Figure 2.2: xy-cuts of self-generated electric and magnetic fields in SBLs. The first row, figures (a)-(c), show the self-generated magnetic field, the bottom row, figures (d)-(f), shows the electric field. Plots (a) and (d) in the first column show results from electron-ion plasma. The second column shows results from a hybrid configuration with 90% electron-ion and 10% pair plasma. The third column, figure (c) and (f) shows results from a pure electron-positron pair plasma in the jet.

Figure 2.2 shows the comparision of the evolution of 2D structures of magnetic field and electric field in SBLs for different composition of the jet plasma. Blue and yellow colours represent opposite polarities. The triple layers formed at the interface in the case of a hybrid configuration of plasma are thinner (figure (b) & (e)) than the pure electron-ion plasma (figure (a) & (d)), where the wavy electromagnetic fields are created outside the layers (figure (b) & (e)), which provide the supplementary channels of particle energisation. The shear boundary layers are most unstable in the case of pure electron-positron plasma (figure (c) & (f)) whereas pure electron-ion plasma favours the stability of SBLs most (figure (a) & (d)).

3. Numerical challenges

Though the PIC method is widely used, it exhibits numerical instabilities that can cause unphysical simulation results. As the cell size (Δx) is greater than the Debye length (λ_D), it can cause numerical heating and poor energy conservation. This kind of numerical instability, called finite grid instability (Birdsall et al. 1991) can simply be minimized by resolving the Debye length and hence it is usually not considered as a major issue. We did several test runs of different box sizes, cell sizes, particles per cell (PPC), cells per skin depth (CPS) and field solvers to be sure that our setup gives the best possible energy conservation (figure 3.1). We found that, the larger the PPC and CPS, the better is the energy consevation (see blue line in figure 3.1). The electromagnetic field solver, M24 (Hadi et al. 1997) also contributes to the good energy conservation and suppression of the numerical Cherenkov instability (NCI) (Godfrey et al. 1974). (figure 3.1 & 3.2, b). Moreover, current smoothing and current filtering also aid in improving the energy conservation during the simulation run. The spatial distribution of the particle quantities within a macroparticle, called form factor plays a vital role in the computational feasibility of the simulation (Kilian et al. 2013). We did several test runs to make sure that the form factor that we used in our setup gives physically realistic simulation and minimizes computational cost. As a result, we used piecewise quadratic spline (PQS) as a form factor in the simulation.

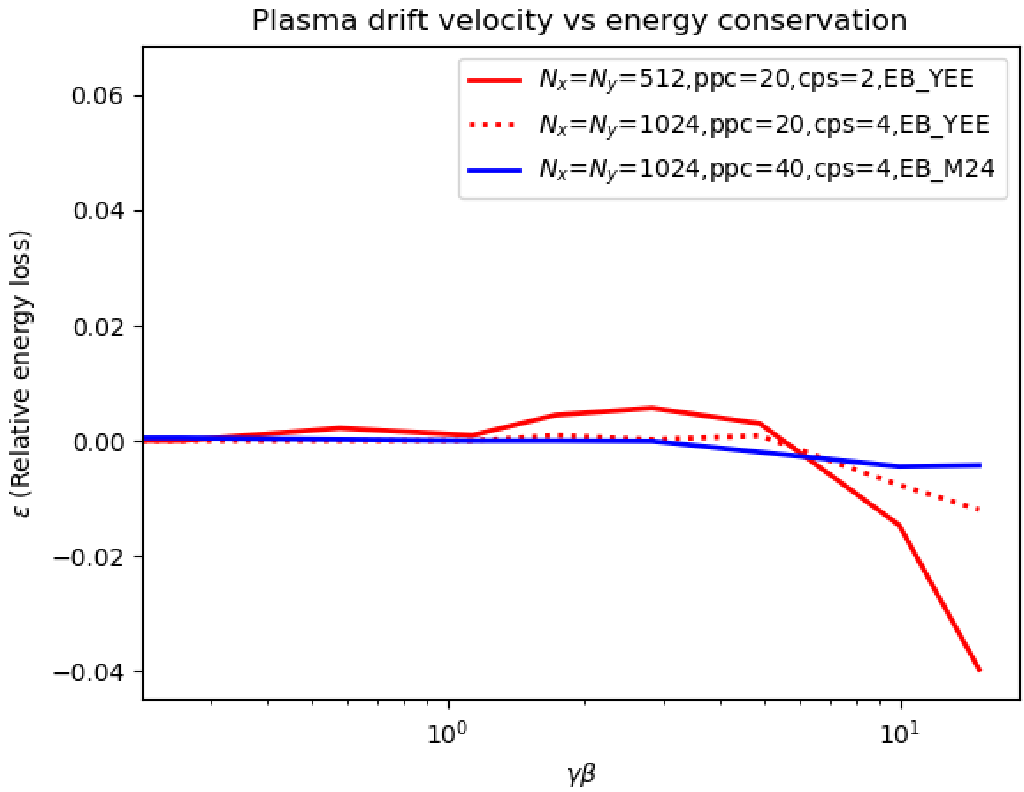
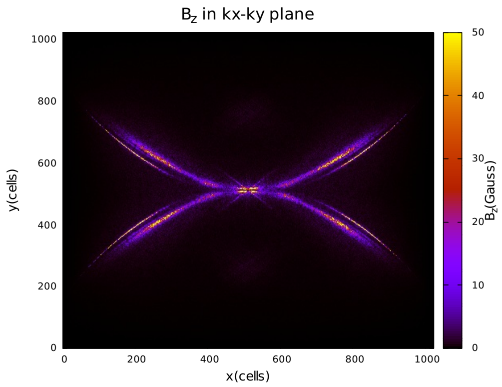
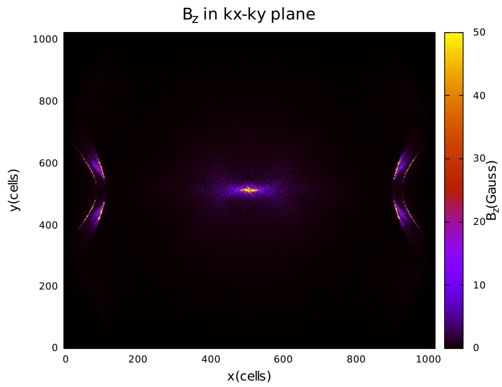


Figure 3.1: Variation of the energy conservation with plasma drift velocity. X-axis represents the plasma drift velocity divided by speed of light and multiplied by Lorentz factor and relative energy loss is represented by y-axis.

The most relevant numerical instability in PIC simulation is the numerical Cherenkov instability (NCI), which arises due to the coupling between numerically distorted electromagnetic modes and beam modes (Godfrey et al. 1974). It needs to be suppressed so that the PIC simulation gives a realistic output. By using a suitable field solver, e.g., the modified fourth-order finite-difference time domain (FDTD) or M24 scheme (Hadi et al. 1997), the NCI can be mitigated significantly. Figure 3.1 shows the 2D maps of B_z in $k_x - k_y$ plane, where k_x & k_y are coordinates in Fourier space and are in units of reciprocal of cell size (Δ_x or Δ_y). In figure 3.2(a), main NCI is dominant in the form of numerical Cherenkov radiation, whereas in the figure 3.2(b), the main NCI is eliminated using the M24 Maxwell solver. While the bright dots at (0,0) denote the desirable dc field or organized quasi-stationary electromagnetic field generated at the shear boundary, the spider leg shapes around it represent the NCI present in shear flow runs. Although the secondary NCI is present in our simulation, it has no effect on the overall particle energization and distribution because the maximum amplitude of the NCI noise is always at most a few percent of the dc field energy, showing no significant dependence on p_0 and time-step, Δ_t as studied by Liang et al. (2017).



(a) Presence of primary NCI in shear flow runs.



(b) Elimination of primary NCI in shear flow runs.

Figure 3.2: 2D maps of B_z in $k_x - k_y$ plane

4. Conclusion

We simulated the self-generation of electric and magnetic fields in SBLs of jets from initially unmagnetised plasma using a PIC code, ACRONYM. We tested the relativistic Cherencov instability and other numerical instabilities which we are able to suppress significantly where the energy is conserved so well that deviations from the initial energy are less than 0.01% at all times. Our simulation of self-generated magnetic and electric fields shows that the shear boundary layers in relativistic jets are highly unstable to both P and T modes in the case of electron-positron composition of jets, mildly stable in the case of electron-ion jets, and remarkably stable with well organised quasi-stationary electromagnetic fields in the case of electron-ion jets. Our next step will be to develop modules for radiation diagnostics in the SBLs of relativistic jets or GRBs and their implementation in the ACRONYM code. High energy particles are energized at SBL across the field lines, which leads to anisotropic momentum distrubution with efficient synchrotron radiation (Liang et al. 2013a). We will study the anisotropic particle distribution emanated from the plasma instabilities at relativistic SBLs. In most of the simulations conducted so far, the effect of the radiation reaction force on the relativistic particle acceleration is ignored even when studying the radiation from accelerated relativistic particles at SBLs, although it may considerably affect the dynamics of such particles. We aim to include a radiation-reaction cooling term in the electron dynamics subroutine ("particle pusher") and develop routines to evaluate the synchrotron and Compton outputs corresponding to this radiation reaction. Using the upgraded ACRONYM code, we will then perform PIC simulations of relativistic SBLs with different plasma compositions, e.g. electron-ion, electron-positron and hybrid plasma.

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[1]Any opinion, finding and conclusion or recommendation expressed in this material is that of the authors, and the NRF does not accept any liability in this regard.

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