3D PIC SIMULATIONS OF RELATIVISTIC JETS WITH A TOROIDAL MAGNETIC FIELD

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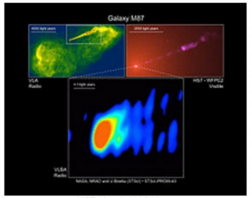
Abstract: The properties of relativistic jets, their interaction with the ambient environment, and particle acceleration due to kinetic instabilities are studied self-consistently with Particle-in-Cell (**PIC**) simulations. An important key issue is how a toroidal magnetic field affects the evolution of an electron-positron and an electron-**ion** jet, how kinetic instabilities such as the Weibel instability (WI), the mushroom instability (MI) and the kinetic Kelvin-Helmholtz instability (kKHI) are excited, and how such instabilities contribute to particle acceleration comparing simulations without a toroidal magnetic field (Nishikawa et al. 2016). We show that WI, MI and kKHI excited at the linear stage, generate a quasi-steady x-component of an electric field which accelerates and decelerates electrons. In this work, we use a new jet injection scheme where an electric current is self-consistently generated at the jet orifice by the jet particles. We inject both electron-positron and electron-proton jets with a toroidal magnetic field (with a top-hat jet density profile) for a sufficiently long time in order to examine the non-linear effects of the jet evolution. We observe significant differences in the structure of the strong electromagnetic fields that are driven by the kinetic instabilities. We find that different jet compositions present different strongly excited instability modes. The magnetic field in the non-linear stage generated by different instabilities becomes dissipated and reorganized into a new topology. The 3-dimensional magnetic field topology indicates possible reconnection sites and the accelerated particles are significantly accelerated in the non-linear stage by the dissipation of the magnetic field and/or reconnection. This study will shed further light on the nature of astrophysical relativistic magnetized jet phenomena.

1. Introduction

Relativistic jets are ubiquitous in astrophysical systems,
such as active galactic nuclei and gamma ray bursts.

Understanding jet composition, particle acceleration, and emission of radiation is still an ongoing work among many research groups (including Nishikawa et al. since 2009) with **PIC simulations of global jets containing helical magnetic fields** (Nishikawa et al. 2016, 2020)



M87 (Credit NASA)

1.1. Key scientific questions

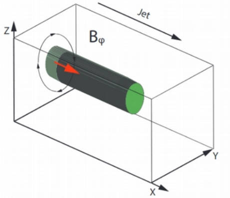
- How do global jets evolve with different particle species?
- How do **toroidal magnetic fields affect the kinetic instabilities** in plasma jets and their **nonlinear evolution**, as well as the
- magnetic reconnection?
- Jets in Jets really happen due to **magnetic reconnection**

1.2. Why do we need to perform PIC simulations of relativistic jets

- **Kinetic instabilities** (e.g., kinetic Kelvin-Helmoltz Instability (kKHI), Mushroom Instability (MI), and Weibel Instability (WI)) are a key issue in understanding jet evolution besides the kink instability in Relativistic Magnetohydrodynamic (RMHD) simulations
- Helical (toroidal) magnetic fields are crucial in understanding these instabilities
- PIC global jet simulations are a new and innovative approach which provides insights of the complex **evolution of relativistic jets with kinetic processes including emission of radiation** which cannot be performed by RMHD simulations
- Nonthermal acceleration due to reconnection may generate flares

2. Simulation set-up

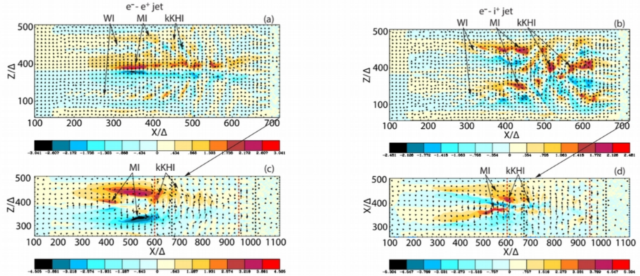
- Develop a **new jet injection** scheme: a cylindrical jet is injected into the ambient plasma at rest, which propagates in the x-direction, with a toroidal magnetic field; Plasma jet is composed of **electrons and positrons** and of **electrons and ions** (with $m_i/m_e = 4$), respectively
- The jet is injected at $x = 100\Delta$ in the center of the y-z plane at (y_{jc}, z_{jc}), and propagates in the x-direction
- Jet radial width in cylindrical coordinates is $r_{jet} = 100\Delta$
- Equations of toroidal magnetic field (B_φ) followed from Mizuno et al. (2014) and Nishikawa et al. (2020), where the components of B_φ are written in Cartesian coordinates (B_y and B_z), and B_x=0
- Equation for the **current J_x** follows from $\partial E/\partial t$ =curl B = J
- Use a **top-hat density profile** for the jet head
- In the new scheme, the magnetic field is co-moving with the jet and is generated by the current that is self-consistently created by the jet particles
- To sustain the current in the jet, the toroidal magnetic field is gradually applied at the jet orifice ($x/\Delta = 100 - 102$), and a **motional electric field** is set-up, $\mathbf{E}_{mot} = -\mathbf{v}_j \times \mathbf{B}$; Δ is the grid cell size and $v_j = v_{j,x}\,\hat{x}$, where $v_{j,x}$ is the x-component of the jet velocity



The schematic jet injection scheme with a toroidal magnetic field (Bφ). The jet electrons and positrons (**ions**) are injected so that the current (indicated with the red arrow) is generated to support the toroidal magnetic field.

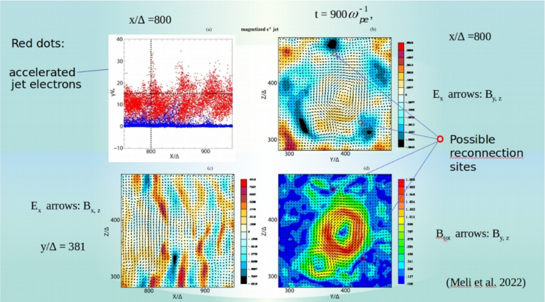
3. Results (Meli et al. 2022, in preparation)

3.1. Generation of kinetic instabilities and global evolution of the jets containing toroidal magnetic fields

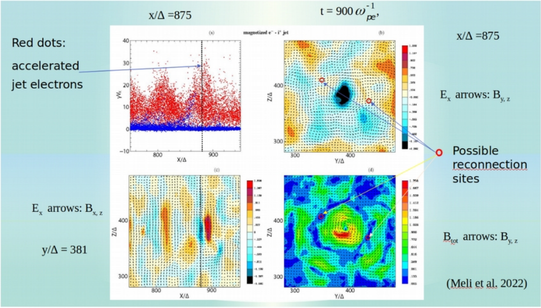


Color maps of the magnetic field amplitude By and **arrows depicting the magnetic field components** in the x - z plane, both at $t = 600\omega_{pe}^{-1}$ (upper panels) and $900\omega_{pe}^{-1}$ (lower panels), respectively. The jet is injected at x = 100Δ in the middle of the y - z plane and propagates in +x-direction. Panels (a, c) are for an e± plasma while panels (b, d) are for an e⁻ − i⁺ composition.

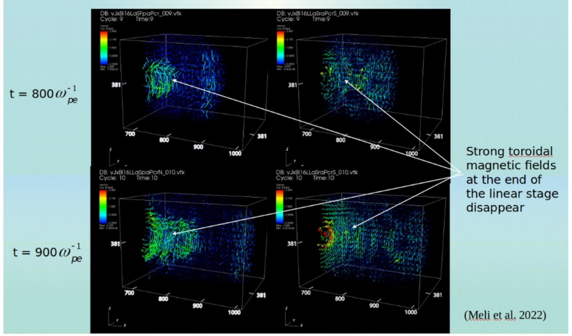
3.2. Electromagnetic fields and particle acceleration



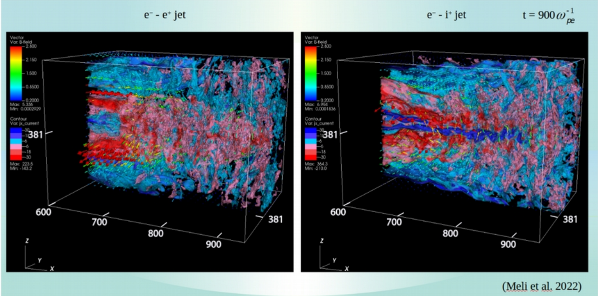
For an e± plasma jet: Panel a: x - γv_x phase-space distribution of jet (red) and ambient (blue) electrons. Panels b, c, & d: structures generated due to different MI modes. Panels b & c: possible magnetic reconnection sites.



For an e⁻ − i⁺ plasma jet: Panel a: The x - γv_x phase-space distribution of jet (red) and ambient (blue) electrons. Panels b, c, & d: structures generated due to different MI modes. Panels b & c: possible magnetic reconnection sites.



3D evolution of the magnetic field near the jet head: Left-hand panels for an e± plasma and right-hand panels for an e⁻ − i⁺ composition. Acceleration of the electrons in the non linear stage, between 800 < x/Δ < 1000 is not due to the electric field of the generated instabilities, but is correlated to the dissipation of the magnetic fields.



The J_x structure and magnetic fields.

Color map: Structure of the current along jet direction of propagation, J_x **Thin lines**: Magnetic field.

Left panel shows the growth of the kKHI and MI (and WI), as well as the generation of two modes of MI, with twisted magnetic fields in the region 750 < x/Δ <950 which shows the non-linear saturation at x/Δ < 950 indicating the non-linear saturation of the grown instabilities.

Right panel shows the strong negative current in the center of the jet and the toroidal magnetic field which is opposite to the original direction.

4. Summary

- We simulated **electron-positron and electron-ion relativistic jets containing toroidal magnetic fields**
- For an electron-positron jet a MI is excited and combined with a kKHI while a quasi steady E_x modulates jet particles
- For an electron-ion jet, kinetic instabilities are **dominated by the MI**
- MI and kKHI produce quasi-steady electric field (E_x) for both types of plasma jets
- These electric fields accelerate and decelerate electrons and ions
- Electrons are **further accelerated** due to turbulent magnetic fields generated **by dissipations of helical magnetic fields** (reconnection)
- **Further investigations** is important in order to confirm and/or find other acceleration mechanisms with varying simulation parameters such as, jet radius, magnetization factor, jet structure (Gaussian shape), etc.

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