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Magnetohydrodynamic-particle-in-cell method and its applications

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Energetic particles, i.e., cosmic-rays (CRs), are prevalent in astrophysical and space plasmas. Numerical studies on the kinetic aspects of these particles suffer from the issue of scale-separation: the gyro-radii of these particles are generally much larger than the micro-scales in the background plasmas that must be resolved in the conventional PIC methods.

I will introduce and give an overview of the MHD-PIC method (Bai et al. 2015), which is developed to study the kinetic physics of CRs interacting with a background thermal plasma. It treats the cosmic-rays as particles using the conventional PIC approach, while treat background plasma as a fluid described by MHD. This method substantially alleviates the issue of scale separation encountered in conventional PIC approach, and enabled a wide range of plasma applications.

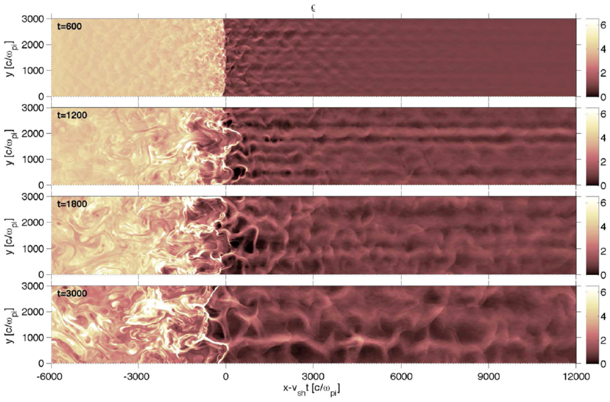

Figure 1. Snapshots of an MHD-PIC simulation of non-relativistic shock from Bai et al. (2015). Shown are gas densities with the Bell instability developed in the shock upstream.

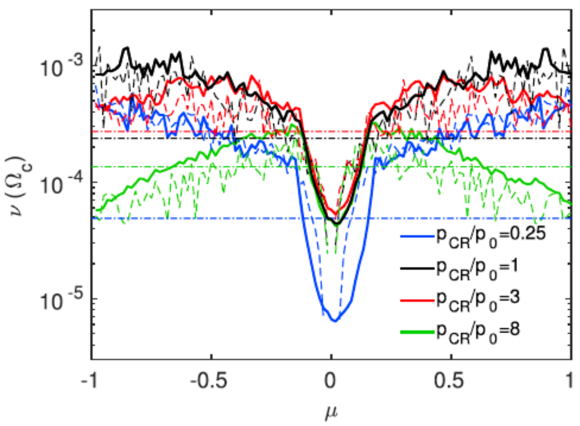

Figure 2. The measured pitch angle scattering rates as a function of pitch angle cosine for different CR momenta from the first-principle simulations of the CR streaming instability. Taken from Bai (2022).

As examples, I will show simulations of particle acceleration in non-relativistic shocks (Figure 1), where results similar to hybrid-PIC can be obtained at dramatically reduced computational cost. I will also describe the first simulations of CR transport and feedback from the CR streaming instabilily (Bai et al. 2019, Plotnikov et al. 2021, Bambic et al. 2021), where we can measure the transport coefficients from first principles (Bai 2022, Figure 2).

I will also discuss the extension of this method to further leverage the scales, where one can replace orbital integration by guiding-center motion. This approach may permit multi-scale simulations of the dynamics and particle energization in magnetic reconnection (Figure 3), and has the potential to be extended to truly macroscopic scales.

Both methods have been implemented to the Athena++ MHD code (Sun & Bai, to be submitted and Hu & Bai, in prep) and have been well tested.

References
Bai X.-N., Caprioli D., Sironi L., Spitkovsky A., 2015, ApJ, 809, 55
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Plotnikov I., Ostriker E.C., Bai X.-N., 2021, ApJ, 914, 3
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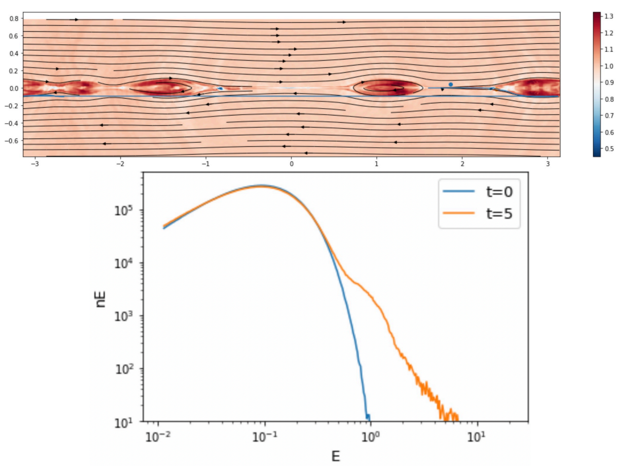

Figure 3. Sample simulation of magnetic reconnection in 2D, with guiding-center particles. Also shown is the development of a non-thermal particle population over time. From Hu & Bai (in prep).

Note: Abstract should be in (full) double-columned one page.