SIMULATING MAGNETIZED PLASMA TURBULENCE FROM MACRO TO MICRO SCALES

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PI: Kirit Makwana[1]
Co-PIs: Fausto Cattaneo[1], William Daughton[2], Hui Li[2]
Collaborator: Vladimir Zhdankin[3]

[1]University of Chicago
[2]Los Alamos National Laboratory
[3]University of Wisconsin-Madison

EXECUTIVE SUMMARY:

Magnetized plasmas are ubiquitous in space, astrophysical, and laboratory environments. Energy is injected in them at large scales by external forcing or some intrinsic instability of the system. This energy gets transferred to smaller scales by the nonlinear interaction of the system and ultimately is converted into heat. We simulate this process using both magnetohydrodynamic (MHD) and kinetic (particle-in-cell) codes. We observe striking similarities between the two codes in their energy dynamics and energy spectrum. Thin, current-sheet-like, dissipative structures are formed in both codes. A statistical analysis of their morphological characteristics is performed, to reveal that their length scales with the driving scale of the turbulence. The kinetic simulation reveals that their thickness is the skin-depth scale. A scan over the plasma beta parameter is performed to reveal significant non-thermal particle energization at low beta. This is linked with reconnecting current sheets in the simulation.

INTRODUCTION

Plasma turbulence is present in a variety of laboratory, space, and astrophysical plasmas. For example, the solar corona is interspersed by magnetic field lines that are constantly moving, led by their footpoint motion [1]. This motion launches Alfven waves in the corona which then reflect, interact, and produce turbulence. Turbulence cascades energy from larger to smaller scales, where it is converted into heat. This process has the potential to explain the observed heating of solar corona and solar wind [2]. Similar processes occur or are thought to occur in laboratory tokamaks, in planetary magnetospheres, in accretion disks, and nearly all turbulent plasmas. Understanding the turbulent cascade process and its consequential heating is thus a very important problem with numerous applications to various systems.

Past simulations have mostly used the magnetohydrodynamics (MHD) framework, which is applicable at macro-length scales larger than the ion gyro-radius scale. However, in typical collisionless plasmas, the conversion of turbulent energy into heat occurs due to wave-particle interactions below this scale. For understanding of this process, kinetic simulations are required. In this project, we simulated the turbulent cascade of energy using both MHD and kinetic codes. This tells us whether MHD is the correct limit of plasma turbulence at macro scales. It also tells us where MHD breaks down and kinetic physics becomes important. We were able to analyze the dissipative, current sheet structures that form in both simulations. This project advanced our understanding of dissipation in plasma turbulence.

METHODS & RESULTS

We used the MHD code PLUTO [3] and the particle-in-cell code VPIC [4]. We simulated decaying plasma turbulence by specifying an initial condition and allowing the system to decay. The initial condition for both codes was an ensemble of superimposed shear Alfven waves. As these waves interact, they generate turbulence, which cascades energy to smaller scales, where it is converted into heat.

We found remarkably similar decay rates in both the simulations, despite the fact that the small-scale dissipation physics in the two codes is very different. Our MHD simulations relied purely on artificial numerical dissipation, whereas the PIC simulations included all kinetic processes involved in dissipation. Still the dissipation rate was the same, indicating that the dissipation scales adjust themselves to balance the rate of energy transfer arriving from larger scales. The energy spectra also matched between the two codes. This showed that MHD simulations of turbulence produce reliable energy dynamics.

At smaller scales, important differences appear between the two descriptions. We observed formation of current sheets in both the codes, as shown in Figure 1. The thickness of current sheets in MHD depends directly upon the grid-size, which is unphysical. However, VPIC correctly identifies the current sheet thickness as the skin-depth, which is a kinetic scale. We also find generation of a significant non-thermal tail in the particle energy distribution function in VPIC at low plasma beta (ratio of thermal to magnetic energy density). We are currently investigating the link of magnetic reconnection in current sheets with this non-thermal particle energization.

This project shows that we can achieve a direct comparison between the MHD and fully kinetic description of plasma turbulence. It gives us the confidence that MHD simulations of turbulence produce reliable energy dynamics. Conversely, it also shows that high-performance computing, and Blue Waters specifically, are now capable of reproducing MHD results from first principle, particle-in-cell simulations. This opens up the small scale physics of energy dissipation to investigation by first principle codes. We can expect to unravel the mystery of collisionless dissipation in hot plasmas, which will inform us about plasma heating and particle energization in the solar corona, solar wind, and planetary magnetospheres. This will help in understanding space weather and its implications for our technology, which is hugely affected by space weather.

WHY BLUE WATERS

The petascale computing ability of Blue Waters was essential for carrying out this project. The VPIC code we used for the kinetic simulations is part of the NCSA Blue Waters Sustained Petascale Performance (SPP) suite. NCSA and Cray improved compiler optimization of loops not already using optimized vector compiler intrinsic functions, optimized to eliminate extra data copies, added FMA4 compiler intrinsic functions to improve performance, and used Cray I/O buffering functionality. Our simulations used a 1024x1024x1024 cell domain with 3.758 billion particles.

The Blue Waters project staff was also helpful in the data analysis and visualization. They helped us in using Paraview to visualize the data in 3D. Figure 1 shows an example of 3D visualization of the current sheets that form in our simulation.

The next Track-1 system can help us in simulating plasmas with even lower beta, thereby giving significant non-thermal particle energization. This is more attractive for explaining the abundance of non-thermal particle distribution functions observed in astrophysical plasmas.

PUBLICATIONS

Makwana, K., et al., Energy dynamics and current sheet structure in fluid and kinetic simulations of decaying magnetohydrodynamic turbulence. *Physics of Plasmas,* 22 (2015), 042902.

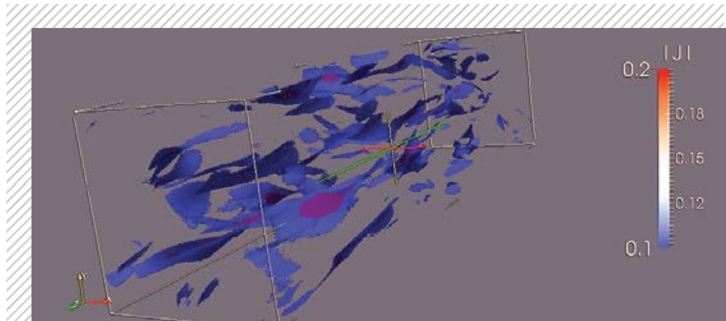

FIGURE 1 : The large-scale Surfaces of constant current density in the rectangular simulation domain. The simulation domain is elongated along the background magnetic field. The two colors are for two current density values. We can clearly see the sheet like structure of current density isosurfaces. The sheets have three typical dimensions. They are longest in the direction parallel to background magnetic field. Perpendicular to the field they have an intermediate width, and very small thickness.