Driven-Turbulence Simulations of High-Energy-Density Plasmas

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Abstract

The magnitude of magnetic fields in the observable universe leads to questions regarding the physical processes that can grow and maintain them. One leading theory is fluctuation dynamo, which can amplify seed magnetic fields in a turbulent plasma to the point where the magnetic energy becomes an appreciable fraction of the available turbulent kinetic energy. Since the seminal numerical demonstration of fluctuation dynamo by Meneguzzi et al.,[1] several numerical studies have pushed simulations codes and leveraged high-performance computing resources to explore fluctuation dynamo in magnetized turbulence at different regimes (for a recent review see Rincon[2]), although limited in the resistive magnetohydrodynamics (MHD) ansatz. Inspired by the recent experimental demonstrations of fluctuation dynamo by the turbulent dynamo (TDYNO)collaboration[3,4] via laser-driven, high-energy-density (HED) experiments at the Omega Laser Facility at the University of Rochester's Laboratory for Laser Energetics, we present a series of 3-D FLASH simulations of driven turbulence that aim to study HED turbulence in regimes where plasma physics processes are important and extend beyond the one-temperature resistive-MHD ansatz broadly employed in existing theoretical and numerical models. The effort leverages FLASH's new extended MHD and HED physics capabilities and will furnish the theoretical foundations for future TDYNO experiments.

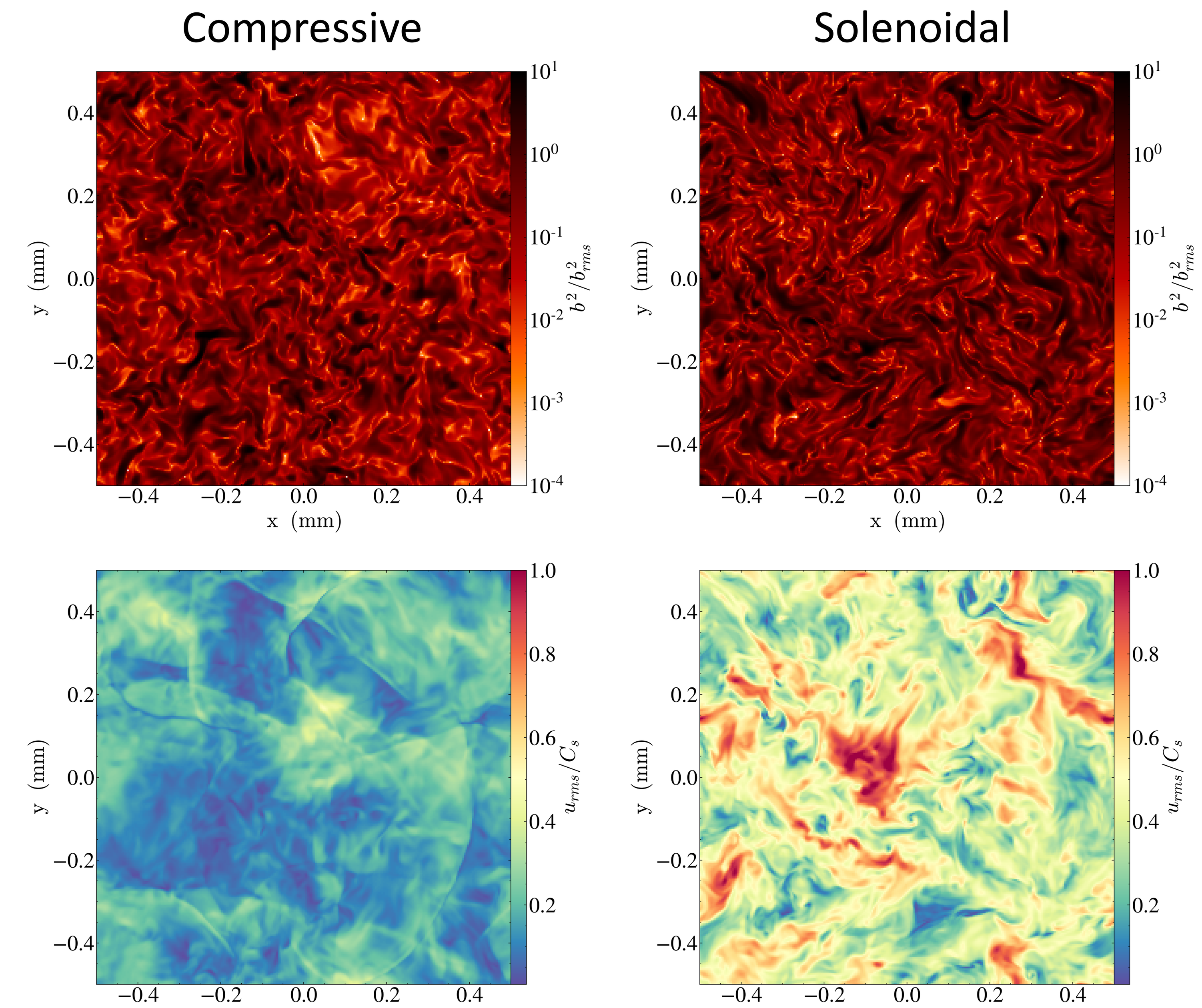
Multiphysics Driven Turbulence with FLASH

The FLASH code is under continuous devolvement at the Flash Center for Computational Science [https://flash.rochester.edu] in the Department of Physics and Astronomy at the University of Rochester. FLASH[5] is a multi-physics, parallel, adaptive mesh refinement (AMR), finite-volume Eulerian hydrodynamics and magneto-hydrodynamics (MHD) code. The code is a professionally managed software with version control, extensive documentation, user support, integration of code contributions from external users, and is tested daily through automated regression test suite, on several compliers. Under the auspices of the U.S. DOE NNSA, the Flash Center has added extensive HED-relevant physics and extended-MHD capabilities in FLASH[6], allowing for high-fidelity simulations of laser-driven HED laboratory astrophysics and plasma experiments. Relevant to this work additions include: three-temperature extensions to the hydrodynamic and MHD solvers, multigroup radiation diffusion, tabulated multi-material equations of state (EOS) and opacities, heat-exchange, as well as realistic viscosity, thermal conductivity, and magnetic resistivity. These additions allow the FLASH code study MHD and HEDP physics. Limited by resolution and algorithmic constraints, previous generations of numerical simulations of driven turbulence were limited to magnetic Prandtl numbers of order unity, and rarely ventured beyond the resistive MHD ansatz. While in recent years the effects of supersonic turbulence have been investigated[7,8] the effects of radiation and electron physics represent "uncharted plasma physics" regimes, as noted by Rincon[2]. These unexplored physics effects on magnetized turbulence and dynamo guide the overarching questions of our work. What are the statistics of driven magnetized turbulence for full-physics HED plasmas? How do thermal conduction, radiation losses, and shocks change the turbulent energy cascade? Is transport altered in HED magnetized turbulence, particularly in the collisional MHD Braginskii limit[9]?

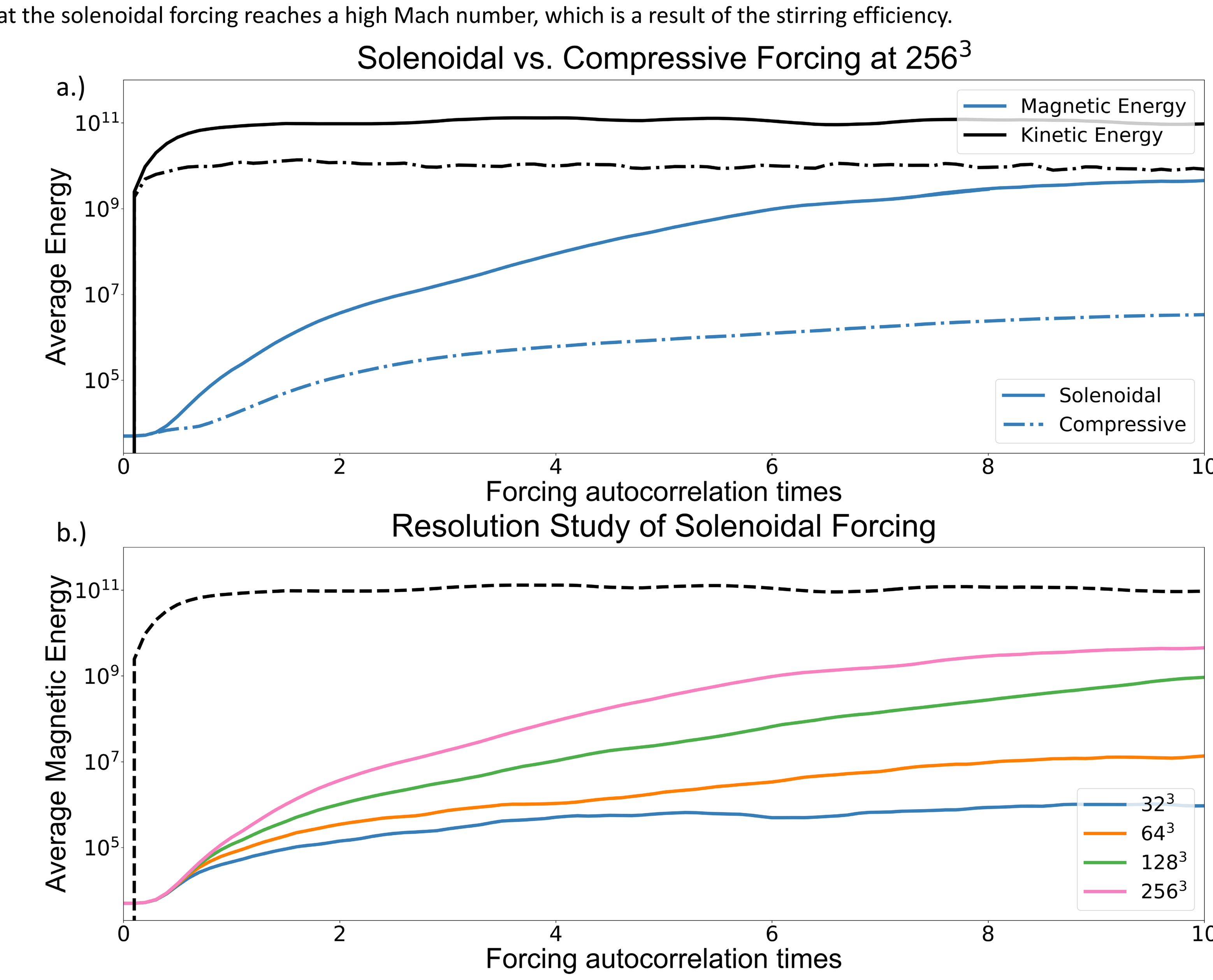
Simulation Design and Configuration

All simulations are preformed in a millimeter-side cubic box with periodic boundary conditions. The system is advanced using FLASH's third order PPM[10, 11] solver with characteristic tracing, a HLLC Riemann solver with van Leer Slope limiter, and constrained transport[12,13] for maintaining solenoidality at machine precision. The simulations are stochastically driven in Fourier space at the three largest wavelengths, which are then Fourier transformed to real space into accelerations. The forcing module uses an Ornstein-Uhlebeck process as devolved in FLASH by Federath et al.[14] The forcing is then chosen to be either purely compressive ($\boldsymbol{\nabla} \times \boldsymbol{F}_{stir} = \mathbf{0}$) or solenoidal ($\boldsymbol{\nabla} \cdot \boldsymbol{F}_{stir} = 0$). The simulations are initialized with a CH plasma whose electron, ion, and radiation temperatures, density, and ionization values that are similar to those attained in the TDYNO experiments.[3,4] The equation of state and opacity table for CH are computed with PROPACEOS[15] for the full-physics runs or follow an ideal gamma-law (γ = 5/3) for the ideal runs.

Baseline MHD Results with Ideal EOS

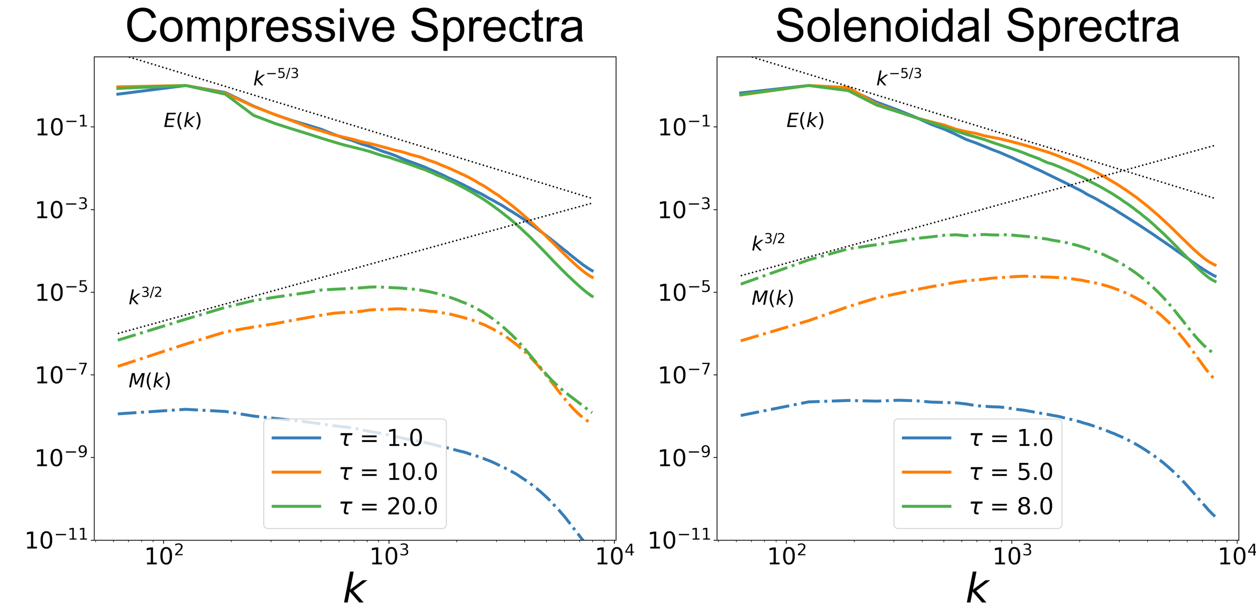


[**Figure 1]** Slices at 256^3 resolution, through the center of the simulation The comparison between the drives shows similar distributions in magnetic field energy by its root mean square (RMS) value . The comparison between the Mach numbers shows that the solenoidal forcing reaches a high Mach number, which is a result of the stirring efficiency.



[Figure 2] a.) Graph comparing the resulting kinetic and magnetic energy vs forcing autocorrelation time for otherwise identical compressive and solenoidal forcing. The graph show that both kinetic and magnetic energy are greater for the solenoidal case.
b.) A resolution study showing the effect of increasing resolution on average magnetic energy, as resolution increases so does the magnetic energy.

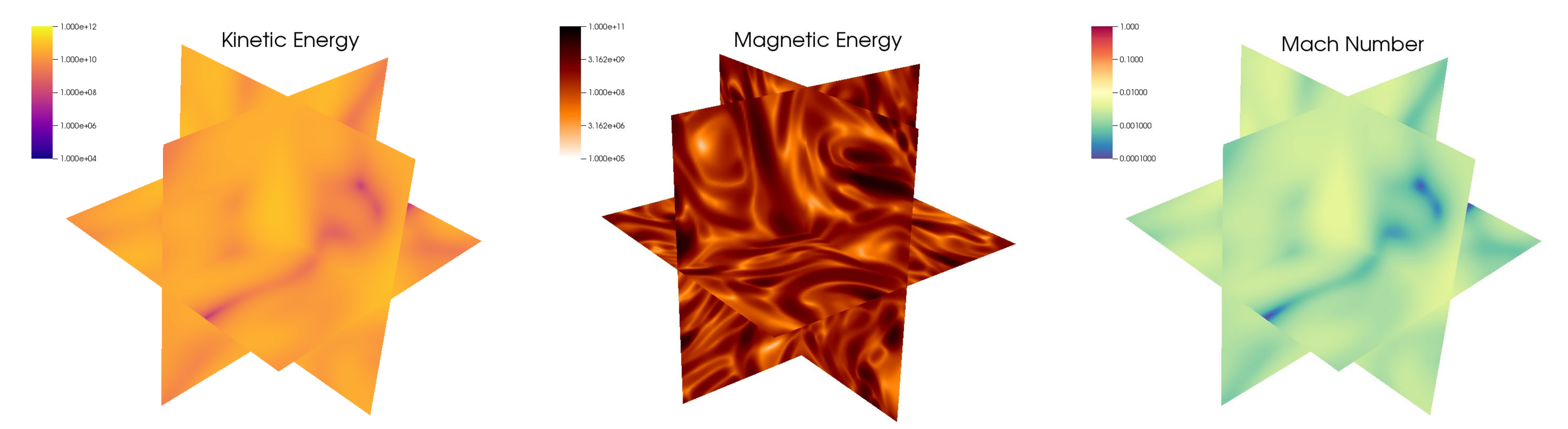
[Figure 3] The kinetic and magnetic energy spectra normalized by the maximum value of the kinetic energy. Despite being slightly more compressive, the solenoidal forcing produces energy spectra that are more consistent with Kolmogorov power-law scaling in the kinetic energy, and Kazantsev power-law scaling in the magnetic energy.



Discussion

The investigation begins in the ideal MHD regime, wherein the diffusion is only attributable to the inherent numerical diffusivity of the numerical schemes used and the grid resolution. These simulations have magnetic Prandtl numbers of order unity, since the viscous and resistive dissipation scales are set by the cell size. Already by simply relaxing the isothermal EOS assumption,[14] we see that the two types of drive (Figure 1), for the same energy input, differ significantly in terms of drive efficiency: The solenoidal drive results in larger RMS velocities compared to the flow velocities attained with the compressive drive (Figure 2). Thus, the magnetic Reynolds numbers characterizing the solenoidal-drive simulations are larger compared to those characterizing the compressive-drive simulations. The difference is significant enough for the former to enter the fluctuation dynamo regime, whereas the latter only exhibits magnetic tangling,[16] saturating at lower magnetic-to-kinetic energy ratios. Further, as resolution increases, the numerical diffusivities decrease $\propto 1/\Delta x^2$, which again leads to an increase in the magnetic Reynolds number, increasing the growth rate and magnetic energy at saturation (Figure 2). As shown by the time evolution of the solenoidal-drive spectra (Figure 3), the normalized kinetic energy power spectrum is consistent with a Kolmogorov power-law scaling ($\propto k^{-5/3}$), and the magnetic energy at the largest scales follows a Kazantsev[17] power law ($\propto k^{-3/2}$). The TDYNO experiments are expected to have a combination of the two drives, on account of the shearing colliding flows.[3] The ideal MHD simulations will be used as the null case to compare against full-physics HED driven turbulence simulations.

Preliminary HED Driven Turbulence Simulations



In Preparation & Next Steps & Conclusions

These results show promise in approaching new physical regimes that will inform future directions for the TDYNO experimental campaigns. We plan to meticulously dissect the effects of the HED physics processes at play in the full-physics simulations.

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