Astrophysical magnetized turbulence and turbulent dynamo in laser-driven plasma experiments

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Overview: Astronomical observations that are based on Faraday rotation and polarization measurements, Zeeman effect, magneto-bremsstrahlung, and *in situ* measurements of proximal astrophysical objects, reveal the broad range of values of cosmic magnetic fields (Zel'dovich et al. 1983): from microgauss in galaxies and galaxy clusters to milligauss in molecular clouds, a few gauss in planets, tens of kilogauss in stars and accretion disks, megagauss in white dwarfs, and many teragauss in the vicinity of black holes and neutron stars. Space is thus permeated by magnetic fields (Parker 1979) that play critical roles in myriad astrophysical phenomena.

The consensus among cosmologists and astrophysicists is that cosmic magnetic fields are the result of dynamo amplification of tiny seed fields in turbulent magnetized plasmas (Parker 1979; Kulsrud et al. 1997). Tapping into its kinetic energy reservoir, the turbulence "stretches", "twists", and "folds" the tiny seed fields (Batchelor 1950) a sequence of transformations that results in the exponential amplification of the magnetic energy density, until it quickly becomes a sizable fraction of the available kinetic energy density of the turbulent motions (Haugen et al. 2004; Schekochihin et al. 2004). After that, large-scale dynamos operate on the amplified fields and generate the coherent, large-scale structures we observe in planets, stars, and galaxies (Brandenburg & Subramanian 2005).

Despite the broad consensus among astronomers that magnetic field amplification via turbulent dynamo is behind the observed cosmic magnetism, the specifics of the process are poorly understood. Even though conditions favorable for dynamos are common in astrophysics, they are extremely difficult to realize in laboratory experiments (Verhille et al. 2010). The turbulent wrapping of the magnetic fields operates against the magnetic diffusivity of the plasma that results in the field lines diffusing through the motions of the turbulent eddies. This interplay is characterized by the plasma's non-dimensional magnetic Reynolds number (Rm), the ratio of the diffusion timescale over the advection timescale. For turbulent dynamo to operate Rm must surpass a critical value Rm_C that theory predicts to be of order of a few hundred (Schekochihin et al. 2004; 2007), a value that is difficult to achieve in terrestrial laboratories. Moreover, the turbulence must persist for multiple eddy-turnovers for amplification to occur; since high Rm implies large velocities, such a system is challenging to realize.

With the advent of high-power lasers and pulsed-power devices, we are now able to reproduce astrophysical environments in the laboratory (Remington et al. 1999). This has led to an increase in research momentum, as several groups are attempting to study astrophysical processes in scaled laboratory experiments, such as magnetic reconnection (Li et al. 2007, Rosenberg et al. 2015); collisionless magnetized shocks (Schaeffer et al. 2017); Weibel-mediated shocks (Park et al. 2012, Huntington et al. 2015); and the generation of magnetic seeds at shocks by the Biermann effect (Gregori et al., 2012). In conjunction with new enabling technologies in high-performance computing (HPC), these developments have set the stage to achieve significant scientific advances – and establish a much-needed experimental component – in the study of magnetized turbulence and turbulent dynamo.

TDYNO experiments – experimental demonstration of turbulent dynamo: Over the last seven years the University of Chicago and the University of Oxford have developed a concerted research program to conduct innovative experimental campaigns to reproduce turbulent dynamo amplification of magnetic fields in a controlled environment. Their seminal experiments were performed using the Vulcan laser at the Rutherford-Appleton Laboratory (RAL) in the UK, where they demonstrated the amplification of seed magnetic fields by turbulence (Meinecke et al. 2014; Tzeferacos et al. 2015), managing to reach a regime that is a precursor to turbulent

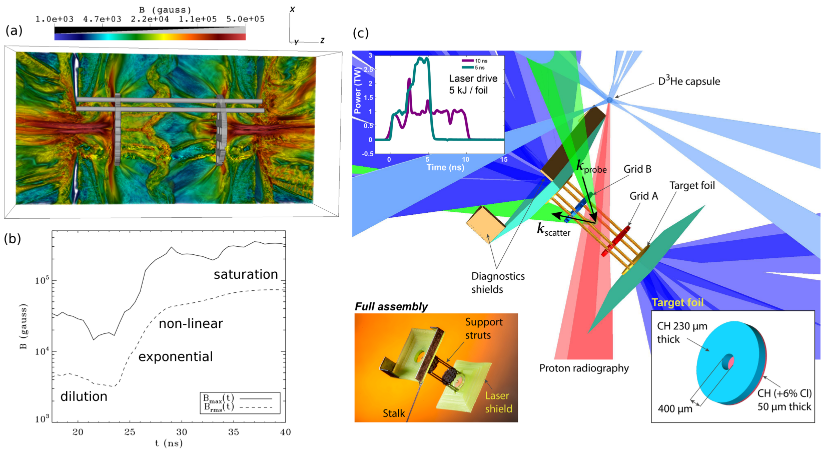

Figure 1: FLASH simulations of the TDYNO platform (from Tzeferacos et al. 2017; 2018). (a) Volume rendering of the turbulent magnetic field. (b) Time history of the magnetic field in the turbulent interaction region. (c) The TDYNO platform as deployed at Omega, demonstrating turbulent dynamo for the first time in the laboratory.

dynamo (Meinecke et al. 2015). Leveraging the designs and results of the Vulcan experiments, they performed extensive large-scale 3D simulation campaigns on the *Mira* supercomputer at Argonne National Laboratory (Tzeferacos et al. 2017) with the FLASH code (Fryxell et al. 2000; Dubey et al. 2009; Tzeferacos et al. 2015), to design a novel platform for the Omega Laser Facility that promised to generate high-Rm magnetized turbulence (Figure 1a), which could persist for enough eddy-turnover timescales for the seed magnetic fields to be amplified to dynamically important values, and capture the kinematic (exponential), non-linear, and saturation phases of the dynamo (Figure 1b). The assembly (Figure 1c) is comprised of two composite foil/washer targets and two grids with offset hole patterns that break mirror-symmetry. The laser beams drive the targets to form a pair of inwards-moving plasma flows that advect Biermann battery-generated fields. The flows traverse the grids, collide, and shear to form an interaction region of hot, subsonic turbulent plasma. The turbulence persists for multiple eddy turnovers and amplifies the advected seed fields until the mechanism saturates.

The experiments conducted by the TDYNO collaboration at Omega took advantage of the facility's rich diagnostic capabilities. More specifically, to characterize the interaction of the colliding flows and assess the properties of the turbulent plasma they utilized X-ray imaging (Figure 2a), the spectral analysis of which confirmed Kolmogorov turbulence (Figure 2c). Using optical Thomson scattering they recovered the plasma's electron temperatures and densities, as well as its bulk and turbulent velocities, as a function of time (Figure 2b), to reveal subsonic,

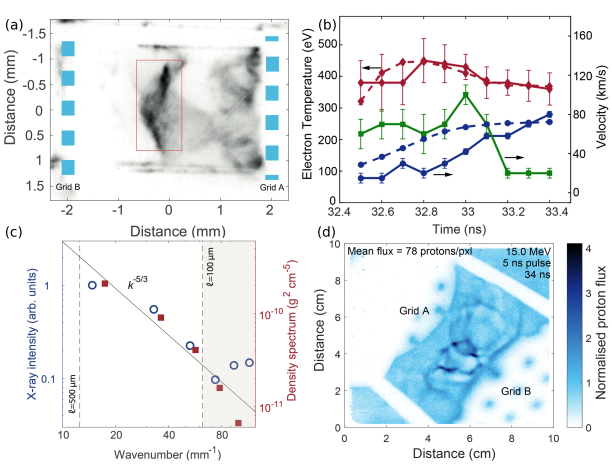

Figure 2: Omega TDYNO experiment demonstrating turbulent dynamo (from Tzeferacos et al. 2018). (a) X-ray image of the turbulent interaction region. (b) Electron temperatures (red) and flow velocities (blue-bulk and green-turbulent), obtained from Thomson scattering (solid lines) and FLASH predictions (dashed lines). (c) Power spectrum of the X-ray intensity fluctuations (blue) and the density power spectrum from the FLASH simulations (red). (d) Proton radiograph of the turbulent interaction region. The filaments are indicative of strong turbulent magnetic fields.

small magnetic-Prandtl turbulence with root-mean-square (rms) values of Rm ≃ 600, above the critical threshold predicted by theory. To measure the magnetic fields and their amplification they deployed two independent diagnostics, Faraday rotation (Rigby et al. 2018) and proton radiography (Graziani et al 2017; Bott et al. 2017; Fig. 2d), to find that the advected seed fields ($B_{rms,seed} \lesssim 4$ kG) were amplified to saturation values of $B_{rms,sat} \simeq 100$ kG, about ~ 5% of the available turbulent kinetic energy, demonstrating thus the turbulent dynamo mechanism for the first time (Tzeferacos et al. 2018). The platform has since been fielded successfully at Omega, the National Ignition Facility, and the Laser Megajoule (LMJ) Facility in France, enabling a broad research program on the workings of turbulent dynamo in different plasma regimes.

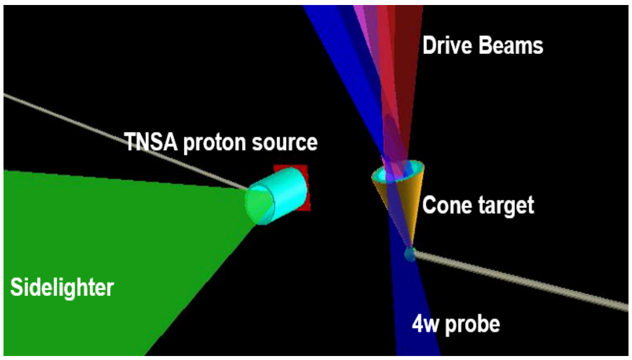

Figure 3: LANL turbulent dynamo platform deployed at Omega-EP (Liao et al. 2019a). The target consists of a CH cone whose inner surface is illuminated with 2 or 3 beams delivering 0.5 TW with a 10 ns pulse. The ablation of the inner surface of the target forms a hot, turbulent plasma flow that propagates out of the cone target. The flow is probed using a 4ω Thomson scattering diagnostic and the magnetic fields are imaged with TNSA.

LANL experiments at Omega-EP: More recently, an experimental group from Los Alamos National Laboratory developed a new platform (Liao et al. 2019a) using FLASH simulations to study turbulent dynamo. The platform was successfully fielded at the Omega Laser Facility using the Omega-EP laser. The platform adopts a cone design (Figure 3) that briefly traps the colliding plasmas produced by laser beams illuminating the inside surface of the cone. The rising turbulent plume reaches high temperatures and high magnetic Prandtl number, enabling turbulent dynamo. The magnetic field evolution was inferred from Target Normal Sheath Acceleration (TNSA) proton-deflectometry (Figure 4, left). Using the proton radiography reconstruction technique of Graziani et al. (2017), they were able to infer the power spectra of the magnetic energy and show magnetic field amplification.

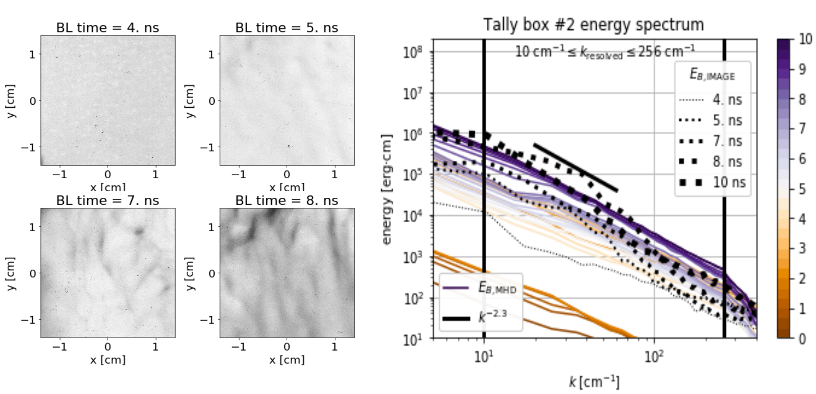

Figure 4: Left: TNSA deflectometry images of the flow as function of time (Liao et al. 2019b). Right: Inferred magnetic field power spectra (derived from the images) that show the exponential growth and saturation of the magnetic field, consistent with turbulent dynamo.

Discussion & outlook: These recent advancements in the experimental study of magnetized turbulence and turbulent dynamo open new opportunities for reproducing astrophysical processes in a controlled laboratory environment and position us to address long-standing, fundamental questions of plasma astrophysics (FPSPR 2015): *What is the origin of magnetic fields in the Universe? How do they regulate the transport of heat, particles, and momentum? How do field* *line topologies change during magnetic reconnection and what controls its onset and rate? What are the fundamental acceleration mechanisms behind cosmic rays? How and why is energy in the Universe partitioned into various forms?* Laboratory astrophysics experiments are now in a position that can bridge the gap among observations, theoretical understanding, and numerical modeling, obtaining results of broad interest to the plasma and astrophysics communities.

To ensure that this research momentum is maintained, we specifically call out the following areas:

1. **Need to advanced theory, simulations and numerical techniques** to model the turbulent, magnetized high energy density (HED) plasmas. Current studies clearly demonstrate that turbulent HED plasmas are intrinsically self-magnetized. This introduces new challenges and opportunities in a suite of important problems that have been treated traditionally without magnetic fields, such as instabilities, turbulence, mix, and transport. Such highly non-linear, anisotropic processes are currently not well understood.
2. **Need to develop *specialized* experimental diagnostics** in order to characterize plasmas *at scales* and *in ways* that untangle the complex nature of astrophysical plasma processes. These include high-resolution X-ray and proton radiography imaging to resolve turbulent power spectra and the energy cascade; high-bandwidth instruments that spatially characterize heat, particles, and plasma momentum; *in situ* magnetic field diagnostics to locally characterize magnetic field topologies and strengths; and new (monochromatic) charged particle sources and high-resolution spectrometry to resolve the non-thermal tails of accelerated particles.
3. **Need to understand the backreaction of the plasma onto energetic particles**. The transport of high-energy cosmic rays and their acceleration to ultra-high energies (up to 10^{11} GeV) remains one the greatest unknowns in high-energy astrophysics. Since the rigidity of those energetic particles in the Galactic magnetic field is the same as the rigidity of MeV protons crossing a turbulent magnetized laboratory plasma, as in the TDYNO platform (Chen et al. Arxiv), there is significant scope for experiments to provide novel predictions and new discoveries to take place.
4. **Need to develop validated multi-physics numerical modeling to design, analyze, and interpret laboratory astrophysics plasma experiments.** A concerted effort is needed to develop and maintain *open* radiation-MHD and kinetic codes that can leverage HPC architectures. Furthermore, there is a need to foster partnerships among experimental physicists, computational scientists, and applied mathematicians, to take advantage of cross-disciplinary knowhow and enhance the predictive capabilities of our simulation tools.
5. **Need to explore multiple synergistic platforms to increase the number of experiments**. Innovative platforms should be developed to take advantage of high repetition rate laser experiments, using existing lasers systems such as Omega, Omega-EP, and facilities within LaserNetUS[1]. Experiments dedicated to examining particular physical processes should be encouraged. Experiments sharing similar overarching goals but different approaches should be encouraged as well.
6. **Need to bring new scientific talent into the fields of laboratory plasma astrophysics and HED plasma physics**. Workforce development is critical for the vitality of this young field and this can best be done together with exciting discovery science topics and state-of-the-art experimental and numerical facilities.

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[1] https://www.lasernetus.org

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