White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	P
• Interactions of plasmas and waves	S
• Plasma self-organization	P
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	

Title:	Hydromagnetic turbulence, dynamo amplification and non-thermal particle acceleration
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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)

- ***Describe the research frontier* and importance of the scientific challenge.**

It is a firmly established observational fact that Universe is magnetised: planets, stars, galaxies, clusters of galaxies (Zweibel & Heiles, 1997) and even the (relative) voids in between (Neronov & Vovk, 2010) have magnetic fields. However, the origin and strength of these fields are not fully understood.

Consider galaxy clusters, which are the largest (~Mpc) structured objects in the Universe. The intracluster medium (ICM) is a hot (~10^7 K), diffuse (particle density ~10^{-2}–10^{-3} cm^{-3}) X-ray emitting plasma. Observations suggest that it is in a highly disturbed state: by infalling chunks of dark matter (cluster mergers) and resulting gravitational instabilities, by active galactic nuclei (AGN) ejecting jets and blowing buoyant bubbles, and by galaxy wakes. Thus, the ICM is believed to be turbulent, with both physics-based estimates and cosmological simulations giving turbulent velocities at a finite fraction of the speed of sound (10^2–10^3 km/s). The magnetic fields observed in the ICM (principally via radio observations of Faraday Rotation) are stochastically tangled and tend to be in the range of ~1-10 μG (see Figure 1). This makes the magnetic-energy density comparable to the energy density of the mean plasma flows, so the magnetic fields are essential players in the dynamics of the luminous matter in the Universe. The total magnetic energy represents a sizable fraction of the cosmic energy budget.

The fact that cosmic magnetic fields are ubiquitous, stochastic, and dynamically strong suggests that a universal physical mechanism of *in situ* field generation is at play. It also appears rather difficult to find a

physical scheme that would make fields of observed strength and structure via a purely primordial process. The most popular scenario of the cosmic magnetogenesis (e.g., Ryu et al., 2008, Schekochihin & Cowley, 2006, Subramanian et al., 2006) is that the field grows via some form of ***turbulent dynamo*** – fast (exponential) amplification of stochastic field by turbulent motions into which it is embedded, starting from an initial small seed. The initial seed can also be made via a fundamental physical effect: the Biermann battery (i.e., baroclinic generation of magnetic fields), believed to generate seed fields of at least ~10^{-21} G (Kulsrud et al., 1997; Gregori et al., 2012).

Understanding magnetogenesis is part of the broader challenge of understanding cosmic turbulence: the energy injected into the ICM by mergers, AGN ejecta, and galaxy wakes, typically on scales of order 10 to 100 kpc, is passed on to small scales through a number of channels – velocity, magnetic, compressive fluctuations – and converted into heat, keeping (it is believed) the ICM hot in balance with radiative cooling. Exactly how thermally stable temperature profiles are achieved is another unsolved puzzle. So is the structure of the magnetised turbulent cascade.

The presence of energetic particles in the Universe is also a known fact, with measurements of the cosmic ray (CR) spectrum extending up to 10^{20} eV (Protheroe & Clay, 2004; Abraham *et al*., 2007). However, the exact mechanism(s) that lead to such high-energy particles still remain controversial. Although many different processes may result in CR acceleration, there is a consensus at present that shock waves and turbulence play an essential role in energising both the electrons and ions present in the interstellar medium. A mechanism for CR acceleration by turbulence or plasma waves was first proposed by Fermi (1949), whereby CRs are produced as charged particles gain energy in random scattering events with magnetized clouds moving with an average speed u. This is usually referred to as 2nd order Fermi acceleration (i.e., second order in the velocity). The scattering medium could either be a turbulent magnetized plasma or a turbulent wave spectrum (Kulsrud & Ferrari, 1971; Cowsik & Sarkar, 1984). A more efficient acceleration mechanism was suggested by Fermi (1954). He proposed that, in a converging flow of clouds, particles gain energy at each collision, and thus the acceleration goes more efficiently as u/c. This is now referred to as 1st order Fermi acceleration. It was later realised that shock waves provide the ideal setting in which 1st order acceleration can occur (Bell, 1978; Blandford & Ostriker, 1978), a process also referred to as diffusive shock acceleration (DSA).

A particularly attractive feature of DSA is that, in the simplest test-particle theory, the accelerated particles naturally develop power-law spectra consistent with those inferred from multi-wavelength measurements. In particular, supernova remnant shocks are believed to explain galactic CRs, up to the "knee" in the spectrum at 10^{15} eV. While the DSA model is promising, the details of the process are still uncertain (Protheroe & Clay, 2004; Petrosian, 2012; Drury, 2012). An important issue is that the efficiency of the acceleration relies on the ability of particles to cross the shock surface many times. This is possible only if the particles already have sufficient initial energy to overtake the shock and start the acceleration process. This is known as "the injection problem" (Riquelme & Spitkovsky, 2011), and at present it is not fully understood.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

The gap between astrophysical observations, theoretical understanding and numerical modeling can be bridged by providing a laboratory-based experimental platform that can be used to investigate magnetized turbulence and the acceleration of electrons by shocks created under well-controlled laboratory conditions. With the advent of high-power lasers, a new field of research has opened where, using simple scaling relations (Ryutov et al., 1999, 2000), astrophysical environments can be reproduced in the laboratory (Remington, 1999). Over the past few years we have seen the development of several experimental programs aimed at the investigation of the properties of high-Mach-number shocks and MHD turbulence in scaled laboratory experiments (Kugland et al., 2012; Mondal et al., 2012; Merritt et al., 2013; Fox et al., 2013; Fiksel et al., 2014; Huntigton et al, 2015). This has led to the successful demonstration of the generation of magnetic seeds at shocks by the Biermann effect (Gregori et al., 2012)

and, more recently, of small magnetic fields being amplified in plasmas by turbulence as shocks interact with strong density inhomogeneities (Meinecke et al., 2014; 2015) (see Figure 2). These preliminary experiments were only able to achieve a regime where magnetic diffusion still remains important. In order to reach conditions that are truly relevant to ICM plasmas, we need large magnetic Reynolds number. Achieving large Reynolds numbers requires experiments that produce high velocities and temperatures. This is only possible at the largest laser facilities, such as Omega and NIF (Drake & Gregori, 2012) (see Figure 3). The development of platforms at these facilities that are able to produce sufficiently high velocities and temperatures is thus an important goal.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

The origin and generation of magnetic field remains an unsolved mystery in present-day astrophysics. Laboratory experiments will also help in shedding light onto the origin and acceleration of ultra high-energy cosmic rays. Experiments will then establish the required experimental platform where computation and theoretical astrophysicists could test and validate their models.

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Figures

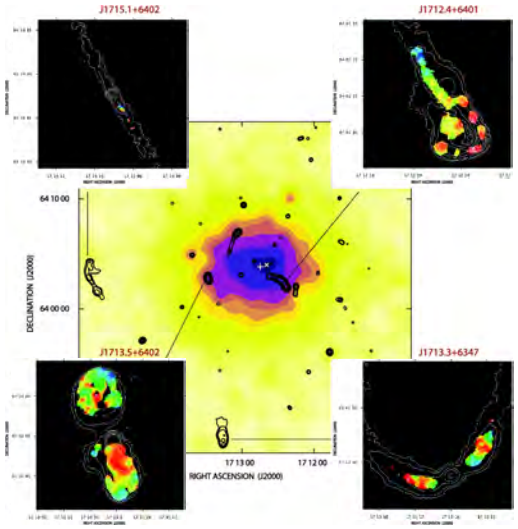

Figure 1. Radio contours of the A255 cluster of galaxies overlaid on the ROSAT X-ray image of the cluster. The white "+" and "x" symbols show the positions of the centroid and peak of the cluster X-ray emission. The images at the corners of the figure show the Faraday rotation measure (FRM) for four radio galaxies in the cluster. The FRM measurements of the radio halo at the cluster center and these four radio galaxies imply a magnetic field strength that declines from the cluster center outward, with a field strength of 2.6 micro Gauss at the cluster center and an average magnetic field strength of ~ 1.2 micro Gauss in the cluster core. Image Source: after Govoni et al. (2006).

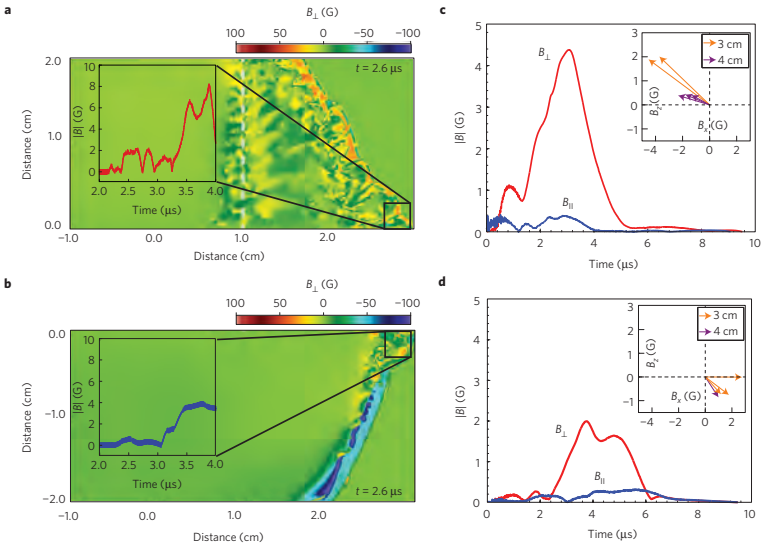

Figure 2. (a) FLASH simulation of the shock propagation through a grid at t=2.6 μs. The inset shows the time variation of the magnetic field at 2.8 cm from the grid position along the symmetry axis (b) Same as (a) but with no grid. (c) The components of the magnetic field measured at 3 cm from the carbon rod target. The inset shows the projection of the magnetic field at the time of its maximum intensity. Each vector corresponds to different shots. Data obtained at a distance of 4 cm from the carbon rod are also shown in the inset; in this case, the field is smaller. (d) Same as (c) but without the grid. Adapted from Meinecke et al. (2014).

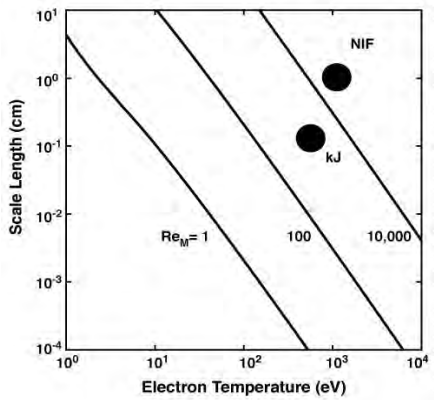

Figure 3: Lines of constant magnetic Reynolds number, Re_M, for a fully stripped B plasma. (They do not move much on such a log-log plot as materials change.) Values achievable by NIF and by kJ-class lasers are indicated.
The magnetic Reynolds numbers achievable in experiments at NIF could enable the first studies of turbulent magnetic field generation. Drake and Gregori (2012).