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Magnetic field generation, Weibel-mediated collisionless shocks, and magnetic reconnection in colliding laser-produced plasmas

W. Fox[1,†], A. Bhattacharjee[1,2] and G. Fiksel[3,4]

[1]Princeton Plasma Physics Laboratory
P.O. Box 451, Princeton, NJ 08543 USA

[2]Princeton University, Dept. of Astrophysical Sciences
Princeton, NJ 08543 USA

[3]University of Rochester, Laboratory for Laser Energetics
Rochester, NY 14623, USA

[4]University of Michigan, Dept. of Nuclear Engineering and Radiological Science
Ann Arbor, MI 48109, USA

[†]email: `wfox@pppl.gov`

Abstract. Colliding plasmas are ubiquitous in astrophysical environments and allow conversion of kinetic energy into heat and, most importantly, the acceleration of particles to extremely high energies to form the cosmic ray spectrum. In collisionless astrophysical plasmas, kinetic plasma processes govern the interaction and particle acceleration processes, including shock formation, self-generation of magnetic fields by kinetic plasma instabilities, and magnetic field compression and reconnection. How each of these contribute to the observed spectra of cosmic rays is not fully understood, in particular both shock acceleration processes and magnetic reconnection have been proposed. We will review recent results of laboratory astrophysics experiments conducted at high-power, inertial-fusion-class laser facilities, which have uncovered significant results relevant to these processes. Recent experiments have now observed the long-sought Weibel instability between two interpenetrating high temperature plasma plumes, which has been proposed to generate the magnetic field necessary for shock formation in unmagnetized regimes. Secondly, magnetic reconnection has been studied in systems of colliding plasmas using either self-generated magnetic fields or externally applied magnetic fields, and show extremely fast reconnection rates, indicating fast destruction of magnetic energy and further possibilities to accelerate particles. Finally, we highlight kinetic plasma simulations, which have proven to be essential tools in the design and interpretation of these experiments.

Keywords. plasmas, magnetic fields, shock waves, acceleration of particles

1. Introduction

The collision of high velocity flowing plasmas allows the conversion of kinetic energy into other forms, including heat, magnetic fields, and perhaps most interestingly, the acceleration of particles to form high energy, super-thermal particle populations. In astrophysical contexts, such systems appear to be the sites, where particles are accelerated to extremely high energies to form the cosmic ray spectrum (Ackermann *et al.* 2013). Since astrophysical plasmas are typically collisionless due to the high energy of the plasma, kinetic plasma processes govern the interaction and particle acceleration processes, including shock formation, self-generation of magnetic fields by kinetic plasma instabilities, and magnetic field compression and reconnection. How each of these contribute to the

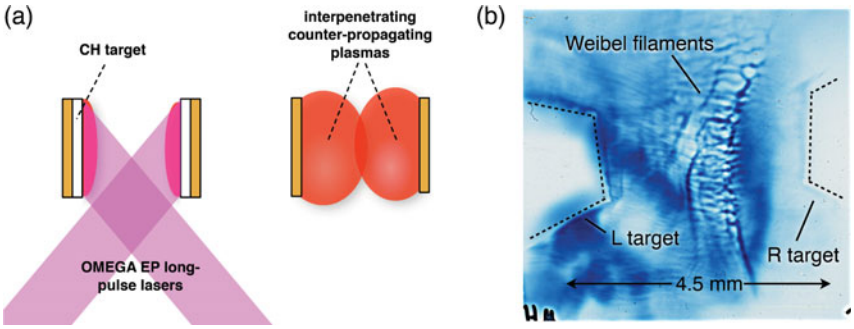

Figure 1. Diagram and proton radiography data from unmagnetized experiments showing development of filaments from ion-driven Weibel instability (Fox *et al.* 2013). The diagnostic uses a beam of protons to probe electromagnetic fields in the experiment volume; here, the filamentary magnetic fields of the Weibel instability lead to a characteristic filamentary proton intensity pattern on the detector film stack.

observed spectra of cosmic rays is not understood, and in particular two paradigms, shock acceleration (Bell 1978) and magnetic reconnection, have been proposed (Drake *et al.* 2010).

A recent generation of laboratory high-energy-density physics facilities, both laser and pulsed-power, has opened significant physics opportunities for experimentally modeling these processes. These experimental platforms are very interesting for laboratory astrophysics due to the high energy densities, which allows them to reach very low dissipation regimes, and to have good separation of scales from macroscopic to kinetic scales. This paper will highlight some recent results from these laboratory experiments toward understanding astrophysical magnetic field generation and particle acceleration mechanisms.

2. Collisionless shocks and ion-Weibel instability

The Weibel instability (Weibel 1959, Davidson *et al.* 1972) is among the few processes that generates magnetic field *de novo* in astrophysical and laboratory plasmas. This instability has received significant attention lately as a mechanism to mediate astrophysical collisionless shocks (e.g. Kato & Takabe 2008, Spitkovsky 2008). Coulomb collisions alone are typically too weak to sustain shocks in high-temperature astrophysical plasmas, since the ion mean-free-path is typically significantly larger than the observed shock width. Instead, collective electromagnetic fields are required. In cases, where ambient fields are weak or non-existent, the *Weibel instability* has been proposed to generate the fields required to sustain the shock. The interpenetration of plasmas in an initially unmagnetized shock front generates local counterstreaming beam conditions, which drive the Weibel instability. Weibel instability has been proposed to mediate shocks in systems ranging from gamma ray bursts to supernova remnants. Once a shock forms, particles are accelerated by repeated reflection off the plasma flows converging into the shock via the diffusive shock acceleration mechanism (Bell 1978).

Recent experiments made the first laboratory identification of the ion-driven Weibel instability between colliding unmagnetized plumes through experiments conducted on OMEGA EP (Fox *et al.* 2013) and OMEGA (Huntington *et al.* 2015), at the University of Rochester Laboratory for Laser Energetics, see Fig. 1. Large-scale particle-in-cell simulations provided *ab initio*, first principles simulations, which included the plasma ablation from the targets, collision of the two plumes, and in identifying the resulting Weibel instability (Fox *et al.* 2013). These results open up significant new questions and

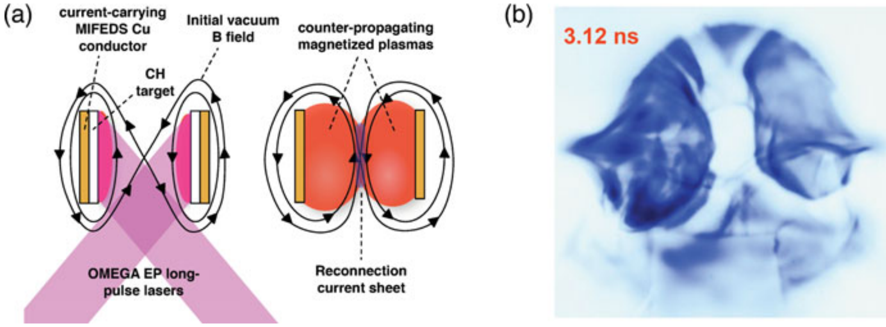

Figure 2. Diagram and sample proton radiography from magnetized experiment showing collision of magnetized plasmas and current sheet formation (Fiksel *et al.* 2014). The white bands reflect regions of highly-compressed magnetic field on the edge of the each plume. The magnetic topology is such that the collision of the plumes drives magnetic reconnection. The cellular pattern in the collision region possibly indicates the breakup of the current sheet into a few islands.

opportunities to study the astrophysical ion-Weibel instability. Future work should attempt to benchmark the dispersion relation in detail, and model the growth and saturation of the instability in 2-d and in 3-d under realistic scenarios. Experiments with embedded magnetic fields can study the suppression of Weibel instability by finite fields and thereby compare the shock mechanisms based on Weibel instability versus compression of a pre-existing upstream field.

3. Magnetic Reconnection

Throughout the Universe, magnetic reconnection is a ubiquitous process allowing the change of magnetic topology and the explosive release of stored magnetic energy (e.g. Yamada *et al.* 2010). Vivid examples of magnetic reconnection are solar and stellar flares, substorms in the Earth's magnetotail, which power the aurora, and sawtooth crashes and relaxation processes in tokamaks and reversed-field pinches. Key questions in magnetic reconnection research include the rate of reconnection, i.e. how fast can the magnetic energy be converted, the structure of reconnection current sheets, in particular a question of the importance of current sheet breakup into multiple magnetic islands, and finally the energization of particles by reconnection. In large reconnection systems, where reconnection occurs via multiple islands, a Fermi-type acceleration process again plays a role, where the particles interact with multiple reconnection outflows in a turbulent reconnecting current sheet (e.g. Drake *et al.* 2006).

In recent years a new set of magnetic reconnection experiments has been conducted in HED laser-produced plasmas (e.g. Nilson *et al.* 2006, Li *et al.* 2007). These laser-driven reconnection experiments collided plasma plumes and observed the reconnection of self-generated (e.g. Biermann battery) magnetic fields. Laser-driven experiments hold the possibility to observe reconnection dynamics in the large-system-size, turbulent regime; the large laser energy provides access to large energized volumes (when measured in fundamental plasma units such as the ion skin depth) and high-temperature, low dissipation regimes.

New experiments (Fiksel *et al.* 2014) have now demonstrated controlled magnetization of ablated plasma plumes using a choreography of externally applied magnetic fields, a "background" plasma, and "driver" plasma plumes. The results are shown in Fig. 2. Distinct white bands on the proton radiography observations indicate regions of strong magnetic field, where the pre-applied magnetic field is compressed from its initial $\sim$10 T at the targets to $\sim$25 T. Collision of oppositely magnetized plumes drives magnetic reconnection and generates bubble-like structures, which possibly reflect the breakup of the current sheet into multiple-island structures by a tearing instability. The experiments were successfully modeled by large-scale particle-in-cell simulation, which simulated the full evolution of the experiments starting from the formation of the two magnetized plasma plumes through to the collision and driven reconnection (Fiksel *et al.* 2014).

4. Conclusions

We have developed new techniques allowing laboratory experiments on the kinetic behavior of colliding magnetized plasmas, including magnetic field generation, compression, and reconnection. These offer significant opportunities for studying the mechanisms behind astrophysical collisionless shock formation and particle acceleration. Future work can study how both the reconnection and Weibel instability can heat and energize particles, both in the linear Weibel regime of the present experiments and eventually full-fledged shocks. In this case, comparison with magnetized experiments can allow comparison of shock-heating mechanisms (diffusive shock acceleration) with magnetic reconnection, on a common experimental platform (Deng *et al.* 2015). Large-scale, fully-kinetic particle simulation will continue to play a key role in designing and interpreting these experiments.

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