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Interrelationship between Lab, Space, Astrophysical, Magnetic Fusion, and Inertial Fusion Plasma Experiments

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Review

Interrelationship between Lab, Space, Astrophysical, Magnetic Fusion, and Inertial Fusion Plasma Experiments

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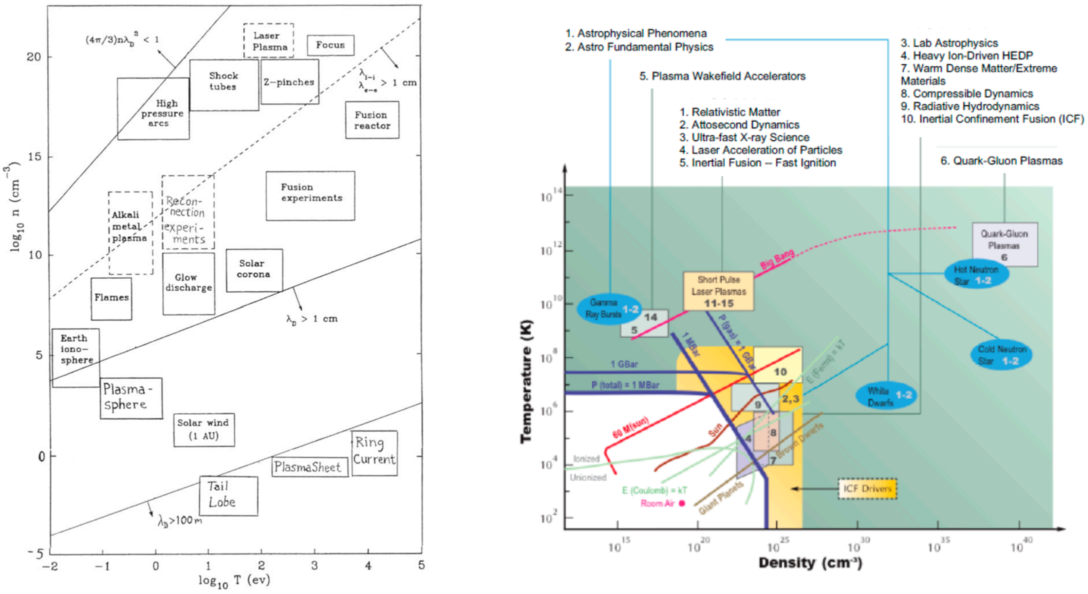
Abstract: The objectives of this review are to articulate geospace, heliospheric, and astrophysical plasma physics issues that are addressable by laboratory experiments, to convey the wide range of laboratory experiments involved in this interdisciplinary alliance, and to illustrate how lab experiments on the centimeter or meter scale can develop, through the intermediary of a computer simulation, physically credible scaling of physical processes taking place in a distant part of the universe over enormous length scales. The space physics motivation of laboratory investigations and the scaling of laboratory plasma parameters to space plasma conditions, having expanded to magnetic fusion and inertial fusion experiments, are discussed. Examples demonstrating how laboratory experiments develop physical insight, validate or invalidate theoretical models, discover unexpected behavior, and establish observational signatures for the space community are presented. The various device configurations found in space-related laboratory investigations are outlined.

Keywords: laboratory plasma; astrophysical plasma; fusion plasma; lasers; stars; extragalactic objects; spectra; spectroscopy; scaling laws

1. Introduction

Many advances in understanding geospace, heliospheric, and astrophysical plasma phenomena are linked to insight derived from theoretical modeling and/or laboratory plasma experiments [1–3]. Geospace plasma physics includes space weather during periods of magnetic storms, substorms, and geomagnetic quiet; nonlinear plasma behavior such as structure evolution in turbulence and particle transport, fluid and kinetic instabilities, wave–particle interactions, ionospheric-magnetospheric-auroral coupling; solar-wind interaction with magnetospheres; and solar-corona heating. Heliospheric physics is concerned with investigating the interaction of the Sun's heliosphere with the local interstellar medium, as well as with the origin and evolution of the Sun and solar wind, the magnetospheres of the Earth and outer planets, and low-energy cosmic rays. High-energy (HE) and high-energy-density (HED) astrophysics is the study of electromagnetic radiation, from ultra-energetic cosmic phenomena ranging from black holes to the Big Bang, and of ionized matter at ultra-high pressure (~1 Mbar to 1000 Gbar, i.e., 1 million to 1 trillion Earth-surface atmospheres of pressure), density, and temperature (i.e., stored energy in matter >10^{10} J/m^3, e.g., solid-density material at 10,000 K (~1 eV)) for which observations are made in the extreme-ultraviolet (EUV), X-ray, and gamma-ray bands. Examples of places where these HED conditions occur are in Earth's, Jupiter's, and Sun's core and inside igniting Inertial Confinement Fusion (ICF) implosions (~250 Gbar). Figure 1 illustrates the wide ranges of density and temperature naturally occurring in geospace, in the heliosphere, and in astrophysical environments and artificially occurring in larger magnetic and inertial fusion devices, as well as in smaller university-scale laboratory devices.



(**a**) (**b**)

Figure 1. Typical parameters of lab and nature's plasmas: Cartesian representation of density and temperature range associated with (**a**) heliospheric (10^2–10^9 K) [2] and (**b**) astrophysical (10^2–10^{14} K) plasma [4]. Upper-right region corresponds to pushing parameters toward nuclear fusion ignition.

Modern facilities and new experimental techniques have provided access to novel plasma regimes, such as those associated with the ultra-relativistic, beam-in-plasma interaction at the SLAC National Accelerator Laboratory, the ultra-cold, highly correlated plasmas being studied at NIST, University of Maryland, European Organization for Nuclear Research (CERN), and University of Michigan, and the low-temperature micro-discharges that simultaneously share aspects of the solid, liquid, and plasma states while being created to explore novel plasma chemistry in numerous academic and government research laboratories. Plasma source, boundary conditions, and configuration geometry affect space and lab plasma and processes. In geospace cases, the major plasma domains of the magnetospheric boundary layer, bow shock, plasmasphere, plasma sheet boundary layer, polar caps, and lobe region constitute examples of important sources, interfacial layers, and configuration geometry. In astrophysical cases, the major plasma domains associated with plasma jet direction, shock front interface, and coherent radiation- and particle-beam boundaries are examples of the source, gradient, and directional factors. The unexpected new phenomena that now frame the cutting edge of discovery plasma science elevate these new regimes to a common priority in fundamental and applied research that is better illustrated by a circular plasma-parameter space (Figure 2) rather than the cartesian plasma-parameter space familiar in the quest for fusion.

Circumnavigating the range of temperatures, densities, and magnetic fields shown in Figures 1 and 2 are a number of pervasive themes in plasma behavior that can be characterized in terms of universal processes that are, at least partially, independent of the specific process being investigated. Some of these processes are well understood and predictable, whereas many others are neither. Advances for which (a) lab experiments helped explain phenomena and processes, (b) lab data influenced the interpretation of space data, and (c) laboratory validation of atomic and molecular spectroscopic processes contributed to telescopic probing of distant events are itemized in Sections 2–4. As identified in the Plasma 2010 report of the National Academies [5], six critical plasma processes define the research frontier.

- Explosive instability in plasmas
- Multiphase plasma dynamics
- Particle acceleration and energetic particles in plasmas

- Turbulence and transport in plasmas
- Magnetic self-organization in plasmas
- Correlations in plasmas

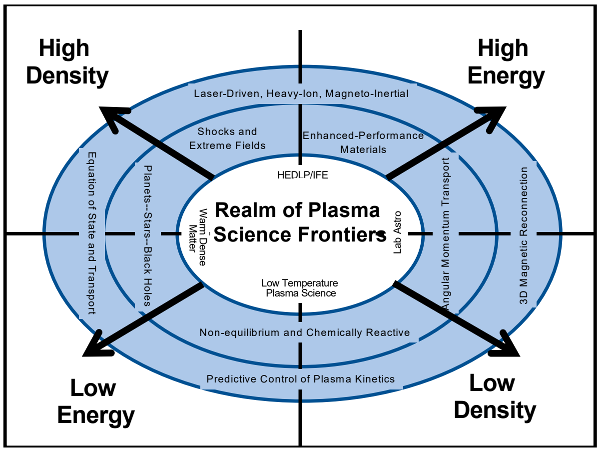


Figure 2. Phenomenological regimes depicted on a circular energy–density range. Angular dispersion of regimes emphasizes their unbiased priority assignment in discovery science.

2. Geospace–Lab Interrelationship

Fälthammar [1] describes the previous generation of lab-magnetospheric plasma interrelations as exploratory measurements in simulated configurations. Partial scale-model experiments, such as Birkeland's Terrella [6] having a magnetic neutral sheet in the simulated nightside magnetosphere, were used to validate Störmer's orbit theory [7] and Alfvén's perturbation theory [8]. Advances in understanding iconic features in the solar-terrestrial environment, such as Birkeland currents, electric fields along B-lines, and electrostatic particle acceleration, were made with these "configuration simulations" and the role of current filamentation and inhomogeneity was debated. Birkeland [9], Danielsson and Lindberg [10], Podgorny [11], Ohyabu and Kawashima [12], and Bratenahl and Yeates [13] were primary laboratory contributors.

A sophisticated physics-orientation effort ("process simulation") was needed, in which suitably designed lab experiments could be performed for clarifying physical processes. Accomplishments in understanding collisionless resistivity, the interaction between a plasma and a magnetic field (magnetic-field penetration), the beam–plasma interaction, parallel electric-field generation in a magnetic mirror geometry, and electric-charge double-layer formation were responsible for widely recognized highlights during this period of investigation. Noteworthy laboratory contributions include the discovery of a double sheath (layer) [14], a high-voltage parallel potential drop [15,16], an instability due to a perpendicular ion beam [17], and fast-electron production by an electrostatic beam-plasma wave [18].

An international workshop, held in 1980, on the relation between laboratory and space plasmas [19] gathered researchers working on the following topics: critical ionization velocity, formation of double layers, active stimulation (by high-power pulse and high-frequency transmitter) of the auroral ionosphere, energetic electron-beam experiments (in a 17 m × 26 m chamber and from rockets), plasma potential in the presence of strong ion-cyclotron turbulence, a magnetic field-line reconnection experiment, space experiments with particle accelerators (SEPAC) on Spacelab, and the EXOS-B/Sipole-station VLF wave–particle interaction experiment. Significant attention was given to plasma instabilities, for example, from electrostatic shocks in the lab and by the S3-3 satellite, in the high-latitude ionospheric F region, in electrojets, and in the auroral acceleration region.

One workshop focus was documenting the advances in explaining and validating phenomena and processes relevant to probing astrophysical events. The critical ionization velocity experiments were shown to contribute to explaining the pattern associated with ionizing discontinuity driven by stellar UV radiation at the heliospheric shock. Establishing the observational signatures of broad, thin, reconnecting neutral sheets, of the dynamics and topology of magnetic field-line reconnection, and of the effects of high-β was emphasized as an important influence of laboratory experiments to interpreting space and astrophysical data. The topic "Laboratory experiments on quantifying resistivity" was considered an excellent example of the benefit of the lab–space collaboration.

A more recent review paper on the interrelationship between laboratory and space plasma experiments [2] outlined the following benefits of lab experiments to the understanding of space plasmas: illustrating what a spacecraft would detect for specific processes, pioneering diagnostic methods, and being a source of citations on controlled-parameter experimental evidence for space researchers. The number and scope of interdisciplinary (i.e., lab–space) activities are expanding as space missions resemble more and more the multi-point data acquisition associated with laboratory experiments and as present-day activities become more overlapped. Many space plasma physicists concur with the ideas that:

- lab experiments are generally complementary to space observations;
- a well-designed lab experiment has the potential to provide measurements in detail far greater than those that can currently be obtained by in situ measurements;
- such detail can provide new insight into the mechanisms involved and can help direct the development of theories to explain the space observations; and
- future collaboration between space and lab communities would be profitable.

3. Heliosphere–Lab Interrelationship

In reviewing laboratory investigating of the physics of space plasmas, Howes [3] highlights key open questions and lab–space physics successes enumerated in solar corona, solar wind, planetary magnetospheres, and outer boundary of the heliosphere. He identifies velocity space as a key new frontier and outlines a strategy for future lab–space physics investigations on the following topics:

- Plasma turbulence
- Magnetic reconnection
- Particle acceleration
- Collisional and collisionless shocks
- Kinetic and fluid instabilities
- Self-organization
- Physics of multi-ion and dusty plasmas
- Astrophysical connections
- Improved diagnostic capabilities
- Novel analysis methods

From this list, turbulence, magnetic reconnection, particle acceleration, and kinetic instabilities are recognized as four grand challenges. Earlier lab experiments suffered from an inability to model the large scales (relative to kinetic length scales) that are characteristic of space plasma processes, whereas present-day intermediate-scale facilities can generate plasma spanning a substantial dynamic range above the typical kinetic length scales. For example, UCLA's Large Plasma Device-Upgrade (LAPD) produces a 2-mm ion-gyroradius, 17-m long, 60-cm diameter, magnetized plasma column able to axially contain magnetohydrodynamics (MHD) waves with frequencies below the ion cyclotron frequency. The plasmoid instability can be studied in collisional and collisionless regimes when the current-sheet length relative to the ion inertial length or ion Larmor radius exceeds 1000, which is within reach of present-day intermediate-scale facilities. Lundquist number $>10^5$ is possible in soon-to-be inaugurated intermediate facilities. Many other space-related lab devices, not quite at the intermediate scale, are mentioned in terms of their contributions to space, heliospheric, and astrophysical plasma research.

The New Frontier Science Experiments (FSE) Campaign [20] on the DIII-D tokamak, launched in 2017, contributes insight from lab and theory. Subproject titles from the DIII-D FSE initiative are listed below. Four FSE experiments were conducted in FY2017 and another four were conducted in FY2018. Four undesignated slots are tentatively scheduled for the FY2020 campaign. The last experiment on the list is positron generation, a fundamental physics challenge, being taken to new higher yields by using the higher density, higher temperature plasmas confined toroidally in a tokamak. Many positron-related space physics questions motivate this work: Why does matter dominate over antimatter in the universe? Where do gamma-ray bursts originate in space? How do black holes form? The study of positrons provides insight.

(1a) Self-organization of unstable flux ropes (1 day of 2017 runtime)
(1b) Magnetic reconnection and self-organization of flux ropes in tokamak sawteeth (1 day in 2018)
(2) Impact of magnetic perturbations on turbulence (1 day of 2017 runtime)
(3a) Interaction of Alfven/whistler fluctuations and runaway electrons (0.5 day of 2017 runtime)
(3b) Interaction of Alfven/whistler fluctuations and runaway electrons (0.5 day in 2018)
(4) Field-line chaos: Self-consistent chaos in magnetic field dynamics (0.5 day of 2017 runtime)
(5) Electromagnetic ion-cyclotron emission (1 day of 2018 runtime)
(6) Positron generation in tokamaks (0.5 day of 2018 runtime)

4. Astrophysics–Lab Interrelationship

High-energy-density (HED) astrophysics explores a wide range of topics by exploiting the extreme physical conditions achievable through the use of large off-site facilities specially designed for HED physics and inertial confinement fusion research. Laser energy is used to compress capsules filled with fuel material to high density and pressure in order to generate fusion reactions with the goal of self-sustained fusion burn ("ignition") and the generation of energy. Such work is primarily executed using the 30-kilojoule OMEGA laser at the University of Rochester and the 2-megajoule laser at the National Ignition Facility (NIF). Special diagnostic instrumentation has been developed that makes it possible to study spatial and temporal variations in plasma properties and electromagnetic fields through spectral, temporal, and imaging measurements. Researchers actively collaborate and sometimes lead teams in planning experiments at the facilities and in analyzing the results. Major research topics common to the inertial fusion realm fall within the science of extreme astrophysical phenomena:

- Physics of inertial confinement fusion
- Properties of warm dense matter
- Stellar and Big Bang nucleosynthesis
- Basic nuclear physics
- Astrophysical jets
- Magnetic reconnection
- High-energy-density hydrodynamics
- Nonlinear optics
- Relativistic HED plasma and intense beam physics
- Magnetized HED plasma physics
- Radiation-dominated HED plasma physics

We can test hypotheses concerning the physics of an observation that took place millions or even billions of light years away when dimensionless quantities retain their qualitative ordering. Thus, lab experiments develop, via computer simulation, credible scaling of physical processes. New space telescopes permit observations of ultra-high-energy events, helping us probe these spatially and temporally distant events. The goal of laboratory plasma astrophysics is, quoting from the National Academy of Sciences report [21], Connecting Quarks with the Cosmos, to "discern the physical principles that govern extreme astrophysical environments through the laboratory study of HED physics." The challenge here is to develop physically credible scaling relationships that enable laboratory experiments on the centimeter or meter scale to illuminate physical processes taking place in a distant part of the universe over enormous length scales.

Spectacular outbursts from the notoriously steadily glowing Crab Nebula are altering the theories that have long explained charged-particle accelerations to high energies [22]. Recently, the nebula's gamma-ray flares were observed to fluctuate on time scales of only a few days and even shorter, over just one to three hours, indicating that the charged particles were accelerated within a region representing an infinitesimal fraction of the vast Crab. It is proposed that the electron-positron plasma particles are accelerated near the nebula's center where rapid magnetic reconnection unleashes enormous amounts of energy in the presence of a strong electric field [23]. Laboratory experiments, together with theoretical models, are providing evidence that magnetic reconnection can explain the space observation of this rapid extreme particle acceleration and gamma-ray flaring in the Crab Nebula [23,24].

The remarkable discovery by the Chandra X-ray observatory that the Crab Nebula's jet periodically changes direction provides a challenge to our understanding of astrophysical jet dynamics. It has been suggested that this phenomenon may be the consequence of magnetic fields and MHD instabilities, but experimental demonstration in a controlled laboratory environment remained elusive until experiments were reported [25] that use high-power lasers to create a plasma jet that can be directly compared with the Crab jet through well-defined physical scaling laws, as documented in Table 1. The jet generates its own embedded toroidal magnetic fields; as it moves, plasma instabilities result in multiple deflections of the propagation direction, mimicking the kink behavior of the Crab jet, as illustrated in Figure 3. The experiment was modelled with 3-dimensional numerical simulations that show exactly how the instability develops and results in changes of direction of the jet.

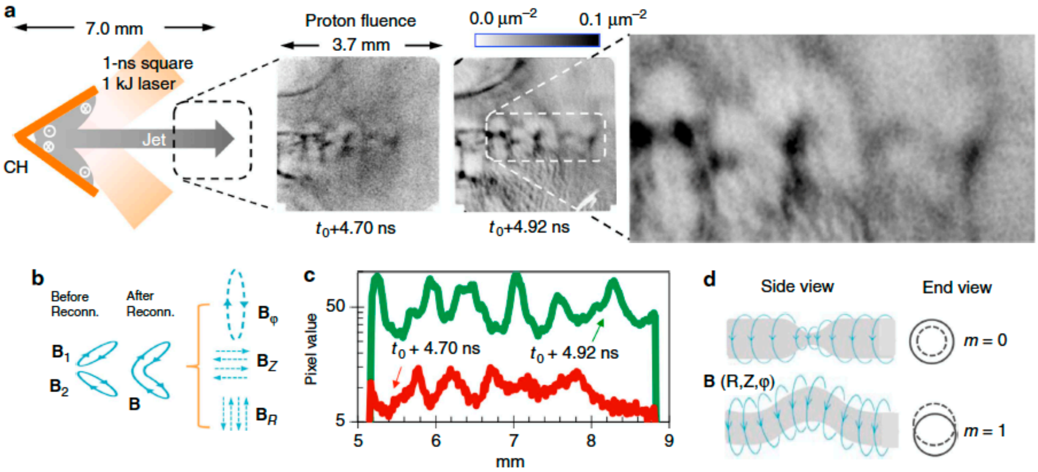


Figure 3. Side-on image [25] shows sequence of clumps and wiggles, resulting from embedded toroidal B fields, indicating MHD current-driven instabilities: mode $m = 0$ (sausage) and $m = 1$ (kink).

Table 1. Scaled lab experiments (refer to Figure 3) explain kink behavior of the Crab Nebula jet [25].

Parameters and Scales		**Plasma Jet in OMEGA Experiment ***	**Scaled to the Crab Nebula †**	**The Kinked Jet in the Crab Nebula †**
Temperature	T_e	~300 eV		~1–130 eV
Ionization state	Z	~3.5		~1
Number density	n_e	~5 × 10^{19} cm^{-3}		~10^{-2} cm^{-3}
Pressure	P	~4 × 10^5 bar		~4 × 10^{-14} bar
Jet radius	r_j	~5 × 10^{-2} cm		~1 pc
Jet velocity	v_j	~400 km s^{-1}	**< 3 × 10^5 km s^{-1}**	**~1.2 × 10^5 km s^{-1}**
Time scale	τ	~10^{-9} s	**~1.5 years**	**~few years**
Magnetic field	B	~2 MG	**~0.6 mG**	**~1 mG**
Thermal plasma beta	β	~0.1–1		<<1
Magnetization parameter	σ	~1–6		≥1
Mach number	M	~3		>>1
Reynolds number	R_e	~2 × 10^5		~2 × 10^{17}
Peclet number	P_e	~1–5		~4 × 10^{15}
Magnetic Reynolds number	~3 × 10^3		~1 × 10^{22}	
Biermann number	Bi	~6		~6 × 10^8
Radiation number	$\prod$	~3 × 10^5		~1 × 10^{18}

Note: * Near the region of jet launching. † Near the region of the pulsar pole. The bold entries show the physical quantities from the two systems that can be directly compared through the scalings in Equation (3), manifesting how the laboratory experiment parameters scale to match those of the Crab nebula jet.

Understanding the equation of state and chemistry of even more extreme matter stands as a central challenge in validating theoretical models in planetary physics and astrophysics. The interiors of giant planets exist in a density, temperature (n,T) regime where accurately calculating the equation of state is difficult. Molecules, atoms, and ions coexist in a fluid that is coupled by Coulomb interactions and is highly degenerate (free electrons governed by quantum and thermal effects). These strong interactions dominate in the steady-state interiors of giant planets such as Saturn and Jupiter and in brown dwarfs where phase transitions play an important role. Understanding the high-pressure phases of carbon is important since carbon is a major element of giant planets such as Uranus and Neptune. Petawatt-laser-driven shock-wave measurements of diamond's principal Hugoniot curve have been made at pressures between 6 and 9 Mbar using the Laboratory for Laser Energetics (LLE) OMEGA laser. The Hugoniot curve traces the path accessed by the laser-induced shock driven in the material, indicating that, in the solid–liquid coexistence regime in that range between 6 and 10 Mbar, the mixed phase is slightly denser than the one that would be expected from straightforward interpolation between liquid and solid Hugoniot curves.

Near Jupiter's surface (10^{11} Pascal and a fraction of an eV), hydrogen exists in molecular form. However, it dissociates and ionizes deeper into the planet's core (>10^{12} Pascal and a few eV). This transition from insulator to conductor in the convective zone is believed to be responsible for Jupiter's 10 to 15 Gauss magnetic field. An open question is whether there is a sharp plasma phase transition. Experiments performed on the Nova laser at Lawrence Livermore National Laboratory initially suggested that the transition was continuous, and subsequent experiments unambiguously demonstrated that the transition from non-conducting molecular hydrogen to atomic metallic hydrogen at high pressure is a continuous transition. This suggests that the metallic region of Jupiter's interior extends out to 90 percent of the radius of the planet and may explain why the magnetic field of Jupiter is so much stronger than that of the other planets of our solar system.

The study of astrophysically relevant, magnetized high-energy-density (HED) plasmas relies heavily on numerical simulations in limited parameter regimes, where the thermal and magnetic pressures balance (β ~ 1) and where the magnetic field advects with the plasma (Re_M >> 1), and has had little guidance from controlled laboratory experiments to test underlying principles, even though magnetized plasmas are ubiquitous throughout our universe. Using high-energy lasers, plasma conditions similar to those found in astrophysical systems can be created. Specifically, supersonic plasma flows can arise from irradiating a thin (10 s of μm) solid material with a high-energy laser pulse in an externally seeded magnetic field. This regime allows us to study the structure of accretion shocks and how the shocks are affected by magnetic fields, which will aid in understanding the spatial structure of hotspots on the surface of a young star [26]. Experimental conditions can be created where a plasma flow encounters a magnetic obstacle, which is similar to a planet's magnetosphere interacting with the stellar wind [27]. Finally, the effects of magnetic fields on collimated outflows, which are observed in young stellar objects [28], can be studied.

The astrophysical Weibel instability has been reproduced for the first time in counter-streaming laser-produced plasmas [29]. The Weibel instability, by generating turbulent electric and magnetic fields in the shock front, is responsible for the requisite interaction mechanism in shock formation in the limit of weakly magnetized shocks. This work confirms its basic features, a significant step toward understanding these shocks. In the experiments, a pair of plasma plumes are generated by irradiating a pair of opposing parallel plastic (CH) targets. The ion–ion interaction between the two plumes is collisionless, so as the plumes interpenetrate, supersonic and counter-streaming ion flow conditions are obtained. Electromagnetic fields formed in the interaction of the two plumes were probed with an ultrafast laser-driven proton beam, and the growth of a highly striated, transverse instability with extended filaments parallel to the flows was observed. The instability is identified as an ion-driven Weibel instability through agreement with analytic theory and particle-in-cell simulations, paving the way for further detailed laboratory study of this instability and its consequences for particle energization and shock formation. Astrophysical shocks, which often manifest as collisionless, typically require collective electromagnetic fields to couple the upstream and downstream plasmas. These shocks can energize cosmic rays in the blast waves of astrophysical explosions and they can generate primordial magnetic fields during the formation of galaxies and clusters [29].

5. Conclusions

An alliance exists between laboratory plasma physicists and space scientists to investigate basic and fusion plasma phenomena relevant to space. Dedicated lab studies (1) probe and elucidate fundamental plasma physical phenomena and processes, (2) provide benchmarks for validating theory and modeling, (3) discover unexpected behavior, and (4) establish observational signatures, all in support of interpreting rocket, satellite, and telescope data.

As concluded in the Plasma 2010 report [5], "progress in understanding the fundamental plasma processes in many space and astrophysical phenomena is greatly leveraged by close communication among space, astrophysical, and laboratory plasma scientists." The connections between the different plasma regimes studied in geospace, heliospheric, and astrophysical plasma and the related fields of laboratory plasma physics have led to significant scientific progress in many research areas. Studies of common plasma processes, rather than comparing the large-scale morphology of observed systems, link the different plasma physics communities. Consequently, maintaining and strengthening the linkages between communities is highly desirable.

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