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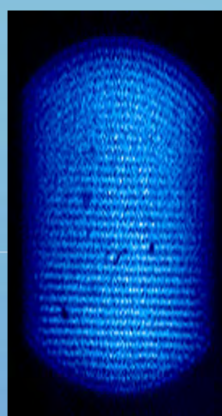
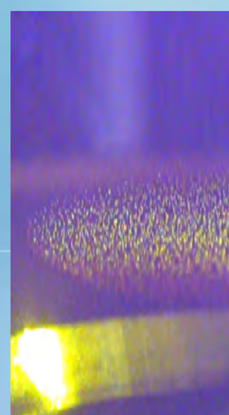
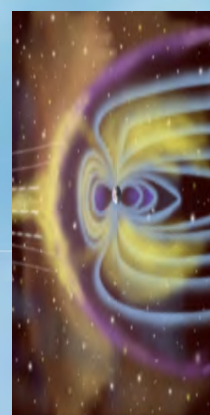
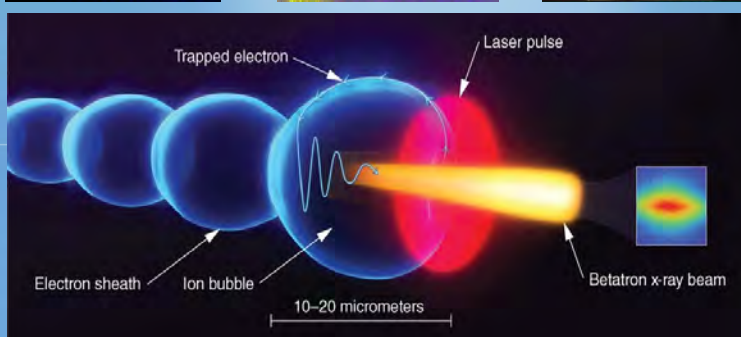
Preliminary Draft

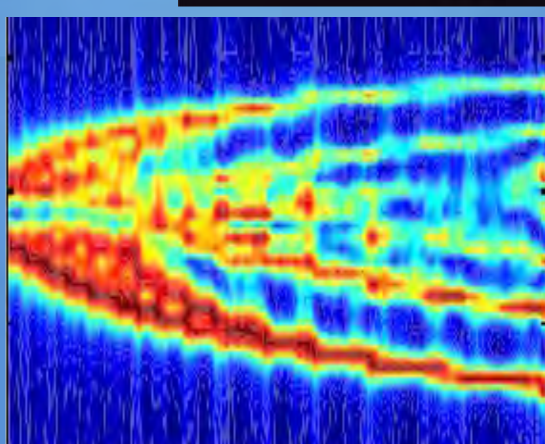
Report of the Panel on Frontiers of Plasma Science

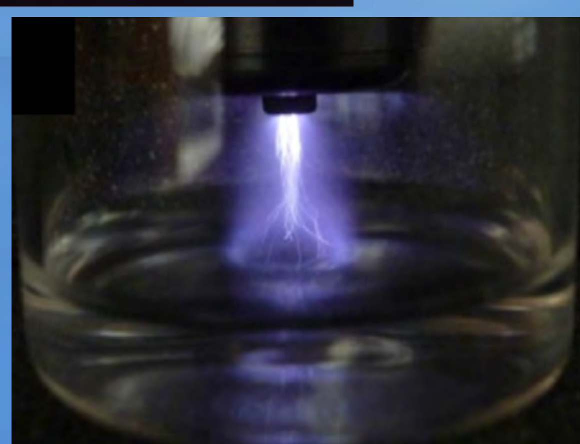












Preface

In February 2015, the Department of Energy Office of Fusion Energy Sciences (OFES) announced the formation of four technical workshops “to seek community engagement and input for future program planning activities.” Three of these workshops focused on the science and technical challenges we must address to meet the emerging needs of ITER and to allow exploration of fusion burning plasma physics in the laboratory. This report represents the work of the fourth workshop that focuses on the broader scientific opportunities at the frontiers of plasma science. The primary charge to the Panel authoring this report was “to identify compelling scientific challenges at the frontiers of plasma physics” and “to identify research tools and capabilities to address these challenges in the next decade.” This report aims to inform the newly constituted OFES Program in Frontiers of Plasma Science on science opportunities and strategy moving forward. This program was created in FY2015 by combining topics from general plasma science, high energy density laboratory plasmas, and exploratory magnetized plasma into a single program area.

The Executive Summary, chapter introductions and sidebars to the chapter are intended to provide more general overviews of the findings of the panel. The chapters provide more details following these themes

Procedural Background

The charge to the Panel authoring this report (see Appendix A), was to engage the plasma community to identify the compelling scientific challenges at the frontiers of plasma science. This community engagement would be achieved by input in the form of white papers, through an open workshop where the scientific challenges at the frontiers were discussed, and several discussions with Panel members focused on the presentation of frontier research to the broad scientific community. This report highlights future research opportunities, although no attempt was made to carry out a comprehensive review of the status of the field.

The Panel leadership consisted of the Chair and co-Chair and ten working group leaders. They were assisted by the rigorous work of forty panel members. A list of the panel members is in Appendix B.

The goal of this report is to assist OFES in developing and executing its strategic vision for the stewardship of the plasmas science. Prior reports from the Fusion Energy Sciences Advisory Committee and the National Research Council served as the starting point for this effort.

Description of Panel Activities

The members of the Panel were selected to broadly represent the diverse community of researchers in areas representing plasma frontiers. The membership includes national laboratory and university-based scientists, and scientists engaged in research across the wide range of plasma science. The goal of a bottoms-up, rather than tops-down, process led to the selection of scientists and engineers having a broad range of experiences at all points in their careers.

The Panel solicited input from the wide community of scientists and engineers, in academics, national laboratories and industry working at the frontiers of plasma science. The panel received ≈200 white papers [http://www.orau.gov/plasmawkshps2015/] and held a two-day Town Hall Meeting (THM) June 30 – July 1, 2015 consisting of community presentations selected from the contributors of white papers. The THM and the white papers were organized around the broad fundamental physics areas that characterize plasma science:

1. Plasma Atomic Physics and the Interface with Biology and Chemistry
2. Plasma Turbulence and Transport
3. Interaction of Plasma Waves and Particles
4. Plasma Statistical Mechanics
5. Plasma Self-Organization.

The community input received by the Panel was significant and responsive. Thoughtful and high-quality presentations were roughly evenly distributed across the five fundamental physics areas. Due to the large number of requests to speak at the THM, all of which could not be satisfied, the Panel engaged in further community outreach, including four online meetings. The goal of the on-line meetings was to accommodate speakers who either could not attend or for whom there was not an opportunity to speak at the THM. On-line meetings were held on the topics of Theory and Computation, Laser-plasma interactions, High-Energy Density Physics and Self-Organization. In total, there were about 100 presentations, counting those conducted in-person at the THM and on-line.

Following the THM and on-line meetings, the Panel met at two closed meetings, both in Washington, D.C, to discuss the material presented by the community. The first Panel meeting was held August 20-21, 2015, and discussed all white paper contributions and THM presentations. The second Panel meeting was held October 22-23, 2015 and finalized the narrative used to describe the scientific frontiers and the organization of this report.

The sheer volume of responses to the white-paper solicitation reflected the diversity of the community of scientists working on fundamental plasma science and its importance to applications. This vitality was demonstrated by the recent experimental, theoretical, and numerical, advances described in the white papers and in the presentations to the Panel. The THM amplified on the themes described in the white papers and provided some unique opportunities for attendees from the different sub-disciplines of plasma science to discover that there are common science challenges that overlap the sub-fields. The Panel engaged in thoughtful discussion on where the frontiers of plasma science lie and how we can advance towards and beyond them. The second task, the definition of facilities required to enable plasma frontier research over the next decade, was not completed in this effort. However, wherever possible, facility and research needs are listed in this Report when they can be motivated by community white papers and discussion among Panel members.

The organization of the chapters of this report differs somewhat from the physics categories used to initially sort the white papers and presentations at the THM. The unity and diversity of the plasma science frontier seemed to be best reflected by five chapters which span the spectrum of questions motivated first by fundamental physics, secondly by a desire to understand observed natural plasma phenomena, and finally by the need to understand the physics basis of important potential applications. In particular, the topics of Plasma Atomic Physics and the Interface with Biology and Chemistry, and the Interaction of Plasma Waves and Particles were reorganized. Some topics were shifted between chapters, and the fundamental topic of self-organization was redistributed according to whether the phenomena were predominantly electric (Chapter 3) or magnetic (Chapter 4) in character. No system was evident which could totally isolate the field into five separate categories. This reflects the unity of plasma science—a situation that the panel was pleased to observe in light of the diverse goals of the final products of the research. A by-product of this effort was the conclusion that there is a need for follow-on open workshops that address the frontiers of plasma science at a broader, discipline encompassing level to take advantage of these synergies.

Prior reports on plasma science

There have been several reports on different aspects of plasma science that preceded this report. We list below those that overlap with areas discussed in this report. While the charge to the committees authoring these reports differed from the charge to this panel, there are areas of overlap with the topics covered in the reports described below. Indeed, the impetus for the development of some of the facilities described in this report was provided in part by the prior reports listed below:

1. *Frontiers in High Energy Physics: The X-Games of Contemporary Science*, NRC, National Academy of Sciences (2003), available at http://www.nap.edu/catalog/10544/frontiers-in-high-energy-density-physics-the-x-games-of
2. *Plasma Science: Advancing Knowledge in the National Interest,* NRC, National Academy of Sciences (2007), available at http://www.nap.edu/catalog/11960/plasma-science-advancing-knowledge-in-the-national-interest .
3. *Low Temperature Plasma Science: Not Only the Fourth State of Matter but All of Them*, Report of the DOE Workshop on Low Temperature Plasmas (2008). available at http://science.energy.gov/~/media/fes/pdf/workshop-reports/Low_temp_plasma_workshop_report_sept_08.pdf
4. *Advancing the Science of High Energy Density Laboratory Plasmas*, FESAC Panel on High Energy Density Laboratory Plasmas (2009), available at http://nnsa.energy.gov/sites/default/files/nnsa/01-13-inlinefiles/Advancing%20the%20Science%20of%20HEDLP_2009.pdf
5. *Research Opportunities in Plasma Astrophysics,* Report of the Workshop on Opportunities in Plasma Astrophysics, (2010), available at http://w3.pppl.gov/conferences/2010/WOPA/index.html

Fred Skiff, Chair
Jonathan Wurtele, Co-Chair

Chapter 1 Executive Summary

Overview

Plasma phenomena occur throughout the Universe, in laboratory and natural settings, covering an enormous range of scales and parameters. For example, spatial scales extend from nanoscale radiation sources to galactic scale magnetic fields, while temporal scales range from attosecond x-ray laser plasma interactions to dynamo magnetic fields varying over centuries. Parameters such as temperature and density vary over more than ten and twenty-five orders of magnitude, respectively. Nevertheless, plasmas exhibit common physical phenomena over these enormous ranges.

This commonality of physics enables synergistic advances in both science and technology.
At one extreme, plasma science in part governs the evolution of the universe through astrophysical phenomena ranging from galactic jets to supernovae. At the other extreme, plasma science is the basis of many technologies that are vital to modern society, from microelectronics to human healthcare. It is rare to find a field of study where investigating fundamental science challenges will answer questions as diverse as "Where do magnetic fields in the universe come from?" and "How can we improve wound healing?". Clearly, plasma science is a broad yet surprisingly cohesive discipline with a many-fold rational for its investigation.

Landmark advances in our understanding of a broad range of fundamental plasma science challenges have occurred over the past decade – understanding that is advancing our knowledge of both terrestrial and astrophysical phenomena. This improved understanding has enabled the creation of plasmas of only a few millimeters in size to provide heretofore-unachievable insight into astrophysical phenomena. The origins of nonlinear self-organized plasma structures are being explored in an ever-widening range of contexts, from the laboratory to the near-earth environment. Intense short-pulse lasers manipulate relativistic plasmas to create compact high-gradient accelerators and ultrahigh intensity x-ray sources.

Upon leveraging scaling laws, high energy density plasmas can also be created in the laboratory with conditions that enable the study of the physics of the inner core of stars and planets. At the same time, plasmas are being investigated for important applications to human health: The field of plasma biology—the interface of plasmas with biological systems—has emerged in recent years with much promise for the future.

These advances are not happen-stance occurrences. They resulted from years of intense research enabled by state of the art facilities and diagnostics that translated into greatly improved understanding of plasma phenomena across all scale-lengths, with applications that could not have been predicted at the start. New innovative diagnostics with ever-increasing resolution in both space and time have enabled previously inaccessible phenomena to be measured and quantified. Advances in theory and computer simulation have leveraged these diagnostics to explain how fundamental theories link laboratory plasmas to supernovae and how hand-held-plasma-jets might be used for treating cancer. These advances were made possible by the development and exploitation of world-class physical infrastructure, with a range of institutional facilities, supported by Federal agencies. These facilities range from single-investigator experiments that occupy table-tops, through multi-investigator intermediate scale magnetized plasma and laser plasma facilities, to national-laboratory scale facilities that have unique capabilities to create and study plasmas with extreme conditions.

Research in plasma science is driven both by the desire to understand fundamental phenomena and by the desire to develop applications for societal benefit. These desires enable new insights into how the structure of the universe came to be and how the energy from our Sun enables and powers life itself. This diversity in motivation results in a rich set of research thrusts spanning an equally diverse array of science and technological applications, a diversity that is built on a foundation of common theoretical descriptions, basic science concepts, and experimental techniques. This report on the Frontiers of Plasmas Science shares a foundation with the other workshops on fusion science sponsored by OFES and, importantly, it shares common themes that underlie plasma science and technology critical to the missions of other offices of DOE, as well as other science and technology based Federal agencies, including DOD, NSF, NNSA, NASA, EPA and NIH. Our interdisciplinary field would be well served through strengthened interagency collaborations that build on this commonality in the basic science needed to achieve different agency missions.

Support for fundamental plasma science by DOE and partner agencies provides return-on-investments that create opportunities for technological advances in the future, just as they have in the past. In some instances, these returns come from single-investigators performing table-top experiments and computational modeling that runs on laptop computers. In other cases, medium-scale multi-user facilities are necessary to create this new knowledge, a new mode-of-operation for addressing phenomena that require special capabilities or diagnostics. Advanced predictive capability requires the leveraging of sophisticated theory and model building with state-of-the-art computer engineering and algorithm development.

The discussion of the facilities needed to advance the state-of-the-art in plasma science will always be a complex discussion, because the scale of these facilities differs dramatically between sub-fields. Experiments on high-energy-density plasmas relevant to astrophysical phenomena generally require larger facilities than those investigating self-organization or interfacial plasmas, which are in turn large compared to those required to investigate plasmas for materials synthesis and biotechnology. Although well defined for a few subfields of plasma science, for other sub-fields this report represents only the first step toward defining future facility needs. Follow-on workshops are likely required to define these specific research facilities needs.

The Frontiers of Plasma Science

Extreme States of Matter and Plasmas (Chapter 2)

- *How do plasmas behave under extreme conditions where our current descriptions fail?*

Recent progress has witnessed the development of the tools and techniques for creating plasma states with unprecedented temperature and density. Experiments to determine plasma behavior in these states will test new physics in parameter regimes where, in many cases, various models offer diverging predictions. These extreme states of matter and plasmas that we form and control in the laboratory may shed light on the age of our galaxy and mimic the dynamics of complex and correlated plasmas that exist in the cosmos.

Understanding the Physics of Coherent Plasma Structures (Chapter 3)

- *How does plasma electrical self-organization work, both in physical space and in phase space, and how can we control it?*

One of the major challenges of nonlinear science is to understand and control the synchronization of interacting particles. This phenomenon is common in diverse types of biological, chemical, and physical systems. In plasmas, synchronization typically involves the formation of physical space or phase space coherent structures, and has linear and nonlinear regimes. These structures are created through the electrical self-fields of the plasma and its interactions with waves (magnetically dominated structures are discussed in the next section). The frontier is driven by both fundamental questions in the nonlinear dynamics of strongly interacting systems, by interest in understanding complex environments such as planetary magnetospheres, and by the development of technologies that rely on self-organization, such as for plasma propulsion. Moreover, understanding the phase space dynamics of charged particle beams with intense self-fields may lead to new classes of accelerators that may be used for scientific and industrial applications.

Understanding the Energetics of the Plasma Universe (Chapter 4)

- *What processes control the transformation of energy between forms, the transfer of energy across vast differences in scale, and the transport of plasma energy in the Universe?*

Plasmas exhibit unique mechanisms for transferring energy across wide ranges of spatial scales. Plasmas play an important role in energy flow across the entire visible universe. Increasingly, these fundamental phenomena can be studied in the laboratory. Plasma within our solar system is associated with the energetics of life, and astrophysical plasmas, powered by the immense gravitational energy of stellar objects and black holes, give rise to an incredible array of mysterious and beautiful phenomena that have captivated the imagination of the scientist and layperson alike.

The Physics of Disruptive Plasma Technologies (Chapter 5)

- *How can efficient interactions between electromagnetic fields and particle motion be established and controlled?*

New technologies are emerging which exploit the powerful and controllable interactions that occur between plasmas and electromagnetic fields. High-density plasmas are difficult to confine for long periods of time, but these plasmas are both malleable and robust: they can be shaped or controlled with magnetic and electromagnetic fields, and can withstand field intensities that would destroy normal matter. The field of relativistic plasma engineering—the shaping of plasmas by lasers to create customized structures for acceleration, pulse compression, radiation generation and other applications—has matured from its infancy over the last decade. The sophistication of techniques used to create and control these plasmas is ever increasing, and high-power lasers are becoming more widely available. This ability to shape plasmas on nano- to femto-second time scales has motivated many groups to set out on the quest for plasma-based compact particle acceleration and x-ray sources, for ultra-intense pulse generation, and for new photonic systems.

Plasmas at the Interface of Chemistry and Biology (Chapter 6)

- *How can we describe and control the interaction of plasmas with solids, liquids, and gases?*

Low-temperature plasmas (LTPs) enable processes that have led to profound breakthroughs that revolutionized and enabled modern societies. Areas in which the impact of low-temperature plasmas are critical include the microelectronics industry, which is central to our modern society and which is enabled by beneficial plasma-surface interactions that deposit and remove materials with nm resolution in the fabrication of microprocessors and other devices. Other examples include breakthroughs in the development of low-cost, high-efficiency lighting technologies, low-cost solar cells, and bio-compatible human implants. Most recently, novel effects discovered by observing the interaction of plasmas with liquids and solids are opening new sub-fields from plasma medicine to High Energy Density (HED) chemistry with promising applications for health, food, and water.

Low-temperature, non-equilibrium plasmas have electron energies well situated to produce activated states of neutral matter that drive chemical reactions; ions in the boundary layers of plasmas enable activation of surface processes that lie at the core of many manufacturing techniques and photons that disinfect water and process polymers. The net energy transfer between a low temperature plasma, which is often only partially ionized, is small enough that they can be in non-destructive contact with a surface. This beneficial contact with surfaces now extends to liquids, such as plasma-activated water, which has led to the emerging field of plasma medicine. LTPs may also interact in a non-destructive and beneficial manner with surfaces internal to the plasma, such as in a particle or aerosol-laden dusty plasma. This is an example of a multi-phase plasma. The concept of multi-phase LTPs extends to plasmas sustained within liquids and plasmas in bubbles within liquids, both of which are now being investigated for chemical processing and medical applications.

Cross-Cutting Motifs (Chapter 7)

Theory and Computation

Despite the enormous range of scales and parameters and their seemingly diverse detailed descriptions, plasmas share a theoretical framework with a complicated hierarchical nature. From this fundamental framework emerge concepts central to plasma physics, including the notions of Landau damping, collective acceleration, frozen flux and magnetic reconnection, invariant tori/magnetic surfaces and chaos, etc. Indeed diverse plasmas share a theoretical framework that produces models with sophisticated mathematical structure and properties, and is a branch of theoretical physics in its own right.

Theory is essential to one of the three broad research thrusts that have converged to make the next decade promising for significantly improved computation and modeling: The first is the increasing use of advanced theoretical ideas in the design of algorithms. The second is the increased speed allowed by using both CPU and GPU computation. The third is the improved diagnostics in plasma systems that allow for ever more detailed comparison between theory and experiment. The cost of future facilities demands careful parameter choices that take into account the accessible physics and actual experimental conditions. Advances in computational resources alone will not suffice for this – one must implement physics models and algorithms at the forefront of plasma theory and computational science.

Plasma Diagnostics

Diagnostics enable the rigorous tests of theories that are required to advance plasma science. There is a constant need to innovate diagnostics as new regimes of plasma conditions are explored because the interactions most usable for measurement techniques depend on plasma conditions. Furthermore, the advent of new technologies, for example new radiation and laser sources, also facilitates the enhancement of existing techniques as well as the development of novel means of probing plasmas.

Data Resources

How can atomic, molecular and optical (AMO) data be generated and validated for extreme environments ranging from HED to medical plasmas intersecting with living tissue? Both for diagnostics and for understanding the kinetics and thermodynamics of plasmas in almost every regime, from low temperature plasmas to plasma astrophysics, the phenomena of AMO physics are important. At certain points, advancing plasma science and AMO physics are bound together. Especially in extreme environments, where the boundary between bound and free states becomes blurred, advancing our understanding of the plasma is critically dependent on a robust source of AMO data.

Conclusion

Plasma science is perhaps the most diverse of the physical (and now biological) sciences while also being built upon a foundation of common scientific concepts and challenges. Plasma science underlies x-ray sources that probe the insides of cells and proteins, enables laboratory investigation of the origins of magnetic fields in the galaxy, creates energy densities so high they mimic the interior of planets, allows for novel accelerators, and leads to innovative technologies that directly benefit society through an expanding range of applications to the environment and manufacturing. The community coming together around the study of this common core of fundamental questions at the frontiers of plasma science will enable the future advances discussed in this report.

Fundamental plasma science is a dynamic and exciting endeavor with a history of producing new knowledge and society benefiting technologies. It has at its core, questions that unify the many sub-fields of plasma science as a discipline and an incredibly rich set of fundamental and applied scientific challenges. The field is well positioned for significant advances over the next decade.

The pursuit of plasma science not only enhances our national scientific prestige, it offers the potential for significant public gain and improved global competitiveness. With wise stewardship of the plasma science frontiers from scientists and funding agencies, the most exciting times lay ahead of us.

Chapter 2 Extreme States of Matter and Plasmas

Extreme states of matter and plasmas reveal the age of our galaxy, they can lead to the formation of matter from boiling the vacuum, and they determine the dynamics of complex and correlated plasmas that exist in the cosmos and can be created and controlled in the laboratory.

Overview

The warm dense matter (WDM) exhibiting quantum degeneracy within white dwarf stars, the classical strongly coupled plasmas giving rise to crystalline-like structures in laboratory experiments, and the boiling soup of photons and electron-positron pairs potentially created in intense photon colliders are all examples of extreme states of matter. Such matter exhibits complicated collective behavior characteristic of the plasma state, but unlike traditional plasmas that are non-quantum mechanical and weakly coupled, the extreme states that are the subject of this chapter possess strong coupling, possible quantum degeneracy, and relativistic effects.

Gazing at the stars and wondering what the light we detect tells us about celestial bodies is an early memory of many scientists. Yet, decoding a fuller story this light tells requires understanding extreme states of matter and plasmas. In recent years powerful tools have been developed that allow us for the first time to form conditions in the laboratory that we think are present in stars. These laboratory experiments with powerful lasers and particle beams complement observations, which promises major advances in our understanding of the physics of stars and planets in the next years. Understanding the roles played by strong coupling and quantum degeneracy is facilitated by other laboratory experiments that benchmark the role of coupling without degeneracy. Applications are likely to arising from the study of extreme states of matter and plasma; in particular, from fundamental studies of the dynamics of warm dense matter we will very likely be able to drive materials into novel phases with tailored properties for applications in advanced opto-electronics.

Scientific and Technical Challenges

Figure 1 indicates the conditions at which the extreme states under consideration can be found. Here, the vertical axis is temperature while the horizontal is the charged particle density. Two parameters can be used to indicate regions of interest: the Coulomb coupling parameter Γ, defined as the typical electrical interaction energy divided by the average kinetic energy, and the degeneracy parameter θ defined as the square of the ratio of the typical de Broglie wavelength to the typical inter-particle spacing. The parameter Γ measures the degree to which interparticle interactions affect the thermal motions of particles, with

$\Gamma<<1$ corresponding to the familiar plasma regime of weak coupling. The parameter θ measures wave function overlap, with $\theta<<1$ corresponding to non-degeneracy and the unimportance of quantum mechanical effects. In the degenerate state, electron coupling is measured by the Brueckner parameter r_s defined as the ratio of the mean inter-particle spacing to the Bohr radius, with $r_s<<1$ indicating weak coupling. The figure indicates the crossover lines $\Gamma=1$ and $r_s=1$ that separate weak from strong coupling, as well as the $\theta=1$ line that separates degenerate from non-degenerate plasmas.

In this chapter, Section A describes the WDM frontier, which corresponds to the lower right portion of Fig. 1, below both the $\Gamma=1$ and $\theta=1$ lines. We will see that WDM, characterized by classical strongly coupled ions and electrons that are degenerate and weakly to moderately coupled, is prevalent in both laboratory experiments and in nature. Our understanding and mastery of WDM is in its infancy and studies of WDM are an exciting frontier of plasma science. Among the many ramifications of a better understanding of WDM, we single out in Sidebar Box I how WDM is a throttling material for white dwarf cooling, which is a critical component of some models used to estimate the age of galaxies and of the universe. Section B addresses the region of the lower left of Fig. 1, where coupling is strong but quantum effects are negligible. Here, effects of quantum degeneracy can be disentangled from strong coupling. Importantly, this regime is amenable to precise table-top experimentation allowing comparison with emerging theoretical tools. Sidebar Box II describes a collection of laboratory experimental approaches with some of their results. Section C is about high energy density physics, which lies at the upper-right of Fig. 1. Sidebar Box III describes the intriguing possibility of boiling the vacuum using light to create a plasma composed of electron-positron pairs.

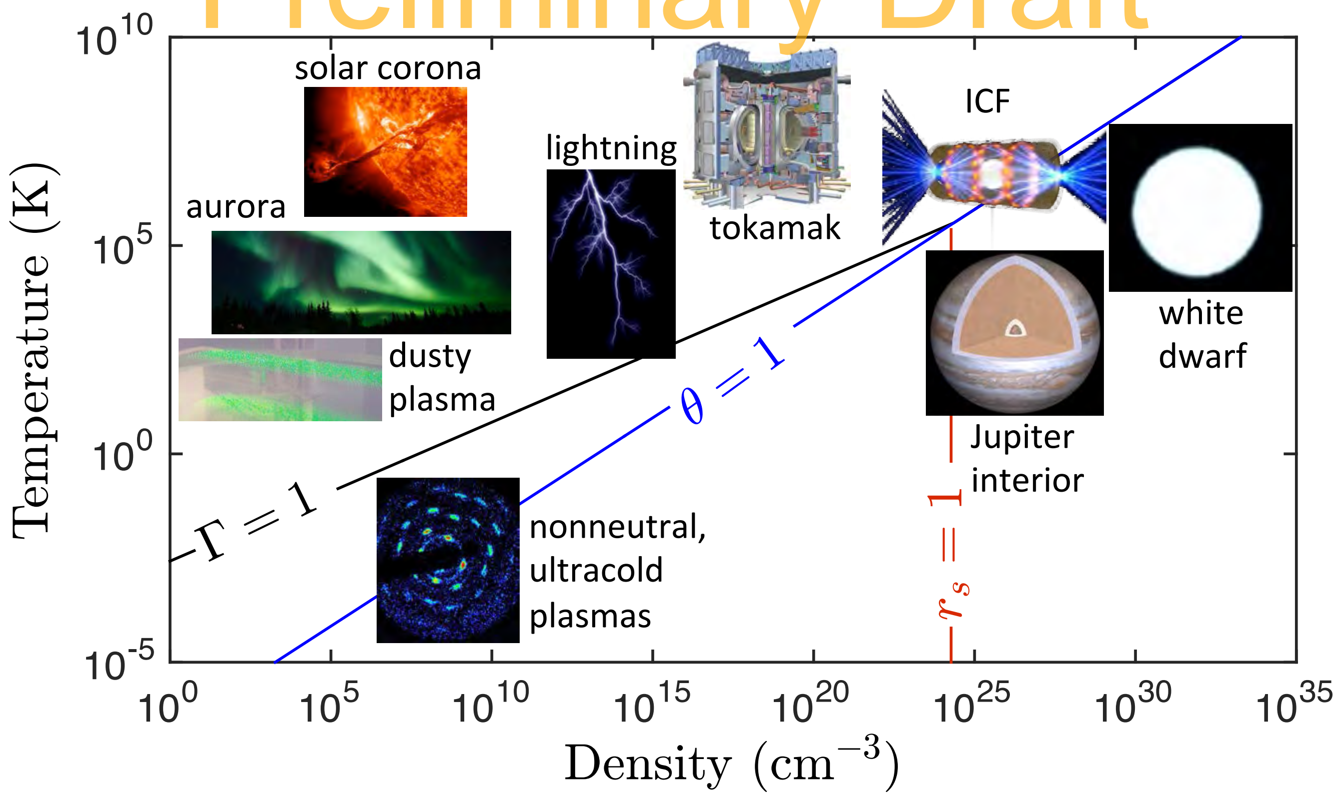


Figure 1. Extreme conditions with strong coupling and quantum degeneracy can dominate the behavior of plasma in astrophysical and laboratory settings. With strong coupling, charged particles collide often with nearest neighbors, allowing self-organization as in crystals, liquids or non-ideal gases. With quantum degeneracy, the spatial extent and wave-like nature of electrons influence plasma properties. This diagram, for equilibrium conditions, divides parameter space into four portions according to temperature and number density of charged particles. Traditional plasmas, which are weakly coupled and non-degenerate, are found in the upper left corner with colder more highly coupled dusty plasma of interest in this chapter found below. Extreme conditions of interest for this chapter are to the right. Warm dense matter is characterized by classical strongly coupled ions, and degenerate weakly-to-moderately coupled electrons. This region is found near the intersections of the lines in this figure. At very high energy density, electromagnetic fields can spark electron-positron pairs from the vacuum.

A. The Warm Dense Matter Frontier

At the confluence of the four fundamental states of matter, namely solid, liquid, gas and plasma, lies the little understood yet important warm-dense-matter (WDM) regime. The physical properties of the WDM regime are at the heart of many unsolved problems in fusion energy science, planetary science and stellar astrophysics. For instance, WDM is formed during the compression phase of inertial confinement fusion experiments, and its material and transport properties have a direct bearing on the integrity of the implosion. In astrophysics, a better understanding of WDM is crucially needed to improve the accuracy of “cosmic clocks”, the long-dead stars called white dwarfs used to determine the age of the Galaxy and its components (see sidebar). Thorough knowledge of WDM is also essential to understand the formation and evolution of planets in our solar system and beyond, and to place limits on their composition and structure. This is particularly timely given the wide diversity of exoplanets that have recently been discovered (nearly 2000 exoplanets have been discovered as of today), which challenges our current understanding of planetary formation.

The boundaries of the WDM regime are not sharp and depend on the material but, roughly speaking, WDM conditions occur for temperatures between a few thousand and a few million kelvins and densities a fraction to several tens of times solid density. Under these conditions, a significant fraction of electrons are ionized and free to move through the matter, but the plasma thus formed is far from ideal. In addition to the collective effects typical of plasmas, electric forces between ions in WDM are strong and the individual motion of an ion is strongly coupled to the motion of its neighbors, an effect that is particularly challenging to describe theoretically. On the other hand, WDM is cold enough for the free electrons to fully reveal their quantum nature. Moreover, the internal electronic structure of the ions and the residual chemical bonds are strongly affected by the surrounding plasma. To further complicate things, in many applications, we must consider not only single element systems but also mixtures of chemical species, and the mixture can be out of equilibrium.

Understanding how the interplay of quantum and strong coupling effects gives rise to the physical properties of WDM is a frontier of plasma physics, which equally challenges both experiment and theory. Tremendous progress has been made in the last decade on both the experimental and theoretical fronts to unravel the properties of this awkward intermediate regime. New facilities with better drivers and diagnostics have appeared that can create well-controlled WDM conditions, yielding new measurements over a range of WDM parameters. Theoretical advances have also been made, in particular in the domain of quantum molecular dynamics and Monte Carlo simulations. Notwithstanding the recent achievements, the study of WDM is still in its infancy.Much remains to be done, and important discoveries are yet to be made. In the following, the grand challenges that the field is facing are enounced in the form of four questions that, if answered, would constitute major breakthroughs. With the new experimental facilities and emerging theoretical capabilities, the scientific community is well positioned to answer these questions in the next decade.

- *How can we probe the warm dense matter regime?*

Both robust and visionary experiments are crucial to WDM science in order to gain physical insights, to validate existing models and guide the development of improved ones, and to reveal novel effects. The experimental challenges rest with the difficulty in generating high-quality samples (ideally uniformly heated and of large volume) and diagnose them with great precision. A critical need is to develop self-consistent measurements of both thermodynamic and transport properties. In addition, a strong synergy between experiment and theory is required in order to decipher the measurements and relate them to relevant physical properties.

- *What are the material properties of WDM and how can we predict them***?**

Of overarching importance for both the fundamental understanding and the applications of WDM are equations of state, which relate the state variables such as pressure and temperature that characterize matter in thermodynamic equilibrium, the electronic and ionic structures, which are necessary to characterize the phase of the material, the phase transitions at the border and within the WDM regime, the optical properties and radiative opacities, which describe the absorption and scattering of radiation.

- *How does WDM transport energy and particles?*

Transport properties are another essential component of the exploration of the WDM regime. This includes the experimental and theoretical determination of the transport coefficients, such as electrical and thermal conductivity, mutual diffusion, viscosity, etc. The ability to model dynamical processes and non-equilibrium conditions must also be developed since WDM experiments produce time-dependent situations and many fundamental processes such as the energy deposition by charged projectiles in WDM are inherently non-equilibrium.

- *Can we gain an understanding of the physics of dense bodies in the cosmos through what we learn in the laboratory experiments and theoretical tools developed to answer the previous questions?*

Both material and transport properties of WDM are essential to a wide variety of important problems in astrophysics, including the accuracy of cosmic clocks (see sidebar), the diversity of exoplanets, the formation of the solar system, the source of Saturn's anomalous luminosity, the origin of the large magnetic field of Jupiter, and so forth. Here, appropriate relations should be developed to maximize the cross-fertilization of information between the WDM and astrophysical communities.

Research Needs

<u>Experimental Needs</u>

The last ten years have seen remarkable progress in our ability to form WDM in the laboratory. Enabled by advances in high power laser technology (both long pulse, nanosecond and short pulse, femtosecond), pulsed power and the advancement of ion beam drivers (accelerator based and derived from laser plasma interactions), researchers can now form WDM states in much more reliable ways, more controlled and coupled to much improved diagnostics. These advances have shown that WDM is a very rich field of research, ripe for important fundamental discoveries on the dynamics of highly excited matter at the boundary between solid state and plasma. Gaining important fundamental science insights requires that researchers can form WDM reliably and in highly controlled ways, in large enough volumes so that precision diagnostics can be applied to unravel its intriguing dynamics.

The discovery potential of WDM research can be realized when a range of drivers is available for a community of users in mid-scale and large facilities. The large-scale flagship facilities in the Office of Science, Linear Coherent Light Source (LCLS), and in NNSA, such as National Ignition Facility (NIF), Omega and Z, provide unprecedented access to the formation of WDM. Access to these facilities for a community of users is imperative as is tooling of these facilities with cutting edge pump-probe capabilities and diagnostics. One example is the Material under Extreme Conditions (MEC) end station at LCLS, where the unique and currently world leading x-ray free-electron laser (FEL) capabilities of LCLS must be complemented with internationally competitive driver options with high-energy long pulse and petawatt-level short pulse lasers.

In addition to large scale flag ship facilities, the rich depth of WDM research also requires mid-scale facilities, where e.g. stand-alone petawatt lasers can be coupled with laser derived secondary beams for creative pump-probe experiments. Further, ion beam drivers offer exciting complementary capabilities to uniformly excite large volumes of matter to WDM states, where ion beam pulses can be formed in advanced accelerators or derived from laser – plasma interactions. The latter is a prime example where an area of fundamental science of high field laser – matter interactions now spawns first applications that enable both deeper studies of WDM and also show promising directions for spin-offs of laser based particle accelerators with applications e. g. in homeland security and medicine.

Next generation drivers will include multi-petawatt level, high repetition rate and high average power femtosecond lasers and upgrades to x-ray FELs (most prominently in the US with LCLS-II). Here, reaching ultra-high levels of laser irradiance will soon require the development of a laser technology beyond the now leading Ti:sapphire based lasers. Clever relativistic engineering of “flying mirrors” might extend peak intensity levels with petawatt lasers and this might allow us to peak into the realm of novel physics territory. While the development of advanced high power lasers is outside of the scope of basic plasma science, it is clear that researchers and funding agencies in plasma science have a keen interest in being closely connected to the development of laser technology as next generation, ultra-intense lasers will be needed to reach power levels above 10^{25} W/cm^2 where novel physical phenomena are expected to become dominant. Creative application of single digit petawatt lasers might already grant access to the rim of this frontier physics regime, but ??>>1 petawatt lasers, possibly based on emerging fiber laser or other laser technologies, will be needed to gain full access to this exciting frontier.

In concert with drivers, to develop the fundamental understanding of the physical and structural properties of warm dense matter and strongly coupled plasmas it will be important to continue developing accurate experimental probing techniques. This effort will need to deliver the experimental and theoretical understanding of the applicability, limits, and uncertainties of diagnostics and should fully explore the capabilities that have recently become available by x-ray lasers, e.g., LCLS, and by high-power laser-driven particle and x-ray sources, along with future source development. In recent studies, x-ray Thomson scattering and x-ray imaging have begun providing new insights into the physics of dense plasmas where traditional techniques that e.g. employ optical probing are no longer applicable. However, the potential of these x-ray techniques is still being explored by the community and achieving the full impact for discovery science and fusion physics will require a dedicated effort. Similarly, diagnostics that employ particle probing have also shown great potential, but will need further development to provide precision and reproducibility of x-ray probing techniques. Both x-ray and particle probing techniques have great potential for future applications to provide critical experimental tests of simulation capabilities or for making discoveries in the physics of dense plasmas.

Global competition in this rich, promising and rapidly emerging area of science is fierce with large investments in novel free electrons lasers and high power laser facilities underway in Europe and Asia. For the US to remain competitive it is of the highest importance that strategic investments into the facility infrastructure at large and mid-scale facilities, at national laboratories and at universities continue to be made.

Theoretical Needs:

1. Simulations.

By its intermediate nature, the WDM regime does not fall neatly within the parameter space typical of either ordinary condensed-matter physics or plasma physics, and the standard simplifying approximations of these fields no longer apply. As a consequence, our theoretical understanding of this extreme state of matter has relied heavily on advanced computer simulations. These tools are particularly useful to validate practical models, to give insights into the microphysics, and to support the experiments. As discussed below, a number of methods have been successfully used that differ in their accuracies and domains of applicability. The research opportunity here is to develop advanced theoretical and computational tools appropriate to the warm dense matter regime, and perhaps to a comprehensive first-principles framework.

a) Equilibrium approaches
Typically these simulations aim at describing accurately the behavior of a large enough number of ions and electrons in thermal equilibrium in a simulation cell, in order to link those descriptions to physical quantities of relevance at higher length scales, such as the equations of state, the degree of ionization and the transport properties.

i) Kohn-Sham Density Functional Theory.
Currently, the prevalent simulation method for studying WDM is *Kohn-Sham density functional theory* (KS-DFT), which, is also the most widely used technique in the various branches of materials science and chemistry. This approach maps the many-body electron problem onto an efficiently solvable single-particle problem, while the strongly coupled ions propagate classically according to Newton's equations. While the mapping is in principle exact, in practice, a quantity called the exchange-correlation functional must be approximated. Detailed information about the equation of state, optical and transport coefficients can currently be self-consistently calculated with this method. Despite its successes, KS-DFT suffers from a number of limitations and a wide variety of important conditions and processes remain outside its scope. Lifting these limitations would have a high potential payoff. For instance, even with massive calculations on a supercomputer, current algorithms are limited in the physical conditions, system sizes and time-scales it can reach (temperatures up to a few tens of thousands kelvins, for a typical sample size of a few hundred atoms and a few thousand time steps). The limitation resides in the nature of the KS-DFT method that describes electrons with orbitals: the number of required orbitals increases with temperature, density and system size, while the KS-DFT method scales as the cube of the number of orbitals. Another research need for a wider application of the method is the development of better approximations for the finite-temperature exchange-correlation functional that are more robust against the variety of physical conditions encountered in the WDM regime. This would help reduce the existing inaccuracies and inconsistencies found between the different approximations, as well as with experimental measurements. Finally, in all the implementations of the KS-DFT method, the electron-ion interactions are handled in the Born-Oppenheimer approximation, which assumes that electrons readjust instantaneously to their ground state on the time-scale of the ionic motion. The frictional and fluctuating forces that result from the couplings between the classical (ionic) and quantum (electronic) degrees of freedom are completely neglected in this approximation.

ii) First-principle simulations.
The most accurate method to compute thermodynamical properties of WDM at finite temperature is the Path Integral Monte-Carlo (PIMC) method. Unlike DFT it does not involve approximate functionals but it solves for the relevant equilibrium quantities exactly and is the natural extension of classical Monte-Carlo methods to the quantum world. PIMC can treat several hundreds to thousand particles at elevated temperature. However, at lower temperatures when quantum effects dominate the particle behavior, in the case of fermions (e.g. the electrons) it is hampered by a fundamental problem: the "fermion sign problem" (FSP). The FSP has, so far, limited exact simulations to small systems and atoms with few electrons (Hydrogen, Deuterium, and Helium) at moderate quantum degeneracy. While there is no direct solution of the FSP, new developments show that it can be avoided in some cases.

The trick is to combine PIMC with other methods. Using PIMC at high temperature and combining it with DFT at low temperature resulted in very good results for many heavier elements. A second successful idea is to combine PIMC with quantum Monte Carlo in a different representation (using Fock states) that has a FSP in a very different parameter range. These developments indicate a promising route for future first-principle simulations of more complex systems in the WDM regime. PIMC simulations can, in principle, be extended to dynamical properties such as the response functions or the dynamic structure factors. The basic idea is an analytical continuation to real frequencies. Recently, numerical methods have been proposed to efficiently conduct the calculation (using stochastic approaches and genetic algorithms), which show great promise of application in the WDM regime.

iii) Alternative DFT-based approaches.

Orbital-free DFT methods offer access to a much larger range of temperature in comparison to orbital-based methods because they avoid the unfavorable scaling of computational cost with temperature associated with Kohn-Sham orbitals. While this speed-up has traditionally resulted in a trade-off in accuracy, recent developments have shown that the method is potentially capable of being competitive with KS-DFT accuracy. OF-DFT is still limited to simulations of a few hundred particles and relies on a pseudopotential and exchange-correlation approximations, but it is also capable of computing transport and optical properties.

In an effort to make even greater gains in efficiency, DFT-based average-atom models make further approximations in which the properties of a single atom are solved for within the plasma. Such models have been shown to predict the electronic structure of the atom well, and recent developments have begun a more consistent treatment of ionic structure that allow it to achieve accuracy on a par with Kohn-Sham and orbital-free DFT calculations, and provide transport and optical properties.

b) Non-equilibrium approaches

i) Time-dependent DFT, kinetic simulations and hydrodynamics.

The simulation methods discussed thus far assume equilibrium conditions. In addition to these the ability to model dynamical and non-equilibrium systems must be developed if we are to maximize the scientific impact of future experiments. Indeed, in addition to in-situ measurements of the state of plasmas (e.g., temperature, density, charge state), future facilities will make it possible to measure genuine dynamical properties of dense plasmas like the transport coefficients. Moreover, dense plasma experiments generally produce transient (i.e., non-equilibrium) situations, and measurements may be difficult to interpret if recorded while the diverse plasma species are out of equilibrium. Finally, time-dependent simulations are required to support application-driven experiments, e.g. to assess the effectiveness of energy deposition by charged projectiles in WDM. While a number of approaches exist in principle, including the time-dependent extension of KS-DFT, the solution of quantum kinetic equations and the solution of hydrodynamic equations, significant developments on the basic ingredients of these methods (e.g. proper time-dependent exchange-correlation functionals, proper collision operators, proper constitutive physics) and on the numerical methods to solve them are needed in order to apply them to the WDM regime.

ii) Multiscale simulations.

The first-principles simulation tools discussed before are bound to the microscopic realm and cannot be applied directly to larger, more complex systems. Experiments on dense plasmas, however, often entail much greater ranges of length and time scales from Angstroms and attoseconds up to many millimeters and microseconds. In addition, experiments such as those involving laser or ion heating of solids, span various physical regimes requiring multiple, high-fidelity models in order to understand them. For example, simulating a full experiment at the Linear Coherent Light Source facility from the solid through the warm dense matter phases requires including complex electronic structure, strong ionic coupling, and radiation coupling under non-equilibrium conditions. This span of many orders of magnitude in space and in time and of various physical regimes is clearly intractable to current or near term computer technology. Although high-fidelity, microscopic approaches like molecular dynamics are gradually reaching toward larger scales (over the past couple decades molecular dynamics went from simulating few hundred particles to modeling trillions of particles), the length scales on which dense plasma are simulated remain limited to sub-micron scales and require hours of massively parallel computation time per femtosecond of plasma dynamics. To overcome these limitations that loom large for the foreseeable future, it has been proposed that microscopic and macroscopic approaches be combined into a single computational approach. A promising multiscale approach to understanding dense plasma properties, which starts with quantum mechanical interatomic potentials that are inserted into molecular dynamics simulations; these simulations are passed upward to plasma formation dynamics that ultimately connect to continuum code simulations at the macroscopic scale. The result could be a powerful probe of material properties at extreme high-energy density conditions that would allow the direct simulation of measurable quantities at all relevant time and length scales, and would allow independent predictions. The research opportunity is to creatively exploit advanced computational systems to produce new models that can accurately handle a far wider range of phenomena than can any single current model.

c) Advanced architectures

Simulation capabilities have benefited from an increase in computer power over time, including increased CPU power (Moore's Law) and better supercomputing clusters. As the next generation of supercomputers will rely on GPU's and hybrid architectures, there will be both a challenge and an opportunity for first-principles and multi-scale approaches to continue to benefit from new computers. Novel strategies for parallelization and mapping the computations onto heterogeneous architectures will be critical.

2. Modeling and analytical theory.

In addition to first-principles simulations, theoretical needs include the development of physical models to support experiments and applications. For instance, hydrodynamic simulations typically demand that calls to routines providing the material and transport properties be fast, such as a table lookup or evaluation of a closed-form equation. Of particular value are models that are developed based on fundamental theory, or are physically motivated and reduce to the correct limit when extrapolated to the plasma and condensed-matter regions.

In addition, new models are necessary to link the experimental measurements with the fundamental physical quantities. For instance, such an effort is necessary to reap the full benefits of the recent advances in experimental X-ray scattering techniques. The current and widely used paradigm for calculating the X-ray scattering cross sections of WDM was developed for simple plasmas and is based on a clear separation between core, valence, and ionized electrons. This assumption is not valid under conditions of pressure ionization and is unable to handle plasmas where chemical bonds may be present. Ideally, the warm dense plasma and the X-ray scattering theory should be developed consistently at the same level of physical approximation.

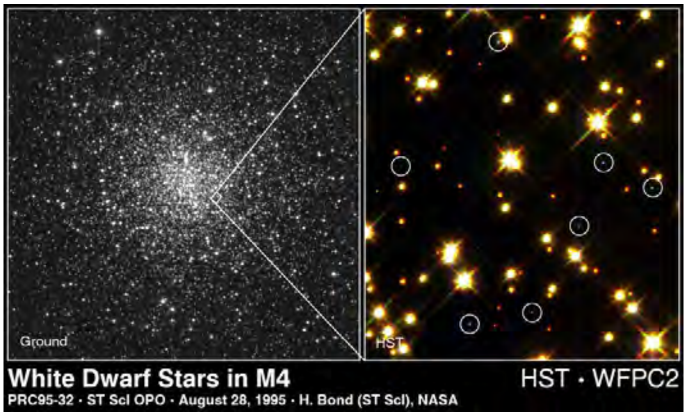
Last but not least. Until now most of the theoretical studies of the WDM regime have relied on advanced numerical simulations. The analytical theory of WDM has been set aside under the pretext that no small parameter expansion and perturbation expansion is possible. However, first-principle modeling with the ability to produce analytical solutions in limiting cases is an essential element of progress in the physical sciences that provides basic explanations and is a source of discoveries. Ideas that seek to unravel the theoretical principles that govern the WDM regime should be encouraged.

Connections to other areas of science and industry

The research on WDM will reach far beyond its border. WDM research offers a unique opportunity for physicists studying high-energy density plasmas to contribute significantly to the understanding of exoplanets and other areas of astrophysics. The efficient, high energy density drivers required to produce WDM can be used to generate other high-energy density conditions in the laboratory. Recent advances in ramp compression techniques enable studies of new regimes of high-pressure condensed matter physics up to warm dense plasma. High resolution, high gain gated x-ray detectors are not only essential to WDM studies but are also indispensable to high-energy physics and medicine. The innovative physical models and numerical algorithms capable of describing the properties of WDM will push the predictive capability of materials theory to significantly higher temperatures, which will enable novel applications of materials under extreme environments. Here, one intriguing prospect is to drive materials into novel phases in the WDM regime and, through rapid quenching, stabilize these phases that cannot be formed in any other way. Based on model predictions, specific materials properties could be optimized in novel meta-stable phases, e. g. spin properties of color centers in diamond for applications in ultra-sensitive sensing and quantum information science. Given the success of laser technology in manufacturing (e. g. some car makers now use lasers for welding and have more laser power installed than the National Ignition Facility), the study of WDM is a prime example where advances in basic plasma science lay the foundations for spin-offs in applied science and technology, with very high future impact potential.

SIDEBAR BOX I:

Warm Dense Matter and the Age of the Galaxy.



Stellar graveyard: view of Messier 4, the nearest globular cluster to Earth (7000 light-years away). The cluster contains hundreds of thousands of stars, of which an estimated 40000 are white dwarfs (circled in the right panel). Using white dwarf cooling models, the age of the cluster was determined to be 12.7 ± 0.7 billion years. (Image: http://hubblesite.org/newscenter/archive/releases/1995/32/)

The vast majority of stars end their lives as white dwarfs, and this will be the fate of the Sun about 5 billion years from now. White dwarfs are made of plasma, which varies tremendously from the surface to the center of the star from a nearly ideal, partially ionized plasma of hydrogen at a temperature of about 10000 degrees Kelvin, to a fully ionized, solid density helium plasma and up to a strongly coupled plasma of carbon/oxygen nuclei with fully degenerate electrons at a density of a million grams per cubic centimeter and a temperature of several millions of degrees Kelvin.

Like a dying ember, a white dwarf slowly cools and fades away at a predictable rate. White dwarf temperatures can thus be used as “cosmic clocks” for constraining the age of our Milky Way galaxy and its components. The accuracy of these cosmic chronometers is limited by uncertainties in the rate of energy flow through the warm dense matter region in the white dwarf envelope. To reduce these uncertainties, a better understanding of plasma in the warm dense matter regime is required, including its equation of state properties, transport properties and radiative opacities. New experimental facilities for high-energy density laboratory experiments and emerging theoretical capabilities are well positioned to address this need in the next decade.

B. Disentangling the Physics of WDM Plasmas and Probing Fundamental Symmetries of Nature with Classical Strongly-Coupled Plasma and Antimatter Plasmas

In experiments with dusty plasmas, trapped non-neutral plasmas, ultracold plasmas, and anti-matter plasmas, we encounter matter that is extreme in a different sense of the word. Plasma physicists use these systems for discovery science – creating new types of plasmas never seen in a laboratory, exploring the limits of strongly coupled plasmas, characterizing transport and collective mode structure beyond the regime of standard theories, and in some cases testing the most fundamental theories of the universe. Such research has a proven track record of leading to technological innovation, and it also satisfies our innate curiosity to explore and understand the world around us.

- Can trapped antimatter plasmas probe symmetries of nature and recreate conditions of exotic astrophysical plasmas?

Research with trapped positrons has been at the forefront of discovery in plasma physics for several decades. This has led to applications in materials characterization and probes of molecular structure, and there continues to be great focus on improving the ability to accumulate and store positrons, studying the properties and pushing the limits of these unusual systems, and on finding new applications. Here we mention two promising directions.

Several international collaborations working at CERN are developing techniques to create and trap sufficient quantities of anti-hydrogen to study fundamental questions on the nature of antimatter, such as how it interacts with gravity, and the origin of the matter-antimatter asymmetry in the universe. The leading techniques involve combining trapped plasmas of positrons and anti-protons and forming anti-hydrogen through inelastic collisions. Progress in this high impact area of discovery plasma science would not be possible without a mastery of the underlying plasma physics.

In electron-positron “pair” plasmas, three-wave coupling vanishes identically, and so parametric processes (e.g., Raman and Brillouin) are absent. Electromagnetic waves in such plasmas are linearly (as opposed to circularly) polarized, and nonlinear Landau damping is stronger by the ion/electron mass ratio, as compared with the behavior expected in an ordinary electron-ion plasma. Ion acoustic waves are expected to be heavily damped, and solitary-wave behavior is expected to be prominent. Similar effects have been predicted for the astrophysically relevant case of relativistic pair plasmas, such as those expected at the poles of neutron stars. In spite of extensive theoretical work on pair plasmas, they have not yet been studied in the laboratory. Progress in the accumulation and manipulation of antimatter made over the past two decades is now at the cusp of making experimental studies of pair plasmas possible.

- What can be learned about structure and dynamics of strongly coupled plasmas by studying classical systems that can be well diagnosed in table-top scale experiments?

The interplay of quantum and strong coupling effects greatly complicates our efforts to understand the physical properties of WDM in astrophysical and large-scale laboratory experiments. A promising strategy to address part of this challenge is to isolate the effects of strong coupling in systems that are not quantum degenerate. This can be done using recently developed table-top experimental methods and emerging theoretical tools that explore the parameter space in the lower left corner of Fig. 1.

Under strong coupling, charged particles do not fly past one another like atoms in a dilute or non-interacting gas, but instead collide often with nearest neighbors, so that they have a microscopic structure that is analogous to a crystal, liquid, or nonideal gas. The effects of strong coupling are manifested in structure and dynamics. Structure is the microscopic arrangement of particles due to their interactions with neighbors, which shows signatures of ordering in crystals or in liquids, but not in traditional weakly coupled plasmas. Dynamics include waves, instabilities, transport, and equilibration, which can all be modified by strong coupling.

Experiment

New kinds of instrumentation often open the door to understanding natural phenomena that were previously unobservable. This is demonstrated by three tabletop methods of generating and detecting strongly coupled plasmas: pure ion plasmas, dusty plasmas, and ultracold plasmas. (See SIDEBAR BOX II.) All three allow the easy formation of a strongly coupled plasma, with a Coulomb coupling parameter Γ spanning a range from about unity (like warm dense matter) to extreme levels of many thousands. An advantage of these experiments is their ease of observing the charged particles in the plasma, as they move about, using video imaging and light scattering. A fourth tabletop method is now emerging: a dense cold plasma made in bubbles by a pulse of sound waves, within the liquid of a sonoluminescence device.

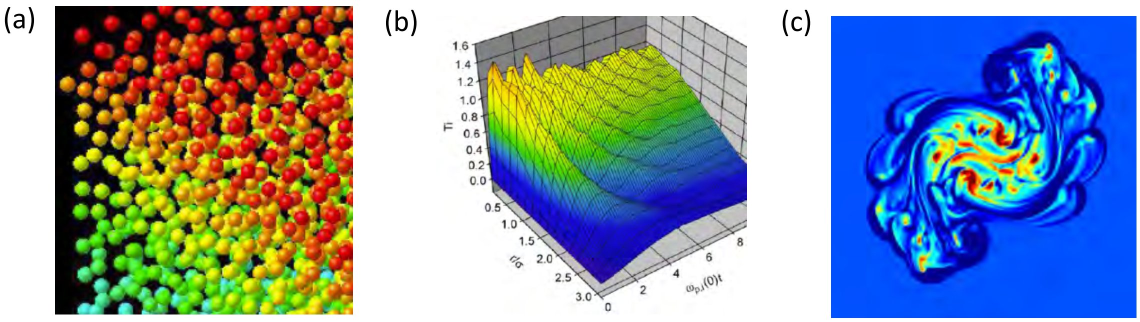
New theoretical tools are needed to understand these systems. For example, everything we learn about collision processes in such plasmas will impact our understanding of plasma kinetic theory beyond the usual Fokker-Planck approach and provide validation for collision models in plasma modeling codes. The scale of the table-top experiments and the quality of their diagnostics are ideal for validating such models, which can have wide utility and impact in the plasma physics community.

Theory and Computation

Plasma theory describes the fascinating collection of phenomena that emerges from complex interactions between charged particles and electromagnetic fields at microscales, giving rise to many-body collective motions at mesoscales, and ultimately determining the transport properties of a plasma at macroscales. Untangling this complex web of phenomena is particularly challenging for strongly coupled plasmas because the constituent particles interact simultaneously with many neighbors in a highly correlated manner. These correlations emanate through space and time scales, giving rise to behaviors akin to liquids or solids, rather than the gaseous-like nature of traditional hot plasmas. Describing this novel regime faces the full complexity of the statistical closure problem that pervades many fields of the physical sciences, including turbulence theory, quantum field theory, and stochastic differential equation theory. Progress requires a hierarchy of complementary theoretical approaches ranging from first-principles simulations of all particles in model systems, to kinetic theories describing statistical averages of the properties of constituent particles, to hydrodynamic theories aimed at modeling the largest-scale dynamics of plasma in a laboratory experiment.

Figure 2 depicts computational results of microscale, mesoscale and macroscale phenomena described in turn below.

Figure 2.



(a) Microscale: Snapshot of individual particles in a molecular dynamics simulation of a dusty plasma (IEEE Trans. Plasma Sci., 42, 2686 (2014)). **(b) Mesoscale**: Wavelike oscillations emerging from statistical averages of many particle trajectories in a hybrid molecular dynamics simulation of an ultracold plasma (J. Phys. Conf. Series 11, 223 (2005)). **(c) Macroscale**: Vortices arising in a visco-elastic fluid simulation of a strongly coupled plasma (Physics of Plasmas 21, 073705 (2014)).

Microscale: The advent of high performance computing has enabled direct simulation of sufficiently many particles and over long enough timescales to model statistically meaningful processes occurring in strongly coupled plasmas. Classical molecular dynamics simulations are a prevailing method used to test theory and to provide insights into the microphysical mechanisms that theory must address. This will continue to be a frontier area. More powerful computers and more efficient algorithms will enable simulations to progress beyond idealized near-equilibrium one-component systems to address realistic features of experiments. In fact, it may soon become feasible to perform full plasma simulations over a significant fraction of time for some dusty, ultracold neutral and nonneutral plasma experiments. A few areas are particularly likely to see significant progress over the next decade. Addressing the non-uniform, often far from equilibrium, conditions that are common in many experiments is one such area. Although it is a common simulation geometry, no experiment is conducted in a periodic box. Modeling realistic boundary conditions is likely to lead to significant advances. Another area ripe for progress is addressing multicomponent plasmas, including both electrons and mixtures of ionic species. This is challenging because the lightest species typically sets the fastest timescale that must be resolved, while the heaviest species determines the longest timescales of interest. In strongly magnetized plasmas, resolving the gyrofrequency of the lightest species is an even stricter requirement that is becoming achievable with modern computers. It has recently become feasible to push simulations to a low enough coupling strength to connect with weakly coupled plasma regimes. Bridging the gap between strong and weak coupling is essential as many of the experiments contain species with mixed coupling strengths.

Mesoscale: Tracking every particle provides the most comprehensive description of a plasma, but it is typically far more information than is either manageable or desired. Kinetic theory characterizes the collective properties that emerge from statistical averages of the enormous number of constituent particle trajectories, retaining information on how properties change in both space and momentum phase-space. Kinetic theory of strongly coupled plasmas is a significant frontier topic. Traditional plasma physics has advanced based on the solid foundation of Landau's kinetic theory and Braginskii's transport theory. This forms a basis from which more complicated scenarios, such as turbulence, are addressed. An analogous theoretical foundation for strongly coupled plasmas is only beginning to emerge. This is a challenge because as the coupling strength of a plasma increases, the mutual interactions between particles are no longer a small perturbation to their ballistic motion, causing a large number of deflections that hampers their mobility. As a result, plasma dynamics shows transition from a nearly collisionless gaseous regime, continuously through an increasingly correlated liquid-like regime, on to solidification.

What is ultimately desired is a field theory derived systematically from first principles using well-controlled approximations. It is not clear that this will be attainable in the near future, but continued progress in this direction is clearly a frontier that should be pursued vigorously. Alternative approaches based on semi-phenomenological extensions of condensed matter or plasma theories also provide promising avenues for progress. These can be well supported by simulations and experiments, and may also indicate directions toward a comprehensive theory. These methods often have the additional advantage of conforming to familiar paradigms for describing macroscopic transport behaviors. In parallel with analytic theory, development of numerical methods to solve kinetic equations is imperative. This enables detailed modeling of kinetic features of experiments, while remaining computationally tractable on large spatial scales. This is an area that should be systematically developed and extended to other scattering, excitation, ionization and reaction processes. Promising paths include direct simulation of model kinetic equations, as well as hybrid or multiscale techniques. Examples of the latter include combining continuum kinetic solutions with molecular dynamics, or combining particle-in-cell methods with Monte Carlo collision routines based on kinetic theory.

Macroscale: The design and interpretation of experiments relies on accurate hydrodynamic or magnetohydrodynamic descriptions of macroscopic plasma behavior. Microphysics processes that emerge at the macroscale can be classified in terms of static properties, such as the equation of state, or dynamic properties, such as transport coefficients. Examples of transport coefficients include diffusivity, electrical and thermal conductivities, and viscosity. Hydrodynamic models are often developed from appropriate statistical averages of underlying kinetic theories. They describe large-scale dynamics in terms of experimentally observable properties such as density, temperature, flow velocity and pressure. As such, advances in kinetic theory at the mesoscale must also be accompanied by advances in the techniques required to solve these for macroscopic equations of motion. Standard methods are based on the age-old techniques of Chapman and Enskog or Grad to bridge the gap from kinetic to fluid scales. New kinetic theories that treat strong coupling require alternative approaches that are only beginning to emerge. Likewise, advanced hydrodynamic theories or multiscale approaches, which are needed to accurately simulate and predict the dynamic behavior of experiments, may require advances in numerical algorithms.

Research Needs

Experimental facilities for classical strongly coupled plasmas are mostly single-investigator university labs. Robust support for small-scale, university-based research is necessary for activities such as these and many similar efforts in plasma physics to thrive and continue to spawn new innovations. This has many other important benefits, such as maintaining the educational pipeline for young plasma scientists. Advances in antimatter physics also occur primarily through the efforts of small-scale research groups, although antihydrogen research is led by international collaborations involving up to a dozen principal investigators.

Larger user facilities are needed for magnetized dusty plasmas and for microgravity. Under 1-g lab conditions, gravity causes micron-size charged dust to sediment into a two-dimensional layer at the bottom of a plasma, while microgravity conditions enable the formation of three-dimensional clouds of dust, which are of broader interest. Microgravity conditions required are accelerations well below 0.01 g for durations of a few hours for an experiment; these are possible on the International Space Station. Different facilities allow different operating conditions: anisotropic vs. isotropic structures in the cloud of dust particles, using DC vs. radio frequency plasmas, respectively.

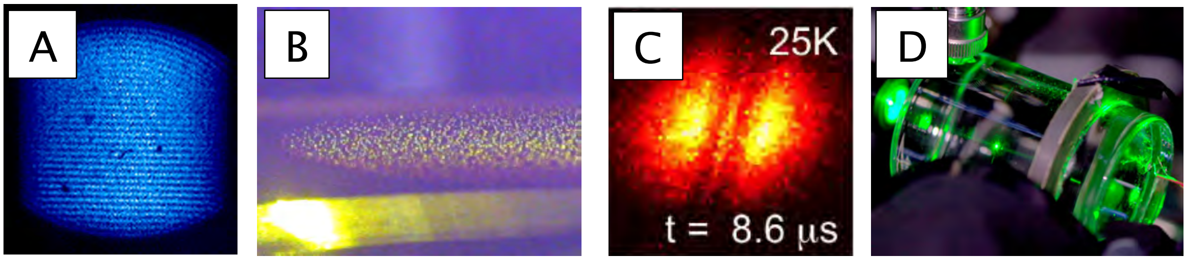
Theoretical research needs include the development of models described above.

Connections to other areas of science and industry

Experiments with classical strongly coupled plasmas and anti-matter plasmas have rich interdisciplinary connections. Improved positron sources are being developed for probes of atomic and molecular structure, medical applications, and materials diagnostics. In addition, dusty plasmas occur naturally in our solar system and in molecular clouds, and they pose a contamination problem that must be mitigated in magnetic fusion plasmas and semiconductor manufacturing. Soft condensed matter physics has a great overlap with these tabletop physics approaches, with colloidal suspensions displaying much of the same physics and with unique opportunities for cross-fertilization based on ground breaking results from basic plasma science experiments. Ultracold plasmas are being developed as improved sources for bright electron and ion beams with improved resolution for imaging and nanomachining with many applications in applied physics, industry and manufacturing.

SIDEBAR BOX II:

Experimental Approaches for Studying Classical Strongly Coupled Plasmas



In classical strongly coupled plasmas, the Coulomb interaction energy between neighboring charged particles exceeds their thermal energy. This gives rise to structural order, and it fundamentally changes transport properties. These effects play an important but incompletely understood role in astrophysical, warm-dense-matter, and inertial-confinement-fusion plasmas. Relatively simple table-top plasma experiments, with powerful optical diagnostics, can isolate the effects of particle correlations on waves and transport and inform our understanding of more complex systems. Often studied in a university setting, they also increase access to the excitement of discovery science in plasma physics.

(A) Ions trapped by electric and magnetic fields can be laser cooled to a few millidegrees Kelvin to form strongly coupled non-neutral plasmas. The ions settle into fixed positions, forming Coulomb crystals with long-range spatial correlations. Similar instrumentation allows trapping antimatter plasmas to study positron physics and antihydrogen. (Image: Phys. Rev. Lett. 94, 025001 (2005))

(B) Dusty plasmas are formed of multiply charged, micron sized particles in a room-temperature discharge plasma of background ions, electrons and neutral atoms. The dust particles can be strongly coupled and display spatial correlations, which are imaged directly with high speed cameras, allowing the tracking of all individual particles. This is one of the few experimental systems in physics that allow particle-level study of waves, transport and statistical physics. Dusty plasmas allow Coulomb coupling high enough to observe liquid and solid structure, and they can now be created in large (>1 T) magnetic fields and under microgravity conditions, which have opened new fields for laboratory study. (Image: Univ. of Iowa)

(C) Ultracold neutral plasma (UCNP) is produced by laser photoionization of laser-cooled atomic gases or supersonic beams of atoms or molecules. With ion temperatures of ~1 K and tunable electron temperatures from 1-1000 K, coupling in these plasmas spans the range from weak to moderate. Light scattering is the primary diagnostic. Frontiers include pushing to stronger coupling and explaining equilibration and transport. (Image: Phys. Plasmas 22, 043514 (2015)).

(D) Sonoluminescence experiments can produce pulsed plasmas with temperatures and densities of 6,000-20,000 K and 1-10 $\times 10^{21}$ cm^{-3}. The formation of the plasma is made by sound, with bubbles in a liquid that emit intense flashes of light. The least mature of the four experimental methods, the tiny plasmas that are made could provide a test bed for theories of dense astrophysical and fusion plasmas. (Image: http://physics.aps.org/articles/v7/72)

C. The High Energy Density Plasma Frontier: from Boiling the Vacuum, to Generation of Pair Plasma, and non-linear QED plasmas

The building of new laser facilities and the development of our theoretical understanding lead us to envision exciting new frontiers of high energy density plasma science. We give illustrative examples of the broad range of new scientific goals, but one major frontier question is the following:

- *Is there a fundamental limit to how hot a laser-produced plasma can become, and can we form conditions of sufficient light intensity that result in the creation of dense electron-pair plasmas from vacuum?*

Electromagnetism, the fundamental force that underpins a large part of modern technologies, ranging from computers to wireless communication and the internet, is well-understood. We have achieved a very high degree mastery of the propagation of electromagnetic waves, including optical light, and its interaction with materials in a broad range of intensity regimes. As scientists we naturally seek to push the envelope and explore the extreme limits of light and matter given by existing and future technology.

Currently available lasers are powerful sources of focused light with sufficient intensities that materials exposed to laser pulses evaporate and form plasmas. Experience has shown that when pushed to ever increasing laser intensities, the temperature of the formed plasma continues to increase. However, should we expect this to continue? Or, as intensities increase will new phenomena occur? We have all experienced sparks, rapid discharges of electric currents that ensue when voltages are so large that electrons are ripped out of atoms and molecules of a gas such as air. Similarly, at very high intensities of light, theories predict that the vacuum - empty space itself - can “spark”, thereby exhibiting a fundamental, yet currently poorly understood, limit on the temperature and energy density of plasmas.

“Empty” space is not empty at all, but rather filled with a sea of virtual particles that fluctuate in and out of existence for brief moments, yet on average cancelling each other out before they can be observed. Indeed, these “quantum fluctuations” are thought to have seeded the large-scale structure of matter in the universe. Can ultra-intense laser pulses mimic this by continually creating electrical fields large enough for pairs of electrons and positrons to emerge by “boiling the vacuum”? Theories predict that ultra-intense laser pulses can indeed cause electron-positron pairs to be formed and to remain in existence long enough for studies and possible enabling storage of dense anti-matter plasmas. And we are presently on a path to access this extreme regime of producing matter out of light.

Examples of the basic processes of pair creation were observed in early experiments at the Stanford Linear Accelerator Center in the late 1990s and also in relativistic heavy ion collisions. But now, advances in our theoretical understanding of nonlinear quantum electrodynamics (nQED), improved modeling capabilities, the maturation of petawatt laser technology, and our increased finesse in “relativistic engineering” promise to enable experiments where large quantities of electrons and positrons could be formed. Creation of sufficient electron-positron pairs so as to make a plasma will boost our understanding of the fundamental structure of matter, light, and space and enable groundbreaking advances in novel technologies through “relativistic engineering”.

An example of emerging relativistic engineering is the design and construction of “flying mirrors”, a basic concept introduced by Einstein in 1905. When intense laser pulses interact with a thin solid sample, electrons can be accelerated to near the speed of light, forming a flying mirror surface. This flying mirror can then scatter light from a second laser beam, while upshifting the wavelengths of the photons of the second pulse and also, potentially, focusing the upshifted pulse to a smaller spot. Early experiments have shown that the effect is real, giving credence to the possibility of using flying mirrors to boost laser intensities to boil the vacuum with such efficiency that we can form electron-positron plasmas that exhibit collective behavior.

These advances in high energy density plasma physics are also intimately related to astrophysical phenomena. High energy density plasmas are widely observed in the universe, e.g., they are associated with supernovae, active galactic nuclei and relativistic jets. With high power lasers and advances in our ability to model and control high energy density plasmas we can form conditions in the laboratory that are similar to those observed in the most exotic matter in the universe. While much progress has been made in the last years in the observation of high energy gamma cosmic rays, the fundamental physical mechanisms of their production remain unclear. Consequently, we can now aim at performing scaled experiments to create relativistic astrophysical conditions in the laboratory. This will boost our basic understanding of the life cycle of stars and galaxies, and can lead to novel technology applications such as compact sources of high-frequency radiation for use as tools for discovery in biology and materials science and as advanced tools for applications in homeland security and medicine.

Research Needs

Theoretical Needs:

Since the early work of Schwinger it has been known that static spatially uniform sufficiently strong electric fields can “spark the vacuum” to produce electron-positron pairs. This nonlinear quantum field theory phenomenon is theoretically important because it goes beyond perturbation theory and is physically important because it may be associated with astrophysical phenomena, e.g., it may occur near black holes and give rise to gamma ray bursts. Unfortunately, production of the necessary static fields in the laboratory does not seem possible. However, with the continual increase in the intensity of laser sources creates the possibility of pair production by optical fields. Recent theoretical developments have shown that high frequency AC fields can dramatically lower the production threshold. Further, using short pulses with appropriate pulse shaping can also enable pair production. Indeed, this possibility will be an exciting topic for the next 10 years.

If sufficient numbers of pairs are produced then collective effects come in to play and plasma techniques are required to describe the physics. In recent years various kinetic and other theories of nQED plasmas with quantum versions of the radiation reaction effect have been developed. If the density of pairs becomes large, then Pauli blocking is an additional element that is crucial for accurate predictions. It appears that more fundamental physics is likely to be discovered in this area; to remain competitive, it is important to maintain a vibrant theoretical effort. This should be an interdisciplinary effort with plasma physics being a central component.

Experimental Needs:

The experimental tools required to reach scientific goals at the frontier of high energy density plasmas and nQED are high power laser drivers and advanced diagnostics and they are closely linked to the drivers and diagnostics needs for Warm Dense Matter research. Laser drivers deliver pump pulses that excite matter into a high energy density plasma state. Prime examples are petawatt (1 PW = 10^{15} W) lasers and X-ray free electron lasers (FELs). PW lasers based on Ti:Sapphire oscillators have rapidly matured in the last ten years. They are now available in select mid-scale laboratories in the US. Improving the infrastructure for (multi-) PW laser laboratories, including adding capabilities to focus laser light to the required ultra-high intensities with state-of-the art PW lasers that perform at high repetition rates (e.g. 1 Hz or higher) will enable a community of researchers to access the exciting frontier regime of extreme intensity for systematic studies and discoveries in the realm of relativistic, non-linear quantum electrodynamics. This promises to enable disruptive breakthroughs e.g. to allow us to reliably boil the vacuum through clever relativistic engineering.

The advent of X-ray FELs has made pulses of energetic photons with unprecedented intensities available for a community of users. The construction of the Linear Coherent Lightsource upgrade (LCLS-II) at the Stanford Linear accelerator Laboratory (SLAC) is now underway and will provide world leading X-ray capabilities for research in high energy density plasma physics. Pulses from the X-ray FEL can act as both the pump to excite matter and form a highly dense plasma and also to probe such a high density plasma state. Here, the penetrating power of hard X-rays, delivered in femtosecond pulses, is of particular importance as it allows penetration of thick and dense matter in a highly excited state. However, X-ray FEL capabilities must be accompanied with additional optical driver and diagnostic pulse capabilities. For example, conditions of relativistic astrophysical plasmas can be formed with an optical laser pump pulse, while an X-ray FEL pulse probes the ensuing structure revealing the dynamics of the dense plasma. Petawatt optical lasers can deliver tens of joules of energy into micron scale samples with repetition rates of order 1 Hz. The maturation of PW laser technology has enabled mid-scale facilities to access the frontier of high energy density plasma science and there are exciting opportunities to adapt highly optimized (multi-) PW-lasers with high repetition rates (~1 Hz and higher) and high contrast optics for experiments in this area. This is particularly exciting, because experiments with high repetition rates and large numbers of shots will complement and build on studies with relatively low repetition rate lasers that are typical today, where pulses fire e. g. once every few hours. With high repetition rates at a high intensity laser, systematic studies can be performed for the first time, enabling disruptive advances in precision and reduction of error bars, which will very likely lead to many discoveries in this rapidly developing and internationally highly competitive field of high energy density plasma science.

Further, precise diagnostic beams can be derived from petawatt lasers and these can be coupled both with petawatt-laser drivers and with X-ray FELs. Development of laser technology also promises advances of relativistic engineering that will lead to exciting spin-offs. Here, promising examples are based on laser-plasma acceleration of electrons and ions that are bound to enable table-top radiation sources for industry, homeland security and medicine.

A deep understanding of high Z atomic physics is of critical importance both to design experiments and to interpret the results at the frontiers of high energy density plasma science because, e.g., the ionization dynamics and resulting radiation signatures of dense plasmas change when pressures rise above several Mbar and temperatures increase to several millions of degrees.

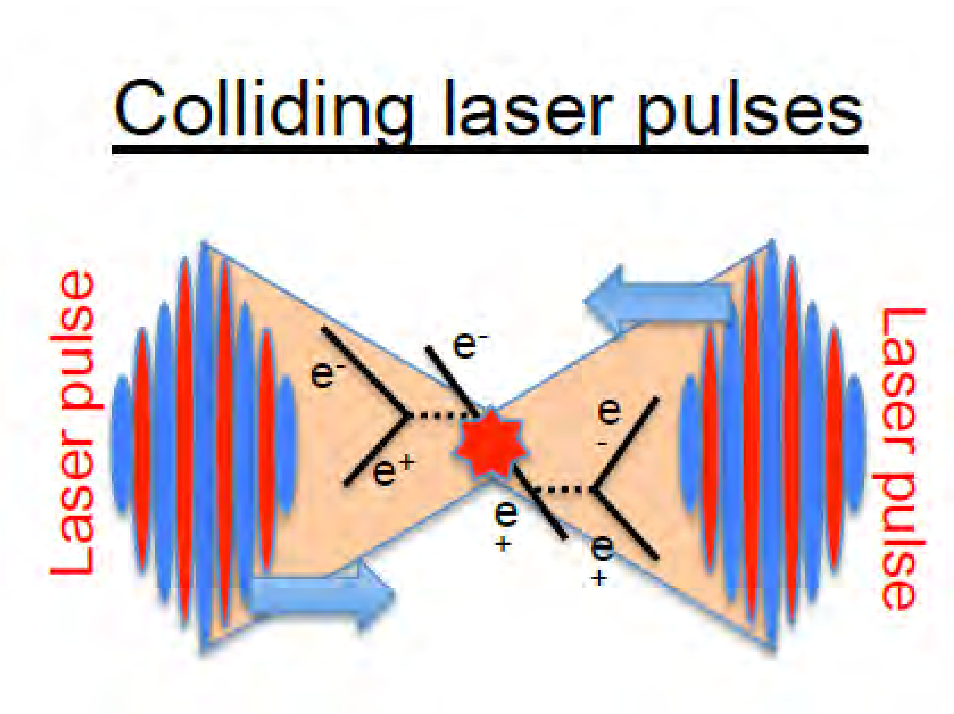
Connections to other areas of science and industry

The scientific goals at the frontiers of high energy density plasma science are intimately connected with the goals and frontiers of astrophysics. We have truly game changing prospects for reliably reproducing phenomena of relativistic astrophysics in the laboratory. Also, the issue of antihydrogen and matter–antimatter symmetry is of great fundamental physics interest. Laser created electron-positron plasmas have an interesting overlap with pair plasmas and ultracold antimatter production in traps as discussed in Section B.

On a practical level, understanding high energy density plasmas will also aid our quest to understand and one-day master fusion processes, which is imperative for one path to sustainable fusion as an energy source. The underlying physics also informs the stewardship of the US nuclear weapons stockpile. Spin-offs from advances in relativistic engineering are bound to have major societal impact as tools for discovery in areas such as basic condensed matter physics, biology and applied energy science, e.g., when table-top sources of coherent hard X-rays can be used to characterize the formation dynamics of chemical reactions and of living cells, or to track the degradation of electrodes in advanced batteries *in operando*. Further, beams of intense gamma rays derived from petawatt-laser pulses and laser-accelerated electrons can enable detection of concealed nuclear material and laser accelerated ions, formed with acceleration gradients much larger than a GeV/m, might soon allow the treatment of cancer with a foot print and cost orders of magnitude lower than what they are today.

SIDEBAR BOX III:

Boiling the Vacuum.



Colliding laser pulses with intensities of about 10^{25} W/cm^2 can "boil the vacuum", forming electron-positron pairs. (Image: https://www.orau.gov/plasmawkshps2015/whitepapers/general-Bulanov_Stepan.pdf). Such a photon collider with significant production of electron-positron pairs (Breit-Wheeler process) concomitant with electron or positron emission (Compton effect) could result in an extreme pair plasma soup with sufficient number density for collective effects to be observed for the first time.

When pairs are produced while photons emitted via the Compton effect that carry sufficient energy, quantum effects come into play. In this regime non-perturbative quantum field theory or nonlinear quantum electrodynamics (nQED) applies, as theoretically predicted by Schwinger for static electric fields. In this regime, external field approximations break down and we must consider the backreaction of non-linear quantum electrodynamics processes. A complete description, which would involve collective effects in this dense photon-pair plasma soup, together with experiments will greatly propel our fundamental understanding of light and matter in extreme electromagnetic fields and manifestations of physics beyond the Standard Model may potentially be observed in such high intensity laser-matter interactions.

Chapter 3 Understanding the Physics of Coherent Plasma Structures

Self-organization leading to structure formation is a fundamental physical process that occurs in many nonlinear systems. Plasmas exhibit a great variety of nonlinear dynamics such that structures are observed to occur at all scales in time and space – from days-long processes in geophysical plasmas to sub-microsecond, nanometer-scale phenomena in technological plasmas. In plasma systems there exist the usual factors of energy flow with dissipation, but additional degrees of freedom, long-range forces and boundaries induce a wide range of phenomena. The boundaries may be either physical boundaries such as solid, liquid, or gas layers, or electromagnetic boundaries such as double-layers or beam-plasma layers. A fundamental research question for all of these processes is how does the redistribution of energy, momentum, and angular momentum in physical or phase space give rise to coherent plasma structures at all scales.

Overview

Coherent structures, i.e., self-organized patterns, are a complex and fascinating phenomena that occurs in a wide variety of biological, chemical, and physical systems. Their occurrence is associated with the supply of energy to an open system, leading to instability, symmetry breaking, bifurcation, and ultimately to the formation of coherent structures. Coherent structures can be observed in a wide diversity of space and laboratory plasmas and high-intensity beams. In the laboratory this includes, but is not limited to nonneutral plasmas, dusty plasmas, charged particle beams, glow discharges at low and high pressure, dielectric barrier discharges, discharges with crossed electric and magnetic fields (magnetrons) and electric propulsion (Hall thrusters). An example of electrode spots is shown in figure 1.

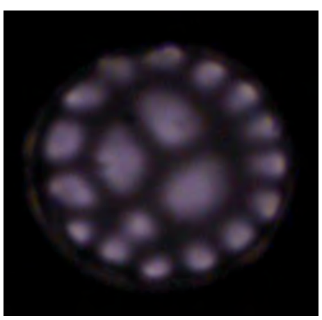


Figure 1. Example of pattern formation near electrodes. [Image from white paper of Wei-Dong Zhu, Saint Peter's University].

Important differences exist between the formation of coherent structures in plasmas and in biological, chemical, and fluid systems because of the long-range interactions that occur in plasmas. These interactions are caused by the self-consistent electromagnetic fields generated by the particle charges in plasma structures. These electromagnetic fields can transfer energy from fast particles to slow particles without binary collisions in a way that frustrates the fluid model of a plasma. Consequently, the processes of coherent structure formation in plasmas often depend on the details of the velocity distribution of the particles. The current level of advanced diagnostics, as well as recent progress in numerical and analytical modeling, now make it possible for the first time to understand the mechanisms of coherent structure formation with unprecedented accuracy on the particle-kinetic level by measuring and simulating the dynamics of plasma particle velocity distribution functions. This is an important extension beyond earlier diagnostics and models based on average plasma parameters (density, temperature, particle fluxes). When mechanisms of coherent structure formation are established, this knowledge can be actively used in a great variety of plasma applications for active and beneficial control of these structures in applications as discussed below.

Although much knowledge has been acquired about specific structures that occur in particular contexts, there remains a need to develop a comprehensive picture that can explain pattern formation. Why, for example, do similar patterns appear is radically different physical contexts? The features normally associated with self-organization: feedback, threshold nonlinearity, and non-equilibrium thermodynamics, are all generally present. In addition, however, plasmas display a unique interplay of boundary effects, particle distributions, and energy flow to create situations rich in dynamical possibilities. On the other hand, plasmas exhibit phase space conservation laws - associated with symmetries - that can cause the dynamics to be surprisingly organized. Finally, the fact that plasmas generally form sheaths (space-charge layers) near boundaries is another unifying principle that affects pattern formation.

In naturally occurring plasma systems, such as the earth's magnetosphere, the formation of structures is of vital importance to understanding the environment and the connection between the sun and the earth. Furthermore, because technological applications of plasmas generally also involve the spontaneous generation of structure, a fundamental understanding of pattern formation in plasmas is of great scientific and practical importance at the same time.

Scientific and Technical Challenges

Experimental and theoretical studies of the processes that lead to the formation of coherent structures represent a significant body of work in fundamental plasma science. While it is known that it is the modification and redistribution of energy and momentum in the plasma that leads the formation of structures, a single framework that encompasses observed phenomena from geospace to the laboratory has not yet been achieved. This is a timely research frontier produced by the availability of new experimental and computational research capabilities that offer researchers the opportunity to perform the complex, multi-scale investigations that are required to understand how coherent structures are formed in plasmas. Advanced diagnostic tools such as high-speed imaging (at thousands of frames/second) and time resolved (at sub-microsecond) optical diagnostics of plasma emission coupled with the ability to efficiently perform large-scale (e.g., millions of particles) plasma simulations that resolve electron and ion dynamics in a self-consistent manner and that include the effects of boundary conditions present an opportunity to finally develop a framework that may describe the broad range of plasma systems in which the formation of coherent structures is present.

To illustrate the variety and ubiquity of coherent structures we choose several examples:

(A) spokes in discharges with crossed electric and magnetic fields (or ExB discharges for short);
(B) patterns formed in dusty plasmas;
(C) structures in phase space;
(D) coherent structures in geospace;
(E) nonneutral plasmas and beams;
(F) structures formed near plasma boundaries.

Magnetic structures in astrophysical plasmas are discussed in Chapter 4.

A. Spoke Phenomena in Discharges with Crossed Electric and Magnetic Fields

Despite great variation in size, power and method of generation, geometrical design, operational pressure, and applications, gas discharges generally produce weakly-ionized plasmas with an electron temperature of a few electronvolts. The degree of ionization (fraction of the gas ionized to plasma) is low in these plasmas in contrast to the nearly fully ionized plasmas in fusion experiments. Due to the low degree of ionization, the dynamics of ionization can very important in the formation of structures which are localized regions of enhanced plasma density and/or optical emission. Typical examples are shown in Fig. 2. Structures in partially-ionized plasmas include “contracted” discharges (structures formed transverse to the direction of current flow) and striations (structures formed parallel to the direction of current flow).

It is critical to gain deeper understanding of the plasma processes that are responsible for the generation of self-organized structures in ExB discharges for a large range of operating conditions, and the consequences of structures on cross-field particle transport. Transport in these structures is rather complex because of structure on multiple scales.

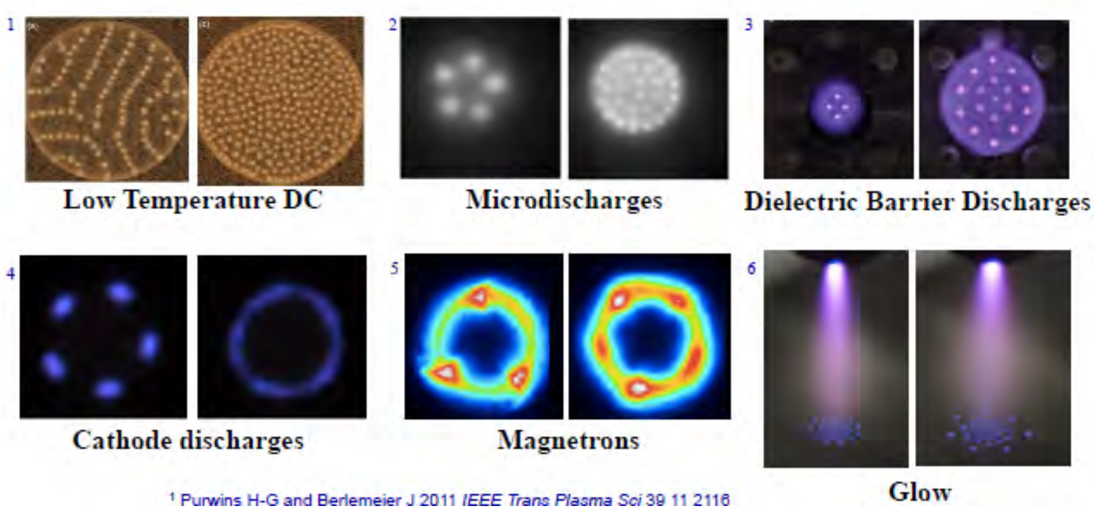


Figure 2. Examples of structures formed transverse to the current flow direction. [Image from white paper of J. Trelles].

ExB discharges exhibit instabilities associated with the relative motion of magnetized electrons in crossed fields. Figure 3 shows structure formation in various ExB discharges.

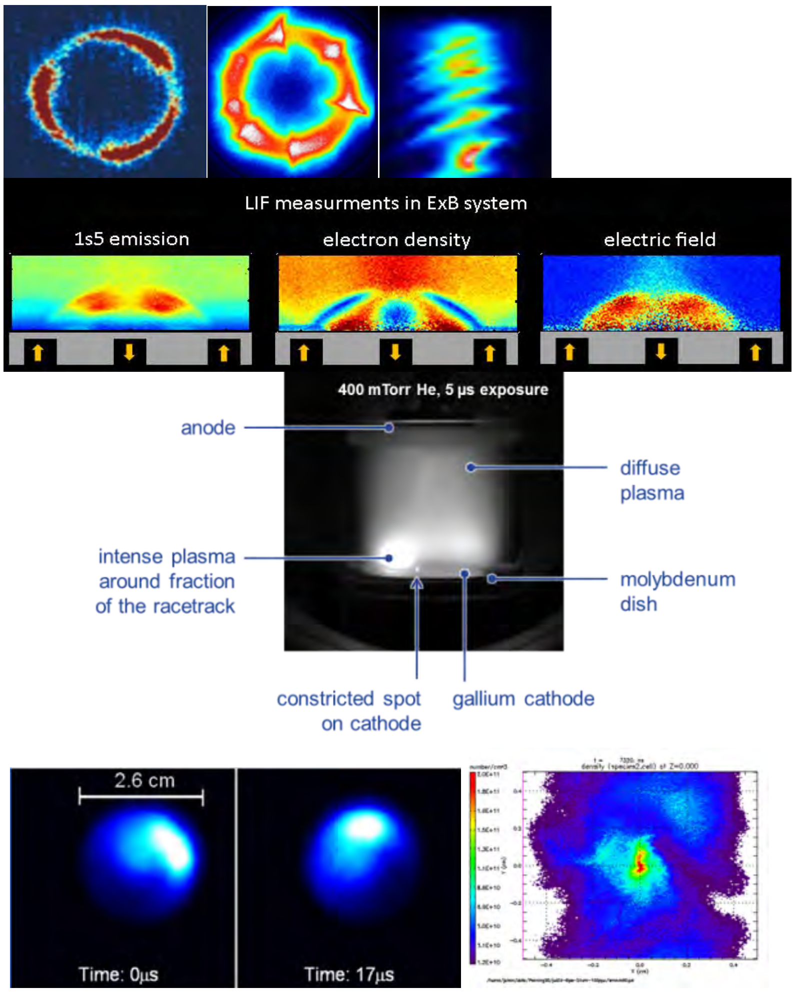


Figure 3. Images of Coherent structures: first row, left: light emission from a micro-hollow cathode at high pressure; first row, center: light emission from a magnetron operating in the "HiPIMS" mode; first row right: streak image of ionization waves in magnetrons at low pressure; second row: laser-induced fluorescence (LIF) images of a magnetic cusp discharge; third row: fast image of cathode spot followed by virtual "anode ball" rotating structure in a plasma switch for electric grid system; fourth row: Fast camera images of the rotating spoke instability in a cylindrical Hall thruster and an example of a particle-in-cell simulation of this phenomenon. [Images: Top and second row: from white paper of A. Andres; third row from white paper of T. Sommerer. Lowest row: Left and Center: courtesy Y. Raitses, PPPL and Right: courtesy of J. Carlsson, PPPL.].

Some of the important frontier questions in this area include:

- *What are the dominant modes of instability responsible for the observed level of anomalous electron current?*
- *What is the range of the spatial and temporal scales of fluctuations that contribute to the anomalous transport?*

- *What is the role of ionization and kinetic effects, e.g. role of high-energy electrons?*
- *Do these structures originate from some primary low frequency large scale instability or are they generated as a result of the secondary nonlinear processes of condensation and self-organization of small scale turbulence similar to zonal flow dynamics in fully magnetized plasmas?*
- *What are the controlling parameters that determine the mode transition between homogenous turbulence and various modes with coherent structures?*

Research Needs

These structures arise from multi-scale processes that involve the transport and redistribution of energy, momentum, and angular momentum in phase space. Because of advances in the temporal and spatial resolution of both plasma diagnosis and plasma modeling, the opportunity now exists to make significant scientific progress in the understanding of these systems.

Beyond the development of diagnostic and numerical tools, it is also envisioned that the development (or enhancement) of a few mid-scale, multi-user scientific facilities can also make a significant impact on this area of research. It is envisioned that these mid-scale facilities would require modest resources to build and operate – but should be well-instrumented to maximize the opportunity to make highly detailed scientific measurements. Advancement depends on the availability and further development of primarily non-invasive techniques, based on (pulsed) lasers and fast sensors. The frontier questions can be best addressed by capturing plasma data with unprecedented high resolution in space and time, making use of advances in laser, sensor, data acquisition, data storage and processing technology. Emphasis should be on the combination of complementary techniques and techniques that allow capturing data during a single event, avoiding significant information losses associated with averaging over many pulses. Techniques should capture plasma information from different directions, leading to plasma tomography. Data presentation should be coupled to advanced graphic visualization and compared to modeling, i.e., suitable modeling effort and computation capabilities are integral part of any advanced plasma facility.

B. Patterns in Complex/Dusty Plasmas

A hallmark of complex/dusty plasma research is the ability of charged nano-/micro-particles (“dust”) to form organized structures in a plasma. The formation of these structures is due to the strong electrostatic interactions among the particles coupled to the complex interactions with the surrounding plasma and boundaries. Depending upon the plasma parameters and boundary conditions, a rich variety of structures can be formed. While the patterns can be readily classified, there remain significant gaps in providing a unified theoretical framework for describing all of these processes. Some examples are shown in Fig. 4.

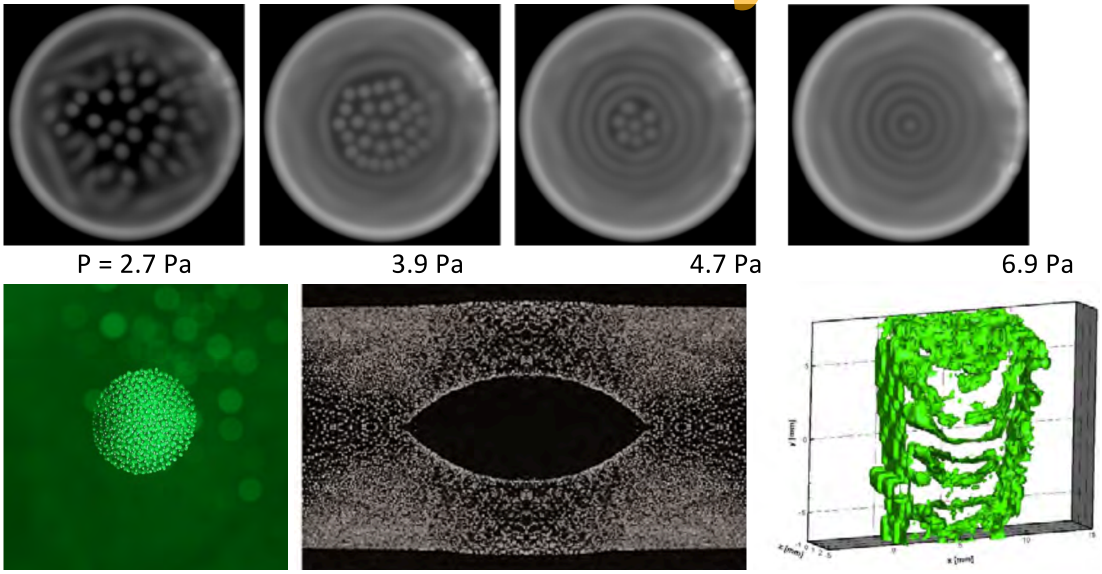


Fig.4 Examples of pattern formation in complex/dusty plasmas. Top row: structures/filaments formed in a highly magnetized plasma generated by a rf discharge at B = 1 T, Bottom row: left: agglomeration of dust in plasma; middle: void (dust-free region) formation in a microgravity dusty plasma; and right: contour plot showing the three-dimensional wave structure of the naturally occurring dust acoustic wave. Top row: structures/filaments formed in a highly magnetized plasma generated by a rf discharge at B = 1 T [Image from Phys. Rev. Lett. **106**, 215004 (2011).] Bottom row: Left: Image from Phys. Plasmas **12**, 122102 (2005); Phys. Plasmas **13**, 090701 (2006).],Center: from Phys. Rev. Lett. **83**, 1598 (1999); Phys. Plasmas **18**, 013704 (2011).], Right: white paper of J. Williams]

Dust particles act as both a source and sink of plasma – leading to the formation of sheaths that govern the dust particle charge. The transport and charging of particulates in plasma have been extensively studied over the last few decades. At the same time, more complex structure phenomena in such plasmas are not well understood. For example, the experimentally observed structures shown in Fig.4 are currently unexplained. Self-organization of dusty plasma is also an important topic for space physics. Frontier studies will address the nonlinear synchronization of modulated waves, and the merging of wavefronts due to nonlinearity. In the laboratory, the physics of dust in plasmas with high magnetic fields is important for experiments on magnetically confined thermonuclear fusion. Because of the complexity of fusion experiments, the relevant dust phenomena warrant study in dedicated experimental facilities.

Emerging, and very important for practical applications, is the circumstance where particulates are not externally injected but instead spontaneously grow due to chemical processes inside the plasma. For example, such plasmas can produce metal nanoparticles by decomposing a metal-containing gas, or produce nanoparticles of the IV,V-group of elements of the periodic table (C, B, Si, N etc.). Nanoparticles are synthesized by either decomposing background gases or by ablating electrodes containing these elements (Fig. 5). The plasma environment possesses a number of features that permit the synthesis of nanoparticle materials that are otherwise very hard to produce. These unique capabilities of nanodusty plasmas have already enabled technological advances such as the generation of nanometer-sized metal particles, diamonds, stable silicon-nanocrystal anodes for lithium ion batteries, high-mobility transparent conductive oxide films based on zinc oxide nanocrystals, etc. (See Chapter 6 for more details on the interface with Chemistry).

Some of the important frontier questions in this area include:

- *What are the plasma characteristics where nucleation and growth of nanoparticles occur?*
- *What are the physical mechanisms, governing these plasma characteristics? How are plasma and materials processes self-organized?*
- *How can plasma processes (e.g. convection, instabilities) affect and control selectivity? What are the effects of mutual interactions of nanoparticles with plasma (charging, radiation emission and absorption, heating) on nucleation and growth of nanoparticles and their transport in plasma (agglomeration, disintegration, separation etc.)?*
- *To what extent can the presence of plasma enable a reduced synthesis temperature compared to chemical methods?*
- *What are suitable diagnostic tools for measurements in plasmas with nanoparticles? Which plasma simulation methods can effectively predict plasma characteristics with nanoparticles?*

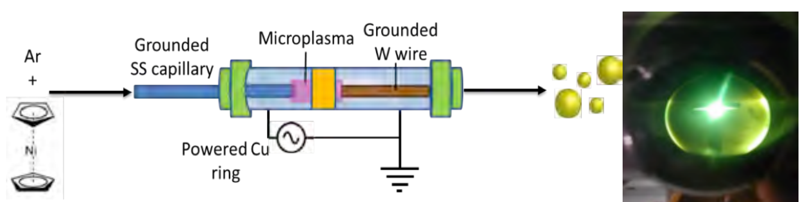


Figure 5 Plasma devices for production of nanoparticles. Left: Microdischarge plasma for production of nanoparticles. Right: arc for production of carbon nanostructures (fullerens, carbon nanotubes, etc.). [Image courtesy M. Snakaran and Y. Raitses.]

Research Needs

The frontier of complex plasma research involves advancing the parameter space in which studies are performed in order to more accurately capture phenomena in naturally occurring systems as well as advancing the technological application of complex plasmas. Capabilities should include the ability to perform detailed, non-invasive measurements of the plasma parameters and offer opportunities to study both injected particles and *in situ* growing particles. While the motivation for these facilities will be to study the properties of complex/dusty plasmas, these facilities will also extend the parameter space for studying low temperature plasmas. Among the facility types that are under consideration are:

A facility that enables the study of a "fully magnetized" plasma in which the dynamics of all of the charged species: electrons, ions, and the charged microparticles, are dominated by the presence of the magnetic field. Facilities should provide sufficient particle-confinement lifetimes to allow all charged species to execute many gyro-orbits. Facilities should provide substantial multi-user access and an advanced diagnostic suite.

A facility in microgravity conditions, capable of operating an experiment for greater than 30 minutes (that would require a space station vs parabolic flights and sounding rockets), equipped with various manipulation features. Two variants would be attractive: DC and RF, where the DC version is well suited for studies of waves and inter particle interactions under strong ion flow, statistics under strongly non-equilibrium conditions while the RF version is well suited for studies of statistical physics under more nearly equilibrium conditions, macroscopic self-structuring, crystalline vs liquid phase behavior, and other related phenomena.

A facility that can provide *in situ* measurements of nanomaterial synthesis processes in plasmas and uncover mechanisms of their growth. Advanced computational tools that combine plasma simulation codes with molecular dynamics codes based on DFT approaches (discussed in chapter 2) can aid understanding of complicated processes during nanomaterial growth and considerably advanced the field.

C. Structures in Phase Space

As mentioned above, differences between coherent structure formation in plasma and fluid systems result from the effects of the self-consistent electromagnetic field and the low rate of binary collisions. The electromagnetic field can transfer energy from fast particles to slow particles in these structures without collisions and, consequently, the processes of coherent structure formation often require a particle-kinetic description. Much progress has been made in understanding these processes by developing advanced diagnostic and computational tools that can much better resolve the fine features of these structures. Examples of such structures are shown in Fig. 6.

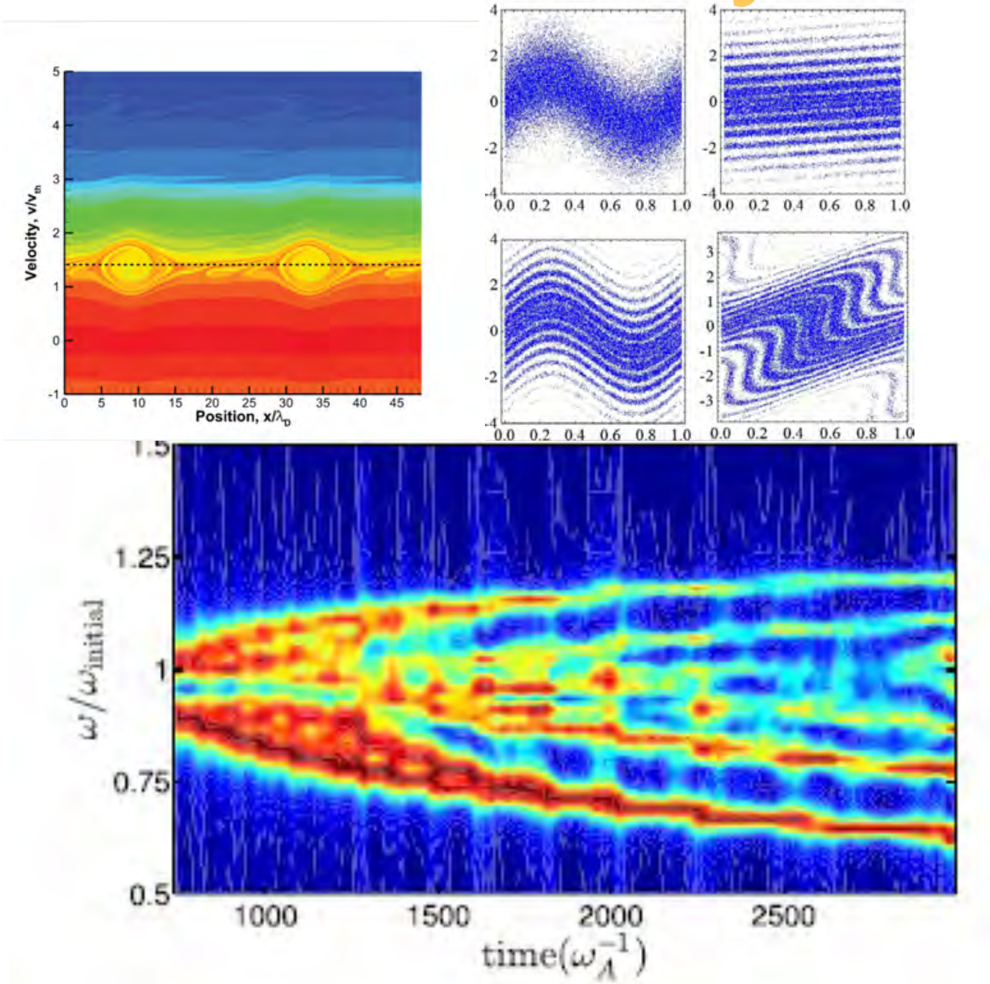


Figure 6. Top row: “plasma echo” phase space patterns in the 4th generation X-ray Free-Electron Laser. Bottom row: Spectrogram of a self-organized frequency chirping phenomena associated with phase space structures in a tokamak plasma. [Top row images: Left: from Phys Plasmas **22**, 02210 2015; Right: from Phys. Rev. Lett. **102**, 074801 (2009); Bottom row image: from Phys. Lett. A **234**, 213 1997.]

Novel kinetic waves have recently been predicted by theory and observed experimentally on plasmas with non-Maxwellian particle velocity distributions. An entire new class of waves has recently been identified in plasmas with velocity distributions flattened at velocities resonant with the phase velocity of the wave, allowing waves with a given wave number to propagate at a range of frequencies. Experiments suggest that velocity distributions can spontaneously evolve to make the plasma resonant with a range of driver frequencies. Understanding this driven plasma response is of broad interest to a variety of applications.

Past studies suggest that the frequency and wavelength properties of nonlinear waves can significantly differ from the predictions made for small-amplitude waves on a given equilibrium (a Maxwellian) velocity distribution function. Early theories suggested that these nonlinear waves require carefully tailored distribution functions, and might not be readily excited in real experiments. However, recent experiments and simulations have shown that nonlinear plasma waves can easily be excited and form robustly. Strong modification of an initially Maxwellian velocity distribution function is produced when a specially designed perturbation is applied over long period of time (as in autoresonance). These nonlinear waves can also be excited in many plasmas with intense drivers, see Figs. 6 and 7 for example of such driven systems.

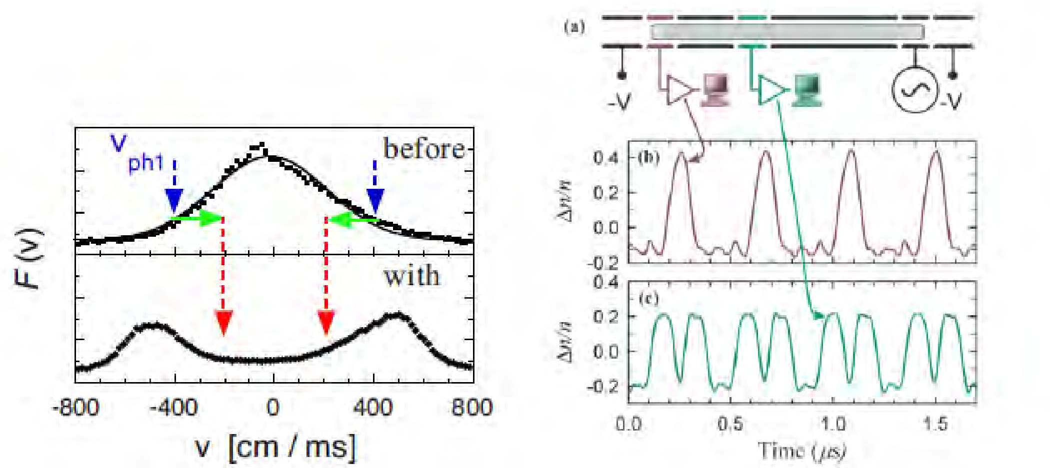


Figure 7. Examples of strong modifications of the velocity particles distribution functions in ion plasma and large amplitude plasma waves measured in electron plasma [lamge from white paper of F. Anderegg].

Key research questions:

- How do phase space structures develop in driven plasma systems where the velocity distribution function is strongly modified by an external drive?
- What are the limits of autoresonance as a description of nonlinear plasma waves in 2-D and 3-D?

Research Needs

Developing nonperturbitive diagnostics and advanced computational tools that can resolve the phase space structures in multidimensional plasma configurations are crucial for progress in this area. Innovative theoretical approaches will also be required to construct computable models of particle-kinetic dynamics (Chapter 7).

D. Coherent Structures in Geospace

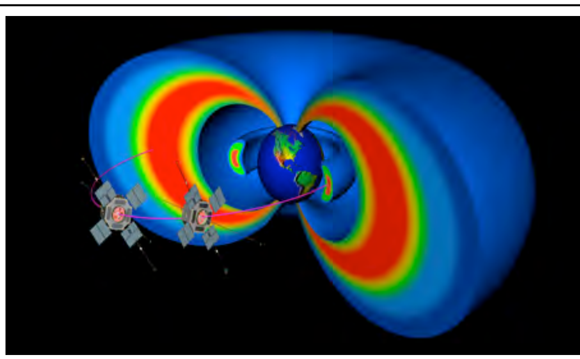


Figure 8. Schematic of radiation belts around earth.

The Sun produces a flow of mass, energy, and momentum across space into the near earth region. The plasma state in the near earth region has many important effects and is called “space weather”. Certain solar processes, such as eruptive events (coronal mass ejections) and the solar wind's co-rotating interactive regions, are especially effective in determining space weather. As the solar wind interacts with the Earth's dipolar magnetic field, a unique interaction takes place that couples the solar wind plasma, momentum, and energy into geospace. At the largest scales, the significant coupling process is magnetic reconnection between the interplanetary magnetic field and the geomagnetic field. This coupling leads to the formation of boundary layers with scale sizes as small as a few ion gyroradii, which separate plasmas of different characteristics. These are dynamic regions characterized by intense coherent quasi-static electric fields as well as broadband electromagnetic emissions and they display spontaneous and induced nonlinear phenomena. Trapping of the energetic particles originating from the sun in the earth's dipolar field creates the meso-scale structures called the radiation belts. The orbital lifetime of satellites is inversely proportional to the population of the energetic particles in the radiation belts. Between the reconnection scale and the boundary layer scale there is a huge range of both temporal and spatial scales. This range constitutes an extraordinary challenge for both experimentalists and theorists (see also Chapter 4). The ability to understand and predict the plasma state generated by cross-scale couplings, and controlling it in proximate geospace, is a frontier in fundamental plasma physics. The proximity of the ionosphere to the earth makes it a unique outdoor plasma physics laboratory to study large, unbounded plasma systems.

As plasmas interact nonlinearly in the electromagnetic environment of space, coherent structures are created, and these structures play a critical role in transport processes within the magnetosphere. Two regions of particular interest are (1) the magnetopause boundary layer, where coherent vortex structures transport mass, momentum, and energy from the solar wind to the magnetosphere and (2) the plasma sheet, where intermittent coherent structures, known as "bursty bulk flows," inject plasma sheet populations into the inner magnetosphere, which can build up the ring current and hazardous radiation belt populations.

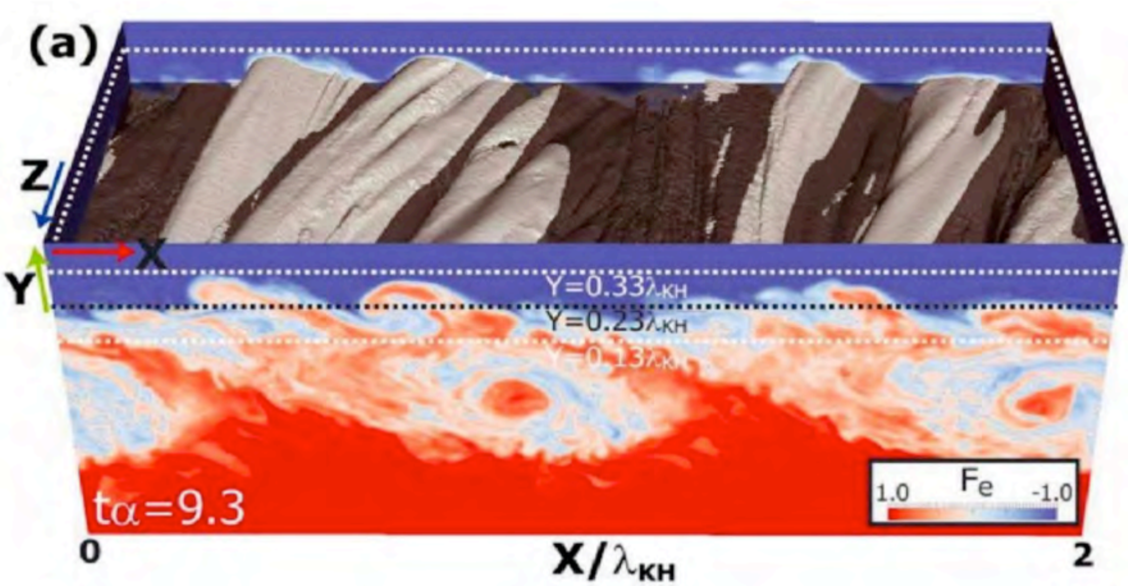


Figure 9. Three dimensional simulations of plasma structures forming at Earth's magnetospheric boundary [Image from Geophys. Res. Lett. **41**, 8704 (2014)].

Shear flow at the magnetopause interface can excite Kelvin-Helmholtz waves, which are analogous to waves driven by wind blowing over water.

Some key questions for future research are:

- *What is the role of magnetic reconnection versus the role of wave mixing for plasma transport?*
- *Do shocks that form at the edge of vortex structures heat plasma and increase the entropy as observed?*
- *How can one perform kinetic modeling of the coupling between these structures and the ionosphere (including aurora)?*

Research Needs

Advances in computation have now enabled dramatic advances in understanding of coherent structures in space plasmas. High resolution fully kinetic 3D simulations are regularly applied to study reconnection and boundary layer phenomena. These simulations are ideal to study kinetic-scale structures associated with reconnection and velocity-shear driven instabilities at the scales that are now detected by high resolution instruments on tightly configured satellite clusters. While global kinetic simulations in space are not yet feasible, reduced models that retain important kinetic effects have reached the point where it is possible to describe cross-scale coupling. For example, global hybrid simulations (fully kinetic ions and fluid electrons) are regularly performed to examine the magnetospheric response to solar wind driving. The hybrid simulations enable a description of the development of fast flows from reconnection, their global convection into the inner magnetosphere, and the kinetic dissipation that occurs as the flows slowdown in the inner magnetosphere. Sophisticated models of the inner magnetosphere have been developed, which describe how wave-particle interactions affect the ring current and radiation belt populations. A key direction of future research is the coupling of models that describe various regions to the magnetosphere to ensure that the effects of coherent structures involved in coupling processes are properly described.

An impressive array of satellites and space probes, both domestic and international, are providing us with unprecedented data about the sun, the solar wind, magnetosphere, radiation belts, and the ionosphere. This data is available to the geoplasma physics community from NASA, NOAA, and other agencies and should be utilized to provide *in situ* “space measurements”. The ionosphere has also traditionally been subject to ground-based investigation via radars, magnetometers, lidars, interferometers, photometers, and imaging. The proximity of the ionosphere makes it a suitable outdoor plasma physics laboratory. In addition, detailed measurements through laboratory experiments are necessary to isolate and understand the key physics affecting the space plasma phenomena.

The key to advancing the laboratory investigation of space plasma phenomena is the availability of facilities with sufficient flexibility in plasma parameters, magnetic field strength, and plasma species selection to allow proper scaling to important dimensionless parameters. Plasmas large enough to support the long transverse and magnetic-field-aligned wavelengths that characterize space plasma waves, while also allowing sufficient vacuum gap between the plasma and chamber walls to minimize boundary effects are required. For example, the micro-scale phenomenon involved in the collisionless dissipation of plasma instabilities is amenable to scaled laboratory studies under controlled and repeatable conditions. This offers the possibility of benchmarking and refining theoretical models that can then be applied to space relevant parameters with increased confidence, which is necessary to advance the frontier of space plasmas.

E. Nonneutral Plasmas and Beams

Nonneutral plasmas, either single-species or mixed species, are good experimental testbeds for many fundamental plasma phenomena and many coherent structures are observed in these systems. Nonneutral plasma techniques have been crucial to recent successes in trapping anti-hydrogen at CERN, and have been used to address myriad questions in atomic physics, vortex dynamics, strongly-coupled plasmas, quantum computing, and particle beam physics. The strong electric fields present in nonneutral plasmas, as compared to quasineutral plasmas, lead to long-range forces that can play a role in the formation of coherent structures.

One major area of research where long-range electric fields are seen to change the dynamics is the study of long-range collisions occurring at magnetic fields strengths sufficient for the cyclotron radius to be smaller than the Debye shielding length. Experiments and theory show that the damping associated with collisional viscosity is up to 10^5 times higher than the classical value for local collisions and that the cross-field heat conduction is large and independent of magnetic field. An extreme example of long-range interactions occurs in stellar plasmas, where high-energy fusion collisions are enhanced by inter-particle correlations. Surprisingly, these conditions are directly analogous to enhanced perpendicular-to-parallel collisions in magnetized nonneutral plasmas.

Phase space structures naturally play an important role in understanding nonneutral plasma systems. One example is the wave damping and particle transport caused by particles trapped in weak magnetic ripples and strong magnetic mirrors. Here, electron experiments and theory from several perspectives show that dissipation at the velocity-space separatrix remains strong even as inter-particle collisions become weak, as in fusion regimes. Dissipation at a separatrix is inherently non-linear, combining parallel kinetics with perpendicular drift dynamics. Further understanding will require well-controlled experiments targeted towards testing specific aspects of theory.

Phase space structure produced by autoresonance has been extensively developed in nonneutral plasma systems and has proven to be a useful tool. In autoresonance, many-particle plasma systems respond coherently to an external drive with a swept frequency. Collective oscillations can be excited to large, nonlinear, amplitudes while remaining phase-locked to the drive, allowing precise control over the system. This technique has proved to be robust, for example, in antihydrogen experiments at CERN where autoresonant axial excitation of antiprotons is used to mix them with positrons without excessive particle heating. Increasing the synthesis of trappable antihydrogen by better understanding of factors that determine the minimum realizable plasma temperatures, rotating wall compression, and efficient mixing of antiprotons and positrons is a major objective in the quest for precision antihydrogen measuments.

Nonneutral plasmas in strongly magnetized Malmberg-Penning traps have been used to study coherent structures such those observed in inviscid 2D vortex dynamics, including vortex merging, shearing, and crystallization. Experiments are made possible through the analogy between the plasma and fluid dynamics where, among other analogs, plasma density is analogous to fluid vorticity. New experiments have studied the effect of externally-imposed flows, the analog of externally applied wall voltages, on highly elliptical vorticity distributions. The two rows of images in Figure 11 show, from left-to-right in the figure, the evolution of two different initial vorticity distributions with different initial ellipticity. In one case, the external flow creates spiral arms of vorticity extending from the core, while in the other case, a Kelvin-Helmholtz instability occurs as well, leading to the breakup of the core into two vortices.

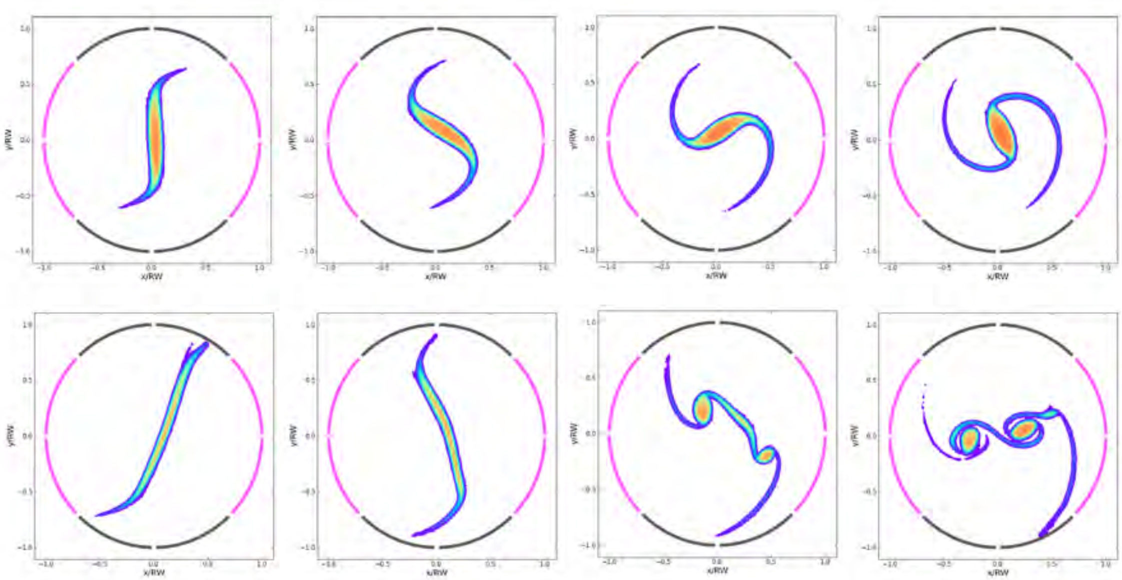


Figure 11 Two different vorticity distributions as subjected to the same externally-imposed flow. [Courtesy of N. Hurst, UCSD]

Laser-cooled ions in nonneutral plasmas traps can form coherent strongly-coupled structures such as Coulomb crystals, as is done for quantum computing applications, New results have verified the entanglement of up to 219 ions. It is important to understand the crystal structure in order to understand the dynamics of entanglement generation.

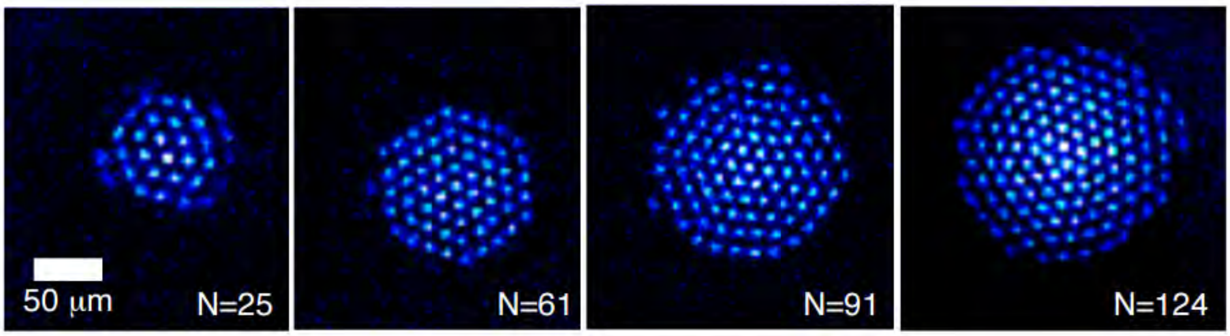


Figure 12 Laser-cooled beryllium ions form strongly-coupled Coulomb crystals that can be used for quantum computing studies. [Image from http://arxiv.org/pdf/1512.03756v2.pdf]

Electron and ion beams in accelerators are other examples of nonneutral plasmas. Understanding stable transport of intense, nonlinear beams is an area on the frontier of research. More so because of the recent trend of the high-energy physics community to develop high-intensity beams (SNS, CERN, GSI FAIR upgrade, Fermilab's NOVA experiment, and Long Baseline Neutrino Experiment) for so-called Intensity Frontier research – fully supported by the 2013 HEPAP P5 subpanel report as the priority for U.S. high-energy physics - call for much better control of intense beam transport over long-distance propagation (prevention of halo generation and beam scraping the walls). Systems with additional highly nonlinear integrals of motion – like McMillan-Danilov potentials in particle accelerators – have recently been suggested for improved stability and control, but their robustness has not yet been fully proven. Deep theoretical insights, extensive modeling and experimental studies are needed to understand underlying physics of such complex nonlinear plasma systems as space-charge dominated beams interacting with nonlinear focusing fields.

Currently, plasmas are also used for additional control of transport and focusing of intense charged particle beams (LBNL, Michigan, Fermilab). Beam-plasma systems may be subject to deleterious instabilities. However, in many cases it is known that robust operating windows exist where instabilities can be effectively mitigated (NDCX-II LBNL). Morebroady, beam-plasma interaction studies can be used for laboratory investigations of astrophysical phenomena. Examples include collisionless shocks (NDCX-II and UMER), and coherent structures such as solitons (UMER). Fermilab is building a dedicated Integrable Optics Test Accelerator (IOTA) facility to support experimental R&D devoted to high intensity beams of protons, including such plasma-based techniques as electron lenses, electron columns (traps) for space-charge compensation, and nonlinear beam focusing optics.

A significant advantage of nonneutral plasmas is that they can be studied using small University-scale experimental facilities that are ideal for hands-on student training not possible on larger machines.

Some of the important frontier questions in this area include:

- *How do long-range electric fields affect transport properties in plasmas?*

- *How can nonlinear manipulation techniques be applied to complex many-body systems?*
- *What mechanisms govern the evolution and ultimate final state of vortex dynamics?*
- *How can 2D and 3D strongly-coupled plasma systems be controlled?*
- *How can intense charged-particle beams be transported over long distances/long times while maintaining high brightness and low emittance?*
- *What are the mechanisms of emittance growth and halo particle production, and can they be controlled or mitigated?*
- *Can nonlinear transport systems or/and space-charge compensation be developed to manipulate or control the phase space of charged particle beams?*

Research Needs

Many laboratory facilities are already in place for studies of nonneutral plasmas. Some focus their research on electron plasmas, while others focus theirs on single-species ion, multi-species ion, or positron plasmas. Many of these facilities, however, would benefit from modifications or upgrades to exploit their flexibility to directly address key scientific questions as they are identified. Many Penning traps and Paul traps are currently used by researchers, including cylindrical, hyperbolic, and toroidal. Some would require reconfiguration and enhanced diagnostics to carry out frontier research. Cost-effective scaled experiments and test stands for concept development are already in use. For example, UMER. The PPPL Paul trap is an excellent scaled experimental resource for better understanding beam dynamics. Existing plasma-based ion sources can be coupled with existing Penning traps in order to develop beam neutralization concepts. In some cases, it may be desirable to construct new small-scale facilities to explore new ideas.

F. Structures Formed near Plasma Boundaries

As mentioned above, plasmas generally possess a thin layer of space charge near boundary walls called a sheath. Walls naturally charge negatively to reduce the electron flux until it becomes equal to the ion flux. Therefore, only energetic electrons are typically able leave plasmas whereas low energy electrons are trapped inside the plasma. Correspondingly, plasma interaction with the walls has to be treated particle-kinetically. The constant absorption of plasma at the wall creates a plasma perturbation on the ion mean free path scale often called a presheath. After 80 years, presheath and sheath characteristics are only well understood in single ion species, weakly collisional, unmagnetized plasmas. In two ion species, unmagnetized plasmas, the presheath structure can be affected by various instabilities such as ion-ion two stream, loss cone instability, and secondary electron emission and ExB flow driven instabilities. The result is that the plethora of plasma applications where such processes occur are poorly understood. Recent advancement in Laser Induced Fluorescence (LIF) and probe diagnostics (see Fig.13) and computational tools can lead to rapid progress in the understanding of these processes.

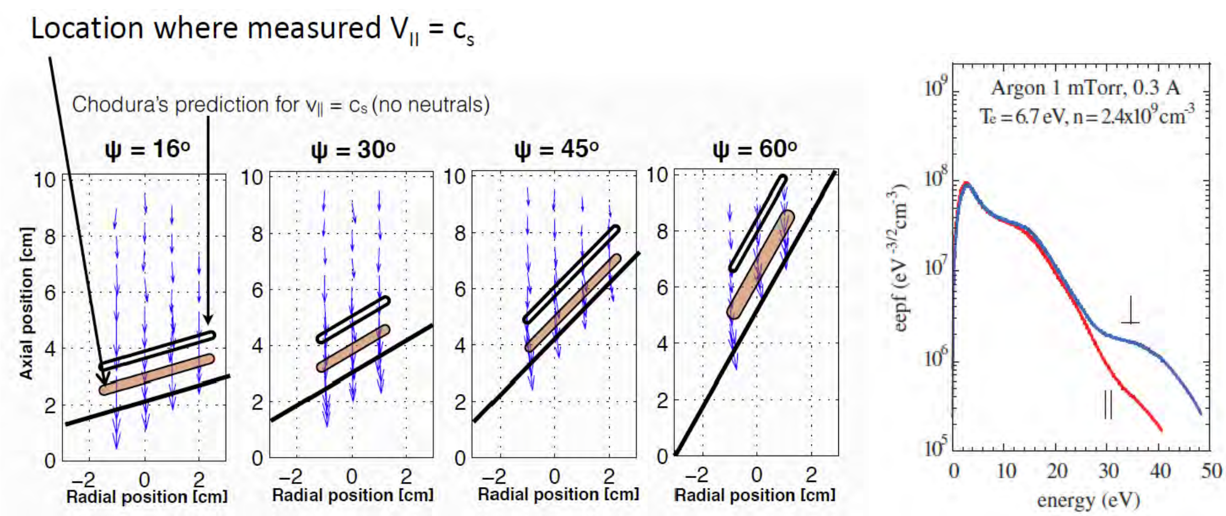


Figure 13. Examples of recent LIF and probe diagnostics. Left: Ion drift velocity along the perpendicular direction of an electrode plate; [Courtesy G. Severn, University of San Diego.] Right: Electron Energy Probability function measured in the positive column of Ar DC discharge. Red and blue correspond to radially and axially oriented cylindrical probe respectively. [Image from Plasma Sources Sci. Technol. **24** 052001 (2015).]

Electrical “double layers” are a further interesting example of coherent structures that form inside plasma, often in unpredictable locations. Laboratory studies of double layers are continuing in the USA and around the world. The discovery of spontaneously forming double layers in expanding plasmas over a decade ago triggered additional theoretical and experimental studies. Double layers have been observed in the auroral acceleration region and are thought to play a key role in auroral arcs. Ion acceleration in self-organized double layers is the basis of one strategy to produce electric propulsion for spacecraft.

The open questions in double layer physics include:

- *What is the role of streaming instabilities in limiting the strength of the double layer and in limiting differential flow speeds between different species ions?*
- *What is the three-dimensional structure of the double layers forming in expanding magnetic geometries and in reconnection exhausts?*
- *What is the role of counter-streaming fast electrons in maintaining the upstream density and thermal pressure near a double layer?*
- *What is the scale size of the pre-sheath upstream of the double layer?*
- *What is the role of boundary conditions in triggering double layer formation in expanding plasmas.*

All these questions are at the frontier of theoretical, computational, and experimental studies.

Research Needs

Many laboratory facilities (plasma chambers and sources) exist that can be adapted for the study of structures formed near plasma boundaries. Many facilities, however, would benefit from modifications or upgrades to enable them to more directly address the key scientific questions. Advanced multidimensional simulation codes and nonperturbative optical and probe diagnostics are crucial for progress in understanding these phenomena.

Transition from description to control of coherent structures

Advancing the field of coherent structures also requires making the step from observation to control. By control, we mean manipulating plasma conditions so as to selectively either form or suppress a desired coherent structure. Control is clearly integral to understanding the properties of a structure as well as being essential for applications. One research frontier is therefore the development of predictive models and experimental tools that enable the control coherent structures.

Certain types of coherent structures and patterns are well known. For example, Bernstein-Greene-Kruskal (BGK) modes, Kapchnisky-Vladimirsky (K-V) distributions, high-order echo patterns, etc. To obtain desired structures in the plasma means to solve the *inverse problem* of finding external and internal parameters, fields and configurations which would result in robust and sustainable patterns that are desired. An example of a desired structure would be a highly charged nonneutral plasma (a beam or trap) with low particle loss. The list of phenomena that one might like to control is large. We will briefly discuss plasma processing, electric propulsion, and energetic particles in geospace.

An important application for plasma control is the world of “post 5 nm” semiconductor device manufacturing. Plasma processing for device manufacturing provides vast opportunities for scientific discovery with paradigm changing impact. With 5 nm and smaller devices the control of fluxes impinging on the surface needs to be made at the level of single atoms, electrons and ions. Dopants must be inserted with atomic scale precision. Films require deposition with atomic level uniformity over scales of nearly 1 m. Atoms must be removed with the same level of precision. Plasmas must control *everything, everywhere all the time* on a surface. Controlling *everything, everywhere all the time* means *chemistry control* and chemistry control ultimately means *controlling the fate of electrons* in the plasma and at surfaces. In the parlance of plasma science this translates to electron energy distribution function control. See Chapter 6 for more details on the interface with Chemistry.

Structure control is important in electric propulsion (Figure 14). When a feedback system is applied to a segmented anode, a coherent structure (a spoke) can be created or destroyed. The spoke structure affects Hall thruster properties and allows for the effective control of thrust.

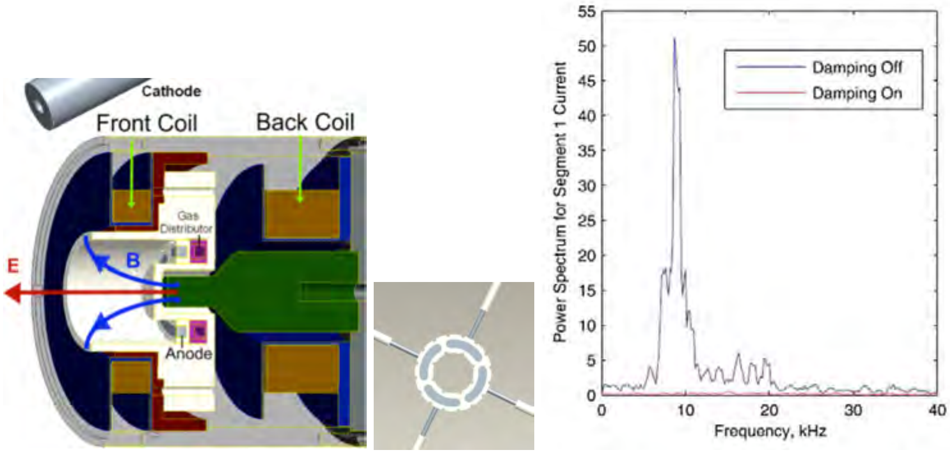


Figure14. Example of application of control of coherent structures in ExB discharge- Hall Thruster (shown in the left figure). When a feedback system is applied to the segmented anode (shown in the middle figure) the spoke disappears as evident in the right figure. [Image from Phys. Plasmas **19**, 053506 (2012).]

Finally, a critical need in the near future will be to control or influence the plasma state in the immediate geospace in order to assure uninterrupted functioning of space assets, which are becoming indispensible to military as well as civilian sectors. An example is the adverse effect of enhanced radiation belt structures, which are known to destroy Low Earth Orbit satellites. Innovative ideas of controlled precipitation of the satellite-damaging trapped electron structures from the radiation belts are frontier topics in space plasma physics. Other topics include modifying the ionosphere trough local heating to create plasma structures for radio wave reflection for emergency communication.

New advances in observations and theory also provide the opportunity for active experiments in space. The High-frequency Active Auroral Research Program (HAARP) has been used to analyze the ionosphere and investigate the potential for improvements in communication. The facility provides the opportunity to study coherent structures by radio waves and excitation of waves and stimulated electron emissions. Electron beams provide another method to actively probe the magnetosphere. Beams launched from rockets and satellites can be used to trace field lines and provide a source for the generation of instabilities that are known to interact with radiation belt particles.

Chapter 4 Understanding the Energetics of the Plasma Universe

The Universe is an energetic place: stars, galaxies, explosions, implosions, collisions, shocks, flowing radiant matter, and wound up magnetic fields. Beginning with the massive release of energy of the Big Bang, particles emerge, clouds form, and stars burn brightly to provide the energy that powers the chemistry necessary for life.

Overview

Underlying all the manifestations of energetics is the pervasive plasma state made from brightly radiating ionized matter. Illustrated in Fig. 1 is the formation of giant structures (galaxies and clusters of galaxies) in the Universe as the big bang matter expands and cools and, then, with gravitational collapse, stars form in dense clumps within molecular clouds and ultimately creating planetary systems and a planet suitable for life. Figure 1 also illustrates the great diversity of energetic phenomena in the Universe including the Eagle Nebula, a cluster of more than 1000 stars, and dynamic variable stars, like the nearby *Eta Carinae* system, which briefly became the second brightest star system in the sky over one hundred years ago. The energetics of plasma phenomena is common during all of these epochs: the formation and evolution of our Universe and the energetic plasma phenomena that underlie the processes through which our Sun powers all life on our planet.

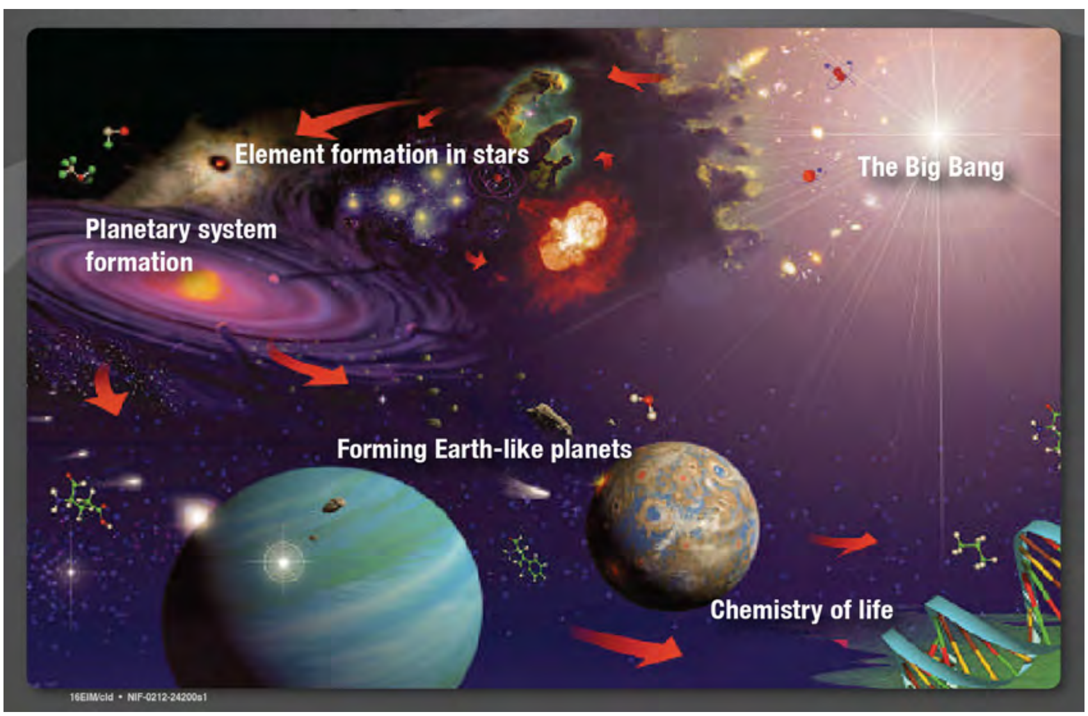


Figure 1. Taken from the Committee on the Physics of the Universe (CPU), which lead to the Quarks to Cosmos report of the National Academies of Science. [Turner 2003]

Just as nature shows a wide range of energetic plasma phenomena, scientists use a wide range of laboratory experiments, telescope and satellite observatories, and state-of-the-art computer simulations to advance the fundamental understanding of the energetics of the plasma Universe.

For example, radiation opacities are notoriously difficult to predict, yet they are a dominant source of uncertainty in models of star birth and stellar evolution. Sophisticated opacity experiments have been carried out over the past decade, and recent results suggest that the opacities assumed in the standard models for the Sun's interior must be significantly improved. Similarly, as we now understand it, magnetic fields are a prerequisite for planets to be suitable for life. Understanding magnetic fields requires understanding planetary formation dynamics, planetary interiors, and magnetohydrodynamic dynamos. Magnetic fields are also believed to control accretion in systems like protostellar disks and around supermassive black holes found in the center of most galaxies; plasma experiments are now studying the accretion in Keplerian flows and the formation of jets that are often associated with accretion. Another example, understanding the turbulent dynamics of exploding stars and the extreme conditions around black holes requires sophisticated yet very difficult multi-dimensional radiative hydrodynamic and radiative kinetic simulations that can be tested in the laboratory with high energy density (HED) experiments (cf. Chapter 2). Understanding turbulent hydrodynamics is also necessary to understand the mysteries behind the plasma energetics of our nearest star: the Sun. Through complicated nonlinear processes the sun emits a stream of energetic charged particles, the solar wind. This changing wind shapes our terrestrial plasma environment, deforming the magnetic field of the Earth. The Sun's energy often appears in violent outward bursts of plasma creating space weather and affecting humanity, potentially severely, both on Earth and in the space plasma environment surrounding Earth. Understanding the formation mechanisms of collisionless shocks, the generation of magnetic fields in the Universe, and the influence of magnetic fields on the flow and conduction of plasma energy, mass, and momentum is being informed by important experiments in the laboratory, careful numerical simulation, and data from solar and astrophysical observatories. A third example is the understanding of magnetic reconnection which rearranges magnetic fields in plasma leading to dramatic and often impulsive restructuring of plasma energy and flow. Fortunately, rigorous theoretical scale transformations have been worked out to be able properly relate frontier plasma experiments to relevant observations found in our solar system, in stars, and throughout the Universe. These are just a few examples of the many fundamental scientific opportunities for active connections between laboratory plasma experiments, numerical simulations, and astrophysical and planetary observatories revealing the energetics of the plasma universe.

Scientific and Technical Challenges

The challenge and opportunity for frontier plasma science over the next decade is to help answer several overarching questions in our efforts to understand the energetics of the plasma universe:

- *What is the origin of magnetic fields in the universe, from planetary dynamos, to stellar flares and winds, up to galactic jets and relic shocks? And, how do these magnetic fields regulate the transport of heat, particles, and momentum from nature's sources of energy sources, like a stars and galaxies?*
- *How can laboratory experiments, spacecraft measurements and astronomical observations uncover the fundamental acceleration mechanisms? How do energetic particles modify, and even regulate, their environments? And, what are the power sources and mechanisms for the acceleration of cosmic rays?*
- *How and why is energy in the universe partitioned into various forms (kinetic, magnetic, turbulent)? And, how does nature couple energy from one form to another, creating extreme particle acceleration in plasmas and beautiful self-organized structures, in apparent defiance of usual thermodynamics?*

Under the heading *Understanding the Energetics of the Plasma Universe*, a common theme unifies these questions: understanding the transformation of energy between forms and across scales. Because these transformations often occur in ionized radiant matter, the physics of the pervasive plasma state is fundamental. Through collective dynamics of plasma and the long-range interactions caused by plasma currents and magnetic fields, the energetics of plasma is strongly interconnected. These interconnections between physical processes are striking and important, and they are illustrated in Fig. 2. Figure 2 represents the inherent feedback and correlations that link sources of energy and particles through self-generated forces and collective instabilities causing highly complex phenomena: the formation of magnetic fields, self-organization, turbulence, and plasma flow that are the natural characteristics of the plasma universe.

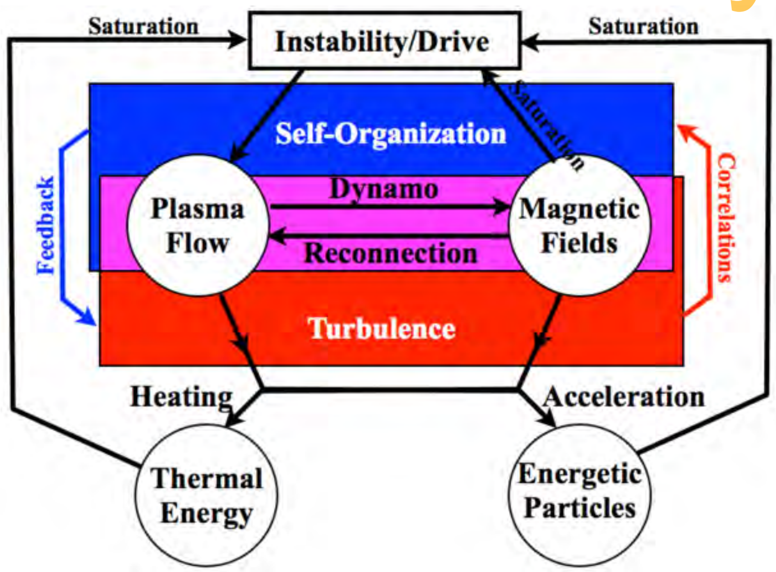


Fig. 2. Connections between the different components that drive the energetics of the universe.

In the following sections, we first discuss the transformation of energy from flows to magnetic fields, an example of which is the turbulent dynamo process, in Sec. A. In Sec. B, we describe the transformation of magnetic field energy to flows and energetic particles through the reconnection process. Highlights from the dynamics and energetics of plasma particle acceleration are described in Sec. C. Then we consider the transfer of energy between scales in the context of the forward and inverse cascade processes and dissipation of evolving turbulence in Sec. D. We examine the generation of coherent structures from a turbulent flow via self-organization in Sec. E, then describe the transport of plasma particles, momentum, and energy through space in Sec. F. We conclude our chapter on the *Energetics of the Plasma Universe* with a discussion of the Research Needs for the field.

A. Energy Transformation: Flow to Magnetic Field (Dynamos)

Plasmas constitute the majority of visible matter in the Universe. Within the plasma universe, the magnetic field, and the generation of magnetic fields, play a vital role in many fundamental astrophysical processes. These include star and planet formation, stellar evolution, jet formation, and particle acceleration. Magnetic fields may even be responsible for life itself by shielding the Earth from harmful cosmic radiation, establishing the chirality of DNA, and protecting the Earth's atmosphere from the Sun's solar wind.

The observed strength and structure of magnetic fields in the present-day Universe is set by the *dynamo process*, by which mechanical energy is converted into magnetic energy and sustained against dissipation. In the majority of astrophysical settings — stars, galaxies, accretion disks, jets, galaxy clusters, and the interstellar medium — the energy content of the magnetic fields is comparable to that of the plasma motions. Understanding how this is achieved and maintained is a defining task of modern plasma physics research. There are also reasons to study dynamos that are closer to home: the solar dynamo underlies solar magnetic activity, which drives space weather and affects the Earth's climate.

Astrophysical dynamo models are almost always *flow-dominated*: the main energy reservoir being the kinetic energy of the flowing plasma. This is in stark contrast with the majority of laboratory plasma experiments, which are often magnetically dominated. In some systems – accretion flows, disk galaxies, and some stars – differential rotation is the dominant form of this kinetic energy. In other systems, small-scale turbulence provides additional amplification, which in turn allows the large-scale field to regenerate. The sources of this turbulence are myriad: convection, supernovae, cosmological flows, centrifugal flows, and even plasma instabilities facilitated by the magnetic field itself. Astrophysical dynamos are also *self-organizing*, in that the complex geometry, boundaries, interfaces, and inhomogeneities across a wide range of scales conspire to enable the emergence of large-scale coherence.

The scientific challenge here is broad; namely, to explain the emergence of large-scale coherence, which often occurs in surprising ways. The classic example of this is the well-known 22-year solar cycle, for which no predictive theory exists. Like many of the questions at the frontier of plasma physics, scientists aim to understand highly nonlinear interactions by combining ingenuity and systematic study to stitch together the many linked processes, shown in Fig. 2, to achieve a predictive theory.

There is no substitute for being able to create a plasma in a laboratory, subject it to stirring, differential rotation, and magnetic fields, and measure its response. For dynamo studies, one must produce highly conductive, flow-dominated plasma that endures and sustains its magnetic fields for times much longer than those required for resistance to the driven currents to dissipate the initial magnetic fields. This frontier regime is novel for laboratory study. Flow-dominated plasmas have been created in HEDP research, but as yet are too resistive and short lived. During the next 10 years, it appears possible for plasma experiments (both magnetically confined and HEDP-based) to produce and observe the kinematic dynamo and the small-scale dynamo, and to study their dependence upon plasma properties. Systems mimicking the centrifugal launching of winds or jets also appear achievable, enabling novel investigations of magnetic linking.

On the theoretical side, extended magnetofluid models have revealed preservation of generalized fluxes and concomitant helicities, thereby opening the study topological plasma properties. On the computational side a major frontier for the next decade lies in *System and multi-scale, multi-physics modeling* and *kinetic modeling of plasma dynamos*. An essential element of both will be a serious validation effort to compare experiment with simulations and theory, especially with regards to sub-grid models and interface dynamics. To enable this, flexible, publicly available, numerical codes are needed that allow the user to switch between relevant physical models and boundary conditions, and adequate computational resources are needed.

B. Energy Transformation: Magnetic Field to Flow (Reconnection)

Magnetic reconnection is the driver of explosive restructuring events of plasma found in nature and in laboratory experiments. Reconnection degrades energy confinement in magnetic bottles by driving disruptions and converts magnetic energy to particle energy in other laboratory systems. Magnetic reconnection drives flares on the Sun that produce coronal mass ejections, which control space weather and negatively impact communications, electrical grids and the safety of astronauts. In the broader universe, reconnection drives flares in stars and pulsar magnetospheres, facilitates accretion around black holes, accelerates particles in gamma-ray bursts and astrophysical jets, and might contribute to the highest energy cosmic rays, as illustrated in the selection of relevant objects in the universe in Fig. 3, where reconnection is thought to be one of the sources of the energy driving these phenomena.

Key open issues for reconnection include the details of how magnetic field line topologies change, what controls the onset and rate of reconnection, how the magnetic energy energizes the particles and why energetic-particle spectra are typically power laws, and the relation between two- and three-dimensional behavior. Further issues arising under extreme conditions include how relativistic effects, radiation or pair-production impact the dynamics.

Much is happening in this area but more progress is possible. The recent launch of the four-satellite magnetospheric multi-scale mission (MMS) is now producing unprecedented resolution of the structure and energetics of reconnection events, allowing plasma scientists to monitor the transport of particles and energy throughout the magnetosphere protecting our Earth. This year, NASA's Juno mission will arrive at Jupiter to help understand the origins of our solar system and to understand the energetics of the Jovian magnetosphere, especially the transport of particles and energy into the polar aurora. In two years, the Solar Probe Plus (SPP) mission will be launched with the goal of traveling to within 10 solar radii of the sun to explore how turbulence and reconnection heats the corona to drive the solar wind. The Fermi gamma-ray telescope is the first gamma-ray observatory to measure the entire sky each day, and Fermi also measures the energetics of reconnection by measuring the gamma-ray spectra from solar flares. Even with these many observatories, significant challenges must be overcome to understand reconnection in the exotic regimes of many astrophysical objects and in the magnetized energetic plasma in our solar system.

Emerging laboratory experimental facilities to explore reconnection include the NSF-funded FLARE and TREX experiments. These facilities will complement MMS in providing key data on the structure of the reconnection-driven current layers but with the ability to vary ambient parameters and therefore understand the different regimes of reconnection. An important goal of these experiments is to identify the conditions under which reconnecting systems transition from single to multiple reconnection sites, a topic of great importance for understanding both the rate of reconnection and the mechanisms for particle energy gain. Experiments in high-power laser facilities have the potential to address relativistic, radiative, and pair-plasma regimes. They will provide key input to the astrophysical theory and modeling effort beyond the photon signatures that characterize observations.

Theory and modeling have continued to predict how reconnection works, identify signatures that can be tested with observations and explain what is actually being measured in the laboratory and space. Reconnection simulations in 2D systems are now well developed although the separation between electron, ion and macro-scales remains a significant challenge. The scale separations in the case of solar flares are well beyond the capability of any computer on the horizon. Thus, new ideas for how to model reconnection and particle acceleration in very large systems must be a key goal of the modeling effort. Simulations of reconnection in 3D systems have begun, although achieving an adequate separation of scales is a challenge.

Figure 3. Examples of regions where magnetic reconnection occurs in the Universe include solar-wind interactions with the Earth's magnetosphere, gigantic solar flares and coronal mass ejections from the Sun, accretion disks, astrophysical jets, and distant pulsars.

C. Acceleration of High Energy Particles in Plasma

Astrophysical and space plasmas from galaxy clusters to the Earth's magnetosphere are permeated by high-energy particles. In astrophysics these particles are known as cosmic rays. In planetary magnetospheres, these are the energetic radiation belt particles that threaten spacecraft and are the key component of space weather. In the Milky Way, cosmic rays represent only about 10^{-9} of interstellar particles, but carry as much energy as the thermal ambient plasma. Energetic particles affect their environments: they drive interstellar chemistry, excite waves and instabilities, support thermal gas against gravitational collapse, and may even drive galactic winds and impact galactic dynamos. The most energetic cosmic rays, those with energies above

10^{18} eV, are not magnetically confined to the Galaxy and probably originate outside of it. While the average flux of cosmic rays at the Earth is believed to be relatively constant over the age of the Solar System, TeV flares from active galaxies and our own Crab Nebula demonstrate that particle energization can be an impulsive process. The montage of figures below in Fig. 4 illustrate some aspects of particle energization in astrophysics.

The remarkable impact of energetic particles is encapsulated by two questions:

- *How does nature extract extremely energetic particles, called non-thermal tails, from plasmas, in apparent defiance of thermodynamics?*
- *How do energetic particles modify, and even regulate, their environments?*

There is substantial evidence from both nature and the laboratory that particles are accelerated by shocks, by turbulence, and by magnetic reconnection, sometimes operating within the same system. Theory and computation have identified specific mechanisms, such as wave-particle resonances and Fermi reflection that drive particle energy gain. How energetic particles react back on their drivers, limiting energy gain, remains an open topic. In both the physics and astronomy communities interest in cosmic rays and more broadly the impulsive sources of energetic particles such as seen in flares and Gamma Ray Bursts is strong. Specifically, the photon spectra from impulsive events are important windows into the dynamics of these remote systems so the number of radio telescopes, γ-ray telescopes, and direct detectors currently operating or planned is substantial. The recent detection of PeV neutrinos opens a new window on high-energy hadronic processes in the cosmos.

A strong, multifaceted program in energetic particle research would encompass several elements:

- Creating and diagnosing high Mach number, magnetized, collisionless shocks in the laboratory that can be compared with *in situ* satellite observations and simulations. Despite the success of the theory in explaining observations covering a broad range of astrophysical phenomena, from interplanetary and supernova remnant shocks to radio galaxies, a complete understanding of the mechanism is still lacking. Perhaps the biggest uncertainty in the theory of shock acceleration is how and in what quantity particles are lifted from the thermal background and injected into the acceleration process – proposed experiments could address this issue. The ability to successfully perform experiments to study diffusive shock acceleration in controlled laboratory environments would represent a major advance in the field.
- Establishing a comprehensive theoretical/modeling effort that would include kinetic simulations of shocks, reconnection, and turbulence which span particle to fluid scales and run long enough to capture the growth and saturation of important instabilities and the acceleration of particles from thermal to relativistic energies.

Working closely with astronomers and space plasma physicists to create observational diagnostics of particle populations and photon spectra that can test the theories and the results of simulations.

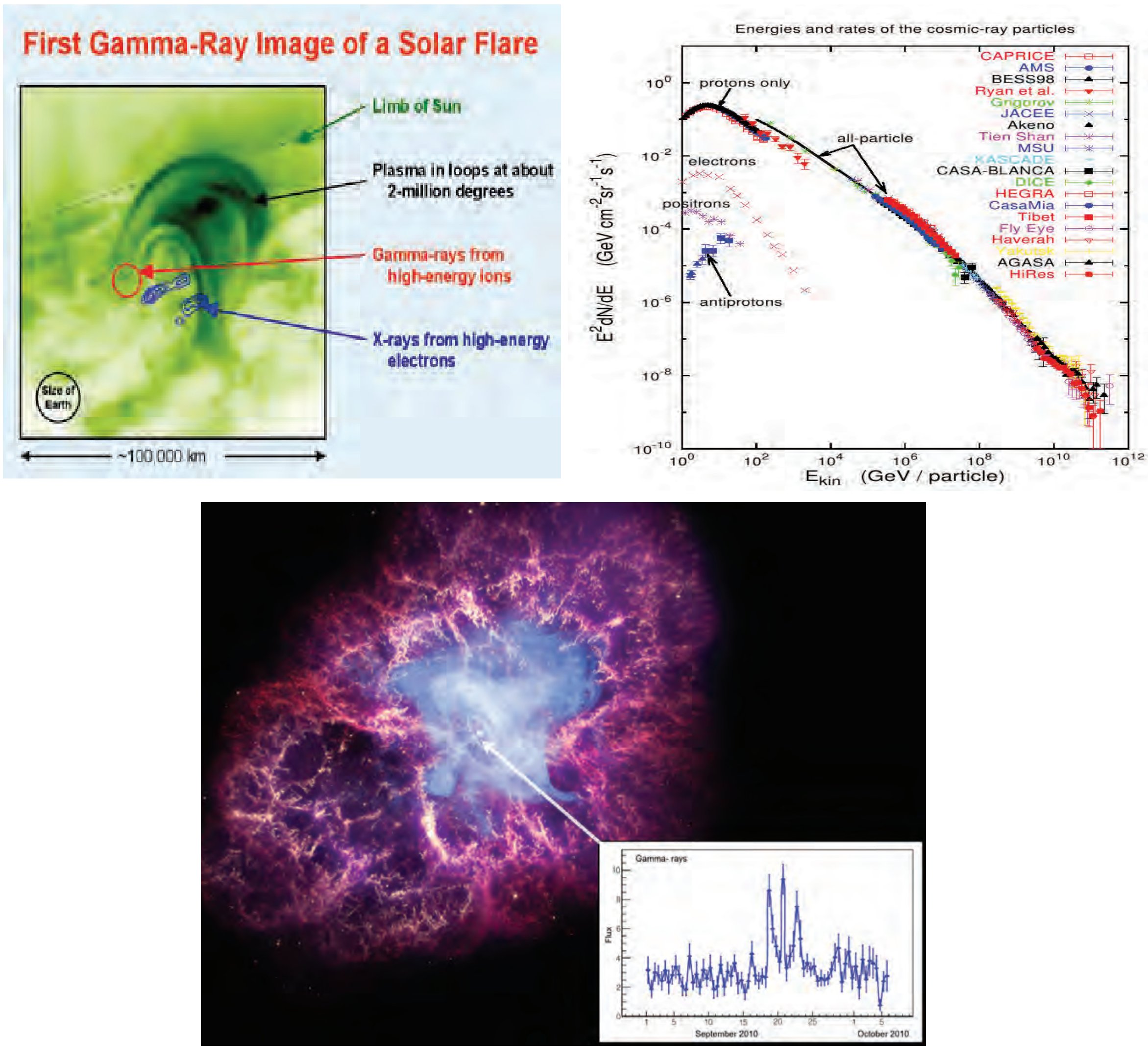


Figure 4. Examples of particle acceleration. Top left: Gamma-ray and microwave emission from a solar flare. Top right: The cosmic ray spectrum detected at Earth. Bottom: Gamma-ray flare from the Crab Nebula.

D. Turbulent Cascade and Dissipation

As with reconnection and particle acceleration in plasma, turbulence also mediates the conversion of the energy of plasma flows and magnetic fields at large scales to plasma heat or another form of particle energization. In a typical turbulent system, an energy source excites an instability, or other driving mechanism, that injects energy into electromagnetic field and plasma velocity and density fluctuations that nonlinearly couple dynamics at one length scale to another. These fluctuations grow in amplitude until complex plasma interactions become strong enough to yield a significant transfer of plasma energy to collective fluctuations. Successive nonlinear interactions proceed to support a continuous cascade of the turbulent fluctuation energy. In large systems like the solar wind or the magnetosphere of Jupiter, large scale flows and fluctuations cascade down to smaller and smaller scales where some physical mechanism can remove energy from the small-scale flows and magnetic fields and convert turbulent energy into thermal heat of the plasma species. In some strongly magnetized systems, like many magnetized plasma experiments, the turbulent fluctuations cause an “inverse cascade”, where turbulent flows combine to create larger and larger eddies that ultimately reach the scale of the whole plasma, like the zonal flows that appear in magnetic fusion experiments and the rotating bands in Jupiter’s atmosphere.

In a hydrodynamic system, the small-scale dissipation is accomplished by viscosity; in a plasma, additional mechanisms exist by which the energy can be thermalized or radiated away. The turbulent fluctuations at all scales in the cascade can also enhance the transport of mass, momentum, and energy along gradients in the system, effectively cooling hot regions of the plasma and enhancing mixing (see Sec. F), as illustrated in Fig. 5. In addition, the naturally arising correlations of the turbulent fluctuations often lead to coherent structures that can alter the macroscopic behavior of the system (see Sec. E). The dissipation of the turbulent fluctuations and consequent plasma heating also impacts the long-term evolution of the system. The nature of the turbulent cascade and dissipation depends on the scale and mechanism of the energy injection, whether the plasma is magnetized or unmagnetized, collisional or collisionless, and other plasma parameters.

- *The key scientific question is, how does one understand the physical processes governing the nonlinear turbulent cascade and the dissipation of the turbulent fluctuations and resulting plasma heating, with the ultimate goal to develop the capability to predict the evolution of any turbulent plasma system?*

Developing a fundamental understanding of the turbulent cascade and dissipation will enable transformative progress across a tremendous range of scientific topics. Identifying the physical mechanisms that lead to plasma heating will help to answer long-standing astrophysical questions, such as why the solar corona is nearly a thousand times hotter than the surface of the Sun. To interpret observations of stellar mass black holes and the supermassive black hole at the center of the Milky Way, it is necessary to understand how turbulence mediates the conversion of the gravitational energy released by in-falling material into plasma heat, which dictates the emission radiation that is observed at the Earth. Turbulence enhances the loss of energy and particles from magnetic fusion devices, limiting their efficiency, but also is responsible for the natural emergence of zonal flows that serve to suppress turbulent transport. The mixing of materials in turbulent supernova explosions governs the distribution of high atomic number elements throughout the universe, the same heavy elements that make up the planets and our own human bodies. In inertial confinement fusion, unwanted mixing of material from the fuel capsule shell disrupts the hot-spot formation, inhibiting the fusion reactions. In magnetic confinement fusion, understanding the turbulent transport of energy, particles and momentum remains a critical challenge of the world’s research effort.

Exciting new developments in observational and experimental capabilities and steady advances in supercomputing resources have brought us to the brink of making major progress in our understanding of the turbulent cascade and dissipation.

Existing (Van Allen Probes, THEMIS, MMS), upcoming (Juno, Solar Orbiter, and Solar Probe Plus), and proposed (THOR and EDDIE) spacecraft missions will explore the turbulent dynamics at the small dissipative scales in the weakly collisional solar wind

SIDEBAR BOX:

Spacecraft Missions

The current Magnetospheric MultiScale (MMS) mission provides multi-point, high cadence measurements of electromagnetic field and particle velocity distribution fluctuations. The upcoming Solar Probe Plus and Solar Orbiter missions will delve into the near-sun environment, as yet unexplored with modern measurement capabilities. Finally, proposed missions, such as the Turbulent Heating Observer (THOR) and ElectroDynamics and Dissipation Interplanetary Explorer (EDDIE), aim to directly target with unprecedented measurement resolution the characteristic ion and electron scales at which the dissipation mechanisms operate.

and solar corona and the strongly magnetized plasma within magnetospheres. These observatories will provide significant opportunities to confront our theoretical predictions and numerical calculations with *in situ* measurements of a weakly collisional, turbulent plasma.

Related to these new space-based observatories is the development of well-diagnosed, experimental laboratory facilities that can generate a collisionless, turbulent magnetized plasma capable of exploring a wide range of plasma pressure and density. When the plasma pressure reaches or exceeds the magnetic pressure, called unity plasma beta, the ion inertial and gyro scales become equivalent, and frontier investigations of the kinetic dissipation mechanisms under controlled laboratory conditions become possible for the first time. Direct measurements of the turbulent dissipation in the weakly collisional solar wind will be possible using both laboratory facilities and small multi-spacecraft missions to directly target, with unprecedented resolution, measurements of the electromagnetic fields and plasma velocity distributions on the characteristic ion and electron scales at which the dissipation mechanisms operate.

Improving our capabilities for numerical simulation of kinetic plasma turbulence will require continued investment in national supercomputing facilities and the development of partnerships among computational scientists, applied mathematicians, and professional software developers to leverage the power of new and better algorithms running on modern computer architectures. Finally, a specific theoretical effort focused on developing and refining the kinetic theory of plasma turbulence will be essential to maximize the scientific return from the substantial investment in spacecraft instrumentation, experimental facilities, and numerical resources.

Advances in numerical algorithms and the development of sophisticated kinetic plasma simulation codes, coupled with steady improvements in computer architectures, now enable the numerical simulation of the 3D turbulent dynamics over the multiple-scale problem (covering both ion and electron scales in a single simulation) with the inclusion of kinetic effects. Complementary to these ground-breaking kinetic simulations is the effort to apply kinetic plasma theory to illuminate the physical mechanisms at play in the dissipation of weakly collisional plasma turbulence.

For unmagnetized plasma turbulence, laser facilities are now approaching the ability to drive sufficiently long pulses to excite and drive a specific instability, reach nonlinear saturation, and diagnose the transition to turbulence. The overall readiness of the community to tackle this grand challenge is illustrated by a recent investigation of the nonlinear interaction underlying the turbulent cascade of energy to small scales in a magnetized plasma, in which the nonlinear mechanism was analytically predicted, numerically validated using kinetic numerical simulations, and experimentally verified in the laboratory at the UCLA Large Plasma Device.

As another example, laser-driven experiments have been fielded which recreate scaled versions of supernova blast-wave-induced mixing between stellar layers, experiments that can be used, along with focused theoretical and computational efforts, to directly address important astrophysical problems (cf. Chapter 2). Exploring long-pulse driving at laser facilities and introducing a background magnetic field will also enable the study of new regimes in high-energy-density plasma turbulence. The increasing capabilities of our major laser facilities will expand the regimes of physics these scaled experiments can investigate. Within the next decade, it is likely that the critical pathways to plasma heating in kinetic turbulence will be definitively identified, opening the door to the development of a predictive capability for the heating of turbulent plasma systems.

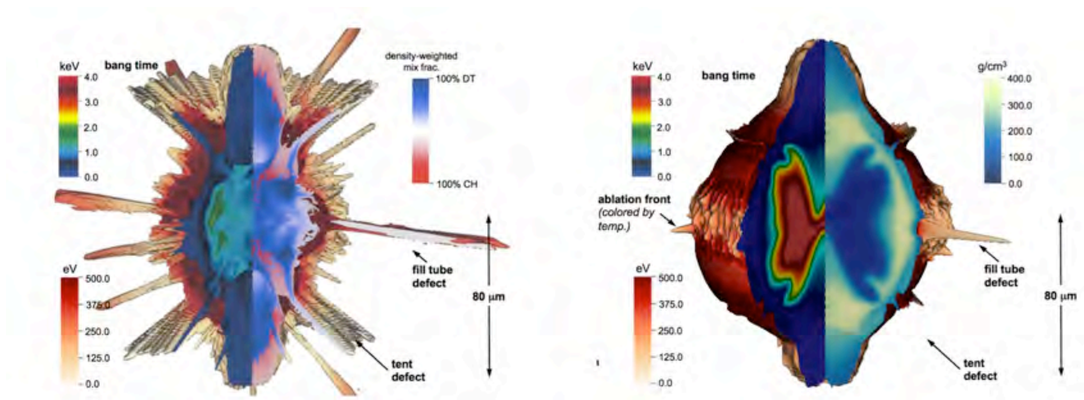


Figure 5. (a) 3D post-shot simulation of a highly mixed, highly unstable ICF capsule implosion on NIF, based on a high convergence, high density, low adiabat design. (b). 3D post-shot simulation of a largely unmixed "clean", much less unstable ICF capsule implosion on NIF, based on a somewhat lower convergence, lower peak density, higher adiabat design. This shows one avenue to understanding an controlling turbulence by controlling the adiabat in ICF implosions. Maintaining a "clean" (unmixed) DT hot spot is of paramount importance for the achievement of ignition and gain. [Courtesy D. Clark].

E. Self-Organization: Generation of Coherent Structures from Turbulent Flow

Turbulence is best known for transferring energy in fluid flow and magnetic fields from large spatial scales to smaller scales, but its nonlinear nature also allows an inverse cascade where energy at small scales is transferred through the turbulence and accumulates at large scale, even defining the maximal extent of the system in some cases. Examples of the generation of coherent structures in astrophysical and terrestrial plasmas are numerous. The formation of current sheets in turbulence and plasmoids in magnetic reconnection rely on this coherent interaction over multiple length scales. Astrophysical jets driven by compact objects in the core of a galaxy can rise to super-galactic scale, forming some of largest coherent structures in the universe. Zonal flows, i.e., narrow regions of self-generated uniform flow embedded within the turbulence, appear in the convection zone of the Sun and are essential to the solar dynamo process. Indeed, understanding the origin of large-scale magnetic flux (in addition to magnetic energy) in a variety of astrophysical settings relates fundamentally to coherent structure. Large-scale convective flows in magnetospheres are sustained by planetary rotation and cause outward mass transport, called "planetary wind", in the gas giants of Saturn and Jupiter. Zonal flows appear spontaneously within magnetically confined plasmas, forming self-generated barriers to the transport of heat, particles, and momentum that might be essential to achieving fusion power on earth. These self-organized flows can appear preferentially as electron current that creates part of the magnetic field that confines and sustains a fusion plasma, as in the reversed field pinch and compact tori configurations.

Understanding the formation of coherent structure in plasmas is a frontier topic in several respects. The ability to observe and measure coherent structures has never been better. Observations of the magnetic structure in the solar corona and wind are being extended to both larger and smaller scales simultaneously. Diagnostics in magnetically confined plasmas are able to resolve the turbulence and coherent structure with increasing fidelity in both spatial and temporal scales. Direct measurement of multi-wave turbulent interactions is one of the surest ways to expose the inherent nonlinear interactions that drive both forward and inverse cascades of plasma flow and magnetic field. Next generation radio observations are even helping to expose magnetic structure at the interstellar and galactic scales.

A variety of observational and experimental platforms already exist that reveal coherent structure in both astrophysical settings and terrestrial laboratories for basic and fusion plasma science. Critical experimental and observational research needs include diagnostic and measurement capabilities that resolve turbulence at multiple scales at the same time and location. These must also span the global scale sufficiently well to observe the fullest extent of self-organized flows and field. New experiments and observational platforms should build in these capabilities. There is also a need for strong coordination between experiment, observation, and theory and modeling. The capability for computation that spans the system size to dissipation scale with relevant plasma parameters has never been greater, but this remains extremely challenging and resource consuming. The measurement and observational tasks are similarly demanding. A dialog that recognizes the strengths and limitations in both the experimental/observational and theoretical/computational realms is essential to facilitate efficient progress.

F. Transport of Plasma Particles, Momentum and Energy Through Space

Plasmas occur in environments with spatially distinct sources and sinks of particles, momentum and/or heat. These localized sources create spatial gradients and excite macro-scale fluid and micro-scale kinetic instabilities that grow to large amplitudes over a range of spatiotemporal scales. Disturbances with different spatiotemporal scales nonlinearly interact, resulting in the formation of a broad spectrum of disturbances in the plasma conditions. Self-organization associated with symmetry-breaking processes (e.g. shear-flow amplification by turbulent Reynolds stresses, magnetic field formation via dynamo action) can then have a profound impact on rate of transport and thus on development of system-scale behavior.

In magnetized plasmas, the development of turbulent-driven sheared plasma flows results in the formation of structure on an intermediate, or mesoscale, between the turbulent eddy scales and the system scales. As the turbulence and organized flows develop, the plasma stays close to the conditions needed for the onset of instability that drives the turbulence. The existence of multiple spatial and temporal transport scales results in complex dynamical behavior such as front generation and propagation, transport barrier formation and bifurcation, and rapid nonlocal transport responses triggered by spatiotemporally localized disturbances.

In inertial confinement fusion, the material transport and mixing that the turbulent fluctuations produce are believed to play a role in disrupting the hot-spot formation with cold material and inhibiting the fusion reactions. This mixing is thought to be powered by the interaction of the strong shock waves launched by the laser interacting with the spectrum of roughness and imperfections on the target capsule surface. Experiments are underway to study the evolution of instabilities mode by mode and mechanism by mechanism, taking advantage of large facilities that can continuously drive the flow for long enough timescales to allow instabilities to develop from their initial linear state all the way to fully developed turbulence.

Understanding the physics underlying the development of turbulence and formation of self-organized structures and processes in the system is critical for understanding the large-scale, slow timescale evolution of the system. For example, in the laboratory, these dynamics may play an important role in determining the rate of heat loss in a fusion system, the threshold for the onset of transitions into improved states of confinement, and the spontaneous generation of strong plasma rotation processes that can impact the macrostability of the system. Thus, this physics is directly linked to predicting how such a fusion energy system must be designed to achieve energy production.

These processes also have important implications for astrophysical systems. In stars, similar flow organization processes are thought to play in the formation of the thin solar tachocline region that separates the deeper radiative zone from the outer convection zone, and may impact the magnetic dynamo thought to be operative in the convection zone. The dynamic interaction between the sheared flow at the tachocline and the dynamo mechanism can then give rise to buoyancy driven convection which then acts to transport heat and magnetic flux upwards to the stellar surface. In accretion disks, these self-organization processes would work to corrugate the shear rate and mass density distribution in accretion disks, thereby initiating segregation of the disk into rings regulating the rate of turbulent Reynolds-stress mediated angular momentum transport that leads to mass accretion on the central mass. Such processes, in turn, can then impact subsequent formation of planetismals and protostellar objects in newly formed star systems, or control the rate of accretion, disk heating, and radiation generation in disks surrounding dense compact objects such as neutron stars and black holes.

Self-organization processes such as turbulent flow generation or dynamo action involve the nonlinear transfer of energy across spatiotemporal scales and the formation of structures at the intermediate scale between the turbulence and system scales. These processes can transform energy from one form into another (e.g. kinetic energy to magnetic field energy in the case of dynamos).

Within a number of scientifically and technologically interesting plasma systems, it is crucial to obtain a deep understanding of the interaction and interplay between plasma turbulence, self-organization, turbulent transport and subsequent system scale behavior. Scientific progress requires an approach that links theory, multi-point measurements, and state-of-the-art computation.

Theory provides guidance for identifying relevant instabilities, nonlinear turbulence saturation mechanisms, and self-organization processes for a wide range of laboratory and astrophysical plasma systems. Computational techniques, model approaches and technologies have now advanced to the point where turbulence simulations in relevant conditions and configurations are beginning to be carried out. Finally, recent advances in diagnostics, data acquisition technology, and data analysis techniques now permit development of unprecedented detailed measurements so one can begin to address the underlying physics of plasma transport in configuration space.

Multi-point, multi-field measurements of turbulence provide the relevant turbulent fluxes (e.g. particle, momentum and heat flux for fluid-like processes) through space; together with background measurements these can provide flux-gradient relationships (or the equivalent for fundamental kinetically driven processes) which can be used to build reduced models that can then explore a wide range of parametric conditions. The highly nonlinear nature of the transport can often lead to distinctly different regions in parameter space that are bounded by transitions and bifurcations that need to be clearly identified and understood.

The combination of theory and modern computation guides the design and interpretation of relevant multipoint, multi-field measurements used to directly measure these nonlinear processes in suitably designed experiments. Many of these experiments exist today or can be conducted cost-effectively in new facilities at the intermediate scale. In some cases, such measurements are already feasible; in others, they will require development of suitably resolved field measurements in the plasma. These studies can also be carried out using synthetic, digital versions of the diagnostics in the analysis of results from turbulence simulations. In this manner, a direct comparison of the relevant physics, using relevant observables and analysis techniques can be made. To the extent possible these approaches should be supported and used in existing facilities; this also requires a careful coordination and focusing of theory, experiment and computation together – approaches that historically have not often worked hand-in-hand. In some cases, the physics problems of interest may require either new diagnostics, simulations, or experimental facilities.

Research needs

Progress in laboratory measurements, satellite observations, and scientific computing has opened the possibility of achieving one of the most important challenges of plasma physics: understanding the transport and transformation of energy by plasma turbulence across an extreme range of scales. Today, laboratory physicists are able to design experiments capable of creating plasmas across an enormous range of normalized pressure (β), normalized flow speed (M_A), normalized collisionality (R_M), and normalized size (ρ*, λ*). Sophisticated diagnostics can now be combined to detect both large-scale plasma structures and small-scale fluctuations. And computational tools can be used to model, and partially understand, the turbulent processes that occur at the enormous scales that characterize astrophysical plasma processes, the plasma transport within our solar system, and related processes that can occur at large laboratory facilities for the scientific study of fusion energy production, at intermediate scale facilities for controlled studies of plasma turbulent processes, and at national facilities capable of exploring the physics of high energy density plasmas. At each of these facilities, modern multi-point measurements and imaging can lead to the identification of the critical processes involved with the fundamental transformations of energy within plasmas, plasma heating by way of kinetic turbulence, the plasma dynamo, and the acceleration of plasma particles.

While the ingredients for progress exist, understanding the energetics of the plasma universe will require a coordinated approach that leverages existing know-how and combines research from multiple capabilities. Our workshop did not attempt to specify specific instruments, facilities, or theoretical and computational efforts, but we identified research capabilities, tools, and facilities that are both possible today and will also allow significant progress during the next decade. For a topic so central and broad as turbulence, transport, and energetics, comprehensive progress will be possible only through coordination of multiple diagnostics, multiple facilities, and multiple theoretical and computational efforts. One can identify desirable characteristics of such efforts:

- There is a need for multi-field, multi-point, high-bandwidth diagnostics of turbulent phenomena. Multiple instruments are used to characterize heat, particle, and momentum through space.
- There is a need for system and multi-scale, multi-physics modeling and kinetic modeling of plasma turbulence and transport. A key component of this modeling effort should be a serious validation effort comparing experiment to simulations, especially with regards to sub-grid models and interface dynamics. This requires facilities capable of adjustable parameters that range from the more collisional conditions we can model well to the much more challenging conditions found in highly collisionless astrophysical and space plasmas. Improving our capabilities for numerical simulation of kinetic plasma turbulence will require the continued investment in national supercomputing facilities and the development of partnerships among computational scientists, applied mathematicians, and professional software developers to leverage the power of new and better algorithms running on modern computer architectures.
- There is a need for the creation and exploration of new regimes in the laboratory. As one example, a well-diagnosed, experimental laboratory facility that can generate a collisionless, turbulent plasma whose normalized plasma pressure is near or above unity will enable investigations of the kinetic dissipation mechanisms under controlled laboratory conditions. A worthwhile range of facilities would explore novel regimes in collisionality, pressure, and flow speed, as well as a range of geometries.

- Spacecraft Instrumentation: Direct measurements of the turbulent dissipation in the weakly collisional solar wind will be possible using a small spacecraft mission to directly target, with unprecedented resolution, measurements of the electromagnetic fields and plasma velocity distributions on the characteristic ion and electron scales at which the dissipation mechanisms operate.
- Theory: A concerted effort to apply kinetic plasma theory to understand the nonlinear turbulent dynamics and dissipation in the turbulent, weakly collisional plasma conditions relevant to space and astrophysical plasmas as well as high-temperature fusion plasmas.

Our workshop also recognized another critical need for advancing the broad Frontier of plasma energetics. No single machine, single instrument, or single effort can address the range of phenomena at the Frontier. Additionally, the scientific opportunity for understanding the Frontier of plasma energetics is recognized by multiple agencies: including DOE, NSF, NASA, AFSOR, and ONR. These opportunities motivate a new approach that embraces the capabilities of many our national research facilities are needed and the overlapping mission needs of multiple agencies. This is especially the case for the major national facilities for producing and measuring plasmas in the laboratory for our nation's MFE and IFE missions and also applies to new observational missions from the space and astrophysics communities. With state-of-the art diagnostics and the ability to explore a wide range of fundamental processes, a strong commitment must be made to scientific exploration of the frontier of plasma energetics and for investment in complementary theoretical, numerical, and experimental capabilities.

Chapter 5 The Physics of Disruptive Plasma Technologies

The understanding of novel plasmas has implications beyond the advancement of basic knowledge. With controlled laboratory experiments we learn to form and predict the behavior of short-lived relativistic plasma states that lay the foundation of revolutionary technologies for particle and photon production.

Overview

The complexity of the plasma state of matter ensures that different areas of plasma physics exhibit different readiness levels for technological applications. While some of the areas covered in this report represent fundamental research that is decades away from practical uses, multiple sub-fields have emerged in the past few decades that appear to be ready for immediate technological applications. Broadly speaking, these applications take advantage of unique properties that distinguish plasmas from any other physical medium. Specifically, plasmas (i) are capable of withstanding extremely high electric and magnetic fields without breakdown and (ii) represent a truly regenerative medium that can be reconstructed at negligible cost and at high repetition rate.

In the same way that spectroscopy and experiments with electrical discharges one hundred years ago led to the development of x-ray tubes for medicine, basic research at the frontiers of discovery plasma science now lays the foundation for 21st century technologies by exploiting these two remarkable properties of plasmas. Numerous examples of such technologies are discussed in this chapter. Raman backscatter amplification may generate laser intensities of order 10^{24} W/cm^{-2}. This unprecedented intensity would open new regimes of laser-plasma and laser-solid interactions. The development of plasma-based compact ultra-short X-ray pulses breaks open new frontiers in real-time, high-resolution x-ray imaging and diffraction. A major group of applications is centered on ultra-compact plasma-based accelerators for electrons and ions. These particle beams can be tools for discovery, can be employed to detect concealed contraband for Homeland Security, and can enable more efficient and lower cost medical treatments, such as the non-invasive treatment of cancer with energetic charged particles as opposed to x-rays. Laser-plasma interactions may create novel photonic structures in air, including atmospheric waveguides and gratings, and accelerators. Nanotube arrays irradiated by intense pulses may offer a new path to ultra-high energy density plasmas while another approach builds on advances in Z-pinch technology and techniques.

Scientific and Technical Challenges

These emerging technologies aim to exploit the powerful and controllable interactions that occur between plasmas and electromagnetic fields. Many aspects of the nonlinear interactions of plasma with electromagnetic radiation are not understood. The description and quantitative understanding of the nonlinear interactions between multiple laser pulses in plasmas, many of which are routinely observed in Inertial Confinement Fusion and High-Energy Density Physics experiments (see Chapter 2), is one of the central problems in modern plasmas physics.

The scientific challenges facing the realization of these ideas can be described as aspects of an overarching challenge

- How can efficient interactions between electromagnetic fields and particle motion be established and controlled?

This broad question naturally leads to both fundamental scientific and technical challenges for the different plasma-based technologies:

- How can ultra-high intensity ($I \sim 10^{24}$ W/cm^{-2}) be reached in plasmas? Does Raman compression work in realizable plasmas at high efficiency with focusing pulses?

- What are the limits on the spectral brightness, wavelength, and efficiency of plasma-based x-ray sources?

- What controls the acceleration of particles via collisionless shocks in laser produced plasmas?

- What are the limits to radiation pressure acceleration? Can it be used to accelerate ions to energies of 100's of MeV with lasers beyond the Petawatt level?

- What determines and limits the phase-space characteristics of laser generated particle beams? How can these characteristics (energy spread, peak current, transverse emittance) be tailored for specific applications?

While some of the questions above may have technological limits associated with, e.g., the homogeneity and shot-to-shot jitter of plasma sources and performance characteristics of conventional lasers, most questions above have answers that depend on unexplored areas of laser-plasma interactions and, moreover, the limits may be overcome by ingenuity coupled with understanding of the basic plasma science.

Four plasma-based concepts for technologies that appear to be poised for significant advance over the coming decade are described below. They have in common the exploitation of the remarkable properties of plasmas described above. In particular, we consider (A) compression of ultra-intense laser beams, (B) generation of high-flux high-intensity X-rays, (C) plasma-based accelerators, and (D) plasma photonics.

A. Compression of Ultra-Intense Laser Beams

Plasma-wave laser amplifiers promise to be the enabling technology for extending intensities beyond current limits, however, a more complete understanding of the nonlinear dynamics of plasma waves is required. The technologies used in laser systems currently under construction internationally for accessing intensities of 10^{23} W/cm^2 appear to be fundamentally limited to these intensities. Exceeding focused intensities of 10^{24} W/cm^2 is a grand challenge that will enable tests of quantum electrodynamics in the unexplored low-energy, strong-field regime where signatures for new physics may arise (see Chapter 2). The behavior of matter under such extraordinary conditions is a rich and fascinating subject, not only in its own right in fundamental plasma physics, but for the many potential applications that promise to enrich the natural sciences. The realization of multiple petawatt pulses using parametric amplification in plasmas promises a breakthrough in the current intensity frontier.

High intensity light may be better compressed using plasma rather than material gratings. For picosecond visible light, material gratings are limited to about a joule per square centimeter, requiring huge and impossible gratings to reach the next generation of intensities. However, plasma-based compression occurs efficiently through irradiating plasma by a long pump laser pulse, carrying significant energy, which is then quickly depleted by a nonlinear parametric process in the plasma by a short counter-propagating pulse (Fig.1). Such parametric processes occur in either resonant (Raman) regime, or in the non-resonant (super-radiant) regime. At high power, and micron wavelength, pulses in the range of many picoseconds can be compressed to pulses in the range of many femtoseconds.

Parametric amplification by stimulating plasma waves through the interaction of multiple laser beams has the potential to transfer significant energy from an energetic long-pulse laser to a low energy short-pulse seed over millimeter-scale interactions (Fig. 1). This process takes advantage of the plasma's ability to sustain large amplitude plasma waves, which generate large electric fields over small spatial scales (comparable to the laser wavelength). The large amplitude plasma waves are excited by the electromagnetic beat wave generated by two laser beams. This beat wave locally seeds the growth of the plasmas waves and mediates the transfer of energy from the long-pulse beam to the short pulse seed.

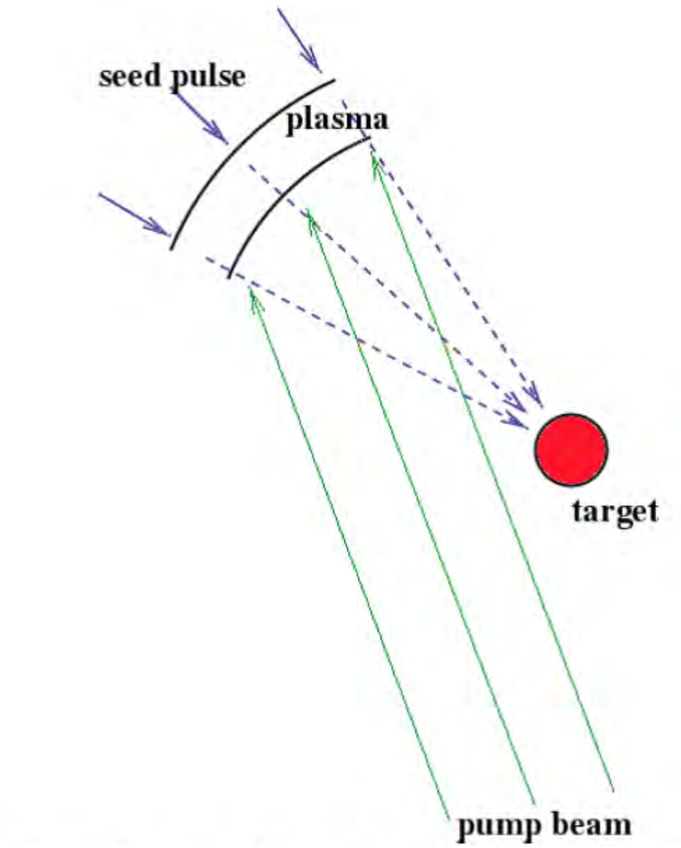


Figure 1. Schematic of Laser Compression in Plasma. [Image from Phys. Rev. Lett. **82**, 4448 (1999).]

Research Needs

The challenges of realizing a practical plasma-wave laser amplifier stem from the interactions of particles and the large amplitude plasma waves. These interactions lead to nonlinearities in the wave and particle dynamics that must be understood and ultimately carefully controlled.

Complex phenomena such as particle trapping in the nonlinear beatwave of two lasers, Dicke-like super-radiant amplification of the seed pulse, and many others need to be understood before this exciting application comes into being. Other challenges in realizing these breakthrough sources include the control of plasma inhomogeneities, the control of the laser through chirping or other techniques, and the control of additional, unwanted effects that occur in competition with the desired effects at high intensity. No showstoppers have yet been identified for realizing this disruptive laser technology. However, much ingenuity will have to be exercised to reach the theoretical limits of this technology. Controlled, diagnosed, and carefully modeled experiments at high power and reaching pulse energy transfer with high efficiency need to be pursued.

B. Generation of High-Flux High-Intensity X-Rays

Many fields of science and technology will benefit from bright high-quality light sources in the extreme ultraviolet (EUV) and x-ray spectral regions. These sources are key enabling tools for nanoscience and nanotechnology, materials science, chemistry, biology, physics, and plasma science. The actual and potential impact of such sources is vast. It includes ultra-high resolution imaging tools for material science, nanotechnology, biology and medical science, mapping the atomic and chemical composition of objects with nanoscale resolution, printing the next generations of computer processors, as well as advances in the search for new energy sources and improved energy storage, and breakthroughs in material sciences (e.g. through recording high temporal resolution snapshots of melting, shock propagation, and other phenomena in materials), chemistry, nuclear physics, and even astrophysics.

While modern third- (synchrotrons) and fourth-generation (free-electron lasers) brilliant x-ray sources are delivering a wealth of new science, the pursuit of compact and considerably less expensive plasma-based “table-top” sources, as well as the sources of spatially coherent, extremely short-pulse x-ray beams that exploit the interaction between plasmas and electromagnetic (laser) fields can lead to an outbreak of new frontiers in real-time, high-resolution x-ray imaging and diffraction. A fundamental and technological challenge is the development of new plasma-based EUV, x-ray, and gamma-ray sources to outperform existing light sources through their spectral and temporal properties including spatial and temporal coherence, power efficiency, compactness, and accessibility.

Plasma-based sources can produce (i) intense coherent soft x-rays through x-ray lasing in dense plasmas, attosecond (and even zeptosecond) pulsed x-rays through high harmonic generation by electrons in solid-density plasmas (coherent synchrotron emission), and free-electron lasing of laser-plasma-accelerated electron bunches in miniature undulators; (ii) bright incoherent/partially-coherent femtosecond x-rays and gamma-rays through line radiation (high average power incoherent EUV/soft x-ray radiation from atomic transitions and unresolved transition arrays in multiply ionized ions), bremsstrahlung, nonlinear Thomson and Compton backscattering, as well as betatron emission from laser-plasma-accelerated electron bunches.

The major challenges of plasma-based x-ray sources include improving their efficiency and spectral brightness, extending their wavelength range to shorter wavelengths, reducing their pulse width, increasing their average power, reducing the shot-to-shot pointing, flux, and spectrum instability, creating new plasma targets and drivers for more efficient and high-repetition-rate ultrashort wavelength radiation generation.

Plasma-based x-ray lasers. Dense plasma columns created by high power lasers or fast electrical discharges provide the opportunity to develop compact table-top sources of bright coherent x-ray laser radiation from population inversion in atomic transitions excited by a variety of atomic mechanisms that include electron impact excitation, collisional recombination, and photoionization. Plasma-based soft x-ray lasers have the advantage of producing bright pulses with a large number of photons per pulse in a compact set up. Currently compact EUV/soft x-ray plasma amplifiers operating in the gain-saturated regime produce pulses with energies ranging from millijoule-level at 47nm to several microjoules at wavelengths at down to 8 nm. Seeding of plasma soft x-ray amplifiers with high harmonic pulses can produce energetic soft x-ray pulses with full spatial and temporal coherence. New compact plasma-based x-ray lasers are already making it possible to visualize nano-scale dynamic phenomena by sequential single-shot imaging, to diagnose very dense plasmas with densities and gradients that are beyond the reach of optical and ultraviolet lasers, to develop analytic nano-probes that can map in 3-D the chemical composition of biological micro-organisms, and to make defect-free patterning of nano-structures. Major goals are to extend these plasma-based table-top lasers to shorter wavelength, increase their repetition rate, average power and efficiency, and reduce their pulse width while making them readily accessible by generating intense coherent beams at the site of the experiment or industrial application. The scientific challenge is to better understand the laser-matter interaction to facilitate the development of new plasma schemes that in combination with new high repetition rate laser driver technology will lead to an increase in the efficiency, power, and wavelength range of these x-ray plasma sources.

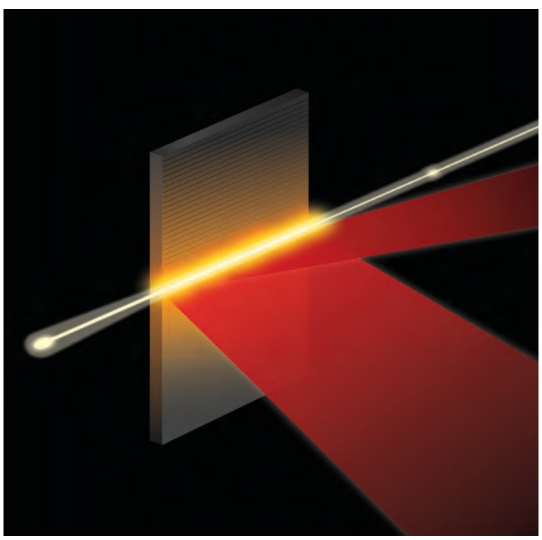


Figure 2. Schematic diagram of the generation of fully coherent soft x-ray laser beam by amplification in an inverted atomic transition in a dense plasma column. The soft x-ray plasma amplifier is generated by irradiation of a solid target with intense optical laser pulses. The amplifier is seeded with a fully coherent seed pulse. [Image from Phys. Rev. Appl. **89**, 05820 (2014).]

High-order harmonic generation by relativistic electrons in overdense plasmas. The introduction of laboratory-scale lasers capable of intensities greater than 10^{18} W/cm^2 has allowed the experimental study of relativistic high-order harmonic generation (HHG) driven by the interaction of intense femtosecond laser beams with solid targets (see Fig. 3). This process supports the production of EUV and x-ray attosecond pulses at potentially greater efficiencies and intensities than what is available from HHG in gases, possibly reaching the intensities useful for x-ray pump-probe spectroscopy. The spectrum of this radiation is generally a decreasing function of frequency, which has been shown experimentally to extend up to at least the 850th harmonic (> 1 keV) of the fundamental.

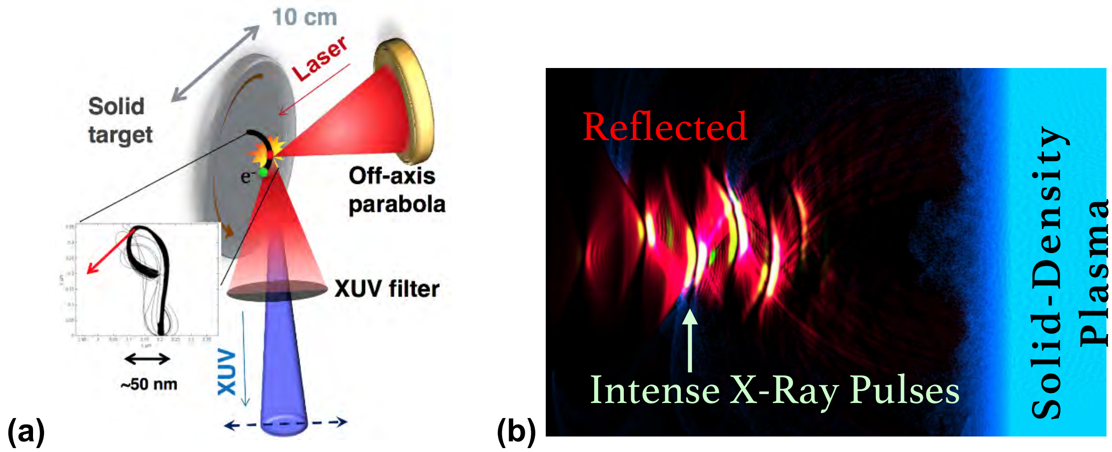


Figure 3. The interaction of relativistic-intensity lasers and dense plasmas can be used to create intense attosecond bursts of extreme ultraviolet and soft-x-ray radiation. (a) schematic of relativistic high-order harmonic generation experiment: a high-intensity laser (red) focused on the surface of a solid (grey disk) creates a solid-density plasma (yellow) with a steep density profile, and accelerates electrons that follow relativistic synchrotron-type trajectories near the target surface and coherently emit attosecond soft x-rays. (b) The process can be numerically studied with particle-in-cell simulations of plasmas, showing intense attosecond soft-x-ray pulses (white peaks) traveling with the laser (red) reflected from the solid-density plasma surface (blue). [Image courtesy of Julia Mikhailova Princeton University.]

X-ray sources from laser-plasma accelerated dense ultra-short electron bunches. Betatron emission produced intrinsically in laser-plasma acceleration from oscillations of the electron bunch results in the generation of broadband femtosecond x-rays (Fig. 4). This emission is regulated by the electron bunch energy and emittance. Detailed understanding of electron acceleration and injection into plasma waves remains an active area of research, with multiple injection scenarios such as ionization injection, self-injection by rapidly evolving plasma waves, and plasma electron injection due to steep density gradients being explored in experiments and simulations. Broadband photon fluxes are in the range of 10^8- 10^{10}ph/shot/SR/keV.

Nonlinear Thomson and Compton scattering. from dense accelerated electron bunches is another promising approach to producing coherent X-ray beams. This approach uses an additional, counter-propagating laser as an electromagnetic wiggler for the electron bunches to produce x-ray and gamma-ray radiation. It may result in higher energy and flux than that of betatron emission. The ongoing research on novel laser/beam geometries, such as utilizing plasma mirrors for reflecting the same laser pulse that accelerates the electrons, shows considerable promise of this approach.

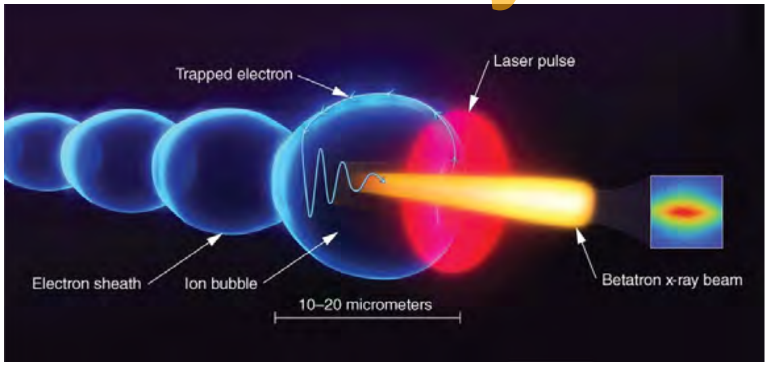


Figure 4. Principle of betatron x-ray emission. Electrons in a wake-field created by the laser in underdense plasma are subject to transverse and longitudinal electrical forces; they are subsequently accelerated and wiggled to produce broadband, synchrotron-like radiation in the keV energy range. From "Laser wakefield accelerator based light sources: potential applications and requirements. [Image from Plasma Phys. Control. Fusion **56,** 084015 (2014)].

C. Plasma-Based Accelerators

For more than eighty years, accelerators of continually increasing energy have been used to probe the fundamental structure of the physical world. This has culminated in the Large Hadron Collider at CERN. With this accelerator, the Higgs boson, the particle that attributes mass to the fundamental particles, was recently discovered in proton–proton collisions. However, although the Standard Model has been incredibly successful at describing the fundamental particles and the forces that act between them, there are still many unexplained phenomena that pose some of the biggest questions in science (e.g., the masses of the fundamental particles, the number of families of quarks and leptons, the division between matter and anti-matter in the universe, dark matter, dark energy, and the existence of a Grand Unification Theory).

That the Standard Model cannot answer all of these questions points towards the need for new theories or phenomena such as Supersymmetry, which unifies the forces at high energies, or extra spatial dimensions, such as required by string theory. It is widely held that such questions will require the next energy frontier accelerator which will collide electrons and positrons at the Teraelectron Volt (TeV) energy scale. As electrons and positrons are point-like, a significantly cleaner interaction is possible than at the LHC – which is a proton collider. Such a future electron–positron collider would therefore have the potential to search for new physics as well as being able to measure to high precision phenomena discovered already at the LHC.

However, even beyond the use of accelerators for particle physics, at lower energies, it is difficult to overstate the impact of accelerators as a tool in modern society. They have had a profound impact, not only as a key enabling tool for the modern scientific edifice, but also for societal applications such as cancer therapy and diagnostic x-ray generation.

Conventional accelerator technology, however, is constrained by limitations on peak particle beam energy and beam intensity. The gradient at which charged particles can be accelerated using present day radiofrequency (RF) or microwave technology is limited to less than 100 MeV/m by RF breakdown as well as by fatigue of the accelerator walls. To reach the TeV scale in a linear accelerator, the length of such machines will therefore be many tens of kilometers. Circular electron colliders are feasible at these energies only at the 100 km scale due to limitations imposed by synchrotron radiation. At such scales it becomes difficult to find a suitably stable geological site and the construction cost of such a machine is estimated to be in the range of tens of billions of dollars. Therefore, a new high-gradient accelerator technology must be developed to ensure that the energy frontier in particle physics can be investigated experimentally within affordable cost, time-scale and space constraints. More compact, cheaper and higher flux accelerator technology for lower energy electron and ion beams would also be a boon to scientific research and technology by enabling, for example, much easier access to synchrotron radiation sources.

Plasmas with densities even a thousand times lower than that of the atmosphere, can sustain accelerating gradients (> 10 GeV/m) which are orders of magnitude larger than those from RF structures. These large fields are due to the collective response of the plasma electrons to the electric field of a laser pulse or of a charged particle beam driver. The plasma can support large amplitude electrostatic waves in the wake of these pulses which have phase velocities near the speed of light – ideal for acceleration of particles to relativistic energies. These wakefields have a longitudinal component able to extract energy from the driver and transfer it to a trailing witness bunch of electrons. The wakes also have transverse electric field components with focusing strength orders of magnitude larger than that of conventional magnets, allowing for beams to remain transversely small over long distances. This combination of large plasma fields and long propagation distances can potentially lead to the energy gain necessary for high-energy physics or other applications, but over much shorter distances than with present technology.

Acceleration of ions using plasmas has proven to be more difficult due to their high mass so that they cannot be efficiently accelerated by wakefields. Consequently there is a significant remaining challenge to develop techniques for proton and ion acceleration to relativistic energies using plasmas.

Laser-driven electron accelerators

The past decade has witnessed developments in laser technology which have enabled the probing and control of matter with unprecedented precision. Many national reports (including several studies by National Academy committees) have recognized the revolutionary and transformational nature of the science enabled by the intensity, coherence and ultra-short pulse duration of these radiation sources. In particular, the criteria for relativistic motion of electrons in the laser focal region ($I \sim 10^{18}$ W/cm^2) is now being exceeded by many orders of magnitude through the development of Petawatt-class lasers which are opening new regimes in physics – including relativistic plasma physics, non-linear QED, laboratory astrophysics, fast-ignition fusion and compact plasma based particle accelerators.

In a laser driven plasma accelerator a laser pulse is focused into a low density plasma consequently exciting a large amplitude plasma wave in its wake which contains electric fields useful for accelerating electrons. If the fields are strong enough, all of the ionized plasma electrons can be removed from the center of the wake, this is known as the "blowout regime". Although the particles are not moving quickly during this period, macroscopically it appears that a "bubble" of charge is moving through the plasma at close to the speed of light (see figure). The bubble is the region cleared of electrons that is thus positively charged, followed by the region where the electrons fall back into the center and is thus negatively charged. This leads to a small area of very strong potential gradient following the laser pulse. It is therefore this "wakefield" that can be used for particle acceleration. A particle injected into the plasma bubble near the high-density area will experience an acceleration that continues as the wakefield travels through the column, until the particle eventually outruns the wakefield.

Single stage acceleration is limited either by the driver beam energy or the driver laser pulse power density (peak and average), and usually requires low density plasmas of 10^{16-18} cm^{-3}. Effective staging of separate acceleration sections – the way to very high final energies – faces numerous challenges with regard to transverse and longitudinal matching and focusing of the beams, and requires even lower densities 10^{14-16} cm^{-3}, and consequently lower acceleration gradients – a regime which has not yet been explored.

An alternative method calls for continuous higher density (of order $10^{20-22}cm^{-3}$) plasma channels that simultaneously accelerate and guide the charged particles. Such systems would require x-ray or particle beam drivers and could produce potential gradients of ~1-10 TV/m. This could be based on the particle channeling acceleration in crystals or regular structures, such as carbon nanotubes. Such techniques are on the border between plasma and solid state physics and their realization requires significant further theoretical and experimental studies.

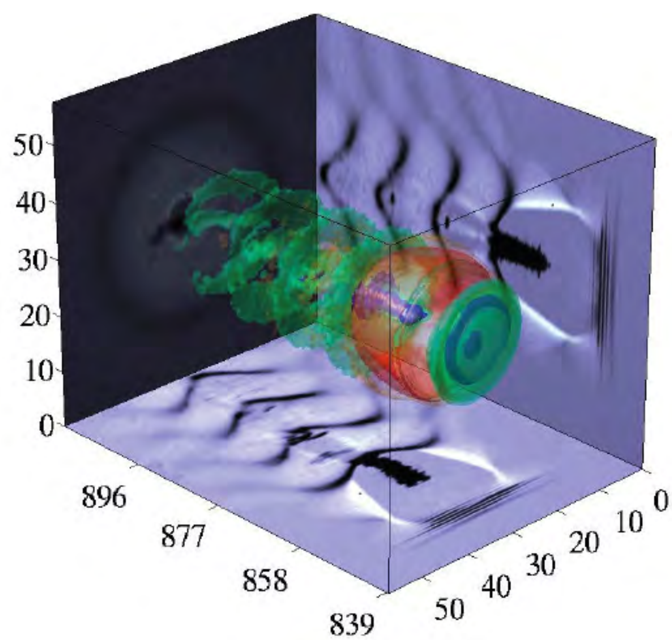


Figure 5. Laser wakefield accelerator: Isocontours of longitudinal current density from an OSIRIS simulation in a moving window showing stable wakefield formation, electron trapping and acceleration. [Image courtesy of Warren Mori of UCLA.]

There are several fundamental scientific questions which confront present research on laser wakefield electron acceleration:

- *What controls the energy spread of laser driven electron beams? Can this be reduced to that needed for a compact Free Electron Laser (DE/E ~ 10^{-3})?*

- *How can focusing and phasing of GeV electron beams be controlled in a plasma for staging of laser wakefield accelerators?*

- *What limits the ultimate electron beam energy for laser wakefield accelerators driven by Multi-Petawatt laser pulses?*

- *What is the source of emittance growth (reduced beam quality) in a laser wakefield accelerator? Can it be controlled during acceleration and propagation through plasma?*

- *How can coherent control (feedback) be used to understand and optimize wakefield acceleration driven by very high repetition rate, high power lasers (> 1kHz)?*

Laser driven ion accelerators

When an intense laser pulse interacts with a thin solid target it instantaneously turns the front surface into dense plasma and produces highly energetic electrons with multi-MeV energies that propagate through the material. These hot electrons produce a strong electrostatic field in a plasma sheath at the back of the target which can accelerate protons up to energies of many tens of MeV and ion beams to hundreds of MeV.

For nanometer scale "ultra-thin" targets in the regime of radiation pressure acceleration (RPA) such sheath acceleration is less important and during the interaction a steady state can be established such that the restoring force due to charge separation of electrons and ions is equalized by the laser radiation pressure. This balance causes a compression of the electron population (which remains opaque for the laser) and subsequently enables the acceleration of ion bunches with almost solid densities, exceeding the ion density achievable from classical sources by many orders of magnitude. The laser energy is then transferred to the accelerated plasma by the relativistic Doppler effect. Momentum is thus imparted directly by the laser to the ions in the target material so that the plasma acts as an accelerating mirror (light sail). Alternatively, monoenergetic proton beams of lower energy can be produced using collisionless shock acceleration of ions in low density gas targets.

All of these mechanisms have been observed experimentally but, due to the ultra-short timescales and small spatial scales, diagnostic techniques in this regime are difficult. There remain important questions with regard to what controls the energy spread, emittance, peak energy and stability of the ion beams produced.

Beams of highly energetic ions have a wide array of potential applications such as compact sources of radioactive isotopes and ion injector sources. Beams of energetic protons can also be used to generate quasi-homogeneous warm dense matter by isochoric heating of solids and can be used as a radiography source to detect and study the dynamics of electric and magnetic fields in high energy density plasmas. There are also possibilities for using beams of laser driven ions for hadron radiation therapy, fusion research, and even for production of elementary particles.

Many of the important applications of energetic ions also require monoenergetic beams that have proven difficult to achieve experimentally. For example, to make a laser-driven ion acceleration system suitable for biomedical applications, especially for radiation therapy related studies, the beam should be accelerated up to 250 MeV for protons or ~ 400 MeV/nucleon for carbon ions. A very well controlled energy spectrum in which energy spread of 1% or less is also critical for such applications.

Fundamental physics questions in laser driven ion acceleration are:

- *At ultra-high intensity (I ~ 10^{24} W/cm^{-2}) can relativistic protons beams (> 1 GeV) be directly generated from the laser plasma interaction? Can ultra-high power lasers be focused to such intensities in a plasma?*

- *What controls the acceleration of particles via collisionless shocks in laser produced plasmas?*

- *What are the limits to radiation pressure acceleration? Can it be used to accelerate ions to energies of 100's of MeV with lasers beyond the Petawatt level?*

- *What determines the emittance and beam quality of a laser generated proton/ion beam in the various acceleration regimes?*

Beam-driven accelerators

A beam-driven wake can be created by sending a relativistic electron bunch into a low density plasma or gas. In some cases, gas is ionized by the electron bunch, so that the electron bunch both creates the plasma and the wake. This requires a short bunch with relatively high charge and strong fields. The high fields of the electron bunch then push the plasma electrons away from the path of the beam, creating a plasma wake which can be used to accelerate a trailing witness bunch similar to laser driven wakefields.

Recent experiments have demonstrated acceleration gradients of more than 50 GV/m. However, the energy gain is limited by the energy carried by the driver as well as by the propagation length of the driver in the plasma (~ 1 m). The electron bunch driver scheme may also require staging similar to that required for laser wakefield acceleration, i.e., the stacking of many > 25 GeV plasma acceleration stages to reach TeV-scale energies per particle.

It has also been proposed to use a very high energy proton bunch to drive the wakefields for beam driven electron acceleration. Proton beams with greater than 100 kJ of energy (the CERN LHC 4 TeV beam) are produced routinely today. Because of their high energy and mass, proton bunches can drive wakefields over much longer plasma lengths than other drivers. They can take a witness bunch to the energy frontier in a single plasma stage as was demonstrated in simulations. This proton-driven scheme therefore greatly simplifies and shortens the accelerator. In addition, because there is no gap between the accelerator stages, this scheme avoids gradient dilution. There are, however, issues for this scheme using present facilities due to the long pulse duration of proton bunches at CERN.

Consequently frontier questions for beam driven plasma accelerators are:

- *What are the physical limits to the energy spread of beams accelerated in a plasma wakefield accelerator?*

- *How can beam driven wakefield accelerators be staged?*

- *How can long pulse proton beam drivers be used to generate a large amplitude wakefield for accelerating electrons?*

- *How can positron beams be controlled and accelerated in a plasma wakefield driven by high energy electron or proton beam?*

Plasmas as compact sources of other particles: positrons, pions and muons

Laser driven electron beams can subsequently be used to produce very compact secondary sources of particles such as positrons, pions and muons if the beams are of sufficiently high energy. Beams of positrons are now routinely generated from the relativistic electrons created in solid targets during laser interactions and have been used to generate relativistic electron positron plasmas. The collection of positrons and subsequent injection into a plasma accelerating structure for use in a electron-positron collider scheme has yet not been addressed. The efficient generation of “table-top” sources of “exotic” particles i.e., pions and muons beams requires high flux GeV electron beams.

Questions confronting researchers developing these laser driven sources are:

- *What limits the flux of relativistic positrons produced by intense lasers and the subsequent production of “confined” relativistic electron positron plasma?*

- *How efficiently can positrons be produced, collected, and then accelerated by laser or beam driven plasma wakes?*

- *What are the limits of pion and muon production from a compact laser driven source?*

Research Needs

The rapid development of laser technology has made possible the generation of very intense and ultra-short bursts of laser light which has inspired the rapidly growing area of high field science aimed at the exploration of a wide range of novel physical processes. In particular, laser acceleration of charged particles is considered to be one of the main scientific research areas for many laser facilities. There are, however, very few lasers that are dedicated exclusively to acceleration research.

Consequently, many new, ultra-high intensity laser facilities are being proposed, are under construction, or are already in operation around the world, indicating a high level of interest for the study of the science in this regime.

For example, there are five new laser facilities under construction in Europe each aiming to operate 10 Petawatt laser systems and there are several more under construction on the scale of a “few” Petawatts. In addition, there are multi-Petawatt lasers under construction in China, Korea and Japan. At present there are no plans for a multi-Petawatt laser facility in the US. Some investment in this area in the US may be required in order remain competitive.

One of the main issues for the practical application of laser accelerators is the requirement of a significant increase in the repetition rate (average power) and “wall-plug” efficiency of the laser drivers. However, high repetition rate also enables a wider range of experiments enabling feedback and coherent control of the plasma waves. Such high repetition rates also allow the use of new diagnostics and enhanced data collection.

The US is already a world leader in beam driven plasma acceleration due to the existing facilities at SLAC and BNL. There are planned upgrades to both of these facilities that will enable continued scientific leadership in this area. In Europe there are longer term plans for proton driven plasma acceleration of electron beams at CERN however there is no corresponding experimental research effort in the US.

D. Plasma Photonics

Plasma Filaments and Plasma Waveguides

High power femtosecond laser propagation in gases combines the fundamental study of high field non-perturbative interactions with atoms, molecules, and plasma with the study of how these effects influence macroscopic beam propagation in a regime of field strengths far from traditional nonlinear optics. Such a beam typically undergoes nonlinear self-focusing collapse and filamentation, developing an on-axis region of high intensity that generates a long track of plasma as it propagates over a range greatly in excess of its natural diffraction distance. As one example, this effect could be used to 'write' programmable plasma microwave mirrors in the atmosphere. Another application of filamentation is the remote nonlinear deposition of optical energy for the purpose of imprinting controlled air density profiles. One realization of the latter goal has been the development of air waveguides, as illustrated in Fig. 6, which shows the effect of a filamenting TEM_{11} mode in air. Waveguides are generated on two timescales: one from collisions of single-cycle acoustic waves launched from the filament locations and the other from the long-time thermal depressions in air density left at the filament locations.

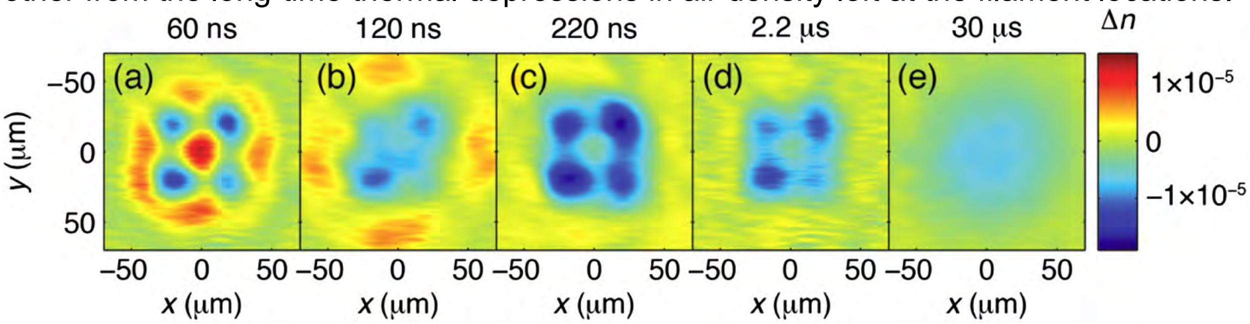


Figure 6. Interferometric measurement of the air density evolution induced by a filamenting TEM_{11} ultrashort laser pulse, and useful for air waveguides. (a) The acoustic waves generated by each filament cross in the middle, generating a positive index shift, producing the acoustic guide. (b) The acoustic waves propagate outward, leaving behind a density depression at the location of each filament. (c) These thermal depressions in density produce the thermal guide, with a higher central density surrounded by a moat of lower density. (d, e) The density depressions gradually fill in as the thermal energy dissipates. The refractive index changes associated with the air density evolution are mapped by the right-side color scale. [Image from Phys.Rev.X **4,** 011027 (2014)].

Among the most important technical yet fundamental challenges in the area of high intensity femtosecond pulse propagation is the development for reduced atomic response models for propagation simulations. Because the fundamental optical field-atom/molecule interaction is generally not describable by perturbation theory, one most incorporate more sophisticated nonlinear dipole response models in propagation simulations that seamlessly link the bound and free electron response. Including a full TDSE (time domain Schrodinger equation) calculation of the medium's dipole response at each space and time point of a propagating field is computationally forbidding, and so the development of reduced but high fidelity models is needed. Such models can only be tested by high time- and space- resolution diagnostics that examine the atomic and plasma response on timescales much shorter than the femtosecond laser pulse itself.

Ultra-high energy density laboratory plasmas

Ultra-high energy density plasmas (UHED) are an extreme state of matter defined by energies of > 1 x 10^8 J cm-3, corresponding to pressures of > 1 gigabar, is found in the interior of stars and in the core of spherical compressions in inertial fusion confinement experiments (see Chapter 2). UHED plasmas are created in the laboratory as the result of spherical compression with high energy lasers. An approach that can facilitate the study of the physics in this extreme regime with compact lasers that can fire at increased repetition frequency is the trapping of ultrashort laser pulses of relativistic intensity in aligned arrays of nanowires.

Recent experiments have shown that the irradiation of ordered nanowire arrays with femtosecond laser pulses of relativistic intensity can volumetrically heat plasmas with electron densities nearly 100 times greater than the typical critical density to multi-keV temperatures, generating dense ultra-hot plasmas with extreme degrees of ionization (eg. Ni+26, Au+52). This approach for heating near-solid density matter provides the opportunity of studying, for example, the atomic physics of highly charged ions at extreme density and temperature conditions. These UHED plasmas also allow for the efficient conversion of optical laser radiations in to bright short flashes of X-rays.

Figure 7. Artistic representation of the generation of ultra-high energy density matter by intense ultrashort laser pulse irradiation of ordered nanostructure arrays. [Image from Nature Photonics **7,** 796 (2013)].

Pulsed power represents yet another pathway toward high energy density laboratory plasma. Based upon the modernization of pulsed power technology away from the inherently single pulse mode of operation characterized by Marx-generators and pulse-forming lines toward a much more efficient and physically more simple technology called the Linear Transformer Driver (LTD), it is now possible to consider the development of pulsed power driven high energy density plasmas for high repetition rate radiation source applications. First, however, it is necessary to undertake fundamental and applied science studies the physics of the plasma formation, the dynamics (both stable and unstable cases) and the atomic physics (including ionization kinetics) of the magnetized HED plasmas so that specific configurations can be optimized for a particular application.

The research challenge that must be addressed for industrial applications to become feasible is to achieve a thorough understanding of the dynamics of these "Z-pinch plasmas," including developing the capability to control the unstable growth of magneto-

Rayleigh-Taylor instabilities, and developing a theoretical and experimental understanding of the atomic physics of extremely rapid ionization and excitation in high energy density plasmas with a range of atomic numbers. Specifically, there are several fundamental questions to be addressed to understand the deceptively simple process of transferring electrical energy to radially imploding plasma flow in cylindrical geometry, to a highly ionized stagnating plasma on axis to hot electrons that will efficiently and rapidly emit UV, XUV or soft X-rays in some energy band. For example, a millimeter-scale XUV plasma radiation source might find application at high rep-rate using LTD technology in any situation in which chemical reactions that do not occur in an equilibrium reactor can be driven with photons above a specific threshold energy. Initially, such HED plasma configurations will be very interesting objects of applied research to determine just what can be done with copious quantities of, for example, extreme ultraviolet photons, either in broad band or narrow band photon sources.

Research needs

Future advances in the generation of high flux, high intensity, x-ray sources are linked to the availability and advances in high intensity ultrashort pulse lasers. While many proof–of-principle experiments can be conducted on a single-shot basis or at low repetition rate, the demonstration of future practical high average flux plasma-based x-ray sources will require intense efficient ultrashort pulse lasers that can operate at high repetition rates with high average power (kW and beyond). This need overlaps with that for the development of practical plasma-based particle accelerators. New array detectors that can operate at high repetition rate will also be needed to take full advantage of these x-ray sources.

Chapter 6 *Plasmas at the Interface of Chemistry and Biology:*

Addressing Societal Needs Through Enabling Technologies for Health, Food, and Water

Precision control of free electrons: Making electrons do our bidding to benefit food, water, health, and economic security. In a future where renewable electricity is our primary and abundant energy source, plasmas become the ubiquitous tool to enable a better life.

Overview

Why are low temperature plasmas ubiquitous and unique?

Low temperature plasmas (LTPs), and the processes that they enable, improve our lives in many different ways. LTPs have played and continue to play major roles in breathtaking technological advances, which range from the development of cost effective lighting to microelectronics, which have improved our quality of life. LTPs are continuing to enable technological advances in new fields, such as now leading to new processes in human healthcare. All of these advances are enabled by the unique properties of low temperature, non-equilibrium plasmas and the chemistry they drive. As a field, LTPs are the plasmas associated with electron-volt (eV) science and technologies. LTPs have characteristic electron temperatures of a few eV to 10 eV with fractional ionizations that are typically small. Since LTPs have electron temperatures commensurate with the threshold energies of excited states in neutral atoms and molecules, power transfer from electrons to these atoms and molecules efficiently produces activated species (e.g., radicals, excited states, photons) which in turn drive chemical processes in ways that other techniques cannot. In addition, the acceleration of ions in the boundary layers (sheaths) of LTPs to energies of tens to hundreds of eV enables activation of surface modifying processes such as sputtering, etching, and deposition. With such properties, LTPs have become essential tools that have enabled many of the technical advances of the last 60 years, and show no sign of decreasing their utility in improving societal needs.

LTPs are also typically non-equilibrium, implying that the electron temperature T_e, is much higher than the ion temperature T_i, which in turn is higher than the gas temperature T_g. Due to the partially ionized nature of LTPs, although some of the particles are extremely energetic (i.e., electrons and often ions), the specific energy content of the plasma is low, because the energy content is dominated by the far more abundant neutral gas. This situation provides a unique set of conditions wherein plasma species contact surfaces beneficially and non-destructively. For example, the entire microelectronics industry which forms the technological base of modern society is enabled by the beneficial plasma-surface interactions that deposit and remove materials with nm resolution in the fabrication of microprocessors. This beneficial contact with surfaces now extends to liquids, such as plasma activated water, which has led to the emerging field of plasma medicine. LTPs may also non-destructively and beneficially interact with surfaces internal to the plasma, such as in a particle or aerosol-laden *dusty* plasma. This is an example of a multi-phase plasma. The concept of multi-phase LTPs extends to plasma sustained within liquids and plasmas in bubbles in liquids, now being investigated for chemical processing and medical applications.

Scientific and Technological Challenges

LTPs have been the source of many of the fundamental physical principles that form the basis of other fields of plasma physics. For example, the fundamental concepts of electron and ion transport, cyclotron resonance, electromagnetic wave interactions with plasmas, electrical probes, interferometric diagnostics, charged particle distribution functions, high energy beam produced plasmas, laser-induced-fluorescence, radiation transport in plasmas and non-ideal plasmas were all first developed (and continue to be developed) in the context of LTPs. However this incomplete list of scientific impacts and societal benefits does not mean that the plasma physics of LTPs is well understood – many scientific challenges remain because our experimental tools and modeling capabilities are not now adequate to address the extreme conditions inherent in LTPs. One of the key unifying challenges of the field is centered on the control of power channeled through the plasma for the selective production of excited states, ions, photons, and surface reactivity. The fundamental science issues addressed by the community revolve around control of the distributions of energetic particles in these plasmas. LTPs interact with atoms and molecules for the purpose of producing excited states, radicals and photons, with surfaces for the purpose of beneficially modifying their properties, and with dust particles in multi-phase plasmas. These interactions ultimately depend on the shape and evolution of the charged particle (electron, positive ion and negative ion) velocity distributions, $f(\vec{r},\vec{v},t)$. Due to the partially ionized nature of LTPs, these velocity distributions are dominantly non-Maxwellian. As a result, there is an opportunity to uniquely craft $f(\vec{r},\vec{v},t)$ to achieve a desired rate of interaction. In fact, lying at the very heart of advancing LTP science is the ability to predictably control and shape $f(\vec{r},\vec{v},t)$ for beneficial interaction with atoms, molecules, solid- and liquid-phases. Obtaining this predictive control is an incredibly challenging goal, *a grand challenge,* considering the extreme diversity and complexity of the field.

The field of LTPs is exceedingly dynamic. Although the very basic and fundamental science issues are longer lived, their context rapidly changes in response to how societal benefit is best produced. For example, during the past five years, in spite of there still being many scientific and technological challenges in low pressure plasmas, much of the research in LTPs has transitioned from sustaining plasmas at lower pressures to uses of plasmas at higher pressures of up to 1 atm (and including liquids). This transition has been motivated, in part, by advances in the use of LTPs in material processing and human healthcare. These motivating applications very often include multiphase systems and the interaction of atmospheric pressure plasmas with liquids. Although the fundamental science issue of controlling of $f(\vec{r},\vec{v},t)$ persists, rapid transitions of motivating applications is a hallmark of LTP research and, in part, is why LTPs are so impactful in investigating the science and developing the technologies resulting in societal benefit.

LTPs also cover an enormous dynamic range of operating conditions. For example, typical areas being investigated by the LTP community span a range of 10^9 in pressure (< 1 mTorr, as might be used in plasma etching, to liquid densities, as used in environmental applications and healthcare), 10^9 in spatial scale (nm for plasma transport in nano-porous material, to meters for flat panel display deposition) and 10^{12} in time (10s ps for formation of space charge layers in streamers to minutes in plasma surface interactions). The plasma chemical systems of interest number in the hundreds or even thousands, ranging from rare gases as used in displays to the multi-component gas mixtures used in microelectronics processing (e.g., $Ar/C_5F_8/O_2/CO_2/N_2$). The bounding surfaces to these plasmas range from silicon to living tissue. The motivating applications range from healthcare to spacecraft propulsion. This dynamic range of scientific investigation and applications is likely unique in plasma science and perhaps unique across the physical sciences.

Due to the extremely dynamic range of LTPs, there is no single overriding scientific challenge, beyond perhaps control of $f(\vec{r},\vec{v},t)$, that unites the field. There are however, highly linked and intermeshing sets of scientific and technological challenges that provide a broad front with which the science and technology frontiers in LTPs are advanced. Those frontiers are outlined below.

A. Interfacial Plasmas

Many of the leading edge applications of LTPs involve interacting with a liquid interface. Plasma applications such as human healthcare, purification of water and chemical reforming of liquid feedstocks are all examples of an LTP coming into contact with liquid to produce new chemical reactivity through a gas-liquid interface. This is a phenomenon referred to as interfacial plasmas. To induce this reactivity, the gas phase plasma is sustained remotely from the liquid (with transport of plasma activated species to the liquid), on the liquid or in the liquid, either in bubbles or directly in the liquid phase. To obtain quantitative insights into interfacial plasmas and plasmas generated directly in liquid phase, some of the key questions that need to be answered are:

- How are electrons generated and transported in liquids?
- What is the effect of the liquid properties (such as polarizability, dielectric constant, conductivity, secondary emission coefficient) on development of plasma and radical generation at a plasma-liquid interface?
- What is the method of transport of electrons, ions and neutral through the plasma-liquid interface, over a wide range of time scales (sub-ns to seconds or minutes)?
- What is the effect of charge solvation and transport through the liquid on ion-molecule reactions in the liquid phase?
- Can kinetics of ionization, charge transport, and ion-molecule reactions in dense, amorphous media (water, bodily fluids, polymers) be understood in terms of an

"isolated binary collisions" model? At what conditions and for what types of processes do multi-body collision dynamics effects become dominant?

- What is the effect of plasma enhanced kinetics (vapor, surface, and liquid phase) on species concentration and phase equilibrium at the interface?
- What are the conditions when the plasma may be generated directly in the liquid phase (rather than in pre-existing micro-bubbles), e.g. using extremely high peak electric field, sub-ns duration pulses?
- What processes control symbiotic self-organization at the plasma-liquid interface induced by non-linear coupling between plasma fields and surface impedance.

Figure 1 – Atmospheric pressure plasma jet incident onto a biological liquid. [[V. Columbo, D. Fabiani, M. L. focarete, M. Gherardi, C. Gualandi, R. Laurita and M. Zaccaria, "Atmospheric Pressure Non-Equilibrium Plasma Treatment to Improve the Electrospinnability of Poly(L-Lactic Acid) Polymeric Solution, Plasma Proc. Poly. 11, 247 (2013) DOI: 10.1002/ppap.2013.00141]

B. Plasmas for Human Healthcare

The use of plasmas in human healthcare has extreme science challenges and is among the most interdisciplinary areas of plasma physics. Plasmas for human healthcare share many of the science challenges of Interfacial plasmas. Ultimately, the plasma produced chemical reactivity must be delivered through multiple interfaces (i.e., liquid, tissue) to provide the therapeutic effects to cells or killing effects to bacteria or cancer. The science challenges motivated by plasmas in healthcare include:

- Building on the observations that plasmas can induce beneficial effects in biological systems – healing wounds and reducing cancer tumors – can we understand the complicated interaction pathways that provide such biological benefits?
- How can we control and understand interactions of plasmas at permeable, reactive, dynamic, charged interfaces exemplified by liquids (e.g., biological fluids), soft matter (e.g. cells and tissues) and polymers (e.g., biocompatible materials and scaffolding)?
- What is the effect of plasma (electric field, electrons, ions, photons, reactive oxygen and nitrogen species) on large molecules (including polymers and proteins), and on cell tissue?
- How do electrons and moderate energy ions (e.g., 10s of eV) cascade, deposit energy and modify chemistry within high density, amorphous materials such as water, polymer or bodily fluids?
- What are the synergetic effects of multiple reactive species, electric field, current and radiation in humid environments, and their combined effects on biological systems?

- Can plasma be appropriately controlled to generate desired radicals, ions and photons intended to provide beneficial biological effects?
- In the case of plasmas inside amorphous, reactive condensed phases – how does energy propagate, influence radical chemical production?

Although the focus of this report is on the science challenges motivated by society benefiting applications, it is difficult to frame those challenges in the absence of the desired outcomes of the motivating technologies. This is particularly the case for plasma for healthcare. Mastery of the science challenges enables addressing key related challenges.

- How are the beneficial chemical and charged particle activation produced by plasma coupled to biochemistry?
- How can biological processes be modified and targeted by customizing reactivity produced by plasmas?
- Can a scientific basis be established for plasma medical applications in cancer treatment, wound healing, dermatology, resistant microorganisms, biocompatible surface functionalization through precise control of plasma properties intercepting biological pathways?

C. Control of Plasma-Electromagnetic Interactions

Power is dominantly coupled into low temperature plasmas by absorption of electromagnetic waves. There is a rich history of fundamental research in plasma production and control by successively higher frequency regimes – from dc to radio-frequency to microwave. In each case, new challenges arose and new opportunities were created. For example, fundamental understanding of how radio-frequency electromagnetic power produces controllable plasmas has enabled the entire microelectronics industry through plasma etching and deposition processes. The next frontier in plasma-electromagnetic interactions is terahertz (THz = 10^{12} s^{-1}) radiation – the frequency range with wavelengths of 0.1 to 1 mm (100 μm to 1000 μm). The advent of THz radiation technologies opens a new regime of plasma science. The void in the frequency spectrum between electronics and lasers (“The THz Gap”) is being filled by advances in semiconductor devices and quantum cascade lasers. This range of frequency and wavelengths has unique opportunities to couple with intrinsic time and scale lengths in LTPs. The electron collision frequency in atmospheric pressure LTPs is about 10^{12} s^{-1} which results in atmospheric pressure plasmas being essentially in time-equilibrium with even ns pulses. THz excitation provides new opportunities for capitalizing on non-equilibrium transient behavior of charged particle distribution functions. The Debye length of LTPs is typically much smaller than any rf or microwave wavelength, but may be commensurate to THz wavelengths. This again opens up new opportunities for unique coupling between the electromagnetic waves and plasma properties.

- What are the fundamental properties of THz radiation interactions with plasmas and what can we learn from power coupling at this frequency? This new domain can broaden our understanding of basic plasma physics including the connecting laser produced plasmas and electric discharges
- Interactions of THz radiation with microplasma arrays or structured plasmas addresses the challenge of steering and control of THz radiation using adjustable plasma density, reconfigurable spatial plasma configuration and plasma volume. How does scattering, absorption and phase shifting properties of microplasmas in response to THz waves produce controllable configurations of radiation and plasma?
- How can THz and plasma interactions scale the plasma "photonic crystal" concept from the microwave band into the THz band.
- How does THz radiation initially produce plasma and ultimately result in self-organized structures? .

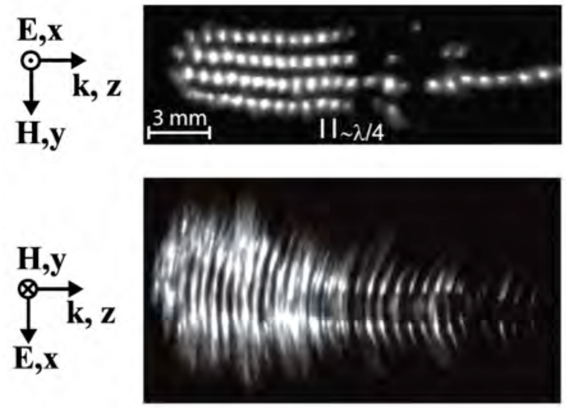


Figure 3 - *Millimeter wave scattering and diffraction in 110 GHz air breakdown plasma,* Alan M. Cook, Jason S. Hummelt, Michael A. Shapiro, and Richard J. Temkin, Physics of Plasmas 20, 043507 (2013)]

D. Plasmas for the Environment: Plasma Catalysis

The use of catalysts in industrial chemical processing is essential and widespread. The vast majority of the petrochemical and emissions control industries rely on the use of catalysts to reduce reaction temperatures and improve selectivity of processing – and would likely not exist in their present form in the absence of catalysis. *Plasma catalysis* combines the ability of plasmas to efficiently produce radicals and ions at low temperature and low energy cost, with the ability of catalysts to promote surface chemical reactivity and selectivity. This combination of plasma reactivity and catalyst selectivity potentially represents here-to-fore unachieved energy efficiencies in chemical conversion from both traditional and renewable feedstocks. Current investigations in plasma catalysis are concentrated on environmental cleanup (e.g., removing toxic gases from air or disposing of volatile compounds) and reforming gases.

Conventional catalytic processing reduces the temperature required to promote chemical reactions by introducing transition states that reduce the activation energy required to break bonds. Selectivity is achieved through the interaction of electronic states of the catalysts and electronic states of the gases adsorbed on the catalyst, and so there is limited flexibility between pairs of catalysts and feedstocks. Due to this discrete pairing, it is difficult for a single catalyst to address a series of chemical reactions which requires multiple catalysts. Plasma catalysis has the potential to greatly improve the overall efficiency of chemical processing by dissociating feedstock gases at low temperature producing radicals which are then processed by catalysts. The basic catalytic efficiency will be improved due to the more reactive electronic configurations of the radicals compared to closed shell feedstocks, and, perhaps more important, an entirely new class of potentially more efficient catalysts may be used that can promote reactions with radicals but not closed shell molecules. Multi-stage catalytic processing may be replaced with the plasma-catalyst combination.

Plasmas in contact with catalysis have the potential of affecting the basic operation of the catalysts. The plasma generates electric fields and surface charging that can alter the electronic interaction between the catalyst and the adsorbed species. The plasma produces activation energy in the form of energetic ions and photons that can regulate surface coverage of adsorbates. Such interactions can potentially provide a means of tuning catalyst activity by, for example, turning-on or turning-off selectivity for a given feedstock.

In the future, non-renewable resources (e.g., petroleum) for producing essential chemicals for industry and consumers will be replaced by renewable resources (e.g., biomass). Plasma catalysis will be a critical technology in introducing renewable feedstocks to industrial processes. Having said that, there is an enormous installed capital investment in conventional chemical processing. The most rapid acceptance of renewable feedstocks will be for those processes which can utilize existing infrastructure, which may require the flexibility of plasma catalysis. Even if plasma catalysis were to only improve the efficiency of conventional industrial use of catalysts, the energy savings would be enormous.

Achieving the potential of plasma catalysis must address many science challenges, particularly in the development of the plasma sources and matching the plasma sources with catalysts. Approaches to date have combined conventional plasma sources (e.g., dielectric barrier discharges) with conventional catalysts (e.g, $Al_2O_3-MnO_2$). These choices are usually made based on the currently available technologies on the plasma and catalysts sides. There has been little work on, from a first principles basis, customizing both the plasma source and the catalyst to take advantage of their symbiotic properties. Although the potential of plasma catalysis is great, it will not be a universal solution for all chemical and environmental processing. Therefore source development, end application and catalyst choice or development must all be considered in advancing this technology. A wholly untouched area of plasma catalysis is their in-water use, which opens possibilities for greatly improving the efficiency of water purification.

- How can the energy distribution and radical chemical production in low temperature plasmas be optimized to drive advances in surface and water catalysis?

E. Plasma Aided Combustion for improved energy utilization

Over the last decade, remarkable progress has been made demonstrating the utility of non-equilibrium plasmas for augmentation of combustion phenomena, such as reduction of ignition delay time and ignition temperature, as well as increases in flame stability and flammability limits. High peak voltage, nanosecond pulse duration discharges are of particular interest for plasma assisted combustion since these systems can generate diffuse nonequilibrium plasmas at high pressures (~1 atm) and high pulse repetition rates (up to ~100 kHz), and produce high peak reduced electric fields, E/N, of several hundred Townsend (1 Td = 10^{-17} V·cm^2). At these high values of E/N, a significant fraction of the discharge input energy populates excited states of molecules (vibrational and electronic), as well as dissociating and ionizing molecules by electron impact. Collisional quenching of the excited states and reactions of radical species generated in the discharge considerably expand the variety of chemical reactions in low-temperature fuel-air mixtures, resulting in fuel oxidation and ignition.

Plasma aided combustion is a single example of the potential for pulsed plasmas to dramatically improve and enhance conventional chemical processes, and open up entirely new parameter spaces for chemical processing that were not practical (or possible) by the usual thermal processing. An entire new field for plasma aided chemistry is the processing of renewable bio-feedstocks. From a fundamental kinetics perspective, the dominant energy transfer and chemical reaction processes in these plasmas are not well understood. This is particularly true when using complex hydrocarbon feedstocks, as are the fuels in plasma aided combustion. Quantitative insight into high pressure plasma chemistry, including fuel-air plasma kinetics, as well as plasma assisted ignition and flameholding, remains a formidable challenge. Some of the pressing technical issues in the use of high pressure, plasma aided chemistry include:

- Why does the application of plasmas to flames improve the fuel efficiency and flame stability?
- How can pulsed plasmas be controlled to improve the efficiency of chemical processing?

Measurements and modeling of electric fields, electron density, gas temperature, and vibrational level populations in high-pressure pulsed plasma chemical systems are key to improving our predictive insight into how to optimize partitioning of discharge energy. This need for measurements and modeling extend to molecular electronic states and key radical species (e.g., O, H, OH, and NO) which are critical for quantifying their effects on pulsed plasma chemistry, including fuels. Such measurements and modeling will lead to improved understanding of critical processes such as the role “rapid” heating (coupling of electronic to translational states) and moderately excited vibrational species that can broach activation energies of reactants.

F. Plasma Aided Aeronautics

Another rapidly developing application of high-pressure nanosecond pulse duration discharges in air is to high-speed flow control. Recent experiments and kinetic modeling predictions demonstrated that the dominant effect of these plasmas on the flow is due to rapid energy thermalization on sub-acoustic time scales, resulting in formation of a high-amplitude compression. Energy thermalization and rapid temperature rise in these plasmas occur in two stages -"rapid" heating occurring on sub-microsecond time scale dominated by quenching of excited electronic states of N_2 molecules, and "slow" heating, on the time scale of ~10-100 μs, caused by N_2 vibrational relaxation. In surface dielectric barrier discharges used for plasma flow control, the effectiveness of these processes may be severely limited by charge accumulation on dielectric surfaces. Insight into kinetics of these processes, and developing the capability to control their rates would considerably enhance the ability to control flows for aerospace vehicles.

G. The Interface between Plasma and Solid-State Physics

The frontier of extreme plasma processing will investigate fundamental physics required to develop novel materials. The potential benefits include low-cost, high-volume production of photovoltaic systems. This research area combines low temperature plasma physics and solid-state physics. Intense plasma fluxes alter material properties in unexplored ways. The parameter space includes:

- The electron density and Debye lengths in the plasma and the solid are comparable
- Plasma-solid interactions may not be treated as isolated binary collisions
- Plasma fluxes disrupt the solid's surface layer which becomes spatially ill-defined and porous on the atomic scale
- The plasma electric field at the surface penetrates into the bulk

A specific example of this frontier is the emerging field of microplasmas which involves high power density plasmas having microscopic dimensions. The plasma density approaches that of fusion plasmas (10^{14} – 10^{17} cm^{-3}) but the non-equilibrium plasma temperatures are the order of 1 eV for electrons and 0.1 eV for ions. These "cold" atmospheric pressure (or greater than atmospheric pressure) plasmas are weakly ionized and highly collisional. Electron collisions with atomic species that are considerably more complex than hydrogen also generate a dense, energetic fluid of metastable states. Molecular species approach full dissociation. Since the plasmas are non-thermal, the plasma-solid interface is distinct from that of arcs for which thermal effects dominate (e.g., phase transitions).

The boundary layer between the plasma and the solid state surface is characterized by a microscopic plasma sheath in which an intense electric field promotes barrier lowering and Fermi level shifts in the solid, field emission of electrons, and field ionization in some cases. The interaction of dense cold plasma with the solid-state is a largely unexplored topic with the strong emission of electrons and ions back into the plasma producing potentially chaotic phenomena. The proposed use of high aspect ratio asperities –such as carbon nanotubes – to enhance electric field-assisted electron injection into the plasma requires a substantially improved physical understanding through direct experimentation and plasma-solid modeling. Intense plasma fluxes may also alter the fundamental materials properties of the interfacial surface, affecting field emission or opening a new field of material processing.

Although the high density microplasma is relatively cold, the fluxes of electrons, ions, and metastable species exceed those of in processing plasmas typically used for microelectronics fabrication by at least two orders of magnitude. The response of materials to such intense low-energy (<1 eV) fluxes is generally unknown, but there is evidence that new physics awaits. For example, it has been shown that the intense particle flux from a microplasma enhances sp^3 coordination and transitions polymeric film growth into a tetrahedrally-bonded diamond-like film. This effect has previously only been observed for low fluxes of much more energetic ions (>100 eV). One hypothesis requiring investigation is a thermal-spike model in which multiple low-energy collisions coincide within the energy relaxation time of the surface. Synergistic roles of metastable fluxes and photon fluxes with solid-state materials are additional avenues of inquiry.

- What are the detailed physics of the collisional, high density plasma interface with solid state materials? What are the species fluxes and energy distribution functions both in the plasma and at the surface?
- How does the intense sheath electric field modify the solid interface? What plasma and surface conditions promote field emission and field ionization? How do these factors influence the distribution functions and fundamental behavior of the plasma?
- What is the nature of the plasma at the disrupted porous transition region near the material interface? How can this interfacial condition be leveraged toward novel applications?

Research Needs

To address the frontier science challenges in low temperature plasmas, expansion of capability and enhanced utilization of existing facilities, as well as new capabilities, are required. Discovery-based plasma science represents a vibrant component of plasma science research and will likely to remain so in the foreseeable future. To ensure that such discovery-based research is properly encouraged and nurtured, facilities are needed to enable the initiation and execution of risky but high-pay off research leading to impactful discoveries and technologies. The infrastructure required for initiating such an effort for, for example, a single measurement in low temperature plasmas is not physically large. The plasma source and diagnostics can usually fit on at most a few laboratory tables. While the experiment can be of modest size, a single diagnostic to understand the experiment can be expensive and many such diagnostics are required to characterize the system. ***In the field of low temperature plasmas, the plasma sources are hugely diverse while being individually relatively inexpensive – the largest costs are in the diagnostics***. ***Therefore, advancing the field through investments in facilities should not be in building a large universally used plasma source, but rather by providing access to suites of the more expensive diagnostics to which plasma sources are transported***. Due to this rather unique situation, it would be beneficial for the low temperature plasma community to form "dynamic exploratory clusters" to mitigate risk and maximize potential payoff from unique, one off, diagnostics.

Dynamic describes the relatively short time frame interactions during which collaborators discuss ideas, plan and execute key measurements that would yield go/no-go decisions. Should the initial results be promising, groundwork would be established for follow-on proposals.

Exploratory conveys that a higher-level of risk and or uncertainty is associated with the efforts. Much of the risk would be mitigated through identifying key locations that have most of the required infrastructure in place.

Cluster refers to a team performing the research. The size of the cluster would be flexible enough to assemble an appropriate team needed to achieve a stated objective.

Due to the high cost of developing state-of-the-art plasma diagnostics, the high-levels of expertise required to operate the equipment, and the limited number of research groups having a wide range of diagnostic capabilities, *designated user facilities* (*DUF*) may have significant potential for advancing fundamental and applied research in low-temperature plasmas. In the field of low temperature plasmas, a user facility is likely to be of the scale of a several laboratories within a single building. Much of the equipment, at least at the beginning of the facility would already be existing infrastructure until a clear need is defined for updated or expanded capital purchases. Collectively *DUFs* should be able to provide a broad spectrum of plasma parameter measurements including velocity distributions and characterization of plasma contacting surfaces. Examples of the instruments that might be available at *DUFs* include: Thompson scattering, two-photon absorption laser induced fluorescence (TALIF), ultra-short pulse laser diagnostics, sophisticated mass spectrometers, NMR, electron paramagnetic resonance (EPR) spectroscopy.

Development and maintenance of the network of *DUFs* would enable low temperature plasma researchers access to a suite of state of the art diagnostics at reasonable cost. Conceptually the user of the *DUF* would bring a plasma source to the facility or arrange with the facility to have it built. The *DUF* would be able to accept different user's plasma sources after small modifications based on availability of access points for gas, pumping and power. The shared network of instrumentation represented by *DUFs* could be potentially coordinated and facilitated by *DOE*. Such effort would strengthen the collaborative nature of research, increase facility utilization and leverage existing equipment. In addition, *DOE* might support regular workshops and summer schools to facilitate sharing experience, graduate student education and ideas exchanges.

Operationally, there are several governance models of *DUFs*. In the simplest, a research group with a certain diagnostic capability would be open to relatively short-term (several days to several months) visits by students and post-doctoral researchers from other groups working in the same field, to conduct joint measurements. During the planning stage of the visit, the host group would designate an experienced research staff member, who would discuss the scope of the work, the approach, the resources required, the time frame, the budget, and the objectives with the visitors. The visitors may need to bring along or have delivered some of the custom-designed experimental components, such as plasma cells, as well as other equipment that may not be available at the host group but is easily transportable, such as power supplies. The measurements planned would be conducted by the visitors under the guidance and supervision of the designated researcher from the host group, who would also provide help with the data analysis, if necessary. The results of the work could be jointly published.

Research exchanges fostered by the DOE Plasma Science Center for Predictive Control of Plasma Kinetics serve as an indication of the demand for access to unique diagnostic capabilities and the value from improved scientific interactions. In one example, seven of the ten research publications produced by members of the Center at Sandia National Laboratory resulted from short term (weeks to months) dynamic exploratory interactions with their fellow Center groups. In another case, the Nonequilibrium Thermodynamics Laboratory (NETL) at the Ohio State University hosted students from the Ruhr University Bochum (RUB) to quickly measure the time-resolved electric field vector in a surface ionization wave discharge and share their understanding. Since development of advanced diagnostics from scratch takes many years of prior experience, up to several person-years in the actual development and several hundred thousand dollars of capital investment, increasing the utilization of these facilities is one simple way to improve research efficiency.

In addition to experimental diagnostics and capabilities, computational resources should also be an element of the *DUFs*. Many of the most challenging unsolved problems in low temperature plasmas require models that span large dynamic ranges in time, space, electric field, energy, velocity and density with user specified chemistries. These elements challenge the capability of even the most high-performance computing machines. Colocation of visiting experimentalists and modelers, even for short periods of time will produce advances in understanding.

Chapter 7 Cross-Cutting Motifs

Theory and Computation

Plasma theory is based in major part on the fundamental electromagnetic interaction; however, collective phenomena emerge from this basis in the form of a hierarchy of plasma theories obtained by reduction of the n-body problem of a large number of interacting charged particles to mean-field kinetic theories such as the Vlasov system. Further reductions may yield other kinetic theories or various magnetofluid theories that encapsulate the myriad of plasma phenomena. These various theories possess a common mathematical form, composed of a generic Hamiltonian structure together with clearly identifiable dissipative and drive processes. The Hamiltonian form of the electromagnetic interaction spawns that of the reduced models, which is the source of the conservation of energy and other invariants of motion for their nondissipative parts. Additional structure may also emerge, such as flux conservation and the magnetic and cross helicities of MHD and those of more general magnetofluid models. Invariant topological structures lie at the heart of such notions as magnetic reconnection and dynamo action.

The deep physical insights provided by fundamental theory are not only valuable in their own right for understanding the properties of physical phenomena, but they also enable the development of algorithms and reduced descriptions making possible computations which faithfully capture complex dynamics - preserving the relevant conservation laws on available computer hardware.

Plasma dynamics are characterized by a wide range of spatial and temporal scales covering particle transport and electromagnetics. Depending on conditions, transport of neutral and charged particles in partially ionized plasmas is best described by either phase space (kinetic) or continuum (fluid) models. Adaptive kinetic-fluid simulations apply kinetic solvers in selected regions of phase space for efficient description of different scales. Appropriate models are selected using sensors locally detecting phase space regions where a kinetic approach is required. For gas dynamics in mixed rarefied-continuum regimes, this methodology has been successfully implemented using an Adaptive Mesh *and* Algorithm Refinement (AMAR) methodology first introduced for DSMC-fluid coupling. The extension of the AMAR technique to plasma simulations poses scientific challenges due to the disparity of temporal and spatial scales typical to plasmas. Continuum breakdown criteria for electrons, ions and neutrals are quite different and strongly depend on plasma conditions. Furthermore, different kinetic models could be used for electrons depending on electron energy and the plasma type Nevertheless, first steps towards adaptive physics algorithms that dynamically create and remove localized kinetic patches within global fluid plasma models have been made. In particular, two-way coupling of a global Hall magnetohydrodynamics with a local implicit PIC model (MHD with Embedded PIC regions (MHD-EPIC)) has been demonstrated for space plasmas. Multi-fluid plasma models can capture essential physics of multi-component reacting mixtures of ions, electrons, and neutrals. Such models have been successfully implemented using finite volume and high-order discontinuous Galerkin methods with the treatment of atomic and molecular physics. High-order finite volume methods have been applied to solve the kinetic Vlasov equation. The two-fluid plasma model has been used to study drift turbulence instabilities, which may be related to the experimentally observed anomalous resistivity.

The modeling and simulation of interfacial plasmas has significant challenges to represent these complex physical phenomena. A dramatic density jump at the plasma-liquid interface increases complexity of analysis of these processes. Specifically, ionization, charge transport, and ion-molecule reactions (i) at phase interface and (ii) in liquid phase may involve complex chemical dynamics, including potential energy surface hopping. Another example is the effect of extreme electric fields on liquids, including polarization of the near-surface layer of the liquid and formation of nano-voids by electrostriction, both of which may control breakdown and plasma formation directly in the liquid phase.

Modeling of plasmas in these environments is extremely challenging, because of an extremely wide range of time scales and spatial scales involved in highly transient plasmas and propagating ionization waves in the presence of high spatial gradients and evolving surfaces. This necessitates the use of molecular dynamics simulations, dynamic switching algorithms between kinetic and fluid plasma solvers, adaptive mesh refinement, and use of massively parallel, heterogeneous CPU-GPU systems.

Diagnostics

As for any experimental science, physical measurements are at the heart of advancing our descriptions of natural phenomena and lead to advances in understanding. Throughout the frontiers of plasma science, a recurring theme is the importance of continued refinement and innovation in diagnostics. Whether it is devising ways to measure the thermodynamic properties of WDM, inventing ways to diagnose the background plasma surrounding suspended particulates, devising ways to estimate wave absorption in turbulence, probing the structure of a plasma wake, or devising new non-invasive optical diagnostic techniques for low-temperature plasmas, the development of diagnostics is in-itself a cross-cutting frontier. It is also a frontier that connects plasma experiments with research in almost every area of physics. Plasma diagnostics cover the electromagnetic spectrum, involving both detection as well as a wide array of incoherent and coherent sources. A wide array of particle beams and detectors are also employed. Plasma diagnostic development, in turn, has an impact on a wide array of physics research and technology.

Atomic, Molecular and Optical Physics: *Fundamental Data* Needs

Terrestrial and space plasmas exist over an enormous range of physical conditions, with temperatures ranging from the 3K cosmic background to those found in stellar cores, and from densities that are so low that collisions occur only on gigayear timescales to almost solid densities where collision frequencies are 10^{15} s^{-1}. At one extreme high-energy-density plasmas occur within the cores of neutron stars and the centers of inertial confinement devices, while low density cool photoionzed plasmas may be found irradiated by a hot star or X-ray laser. These plasmas are all typically highly ionized. At the other extreme, are the low temperature, partially ionized plasmas found in technological applications such as material modification and biotechnology in which electrons and ions largely interact and collide with neutral atoms and molecules. Interpreting and modeling the physics occurring within these plasmas requires high-precision and sophisticated (often relativistic) calculations and measurements of atomic, molecular, and optical (AMO) cross sections, rate coefficients, and emission wavelengths, along with reliable error estimates. This knowledgebase is collectively called *fundamental data*. With this fundamental data, models and simulations can be constructed of complex plasma phenomena, direct diagnostics can be performed by opacity measurements or line ratios, and theoretical understanding of plasma phenomena can be developed within the framework of a complex MHD simulation.

The current state of the art of plasma modeling and simulation, and of interpreting experimental measurements, is constrained the lack of a comprehensive, robust, validated and dynamic database of fundamental cross sections, rate coefficients, opacity and emission coefficients. That is, progress in improving our fundamental understanding of nearly all fields of plasma physics is rate limited by the lack of fundamental data.

The importance of an accurate and robust knowledge base of fundamental data cannot be overstated. For example, in cosmic plasmas, all elements other than H and He are impurities whose optical emission can provide powerful diagnostics of the interior plasma dynamics. In a diffuse cosmic plasmas, the temperature, density, and electron velocity distribution can be measured if the underlying atomic data for elements with $Z > 2$ are available and accurate. The situation is more complex in optically thick plasmas, however the same dependence on complete knowledge bases of fundamental data is also critically important. Some strong emission lines in hot collisional plasmas, such as those from neon-like iron, have large discrepancies between theory and experiment that can be traced back to uncertainties in the underlying fundamental data. This situation brings into question the ability to derive plasma parameters through model comparisons with experiments. Photoionized plasmas are dominated by cool electrons with low kinetic energies compared to the ionization energies of ions. These relatively cool electrons can be produced by relativistic jets around black holes, X-ray lasers and laboratory Z-pinch devices. Even fundamental questions about the equilibrium states of such plasmas suffer from uncertainties due to inadequate or inaccurate data.

The importance of an accurate and robust knowledge base of fundamental data for low temperature plasmas where electron and ion collisions are dominated by neutral atoms are molecules is also important. The situation is in many ways more complex and more diverse than for highly ionized, high temperature plasmas where all collision partners are atoms. The current state of the art for computing cross sections for electron collisions with neutral atoms provides accurate cross section values for smaller atoms. However these methods become increasingly more challenging for larger atoms, transition elements and for excited states of those atoms. The challenges for producing electron impact cross section with molecules are even greater due to the more complex electron orbital structure (and more electrons) in molecules, and the open orbitals in molecular radicals. One of the biggest challenges in predicting electron impact cross sections for molecules is determining the exit channel. Many of the electronic molecular states produced by electron impact are dissociative – that is, when the molecule is electronically excited, it quickly falls apart into fragments. The identity of the fragments is exceedingly important of accurately predicting the chemical reactivity produced by electron collisions on molecules. There are desperately few active experimental electron beam and electron swarm apparatus in the US capable of producing electron collision data for atoms and molecules of interest to low temperature plasmas.

Validating AMO Data and Benchmarking experiments of AMO data: A common challenge in interpreting complex simulations of plasmas and making comparisons to experiments is determining whether inconsistencies are the result of the underlying physics or the accuracy of the fundamental data used as input to the models. The atomic physics models within many plasma hydrodynamics simulations would certainly benefit from having more atomic levels and more complete interactions between those levels. However, there is a limit to the return-on-investment of making such models more complex if the underlying fundamental data is not accurate and validated. To characterize theoretically derived fundamental data through benchmarking, experiments need to be designed and carried out under well-controlled conditions. For fundamental data addressing fully ionized systems, the Electron Beam Ion Trap (EBIT) is an option, which enables the benchmarking of the atomic data by simplifying complicated spectra into a few ionization stages and controlling the processes involved. Combined with data from other plasmas sources, such as tokamaks and X-ray lasers, along with a substantial theoretical effort, reliable methods could be developed to provide accurate error estimates with theoretical AMO calculations in the fully ionized regime.

Atomic plasma and statistical physics: Hot electrons are frequently observed in non-equilibrium, highly ionized plasmas of very different temperatures and densities, from astrophysical to tokamak plasmas to high-energy-density plasmas. However, little is known about the influence of such electrons on radiative properties of highly ionized plasmas when both thermal Maxwellian and hot non-Maxwellian electrons are both present. Accounting for the non-Maxwellian nature of the distribution functions in interpretation of diagnostics and in development of models is critical to advancing our fundamental understanding of these complex highly ionized systems. Development of advanced diagnostics and independent measurements of distribution functions of hot electrons concurrent with improved calculations of the rates of atomic processes in non-equilibrium plasmas is critical to our future understanding of highly ionized plasmas plasmas. Addressing non-Maxwellian electron energy distributions is also important in partially ionized plasmas where electron-molecule interactions may dominate. The techniques for simulating, analyzing and interpreting diagnostics for low temperature plasmas are advanced compared to the highly ionized plasma and HED communities, and so there may be opportunity for leveraging each other's knowledge.

Opacity and Radiation Transport: The interiors states of normal stars and the dynamics of HED terrestrial plasmas — as well as their observed spectra — can be derived only if the opacities resulting from a broad of ions are known. For example, experiments have shown that theory has substantially underestimated the opacity of iron, leading to inconsistencies between abundances required by radiative hydrodynamical models of the sun and its interior structure inferred from helioseismology. High-accuracy opacities using state-of-the-art methods have been calculated for only a few special cases. An important challenge is improving our ability to calculate opacities of highly ionized plasmas which requires improved understanding of radiation transport. This improved capability will lead to a wide range of benefits, from understanding and modeling the radiation pressure that prevents core collapse in late stage stars and in the accretion disks around black holes, to accurately predicting the compression of pellets in inertial confinement fusion.

Atomic Physics under extreme conditions – environmental effects: Our present understanding of the impact of the plasma environment on AMO structure and rates is largely conceptual. Although atoms, ions have unlimited number of bound states, the surrounding charged particles will produce perturbations sufficient to affect atomic structure that produces new phenomena. For example, “continuum lowering” results in truncation of the bound states and reduction of the ionization potential. This effect is already observed in high power laser experiments and in the arcs of low temperature plasmas. At best, this and related phenomena are described only phenomenologically. Understanding these environmental effects are critical to our ability to predict and interpret plasma phenomena across the entire range of the field.

Data Storage & Exchange : Simply creating and publishing fundamental AMO data does not ensure that it will be available in usable form to the community. Interactive databases, with well-defined interfaces, are needed to curate new data and maintain existing results, including validation and verification of the data. While the needs will differ between communities, database developers must interact with each other to share data and establish best-practices for community access.

Appendix A: Charge to the Panel

Workshop on Plasma Science Frontiers
Chair: Fred Skiff (U Iowa), Co-Chair: Jonathan Wurtele (UC Berkeley)

Background
The reorganization of the Fusion Energy Sciences (FES) budget structure in FY 2015 brings together three program elements at the frontiers of plasma science–viz., general plasma science, high energy density laboratory plasmas, and exploratory magnetized plasma. These three activities support a rich and diverse portfolio of plasma science, sharing many common intellectual threads with the potential for broadening connections between the fusion energy sciences portfolio and related fields.

Objective
The Plasma Science Frontiers (PSF) activities in FES seek to engage the community of scientific experts working in the fields of general plasma science, high energy density laboratory plasmas, and exploratory magnetized plasma in a series of two community-led workshops to identify:

1. Compelling scientific challenges at the frontiers of plasma physics, and
2. Research tools and capabilities that exist presently, as well as the general requirements necessary to address these challenges in the next decade.

The report(s) generated from these workshops will inform FES in planning and executing its strategic vision for the FES stewardship of the PSF activities, taking into consideration the recommendations from the Fusion Energy Sciences Advisory Committee [1] and the National Research Council [2].

Organization
The first workshop, "Scientific Frontiers," will focus on identifying the grand scientific challenges in plasma science. The starting point will be the six critical plasma processes that were identified in the 2007 National Research Council plasma science report [2] as being not well understood: explosive instabilities, magnetic self-organization, turbulence and transport, correlations in plasmas, multiphase plasma dynamics, and particle acceleration and energetic particles. The goal of the workshop will be to bring together input received from across the community (via one-page white papers) on updates to the state of the art and where the frontiers are since the 2007 report.

The second workshop, "Research Needs," will focus on identifying the research needs required to address scientific challenges at the forefront of plasma physics. It will specifically address existing experimental tools and capabilities, as well as future performance requirements at the intermediate scale and computational hardware and software needs.

Both workshops will follow the format of the successful Office of Science Basic Research Needs series of workshops. FES will select the chair and co-chair(s), who will define the various workshop panels and sub-panels (including any crosscutting panels) and select the panel leads. The chair, co-chair(s), and panel leads will make up the Executive Group of the workshop. The panel leads will select the panelists and any sub-panel leads. The workshop report will be written by the chair, the co-chair(s), the panel leads, and any panelists designated as writers. Input from the entire community will be solicited during the preparation for the workshop, and participation will be open, but the total number of attendees will be limited to preserve the "working meeting" character of the workshop. A substantial amount of work via teleconferences and other means will be done prior to the workshop to allow the preparation of a draft report during the last day of the workshop.

[1] "Report on Strategic Planning: Priorities Assessment and budget scenarios" (2014)
[2] "Plasma Science: Advancing Knowledge in the National Interest" (2007)

Appendix B: Panel Membership

[Boldface indicates sub-panel leads]

Igor	Adamovich	The Ohio State University
Andre	Anders	Lawrence Berkeley National Laboratory
Scott	Baalrud	University of Iowa
Stuart	Bale	University of California, Berkeley
Michael	Bonitz	Christian-Albrechts-Universität zu Kiel
Alain	Brizard	St. Michael's College
Troy	**Carter**	University of California, Los Angeles
John	Cary	University of Colorado, Boulder
Jerome	Daligault	Los Alamos National Laboratory
James	Danielson	University of California, San Diego
Forrest	Doss	Los Alamos National Laboratory
James	Drake	University of Maryland
R. Paul	Drake	University of Michigan
Nathaniel	Fisch	Princeton University
Cary	**Forest**	University of Wisconsin
Garudas	Ganguli	Naval Research Laboratory
S. Peter	Gary	Los Alamos National Laboratory
Siegfried	Glenzer	SLAC National Accelerator Laboratory
John	**Goree**	University of Iowa
David	Graves	University of California, Berkeley
Gianluca	Gregori	Oxford University
Gregory	**Hebner**	Sandia National Laboratory
William	Heidbrink	University of California, Irvine
Jeffrey	Hopwood	Tufts University
Gregory	Howes	University of Iowa
Chan	Joshi	University of California, Los Angeles
Igor	**Kaganovich**	Princeton Plasma Physics Laboratory
Michael	Keidar	George Washington University
Thomas	Killian	Rice University
Karl	Krushelnik	University of Michigan
Matthew	Kunz	Princeton University
Mark	**Kushner**	University of Michigan
Donald	Lamb	University of Chicago
Martin	Laming	Naval Research Laboratory
Michael	**Mauel**	Columbia University
Julia	Mikhailova	Princeton University
Philip	**Morrison**	University of Texas at Austin
Bruce	**Remington**	Lawrence Livermore National Laboratory

Jorge	Rocca	Colorado State University
Robert	Rudd	Lawrence Livermore National Laboratory
Dmitri	Ryutov	Lawrence Livermore National Laboratory
Alla	Safronova	University of Nevada, Reno
John	Sarff	University of Wisconsin
Thomas	Schenkel	Lawrence Berkeley National Laboratory
Uri	Shumlak	University of Washington
Vladimir	Shiltsev	Fermi National Accelerator Laboratory
Gennady	**Shvets**	University of Texas at Austin
Daniel Brian	Sinars	Sandia National Laboratory
Randall	Smith	Harvard-Smithsonian Center for Astrophysics
Frederick	Skiff	University of Iowa
James	Stone	Princeton University
Edward	Thomas	Auburn University
George	Tynan	University of California, San Diego
Anne	White	Massachusetts Institute of Technology
Jonathan	Wurtele	University of California, Berkeley
Stewart	Zweben	Princeton Plasma Physics Laboratory
Ellen	Zweibel	University of Wisconsin