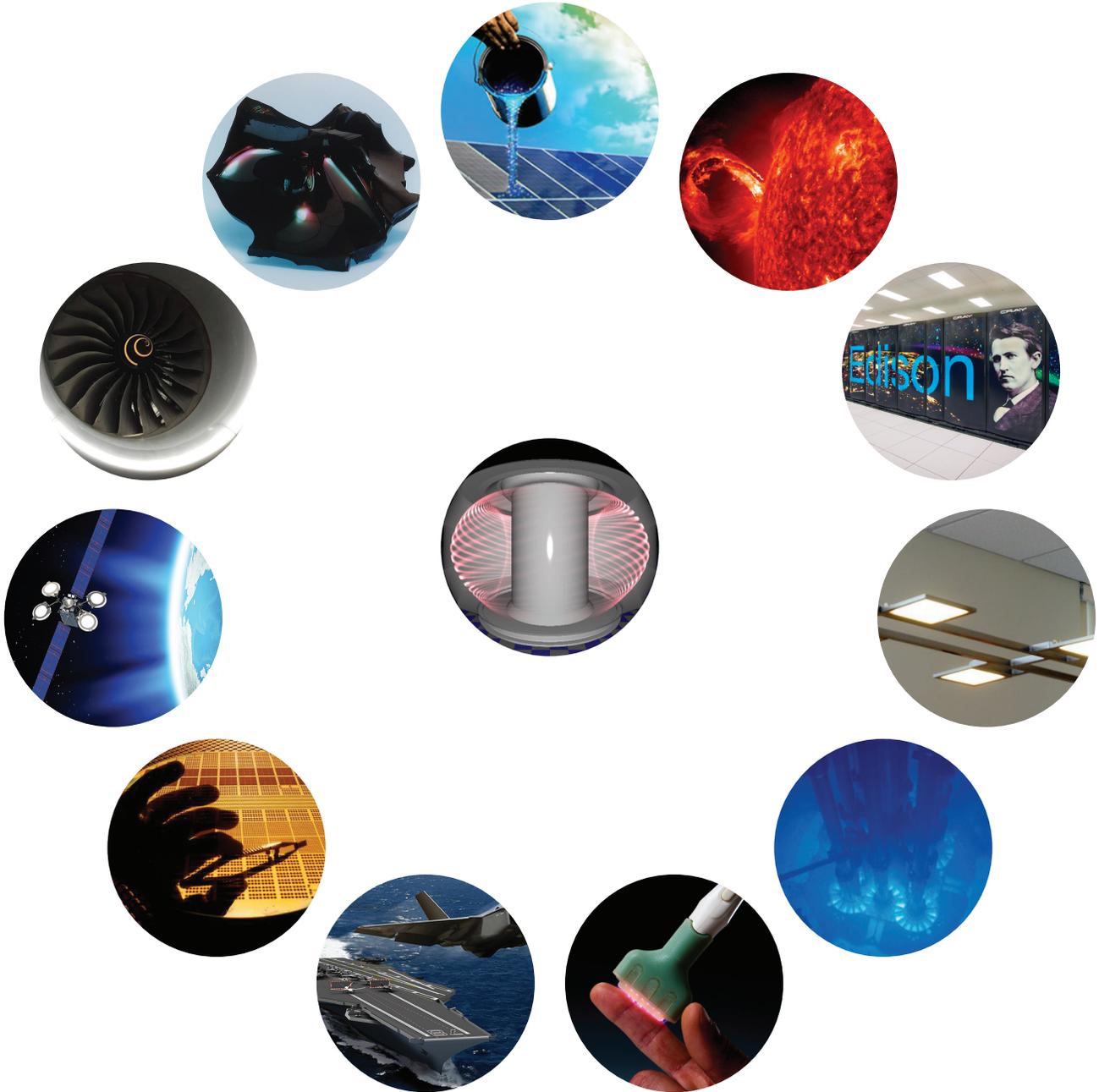


Applications of Fusion Energy Sciences Research

Scientific Discoveries and New Technologies Beyond Fusion



**Prepared by the FESAC
'non-fusion applications'
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Executive Summary

Report Overview

Since the 1950s, scientists and engineers in the U.S. and around the world have worked hard to make an elusive goal to be achieved on Earth: harnessing the reaction that fuels the stars, namely fusion. Practical fusion would be a source of energy that is unlimited, safe, environmentally benign, available to all nations and not dependent on climate or the whims of the weather. Significant resources, most notably from the U.S. Department of Energy (DOE) Office of Fusion Energy Sciences (FES), have been devoted to pursuing that dream, and significant progress is being made in turning it into a reality.

However, that is only part of the story. The process of creating a fusion-based energy supply on Earth has led to technological and scientific achievements of far-reaching impact that touch every aspect of our lives. Those largely unanticipated advances, spanning a wide variety of fields in science and technology, are the focus of this report.

There are many synergies between research in plasma physics, (the study of charged particles and fluids interacting with self-consistent electric and magnetic fields), high-energy physics, and condensed matter physics dating back many decades. For instance, the formulation of a mathematical theory of solitons, solitary waves which are seen in everything from plasmas to water waves to Bose-Einstein Condensates, has led to an equal span of applications, including the fields of optics, fluid mechanics and biophysics. Another example, the development of a precise criterion for transition to chaos in Hamiltonian systems, has offered insights into a range of phenomena including planetary orbits, two-person games and changes in the weather.

Seven distinct areas of fusion energy sciences were identified and reviewed which have had a recent impact on fields of science, technology and engineering not directly associated with fusion energy:

- Basic plasma science
- Low temperature plasmas
- Space and astrophysical plasmas
- High energy density laboratory plasmas and inertial fusion energy
- Particle accelerator technology
- Fusion nuclear science
- Magnetically confined plasmas

Individual sections within the report summarize applications associated with each of these areas. These sections were also informed by a survey that went out to the community, and the subcommittee wishes to thank those who responded, as well as to the national labs and universities that contributed photographs. For more details on the survey, including contributors and methodology, please see Appendix B.

Major Categories of Non-Fusion Applications

After reviewing the information collected during this study, the subcommittee found major categories among the identified applications, common to multiple research areas. The categories are listed in Table 1, and for each category, an exemplary application has been included illustrating that category. Further detail and additional examples are provided in the main body of the report.

Table 1: Major Categories of Non-Fusion Applications & Example Applications

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Basic Materials Science

FES researchers have created dusty plasmas to generate nucleation ‘factories’ for the production of nanoparticles and nanocrystals developed for efficient solar cells and fuel cells.

DOE Basic Energy Sciences Energy Frontier Research Centers. *Photo courtesy of Los Alamos National Lab with the University of Minnesota.*



Basic Plasma Science

Magnetic reconnection is the dominant process for dissipating magnetic energy in the universe. FES experiments have resolved discrepancies between computer models and space observations.

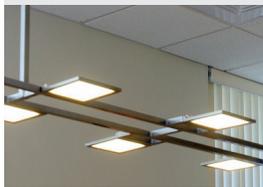
Solar coronal mass ejection. *Photo courtesy of NASA.*



Computational Tools and Methods

FES high-performance computer codes developed for heavy ion fusion energy were applied in the design of today’s high-power accelerators and colliders used by the nuclear and particle physics and materials science communities.

Leadership class computer simulations. *Photo courtesy of Berkeley Lab.*



Lighting

FES Small Business Innovation Research programs have advanced flat, low profile, energy-efficient micro-plasma light sources now commercially available. These sources have been fashioned into almost any shape to blend function with form and aesthetics.

Low profile, versatile lamps. *Photo courtesy of Eden Park Illumination, Inc.*



Materials Science Applications

Radiation-tolerant ceramic-matrix composites developed by FES researchers are central to fuels and core technologies being developed for current and next-generation nuclear reactors to better survive severe accidents.

Advanced Test Reactor at the Idaho National Engineering Laboratory. *Photo courtesy of Argonne National Lab.*



Medical/Health

Atmospheric and non-neutral plasma physics as well as FES technology spinoffs have enabled a wide range of new medical procedures ranging from plasma surgery to non-invasive imaging to cancer therapy.

Plasma tissue welding. *Photo courtesy of Ion Med Ltd.*



National Security

The Electromagnetic Aircraft Launch System, a spinoff from FES development of precision control of sequencing magnets, is now replacing the Navy's steam catapults on aircraft carriers. USS Gerald Ford was the first carrier to use the Electromagnetic Aircraft Launch System.

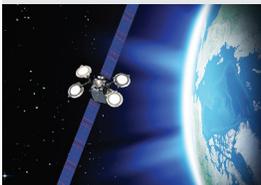
Electromagnetic Aircraft Launch Systems. *Photo courtesy of General Atomics.*



Semiconductor Manufacturing

Plasmas play critical roles in the fabrication of silicon-based integrated circuits that are the core components of all electronic devices. FES-trained scientists have contributed to improved physics understanding and product throughput and yield in the U.S. semiconductor industry.

Semiconductor manufacturing. *Photo courtesy of Fermilab.*



Space Propulsion

Plasma propulsion is fuel efficient with exhaust velocities 10 to 100 times that of traditional chemical rockets. Over 200 spacecraft have flown plasma thrusters for station keeping or primary propulsion.

Direct TV communication satellites. *Photo courtesy of Boeing.*



Transportation

Safer, more efficient jet engines have been created by spray coating their turbine blades with a ceramic powder that was injected into a flowing plasma jet.

Plasma spray-coating improves jet engine turbine blade efficiency and safety. *Photo courtesy of JETPOWER.*



Waste Treatment

FES researchers have developed commercial plasma arc heating technologies to transform hazardous waste into vitrified products—a stable, solid form suitable for safe long-term disposal.

Plasma arc vitrification. *Photo courtesy of Pacific Northwest National Laboratory.*

Specific Findings

The subcommittee had a number of specific findings, listed below, in addition to the detailed section discussions and the major categories of applications listed above.

- 1.** In the quest for fusion energy, numerous new scientific frontiers and technologies have been, and are being, created. Many of these innovations and insights are proving to be invaluable in applications far afield from fusion energy research. The subcommittee reiterates the breadth and impact of the field of plasma science as discussed in the National Research Council *Plasma Science: Advancing Knowledge in the National Interest* and other reports.
- 2.** The legacy generated by the research in fusion energy sciences is both wide and ubiquitous. It has contributed to the fidelity of the Standard Solar Model by measuring the x-ray opacity of iron at conditions found in the interior of the Sun. It has also contributed to the extension of Moore's Law through the development of advanced plasma reactors for the fabrication of ever-smaller transistors in the computer chips that form the 'brains' of our computers, cell phones and other electronic devices.
- 3.** The tools, diagnostics, modeling and basic understanding for the generation and control of intense fusion plasmas have led to observations, improvements and understanding in the areas of the phenomena occurring in the universe around us. This includes a better understanding of our Sun, as well as advanced space thrusters, medical testing and surgical procedures, enhanced properties of materials, and hazardous waste decontamination and destruction.
- 4.** Spinoff technologies derived directly or indirectly from fusion investments have had a transformative effect on society with the public benefitting greatly from modern electronics, lighting, communication, manufacturing and transportation. Further benefits from these investments are increased energy efficiencies and reduced environmental impacts. Advances in medicine, environmental hazard mitigation and water and food purification have also been made possible by these investments.
- 5.** FES research has yielded advances in computational science, including new simulation codes and algorithms, applicable to a wide variety of non-fusion problems. Examples include simulation tools for accelerator design and modeling of supernovae and other astrophysical phenomena.
- 6.** Owing to its interdisciplinary nature, many scientific fields of study have benefited from efforts in Fusion Energy Sciences. Examples of basic science contributions to space physics, condensed matter physics, physical chemistry and materials, quantum mechanics, and particle physics are provided within the report.

- 7.** Another significant contribution is the cadre of scientists and engineers who have worked and trained in the pursuit of fusion energy and have taken their skills and knowledge out to other scientific, engineering, and manufacturing communities worldwide.

- 8.** The economic impact of non-fusion applications benefiting from Fusion Energy Sciences is unquestionably large. However, economic impact data for Fusion Energy Sciences' investments are limited, and most of what are available is 10–15 years old. Furthermore, disentangling the share of the impact that can be attributed to FES is complicated by the involvement of multiple disciplines as well as multiple sources of funding for some technological applications. Although the available figures have been summarized in the report, the subcommittee's effort was limited to an evaluation of technical impact, and a complete economic analysis was beyond its scope.

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Introduction

2.1 Scope

This report was prepared in response to a request from the U.S. Congress to the Department of Energy (DOE) for a description of “the contributions of fusion energy sciences to scientific discovery and the development and deployment of new technologies beyond possible applications in fusion energy.” Dr. Patricia Dehmer, the Acting Director of the DOE Office of Science, charged the Fusion Energy Sciences Advisory Committee (FESAC) with producing the report. Please see Appendix A for a copy of the charge. FESAC appointed a subcommittee of seven members to draft a report for their consideration, with representation across the subfields highlighted in the charge. The subcommittee consisted of the following researchers, with expertise in the areas indicated:

Professor Amy Wendt, Chair

University of Wisconsin-Madison
low-temperature plasma science and technology

Dr. Richard Callis, Vice Chair

General Atomics
magnetic fusion energy science and technology

Dr. Philip Efthimion

Princeton Plasma Physics Lab
diagnostics and technology

Professor John Foster

University of Michigan
low-temperature plasma science and technology

Professor Christopher Keane

Washington State University
inertial fusion energy science and technology

Dr. Terry Onsager

National Oceanic and Atmospheric Administration
space weather applications

Professor Patrick O’Shea

University of Maryland
nano-science, particle accelerator technology

In addition to regular consultations from late March through June 2015, the work of the subcommittee was also informed by a survey of experts across the fusion energy sciences community. For a description of the survey and its respondents, please see Appendix B.

An overview of the DOE Fusion Energy Sciences (FES) program has been provided later in this introduction, as well as a description of the FES research portfolio, since those two elements offered context for the science and technology applications discussed, and they also defined the scope of applications appropriate for inclusion in the report.

The subcommittee identified seven topical areas related to the FES portfolio for review:

- Basic plasma science
- Low temperature plasmas
- Space and astrophysical plasmas
- High energy density laboratory plasmas and inertial fusion energy
- Particle accelerator technology
- Fusion nuclear science
- Magnetically confined plasmas

Separate sections of this report cover each of these areas, starting with a short overview of the subfield and its relationship to FES, followed by a table listing non-fusion applications organized into topical areas, and then concluding with expanded descriptions of a few highlighted examples. Some applications span more than one of these topical areas and thus appear in multiple categories.

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Those applications and advances beyond fusion energy research may be incomplete; for the field is still growing and new technologies are still emerging, and due to time constraints on the preparation for this report, there are inevitable omissions. Nonetheless, the basis set of examples that informed the report is comprehensive and representative of the many scientific and technological contributions made by the FES community.

The subcommittee considered economic impact of FES investments, and found that the majority of the most recent data is 10 to 15 years old. Furthermore, disentangling the share of the impact that can be attributed to FES is complicated. Some of the applications described in this report include contributions from chemical engineers, NASA engineers and scientists, ion beam researchers, nuclear and particle physicists, materials scientists and others not directly affiliated with FES. The science and engineering associated with fusion is highly multidisciplinary, as are many of the applications described, and their development often benefits from a mix of funding sources, some of which are not FES-related. Some economic impact estimates were reported in the 2010 plasma decadal survey conducted by the National Research Council¹ and a report on the global economy of the 21st Century by the National Academies.² Finally, a study of economic impact of plasma technology in Germany³ includes estimates that may be comparable to those in the U.S., after correcting for differences in GDP between the two countries. Due to their ages, these reports do not reflect ongoing growth and recent development of new technologies related to FES, nor are they comprehensive in including all areas of technological development with contributions from FES efforts. Nevertheless, it is evident from these reports that the direct and indirect economic benefits from FES-related technologies are significant.

Furthermore, FES research has made a tremendous contribution to our science and engineering workforce, through the training of students and researchers who have subsequently led or contributed to the applications presented herein, as well as those omitted or in other fields. FES research is demanding and interdisciplinary, and thus provides an excellent training ground for the highly skilled and flexible thinkers who contribute to scientific and technological innovation.

2.2 U.S. Department of Energy—Fusion Energy Sciences (FES)

Mission

The FES program mission is to expand the fundamental understanding of matter at very high temperatures and densities and to build the scientific foundation needed to develop a fusion energy source. This is accomplished by studying plasma and its interactions with its surroundings across wide ranges of temperature and density, developing advanced diagnostics to make detailed measurements of its properties and dynamics, creating theoretical and computational models to resolve essential physics principles, and developing the requisite supporting technologies such as advanced materials that can withstand the extreme environment of a fusion reactor, and fusion fuel cycle essentials such as tritium breeding, injection, recovery, and reprocessing.

Background

The FES research program has been laying the groundwork for many years, to enter the next frontier in fusion research—the burning plasma era. The study of burning plasmas will be carried out as part of a program that includes advancing fundamental understanding of the underlying physics and technology, advanced theory and integrated computational simulation, innovative measurements, and optimization of magnetic confinement configurations. The current major focus of the U.S. fusion research program, as well as that of the world’s program, is the construction and eventual operation of ITER, an international project to design and build an experimental fusion reactor based on the ‘tokamak’ concept.

To achieve the mission goals to position FES to capture the scientific benefits generated from operating ITER, the FES research portfolio has been divided into four subprograms:

- Burning Plasma Science: Foundations
- Burning Plasma Science: Long Pulse
- Burning Plasma Science: High Power
- Discovery Plasma Science

A brief description and the key objectives for each of these categories, along with the major elements of the subprogram, are provided in the following paragraphs. More details can be found on the FES website <http://science.energy.gov/fes/>.

Burning Plasma Science: Foundations

This subprogram supports foundational experimental and theoretical research aimed at resolving magnetic-confinement fusion plasma science issues that will be faced in the next generations of machines, including ITER. This subprogram will establish the scientific basis for the optimization of both the advanced tokamak and spherical tokamak approaches to magnetic confinement fusion, develop a predictive understanding of burning plasma behavior, develop technologies that will enhance the performance of both existing and next-step machines, and provide necessary

infrastructure improvements across the FES program. The elements of the program included in this category are as follows:

- The research and operations of the three major U.S. machines at General Atomics (DIII-D), the Massachusetts Institute of Technology (Alcator C-Mod) and the Princeton Plasma Physics Lab (NSTX)
- Theory and Scientific Discovery Through Advanced Computing (SciDAC) Activities
- Smaller research projects
- Plasma technology

Burning Plasma Science: Long Pulse

This subprogram supports experimental research that addresses new and unique scientific regimes that can be achieved with long-duration superconducting international machines and development of the materials required to withstand the harsh conditions that must be faced in a burning plasma environment. This subprogram utilizes new capabilities to accelerate our scientific understanding of how to control and operate a burning plasma, as well as to develop the basis for a future fusion nuclear science facility that, together with ITER, will provide the required basis for fusion energy. The elements of the program are as follows:

- International Research Program
- Domestic Stellarator Research
- Advanced Design and Materials Research Program

Burning Plasma Science: High Power

This subprogram supports the U.S. Contributions to the ITER Project, which includes in-kind hardware components, personnel, and direct funding to the ITER Organization for the ITER construction phase, established by the terms of the ITER Joint Implementing Agreement. The key objective of this subprogram will be the completion of all activities associated with the U.S. Contributions to ITER Line Item Project. The element of the FES program that will be included in this subprogram is as follows:

- U.S. Contributions to ITER Line Item Project

Discovery Plasma Science

This subprogram supports investigations into fundamental plasma properties and processes, innovative diagnostic techniques, and validation of state-of-the-art theoretical models and simulation codes on small- and intermediate-scale, single-purpose experimental platforms. This subprogram is to expand and enhance the knowledge base of general plasma physics, particularly as it pertains to fusion-plasma science, and to uncover directions for future plasma-related contributions to the DOE missions. The elements of the program to be included in this category are as follows:

- General Plasma Science Program
- High Energy Density Laboratory Plasmas (HEDLP) Program
- Innovative Measurements Program
- Madison Symmetric Torus (MST) Research Program
- Exploratory Magnetized Plasma Program

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Applications by Area

3.1 Basic plasma science

Plasmas are ionized gases, composed of a mixture of particles, including neutral atoms and molecules as well as freely-roaming electrically charged ions and electrons. Basic plasma science is the study of fundamental processes taking place in plasmas—the state of matter occupying 99% of the visible universe. Examples of these fundamental processes include: 1) multi-phase phenomena such as dusty comet tails, 2) explosive instabilities such as those that occur on the flaring sun, 3) naturally-derived particle acceleration processes such as fantastically high energy cosmic rays, 4) magnetic reconnection associated with twisting magnetic field lines in plasma which, for example, occurs on the sun 5) self-organization associated with remarkable pattern formation within plasmas, 6) spatially localized plasma turbulence and 7) strongly correlated plasmas (warm dense matter, strongly coupled waves and particles). A fundamental understanding of these physical processes not only advances our understanding of plasma physical phenomena, but this knowledge also provides the pathway or bridge to addressing technological problems here on Earth. Basic plasma science research involves the study of complex multi-scale, non-equilibrium and non-linear phenomena, often overlapping into other disciplines. Investment in the field therefore goes well beyond applications, as it contributes to a better understanding of other fields as well. Indeed, the field is interdisciplinary, cutting across fluid dynamics, condensed matter physics, atomic physics, space physics, and statistical mechanics.

Applications to science and technology beyond fusion

Plasma science research contributing to the fusion effort and/or supported by DOE has led to outcomes benefitting many other fields. A list of contributions is provided in Table 2, which is organized by major categories. Basic plasma science research is driven by curiosity and pursued in wonder. Researchers in this exciting field are exploring the discovery frontier while at the same time providing a basis that influences other scientific communities, and new applications that support both the economy and national security. The field as a whole is broad, and here we provide four example areas of research: non-neutral plasmas, dusty plasmas, magnetic self-organization and micro-plasmas.

Table 2: Contributions from basic plasma science research to non-fusion science and technology.

Basic Science <hr/> <ul style="list-style-type: none">• particle physics• astrophysics: turbulence, magnetic energy release, particle accelerators, dynamos and energy transport• planetary sciences: planetary magnetospheres and ionospheres	National Security <hr/> <ul style="list-style-type: none">• chemical sensing
Lighting <hr/> <ul style="list-style-type: none">• low profile, efficient room lighting	Semiconductor Manufacturing <hr/> <ul style="list-style-type: none">• computer chips—improved throughput and yield with smaller features
Materials <hr/> <ul style="list-style-type: none">• Improved solar cell efficiency• antimatter-based material characterization methods	Space Propulsion <hr/> <ul style="list-style-type: none">• Hall thrusters• double layer thrusters
Medical/Health <hr/> <ul style="list-style-type: none">• Positron Emission Therapy (PET)• anti-proton tumor treatment• enhanced wound healing• ozone generators for medical sterilization, food preparation, and water purification	Transportation <hr/> <ul style="list-style-type: none">• durable jet engine turbine blades

Non-neutral plasmas

Non-neutral plasmas are, as the name implies, essentially collections of either charged electrons or charged ions. That makes them different from normal plasmas, which have roughly equal numbers of positive and negative particles, and gives rise to their similar, and yet distinctive, properties.

For instance, non-neutral plasmas exhibit dynamic behavior in a manner similar to normal plasmas, and are also capable of supporting collective behavior such as oscillations, wave propagation, and electrostatic shielding. However, non-neutral plasmas also exhibit behaviors that are quite different from regular plasmas. Interestingly, these plasmas can be confined stably and indefinitely using electric and magnetic fields, a feat that has proven to be particularly elusive in normal plasmas with equal numbers of negative and positive charges. Also unlike normal plasmas, cooled non-neutral plasmas display rather exotic and bizarre properties, such as crystallization and liquid-like behavior.

Those distinctive properties give non-neutral plasmas myriad of technical and practical applications. One of the most essential is the common magnetron, in which trapped electrons interact with slow-wave structures immersed in crossed electric and magnetic fields, producing microwaves. This is the basis of all our high power microwave sources ranging from radar to heating fusion plasmas to warming up lunch!

Highlighted examples of non-neutral plasma applications

Fundamental particle physics

Perhaps one of the higher profile applications of non-neutral plasmas lies in the exotic realm of antimatter research. One goal of the field is to accumulate large amounts of this antimatter for study. This is typically achieved using an electromagnetic trap to capture exclusively either positive or negative antiparticles (to prevent annihilation). Antimatter is subsequently examined, in the form of a non-neutral plasma. Non-neutral plasma traps are used to trap both antiprotons and antielectrons—a.k.a. positrons. In non-neutral plasma traps, antimatter can be confined and studied for long time periods. Combining positrons and antiprotons from the respective traps allows for the production of anti-hydrogen. There is much we don't know about antimatter—for example we don't know the reason for the lack of abundance of antimatter in the universe. In this regard, basic plasma science is the driver for obtaining a better understanding of big questions ranging from quantum field theory to particle physics to astrophysics.

Engineering better materials

Antimatter in the non-neutral plasma state also serves as a tool to enhance our understanding of materials. For example, structural wear in nuclear reactors can be detected using positron beams. Such studies improve the reliability of reactors and allows for accurate assessment of projected reactor lifetime. Semiconductor devices are the basis for the instruments of our modern world (e.g., smart phones). The concentration of engineered defects in these materials which determines their functionality are studied using positron beams.

Medical diagnostics and treatment

Non-neutral, positron plasma traps can fuel intense positron beams for medical imaging applications and cancer treatment. For example, positron beams are being considered for external imaging in contrast to conventional positron emission tomography, PET, where a radioactive positron source has to be injected into the body. The external approach features annihilation of positron beams outside the patient, producing radiation that is then directed to create a medical image. Antiproton beams are being studied for cancer tumor treatment. Antiproton beams have been shown to be four times more effective than conventional proton beam therapy because the antiproton annihilates upon impact thereby releasing much more energy into the tumor.

Exploring the final frontier—future flight

Non-neutral antimatter plasma traps have also been studied for space propulsion applications in the future. Here antiparticles exiting the non-neutral plasma trap annihilate in a magnetic nozzle ‘combustion chamber.’ The resulting exhaust products travel at near the speed of light. Antimatter propulsion would be the ultimate solution to in-space rocketry. This energetic exhaust may one day propel humans to the farthest reaches of the solar system. Such envisioned applications such as the aforementioned innovations, would not be possible if it were not for investments in the study of non-neutral plasmas.

Dusty Plasmas

Dusty plasmas are ubiquitous in nature. They give rise to a wide range of visually stunning images associated with outer space ranging from galactic clouds to the rings of Saturn. A dusty plasma is essentially an ionized gas which also contains suspended electrically charged particulates—dust. These typically micron-sized particulates pick up charge in the presence of a plasma and thus act as super-massive, charged molecules. The dynamics of dusty plasmas differ from conventional plasmas owing to the extreme mass difference between ions and dust particles. Because these particles are charged, a dusty plasma is strongly coupled, as the charged dust can exert electrostatic forces. Indeed, dusty plasmas manifest fluid-like behavior and even crystallization, where the dust particles are distributed in an orderly 2-D array. Dusty plasmas are studied in laboratories here on Earth by applying an electric field that cancels the gravity force, allowing the dust particles to levitate.

Highlighted examples of dusty plasma applications

Basic planetary and astrophysical science

It has been theorized that the very formation of the solar system started with the coagulation of dust particles in a primal dusty plasma. Striking evidence for this is seen in dusty disks surrounding young stars. Magnetized plasmas are currently being studied at the FES-funded Magnetized Dusty Plasma Experiment at Auburn University, and at several facilities around the world, which allows for direct studies that improve our understanding of interstellar clouds, star formation regions, and even comet tails. Basic plasma science research of dusty plasmas therefore improves our understanding of the formation of collective structures in space.

Improving throughput and yield in computer chip manufacturing

Plasmas play critical roles in the fabrication of silicon-based integrated circuits (IC) that are the core components of all electronic devices. Plasmas are used to etch and deposit materials on thin silicon substrates, in a series of carefully planned steps that result in the formation of tiny transistors and capacitors, and the tiny wires that connect them into complex, integrated circuitry. Advances in plasma technology fuel Moore's law, thus giving us improved electronics performance and leading to a doubling of the number of transistors on a chip every 2 years or so. This translates to smaller, lighter, and more efficient and capable cell phones, for example.

In the semiconductor manufacturing plasma environment, nucleation reactions within the plasma can lead to atomistic formation of dust particles, building up layer by layer. Charged by the surrounding plasma, these particles levitate electrostatically above the silicon wafer being processed. When the process step is complete and the plasma is shut off, the particles fall to the substrate surface, statistically damaging the newly fabricated circuits, ultimately leading to a loss in yield. The formation of the dust particles in the plasma is still not completely understood, but its ultimate resolution as a result of ongoing research will not only solve a technological problem, but will also provide insight into dust formation processes taking place in the upper atmosphere and space.

Safer, more efficient jet engines

Dusty plasmas are also utilized in a number of other manufacturing arenas, such as spray coatings. Jet engine turbine blades are typically spray coated with ceramic particles for thermal protection. This is achieved through the injection of ceramic powder into a flowing plasma jet, forming a dusty plasma. The plasma jet melts the particles and carries them to the substrate where they deposit as splats on the blades. Research on the charging and melting processes of these injected particles—fundamental dusty plasma physics—has been key in understanding and optimizing this process.

Efficient solar cells and fuel cells

Dusty plasmas can be utilized as nucleation 'factories' for the production of nanoparticles and nano-crystals. These particles have special electronic properties that can be used to improve the efficiency of photovoltaic solar cells. Use of nanocrystal quantum dots improves solar cell energy efficiency to levels well above 25%, the current state-of-the-art. Nanoparticles fabricated through plasma nucleation have also been exploited as nano-catalysts for hydrogen conversion, and used to improve performance of advanced quantum dot electronic devices.

Magnetic self-organization

The magnetic field plays an important role in the field of plasma physics. In both technological application and experiment, in many cases plasma is confined using a magnetic field. In a plasma discharge in which current is flowing, a self-magnetic field is formed, which in turn interacts with the charged particles. The combination of self magnetic field and an applied magnetic field gives rise to complex charged particle motion.

Under some circumstances, the magnetic field in a plasma will self organize into spatially coherent magnetic structures. This phenomenon is not well understood. Magnetic self-organization is an important subfield of basic plasma science. Research in this area influences not only our understanding of plasma confinement, but also our understanding of the basis of the Earth's magnetic field.

Highlighted examples of magnetic self-organization applications

Basic astrophysical theory

If one surveys the universe, the magnetic field and its effects are ubiquitous. The structure of galaxies and nebula are all influenced by the magnetic field. One big unanswered question of our time is, *where does the magnetic field come from in nature?* There is no mythical bar magnet or electromagnet at the center of a galaxy that gives its shape. The honest answer is that we really don't know but basic plasma physics experiments are converging on the answer. Spontaneous magnetic field generation via 'dynamo action' is believed to be at play in the formation of nascent magnetic field lines. Such physical processes are believed to be the underlying origin of the Earth's magnetic field. By dynamo action we refer to the conversion of electrically conductive fluid motion to magnetic field energy. Whether at the center of a galaxy or the core of the Earth, the turbulent motion of a highly conductive fluid such as plasma or liquid metal (as in the Earth's core), is predicted to give rise to a magnetic field through self-organization processes. Seed magnetic field lines grow to the large-scale structure that we observe today. A number of dynamo experiments, including the FES-funded Madison Plasma Dynamo Experiment, are investigating electromagnetic agitation of conductive plasma as an analogue to the conductive core of the Earth. Modeling that complements experiment targets understanding the origin of Earth's magnetic field. Here basic plasma science links plasma physics to both geophysics and astrophysics.

Electric thrust—plasma rockets

Self-organization is also observed in plasma devices with technological applications here on Earth. The Hall Effect thruster is a rocket engine that accelerates ions to produce thrust. The device has a fuel efficiency that is over 10 times that of a chemical rocket, which means less fuel is required to make the same propulsive maneuver. The Hall Effect thruster is currently used to maintain orbits of both commercial and military satellites, as well as provide primary propulsion for orbit transfer to destinations beyond Earth orbit. Under certain conditions, the plasma self-organizes, forming essentially spatially coherent blobs of plasma that rotate in a direction perpendicular to both the direction of the magnetic and electric field in the device. The process, though poorly understood, is believed to play a key role in determining overall engine efficiency and stability. Such phenomena have also been observed in pulsed magnetron devices used for materials processing. Research investments aimed at understanding these processes will extend the capability of these devices. Interestingly, the rotating phenomenon may be driven by a theorized astrophysical phenomenon known as critical ionization, which has been postulated as a mechanism leading to the formation of the planets. In this respect, Hall thruster applied research can shed light on fundamental processes active in nature!

Micro-plasmas

Plasmas can now be produced on submicron length scales, at high pressure (at or above atmospheric pressure). These exceptionally thin-layered plasmas pack power densities as high as 1 MW/cm^3 —that's higher than a nuclear power reactor or even the core of a star! Plasmas in this range of parameter space are known as micro-plasmas. The surface area to volume ratio of these tiny plasmas is incredibly large. This means that the discharge is highly coupled to the surfaces it contacts. Understanding the behavior and application of such plasmas is an active area of research in the field of basic plasma science. Micro-plasmas open new doorways into the realm of multi-disciplinary science. The micro-plasma state can couple directly to energy band levels in semiconductor materials thus giving birth potentially to a new class of plasma coupled semiconductor devices.

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Highlighted examples of micro-plasmas applications

Plasma-based electronics

Novel electronic devices not possible with conventional semiconductors such as micro-plasma-based photodetectors and transistors can greatly improve the speed and capability of existing electronics. These tiny plasmas can also serve as the excitation source for compact chemical sensing detectors, enabling so-called 'lab on a chip' devices to detect, for example uncontrolled releases of chemical agents. Such devices have the potential to not only support homeland security detection but to also improve safety in industrial settings. Micro-plasma arrays can be scaled in size according to application. For example, to adjust illumination for lighting, one can simply change the number of active micro-plasmas.

Cool, efficient lighting

Flat, low profile, energy efficient light sources have been developed based on micro-plasma discharges. These light sources can be fashioned into almost any shape making them ideal for seamless integration into wall or ceiling surfaces. Similar platforms are also being developed as commercial sources for ozone production, supporting sterilization of surfaces in medical treatment and food preparation facilities, wound sterilization, as well as water purification.

3.2 Low temperature plasmas

Low Temperature Plasmas (LTPs) have several distinctive features compared to other plasmas, characteristics which have made them uniquely enabling for a vast range of technology applications. Their study has presented cutting-edge scientific and technological possibilities and provided foundational support across areas of plasma and fusion energy sciences.

LTPs are relatively cool when compared to other types of plasmas, such as the 'hot' plasmas required to achieve controlled fusion, although they are quite hot compared to conditions in daily life, with electron temperatures hotter than the surface of the Sun. That's precisely the characteristic that gives LTPs such significant and far-reaching technological utility. LTPs also contain significant numbers of neutral atoms and molecules, in addition to ions and electrons, which means they function much like factories, with chemical reactions and electronic excitations producing desired products at the atomic scale.

Compared to massive astrophysical plasmas (such as in stars) and to those under development for controlled fusion, LTPs are generally small in size, with dimensions in the range of 1 meter down to less than a millimeter. LTP 'discharges' may be formed in air or in a liquid, but most often are created in a vessel with a selected gas at sub-atmospheric pressure.

As illustrated in Figure 1, the ability to harness LTPs has had a tangible impact on many aspects of modern society including computer chips, flat screen TVs and monitors, water purification, nanotechnology and health care treatments. Manufacturing of jet engines depends on LTPs, as do artificial hip joints and cell phones. Additional examples in the domain of fusion energy include 'neutral beams' for heating of magnetically confined plasmas and high power lasers for inertial confinement fusion.

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Figure 1: A household scene shows many examples of how low-temperature plasma applications enhance everyday life.¹

- | | |
|---|--|
| 1. Plasma TV | 13. Plasma-deposited silicon for solar cells |
| 2. Plasma-coated jet turbine blades | 14. Plasma-processed microelectronics |
| 3. Plasma-manufactured LEOs in panel | 15. Plasma-sterilization in pharmaceutical production |
| 4. Diamondlike plasma CVD eyeglass coating | 16. Plasma-treated polymers |
| 5. Plasma ion-implanted artificial hip | 17. Plasma-treated textiles |
| 6. Plasma laser-cut cloth | 18. Plasma-treated heart stent |
| 7. Plasma HID headlamps | 19. Plasma-deposited diffusion barriers for containers |
| 8. DB-Plasma-produced H ₂ in fuel cell | 20. Plasma-sputtered window glazing |
| 9. Plasma-aided combustion | 21. Compact fluorescent plasma lamp |
| 10. Plasma muffler | |
| 11. Plasma ozone water purification | |
| 12. Plasma-deposited LCD screen | |



Many of the fundamental concepts central to other branches of plasma physics originated in the study of LTPs. The field of LTPs continues to hold fundamental scientific challenges, largely centered on the control of power through the plasma for the selective production of reactive atoms and molecules, ions, and photons. To get a sense of the current status of societal contributions of LTP science, one needs to look no further than the *Engineering Grand Challenges* (<http://www.engineeringchallenges.org>) for the 21st century compiled by the National Academy of Engineering. Of the fourteen challenges on the list, LTPs are playing a direct role in the solutions for at least six:

- Make solar energy economical
- Provide energy from fusion
- Develop carbon sequestration methods
- Provide access to clean water
- Engineer better medicines
- Engineer the tools of scientific discovery

Applications to science and technology beyond fusion

Applications of low temperature plasmas to science and technology beyond fusion are so numerous that an exhaustive listing of every application is beyond the scope of this report. Nevertheless, Table 3 includes a large enough number of applications to capture the scope and interdisciplinary reach of LTP science and technology, while many other LTP applications appear in other sections of this report. In addition, three sub-areas of LTP science and technology—nanomaterials, thrusters for space propulsion and atmospheric plasmas for biomedical and other applications—have been highlighted, with descriptions in greater detail.

Table 3: Contributions of low temperature plasmas to non-fusion science and technology.

<p>Basic Science</p> <ul style="list-style-type: none"> • Interfaces and multiple phases in plasmas; plasma biochemistry • predictive control of plasma kinetics • plasma collective behavior and nonlinear transport <p>Light sources and displays</p> <ul style="list-style-type: none"> • fluorescent light bulbs • high intensity discharge lamps • LCD displays & TVs; LEDs: plasma fabrication methods • discharges for gas lasers <p>Materials</p> <ul style="list-style-type: none"> • surface treatments/plastics and polymers: for personal care, medical, and adhesive products, packaging, etc. • physical vapor deposition for decorative and functional coatings • nanomaterials synthesis: graphene films, carbon nanotubes • economical solar cells: fabrication with plasma processing • electric power grid: high power plasma switches • energy saving controls, enabled by compact powerful microprocessors • glass skyscraper temperature control: plasma deposited window glazings 	<p>Medical/Health</p> <ul style="list-style-type: none"> • antimicrobial treatments, medical instruments, fresh produce • dermatology: wounds, dental, cancer and HIV • drinking water purification • plasma surgical scalpel • biocompatible surfaces for tissue engineering • surface hardening/prosthetic implants <p>National Security</p> <ul style="list-style-type: none"> • chemical sensing <p>Semiconductor manufacturing</p> <ul style="list-style-type: none"> • improved fabrication throughput and yield • next generation semiconductor fabrication: plasma etching, thin film deposition, plasma doping <p>Space Propulsion</p> <ul style="list-style-type: none"> • Hall thrusters: double layer and VASIMR • gridded ion thrusters <p>Transportation</p> <ul style="list-style-type: none"> • durable jet engine turbine blades <p>Waste Treatment</p> <ul style="list-style-type: none"> • plasma assisted combustion • municipal waste gasification • hazardous waste vitrification • greenhouse gas conversion
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Select examples of low temperature plasma applications

Nanomaterials

Nanomaterials have the potential to revolutionize many fields of science and technology, including electronics, chemical synthesis, energy storage, and environmental and pharmaceutical applications. What makes nanomaterials revolutionary is that their properties can be radically different from their feedstock material because of their high surface to volume ratio, lack of structural defects, and quantum effects. For example, carbon nanomaterials can be stronger, have higher electrical conductivity and lower thermal conductivity than carbon, depending on their size and shape. By definition, nanomaterials have at least one dimension smaller than 100 nanometers. They can be extremely chemically active because of their enormous ratio of surface area to volume.

Commercialization of nanomaterials requires reliable, predictable, large-scale and low-cost synthesis. Presently adopted chemical synthesis techniques are reliable and predictable, but nanomaterial growth is slow and not low cost. Plasma synthesis has the potential to make manufacturing economical, with its high throughput, short nanostructure growth time, low cost, and optimized material properties. The present cost of chemical synthesis processes limits nanomaterial application development. In contrast, plasma nanoparticle synthesis not only sustains a higher yield both in volume production and on surfaces, but also often can be achieved at lower process temperature and higher chemical purity compared to conventional chemical synthesis. FES is supporting research to understand plasma processes and their control because plasma control can potentially lead to commercialization of plasma synthesis with specifically tailored nanoparticle structures and properties.

Highlighted examples of nanomaterials applications

Present nanomaterial research is producing exciting new materials with a diversity of applications. Highly insulating materials are being created to package food with no air diffusion and building materials are being created that are stronger and have better insulation. Pharmaceuticals are using nanoparticles to efficiently and selectively deliver drugs that allow for a reduction of dosage and a reduction of side effects. Ultra-thin nanolayers allow for more efficient absorption of light in solar cells and will vastly improve their efficiency. Another innovative nanostructure is the nanotube. They are hollow on the order of 10 nanometers in diameter and 100s of nanometers in length. Plasma synthesis of nanotubes is an enabling technology for applications such as chemical purification and chemical synthesis. Furthermore, they have been used in photo-catalytic dissociation of water into hydrogen and oxygen.

Graphene supercapacitors

Battery replacements called ‘supercapacitors,’ containing nanostructures fabricated using LTP deposition processes, will increase energy storage capacity and lifetime in computers and cell phones. Of even greater impact, supercapacitors have the potential to enable high-energy-density storage and rapid charging for electric vehicles. Nanosheets of carbon, called graphene, form a crystal that is only a single atom thick, giving the supercapacitors a considerable size advantage. In addition, their high strength, electrical conductivity, low thermal conduction and their semiconducting properties make them a potential replacement for silicon in high performance transistors and integrated circuits.

Thrusters for space propulsion

An exciting application of low temperature plasmas is advanced space propulsion otherwise known as electric propulsion. Electric propulsion is a facet of rocket science that considers those engine systems that utilize electricity to produce thrust. Typically, these engines convert propellant gas into a low temperature plasma and then apply electric and magnetic fields to accelerate the plasma particles to produce thrust. Whereas the energy source in chemical rockets is stored in the chemical bonds of the fuel and is thus energy-limited, in plasma rockets, the energy source is a power supply. Energy and fuel are therefore separate in this case, allowing one to add arbitrary amounts to energy to the propellant thereby achieving high exhaust velocities—10 to 100 times that of chemical rockets. These efficient engines are currently being used for station-keeping on orbiting platforms such as the Boeing Direct TV communication satellites.

Highlighted application of thrusters for space propulsion

Gridded ion thruster

The gridded ion thruster is a type of plasma rocket that accelerates and expels ions to produce thrust. This engine has been used to propel a space probe to multiple objects such as the dwarf planet Ceres and the massive asteroid Vesta on the DAWN mission.

Atmospheric pressure plasmas and biomedical applications

Low temperature plasma science experiments and technological applications are traditionally carried out at reduced atmospheric pressure, *i.e.*, in vacuum chambers. A recent development in this field of plasma science is the expansion of low temperature plasma applications to atmospheric pressure and higher. Because vacuum chambers are no longer needed, atmospheric pressure plasma operation can reduce costs while increasing process rates. In addition, atmospheric plasmas can be used for applications involving substrates that cannot withstand vacuum, such as human tissue. In some atmospheric plasmas, as with their low-pressure counterparts, the gas molecules and ions that make up the plasma are at room temperature.

The electrons on the other hand are the energetic species. Electrons in such high-pressure plasmas produce light by exciting the background gas and produce highly reactive atoms and molecules called ‘radicals,’ in addition to ions via collisions. Radicals then drive chemical reactions in the gas phase and at bounding surfaces. The end result is a glowing reactive gas that can be used for a range of applications. In this operating regime, the physical processes at the atomic and molecular level that dominate outcomes are sufficiently different that they create new research challenges in scientific experiment and modeling.

In other atmospheric plasmas, known as ‘thermal plasmas,’ electric power is applied in a sufficiently high concentration that all the plasma particles reach an elevated temperature. Thermal plasmas are used in a number of applications as an efficient means to convert electrical power to a localized heat source.

Municipal water purification

Ozone (O₃) is increasingly replacing chlorine use for treatment of municipal drinking water supplies, due to its effectiveness at destroying viruses and bacteria with minimal environmental impact. Large-scale ozone generation for municipal and industrial purposes is based on atmospheric pressure LTPs generated in pure oxygen. Improved understanding of LTP discharge dynamics has enabled recent advances in efficiency and cost for ozone treatment facilities.

Microbial decontamination

Plasmas created in air have also been found to produce antimicrobial effects. Treatments with air plasmas require no vacuum or gas handling equipment, reducing cost and making them adaptable to many substrate geometries and materials. Microbicidal activity is attributed to multiple agents produced in air LTPs, including reactive oxygen and nitrogen-containing species, UV radiation and charged particles, and has been shown to inhibit the spread of even antibiotic resistant bacteria (e.g., MRSA, CREs and C-DIFF). Applications include purification of drinking water, sterilization of medical instruments such as surgical tools, endoscopes and central venous catheters, as well as equipment for food preparation and even food products such as fresh fruit and meat.

Plasma medicine

The new and emerging field of plasma medicine has been enabled through the study of the chemical interaction of atmospheric pressure LTPs with living organisms. Plasma interactions with cells lead to activation of chemical pathways that may be utilized in cancer therapy, wound sterilization and healing, treating dental infections and HIV therapy. Control of the production of reactive chemical species, especially those containing oxygen and nitrogen, formed in the plasma adjacent to living tissue is central to effective treatments. The creation of molecules of appropriate chemical composition at room temperature, to avoid burning or otherwise injuring the tissue, is possible only due to the low-energy-density, but high particle-specific energy, properties of LTPs.

3.3 Space and astrophysical plasmas

Space and astrophysical plasma research involves the study of plasma physics occurring throughout the universe, extending from Earth's upper atmosphere to the farthest reaches of the cosmos. Space physics encompasses phenomena primarily within our solar system, including Earth's upper atmosphere, ionosphere, and magnetosphere; the Sun; the solar wind; the ionospheres and magnetospheres of other planets; the interaction of the solar wind with the interstellar medium; and galactic cosmic rays. Plasma astrophysics primarily encompasses the realm beyond Earth's solar system, but has important overlaps with space physics. Astrophysics research includes star and planet formation; magnetic field generation in stars, galaxies, and clusters; explosive events such as stellar and solar flares; energetic particle acceleration; and the formation and evolution of plasma jets.

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Space and astrophysical plasmas cover a broad range of physical parameters that overlap parameters of laboratory and fusion energy plasmas. Consequently, many complementary research areas exist whereby knowledge gained through fusion energy experiments can be utilized for the understanding of space and astrophysical plasmas, such as magnetic reconnection, plasma turbulence, magnetic dynamos, and multi-scale transport. The development of numerical models and the assimilation of data into predictive models are also areas of fruitful overlap.

Space plasma physics is a discipline that combines fundamental physics research with applications having direct societal benefit. As described in the most recent decadal survey *Solar and Space Physics: A Science for a Technological Society (2013–2022)*, plasma physics is at the core of the basic and applied research needed to understand and predict the dynamics of the Sun-Earth environment. To develop this understanding, the space plasma environment serves as a vast natural laboratory, which with our national and international space-based and ground-based observing infrastructure allows the direct study of solar activity, multi-scale coupling to Earth's magnetic field, and interactions with our atmosphere.

Through recent developments in technology and the global integration of our economic and security infrastructures, space physics also has an essential role in safeguarding the technologies that underpin modern society. The electric power grid, global navigation systems, satellite operations, and our air and space travel are all impacted by the dynamics of the space environment, referred to as space weather. Consequently, the understanding of plasma physics and the development of predictive numerical models are essential, both to safeguard our modern infrastructure and to enable future exploration and utilization of space.

In the last 15 years FES, together with other agencies, has supported laboratory experiments focused upon improving the understanding of astrophysical, solar, and space phenomena. This new field is referred to as laboratory plasma astrophysics. In a properly scaled and controlled laboratory experiment, the subtle physics details can be studied using plasma diagnostics with extraordinary spatial and temporal resolution.

Space and astrophysical plasma research has benefited from rapid advances resulting from huge strides in observational and computational capabilities. Satellite and ground-based observations measure plasma processes from the solar interior to accretion disks. In-situ measurements of local plasma properties have been expanded throughout our solar system: Earth’s magnetosphere, the solar wind, other planets magnetospheres, and the boundaries of our solar system. Multiple, coordinated satellites have greatly improved spatial and temporal resolution of magnetospheric measurements. Remote-sensing observations from both space and ground have moved beyond the traditional visible wavelengths to almost every wavelength band from far infrared emission from cold, partially ionized plasmas during star formation, to hard X-ray emission from extremely hot plasmas. In many cases, astrophysics and plasma computation can improve our interpretation of these observations.

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Whereas space-based and ground-based instruments allow the in-situ and remote sensing of many aspects of the space plasma environment, laboratory plasma studies enable the investigation of controlled and reproducible plasma conditions not possible in space. Fusion energy research, therefore, provides a valuable, complementary approach to understanding basic and applied space plasma physics. Laboratory plasma investigations that have been valuable for space plasma research include: magnetic reconnection, atomic spectroscopy, plasma wave generation, wave-particle interactions, collisionless shocks and ionization/charge exchange cross sections. Other astrophysical phenomena being studied in controlled laboratory experiments that have been supported by FES include momentum transport in accretion disks and proto stars, atomic kinetics and opacity pertinent to photo-ionized plasma surrounding black-hole accretion disks, white-dwarf photospheres, and warm, absorbing environments associated with active galactic nuclei.

Applications to science and technology beyond fusion

Contributions from space and astrophysical plasma science in areas that overlap with the FES program portfolio are summarized in Table 4, which is organized by topic. In addition, brief descriptions of selected examples are also included.

Table 4: Contributions from space and astrophysical plasmas to non-fusion science and technology.

<p>Astrophysics</p> <ul style="list-style-type: none"> • plasma spectroscopic techniques to interpret astrophysical observations • laboratory studies: formation/generation of collimated astrophysical plasma jets • plasma wave applications to space plasma modeling • fusion-developed gyrokinetic codes for space weather <p>Ionospheric physics</p> <ul style="list-style-type: none"> • ionospheric plasma stability and turbulence (e.g., GPS interference) 	<p>Magnetospheric physics</p> <ul style="list-style-type: none"> • magnetic reconnection geomagnetic storm prediction • radiation belt acceleration and transport • mitigation of spacecraft charging • boundary layer formation and dynamics • structure of planetary magnetospheres • spacecraft propulsion <p>Solar physics</p> <ul style="list-style-type: none"> • magnetic reconnection solar flare prediction • solar energetic particle acceleration • solar coronal evolution and heating • spectroscopic diagnosis of solar irradiance • improved telescope optical filters
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Magnetic Reconnection

Magnetic reconnection is the dominant process for dissipating magnetic energy in the universe. It has dynamical importance in a broad range of space and astrophysical and laboratory fusion plasma phenomena. It also has intrinsic scientific interest because the release of magnetic energy in a macroscopic system is linked to the dynamics of a narrow boundary layer where dissipation facilitates the breaking of magnetic field lines. Magnetic reconnection is seen in the evolution of solar flares, coronal mass ejections, and interaction of solar wind with the Earth's magnetosphere. It controls the energy storage and release processes responsible for major solar eruptions, such as coronal mass ejections, and for geomagnetic activity that impacts critical infrastructures such as the electric power grid. It is also considered to occur in the formation of stars. It occurs as the self-organization process in current carrying fusion plasmas, typically observed in major and minor disruptions of tokamak discharges, and in relaxation processes in reversed field pinch (RFP) and spheromak plasmas. Magnetic reconnection involves a topology change of a set of field lines, which leads to a new equilibrium configuration of lower magnetic energy. During this process magnetic energy is converted to kinetic energy.

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One dedicated laboratory experiment funded by FES has made significant progress in the understanding of magnetic reconnection, the Magnetic Reconnection experiment, MRX, at the Princeton Plasma Physics Laboratory. The experiment was noted for resolving a fifty year-old problem in understanding the rate of reconnection in collisional plasma. The Sweet-Parker model (1963) predicts the rate of reconnection, but it predicted orders of magnitude slower rates than observed for solar, space, astrophysical, and laboratory plasmas. The experiment observed the scaling of the Sweet-Parker reconnection rate, and was in good agreement when the theory was generalized by using the observed enhanced plasma resistivity instead of the classical resistivity. Understanding how magnetic reconnection is triggered and how it evolves to drive mass, momentum, and energy transport is one of the primary challenges identified in the most recent Solar and Space Physics Decadal Survey. NASA's recent Magnetosphere Multiscale Mission (launched in 2015) is designed to study magnetic reconnection and to develop predictive understanding needed for space weather forecasting of geomagnetic storms. MRX has been funded by NASA to provide support to this NASA mission. Besides other advances in understanding reconnection, recently measured the conversion of magnetic energy to kinetic and thermal energy to be approximately 60%. Although theorists believed, and observations suggested, the energy conversion efficiency should be high, only the MRX experiment actually measured it, and is currently studying the energy conversion mechanisms.

Electron Acceleration and Earth's Radiation Belts

Satellites in orbit around Earth experience a harsh and dynamic radiation environment due to bands of relativistic electrons, named the Van Allen radiation belts. These energetic electrons cause electrostatic charging and the disruption of satellite functionality and can also pose a hazard for astronauts during extra-vehicular activities. The electron radiation levels are highly dynamic, varying by many orders of magnitude on time scales ranging from minutes to years, driven by short-term geomagnetic activity as well as long-term solar cycle changes. NASA's Van Allen Probes mission, launched in 2012, is designed to investigate the numerous acceleration and transport processes and to understand how the radiation belts are controlled by geomagnetic storms.

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Numerical simulations supported by FES have been applied to the wave environment near Earth to investigate particle energization, transport, and loss important for the prediction of the radiation belt dynamics. In particular, the LArge Plasma Device (LAPD) at UCLA has made important contributions to understanding the basic physics of fusion and space plasmas, including the interactions of energetic ions and electrons with plasma waves, the detailed properties of Alfvén waves in inhomogeneous plasma conditions, and magnetic reconnection during the collisionless interaction of an energetic laser produced plasma with a large magnetoplasma.

Global Navigation Satellite Systems and Ionospheric Disturbances

The Global Positioning System (GPS), one of a growing number of Global Navigation Satellite Systems (GNSS), provides critical positioning, navigation, and timing information utilized by nearly all facets of modern technology. From a distance of nearly 20,000 kilometers, the faint signal transmitted by the GPS satellites can easily be scattered by disturbances in the ionosphere, which is the dense plasma layer that lies between the GPS satellites and Earth's surface. Laboratory experiments are used to investigate the stability of plasmas and the subsequent relaxation by plasma turbulence. These experiments advance our understanding of the formation of and instabilities in ionospheric plasmas and of the potential disruption of satellite signals and communication.

3.4 High energy density laboratory plasmas and inertial fusion energy

FES is a major national steward for basic science and technology related to plasma physics and fusion energy research. FES has been involved in two particular programs relevant to the plasma physics of inertial confinement fusion (ICF), inertial fusion energy (IFE), and related topics.

FES and the DOE National Nuclear Security Administration (NNSA) launched the Joint Program in High Energy Density Laboratory Plasmas (HEDLP) in FY2007 to improve stewardship of the important and rapidly emerging area of fundamental high energy density (HED) science. A series of National Research Council and other reports documented the scientific importance of this area of research. The 2003 National Research Council (NRC) report *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science* defined HED conditions as those environments associated with total pressures exceeding 1 million atmospheres. Examples of extreme environments now scientifically accessible with current facilities include the center of the earth (pressures of approximately 4 million atmospheres), the interiors of Jupiter, Saturn, and large exoplanets (pressures of approximately 50 million atmospheres), and the center of the Sun (pressures of approximately 1 trillion atmospheres).

FES and NNSA jointly developed a set of specific scientific opportunities in HED science via a traditional DOE Office of Science research needs workshop process in FY2009.⁴ The field has made strong progress since this time. The various large-scale NNSA ICF/HED science facilities (NIF, Omega, and the Z-machine) have developed or continued basic science user programs as recommended in federal reports. More recently, FES has consolidated much of their HED science effort at the Materials at Extreme Conditions (MEC) end station at the Linac Coherent Light Source (LCLS). International activity in the field of HED science is strong, with major user programs at various facilities including the Laser Megajoule (LMJ) in France, the Vulcan laser at the Rutherford-Appleton Laboratory in the UK, and the X-ray Free Electron Laser (XFEL) in Germany.

The NNSA High Average Power Laser (HAPL) program, funded by Congressional direction within the NNSA ICF and High Yield Program, ran from FY2000 to FY2009. This program, established to explore key scientific, technological, and engineering questions associated with IFE, developed science and technology that have found application outside of fusion energy research. Technologies with broader application developed by the HAPL effort included high average power lasers, repetitively pulsed projectile launching and tracking, and advanced target fabrication techniques.

Research capabilities for high energy density laboratory plasmas and inertial fusion energy

Probing of matter at extreme conditions of temperature, density, and pressure typically involves the study of smaller plasmas (millimeter-scale and smaller) of shorter duration (picoseconds to nanoseconds) than the meter-scale and second-duration plasmas encountered in magnetic fusion. Advances in areas such as laser and pulsed power technology, high-speed photonics instrumentation, precision materials

science, and computational simulation have been crucial to the ability to produce, diagnose, and study these plasmas in detail and thereby explore the fundamental properties of matter at extreme conditions.

The range of facilities on which university researchers can perform HED plasma experiments has increased in recent years, reflecting increased access to major research facilities, the construction of the MEC end station, and also an increase in the number and capability of relevant smaller facilities at universities. This has opened a new area of research in the physical sciences, as noted in the 2003 NRC *High-Energy-Density Science*⁵ and other reports.⁶

Large scale facilities

The NNSA National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) is the world's most energetic laser facility. NIF's 192 beams produce approximately 1.8 million joules of energy in a pulse several nanoseconds in duration. Focusing NIF beams on various target types can produce pressures exceeding tens to hundreds of millions of atmospheres. NIF has a program to support basic science experiments by university and other researchers.

The NNSA Omega Facility at the University of Rochester Laboratory for Laser Energetics (LLE) provides two large lasers (OMEGA and OMEGA EP) for inertial fusion and high energy density science research. The National Laser User Facility (NLUF) program at Omega has hosted 189 HED science research projects from US universities and companies since 1979. Approximately 30% of available time at Omega is dedicated to basic scientific research.

The Z-machine at Sandia National Laboratories (SNL), a NNSA facility, uses magnetic fields arising from 24 mega-ampere ultra-high electrical currents to compress and heat matter to high energy density conditions. Similar to NIF and Omega, Z has a basic science user program that leverages and complements NNSA programmatic inertial fusion and high energy density science activities.

Intermediate scale facilities

Intermediate scale facilities have a significantly higher shot rate than NIF, Omega, or Z, and typically require several scientists and technicians to support operations. Examples of U.S. intermediate scale facilities include the Texas Petawatt laser at the University of Texas Austin, the Jupiter, Trident, and Nike lasers at Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and the Naval Research Laboratory, respectively, and the Hercules laser at the University of Michigan. The laser facility within the Materials at Extreme Conditions (MEC) end station at the Linear Coherent Light Source (LCLS) is also an intermediate scale facility. The use of LCLS to probe matter compressed by the MEC laser source represents an important new area of scientific opportunity.

Intermediate scale facilities are national resources that operate user programs and provide a much more 'hands-on' experience, an appropriate component of graduate education. Technological advances have enabled facilities of this scale to achieve matter conditions, albeit typically with smaller plasma volumes, that a few years ago

would only be available at large facilities. Intermediate scale facilities provide a crucial link between individual investigator level efforts and experiments at the large-scale facilities.

Research in basic HED science and IFE related science and technology has also produced a wide range of computational tools of benefit beyond fusion. HED science researchers have developed and validated computational models of stellar evolution, nucleosynthesis, photon emission from accretion disks, and other astrophysical phenomena. Simulation tools such as the Warp code at Lawrence Berkeley National Laboratory described below have been applied to a diverse range of topics including basic plasma science medical therapy, accelerator design, and ultra-high intensity laser-matter interactions.

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Non-fusion applications of HEDLP and IFE

Table 5 summarizes non-fusion applications of basic HED science and the High Average Power Laser Program (HAPL).

Table 5: Contributions from high energy density laboratory plasmas and inertial fusion energy activities, including the joint program in HEDLP and the HAPL program, to non-fusion science and technology.

<p>Accelerator physics</p> <ul style="list-style-type: none"> • laser wakefield acceleration • plasma wakefield acceleration • intense laser/plasma and beam/plasma interactions • particle beam transport <p>Basic plasma science</p> <ul style="list-style-type: none"> • radiation dominated dynamics/properties • magnetized HED plasma physics • nonlinear optics of plasmas • laser-plasma interactions • relativistic HED plasma and intense beam physics • high energy density hydrodynamics <p>Computational tools and methods</p> <ul style="list-style-type: none"> • simulation codes for: beam physics, astrophysics, etc. • computational algorithms and methods <p>Enabling technologies</p> <ul style="list-style-type: none"> • high average power laser technologies • high peak power laser technologies • optical, x-ray and particle diagnostics • pulsed targets and target tracking • robotics for target fabrication <p>Laboratory astrophysics</p> <ul style="list-style-type: none"> • fluid dynamics: e.g. supernovae, etc. • x-ray transport: stars and other hot objects • jet formation/propagation • high energy astrophysics • radiatively-driven dynamics: molecular clouds, young stars, etc. • accretion disks in: black holes, neutron stars, star formation 	<p>Materials science and applications</p> <ul style="list-style-type: none"> • attosecond x-ray probing of materials • designer materials: e.g. advanced foams, mass precision coating of particulates • non-destructive testing: x-ray, neutron and particle beam sources • radiation processing of materials • radiation damage of materials • surface modification w/electron beams • processing of wide bandgap materials <p>Matter at extreme conditions</p> <ul style="list-style-type: none"> • exotic matter at ultrahigh density • warm and hot HED matter: atomic/electronic structure, fundamental material properties <p>Medicine and molecular biology</p> <ul style="list-style-type: none"> • precision radiographic imaging • Positron Emission Tomography (PET) • intense particle beam generation: cancer therapy and other applications <p>National security</p> <ul style="list-style-type: none"> • Next generation directed energy weapons <p>Nuclear physics</p> <ul style="list-style-type: none"> • nuclear physics in dense plasma environments • nucleosynthesis—s, r, p process reactions • validation of stellar evolution models <p>Planetary physics</p> <ul style="list-style-type: none"> • equation of state • material structure at ultra-high pressure • planetary internal energy production • exoplanet properties • pyconuclear reactions <p>Transportation</p> <ul style="list-style-type: none"> • Next generation laser peening of aircraft components <p>Waste treatment</p> <ul style="list-style-type: none"> • destruction of fossil fuel NOx emissions
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Properties of giant planets and exoplanets—new frontiers in condensed matter physics

To date, planetary scientists have detected nearly 2,000 planets outside our solar system. For some of these planets, advanced observational techniques allow us to determine the mass and radius of these planets. However, due to lack of knowledge regarding the properties of matter in the deep interiors of these planets, typically at pressures in the 100 million-atmosphere range, we have little understanding of the structure and evolution of these planets or their ability to host life. Experiments at NIF, the Omega laser, and elsewhere are now accessing these conditions in the laboratory, where accurate measurements of the properties of diamond (thought to form the core of many large planets) at pressures up to 50 million atmospheres are being compared to planetary evolution models. These experiments are providing insight into exoplanets and opening new frontiers in condensed matter physics.

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Astrophysics in the laboratory—understanding energy transport in the sun

Iron is important for understanding energy transport in the sun due to its relatively high x-ray absorption, or opacity. Experiments at the Sandia National Laboratories Z Machine have precisely measured the x-ray opacity of iron at solar interior conditions. These experiments, made possible by the Z Machine's unique capabilities, heated an iron sample to temperatures above 2 million Kelvin and revealed that iron opacity is approximately 30–400 percent greater than predicted. These new results help resolve a long-standing problem in solar physics: Standard Solar Model predictions disagree with observations, a dilemma that affects our understanding of every sun-like star in the sky. The higher opacities change the predicted structure of the solar interior and significantly improve agreement with solar observations. This experiment is one of many examples in the flourishing area of laboratory astrophysics that involves the use of HED facilities to investigate star formation, supernova explosions, the synthesis of elements in stellar interiors, black hole physics, and other exotic phenomena previously not accessible in the laboratory.

Probing structure of matter at the atomic scale: experiments with the world's brightest x-ray beam

The science and applications of ultra-intense laser-matter interactions have emerged as frontier areas of research for the 21st century. The creation of the shortest known light pulses, the formation of new states of matter in extreme conditions, and the promise of intense directional sources of energetic particle beams and hard x-rays are poised to revolutionize many fields in the physical and life sciences.

Experiments at the MEC end station at LCLS couple the world's brightest x-ray beam with high-power optical lasers to resolve the ultrafast heating dynamics of matter and observe structural changes on atomic scale lengths. A recent example demonstrated the ability to measure how atoms interact with each other as matter transitions from a solid to the plasma state, improving our fundamental understanding of modifications to atomic structure in high-density environments. This very important result will have significant impact in areas such as computational simulation of high-density plasma behavior.

Inertial fusion energy simulation tools for accelerator design and other applications

The Warp code is a particle beam and plasma simulation capability developed originally for heavy-ion-beam driven inertial fusion energy. Warp has been broadly adopted by the scientific and engineering research community. Warp applications include accelerator design, medical therapy, border security, and basic plasma science. Specific accelerators where Warp has been applied include the Large Hadron Collider (LHC), the Spallation Neutron Source (SNS), the Relativistic Heavy Ion Collider (RHIC), and the Rare Isotope Accelerator (RIA) at the Facility for Rare Isotope Beams (FRIB).

3.5 Particle accelerator technology

An accelerator particle beam is a non-neutral plasma where the thermal energy is much less than the directed energy along the path of the beam. Accelerator particle beams may be composed of ions or electrons, and can penetrate through and/or scatter off of atoms and molecules. That capability, when coupled with state-of-the-art detectors and sophisticated computer imaging technology, has given scientists the ability to visualize a whole host of materials at atomic-level resolution. As a consequence, particle beams have given researchers new insights into everything from viruses and important cellular signaling proteins to essential and exciting materials such as stainless steel and metallic glass. In this section we focus on scientific and practical applications of particle beams and accelerators where collective or plasma phenomena are important in either acceleration or beam transport processes.

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Particle Acceleration

Plasma wakefield acceleration is a technique for charged particle acceleration in which plasma processes play a direct role in forming the accelerating electric fields. In a plasma accelerator, the conventional fixed accelerating structures (such as massive high-power superconducting radio frequency cavities) are replaced with a much smaller structure formed dynamically with a plasma column, where very large electric fields for acceleration of particles can be produced by separation of electrons and ions in a dense plasma. A plasma wakefield can be generated by either an intense laser or an electron beam. In demonstration experiments, laser- and beam-driven plasmas have achieved electric fields three orders of magnitude greater than those of conventional accelerators. Wakes with electric fields 6 orders of magnitude larger than in conventional accelerators appear to be possible. In principle, this would allow developers to reduce the size of accelerators from kilometers to millimeters, and the costs of building them by similar orders of magnitude. Developing practical plasma accelerators will take additional research and engineering, requiring the generation of extended stable wakefields, the controlled synchronized injection of particles into the wave ‘buckets,’ and the generation of mono-energetic beams.

Particle Beam Transport

From the perspective of plasmas physics, particle beams can be divided broadly into two classes with the following extremes: beams dominated by externally applied forces (emittance dominated), and those dominated by internal or collective forces (space-charge dominated or intense). The phenomena associated with collective effects in beam physics are closely aligned with plasma physics. In general, non-linear or time dependent collective effects have a negative impact on beam quality. Non-linear space charge forces act on the beam in the same way as a non-linear lens would on an optical beam, and can result in an entangled beam distribution of poor optical quality that is difficult to focus and control. Some examples of accelerators where collective effects are important include those for spallation neutron sources, free-electron lasers, and for fusion energy applications.

Spallation Neutron Sources

Spallation neutron sources in current use for materials science studies—such as the facility at Oak Ridge National Lab—are driven by intense proton beams with

energies of up to 1 GeV and average powers of up to 1.4 MW. The high beam power makes control of beam loss an important aspect of current and future projects. Controlling beam loss and instabilities in accelerators for neutron science requires improved methods, including understanding beam-loss mechanisms and improving beam control. This effort includes beam diagnostics for intense beams, and verified simulation models, and novel methods of beam-distribution control and feedback. Neutron research helps scientists improve materials used in a multitude of different products, such as high-temperature superconductors, powerful lightweight magnets, aluminum bridge decks, and stronger, lighter plastic products.

Free-Electron Lasers

Free-electron lasers (FELs) use electrons to produce extremely intense coherent photon beams, which can then be focused like a laser onto targets at incredible temporal (on the order of femtoseconds) and with astonishing spatial (at the level of individual atoms) resolution. FELs are coming into their own in biomedical imaging and materials characterization. For instance, the Linac Coherent Light Source, a free-electron x-ray laser at DOE's SLAC National Accelerator Laboratory, has given new insights into key cellular signaling proteins known as G protein coupled receptors, as well as shown scientists the first glimpse of a chemical bond being born.

Accelerators for Fusion Energy

Accelerator technology plays a key role in both magnetic and inertial confinement fusion, either as a supporting technology in certain aspects of fusion plasmas or as the central component for ion-beam-driven inertial fusion energy and related aspects of high energy density physics. Accelerators also play a central role in the development of materials required by fusion technologies. The need for an intense neutron source to perform accelerated evaluations of materials for fusion power systems has motivated fusion scientists to propose the International Fusion Materials Irradiation Facility, a joint Japan-European Union project that is part of the ITER Broader Approach.

3.6 Fusion nuclear science

Fusion Nuclear Science covers the broad science and technology programs needed to support the production and sustainment of multi-megawatt fusion plasmas. These programs can be arranged into four topical themes, which describe the scientific and technical issues that must be resolved to achieve practical fusion energy: (1) controlling high-performance burning plasmas (ITER), (2) taming the plasma-materials interface (substantially, but not completely, addressed by ITER), (3) conquering nuclear degradation of materials and structures, and (4) harnessing fusion power (tritium science, chamber technology and power extraction). The scientific and technical challenges associated with these themes are extraordinary and will require exceptional, world-leading experiments to address them. This is because the materials directly in contact with the fusion plasma will experience extreme fluxes of heat and particles, while simultaneously suffering neutron radiation damage, which involves coupled physical phenomena over a wide range of time and length scales.

Creating and Controlling High-Performance Burning Plasmas

The goal of this theme is to establish the state of knowledge sufficient for the construction, with high confidence, of a device that permits the creation of sustained plasmas which meet simultaneously all the conditions required for practical production of fusion energy.

Taming the Plasma-Materials Interface

The goal of this theme is to establish the state of knowledge sufficient to design and build robust material components facing the hot plasma in the presence of very high neutron fluences.

Conquering Nuclear Degradation of Materials and Structures

The goal of this theme is to design high-performance, self-healing material architectures.

Harnessing Fusion Power

The goal of this theme is to establish the state of knowledge sufficient to design and build, with high confidence, robust and reliable systems that can convert fusion products to useful forms of energy in a reactor environment, including a self-sufficient supply of tritium fuel.

Non-Fusion Applications

Table 6 provides a simplified list of contributions to the non-fusion areas in science and technology that research on Fusion Nuclear Science and use of DOE national lab test stands by industry and small businesses have made. They are organized by category: Medical/Health, Space Propulsion, Materials, Transportation/Pulsed Power, and Basic Science.

Table 6: Contributions from fusion nuclear science research to non-fusion science and technology.

Basic Science <hr/> <ul style="list-style-type: none">• improved SLAC PEP-II accelerator• high intensity beams of rare isotopes• simulations to understand ionospheric plasmas	Medical/Health <hr/> <ul style="list-style-type: none">• Compact neutron sources for boron neutron capture therapy• improved x-ray diffraction tubes• Terahertz sources for medical imaging
Materials <hr/> <ul style="list-style-type: none">• improved strength stainless steel radiation-tolerant ceramic-matrix composites• multi-scale materials modeling applied to nuclear fuel performance• Improved chambers for plasma etching• prompt-gamma neutron activation analysis to improve quality and consistency of materials	Transportation/Pulsed Power <hr/> <ul style="list-style-type: none">• improved car radiator performance• refractory high temperature foams for Brayton cycle applications
	Space Propulsion <hr/> <ul style="list-style-type: none">• improved space-based heat rejection• simulations for understanding hypersonic re-entry and the blackout

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Highlighted applications of fusion nuclear science

Boron neutron capture therapy.

The RF-driven multicusp ion source developed at Lawrence Berkeley National Laboratory (LBNL) has found numerous applications ranging from neutral beam injection systems for fusion reactors to particle accelerators, proton therapy machines for cancer treatment and ion implantation systems. Recently, LBNL has developed a compact, sealed accelerator-tube neutron generator capable of producing a neutron flux in the range of 10^9 to 10^{10} D-T neutrons per second, which can be moderated to therapeutically useful energy ranges for Boron Neutron Capture Therapy, (BNCT), resulting in a 65% higher dose in the center of the brain over normal BNCT systems. The strength of the dose rate is limited by the heat flux tolerance of the target plate. LBNL optimized the target plate thermal management by testing prototypes on the High Heat Flux Test Stand located at Sandia National Laboratories.

High Performance Stainless Steel

ORNL researchers developed a new cast stainless steel that is 70% stronger than comparable steels. Casting results in additional benefits, including the ability to make complex shapes and a reduction in the material loss in traditional drilling and machining operations. The high performance steel, which has improved resistance to stress and radiation, was developed for fusion environments such as the ITER tokamak, but also has applications to next generation nuclear power plants. These alloys will also help engine manufacturers meet emission regulations for diesel, turbine, and gasoline engine applications.

Refractory High-Temperature Foams

In a cooperative research and development agreement or CRADA with Ultramet Inc., Sandia National Laboratories tested a high temperature heat exchanger in which heat was exchanged between liquid lithium and helium. The Li/He Refractory HX was an application for use in space and among its innovative uses is a surface of tiny molybdenum needles to enhance heat transfer with the lithium and molybdenum foam through which the helium flowed.

Radiation-Tolerant Ceramic-Matrix Composite

Today, certain ceramics are known to possess exceptional tolerance against neutrons and other types of radiation. FES materials science researchers at ORNL had found the intrinsic radiation-insensitivity of silicon carbide and developed highly radiation-tolerant silicon carbide ceramic composites for nuclear thermo-structural applications. The nuclear grade silicon carbide ceramic composites are now central to the accident-tolerant fuels and core technologies, which are being developed for the current and next generation nuclear reactors to survive severe accidents. These composites are also considered for applications to various Generation IV advanced nuclear reactor concepts.

Multiscale Materials Modeling Applied To Nuclear Fuel Performance

The hierarchical, multiscale materials modeling of high-energy neutron-induced materials degradation, which was developed within the U.S. fusion materials program, has been implemented within the Consortium for the Advanced Simulation of Light water reactors (CASL) to improve the physical fidelity of fuel performance modeling. This approach, in which atomistic and micro-structural data inform the engineering scale data, leads to the development of improved models of irradiation creep of zirconium alloy cladding, and is providing improved assessments of the safety margins of current and next generation nuclear power plants.

3.7 Magnetically confined plasmas

Understanding the plasma science and the materials science associated with magnetic fusion energy environments is essential to the development of practical fusion energy. Although fusion has now evolved from a dream to a laboratory reality, there are still major challenges which must be met before it can become a practical energy source. Addressing these challenges has and will continue to yield rich benefits for other fields of science and technology. Areas of understanding and technology that must be improved include:

- The physics of high temperature plasmas (which have very complex behavior)
- Cutting edge computational capabilities
- Sophisticated methods for heating fusion plasmas to 100s of millions of degrees
- Innovations in materials, magnets and control mechanisms
- Creation of new diagnostics and sensors (*e.g.*, how do you measure temperatures and pressures in something that is 100,000,000 degrees?)
- Complex engineering innovations (including heat removal, remote maintenance, and impurity removal)

The great progress that has been made to date in fusion research has been the result of a long series of important breakthroughs in both science and technology. Meeting these challenges has resulted in and will continue to result in important spinoffs and contributions to other areas of science and technology. Some of these spinoffs and contributions have been in the areas of superconductivity, medical/health, space propulsion, semiconductor manufacturing, improvements in materials, waste remediation, transportation/pulsed power, national security, and basic science.

Magnetic Confinement

Because plasmas consist of free charged particles, they can be bent, compressed, confined or otherwise held by magnetic fields. Magnetic confinement fusion devices are designed to confine hot, dense plasmas for a sufficient period of time (a few seconds) for nuclei to fuse by overcoming their natural repulsive forces. An operating fusion energy reactor must attain sufficiently high energy density for the fusion to become self-sustaining (ignition) and generate economically significant energy gains. Magnetic confinement can be produced in a straight configuration, solenoid, or curved back onto itself to form a toroid. There are several toroidal magnetic configurations that have been investigated (stellarator, reversed field pinch, and the levitated dipole), but the most successful in producing high density, high temperature, high confinement plasmas is the 'tokamak.' The tokamak is characterized by toroidal symmetry with a helical magnetic field produced by a combination of current driven within the plasma and external field coils.

Non-Fusion Applications

Table 7 provides a simplified list of the non-fusion areas in science and technology to which research on magnetically confined plasmas has made contributions. They are organized by category: Superconductivity, Medical/Health, Space Propulsion, Materials, Waste Treatment, Transportation/Pulsed Power, Semiconductor Manufacturing, National Security, and Basic Science.

Table 7: Contributions from magnetically confined plasma research to non-fusion science and technology.

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Basic Science

- basic plasma physics
- nonlinear dynamics and chaos
- computational science
- space plasma physics
- atomic physics and x-ray lasers
- high-performance supercomputers and networking communications
- advanced simulation methods

Materials

- ion implantation for surface hardening
- UV drying of inks, coatings and adhesives
- conformal ceramic coatings
- microwave/RF sintering of ceramics
- manufacturing of diamond films
- polymer film surface modification
- high performance stainless steels
- polymer-electrode bond—synthetic muscle
- fabrication of carbon fiber
- high heat flux materials
- ‘high temperature’ superconducting cable
- characterization of material composition

Medical/Health

- Magnetic Resonance Imaging (MRI)
- cancer treatment (proton beam)
- skin disinfection
- wound care
- medical isotope separation/production
- grain sterilization and milk pasteurization (pulsed power gamma rays)
- neutron radiography
- RF egg pasteurization

National Security

- Electromagnetic Aircraft Launch System (EMALS) for aircraft carriers
- verification of nuclear warheads
- remote fissionable material detection
- non-lethal crowd control with microwaves

Semiconductor Manufacturing

- plasma materials processing for fabrication of integrated circuits
- plasma electronics, including plasma TVs

Space Propulsion

- Variable Specific Impulse Magnetoplasma Rocket (VASIMR)

Superconductivity

- iron-free superconducting synchrocyclotron
- Nuclear Magnetic Resonance (NMR)
- superconducting synchrocyclotron x-ray lithography
- magnetic separation of materials (e.g., clay)
- high temperature superconducting electrical wires

Transportation/Pulsed Power

- magnetically levitated trains
- Insulated-gate bipolar transistor (IGBT) power conversion for buses, wind turbines, earth movers

Waste Treatment

- toxic waste reduction
- cryo-pellet cleaning of surfaces
- microwave cleaning of surfaces
- smoke stack metal emission monitor
- reducing vehicular pollution
- electron beam destruction of chemical waste
- microwave removal: contaminated concrete

A new era in naval aviation

The Electromagnetic Aircraft Launch System (EMALS developed by General Atomics) is now replacing the Navy’s steam catapults on aircraft carriers. The use of electromagnetics lowers operating costs and improves catapult performance. The enabling innovation came from fusion research development of precision control of sequencing magnets. For EMALS, that precision enables enormous propulsion capacity and expands the range of manned and unmanned aircraft that carriers can now launch.

Cutting the cost of carbon fiber

Oak Ridge National Laboratory researchers developed a more efficient system for microwave plasma processing of carbon fiber at half the cost. Potential commercial applications include:

- Automotive: Lighter weight material can improve vehicle performance
- Wind turbine blades: Enabling longer and lighter weight blades to increase efficiency
- Electronics and consumer goods: Ability to strengthen and cut weight for components of communications electronics and sporting goods

High Frequency Dynamic Nuclear Polarization (DNP) NMR

High frequency gyrotrons, developed for plasma heating in the FES program, are now having a dramatic impact on the field of solid-state Nuclear Magnetic Resonance (NMR) research. Using high frequency microwaves enables the polarization of the electron spin system, eventually leading to polarization of the nuclear spins in a process known as Dynamic Nuclear Polarization (DNP NMR). The increase in signal to noise ratio can be several hundred, an enormous enhancement allowing experiments to be completed in days rather than months. Solid-state NMR is a key technique for investigating the structure of biomolecules.

World's most compact superconducting cable

Oak Ridge National Laboratory researchers have worked with industry to develop high-temperature (68K to 77K) superconducting (HTSC) power cables. The major innovation is the usage of stainless steel laminated second generation HTSC wires, which when deployed produce a voltage along the cable length under fault conditions that limits the fault current. This technology can help electric utilities deliver more power with greater voltage control at high-current densities and fewer transmission losses, resulting in reduced need for additional transmission towers or new underground rights-of-way.

Saving the public from food poisoning

Princeton Plasma Physics Lab fusion researchers working with the USDA have developed a novel technique for rapidly pasteurizing eggs right in the shell in a fraction of the time of conventional methods. The novel technique employs radio frequency (RF) energy, a process used in heating fusion plasmas, to transmit heat through the egg. The USDA estimates that pasteurizing all U.S.-produced shell eggs could reduce the number of egg-borne salmonella cases by up to 85 %, or more than 110,000 cases a year. The new method uses radio frequency (RF) energy to transmit heat through the shell without damaging the delicate egg white.

Broadening availability of cancer treatment

Developing advanced superconducting coils for FES research at the MIT Plasma Science and Fusion Center has led to important innovation in cancer treatment through proton beam radiotherapy. In this medical application, proton beams can be more precisely shaped to the size and thickness of tumors and leave surrounding tissue unharmed. MIT FES researchers developed a compact, superconducting, high-field synchrocyclotron that is about 40-times smaller, lighter (about 25 tons) and an order-of-magnitude less expensive than conventional magnet technology machinery, enabling more hospitals to provide the therapy. They are working on reducing the weight by almost another order of magnitude, by eliminating all iron from the design.

Variable Specific Impulse Magnetoplasma Rocket (VASIMR)

Researchers at Oak Ridge National Laboratory developed a high power (up to 100 kW) radiofrequency (RF) helicon plasma source in collaboration with the Advanced Space Propulsion Laboratory (ASPL) at Johnson Space Center, for use in the VASIMR (Variable Specific Impulse Magnetoplasma Rocket) concept for advanced space propulsion. The source produces a plasma at high density comparable to that found in many present day tokamaks. This plasma is heated by a separate RF system to

millions of degrees, producing an exhaust velocity much higher than that achievable using a chemical rocket. The VASIMR device, which is undergoing further development by the Ad Astra Rocket Company, has many possible manned and non-manned space applications. The high-density helicon plasma source has been adapted for use in plasma-materials interaction studies for fusion and other applications.

Verifying nuclear warheads

Researchers at the Princeton Plasma Physics Laboratory (PPPL), Princeton and Yale Universities are developing a process called a 'zero-knowledge protocol' for verifying that nuclear weapons to be dismantled contain true warheads, thereby facilitating future arms reductions. The process would verify this without collecting any classified information about the materials or the design of the nuclear warheads, which could otherwise lead to nuclear proliferation. The researchers are producing a prototype of the system at PPPL that will test their idea by beaming neutrons at test objects with varying levels of opacity to neutrons.

Millimeter Wave Thermal Propulsion

Using high power millimeter wave sources (gyrotrons) developed by FES for Electron Cyclotron Heating (ECH) of fusion plasmas, NASA is exploring millimeter waves as an alternative approach that bypasses the energy limitations of chemical propulsion. Instead of relying on a chemical reaction as the energy source, energy is supplied externally via a beam of electromagnetic energy produced on the ground. Tests of candidate heat exchanger materials are being performed at General Atomics using one of the gyrotrons from their DIII-D Tokamak ECH System.

Appendix

Appendix A: Charge to FESAC



Department of Energy

Washington, DC 20585

February 4, 2015

Professor Mark Koepke
Chair, Fusion Energy Sciences Advisory Committee
Department of Physics – White Hall 203
West Virginia University
1315 Willey Street
Morgantown, WV 26506

Dear Professor Koepke:

The explanatory statement accompanying the Consolidated and Further Continuing Appropriations Act, 2015 (Public Law 113-235) requires the Office of Science to submit to the Committees on Appropriations of the House of Representatives and the Senate "... a report on the contribution of fusion energy sciences to scientific discovery and the development and deployment of new technologies beyond possible applications in fusion energy." We ask that the Fusion Energy Sciences Advisory Committee (FESAC) prepare a report on this topic.

Your report should consider a wide range of connections between research performed throughout the Fusion Energy Sciences (FES) portfolio and other scientific disciplines and technological applications. Applications beyond fusion energy will naturally focus on the curiosity-driven research areas of the FES portfolio (e.g., basic plasma science, low temperature plasma, space and astrophysical plasma, etc...), but may also involve spin-offs from anywhere in this portfolio.

Also, please consider scientific and technical applications of fusion and related plasma science to other branches of science. Even more broadly, please consider contributions to new scientific developments and technologies beyond possible applications in fusion energy related, but are not limited, to areas such as energy and the environment, materials science, medical diagnostics and treatment, biology, national security, and industry.

In your report, for each connection that you identify, please feel free to comment on how well the contributions of FES are advancing the interests of society and meeting its needs, and ensuring the Nation's competitiveness in the physical sciences and technology.

In preparing your assessment, we request that you engage some experts outside of the FES community to help evaluate possible applications beyond fusion. Please submit your report to me by May 15, 2015.

Sincerely,

A handwritten signature in black ink that reads "Patricia M. Dehmer".

Patricia M. Dehmer
Acting Director, Office of Science



Printed with soy ink on recycled paper

Appendix B: Community Survey

A survey of the U.S. fusion and plasma physics research communities was conducted to solicit suggestions of non-fusion benefits derived from fusion science related investments. An online questionnaire was distributed by email within the professional communities associated with work in fusion energy sciences and its applications in contexts outside of fusion. Over 1000 individuals were contacted, using lists from: DOE, high energy and nuclear physics accelerator communities, major fusion journals, the Burning Plasma Organization, High Energy Density Laboratory Plasmas (HEDLP) and High Average Power Laser (HAPL) participants, user facilities (LCLS/MEC, NIF, Omega, Z, Jupiter, Trident, and Nike) and professional societies including the IEEE Nuclear and Plasma Sciences Society (NPSS), and the American Nuclear Society.

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For the high energy density laboratory plasmas and inertial fusion energy category, activities with direct funding or mission connection to FES were considered. This includes work sponsored by the DOE Joint Program in HEDLP, the former NNSA HAPL Program, and basic science user activities at Omega, Z, NIF and other NNSA facilities. Other non-fusion activities funded by the ICF and High-Yield Campaign or other NNSA programs were not considered.

Although the time to respond to the survey was short, the subcommittee received over 100 inputs. The subcommittee wishes to thank those who contributed, as it was very helpful in directing the evaluation of the contributions fusion science research has made to other fields.

Sample cover letter

Dear colleagues, In response to a request from the U.S. Congress, the Fusion Energy Sciences Advisory Committee (FESAC) has appointed a subcommittee to prepare a report on “the contributions of fusion energy sciences to scientific discovery and the development and deployment of new technologies beyond possible applications in fusion energy.” In order to be comprehensive in listing all relevant activities in the report, we request your input through this survey. We ask that you make one or more entries describing recent developments connected to the activities of the DOE Office of Fusion Energy Sciences (FES), described in detail at <http://science.energy.gov/fes/>.

Survey questions

1. Select NFA category from the list below:

- Basic plasma science
- Low temperature plasmas
- Space and astrophysical plasmas
- High energy density laboratory plasmas and inertial fusion energy
- Fusion nuclear science
- Magnetically confined plasmas
- Other

2. Briefly describe a non-fusion science or technology development in an area supported by or otherwise connected to activities of the DOE Office of Fusion Energy Sciences. (Key groups or individuals may optionally be included in the description.)
3. What societal benefits, including contributions to other areas of science and technology, have or are likely to result from the development described above?
4. Your name and institution (optional)
5. I understand that submitted survey responses may be included in a report on behalf of the DOE Fusion Energy Sciences Advisory Committee in response to a request from the U.S. Congress. (Yes/No)
6. Has the work described been directly supported by the DOE Office of Fusion Energy Sciences? (Yes/No)

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Survey response

The responses have been saved as a pdf file in table format. The total number of responses received was 100 (some including multiple applications), and the number in each category are as follows:

- Basic plasma science: 13
- Low temperature plasmas: 18
- Space and astrophysical plasmas: 22
- High energy density laboratory plasmas and inertial fusion energy: 16
- Fusion nuclear science: 4
- Magnetically confined plasmas: 14
- Other: 13

Reference

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- 2** Committee on Prospering in the Global Economy of the 21st Century: An Agenda for American Science and Technology; Committee on Science, Engineering and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, National Academies Press, Washington D.C., 2007.
- 3** *Evaluierung Plasmatechnik*, VDI Technologiezentrum GmbH, Duesseldorf 2004 (in German).
- 4** Department of Energy Office of Fusion Energy Sciences, Basic Research Needs for High Energy Density Laboratory Physics, Report of the Workshop on High Energy Density Physics Laboratory Research Needs, Washington, DC, November 2009.
- 5** National Research Council, *High Energy Density Physics: The X-Games of Contemporary Science*, National Academies Press, Washington, DC, 2003.
- 6** National Science and Technology Council, Committee on Science, Interagency Task Force on the Physics of the Universe, Report of the Interagency Task Force on High Energy Density Physics, Washington, DC, August 2007.

**Applications of Fusion
Energy Sciences Research**

Scientific Discoveries
and New Technologies
Beyond Fusion

Fusion Energy Sciences
Advisory Committee