Applications of Fusion Energy Sciences Research:

Scientific Discoveries and New Technologies Beyond Fusion

prepared by the

FESAC "non-fusion applications" (NFA) subcommittee

Presented to FESAC on July 17, 2015

NFA subcommittee members

- Amy Wendt, *Chair*, UW-Madison
  - low-temperature plasma science and technology
- Richard Callis, *Vice Chair*, General Atomics
  - magnetic fusion energy science and technology
- Philip Efthimion, PPPL
  - plasma diagnostics and technology
- John Foster, University of Michigan
  - low-temperature plasma science and technology
- Christopher Keane, Washington State University
  - inertial fusion energy science and technology
- Terry Onsager, NOAA
  - space weather applications
- Patrick O'Shea, University of Maryland
  - particle accelerator technology

Charge to FESAC

- full charge included in report, Appendix A
- key elements:
  - charge is response to congressional request
  - report to:
    - include "....contribution of fusion energy sciences to scientific discovery and the development and deployment of new technologies beyond possible application in fusion energy"
    - within FES, include curiosity-driven research areas AND other spin-offs
    - consider applications to other branches of science
    - engage experts outside of FES community

Subcommittee effort: scope and process

- Applications organized into categories:
  - 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
- Community survey conducted

Community survey

- Survey short answer prompts:
  - *Describe a NFA science or technology development*
  - *What societal benefits have or are likely to result from above development*
- Link to web-based survey sent to >1000 individuals, using mailing lists from:
  - DOE, high energy and nuclear physics accelerator communities, major fusion journals, Burning Plasma Org., HEDLP and HAPL participants, user facilities, IEEE NPSS and ANS.
- 100 responses received

Report organization

- Executive summary
  - Topical themes
  - Specific findings
- Introduction
  - Scope of report
  - Overview of Fusion Energy Sciences
- Applications by FES category
- Appendices
  - Charge, economic impact, community survey

Finding: NFA topical themes

- fundamental science
- computational tools/methods
- lighting
- medical/health
- materials science and applications
- national security
- semiconductor manufacturing
- space propulsion
- transportation
- waste remediation

Specific Findings

1. The quest for fusion has led to numerous scientific insights and innovative technologies far afield from fusion energy research
2. The legacy of FES research is wide and pervasive, contributing, e.g., to the solar model AND to high performance computer chips
3. The tools, diagnostics, modeling and understanding derived from FES research apply to other disciplines
4. Spin-off technologies have had transformative societal benefit in many domains. E.g., electronics, lighting, drinking water, communications, manufacturing, transportation, energy savings, medical, environmental hazard mitigation

Specific Findings, cont.

5. FES research has yielded advances in computational science
6. Owing to its interdisciplinary nature, FES fundamental science contribution impact many fields, e.g., space physics, solid state physics, physical chemistry, quantum mechanics and particle physics
7. FES research has contributed a cadre of highly skilled scientists and engineers
8. The economic impact of FES NFAs is unquestionably large, but a complete economic impact analysis has not been conducted

Applications reported, sorted by FES category

- Each subsection consists of:
  - introduction to category
  - table of "applications," including survey contributions, grouped by theme
  - short descriptions of highlighted applications

Basic Plasma Science

- Basic plasma science is the study of fundamental processes taking place in plasmas
  - There are primarily seven fundamental processes that make up the subject matter of basic plasma science :
    1. Multiphase phenomena
    2. Explosive instabilities
    3. Naturally derived charged particle acceleration processes
    4. Magnetic reconnection
    5. Self organization associated with pattern formation in plasmas
    6. Plasma Turbulence
    7. Strong particle correlation
- A fundamental understanding of basic plasma physics not only advances our understanding of plasma physical phenomena, but this knowledge also provides the pathway or bridge for addressing technological problems here on Earth
  - The field is interdisciplinary cutting across fluid dynamics, solid-state physics, atomic physics, space physics, biological sciences and statistical mechanics

Basic Plasma Science Scope

- Basic plasma science research is curiosity-driven
- Basic plasma science as a whole is broad but four key, sub-topical areas give the flavor and some sense of scope of this exciting field :
  - Non-neutral plasmas
  - Dusty Plasmas
  - Magnetic Self-Organization
  - Microplasmas

Basic Plasma Science Derived Applications

Non-neutral plasmas

- Semiconductor device defect probing via positron beams
- Anti-proton sources for envisioned tumor treatment

Dusty plasmas

- Improvement in semiconductor device yield via understanding dust formation processes
- High performance, high temperature plasma-coated jet engine turbine blades

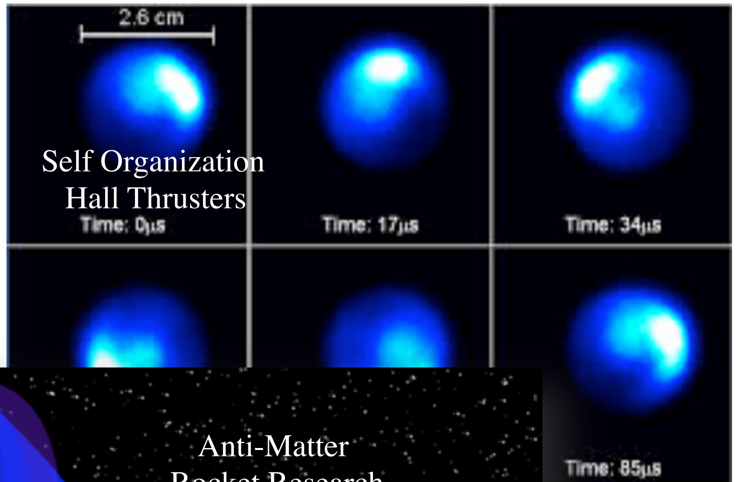
Self-Organization

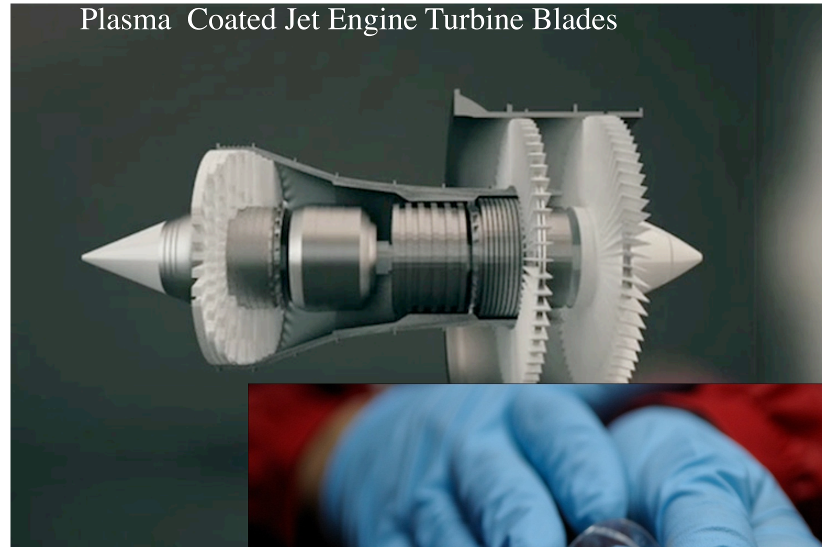
- Understanding the origin of the Earth’s magnetic field
- Understanding plasma self-organization and its effects on performance in Hall thrusters

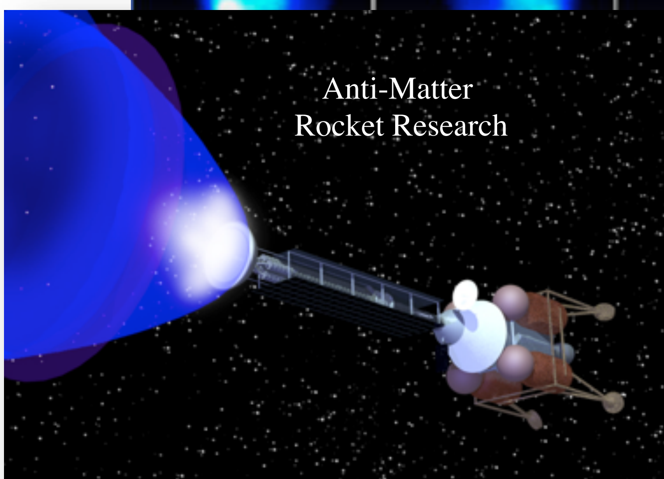
Microplasmas

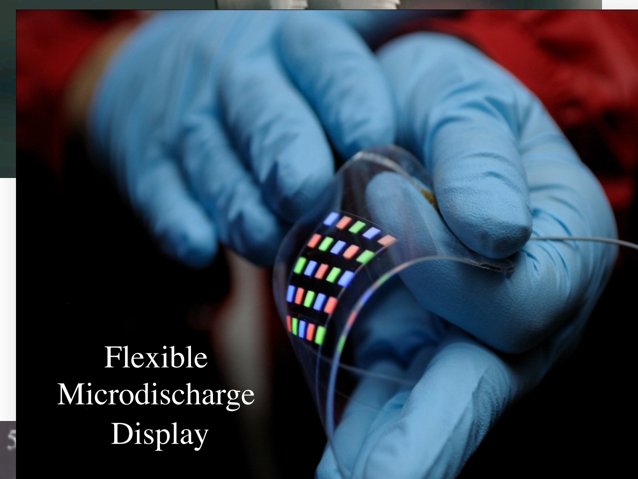
- Low profile, efficient white light sources for domestic and industrial lighting
- Plasma sources for scalable ozone production for water purification and UV sources for sterilization on bacteria contaminated substrates

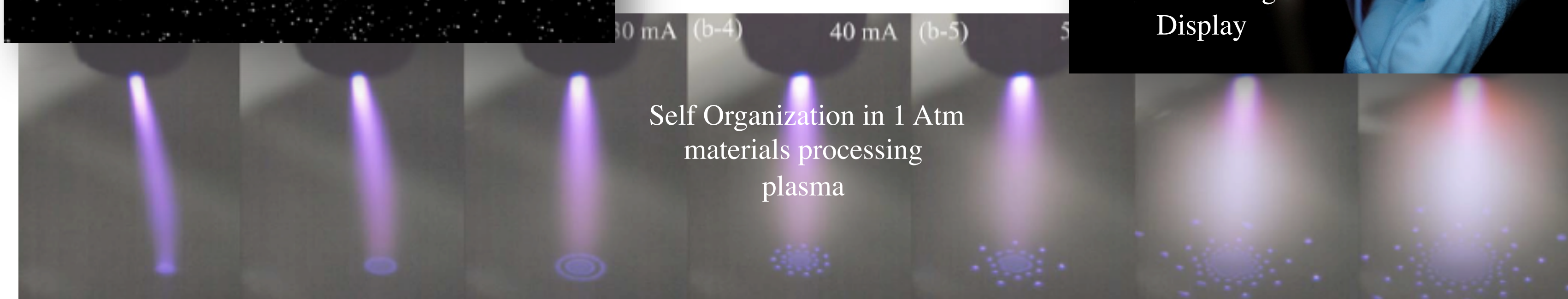
Basic Plasma Science Applications











Low Temperature Plasmas (LTPs)

- Subset of plasma parameter space with electron temperatures in the ~1-10 eV range. Typical distinguishing LTP characteristics include:
  - *Partial ionization* – electron collisions with neutral atoms/ molecules affect charged particle dynamics
  - *Non-equilibrium* – electron temperature much higher than gas and ion temperatures
  - *Molecular gas mixtures* – electron collisions drive "high temperature" gas phase chemistry while substrates remain cool
  - *Magnetic fields* – some, but not all, LTP applications employ magnetic confinement
- LTPs have many "knobs" -- methods of creation/ confinement, power input, operating pressure, gas mixtures -- and an incredibly broad array of applications

Non-Fusion Applications from Low Temperature Plasmas

Medical/Health
Anti-microbial treatments; water purification; dermatalogical treatments; surgical tools; biocompatible surfaces; prosthetic joints

Material Science and Applications
Semiconductor fabrication, surface treatments and coatings, nanomaterial synthesis

Space propulsion – thrusters

Transportation – durable jet engine turbine blades

Energy
Economical photovoltaic cells, high power switches, use conservation through electronic controls, window coatings – temperature control

National Security – chemical sensing

Non-Fusion Applications from Low Temperature Plasmas

Basic Science

Interfaces and multiple phases in plasmas, plasma biochemistry, predictive control of plasma kinetics, plasma collective behavior/ nonlinear transport

Light sources and displays

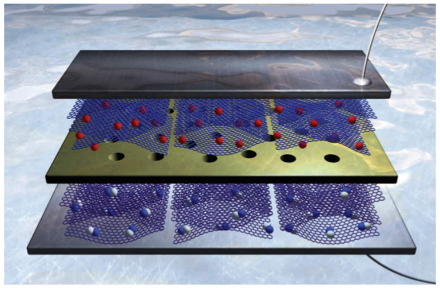
Fluorescent light bulbs, high intensity discharge lamps, display electronics fabrication, LED fabrication, discharges for gas lasers

Waste remediation/reduction

Plasma assisted combustion, municipal waste gasification, hazardous waste vitrification, improved yield in computer chip fabrication, greenhouse gas conversion

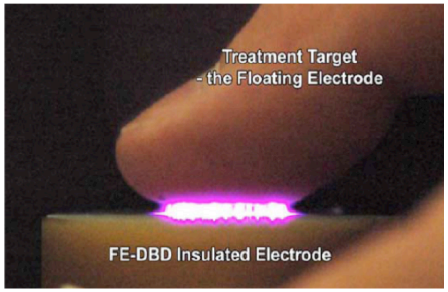
LTP applications: highlighted examples

Nanomaterials: supercapacitors and other graphene devices



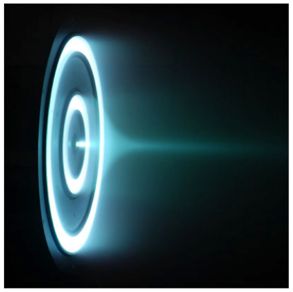
Plasma deposition and etching processes are used to create graphene structures with remarkable electrical and thermal properties. For many applications, batteries for energy storage may be replaced. Supercapacitors with a single graphene layer charge quickly and have a long life.

Atmospheric plasmas for biomedical treatment



The emerging field of plasma medicine is enabled by new understanding about the chemical interaction of atmospheric pressure LTPs with soft and living organisms. Plasmas activate chemical pathways that may be utilized in cancer therapy, wound sterilization and healing, treating dental infections and HIV.

Thrusters for space propulsion



Plasma thrusters make use of LTPs for space propulsion. Thrust is achieved through the expulsion of ions at high energy. Unlike chemical rockets, plasma thrusters use an electrical power source. Plasma thrusters are in current use for maneuvering of near earth satellites, and are under development for interplanetary missions.

Space and Astrophysical Plasma

- Space and Astrophysical Plasma covers the Sun-Earth environment, the solar system, and astrophysical processes throughout the universe.
  - Star and planet formation
  - Magnetic field generation in stars and galaxies
  - Sun-magnetosphere-ionosphere-atmosphere connection

- OFES, with other agencies, has supported laboratory, theoretical, and numerical simulation research advancing space and astrophysical plasma knowledge
  - Magnetic Reconnection Experiment (MRX) – PPPL
  - LArge Plasma Device (LAPD) – UCLA
  - Supports NASA satellite missions and NSF basic research

Space and Astrophysical Plasma

Astrophysics
Plasma spectroscopy to interpret astrophysical observations
Generation of astrophysical plasma jets
Plasma wave modeling and computer simulations for space weather

Solar Physics
Magnetic reconnection – Solar flare prediction
Coronal heating and solar energetic particle acceleration
Solar irradiance spectroscopy and improved telescope filters

Magnetospheric Physics
Magnetic reconnection – geomagnetic storm prediction
Radiation belt acceleration and spacecraft charging mitigation
Spacecraft propulsion and planetary magnetospheres

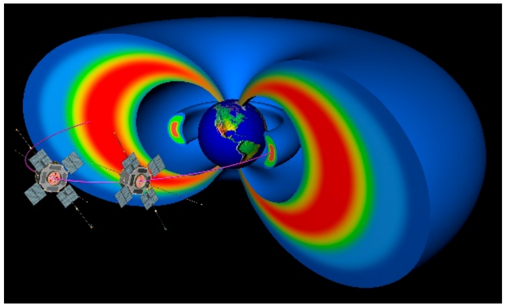
Ionospheric Physics
Plasma stability and turbulence

Space and Astrophysical Plasma Applications

Magnetic Reconnection

- Universal process for dissipating magnetic energy
- Controls solar eruptions and geomagnetic storms at Earth
- Essential component of space weather with impacts on national critical infrastructure
- MRX and LAPD provide controlled experiments of key physical process
- Research coordinated with NASA's Magnetospheric Multiscale mission – dedicated to understanding reconnection

Radiation Belts



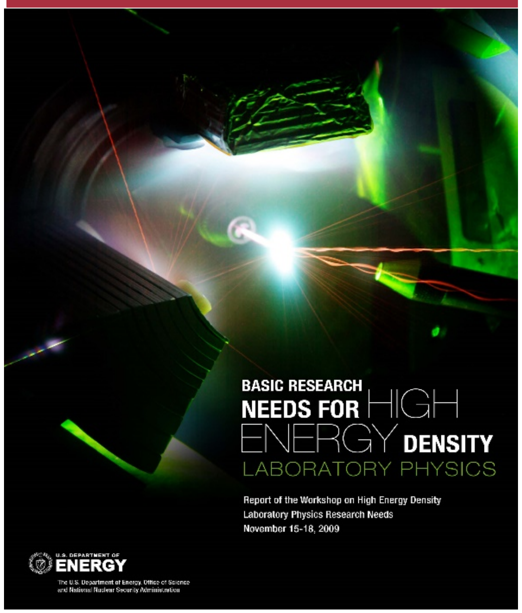
- Involves fundamental processes of energetic particle acceleration and transport
- Poses hazards for satellites and astronauts in space
- Numerical simulations and LAPD experiments investigate the processes operating in the radiation belts
- OFES research is synergistic with NASA's Van Allen probes mission

Ionospheric Disturbances

- Turbulence is a fundamental and universal process in laboratory, space, and astrophysical plasma
- Ionospheric disturbances disrupt communication and navigation with economic and security consequences
- Laboratory experiments investigate plasma stability and relaxation by turbulence
- OFES research can improve prediction and mitigation of impacts

High energy density science and inertial fusion energy (IFE) section includes 3 major activities

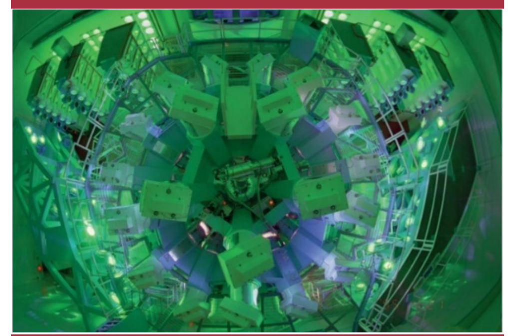
Office of Science/NNSA Joint Program in HEDLP



High Average Power Laser (HAPL) Program (FY2000-FY2009)

Laser, target, and other technologies for IFE

User programs at large and "intermediate scale" facilities



Example: Omega laser (189 projects since 1979)

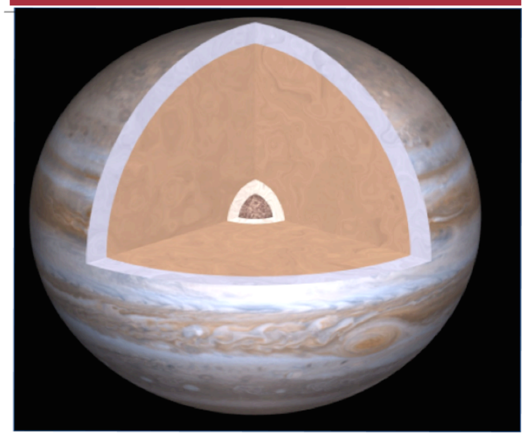
NNSA ICF Program and other activities in support of the national security mission not included

Applications of HED/IFE cover a wide range of activities

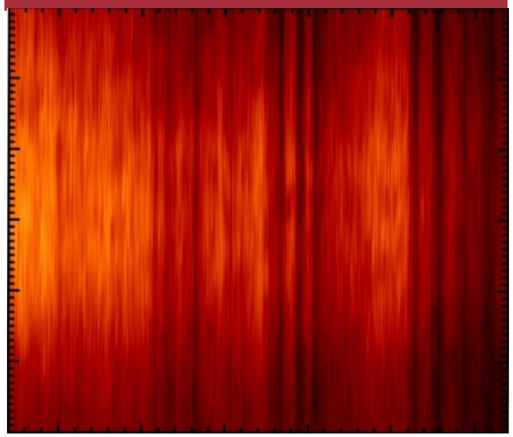
- Fundamental plasma science: Laser-plasm interactions, radiation dominated plasmas, relativistic HEED plasma and beam physics,…
- Laboratory astrophysics: Supernova dynamics, accretion disks, high energy astrophysics
- Planetary physics: material structure at ultrahigh pressure, planetary interiors
- Nuclear physics: Nucleosynthesis, nuclear physics in dense plasmas
- Matter at extreme conditions: Exotic matter at ultrahigh densities, warm dense matter
- Materials science and applications: Designer materials, radiation damage of materials, attosecond x-ray probing of materials
- Medicine and molecular biology: Precision imaging, intense particle beams for cancer therapy and other applications
- Waste remediation- disassociation of NO_x from fossil fuel emissions
- Transportation: Next generation laser-peening sources
- National security: next generation directed energy weapons

Highlighted examples demonstrate the breadth of applications associated with HED science and IFE

Planetary interiors



Astrophysics- iron opacity in the sun



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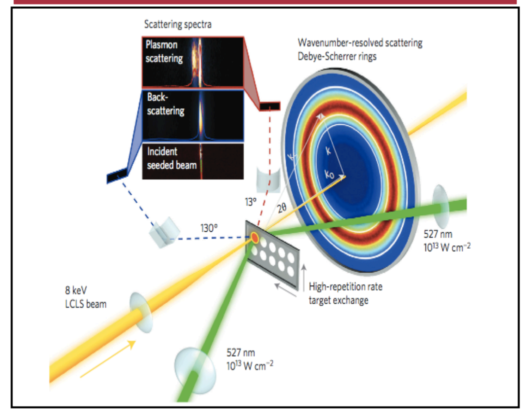
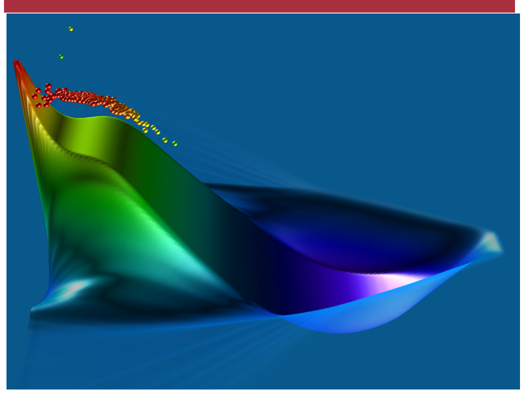
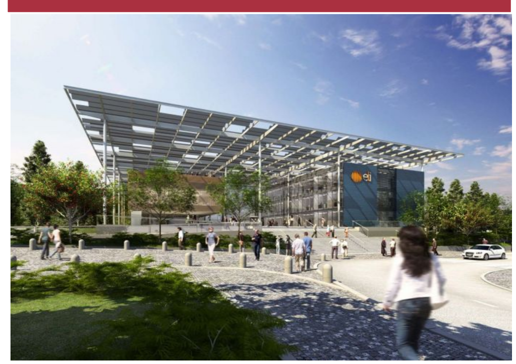
Probing matter at the extremes w/ LCLS



Particle acceleration



Fundamental science with ultrahigh intensity lasers



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,
    2. Taming the plasma-materials interface
    3. Conquering nuclear degradation of materials and structures,
    4. Harnessing fusion power
- Progress in the above areas opens the door to non-fusion benefits

Non-Fusion Applications from Nuclear Fusion Sciences

Computational Tools and Methods
Multi-scale materials modeling applied to nuclear fuel performance
Simulations for understanding hypersonic re-entry and the blackout

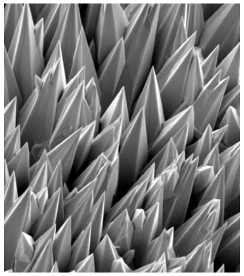
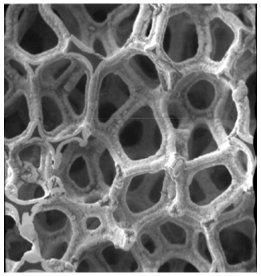
Medical/Health
Compact neutron sources for Boron Neutron Capture Therapy
Improved x-ray diffraction tubes
Terahertz sources for for medical imaging

Material Science and Applications
Improved strength stainless steel
Improved lunar and planetary based heat rejection
Radiation-Tolerant Ceramic-Matrix Composite
Improved chambers for plasma etching
Prompt-gamma neutron activation analysis to improve quality and consistency of materials

Transportation
Refractory high temperature foams for Brayton applications

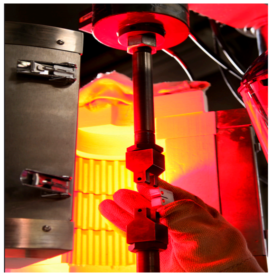
Materials Science Applications

Improved Power Systems for lunar and Planetary Bases

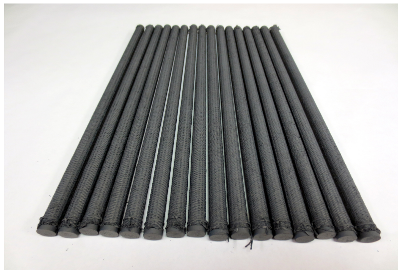
Ultramet adapted previous work on foam-core heat exchangers for plasma-facing components, to construct a high temperature heat exchanger to enhance heat transfer between liquid lithium and helium. The heat exchanger would be used for fission-based power systems for lunar and planetary surface bases.

High Performance Stainless Steel



ORNL researchers developed a new cast stainless steel that is 70 percent stronger than comparable steels. These alloys will help engine manufacturers meet emission regulations for diesel, turbine, and gasoline engine applications.

Accident Tolerant Fission Reactor fuel



Fusion materials science researchers developed highly radiation-tolerant silicon carbide ceramic composites for nuclear thermo-structural applications. These 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 the severe accidents.

To Achieve Fusion Energy a Wide Range of Technology R&D Has and Will be Required

- Progress in the following R&D areas opens the door to non-fusion benefits
  - The complex physics of burning plasmas
  - Cutting edge computational capabilities
  - Sophisticated methods for heating fusion plasmas to hundreds of millions of degrees
  - Innovations in materials, magnets and control mechanisms
  - Creation of new diagnostics and sensors
  - Complex engineering innovations
    - Heat removal, remote maintenance, impurity removal, etc.
  - Micromachining and manufacturing

Non-Fusion Applications from Magnetically Confined Plasmas

Computational Tools and Methods

Advanced simulation capabilities for wide range of research problems

High-performance supercomputers and networking communications

Nonlinear dynamics and chaos

Medical/Health

MRI-Magnetic resonance imaging

Cancer fighting (proton beam therapy)

Medical isotope separation and production

Grain sterilization and milk pasteurization (pulsed-power gammas)

RF egg pasteurization

Ironless superconducting synchrocyclotron

High Frequency Dynamic Nuclear Polarization (DNP) NMR

Material Science and Applications

Ion implantation for hardening of materials

Microwave and RF sintering of ceramics

Production of synthetic diamond films

High performance stainless steels

Radiation resistant dielectric development

High heat flux materials

Carbon fiber production via microwave-assisted plasma processing

High temperature superconducting cable development

National Security

Electromagnetic Aircraft Launch System (EMALS) for aircraft carriers

Verifying nuclear warheads

Non-Fusion Applications from Magnetically Confined Plasmas (continued)

Non-lethal crowd control using microwaves

Lyot optical filter for improved underwater communications

Semiconductor Manufacturing

Superconducting synchrotron for X-ray Lithography

Space Propulsion

Variable Specific Impulse Magnetoplasma Rocket (VASIMR)

Millimeter wave thermal propulsion

Transportation

MagLev trains

IGBT power conversion units for light rail trains, busses, wind turbines, and earth movers

Waste Remediation

Toxic waste destruction

Cryo-pellet cleaning of surfaces

Vitrification of waste

Monitoring of smokestack waste metal emissions

Reducing vehicular pollution

Microwave removal of contaminated concrete

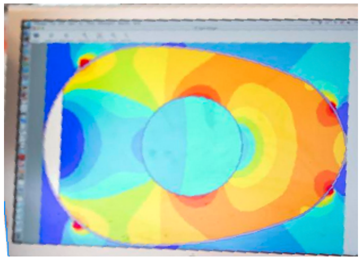
Electron beam destruction of chemical waste

Medical and Health Applications

High Frequency Dynamic Nuclear Polarization (DNP) NMR

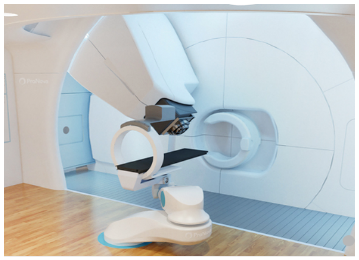
Using high frequency microwaves enables the polarization of the electron spin system, eventually leading to polarization of the nuclear spins in a process known as Dynamic Nuclear Polarization (DNP NMR). The increase in signal to noise ratio can be several hundred, an enormous enhancement allowing experiments to be completed in days rather than months.

Saving the public from food poisoning



PPPL has developed a novel technique, using Radio frequency for rapidly pasteurizing eggs right in the shell, in a fraction of the time of conventional methods. This technology works without damaging the delicate egg white. The process could reduce illnesses from egg-borne salmonella bacteria, a widespread public health concern

Making cancer treatment more available



MIT researchers developed a compact, superconducting, high-field synchrocyclotron. Used in proton therapy. that is about 40-times smaller, lighter and an order of magnitude less expensive than conventional magnet technology machinery, enabling more hospitals to provide the therapy.

Available economic impact data

- Incomplete figures based on:
  - "Plasma 2010" decadal survey (2007)
  - "Rising above the gathering storm" (2007)
  - Economic impact study of plasma technology conducted in Germany (2004)

water purification (2008)	$0.74B
information technology (2012)	$954B
coatings (2014)	$20B
TVs/displays (2010)	$210B
plasma surface treatments (2014)	$25B
plasma technology total (2004)	$266B

Questions?