Applications of Fusion Energy Sciences Research: Scientific Discoveries and New Technologies Beyond Fusion

Presented by
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FUSION POWER ASSOCIATES
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DOE Charge to Fusion Energy Science Advisory Committee February 2015

“The… Appropriation Act, 2015….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.” Doe ask that the Fusion Energy Science Advisory Committee (FESAC) prepare a report on this topic.

Non-Fusion Applications Subcommittee Members

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

A Community Survey Was Held to Gather Input

- **Responders were asked to:**
  - *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

Findings Were Coalesced into Topical Themes

- Fundamental science
- Computational tools/methods
- Lighting
- Medical/health
- Materials science and applications
- National security
- Semiconductor manufacturing
- Space propulsion
- Transportation
- Waste remediation

There Were Eight 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 benefits** in many domains. E.g., electronics, lighting, drinking water, communications, manufacturing, transportation, energy savings, medical, environmental hazard mitigation

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 Was 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

The following slides will cover examples of these categories

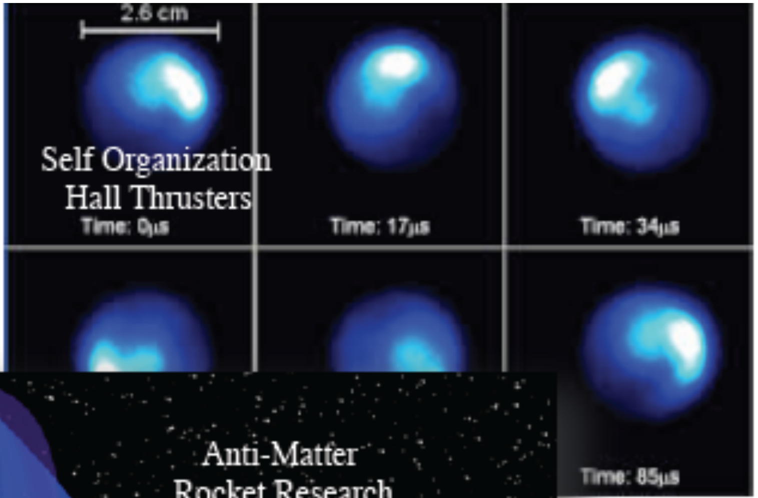
Basic Plasma Science is the Study of Fundamental Processes Taking Place in Plasmas

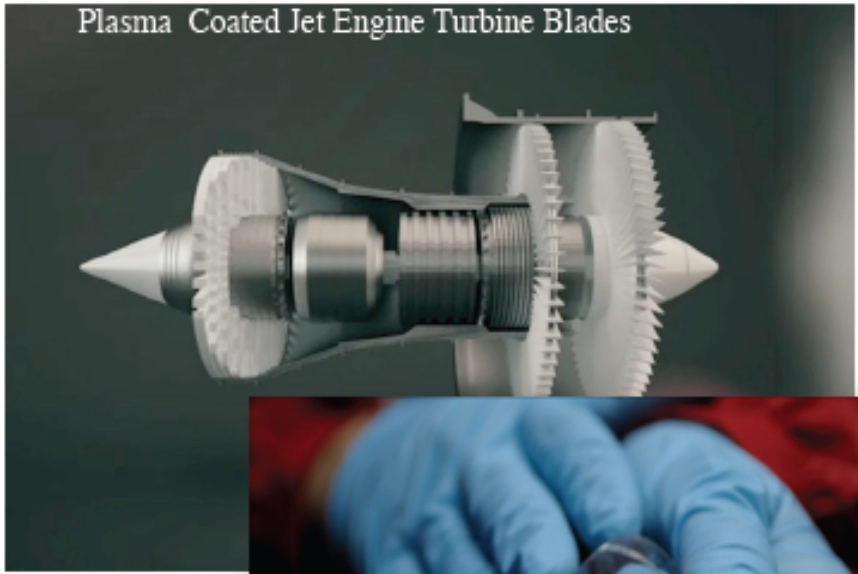
- **A fundamental understanding of basic plasma physics not only advances our understanding of plasma physical phenomena, but this knowledge also provides the pathway or bridge for addressing technological problems here on Earth**
- **Basic plasma science as a whole is broad but four key, sub-topical areas give the flavor and some sense of scope of this exciting field :**
  - Non-neutral plasmas
  - Dusty Plasmas
  - Magnetic Self-Organization
  - Microplasmas

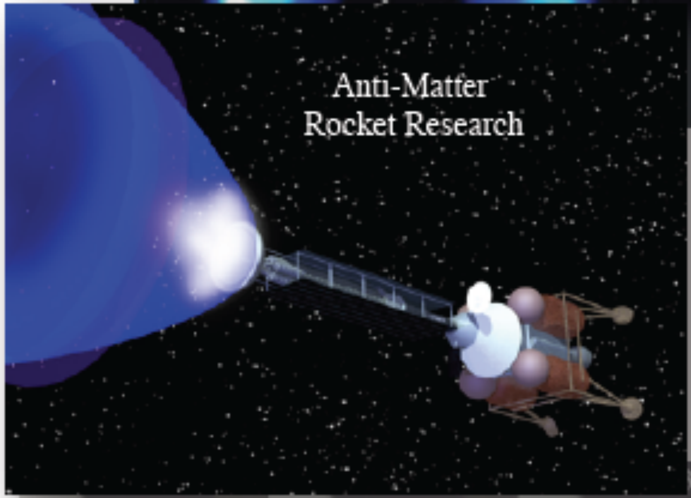
Basic Plasma Science Derived Applications

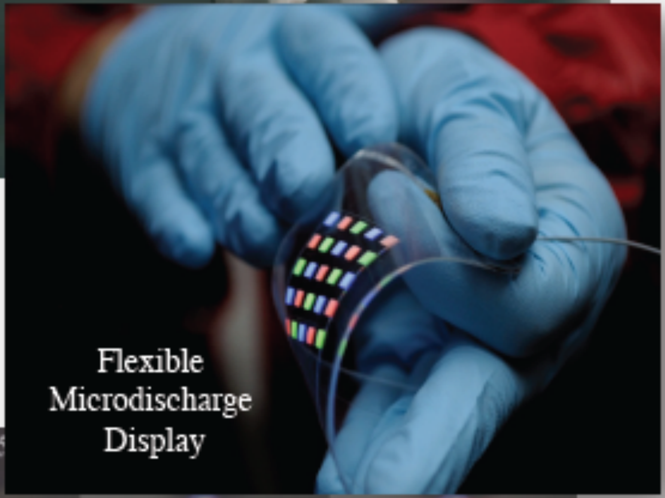
- **Non-neutral plasmas**
  - Semiconductor device defect probing via positron beams
  - Anti-proton sources for envisioned tumor treatment
- **Dusty plasmas**
  - Improvement in semiconductor device yield via understanding dust formation processes
  - High performance, high temperature plasma-coated 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

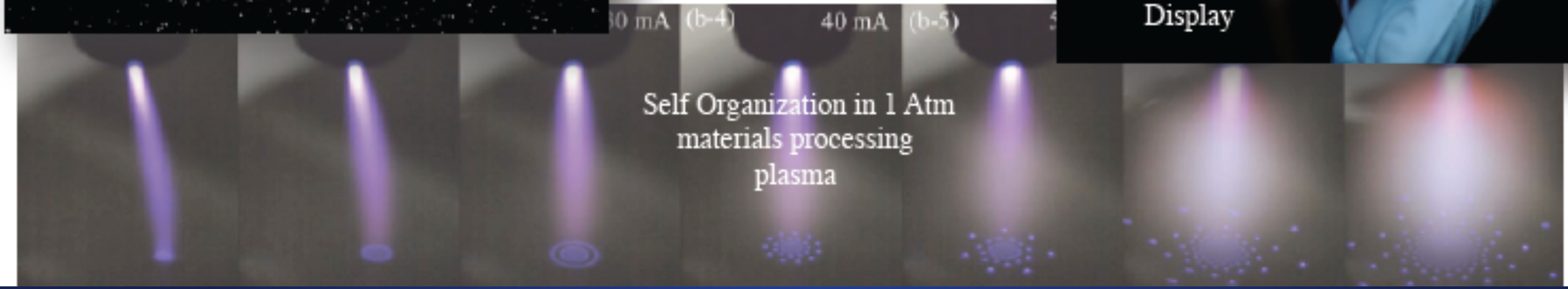
Basic Plasma Science Applications











Low Temperature Plasmas (LTPs)Pparameter Space with Electron Temperatures in the ~1-10 eV Range

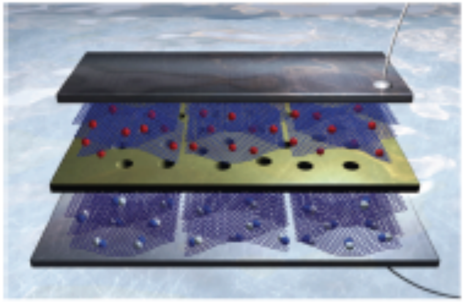
- **Typical distinguishing LTP characteristics include:**
  - ***Partial ionization*** – electron collisions with neutral atoms/molecules affect charged particle dynamics
  - ***Non-equilibrium*** – electron temperature much higher than gas and ion temperatures
  - ***Molecular gas mixtures*** – electron collisions drive "high temperature" gas phase chemistry while substrates remain cool
  - ***Magnetic fields*** – some, but not all, LTP applications employ magnetic confinement

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

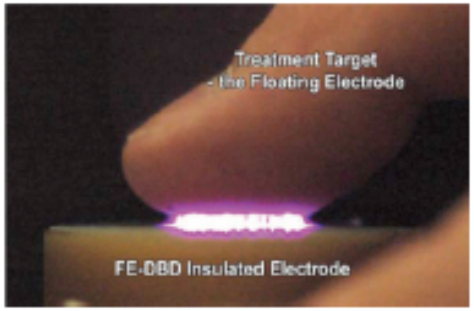
LTP Applications: Highlighted Examples

Nanomaterials: supercapacitors and other graphene devices



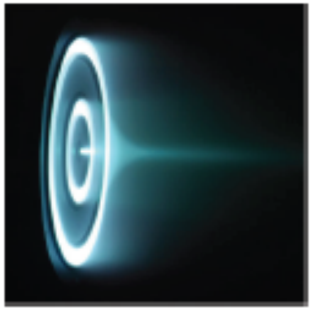
Plasma deposition and etching processes are used to create graphene structures with remarkable electrical and thermal properties. For many applications, batteries for energy storage may be replaced. Supercapacitors with a single graphene layer charge quickly and have a long life.

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**
- **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

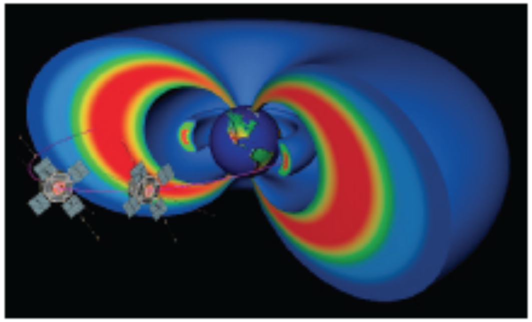
- **Astrophysics**
  - Plasma spectroscopy to interpret astrophysical observations
  - Generation of astrophysical plasma jets
  - Plasma wave modeling and computer simulations for space weather
- **Solar Physics**
  - Magnetic reconnection – Solar flare prediction
  - Coronal heating and solar energetic 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) Includes Three Major Activities

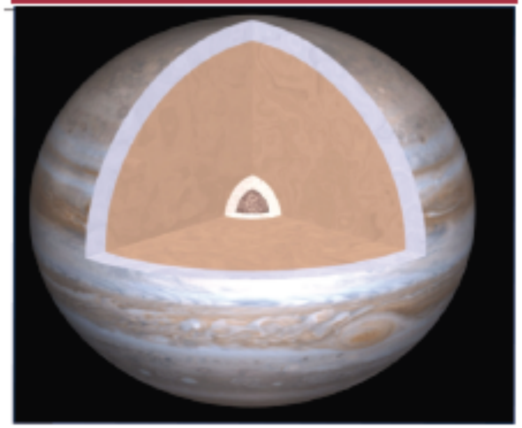
- **Office of Science/NNSA Joint Program in HEDLP**
- **High Average Power Laser (HAPL) Program (FY2000-FY2009)**
  - Laser, target, and other technologies for IFE
- **User programs at large and "intermediate scale" facilities**
  - Example: Omega laser (189 projects since 1979)

Applications of HED/IFE Cover a Wide Range of Activities

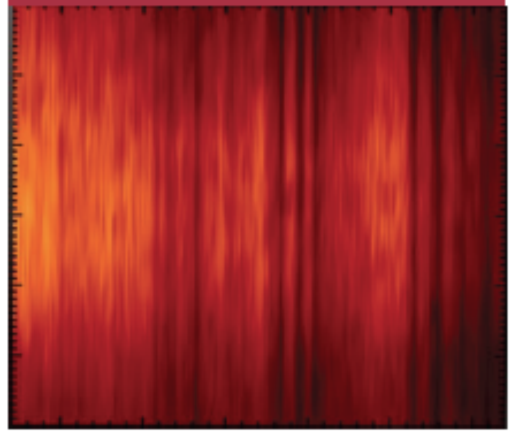
- Fundamental plasma science: Laser-plasm interactions, radiation dominated plasmas, relativistic HEED plasma and beam physics,…
- Laboratory astrophysics: Supernova dynamics, accretion disks, high energy astrophysics
- Planetary physics: material structure at ultrahigh pressure, planetary interiors
- 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 NOx from fossil fuel emissions
- Transportation: Next generation laser-peening sources
- National security: next generation directed energy weapons

Examples Demonstrate the Breadth of Applications Associated with HED Science and IFE

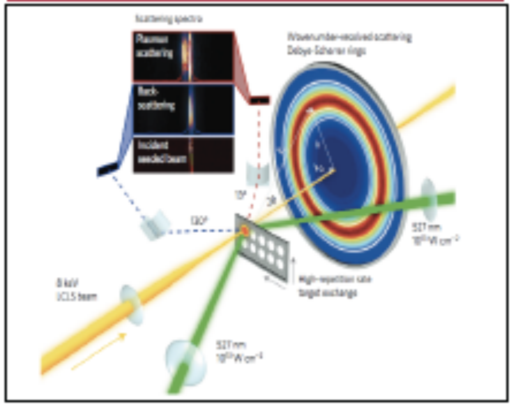
Planetary interiors



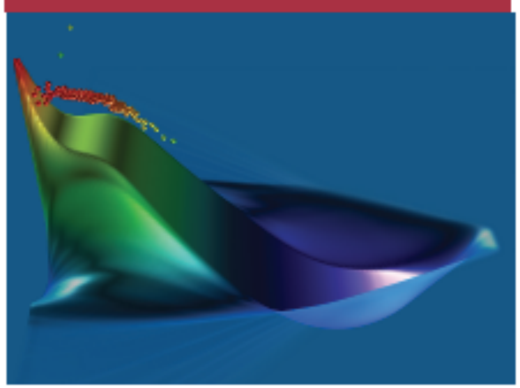
Astrophysics- iron opacity in the sun



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 arranges 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

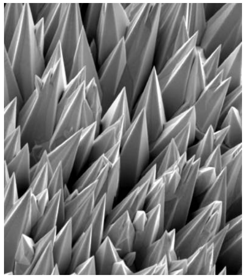
Medical/Health
Compact neutron sources for Boron Neutron Capture Therapy
Improved x-ray diffraction tubes
Terahertz sources for for medical imaging

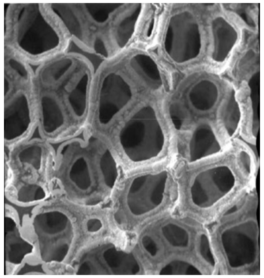
Material Science and Applications
Improved strength stainless steel
Improved lunar and planetary based heat rejection
Radiation-Tolerant Ceramic-Matrix Composite
Improved chambers for plasma etching
Prompt-gamma neutron activation analysis to improve quality and consistency of materials

Transpotation
Refractory high temperature foams for Brayton applications

Materials Science Applications

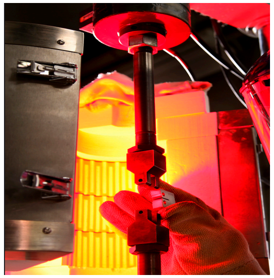
Improved Power Systems for lunar and Planetary Bases





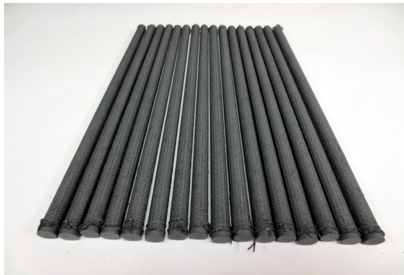
Ultramet adapted previous work on foam-core heat exchangers for plasma-facing components, to construct a high temperature heat exchanger to enhance heat transfer between liquid lithium and helium. The heat exchanger would be used for fission-based power systems for lunar and planetary surface bases.

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

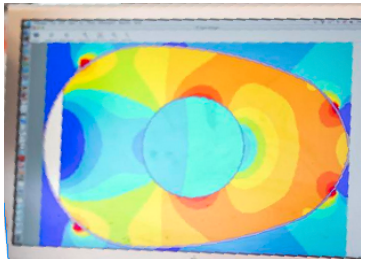
Electron beam destruction of chemical waste

Medical and Health Applications

High Frequency Dynamic Nuclear Polarization (DNP) NMR

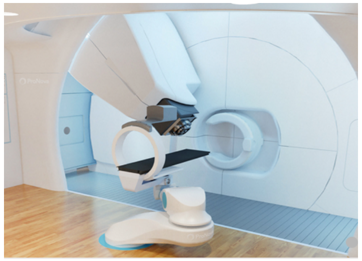
Using high frequency microwaves enables the polarization of the electron spin system, eventually leading to polarization of the nuclear spins in a process known as Dynamic Nuclear Polarization (DNP NMR). The increase in signal to noise ratio can be several hundred, an enormous enhancement allowing experiments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

Summary

- From the Introduction of the FESAC Report

"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. ….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."