The United States Department of Energy's

Princeton Plasma Physics Laboratory

An Overview

Laboratory Mission

The U.S. Department of Energy's Princeton Plasma Physics Laboratory (PPPL) is a collaborative national center for plasma and fusion science. Its primary mission is to develop the scientific understanding and the key innovations which will lead to an attractive fusion energy source. Associated missions include conducting world-class research along the broad frontier of plasma science and technology, and providing the highest quality of scientific education.

Princeton University manages PPPL under contract with the United States Department of Energy. The Laboratory is sited on 88 acres of Princeton University's James Forrestal Campus, about four miles northeast of the main campus.

Through its efforts to build and operate magnetic fusion devices, PPPL has gained extensive capabilities in a host of disciplines including

FY2009 Funding: $80.6 million

Number of Employees*: 425

Faculty:	4
Physicists:	81
Engineers:	82
Technicians:	162
Administrators:	80
Clerical Support:	16
Graduate Students:	34

**As of April 1, 2009*

Aerial view of the U.S. Department of Energy's Princeton Plasma Physics Laboratory.

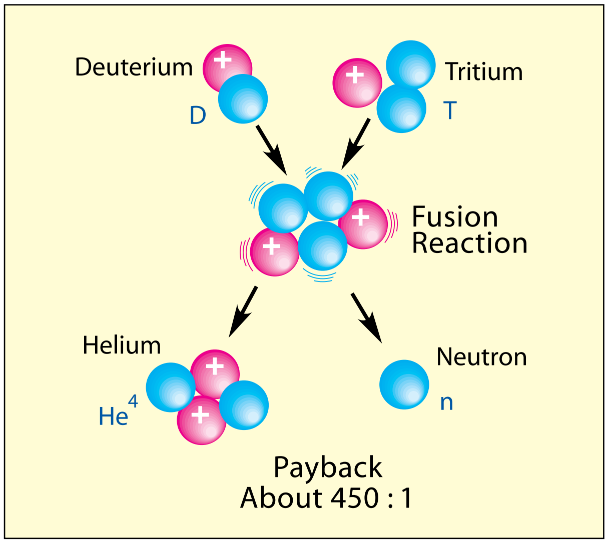
advanced computational simulations, vacuum technology, mechanics, materials science, electronics, computer technology, and high-voltage power systems. In addition, PPPL scientists and engineers are applying knowledge gained in fusion research to other theoretical and experimental areas including the development of plasma thrusters and the propagation of intense beams of ions. The Laboratory's graduate education and science education programs provide educational opportunities for students and teachers from elementary school through postgraduate studies.

Fusion Energy

In the fusion process, light atoms such as those of the isotopes of hydrogen (deuterium and tritium) are fused or joined together at high temperature with an accompanying release of energy. To produce practical amounts of fusion power, the fuel must be heated to more than 100 million degrees Celsius. At these high temperatures, the electrons become separated from the nuclei of the atoms, forming an ionized gas, or plasma. Magnetic fields are used to confine the plasma at the density and temperature required for the production of significant amounts of fusion power. As an energy source, fusion has many advantages, including:

- Worldwide long-term availability of low-cost fuel.
- No chemical combustion products and therefore no contribution to acid rain or global warming.
- No possibility of a runaway reaction.
- Materials and by-products unsuitable for weapons production.
- Radiological hazards thousands of times less than from fission.
- Estimated cost of electricity comparable to other long-term energy options.

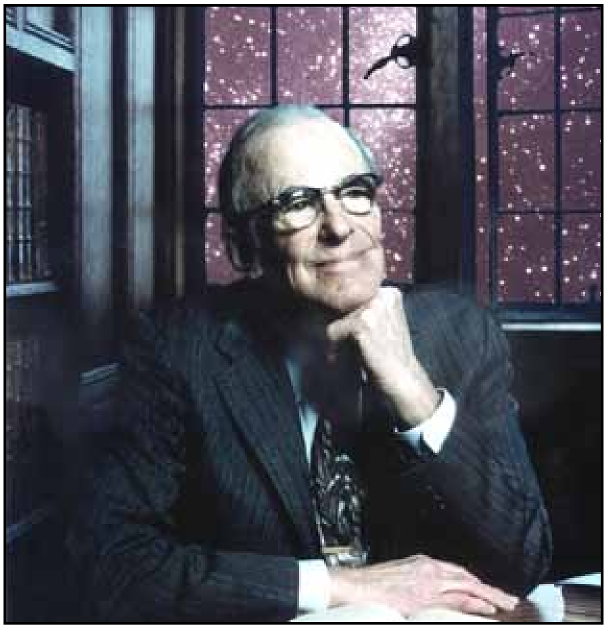
The greatest near-term challenges for the development of fusion energy are to accelerate the advancement of scientific understanding and to determine the approaches most suitable for taking advantage of the newest scientific insights. Thus, concept innovation is the central element of the U.S. Fusion Energy Sciences Program. Near-term goals involve the fullest utilization of existing scientific facilities and the construction of new moderate-scale facilities to investigate optimized plasma confinement configurations. Scientific understanding is being accelerated by recent advances in computational power that contributes strongly to innovation in plasma confinement techniques.



This document provides an overview of PPPL's capabilities and our research efforts that enable the international fusion community to nurture the best new ideas in plasma confinement and fusion energy science. Applications of plasma science and technology by PPPL researchers to solve a broad range of practical problems outside the field of fusion are also discussed.

History and Achievements

Magnetic fusion research at Princeton began in 1951 under the code name Project Matterhorn.

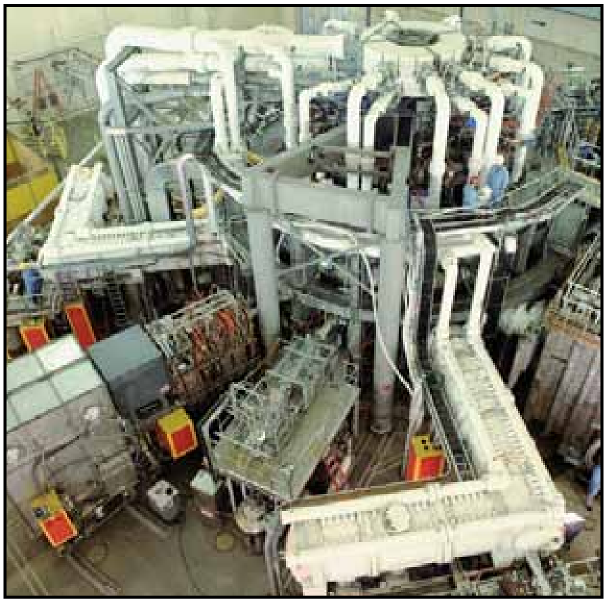


Lyman Spitzer, Jr.

Lyman Spitzer, Jr., professor of Astronomy at Princeton University, for many years had been involved in the study of very hot rarefied gases in interstellar space. Inspired by the fascinating but exaggerated claims of fusion researchers in Argentina, Professor Spitzer conceived of a plasma being confined in a figure-eight-shaped tube by an externally generated magnetic field. He called his concept “the stellarator,” and took this design before the Atomic Energy Commission in Washington, D.C. As a result of this meeting and a review of the invention by designated scientists throughout the U.S., the stellarator proposal was funded and Princeton University’s controlled fusion effort was born. In 1958, magnetic fusion research was declassified, allowing all nations to share their results openly. The name of the project was changed to the Princeton Plasma Physics Laboratory in 1961. Some of PPPL’s most notable achievements include:

Confirmation of Plasma Turbulence Driven by Electron Temperature Gradient — 2008

Measurements on the National Spherical Torus Experiment confirmed the existence of a long-theorized form of turbulence driven by variation of electron temperature across the plasma. PPPL researchers demonstrated that tiny swirls in the plasma stream may be one cause of heat loss from the plasma. The Princeton team directed microwave beams at the plasma and measured how they were scattered by the turbulence. These first-of-a-kind high spatial resolution measurements obtained across the plasma minor radius were made possible by the very open design and unique magnetic filed properties of NSTX.



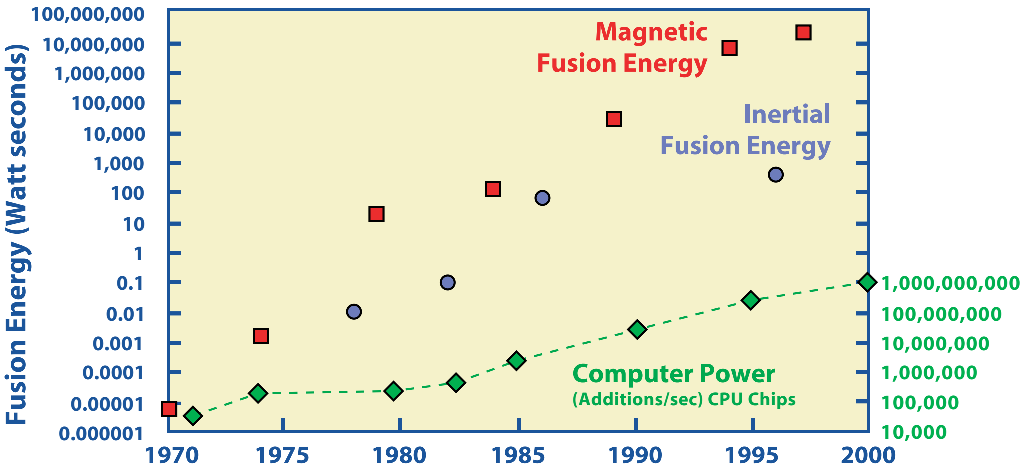
Tokamak Fusion Test Reactor

Record Values of Toroidal Beta Achieved in the National Spherical Torus Experiment — 2004

Neutral-beam injection heating coupled with good confinement resulted in a toroidal beta approaching 40%. Beta is a figure of merit that relates to the economics of fusion power production.

Start-up of National Spherical Torus Experiment — 1999

The National Spherical Torus Experiment produced its first plasma two months ahead of schedule and operated with its full design plasma current (1 million amperes) nine months ahead of schedule. It has since surpassed its design value and attained a 1.4 million ampere plasma current.



Progress in Fusion Power.

Calculation of Zonal Flows in Toroidal Plasmas — 1998

Scientists at PPPL employed massively parallel computations to simulate the suppression of turbulence in toroidal plasmas.

Highest Temperature Ever Produced in a Laboratory — 1995

A plasma was heated to a temperature of 510 million degrees Celsius in PPPL's Tokamak Fusion Test Reactor (TFTR). This temperature is five times that required for the production of practical amounts of fusion power.

Enhanced Reversed-shear Mode Discovered — 1995

During experiments on TFTR, scientists increased the central density of the plasma up to three-fold and reduced particle leakage by a factor of 50 using the enhanced reversed-shear mode of plasma confinement. This could eventually lead to smaller, more economical fusion power plants.

Record Levels of Fusion Power Produced — 1994

The TFTR produced a record 10.7 million watts of controlled fusion power in the world's first series of magnetic fusion experiments using a fuel mixture of 50/50 deuterium/tritium.

Discovery of the Self-sustaining Bootstrap Current — 1986

The TFTR team positively identified the presence of a powerful self-sustaining current in toroidal fusion plasmas at high temperatures and densities. This "bootstrap" current opens the way to steady-state operation of tokamaks, and permits the design of new magnetic confinement concepts such as the Spherical Torus and Compact Stellarator.

New Enhanced-confinement Regime Discovered — 1986

A new enhanced-confinement plasma regime was discovered during experiments on the TFTR. Peaked plasma density profiles were obtained with neutral-beam plasma heating, leading to a reduction in energy leakage by a factor of 2-3.

Development of the Soft X-ray Laser — 1984

PPPL's Soft X-ray Laser demonstrated X-ray lasing at 18.2 nanometers in a magnetically confined laser-produced plasma.

First Achievement of Fusion-relevant Plasma Temperatures — 1978

The Princeton Large Torus achieved, for the first time, ion temperatures in excess of 58 million degrees Celsius, the minimum required for a self-sustaining fusion reaction.

Core Competencies

PPPL has a highly skilled workforce and extensive capabilities for the experimental and theoretical study of fusion and non-fusion plasmas and for the integrated design, fabrication, and operation of experimental plasma facilities of all types. Management by Princeton University provides the institutional framework for a broad laboratory-based program of education in plasma physics and related science and technology. The core competencies of PPPL are:

Plasma Science and Technology

- Experimental analysis of stability and confinement in fusion plasmas.
- Plasma theory for fusion and other applications.
- Computational physics and numerical simulation of plasma processes.
- Physics design of experimental plasma facilities.
- Physics and technology of plasma heating and current-drive, including neutral-beam and radio-frequency techniques.
- Physics and technology of plasma diagnostics and instrumentation.
- Physics and technology of plasma applications to advance industrial technologies.
- Design and implementation of basic plasma physics experiments, such as used for studies of magnetic reconnection or plasma-surface interactions.

Engineering

- Engineering design and analysis of experimental plasma facilities including magnetics, neutronics, thermal, and structural analysis.
- Systems integration and construction management for experimental plasma facilities.
- Operation of experimental plasma facilities.
- Mechanical engineering, including structures, vacuum, cryogenic, and tritium systems.
- Computer engineering, including data acquisition, instrumentation, and controls systems.

- Electrical, electronic, and electro-optic engineering, including power conversion, diagnostic, and radio-frequency systems.
- Environmental, safety, and health aspects of the operation and removal of experimental fusion devices.

Education

- Provision of faculty for an integrated program of courses and research supervision for graduate students in plasma physics and related science and technologies.
- Implementation of a broad science education program for the community-at-large, including undergraduate and precollege students and science teachers at all levels.

Research and Development Program

The National Spherical Torus Experiment

The National Spherical Torus Experiment (NSTX) began operation in 1999. It is a major element in the U.S. Fusion Energy Sciences Program. It is designed to test the physics principles of spherical torus (ST) plasmas. NSTX produces a plasma that is shaped like a sphere with a hole through its center, different from the "donut" shape of the tokamak. The ST configuration may have several advantages, a major one being the ability to confine a higher plasma pressure for a given magnetic field. Since the amount of fusion power produced is proportional to the square of the plasma pressure, the ST concept could play an important role in the development of smaller and more economical fusion reactors.

The NSTX was designed and built jointly by PPPL, the Oak Ridge National Laboratory, Columbia University, and the University of Washington, Seattle. PPPL coordinated the design and construction efforts and has primary responsibility for experimental operations. Including PPPL, the NSTX research team is comprised of 24 U.S. universities, national laboratories, and industry, along with colleagues from 17 other institutions worldwide. Located within PPPL's D-Site facility, NSTX is taking advantage of existing equipment and infrastructure that formerly supported the Tokamak Fusion Test Reactor, which ceased operation in 1997.


National Spherical Torus Experiment

In 1999, NSTX reached its design plasma current of one million amperes, nine months ahead of schedule, and produced all of the plasma shapes needed for its experiments. Since then it has produced a plasma current of 1.4 million amperes.

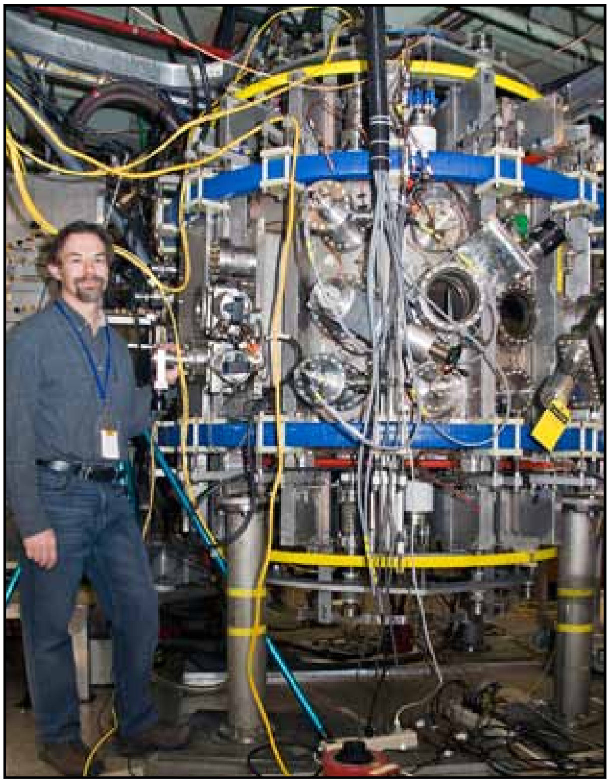
In 2000, NSTX's neutral-beam injection (NBI) system began operation ahead of schedule. In 2004, the use of NBI plasma heating coupled with good confinement resulted in the attainment of a toroidal beta of up to 40%. Beta is a figure of merit that relates to the economics of fusion power production. Furthermore, with the addition of neutral-beam heating, the observed energy confinement efficiency of NSTX improved by as much as a factor of two.

In 2008 measurements on the National Spherical Torus Experiment confirmed the existence of a long-theorized form of turbulence driven by variation of electron temperature across the plasma.

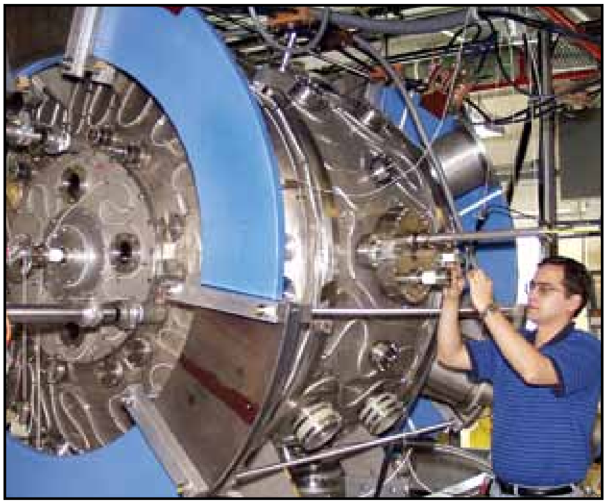
While striving to understand the physics behind NSTX's excellent plasma confinement and high-beta performance, physicists are working on other fundamental goals, including experiments on Coaxial Helicity Injection (CHI) and High Harmonic Fast Waves (HHFW). CHI could lead eventually to the elimination of the central solenoid, resulting in smaller, more powerful fusion reactors. HHFW will heat plasma electrons to high temperatures and sustain plasma current needed for steady-state fusion reactors. Additional information on NSTX is available at: http://www.pppl.gov/projects/pages/nstx.html .

Lithium Tokamak Experiment

Fusion reactor designs call for a lithium blanket to surround the plasma. Fusion neutrons will react with the blanket to produce tritium that would be extracted and used as a fuel. In addition, a liquid lithium layer on the surface facing the plasma would be immune to the high heat loads and radiation fluxes that can damage solid wall materials. For the past several years, the Current Drive Experiment–Upgrade (CDX-U) has been devoted to investigations of plasma interactions with liquid lithium surfaces. Studies with plasmas in contact with a "pool" of liquid lithium have established that it has very desirable properties as a plasma-facing component in a tokamak. The CDX-U experiment has been rebuilt substantially and renamed the Lithium Tokamak Experiment (LTX). This new device has a liquid lithium plasma-facing surface on a solid conducting shell that completely encloses the discharge. LTX produced its first plasma in September 2008. Additional information is available at: http://www.pppl.gov/projects/pages/cdxu.html .



Lithium Tokamak Experiment



Magnetic Reconnection Experiment

Magnetic Reconnection Experiment

A basic plasma physics research facility, PPPL's Magnetic Reconnection Experiment (MRX), is studying the physics of magnetic reconnection — the topological breaking and reconnection of magnetic field lines in plasmas. Scientists hope to understand the governing principles of this important plasma physics process and gain a basic understanding of how it affects plasma characteristics such as confinement and heating. The results of these experiments has relevance to solar physics, astrophysics, magnetospheric physics, and fusion energy research. The MRX is funded by the U.S. Department of Energy, the National Science Foundation, and the National Aeronautics and Space Administration. Detailed information is available at: http://mrx.pppl.gov .

Fusion Theory and Advanced Computing

The primary role of the PPPL Theory Department is to help the Fusion Energy Sciences Program achieve the scientific understanding of the physics of plasmas needed to establish toroidal magnetic confinement as an attractive, technically feasible reactor option. This involves leading the innovative development of improved calculation capabilities and the application of state-of-the-art theoretical and computational tools to the interpretation of experimental results. Realistic physics-based modeling capabilities accelerate breakthroughs in plasma performance by confidently identifying the most attractive designs for new facilities. Additional information on the PPPL Theory Department is located at: http://w3.pppl.gov/theory/ .

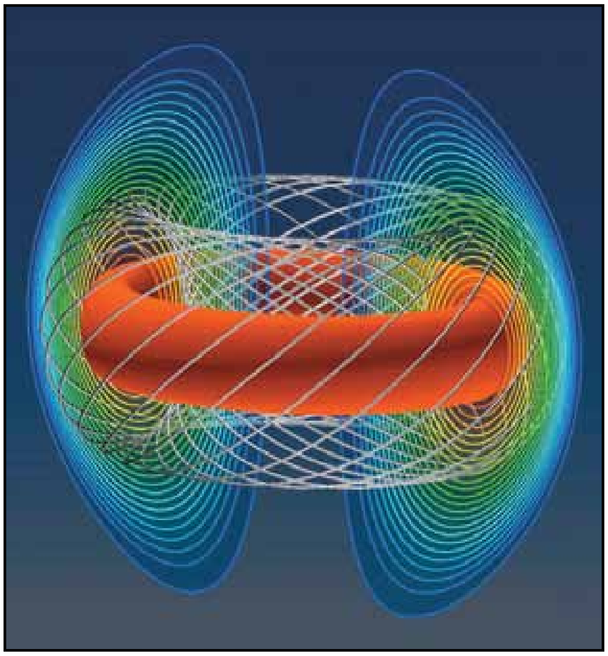
Off-site Research and Collaborations

The purpose of the PPPL Off-site Research Program (Collaborations) is to perform fusion science research at the most relevant facilities. PPPL scientists work with teams of colleagues at other laboratories, foreign and domestic, to carry out measurements, to assist in operation of devices, to loan equipment, and to develop databases. Off-site research presently includes efforts at the DIII-D and Alcator C-Mod tokamaks in the U.S., the Joint European Torus in England, the JT-60U and the Large Helical Device in Japan, and the W7-AS in Germany.

Basic and Applied Plasma Physics

PPPL has an active program in basic and applied plasma physics that supports the Laboratory's mission to create new knowledge in plasma science and to use this knowledge to develop new plasma technologies. Some of the programs are:

Space Plasma Physics: The Earth's magnetosphere and the solar atmosphere provide a "natural" laboratory for understanding a broad range of plasma physics phenomena. Space plasma physics research at PPPL is principally focused on understanding solar and magnetospheric activity, such as solar prominence formation and eruption, solar flares, coronal mass ejections, magnetospheric waves, and magnetospheric substorms, and how the coupling between solar activity, the magnetosphere, and the ionosphere can affect the dynamical evolution of the solar-terrestrial system.



A three-dimensional nonlinear simulation of the National Spherical Torus Experiment using the M3D code.

Hall Thrusters for Space Propulsion: The goal of this research, funded by the U.S. Air Force Office of Scientific Research, is to make improvements in Hall thrusters that can be used for the propulsion of satellites. The Hall thruster is an ion propulsion system that uses a radial magnetic field to inject electrons as a means of eliminating the buildup of positive charge that usually occurs between the anode and cathode of a conventional ion thruster. Additional information on the PPPL Hall Thruster Experiment can be found on the web at: **http://pst.pppl.gov/hall_thruster.html** .

Experimental and Theoretical Studies of Nonneutral Plasmas: A nonneutral plasma is a many-body collection of charged particles in which there is not overall charge neutrality. Research at PPPL, funded by the Office of Naval Research, includes theoretical and experimental programs related to the equilibrium, stability, and nonlinear properties of nonneutral plasmas. Practical applications of these plasmas include improved atomic clocks, antimatter plasmas, and advanced particle accelerators.

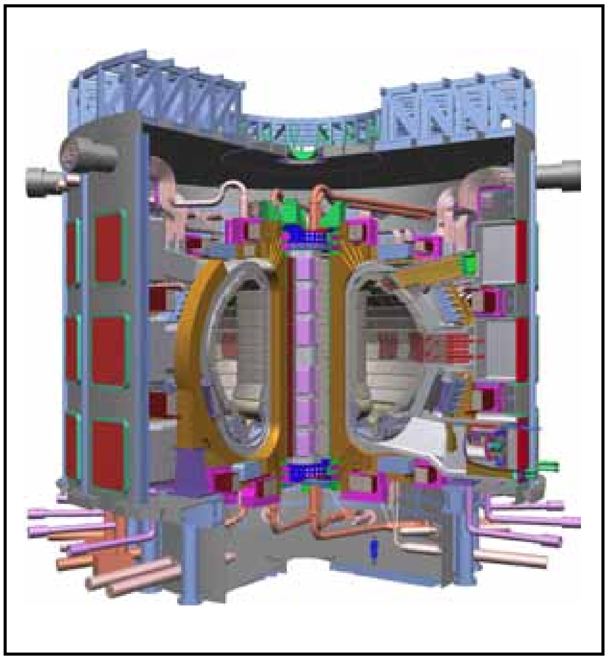
Magnetic Nozzle Experiment: PPPL researchers are studying the flow of magnetized linear plasmas expanding through constrictions formed by increased magnetic field intensity and material apertures. It has been observed that under these conditions, rapid plasma acceleration to supersonic speeds occurs. This phenomenon has applications in the fields of fusion science, space propulsion, materials processing, and lasers.

Princeton Field-reversed Configuration Experiment: This experiment is part of DOE's Innovative Confinement Concepts program in which alternate routes to fusion power are being explored. In this research activity, scientists investigate methods to keep the plasma stable, techniques to heat the plasma to high temperatures, and other scientific questions that must be answered to develop small clean fusion reactors, that is, those that produce only a few megawatts of power and low fluxes of energetic neutrons.

Negative Ion Beams for Heavy Ion Drivers: The possibility of using heavy negative ions as heavy ion drivers for inertial fusion energy has been proposed. Relative to heavy positive ions, negative ions have the advantage that they will not collect electrons from surfaces they pass, and they also can be converted to neutral atoms by photo detachment neutralizers as they enter the target chamber, which can reduce the growth of the beam spot size on the target, and thereby reduce the required beam energy per pulse.

The Paul Trap Simulation Experiment: In PPPL's Paul Trap Simulation Experiment (PTSX), a stationary nonneutral cesium plasma, about two centimeters in diameter and two meters long, is subjected to a time-varying electric field, simulating the experience of particle beam as it passes quadrupole magnets in an accelerator. The physics is comparable, providing researchers with a relatively inexpensive means to study properties of charged particle beams with greater flexibility than possible in an actual accelerator. Research on PTSX could significantly impact several areas of science and technology, including particle physics, heavy ion fusion, nuclear waste transmutation, and high-energy-density physics — wherever charged particle beams are used as tools.

The Magnetorotational Instability Experiment: The formation process of stars and planets remains one of the big questions in astrophysical science. Currently, scientists do not understand the required conditions and the accretion, or matter collection process, involved in star and planet formation. The Magnetorotational Instability (MRI) Experiment at PPPL may shed light on this mystery. The project's primary mission is to test the plausibility of a 1991 theory that indicates MRI, a disruptive plasma process, plays a major role in accretion. Researchers physically simulate an accretion disk with liquid metal "standing in" for the plasma, dust, and other materials.



ITER

ITER

The study of burning plasmas has been identified as the next major step in the world fusion program. The worldwide community of fusion researchers has reached a consensus that the scientific and technological basis is sufficient to proceed to a burning plasma experiment — one in which the plasma is heated predominantly by alpha particles produced in deuterium-tritium fusion reactions.

An unprecedented international collaboration of scientists and engineers has performed needed research and development and designed a burning plasma experiment called ITER, which in Latin means "the way." ITER will produce 500 million watts of fusion power, 10 times greater than the external power delivered to heat the plasma.

The United States has joined the European Union, Japan, the Russian Federation, China, Korea, and India in the establishment of the ITER Joint Implementation Agreement. ITER will be built in Cadarache, France, with operation expected by the end of 2018. Additional information can be found at http://www.iter.org .

The Princeton Plasma Physics Laboratory is operated by Princeton University under contract to the U.S. Department of Energy. For additional information, please contact: Information Services, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543. Tel. (609)-243-2750, e-mail: pppl_info@pppl.gov, or visit our web site at: http://www.pppl.gov.