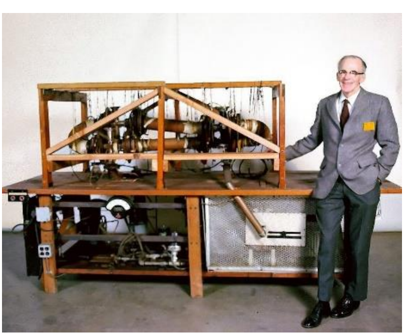
Historic Mechanical Engineering Site
Landmark Designation

Princeton Plasma Physics Laboratory (PPPL)

1 INTRODUCTION

Who among us has not looked up at the sun or at the myriad of stars on a moonless night and wondered about them? How have the stars been able to shine for millions of years, apparently without getting any fuel deliveries? Can we possibly use this same method on earth to provide for all of our energy needs? Lyman Spitzer, a Professor of Astronomy at Princeton University who was long involved in the study of very hot rarified gases (plasmas) in interstellar space, also pondered about the nature of the sun and stars and founded the U.S. Department of Energy's Princeton Plasma Physics Laboratory, which the American Society of Mechanical Engineers has designated a Historic Mechanical Engineering Landmark. Spitzer conceived of a device that he called a "stellarator," which would confine plasmas in a figure-8 shaped tube with external magnets. He presented this concept to the Atomic Energy Commission and, after a scientific review, received funding. Thus, magnetic fusion research at Princeton began in 1951 in a former rabbit hutch on the James Forrestal Campus. Since then, research on fusion has spread to a number of domestic and international research institutions. However, PPPL remains the lead American laboratory for fusion energy and plasma physics.

Dr. Spitzer's first fusion device was the Model-A Stellarator, shown below along with the modest building in which the Princeton program began:



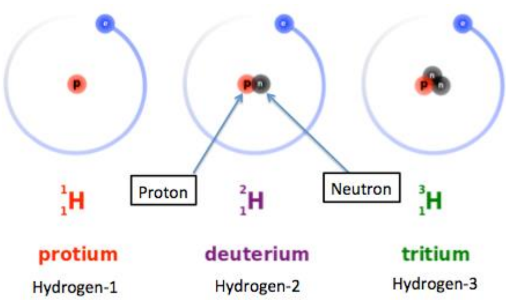
Dr. Spitzer and the Model A Stellarator

The first location of fusion research at Princeton

2 FUSION FUNDAMENTALS

Albert Einstein's famous formula, $E=mc^2$, provides the basis for understanding that mass can be converted into energy. In *fission* reactions*,* (the process used in conventional atomic energy*),* heavy atoms – such as uranium – are split to release the energy that holds them together. In *fusion* reactions, the nuclei of light atoms – such as hydrogen – are fused or joined to produce energy.

Atoms consist of a nucleus, which carries most of the mass, surrounded by negatively charged electrons. The nucleus has a positive electrical charge that is balanced by the electrons' negative charge so that the atom as a whole is electrically neutral. All atomic nuclei contain particles called protons, and all except one form of hydrogen also contain neutrons. Deuterium and tritium, isotopes of hydrogen, are the easiest nuclei to fuse, and are the most likely fuel for fusion energy production.



The figure above shows three isotopes (i.e. different versions) of hydrogen. The isotopes all have the same atomic number (number of protons), but a different number of neutrons.
(from http://study.com/academy/lesson/the-three-isotopes-of-hydrogen.html)

The Deuterium-Tritium (D-T) fusion reaction is illustrated below. Note that electrons are not shown in this diagram, because the electrons are stripped away from the nuclei in the hot plasma.

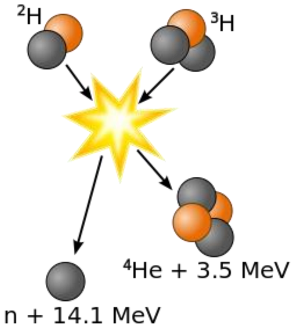


Diagram illustrating the D-T fusion reaction (reference: https://en.wikipedia.org/wiki/Nuclear_)

The fusion process appears easy, but getting nuclei to fuse is extremely difficult due their positive electrical charges that cause them to repel each other. The nuclei must be forced together at extremely high speeds (i.e., at high temperatures) so that they do not merely bounce off each other, but are forced to fuse.

The tremendous sizes and masses of the sun and stars, with their corresponding high gravitational forces, create the natural conditions for fusion to occur. The nuclei are well confined by gravity, heated by gravitational compression, and confined for sufficiently long periods as they travel within the star's tremendous volume. This provides very adequate conditions for a number of different types of fusion reactions to occur. Our sun has a plasma diameter of ~1.4x10^9 m., and gravitational compression produces plasma temperatures of ~15 million C. The billions of stars stand in testimony that fusion is not just a scientist's dream — it is seen throughout the heavens!

The advantages (and reasons for the strong worldwide interest) in fusion are many:

- The major fuel, deuterium, can be readily extracted from ordinary water, which is available to all nations. The surface waters of the earth contain more than 10^{12} tons of deuterium, an essentially inexhaustible supply. The tritium required would be produced in the reactor from lithium, which is available from land deposits or from seawater, which contains thousands of years' supply. The worldwide availability of these materials could eliminate international tensions caused by the current imbalance in fuel supply for power production.

- The amounts of deuterium and tritium in the fusion reaction zone will be so small that a large uncontrolled release of energy would be impossible. In the event of a malfunction, the plasma would strike the walls of its containment vessel and cool.
- Since no fossil fuels are used, there will be no release of chemical combustion products because they will not be produced. Thus, there will be no contribution to global warming or acid rain.
- Similarly, the radioactive products that are formed are far less dangerous and less long-lived than fission products, reducing the handling and disposal problem. Radioactivity will be produced by neutrons interacting with the reactor structure, but careful materials selection is expected to minimize the handling and ultimate disposal of such activated materials.

Magnetic fusion energy (MFE) relies on strong electromagnets to create a "magnetic bottle" to substitute for the gravitational bottle of the stars and our sun. First, a plasma is formed by heating a gas to the point that some or all of the electrons are stripped away from its atoms. This charge separation makes it possible to control the motions of the electrons and atomic nuclei (ions) with magnetic fields.

A variety of methods, including high electrical currents (in the millions of Amperes), radio frequency heating, and energetic beams of neutral atoms are used as a substitute for gravitational compression to heat the plasma. The so-called "Lawson Criteria" quantifies the much more challenging conditions required for net fusion power from a **terrestrial** fusion reactor: a plasma temperature of 100-200 million degrees C, a central plasma density of 1-2 x 10^{20} particles/cu. m., and a confinement time if not heated of at least 1-2 s. The quest of research to develop magnetic fusion energy is to create an efficient magnetic bottle to confine the plasma, and efficient heating to make practical, cost effective energy possible.

MFE research at Princeton has focused on two major concepts, the **stellarator**, which was the concept invented by Lyman Spitzer, and the

tokamak, which was invented in the 50's by Soviet physicists Igor Tamm and Andrei Sakharov [https://en.wikipedia.org/wiki/Tokamak].

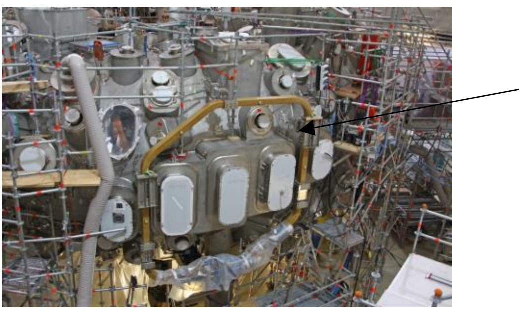
Research at Princeton began with stellarators with figure '8' shaped plasmas. The stellarator's major advantage is that steady state operation – so important for fusion-based power generation — is an inherent feature of this confinement method. The difficulty found in the early stellarators was inadequate plasma confinement. When better performance was reported for tokamaks in the late '60's, Princeton converted its Model C Stellarator to a tokamak in 1968 (see p. 8).

Tokamaks have performed well. In fact, the two experiments operating with fusion fuel of deuterium and tritium to date — PPPL's Tokamak Fusion Test Reactor (TFTR) and UK's JET — are tokamaks. The downside of the tokamak is that steady state operation is difficult to achieve. Tokamaks utilize high currents flowing in the plasma for two purposes: to partially heat it, and to aid in its confinement. In present tokamaks, this current is induced by a transformer, which is time-limited by the transformer's magnetic flux swing. Additionally, tokamaks are prone to plasma disruptions – the sudden loss of plasma current (in the millions of amps) due to plasma instabilities that are still not fully understood. During a disruption, the current flowing in the plasma is suddenly induced in nearby conducting structures, resulting in tremendous electromechanical forces. Structures of tokamaks must be carefully engineered to resist these very high-level forces – this is a significant driver in tokamak design.

A major internationally supported tokamak project, ITER, is currently underway in southern France [ref.: www.ITER.org]. ITER will take magnetic fusion research into the burning plasma regime, where fusion conditions of density and temperature are maintained in a plasma that is self-heated by its own fusion power. PPPL is involved in the development of in-vessel control coils, diagnostics, first wall components, and the steady state power system for ITER.

Another variant of the tokamak is the spherical tokamak (ST) which reduces the size of the core of the torus as much as possible, producing a plasma, which is almost spherical in shape. The advantage of this spherical shape is good performance in a more compact device. PPPL's present major experimental device, NSTX-U (Upgrade), is a spherical tokamak.

Since the early days of stellarator research, engineers and scientists have made significant advances in understanding stellarators. Accordingly, two major stellarators, the Large Helical Device (LHD) in Japan and Wendelstein 7-X (W7-X) in Greifswald, Germany have been constructed. The LHD has been operating since 1998 while W7-X, which achieved first plasma in December 2015, is the world's most advanced operating fusion experiment. This device uses carefully engineered 3-dimensional fields to produce plasma confinement far superior to the original figure-8 stellarators. The researchers plan to operate it for periods of up to 30 minutes as a major step to demonstrating the potential for steady state operation. PPPL engineered and supplied five massive "trim coils", shown below, which can be tuned to correct magnetic field imperfections.

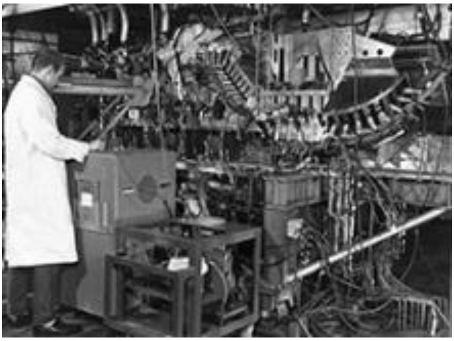


1 of 5 PPPL-supplied trim coils shown installed on W7X. [Photo courtesy of Max Planck Institute for Plasma Physics.]

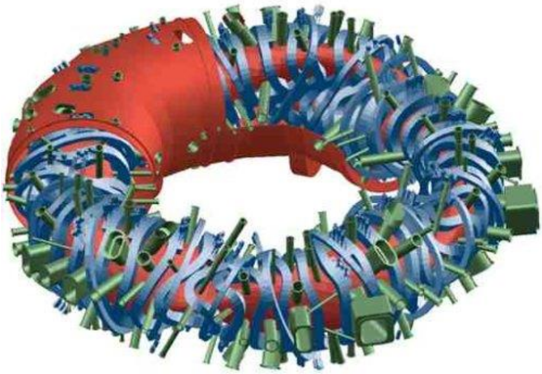
3 Stellarators and Tokamaks

The figures below illustrate the basic differences between the three major types of magnetic fusion energy devices that are mentioned in the following sections. Each concept presents unique challenges from an engineering viewpoint.

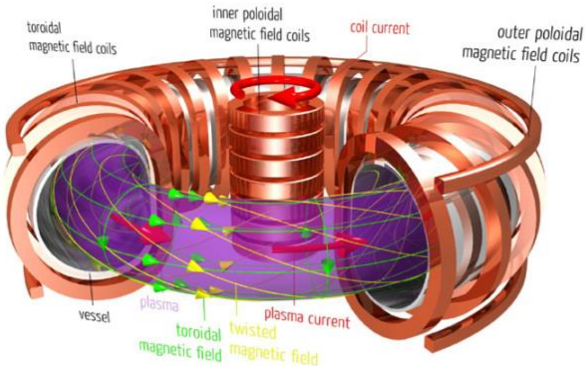
Early Stellarators: The plasma confinement chamber in Spitzer's early stellarators was oval when viewed from the top, with a 180-degree twist in one end to form a figure 8, as shown below.



Modern stellarators like Greifswald, Germany's W7X Stellarator shown below, use 3-dimensional configured confinement magnets to generate an improved stellarator field. Note the array of shapes in the blue confinement magnets. (Figure: Max-Plank Institut fur Plasmaphysics).

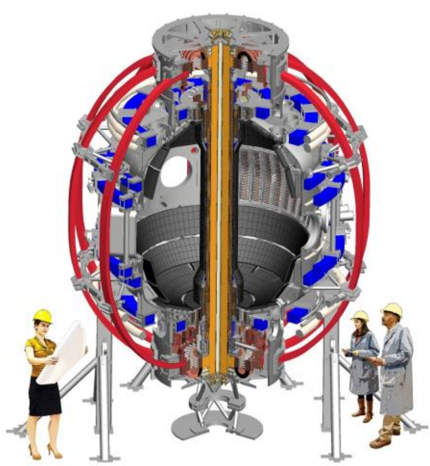


Tokamaks: The figure below shows the major components of a tokamak: the Toroidal Field (TF) coils, which provide the confinement magnetic field; the inner poloidal coils (solenoid), which serve as the primary of the transformer that induces the current into the plasma secondary conductor; and the outer poloidal field coils, which are required for plasma shaping and holding the plasma in equilibrium.



[from https://en.wikipedia.org/wiki/Tokamak]

Spherical Tokamaks: Below is an illustration of PPPL's National Spherical Torus Experiment (NSTX). Notice the low aspect ratio as compared to the tokamak shown above. This results in a compact device with enhanced plasma confinement properties.



4 MECHANICAL ENGINEERING'S ROLE IN FUSION DEVELOPMENT

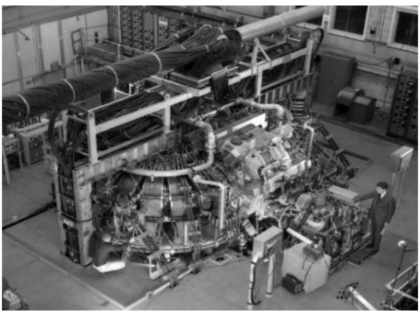
Mechanical engineering plays a key role in fusion development, drawing upon a broad array of engineering disciplines and sub-disciplines. These include systems engineering, structural analysis, fatigue and fatigue crack growth analyses, dynamic analysis, fluids and heat transfer and cryogenics, materials that include metals and composites, and manufacturing and engineering project management. Engineers at PPPL apply a wide variety of tools, while constantly being challenged to maintain state-of-the art knowledge and skills. They interact with physicists, as well as their engineering colleagues at PPPL, with industrial subcontractors, and with the many institutions with which PPPL collaborates.

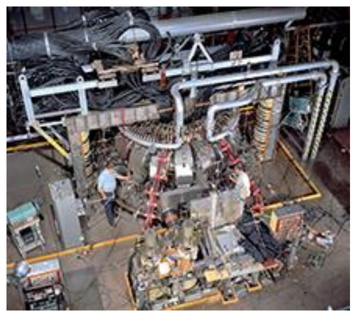
Mechanical engineers were especially prominent in PPPL's coil shop. In 1974, a large shop was located on the south side of the James Forrestal Campus in a large, hangar-like building that was formerly part of the Princeton-Penn Accelerator. This facility, shown below, produced the very large electromagnetic coils for PLT, PDX, S-1, TFTR and ATF (ORNL). Initially the coil shop was located in the "rabbit hutch" shown on p. 1. The coil group had 10 engineers and 22 technicians at its peak. The coil shop was decommissioned as a separate unit in 1986, but elements of the original group have continued to design and produce coils as needed for the Fusion Program.

5 HISTORIC OVERVIEW OF KEY PPPL EXPERIMENTAL DEVICES

Following is an overview of just some of the fusion research devices developed at PPPL. In addition to major devices, PPPL has also developed (and currently operates) some smaller devices aimed at specific areas of fusion research such as diagnostics development, liquid metal walls, and magnetic reconnection.

The Model-C Stellarator and its conversion to a tokamak:





The Model C Stellarator shown in the photo on the right began operation in 1962 following a 4-½ year design and construction effort involving PPPL engineers and physicists and industrial participants. PPPL engineers converted it to a tokamak, PLT, in 1968 in a remarkably short 4 months!

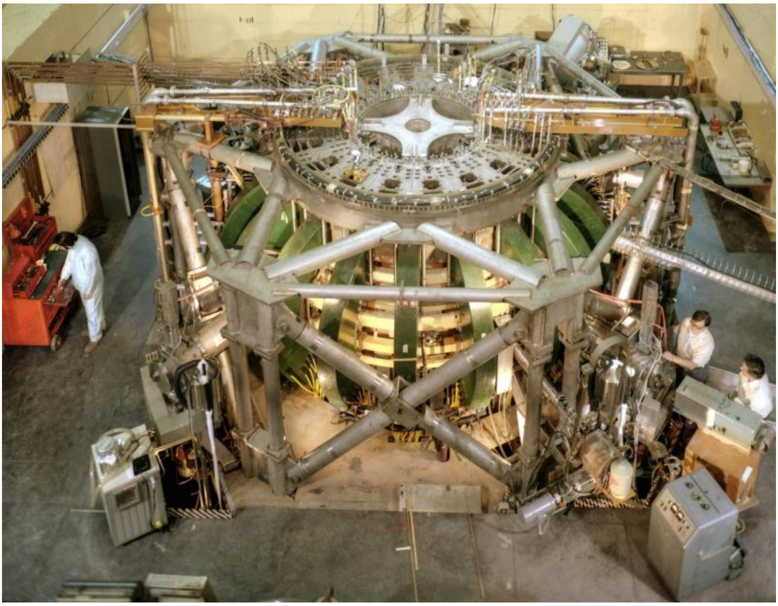
Princeton's Large Torus (PLT):

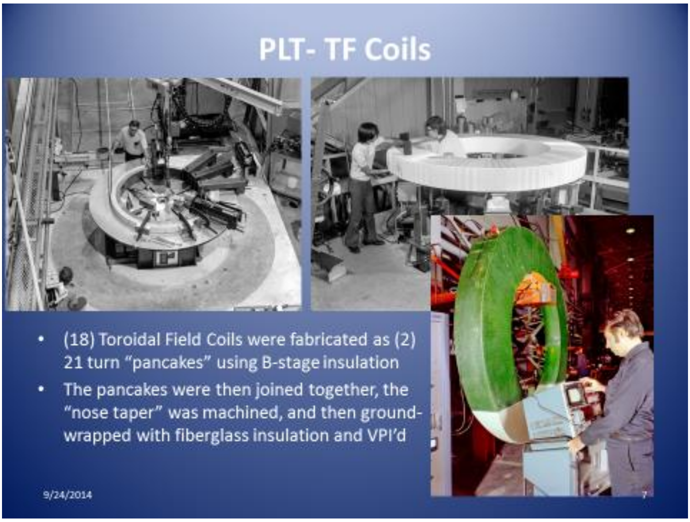
A primary goal of PLT was to permit the first study of magnetically confined plasmas at temperatures approaching reactor levels. A range of auxiliary heating methods, including neutral beam injection and radiofrequency waves were studied. The toroidal field and poloidal field coils, vacuum vessel, and most of the structure were engineered and

[See www.PPPL.gov/ for more information.]

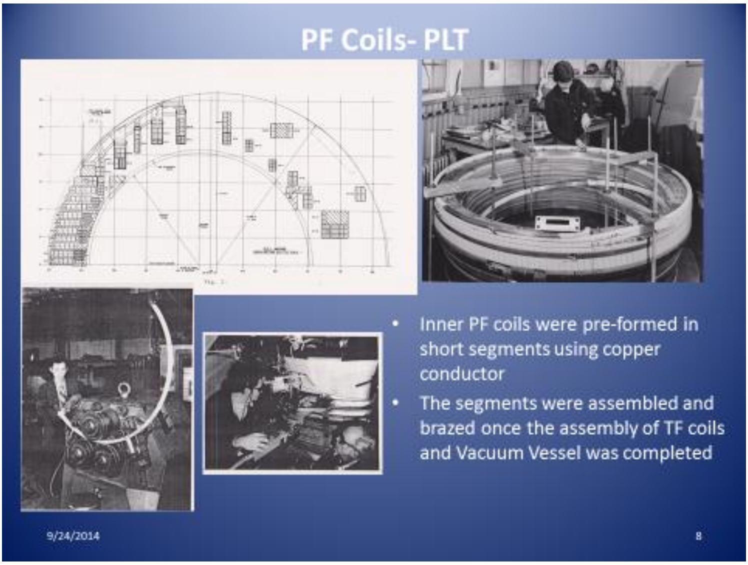
[Ref.: Evolution of Coil Design and Manufacturing at PPPL; James H. Chrzanowski, PPPL, 9/24/14.]

fabricated at PPPL. Note the large external stainless steel torque frame that counteracted forces that could turn the toroidal coil sideways. These forces arise when the poloidal fields cross over the toroidal magnets.



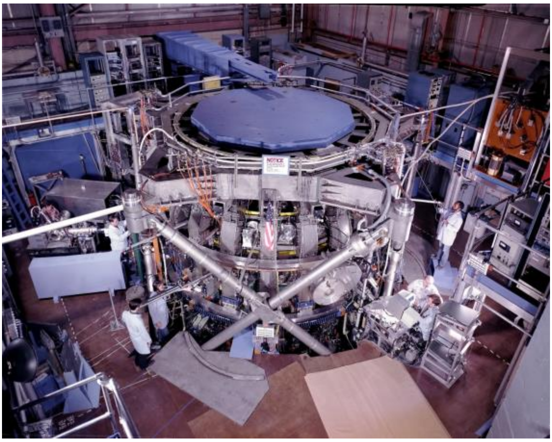


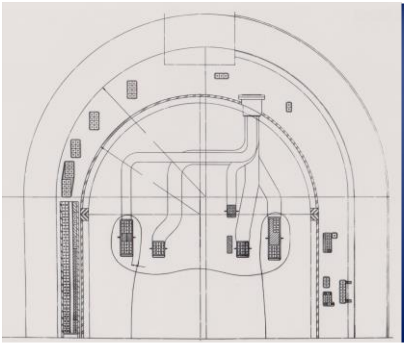
PLT had many Poloidal Field (PF) coils, as shown in the layout in the slide below. These coils were cut into 180-degree segments, and then joined by induction brazing in place around the inner leg of the assembled TF coil array. This was an innovative approach, which required development of specialized tooling and fabrication methods.

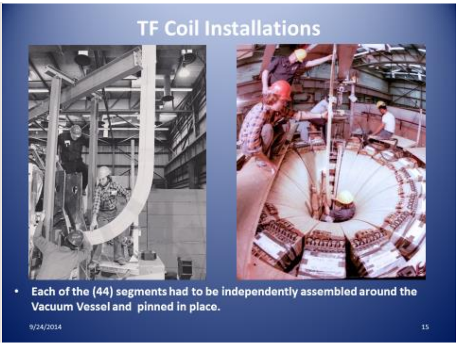


Poloidal Diverter Experiment (PDX)

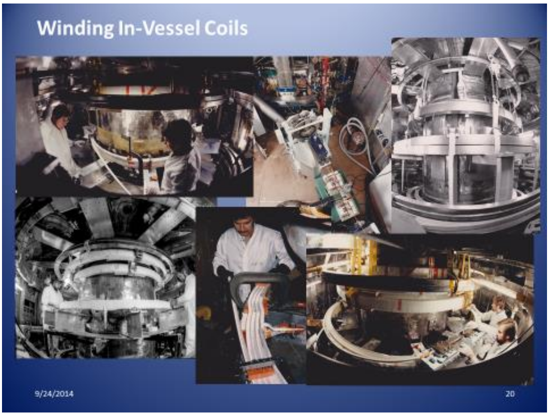
The goal of PDX was to address impurity control using a magnetic divertor to isolate the core plasma from direct contact with the wall. Impurities such as oxygen, carbon, and iron, which enter the plasma when it interacts with the vacuum vessel wall, would increase energy losses and adversely affect the operation of a fusion reactor. PDX employed magnetic field coils located in the vacuum vessel (see right hand photo above) to control the size and shape of the plasma to minimize plasma / first wall interactions and to carry escaping plasma to separate divertor chambers to remove impurities. PDX was completed in 1978. Kaman Aerospace fabricated the TF coils. The PF coils, vacuum vessel, and structure were fabricated by PPPL, with the assistance of subcontractors.







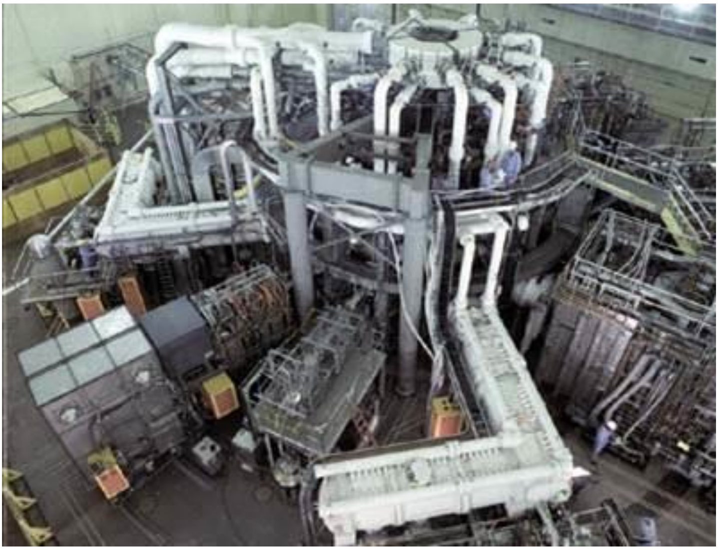
A major upgrade was made in 1978, which involved winding additional coils in-place in the vacuum vessel. Special fabrication methods had to be developed for these coils, which included using a stainless steel vacuum jacket.

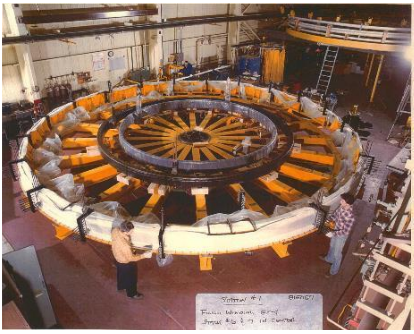


The Tokamak Fusion Test Reactor (TFTR)

Groundbreaking for TFTR took place in 1978. The size and complexity of the device required significant industrial involvement: Ebasco/Grumman were the prime subcontractors for the project; Westinghouse fabricated the TF coils, Asea/Brown Boveri (ABB) fabricated the inner poloidal field coils, and PPPL fabricated the large diameter outer PF coils.

The photos below show TFTR and the large diameter polidal field (PF) coils during fabrication in PPPL's coil shop.





The photo below shows these coils being transported to the test Cell; the following photo shows the beginning of TFTR's assembly.

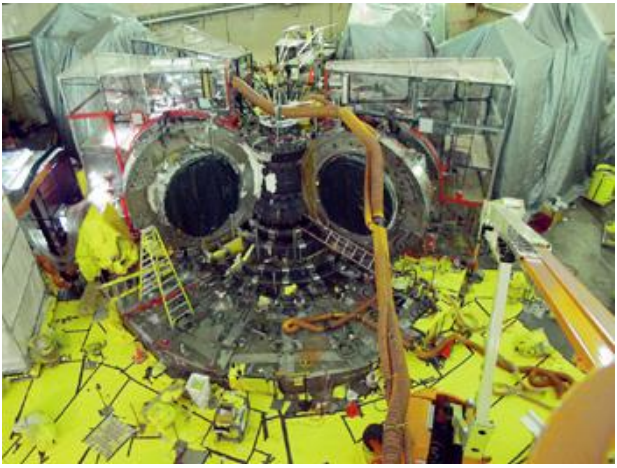
Among TFTR's many achievements:

- TFTR achieved a world record 400 million degrees C ion temperature and fusion power of 60,000 W in deuterium plasmas in 1990.

- TFTR broke this record in February 1995, achieving an ion temperature of 510 million degrees C.

- TFTR achieved 6.3 million watts of fusion power in the world's first magnetic fusion experiments with a 50/50 mixture of deuterium and tritium in 1993. In November 1994, TFTR exceeded this world record when10.6 million watts were achieved. The JET experiment in UK later exceeded this, achieving 16 MW in 1997.

Following the series of successful D-T and related experiments, TFTR was safely disassembled and removed in 2002 by PPPL engineers and technicians. This was completed on schedule and under budget, demonstrating a number of innovative methods of dismantling a D-T fueled fusion device and freeing this advanced facility for future work.

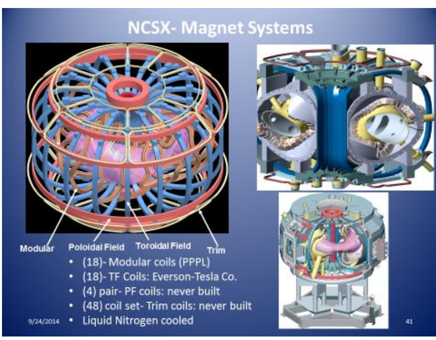


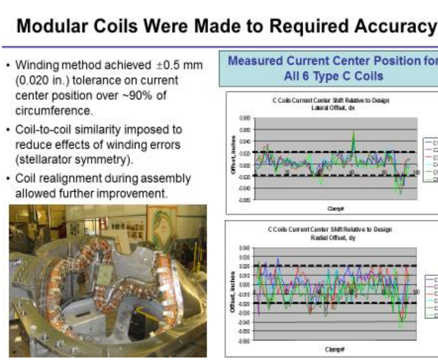
TFTR during decommissioning

National Compact Stellarator Experiment (NCSX)

PPPL began a study of a compact stellarator concept in 1998. Although not completed, this project significantly advanced PPPL's state-of-the art engineering expertise in fields including electromagnetic analysis, complex CAD modeling, "paperless" CAD-CAM fabrication methods, and structural analysis of intricately shaped parts with complex electromagnetic loading. Like modern stellarators, its coils and vacuum vessel were shaped to provide a 3-dimensional stellarator magnetic confinement configuration. The geometry of the stellarator plasma and its coils were designed by PPPL physicists using high-performance computing to optimize properties that govern plasma performance. The NCSX was designed to test a unique physics design strategy known as magnetic "quasi-axisymmetry," in which the motion of plasma particles is the same as in a tokamak. The aim was to obtain the favorable properties of stellarators, stability and inherent ability to operate in steady state in a device with tokamak-like performance, blending the favorable performance characteristics of both concepts. The 18 modular coils that made up the 3-dimensional magnet system were the most challenging ever produced by the PPPL coil shop. All were successfully manufactured, realizing the physics-specified coil geometries to within exacting tolerances.

The complex geometry was challenging to measure – this required that PPPL develop in-house capability to use laser scanners and multi-link measuring systems and software. This capability has now become an integral tool at PPPL. PPPL worked closely with several subcontractors including Energy Industries of Ohio (EIO), Major Tool and Machines of Indianapolis, and MetalTek International of Pevely, Mo. Although the NCSX construction project was ultimately discontinued in 2008, both PPPL and its subcontractors learned much from their efforts on NCSX. Below are slides and photos of some of the NCSX components.

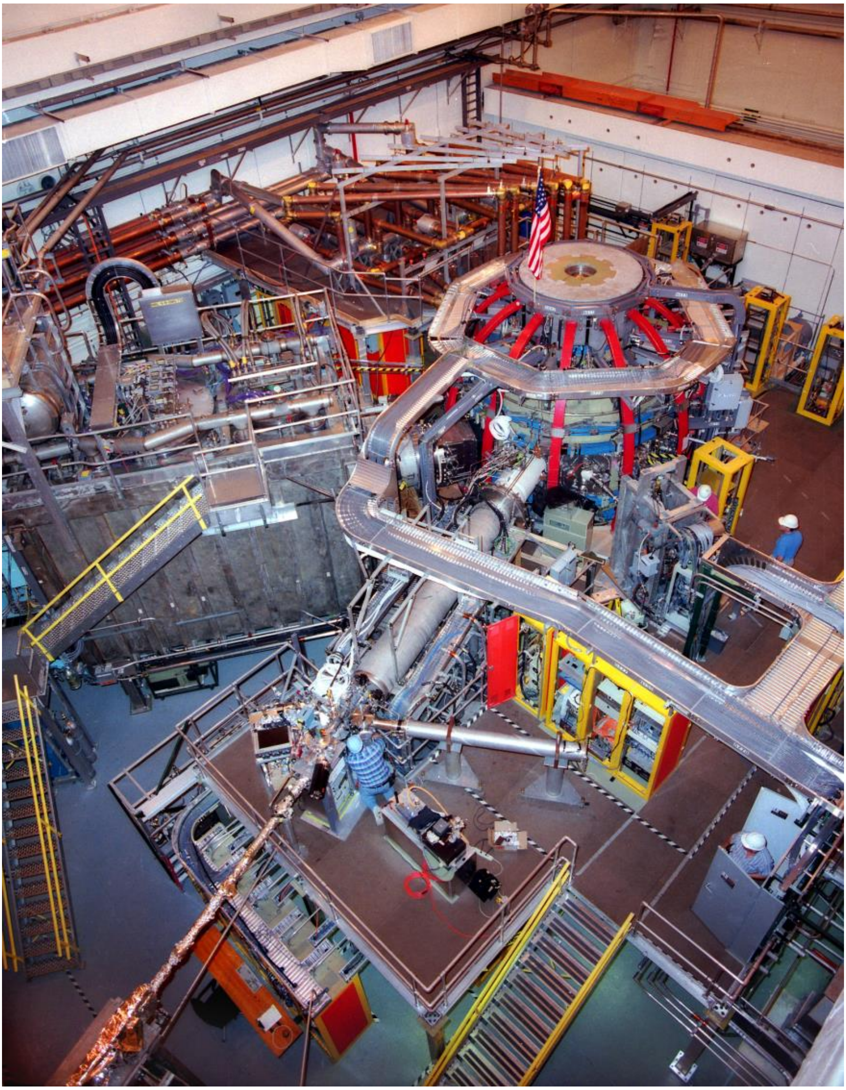




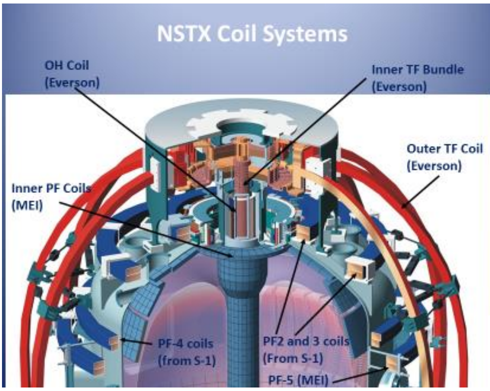
Fabricated NCSX components

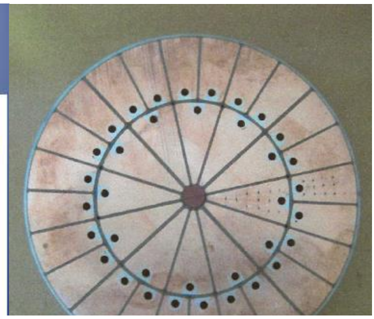
The National Spherical Torus Experiment (NSTX) and its Upgrade

NSTX, shown below, first began operation in 1999.



To achieve a low aspect ratio, the central portion of the toroidal field coil had to be very compact. Custom copper extrusions were arranged in a 2-layer configuration and bonded together with fiberglass and epoxy as shown in the cross-section of it below.





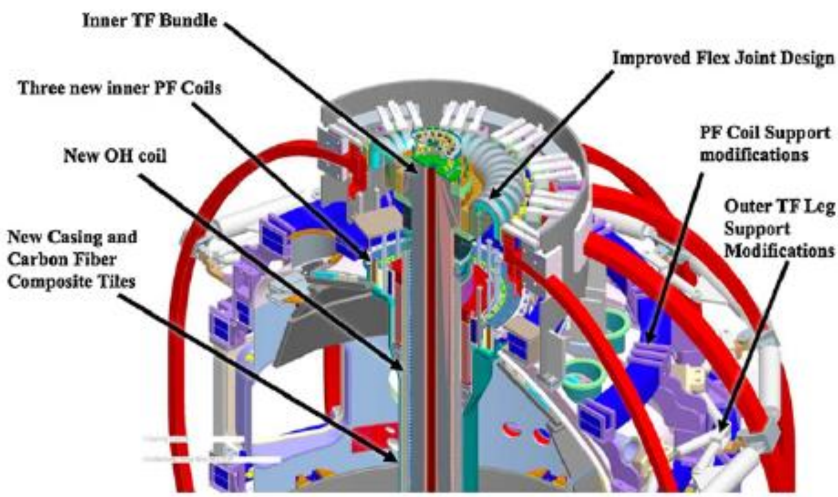
Cross section of the copper bar assembly that produces the toroidal magnetic field.

Steps to fabricate the copper bar assembly that produces the toroidal magnetic field.

Work began on the NSTX Upgrade in 2012 after a very successful experimental program of more than 10 years that demonstrated the capabilities of a Spherical Tokamak device, and its attractiveness as a candidate for next-step power-producing experiments because of its compact size and modularity. The Upgrade includes a number of changes that will greatly expand its research capabilities:

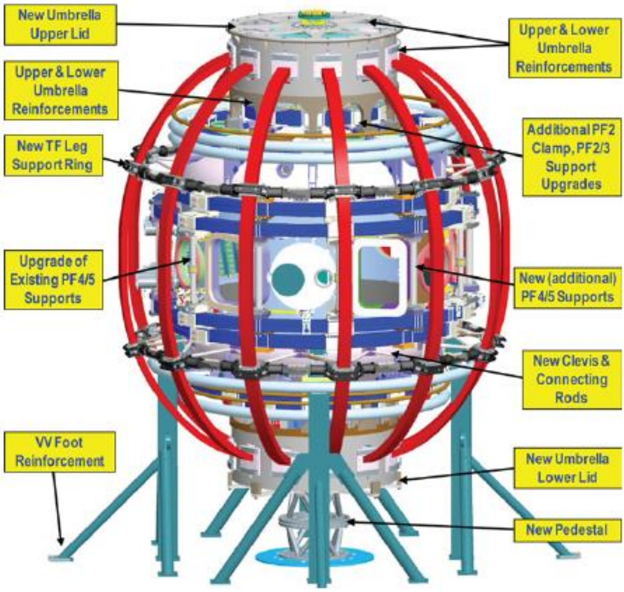
NSTX Upgrade Performance Comparison

	NSTX	NSTX-U
Plasma current, Ip [MA]	1.0	2.0
Toroidal field Bt [T]	0.55	1.0
Pulse length, [s]	1.0	5.0

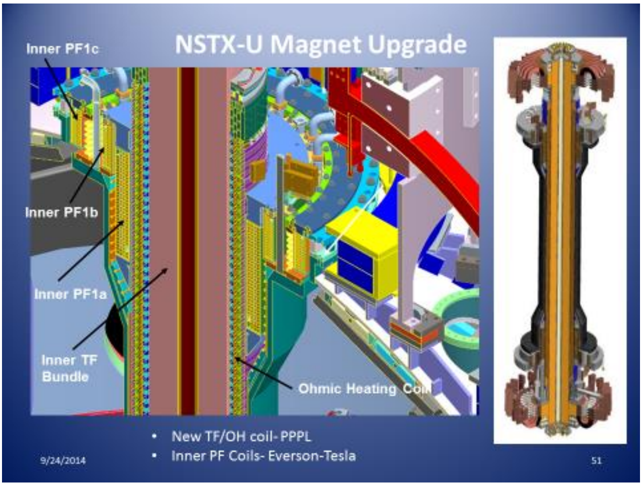


Major machine changes in the NSTX Upgrade

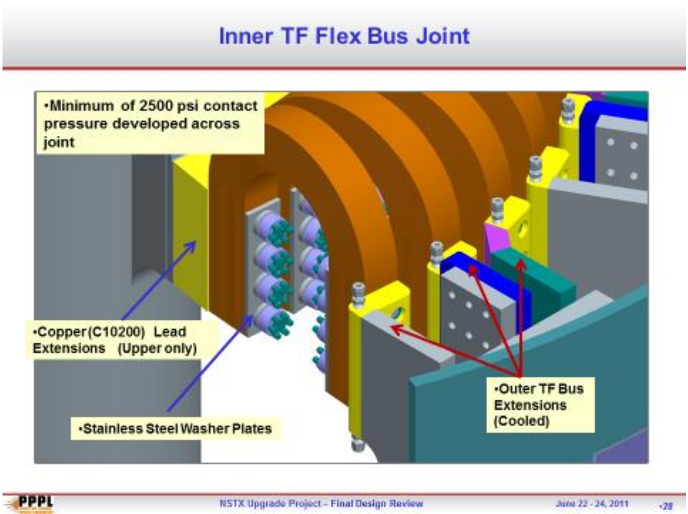
A number of vessel reinforcements and structural changes had to be made to handle the higher forces associated with the upgrade as indicated in the following slide.



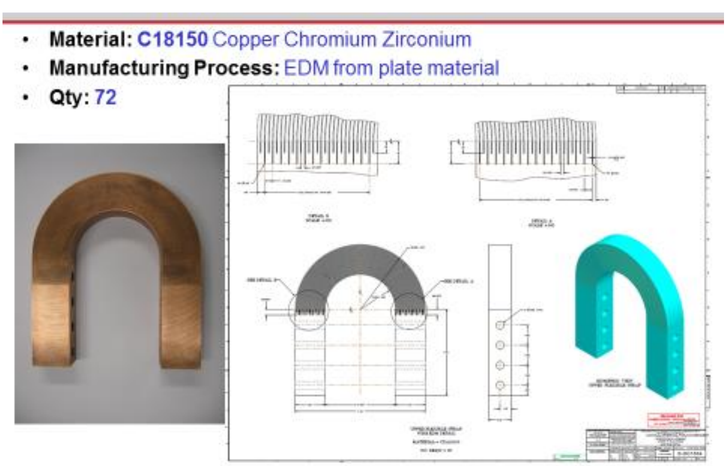
A key component of the Upgrade is the center stack assembly, which consists of the center legs of the TF coils and the ohmic heating solenoid which is wound directly on it:

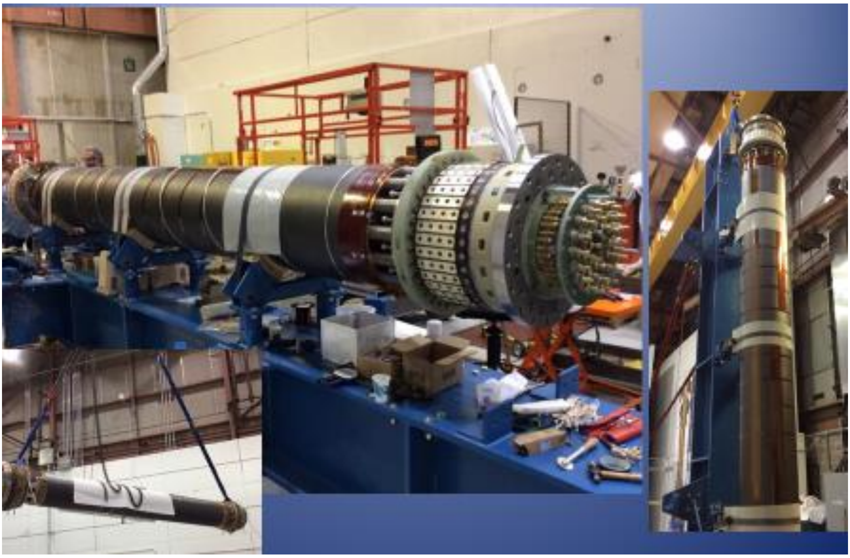


The electrical connections to the center stack are a critical area. This was an area of focus in which a number of design changes were made to accommodate the higher currents and forces of the upgrade while also improving reliability.



- High-strength copper chrome zirconium lead extensions were friction stir welded to the high conductivity oxygen free copper TF inner conductors. The strong copper permits high preload pressure, important for electrical joint conductivity, while the high conductivity copper in the long inner conductors reduces resistance and temperature rise.
- The flexible joint, shown below, was electric discharge machined from a copper chrome zirconium plate. It was fatigue tested to 5X life.





The Completed NSTX-U Center Stack

This photo shows the PPPL staff that worked on the Upgrade. Photos of the upgraded device and facility and a view inside the vacuum vessel are shown above the group.

6 THE HISTORY AND HERITAGE PROGRAM AT ASME

Since the invention of the wheel, mechanical innovation has critically influenced the development of civilization and industry as well as public welfare, safety and comfort. Through its History and Heritage program, the American Society of Mechanical Engineers (ASME) encourages public understanding of mechanical engineering, fosters the preservation of this heritage and helps engineers become more involved in all aspects of history.

In 1971 ASME formed a History and Heritage Committee composed of mechanical engineers and historians of technology. This Committee is charged with examining, recording and acknowledging mechanical engineering achievements of particular significance. For further information, please visit http://www.asme.org

LANDMARK DESIGNATIONS

There are many aspects of ASME's History and Heritage activities, one of which is the landmarks program. Since the History and Heritage Program began, 267 artifacts have been designated throughout the world as historic mechanical engineering landmarks, heritage collections or heritage sites. Each represents a progressive step in the evolution of mechanical engineering and its significance to society in general.

The Landmarks Program illuminates our technological heritage and encourages the preservation of historically important works. It provides an annotated roster for engineers, students, educators, historians and travelers. It also provides reminders of where we have been and where we are going along the divergent paths of discovery.

ASME helps the global engineering community develop solutions to real world challenges. ASME, founded in 1880, is a not-for-profit professional organization that enables collaboration, knowledge sharing and skill development across all engineering disciplines, while promoting the vital role of the engineer in society. ASME codes and standards, publications, conferences, continuing education and professional development programs provide a foundation for advancing technical knowledge and a safer world.

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THE PRINCETON PLASMA PHYSICS LABORATORY HAS LONG BEEN THE SITE OF RESEARCH ACHIEVEMENTS IN THE QUEST TO DEVELOP CONTROLLED FUSION REACTIONS. ENGINEERS HAVE DESIGNED, BUILT AND OPERATED A SERIES OF FUSION ENERGY DEVICES KNOWN AS STELLARATORS, TOKAMAKS, AND SPHERICAL TOKAMAKS. THESE FACILITIES UTILIZE STRONG MAGNETIC FIELDS TO CONTAIN HYDROGEN ISOTOPES MANY TIMES HOTTER THAN THE CORE OF THE SUN TO PRODUCE FUSION REACTIONS THAT RELEASE ENERGY THAT COULD BE HARNESSED FOR THE BENEFIT OF ALL HUMANKIND.

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