The National Compact Stellarator Experiment: An Innovative Fusion Device

The National Compact Stellarator Experiment (NCSX) represents a promising and uncompleted pathway to fusion as a safe, clean and virtually limitless source of energy for generating electricity.

Scientists and engineers at the U.S. Department of Energy's Princeton Plasma Physics Laboratory (PPPL) developed the NCSX as the first of a new class of fusion reactors called "compact stellarators" that are hybrids of the stellarator and more widely used tokamak designs. A key difference between traditional stellarators and the NCSX is that the former controls the plasma solely with external magnetic coils while the NCSX uses coils and what is called a "bootstrap current" that the plasma creates to augment the magnetic field.

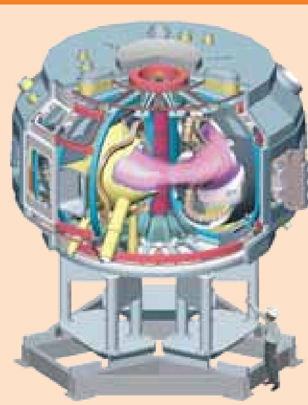
This combination makes the NCSX more compact than traditional stellarators and similar to tokamaks, which use external coils and bootstrap currents to create the field. At the same time, stellarators require less power to operate than do tokamaks, which must induce the plasma current with additional magnets plus an outside current source to supplement the bootstrap effect. The NCSX thus marks an effort to capitalize on the best of both reactor concepts. "We wanted a design that could take advantage of much of what's been learned on tokamaks instead of starting anew," said George "Hutch" Neilson, director of advanced projects at PPPL and a former project manager for the NCSX.

Winding of an NCSX modular field coil.

The goal of the NCSX, like all fusion experiments, is to test the principles needed to produce a sustained fusion reaction. Fusion takes place when two atomic nuclei combine and release a burst of energy. Fusion research seeks to harness this energy to drive electric power plants.

NCSX AT A GLANCE

- **The National Compact Stellarator Effort represents an unfinished effort to capitalize on the best features of the stellarator and tokamak reactor designs.**
- **PPPL scientists ran hundreds of thousands of computer simulations to design the optimal shape for the NCSX.**
- **The simulations were based on mathematical advances developed by Allen Boozer, head of the Theory Department at PPPL.**
- **Magnetic coils for the NCSX were among the most complex and innovative electromagnets ever designed.**



- **Forms for the coils and the plasma containment vessel had to be machined to within one-twenty-thousandth of an inch of specifications.**
- **Some 80 percent of the major components for the NCSX had been built or procured when the U.S. Department of Energy canceled the project in 2008 because of higher-than-anticipated costs.**
- **No other stellarator now built or under construction will replace the NCSX mission of optimizing the stability of plasma under pressure that exceeds the previous limits for such machines.**

A "Star-generator"

PPPL invented the first stellarator in the early 1950s under Laboratory founder Lyman Spitzer, who coined the term "stellarator" to stand for "star-generator," since fusion drives the sun and stars. Spitzer's device used twisting, helically shaped coils to confine the plasma inside a racetrack-shaped containment vessel.

This design was widely copied in the 1950s and 1960s before taking a back seat to tokamaks, whose symmetrical geometry produced good plasma confinement and proved easier to understand and build. The largest project at PPPL today, the National Spherical Torus Experiment, is a compact tokamak that is currently undergoing a $94 million upgrade.

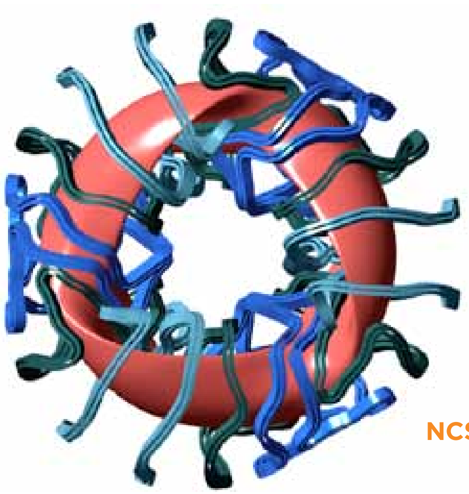
Breakthroughs in computing, mathematical techniques and physics understanding have revitalized interest in stellarators in recent decades and made them the subject of major experiments in Japan and Germany. A key design insight came from Allen Boozer, now interim head of the Theory Department at PPPL, who created a mathematical roadmap for optimizing the confinement of plasma within the stellarator's twisting—or 3-D—magnetic field. "This ability to predict good confinement with certainty is a major advance," said David Gates, stellarator physics leader at PPPL and the Laboratory's chief liaison to the Large Helical Device (LHD) stellarator in Japan and the Wendelstein 7-X (W7-X) stellarator that Germany is constructing.

NCSX developers explored hundreds of thousands of designs using computer simulations based on Boozer's equations to design a machine that could stabilize plasma under higher pressure than previous stellarators had explored. Plasma must remain stable at high pressure for fusion to occur.

Complex Coils

The coils that PPPL developed for the NCSX were among the most complex and innovative electromagnets ever designed and proved challenging to fabricate. Forms for the coils and the containment vessel they surrounded had to be machined to tolerances within one-twenty-thousandth of an inch of design specifications, or about the thickness of a few sheets of paper, in order to maintain the correct shape of the magnetic field. These exacting tolerances ensure that the required magnetic field geometry is achieved with high accuracy.

Modular field coil winding form.



NCSX plasma and modular coils.

Meeting the unprecedented fabrication demands brought higher-than-expected costs once the NCSX construction began in 2004. This ultimately led the DOE, which funds the Princeton University-run Laboratory, to cancel the project in 2008, after some 80 percent of the machine's major components had been built or procured. "We knew that high tolerance costs money," said Neilson. "But we were doing something for the first time and until you actually build something you don't know how much you're really talking about, and so we underestimated the cost."

Many Milestones

The unfinished project achieved milestones during its lifetime. "We showed that you could design a machine on these principles and actually build the parts," Neilson said. "In the course of building them there were all kinds of advances in manufacturing and assembling sophisticated components like these, and there is no doubt that we could have finished the machine."

Completion of the NCSX would have enabled PPPL scientists to test their predictions for what the experimental device could achieve. This included reaching a high level of a key measure called "beta"—the ratio of the pressure of the plasma to the strength of the magnetic field that confines it. The higher the beta the more cost-effective the machine. Success in this effort could have led to a follow-up compact stellarator based on similar design principles and built to permit long-term maintenance, and then to a demonstration nuclear fusion power plant.

PPPL now collaborates with the non-compact stellarator projects in Japan and Germany to remain active in the stellarator field. The Laboratory is designing high-resolution X-ray imaging systems for Japan's LHD, which began operating in 1998, and is building a set of "trim coils" to help fine-tune the shape of the plasma in Germany's W7-X machine that is scheduled for completion in 2015. But neither stellarator will test the innovations for stabilizing a compact, high-pressure plasma that the NCSX was designed to test.

PPPL

The Princeton Plasma Physics Laboratory is operated by Princeton University under contract to the U.S. Department of Energy. For additional information, please contact: Office of Communications, 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: www.pppl.gov.