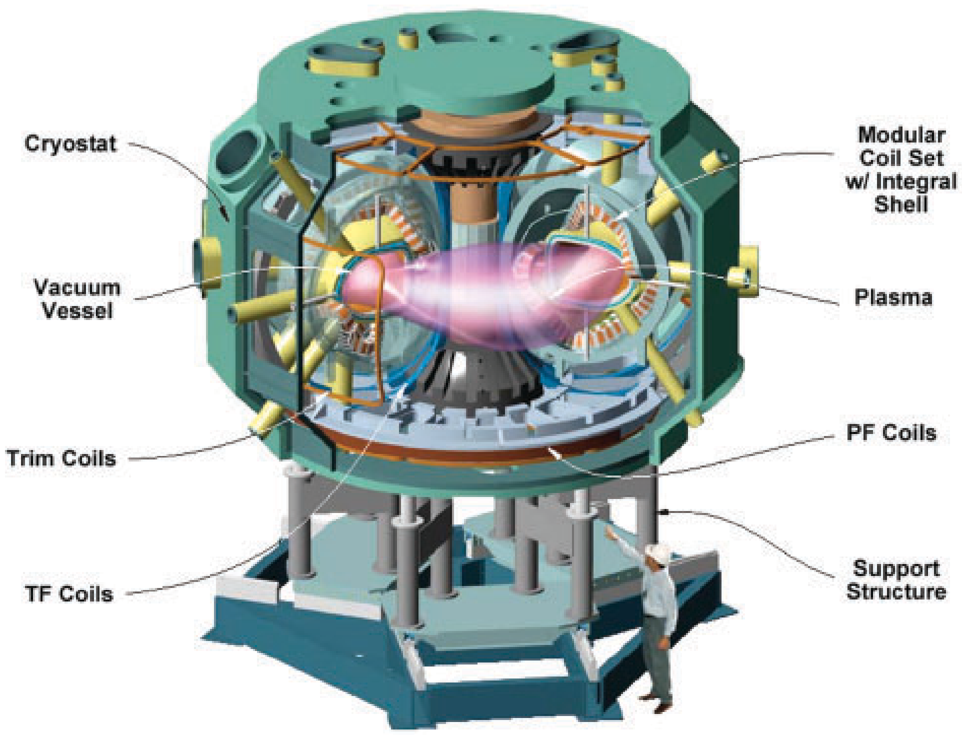
National Compact Stellarator Experiment



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A key goal for fusion energy research is to develop physics solutions for practical magnetic fusion power plants. Stellarators, a family of three-dimensional toroidal magnetic configurations, are of interest because they solve two major problems for magnetic confinement — achieving steady-state operation and avoiding plasma disruptions. There is a substantial effort in stellarator research worldwide, including Japan's Large Helical Device and Germany's Wendelstein-7X, large facilities with superconducting coils. United States researchers have focused on a new variant, the compact stellarator, which shares the attractive properties of existing stellarators, but has additional advantages. Compact stellarators have lower aspect ratio (ratio of the torus radius to plasma radius ≤4.5 versus ≥10) which can improve reactor economics. Also, they have strong physics similarities with tokamaks, allowing them to advance more rapidly and economically by making use of advances in the more mature tokamak concept. A new experimental device, the National Compact Stellarator Experiment

(NCSX) is being built at the Princeton Plasma Physics Laboratory (PPPL), in partnership with the Oak Ridge National Laboratory, as the centerpiece of a national program to develop compact stellarators. In fiscal year 2002, the NCSX project passed a critical U.S. Department of Energy project review and received the approvals needed to start Title I design in fiscal year 2003.

Advances in Stellarator Physics Design

Stellarators with good confinement properties can be made entirely with external coils, so they are sustainable in steady-state without plasma current-drive systems. Compared to axisymmetric configurations such as tokamaks, stellarators provide additional degrees of freedom to design for favorable physics properties, such as high-beta stability. This makes it possible to maintain a high-performance plasma and avoid disruptions without the complexities of current profile control or feedback. In spite of its three-dimensional character, the NCSX magnetic field is designed to be quasi-axisymmetric, so that the charged particles drifting along magnetic field lines in the system see an approximate symmetry direction in the field strength, as in tokamaks, and consequently have similarly well-confined trajectories. Magnetic quasi-symmetry thus provides a fundamental physics link between stellarators and tokamaks.

The NCSX is designed to test compact stellarator physics in a high-beta (>4%), moderate aspect ratio (≤4.4) quasi-axisymmetric stellarator (QAS) plasma configuration that obtains about one-fourth of its edge rotational transform from the self-generated bootstrap current. Its external three-dimensional magnetic field is generated by modular coils (Figure 1) which are designed with modern high-performance computers and numerical methods that incorporate an integrated plasma physics simulation to design the coils for optimum plasma performance.

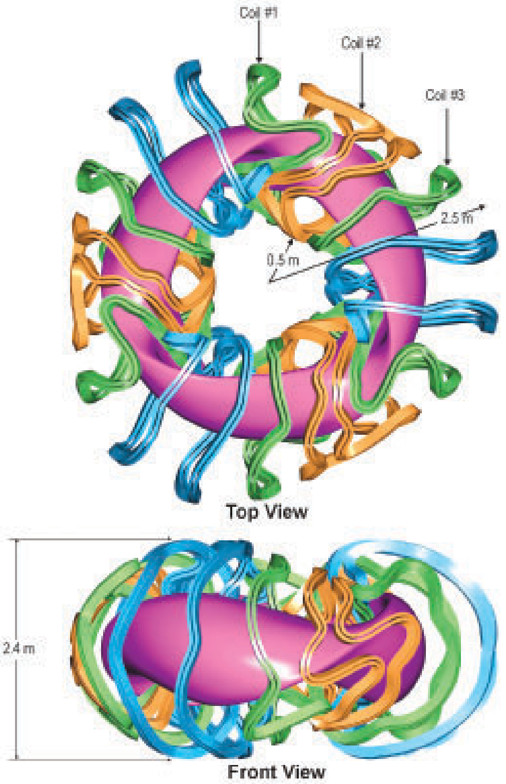

Figure 1. The National Compact Stellarator Experiment modular coils and plasma.

In FY02, stellarator coil design methods were extended to produce feasible modular coil designs satisfying the demanding physics requirements that have been set for NCSX. An initial filamentary modular coil solution is found by minimizing the root-mean-squared component of the magnetic field normal to the surface of a physics-optimized target plasma shape, following the reverse engineering approach pioneered by German researchers. The coil geometry is then modified by a technique which couples coil and plasma optimization tools to obtain a solution which produces a free-boundary target equilibrium possessing the required physics properties and satisfying engineering feasibility constraints. The plasma and filamentary coil properties achieved in the NCSX design are summarized in Table 1. An effective ripple parameter ε_h, characterizing transport in the collisionless regime, measures the degree of quasi-axisymmetry. In the final step, the coil geometry is modified again to reduce the width of residual islands in the free-boundary equilibrium calculated by the PIES code, while preserving the physics and engineering properties. The resulting finite-build coils produce a free-boundary high-beta target equilibrium that has good magnetic surfaces, with the sum of effective island widths <1% (Figure 2).

NCSX Conceptual Design Advances

A conceptual design of the NCSX stellarator facility was developed based on the optimized physics design described above. The stellarator core device includes

Table 1. Summary of Configuration Properties Achieved in Optimized NCSX Stellarator Design with Major Radius = 1.4 m and B = 1.7 T.

Parameter or Property	Achieved	Criteria
Aspect ratio $R/\langle a\rangle$	4.4	Substantially lower than existing optimized stellarator designs.
Stability at $\langle\beta\rangle = 4\%$	Stable to external kink, vertical, and Mercier modes	Sufficient to test stabilization of a sustainable toroidal plasma by three-dimensional shaping.
Shear	$\iota = 0.39$ (center), 0.65 (edge)	Conducive to island self-healing.
Large external iota fraction	~0.75 from coils	Conservative approach for disruption resistance.
Quasi-symmetry	Effective ripple $\varepsilon_h \approx 0.1\%$ (center), 0.4% ($r/a \approx 0.7$)	To minimize ripple-driven losses.
Magnetic surface quality	Total effective island width <10% of toroidal flux	To minimize losses due to equilibrium imperfections.
Coil bend radius	≥10 cm	Acceptable conductor deformation.
Coil-to-coil distance	≥16 cm, ≥37 cm at neutral-beam-injection opening	Adequate space for finite coil build and tangential neutral-beam injection.
Coil-plasma distance	≥18 cm	Adequate space for layers of structures, gaps, and plasma scrape-off.

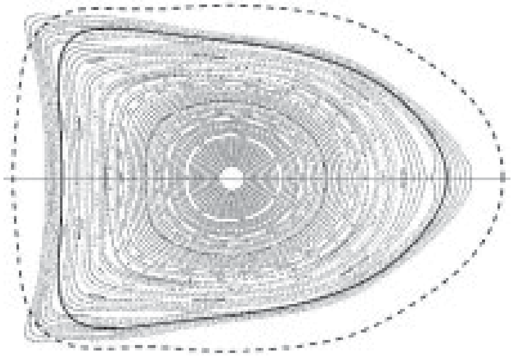

Figure 2. Poincaré plot of National Compact Stellarator Experiment (NCSX) magnetic surfaces for free-boundary equilibrium (calculated by the PIES code) at $\beta = 4.1\%$ for finite cross-section model of NCSX coils. Dashed line, first wall; solid line, equilibrium boundary as calculated by the VMEC code.

an assembly of coil systems, a vacuum vessel, support structures, and a cryostat (since the coils operate at cryogenic temperatures), as shown in Figure 3. Auxiliary systems include 6 MW of neutral-beam plasma heating power, vacuum pumps, magnet power supplies, diagnostics, instrumentation and controls, and structure heating and cooling systems. The NCSX will be located at PPPL's C-Site.

The completed modular coils will be wound with flexible, multistrand cable conductor on a cast-and-machined winding form that provides both the needed accuracy and structural support [Figure 4(a)]. Each coil is split into two winding packs, one on either side of a T-structure extending from the winding form [Figure 4(b)]. This configuration provides good access for winding the conductor and moves the conductor as close as possible to the plasma. The windings are vacuum-pressure-impregnated with epoxy to form a monolithic structure. The winding forms are then bolted together at planar flanges to form a continuous shell structure to resist the electromagnetic loads. This system minimizes the accumulation of geometric errors and provides a very robust structural system. The maximum toroidal field produced by the modular coils at R = 1.4 m with a flattop of 0.5 s is 1.7 T. Toroidal-field

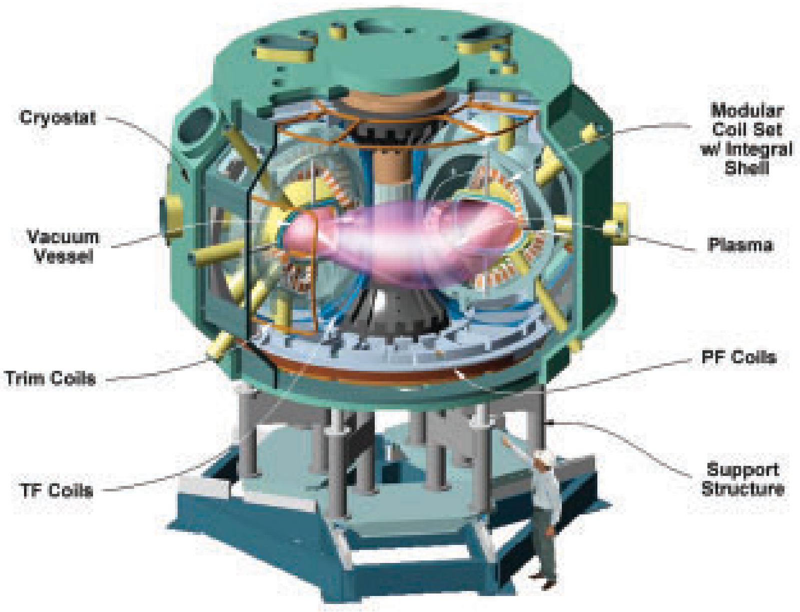

Figure 3. The National Compact Stellarator Experiment stellarator core with major components identified.

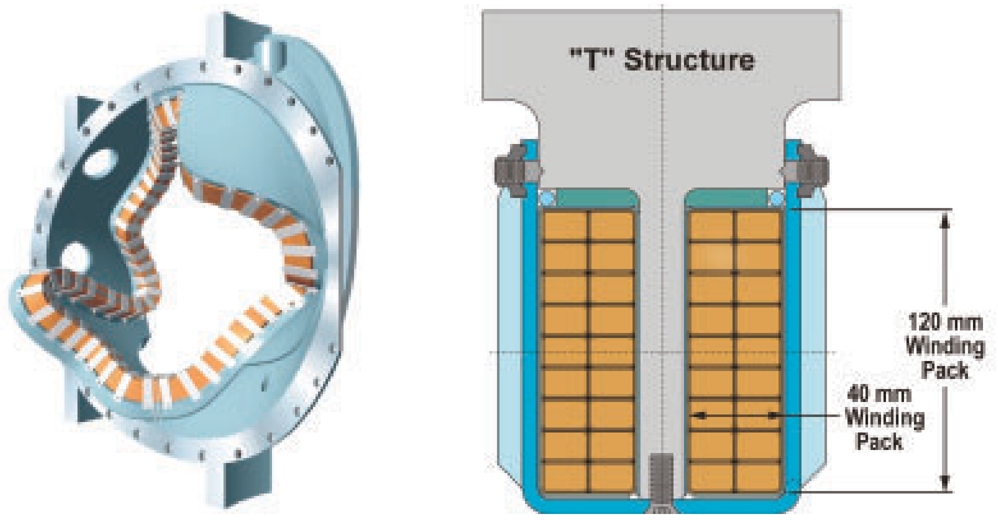

Figure. 4. Modular coils. (a) Completed coil wound on winding form. (b) Cross section of the winding pack.

coils, which are included for flexibility, can raise the toroidal field on axis above 2 T. Due to the high modular coil current density (~14 kA/cm), the coils are cooled to liquid nitrogen temperature.

Nested inside the coil set and surrounding the plasma is a highly contoured vacuum vessel. The vessel consists of three identical, 120-degree segments (corresponding to the three field periods of the magnetic configuration) that are bolted together at double-sealed joints. Each segment is fabricated from 9.5-mm-thick Inconel 625 that is press-formed, explosively formed, or perhaps investment cast to the required shape. Inconel was selected for its low magnetic permeability (even after welding) and high electrical resistivity. As shown in Figure 5, numerous ports are provided for heating, diagnostics, and maintenance access. Several sizes and shapes are used to best utilize the limited access between modular coils. The vessel will be baked to 150 °C and operated at 20 °C using helium gas circulated through tracing lines attached to the vessel exterior. The vessel is insulated on its exterior surface to provide thermal isolation from the modular coils.

The NCSX stellarator core will be assembled from three field-period subassemblies that include six each of the modular and toroidal-field coils and one-third of the vacuum vessel. The coils are assembled over the vacuum vessel segment before the port extensions are welded into place. When all three field-period subassemblies are in place on the machine support base, they will be moved radially into final position and joined together.

Summary and Project Status

In FY02, the NCSX design was documented in a conceptual design report that

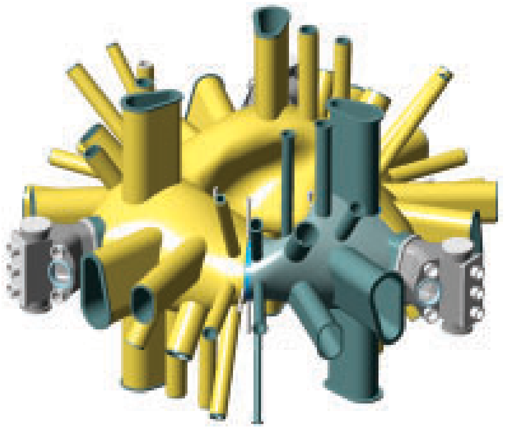

Figure 5. The National Compact Stellarator Experiment vacuum vessel.

included design descriptions, analyses of engineering performance, and cost and schedule estimates. Manufacturing studies of the modular coils and vacuum vessel, performed by industrial suppliers, confirmed the manufacturing feasibility of these critical components and provided cost and schedule information that the project used in developing its estimates. A Department of Energy (DOE) review panel, made up of experts from the fusion community and the DOE, conducted a thorough review of the NCSX project in May, 2002. They found that a sound basis was established in all aspects: physics and engineering design; cost and schedule; management; and environment, safety, and health. Based on the positive review findings, the Under Secretary of Energy approved an Acquisition Plan for NCSX and an Office of Science Acquisition Board approved a preliminary cost and schedule range and initiation of Title°I design activities. The project is planned to start in FY03 and be completed in FY07 at a cost of $73.5 million.