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Design of the national compact stellarator experiment (NCSX)

B.E. Nelson [a,*], L.A. Berry [a], A.B. Brooks [b], M.J. Cole [a], J.C. Chrzanowski [b], H.-M. Fan [b], P.J. Fogarty [a], P.L. Goranson [a], P.J. Heitzenroeder [b], S.P. Hirshman [a], G.H. Jones [a], J.F. Lyon [a], G.H. Neilson [b], W.T. Reiersen [b], D.J. Strickler [a], D.E. Williamson [a]

[a] *Oak Ridge National Laboratory, P.O. Box 2009, Oak Ridge, TN 37831-8073, USA*
[b] *Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08502, USA*

Abstract

The National Compact Stellarator Experiment (NCSX) [http://www.pppl.gov/ncsx/Meetings/CDR/CDRFinal/EngineeringOverview_R2.pdf] is being designed as a proof of principal test of a quasi-axisymmetric compact stellarator. This concept combines the high beta and good confinement features of an advanced tokamak with the low current, disruption-free characteristics of a stellarator. NCSX has a three-field-period plasma configuration with an average major radius of 1.4 m, an average minor radius of 0.33 m and a toroidal magnetic field on axis of up to 2 T. The stellarator core is a complex assembly of four coil systems that surround the highly shaped plasma and vacuum vessel. Heating is provided by up to four, 1.5 MW neutral beam injectors and provision is made to add 6 MW of ICRH. The experiment will be built at the Princeton Plasma Physics Laboratory, with first plasma expected in 2007.

Keywords: Stellarator experiment; Coil systems; Compact stellarators; Modular coils

1. Stellarator core

The NCSX [1] stellarator core includes the assembly of four coil systems and associated structure, the vacuum vessel, and the plasma facing components (PFCs). The coil systems provide magnetic field for plasma shaping and position control, inductive current drive, and error field correction. The coils operate at cryogenic temperatures, so the entire core is surrounded by a cryostat for thermal insulation. A cut-away view of the stellarator is provided in Fig. 1.

1.1. Modular coils

The modular coil set consists of three field periods with six coils per period, for a total of 18 coils. Due to stellarator symmetry, only three different coil shapes are needed to make up the complete coil set. The coils are connected electrically in three circuits such that all the coils of a given shape are in the same circuit. Thus, each coil set can be independently powered to provide maximum flexibility. The maximum toroidal field

* Corresponding author. Tel.: +1-865-574-1507/966-3503; fax: +1-865-576-0024.
E-mail address: nelsonbe@ornl.gov (B.E. Nelson).

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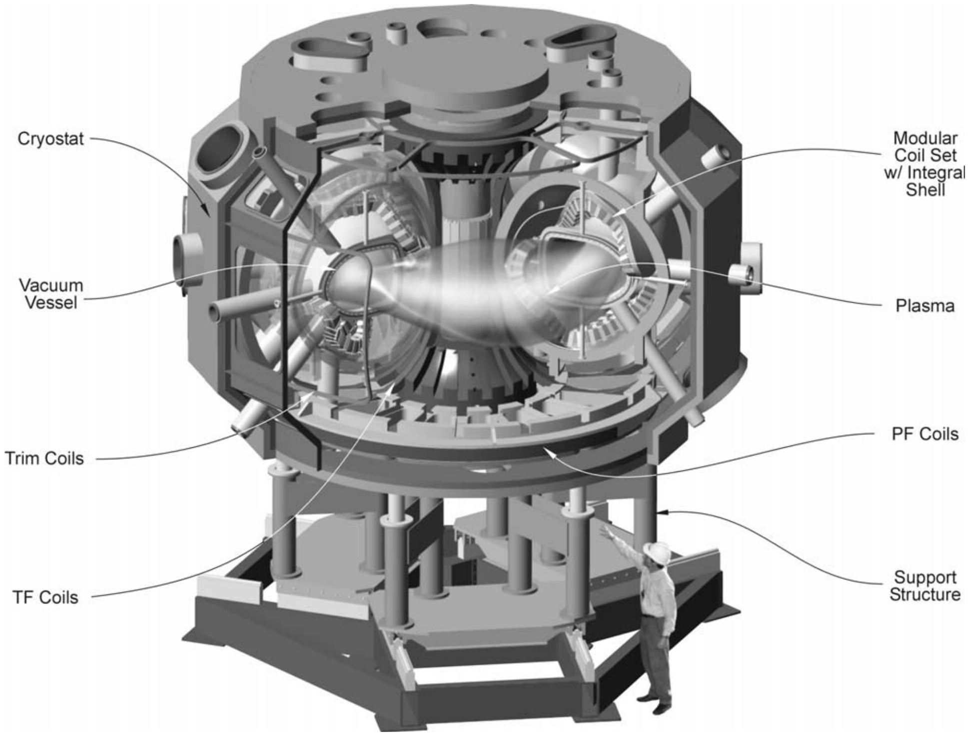

Fig. 1. Cut-away view of NCSX stellarator core.

(TF) at 1.4 m produced by the modular coils with a flattop of 0.5 s is 1.7 T. The TF on axis can be raised above 2 T by energizing the TF coils, which can add ± 0.5 T to the field generated by the modular coils. Fig. 2 shows the geometry of the coil windings.

The design concept uses flexible, copper cable conductor to facilitate winding into the complex shape. The cable is compacted from round cable to a packing fraction of over 75%. Once wound, the conductor is vacuum impregnated with epoxy so the winding pack becomes a monolithic copper–glass–epoxy composite. The coil cross section is shown in Fig. 3 and the basic coil parameters are listed in Table 1. The modular coils are pre-cooled to liquid nitrogen temperature because of the high current density in the coils.

The windings are wound on and supported by the tee-shaped structural member, which is an integral part of the coil winding form. The winding forms are bolted together to form a structural shell that both locates the windings within the ± 1.5 mm accuracy requirement and supports them against the electromagnetic loads. The forces on the winding packs tend to push them radially outward against the shell and clamp them laterally against the central member of the "tee", so only intermittent clamps are provided to preload the windings against the structure.

An illustration of the modular coil fabrication process is shown in Fig. 4. Potential vendors have conducted manufacturing studies to provide feedback on how the coil design could be modified to improve fabricability and reduce cost.

1.2. Toroidal, poloidal, correction coils

A set of 18 identical, equally spaced, TF coils is included to provide flexibility in the magnetic configuration. Adding or subtracting TF is an ideal "knob" for lowering and raising the rotational transform. The coils are wound from hollow copper conductor and insulated with glass–epoxy. They operate at the same temperature as the

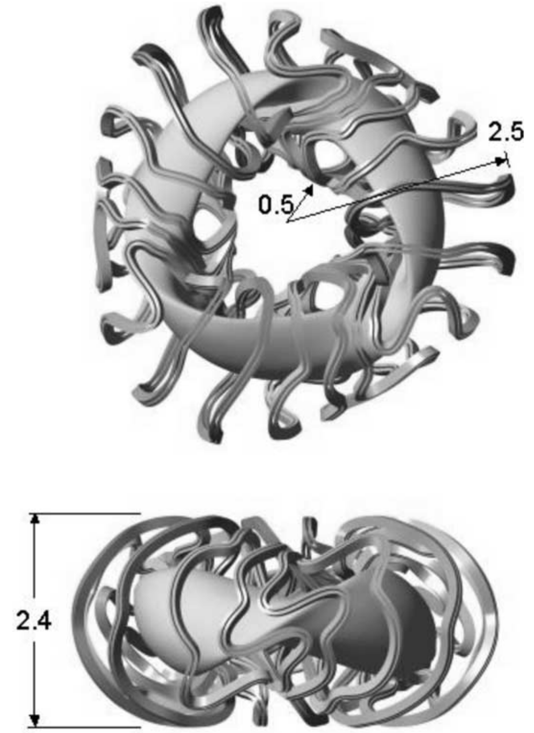

Fig. 2. Modular coil winding geometry (dimensions in m).

modular coil set (~ 85 K) and are connected in series.

A set of poloidal field coils is provided for inductive current drive and plasma shape and position control. The coil set consists of two inner solenoid pairs, and four pairs of ring coils. Coil pairs are symmetric about the horizontal midplane

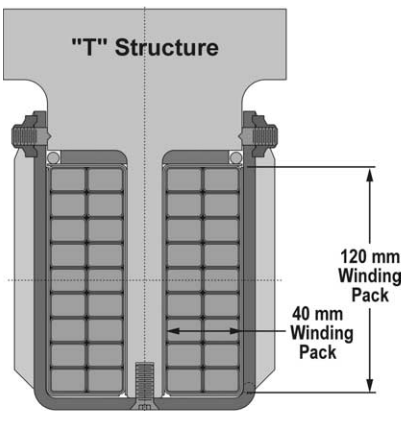

Fig. 3. Modular coil cross section.

Table 1
Modular coil parameters

Number of coils	18 (3 × 6)
Winding length	6.6–7.4 m per turn
Number of turns/coil	36
Gross cross section	2 × 40 mm × 120 mm
Current per coil[a]	Up to 828 kA-turns
Max. current density in Cu[a]	~ 14 kA/cm^2
Temperature operating range	From 85 to 125 K

[a] At nominal 1.7 T operating conditions.

and each coil pair is connected in an independent circuit. The coils are of conventional construction, wound from hollow copper conductor and insulated with glass–epoxy. The PF coils also operate at 85 K. Fig. 5 illustrates the PF and TF coil geometry.

Two types of correction coils are envisioned for National Compact Stellarator Experiment (NCSX). The first is a set of window pane coils,

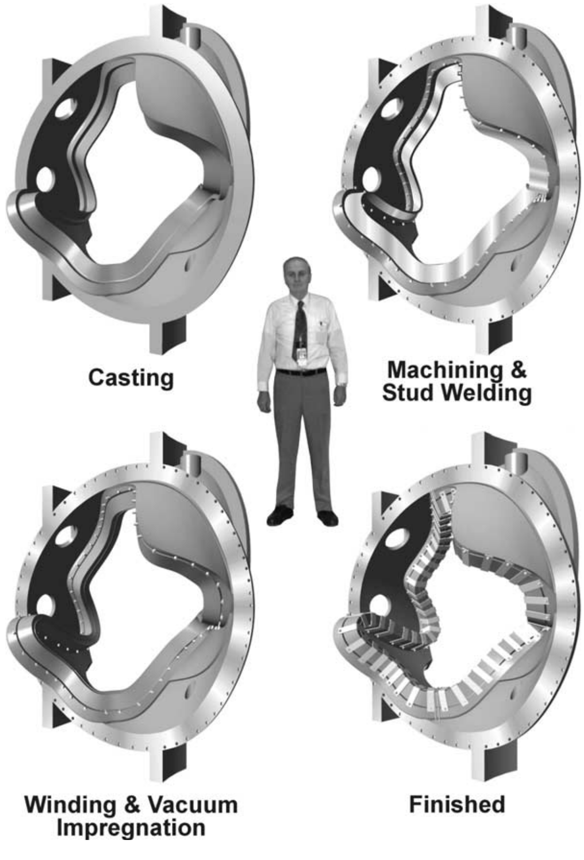

Fig. 4. Modular coil fabrication steps.

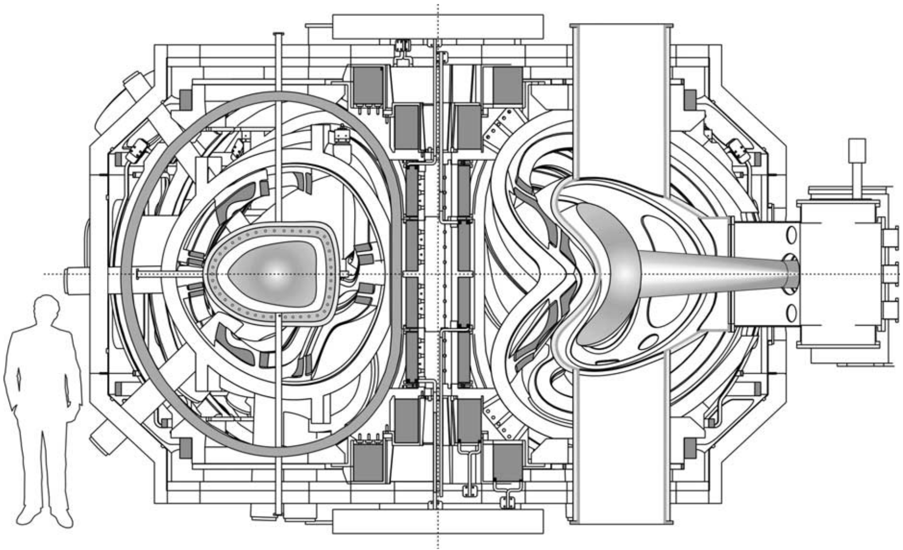

Fig. 5. PF and TF coils relative to NCSX cross section.

referred to as field error correction coils. These are provided on the top, bottom and outside perimeter of the coil support structure to reduce 1–1, 2–1, 3–1, and 3–2 resonant errors that may result from manufacturing or assembly errors in the modular coil geometry. The second set of correction coils are referred to as internal coils, or trim coils. These may be added as a future upgrade to control $m = 5$ and 6 resonant field perturbations.

1.3. Vacuum vessel

The vacuum vessel is a complex, three-period structure nestled inside the modular coil set. The geometry repeats every 120° and is also mirrored every 60° so that the top and bottom sections of the first (0–60°) segment can be flipped over and serve as the corresponding sections of the adjacent (60–120°) segment. The vessel will be constructed in full field periods and joined together at bolted joints. Double seals will be used at the assembly joints to ensure good vacuum characteristics.

As shown in Fig. 6, 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. A spacer section is used between field periods to provide a means for final adjustment and fit-up of the whole assembly. The vessel will be baked to 150 °C and operate 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.

Inconel 625 is the material chosen for the vessel shell. It was selected over stainless steel primarily because of its low permeability and higher electrical resistivity. Higher resistivity results in a

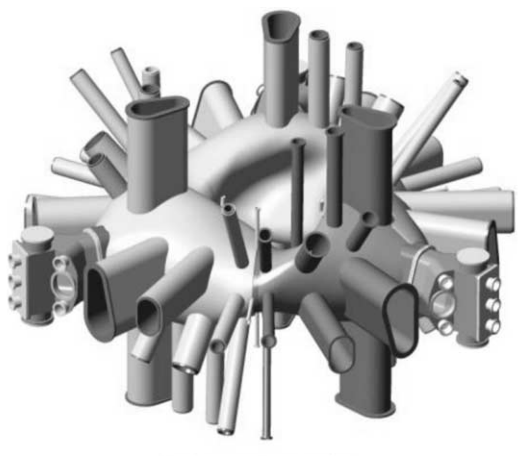

Fig. 6. Vacuum vessel assembly.

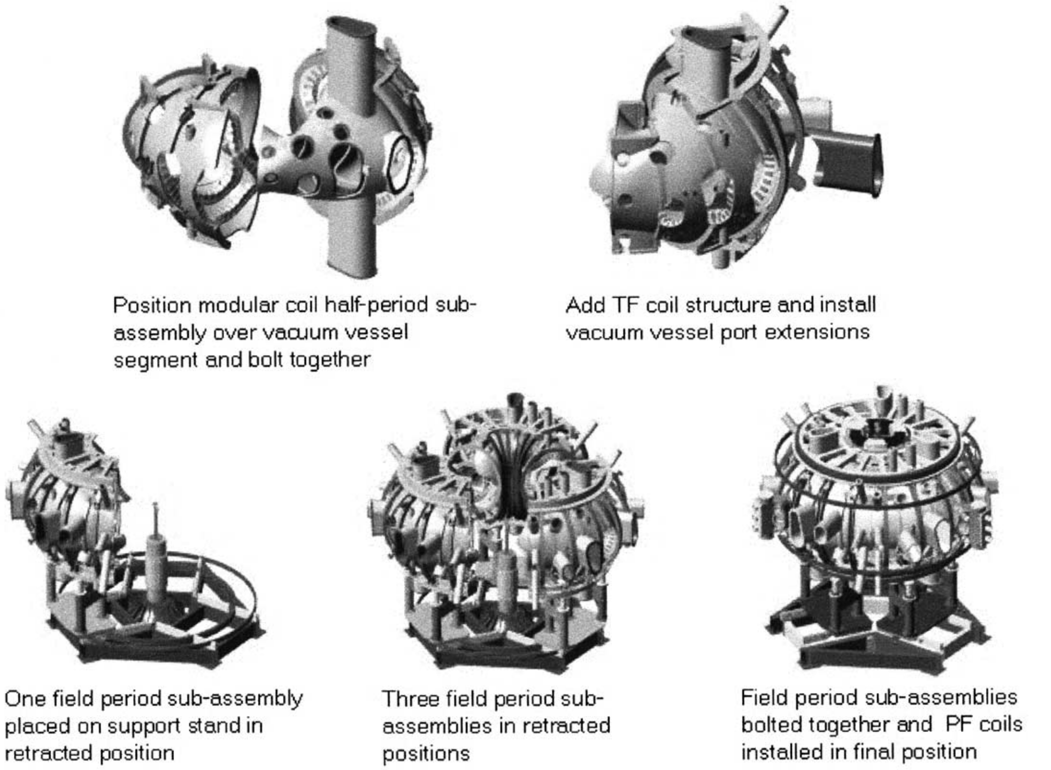

Fig. 7. NCSX core assembly sequence.

shorter vessel time constant, which is beneficial for plasma current profile control.

Several fabrication options are being evaluated for the vessel, including press forming, explosive forming and casting. Potential vendors have conducted manufacturing studies and provided feedback on how the vacuum vessel design could be modified to improve fabricability and reduce cost.

1.4. Plasma facing components (PFCs)

The baseline design consists of simple poloidal graphite limiters at the three “bullet” symmetry planes. The device is designed for an upgrade configuration that utilizes a contoured liner, constructed of molded carbon fiber composite (CFC) panels mounted on a frame of poloidal rings. The plasma-facing surface is located as close to the vacuum vessel as possible to provide maximum flexibility for plasma shaping. Investigations are under way for adding a baffled region at the tips of the plasma (akin to a divertor in a tokamak). The plan is to stage the installation of the liner, with limited wall coverage during the early phases of operation, and with the addition of the remainder of the liner, up to full coverge, during later operation. The liner is baked at 350 °C while maintaining the vessel at 150 °C. During normal operation, the liner will have a lower pre-shot temperature in the range of 20–150 °C.

1.5. Core assembly

The NCSX stellarator core will be assembled from three field period sub-assemblies that are bolted together atop the support stand in the test cell. Each of the three field periods are pre-assembled in a separate area at PPPL, and consist of one third of the vacuum vessel, TF and modular coils, PFC support rings, trim coils and in-vessel diagnostics. The modular coils will be completely pre-assembled at the factory for fit-up, inspection, and testing prior to shipping. The vacuum vessel will be delivered in three sections plus the port extensions.

The TF and modular coils will first be assembled over the vacuum vessel segment. The vacuum vessel will then be supported (hung) from the modular coil structure and the port extensions will be welded into place. The completed field period sub-assembly will be transported to the test cell and placed in a temporary position on the test stand. When all three subassemblies are in place, they are moved radially into final position. All three subassemblies are moved simultaneously to avoid interference with the interlocking modular coil boundaries, which extend past the shell and vessel connecting flanges. The assembly sequence is illustrated in Fig. 7.

2. Design status and conclusion

The NCSX device is presently in the design phase. The configuration has been selected and baseline concepts exist for most of the primary design features. Modular coil and vacuum vessel R&D, detailed analysis and concept refinement will be carried out during the next 2 years, with operation scheduled for 2007.

Acknowledgements

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