DESIGN OF THE NATIONAL COMPACT STELLARATOR EXPERIMENT (NCSX) CORE*

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Abstract—**The design status of the stellarator core for the National Compact Stellarator Experiment (NCSX) is presented. The purpose, configuration, and possible manufacturing and assembly techniques of the various components of the core are described**

I. Introduction

The National Compact Stellarator Experiment (NCSX) is proposed 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 lower current, disruption-free characteristics of a stellarator. The device is based on a 3 field period plasma configuration and has an average major radius of 1.4 m, an average minor radius of 0.32 m and operates with a toroidal magnetic field on axis of up to 2 T. The experiment will be built at the Princeton Plasma Physics Laboratory (PPPL) and will make maximum use of existing equipment and infrastructure. The physics and engineering basis for NCSX are described in detail in reference 1.

The stellarator core is a complex assembly of four electromagnetic coil systems that surround the highly shaped plasma. A cut-away view of the stellarator is provided in Figure 1.

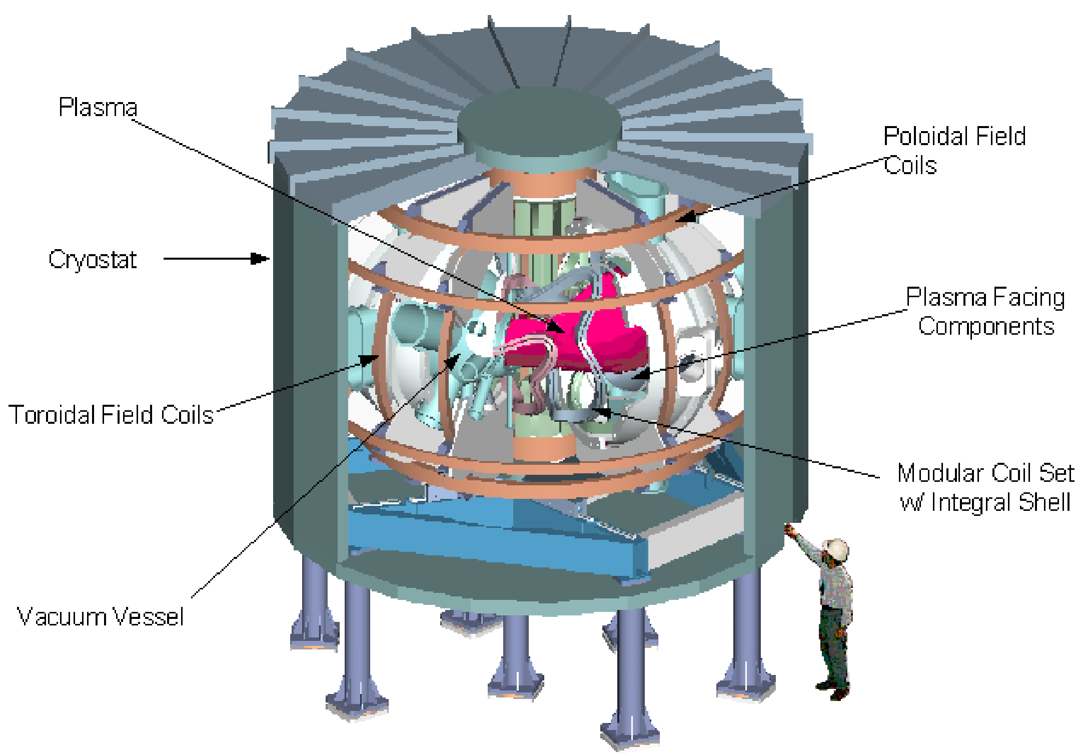

Fig. 1 Cut-away view of NCSX stellarator core

II. MODULAR COILS

The modular coil set consists of three field periods with 6 coils per period, for a total of 18 coils. Due to symmetry, only three different coil shapes are needed to make up the complete coil set. The coils are connected electrically in 3 circuits so like coils are independently powered to provide maximum flexibility. The maximum toroidal field at 1.4 m produced by the modular coils with a flattop of 0.5s is 1.7 T. The toroidal field 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. Figure 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

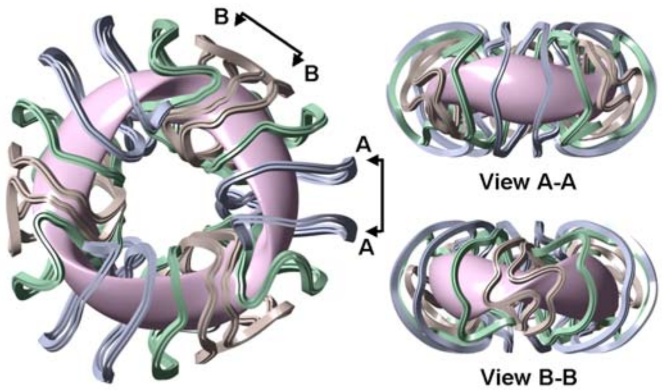

Fig. 2 Modular coil winding geometry

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 Figure 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.

Table 1 Modular Coil Parameters

No. of coils	18 (3 x 6)
Winding length	6.6 to 7.4 m per turn
Number of turns /coil	32
Gross cross section	2 x 40 mm x 120 mm
Current per coil*	551 to 694 kA
Max. current density in Cu*	~ 13 kA/cm^2
Temperature rise*	From 85 to 120 K
Peak power, coil set*	~ 40 MW

* at nominal 1.7 T operating conditions

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

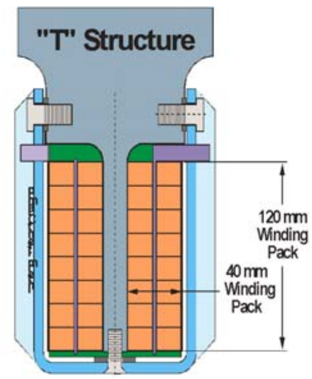

Fig. 3 Modular coil cross section

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 Figure 4. Contracts have been placed with potential vendors to conduct manufacturing studies and provide feedback on how the coil design could be modified to improve fabricability and reduce cost. A more detailed discussion of the coil set is given in Reference 2.

III. TOROIDAL, POLOIDAL, TRIM COILS

A set of toroidal field (TF)coils is included to provide flexibility in the magnetic configuration. Adding or subtracting toroidal field is an ideal "knob" for lowering

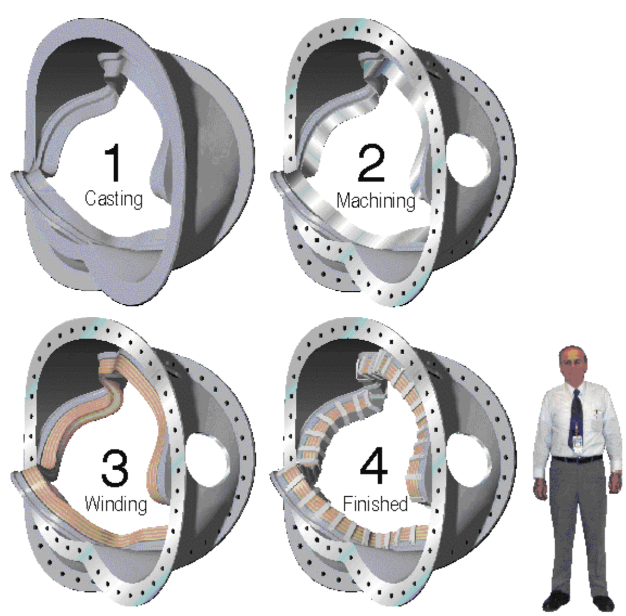

Fig. 4 Modular coil fabrication steps

and raising iota. There are 18 identical, equally spaced coils providing a 1/R field at the plasma. The coils are wound from hollow copper conductor and insulated with glass-epoxy. They operate at the same temperature as the modular coil set (~ 85K) 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 (PF 1 and PF 2), and 4 pairs of ring coils. Coil pairs are symmetric about the horizontal midplane 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 operate at the same temperature as the modular and TF coil sets - nominally 85K (cooled by 80 K nitrogen). Figure 5 illustrates the PF and TF coil geometry.

Trim coils are provided to mitigate field errors, in particular the errors on m=5 and m=6 resonant surfaces. The coils are configured in a saddle geometry, and are located inside the vacuum vessel on the inboard regions of the v=0 (bean-shaped) plasma cross-section. Since the coils are located in the vacuum vessel, they must be vacuum tight (canned) and high temperature electrical insulation will be required. The present configuration includes one coil set per period, but additional coils can be added if necessary. Coaxial leads from each panel will be routed to the outside through continuous conduit.

IV. VACUUM VESSEL

The vacuum vessel is a complex, three-period structure nestled inside the modular coil set. The geometry repeats every 120º and is also mirrored every 60º so that the top and bottom sections of the first (0º to 60º) segment can be flipped over and serve as the corresponding sections of the adjacent (60º to 120º) 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 Figure 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 ports on the ½ symmetry plane and to provide a means for final adjustment and fit-up of the whole assembly. Table 2 lists the main vacuum vessel parameters. The vessel will be baked to 150ºC and operate at 20ºC 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.

Table 2 Vacuum vessel parameters

Material	Inconel 625
Thickness	0.95 cm (3/8 in)
Time constant	<10 ms
Inside surface area (with ports)	~ 50 m^2
Enclosed volume (with ports)	~ 11 m^3
Weight with ports (without pfc's)	5375 kg
Heat loss to coils during bakeout	21 kW
Heat loss to coils, normal oper.	13 kW

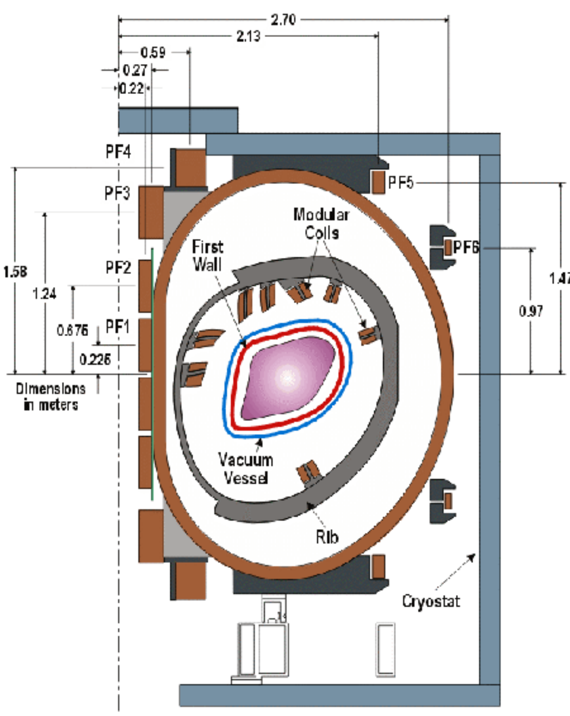

Fig. 5 PF and TF coils relative to NCSX cross section.

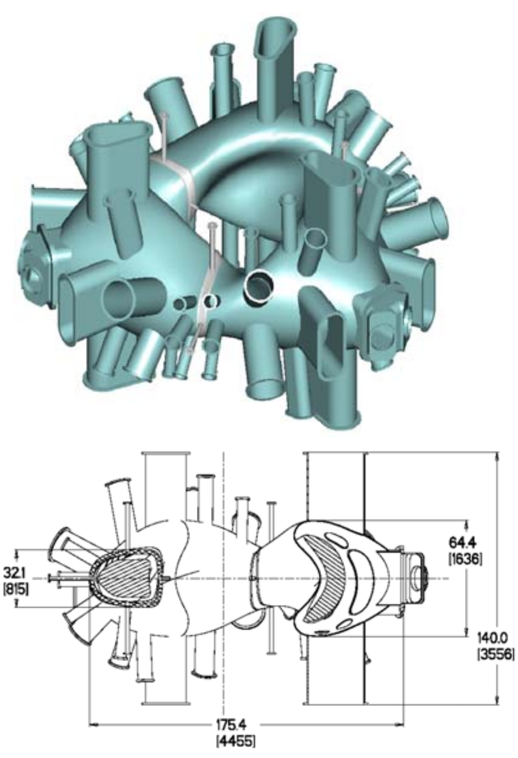

Fig. 6 Vacuum vessel assembly

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 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. Contracts have been placed with potential vendors to conduct manufacturing studies and provide feedback on how the vacuum vessel design could be modified to improve fabricability and reduce cost.

V. Plasma Facing Components

The baseline design 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 very limited wall coverage during initial operation, and with the addition of the remainder of the liner during later operation. When the full complement of panels is installed, they will shield the entire interior surface of the vessel from the plasma.

The panels are attached to 21 stainless steel ribs, which are suspended from the vacuum vessel, but free to move in radial planes. The full complement of ribs and panels is illustrated in Figure 7. Bake out of the liner is provided by circulating He gas through trace lines on the mounting ribs. The tracing also serves to remove the heat deposited in the PFCs during normal operation. The liner is baked at 350ºC while maintaining the vessel at 150ºC. During normal operation, the liner will have a lower pre-shot temperature in the range of 20ºC to 150ºC.

VI. 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 (VV) segment. The vacuum vessel will then be supported (hung) from the modular coil structure and the port extensions will be welded into place. The vacuum vessel segment will then be baked out to 150ºC and a vacuum leak check will be performed. 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

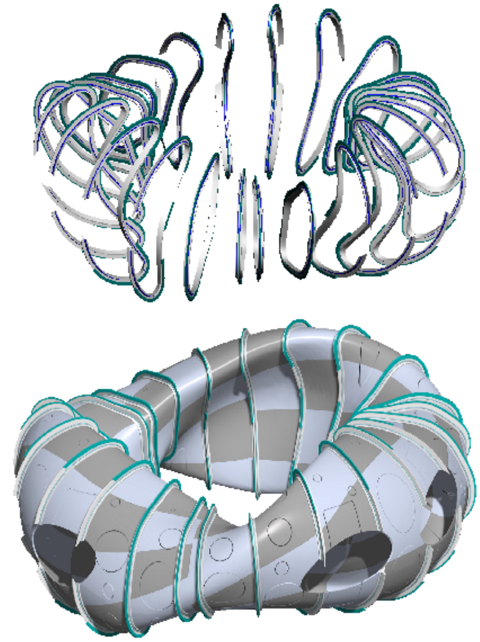

Fig. 7 PFC rib and panel structure.

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 Figure 8.

VII. Design Status and Conclusion

The NCSX device is presently in the conceptual design phase. The general configuration has been selected and baseline concepts exist for most of the primary design features. Detailed analysis and concept refinement will be carried out during the remainder of the conceptual design phase, including the incorporation of suggestions from industrial firms that are providing manufacturing studies.

Acknowledgment

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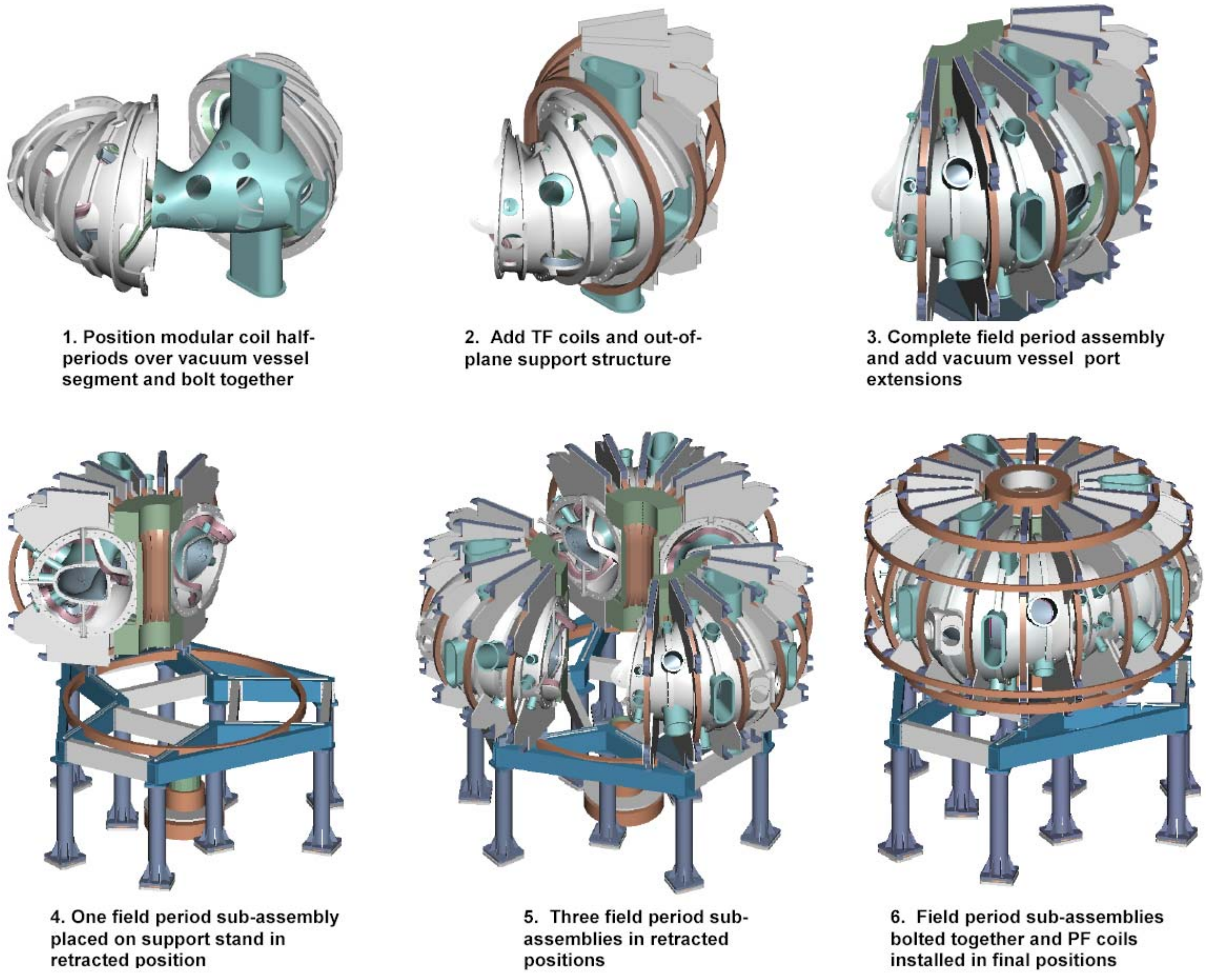

Fig. 8 Stellarator core assembly sequence