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Modular coil design developments for the National Compact Stellarator Experiment (NCSX)

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Abstract

The National Compact Stellarator Experiment (NCSX) is a quasi-axisymmetric facility that combines the high beta and good confinement features of an advanced tokamak with the low current, disruption-free characteristics of a stellarator. The experiment is based on a three field-period plasma configuration with an average major radius of 1.4 m, a minor radius of 0.3 m, and a toroidal magnetic field on axis of up to 2 T. The modular coils are one set in a complex assembly of four coil systems that surround the highly shaped plasma. There are six, each of three coil types in the assembly for a total of 18 modular coils. The coils are constructed by winding copper cable onto a cast stainless steel winding form that has been machined to high accuracy, so that the current center of the winding pack is within ±1.5 mm of its theoretical position. The modular coils operate at a temperature of 80 K and are subjected to rapid heating and stress during a pulse. At this time, the project has completed construction of several prototype components which validate the fabrication and inspection processes that are planned for the production coils. In addition, some advanced techniques for error-field compensation and assembly simulation using computer-aided design (CAD) have been developed.

Keywords: Quasi-axisymmetric facility; Stellarator; Computer-aided design (CAD)

1. Modular coil system

The functions of the National Compact Stellarator Experiment (NCSX) modular coil system are: (1) to provide specified quasi-axisymmetric magnetic field

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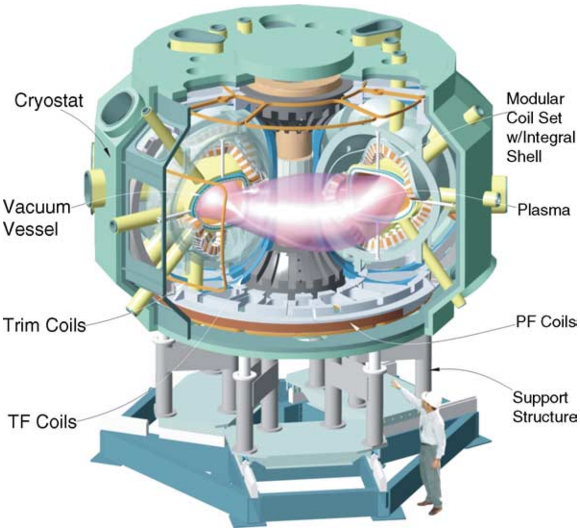
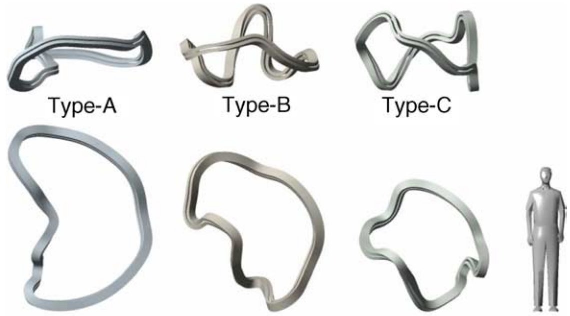


Fig. 1. Configuration of the NCSX stellarator core.



No. Modular Coils	18 (6 x 3)
Winding Length	6.6 to 7.4 m /turn
No. Turns per Coil	20,20,18
Cable Conductor Size	9.5 x 10.5 mm
Current per Coil	830 kA-turns
Max Current Density	14 kA/cm2
Operating Temperature	80 to 130 K

Fig. 2. Modular coil geometry and parameters.

configurations, (2) to provide access for tangential neutral beam injection (NBI), radio frequency (RF) heating, and diagnostics, and (3) to provide a robust mechanical structure that minimizes non-symmetric field errors [1]. The 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 according to type and as such can produce alternate magnetic configurations by independently varying the current for each type. Fig. 1 shows the general arrangement of the coils and structure.

2. Coil optimization

The geometry of the modular coil set has been developed through a physics optimization process that emphasizes both plasma properties and geometric constraints, such as coil-to-coil spacing (a key factor determining the current density) and minimum bend radius. In the optimization code, COILOPT [2], the coils are constrained to lie on a winding surface that is represented by a Fourier series in poloidal and toroidal coordinates. The coil set is represented by approximately 100 independent parameters. Optimization targets the surface magnetic field error, while measures of plasma-coil separation and coil-to-coil spacing are used to control current density. The final design limits the sharp bends to >10 cm at the conductor surface while maximizing the available conductor space. Fig. 2 illustrates the compact design of the modular coil windings and lists the basic parameters of the coil set.

3. Windings and structure

The modular coils are wound onto stainless steel castings which are then bolted together to form a structural shell. As shown in Fig. 3, the winding cavity is a "tee" structure that is located on the inside of the shell. During operation, electromagnetic forces push the windings outward against the shell and laterally toward the "tee", so that only intermittent clamps are required for structural support. Non-linear finite element analysis indicates that, under maximum electromagnetic and thermal load, the windings experience a symmetric displacement of $\sim$1 mm relative to the structural shell.

The toroidal segmentation of the winding forms has received considerable attention during the design phase, owing to the "nested" configuration of the coils. As shown in Fig. 3, the complex shape of the coils results in protruding "wings", which extend beyond the radial flanges and underneath the adjacent coil. In order