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D. Williamson[1], A. Brooks[2], T. Brown[2], M. Cole[1], H. Fan[2], P. Goranson[1], M. Hechler[1]
P. Heitzenroeder[2], B. Nelson[1], W.T. Reiersen[2]

[1] Lockheed Martin Energy Systems, P.O. Box 2009, Oak Ridge, TN 37830-8073
[2] Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543

18th IEEE/NPSS Symposium on Fusion Engineering
October 25–29, 1999
Albuquerque, New Mexico

* Research sponsored by the Office of Fusion Energy Sciences, U.S. Department of Energy under contract DE-AC05-96OR22464, with Lockheed Martin Energy Research Corp.

# DESIGN DESCRIPTION OF THE SADDLE COILS FOR THE NATIONAL COMPACT STELLARATOR EXPERIMENT (NCSX)*

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[1]Lockheed Martin Energy Systems, P.O. Box 2009, Oak Ridge, TN 37831-8073
[2]Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08502

## ABSTRACT

The National Compact Stellarator Experiment (NCSX) is proposed as a test of a low aspect ratio, quasi-axisymetric plasma configuration that exhibits high beta and good confinement in a disruption-free environment. The experiment will be built on the site of the Princeton Beta Experiment (PBX-M) tokamak and utilize many of the existing coils and ancillary equipment. A stellarator core, which includes the vacuum vessel, saddle coils with supporting structure, and a cryostat will be constructed off-site and placed into the existing facility. This paper describes the pre-conceptual design of the saddle coils and structural shell components of the core.

## INTRODUCTION

The compact stellarator is a hybrid configuration that combines plasma current and three-dimensional shaping to obtain tokamak-like performance in a disruption-free environment. Recent advances in computational tools have led to the development of low aspect ratio configurations that meet the physics and engineering requirements for an experimental device.

It is proposed to build the National Compact Stellarator Experiment (NCSX) in order to assess the beta limits and confinement capability of these plasma configurations in a proof-of-principal (PoP) scale facility. The experiment will be built on the site of the Princeton Beta Experiment (PBX-M) tokamak, where it is possible to utilize many of the existing coils and ancillary equipment.

A pre-conceptual design of the stellarator core, which includes a vacuum vessel, saddle coils and structure, and a surrounding cryostat has been developed. This paper will summarize the design features of the saddle coils and structural shell components of the core.

## DESIGN PARAMETERS

The basic design of the saddle coils is developed through a physics optimization process that is somewhat like “reverse engineering”. First, a plasma configuration is developed that meets the physics requirements. Then, a discrete coilset is generated which recreates the plasma shape and its parameters within physics and engineering constraints. The geometry of the optimized coilset is then transformed into a detailed engineering design.

This process has identified a three-field-period, quasi-axisymmetric plasma as the optimum configuration for use with the PBX-M TF coils. The major radius of the plasma is 1.45-m and the aspect ratio is 3.4. Additional plasma parameters are shown in Table-1:

Table 1 – Plasma Design Parameters

| Parameter | Value | Unit |
|---|---|---|
| Major radius, $R_o$ | 1.45 | m |
| Minor radius, <a> | 0.42 | m |
| Aspect ratio, $R_o$/<a> | 3.4 | - |
| Toroidal field, $B_o$ | 2 | T |
| Plasma current, $I_p$ | 330 | kA |
| Pulse length, t | 0.5 | s |
| Auxiliary power, $P_{aux}$ | 6 | MW |

A coilset which recreates this plasma is shown in Fig.-1. It consists of 78 saddle coils, in groups of 13 per half-period. The coils carry 84-kA each with a nominal cross section of 16x70-mm. A larger cross section is not feasible due to the close coil spacing in the plasma’s inboard region. The single-turn length of the coils varies from 0.4-m to 16.7-m. Additional saddle coil parameters are shown in Table-2:

Table 2 - Saddle Coil Design Parameters

| Parameter | Value | Unit |
|---|---|---|
| Configuration | C10-S185.16 | - |
| Plasma/Coil Offset | 18 | cm |
| Num Coils/Period | 26 | - |
| Current/Coil @2T | 84 | kA |
| Num Turns/Coil | 10 | - |
| Min Coil Spacing | 23 | mm |
| Coil Dimensions | 16 x 70 | mm |
| Shortest Turn Length | 0.4 | m |
| Longest Turn Length | 16.7 | m |
| Total Length of Turns | 4080 | m |
| Total Weight of Coils | 2.7 | tonne |

* Work supported by U.S. Department of Energy under Contract DE-AC05-96OR22464

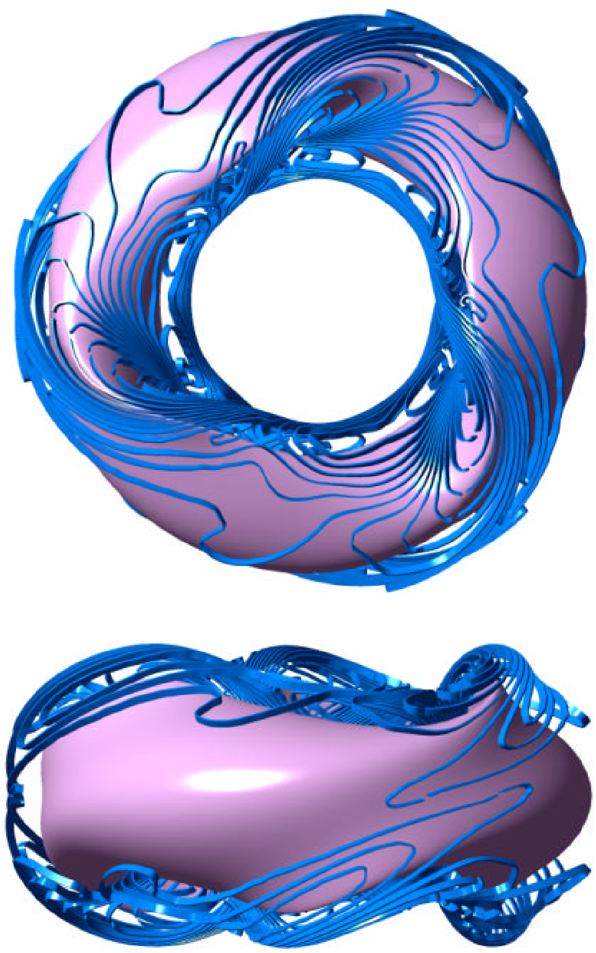

Fig. 1 – Saddle Coils and Plasma

## DESIGN CONCEPT

The stellarator core is composed of close-fitting shells in order to minimize the distance between the saddle coils and plasma, which in turn reduces the coil current. As shown in Fig.-2, the inner shell serves as a bakeable vacuum vessel and mounting structure for the plasma facing components (PFC). Surrounding the vacuum vessel is a structural shell which serves as both a winding form and permanent support structure for the saddle coils. The saddle coils and shell are pre-cooled to 80-K in order to extend the pulse length. The core is enclosed in a fiberglass cryostat (not shown) that separates it from the existing water-cooled TF and PF coilsets. Figure 3 shows a typical cross section through the structure.

The saddle coils and structural shell incorporate many features that derive from functional requirements. First, the shell material is a bronze alloy that has a similar coefficient of thermal expansion (CTE) as the copper saddle coils in order to reduce thermal stresses. The bronze material is also easy to cast and machine.

A second major feature is the segmentation, which derives both from assembly requirements and a desire to reduce the magnitude of eddy currents during operation. Presently, the design includes 24 toroidal electrical breaks, which will reduce the longest eddy current time constant to 20-ms. Further analysis of this requirement is a priority, since the number of segments has a strong influence on the cost of the structure. The third feature is the set of machined slots in the shell, which provide an accurate (+/- 1-mm true position) winding form for the coils and support the large electromagnetic forces on the windings.

The saddle coils are composed of many turns of a flexible, stranded copper conductor, approximately 6-mm square, that is insulated with Kapton tape and glass cloth. Each coil is wound as a double pancake, starting from the crossover which is placed in a special grooved area at the bottom of the machined slot. Co-axial leads for each coil are routed to the outside of the torus in order to provide flexibility in reconfiguring circuits. The coil pack is vacuum encapsulated with epoxy, but the interior of each turn will remain free of epoxy and flexible in order to accommodate rapid thermal expansion during a pulse. The coils are cooled by conduction to the shell.

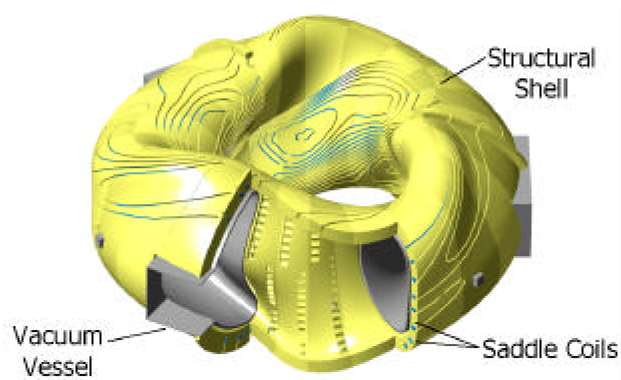


Fig. 2 – Saddle Coils and Structural Shell

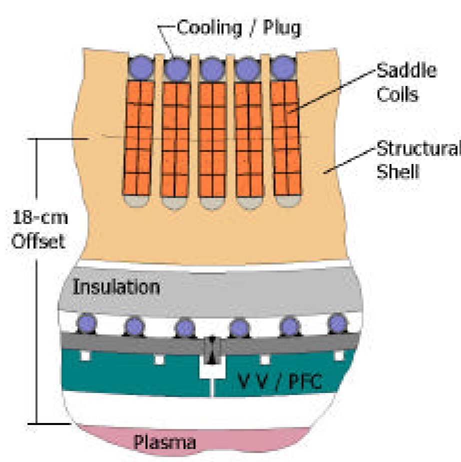

Fig. 3 – Typical Coil Cross Section

## FABRICATION CONCEPT

Fabrication and assembly of the structural shell is critical to achieving an accurate placement of the coils. The bronze shell segments will be fabricated using eight casting patterns, an example of which is shown in Fig.-4. Each casting is about 0.3 x 0.4 x 1.5-m in size and weighs 600-900-kg. The segments are machined on four sides prior to machining undersized slots for the coil windings. The inner surface (plasma side) is also machined to provide a pocket and hole for bolts between segments. It may be possible to form this feature in the casting itself and avoid additional machining.

The 48 shell segments are assembled into inner and outer structures as shown in Fig.-5. Final machining of the coil winding slots is performed on these subassemblies. The structural shell is then ready for placement around the vacuum vessel field-period assemblies.

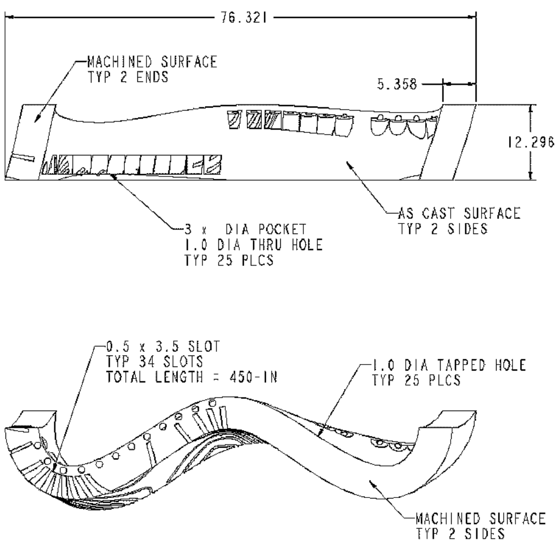


Fig. 4 - Typical Shell Segment
(dimensions in inches)

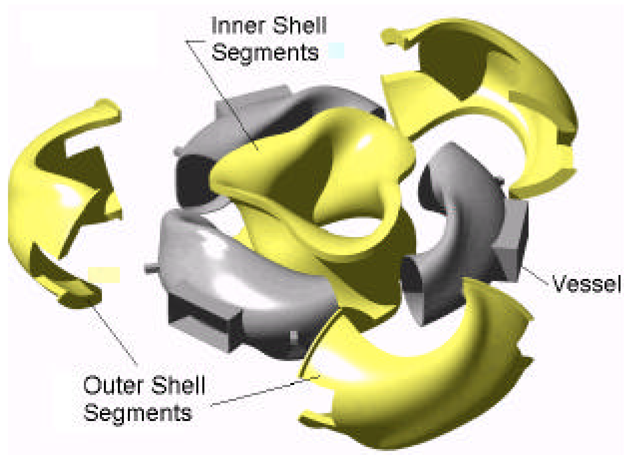


Fig. 5 – Structural Shell Assembly

## PERFORMANCE EVALUATION

A preliminary analysis of the thermal, electromagnetic, and structural response of the saddle coils has been performed. With a current density greater than 15-kA/cm$^2$, it is necessary to pre-cool the saddle coils in order to achieve an acceptable pulse length. This is illustrated in Fig.-6, which shows the temperature in the conductor rising to 130-K during the pulse. The maximum allowable temperature rise depends on the stiffness of the stranded conductor.

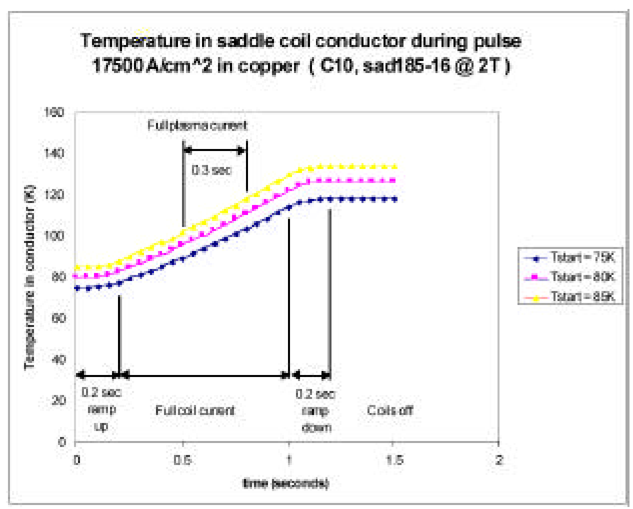


Fig. 6 – Coil Temperature during Pulse

Electromagnetic analysis has also been performed to determine the fields and forces on the coilset. Results indicate that the maximum field on the surface of the saddle coils is 5.6-T, which gives a $B_{max}/B_o$ ratio of 2.8 for 2-T operation. The maximum force on the coils is 344-kN/m (1960-lb/in), and the direction of the force is largely radial, as shown in Fig.-7.

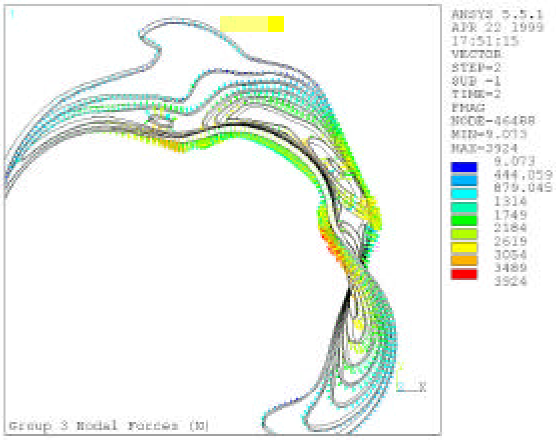


Fig. 7 – Saddle Coil Force Vectors

A structural analysis of the shell has been performed by mapping the coil forces onto a simplified structure without coil slots (Fig.-8). The results indicate that the maximum deflection is less than 0.5-mm and the maximum Von Mises stress is about 65-Mpa.

A two-dimensional analysis of the "ligament" region between the coil windings indicates that the local stress intensity is as high as 165-Mpa (Fig.-9). However, this value can be reduced significantly by increasing the ligament thickness from 6 to 7-mm.

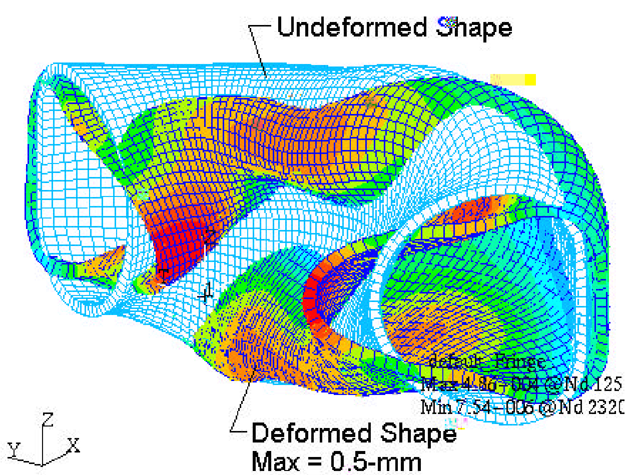


Fig. 8 – Structural Shell Displacement

R&D ACTIVITIES

Many of the uncertanties associated with the manufacture and performance of the saddle coils are being addressed through an early R&D program. First, a fabrication method for the conductor is being developed in cooperation with cable manufacturers. Second, the stiffness of the conductor in compression, which is important in determining thermal stress limits, is being tested for conductor samples of varying copper packing factor. So far, the results indicate that the effective modulus of elasticity is very low at even a 75% packing factor.

In the coming year, it is planned to construct a small race-track shaped coil for thermal/electrical testing, and to develop a protoype casting of a structural shell segment. The casting will be used to verify the extensive numerical controlled (NC) machining required to prepare the coil winding slots.

CONCLUSION

A pre-conceptual design for the stellarator core has been developed and found to meet the physics and engineering requirements for the device. Major issues to be addressed during the conceptual design phase include current density, port access for heating and diagnostic equipment, and overall experimental flexibility.

The coilset for NCSX is still evolving, and there are several alternative configurations, such as modular coils, to be investigated. However, the development and evaluation of this design concept has provided valuable feedback to the coil optimization process.

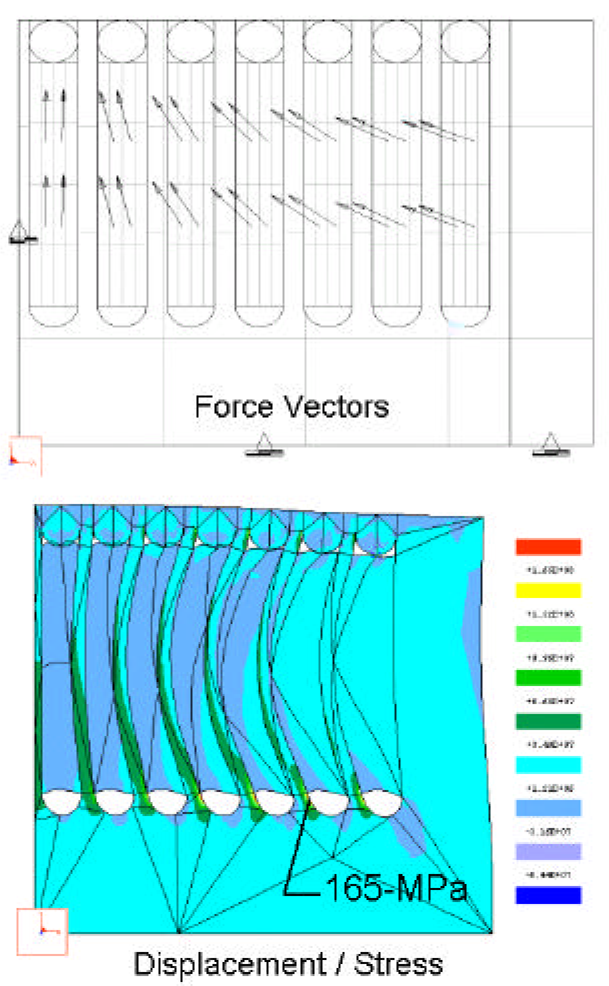


Fig. 9 – Stress Between Coil Windings

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