NCSX Construction Progress and Research Plans

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***Abstract*— Stellarators use 3D plasma and magnetic field shaping to produce a steady-state disruption-free magnetic confinement configuration. Compact stellarators have additional attractive properties– quasi-symmetric magnetic fields and low aspect ratio. The National Compact Stellarator Experiment (NCSX) is being constructed at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge National Laboratory (ORNL) to test the physics of a high-beta compact stellarator with a low-ripple, tokamak-like magnetic configuration. The engineering challenges of NCSX stem from its complex geometry requirements. These issues are addressed in the construction project through manufacturing R&D and system engineering. As a result, the fabrication of the coil winding forms and vacuum vessel are proceeding in industry without significant technical issues, and preparations for winding the coils at PPPL are in place. Design integration, analysis, and dimensional control are functions provided by system engineering to ensure that the finished product will satisfy the physics requirements, especially accurate realization of the specified coil geometries. After completion of construction in 2009, a research program to test the expected physics benefits will start.**

Keywords –stellarator, NCSX, design, construction

I. INTRODUCTION: MISSION

The National Compact Stellarator Experiment (NCSX) is a new fusion confinement experiment being constructed at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge National Laboratory (ORNL). Its mission is to acquire the physics knowledge needed to evaluate compact stellarators as a fusion concept and to advance the physics understanding of 3-D plasmas for fusion and basic science. In addition, technological developments made in the course of constructing NCSX, for example the design and manufacture of complex-shaped parts, are important contributions to fusion technology.

Among the family of toroidal magnetic plasma configurations, stellarators are of interest because they solve important problems for fusion energy — achieving steady-state operation and avoiding disruptions. Stellarators are needed also to resolve scientific issues, for example the effects of 3D plasma shaping and of strong external control on confinement, that are important to all magnetic configurations. For these reasons there is a substantial effort in stellarator research worldwide, including large facilities, LHD [i, ii] and W7-X [iii] that use superconducting magnets. The compact stellarator is a relatively new variant which shares the attractive properties of existing stellarators but has the additional advantages of lower aspect ratio and a quasi-symmetric magnetic field structure. In the case of a quasi-*axi*symmetric stellarator (QAS) like NCSX [iv, v], even though it is non-axisymmetric its charged particle trajectories and plasma flow damping are similar to those of tokamaks, which are axisymmetric. Thus, a QAS is expected to share the tokamak's good confinement performance. This physics link with tokamaks means compact stellarators can advance rapidly and economically, building on advances in the more mature tokamak concept, including the expected future advances in burning plasma physics and technology from ITER. The NCSX plasma is designed to have an aspect ratio of 4.4 instead of the more typical (for stellarators) ~10; to have a quasi-axisymmetric magnetic field with an effective ripple less than 1.5%; to be MHD stable without active feedback control, current drive, or rotation drive; and to have good magnetic surfaces; all at high beta (4%).

The compact stellarator's advantageous properties are due to its 3-D plasma geometry (Fig. 1), but it requires a complex magnetic field. In the case of NCSX, that field is generated by eighteen modular coils, six each of three different shapes. The engineering challenges in the construction of NCSX stem from

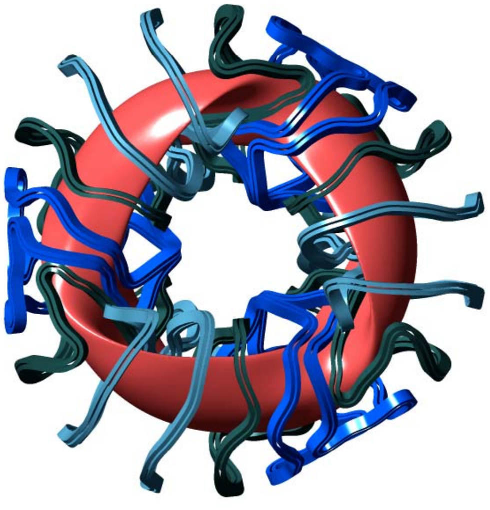

Fig. 1 NCSX plasma and modular coils.

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the complex geometries of these coils and other structures, primarily the vacuum vessel, which must conform to the shape of the plasma. [vi]

II. DESIGN

The NCSX modular coil current-center winding trajectories were optimized to produce a free-boundary high-beta, QAS plasma equilibrium possessing the desired physics properties while satisfying engineering constraints, such as minimum coil-to-plasma spacing, coil-to-coil spacing, and bend radius, for finite component builds and neutral-beam access [vii]. Toroidal field coils, poloidal field coils, and helical-field trim coils complete the magnet system and ensure that the device has sufficient flexibility to vary the plasma configuration and test the physics. Stable equilibria having low effective ripple can be made with β ranging from 0 to 4% and plasma current from 0 to 100% of the calculated self-consistent bootstrap current at $\beta = 4\%$. Stable equilibria at higher beta (at least 6%) can be made with modest increase in ripple. Stability beta limits can be lowered from the nominal 4% to about 1% so theoretical stability limits can be studied over a range of beta values. The effective ripple can be increased by almost an order of magnitude, while preserving stability, to test the dependence of transport on the degree of quasi-symmetry. The rotational transform and its spatial derivative (magnetic shear) can be varied. Start-up pathways from vacuum to high beta through stable equilibria with low ripple and good magnetic surfaces have been calculated.

The NCSX device size (major radius R = 1.4 m), magnetic field range (B = 1.2-2.0 Tesla), pulse length (0.3-1.2 s), and plasma heating power are set to produce the plasma conditions and profiles needed to test critical physics issues over a range of beta and collisionality values. Four 1.5-MW, 0.3-s neutral beam injectors, formerly used on the PBX-M experiment, are available to heat the plasma. They will be arranged for tangential injection with a mix of co- and counter-injection to control the effects of beam-driven currents. With the full complement of neutral beams (6 MW) and B = 1.2 T, the NCSX physics models predict plasmas with $\beta = 4\%$ and collisionality $\nu^* = 0.25$. Radio frequency waves can be launched from the high-field side to more directly heat electrons than with the neutral beams. Electron cyclotron heating options are being evaluated. The NCSX magnet system is designed for pulsed operation with magnetic fields up to 2.0 T (for 0.2 s) for low-collisionality plasma studies and pulse lengths up to 1.7 s (at B = 1.2 T) for experiments with pulse lengths long compared to current equilibration times. The magnet and heating system pulse lengths of NCSX are long

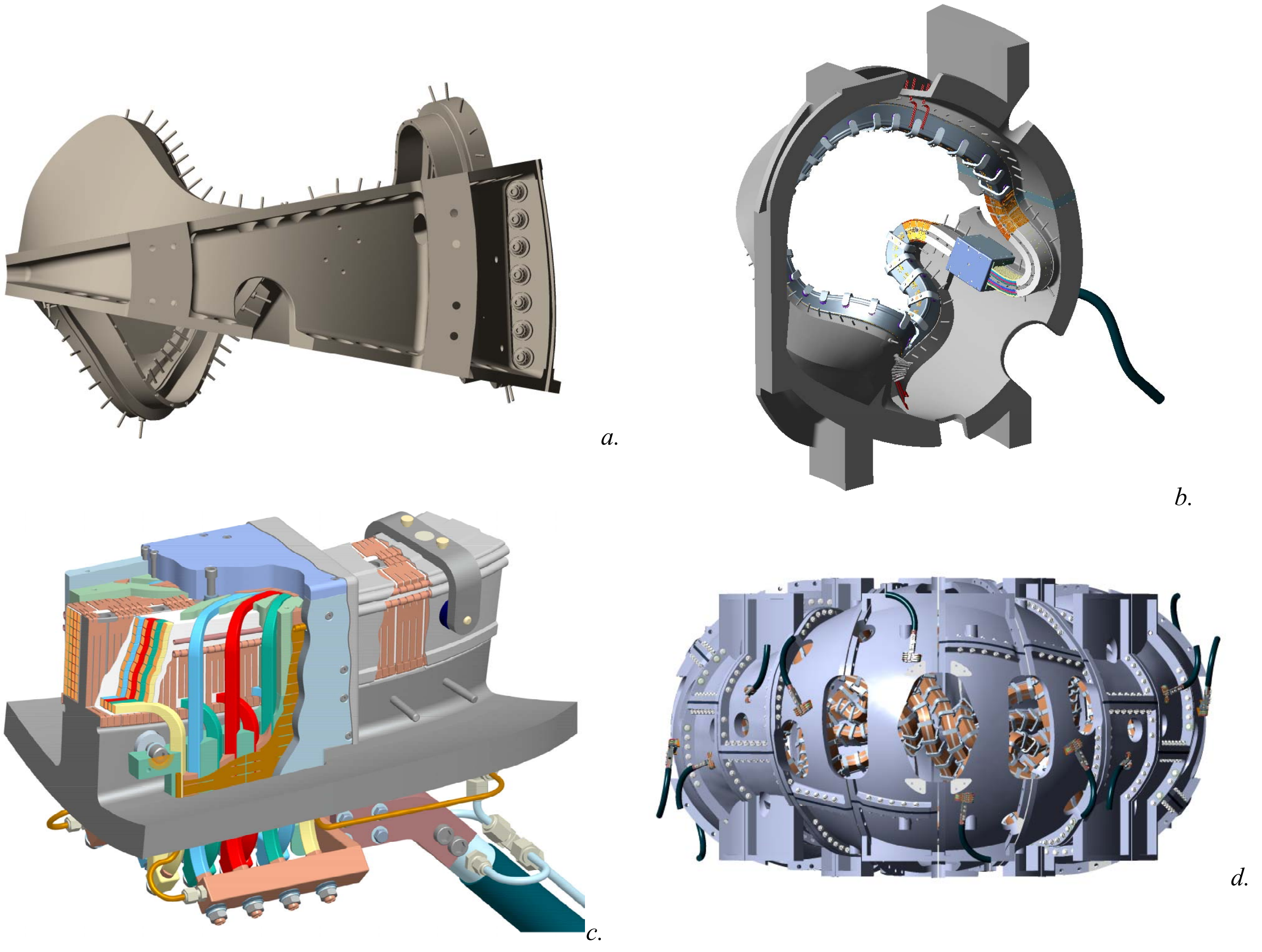

Fig. 2. NCSX modular coil set design. (a) winding form, (b) coil, (c) winding pack and lead details, (d) completed coil set..

enough to produce the plasmas needed to test the physics properties of a high-beta compact stellarator configuration and determine the conditions for disruption-free operation.

In the engineering implementation of NCSX, the key physics requirement affecting the magnets is to produce modular coils whose current centers accurately follow the winding trajectories specified by the physics optimization. This is accomplished by winding each coil on a tee-shaped support feature that is an integral part of a structure called a modular coil winding form, or MCWF (Fig. 2). Each MCWF comprises one-eighteenth of a complete toroidal shell and has the tee feature machined on its interior surface, precisely following the physics-specified trajectory. The coils are wound with a compacted copper cable conductor which is flexible to facilitate handling and placement of its current center within ±0.5 mm of its nominal position on the winding form. The winding forms are bolted together at precision machined flanges to form the structural shell which locates the windings within ±1.5 mm of their nominal position in space and supports them against electromagnetic loads.

The key physics requirements affecting the vacuum vessel (Fig. 3) are to provide: a high-vacuum environment for plasma operation; sufficient interior space for the plasma, its boundary layer, and plasma-facing components; and access for heating and diagnostic viewing. The solution is to locate the vacuum boundary just inside the modular coils and as far from the plasma surface as possible, leaving the minimum assembly clearance to install the modular coils over the vacuum vessel. This results in a non-axisymmetric vacuum vessel shell with a shape that resembles that of the plasma and which must be realized within ±3 mm accuracy. Heating and diagnostic access requirements, including contingencies to allow for future innovations, are accommodated by providing nearly 100 ports of various shapes, sizes, and orientations causing the vacuum boundary to protrude through all available openings in the surrounding magnets.

III. CONSTRUCTION

As previously noted, the geometry is both the source of the compact stellarator's physics benefits as well its key engineering challenge. The aim of the NCSX construction project is the accurate realization of the unusual geometries required of the magnets, vacuum vessel, and associated structures. The adopted project strategy has two parts: 1) development of critical manufacturing processes through R&D prior to production, and 2) management of requirements flow-down from physics specification to finished product through system engineering.

Fig. 3 NCSX vacuum vessel design.

Manufacturing R&D for the MCWF and vacuum vessel was accomplished through a series of contracts with industrial suppliers over a two-year period. For example, vacuum vessel manufacturing studies were conducted by five different suppliers during the conceptual design phase of the project. They examined different methods (e.g., cold, hot, and explosive forming; welding) for realizing the NCSX geometry, identified critical issues, and estimated costs and schedules. These studies prototyped a successful model for electronically transferring the project's design data (CAD models, drawings, product specifications) to suppliers and they established the basic feasibility of constructing the NCSX vacuum vessel. During preliminary and final design, the project contracted with two suppliers to, first, develop specific manufacturing, inspection, test, and quality assurance plans for the vacuum vessel and, then, to apply them by constructing prototype sectors. These contracts demonstrated viable industrial manufacturing processes for meeting the critical requirements

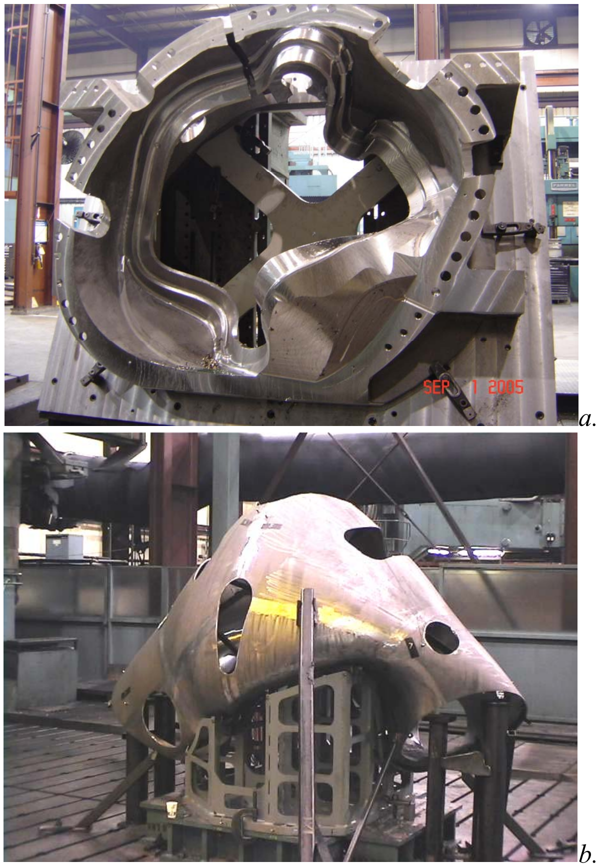

Fig. 4. NCSX components in manufacture: (a) MCWF, (b) vacuum vessel.

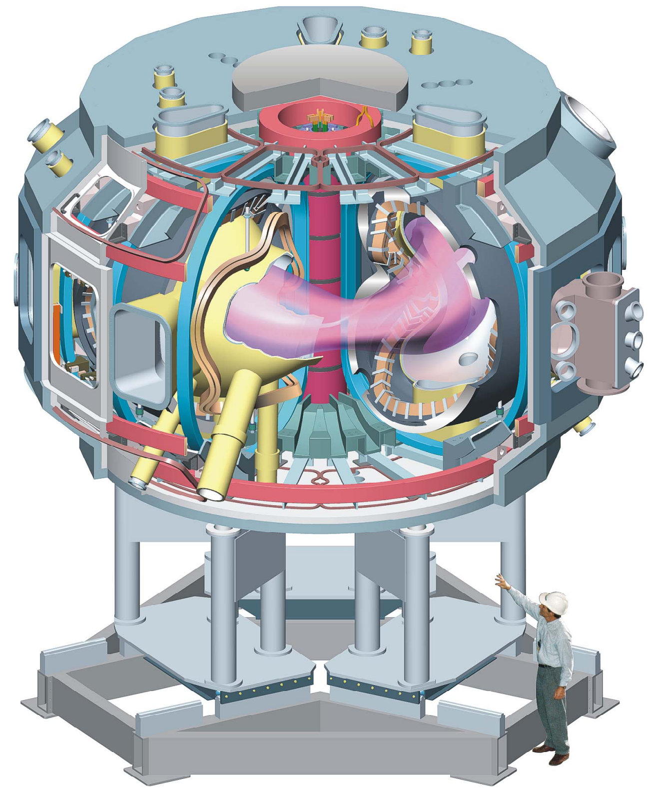

Fig. 5. CAD model of the NCSX stellarator.

(i.e., vacuum integrity, geometrical accuracy, and low magnetic permeability) and qualified two suppliers to compete for the production order. The manufacturing R&D program for the vacuum vessel and MCWF (which followed a very similar R&D path) were successful in preparing for construction. Both components are currently being produced in accordance with project requirements by capable suppliers under fixed-price contracts. (Fig. 4)

Modular coil R&D at PPPL and industrial conductor suppliers supported the design and manufacturing development for the modular coil winding. Initially, small-sample tests addressing both manufacture and performance issues supported decisions on conductor design (i.e., cable construction and dimensions), winding scheme, cooling scheme, insulation system, and epoxy impregnation materials and processes. Winding trials with flexible cable conductor on 2D and 3D tee-shaped winding forms developed methods for feeding the conductor and securing it in place during winding. Finally an integrated manufacturing demonstration was performed by constructing a “twisted racetrack” coil (TRC) on a winding form that is prototypical of the MCWFs in terms of tee cross section and worst-case bends and twists. The manufacturing R&D for the modular coils is now complete and electrical and thermal performance tests of the TRC to validate the analysis predictions are nearing completion. The modular coil R&D program has produced the winding pack design and demonstrated the manufacturing processes for the production coils that can achieve the required geometries and tolerances. Manufacturing procedures, tooling, and staff capabilities developed through this program have fully prepared the project to begin constructing the modular coils upon delivery of the first MCWF.

The NCSX project uses a system engineering approach to ensure that the completed system will be capable of carrying out the physics mission set forth at the beginning of the project. To reduce the risk that unforeseen feasibility issues or interferences will cause performance compromises or delays, the engineering development, from conceptual design through fabrication and assembly, is done in accordance with documented requirements. The self-consistent flow-down of requirements from the top (system) level to lower (subsystem, component) levels is managed using a hierarchy of linked specification documents. An integrated CAD model (Fig. 5) of the system is maintained to aid in the management of interfaces and allocation of space to subsystems and components, consistent with the requirements. A range of methods, such as CAD modeling, analysis, testing, coordinate metrology, and visual inspection, is employed at each stage to verify that the system is developing in conformance with the requirements. Two examples will illustrate the project’s system engineering activities.

The vacuum vessel shell geometry simultaneously satisfies the physics requirement that the interior must be as large as possible and the feasibility requirement that the modular coils must be installed over the vacuum vessel shell (with ports removed). The design solution was found using a CAD modeling technique. The modular coils will be assembled into three-coil sub-assemblies which will then be translated and rotated over the vacuum vessel along an optimum trajectory. Installing the coils one at a time or following an unoptimized trajectory would have resulted in a smaller vessel with less physics capability.

The modular coils must be wound such that, when completed, their current centers accurately follow the trajectories specified by the physics optimization. The overall tolerance (±1.5 mm) budget is distributed equally among the coil manufacture, coil sub-assembly, and final assembly steps. An economical coil manufacturing solution was found that takes advantage of the precision-machined winding form tee and the cable conductor’s flexibility and lack of significant keystoning in the tight bends. Clamping pressure and coordinate measuring equipment are used to achieve a rectangular shape in and accurately position the overall winding packs such that the current center is located within ±0.5 mm of the required trajectory. This strategy eliminates the need for time-consuming shimming and in-process metrology as the coil is being wound and provides the ability to compensate, if necessary, for any inaccuracies in the winding form.

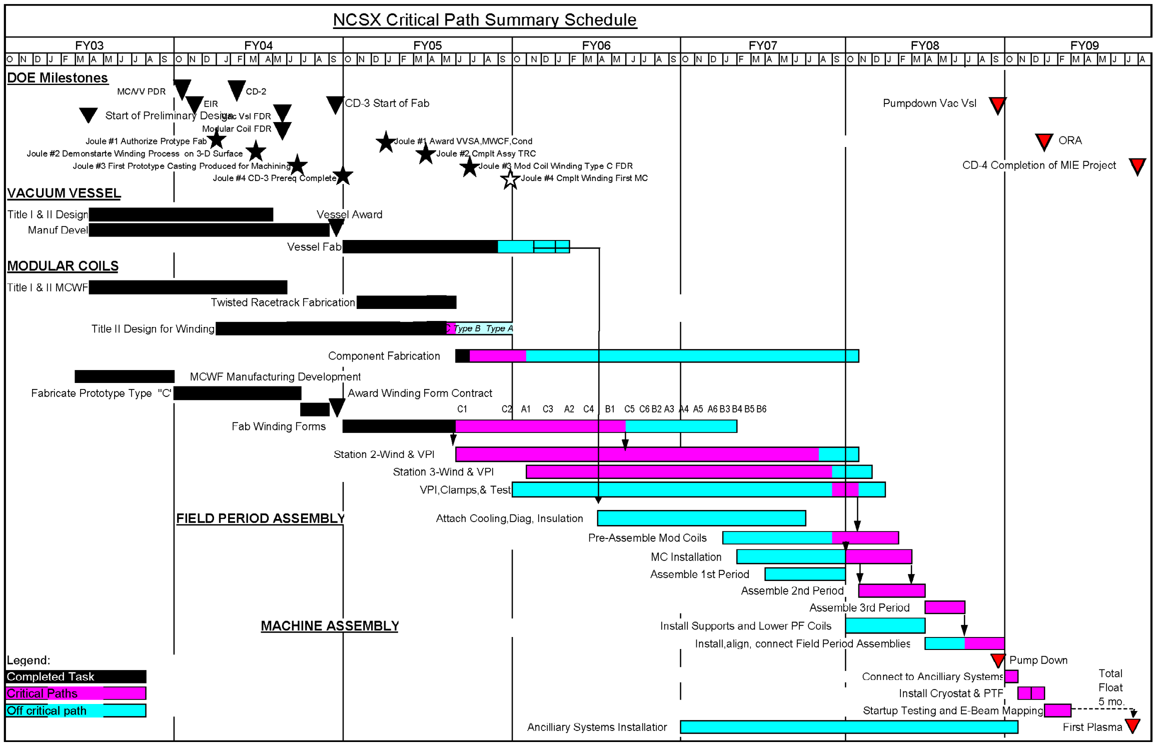

Fig. 6. NCSX Construction schedule.

IV. SCHEDULE FOR COMPLETING CONSTRUCTION

Construction of NCSX began with the award of contracts for the vacuum vessel, modular coil winding forms (MCWF), and modular coil conductor in September 2004 (Fig. 6) Modular coil fabrication at PPPL will begin upon delivery of the first MCWF, expected in September 2005, and will be completed by the end of 2007. Attachment of cooling tubes and other components to the vacuum vessel will begin upon delivery of the first vacuum vessel sector (one-third of the torus), expected in December 2005. Build-up of the three field-period sub-assemblies will start in 2007. Each of these includes six modular coils, six toroidal field coils, and a vacuum vessel sector with associated ports and attachments. Installation of these major assemblies on the machine base will start in mid-2008. Machine assembly and testing will occur in 2009. Electron-beam measurements of the magnetic surfaces will be carried out as a sensitive test of the overall construction accuracy of the magnet system. The construction project will be completed with First Plasma in July, 2009.

V. RESEARCH PLANS

The NCSX research program will proceed in a series of phases, as illustrated in Fig. 7. The first phase of the research program, Magnetic Configuration Studies, will use e-beam mapping apparatus to map flux surfaces, measure magnetic configuration properties, and verify coil flexibility. The next two phases, 1.5-MW Initial Experiments and 3-MW Heating, will address numerous plasma physics research topics using neutral beam injection (NBI) heated plasmas. The research goals will be to first explore the plasma operating space and then characterize confinement, stability, and operating limits with low and moderate heating power. It is expected that heating, diagnostic, and control capabilities will increase throughout these phases as research equipment is brought on line. These capabilities will permit tests of plasma stability at moderate beta and its dependence on 3D shape; investigations of local transport including the effects of quasi-symmetry; characterization of boundary plasma properties to prepare for the first divertor design; and explorations of transport barriers and enhanced confinement regimes. Later phases will use

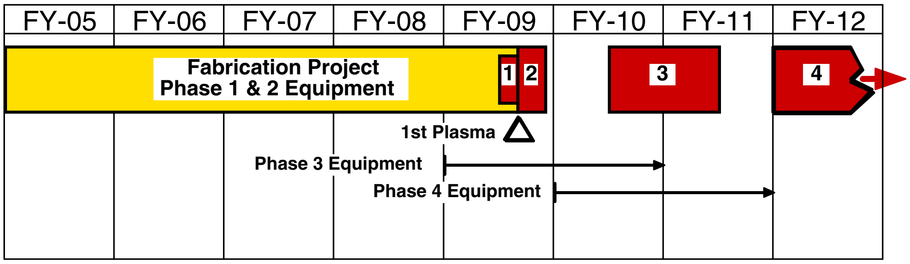

Fig. 6 NCSX Research Program timeline. Numbered research phases are described in text.

increased heating and improved control of the magnetic configuration and boundary conditions to expand the range of accessible plasma conditions. Building on the understanding gained during the earlier phases, the program will explore beta limits, disruption-free operation, enhanced confinement, and long-pulse operation near NCSX design parameters.

VI. SUMMARY

The NCSX is being constructed to test the physics benefits of the compact stellarator, a three-dimensional toroidal plasma configuration. The key engineering challenge, namely the accurate realization of the unusual geometries required of the magnets, vacuum vessel, and associated structures, is being met. The most complex components, the modular coil winding forms and the vacuum vessel, are already being manufactured in industry under fixed-price contracts using processes developed through R&D. The design and manufacturing processes for the modular coils have been developed through R&D. The NCSX project uses a system engineering approach to reduce the risk that unforeseen performance compromises or delays will arise during construction. Optimization of the vacuum vessel shell geometry for physics needs and development of economical procedures for achieving the required coil winding tolerance were key system engineering accomplishments. Though still in progress, the NCSX construction project shows that the engineering realization of compact stellarator geometries is not an obstacle. If the expected physics benefits are confirmed by the research program, it will establish the compact stellarator as an attractive candidate fusion confinement system.

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