Stellarator Constructability and NCSX Experience

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Current Status of NCSX Coil Fabrication and Assembly

Coil fabrication: All 18 modular coils have been fabricated to the required ±0.5mm tolerance. It only remains to epoxy-impregnate the last coil, which will be completed in early July.

Figure 1. Completed NCSX Modular Coil (one of 18)

Assembly: Assembly of the NCSX modular coil system starts with the construction of half-period modules of three coils and two joints each. There are six half-period modules in all. The first two modules are nearly complete and are being completed as part of project closeout. The two joints already completed are within their tolerance allocation, successfully demonstrating the joint design and assembly plan.

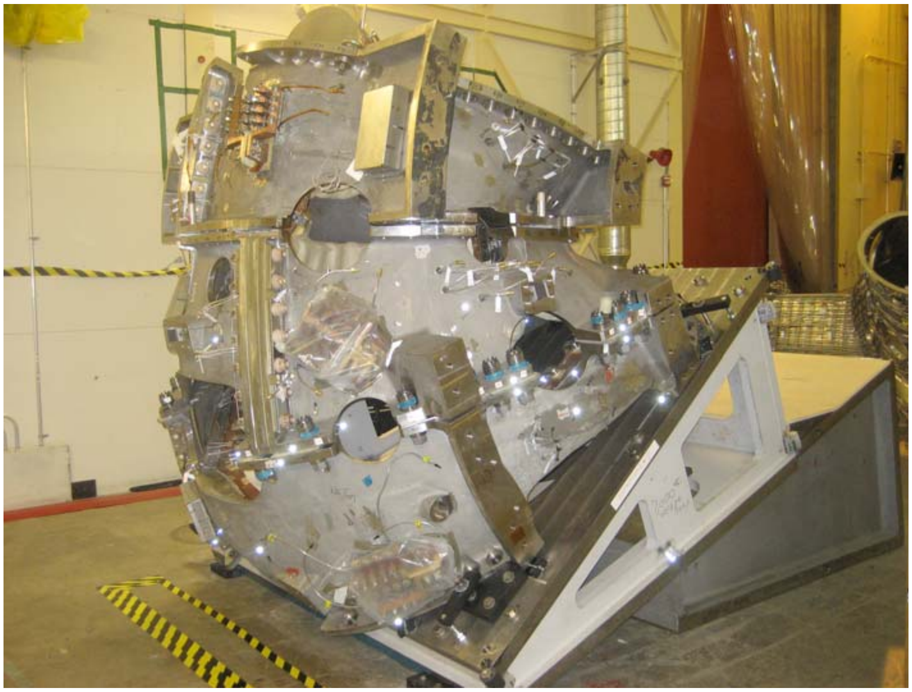

Figure 2. NCSX Modular Coil Half-Period Module under assembly

Construction Feasibility Summary: An engineering review of NCSX was conducted in the Fall of 2007 to evaluate the constructability of the stellarator to within the required tolerances based on the then-current state of the design. In their report, the international review committee stated, "It is the opinion of each member of the review committee that the NCSX Project Team can succeed in building and maintaining this stellarator. We base this opinion on the work and assembly plans presented. We feel that once the first Station 2 Modular Coil Half Period Assembly has been completed and shown to meet the required assembly tolerances then the major issues related to further assembly are similar and manageable with the techniques detailed and will therefore corroborate our opinion." Since that review, the design has advanced and, as noted above, two joints have been completed and the first two modular coil half period modules are nearly complete.

Further R&D is needed to reduce risks in the remaining critical assembly steps. Examples are: welding in the vertical orientation, high-friction insulated shims, more efficient metrology, and positioning / manipulation of large subassemblies subject to deflection. Such R&D will improve the reliability of cost and schedule projections for NCSX and for other designs with similar characteristics. However, the technical feasibility of NCSX construction has been established and no show-stoppers to the successful completion exist.

Problems in the NCSX Coil Fabrication and Assembly Experience

Coil fabrication: In the course of designing and fabricating the modular coils, problems were encountered where planned engineering tools or processes were found to be inadequate and in need of further development. For example, the initial Computer Aided Machining (CAM) instructions for machining the modular coil winding forms, although developed by the vendor with the aid of computer simulations, resulted in collisions between the machining head and casting. The simulations did not adequately address the complexity and unique characteristics of these parts and multiple iterations of the CAM programs were needed to perfect them. Also, the complex geometry required unusually long cutting tools, as shown in Fig. 3, which were prone to chatter and frequent, time-consuming replacement. An extensive cutting tool development effort was required to resolve these issues. The problems were overcome through process improvements, tool developments, and work load balancing among multiple machining centers. After a start-up delay of more than half a year, a reliable production schedule was finally established. Similarly, coil winding processes, once developed, proved to be more costly than originally estimated, although unit costs came down as the team gained experience. A future stellarator project will be able to take advantage of the lessons learned on NCSX to improve their estimates and better optimize their designs and plans.

Figure 3. Machining of a NCSX Modular Coil Winding Form.
Note the extended cutting tool required due to the complex geometry.

Assembly: It took much longer than planned for the NCSX team to resolve the modular coil-to-coil interface requirements and develop the detailed joint designs; consequently the start of half-period assembly operations was delayed by almost a year. The delay was basically due to the detailed interface structural requirements being defined late in the project when more sophisticated finite element analyses focused concern on these critical regions. In addition, the design had to satisfy multiple demanding requirements (large and complex forces, tight dimensional tolerances, electrical insulation, low magnetic permeability) in tight space constraints that limited the range of possible solutions. However, a satisfactory design based on a combination of bolting and welding was finally developed. Fabrication of the joints within a half-period, of which there are 12, has been demonstrated with the two joints already completed. The joint where two half-periods are joined to form a field period, of which there are 3, is similar except for a final weld that is performed in the vertical orientation and which is still under development. The fully-bolted joints between field periods, of which there are 3, require a qualified supplier for production quantities of alumina-coated high-friction shims; candidate suppliers have submitted samples. Prototypes of long-reach tooling required to tighten some of the inboard bolts have been fabricated and demonstrated.

Since actual assembly operations began in early 2008, the work has proceeded on or ahead of schedule. Experience has increased confidence in the ability to accurately position components, saving some steps. Photogrammetry, which can measure the positions of hundreds of points simultaneously, has improved the efficiency of metrology over laser trackers, which measure one point at a time. Improvements such as these have already speeded up the assembly process. Again, future stellarator projects can benefit from what has been learned on NCSX- both the problems encountered as well as the solutions and improvements that were developed.

In summary, the fabrication and assembly problems of NCSX are a reflection of the learning curve associated with executing a technically challenging design for which there was little past experience to draw upon. Future stellarator projects will be able to take advantage of this learning to improve their estimates and better optimize their designs and plans. Cost risks and uncertainties can be reduced by completing as much of the engineering analysis and R&D as possible before budgets and schedules are fixed.

Approach to Simpler Designs for the Future

Although the NCSX design is feasible, simpler coil designs might reduce stellarator construction risks. This issue will be addressed by the stellarator community in a reactor context. The sensitivity of coil design to physics requirements such as the amount of externally-generated transform and the choice of stability criteria, will be examined. Note that experiments are needed to determine acceptable physics criteria. Engineering improvements will be explored including the use of trim coils to allow tolerance relaxation and alternate combinations of coil topologies to control the shaping.