Design and Construction Solutions in the Accurate Realization of NCSX Magnetic Fields[*]

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Abstract. The National Compact Stellarator Experiment, NCSX, is being constructed at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge national Laboratory. The goal of NCSX is to provide the understanding necessary to develop an attractive, disruption free, steady state compact stellarator-based reactor design. This paper describes the recently revised designs of the critical interfaces between the modular coils, the construction solutions developed to meet assembly tolerances, and the recently revised trim coil system that provides the required compensation to correct for the "as built" conditions and to allow flexibility in the disposition of as-built conditions. In May, 2008, the sponsor decided to terminate the NCSX project due to growth in the project's cost and schedule estimates. However significant technical challenges in design and construction were overcome, greatly reducing the risk in the remaining work to complete the project.

1. Introduction

The toroidal assembly of the 18 modular coil winding forms, shown in Fig. 1, is the structural backbone of NCSX. The modular coils, vacuum vessel, toroidal field coils, poloidal field coils, trim coils and cryostat are all supported by this assembly; consequently the interfaces between the winding forms are extremely critical. The loads reacted at each flange interface are a compressive load of ~2600 kN/m and a shear load of ~700 kN/m. The centroid of the modular coil windings must be aligned to an accuracy of +/- 1.5 mm everywhere along the winding path throughout the operational life of the device (i.e., ~1/1000 of the 1.4 m major radius of the machine, which is the alignment requirement historically achieved in stellarators). Additionally, the eddy current decay time constant for the modular coil shell must be short (<20 ms) to minimize its influence on plasma control and stability. The original interface design, shown in Fig. 2, utilized G-10 shims clamped between the flanges of the winding forms by insulated studs located along the flanges in the upper, lower, and outboard regions of the winding form. The inner legs of the winding forms were to be supported by compression shims, since there were no studs in the inboard region because of inadequate space (refer to Fig. 3). At the time of the Final Design Review (FDR) in May, 2004, this design was judged to be satisfactory based on global analyses performed then. Engineering details and analysis models continued to be refined as the project matured. By late 2006 it became apparent that the original interface concept had several shortcomings and issues that needed to be addressed before proceeding:

- Coil alignment depended on precise fit up of the shims which were configured in large arc segments. Achieving this fit-up in practice was judged to be questionable since this would require precise measurement of the entire gap that the shim would occupy and precise 3-D machining of the shim.

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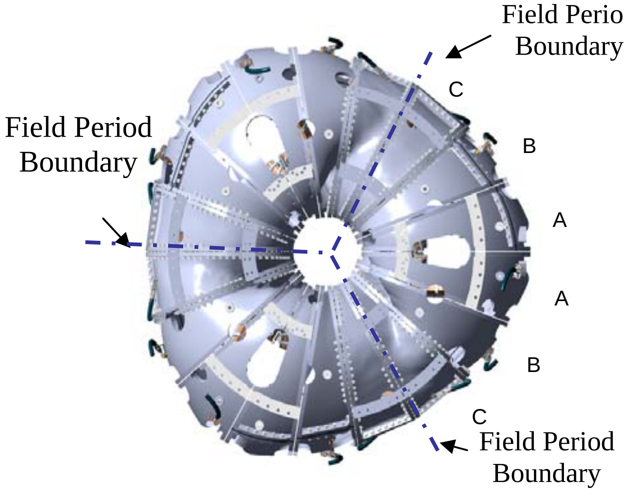
[*] Research supported by the U.S. DOE under Contracts No. DE-AC02-76CH03073 with Princeton University and No. DE-AC05-00OR22725 with UT-Battelle, LLC.

- The primary function of the shims defined for the shims at this point was to react compressive loads. Consequently, the studs needed to react the shear loads, but they were found to have inadequate fatigue life.
- The maximum inner leg deflection, which occurred at the C-C interface, was ~0.5 mm. Although marginally acceptable from the physics point of view, the loads on the end studs of the inner legs were unacceptably high.



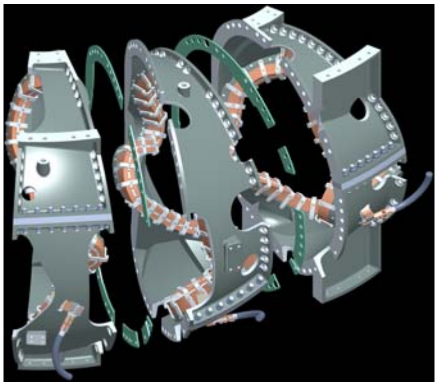
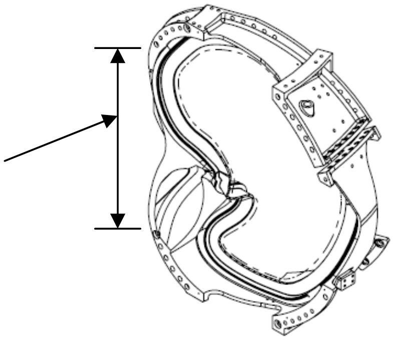


Fig. 1. The modular coil assembly.

Fig. 2. Initial modular coil interface details

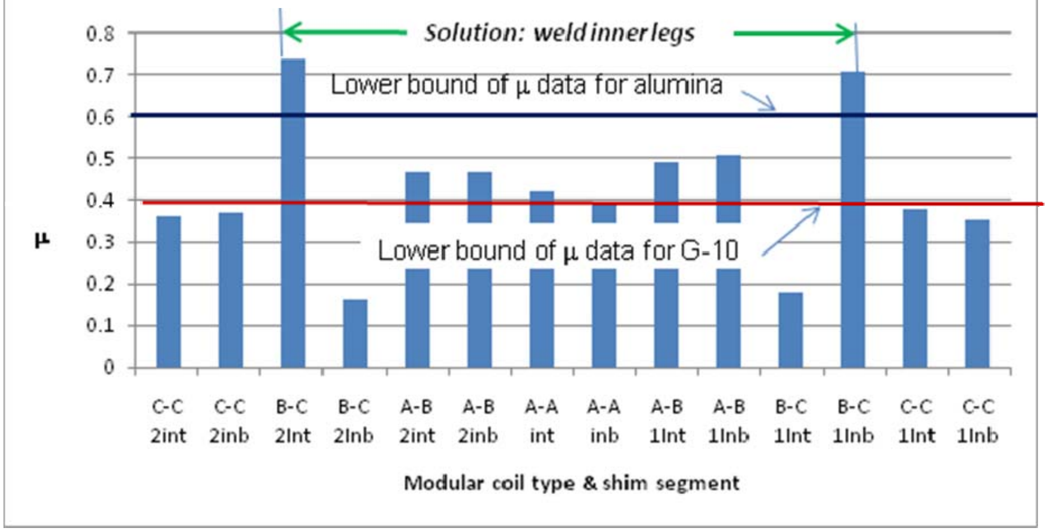
Fig. 3. Isometric view of a modular coil winding form showing flange stud details. (Type A shown): Note that most of the inner leg has inadequate space for studs.



2. Evolution of the Revised Interface Design

A feasibility study was performed to determine if friction shims between the flanges could prevent slippage between the inner legs and reduce the shear loads on the studs. Both alumina coated stainless steel shims and sandwich shims of G-10/ stainless steel / G-10 were tested to determine their coefficients of friction, μ at 80 K . The μ for alumina coated shims ranged from 0.59-0.80; μ for the G-10 shims ranged from 0.40-0.48. Finite element analyses were performed to determine the coefficient of friction required to prevent slippage. The results, shown in Fig. 4, show that alumina coated shims can comfortably assure against slippage for the inter-period C-C interfaces but is insufficient to react the shear in some of the intra-period interfaces. In parallel, electromagnetic studies were performed to determine if welds on the inboard legs could be considered for the intra-period interfaces. These studies indicated a modest and acceptable increase in the time constant for the shells with the legs of the modular coils intra-field period welded and with a fully insulated interface at C-C.

Fig. 4. Friction required to prevent slippage vs. shim friction capabilities



Consequently, the following details were chosen:

- **The inner legs <u>within</u> a field period (i.e., A-A, A-B, and B-C) will be joined by welding; friction shims will be used in all remaining areas (refer to Fig. 6).** The inner legs are connected by a low distortion welded interface, shown in fig. 7. This provides a robust solution in these interfaces, which have inadequate space for the additional studs and friction shims. Weld shrinkage forces that would tend to pull the winding forms together and distort the inner legs are avoided by connecting the winding forms by shear plates welded at opposite ends. Longitudinal welding stresses along the inner legs are balanced to minimize distortion of the inner legs by interleaving the shear plates to minimize bending of the inner legs. The bore-side welds are made first, with the winding forms separated to ease welding and inspection. After collaborations with weld engineers at CERN and W7X, it was decided that MIG welding will be used instead of a TIG since the heat input is significantly reduced. Subsequent trials using MIG with a flux core wire, Metrode Supercore 316NF, produced better penetration and reduced the heat input to the weld further in both a fillet weld and J-Groove configuration. Compared to MIG, the flux core process required approximately 68% of the heat input and less than half when compared to the TIG process. Representative weld samples were tested at full design stress successfully to over 250K cycles (2x life) at room temperature. Distortions of the modular coil after welding of the 3-pack were well within 0.5 mm (0.020")[1]. Another important feature of the interface is the separate limiter puck which is retained in a hole through the shear plate. Each puck is ground to the thickness required for alignment.
- **All friction shims will be segmented.** This permits each shim to be custom-fitted for alignment of the modular coils and to assure the pressure required for friction locking. Initially, alumina coated shims were planned to be used in all locations; however, they

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[1] L. E. Dudek, et. Al; "Status of the NCSX Construction "; 25th Symposium on Fusion Technology (SOFT 2008), Rostock, Germany.

proved difficult to manufacture to the required flatness (+/- 0.05 mm) on a reasonable schedule. Consequently, the alumina coated shims are only used for the C-C interface where the higher coefficient of friction justifies their use. With the inner leg connections welded, the coefficient of friction required to avoid slippage in the outer legs is < 0.15, which is very comfortable for the G10 sandwich shim design with a μ >0.40. Both shim types are shown in Fig. 8. Shown, also, is a Supernut ™, which is used to uniformly tension the studs during assembly.

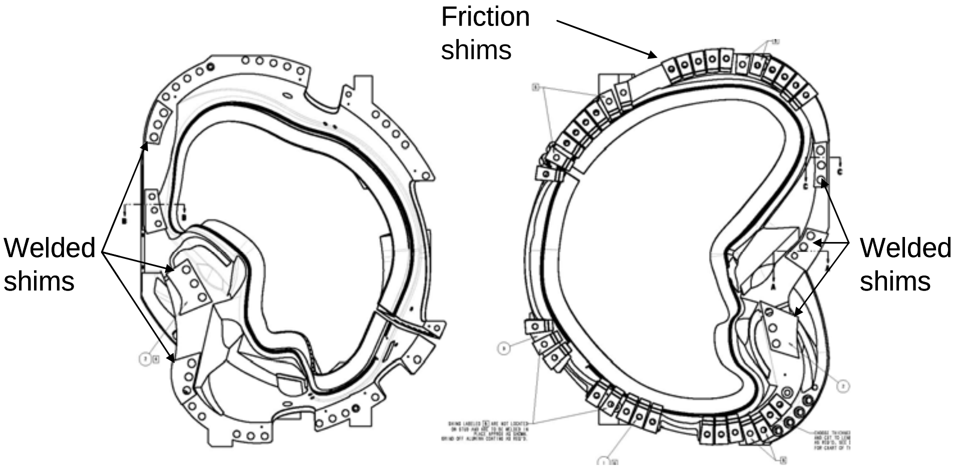


Fig. 6. Intra-period interface details (A-A, A-B, and B-C): Note that the welded shims are interleaved to equalize the weld shrinkage stress on both sides of the inner leg to minimize bending.

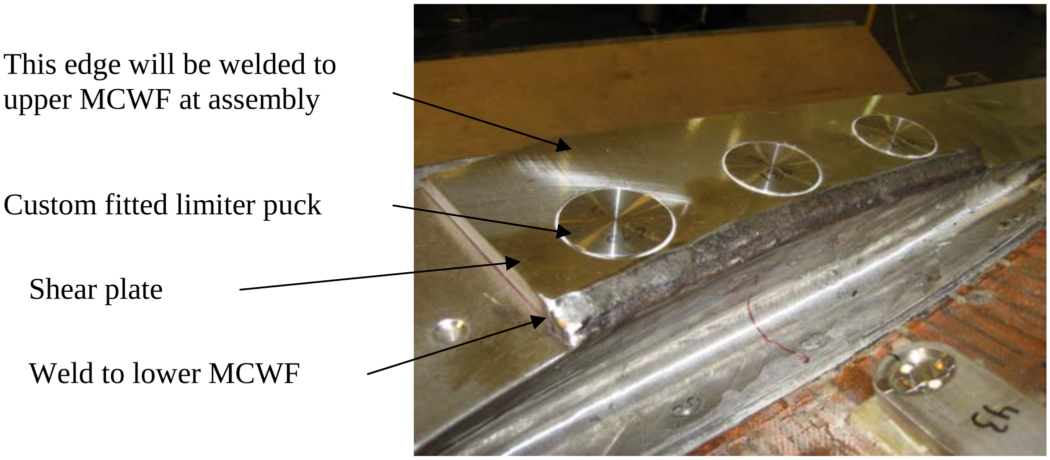
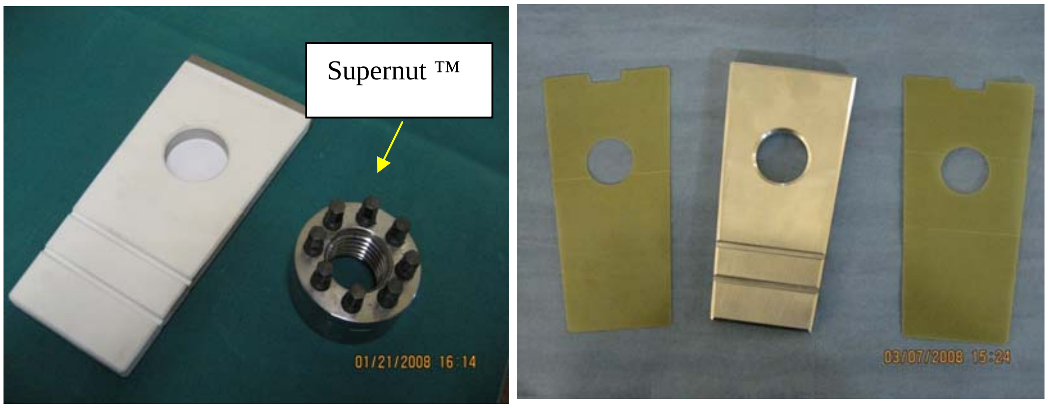


Fig. 7. Low distortion welded interface details



a. Alumina-coated SS shim

b. G-10/ SS / G10 shim

Fig. 8. Friction shims

- **A fully mechanically connected and electrically insulated interface will be retained for the C-C interfaces between the field periods:** The higher friction alumina coated shims will be used for this interface. Six additional studs and friction shims were added to both ends of the inner legs to reduce the load on the studs to an acceptable level to meet fatigue requirements. This revised configuration, shown in Fig. 9, reduces the deflection of the inner leg from 0.5 mm to 0.05 mm.

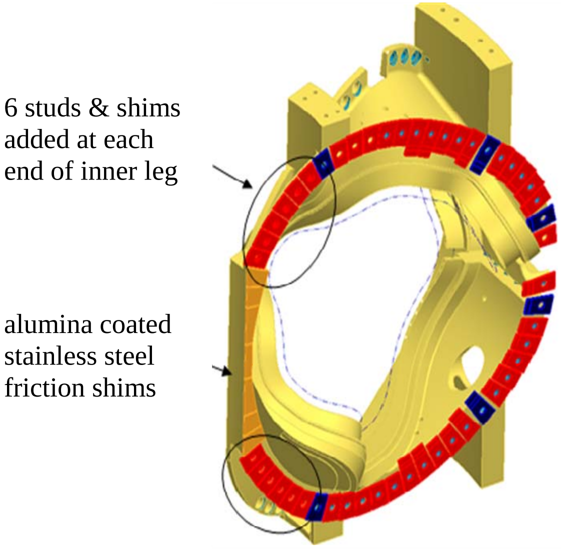


Fig. 9. Revised C-C interface details

- **All studs will be tightly fitted with insulating bushings (refer to Fig. 10):** This feature of the initial design was retained to assure maintenance of coil positioning while studs are tightened and also to serve as a backup to the shims in avoiding slippage.

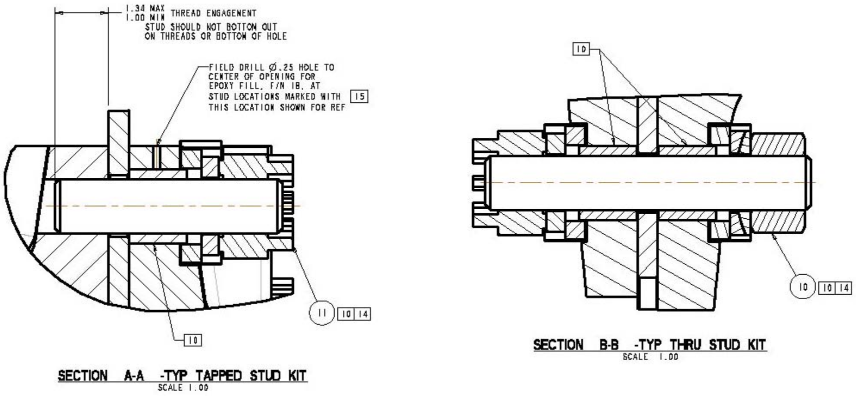


Fig. 10. Insulated stud connection details.

2. Trim Coils

The 48-coil trim coil system shown in Fig. 10 was designed to provide the ability to compensate for fabrication errors and to provide relief for out-of-tolerance conditions. Table 1 shows the performance of the trim coil system for the projected modular coil assembly errors (line 1) and for various displacement conditions for the modular coil "wings" (i.e., the portions of the windings which extend beyond the modular coil winding form shell)in addition to these errors. These results show that the trim coils can reduce the trapped flux in island regions to 3.88% (compared to the 10% specified limit) for the expected winding assembly errors plus each of the wings displaced + or – 1 mm with 100% reserve on the 20kA-t design point for the trim coils. They can be a valuable tool for mitigating schedule delays since this allows out-of-tolerance conditions to be compensated for rather than requiring time-consuming correction.

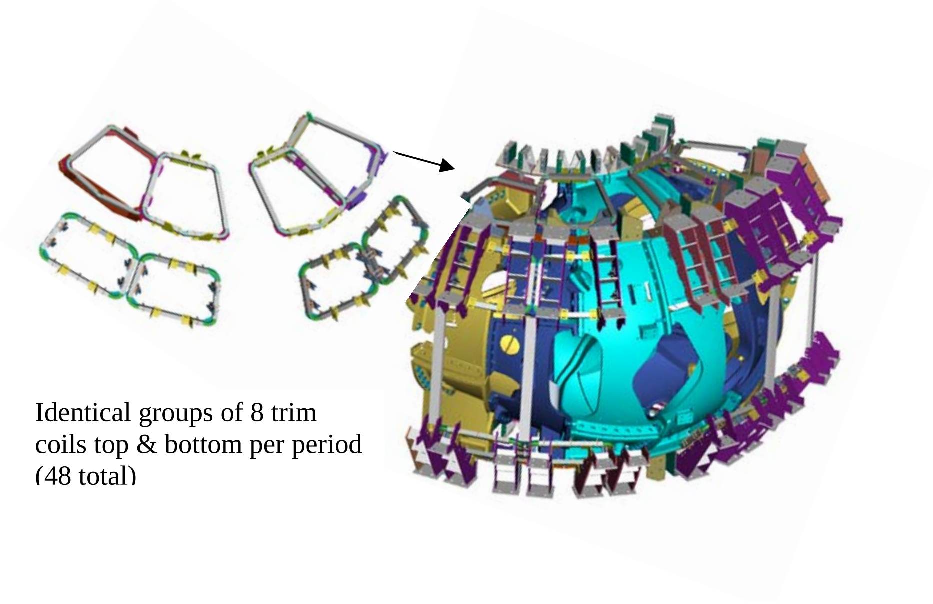


Fig. 10. NCSX Trim Coil System

Condition	Total island size, % of total flux	Max. current, kA-t
Projected modular coil assembly errors	**3.12**	**10**
Projected errors plus all wings distorted +1 mm	**3.88**	**10**
Projected errors plus all wings distorted -1 mm	**3.88**	**10**
Projected errors plus wings distorted –1 mm in 1 half period only (non-stellarator symmetric)	**3.25**	**10**

TABLE 1. NCSX TRIM COIL PERFORMANCE

3. Conclusion

The revised interface designs which are based on a combination of high friction and moderate friction segmented shims, tightly fitted insulated studs, and low distortion, MIG welded shims along the inner legs of the intra-period winding forms provide a robust, practical solution to NCSX's structural and assembly requirements. This, in combination with a capable trim coil system to mitigate construction tolerances on a timely basis, provides sound design and construction solutions for the accurate realization of magnetic fields in NCSX.

References

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