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NCSX Trim Coil Design

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Abstract*— The National Compact Stellarator Experiment (NCSX) was being constructed at the Princeton Plasma Physics Laboratory in partnership with Oak Ridge National Laboratory before work was stopped in 2008. The objective of this experiment was to develop the stellarator concept and evaluate it's potential as a model for future fusion power plants. Stellarator design requires very precisely positioned Modular Coils of complex shape to form 3D plasmas. In the design of NCSX, Trim Coils were required to compensate for both the positioning of the coils during assembly and the fabrication tolerances of the Modular Coils. Use of the Trim Coils allowed for larger tolerances increasing ease of assembly and decreasing overall cost. A set of Trim coils was developed to suppress the toroidal flux in island regions due to misalignment, magnetic materials, and eddy currents. The requirement imposed upon the design forced the toroidal flux in island regions below 10% of the total toroidal flux in the plasma. An analysis was first performed to evaluate candidate Trim Coil configurations iterating both the size, number, and position of the coils. The design was optimized considering both performance and cost while staying within the tight restraints presented by the space limited geometry. The final design of the Trim Coils incorporated a 48 Coil top bottom symmetric set. Fabrication costs were minimized by having only two coil types and using a planar conventional design with off the shelf commercial conductor. The Trim Coil design incorporated supports made from simple structural shapes assembled together in a way which allowed for adjustment as well as accommodation for the tolerance build up on the mating surfaces. This paper will summarize the analysis that led to the optimization of the Trim Coils set, the trim coil mechanical design, thermal and stress analysis, and the design of the supporting Trim Coil structure.

Keywords- NCSX, Trim Coils, Magnets, Error Correction Coils, Princeton Plasma Physics Laboratory, PPPL, Fusion

I. DESIGN OBJECTIVES / REQUIREMENTS

The Trim Coil function is to mitigate errors in the magnetic field due to imperfections in the coils system and overall assembly. These errors can be due to the misalignment of the primary modular coils with respect to each other as well as with respect to the TF and PF coil systems. Field errors may be the result of manufacturing tolerances associated with the current center in any of the coils systems especially the modular coils. Field errors may also be the result of materials whose magnetic permeability exceeds allowable limits and field errors from stray eddy current fields. The Trim Coils are required to correct these errors to the extent that the total flux in the island regions of the plasma does not exceed more than 10% of the total flux in the plasma. As the Trim Coils were designed towards the end of the NCSX program interfaces with the Modular Coils, Vacuum vessel, TF and PF coil support structure were already determined. The Trim coils were required to fit within and mount to these existing systems. In addition to the engineering requirements coil cost as well as the required power supply cost were to be minimized.

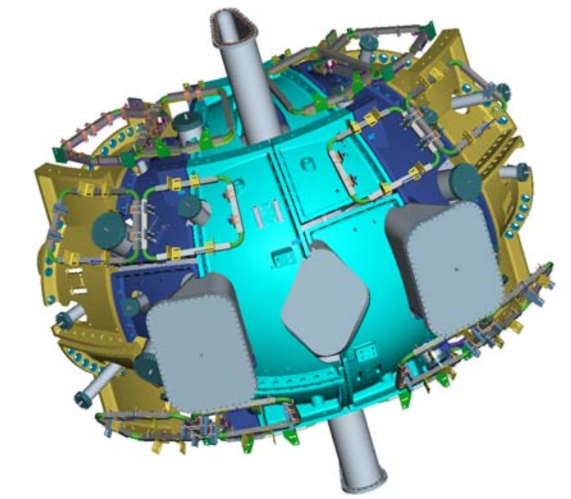

Figure 1. NCSX Structure With Trim Coils

II. DESIGN STUDIES

The first step in the Design of the Trim Coil System was to optimize the position and number of coils required to meet the project requirement for suppression of plasma islands. Due to the fact that the NCSX design was near completion the possible size and location of the coils was constrained by the existing components as well as the associated mounting hardware and structure. For the purpose of analyses rough non symmetric coil shapes where assumed and placed in the available real estate (see fig.2). Starting with this coil configuration the analysis moved forward and evaluated more symmetric coil combinations and then varying numbers of coils. The design was simplified by reducing the number of coil types and optimizing the mounting positions

Figure 2. Intial Coil Configuration

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Trim Coil Configuration	Total Number Coils	Using NLP Solution Total Island Size %Total Flux	 Max Current kA-T
Original 36 coils, 24 circuits	36	3.35	10.00
Original with 12 Midplane Coils	48	2.55	10.00
All Inner/Outer Coils Only (as Modified)	54	2.87	10.00
All Inner/Outer Coils Only (as Modified) (but without Outer AA)	48		
All Inner/Outer & Midplane Coils	66	2.17	10.00
All Inner/Outer & Midplane Coils (but without Outer AA)	60		
All Inner/Outer Coils (port12 split) (with Outer AA Coils)	60	2.89	10.00
All Inner/Outer Coils (port12 split) (without Outer AA Coils)	54	3.00	10.00
All Inner/Outer Coils (port12 split) (without Outer AA and CC Coils)	48	3.12	10.00

Figure 5. Evaluation of Coil Configurations

while measuring each of these designs against the resulting island size. It was found that the coil set could be reduced down to 48 top bottom symmetric coils (see fig.4) with the island size suppressed to below 3.1% of the total flux at 10 KAmp- Turns. This was well within the design requirement of a maximum of 10% islands and only used 50% of the capacity of the Trim Coils which were being designed to be capable of supplying 20KAmp turns.

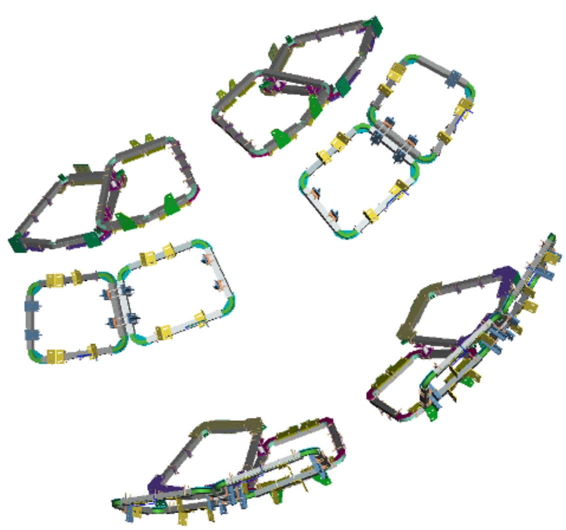

Figure 4. Final Trim Coil Configuration

III. Coil and Structural Design

A. *Coil Cross Section and Insulation Design*

To obtain the desired goal of 20 KAmp-turns (product of the number of turns times the current equals 20,000) the coil was initially designed with 4 large high current carrying capacity turns. This approach however required more costly higher current power supplies and it was determined that increasing the number of coil turns would achieve the design goal at a lower overall cost. A 120 turn coil was settled upon requiring only 167 amps as compared to a four turn coil which would require a 5000 amp power supply. While this drove the voltage requirement for the power supply higher power supplies in the required voltage range are still of a common design and reasonably priced. The resulting coil design with safety factors considered is required to standoff 4.5KV to ground and 1.0KV turn to turn.

The coil conductor is a continuous length of 2mm square copper wire pre-insulated with one half lap layer of Kapton and then one half lap layer of "Dayglass" tape. This conductor is both commercially available as well as familiar to coil manufacturers and makes for a low risk conventional coil design. The ground insulation is applied over the coil turns and is composed of 0.012 inch thick by one inch wide E glass. The E glass is applied in half lap layers to bring the total build of the turn-to-turn insulation to 0.125 inches. The completed ground wrapped assembly is vacuum impregnated using CTD 101K epoxy. The number of layers of ground insulation is optimized so that the compression of the coil in the VPI mold is sufficient to minimize resin rich areas

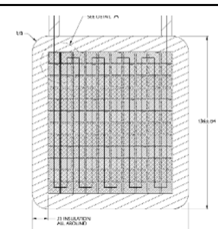

Figure 3. Coil Cross Section

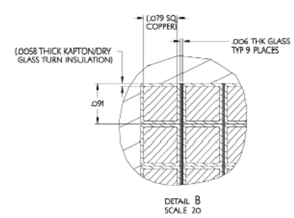

Figure 6. Insulation Detail

B. *Coil Lead Design*

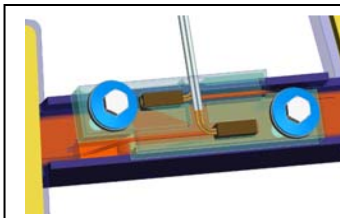

Figure 7. Coil Lead Design

To form the leads the coil conductor is bent out of the coil. Bus leads are soldered to the coil leads via a solder cup and the Bus leads are brought outside the cryostat for easy access. This eliminates less reliable bolted lead connections inside the cryostat and moves all removable connections to where they can be accessed readily.

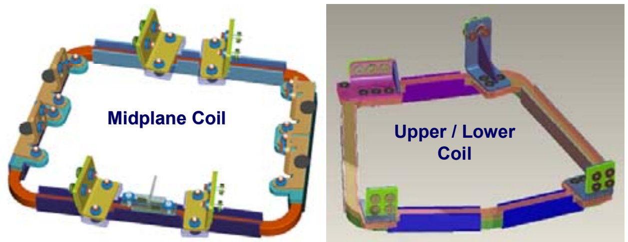

Figure 8. Two Coil Geometries

C. Coil Geometry, Support and Case

The final Trim coil design resulted in down selecting to two trim coil geometries, one rectangular and one five sided. By limiting the variety of Trim Coils to only two the project would realize a substantial cost savings in tooling and manufacturing costs. These two Trim Coil geometries are each then assembled to multiple case supports and bracket arrangements to integrate the coils into the mating locations on the existing NSCX assembly support structure.

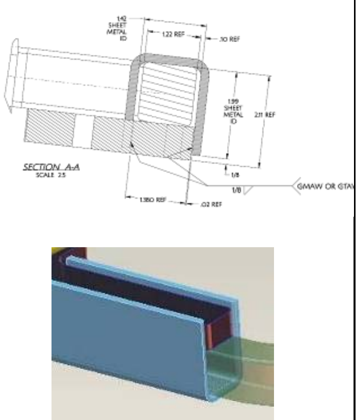

Figure 9. Welding of U Channel to Suport Frame

While the wire rope vacuum impregnation of the Trim Coil winding pack design is low risk and economical it does result in a rather soft bending modulus with respect to reacting out of plane loads. To compensate the Trim Coils are assembled to stiff ¾ inch stainless steel plate frames using stainless U channels. The frames (or separate bars for the Midplane Coils) are cut in a water jet cutter. The U channels are custom bent and the two are assembled about the coil with a fillet weld on the far side of the ¾" plate. This process was developed at PPPL and tested to ensure the feasibility of successfully welding the U channel to the plate without over heating (120C max) and damaging the coil.

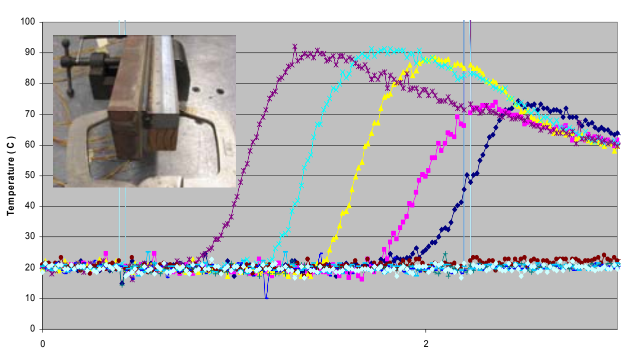

Figure 10. R&D: Temp. vs Time Welding U Channel to Frame

D. Coil Structure and Mounting Supports

The electro magnetic analysis of the Trim Coil installation indicated that running loads on the coils approached 80 lbs per inch worst case. The self loads on the coil were less severe. The use of the plate channel frame concept allowed these loads to be carried from the coil through the coil support frame into mounting points which are attached to the existing TF and PF coil support structure on NCSX. A series of brackets were developed to mate with the request support points. Since the Trim Coils were supported on structure that included a high build up of tolerances (brackets mounted to brackets mounted to brackets) it was necessary that the mounting provisions included the ability to accommodate the requisite degrees of freedom. Fortunately the required installed tolerance of each coil could be as loose as 12mm. (After assembled the installed location of the Trim Coils would be measured to within 2mm). It was necessary that the brackets find their mounting points but not necessary that they locate the coil very precisely in a prescribed location relative to the machine center. Mounting flexibility was accomplished by carefully orienting the support brackets and slotting holes so that the required adjustment was available. Shims would also be used under brackets as required.

Support brackets were required to resist lateral loads, just over 2000 lbf, in friction. To maintain reliable bolted connections in a cryostat where thermal cycles are from room temperature to 77K a series of Bellville washers was required. Each bolt would be assembled with two cupped Bellville washers guaranteeing a minimum clamping force after cool down of 5800lbf per bolt.

All structure and brackets were required to have a magnetic permeability of less than 1.02 Mu This requirement was a substantial material cost driver. Individual mounting brackets were to be fabricated from Inconel. U channel and support plates were to be fabricated from 316 SS. The stainless steel parts were to be heat treated at 1100C for 2.5 hrs as required to bring the magnetic permeability below 1.02 Mu.

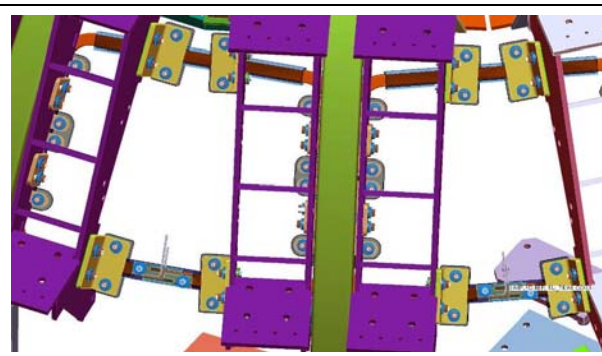

Figure 11. Trim Coils Assembled to TF Coil Supports

IV. Analysis

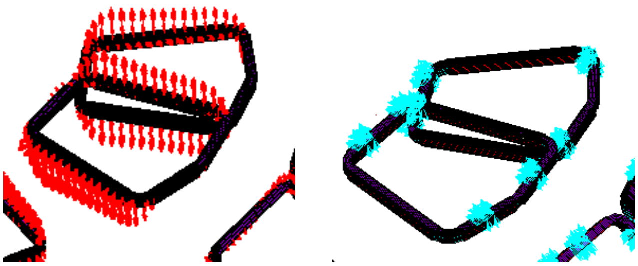

Figure 12. Force Distribution and Assembly FEA Model

A. Structural Analysis

A force scan of all of the seven operational load cases established in the NCSX General Requirements Document was run at five time points. A maximum running load was established as 80 lb/in for the Upper/Lower Coils and a maximum running load of 60 lb/in was established for the Midplane Coils. The output from these forces scans was then applied to the Pro-E geometry and a structural analysis of the final coil assemblies was undertaken using the ANSYS finite element analysis package.

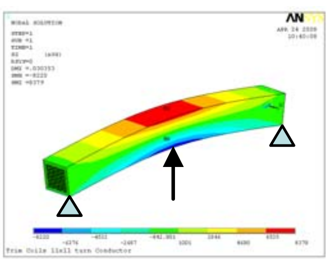

Figure 14. Detailed Winding Pack Finite Element Model

To keep the model size and run time reasonable for the finite element analysis an initial detailed model of the coil winding pack was made. A coil bar was modeled including all individual conductors as well as layer to layer and ground insulation. This model was then used to extract the generic composite properties of the winding pack. These composite properties were then applied to the overall assembly in which the coil / winding pack was modeled as one composite material. Stresses and deflections were determined for the coil frame and the U Channels. Load cases included electromagnetic forces (EM), stress due to cool down, and the combined loading of cool down + EM forces.

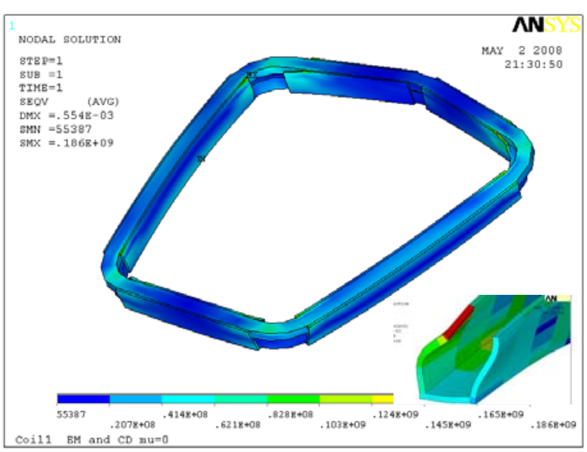

Figure 13. Coil Assembly Stress Results

B. Thermal Analysis

The Trim Coil Assemblies are convection cooled. With the required pulse repetition rate the equivalent average power to be dissipated is 27 watts and each pulse raises the temperature of the winding pack by 2.6C. The analysis indicates that with convection cooling at liquid nitrogen temperatures the maximum temperature rise would not exceed 9.0C before equilibrium is reached. Also there is sufficient margin in the design so that the current could be increased to twice the design requirement supplying a total of 40KAmp turns. At 40 KAmp turns the coil would dissipate an equivalent average power of 107 watts and equilibration would be reached with an increase in temperature of 35C

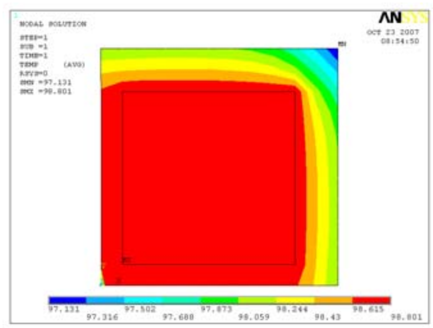

Figure 15. Themal Analysis

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