THERMAL, ELECTROMAGNETIC AND STRUCTURAL ANALYSIS OF NSTX TF COIL

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Analyses for the NSTX upgrade serve two main purposes. The first is supporting the design of new components, principally the centerstack. The second is qualifying the existing components for higher loads, which increase by a factor of four. Two areas representing this effort are presented: analysis of the current distribution in the new centerstack TF inner coils, and analysis of the support structure for the existing TF outer coils. The current diffusion analysis determines the temperature rise, thermal stress and required active cooling parameters. The TF structural analysis aids in the truss design while quantifying the machine loads and stresses.

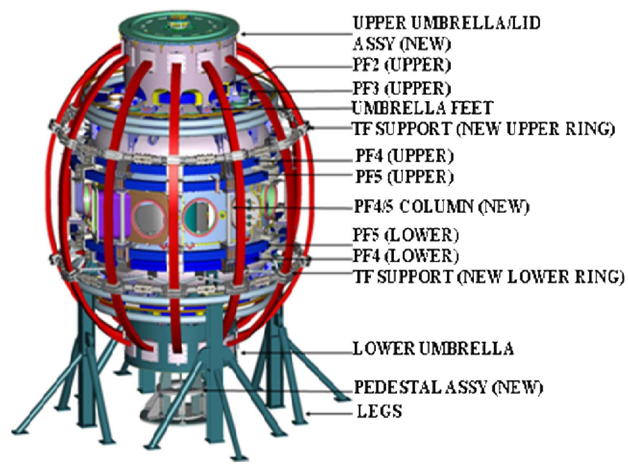

Fig. 1. NSTX upgrade machine.

I. INTRODUCTION

The National Spherical Torus Experiment (NSTX) is a low aspect ratio, spherical torus (ST) configuration device located at Princeton Plasma Physics Laboratory (PPPL), see figure 1. From the previous research, with lower collisionality ν* high fusion neutron fluxes and fluencies could be achievable in very compact ST devices.[1] These researches motivated the upgrade of NSTX to higher TF field B_T from 0.55 to 1 Tesla, increase of the plasma current I_P from 1 to 2 Mega-amperes, and, increase of pulse length from 1 to 7 seconds. Also, addition of a second neutral beam injection (NBI) should increase heating power from 5 to 10 Mega-watt. To achieve this higher B_T, TF current has to increase from 71.2 KA to 130 KA per turn. Loads will increase accordingly by a factor of four. A new centerstack (CS) with doubled outer diameter will replace the existing CS.[1,2]

The upgrade analyses have two goals. The first is to support the design of new components, principally the centerstack. The second is to qualify the existing NSTX components for higher loads and the structural changes to the vacuum vessel. Due to the various structural changes and the addition of the second NBI, electromagnetic (EM) loads increase by a factor of four. This requires two important analyses: the electric current distribution in the new toroidal field (TF) inner coils, and, the support structure of the existing TF outer coils.

II. TF COUPLED THERMAL ELECTROMAGNETIC DIFFUSION ANALYSIS

A current diffusion analysis is performed to investigate the temperature profile and the stresses in the TF inner coils. For the upgrade, the exiting connections between the inner and outer TF coils will be replaced by flags and the laminated copper arches (Fig. 2). TF current will be promoted to 130 KA.

Due to the higher current and the slew rate (Fig. 3), current will distribute non-uniformly. This is caused by the coil resistance, inductance and contact pressure between the flag and arch contact joint (Fig. 4).

This also produces localized high temperatures with associated high thermal stress and the increased risk of overheating the coil insulation. Active water cooling will be added to the inner and outer coils to control the joule heat concentrations. However, the effect of cooling on thermal stresses need to be investigated. This analysis is based on Refs. 3 and 4.

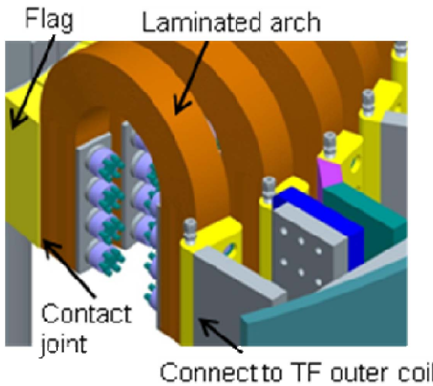

Fig. 2. Connection between TF inner and outer coils.

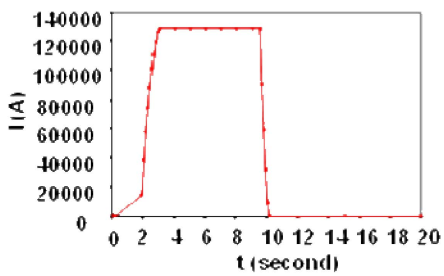

Fig. 3. NSTX TF coil current (unit: A).

II.A. Modeling

This is a transient and coupled field analysis. An EM model (Fig. 4) is used to calculate current diffusion. The resulting heat and Lorenz forces are transferred to the thermal model, similar to Fig. 4. However, the air simulation was removed while end supports and cooling lines were added. This thermal model calculates the temperature distribution, displacement, thermal stress, and contact pressure. Obtained results are then transferred back to EM model.

Temperature dependent material properties include electrical resistivity, thermal conductivity, specific heat, and coefficients of thermal expansion.

The arches are constructed from thin copper sheets which are bent into the required shape. Solid elements are used to simulate this geometry. Therefore, adjusted modulus of elasticity had to be implemented. Data from Ref. 5 was used for this purpose. In addition, the arches are modeled for anisotropic resistivity and thermal conductivity to simulate the lamination geometry. The upper flag uses high strength copper with 1/0.8 resistivity and 80% thermal conductivity of pure copper.

The results show little difference between using high-strength and pure copper, e.g. temperature difference less than 1 °C. The lower flag still uses pure copper. The EM model shows that the contact regions have pressure dependent resistivity, see Ref. 6 (Fig. 5) for complete explanation.

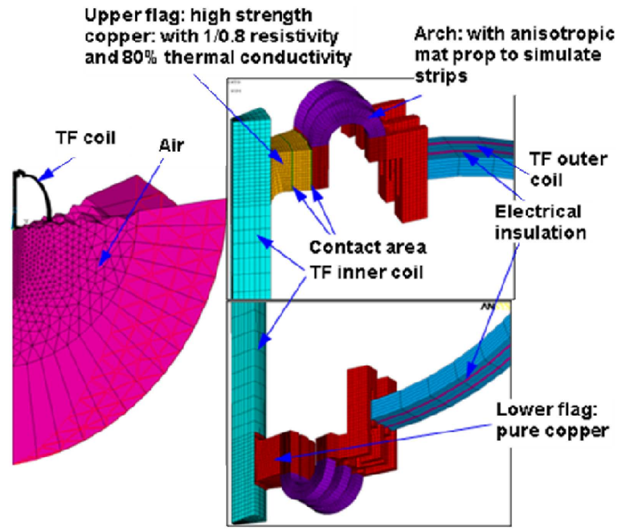

Fig. 4. Electromagnetic Model.

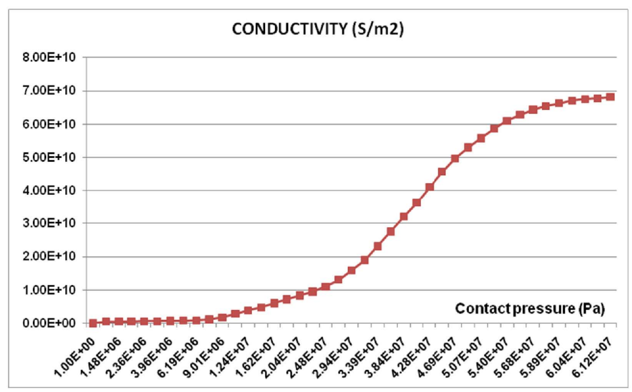

Fig. 5. Contact resistance.[6]

II.B. Results

Coil temperature reaches the maximum at 10.136 seconds, end of the normal operation pulse, see Fig. 3. Without active cooling, during the normal pulse, maximum temperature of the inner coil reaches 117 ºC, located at the inner upper corner of the lower flag. Note, the coil is wrapped with insulating layer which consists of fiber glass fabric and bonded with epoxy. The epoxy temperature limit is 115 ºC. Comparing with Ref. 2, 101 ºC temperature rise, which is based on resistive heating, the current diffusion results show a little higher temperature. Upper flag has more material (Fig. 6) and thus the max temperature is lower, 112 ºC. With active water cooling (0.25" diameter tube, 3 m/s coolant velocity and inlet temperature of 12 ºC), the maximal temperature of lower flag drops to 113.4 ºC and that of upper flag becomes 110.8 ºC (Fig. 6). Coefficients of thermal expansion for copper (1.54E-5 /°C at 0 °C and 1.6E-5 /°C at 100 °C) and epoxy (1.362E-5 /°C) could cause epoxy-copper delamination at above temperatures.

There are two options for cooling line placement, one in the middle of the coil, the other at the side, see Fig 7. Fig. 7 shows that putting cooling line at side produces lower S_{theta} (i.e. stress component that can cause delamination) of 90 MPa when compared to putting cooling lines in the middle. The latter will cool the coil down faster and result in more shrinkage. In these analyses, 0.3” tube is used with 3 m/s velocity and it takes 5 minutes to cool the inner coil down to room temperature. If the cooling process can be slower, for example, by using a 0.25” tube and the same velocity, the stress S_{theta} can be reduced to 48 MPa. To reduce S_{theta}, it is better to cool down slowly. Using thinner tubes, lower coolant speed and different cooling line positions are all possible options to be further evaluated.

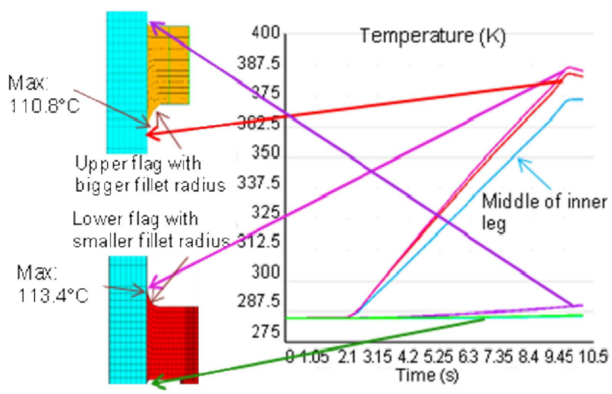

Fig. 6. Temperature rise in TF inner coil with water cooling.

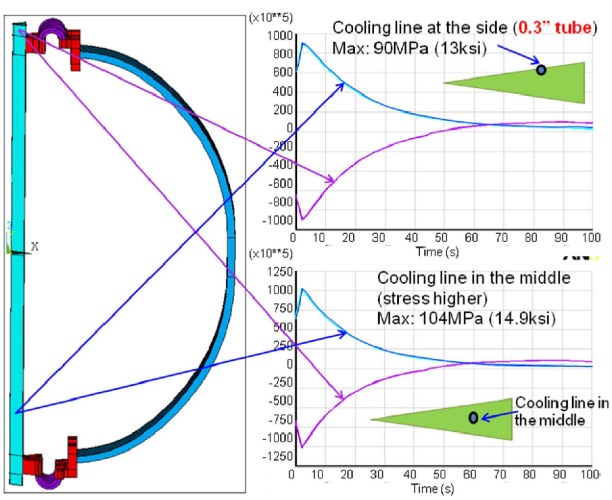

Fig. 7. History plot of stress S_{theta} (Pa) in TF coil with water cooling.

The max temperature in the outer coil reaches only 47 ºC at the end of the pulse. However, to avoid further temperature rise upon subsequent pulses, active cooling is used. With a cooling line of 0.5” tube diameter, 3 m/s velocity and the tube attached to the surface of the outer coil, the coil can be cooled down to 25 ºC in 5 minutes.

Because the upper flag has contact regions, using high strength copper as the flag material can help to maintain high and uniform contact pressure and also lower contact resistance. But high strength copper has higher resistance and lower thermal conductivity. From the analysis, using high strength copper (1/0.8 resistivity and 80% thermal conductivity) causes temperature difference of less than 1 ºC. Thus high strength copper can be used if required to increase the pressure of joint bolt insert load over the capacity of pure copper.

III. ANALYSIS OF TF OUTER COIL

For the upgrade, the TF current will increase to 130 KA, resulting in 4 times the mechanical load, principally the out-of-plane (OOP) load. Consequently, various support structures will be over stressed, namely the umbrellas, and localized regions on the vacuum vessel (VV). To resolve these problems the load path will be modified. By adding structural support to transfer TF outer coil load to the VV at the clevis along with upgrading the clevis, maximum transfer of the OOP load can occur at this connection. This bypasses the umbrella. Furthermore, localized reinforcements will be added. Note, interference with auxiliary systems and supports was troublesome and limited the addition of trusses to help sustain the OOP load. Lastly, support rings will be added between the TF outer coils to reduce the pull-out (in-plane) loads.

For the current NSTX configuration, the TF outer coils are supported by the umbrella structure, turn buckles and tie bars. Previous analysis, based on worst case poloidal field (PF) currents, reveal some structures are over stressed >1 GPa (145 ksi). Evaluating the three components of the load in cylindrical coordinate, the radial load is carried by the cylindrical umbrella and rings. The vertical load and the OOP load are transferred through the umbrella structure producing high stress in the umbrella feet, the arches, and the VV ribs and dome. Thus, the existing support is no longer adequate.

The upgrade design replaces the turn buckles with a sturdy support ring which occupies the space of existing components. The support ring and tie bars transfer some of the in-plane and OOP load to the VV and is effective on both symmetric and asymmetric PF currents. The support ring reduces the pull-out (in-plane) load at the umbrella structure. Note, up-down asymmetric currents result in a net twist load which requires an attachment to the VV. The tie bars can take the net twist and also provided adequate OOP support for symmetric case.

III.A. Modeling

A finite element model (FEM) of the relevant components was created; refer to Figs. 8 and 9. The parametric model was built using ANSYS. It includes vessel and supporting legs, umbrella structure and reinforcements, PF coils, Ohmic heating (OH) coils, TF coils and truss. Also, the TF outer coil was reinforced with additional clamps. The tie bars are pin connected to the new clevises which are welded to the VV. This design is effective on both symmetric and asymmetric PF currents. PF, OH and TF inner coils are modeled using souc36 current element and TF outer coils using solid element. The Lorenz force in TF outer coils are calculated by biot-salvart law. The results from this global model are transferred to other detailed models for further analysis, e.g. ring loads are transferred to a local model for detailed stress and bolt calculations.

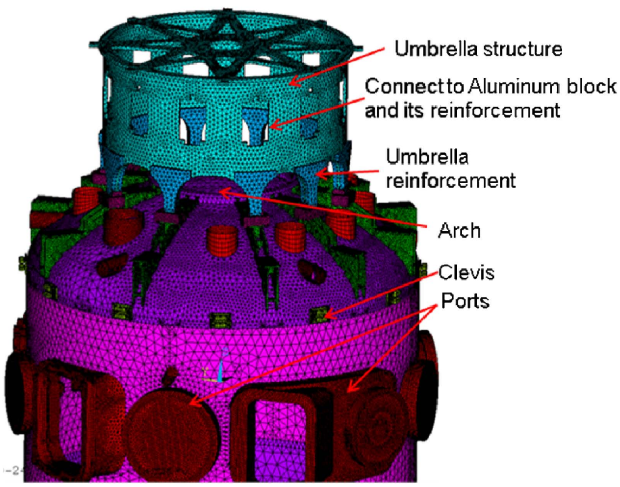

Fig. 8. Modeling of vacuum vessel.

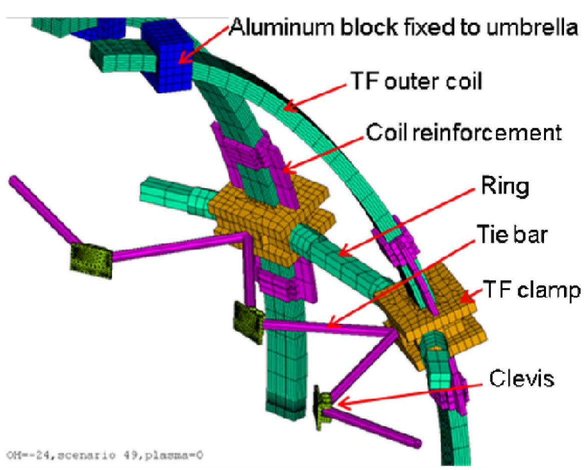

Fig. 9. Modeling of TF outer coil and TF truss.

According to the design criteria,[7] the allowable stress in the TF outer coils should be within 156 MPa (Tresca) or 233 MPa (bending). The epoxy shear stress should be within 16 MPa. Coil circumferential displacement is limited to less than 12.7 mm. The umbrella structure and VV are different stainless steels. The Tresca stress allowables are 150 MPa and 183 MPa respectively, with a bending allowable of 1.5 times.

Several current scenarios with large TF outer coil OOP loads were evaluated which included symmetric and asymmetric PF current combinations. A total 96 current scenarios can be analyzed to ascertain the worst loads and stresses for various components. Note, the PF currents, being either up-down symmetric or asymmetric, result in the TF coils OOP displacement. The TF coil upper and lower halves could deform in the same or opposite direction depending upon the configuration of the PF currents. Upon asymmetric PF currents, there will be a net circumferential displacement. However, with some scenarios, the PF currents are not high but are asymmetric and may result in high OOP displacement and coil stress. Based on our previous analyses, adding plasma current would reduce the OOP load, and thus, to be conservative, it is set to be zero. Plasma current produces flux lines that are parallel to TF coil. Plasma current quench doesn't influence TF coil and plasma disruption effects were not included.

III.B. Results

With the redesigned coil support configuration, maximum displacement has been reduced significantly, originally, from 27 mm to present 1.6 mm. The maximal predicted coil stress is 88 MPa, at the connection between TF clamp and ring (Fig. 10).

The FEM simulates a solid bond between the coil and clamp. In reality, an epoxy layer is between them and may reduce the stress.

The insulation shear stress is within 7 MPa. After reinforcement, the umbrella structure has maximum stress of 110 MPa, see Fig. 11. Stress in umbrella arch prior to reinforcement was 304 MPa and is now 52 MPa with reinforcements (Fig. 12).

The stress in the VV is within 100 MPa. The clevis stress is higher, at 115 MPa, but acceptable. The support ring carries 65 KN of axial force and 5000 N-m bending moment. This data is transferred to detailed models for further design and analysis efforts. During VV bake-out (150 °C), the truss will load the TF outer coil producing a maximal stress of 151 MPa, which is within the allowable.

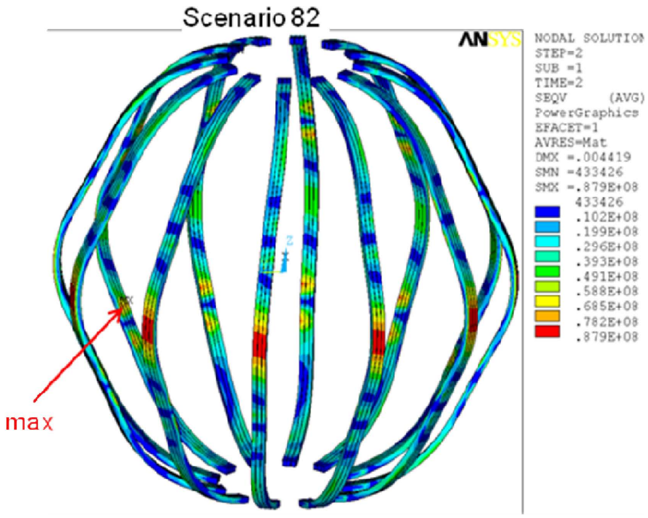

Fig. 10. Coil Von Mises stress (Pa).

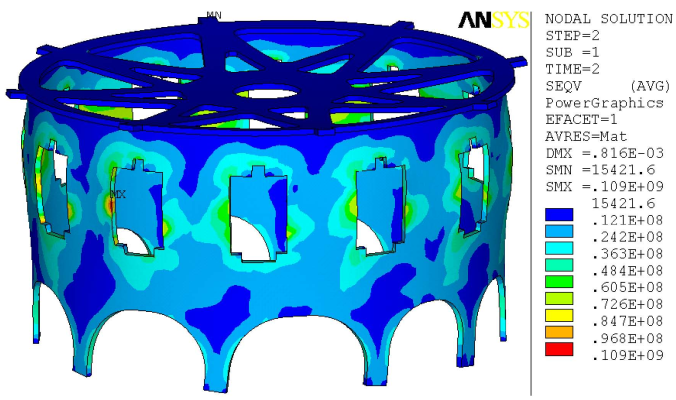

Fig. 11. Umbrella stucture Von Mises stress (Pa).

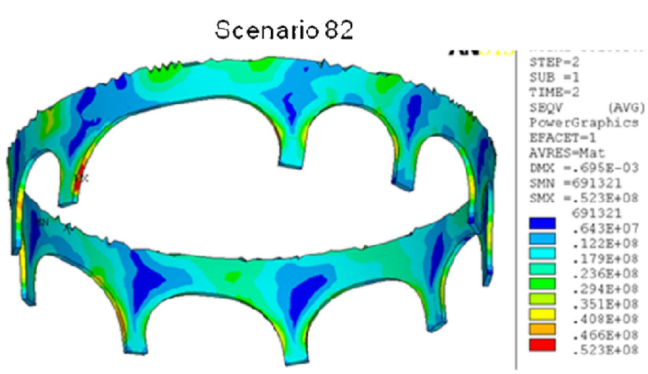

Fig. 12. Von Mises stress (Pa) of umbrella arch.

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