Numerical Analysis of Modified Central Solenoid Insert Design

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The United States ITER Project Office (USIPO) is responsible for fabrication of the Central Solenoid (CS) for ITER project. The ITER machine is currently under construction by seven parties in Cadarache, France. The CS Insert (CSI) project should provide a verification of the conductor performance in relevant conditions of temperature, field, currents and mechanical strain. The US IPO designed the CSI that will be tested at the Central Solenoid Model Coil (CSMC) Test Facility at JAEA, Naka. To validate the modified design three-dimensional numerical simulations were performed using coupled solver for simultaneous structural, thermal and electromagnetic analysis. Thermal and electromagnetic simulations supported structural calculations providing necessary loads and strains. According to current analysis design of the modified coil satisfies ITER magnet structural design criteria for the following conditions: 1) room temperature, no current, 2) temperature 4K, no current, 3) temperature 4K, current 60 kA direct charge 4) temperature 4K, current 60 kA reverse charge. Fatigue life assessment analysis is performed for the alternating conditions of: temperature 4K, no current, and temperature 4K, current 45 kA direct charge. Results of fatigue analysis show that parts of the coil assembly can be qualified for up to 1 million cycles. Distributions of the current sharing temperature (TCS) in the superconductor were obtained from numerical results using parameterization of the critical surface in the form similar to that proposed for ITER. Special ADPL scripts were developed for ANSYS allowing one-dimensional representation of TCS along the cable, as well as three dimensional fields of TCS in superconductor material.

Keywords: Superconducting magnets, Numerical analysis, Computational modeling, Finite element methods

1. Introduction

Details of the design of the modified CS insert coil are presented on Fig. 1. Major difference of the modified geometry, compared to original design presented in [1] is in expansion of the distance between the windings, allowing shorter cable length. Coil design includes two stainless steel flanges: top flange (1t) and bottom flange (1b). Superconducting coil (2) has two spurs (14), and includes superconducting cable (3) enclosed in the jacket (4) which is wrapped up in insulation (5). Two stainless steel spacers: Top Spacer (8t) and bottom Spacer (8b) together with the coil and inter-winding G10 spacers (20) are wrapped up in the coil ground insulation 6. Coil assembly is compressed between the flanges by sixteen aluminum tie-rods (7) with tie-rod nuts (10) and spherical washers (15). Sixty three pushing bolts (9) are used to adjust the pre-compression. Four alignment jacks (11) allow positioning of the CS insert within the CSMC. CS insert is mounted on the CSMC table with four bottom mounting bolts (12) and can be adjusted using four bottom alignment studs. Coil is connected to the bus bars using two terminal joints (17). Description of the original CSI design is presented in [1].

During the test CS insert placed within the CSMC is cooled down to 4K. The coil will be placed in the center of the background magnetic field created by CSMC, and will be charged with 45 and 60 kA current. External magnetic field is adjusted to create 13T maximum magnetic flux density on the coil. Design and performance of CSMC is described in [2].

Fig. 1. Modified CS Insert Design.

Three-dimensional numerical simulations were performed using ANSYS classic coupled solver for simultaneous structural, thermal and electromagnetic analysis. Thermal and electromagnetic simulations supported structural calculations providing necessary loads and strains. Simulations were performed during design process to verify structural integrity. Fatigue and non-linear buckling analyses were also performed.

2. Description of Numerical Model

2.1 Geometry

The modified CS insert model geometry was created using computer aided design (CAD). Geometry simplification is performed using Pro/Engineer software for the purpose of mesh generation by removing most of the fillets from the design. The effect of the fillets is only to reduce peak stresses and their contribution to the global stiffness of the structure is negligible. Fillets of the superconductor cable jacket are also removed. Mounting of alignment jacks to the top flanges is simplified by removing bolt connections, and assuming a unified structure which is bonded to the top flange. Bottom alignment studs fixtures are modelled by rods attached to the bottom flange with the boundary conditions restricting tangential movement

Different types of ANSYS elements were used to mesh the model. SOLID5 elements allow simultaneous solution for coupled structural, thermal, and electromagnetic problem, while SOLID62 elements were used for elastic-plastic analysis. SOLID5 and SOLID62 ANSYS elements require using sweep method for meshing. Thus, the model has to be split into blocks that can be swept. The model is split using ANSYS pre-processor. Splitting of the model into blocks does not introduce any additional geometrical simplifications into model, and is used exclusively for meshing simplification. Meshing is performed using ANSYS pre-processor.

2.2 Loads and Constraints

The model is fixed in axial and tangential direction at four bottom mounting bolts. The other four rods at the bottom are restricted only in tangential direction, representing bottom alignment studs. Axial and radial displacement of the CSMC [3] was used to impose boundary conditions for four radial alignment jacks and top bus support. Initially, a pretension of 100MPa at 293K is introduced in the tie-rods using pretension elements (PRETS179), which convert pretension into displacement at the first step. When the insert is cooled from 293K to 4K, the pretension is increased due to the thermal contraction difference between spacer material and tie-rods. Pre-compression of 25 MPa at 293 K is introduced in the lap joint using PRETS179 elements, converting pre-compression into displacement at the first step. Sliding interfaces are created to simulate the effect of spherical washes and Teflon inserts between the

jacket leads and the spacers. The numerical mesh is split at the interface surface and then displacement components normal to the surface are coupled at the coincident nodes

Constant temperature at all nodes was imposed on the model at each time step. Room temperature results were obtained at 293K. The temperature of 4K represented condition after cool down.

Electrical boundary conditions are imposed on the opposing ends of the superconductor cable chain consisting of coil, upper bus, and copper connectors, to simulate constant electrical current flow. At one end a constant voltage level of zero is imposed, while on the other end nodes were electrically coupled and constant current level condition creates electrical current. Since SOLID62 elements used in elastic plastic analysis of copper connecting parts do not support electrical connection SOLID5 elements were superimposed on the SOLID62 elements and coincident node displacements were coupled. Very low value was assigned as elastic modulus for the SOLID5 elements together with correct values of copper resistivity. This way SOLID5 element provided electrical connection and imposed Lorentz force, whereas SOLID62 elements allowed to model plastic deformation of the copper parts.

The external magnetic field is simulated using current conducting source elements SOURC36, representing geometry and charge of the CSMC windings, and creating vertical magnetic field in the area of CS insert.

2.3 Material properties

Initial state with zero stress was assumed 150°C for jacket, spacers, G10, and insulation. This corresponds to the VPI solidification temperature. Data from [4,5] was used for G10 spacers and insulation and is shown in Table 1. Thermal contraction is from 150°C.

Table 1. Properties of insulation and G10 spacers

	4K	RT
Elastic modulus normal [Gpa]	29.1	22.4
Elastic modulus in plane [Gpa]	35.9	38.0
Poisson ratio normal	0.21	0.144
Poisson ratio in plane	0.211	0.15
Thermal contraction normal	-0.8593%	-0.1482%
Thermal contraction in plane	-0.3630%	-0.1208%

For all other parts initial state with zero stress was assumed at room temperature before pre-tension of tie-rods and pre-compression of lap joints is applied. Values for other material properties are presented in [1].

3. Model Validation

Analysis of the results shows that accurate prediction of the self-field generated by the current conducting SOLID5 elements requires generating a mesh with low aspect ratio of elements in the cable. Three types of meshes were used with the main difference in resolution

on the cable. Mesh characteristics are presented in table 2. Aspect ratio was obtained as a ratio of maximum to minimum side area of each element. Portion on the meshes on the superconductor cable are presented on Fig. 2. Self-field on the mesh was obtained by calculating the half of the difference of the maximum and minimum axial field on the middle section of the cable. This axial field was adjusted by subtracting the external CSMC field, which was obtained for the case of zero charge.

Table 2. Mesh effect on self-field calculation

Overall Number of Elements	Average Element Aspect Ratio in cable	Self-Field at 60 kA [T]	Discrepancy with result (1)
376,871	21.9	0.22	70%
767,760	5.5	0.60	19%
1,504,946	2.4	0.72	2.7%

Fig. 2. Mesh on superconductor cable. Element aspect ratio distributions are shown.

Since the coil diameter of 1.476m is large compared to the cable diameter of 0.0326m self-field in the middle of the coil will be close to the field of the straight wire with the same diameter:

$$B_{straight} = I\mu_0 / (\pi D) \quad (1)$$

where:

$B_{straight}$ – maximum magnetic field on the wire [T]

I – current through the wire [A]

$\mu_0 = 4\pi \times 10^{-7} [N/A^2]$ – permeability of vacuum

D – wire diameter [m]

For the 60kA charge equation (1) results in self field of 0.736T. This result is compared to the values obtained from numerical analysis in table 2, which presents the analysis results for 60kA direct charge. Results for 60kA reverse charge and 45kA direct charge show very similar discrepancy with analytical solution (1). Results show that coarser meshes with high aspect ratios severely underestimate the self-field. Reduction of mean aspect ratio from 21.9 to 2.5 allows reducing discrepancy between numerical analysis result and analytical formula (1) from 70% to less than 3%.

4. Results and Discussion

4.1 Coil Deformation

During cool from 150°C to room temperature after VPI G10 spacers shrink less in plane direction compared to steel components. This creates slight barrel shape deformation of the coil as shown on Fig. 3. Deformation of the flanges is due to pretension. During cool down to 4K the insert coil shrinks due to thermal contraction. Since JK2LB steel and G10 in plane contracts less than stainless steel spacers, difference in radial displacement creates a clear barrel type shape.

Fig. 3. CSI assembly cross-section at room temperature and after cool down to 4K. Deformation scale 100:1. Tie rods are not shown

The “direct charge” is the situation when magnetic field generated by the CSMC and CSI have the same sign on the axis. In this case, the CSI bends in the direction opposing the incomplete portion of the windings due to the action of the Lorentz force. Lorentz force also expands the windings of the coil leading to convex deformation as shown on Fig. 4.

Fig. 4. CSI assembly cross-section 4K. Charge 60 kA. Deformation scale 100:1. Tie rods are not shown

The “reverse charge” is the situation when magnetic field generated by the CSMC and CSI have the opposite sign on the axis. For the reverse charge with 60 kA case, the CSI bends in the direction of the incomplete portion of the windings due to the action of the Lorentz force. This bending effect was minimized by making solid support buffers on top of the coil. Lorentz force also contracts the windings of the coil which leads to a concave deformation as shown on Fig. 4.

2.2 Current Sharing Temperature Distributions

To validate insert performance, distribution of the Current Sharing Temperature (T_{cs}) is obtained from numerical results using parameterization of the critical surface in the form similar to that proposed for ITER. Detailed description of the procedure and parameters of the superconductor material are presented in [1, 6]. Three-dimensional T_{cs} distributions were obtained using ANSYS ADPL script employing Newton-Raphson procedure.

Fig. 5. T_{cs} distribution in the cable. Direct charge 60kA

T_{cs} distributions along the cable are shown on Figs. 5 and 6, together with the distributions of magnetic field and strain. Distribution along the cable is dominated by the large variation of magnetic field intensity. Three dimensional distributions are presented in the cross-section of the winding in the middle of the coil. There is approximately 1K difference between maximum and minimum current shearing temperature in the middle cross-section of the cable due mostly to the difference in magnetic field. For the direct charge minimum of the

current sharing temperature is at the inside edge of the wire, whereas for reverse charge the minimum is at the outside edge.

Fig. 6. T_{cs} distribution along the cable. Reverse charge 60kA.

Acknowledgments

This manuscript has been authored by PPPL under contract DE-AC02-09CH11466 and UT-Battelle, LLC under contract DE-AC05-00OR22725 with the U.S. Department of Energy.

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