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Design and Analysis of the ITER Vertical Stability Coils

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DESIGN AND ANALYSIS OF THE ITER VERTICAL STABILITY(VS) COILS*

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The ITER vertical stability (VS) coils have been developed through the preliminary design phase by Princeton Plasma Physics Laboratory (PPPL). Final design, prototyping and construction will be carried out by the Chinese Participant Team contributing lab, Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). The VS coils are a part of the in-vessel coil systems which include edge localized mode (ELM) coils as well as the VS coils. An overview of the ELM coils is provided in another paper at this conference. [15]

The VS design employs four turns of stainless steel jacketed mineral insulated copper (SSMIC) conductors The mineral insulation is Magnesium Oxide (MgO). Joule and nuclear heat is removed by water flowing at 3 m/s through the hollow copper conductor. A key element in the design is that slightly elevated temperatures in the conductor and its support spine during operation impose compressive stresses that mitigate fatigue damage. Away from joints, and break-outs, conductor thermal stresses are low because of the axisymmetry of the winding (there are no corner bends as in the ELM coils).The 120 degree segment joint, and break-out or terminal regions are designed with similar but imperfect constraint compared with the ring coil portion of the VS. The support for the break-out region is made from a high strength copper alloy, CuCrZr. This is needed to conduct nuclear heat to the actively cooled conductor and to the vessel wall. The support "spine" for the ring coil portion of the VS is 316 stainless steel, held to the vessel with preloaded 718 bolts. Lorentz loads resulting from normal operating loads, disruption loads and loads from disruption currents in the support spine shared with vessel, are applied to the VS coil. The transmission of the Lorentz and thermal expansion loads from the "spine" to the vessel rails is via friction augmented with a restraining "lip" to ensure the coil frictional slip is minimal and acceptable. Stresses in the coil, joints, and break-outs are presented. These are compared with static and fatigue allowables. Design for fatigue is much less demanding than for the ELM coils. A total of 30,000 cycles is required for VS design. Loads on the vessel due to the thermal expansion of the coil and spine are significant. Efforts to reduce these by reducing the cross section of the spine have been made but the vessel still must support loads resulting from restraint of thermal expansion.

I. INTRODUCTION

The elongated plasma of ITER is inherently unstable and requires an in-vessel vertical stabilization (VS) coil system with feedback control to maintain vertical position[5].

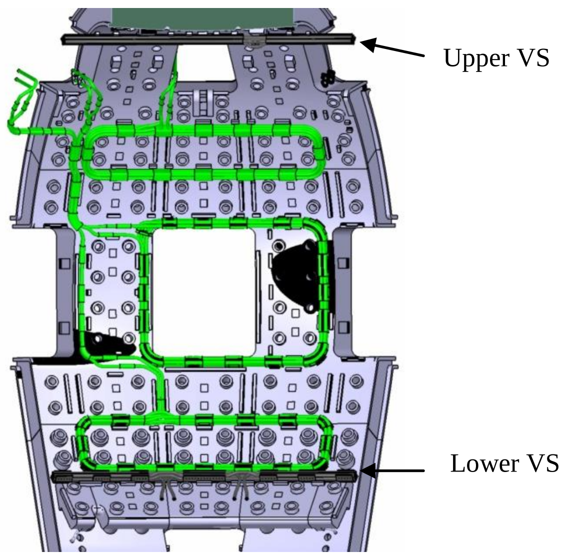

Fig. 1. In-Vessel Coil Systems in ITER Section with Blanket Modules Shown Removed

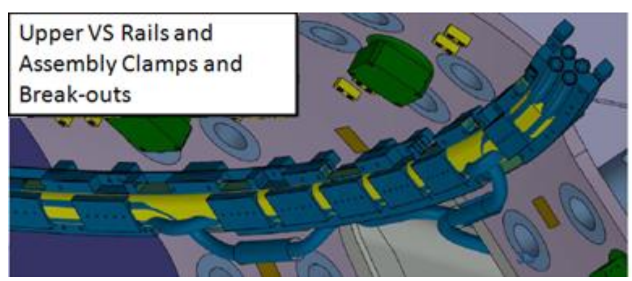

Fig. 2. ITER Upper VS Coil

A view of the upper VS and some of the break-out areas is shown in figure 2.

The VS design employs four turns of SSMIC, shown iln Fig. 3.. Water flowing in the coolant passage at 3 m/s remove both Joule and nuclear heat. Slightly elevated temperatures in the conductor and its support spine impose compressive stresses that mitigate fatigue damage., To maintain conductors above the background vessel temperature may require an active cooling control system, along with resistive preheat of the coil prior to application of Lorentz forces. The break-out or terminal regions are intended to be designed with similar constraint as the ring coils. The details of the support system still require design evolution to obtain the necessary constraint while allowing assembly and nuclear heat removal. The support for the break-out region is made from a high strength copper alloy, CuCrZr. The support "spine" for the ring coil portion of the VS is 316 stainless steel, held to the vessel with preloaded 718 bolts. The transmission of the Lorentz and thermal expansion loads from the "spine" to the vessel rails is via friction is augmented with a restraining "lip" to ensure the coil frictional slip is minimal and acceptable.

Fig. 3. VS Conductor

While Lorentz loads per turn are larger for the VS, mechanical and thermal design constraints are similar to the ELM feeders. Similar design solutions are available for the VS feeders- Lorentz loads will scale by the peak currents which are 60kA for the VS and 15kA for the ELM coils. The runs of the feeders are different - the break-outs for the VS are positioned near ports and do not require any substantial run along the vessel surface as do the ELM coils.

. Conductor thermal stresses are low because of the axisymmetry of the winding (no corner bends as in the ELM). Lead break-outs have bends and consequently will have similar design problems as the ELM corner and thus the VS break-out supports could copy solutions developed for the ELM coils. The preferred alternate is to utilize a fully constrained concept with adequate thermal conduction to remove nuclear heat. This produces challenging design, analysis and manufacturing problems. Good thermal contact between all structures and the actively cooled coils must be maintained, and the complicated bumps and cross-overs produce complicated filler pieces that must be designed in CATIA, meshed in ANSYS and manufactured to sufficiently close tolerances and fit-up such that brazing of these components is possible.

Disruption loads have been quantified with OPERA simulations [10,12]. These simulations include the changes in the VS currents due to plasma disruptions .Appropriate analysis of shared current in the VS structure have been included with upgrades in the OPERA electromagnetic model[13.] Currents shared in the VS support spine are assumed not to degrade the ability of the VS coils to stabilize the plasma. This assumption must still be verified by Physics.

II. STRUCTURAL DESIGN PHILOSOPHY

- Nearly all of the VS is axisymmetric. The VS is a circular structure with no bends until the 120 degree joints and break-outs and leads are encountered.
- Constraint of thermal expansion produces compressive stresses due to full constraint of $E*\alpha*\Delta T$ stress.
- = 117e9*17e-6*20 deg C = 40 MPa (Compressive)
- =80 Mpa Compressive for Bake-Out
- VS Cyclic stresses remain predominantly compressive except near the break-outs and leads – OFHC Copper may be used. Conductor fatigue is not a problem (if conductor is are kept warm)
- Attachment bolt loads must resist radial thermal growth from Joule heat and nuclear heat. –First by friction and then by positive restraint details, lips on the rail shims that capture the spine and limit displacement radially outward
- Mechanical assembly was preferred. Bolted clamps can hold the conductors to the spine, but thermal conduction for nuclear heat especially for the "one turn out" fault will require braze.

Operational life is 20 years or 30,000 Experimental pulses. In some pulses, the VS will experience an average of 3 major pulses to reposition the plasma. There is a small current oscillation arising from magnetic diagnostic noise[4] that is judged not to have any fatigue significance. The project has put a ceiling on the total number of VS pulses of 30,000 "pushes". The logic being that many shots will not require the VS, and if more than 3 are needed for any given shot, the pulse will be terminated. From Appendix D[2] the number of major disruptions is about 3,000 events. For the upper VS, the disruption loading is about the same as for the normal operational loads, and presumably disruptions will be coupled with an attempt to vertically stabilize the plasma 3000 Disruption load cycles are assumed included in the VS normal load cycle count. This can be interpreted as:

30,000 thermal pulses. Of these 10,000 pulses require three VS corrections at full current, 3,000 of these will result in disruption. Guess 15,000 pulses with only Joule heat, 15,000 with nuclear heat, of which 5,000 pulses each require three VS corrections at full current. Thermal loads help by offsetting the tensile stresses. Rigorously Minors Rule should be applied to a shot profile: The conclusion is to use 30,000 full stress pulses. For regions of the coil that experience cyclic tensile stresses, allowable stresses for the 30,000 stress cycles have been established as 125 MPa (R=0, ref(11}) for the copper conductor, and 275 MPa for 316 Stainless steel jackets and spine structures. While the Lorentz forces reverse, the thermal stresses introduce a means stress effect and non-linearity in the Tresca stress. A more rigorous treatment of the alternating and mean stress effects is planned.

III. COMPARISON OF UPPER AND LOWER VS COILS

TABLE I. Comparison of the Upper and Lower VS

Loading or Attribute	Upper VS	Lower VS
Radius	7256 mm	7863 mm
Background Field	At the Upper ELM Toroidal Leg: Radial=.-22T Vertical -1 T Toroidal = 4.2T.	Radial=.1 T Vertical -1 T Toroidal = 4.T. (Section 10.1.1)
Normal Operating Loads	400 kN per sector (Figure 7.0-2)	1.2MN per sector (Figure 7.0-2)
Downward VDE Disruption Loads	500kN per sector (Figure 7.0-3)	1.2MN per sector
MD-UP Disruption Shared Current Loads[1]	-30.1% (Figure 7.0-6)	+ 23.1% (Figure 7.0-6)
Upward VDE Disruption Loads	800 kN(Figure 7.0-3)	550 kN(Figure 7.0-3)
Downward VDE Shared Currents		
Position With Respect to Toroidal Gap	Shifted	Centered
Peak Nuclear Heat	.7 MW/m^3 peak (July results from Mohamed Sawan)	Using 1.8 MW/m^3 peak (at Toroidal Peaks) Mohamed Sawan shows 1.4
Average	~.6	~.8
Rail Length (40 degree sector)	1130(UP)+2061(Low)=3191 mm	1696(UP)+2050(Low)=3746mm
(40 degree sector)	5065	5489
% rail coverage	63%	68%
Rail cuts	Yes	Yes
Break-Out Detail		

1 (36 ms linear decay) MD-UP disruption

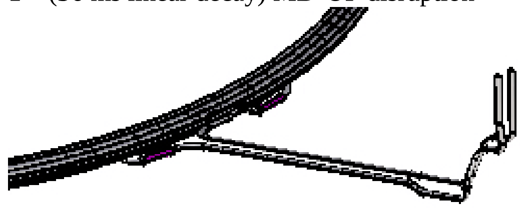

Fig. 4. Upper VS Break-Out and Feeder

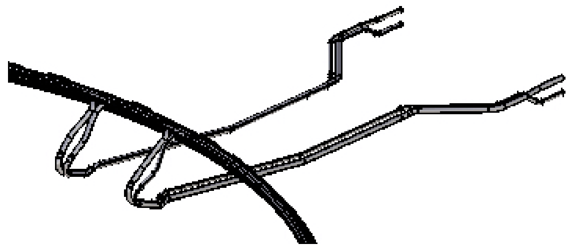

Fig. 5. Lower VS Break-Out and Feeder

The lower VS is more severely loaded and is the subject of more detailed analyses. However the planned prototype being built by ASIPP will be based on the upper VS.

IV. LORENTZ FORCE APPLICATION

IV.A. Load Input for Large Ring Section

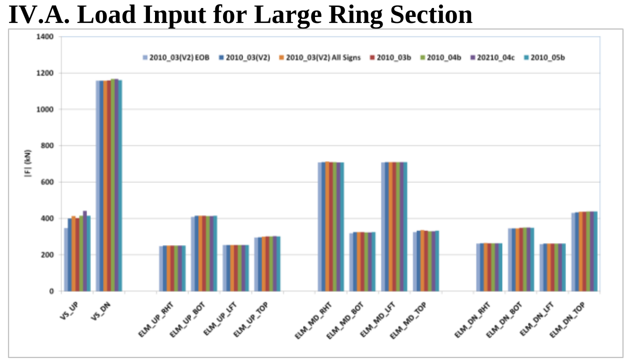

Fig. 6. Normal Operating Loads on the VS and ELM Coils

Normal operating loads are shown in figure 6. These are applied as nodal forces on the conductor elements in the FEA model. The FEA model of the large ring section is a uniformly swept mesh and has equal length conductor elements which allow simply dividing the net forces per sector among the conductor nodes.

In addition to loads induced in the conductor, currents flowing in the vessel enter the VS support spine and add Lorentz loads to the spine, and reactions and the vessel rails. During the Conceptual Design phase, the effect of these extra currents was not included in the load inventory provided by R. Pillsbury and were estimated by doubling the loads on the coils. At the CDR, the VS disruption loads were twice what is being reported now and doubling these produced loads that were difficult to support with clamps and the provided rails. During the PDR effort, the cross sectional area of the "horizontal spine" was provided to R. Pillsbury and this was used to estimate a change in the local resistivity of the vessel wall in the shadow of the VS coil.

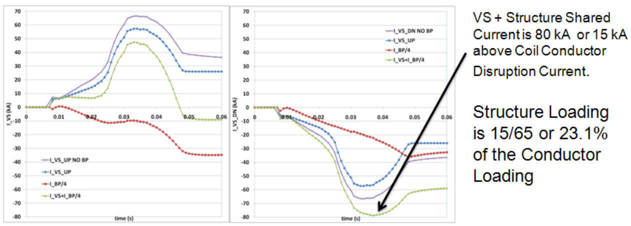

Fig. 7. Upper VS (Left) and Lower VS (Right) Currents and Structural Currents (Based on a per Turn Value)

IV.B. Load Calculation for Break-Outs

ANSYS calculations used a database of values developed by by Jushin Hsiao. The mesh was disconnected from the solid model, using modmsh,detach, then the mid side nodes were removed. using the Emid,remove command, to use the Lorentz force calculation outside ANSYS.

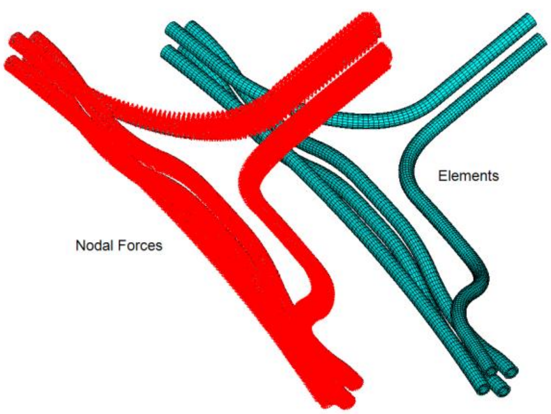

Fig. 8. Upper VS (Left) Break-Out Conductors and Forces

A 4T toroidal field was imposed, also, 1 Tesla vertical PF and .1 tesla radial TF ripple field were applied. The break-out model has 60 elements in a conductor section, 250 amps per element was applied- This assumed that the directions that the elements swept in the model were the current directions. A load file was created which could be brought into the model in Prep7 via /input,brak,mod .This was done with 8 node brick elements and the structural model employs 20 node bricks - so the nodal forces are not locally consistent with the model, but globally the correct load inventory is used.

V. NUCLEAR HEAT

During DT operation, fusion reactions produce 14 MeV neutrons which react with first wall components to produce a range of nuclear radiation products at the VS coil. While the VS coils are behind the blanket modules, and are substantially shielded by these, nuclear heating of the VS coil components introduces significant coil design challenges.

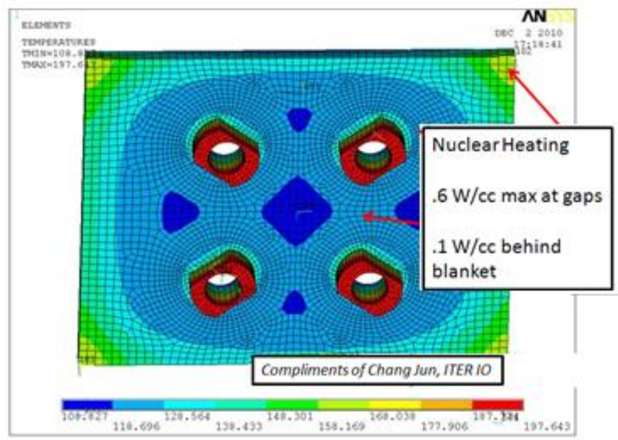

Fig. 9. Vessel Surface Temperature Behind Blanket Module 14, Near the Mid-Elms[7]

As nuclear calculations have progressed and more detailed models of the coil and blanket module have been developed, nuclear heating estimates have gone down. This reduced thermal loading has allowed some easing of mechanical design..

The vessel also sees a portion of the nuclear heat not captured by the blanket modules or coils. The vessel is a double walled water cooled structure and is well anchored at 100C at the inner water volume., However, the temperature on the inboard side of the vessel wall can exceed the 100C water temperature due to nuclear heating. Data indicates that the vessel temperature near gaps between the modules can exceed the 100 C vessel temperature by as much as 70 degrees for the mid-ELM coil, as an example. It may be different at the VS supports. For analysis of the VS, the thermal anchor at the vessel surface is specified to be 128 degrees C. Global restraint of the vessel is assumed to restrain the vessel strain to correspond to a global effective temperature of 100C. Thus TREF in the ANSYS simulations is taken to be 100C with fixed support points at 128C

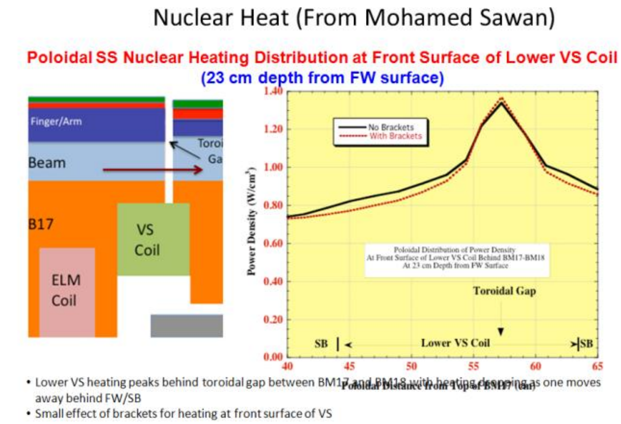

Fig. 10. Nuclear Heat Generation at the Lower VS[14]

Since the water is in direct contact with the copper conductor, Joule heat and nuclear heat induced in the copper and water are readily removed. The MgO must be conductive enough for removal of the nuclear heat in it, the jackets and support structures. For the lower VS, the peak nuclear heat is up to 1.8e-6 watts / cm^3 or 1.8e-6*100^3 watts / m^3 at the points in the support clamps closest to the plasma. The ITER recommended value for CuCrZr thermal conductivity at 100C is 333 W/mK. The nuclear heat is 1.4 MW/m^3 for the thin stainless steel sheath, and the heat generated is 1.4e6*.0019 = 2.66e3 Watts/m^2. The thickness of the MgO is 5 mm or .005m. The thermal conductivity of the MgO is 2.5 Watts/degK/m so the delta T is 5 degrees. The MgO is a relatively good conductor of heat and is relied on to conduct nuclear heat to the actively cooled conductor.

V.A. Steady State Calculations

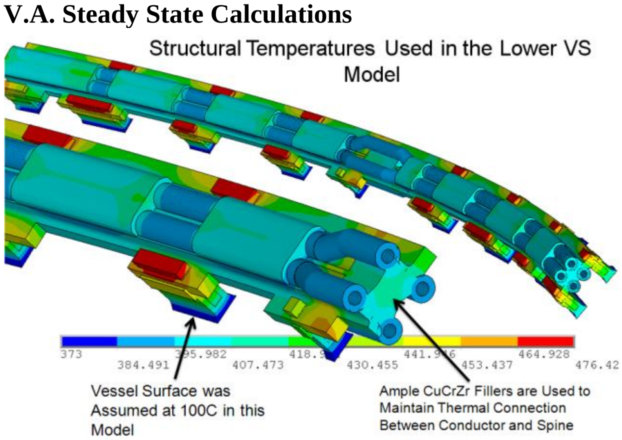

Fig. 11. Nuclear Heat Generation at the Lower VS

Figure 11 shows an earlier analysis that assumed 100C base temperature - subsequent analyses addressed the higher vessel surface temperature. This steady state analysis imposes the vessel surface temperature and the conductor bore coolant temperature as boundary conditions. The solution is read into the structural analysis using LDREAD in ANSYS. Section VI discusses how the nuclear heat shown in figure 10 is applied to the thermal model.

IV.B. Transient Calculations

An assumption is made in the stress analyses that the thermal effects on the VS have reached steady state. There is a spectrum of pulse lengths planned for ITER, and if shorter pulses do not allow enough time for the full temperatures to develop, then the fatigue assessments might be overly pessimistic, given that there will be fewer full length 1500 second pulses.

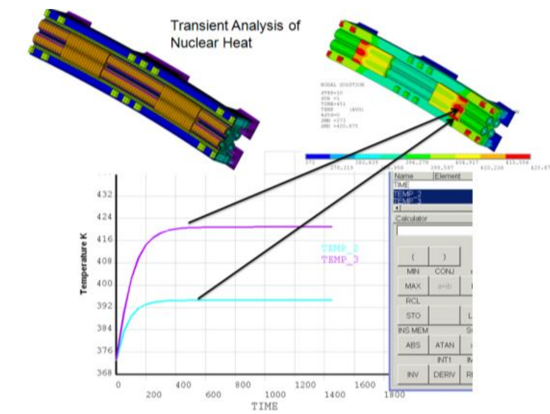

Fig. 12. Transient Nuclear Heat Analysis

Nuclear heat is a significant loading but transient and for some machine pulses the DT burn may not be long enough for the coils to reach thermal equilibrium. However a transient analysis shows that for pulse lengths beyond 200 seconds steady state is reached. Subsequent thermal analyses assume steady state and the structural temperatures are read from a steady state thermal solution.

VI. MODEL CREATION

Because of the axisymmetry of the bulk of the coil system, analysis models are based on a swept mesh of a 2D mesh. Material properties are standard copper and stainless steel properties. The properties used for the MgO layer between the conductor and jacket come from extensive R&D efforts. A modulus of 0.9e9 Pa is used for MgO.

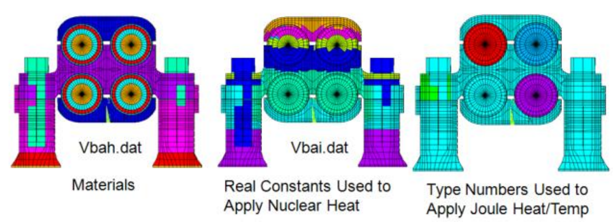

Fig. 13. 2D Mesh Swept to make the 3D model

ANSYS default Poissons ratio and shear modulus are used. Early in the analysis efforts, gapped elements were used at the interface to explore possibilities of slippage at the metal/MgO interface. This turned out to be a small affect confirmed by both analysis and R&D

Primary Loads are supported by a "spine" .. The swept geometry then has various regions "carved away" based on space between the rail lugs and bolt heads.

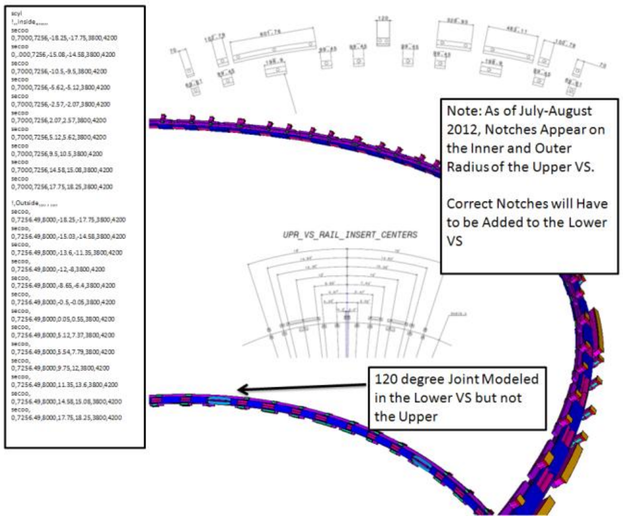

Fig. 14. Upper and Lower Support Bracket and Notch Geometry

Notches are also modeled in the spine. These clear various details of the large number of other components supported of the vessel. Figure 14 shows some of the "maps" used to form the upper and lower support model

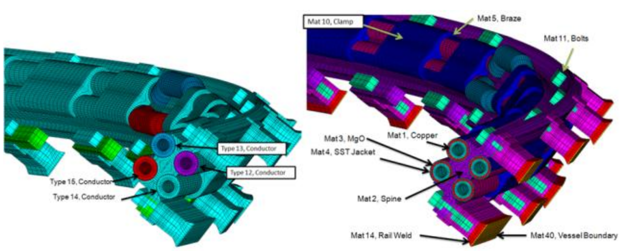

Fig. 15. Lower VS Model with Element Type and Material Assignments. Element types are used to model one turn out loading.

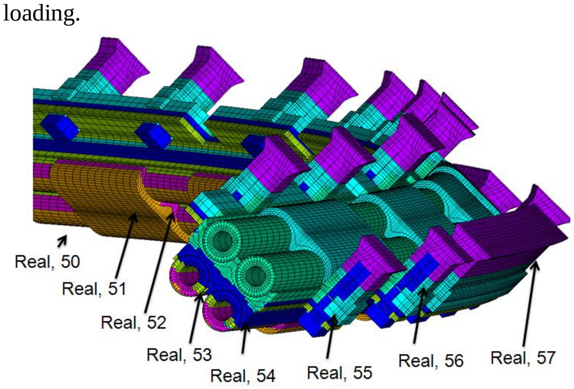

Fig. 16. Upper VS Model with Real Constant Assignments

Real constants , which are not used in ANSYS for the solid elements used in the model, are used as bookkeeping aids to apply nuclear heat.

VII VS CIRCULAR SECTION STRESS RESULTS

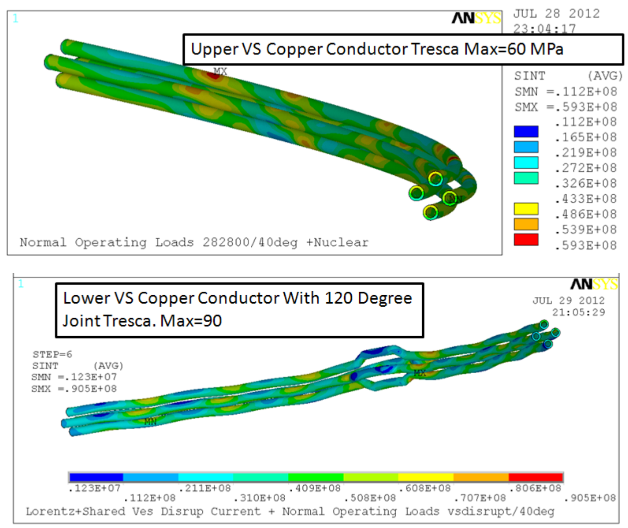

Fig. 17. Tresca Stress in Upper and Lower VS Copper Conductors

The lower VS model includes a representation of the 120 degree joint area. The joint "bulge" is needed to allow orbital welder access to seal the jacket after the braze joints are made

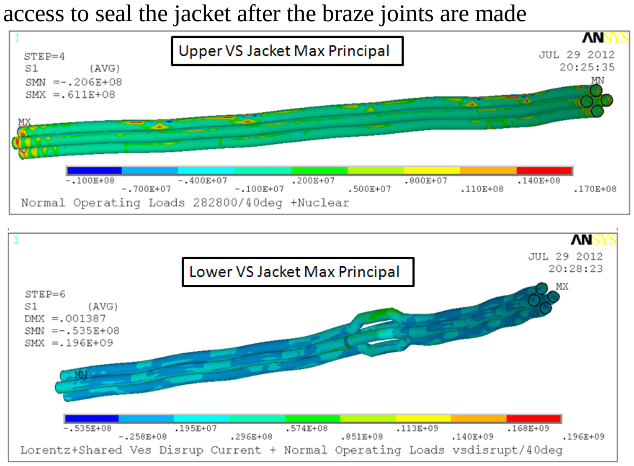

Fig. 18. Tresca Stress in Upper and Lower VS Conductor Jackets

. Fillers are needed to fill the gaps formed by the "bulge" to provide mechanical support of the Lorentz loads and to thermally connect the brazed sections to spine sections which are not actively cooled.

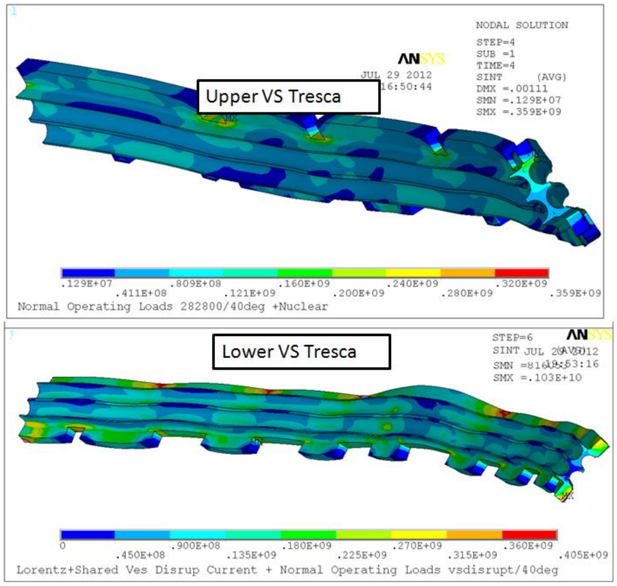

Fig. 19. Tresca Stress in Upper and Lower VS Structural Spine

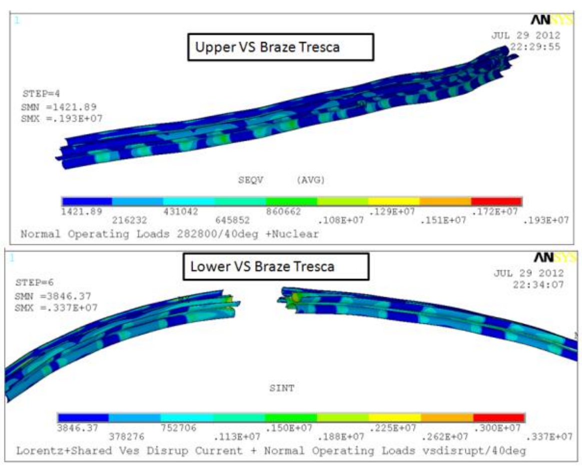

Fig. 20. Tresca Stress in Upper and Lower Conductor to Spine Braze

The choice of braze has not been made yet. The stress in the large surface areas of the conductor to spine brazed connection is low though and would allow for some missing areas.

VIII BREAK-OUT IN UPPER VS

Break-out analyses have required more interface with the detailed CATIA models due to the complex "bumps" and bends. This has meant that as the break-outs were refined to satisfy space constraints, the models had to be re-built many times. The conductors are swept meshed to facilitate calculating Lorentz forces. The remaining components use default meshers and sometimes these produce highly localized stresses that are artifacts of the mesh details.

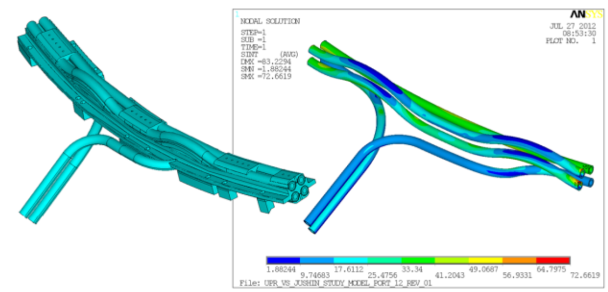

Fig. 21. Upper Break-Out Model and Conductor Tresca Stress

IX. BREAK-OUT IN LOWER VS

The lower break-out was analyzed first, and it showed problems relating to the unsupported lengths of the curved sections. Adding material to support the conductors picked up more nuclear heat and developed more thermal stresses. The solution was to used CuCrZr fillers that were strong, but could conduct heat to the conductor, or to the vessel.

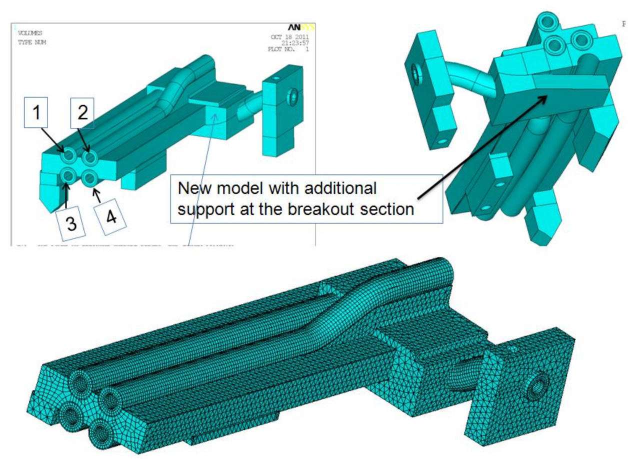

Fig. 22. Lower Break-Out FEA Model

X. RAIL/LUG REACTIONS/STRESSES

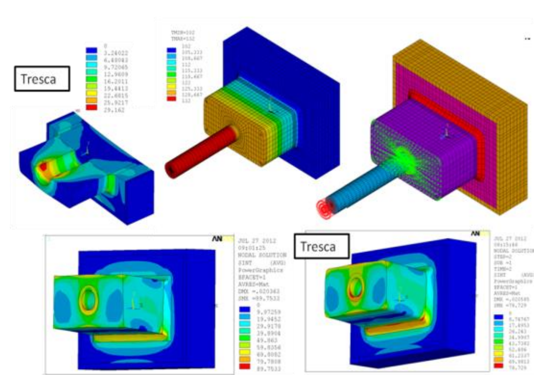

Fig. 23. Single Rail/Lug Analysis Model

Support of the VS spine and coil is only approximately periodic. The support rail geometry is shown in figure 14. In the model, the lug face is coupled in Z to model rotational constraint of the spine. Loading is 35000N per Bolt or .8MN/40 degree Sector. This comes from the reaction loads from the 40 degree global model divided by the number of bolts used for the sector

Figure 23 shows that there is a modest advantage in having rounded corners in the lugs. The weld is a full penetration with a fillet ground to a 1/4inch smooth radius. Bolt stresses during the disruption are within the 100 ksi allowable of 718 high strength bolts. Pre-loading the bolts eliminates the alternating stress component.

XI. FAULT CASE - ONE TURN OUT

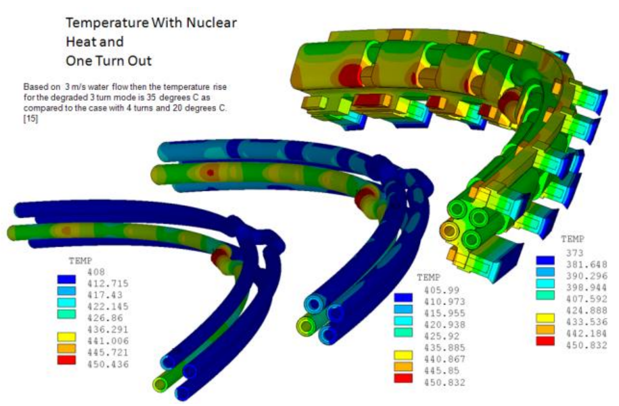

Fig. 24. "One Turn Out" Fault

Currents in the remaining turns are increased by a third to recover the same efficacy of the VS system Based on 3 m/s water flow the the temperature rise for the degraded 3 turn mode is 35C as compared to the case with 4 turns and 20C. Stresses in the "one turn out" simulation are higher than for the nominal operating case. Based on fatigue allowables, the coils can run at full performance, with the over-current, to make up for the lost turn, for about 10,000 cycles

XII. CONCLUSIONS

The current design of the Vertical Stability (VS) coils is adequate and is expected to be fully qualified in Final Design. Conductor and jacket stress are acceptable partly because they are biased towards compression. The break-outs or terminals and the feeders have had initial analysis performed and the main elements of the required supports have been designed, and are undergoing analysis. An active cooling control system may be needed to maintain conductors above the background vessel temperature along with resistive preheat of the coil prior to application of Lorentz forces.

TABLE II, Stress Summary

	OFHC Copper	316 Jacket	316 Spine	Braze
Fatigue Allowable	125MPa	275MPa	275MPa	?
Lower VS Away from 120 deg. Joint	90MPa Tresca 20 MPa Sig1	250 MPa Tresca 2 MPa Sig1	405 Tresca 180 MPa Sig1	3 MPa
Lower VS 120 deg joint	90 MPa Tresca 20 MPa Sig1	250 MPa Tresca 113 MPa Sig1	<450 MPa on either side of notch 180 MPa Sig1	3 MPa
Lower VS Break-Out Thermal Only	86MPa	148 MPa		
Upper VS	60 MPa Tresca	147 MPa Tresca 61 MPa Sig1	359 MPa at Notch Corner, 80 MPa Sig1	2 MPa

The transmission of the Lorentz and thermal expansion loads from the "spine" to the vessel rails is via friction augments with a restraining "lip" to ensure the coil frictional slip is minimal and acceptable. While the stresses are biased towards compression, which mitigates fatigue, the local details of the 120 degree assembly joint and the break-outs, develop tensile stresses and must pass fatigue evaluations. Tensile stresses are below those allowed for 30,000 cycles of major loading. Fracture mechanics calculations are planned to augment the SN evaluation. Currents shared in the VS support spine are assumed not to degrade the ability of the VS coils to stabilize the plasma. Verification of this by those responsible for plasma position control systems, is needed. Proximity of the lower VS to the highly conductive copper shelf, and the thinner notched section employed in the most recent VS designs argue for a minimal impact from VS support spine currents.

ACKNOWLEDGMENTS

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