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Axisymmetric Simulations of the ITER Vertical Stability Coil

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Axisymmetric Simulations of the ITER Vertical Stability Coil

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Abstract **The ITER in-vessel coil system includes Vertical Stability (VS) coils and Edge Localized Mode (ELM) coils. There are two large VS ring coils, one upper and one lower. Each has four turns which are independently connected. The VS coils are needed for successful operation of ITER for most all of its operating modes. The VS coils must be highly reliable and fault tolerant. The operating environment includes normal and disruption Lorentz forces. To parametrically address all these design conditions in a tractable analysis requires a simplified model. The VS coils are predominately axisymmetric, and this suggests that an axisymmetric model can be meaningfully used to address the variations in mechanical design, loading, material properties, and time dependency. The axisymmetric finite element analysis described in this paper includes simulations of the bolted frictional connections used for the mounting details. Radiation and elastic-plastic response are modeled particularly for the extreme faulted conditions. Thermal connectivity is varied to study the effects of partial thermal connection of the actively cooled conductor to the remaining structure.**

Keywords—component; ITER; Vertical Stability;In-Vessel

I. INTRODUCTION

The ITER in-vessel coil system includes Vertical Stability (VS) coils and Edge Localized Mode (ELM) coils. The basic requirements for these coils are outlined in the systems requirements document [1] There are two large VS ring coils, one upper and one lower. Reference [2] considers the full analysis effort for the VS coils, including the 3D models of the large ring coils, break-outs and feeders.

Each VS coil has four turns that are independently connected. The VS coils are needed for successful operation of ITER for most all of its operating modes. The VS coils must be highly reliable and fault tolerant. The operating environment includes normal and disruption Lorentz forces. In the case of a faulted turn, the VS design must allow one to two of the independent coil segments to be jumpered out and allow continued operation with the good turns. . A significant part of operations will have minimal nuclear heat. DT operations will produce significant nuclear heat that is predominantly axisymmetric but includes some 3D varying heat fluxes. Nuclear heat is still somewhat uncertain, given the complexity of modeling the blankets and their cooling manifolds. The boundary conditions imposed by the vessel are also evolving as final details of attachment points are worked out. Joule heat and nuclear heat is removed by water cooling the hollow conductors. Partial failures of active cooling must be simulated to address the required fault tolerant design requirement. There is a potential for elevated temperatures and plasticity for some of the more severe fault conditions. The conductor is a mineral insulated stainless steel sheathed hollow copper conductor. R&D efforts have quantified mechanical properties of the conductor, but there remains some uncertainty in physical properties. To parametrically address all these design conditions in a tractable model requires a simplified model. The VS coils are predominately axisymmetric, and this suggests that an axisymmetric model can be meaningfully used to address the variations in mechanical design, loading, material properties, and time dependency.

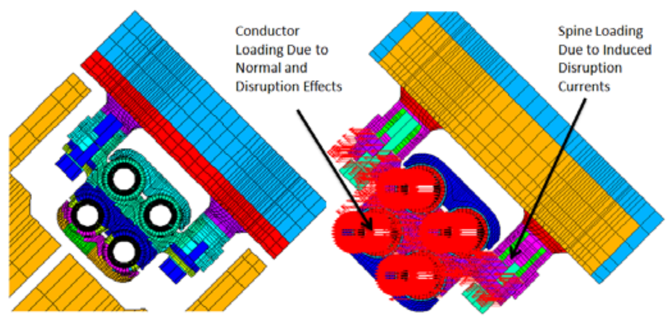

Fig. 1 Axisymmetric Models of the Upper VS. Real Constants Used for Nuclear Heat Input (Left) and Normal and Disruption Loads (Right)

The axisymmetric finite element analysis described in this paper includes simulations of the bolted frictional connections used for the mounting details. Radiation and elastic-plastic response are modeled particularly for the extreme faulted conditions.

Poloidal variations of the nuclear heat can be directly applied. Toroidal variations must be approximated. Variations in thermal and displacement boundary conditions of the vessel are considered. Results for nominal conditions and off-normal conditions are presented along with results of parametric studies.

Electromagnetic (EM) loads are derived from calculations performed by R. Pillsbury [3], [4]. Figure 1 shows these loads applied to the model. Normal operating loads result from normal operating conductor currents crossed with the peak poloidal fields in at the VS coil location. The axisymmetric

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model is not loaded by the toroidal field. The VS breakouts and feeders are part of the non-axisymmetric components of the VS system which are loaded by the toroidal field. Disruption loads include loads from currents induced in the toroidally continuous coil support spine. The loads in figure 1 show the spine loaded as well as the conductor.

II. FRICTIONAL SIMULATION OF BOLTING

A. Requirements and Modeling

The attachment bolt loads must resist radial thermal growth from Joule heat and nuclear heat. –First by friction and then by mechanical restraints. Because of the large radius to build ratio , relatively small radial loads can constrain thermal growth, however some of the most severe disruption loads reduced the preload frictional restraint and because of the uncertain behavior of friction, shimmed lips on the spine are suggested to capture the spine around the rails. Shims do not have to be tightly fit radially, they will bottom out if the VS slips.

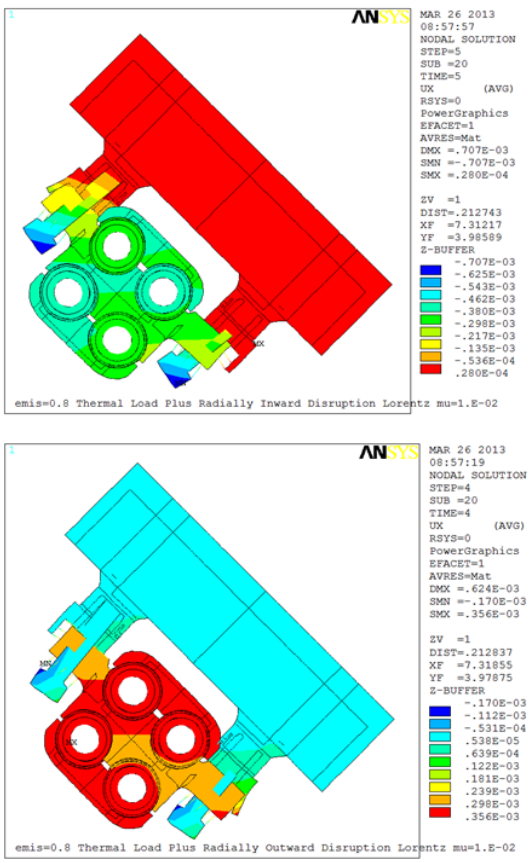

Fig. 2 Low Friction Results Showing Reversing Lateral Motion of the VS Coil

It is expected that the slippage will result from reversed Lorentz Loads plus loads from restraint of thermal expansion of the coil. Reactions are biased towards restraint of expansion. Consequently the “lips are required only on the outer edges of the rail. The bolting design and preload is

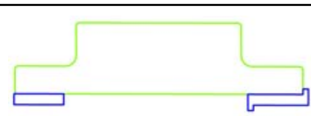

Fig. 3 One-Sided Shim Detail

selected to provide sufficient frictional restraint to support all the applied loads, so actually the lips are redundant features. But because of the cyclic and impulsive nature of the loading, friction is augmented with a restraining "lip" built into the shim to provide positive geometric registration. A friction factor of .3 is used, which, for analysis, needs to accommodate an uncertainty of +/- .15 in accordance with the in-vessel design criteria [2]. This implies a friction surface of .45 is needed. High friction ceramic coatings investigated for the NCSX project are being considered to coat the shims.

B. Frictional Slippage Simulation Results

The results of the frictional slip simulations are presented in figures 4 and 5. Figure 4 shows the results with the spine removed to clearly show the stress in the restraint “lips”

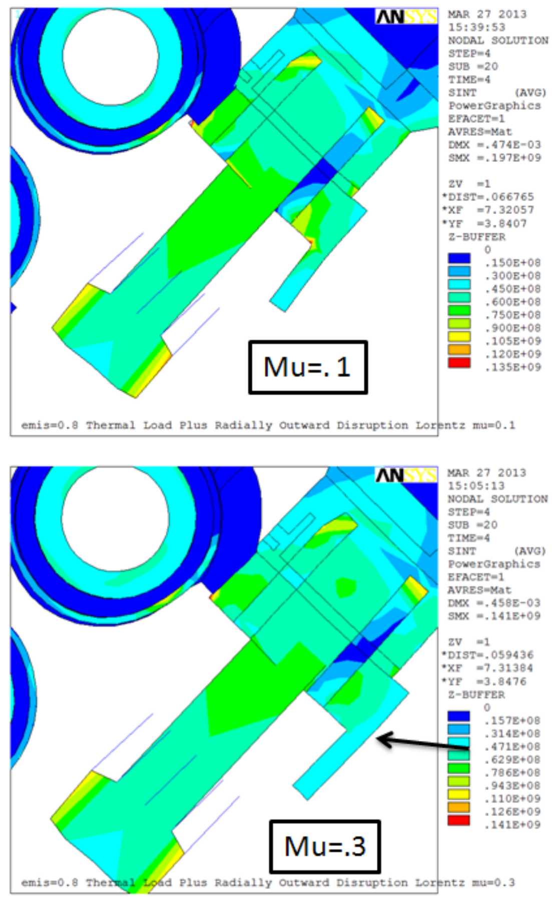

Fig. 4 Contour Plots of the Tresca Stress in the Shim “Lips” as a Function of Friction Factor. Spine Removed for Clarity

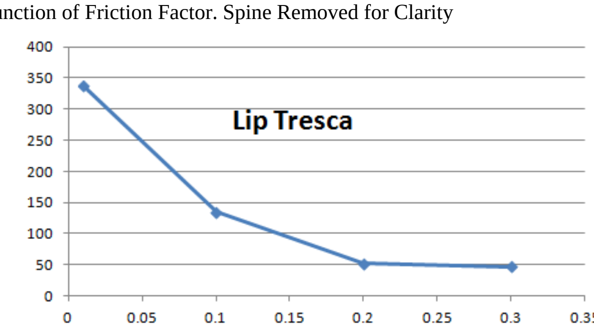

Fig. 5 Tresca Stress in the Shim “Lips” as a Function of Friction Factor

Figure 5 shows the Tresca stress in the lips or ledges of the shims. Ideally, if the frictional connection were adequate, these parts of the shims would not be stressed. With low friction, the lips or ledges provide the geometric restraint of the VS coil. At friction factors beyond .2, the motion is suppressed, and it has fully stabilized at a friction factor of .3. Break-outs and feeders will require more restraint because the thermal expansion will accumulate and concentrate at bends and bumps. This expansion behavior dominated the response of the ELM coils which do not have a completely continuous toroidal run of conductor as in the VS.

III. Simulation of One and Two Turns Failed

The VS coils are intended to operate with one turn out and the other turns providing full amp-turns. A second requirement is that the VS should operate with two turns failed, but at reduced currents. This second requirement was added by Ed Daly in December of 2012. Coil currents in the remaining coil 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.

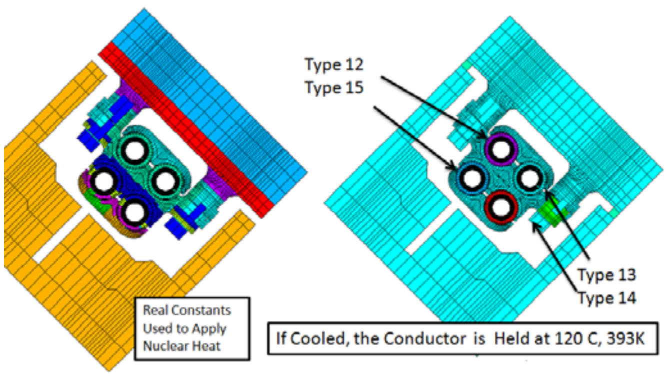

Fig. 6 Axisymmetric Model Characteristics Used in the Fault Analysis

A. Radiation Modeling

Normal operating temperatures, even with nuclear heat applied produce minimal radiation heat transfer. With local areas of the non-functioning turns experiencing higher temperatures, radiation can have a measurable effect. The axisymmetric model lends itself to improving the radiation modeling from one D simulations. Nuclear heating values are provided by M. Sawan [5]. They can be applied with an exponential decay fit to the values in M. Sawan's results. In the axisymmetric modeling, a poloidal variation in nuclear heat can be applied. For the lower VS this allows the peak of 1.4 MW/m^3 to be applied locally where the blanket module gap produces higher nuclear heat. In the one D modeling an estimate of the integrated heat flux at the surface is applied with the appropriate exponential decay. Results of the One D simulation is shown in figure 8.

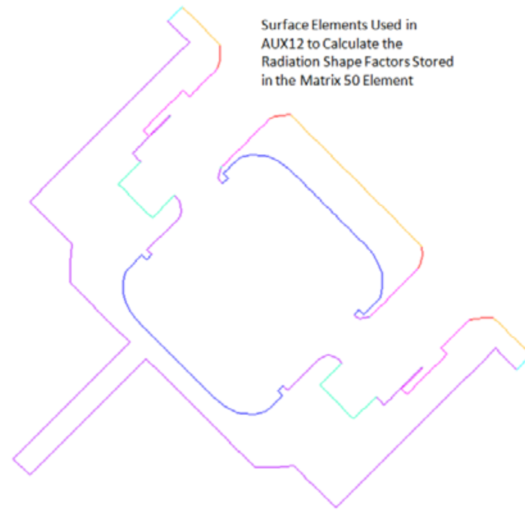

Fig. 7 Surface Elements Used in the ANSYS AUX12 Computation of the Radiation Shape Factors.

Radiation shape factors are computed using the ANSYS AUX12 utility. The ESURF command is used to identify surface elements, VTYPE,0 is used for the axisymmetric modeling. The view factors are saved in the MATRIX, 50 element.

B. One D Multiple Pulse Simulation

In the One D simulation, radiation is included but it is not an important effect until all cooling is lost. The peak (surface averaged) nuclear heat modeled is:

PeakNucPoweru=1.0e6 (Upper VS)

PeakNucPowerl=1.12e6 (Lower VS)

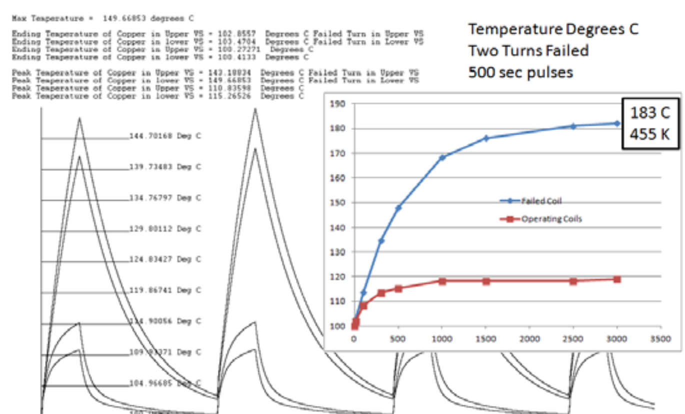

Fig. 8 "One D" Simulation of the Faulted Coil Thermal Response

Figure 8 includes a plot of the results for pulse lengths from 1 to 3000 sec. There is a strong dependence on the pulse length in the temperature of the un-cooled coil. Use of steady state temperatures in the FEA modeling is conservative for the lower pulse lengths. One half hour cooldown between shots is modeled. In these simulations, the failed coil thermally recovers between each shot.

C. Two D Thermal Equilibrium Simulation

Figure 9 is the result of a steady state thermal analysis including nuclear heat for one and two turns disabled. For the two turns out simulation, the peak temperature is 558 K peak and for the very long pulselengths summarized in figure 8 the max temperature in the failed coil is 455 K and still rising a little. The One D simulation smears the temperature in the failed turn. The smeared result would correspond to 517 K in the 2D simulation. The One D simulation estimates conduction paths to the cooled turns, and evidently is overestimating the heat removal capability of the operating coils.

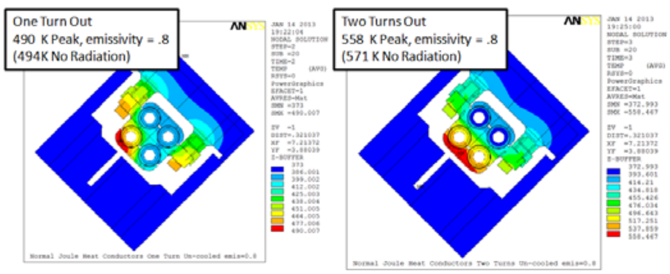

Fig. 9 Steady State Axisymmetric Simulation of the Faulted Coil Thermal Response

The thermal distribution must be qualified mechanically to conclude that the failed turns do not threaten the operation of the remaining good turns, or threaten the vessel wall , blanket or blanket manifolds. Stress levels in the failed coils can indicate worse damage to the already failed turns, but they must not damage the remaining good equipment.

D. Fault Assessment

Stresses in the "one turn out" simulation are higher than for the nominal operating case. Further degradation of the failed coils is considered only in terms of the possibility of the failed turns effecting the integrity of the remaining turns.

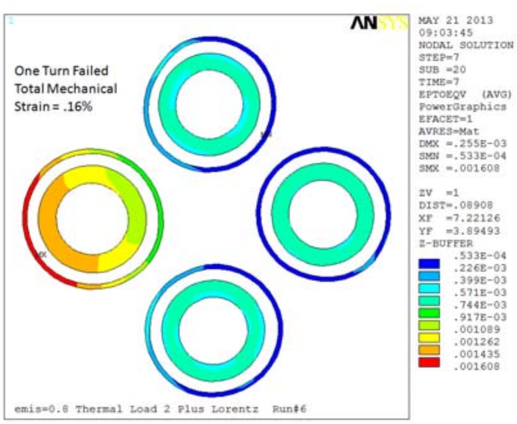

Fig. 10 Von Mises Plastic Strain for One Failed Turns

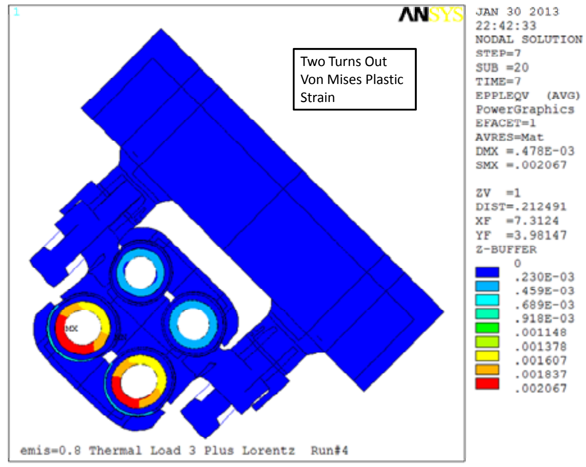

Fig. 11 Von Mises Plastic Strain for Two Failed Turns

Based on fatigue allowables, the coils can run at full performance, with the over-current, to make up for the lost turn, for greater than 100,000 cycles based on the axisymmetric modeling. This analysis was performed using the 3D modeling and the faulted cyclic life was estimated to be about 10,000 cycle.[2] There are some local stresses near intermittent clamps and rail supports that introduce stress concentrations in the 3D model that are not apparent in the 2D modeling

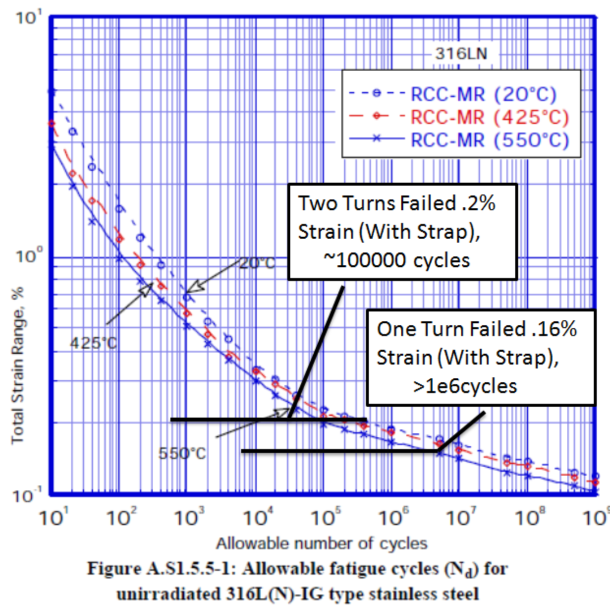

Fig. 12 Von Mises Plastic Strain for Two Failed Turns

IV. Electromagnetic Effects of a Toroidally Continuous Support Structure

The electrically continuous spine and jacket are closely coupled with the copper conductor and will develop counter currents as the transient currents in the VS are applied. R. Pillsbury calculated the time constant for a step change at the plasma in 2010 [72]. This may be sufficient for modeling plasma position control, but to understand the phenomenon in terms of currents that develop in the continuous structures, additional electromagnetic analyses have been performed and are presented in this section. At issue is whether a bit more current will be needed to drive the VS coils. If so, bit more capacity in the power supplies will be needed and more cooling will be needed.

A. VS Correction Currents

The VS coils are designed for 240 kA-t/coil (60 kA/turn) The coil is wound as 4 individual turns with separate leads and feeders. Operational life is 20 years or 30000 Experimental pulses. In some pulses, the VS will experience an average of 3 major pulses or corrections to reposition the plasma. There is a small current oscillation arising from magnetic diagnostic noise These currents and current profiles are described in fig.10. The project has put a ceiling on the total number of VS pulses of 30,000 corrections. 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. The number of major disruptions is less than 3000 shots. 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. Disruption load cycles are assumed included in the VS normal load cycle count.

The electrically continuous spine and jacket are closely coupled with the copper conductor and will develop counter currents as the transient currents in the VS are applied.

These may not have been addressed in the simulations of vertical stability.

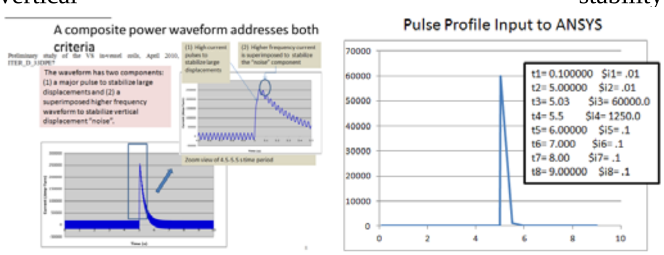

Fig. 13 VS Currents and Current Profiles

B. Model and Analyses

The electromagnetic model is includes the air around the coil and sections of the vessel and blanket shield modules. The model is actually a 3D narrow slice of the coil and surrounding structures. While the 3D modeling is a direct swept expansion of the 2 modeling, the 3D analysis allows familiar elements and constraints that are typically used for disruption simulations. The extent of the model is very limited with respect to the machine scale, but it is expected that even the vessel and blanket shield components will not be as well coupled to the VS conductors as the jackets and spine.

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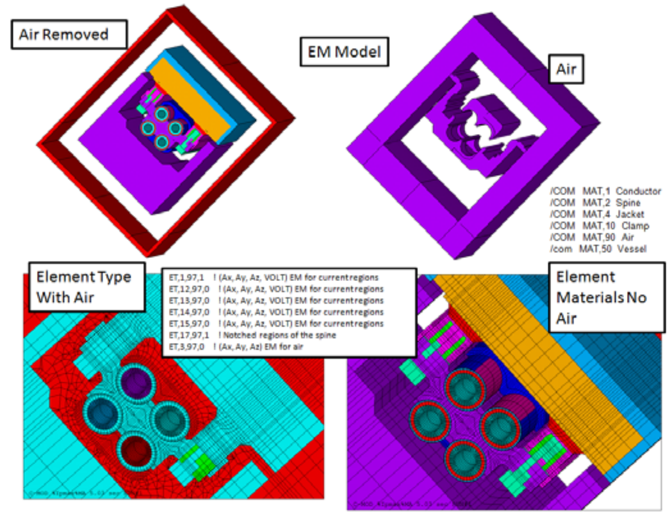

Fig. 14 Electromagnetic Model of the VS

C. Electromagnetic Simulation Results

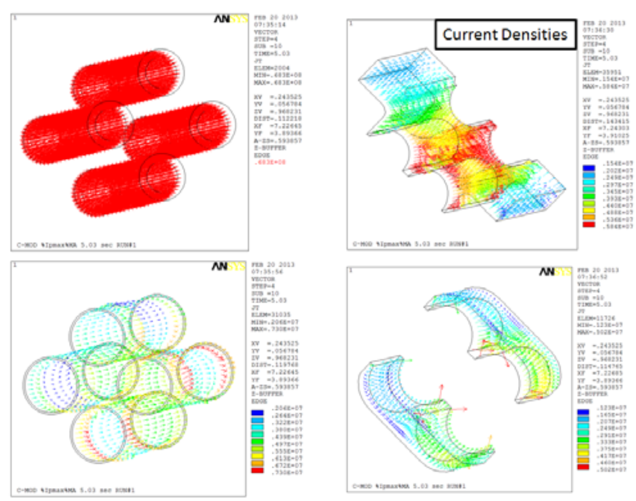

Fig. 15 Current Densities in the VS Due to a Normal Correction

Component	VS Component Currents		
	Area mm^2	***J, Amp/mm^2***	***I for 4 turns***
Conductor	3516	6.83e7	2.40e5
Jacket	1356	-4.97e6	-.0674e5
Spine Center	4113	-4.88e6	-.201e5
Total			2.13e5

The close coupled opposed currents in the continuous jackets and spine produce a loss of about 11% in effective VS Coil current. Depending on how the vertical stability control system is modeled, this may or may not be included.

The vessel passive structures are probably included, but the VS spine and jackets are probably not represented. This means that the VS currents need to be increased by the 11% in order to provide the same efficacy in controlling the plasma position as presently (Feb 2013) assumed.

Acknowledgment

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[6] Extra Ref

[7] Extra Ref.

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