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Mechanical Assessment of the JET TF Coils for 4T Upgrade: The New 3D Hybrid Model

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ABSTRACT

Upgrade of the JET toroidal field (TF) to 4T would allow increased plasma current and thus improved performance with divertor operation. Mechanical assessment of the TF magnet system was performed with the new 3D hybrid model of a TF coil, which allows investigation of localised stress in one of the most critical area of the coil. It was concluded that 4T operation is safe for the TF coils.

1. INTRODUCTION

The JET toroidal field magnet system comprises 32 D-shaped coils originally designed to produce a field of 3.45 T at 2.96 m radius. Water-cooled and lately freon-cooled copper conductors and glass fibres-epoxy resin insulation are the main components of the coils. Interactions between the toroidal and poloidal magnetic fields and the current flowing in the coils create in-plane and out-of-plane forces distributed along the coils. In-plane forces are mainly reacted along the central straight section of the coils by the inner cylinder and out-of-plane forces by the inner cylinder grooves and the mechanical structure supports around the curved outer part of the coils. Among these the collar tooth support area constitutes the most critical point due to the offset of the load [1]. In order to allow for upgrading the JET toroidal field to 4 Tesla new detailed analysis of the TF coils has been carried out and extra safety margin has been found. Sensitivity analysis of the shear stress in the insulation with the shear modulus of elasticity G was carried out and the actual G value was substantiated through measurements with Iosipescu method. Moreover key efficiency and crack propagation analysis show a trend of a crack non-propagation effect.

2. MODELS

A beam model of the TF coil is being used to investigate the averaged stress in the section of the coil under operational load. In order to investigate the level of peak shear stress in the insulation in the collar tooth area, more detailed models which represent the single components of the section are required. The 3D straight partial model is a preliminary model of a section of the coil 800 mm long, fully restrained at both ends, which represents the copper and the insulation in detail with their own mechanical properties. It was aimed to investigate the level of shear stress in the insulation itself, since all previous models were coarse models with smeared properties on the section. Nevertheless the straightness of the model and the assumed boundary conditions do not represent the coil in its whole.

Therefore an hybrid model was developed. This comprises a 3D detailed model of the area of interest and a beam model of the remaining coil, so as to provide more realistic boundary conditions. This 3D curved model with the correct material properties should predict accurately peak stresses, without depending on boundary conditions.

3. ANALYSIS

In order to investigate the level of peak shear stresses in the insulation the section of the coil has to be modelled with its single components, namely the copper conductors and the glass-resin insulation. Due to hardware limitations there are difficulties to represent the whole length of the coil that way. Therefore an artifice has been used and explicit modelling of copper and insulation has been done at the region with the highest stress distribution, while coarser modelling represents the remaining coil.

The hybrid model of the TF coil comprises a 3D detailed model 600 mm long of the collar tooth area and a beam model of the remaining coil, so as to model the whole coil, Fig. 1. Both the sections at the interface brick - beam elements have been modelled with rigid elements, to simulate continuity of the section. These elements connect the central node of the section, correspondent with the beam node, with the other nodes of the section. In this way these nodes are forced to remain in a plane and the mechanical actions may be transferred from the beam to the 3D model. The 3D detailed model with brick elements comprises the single components of the section, namely the copper conductors and the glass - resin insulation, with their material properties. The coarse model with beam elements represents the material with properties averaged in the section. The pad at the collar tooth area has been modelled with rigid elements to maintain plane the correspondent surface. In plane supports by the inner cylinder and out of plane supports by the mechanical structure have been imposed along the coil, Fig.2 [2]. Distributed load has been applied on the copper turn bricks of the 3D model [N/m^3] and on the beams of the beam model [N/m], as for operational scenario with the highest impact on the collar tooth (Pulse 26805). This load is calculated using the magnetic field configuration produced by MAXFEA.

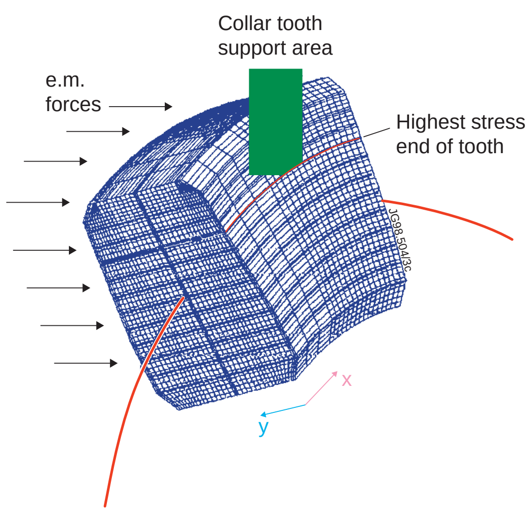

Fig. 1: Collar tooth support area

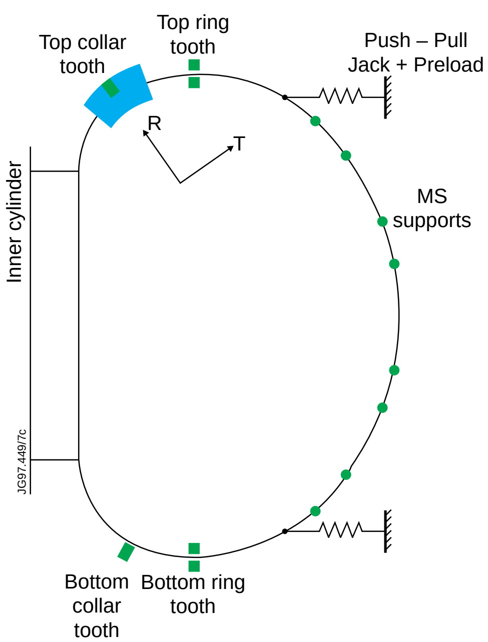

Fig. 2: Hybrid model of a TF coil

Both out of plane forces and in plane forces have been applied: the former are responsible for the high peak shear stress at the third interturn layer in correspondence of the collar tooth position.

4. RESULTS

The peak shear stress at the third interturn is τ = 12 MPa for a correspondent reaction force at the collar tooth F = 570 KN and G = 4000 MPa, Fig. 3, while it is τ = 10 MPa for F = 520 KN and G = 1200 MPa. Fig. 4 shows the distribution of the shear stress in the interpancake insulation in correspondence of the collar tooth area: the peak shear stress is τ=9 MPa.

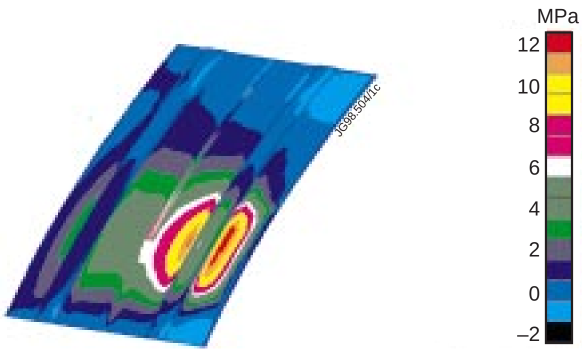

Fig. 3: Shear stress in the 3rd interturn layer

Fig. 4: Shear stress in the interpancake

Comparison with previous analysis proves consistency of the results. Table 1 shows the peak shear stress at the third interturn. A slightly lower stress has been found out with the hybrid model, but the percentage increase of the shear stress with G is the same as for the straight model. The same happens using smeared properties. It must be emphasised that the peak shear stress decreases by 15% from the straight to the hybrid model. This may be due to the curvature of the fibres, which contributes to distribute more evenly the stress in the insulation, because of the higher contribution by the copper and the different sharing of torsion and pure shear stress.

Table 1: Peak shear stress at the third interturn layer [MPa]

MODEL	G = 1200 MPa	G = 4000 MPa	Smeared Properties
Hybrid Model	10.	12.	14.
3D Straight Model	12.	15.	17.
Beam Model	Max shear stress in the section of the coil: 9.5		

Confidence of the result is proved by the following analysis:

- Sensitivity analysis at the interface brick - beam elements: the shear stress at the collar tooth position is not affected by the rigid elements used to model the interface.
- Sensitivity analysis with the number of elements through the thickness of the insulation gives the same result.

- Different simulations with different assumptions on the load distribution and the boundary conditions give about the same value of the peak shear stress at the insulation as long as the collar tooth reaction force remains the same: this implies that boundary conditions and load distribution far away from the area of interest do not affect the result.
- Different models give results that are comparable, Table 1.

Sensitivity analysis of the shear stress with the shear modulus of elasticity of the insulation G has been carried out. Fig. 5 shows the trend of the shear stress across the third interturn for different values of G. The decrease of the stress in correspondence of the keys confirms the key efficiency [1]. For a range of G = 1200 ÷ 4000 MPa the shear stress in the insulation increases up by 25%. The correspondent peak tensile stress in the copper decreases by about 5%. The comparison with the beam model shows good correspondence between the results which is a basis for the model validation, Table 1.

Since the shear stress in the insulation is strongly affected by G, it is of the utmost interest to measure this parameter. Since cylindrical samples for standard measurement of shear properties could not be machined out of the available material of the coil, the Iosipescu method for the measurement of G on rectangular samples was implemented [3]. This is a standard method for G measurement in glass - resin fibres, designed to produce pure shear load. Measurements performed at different temperatures give G = 1200÷4000 MPa for a range T = 90 ÷ 20^0C, Fig.6. This is the range of the coil operating temperatures and the range of G values used for the analysis [4].

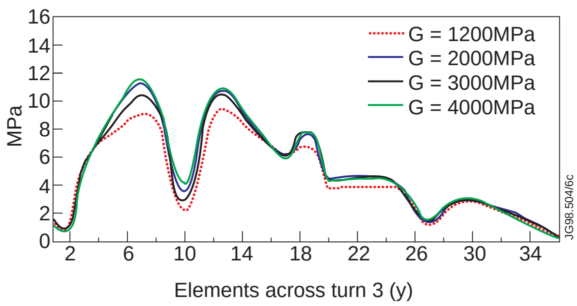

Fig. 5: Sensitivity of the shear stress with G

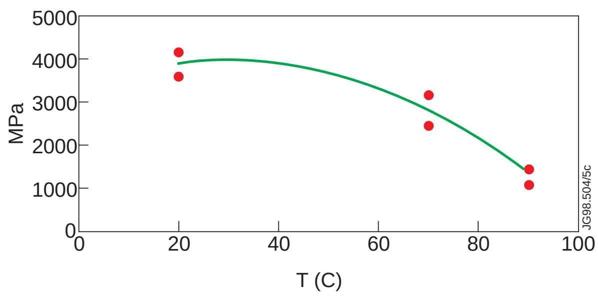

Fig. 6: Sensitivity of G with temperature

5. KEY EFFICIENCY AND DELAMINATION EFFECTS

Delamination effects in case of initiation of a crack in the insulation - copper interface at the third interturn have been investigated, by introducing a crack of variable width on the whole length of the third interturn. Key efficiency has also been investigated through comparison of the results with a modified model where all the keys have been removed and replaced by copper. The keys only affects the distribution of the shear stress across the interturn and contribute to decrease the level of the peak shear stress only in case of delamination.

Furthermore a crack of variable length has been introduced to investigate evolution and crack growth effects. Fig. 7 shows the distribution of the shear stress along the third interturn and Fig. 8 across the same interturn. Fig. 7 gives evidence of the fact that at the tip of the crack the peak shear stress decreases with the length.

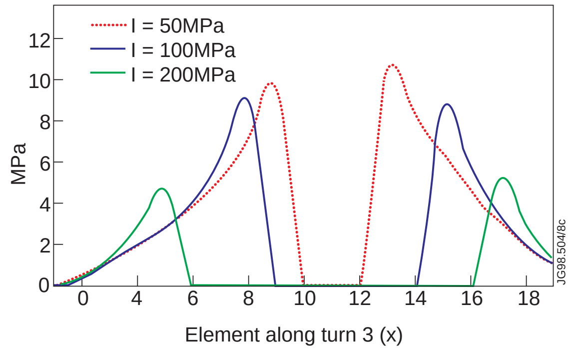

Fig. 7: Shear stress along turn3

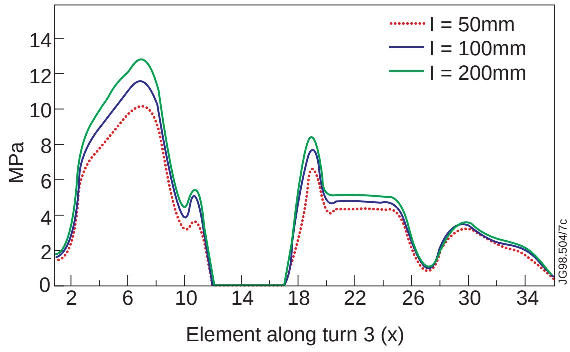

Fig. 8: Shear stress across turn3

6. CONCLUSIONS

- The peak shear stress at the third interturn insulation is τ = 12 MPa for a correspondent reaction force at the collar tooth F = 570 KN and G = 4000 MPa and it is τ = 10 MPa for F = 520 KN and G = 1200 MPa, which is within our admissible τ_{adm} = 16 MPa .
- The peak shear stress decreases down by 15% from the straight model to the curved model of the coil, this giving an extra safety margin with respect to previous analysis. This may be due to the curvature of the fibres, which could contribute to distribute evenly the stress on the insulation.
- The peak shear stress is strictly related to the reaction force a the collar tooth and boundary conditions and load distribution far away from the area of interest do not affect the result.
- The same percentage increase of the shear stress with G has been found for both the hybrid and the straight partial 3D models. The same happens for the smeared properties.
- The key plays a role only in case of delamination.
- There is a tendency of a crack non-propagation effect.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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