3D MODELLING OF THERMAL LOADS DURING UNMITIGATED VERTICAL DISPLACEMENT EVENTS IN ITER AND JET

[1]F.J. ARTOLA, [1]R.A. PITTS, [1]G. SIMIC, [2]M. KONG, the [a]JOREK team and the [b]JET Contributors

[1]ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul-lez-Durance Cedex, France
[2]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland
[a] See the author list of M. Hoelzl et al 2024 Nucl. Fusion 64 112016
[b]See the author list of C.F. Maggi et al 2024 Nucl. Fusion 64 112012

Email: javier.artola@iter.org

1. INTRODUCTION

The modelling of 3D thermal loads during tokamak disruptions remains largely unexplored, with no reliable predictive tools for future machines. During the Thermal Quench (TQ) and Current Quench (CQ) phases of disruptions at high plasma currents, the rapid loss of thermal and magnetic energy can cause severe melting of plasma-facing components (PFC), leading to extremely costly operational delays, especially in nuclear devices. Predictive and as realistic as possible modelling tools are therefore essential to establish disruption mitigation needs and assess the disruption budget for next step tokamaks.

Previous work for ITER CQ loads during upward going unmitigated vertical displacement events (VDE) on the beryllium (Be) main chamber PFCs was performed with the DINA--SMITER--MEMOS-U workflow [1]. There, melting was predicted already for plasma currents beyond I_p ~7.0 MA with severe melt erosion for nominal 15 MA operation. The new ITER 2024 baseline replaces Be for tungsten (W) as main chamber armour [2] which considerably increases the melt limits. Nevertheless, axisymmetric 2D TOKES simulations of the same VDE CQ's still predict melting onset for I_p ~10.0 MA [3]. Although the study in [1] did account for the 3D geometry of the ITER first wall panels (FWPs) and the temporal evolution of the CQ equilibrium, the use of the 2D DINA code required that the plasma parallel heat flux, $q_\parallel$ be assumed toroidally symmetric. The TOKES calculations are also axisymmetric and account for neither the 3D wall structure nor the magnetic equilibrium time variation. However, since the edge safety factor during such CQs typically drops below a value of 2, external kink modes are expected to be triggered, breaking the axisymmetry assumption and leading to strong, time dependent toroidal asymmetries in $q_\parallel$. As a consequence, both the DINA and TOKES simulations are expected to underestimate the localization of thermal loads and it is imperative to assess the impact of 3D plasma effects.

In this study, we present, for the first time, JOREK simulations of unmitigated VDE thermal loads accounting for both 3D plasma loads and wall geometry. We provide thermal load predictions for the ITER W-wall based on previously computed MHD simulations and perform dedicated runs for validation on a specific JET discharge. In this case, melting of the Be main chamber PFCs was known to occur during and upward going VDE.

2. METHODOLOGY

The 3D distribution of $q_\parallel$ is obtained from JOREK MHD simulations, including both TQ and CQ phases. To assess the thermal load impact at ITER, we use the $q_\parallel$ profiles from the ITER 15 MA, L-mode VDE simulations presented in [4], which also describes the model simplifications required to simulate a CQ phase of duration hundreds of milliseconds. These include Dirichlet boundary conditions and an assumption that $q_\parallel$ is entirely governed by parallel conduction. As a result, the simulations are not fully predictive and depend on the chosen floor value for the parallel conduction coefficient ($\kappa_{\parallel,\min}$) used in Spitzer-Harm formula. The influence of this free parameter, which determines the parallel energy loss timescale and thus affects $q_\parallel$, is also analysed.

Once $q_\parallel$ is obtained, it is mapped from the axisymmetric JOREK boundary to the 3D wall elements. To calculate the incident heat flux ($q_\perp$), the parallel heat flux is projected onto the wall normal vectors ($\boldsymbol{q}_\parallel \cdot \boldsymbol{n}$), but only for the wall elements considered as wetted by the plasma. These wetted elements are identified by using field line tracing, in the same way as with the SMITER code. A wall element is considered wetted if its field line extends towards the plasma without intersecting another PFC within a predefined length. As a consistency check, JOREK was successfully benchmarked against the SMITER code for the wetted area calculation on the same 3D CAD model of the ITER FWPs. Once $q_\perp$ is obtained for a series of time slices through the VDE, a 1D heat diffusion equation is numerically solved for each wall element to estimate the temperature rise on the W FWP surfaces due to the disruptive event. A similar procedure is applied to the specific JET discharge, but now with Be PFCs.

3. ITER RESULTS

The thermal load analysis for the ITER 15MA case with a CQ duration of 240 ms (similar to [1]) as seen in Figure 1 (left) indicates marginal W melting on the top surfaces of the FWPs (constituting the main wetted zones). Much higher temperatures (implying melting) are found on panel edges where the heat flux impacts more perpendicularly. Although the maximum temperature rise considering the 3D plasma effect exceeds the toroidally averaged case by about factor of 2-3, the thermal loads are generally more benign than those predicted by the SMITER--DINA--MEMOS-U workflow. The main reason is the broader energy deposition width observed in the JOREK simulations due to MHD activity. Finally, cases with larger $\kappa_{\parallel,\mathrm{min}}$ have stronger parallel losses, leading to shorter CQ durations (τ_{CQ}), slightly narrower deposition widths and larger $q_{\parallel}$. These cases imply rather severe melting on the main FWP top surfaces, according to the expected timescale dependence of the temperature rise ($\Delta T \propto \tau_{CQ}^{-0.5}$). The simulations presented here, nevertheless predict a higher than expected robustness of the new W-wall against CQ loads, somewhat relaxing disruption mitigation requirements.

4. VALIDATION IN JET

To assess the validity of the ITER predictions, new JET simulations with JOREK are conducted for this work. For that purpose, a 2 MA representative VDE is chosen (#84832), which led to significant damage on JET's Be upper dump plates [5]. Initial results shown in Figure 1 (right) are consistent with the required CQ heat fluxes used by MEMOS-U calculations (~0.1 GW/m^2) to explain the observed surface deformations [6]. More detailed analysis is presently on-going and will be reported during the conference.

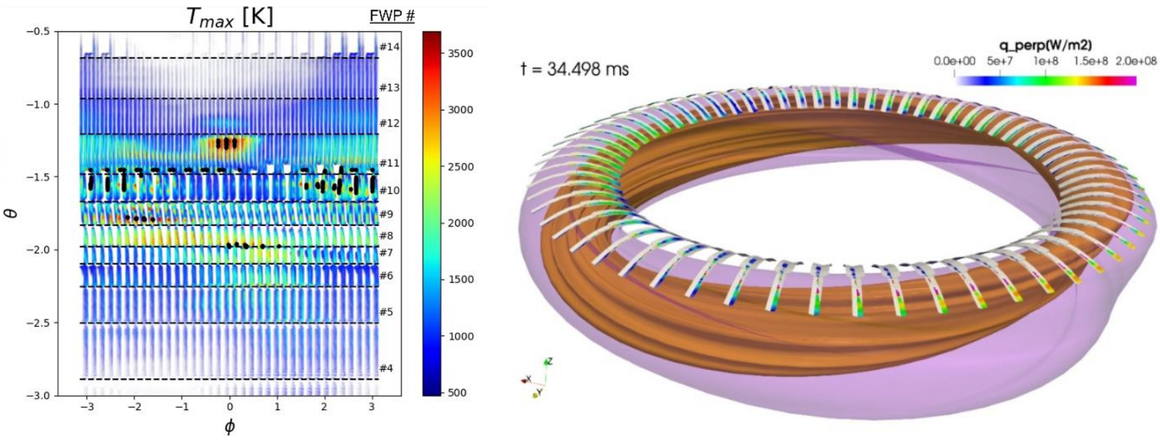

Figure 1: (Left) Maximum surface temperature on FWPs in the upper half of the main chamber during an ITER unmitigated CQ simulation of 240 ms as a function of toroidal and poloidal angles. The black dots represent points with temperatures going beyond the melting point of tungsten. (Right) 3D heat flux on the JET's upper dump plates at $t = 34.498$ ms as modelled by JOREK (rainbow colormap). The orange and purple contours are electron temperature isosurfaces showing MHD activity, with respectively 75 and 50 eV.

ACKNOWLEDGEMENTS

The ITER is the Nuclear Facility INB No. 174. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1] COBURN, J. et al, Nuclear Fusion, **62** (2022) 016001
[2] PITTS, R.A.et al, Nuclear Materials and Energy, **42** (2025) 101854
[3] PITTS, R.A.et al, "TOKES simulations of first wall and divertor damage during unmitigated disruptions on ITER", IAEA-CN-316-2152, presented at the 29th Fusion Energy Conference, London, UK (2023)
[4] ARTOLA, F.J. et al, Plasma Physics and Controlled Fusion, **66** (2024) 055015
[5] JEPU, I. et al, Nuclear Fusion, **59** (2019) 086009
[6] RATYNSKAIA, S. et al, Nuclear Fusion, **60** (2020) 104001