THE USE OF ELECTRON TEMPERATURE COLLAPSES AND EVOLUTION TO FORECAST AND AVOID DISRUPTIONS AND ITS APPLICATION IN THE KSTAR DEVICE THROUGH DECAF

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Disruptions in toroidally confined plasmas have the potential to damage the internal components of tokamak devices and produce unacceptable stresses on the machine's vacuum vessel and external structures. Avoiding or mitigating disruptions is needed to increase a fusion power plant life span and reliability, which is a necessary step towards the deployment of fusion power into the energy sector. The DECAF code [1] is a collection of interconnected physical models aimed to identify disruption precursors in order to keep the plasma within a stable domain, transition to a controlled plasma shut down or trigger disruption mitigation, with such models being constantly validated using up to 9 tokamak databases [2,3]. Recent real-time deployment of key DECAF event modules in KSTAR timely identified and avoided disruptions caused by vertical displacement events (VDE) and Neoclassical Tearing Modes locking to the wall (LTM), ultimately allowing operation in higher performance regimes and longer pulses [4,5].

A recently added capability to the DECAF code evaluates the evolution of the electron temperature profile to monitor events that can trigger a disruption chain. The first order gradient in the electron temperature occurs when the profile collapses following a change in the magnetic flux surfaces. Rapid changes in the magnetic topology that signature nonlinear events such as flux surface tearing or field line stochastization are observed in the electron temperature profile due to the fast thermal transport that follows the opening of the field lines. Examples of such events include but are not limited to sawtooth relaxations (SAW) and edge localized modes (ELM). On a faster time scale, a thermal quench that is followed by a current spike indicates that a fast reconnection event has occurred, which is often followed by a plasma disruption or a vertical displacement event (VDE). On a slower time scale, high-power radiation (often due to tungsten impurities that penetrate into the core) displays a unique asymmetric dynamic that can be identified through the evolution of the electron temperature collapse itself.

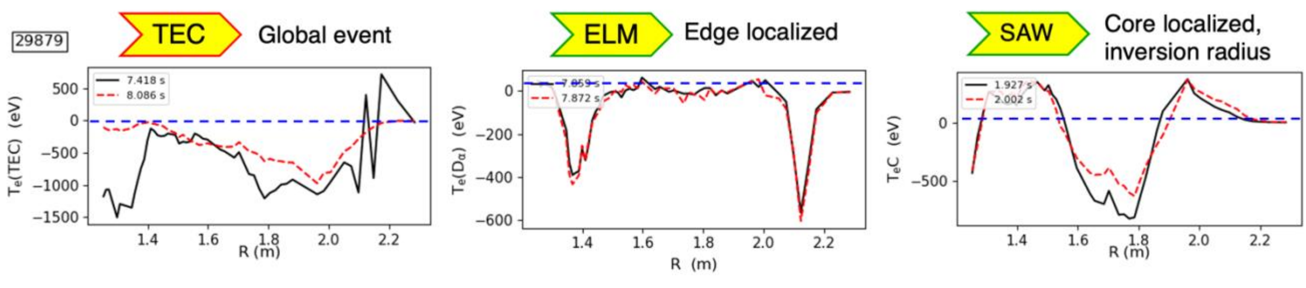

Figure 1 Different types of electron temperature collapses in KSTAR shot 29879: TEC (left) ELM (middle) and SAW (right).

The work presented here studies the electron temperature evolution (with particular emphasis on when it collapses) and its use for disruption prediction and avoidance. First, a general framework to identify and categorize electron temperature collapses is presented. Identification of the crash time and radial location is performed by convolving a subset of electron temperature profile channels with a specialized kernel [6]. Once a collapse event has been identified, all the available channels are used to reconstruct a 'crash profile' containing the features that allow to uniquely tie the crash to a physics event (SAW or ELM) (Figure 1). A more general collapse is also categorized as the newly introduced TEC Event (which stands for T_e collapse), encompassing global electron temperature collapses caused by coupling of several events at different radii, reconnection events or field line stochastization that follows a change in a plasma state. Once the collapse has been categorized, the plasma state along with the features of the crash profile are used to assess the proximity to disruption and to flag the instances where a disruption chain is triggered. Such formalism has been implemented in the DECAF code, allowing the automatic analysis of a wide range of shots, up to the entire machine databases, to test the models developed during this work.

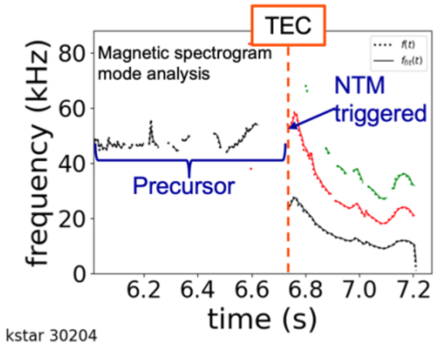

Figure 2 Neoclassical Tearing Mode triggered after a TEC in KSTAR.

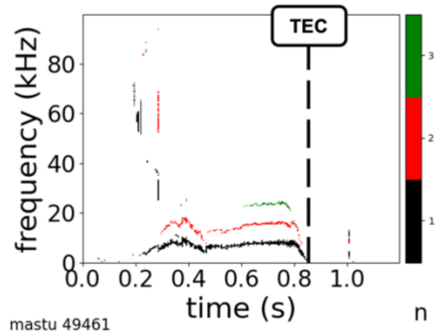

Figure 3 TEC triggered by a change in plasma state due to mode lock in MAST-U.

The offline analysis of KSTAR and MAST-U databases shows that electron temperature collapses that can be tied to disruption chains [1] are correctly identified and categorized. It is shown that global electron temperature collapses (TEC) that occur at high plasma performance as a consequence of a change in magnetic topology are followed by Neoclassical Tearing Modes (NTMs), which can lock and disrupt the plasma (Figure 2). It is worth mentioning that NTMs seeded by ELMs and SAW events are also identified through the same formalism. It is shown that mode locking and other MHD activity can lead to global electron temperature collapses (possibly due to the associated stochastization of the field lines) and can ultimately lead to a disruption event (Figure 3). Both types of dynamics are identified up to several hundreds of milliseconds before the actual plasma disruption, leaving sufficient time to trigger actuation in order to deploy avoidance or mitigation techniques. Moreover, it is shown that the electron temperature evolution leading to the TEC has the potential to be used as a proximity warning to avoid the electron temperature collapse. Finally, analysis of the last two KSTAR experimental campaigns with a tungsten divertor shows a unique dynamic of the electron temperature once impurities enter the plasma: first the electron temperature collapses from the low field side and follows through the core. If there is enough input power, the plasma will recover but the electron temperature profile will have a hollow core, which can trigger MHD activity that likely (together with the ECH injection) can expel the impurities outside the core and allow for a total reheat of the plasma.

The findings presented in this work were tested during the present KSTAR experimental campaign. In a dedicated experiment, a reference discharge with a TEC event was extended by reducing the injected ECH power just before a TEC happened. The reduction in the input power led to a more stable plasma and to the avoidance of a disruptive TEC event. Near-term experiments are planned using a real-time implementation of the TEC detector, electron temperature evolution and corresponding feedback to maintain the plasma in a stable domain.

References

[1] S.A. Sabbagh, et al., *Phys. Plasmas* **30**, 032506 (2023)
[2] Zamkovksa, V., et al., Nucl. Fusion **64** (2024) 066030
[3] M Tobin *et al* 2024 *Plasma Phys. Control. Fusion* 66 105020
[4] Riquezes, J.D., et al., "*Multi-device Born-rotating MHD Mode Lock and Disruption Forecaster with Real-time Feedback for Disruption Avoidance*", this conference
[5] S.A. Sabbagh, et al., *"First demonstration of disruption avoidance by real-time physics-based Disruption Event Characterization and Forecasting on KSTAR"*, this conference
[6] A Gude et al 2017 Plasma Phys. Control. Fusion 59 095009