Core radiative collapse characterisation and integrated modelling in WEST plasmas

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Summary A database survey of the operation of WEST, a full tungsten tokamak with dominant electron heating and no external torque [1] (Lower Hybrid Current Drive and Ion Cyclotron Resonance Heating are used), shows that about 15% of the pulses exhibit a rapid central electron temperature collapse. The collapsing pulses are analysed to understand the key actuators at play. Experimentally, an initial slow reduction of central electron temperature due to a density increase is observed, while the central tungsten profile is flat and constant in time. Then, radiative collapse occurs: the core tungsten profile peaks rapidly, at the same time, the central hard X-ray channel measurement decreases indicating an outward shift of the core LHCD absorption. Integrated modelling is used to explore the causality chain (RAPTOR coupled with QuaLiKiz 10D neural network for the heat transport, using LUKE to compute the LHCD power deposition profile). To capture the collapse speed, both tungsten core peaking and reduction of central LHCD absorption are required. When central LHCD power absorption is reduced, core electron and ion temperature profiles flatten which reduces the tungsten neoclassical thermal screening and leads to the observed core tungsten accumulation and the simultaneous core T_e collapse.

Characterize and understand the dynamics of the radiative collapse

A L-mode database of WEST has been collected by an automatic identification of plateaus at constant current and input power. This database evidences the existence of 2 confinement states, one at high core electron temperature and high $H_{98y,2}$, the other at low T_e and low H98.

The hot branch is characterized by a high central electron temperature, internal inductance (li) and neutron flux, while, the cold one features low temperature, li and neutron fluxes.

We have found that the 25% of the discharges into the hot branch eventually collapse.

These collapsing cases are detected on plateaus on which the initial $T_e(0)$ is between 1.5 keV and 3 keV. This coincides with the temperature range over which the tungsten cooling factor peaks. If $T_e(0)$ decreases, radiation increases and it leads to a further $T_e(0)$ decrease and thus to an instability.

During the unstable plateau, a first slow decrease of the central temperature is observed, at the

same time n_e increases, then, a fast collapse occurs and, at the end, the plasma goes in a degraded confinement state with a central temperature around 1.5 keV and large MHD mods are triggered. The collapse covers a region extending from the core to about $\rho = 0.4$ (figure 1).
The signal of the hard X-ray central channel for the energy band 60-80 keV, a signature of LHCD central absorption, decreases and the estimation of the tungsten central density from bolometry inversion is constant during the first part of the collapse and then starts to increase very quickly until it reaches a peak corresponding to the lowest T. This suggests a tungsten accumulation in the center of the plasma (figure 2).
Potential causes for the central T_e collapse are: the reduction of central LHCD absorption and the increase of core radiation due to larger cooling rate and/or tungsten density.

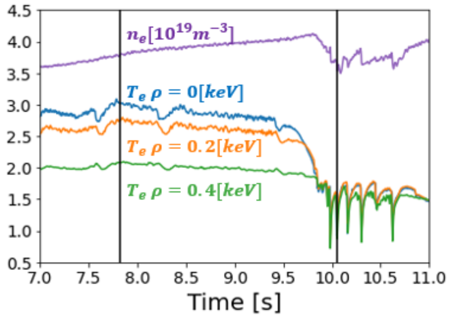

Figure 1: *Electron temperature time evolution at $\rho = 0$ (blue), $\rho = 0.2$ (orange) and $\rho = 0.4$ (green) and the central line averaged electron density (purple).*

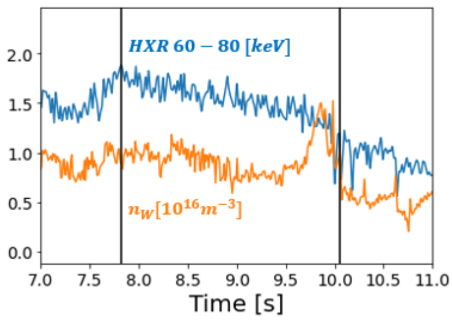

Figure 2: *Signal of the hard X-ray central channel for the energy band 60-80 keV (blue) and the estimation of the tungsten central density (orange).*

Integrated modelling

The modelling framework is composed of METIS [2] for the interpretative modelling needed to prepare the simulations (initial and boundary conditions) and RAPTOR [3] coupled with the 10D QuaLiKiz neural network [4] to predictively model the heat transport thanks to computed transport coefficients. The LUKE code [5], in stand alone, is used to determine the LHCD power absorption profile evolution.
We assume that the tungsten profile can be approximated by a Gaussian symmetric function with respect to the center of the plasma with a constant background. To set the initial tungsten value, the peak reached and the timing of the accumulation, we constraint the bolometry signal to match the measured signal on 16 synthetic chords.
Since the tungsten accumulation plays a key role, its neoclassical transport has been analysed. Neoclassical transport is computed in stand alone using the drift kinetic code NEO [6]. Tur-

bulent transport has also been computed on the same radial grid points using QuaLiKiz. The corresponding D and V have been added to the neoclassical ones to compute the tungsten peaking factors. It is observed that the tungsten peaking increases strongly due to a core T_e flattening, leading to T_i flattening by equipartition, hence reducing the neoclassical temperature screening effect. Therefore, we can conclude that the accumulation is a consequence of the collapse.
LUKE is used in stand alone to prepare the power absorption profiles which are then transferred into RAPTOR. The power absorption in the very core ($r = a < 0.1$) cannot be computed with the required spatial accuracy due to the low absorption, multi-pass regime of the wave. But it can be adjusted to reproduce with RAPTOR the dynamics of the central electron temperature. We find that the core electron heating by LHCD needs to be progressively decreased in order to match the temperature evolution during the slow density rise. Then, it is amplified before the radiative collapse.
To disentangle the respective role of the increase of tungsten inside $\rho = 0.5$ from the decrease of the central LHCD absorption, different simulations of RAPTOR-QLKNN have been run: flat and constant tungsten concentration with LHCD power absorption computed from LUKE (green line in figure 3), only tungsten increase with a constant profile of LHCD (frozen at t=8s) (purple line in figure 3) and with both, the contribution of tungsten and the LHCD central absorption (orange line in figure 3).

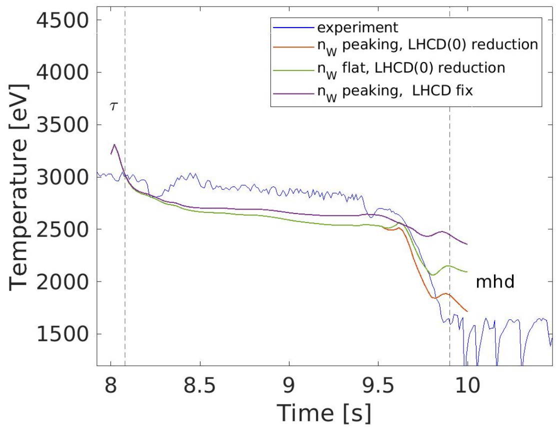

Figure 3: *Time behaviour of different simulations: the blues line corresponds to the central electron temperature taken from the experiment, green dashed line corresponds to the simulations in which the flat tungsten profile is constant with LHCD power absorption decreasing, the purple line is the simulation in which only tungsten increases and the orange line is for both, the contribution of tungsten peaking and LHCD absorption decrease.*

The core tungsten peaking alone is not sufficient to reproduce the slow decrease of $T_e(0)$ prior to the collapse. When the LHCD profiles from LUKE are added, including the adjusted core value, the slow $T_e(0)$ decrease is reproduced. Only if the reduction of LHCD central absorption and the increase of the cooling factor are both taken into account, the collapse occurs but the temperature does not fall below 2keV. On the other hand, if tungsten accumulation is also considered, the temperature decreases below 2keV and the speed of the experimental collapse is captured. This allows us to conclude that the three actuators of $T_e(0)$ collapse are: the reduction of LHCD power core absorption, the increase of the cooling factor due to the drop of temperature and the increase of tungsten accumulation. These parameters may contribute in different percentages depending on the discharge analysed, but they must all be taken into account simultaneously in order to simulate the experimental collapse.

Conclusion

During WEST first phase of operation, 60% of the plateaus are on the “hot branch”. A quarter of these 60% are pulses on which $T_e(0)$ will collapse to the cold branch. We have focused our effort on modelling the Te(0) collapse.

The collapse causality chain can be summarised as follows: continuous density rise, leading to a slight $T_e(0)$ reduction and an increase of the tungsten cooling rate; LHCD core absorption reduced as expected in a colder plasma [7]; this lead to a negative power balance in the core that initiates the temperature collapse; the ∇T_e flattening induces a ∇T_i flattening by equipartition, hence a reduction of tungsten neoclassical temperature screening, therefore, tungsten profile peaks; the core T_e further drops as well as the core LHCD absorption leading to the fast $T_e(0)$ collapse, a broadening of the current profile occurs (drop of li) and MHD activity is triggered.

To avoid core radiative collapses central electron heating is crucial.

In WEST coming campaigns, using dominant LHCD, the central electron temperature will be monitored by raising the ratio of injected power over density. The core electron heating will be maximized, thanks to ICRH dedicated experiments adjusting the frequency and the H minority concentration. From 2023, central electron heating will be complemented by 3 gyrotrons providing 3MW of ECRH.

References

[1] J.Bucalossi et al. *Fusion Engineering and Design* **89** (2014) 907–912.
[2] J.F. Artaud et al. *Nucl. Fusion,* **58** (2018) 105001.
[3] F. Felici. PhD thesis. Ecole polytechnique fédérale de Lausanne. 24 October 2011.
[4] K. L. van de Plassche et al. *Physics of Plasmas ,* **27** (2020) 022310.
[5] Y. Peysson et al. *physics of plasmas,* **15**, 092509 (2008).
[6] E. A. Belli et al. *Plasma Physics and Controlled Fusion,* **50** (2008) 095010.
[7] R. Dumont et al. *Physics of Plasmas ,* **7** (2000) 4972.