Core radiative collapse in WEST LHCD plasmas: characterization and integrated modelling


west.cea.fr/WESTteam

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Dominant electron heating, no external torque.

In this talk: L-mode experiments, in deuterium with LHCD dominant heating.
Two different confinement states in WEST database

Two questions arise from this analysis:

• Why are there two branches?
• Why do the 25% of the discharges in the hot branch collapse?

Phenomena observed in JET during $I_p$ ramp up and FTU

[C.D. Challis NF 2020] [P. Buratti PPCF 1997]
• Characterize and understand the dynamics of the radiative collapse;

• Reproduce the rapid collapse of central temperature using an integrated modelling framework;

• Conclusions.
• Characterize and understand the dynamics of the radiative collapse;

• Reproduce the rapid collapse of central temperature using an integrated modelling framework;

• Conclusions.
Unstable plateaus consistent with W cooling factor unstable range

Prior to the collapse:
• a slow increase of electron density;
• a slow decrease of electron temperature;
• a constant W density;
• a slow decrease of central HXR signal: signature of a lower fast electron production by LHCD.

During the collapse: peaking of the tungsten profile.
• Characterize and understand the dynamics of the radiative collapse;

• Reproduce the rapid collapse of central temperature using an integrated modelling framework;

• Conclusions.
The $T_e(0)$ collapse is captured by the modelling

1D transport code: **RAPTOR** [F. Felici NF 2018]

**Turbulent transport: 10D Neural Network version** trained on **QuaLiKiz.**

[K. van de Plassche PP 2020]

<table>
<thead>
<tr>
<th>$T_e$ and $T_i$</th>
<th>Predicted using QLKNN-10D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{LHCD}$</td>
<td>LUKE</td>
</tr>
<tr>
<td>$n_e$</td>
<td>interpretative</td>
</tr>
<tr>
<td>$n_w$</td>
<td>Interpretative, based on bolometry inversion</td>
</tr>
<tr>
<td>$P_{rad}$</td>
<td>Using ADAS database</td>
</tr>
</tbody>
</table>

**shot 55025**

$T_e$ [keV]  
$P_{LH}$ [MW]  
$n_e [10^{19} m^{-3}]$

**Time [s]**

$T_e (0)$ from ECE [eV]  
$T_e (0)$ from RAPTOR [eV]  

[Graphs showing time evolution of $T_e$, $P_{LH}$, and $n_e$]
LHCD core absorption reduced to capture $T_e(0)$ dynamics

**LHCD multipass absorption computed by LUKE code challenging for core absorption computation.**

$T_e(0) [keV]$ vs Time [s] graph showing $P_{LH}(0) \times 3 [MW/m^3]$ and $t$ values at 8s, 9.5s, 9.6s, 9.7s, and 9.8s.

LUKE profiles with $t = 9.6s$, $t = 9.5s$, $t = 9.7s$, and $t = 8s$. LUKE profiles are shown for $P_{LH}$ at different times.

Experiment and Reconstruction count rate vs Chord index graph with $t = 9.6s$ HXR, [60-80] keV.

Predicted using QLKNN-10D [Peysson FST 2014].
$n_W$ approximated by a **Gaussian symmetric** around the center **on top of a flat profile**.

**Neoclassical transport computed with NEO** [Belli 2008]

- Bolometry inversion
- NEO
- NEO: Only Ti flattening
Tungsten peaking and LHCD core absorption reduction both needed for the collapse dynamics

Only with both the contribution of the **tungsten accumulation** and the **decrease of** the central LHCD absorption the **speed of collapse is reproduced**.

The **collapse** is not reproduced if the **radiated power** inside $\rho=0.1$ does not **overtake the central electron heating**.
• Characterize and understand the dynamics of the radiative collapse;
• Reproduce the rapid collapse of central temperature using an integrated model framework;
• **Conclusions.**
Conclusions

• In the database, L mode **plateaus** where $T_e(0)$ rapidly **collapse** are identified in the range of **1.5 keV** and **3 keV**.

• Time sequence of $T_e(0)$ collapse acceleration:
  
  • The slight density rise leads to less on-axis LHCD power deposition enhancing the central $T_e$ **reduction**;
  
  • $\nabla T$ reduction in core leads to a reduction of $W$ core temperature **screening** hence to core $W$ accumulation.

• even in absence of external torque and particle source, **core electron heating is required** to burn-through $W$ cooling factor.

  • Core ICRH absorption **optimization** ongoing;

  • 3MW of **ECRH** from 2023.
• The database contains the **mean values** and the **standard deviations** of different diagnostic measurements at each **plateau** (quasi-steady-state).
• The plateaus are identified intersecting the **total power plateaus** and the **plasma current plateaus**.
• There are **285** discharges with **732** plateaus in the database.
Automatic identification of radiative collapses within plateaus:

**Exponential fit:** \( T_e(0) = -e^{(a+bt)} + c \)

with \( a < 0 \) for the concavity,

**Linear function fit** with slope \( < -830 \)

Three categories identified: **unstable plateaus** where a collapse takes place, **cold stable plateaus** and remaining plateaus called **stable hot**.
The $T_e$ collapse is captured by the modelling
The same procedure was carried out for the 54802 discharge.

The temperature collapses are associated to variable contributions of LHCD core heating depletion and tungsten peaking.
For quantifying the quality of the confinement time, \( H_{WEST} \) is defined as:

\[
H_{WEST} = \frac{\tau_{mhd,measured}}{\tau_{scaling}}
\]

where \( \tau_{mhd,measured} = \frac{W_{mhd}}{P_{tot}} = \frac{\frac{3}{2} \int_V P \, dV}{P_{ohmic} + P_{aux}} \)
Filter:
- Small reconstruction errors;
- Diverted plasma;
- L-mode plateaus;
- LSN
- Only deuterium shots

\[ \tau = C_{lp}^{\alpha_{lp}} B^{\alpha_B} p_{l}^{\alpha_p} n_{e}^{\alpha_{ne}} M_{\alpha_M}^{\alpha_M} R_{\alpha_R}^{\alpha_R} \varepsilon_{\alpha_\varepsilon}^{\alpha_k} k_{\alpha_k} \]

Example of plateau

\[ \alpha_{lp} = 1.35 \]
\[ \alpha_{ne} = -0.16 \]
\[ \alpha_{Ptot} = -0.75 \]
Bolometry tomography to compute the power emission density profile

A bolometer measures a line-integrated value of the local radiative emissivity along a viewing line of sight.

A concentric layer decomposition of local plasma emissivity is assumed together with asymmetric factors in the SOL and edge. The tomography inversion is computed.

The power emission in $\frac{W}{m^3}$ for each layer are estimated.
Tungsten density profiles from the inverse of bolometry

Above 1KeV the main radiator is the tungsten.

Assuming that all the emission radiation comes from the tungsten, it is possible to use the inverse of bolometry to compute its density at each layer.
for hot and cold branches and collapsing discharges

\[ \frac{P_{\text{tot}}}{n_{e,\text{vol}}} \]
$P_{LH}$ and $n_{e,vol}$ for hot and cold branches and collapsing discharges
The central value is adjusted to find the optimum between $\varepsilon_{slope}$ and $\varepsilon_{temperature}$.

$$\varepsilon_{slope} = \frac{\left| (T_{t-1}^{exp} - T_t^{exp}) - (T_{t-1}^{simu} - T_t^{simu}) \right|}{(T_t^{exp} - T_t^{simu})}$$

$$\varepsilon_{temperature} = \frac{|T^{exp} - T^{simu}|}{T^{exp}}$$
W neoclassical transport

W neoclassical transport (in absence of poloidal asymmetries)

\[ \Gamma_W = -Zq^2 Dn_W \left[ \frac{1}{Z} \frac{\nabla n_W}{n_W} - \frac{\nabla n_i}{n_i} + \frac{1}{2} \frac{\nabla T_i}{T_i} \right] \]

- Diffusion
- Convection due to ion density peaking (inward)
- Convection due to ion thermal screening, outward
The plateaus in H mode in C4:

- In USN 4 plateaus
- In LSN 10 plateaus

Max duration of H mode on WEST 4 s.

The transitions are observed in the hot and cold branches.

The transitions are unstable because $P_{\text{rad}}$ increases when the pedestal is formed and so the power that crosses the separator is reduced and we go back to L mode.

In C6 we will raise the density to high power because we think we were on the low density branch of the L-H transition.