Characterization and integrated modelling of core radiative collapse in WEST plasmas
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To cite this version:
Valeria Ostuni, Jean François Artaud, Clarisse Bourdelle, Jorge Morales, Pierre Manas, et al.. Characterization and integrated modelling of core radiative collapse in WEST plasmas. TTF 2022 - US-EU Joint Transport Taskforce Workshop, Apr 2022, Santa Rosa (CA), United States. cea-03659103

HAL Id: cea-03659103
https://hal-cea.archives-ouvertes.fr/cea-03659103
Submitted on 4 May 2022

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Characterization and integrated modelling of core radiative collapse in WEST plasmas

Outline

- Context;

- **Characterize** and **understand** the dynamics of the **radiative collapse** observed in WEST operation;

- **Reproduce** the rapid **collapse** of **central temperature** using an integrated model framework to **understand** which are the **actuators** that lead to the observed dynamics;

- Conclusions.
Outline

- **Context:**
- Characterize and understand the dynamics of the radiative collapse observed in WEST operation;
- Reproduce the rapid collapse of central temperature using an integrated model framework to understand which are the actuators that lead to the observed dynamics;
- Conclusions.
WEST: superconducting full W environment heated by RF

**Test section with ITER-like Plasma Facing Units (W MBs)**

**Upper divertor**
- W (15µm)/CuCrZr

**VDE/ripple protection**
- W (15µm)/CuCrZr

**Vessel Protection panels**
- Stainless steel

**Inner bumper**
- W (12µm)/CFC (reused)

**Lower divertor**
- W (12µm)/Graphite

**Outer bumper**
- W (90µm)/Mo(80µm) /CFC (reused)

**Baffle**
- W (15µm)/CuCrZr

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**Designed for testing actively cooled ITER-like PFU**

Phase I completed: with lower divertor equipped [Bucalossi NF 2022]

Phase II: plasma duration of 1000s, high performance discharges and investigation operational constraints on long durations in a W environment.

Here we will report on Phase I experiments where LHCD heating dominated.
Plateau Statistics Reduced L-mode Database

- 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.
Two different confinement states coexist in WEST operation

- $T_e(0)$ and $W_{mhd}$
- core tungsten peaking
- $\text{li}$
- less prone to mhd activity
Some of the hot branch discharges go to the cold branch due to a radiative collapse of the central electron temperature.

Two questions arise from this analysis:

• Why are there two branches;

• Why the 25% of the discharges in the hot branch collapse.
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Characterizing the $T_e(0)$ dynamics 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**
- remaining plateaus called **stable hot**.
The **unstable plateaus** range between 1.5 keV and 3 keV. In this range, a **decrease** of electron **temperature** leads to an **increase** of **radiative losses** for the same **W content**.

25% of the **hot branch** is affected by a rapid **collapse** of the central electron temperature.
Collapsing discharge description

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.

This complex interplay requires integrated modelling.
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The 1D transport code **RAPTOR** is used to simulate the **collapse.** [F. Felici NF 2018]

The **transport coefficients** are computed using the **10D Neural Network version** trained on **QuaLiKiz.** [K. van de Plassche PP 2020]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_e) and (T_i)</td>
<td>Predicted using QLKNN-10D</td>
</tr>
<tr>
<td>(P_{LHCD})</td>
<td>LUKE [Peysson FST 2014]</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>Consistent with ADAS database</td>
</tr>
<tr>
<td>(j(r))</td>
<td>predictive</td>
</tr>
<tr>
<td>equilibrium</td>
<td>Self-consistent inside a fixed LCFS</td>
</tr>
</tbody>
</table>
The $T_e(0)$ collapse is captured by the modelling

We will now investigate the role of two key ingredients: the W profile evolution and the LHCD power absorption evolution.
The $T_e$ collapse is captured by the modelling.
LHCD deposition is computed with the LUKE code [Peysson FST 2014]

The power deposition in the very core cannot be computed with the required spatial accuracy. The central value is adjusted in time to match the temperature evolution.

A progressive decrease of the core electron heating by LHCD occurs during the slow density rise. Then it is amplified before the radiative collapse.
It has been assumed that $n_W$ can be approximated by a Gaussian symmetric to the center of the plasma on top of a flat profile. The 16 horizontal bolometry chords are used to constrain the W profile for $T_e>1\text{keV}$ only, where the $L_W$ are known.
W peaking during central $T_e$ collapse captured by reduced neoclassical $T_i$ screening

Neoclassical and turbulent transport computed with NEO [Belli 2008]

Tungsten density reconstructed from transport coefficients (BC at $r/a=0.3$)

In very good quantitative agreement with bolometry inferred tungsten density

W peaking increases strongly due to a core $T_e$ flattening, leading to $T_i$ flattening by equipartition, hence reducing the neoclassical $T$ screening effect.
Tungsten peaking and LHCD core absorption reduction are both needed for the collapse.

Only with both the contribution of the tungsten accumulation and the decrease of the central LHCD injection 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. If core radiative fraction exceeds 1 the collapse occurs.
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.
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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;
  • $T$ flattening in core leads to a reduction of W core temperature screening hence core W accumulation

• Core electron heating is essential in a W environment.

Note: ECRH will be installed on WEST in 2023 to mitigate core LHCD deposition sensitivity
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BACK UP SLIDES
H_{WEST} for quantifying the quality of the confinement time

\[
\tau_{\text{mhd,measured}} = \frac{W_{\text{mhd}}}{P_{\text{tot}}} = \frac{3}{2} \int_V P \, dV \quad \frac{\tau_{\text{mhd,measured}}}{P_{\text{ohmic}} + P_{\text{aux}}} \quad \rightarrow \quad H_{\text{WEST}} = \frac{\tau_{\text{mhd,measured}}}{\tau_{\text{scaling}}}
\]
WEST database aligned with ITER96L

Filter:
- Small reconstruction errors;
- Diverted plasma;
- L-mode plateaus;
- LSN
- Only deuterium shots

\[ \tau = C I_p^{\alpha_{I_p}} B^{\alpha_B} P_{tot}^{\alpha_{ne}} n_e^{\alpha_{ne}} M^{\alpha_M} R^{\alpha_R} \varepsilon^{\alpha_\varepsilon} k^{\alpha_k} \]

Example of plateau

\[ \alpha_{I_p} = 1.35 \]
\[ \alpha_{n_e} = -0.16 \]
\[ \alpha_{P_{tot}} = -0.75 \]

\[ \tau_{scaling} \]
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.
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.

\[ n_W \approx \frac{P_{rad,W}}{n_e L_W(T_e)} \]
for hot and cold branches and collapsing discharges

\[ P_{\text{tot}} / \langle n_e \rangle \]

[\text{MW} / (10^{19} \text{m}^{-3})]
$P_{LH}$ and $n_{e,vol}$ for hot and cold branches and collapsing discharges

$T_e$ center [keV]

$P_{LHCD}$ [MW]

$\bar{n}_e$ [$10^{19}$ m$^{-3}$]

Time [s]
W neoclassical transport (in absence of poloidal asymmetries)

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

Diffusion

Convection due to ion density peaking (inward)

Convection due to ion thermal screening, outward

Profiles of ion and electron density.
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.