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Characterization and integrated modelling of core radiative collapse in WEST plasmas

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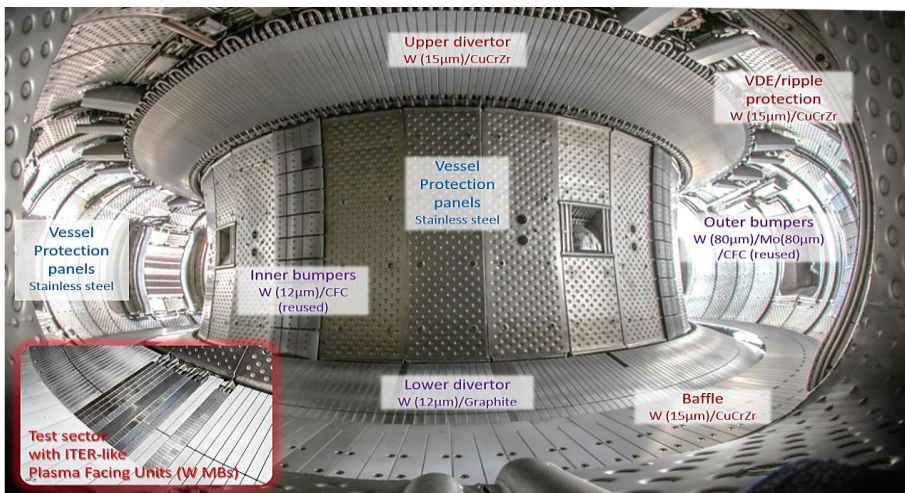
US-EU Joint Transport Task Force 07/04/2022

V. Ostuni, J. Morales, J-F Artaud, C. Bourdelle, P. Manas, Y. Peysson, N. Fedorczak, R. Dumont, M. Goniche, P. Maget & WEST team

- 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.

- **Context;**
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WEST: superconducting full W environment heated by RF



Designed for testing actively cooled ITER-like PFU

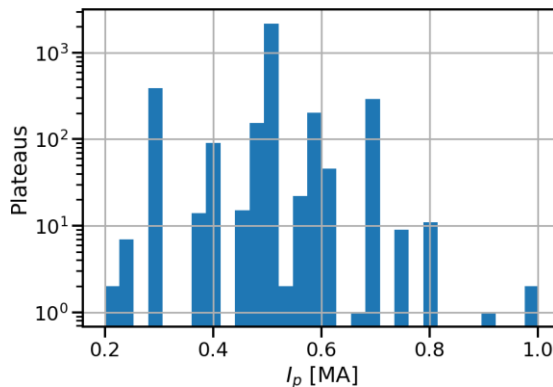
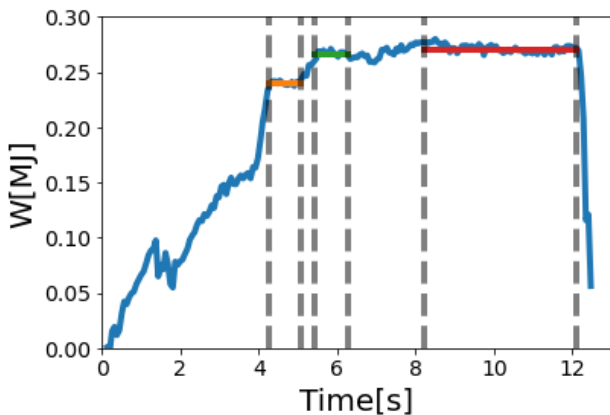
Phase I completed: with lower divertor equipped [Bucalossi NF 2022]

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

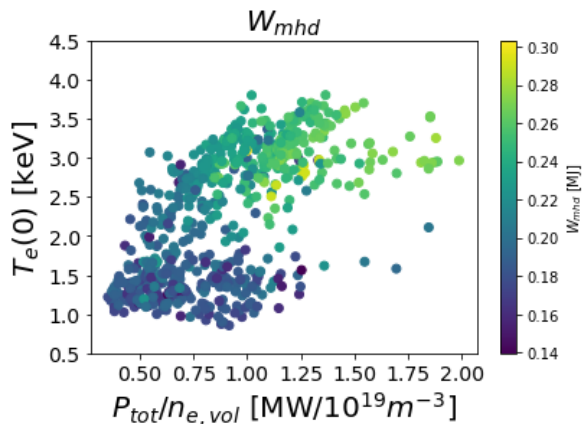
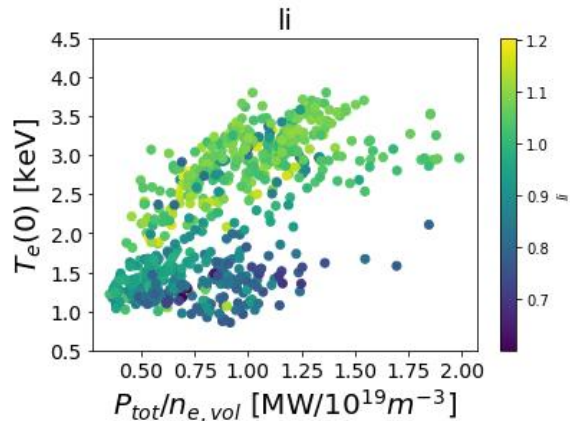
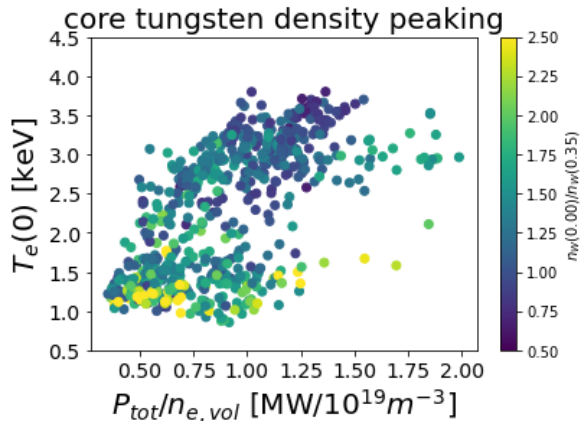
Here we will report on Phase I experiments where LHCD heating dominated.

B_T	3.7 T
R	2.5 m
a	0.4/0.5 m

- 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.

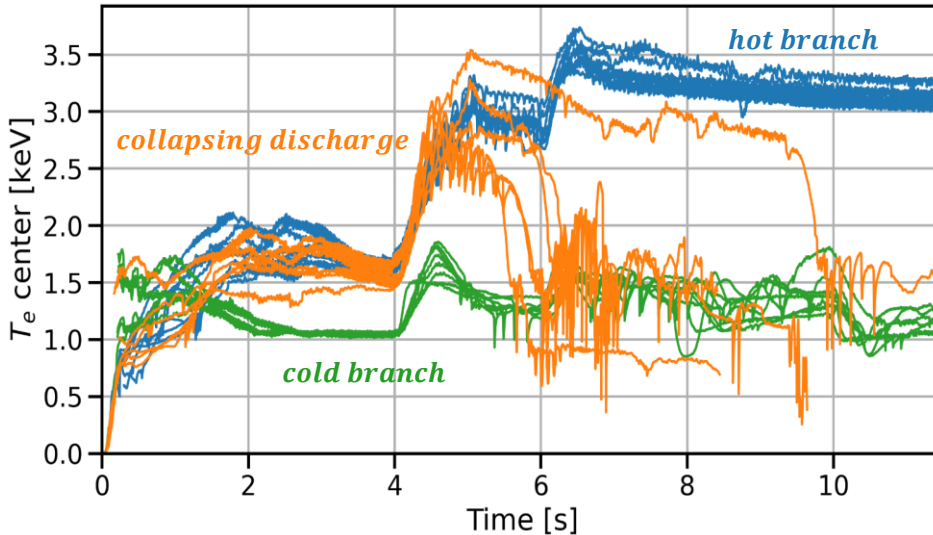


Two different confinement states coexist in WEST operation



- $T_e(0)$ and W_{mhd} ↗
- core tungsten peaking ↘
- li ↗
- ↘
- less prone to mhd activity

Central electron temperature radiative collapse



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:

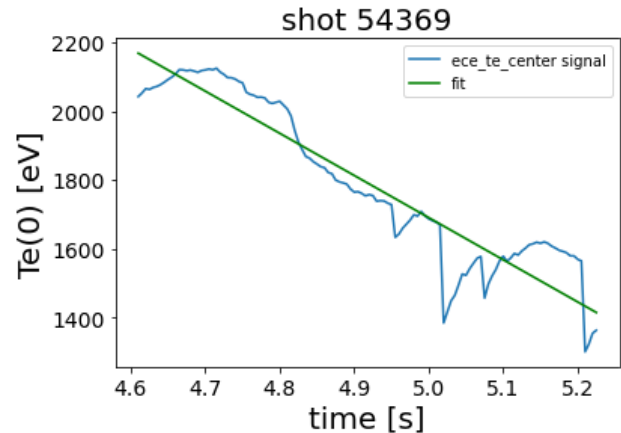
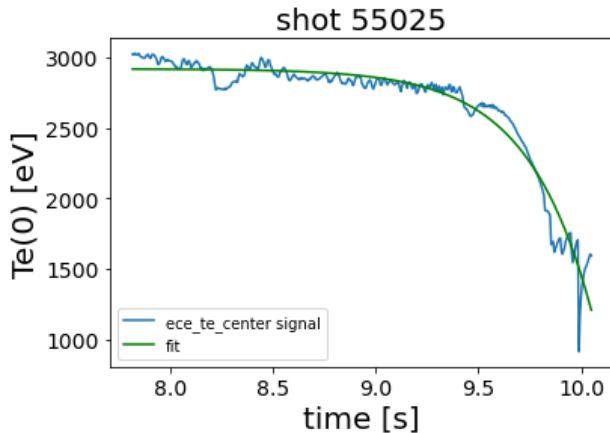
- Why are there two branches;
- Why the **25%** of the **discharges** in the hot branch **collapse**.

- **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.**

Automatic identification of radiative collapses within plateaus:

*exponential fit: $T_e(0) = -e^{(a+bt)} + c$
with $a < 0$ for the concavity,*

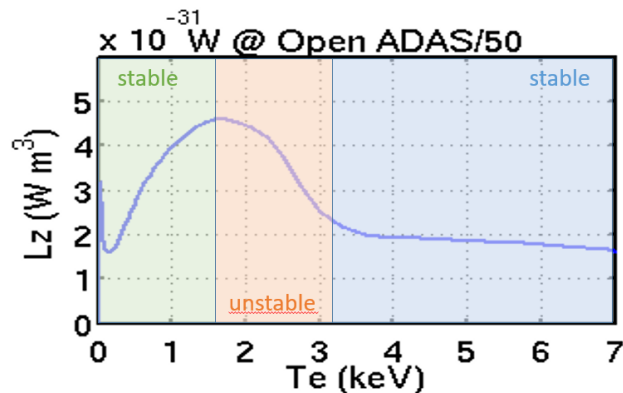
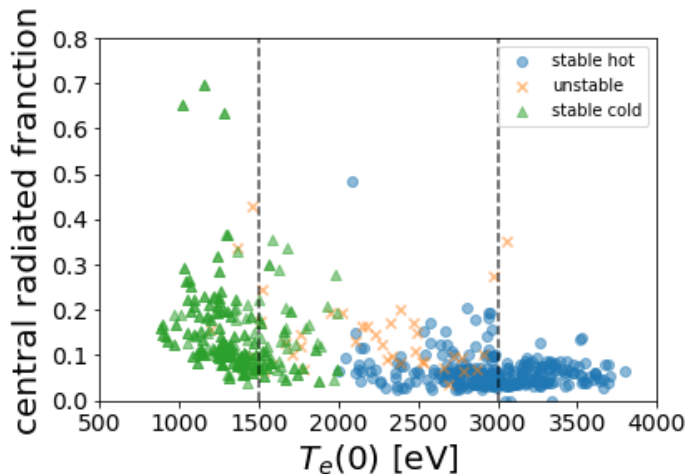
*linear function fit
with **slope** < -830*



Three categories identified:

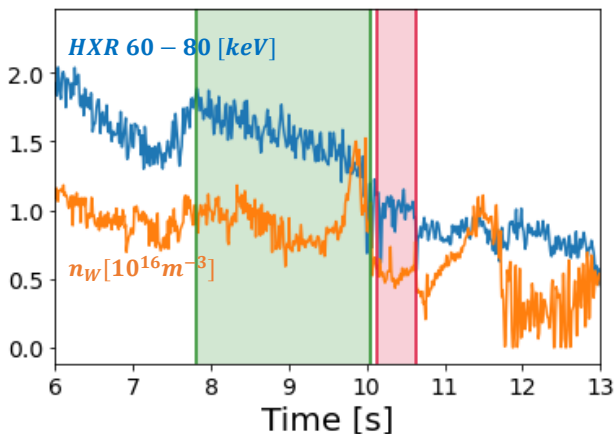
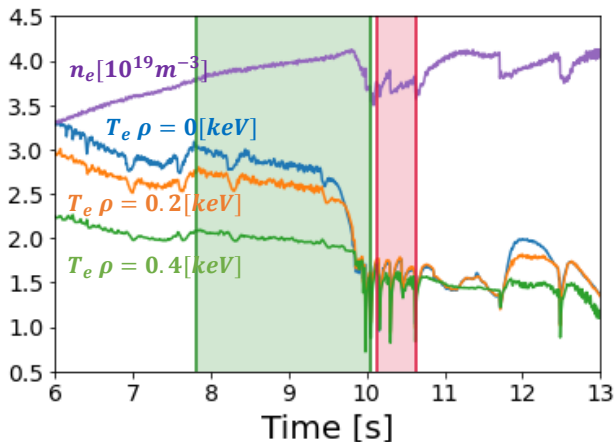
unstable plateaus where a collapse takes place, **cold stable plateaus** and remaining plateaus called **stable hot**.

Unstable plateaus consistent with W cooling factor unstable range



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.



Prior to the collapse:

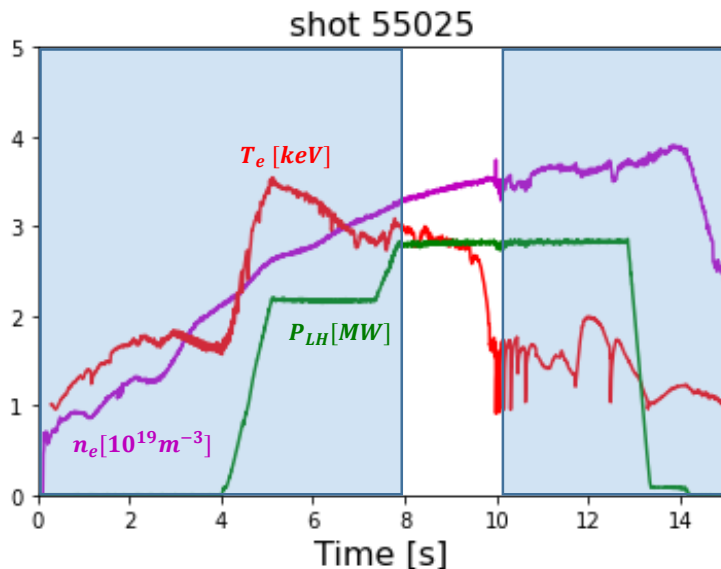
- a slow **increase** of **electron density**;
- a slow **decrease** of **electron temperature**;
- a **constant W** density;
- a slow **decrease** of central **HXR signal**: signature of a lower fast electron production by **LHCD**.

This complex interplay requires **integrated modelling**.

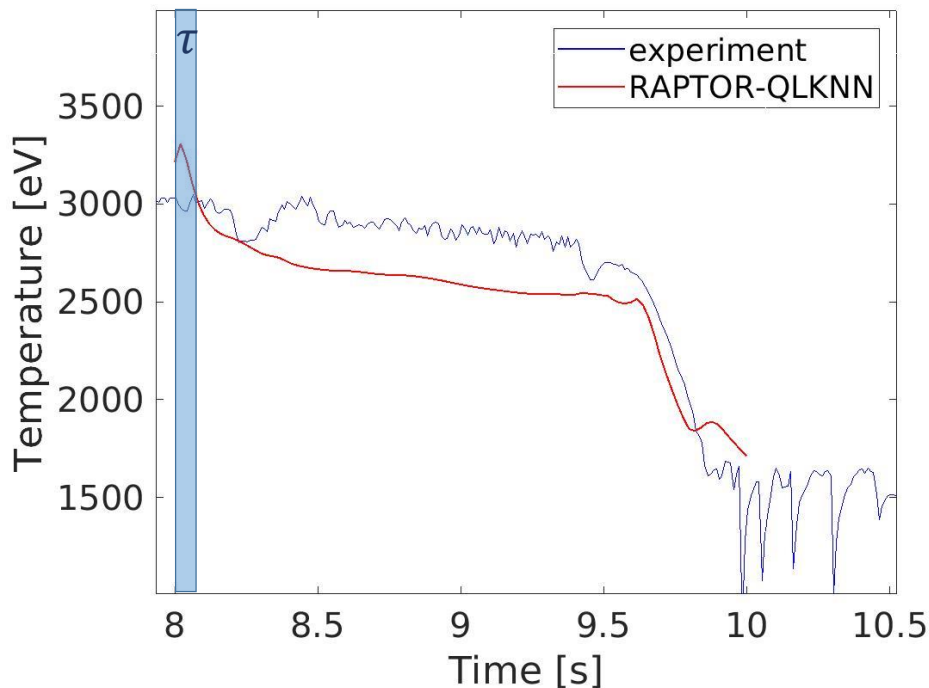
- Context;
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The 1D transport code **RAPTOR** is used to simulate the **collapse**. [F. Felici NF 2018]

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

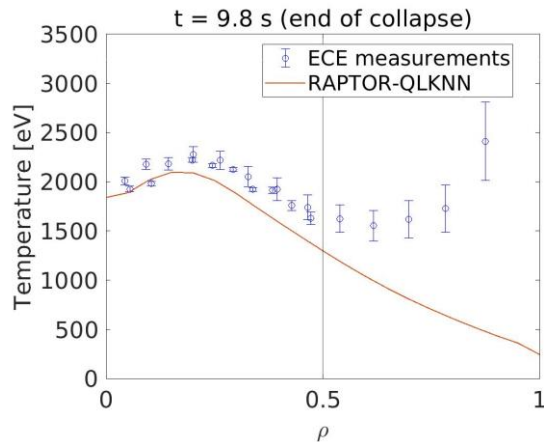
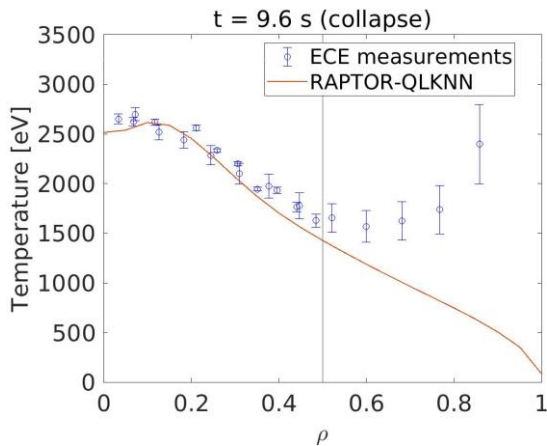
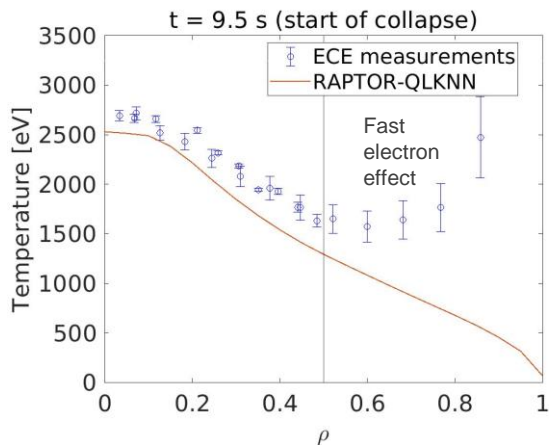


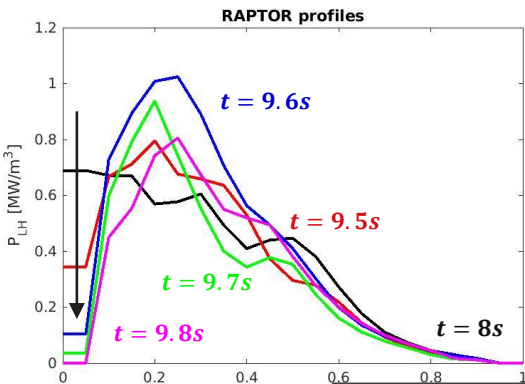
T_e and T_i	Predicted using QLKNN-10D
P_{LHCD}	LUKE [Peysson FST 2014]
n_e	interpretative
n_w	Interpretative, based on bolometry inversion
P_{rad}	Consistent with ADAS database
$j(r)$	predictive
equilibrium	Self-consistent inside a fixed LCFS



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

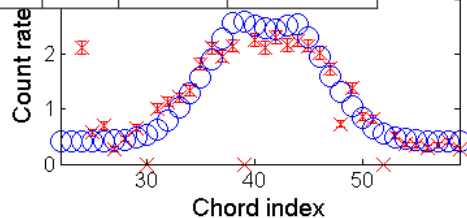
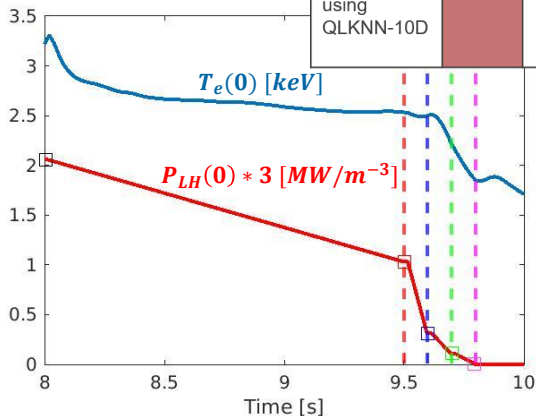




The **power deposition** in the very **core** cannot be computed with the required spatial accuracy. The **central value is adjusted** in time **to match the temperature** evolution.

A progressive **decrease** of the core electron heating by **LHCD** occurs during the slow density rise. Then it is **amplified** before the **radiative collapse**

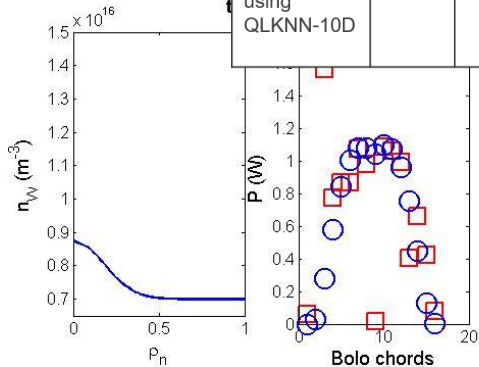
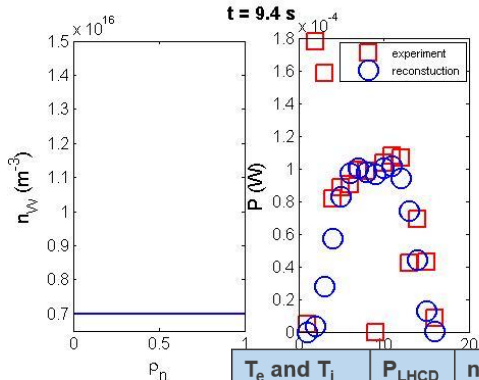
T_e and T_i	P_{LHCD}	n_e	n_w	P_{rad}	$j(r)$	equilibrium	keV
Predicted using QLKNN-10D	LUKE	interpretative	Interpretative, based on bolometry inversion	ADAS	predictive	Self-consistent inside a fixed LCFS	function



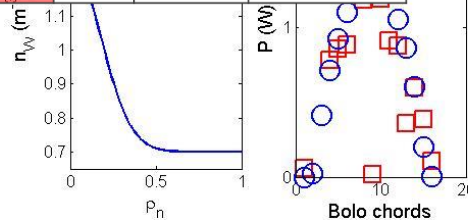
W profile obtained using bolometry measurements

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**.

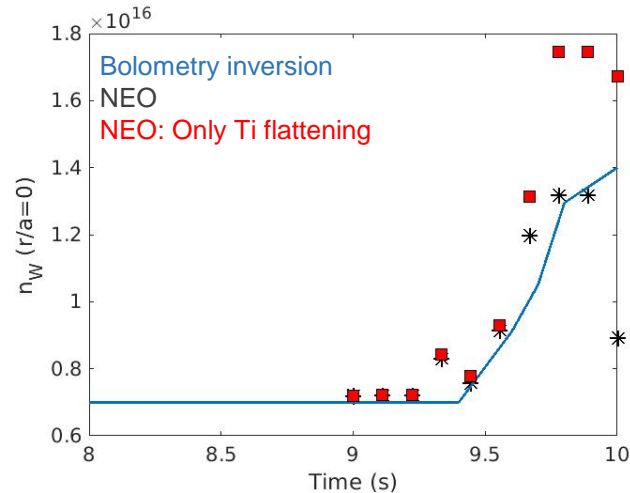
The 16 horizontal **bolometry chords** are used **to constrain the W profile** for $T_e > 1 \text{ keV}$ only, where the L_W are known.



T_e and T_i	P_{LHCD}	n_e	n_w	P_{rad}	$j(r)$	equilibrium
Predicted using QLKNN-10D	LUKE	interpretative	Interpretative, based on bolometry inversion	ADAS	predictive	Self-consistent inside a fixed LCFS



W peaking during central T_e collapse captured by reduced neoclassical T_i screening



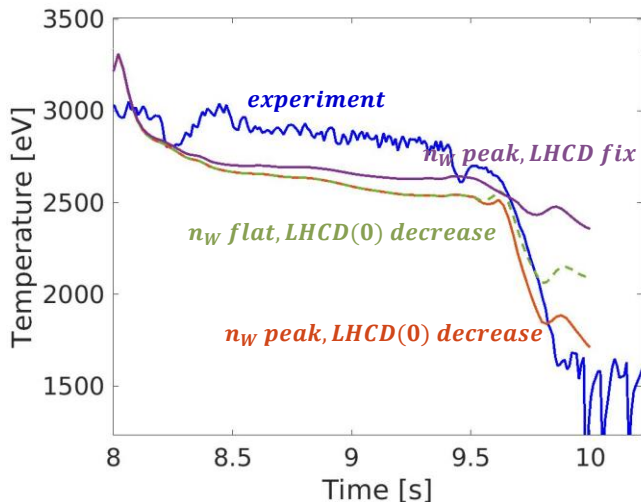
Neoclassical and turbulent transport computed with NEO [Belli 2008]

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

In very good quantitative agreement with bolometry inferred tungsten density

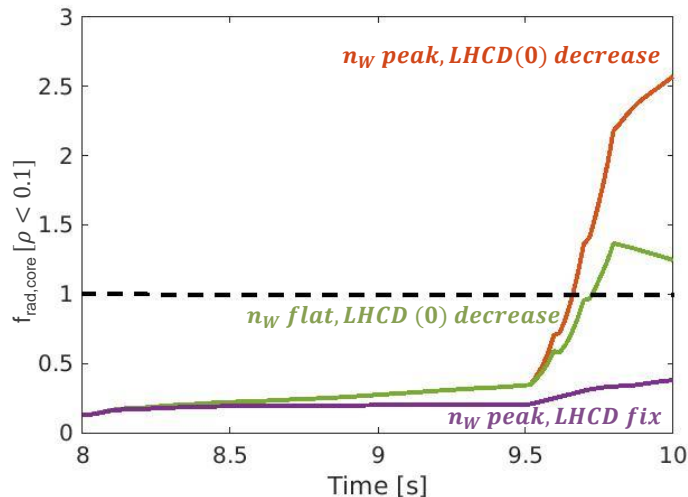
W peaking increases strongly due to a core T_e flattening, leading to T_i flattening by equipartition, hence **reducing** the neoclassical **T screening effect**.

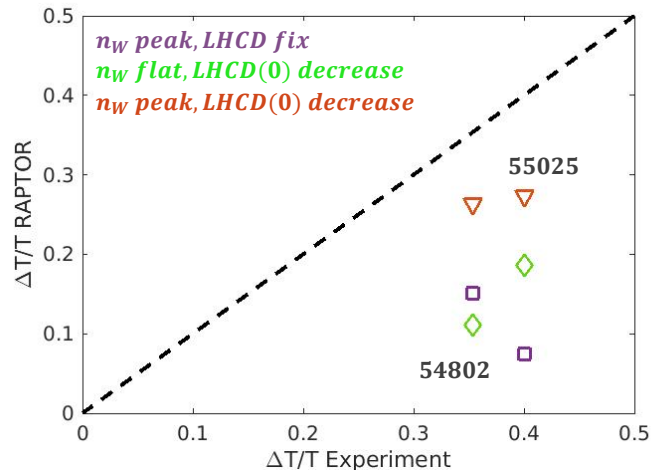
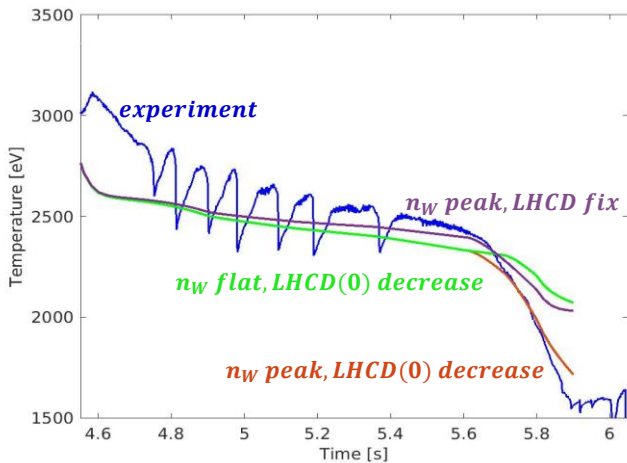
Tungsten peaking and LHCD core absorption reduction are both needed for the collapse



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.

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





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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- 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



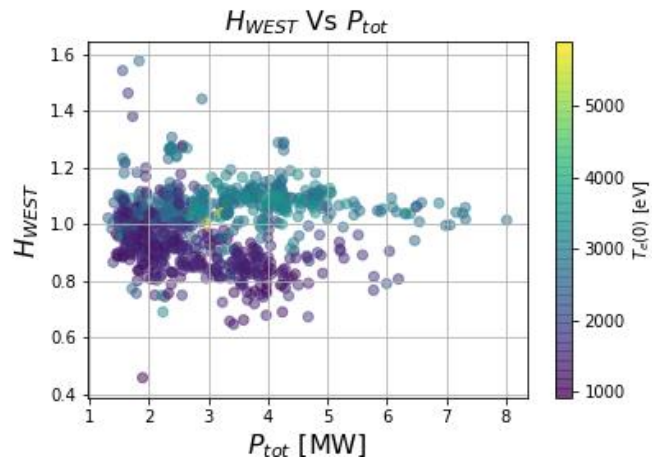
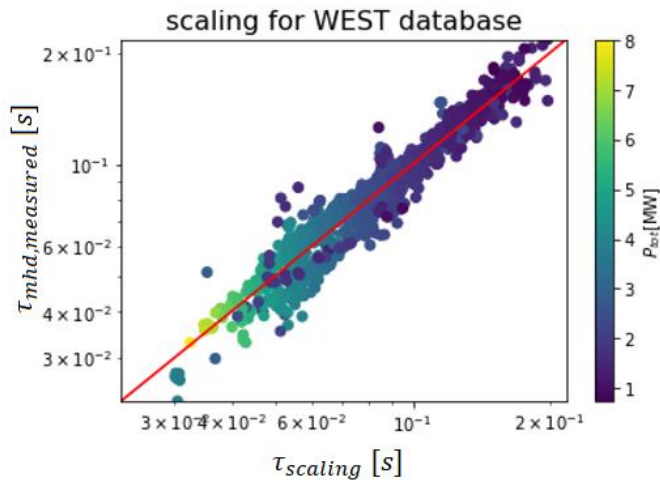
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BACK UP SLIDES

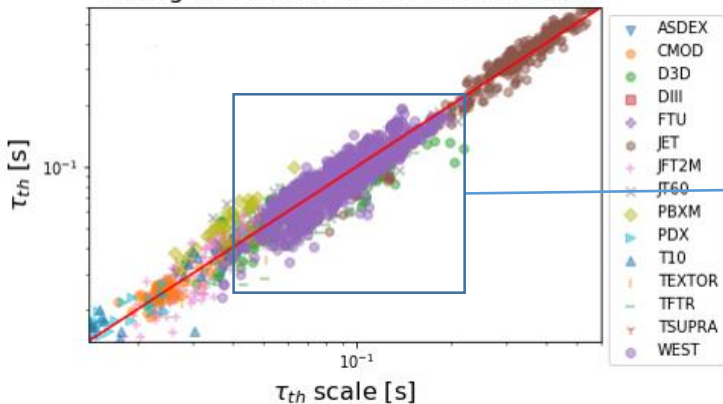
H_{WEST} for quantifying the quality of the confinement time

$$\tau_{mhd,measured} = \frac{W_{mhd}}{P_{tot}} = \frac{\frac{3}{2} \int_V P dV}{P_{ohmic} + P_{aux}}$$

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



scaling for ITER96L with WEST database



Filter:

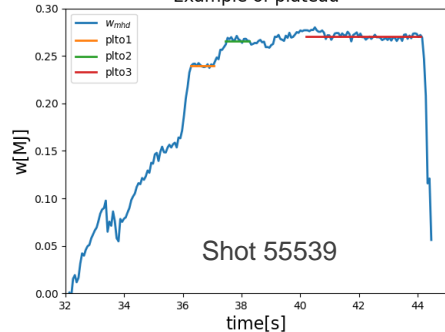
- Small reconstruction errors;
- Diverted plasma;
- L-mode plateaus;
- LSN
- Only deuterium shots

$$\tau = C I_p^{\alpha_{I_p}} B^{\alpha_B} P_{tot}^{\alpha_P} n_e^{\alpha_{n_e}} M^{\alpha_M} R^{\alpha_R} \epsilon^{\alpha_\epsilon} k^{\alpha_k}$$

$$\begin{aligned} \alpha_{I_p} &= 1.35 \\ \alpha_{n_e} &= -0.16 \\ \alpha_{P_{tot}} &= -0.75 \end{aligned}$$

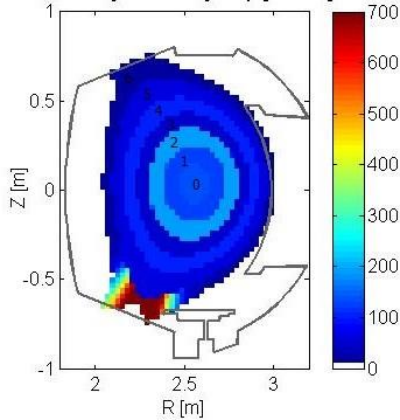
$$\tau_{scaling}$$

Example of plateau

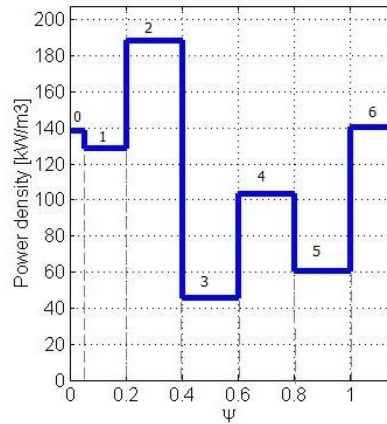


Bolometry tomography to compute the power emission density profile

55025 bolometry emissivity map [kW/m³] 8<t<8.5



55025 inversion profile 8<t<8.5

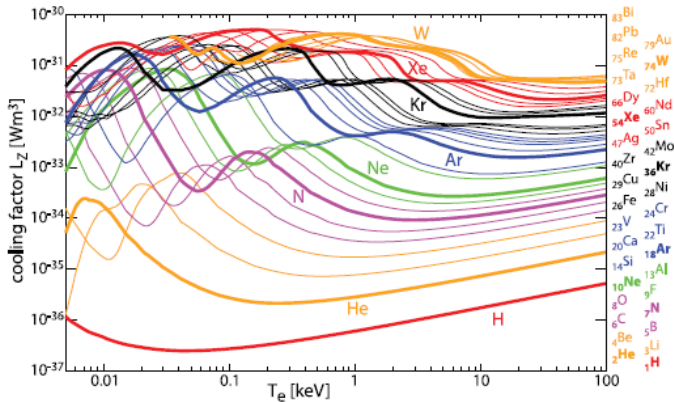


A **bolometer** measures a line-integrated value of the **local radiative emissivity** along a viewing line of sight.

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

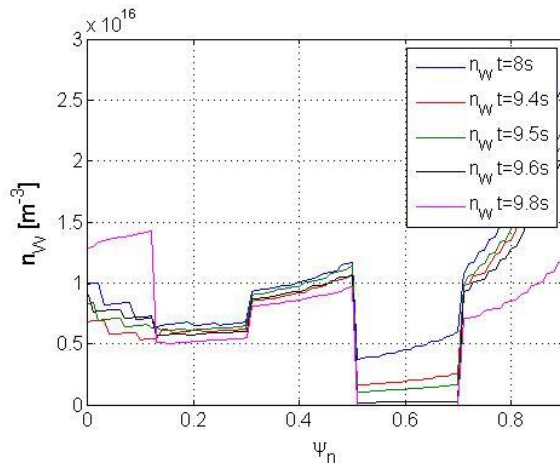
The **power emission** in $\frac{W}{m^3}$ for each layer are estimated.

Tungsten density profiles from the inverse of bolometry

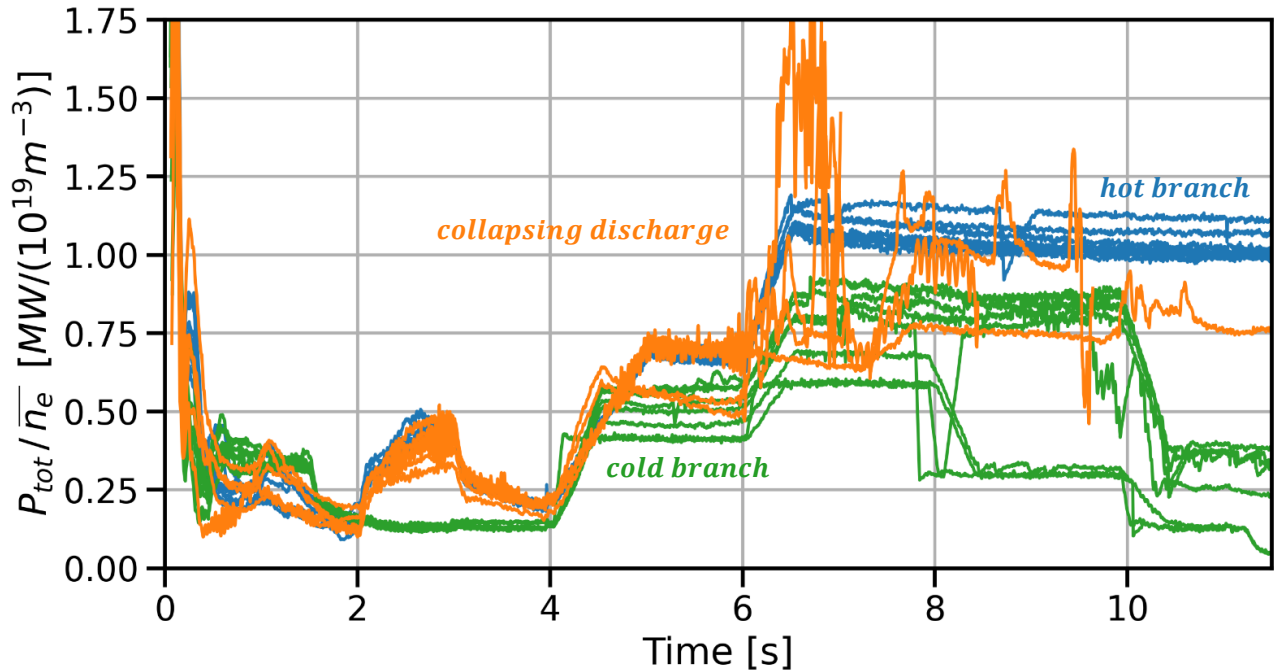


Above **1KeV** the **main radiator** is the **tungsten**.

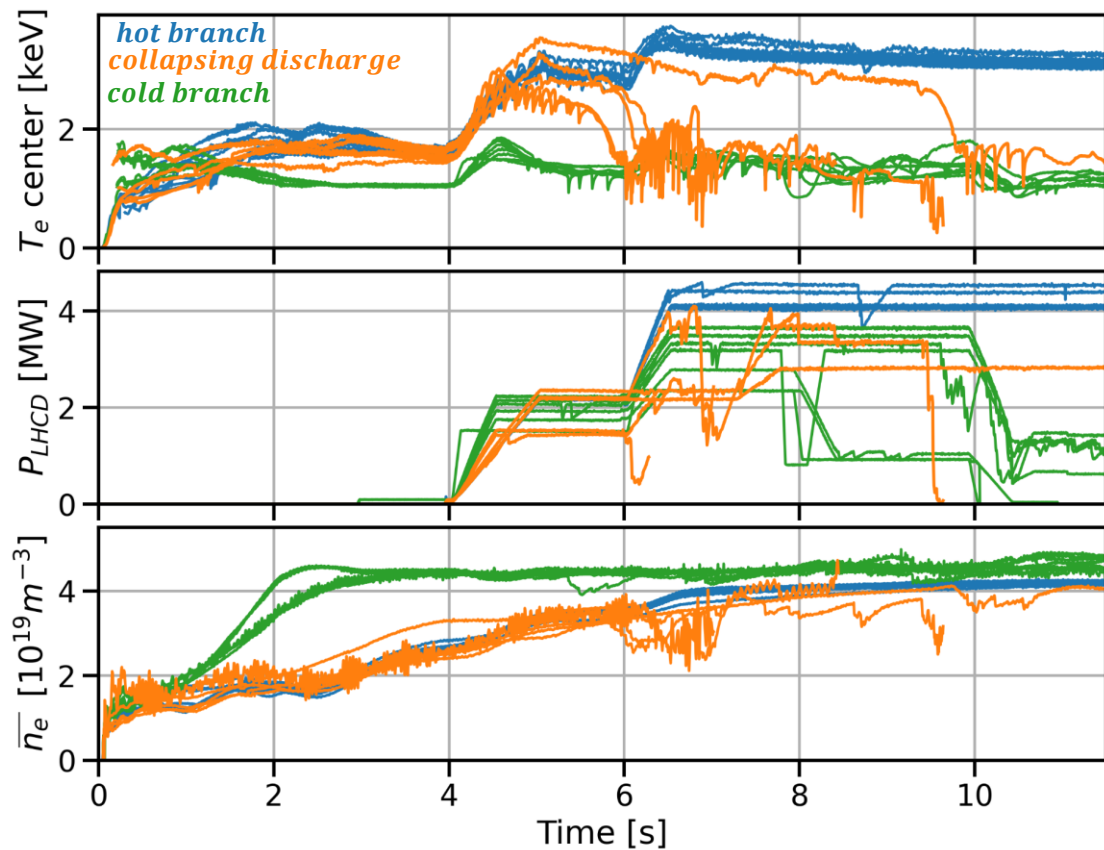
Assuming that all the **emission radiation** comes from the **tungsten**, it is possible to use the inverse of bolometry to compute **its density** at each layer.



$$n_W \approx \frac{P_{rad,W}}{n_e L_W(T_e)}$$



P_{LH} and $n_{e,vol}$ for hot and cold branches and collapsing discharges



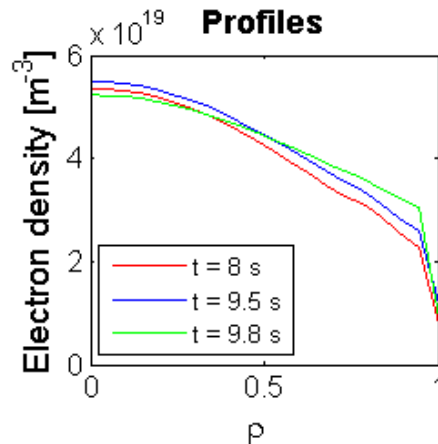
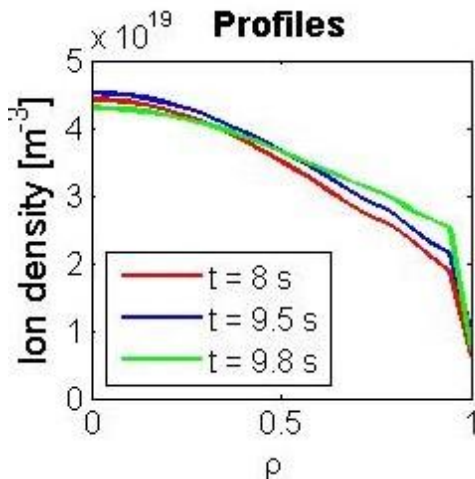
W neoclassical transport (in absence of poloidal asymmetries)

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

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_{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.