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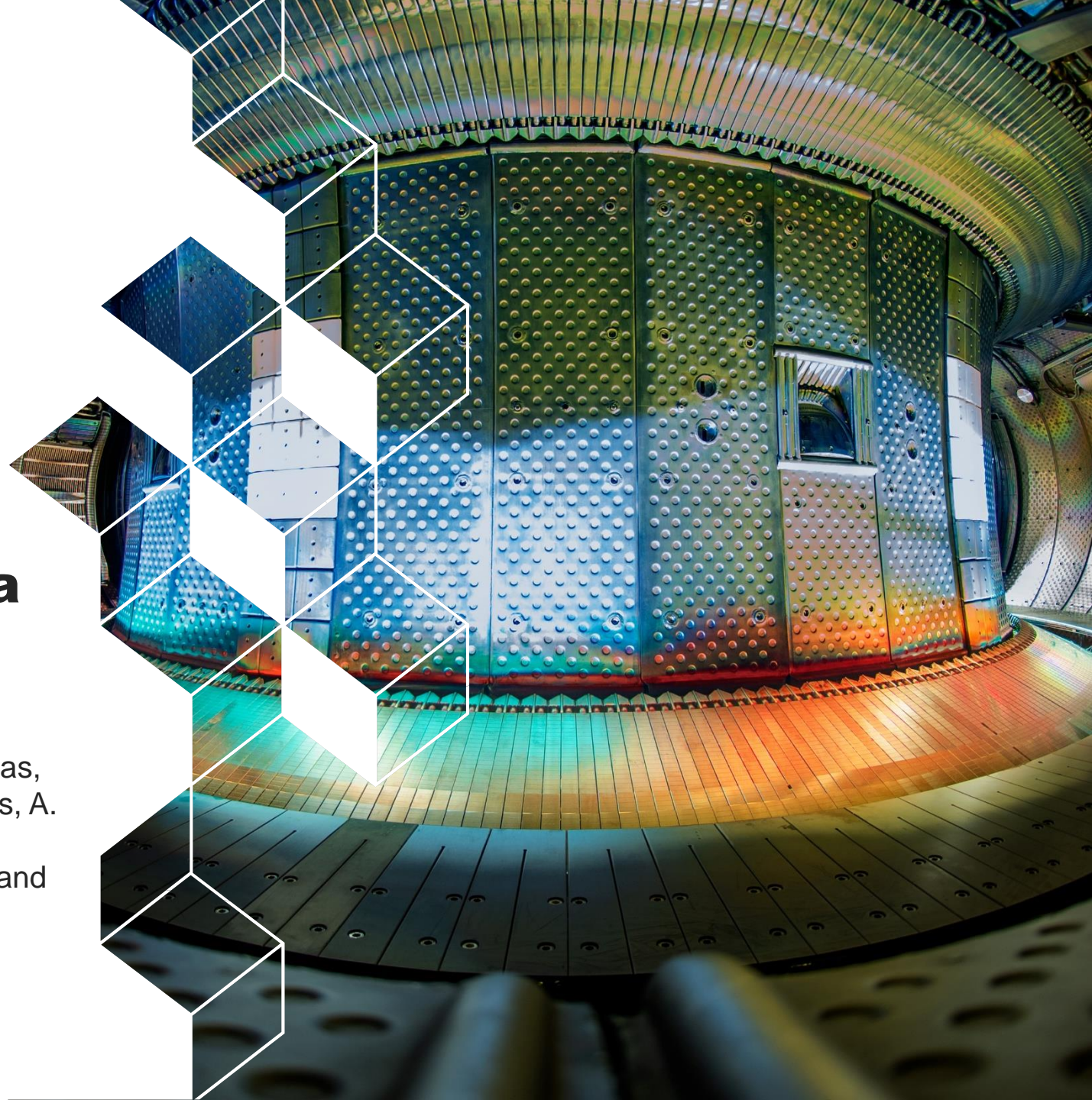


irfm

Improving physical understanding and plasma performances in WEST

J. Morales, C. Bourdelle, V. Ostuni, J.-F. Artaud, P. Manas, P. Maget, R. Dumont, H. Ancher, L. Dubus, M. Doménès, A. Ekedahl, N. Fedorczak, L. Fleury, C. Gil, J. Hillairet, F. Imbeaux, P. Maini, D. Moiraf, V. Moncada, Ph. Moreau and WEST team (west.cea.fr/WESTteam)

49th EPS Plasma Conference, Bordeaux, 3-7 July 2023



Introduction

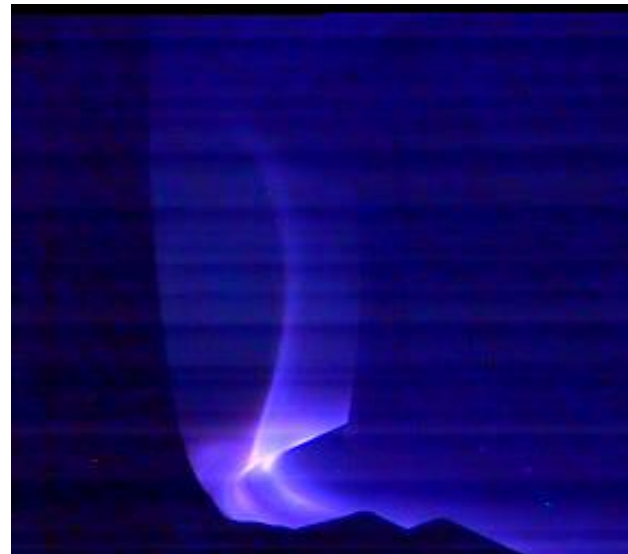
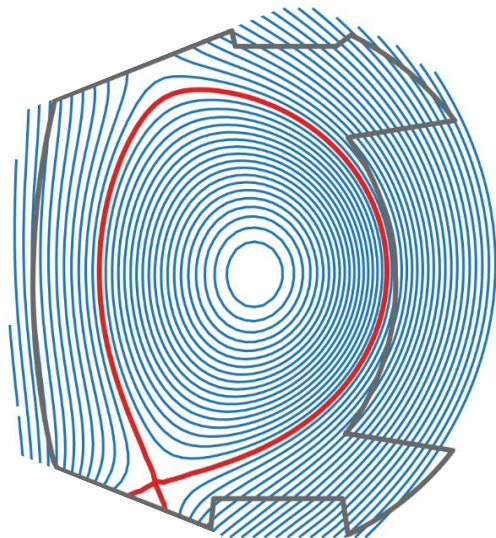


WEST is a device specialized for long pulse operation in a tungsten environment. Testbed for ITER divertor technology (actively cooled tungsten mono-blocks)

Main goal: develop reactor compatible long pulse scenarios

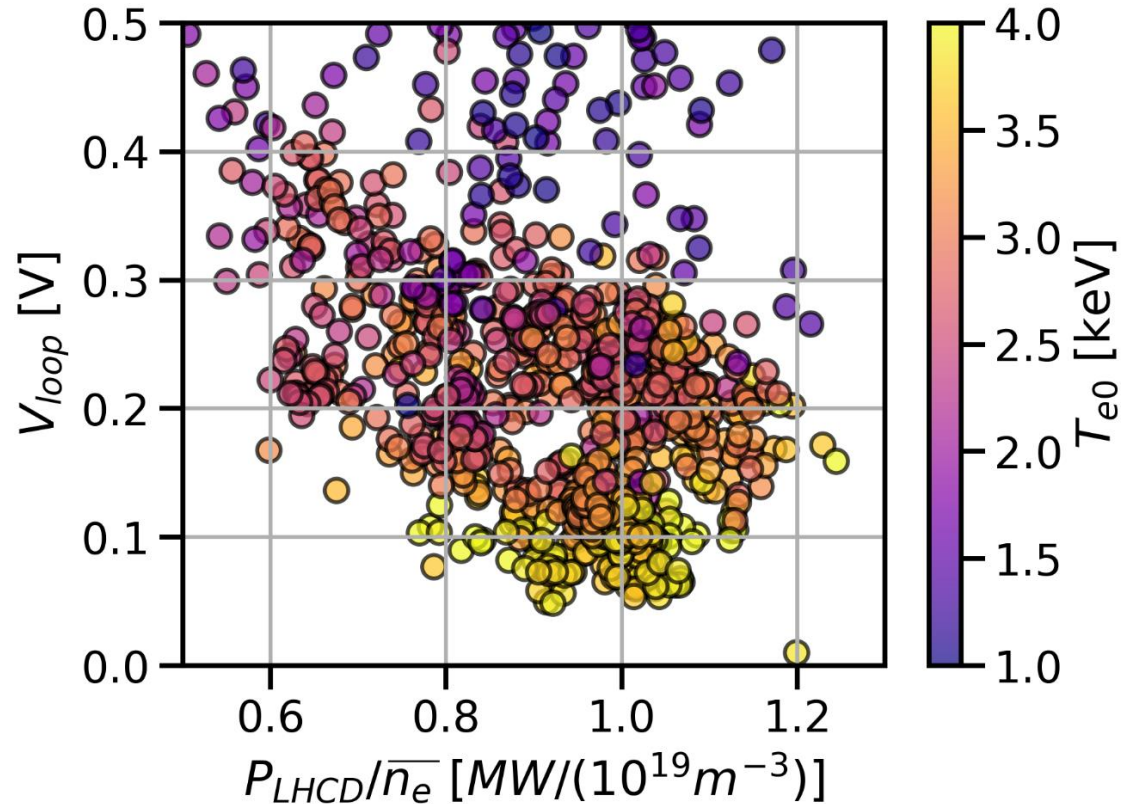
[Bucalossi, Nucl. Fusion, 2021]

[Bourdelle, Nucl. Fusion, 2015]



$I_p (q_{95} \sim 2.5)$	1 MA
B_T	3.7 T
R	2.5 m
a	0.5 m
$n_{GW} (1MA)$	$1.5 \cdot 10^{20} \text{ m}^{-3}$
P_{ICRH}	9 MW
P_{LHCD}	7 MW
$\text{time}_{\text{flattop}}$	1000 s

Access to long pulse operation in a tungsten environment



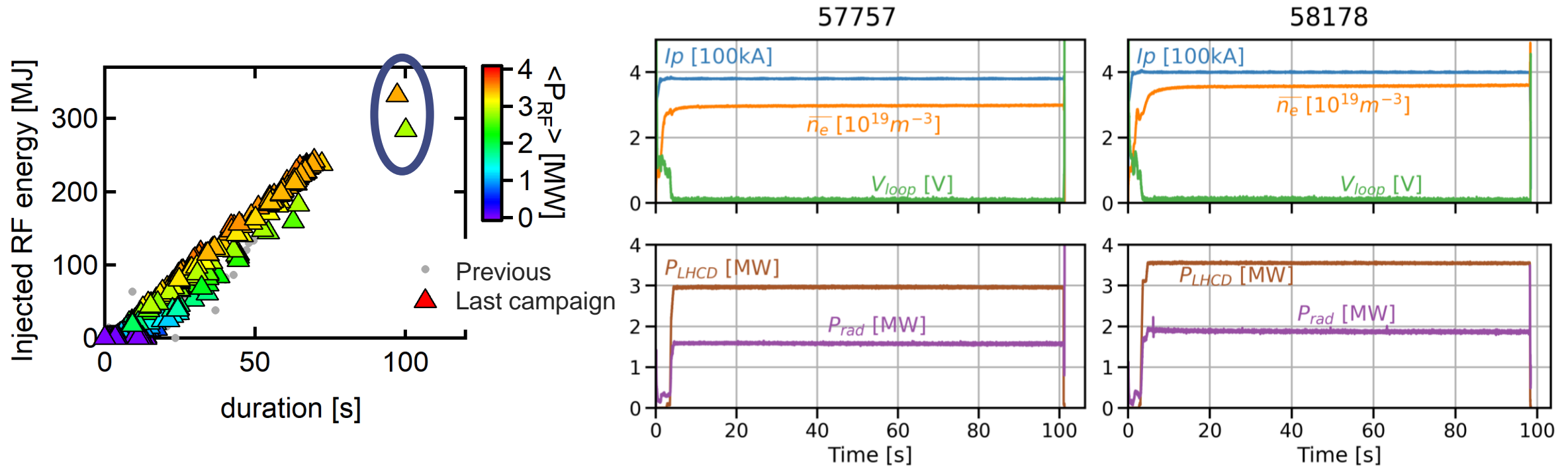
How?

To achieve **long pulses** we need **low loop voltages** (less than 100 mV)

- it is essential to achieve hot plasmas (central electron temperature $T_{e0} > 3$ keV)

P_{LHCD} = Lower Hybrid Current Drive power
 \bar{n}_e = averaged line integrated density

This year experimental campaign achievement: 100s plasma discharge in WEST



- Several hundred pulses with 1 min length
- Pulse 57757: $V_{loop} \sim 50\text{mV}$ during 101s with 3MW LHCD power (injected energy $\sim 290\text{MJ}$)
- Pulse 58178: $V_{loop} \sim 70\text{mV}$ during 98s with 3.6MW LHCD power (injected energy $\sim 340\text{MJ}$)

Access to long pulse operation in a tungsten environment

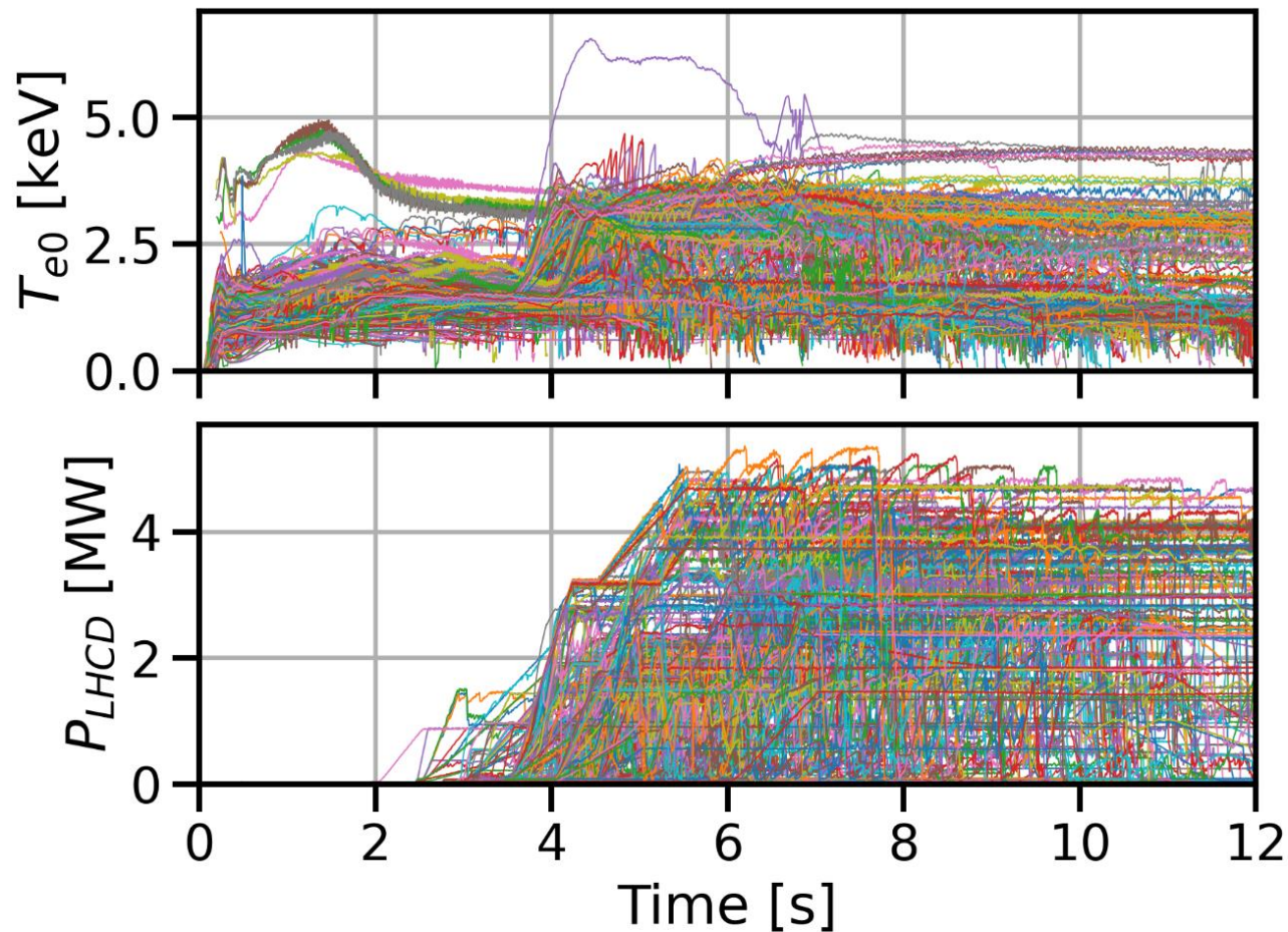
Outline

- Tools for experimental database analysis
- Classification of LHCD heated discharges
- Three main constraints:
 1. the power reflected back to LHCD antennas needs to be below a specified threshold,
 2. in order to burn-through tungsten, density must not exceed an upper limit during LHCD power ramp-up,
 3. fast electron ripple losses must be limited (not in this presentation).
- Physical understanding from integrated modelling

LHCD = Lower Hybrid Current Drive

How efficiently analyze entire experimental campaigns?

Example: 764 pulses from C4 campaign



To efficiently characterize several campaigns: development of a numerical tool for **plateau detection on 1D signals**

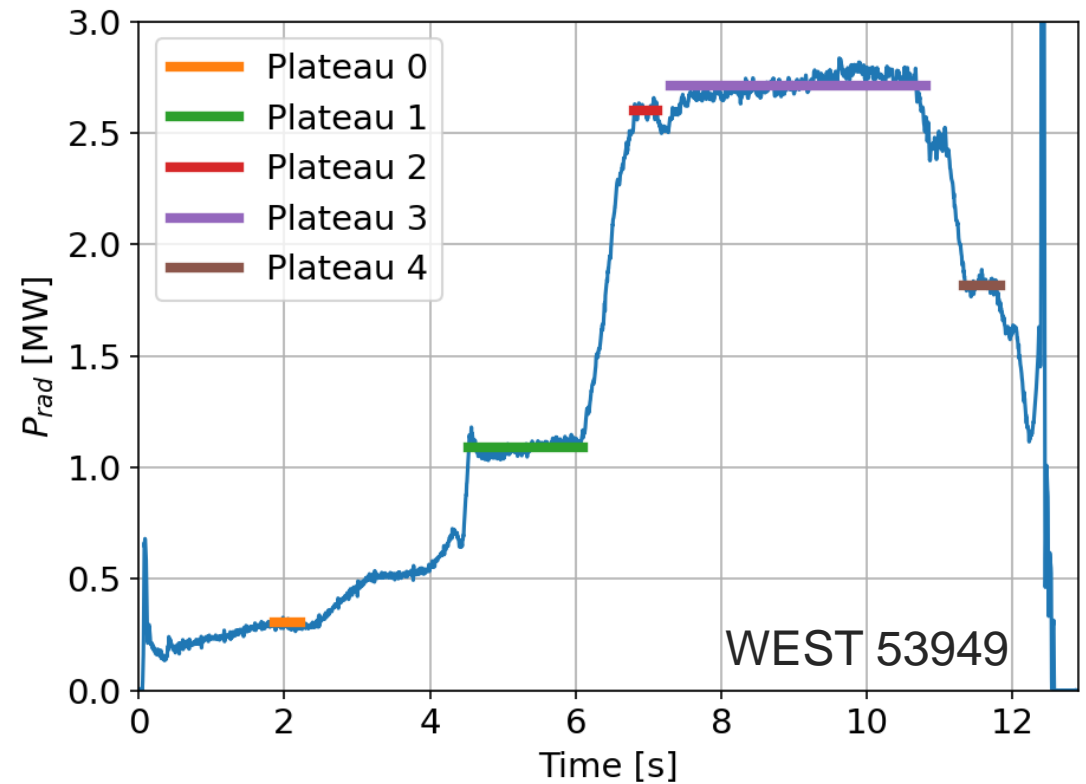
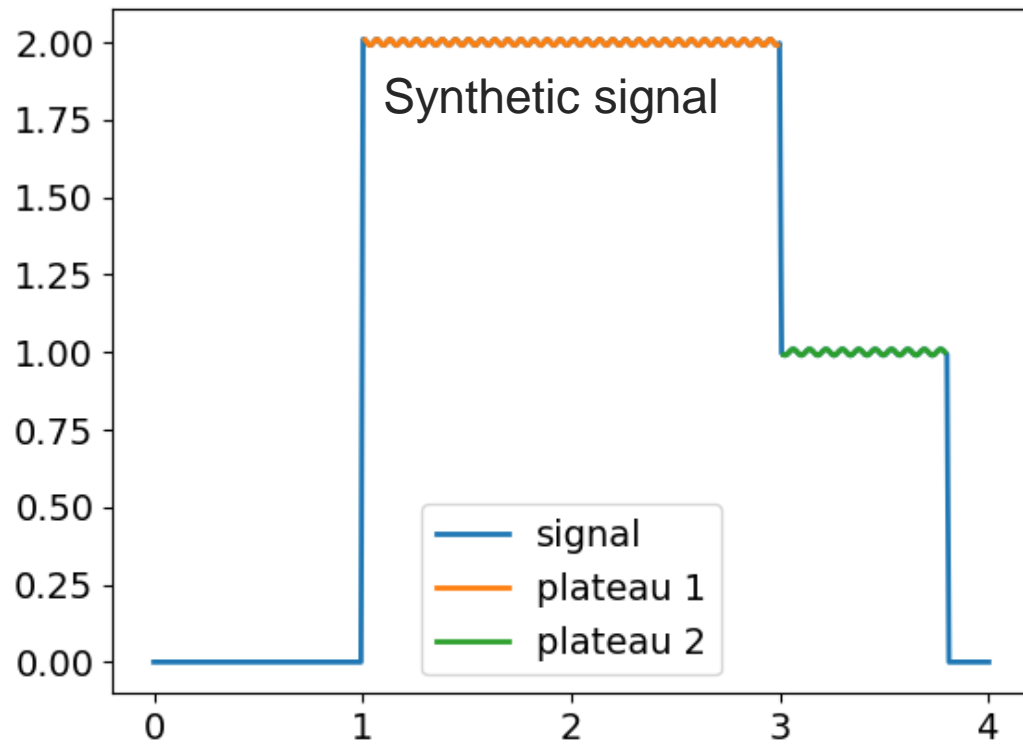
This tool allows to characterize one pulse by a **small number of values**:

1D signal

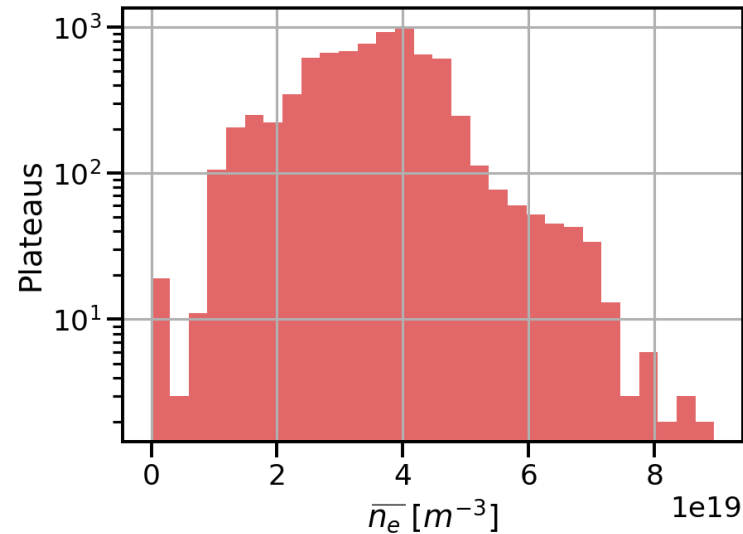
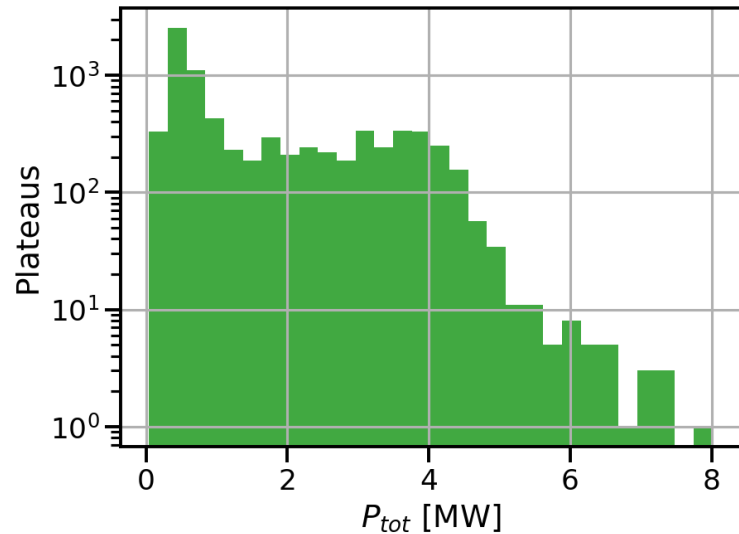
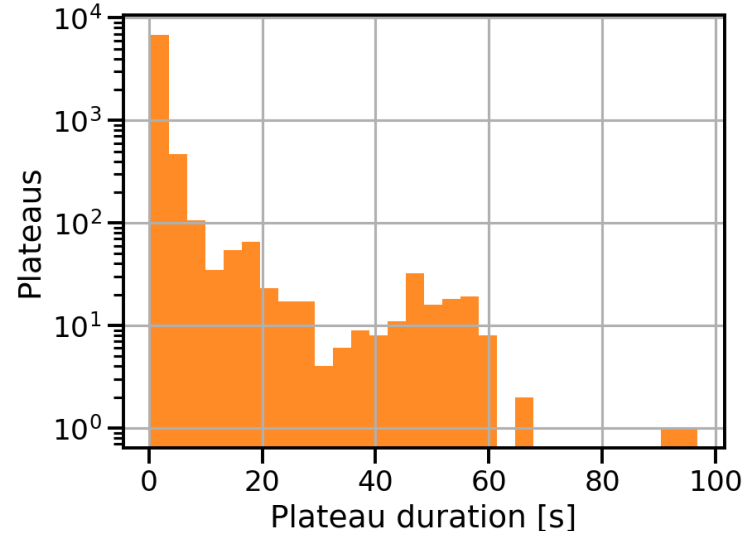
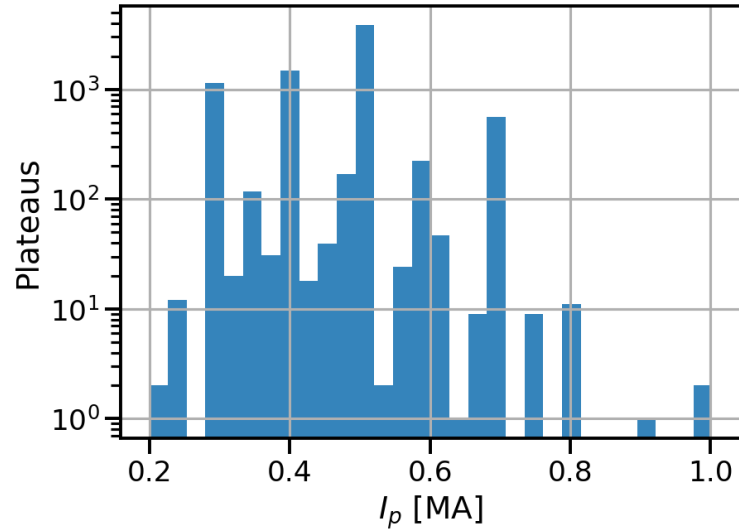
Plateau values:
duration, mean,
standard
deviation...

Plateau detection

- Plateaus (quasi-steady states) are **detected automatically**
- **Code available (open source)** at:
https://github.com/IRFM/signal_plateau_recognition



WEST data



We extract data from IMAS
[Imbeaux, Nucl. Fusion, 2015]

Database includes more than 2000 quantities (as I_p , P_{tot} ...) and 7700 plateaus from 2500 pulses

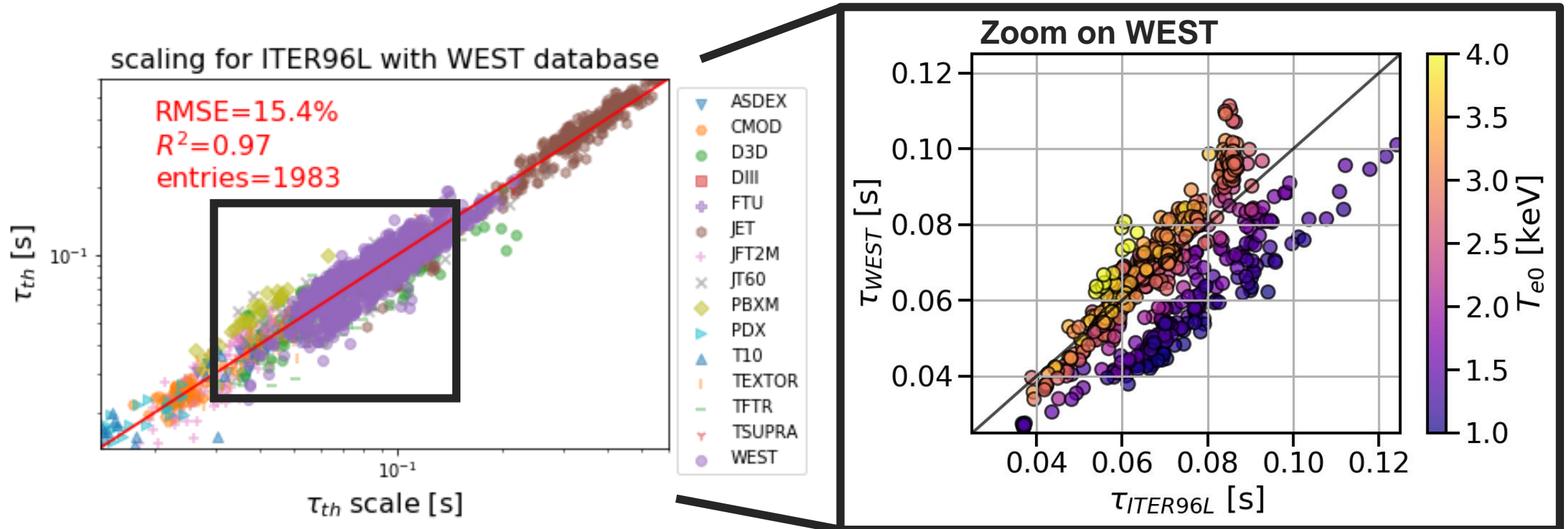
Histogram data: mean quantities in identified plateaus during WEST C4 to C7 campaigns (2019-2023)

Access to long pulse operation in a tungsten environment

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- Physical understanding from integrated modelling

Hot and cold branches in WEST

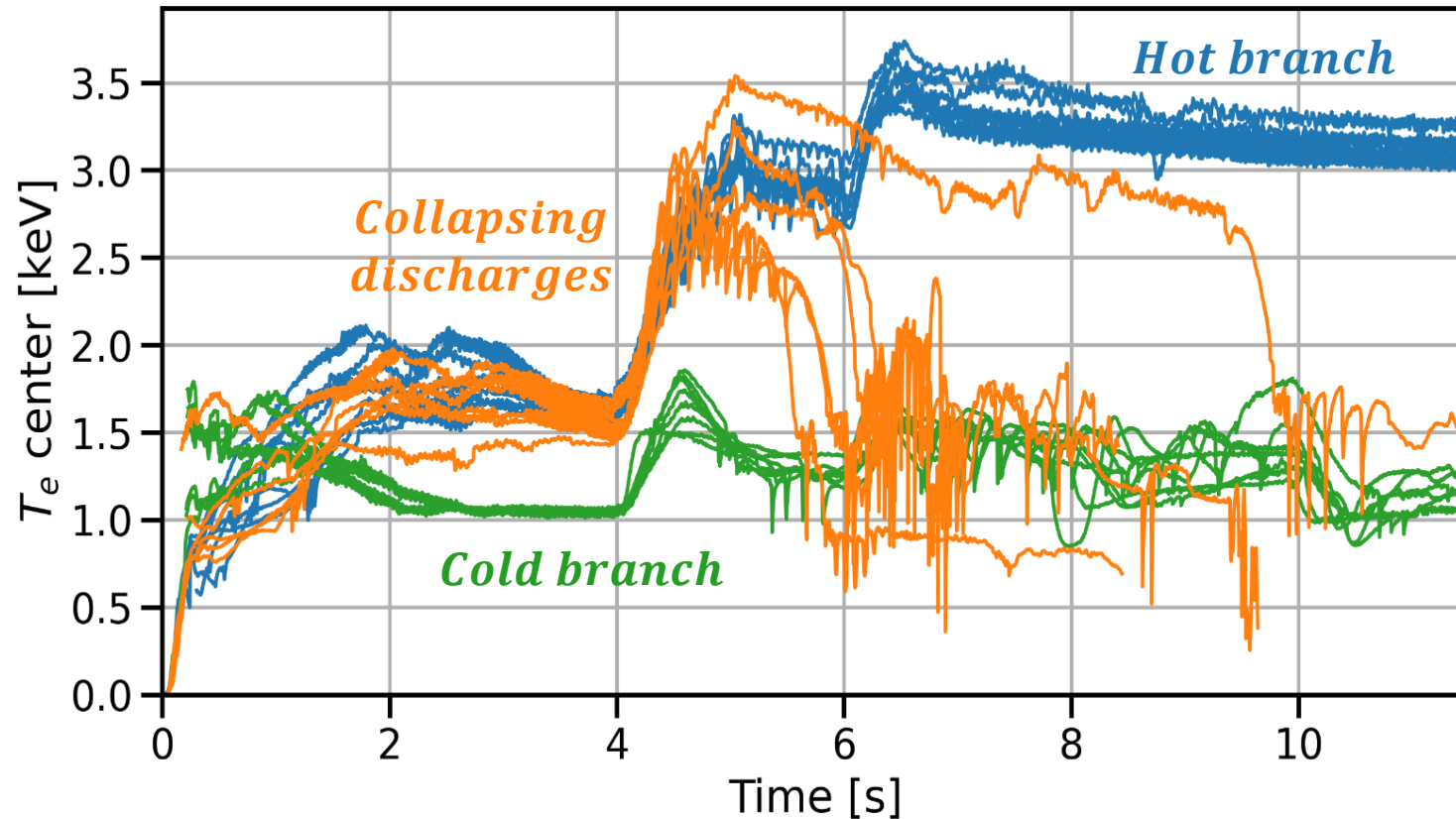


$$\tau_{ITER96L} = 0.023 I_p^{0.96} B^{0.03} P^{-0.73} n_e^{0.4} M^{0.2} R^{1.83} \epsilon^{-0.06} k^{0.64} \text{ [Kaye, NF, 1997]}$$

- Using **plateau averaged quantities**, we find WEST confinement time in L mode **well aligned with ITER96L** scaling law [Goniche, Nucl. Fusion, 2022]
- Two confinement regimes** (clusters) are observed, they are strongly correlated with central temperature (T_{e0}), we call them: **hot and cold branches**

[Ostuni, Nucl. Fusion, 2022]
 [Bourdelle, Nucl. Fusion, 2023]

Type of discharges identified

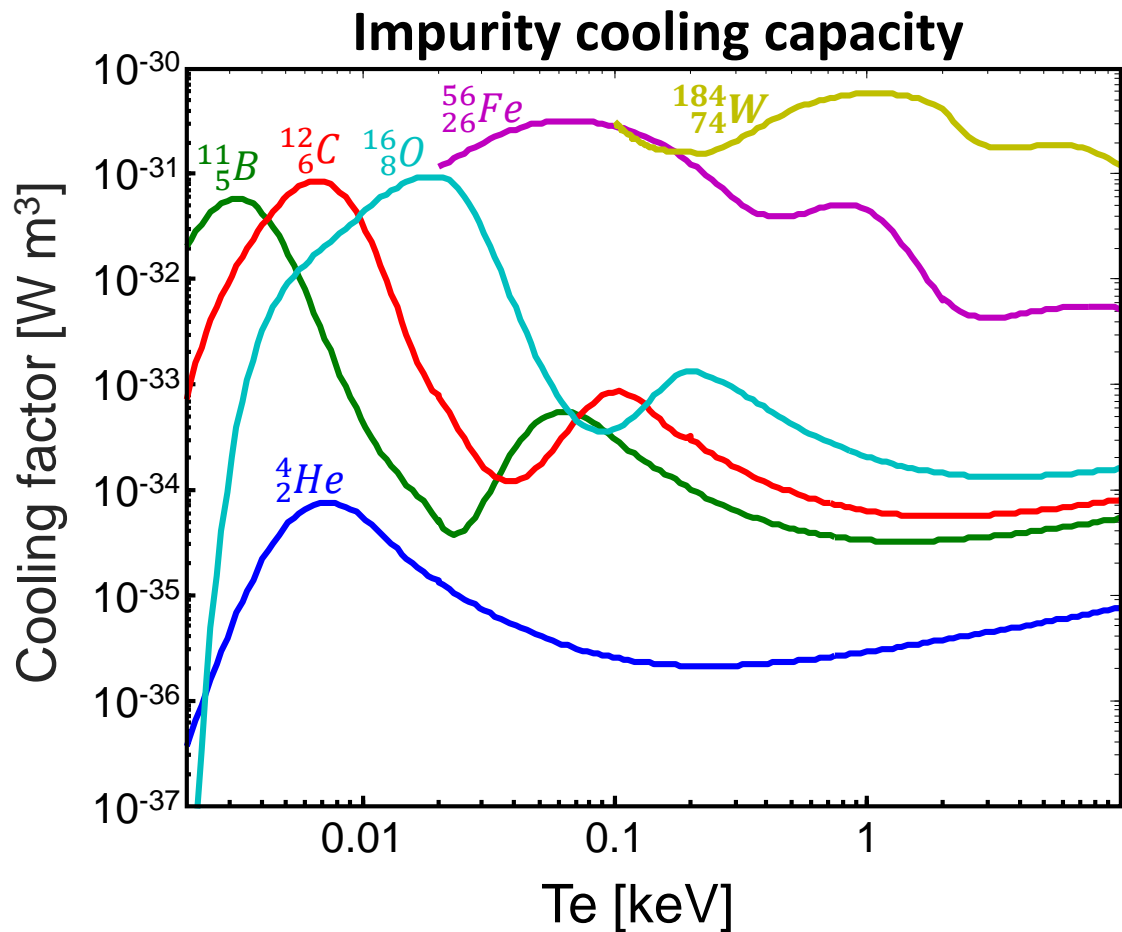


Three different types of discharges are identified:

- Hot branch
- Cold branch
- Collapsing discharges (from hot to cold branch)

[Ostuni, Nucl. Fusion, 2022]

Burn-through plasma impurities



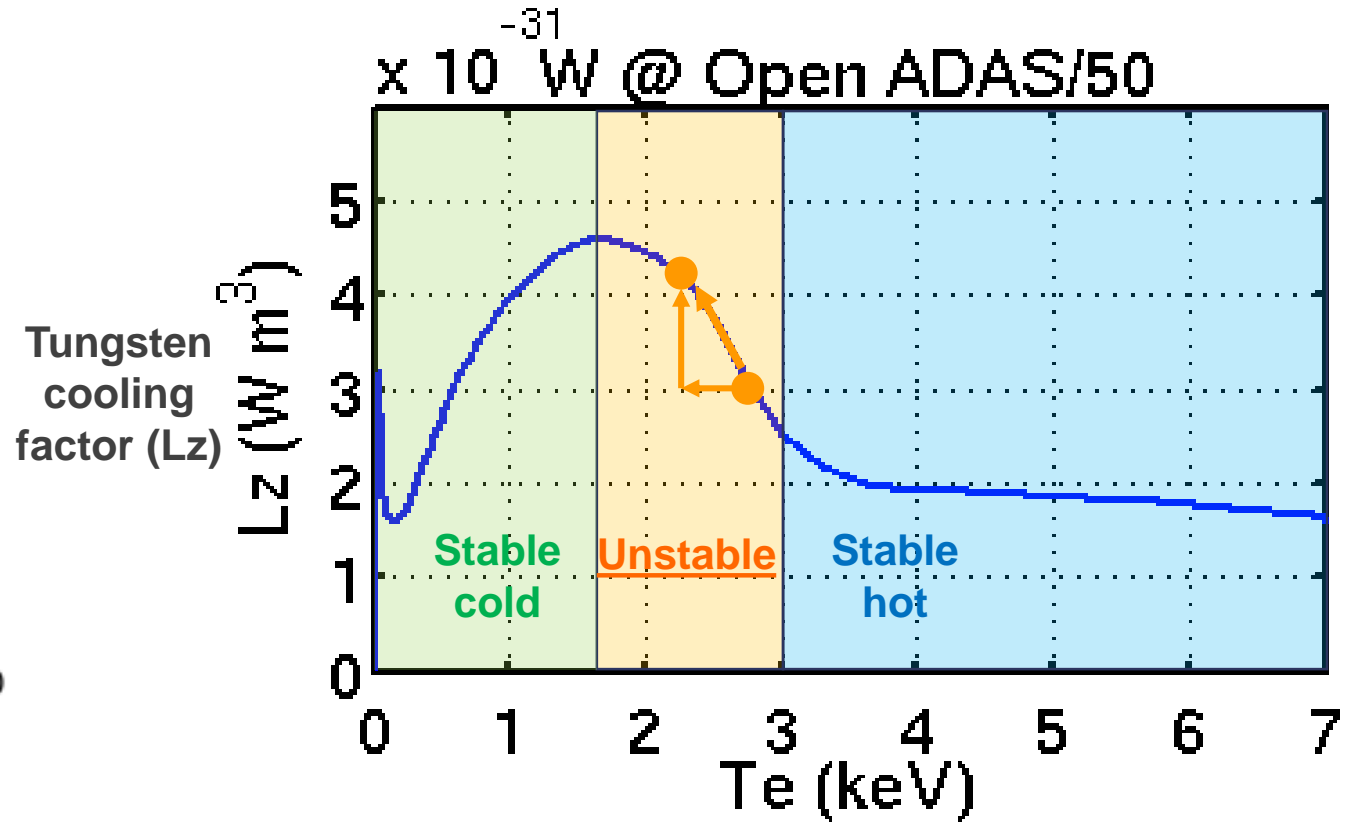
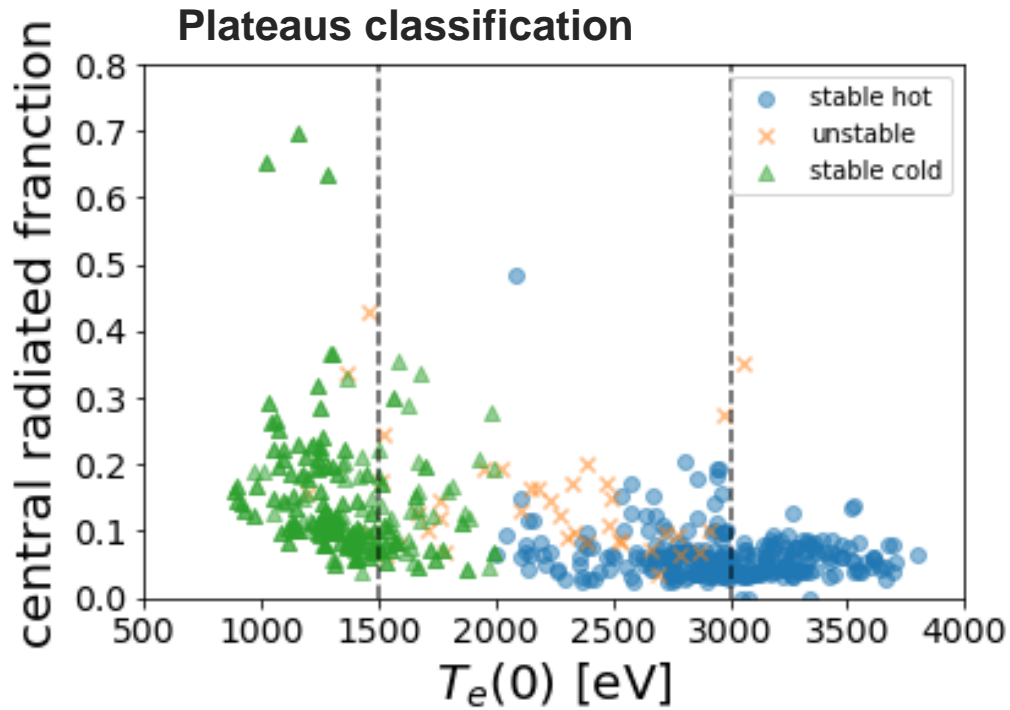
← Tungsten has a very strong cooling capacity

Maximum value in a relatively high temperature range (1 to 2.5 keV)

Tungsten is the prime suspect for **cold branch** and **radiative collapses**

→ **Burn-through**

Burn-through tungsten



Unstable plasmas in the range **1.5 to 3 keV**, in agreement with W cooling factor

$$p_{rad,W} = n_e n_W L_z(T_e)$$

[Ostuni, Nucl. Fusion, 2022]

Access to long pulse operation in a tungsten environment

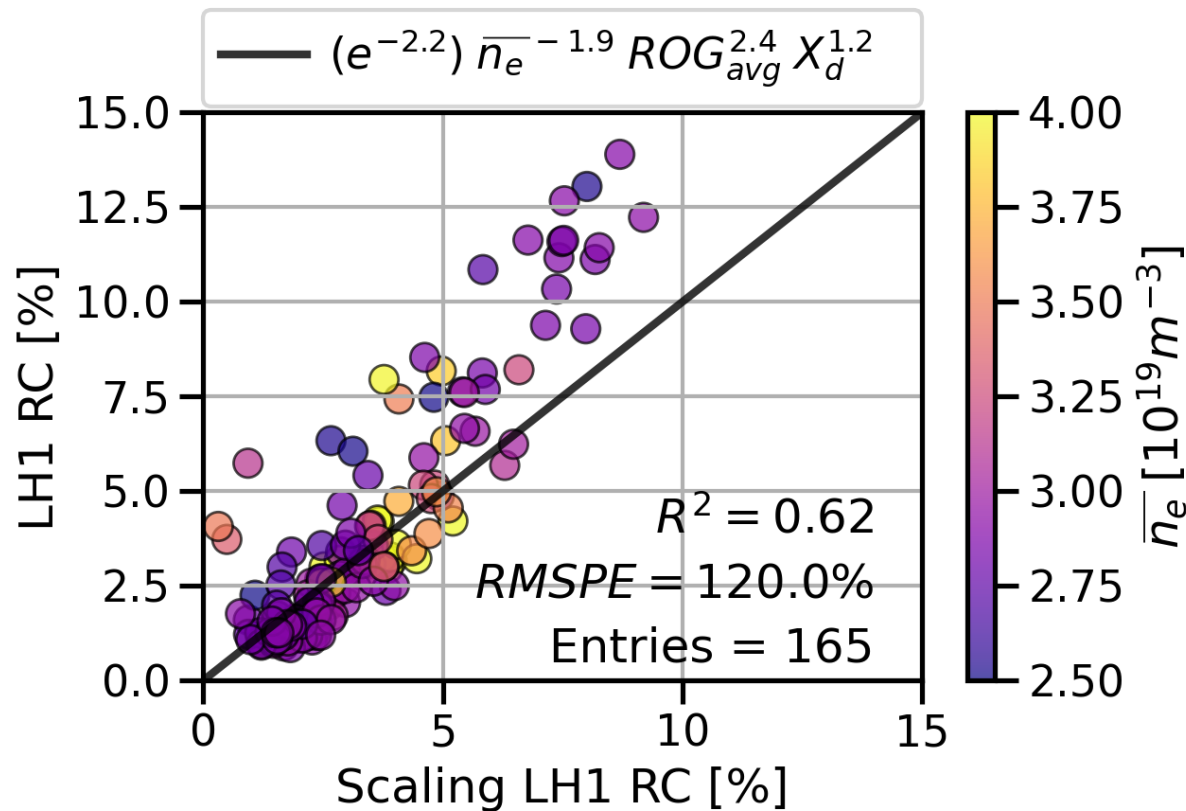
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Lower boundary for density

The stronger constraint is for LH1 antenna averaged reflection coefficient (RC)

RC depends on averaged line integrated density ($\overline{n_e}$), averaged radial outer gap (ROG_{avg}) and X-point height (X_d)



$$\overline{n_{e,min}} = \left(\frac{RC_{max}}{(e^{-2.2}) ROG_{avg}^{2.4} X_d^{1.2}} \right)^{-\frac{1}{1.9}}$$

If we fix standard values for right hand side:

- $RC_{max} = 5\%$
- $ROG_{avg} = 4cm$
- $X_d = 7cm$

Then:

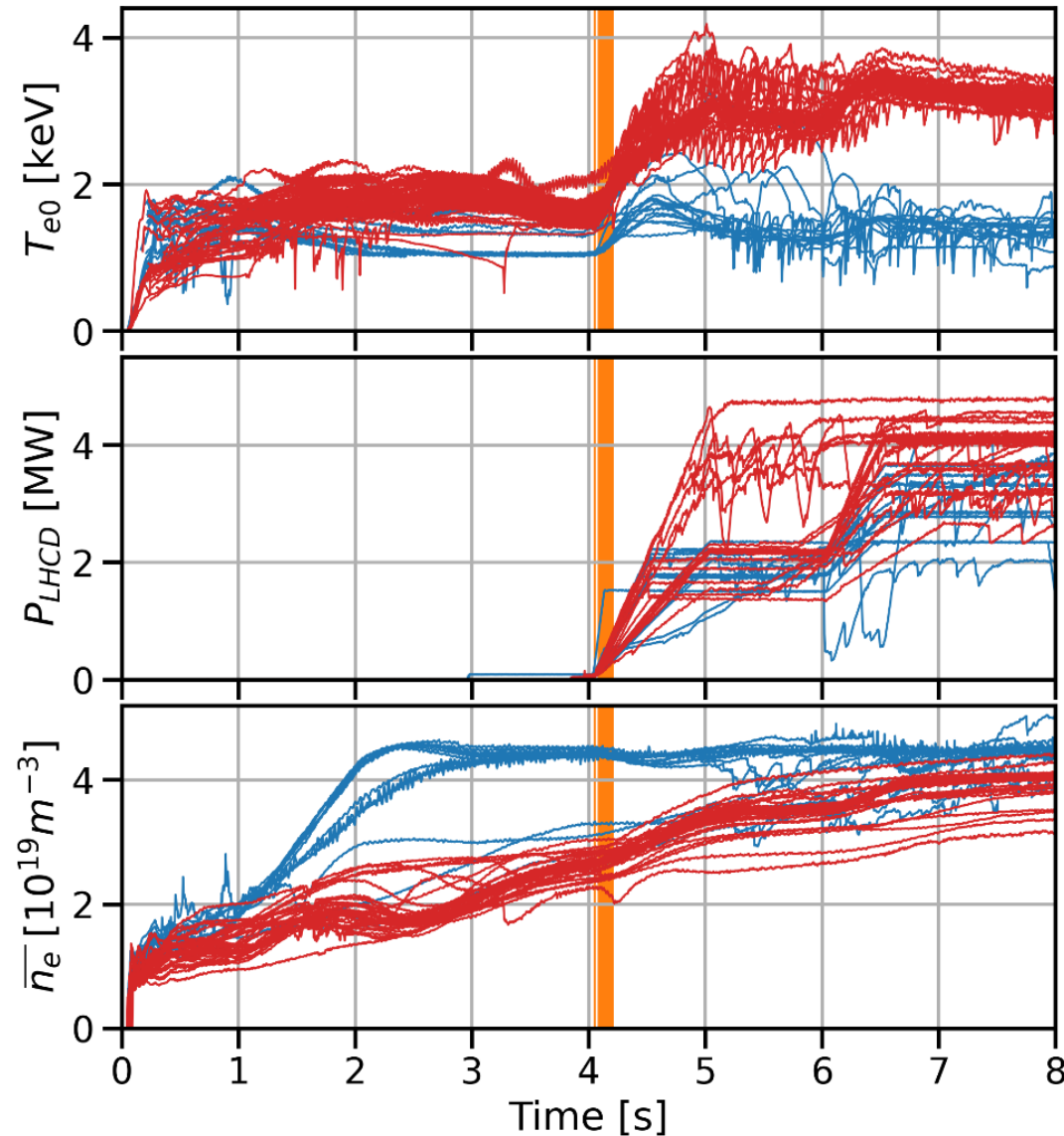
$$\overline{n_{e,min}} = 2.6 \cdot 10^{19} m^{-3}$$

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Time signals of hot and cold branches



Hot ($T_{e0} > 3$ keV)

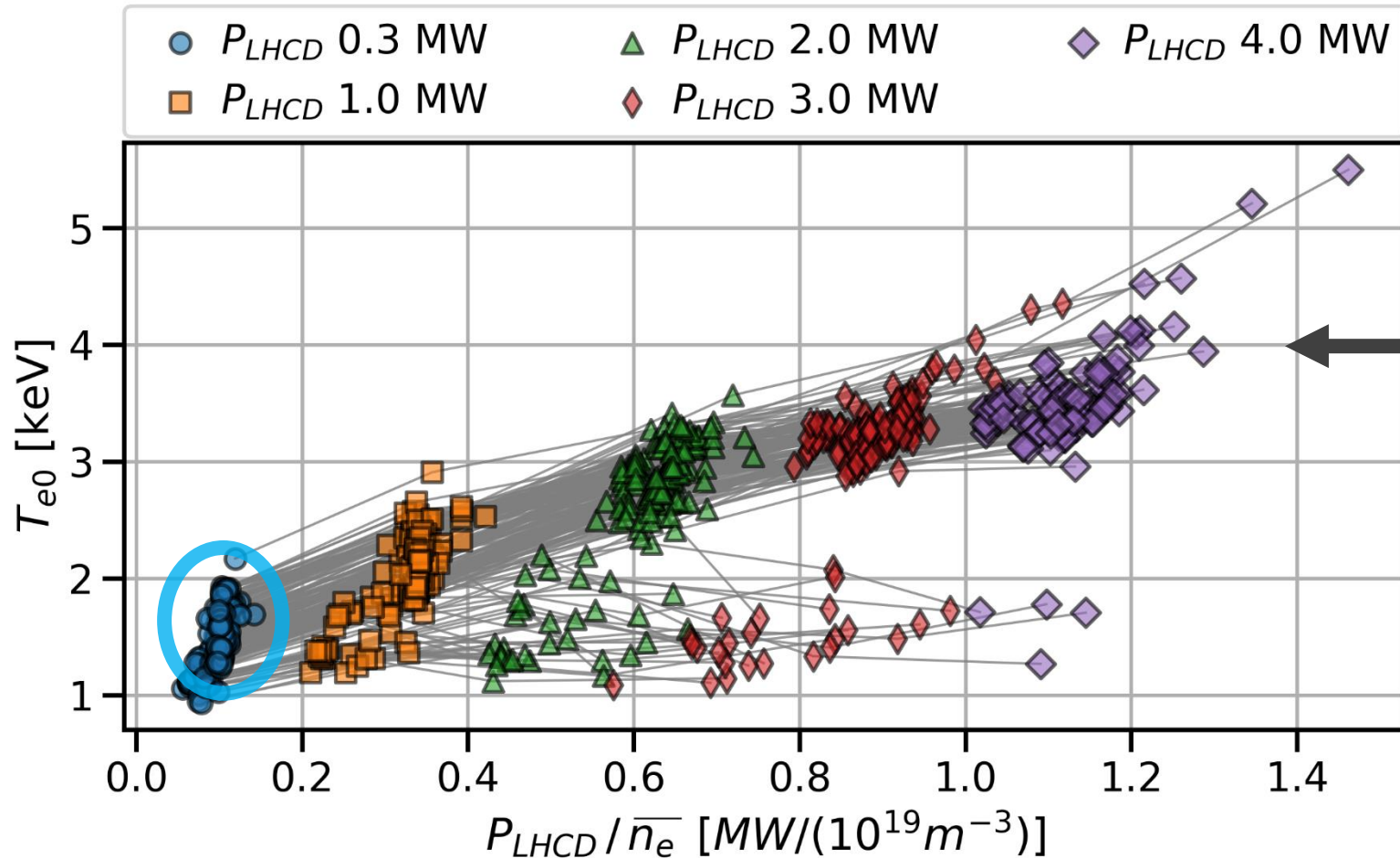
Cold ($T_{e0} < 2$ keV)

Pulses with $P_{LHCD} > 1$ MW and $I_p = 0.5$ MA

Vertical orange lines indicate times when Lower Hybrid power (P_{LHCD}) crosses 0.3 MW (heating onset)

Low densities at heating onset for **hot branch** pulses

Pulse trajectories with increasing power (P_{LHCD})



Goal of heating phase:
burn-through tungsten
and reach **hot branch**
($T_{e0} > 3$ keV)

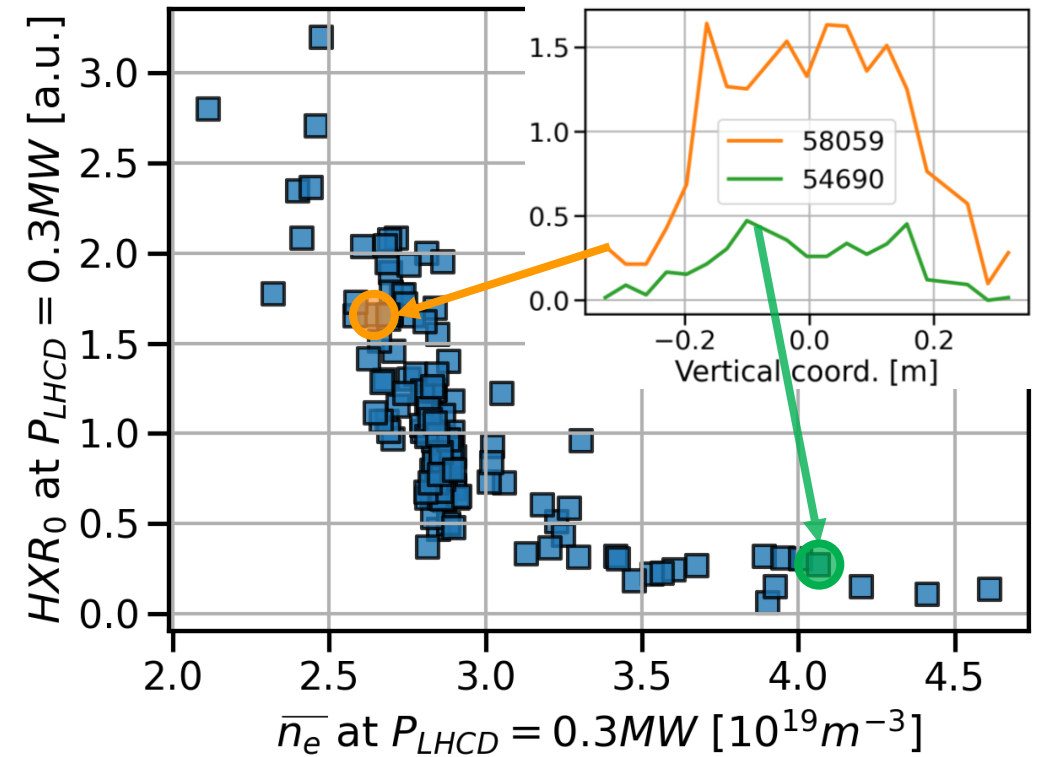
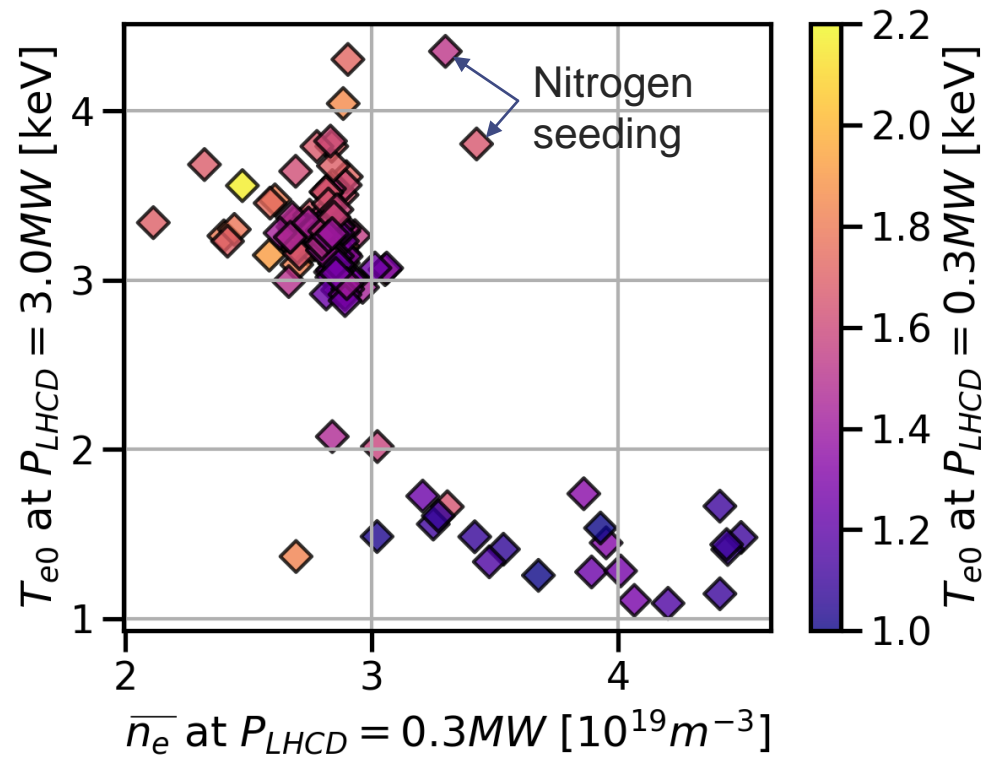
Two trajectories are observed:

- one reaching **hot branch**,
- second going to **cold branch** ($T_{e0} < 2$ keV)

High initial T_{e0} in “good” trajectories

Each grey line follows a pulse trajectory

Strong impact of density on plasma temperature



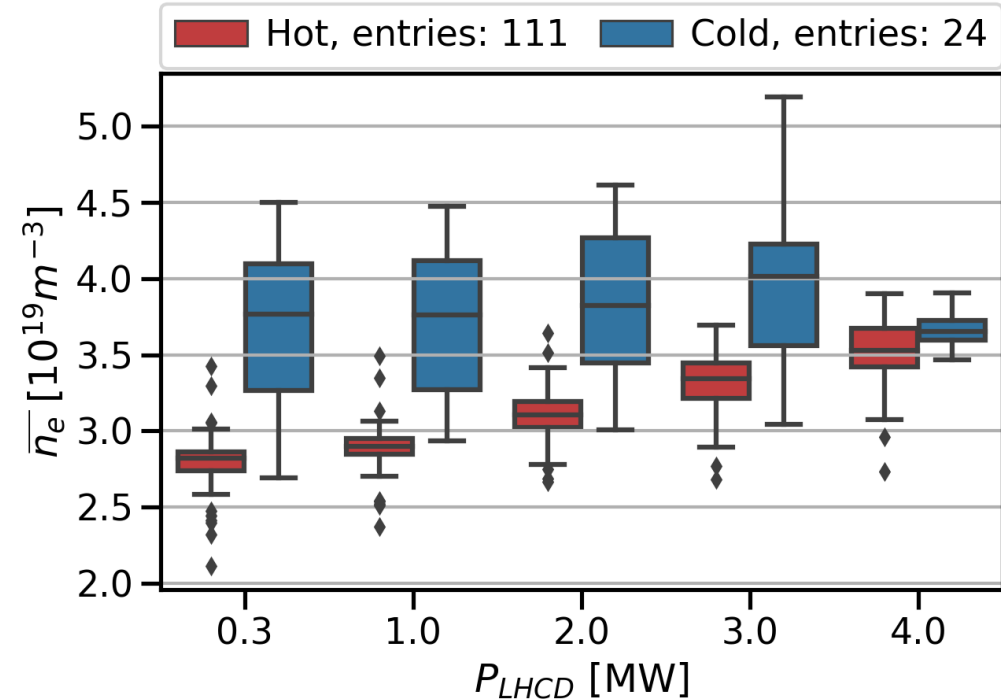
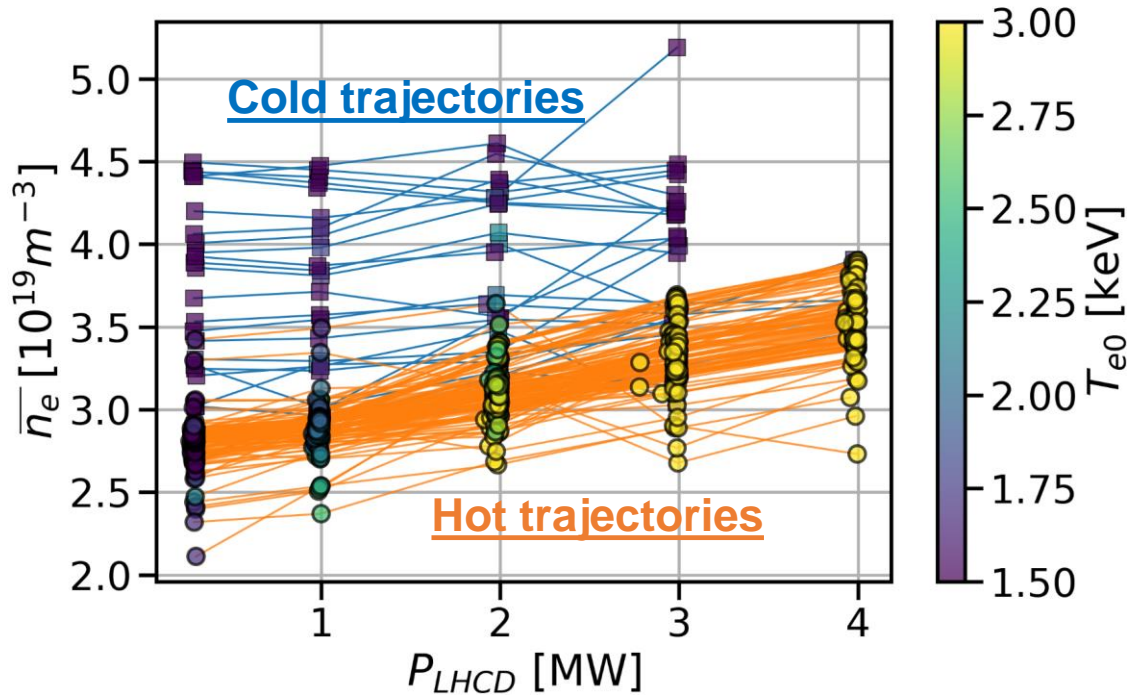
To burn-through tungsten, initial density:

$$\bar{n}_e < \sim 3.0 [10^{19}m^{-3}]$$

Initial low density plays a role:

- Increases initial T_{e0} (facilitating burn-through W)
- Helps improving core LHCD power absorption (clear effect on core hard X-rays 60-80 keV, HXR_0)

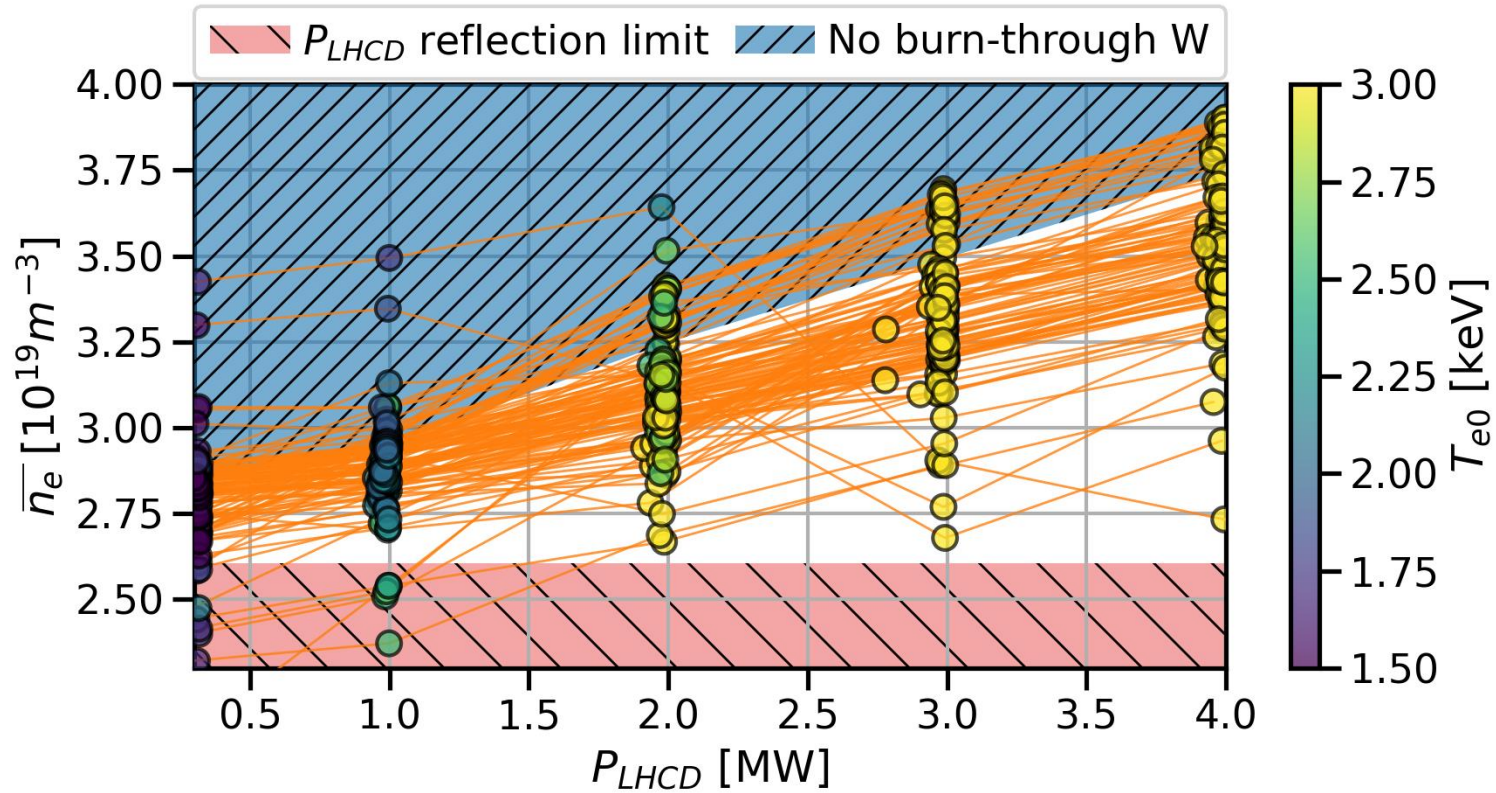
Density trajectory to burn-through W



Hot trajectories fix an upper boundary for density at given LHCD power

Hot boxes (red on the right plot) show a small interval between 25th and 75th percentile, this can be interpreted as a precise density trajectory is needed in order to reach hot branch, but there is a bias because we tend to repeat trajectories that succeeded

LHCD ramp-up operational space



Upper density limit (**No burn-through W**) is taken as the 80th percentile of hot pulses trajectories (conservative)

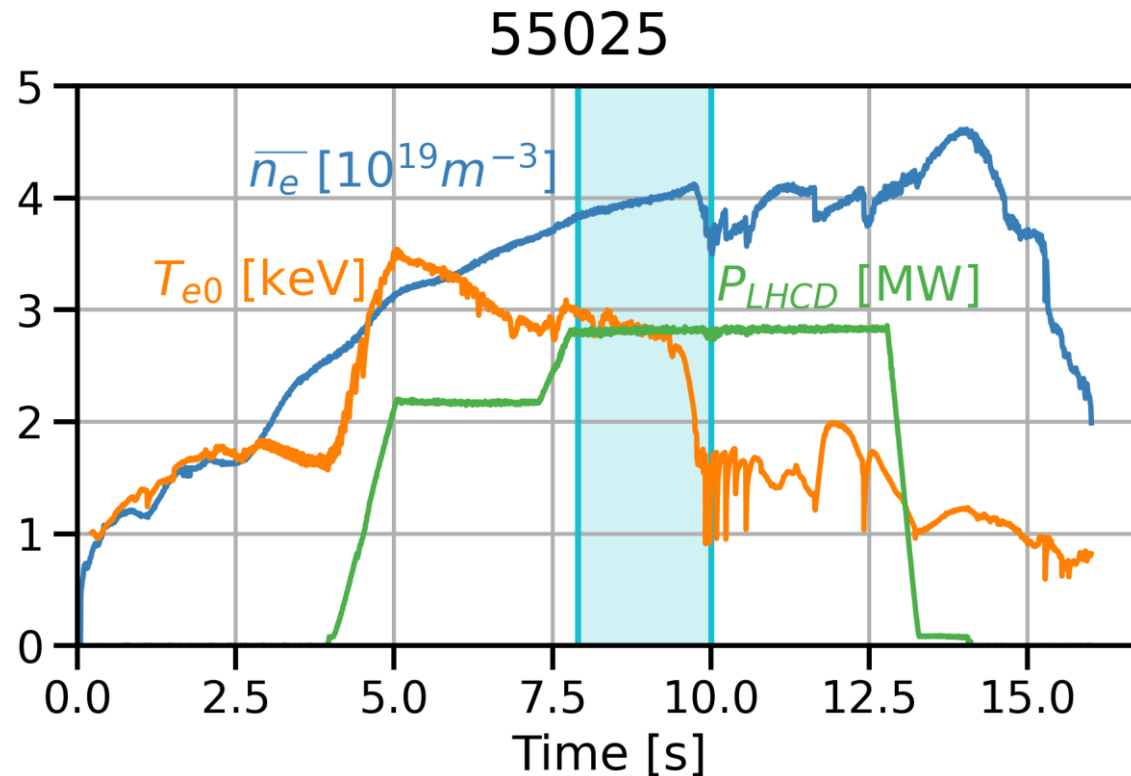
Lower density limit (P_{LHCD} reflection limit) is taken for $ROG_{avg} = 4\text{cm}$ and $X_d = 7\text{cm}$

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Collapse pulse example 55025

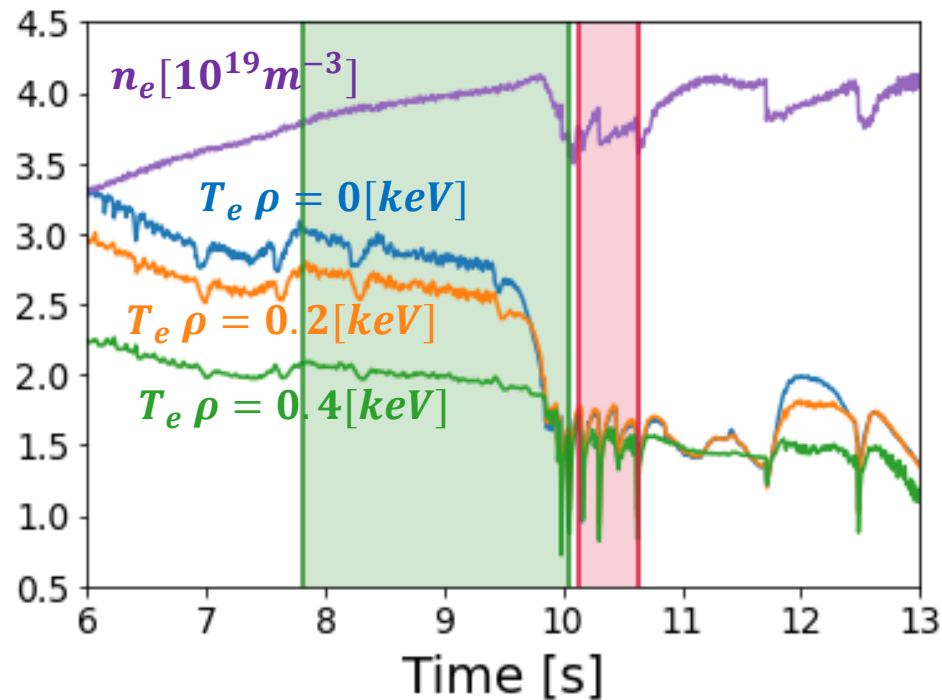


To better understand the radiative collapse physics we choose pulse 55025 between 7.9 and 10s

This pulse is interesting because LHCD power injection is constant during the whole collapse

[Ostuni, Nucl. Fusion, 2022]

Collapse pulse analysis 55025



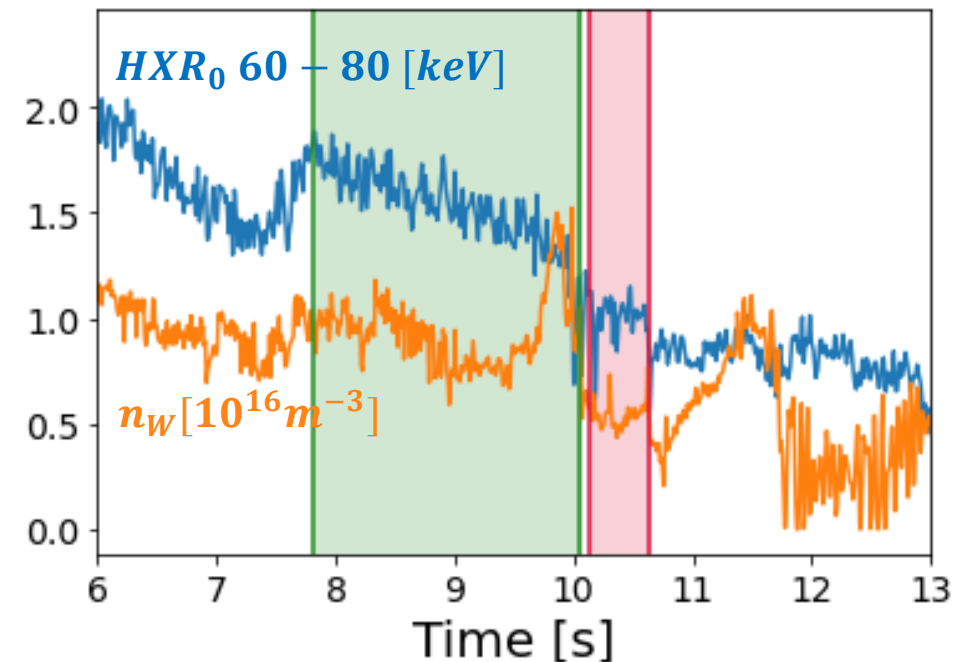
Prior to the collapse:

- a slow increase of electron density
- a slow decrease of electron temperature
- a constant W density
- a slow decrease of central HXR₀ signal: signature of a lower fast electron production by LHCD

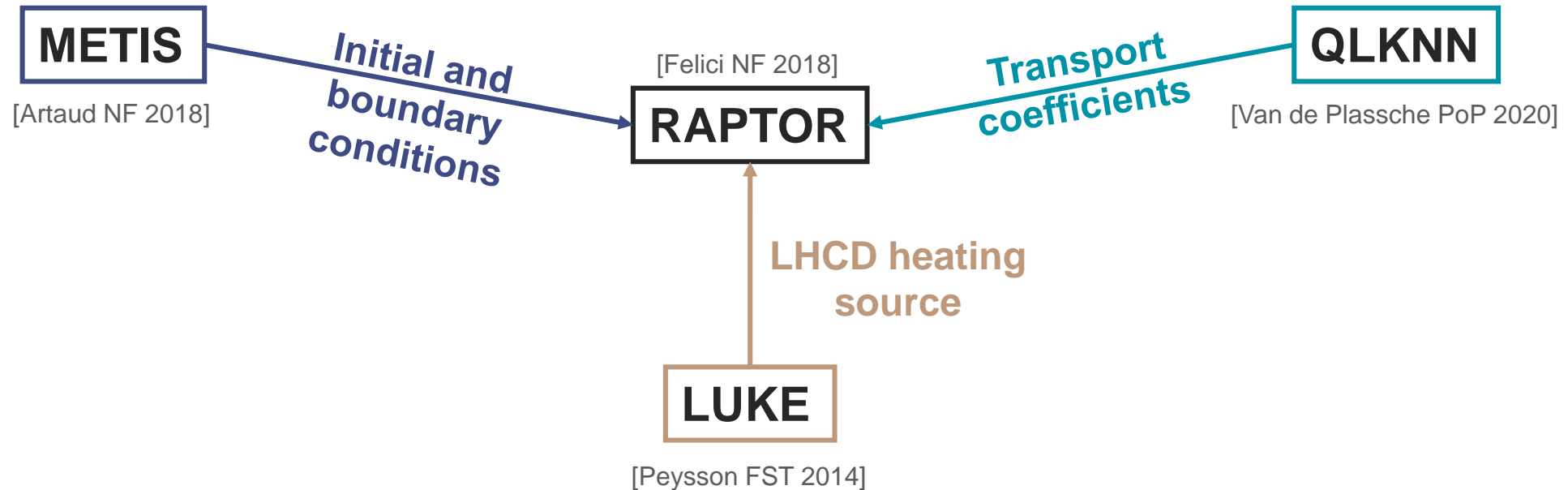
During the collapse:

- a fast decrease of electron temperature
- peaking of tungsten profile

This complex interplay requires integrated modelling

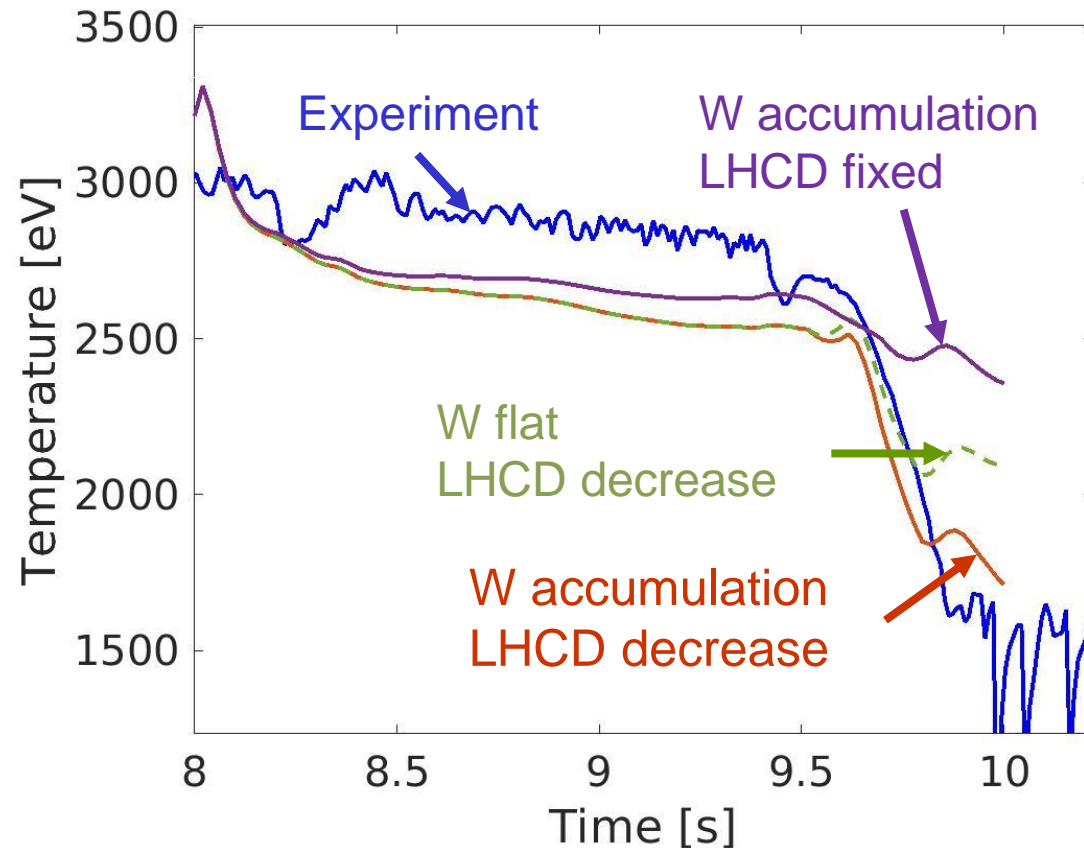


Simulation tools and settings



T_e and T_i	P_{LHCD}	n_e	n_w	P_{rad}	$j(r)$	Equilibrium
Predicted using QLKNN	LUKE	Fixed	Fixed based on bolometry inversion	Consistent with W cooling factor	Predicted	Fixed separatrix but consistent with $j(r)$

Simulation results: two important effects



Three different simulations performed:

- Tungsten accumulation with LHCD fixed
- No tungsten accumulation but decrease of LHCD central power deposition
- With both effects: tungsten accumulation and central LHCD power decrease

To model core radiative collapse speed we need to take into account:

- Decrease of central LHCD power deposition
- Tungsten accumulation

Collapse story:

Density rises → less central LHCD power deposition → T_{e0} reduction → ∇T reduction in core
→ reduction of central W temperature screening → core W accumulation

Conclusion

Three types of LHCD heated pulses are observed in WEST: **hot branch**, **cold branch** and **collapsing pulses**

We need **hot branch** to reach low loop voltages and perform long pulses. During last campaign we performed routinely 1 min plasmas and a 100s plasma was achieved

To reach hot branch:

- **Burn-through tungsten**: we need to be **below an upper density limit**
- Reduce power reflected back to LHCD: we need to operate **above a lower density value** that depends on plasma-antenna distance and X-point height

Collapse story: density rises \rightarrow less central LHCD power deposition $\rightarrow \nabla T$ reduction \rightarrow less W screening and core W accumulation

Therefore **density control and central electron heating are crucial** to avoid radiative collapses

Next: a new 3MW ECRH system will help to reach hot branch and avoid radiative collapses (1MW installed from end 2024)

