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► **To cite this version:**

J Morales, V Ostuni, C Bourdelle, J.-F Artaud, P Manas, et al.. Operational space for Lower Hybrid scenarios in the full tungsten environment of WEST. 64th Annual meeting of the APS Division of Plasma Physics, Oct 2022, Spokane, United States. cea-03863834

HAL Id: cea-03863834

<https://cea.hal.science/cea-03863834v1>

Submitted on 21 Nov 2022

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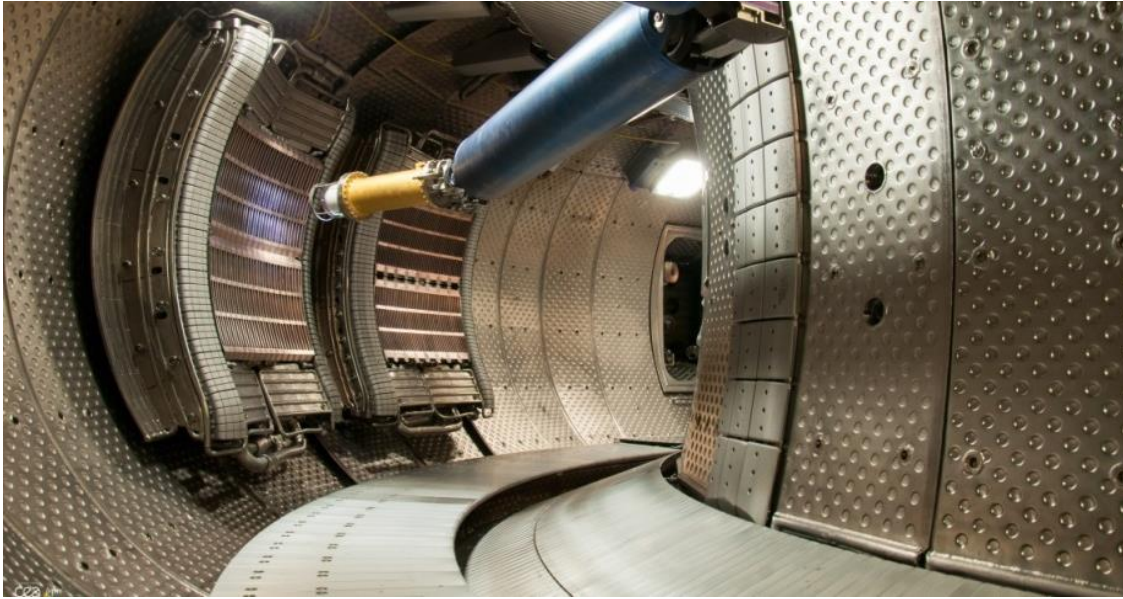


Operational space for Lower Hybrid scenarios in the full tungsten environment of WEST

DE LA RECHERCHE À L'INDUSTRIE

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

64th APS DPP Conference, Spokane, 17-21 October 2022

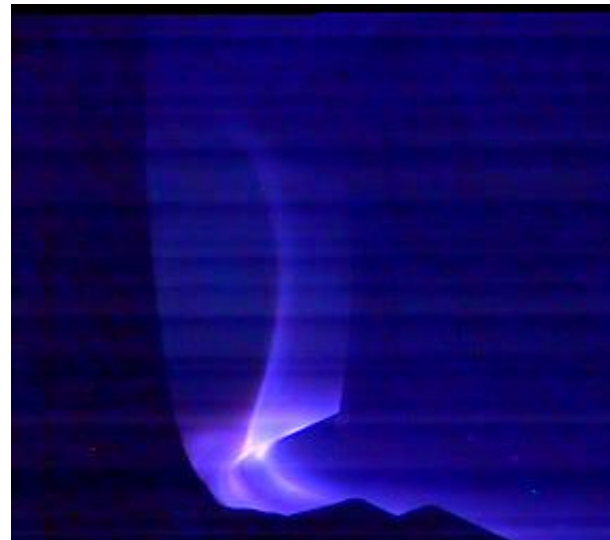
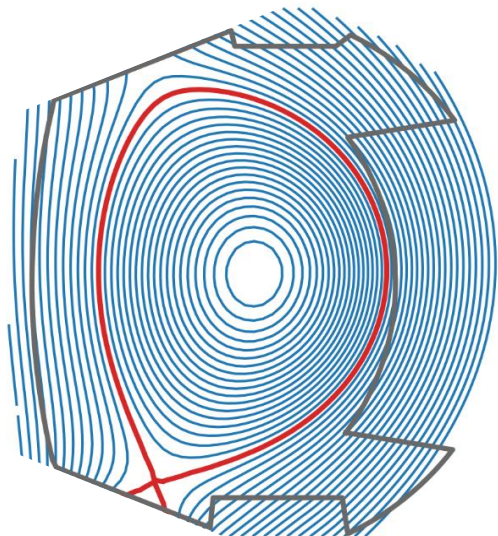


WEST is a device specialized for long pulse operation in a tungsten environment

Main goal: develop reactor compatible high performance long pulse scenarios

[Bucalossi et al., Nucl. Fusion, 2021]

[Bourdelle et al., Nucl. Fusion, 2015]



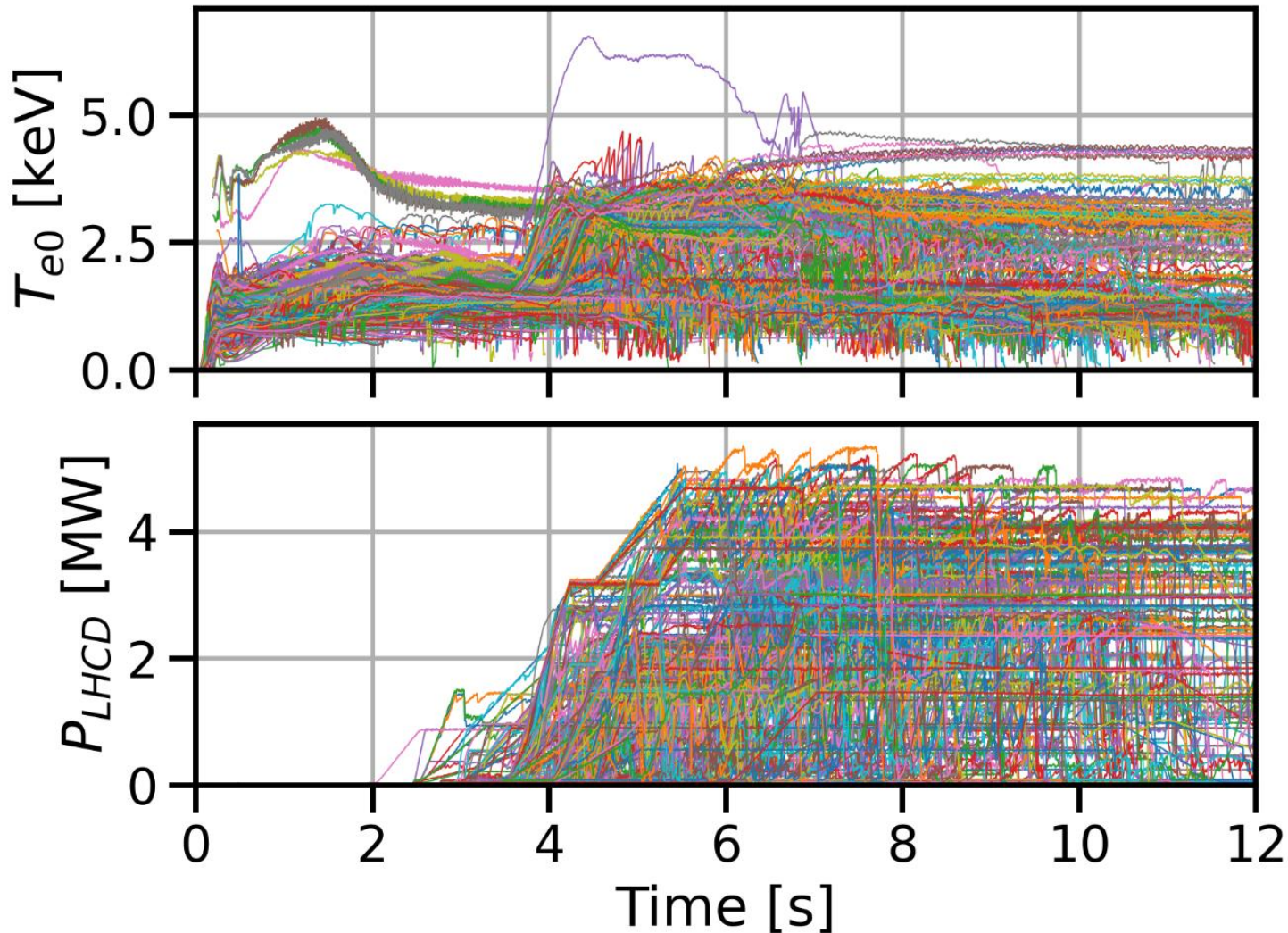
I_p ($q_{95} \sim 2.5$)	1 MA
B_T	3.7 T
R	2.5 m
a	0.5 m
n_{GW} (1MA)	$1.5 \cdot 10^{20} m^{-3}$
P_{ICRH}	9 MW
P_{LHCD}	7 MW
time_{flattop} (0.8 MA)	1000 s

In **WEST**, to achieve **robust steady-state Lower Hybrid Current Drive (LHCD) scenarios**, **three main constraints** need to be considered:

1. power density and initial central electron temperature (T_{e0}) need to be large enough to **burn-through tungsten**,
2. the **power reflected** back to LHCD antennas needs to be below a specified threshold,
3. fast electron **ripple losses** must be limited.

- Experimental data analysis tool
- Conditions to burn-through tungsten
- Obtaining good coupling between LHCD wave and plasma
- Limiting fast electron ripple losses

Example: 764 pulses from C4 campaign



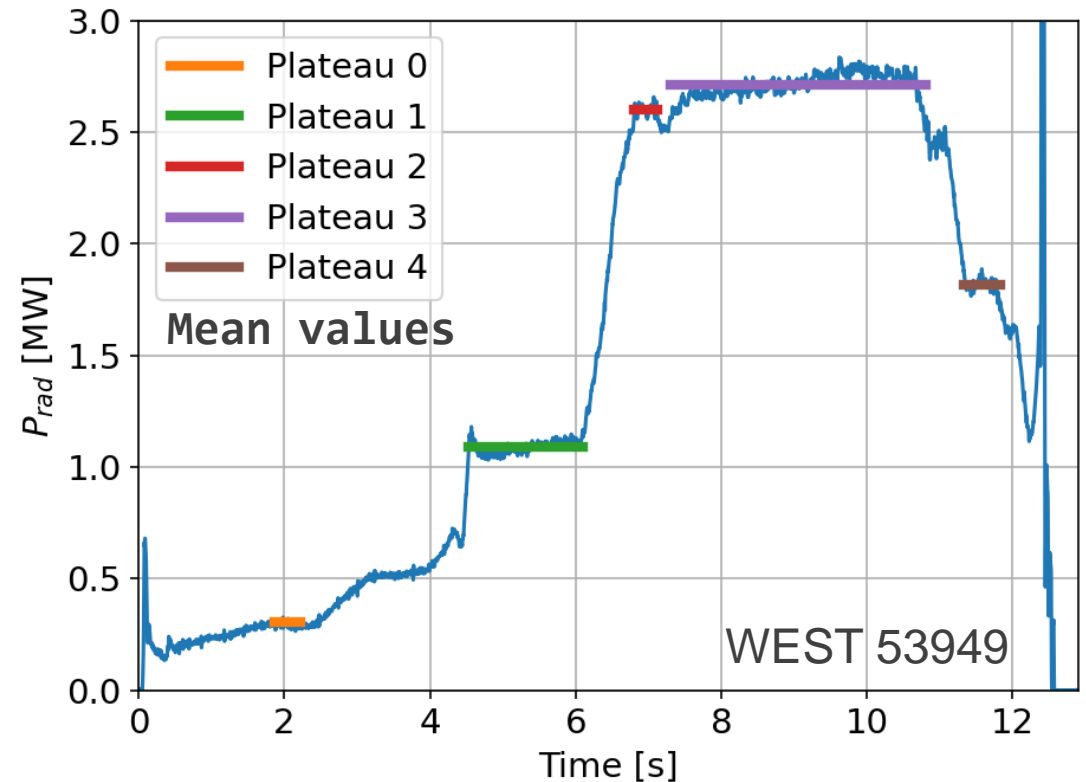
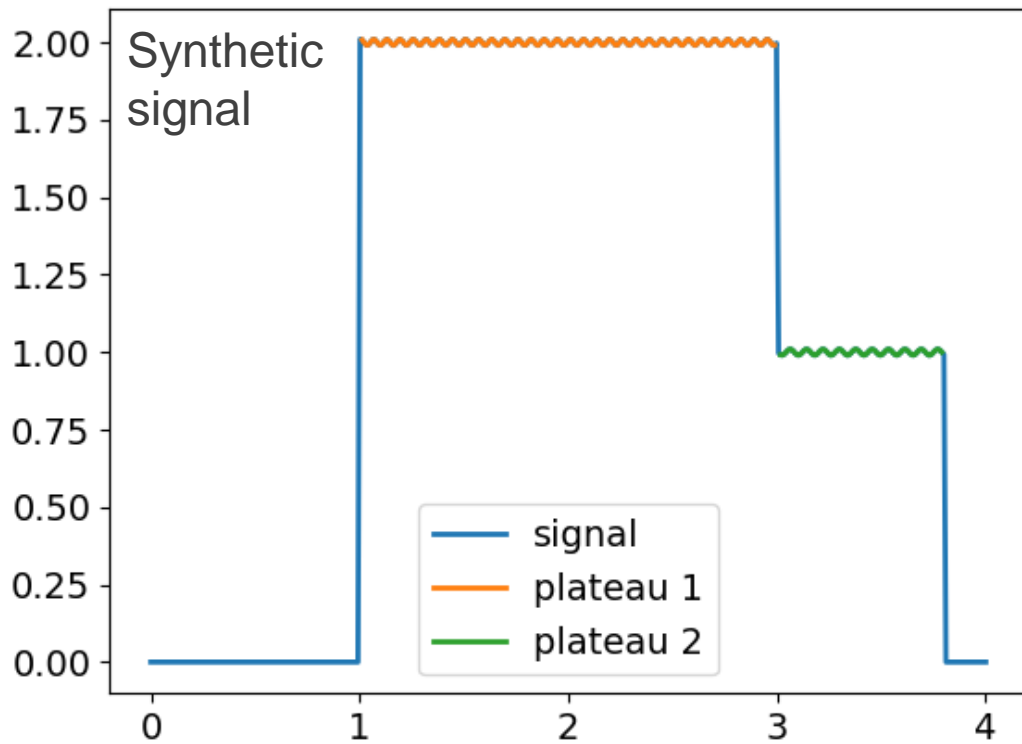
To efficiently characterize one or several experimental campaigns: development of a numerical tool for plateau detections on 1D signals.

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

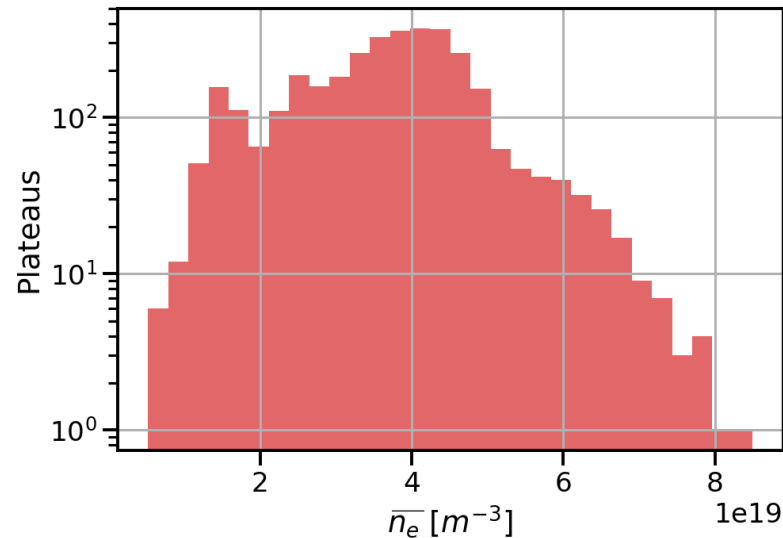
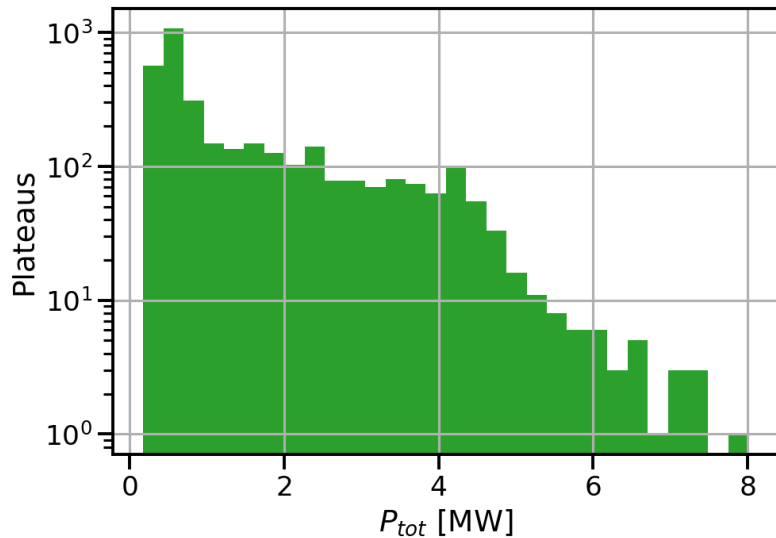
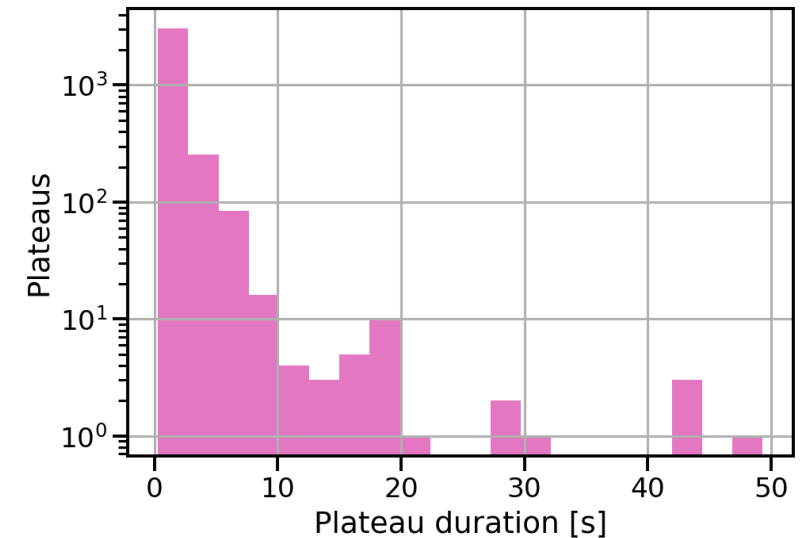
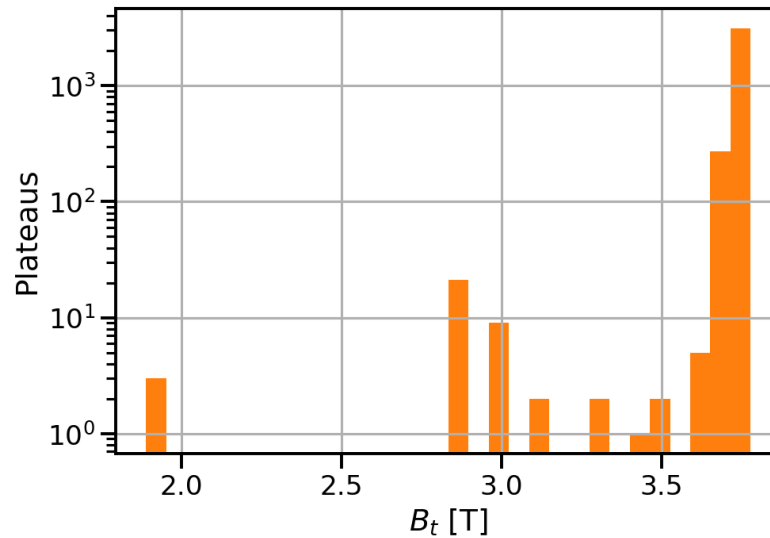
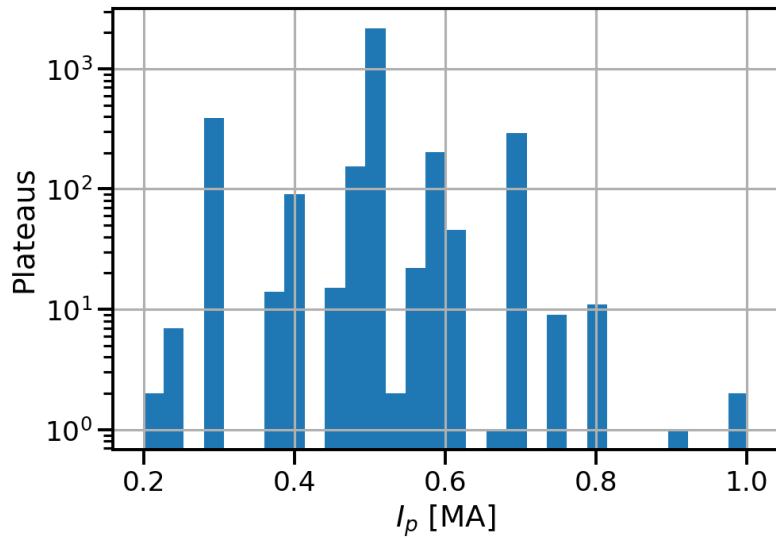
1D signal

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

- Plateaus (quasi-steady states) are **detected automatically**, we avoid a bias that can appear when a human selection is made
- The properties of a plateau (min duration, max deviation, etc.) are explicitly given by the user, **numerical code available (open source)** at:
https://github.com/jmoralesFusion/signal_plateau_recognition



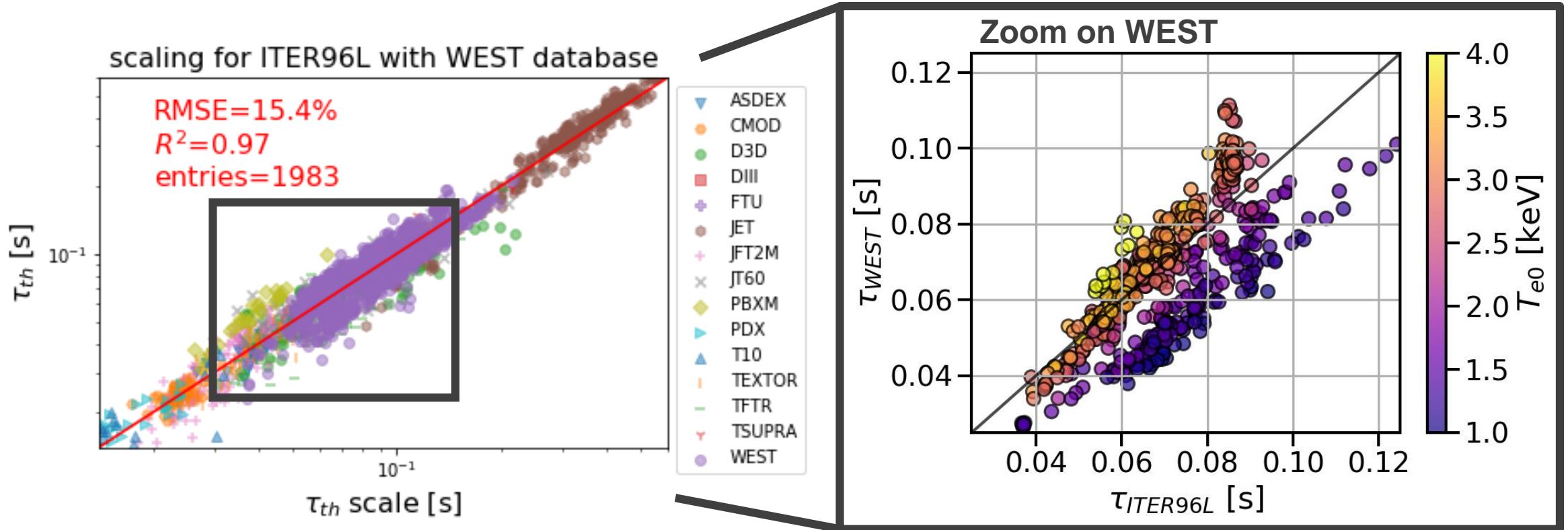
WEST quasi-steady states (plateaus of P_{tot} and I_p)



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

Database includes more than 700 quantities (as T_{e0} , P_{tot} ...)
and 6000 plateaus.

Histogram data: quantities in identified plateaus during WEST C4 and C5 campaigns (2019-2021)

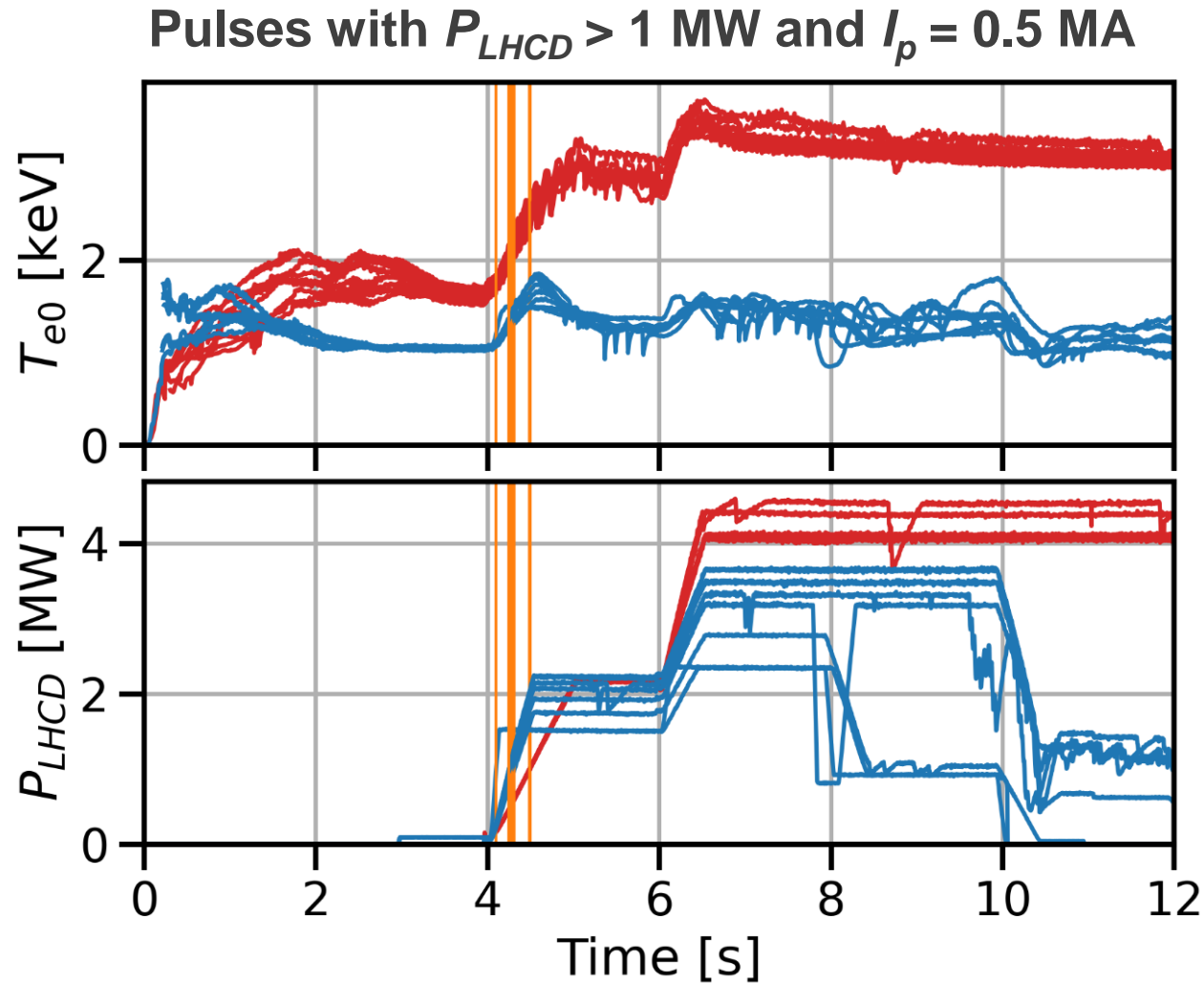


$$\tau_{ITER96L} = 0.023 I_p^{0.96} B^{0.03} P^{-0.73} n_e^{0.4} M^{0.2} R^{1.83} \epsilon^{-0.06} k^{0.64} \text{ [Kaye, NF, 1997]}$$

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

[Ostuni et al., Nucl. Fusion, 2022]

[Bourdelle et al., submitted to Nucl. Fusion, 2022] [Also in this conference: JO05.00012 and TM10.00003]



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

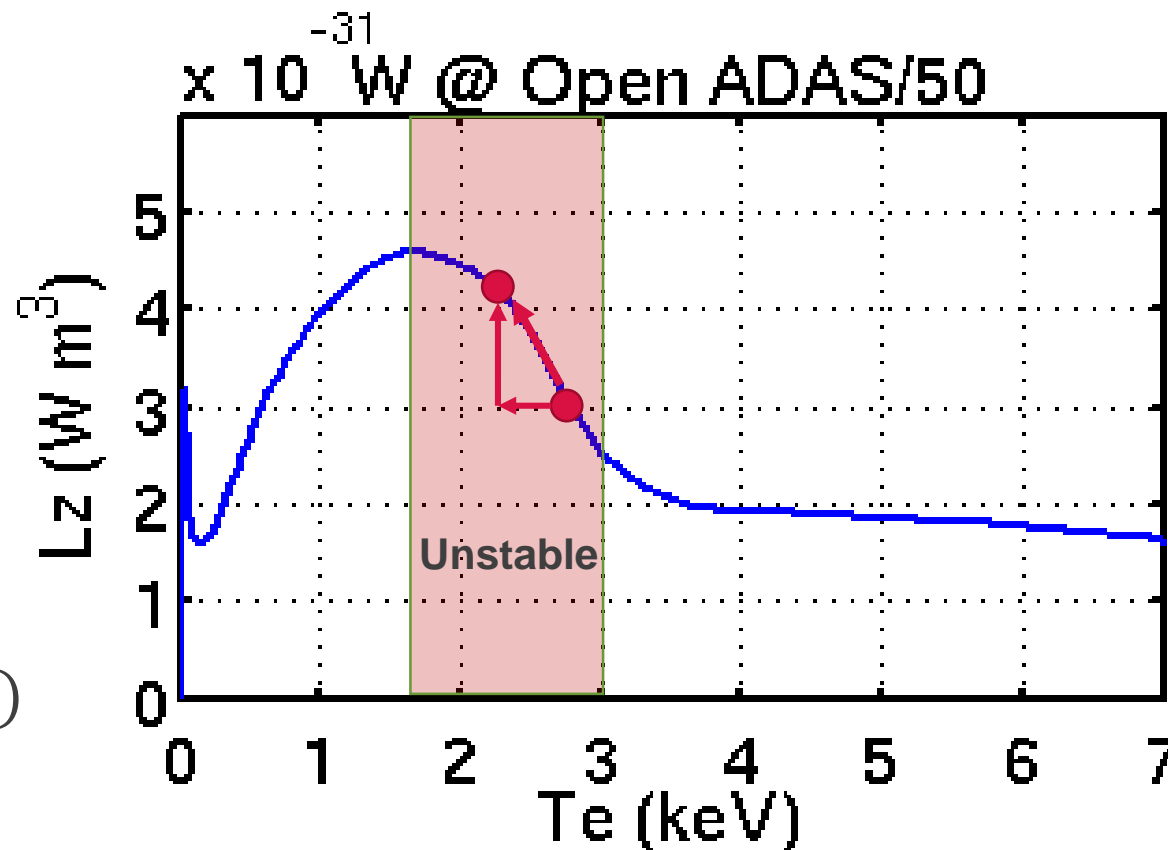
Cold ($T_{e0} < 2$ keV)

Vertical orange lines indicate times when **Lower Hybrid power** (P_{LHCD}) crosses 1 MW (heating onset)

Why $T_{e0} > 3 \text{ keV}$? To burn-through tungsten

Tungsten
cooling
factor
(Lz)

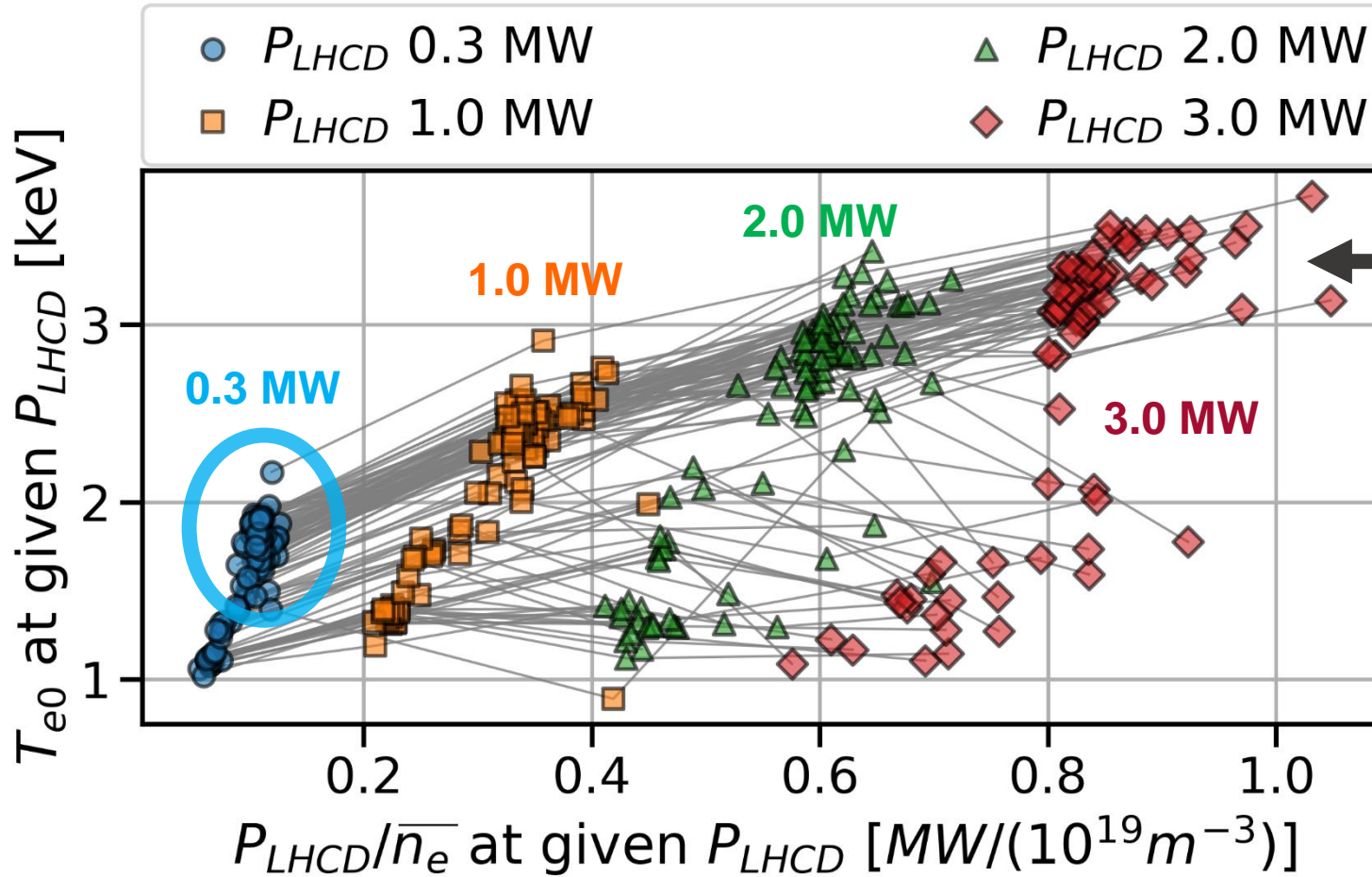
$$p_{rad,W} = n_e n_W Lz(T_e)$$



Unstable plasmas are in the range 1.5 keV to 3 keV.

[Ostuni et al., Nucl. Fusion, 2022]

Pulse trajectories with increasing Lower Hybrid power (P_{LHCD})



Goal temperature of heating phase (reach **hot branch**, $T_{e0} > 3$ keV)

Two trajectories are observed:

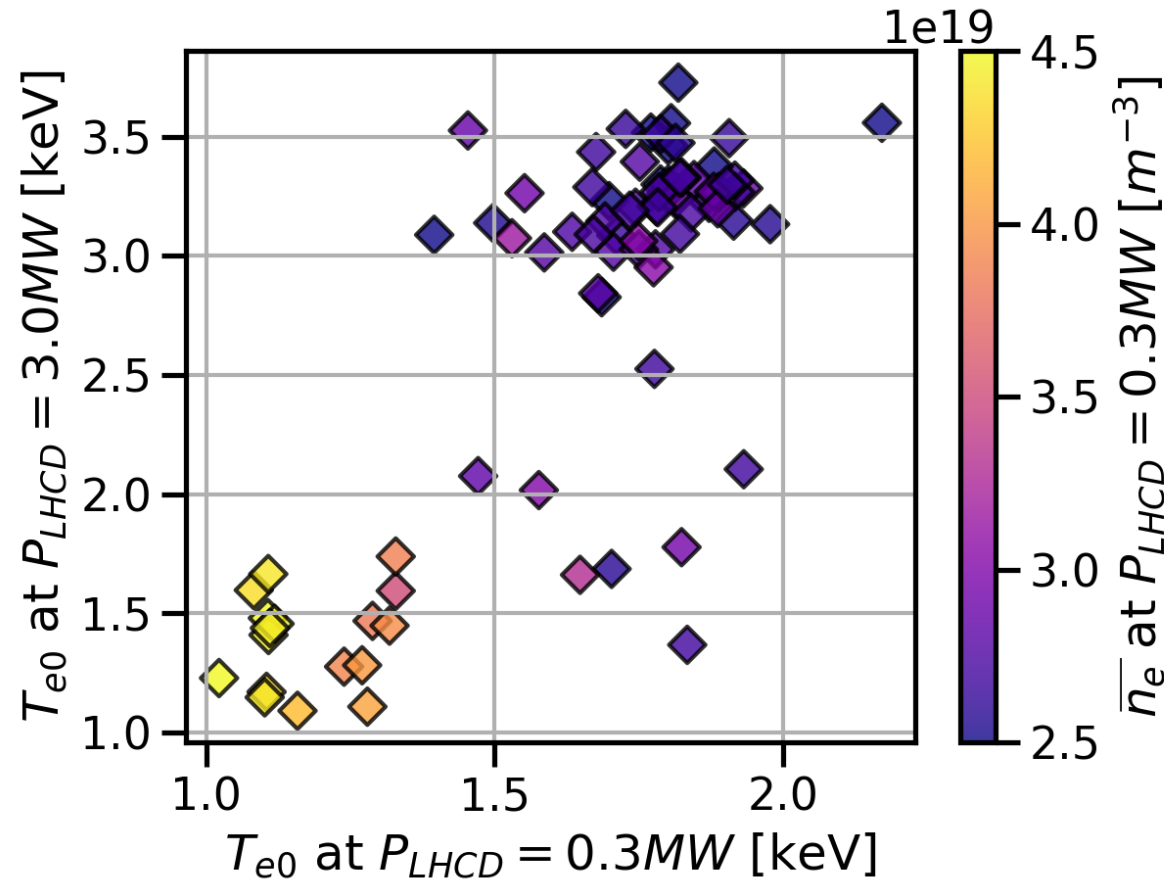
- one reaching **hot branch**,
- second going to **cold branch** ($T_{e0} < 2$ keV)

Each grey line indicates a pulse trajectory

High initial T_{e0} in “good” trajectories

1. High T_{e0} at heating onset needed to burn-through tungsten

T_{e0} at high heating phase

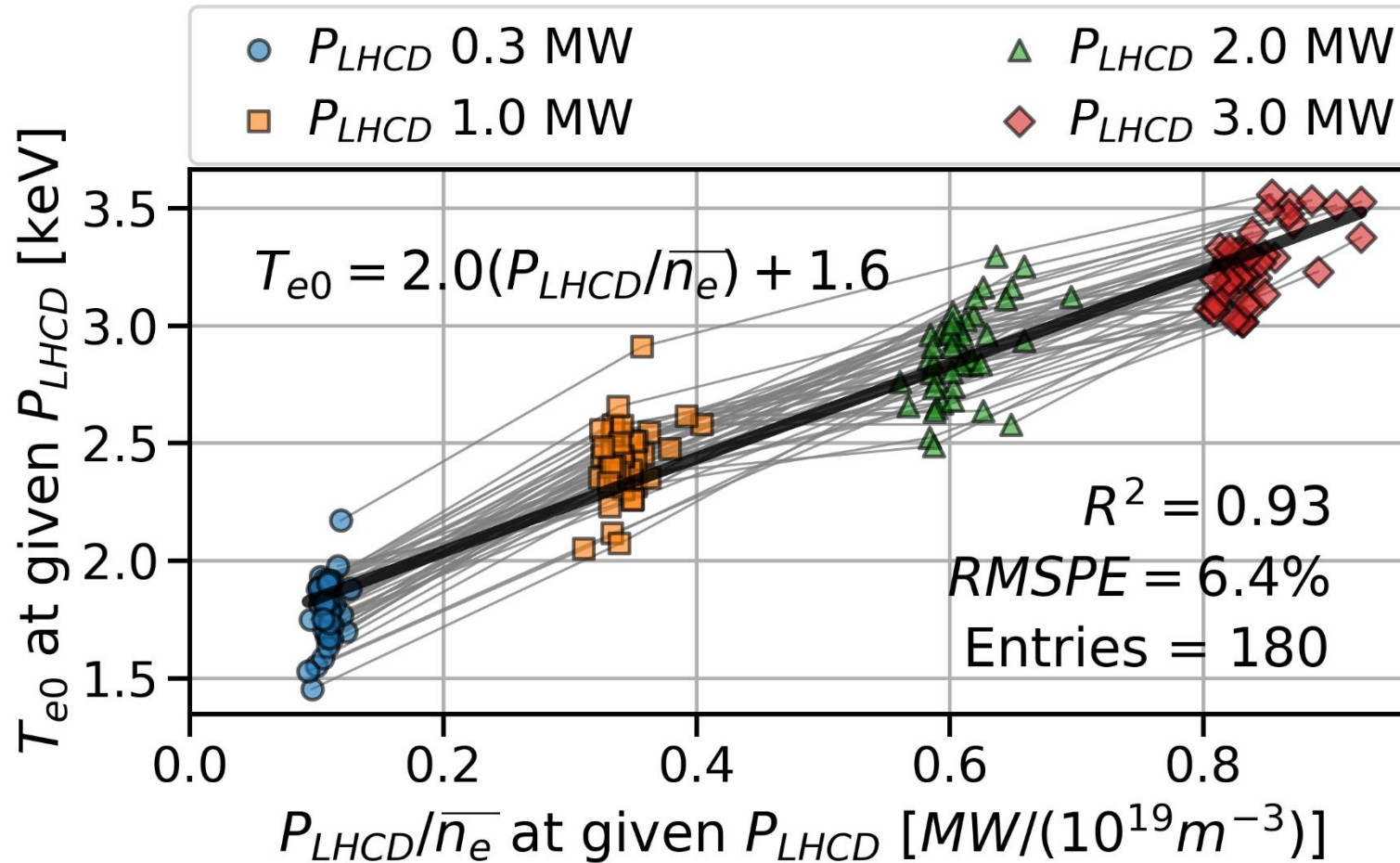


T_{e0} at heating onset

To achieve **large initial T_{e0}** :

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

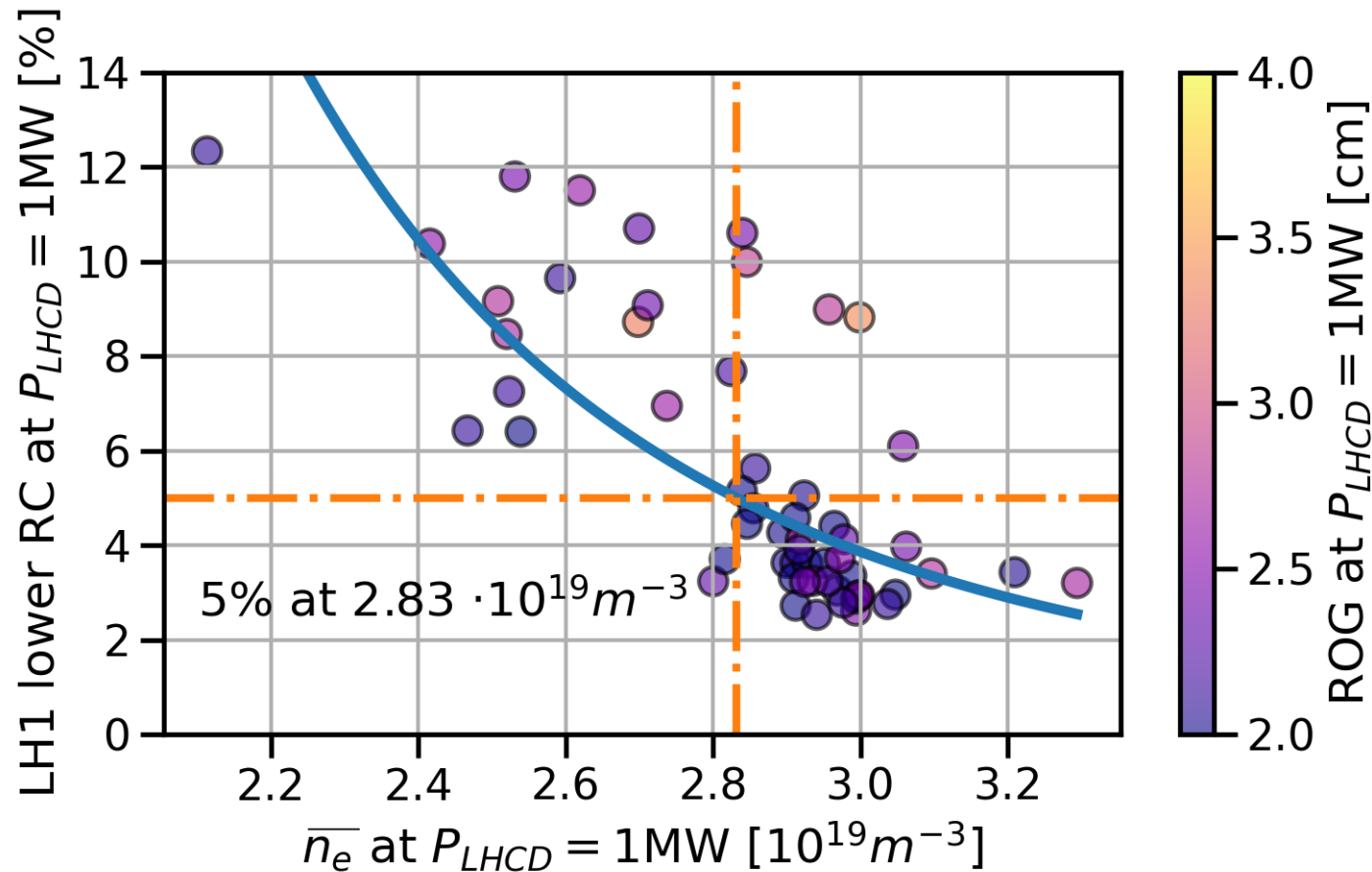
2. High LHCD power density required to burn-through tungsten



To obtain $T_{e0} > 3keV$:

$$\frac{P_{LHCD}}{\bar{n}_e} > 0.7 \text{ [MW}/10^{19}m^{-3}]$$

3. Minimum density to obtain low Reflection Coefficient (RC)



Reflection coefficient on lower LH1 antenna modules
(stronger constraint than in upper modules)

For small Radial Outer Gap (ROG < 4 cm), to achieve RC < ~ 5%:

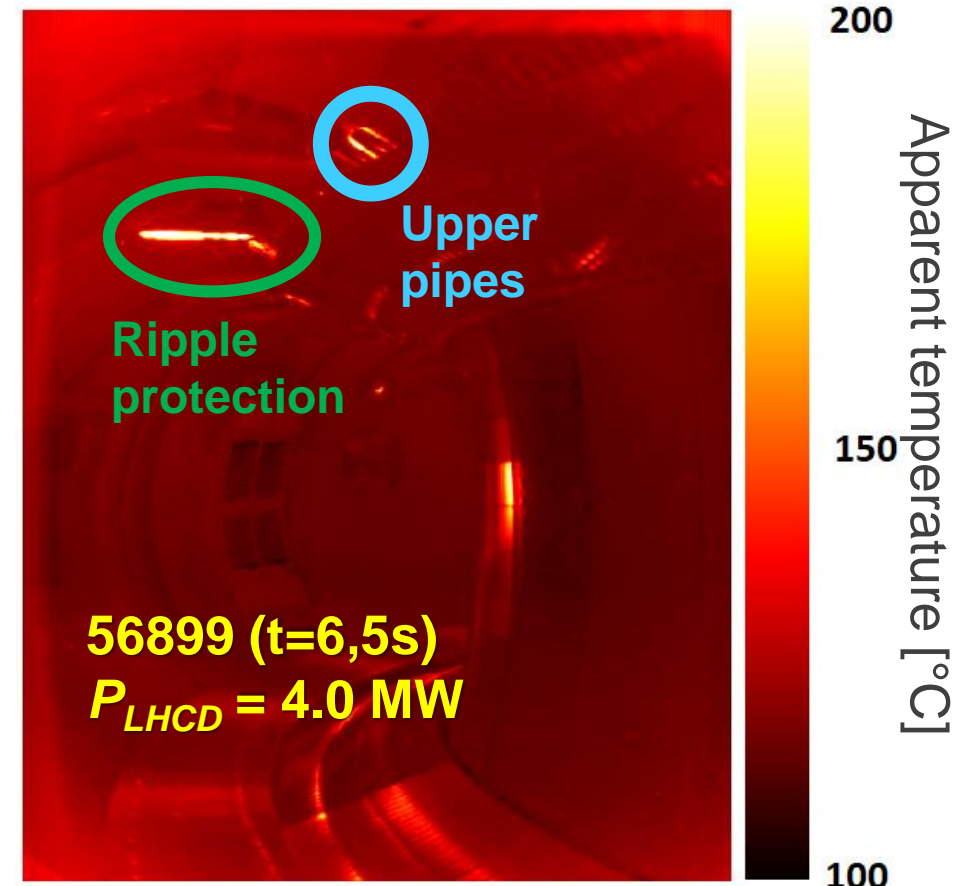
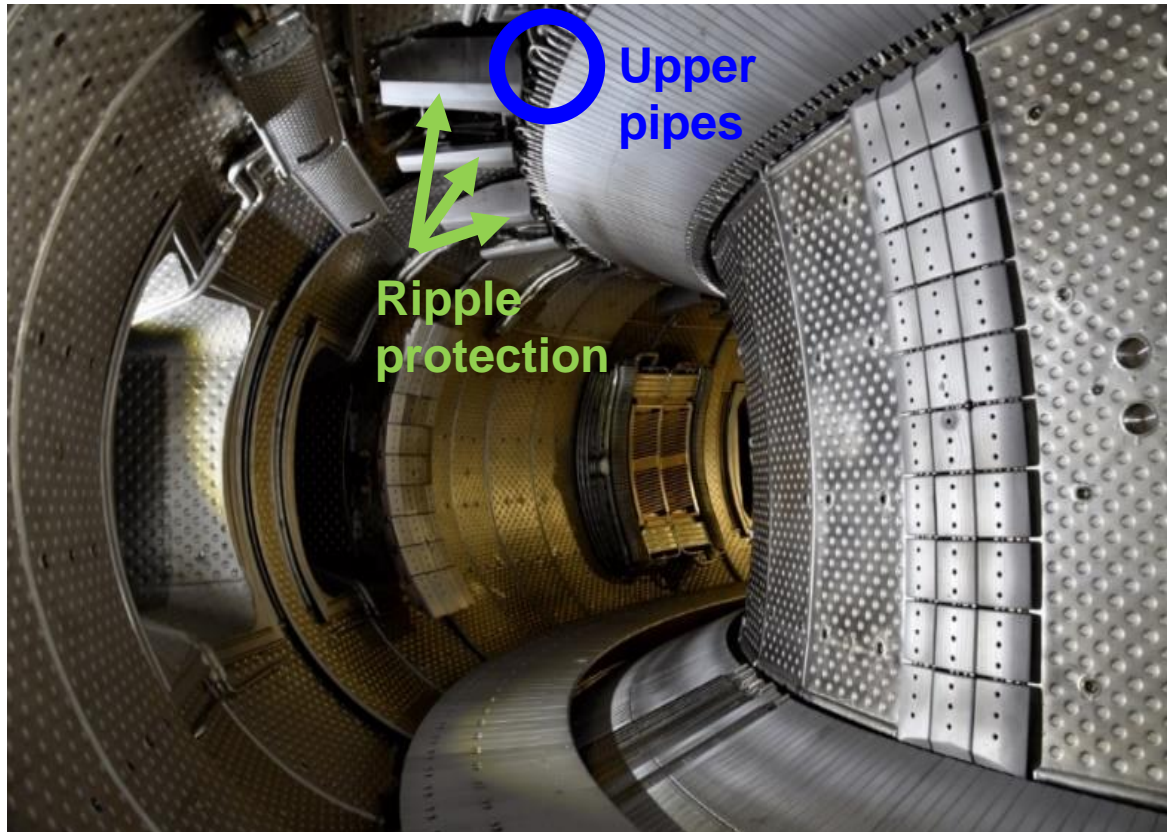
$$\bar{n}_e > 2.8 [10^{19}\text{m}^{-3}]$$

We recall: to achieve large initial T_{e0} :

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

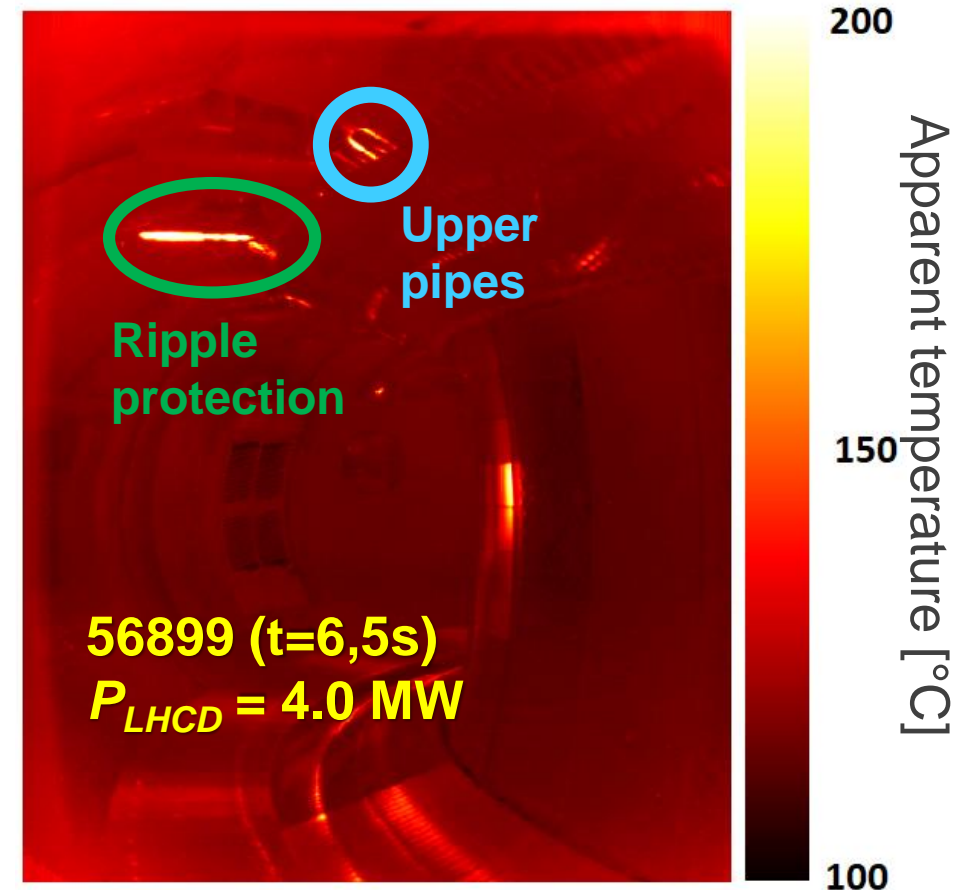
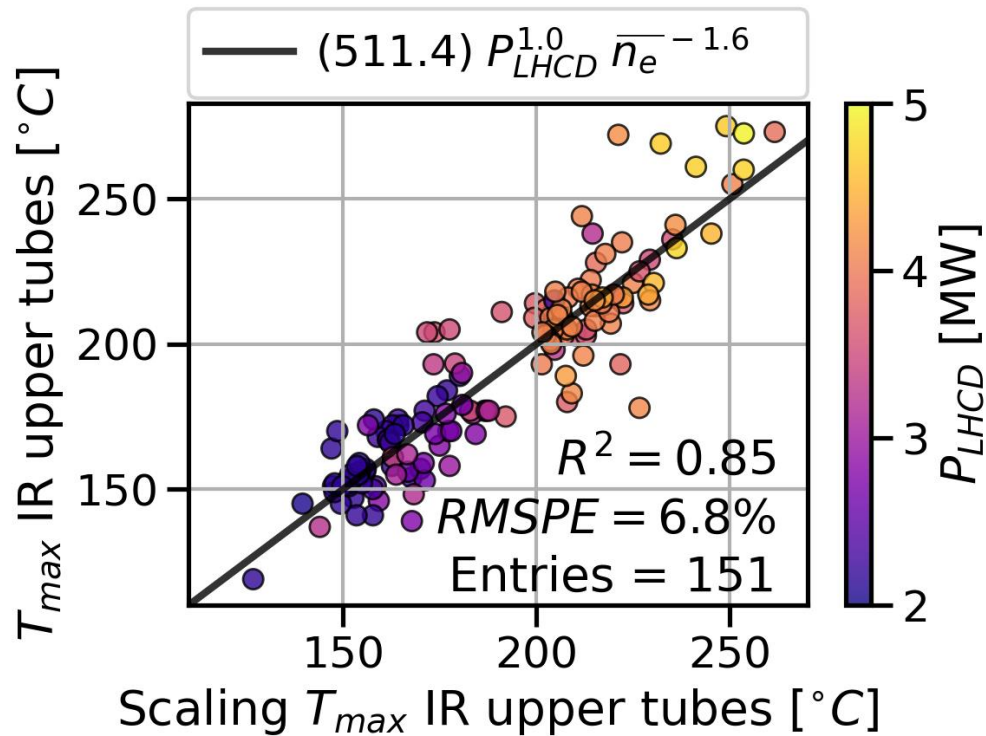
4. Maximum LHCD power density limited by ripple losses

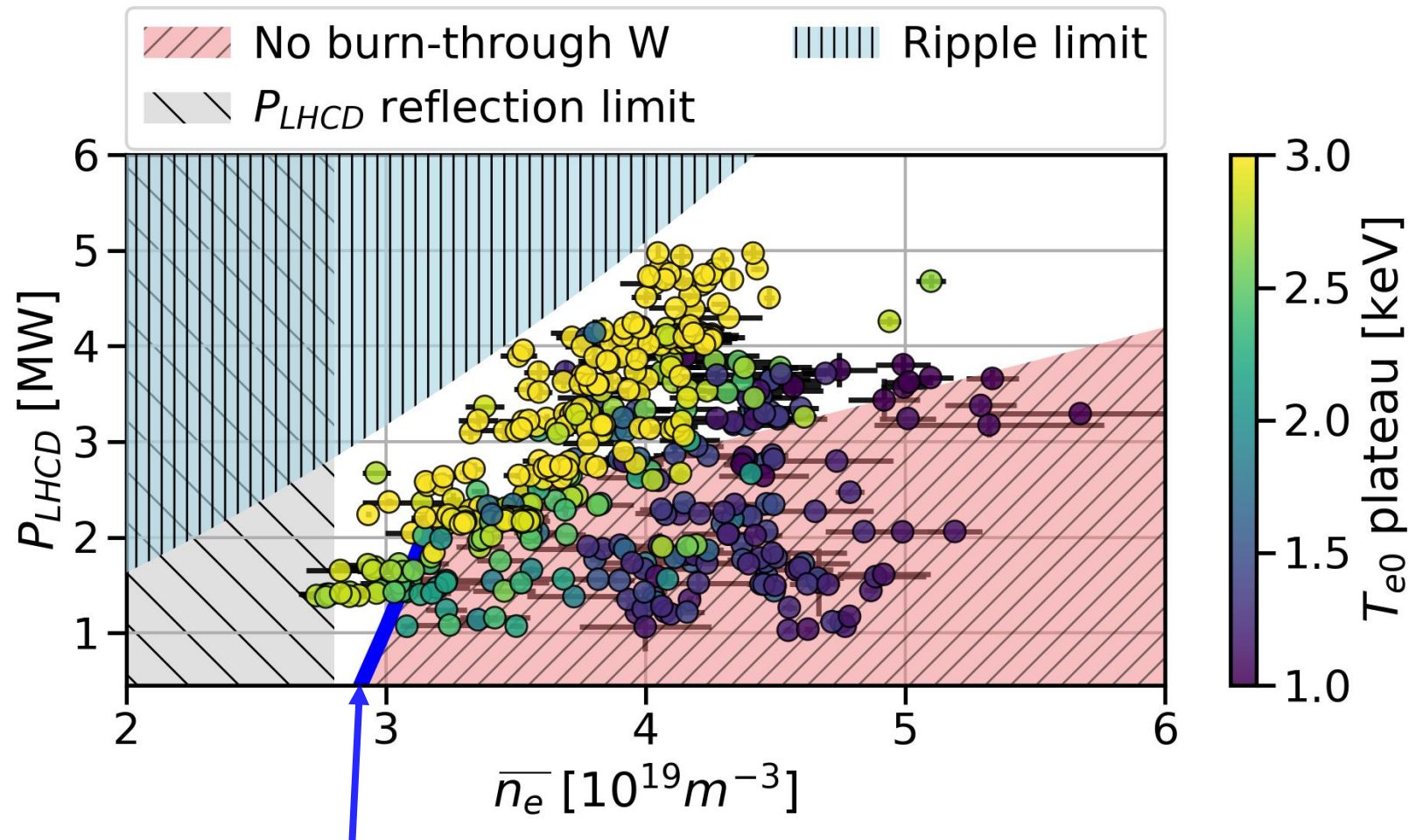
- Electron ripple losses induced by LHCD create hot spots in upper cooling pipes
- To limit the thermomechanical fatigue (to resist at least 2400 thermal cycles) maximal apparent temperature (T_{max}) allowed is **275°C**



4. Maximum LHCD power density limited by ripple losses

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Initial conditions (for high initial T_{e0})
and P_{LHCD} ramp-up to burn-through tungsten