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

J Morales, V Ostuni, C Bourdelle, J.-F Artaud, P Manas, H Ancher, L Dubus, M Doménès, R Dumont, A Ekedahl, et al.

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DE LA RECHERCHE À L'INDUSTRIE

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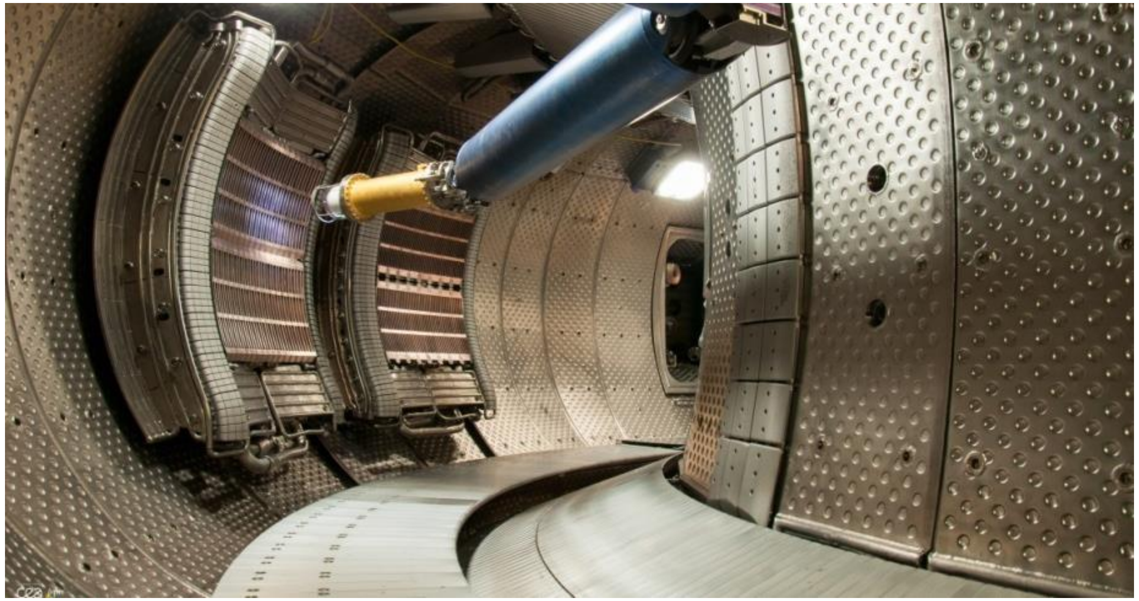
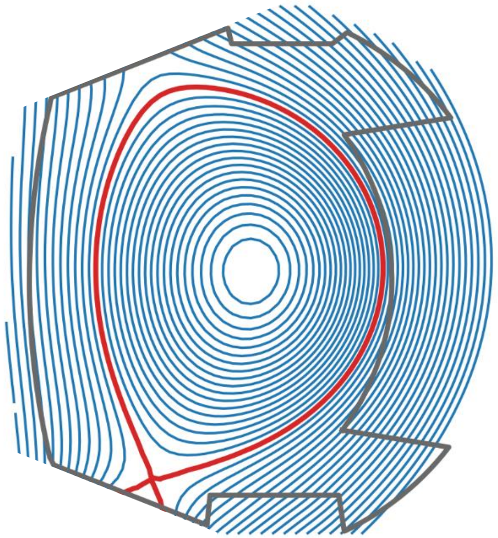
Introduction

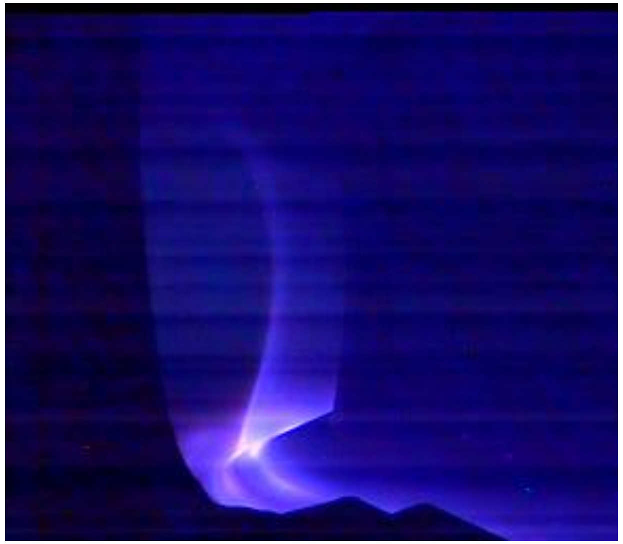


WEST is a device specialized for long pulse operation in a tungsten environment

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}~2.5)	1 MA
B_T	3.7 T
R	2.5 m
a	0.5 m
n_{GW} (1MA)	1.5 10^{20} m^{-3}
P_{ICRH}	9 MW
P_{LHCD}	**7 MW**
time$_{flattop}$ (0.8 MA)	**1000 s**

Introduction

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

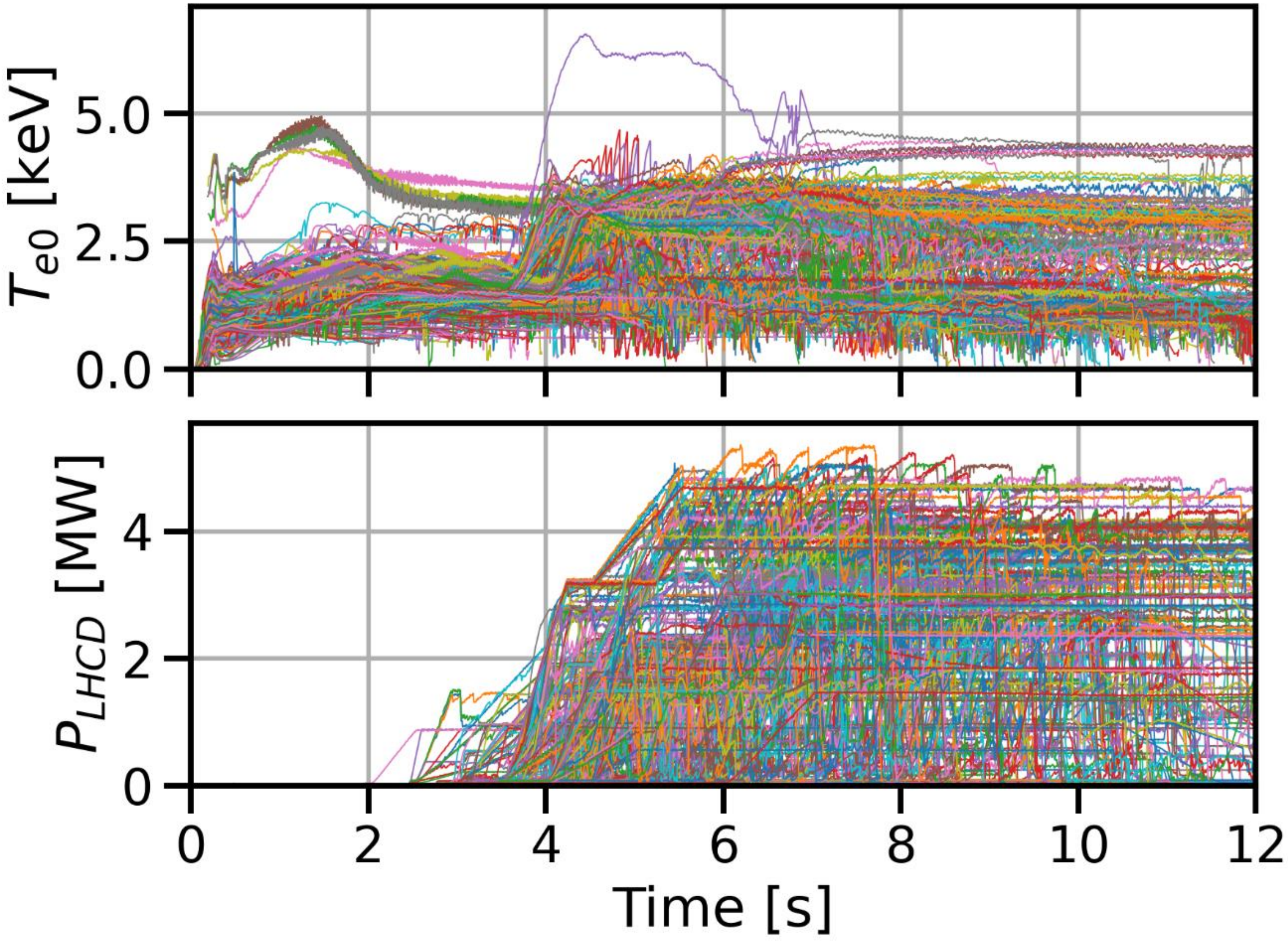
1. power density and initial central electron temperature (T_{e0}) need to be large enough to **burn-through tungsten**,
2. the **power reflected** back to LHCD antennas needs to be below a specified threshold,
3. fast electron **ripple losses** must be limited.

Outline

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

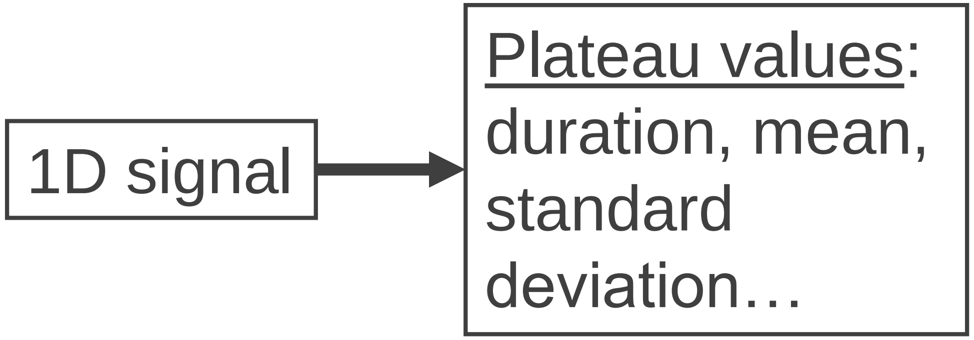
Question: how to analyze entire experimental campaigns?

Example: 764 pulses from C4 campaign



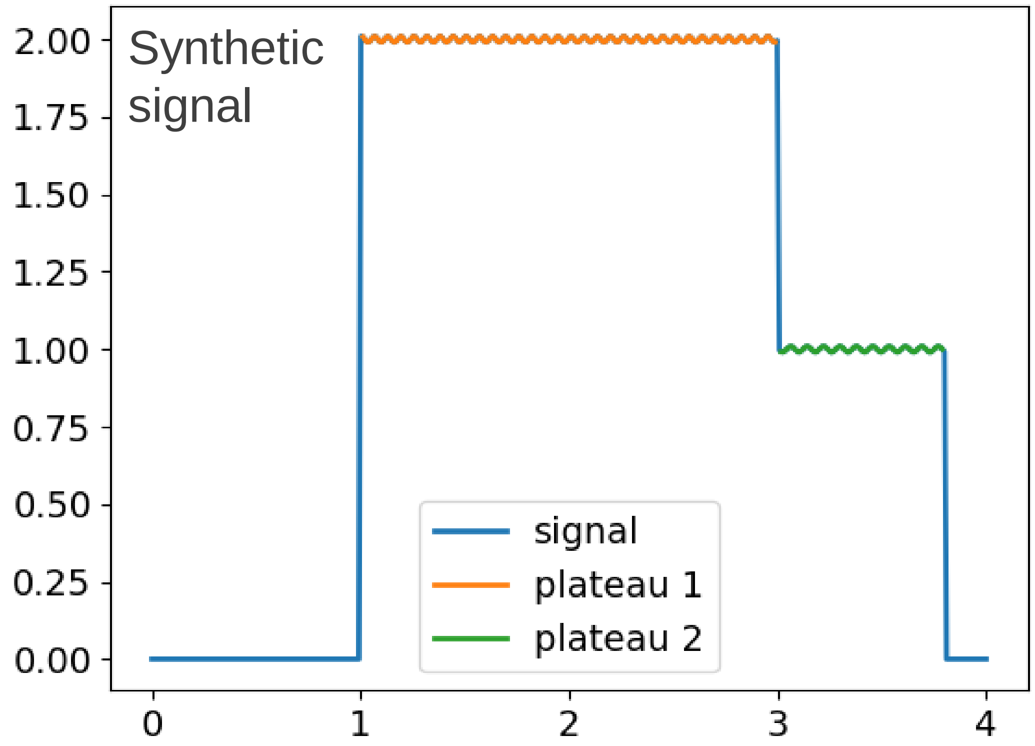
To efficiently characterize one or several experimental campaigns: development of a numerical tool for plateau detections on 1D signals.

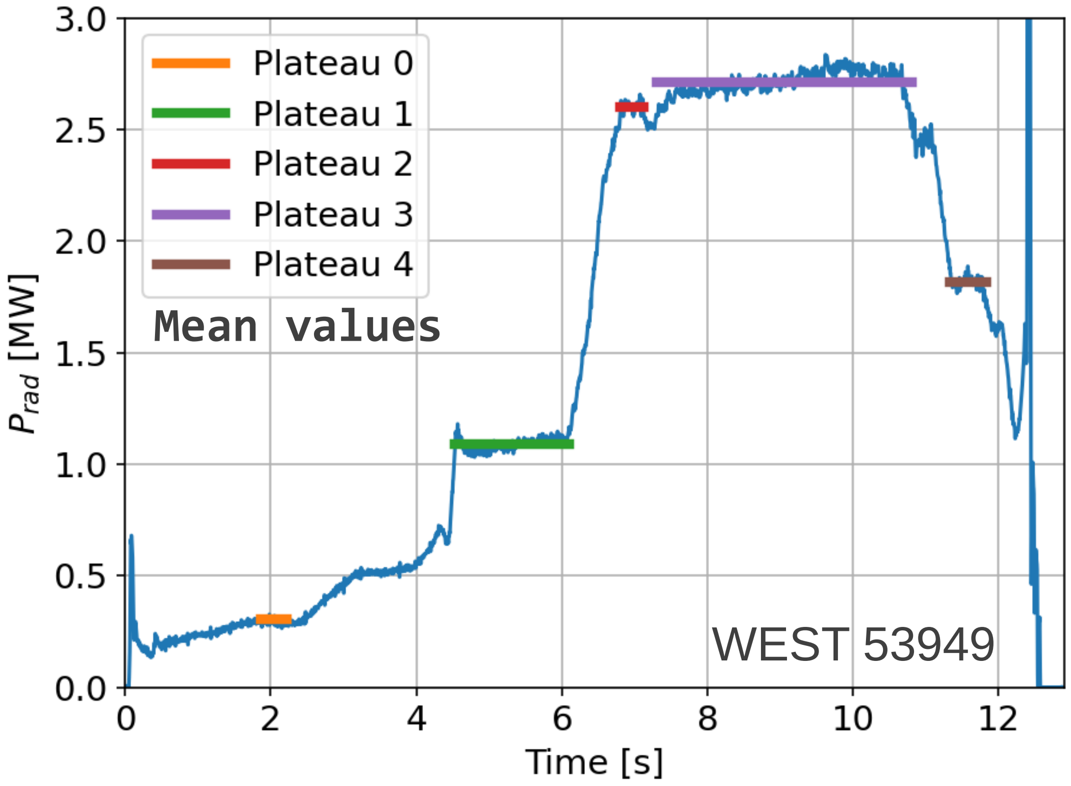
This tool allows to characterize one pulse by a small number of values:



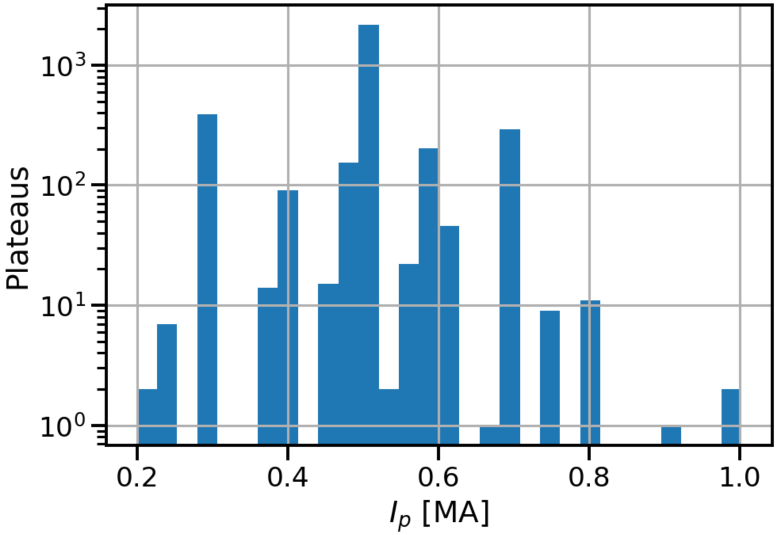
Plateau detection

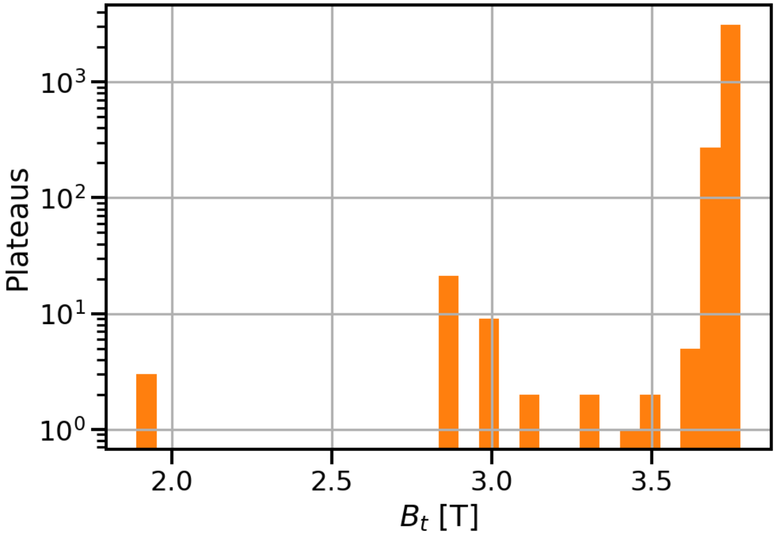
- Plateaus (quasi-steady states) are **detected automatically**, we avoid a bias that can appear when a human selection is made
- The properties of a plateau (min duration, max deviation, etc.) are explicitly given by the user, **numerical code available (open source)** at: https://github.com/jmoralesFusion/signal_plateau_recognition

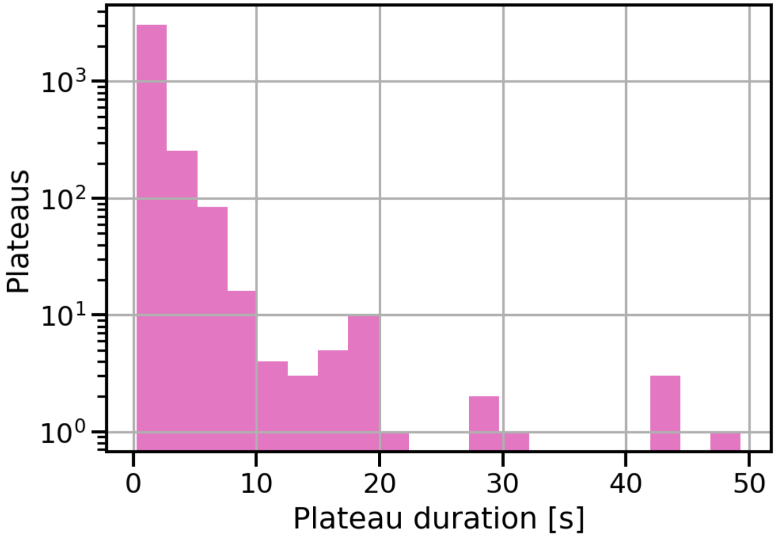


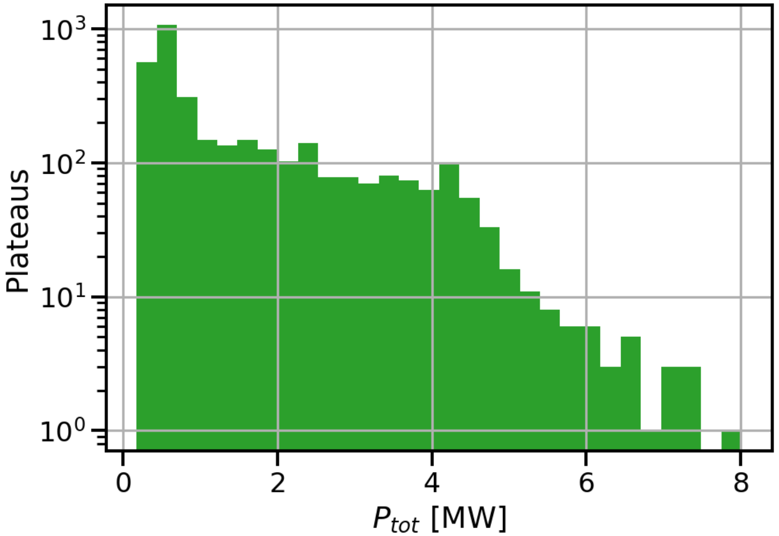


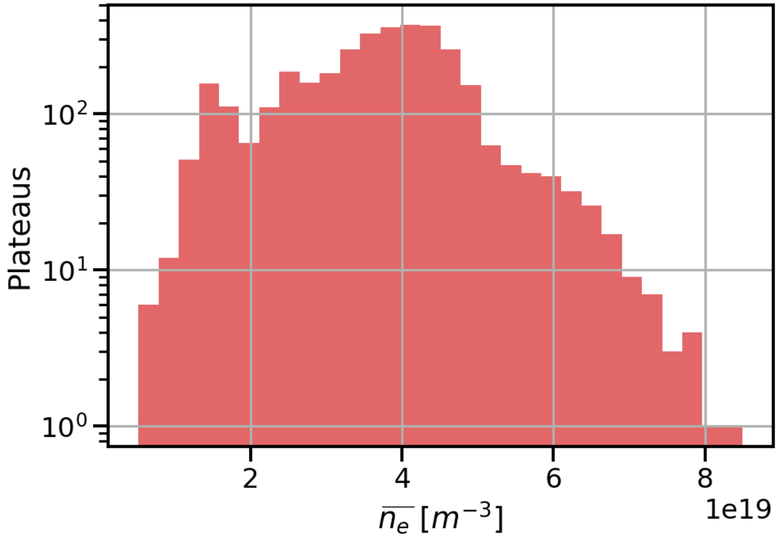
WEST quasi-steady states (plateaus of P_{tot} and I_p)









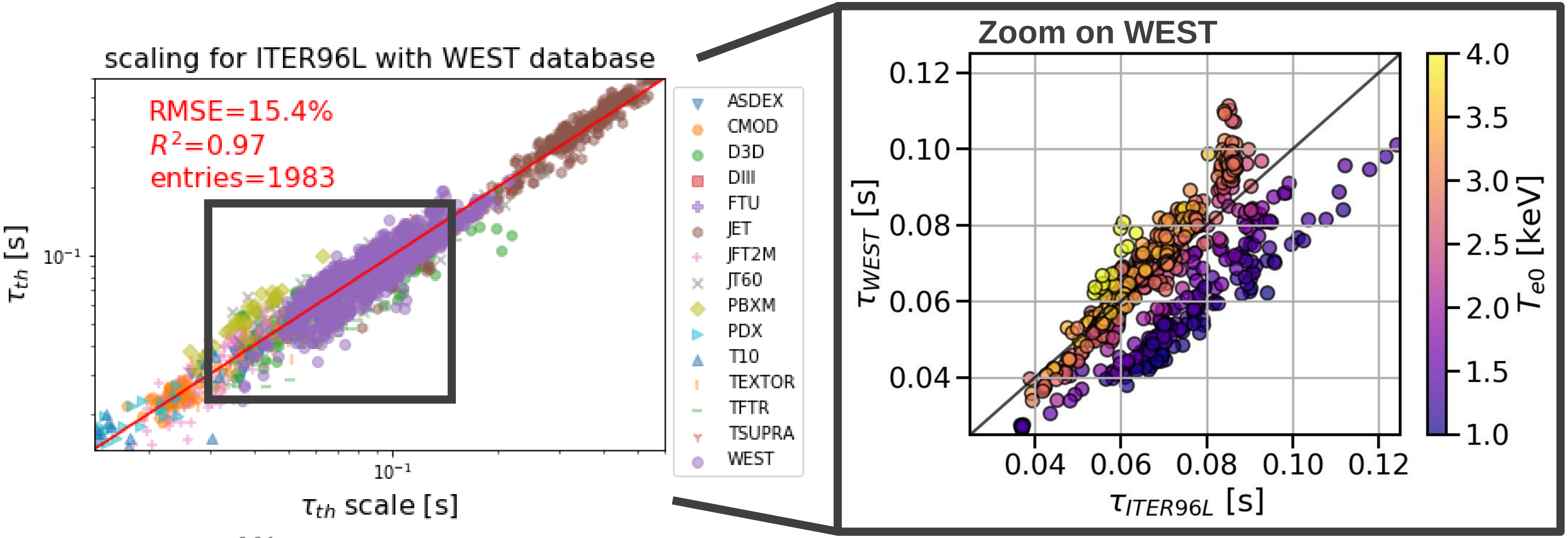


We extract data from IMAS [Imbeaux et al., Nucl. Fusion, 2015].

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)

Hot and cold T_{e0} branches in WEST quasi-steady states



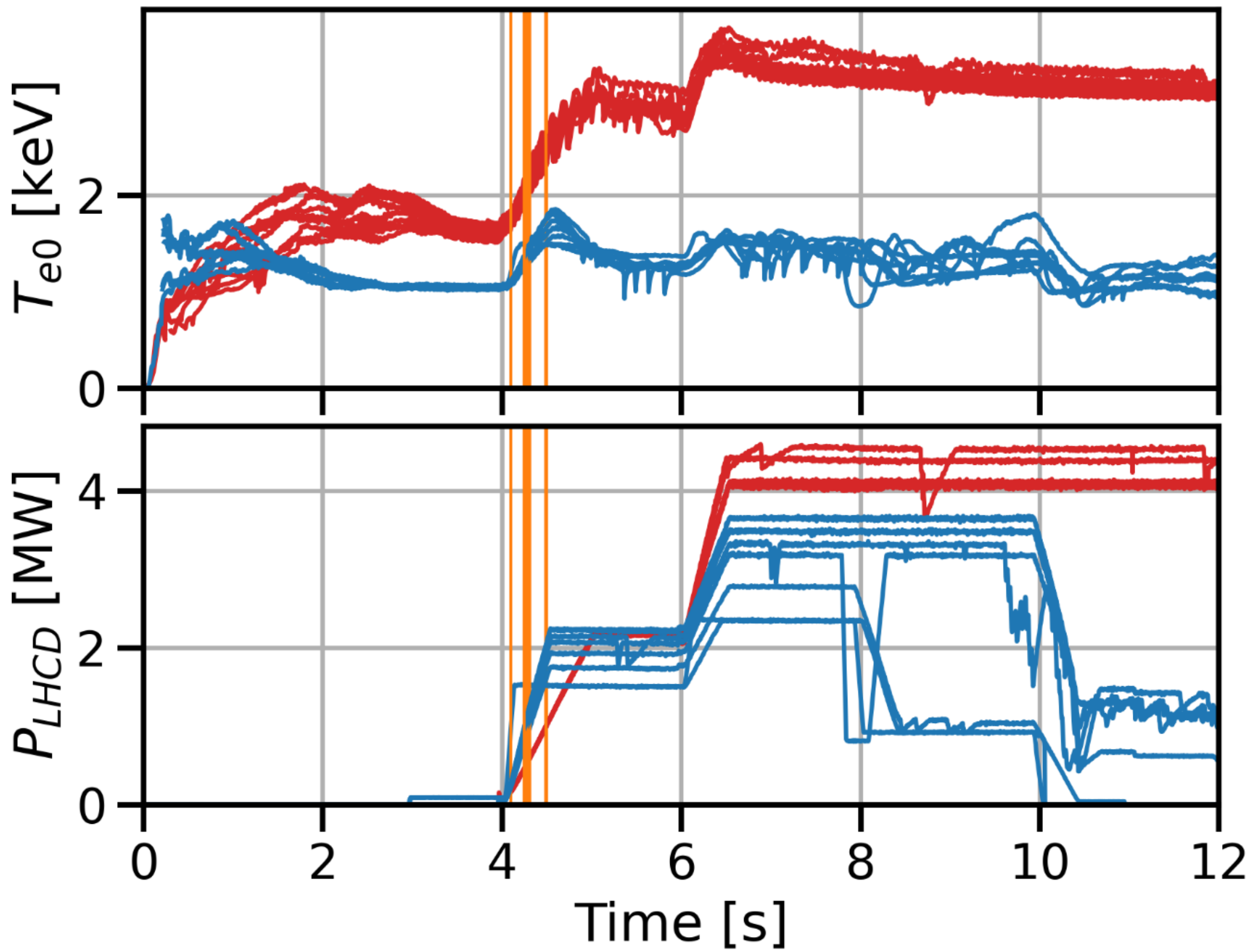
$$\tau_{ITER96L} = 0.023\, I_p^{0.96} B^{0.03} P^{-0.73} n_e^{0.4} M^{0.2} R^{1.83} \varepsilon^{-0.06} k^{0.64}$$ [Kaye, NF, 1997]

- 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]

Time signals of hot and cold branches

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



Hot (T_{e0} > 3 keV)

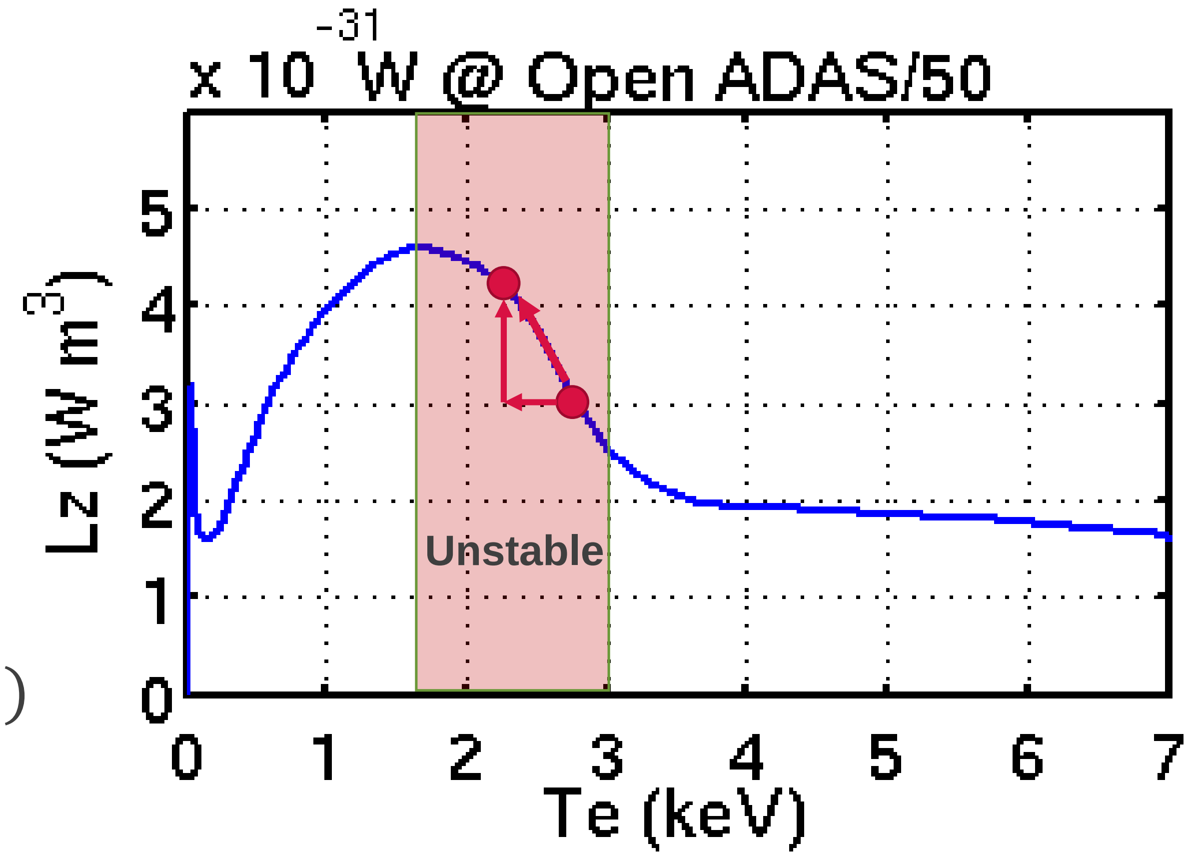
Cold (T_{e0} < 2 keV)

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

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

Tungsten cooling factor (Lz)

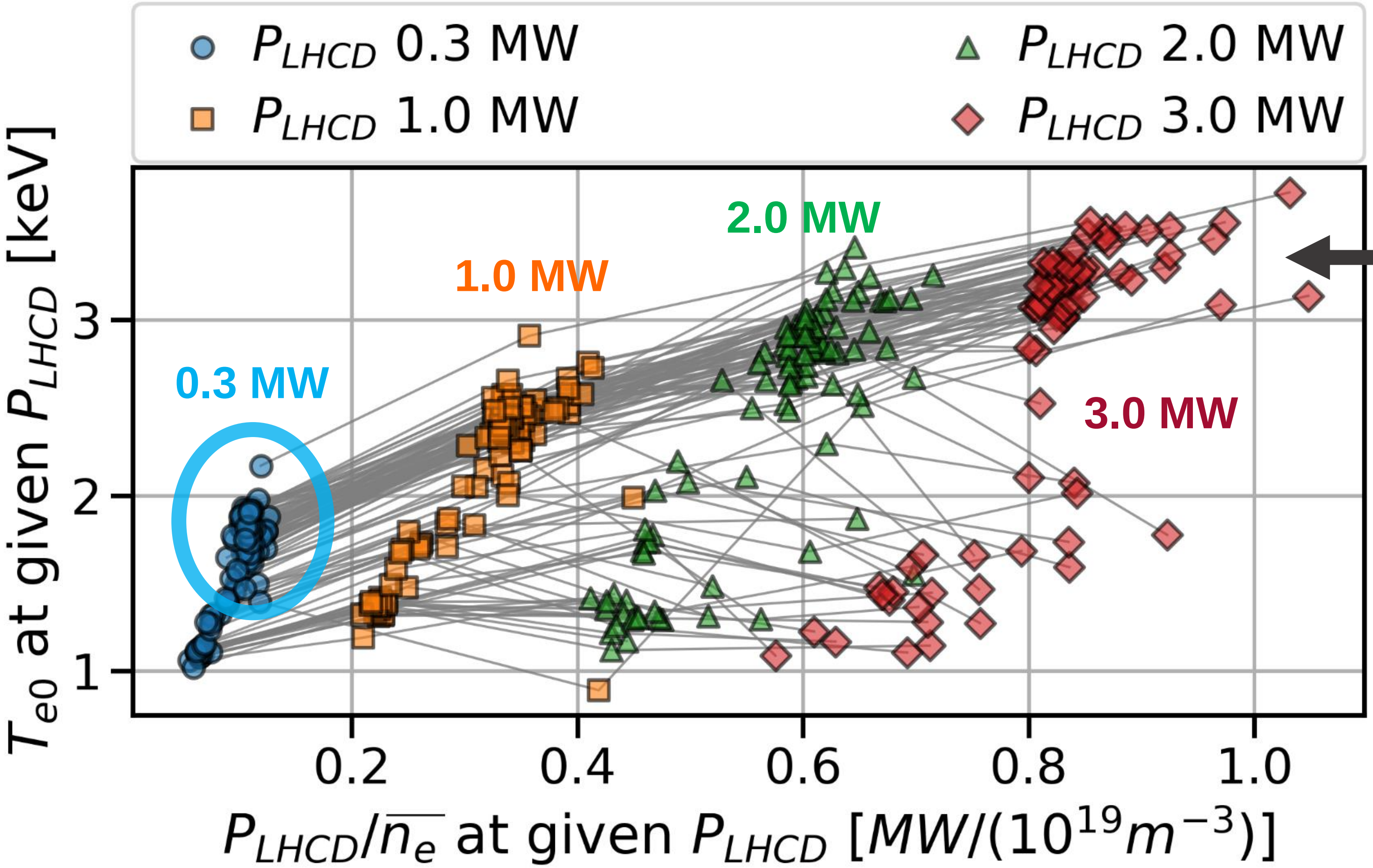
$$p_{rad,W} = n_e n_W Lz(T_e)$$



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})



Each grey line indicates a pulse trajectory

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

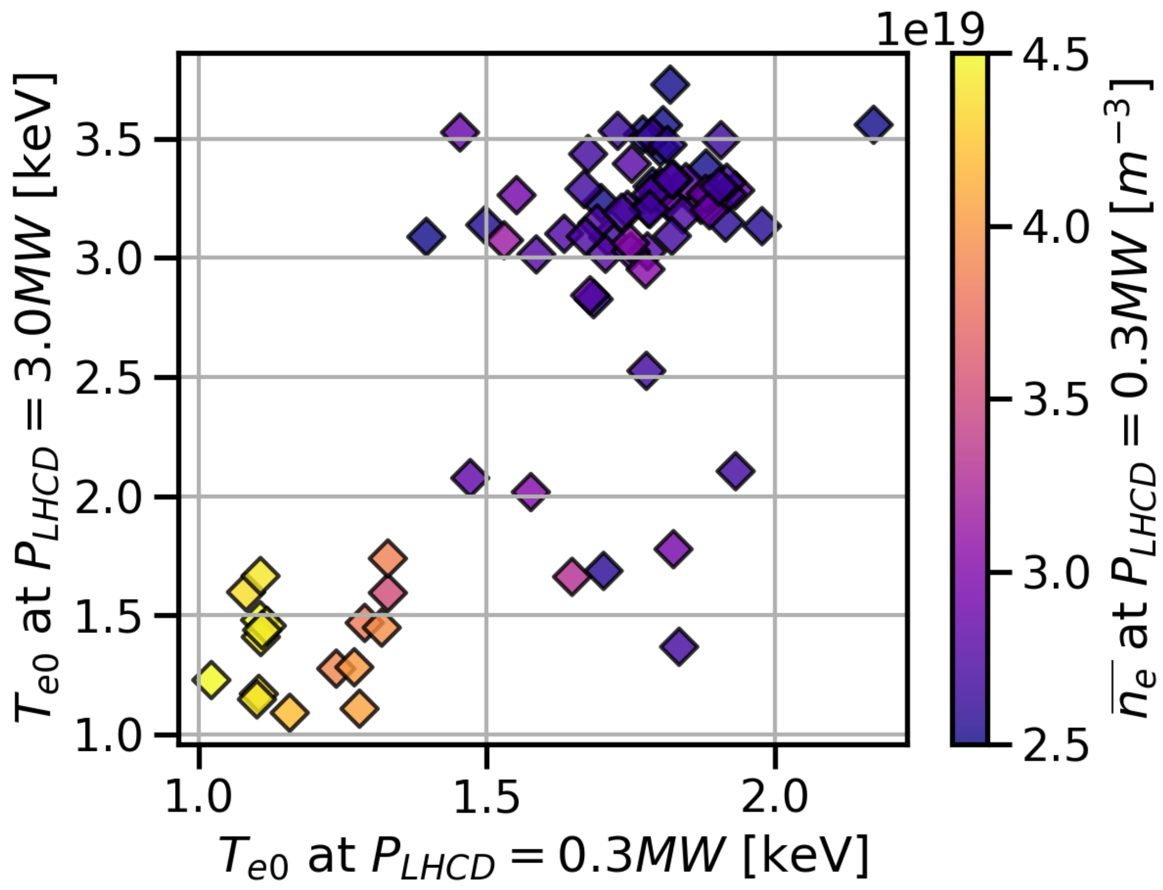
Two trajectories are observed:

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

High initial T_{e0} in "good" trajectories

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

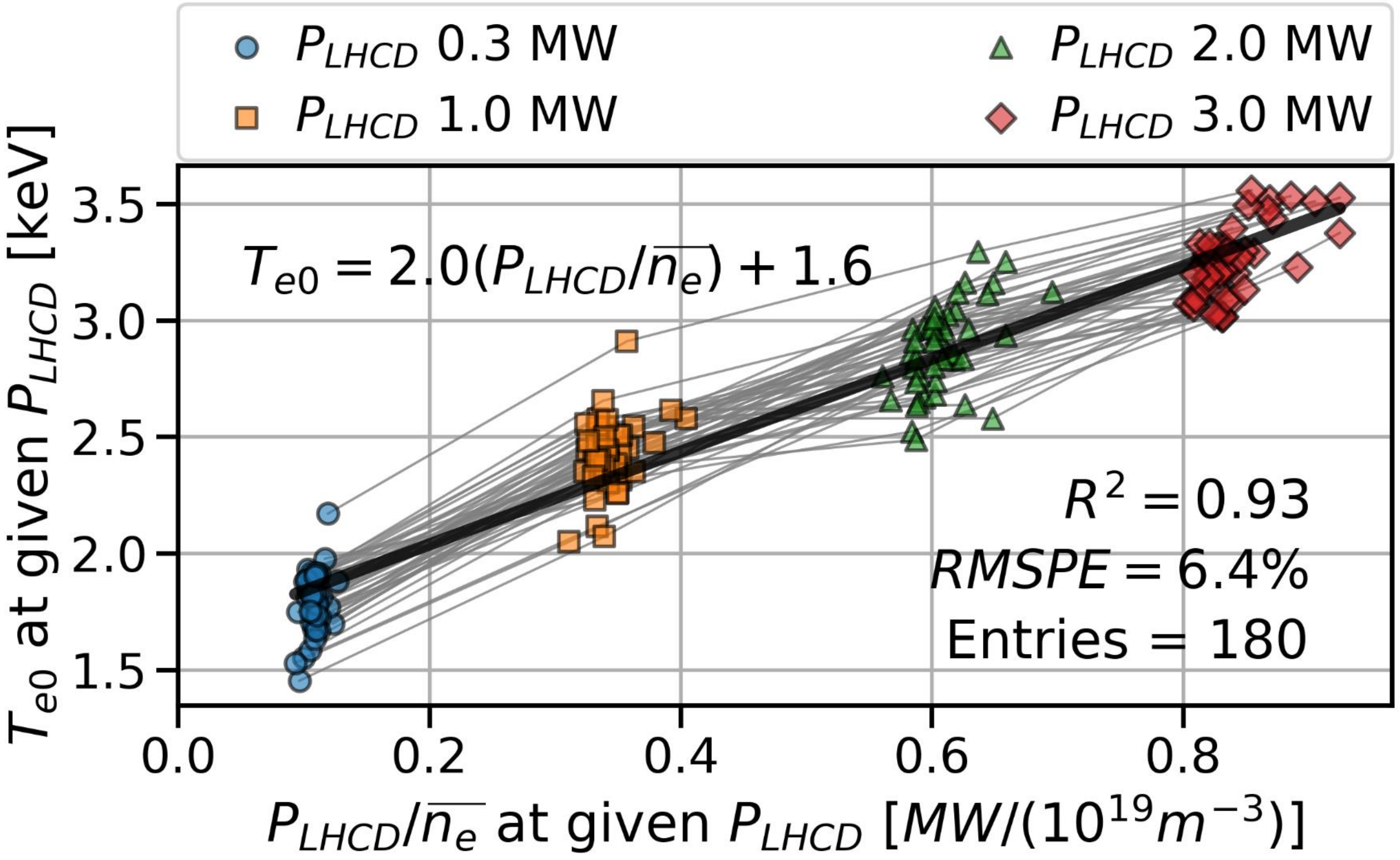
T_{e0} at high heating phase



T_{e0} at heating onset

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

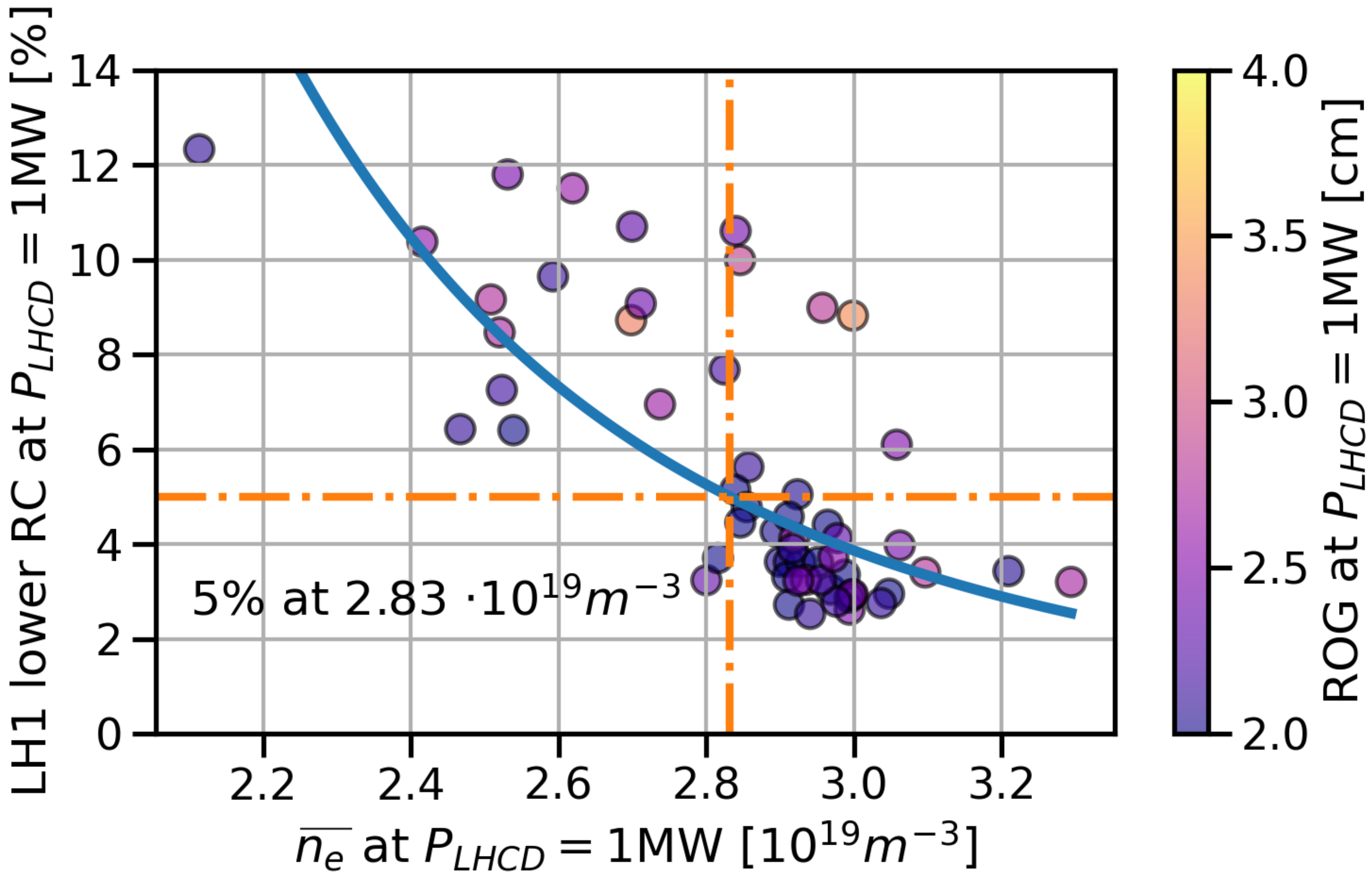
$\overline{n_e} < \sim 3.0\ [10^{19} m^{-3}]$



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

$$\frac{\boldsymbol{P_{LHCD}}}{\boldsymbol{\overline{n_e}}} > \mathbf{0.7}\ \left[\boldsymbol{MW/10^{19}m^{-3}}\right]$$

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%:**

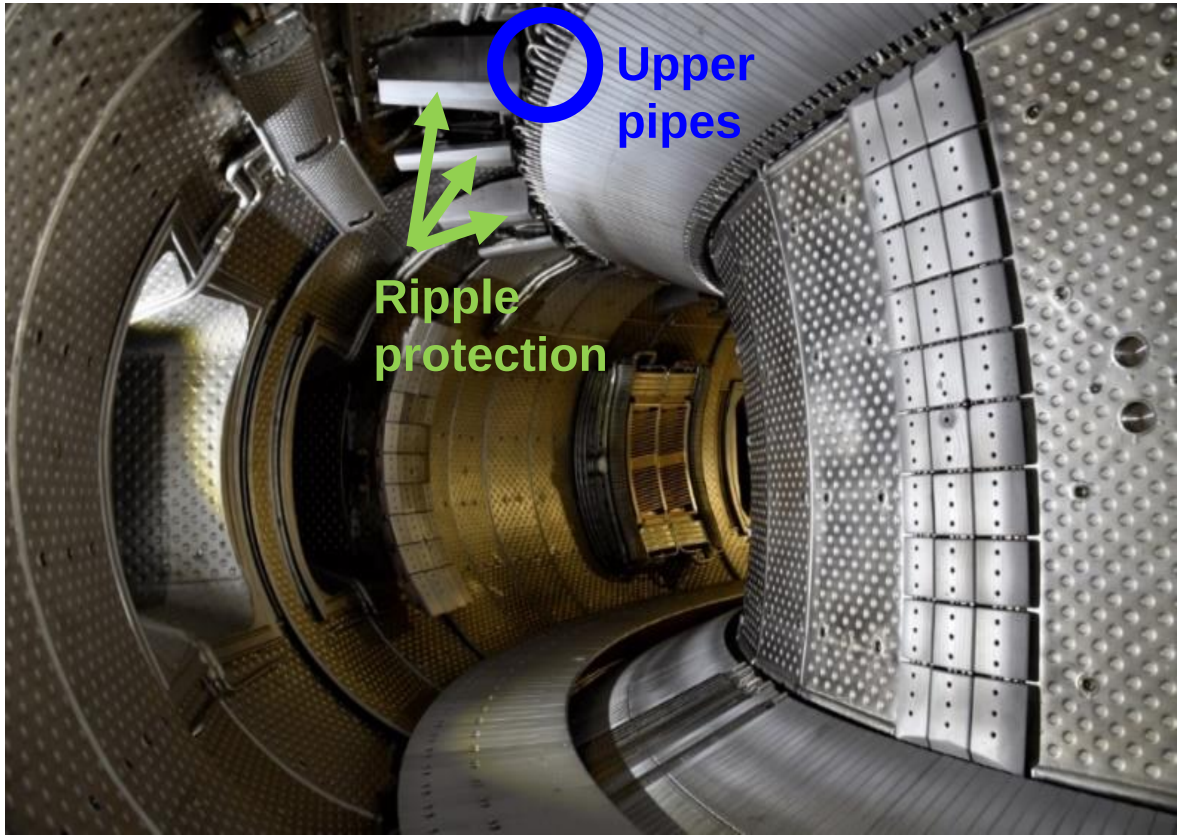
$$\overline{n_e} > 2.8 \left[10^{19} m^{-3}\right]$$

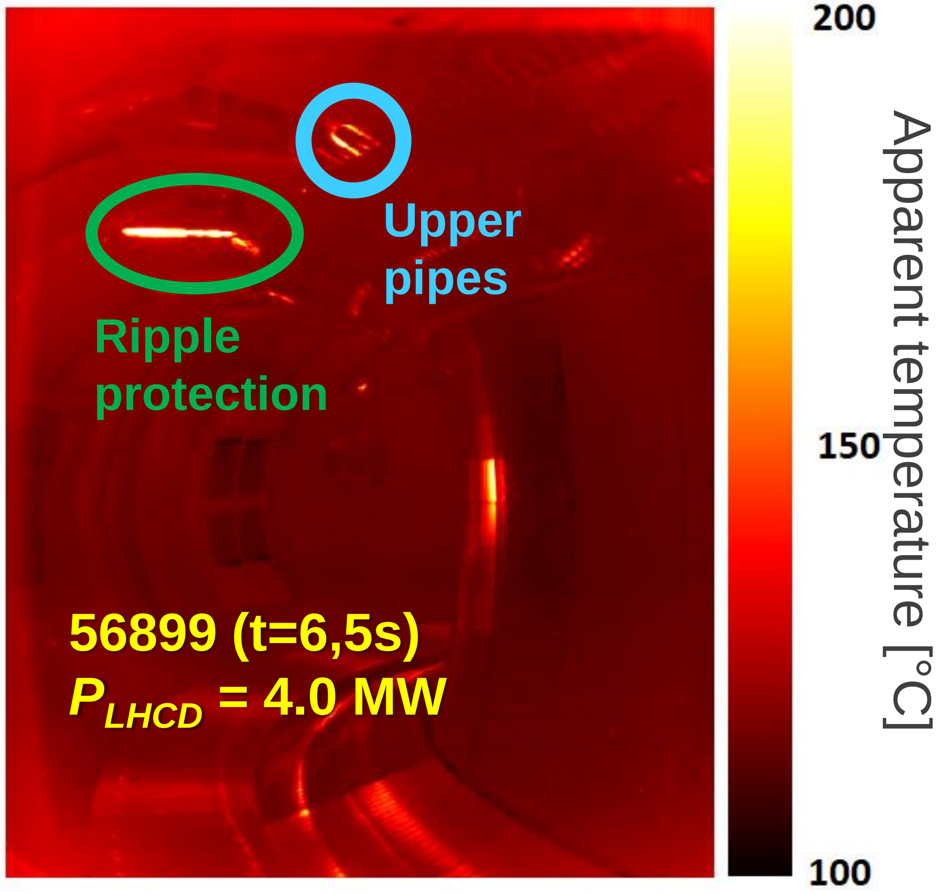
We recall: to achieve **large initial T_{e0}** :

$$\overline{n_e} < \sim 3.0 \left[10^{19} m^{-3}\right]$$

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**





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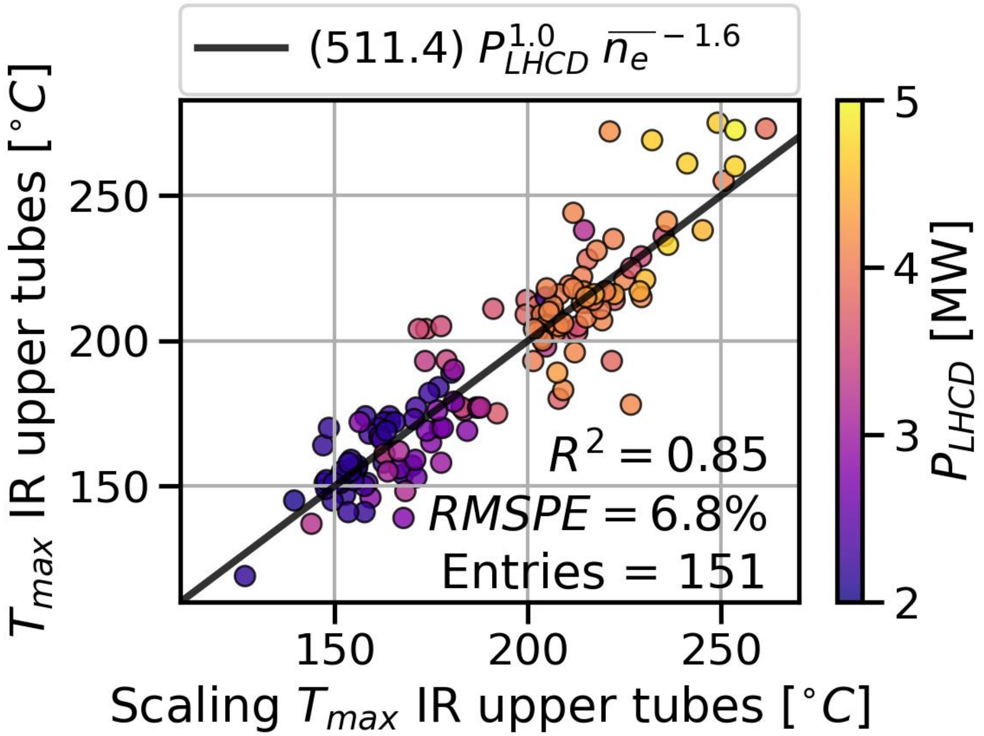
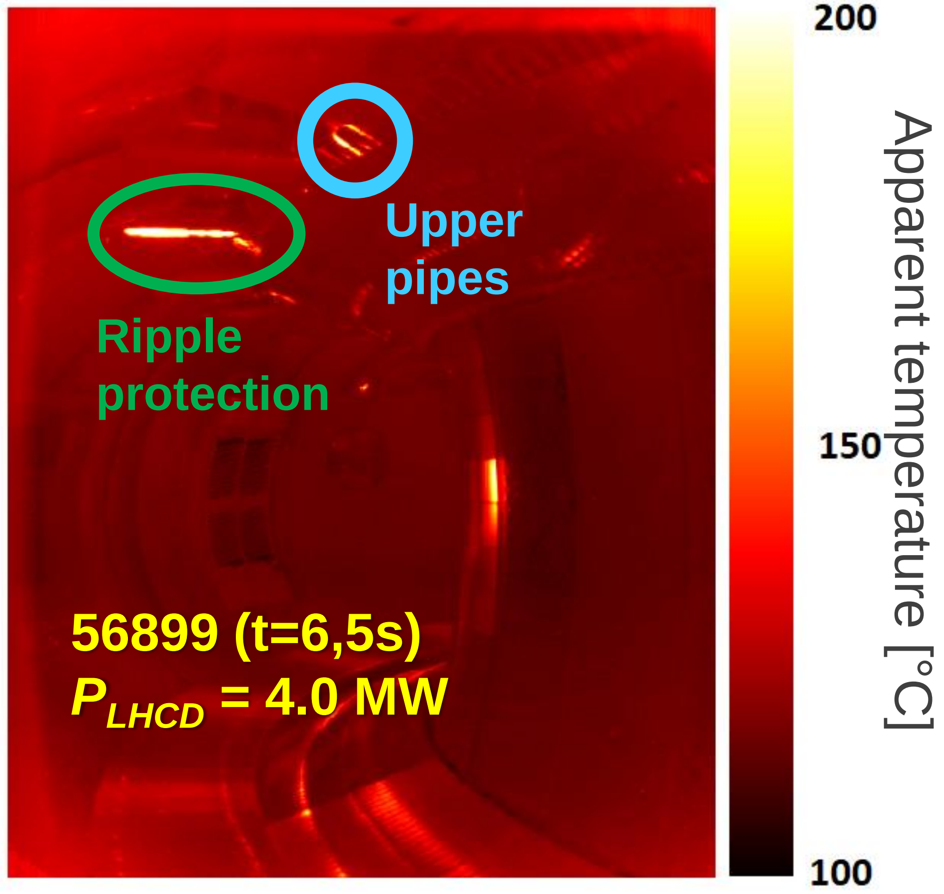
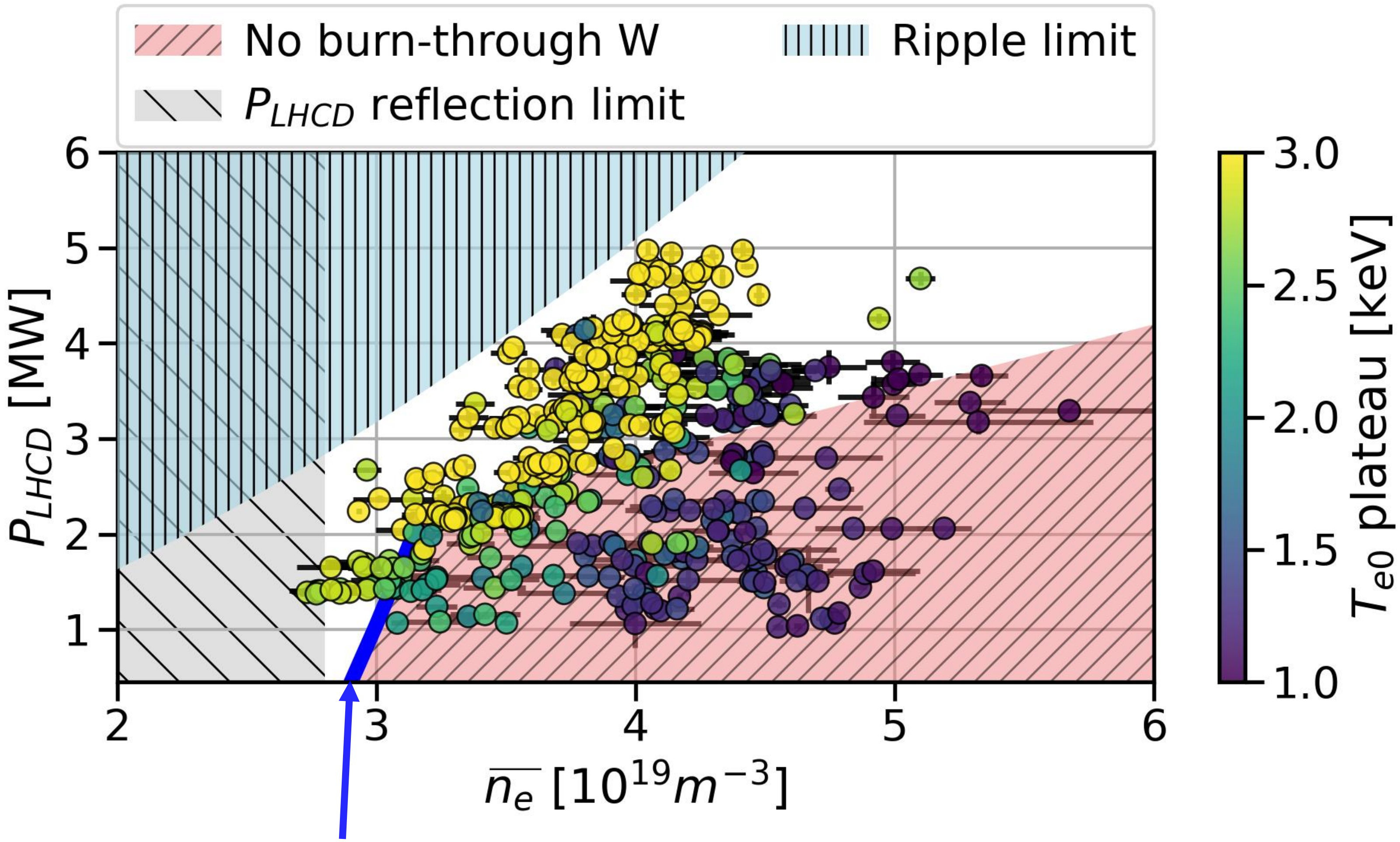




Summary: LHCD operational space for WEST



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