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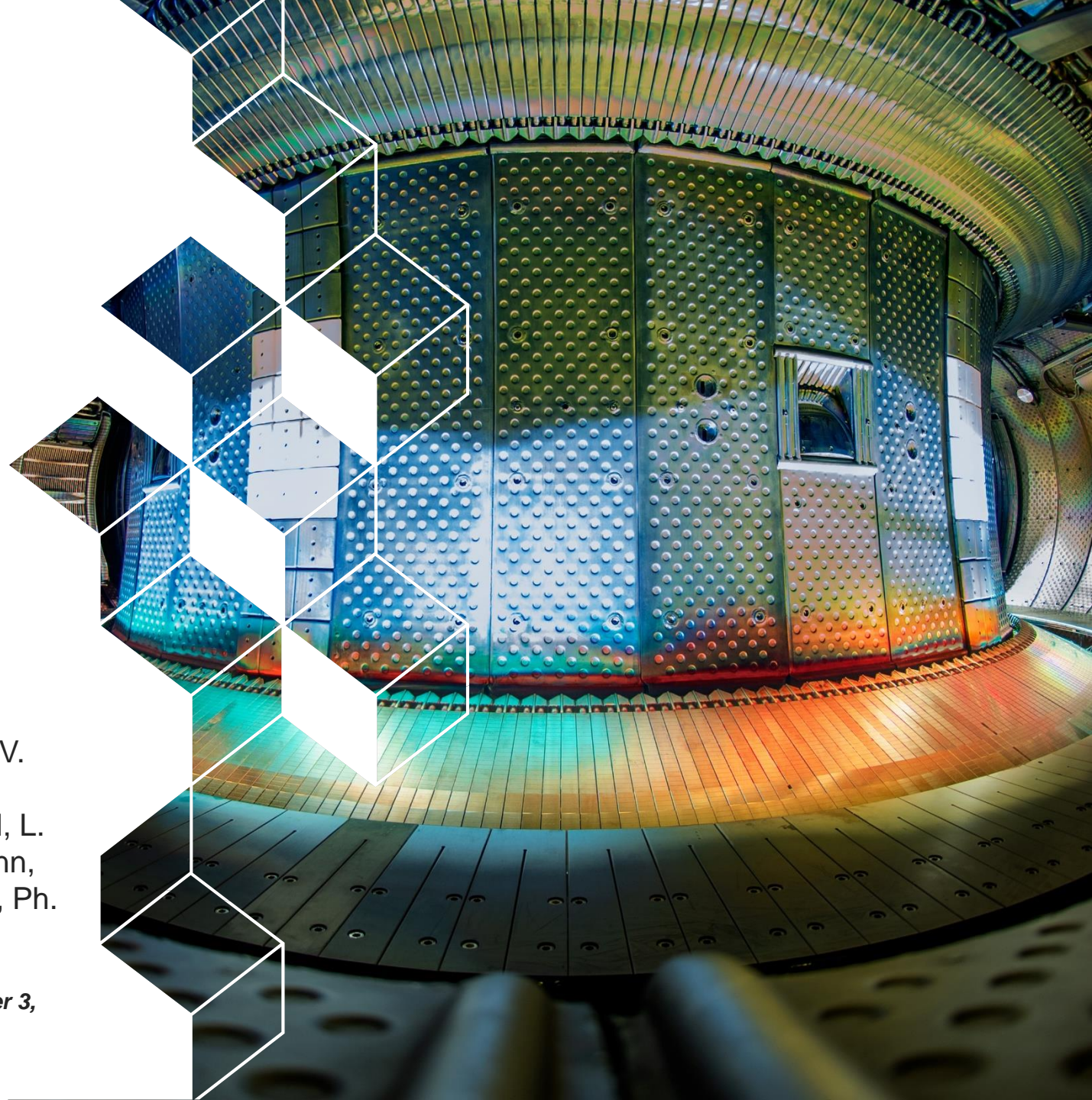


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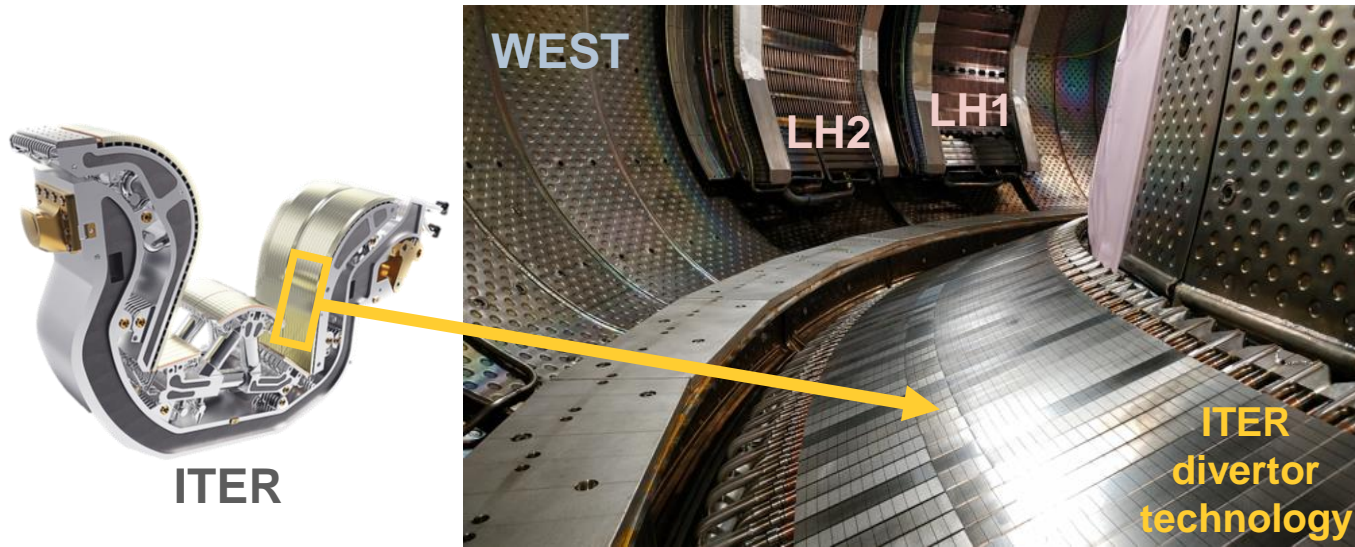
WEST tungsten contamination issues and proposed solutions in support to ITER

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

*65th Annual Meeting of the APS Plasma Division, October 30-November 3,
2023, Denver, Colorado*



Introduction

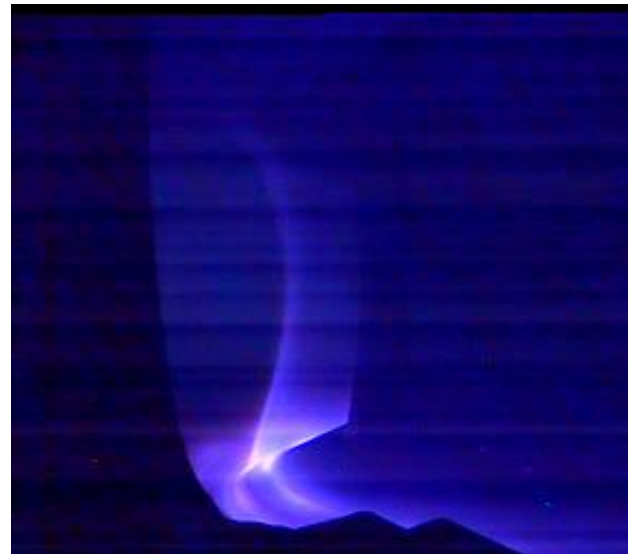
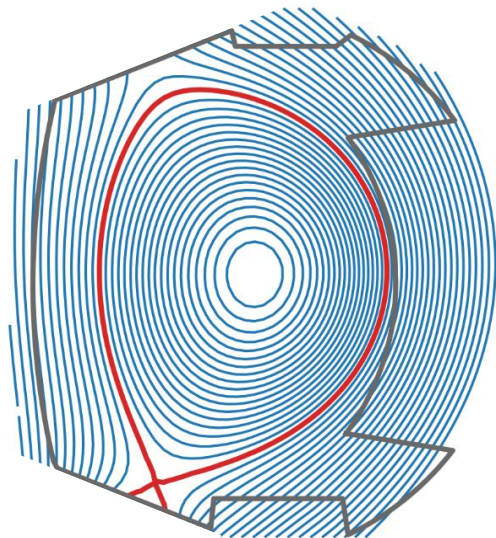


WEST is a device specialized for long pulse operation in a tungsten environment. Testbed for ITER divertor technology (actively cooled tungsten mono-blocks)

Main goal: develop reactor compatible long pulse scenarios

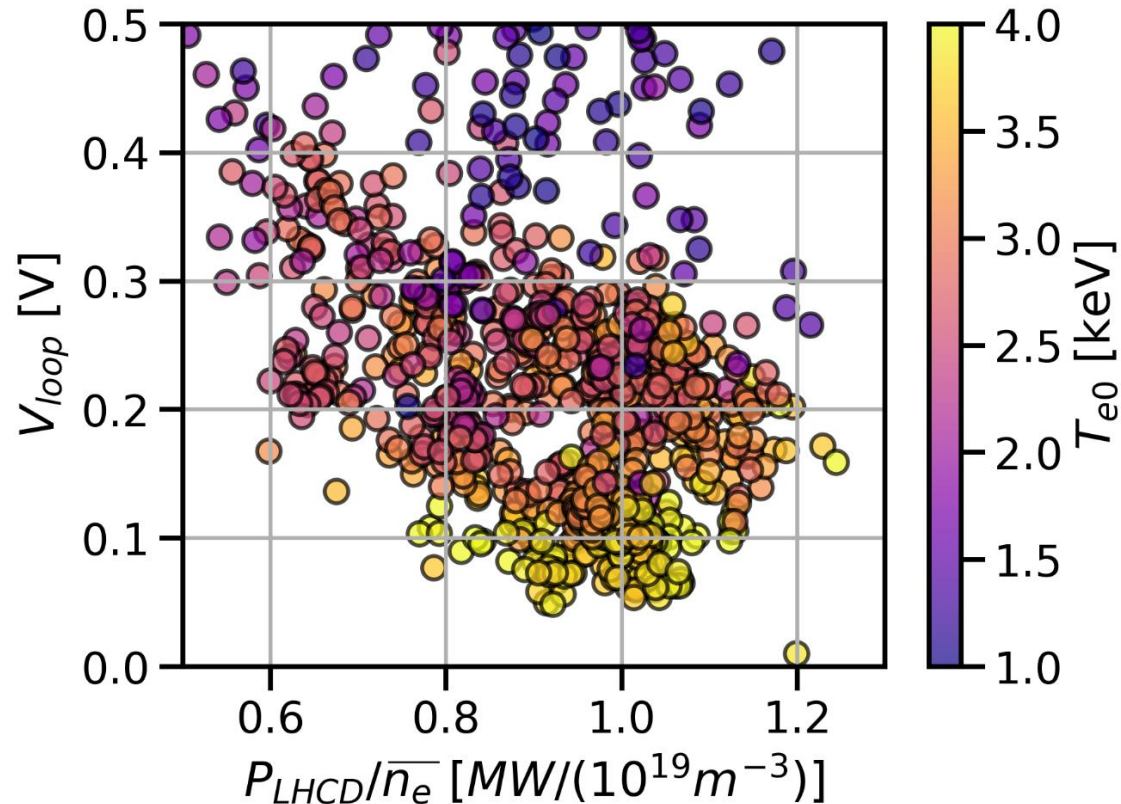
[Bucalossi, Nucl. Fusion, 2021]

[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



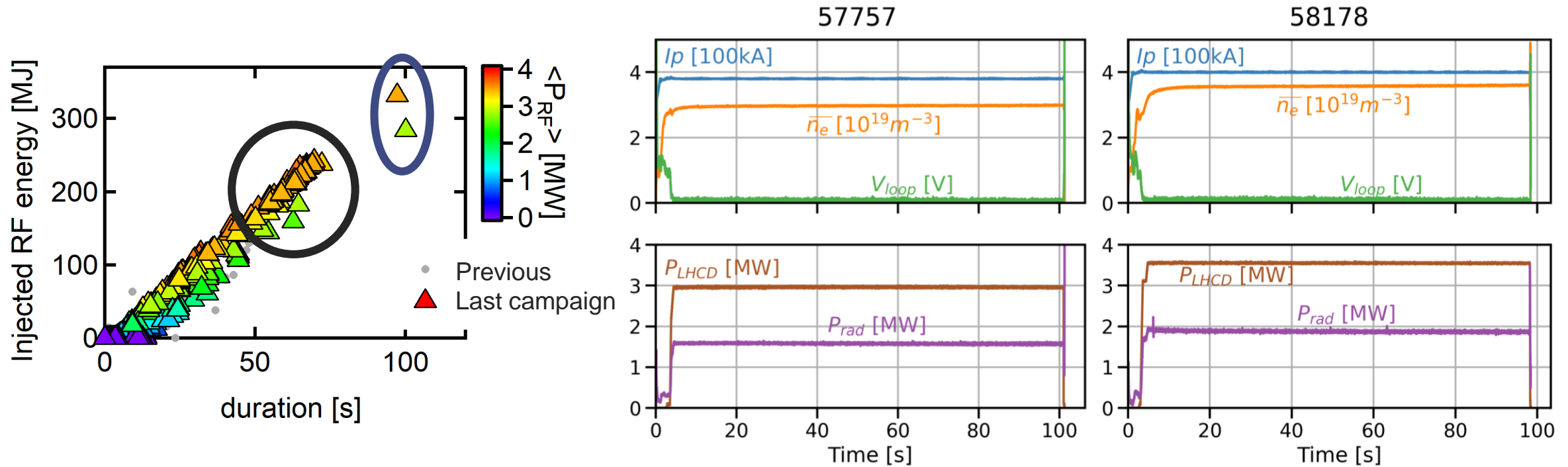
How?

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)

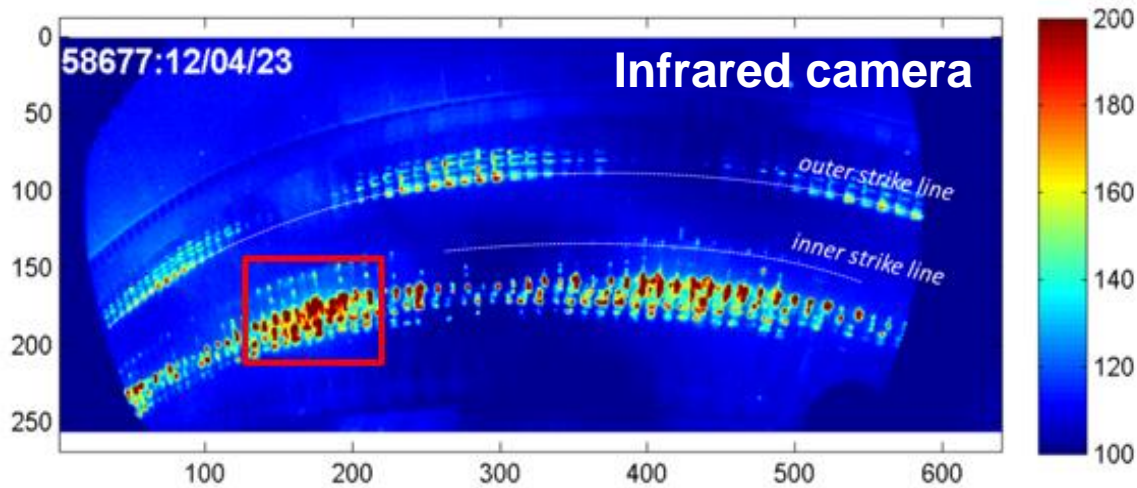
P_{LHCD} = Lower Hybrid Current Drive power
 \bar{n}_e = averaged line integrated density

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

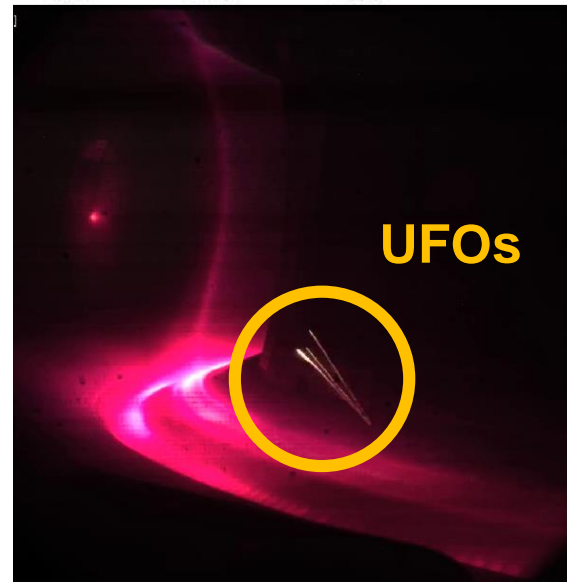
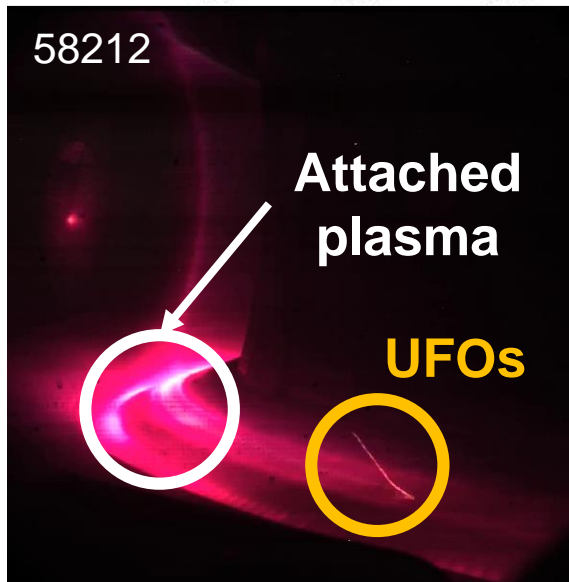


- Several hundred pulses with 1 min length
- Pulse 57757: $V_{loop} \sim 50\text{mV}$ during 101s with 3 MW LHCD power (injected energy ~ 290 MJ)
- Pulse 58178: $V_{loop} \sim 70\text{mV}$ during 98s with 3.6 MW LHCD power (injected energy ~ 340 MJ)

Long pulses achieved, but heat loads with attached plasma are too high (important W erosion)



- Deposit layers form during repetitive long discharges (W erosion and redeposition)
- These layers can detach and enter the plasma where they strongly radiate
- High radiation can lead to disruptions

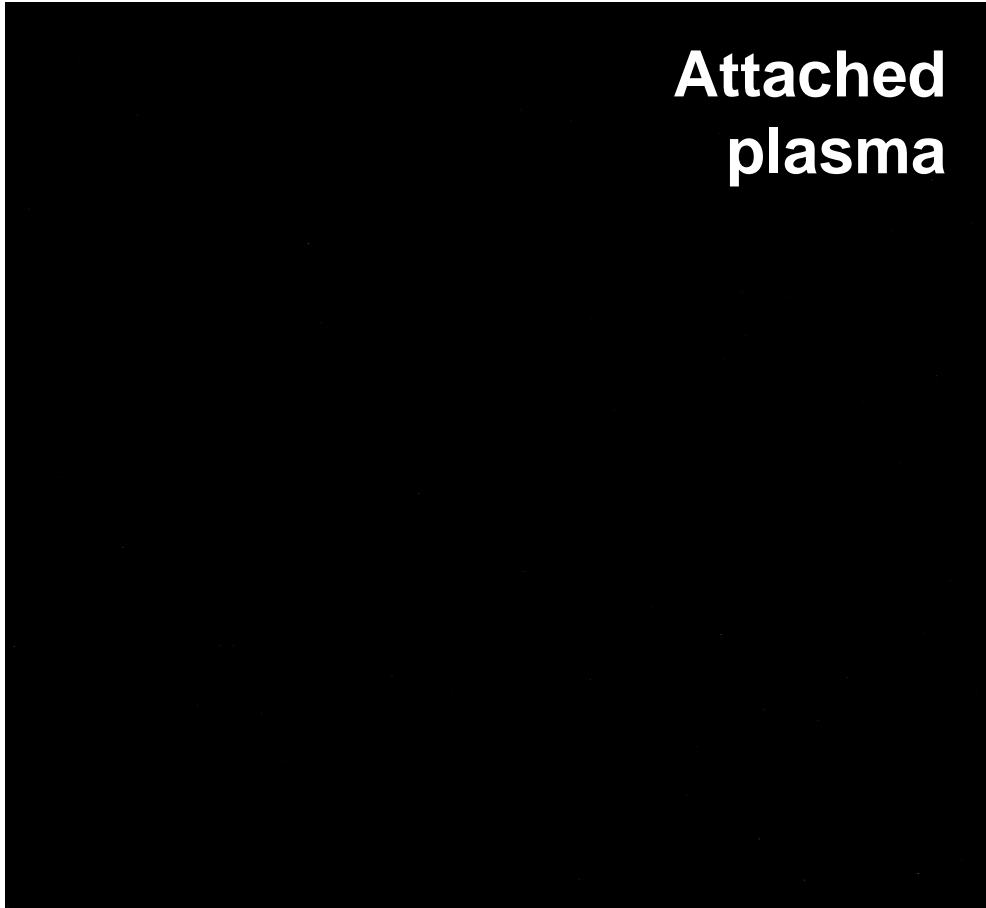


- To limit W erosion semi-detached or detached divertor regimes are required

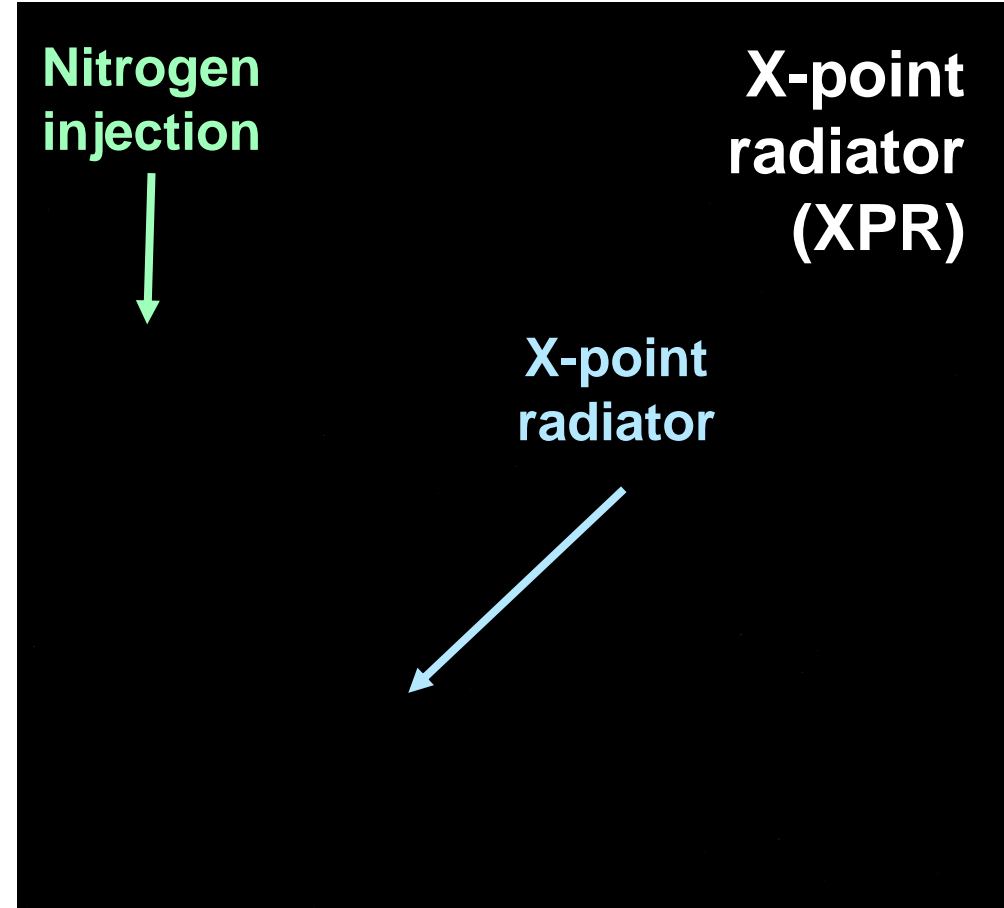
A solution: X-point radiator?



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[Bernert, Nucl. Fusion, 2020] [Lunt, Phys. Rev. Lett., 2023]



Outline

- 1. Long pulse operation:** heating plasmas in a tungsten environment, burn-through tungsten during LHCD power ramp-up
- 2. Reducing divertor heat loads:** X-point radiator regime

LHCD = Lower Hybrid Current Drive

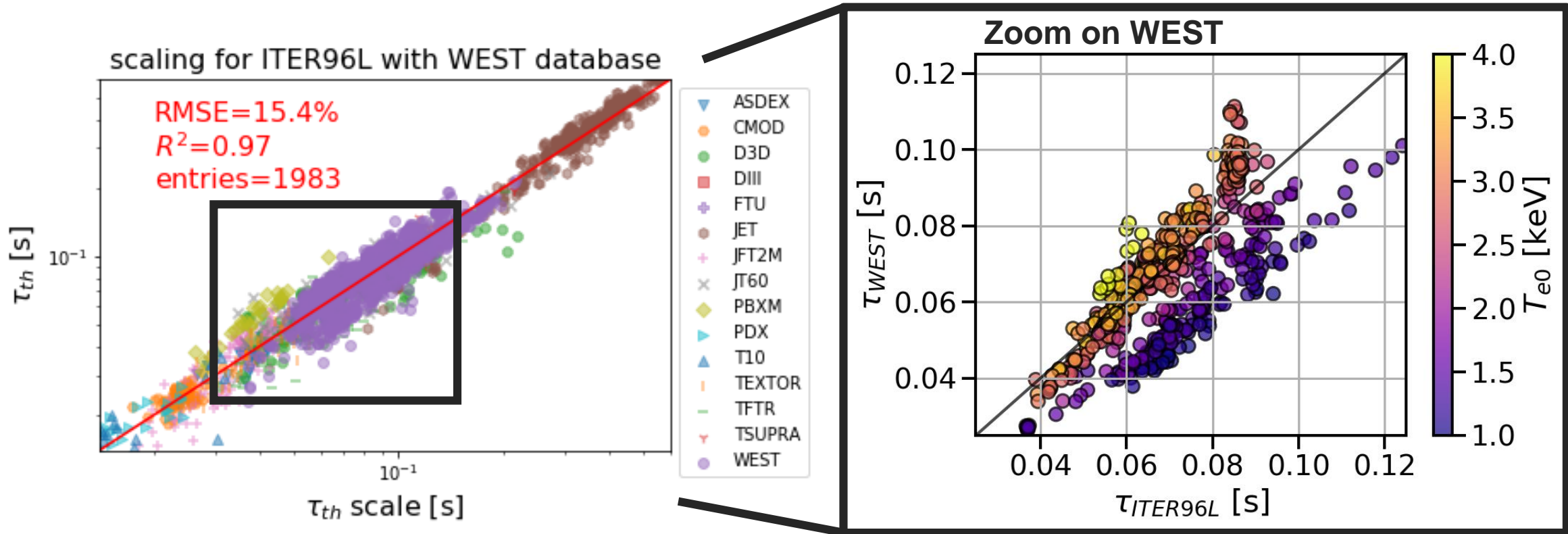


Outline

- 1. Long pulse operation: heating plasmas in a tungsten environment, burn-through tungsten during LHCD power ramp-up**
2. Reducing divertor heat loads: X-point radiator regime

LHCD = Lower Hybrid Current Drive

Hot and cold branches in WEST

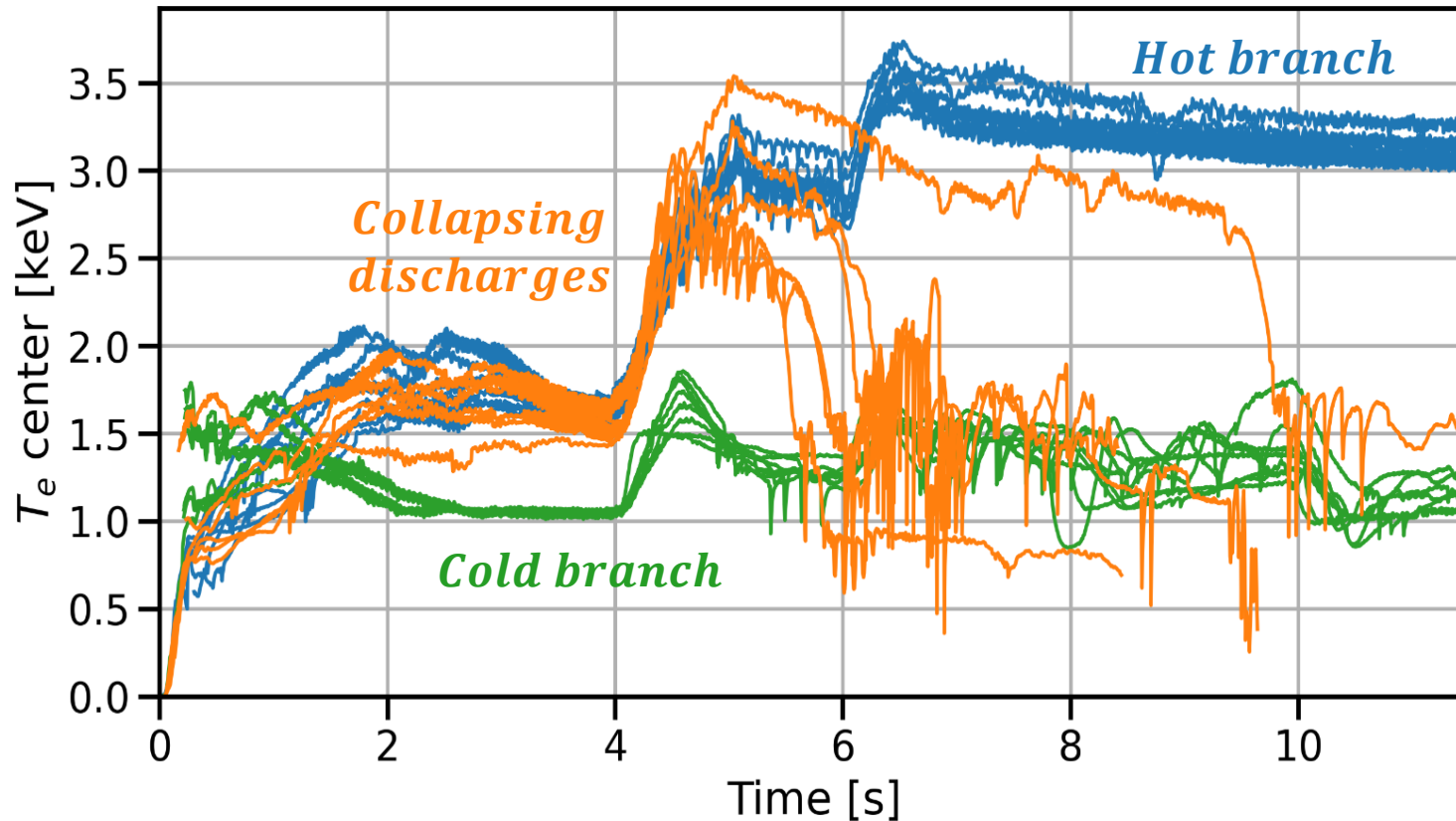


$$\tau_{ITER96L} = 0.023 I_p^{0.96} B^{0.03} P^{-0.73} n_e^{0.4} M^{0.2} R^{1.83} \epsilon^{-0.06} k^{0.64} \text{ [Kaye, NF, 1997]}$$

- 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]

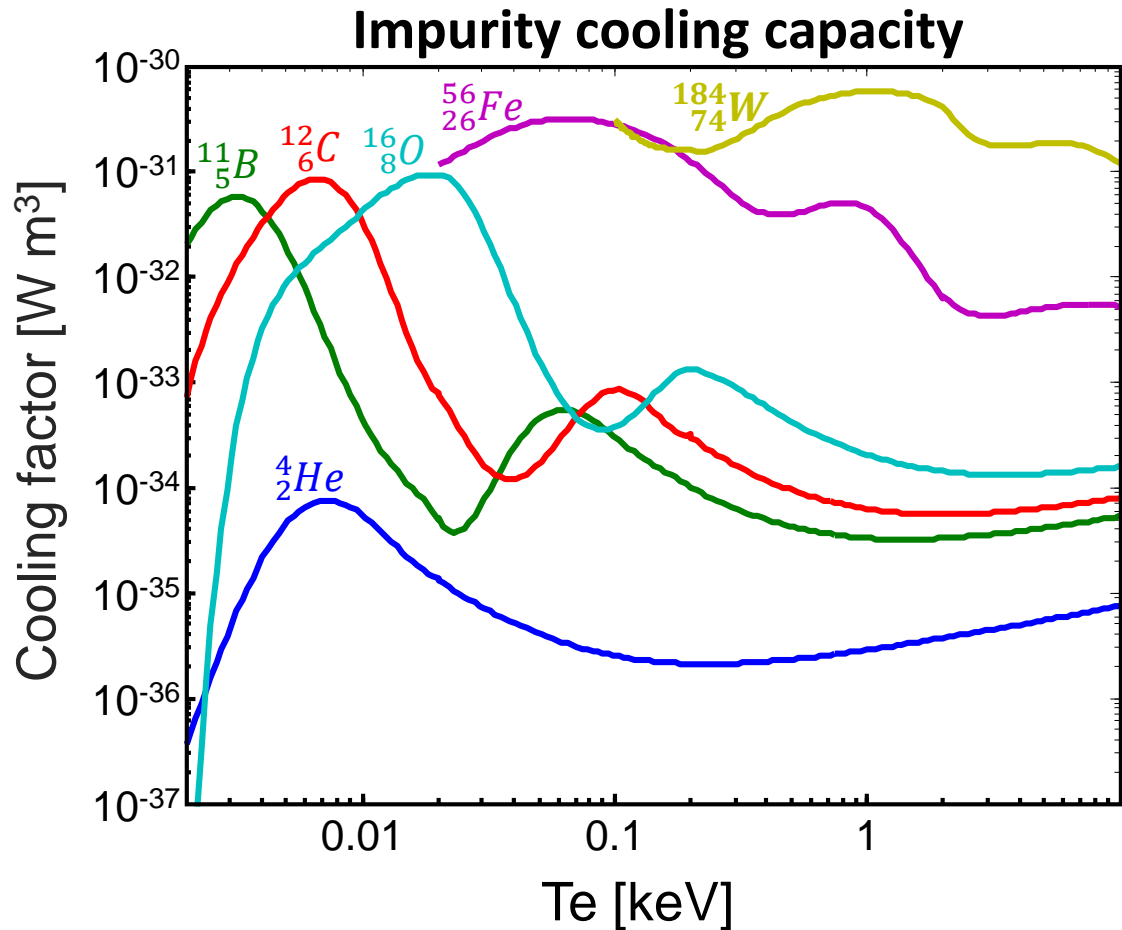
Type of discharges identified



- Three types of discharges are identified:
- **Hot branch** (needed for long pulse)
 - **Cold branch**
 - **Collapsing discharges** (from hot to cold branch)

[Ostuni, Nucl. Fusion, 2022]

Burn-through plasma impurities



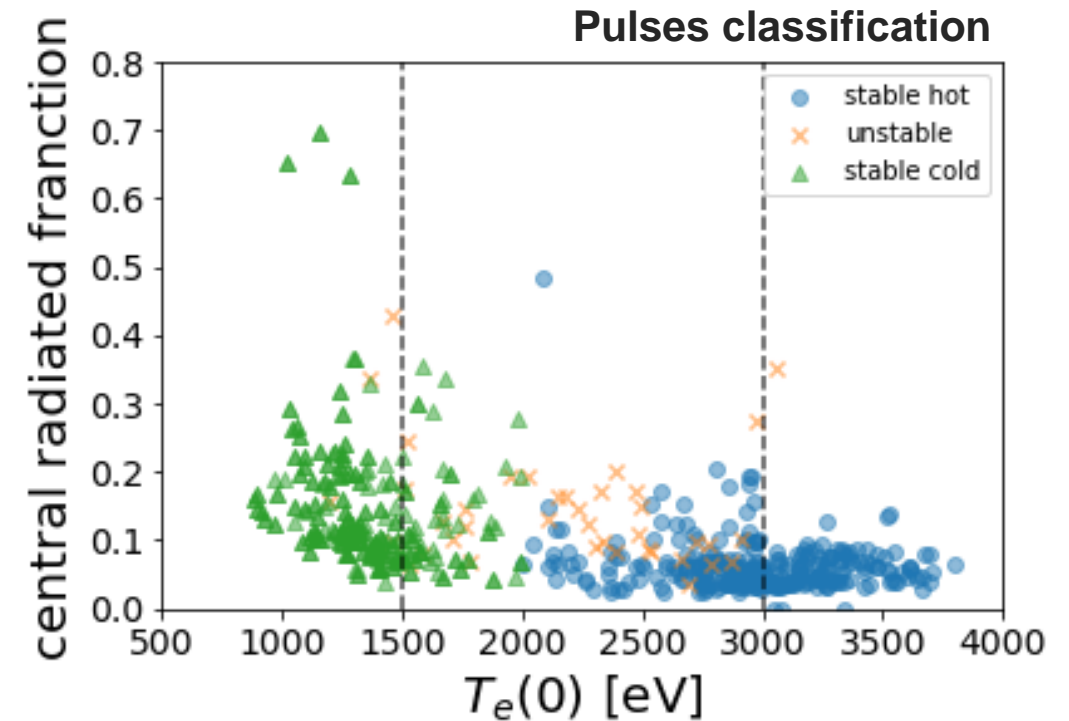
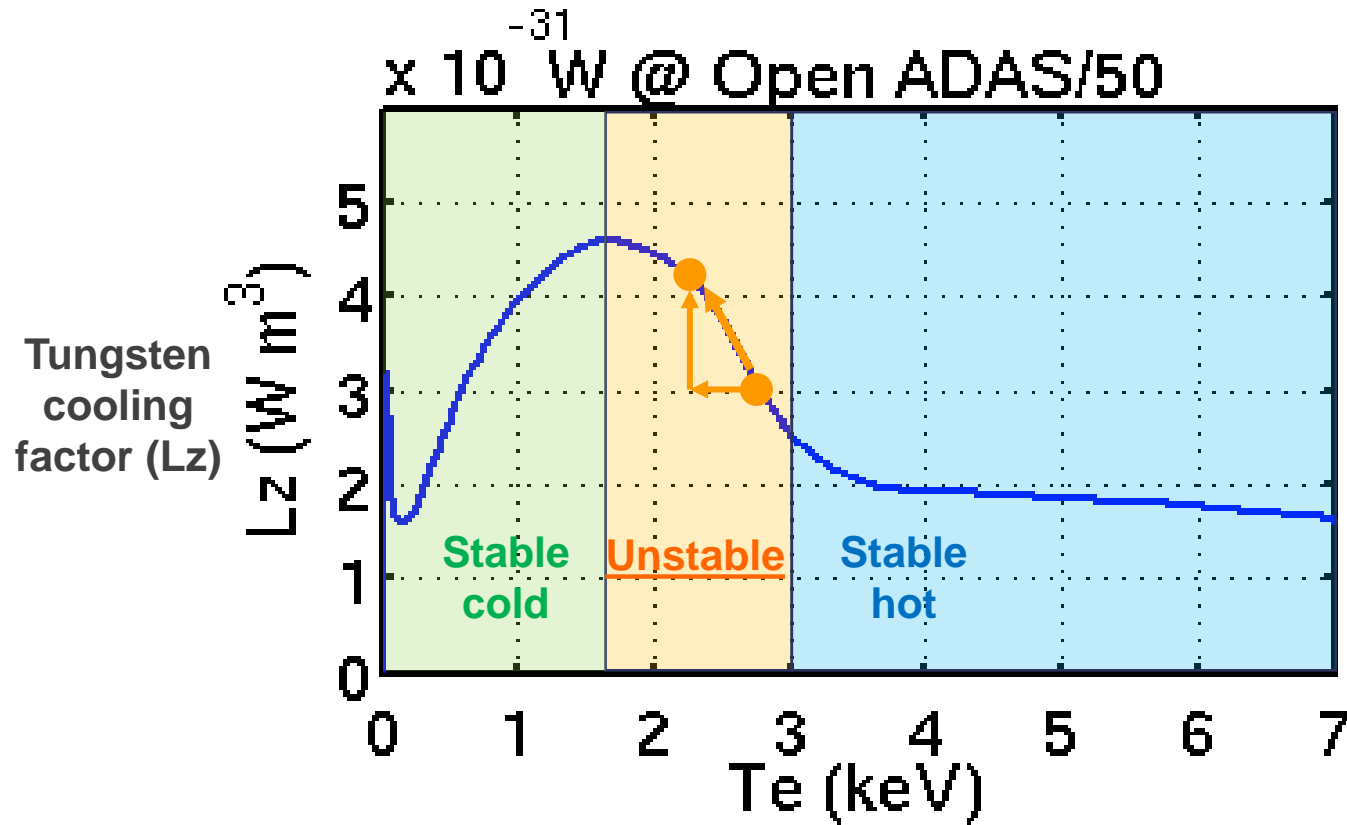
← Tungsten has a very strong cooling capacity

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

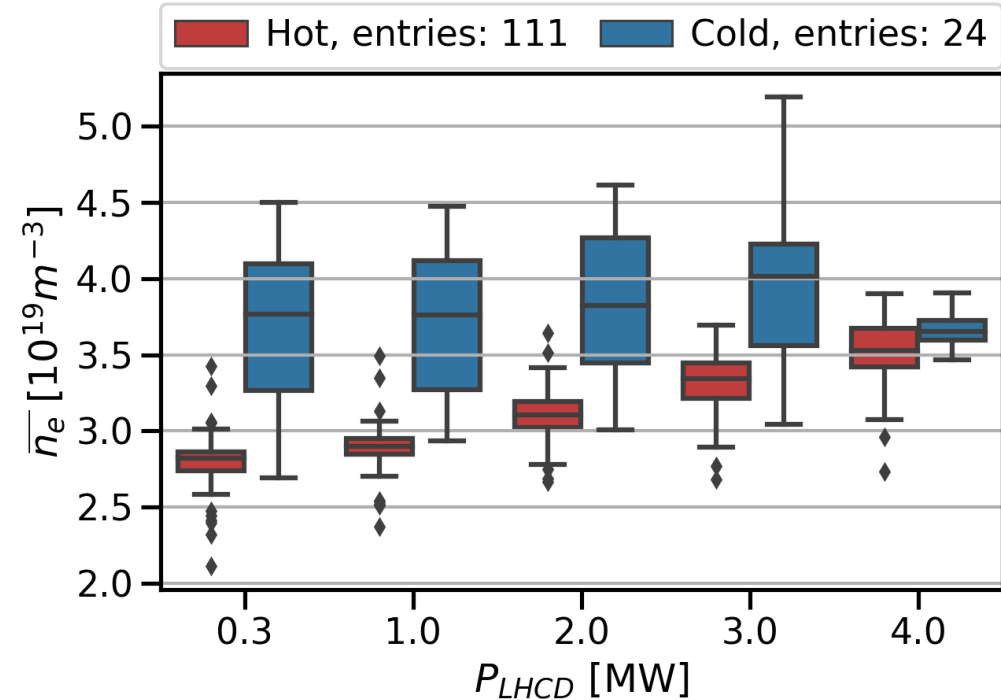
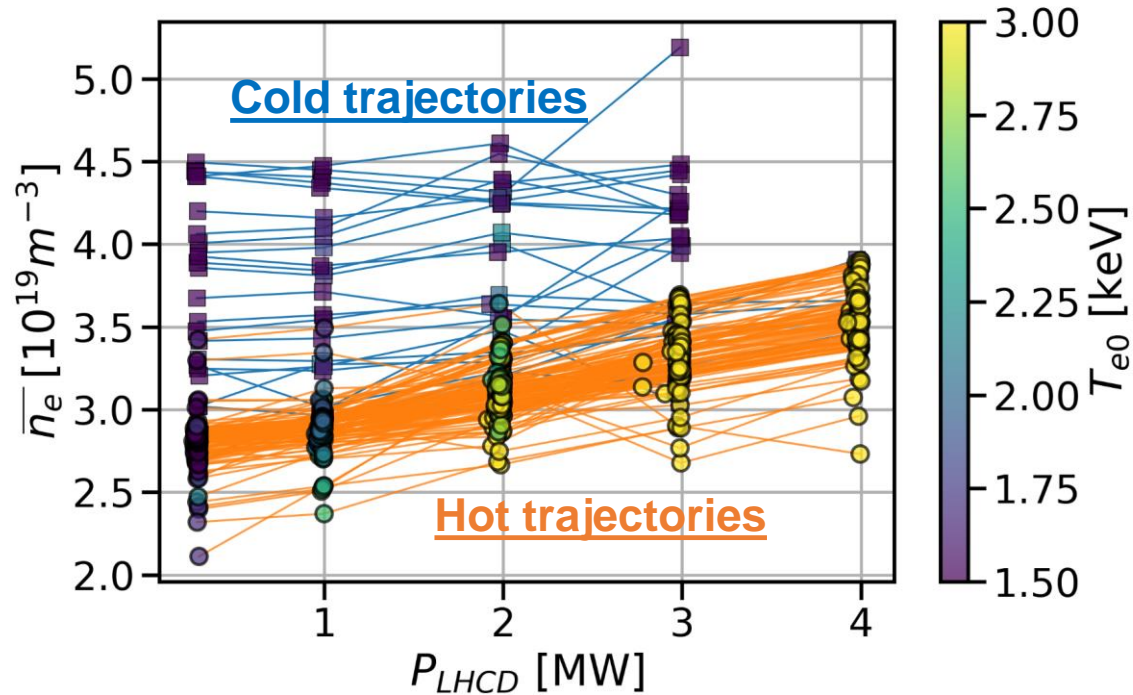


$$p_{rad,W} = n_e n_W Lz(T_e)$$

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

[Ostuni, Nucl. Fusion, 2022]

Density trajectory to burn-through W



To achieve hot trajectories (burn-through W) we need to start and stay below a given density during LHCD power ramp-up

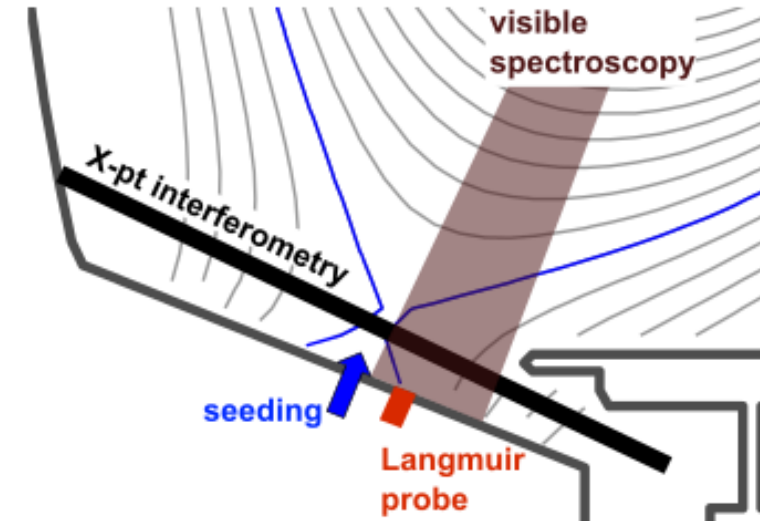
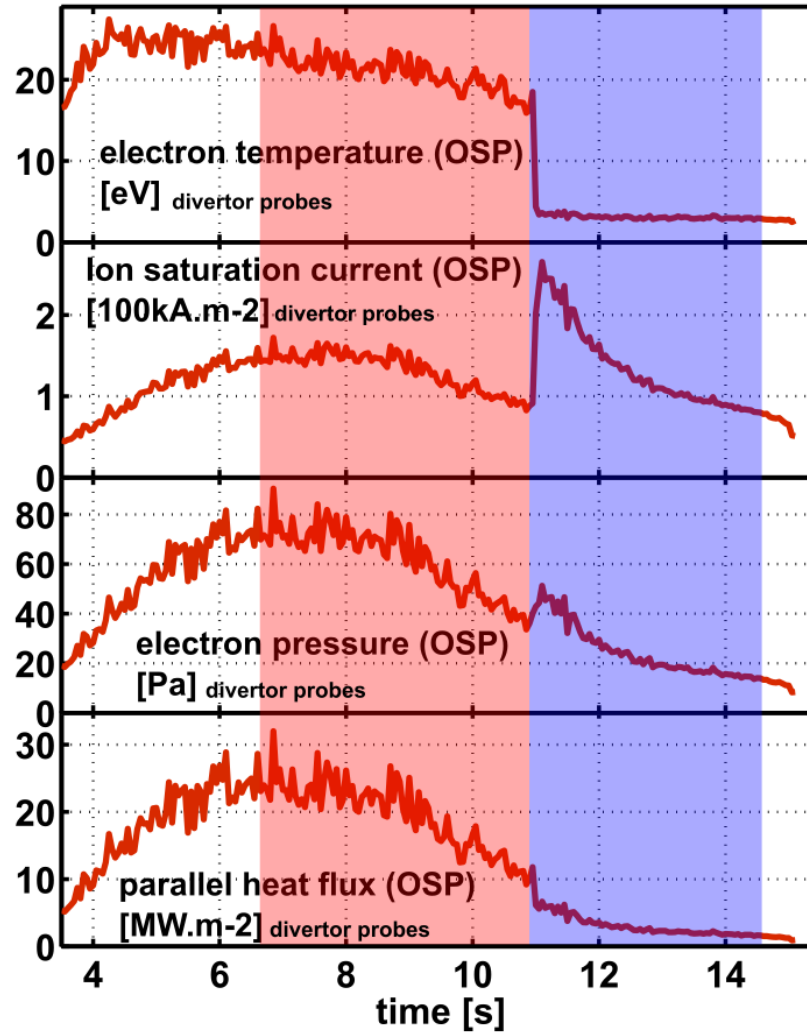
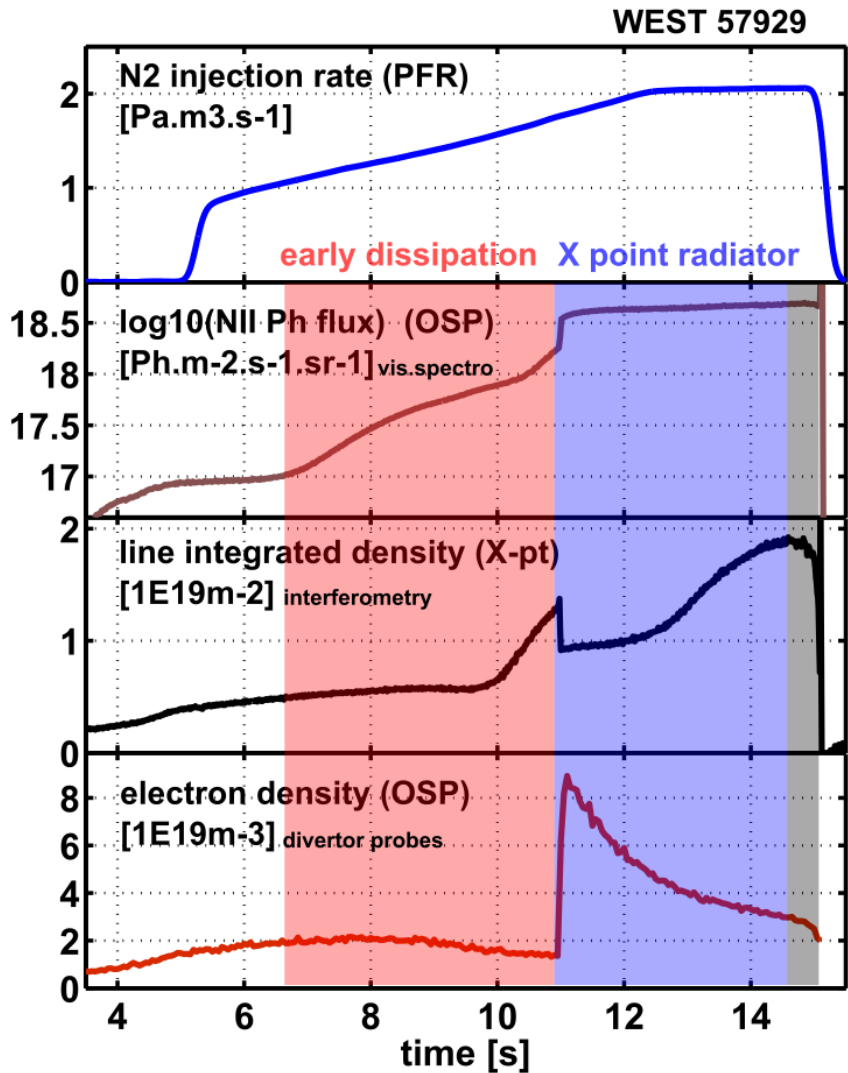


Outline

1. Long pulse operation: heating plasmas in a tungsten environment, burn-through tungsten during LHCD power ramp-up
- 2. Reducing divertor heat loads: X-point radiator regime**

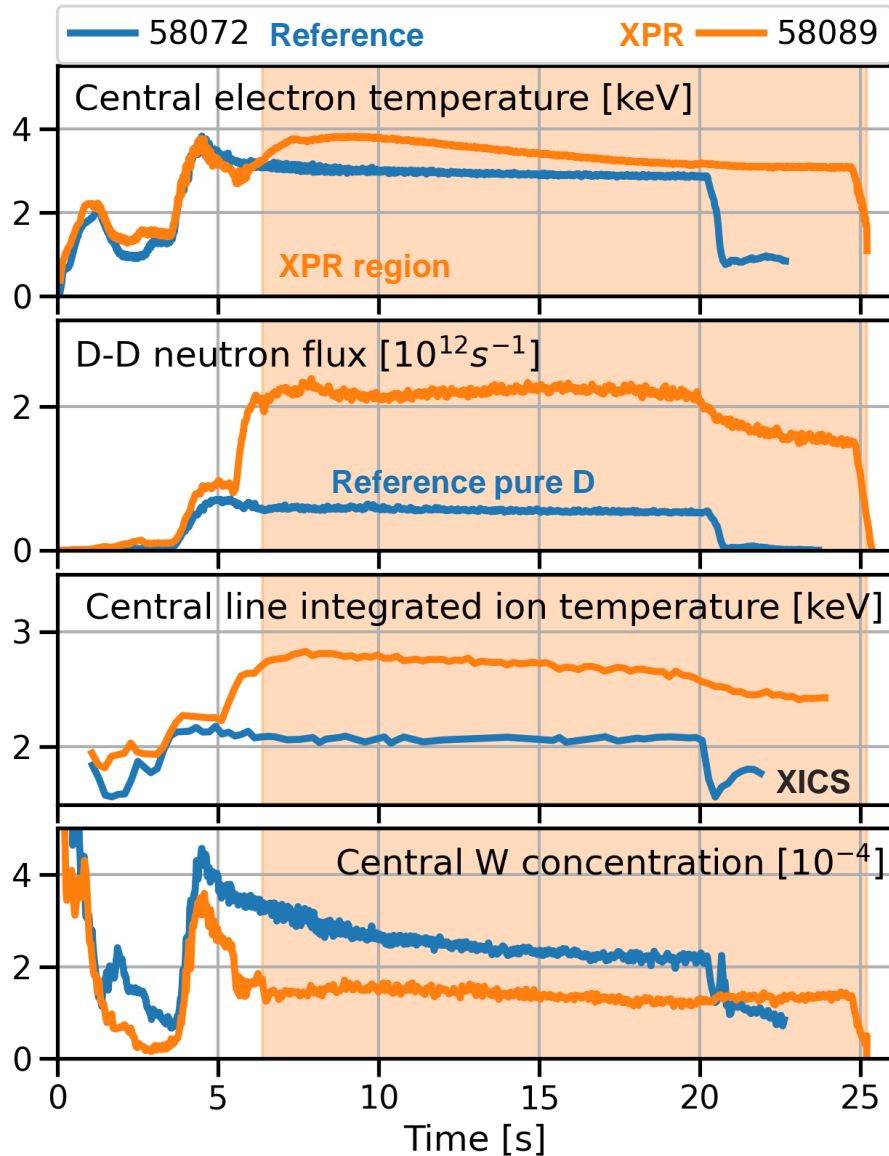
LHCD = Lower Hybrid Current Drive

X-point radiator: divertor behavior



- 5s Seeding starts
- ~8s Outer strike point rollover ($T_e \sim 20\text{eV}$)
- 11s Transition into XPR
condensation into high recycling regime
- T_e 18 \rightarrow 3 [eV]
- n_e 1.3 \rightarrow 9 [10^{19}m^{-3}]

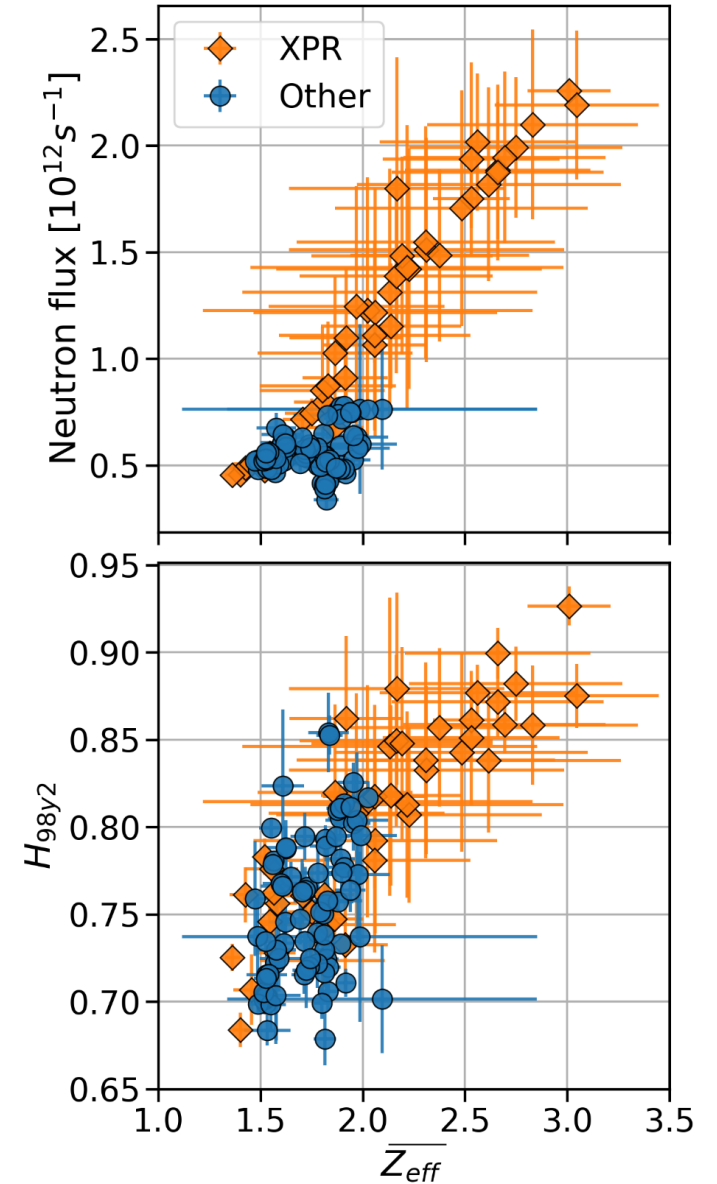
X-point radiator: confinement



- **Better confinement:**
+15% to +30%
- **Higher central electron temperature:** +20%
- **Higher central ion temperature:** +35%
- **Neutron flux:** x 4
- **Central tungsten contamination reduction:** -40%

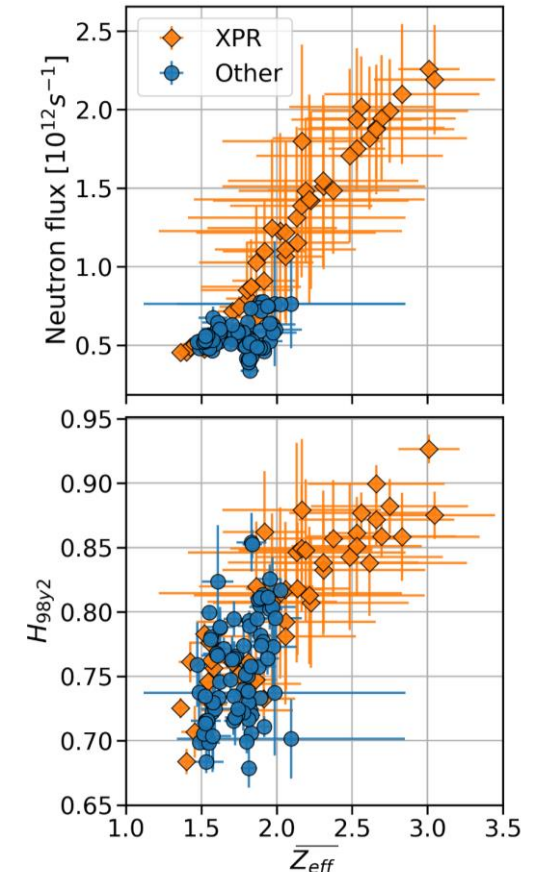
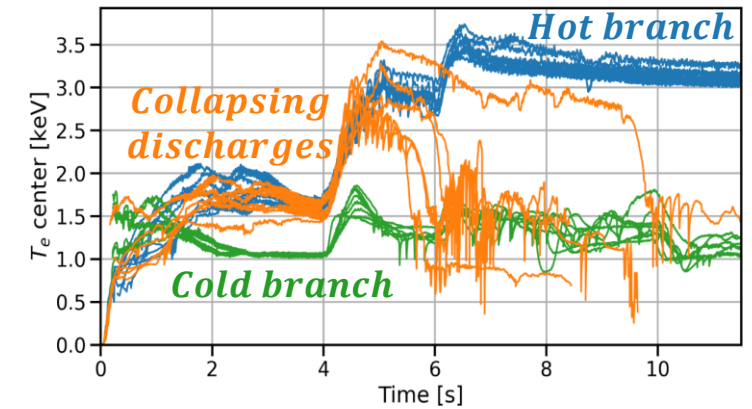
Improved controlled XPR lasting 20 seconds

Important effect of Z_{eff}



Conclusion

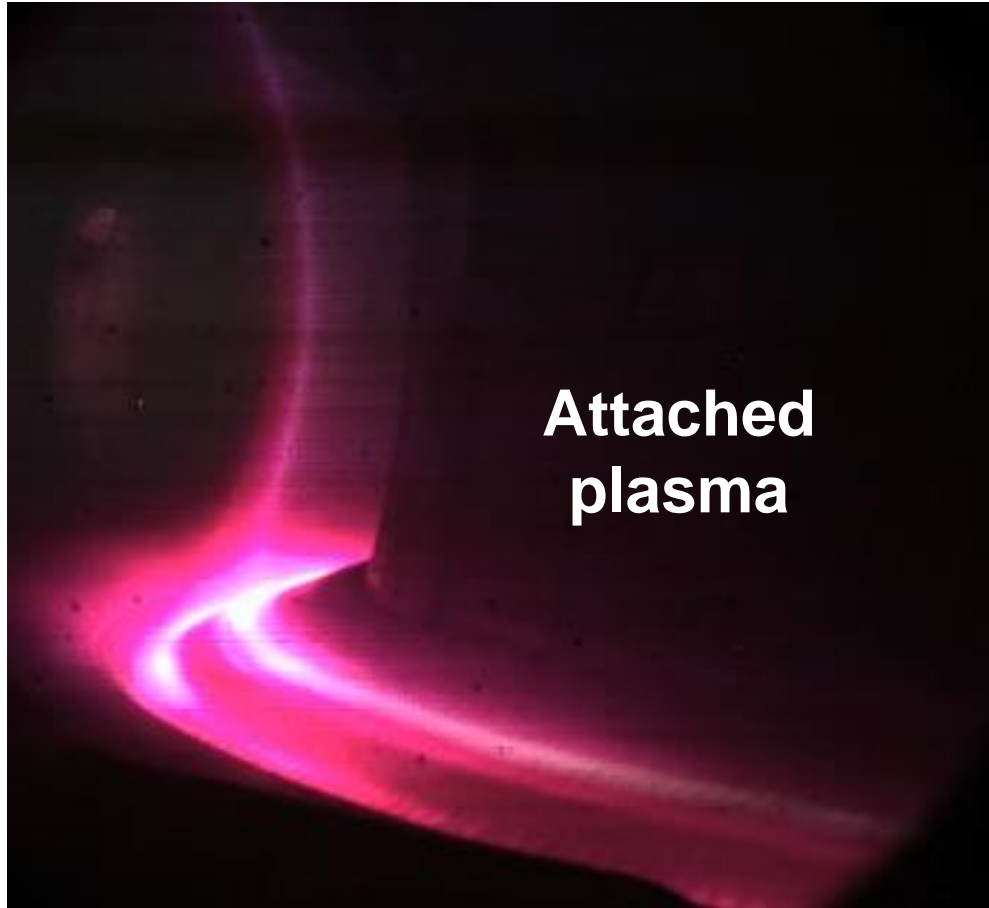
- Long pulse operation: we need **hot branch** to reach low loop voltages. During last campaign we performed routinely 1 min plasmas and a 100s plasma was achieved
- To reach **hot branch**: burn-through W, we need to be **below a given density during power ramp-up**
- **Density control and central electron heating are crucial to avoid radiative collapses. ITER: collapses can occur at current ramp-up (when T_{e0} between 1.5 and 3 keV) but little concern because large electron heating will be installed**
- Low heat loads: X-point radiator is a promising scenario, **low divertor heat flux and improved confinement with reduced core W contamination**. Optimal Z_{eff} to be found (trade-off between confinement improvement and plasma dilution?). **ITER: concern about plasma contamination from W deposit layers. Semi-detached plasmas can mitigate this issue and good news from WEST: semi-detached plasmas can be controlled with good confinement and low central W contamination**
- Next: explore larger Z_{eff} with different impurity mix. Also new 3 MW ECRH system will help to avoid radiative collapses (from end 2024)



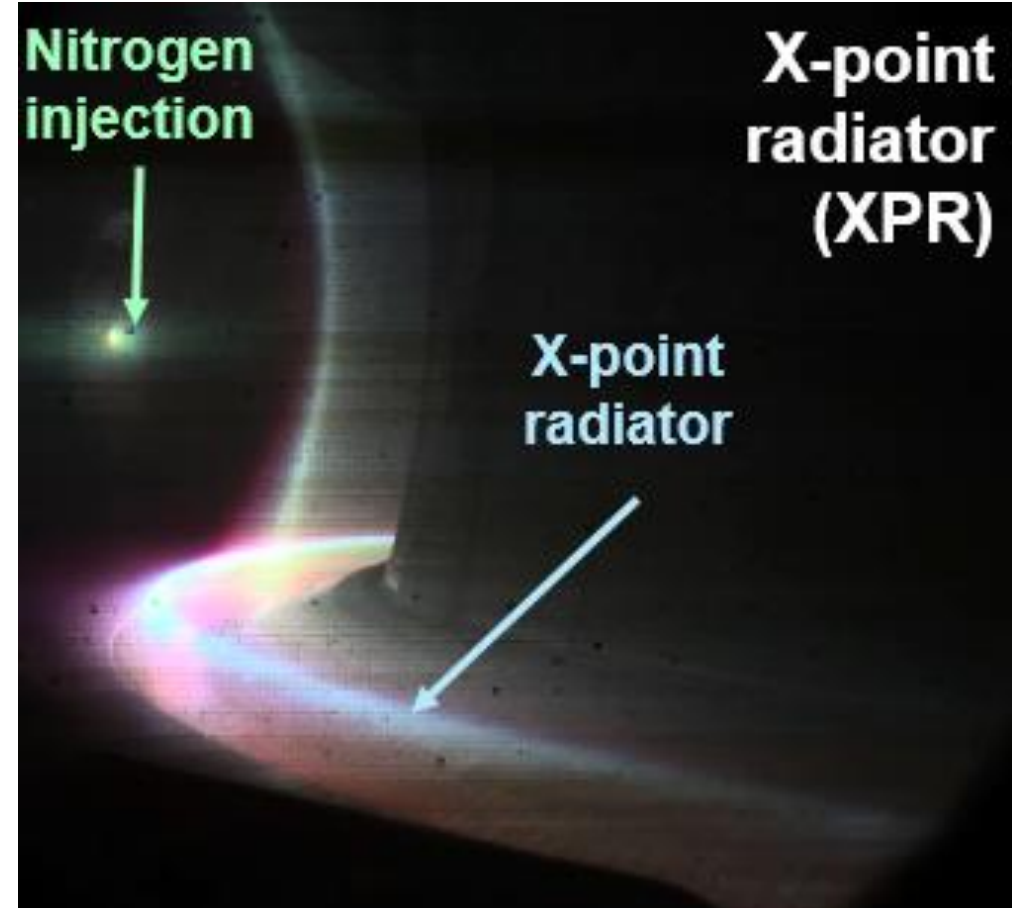
A solution: X-point radiator?



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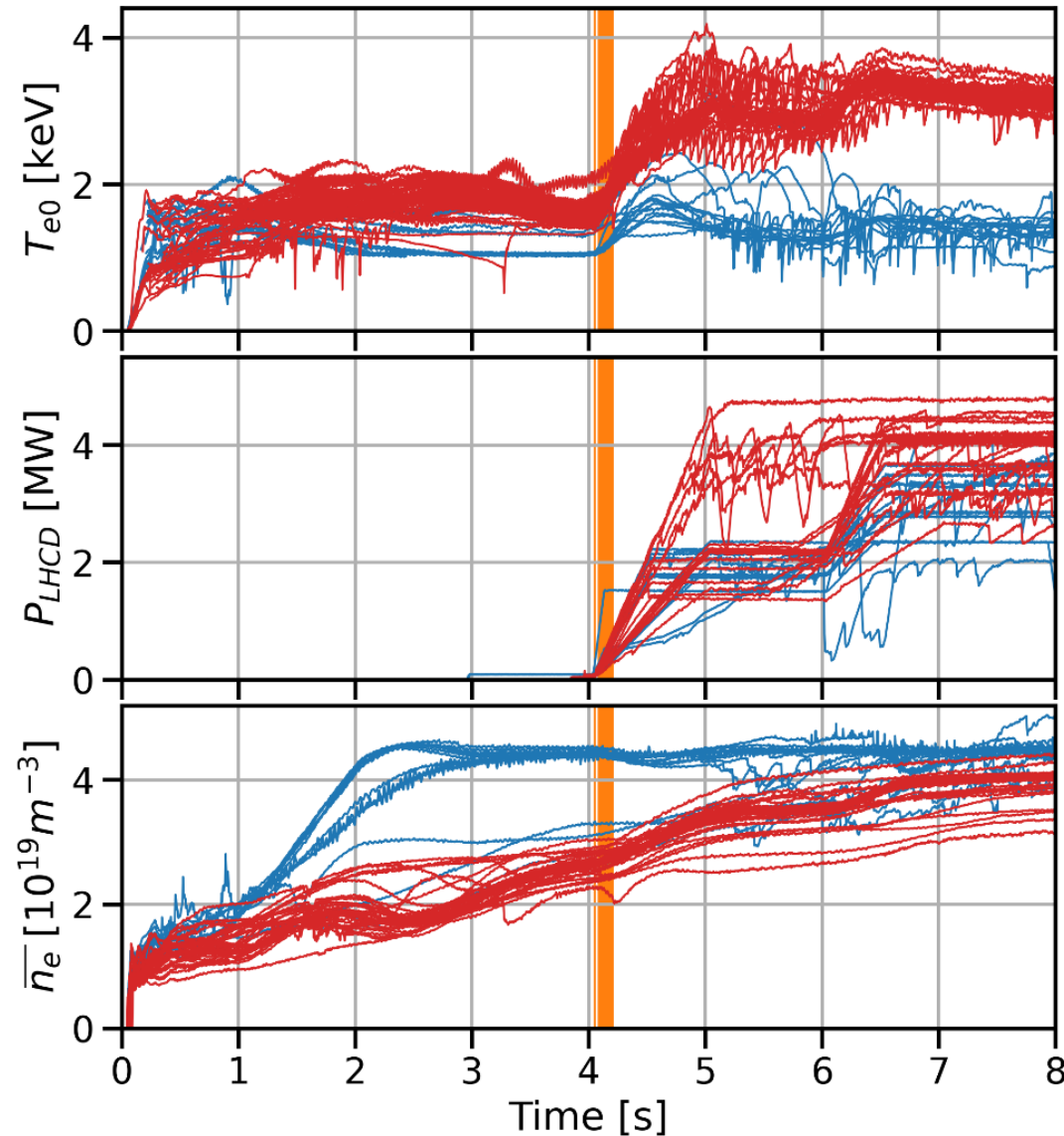


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[Bernert, Nucl. Fusion, 2020] [Lunt, Phys. Rev. Lett., 2023]

Time signals of hot and cold branches



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

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

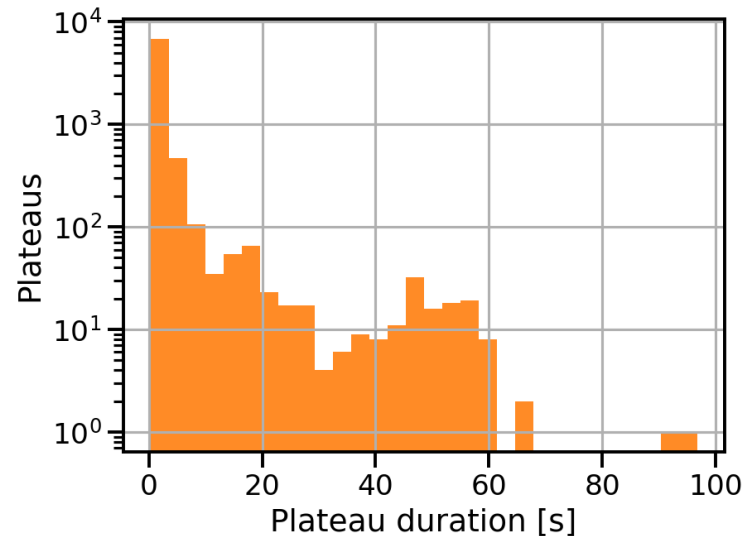
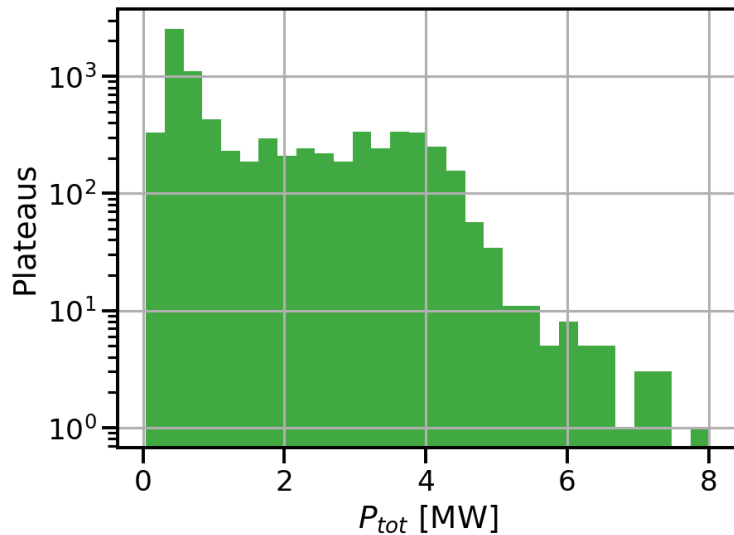
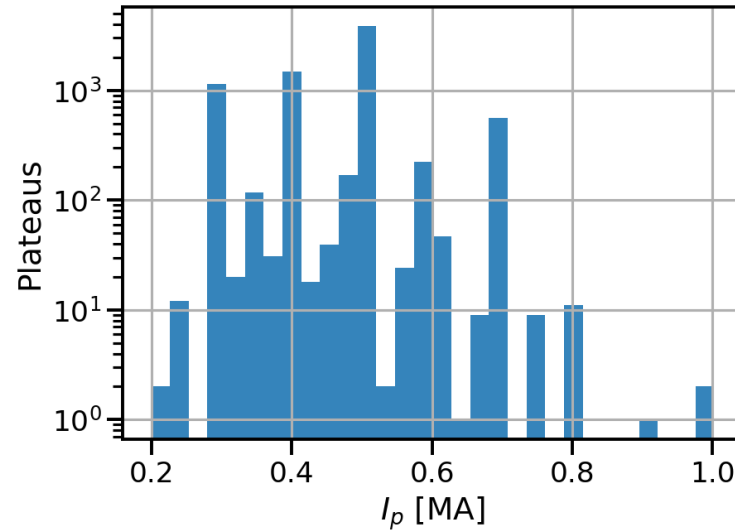
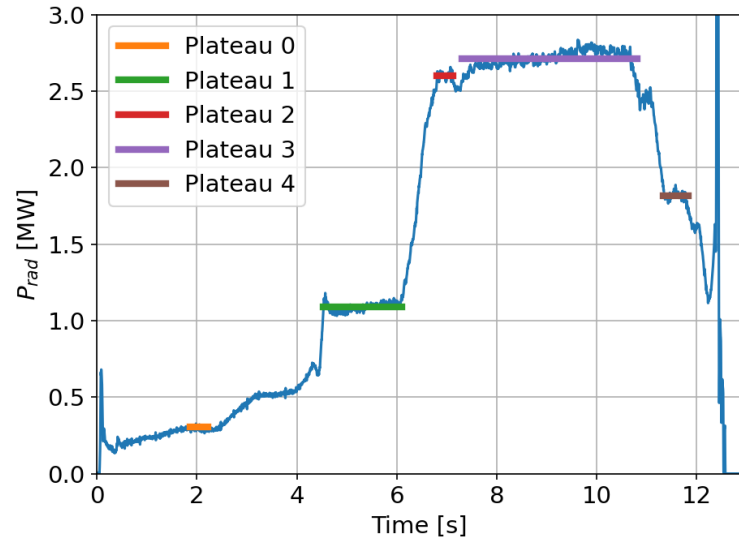
Vertical orange lines indicate times when Lower Hybrid power (P_{LHCD}) crosses 0.3 MW (heating onset)

Two trajectories are observed:

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

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

WEST data



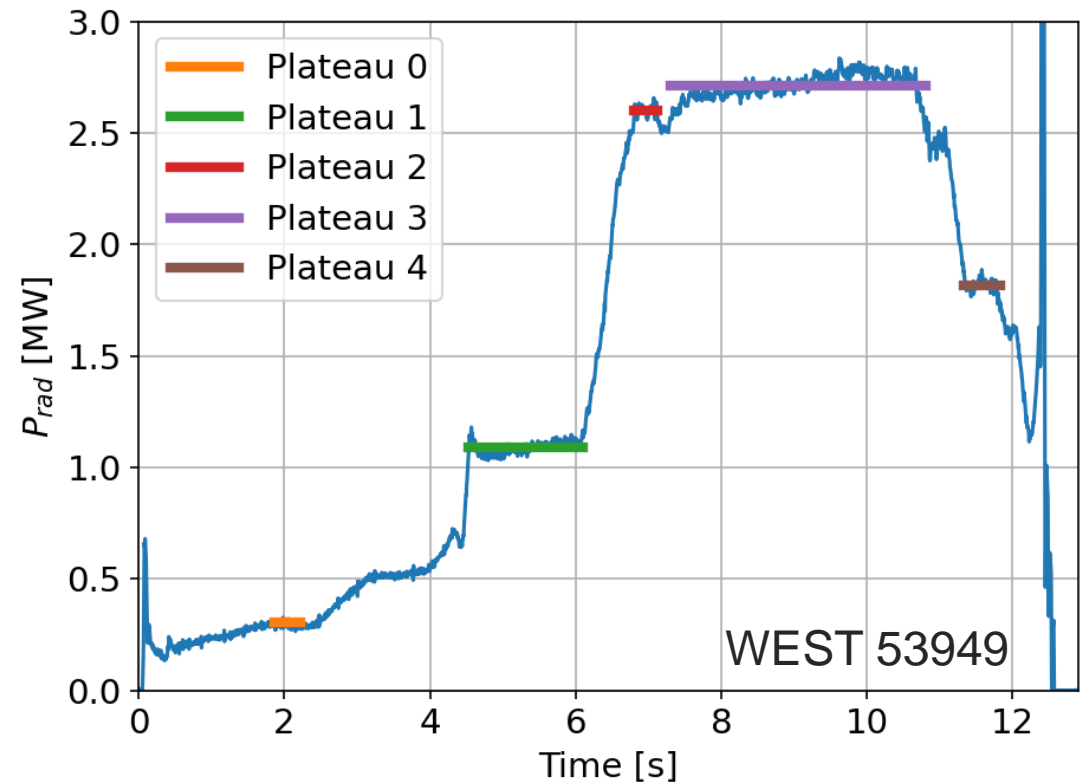
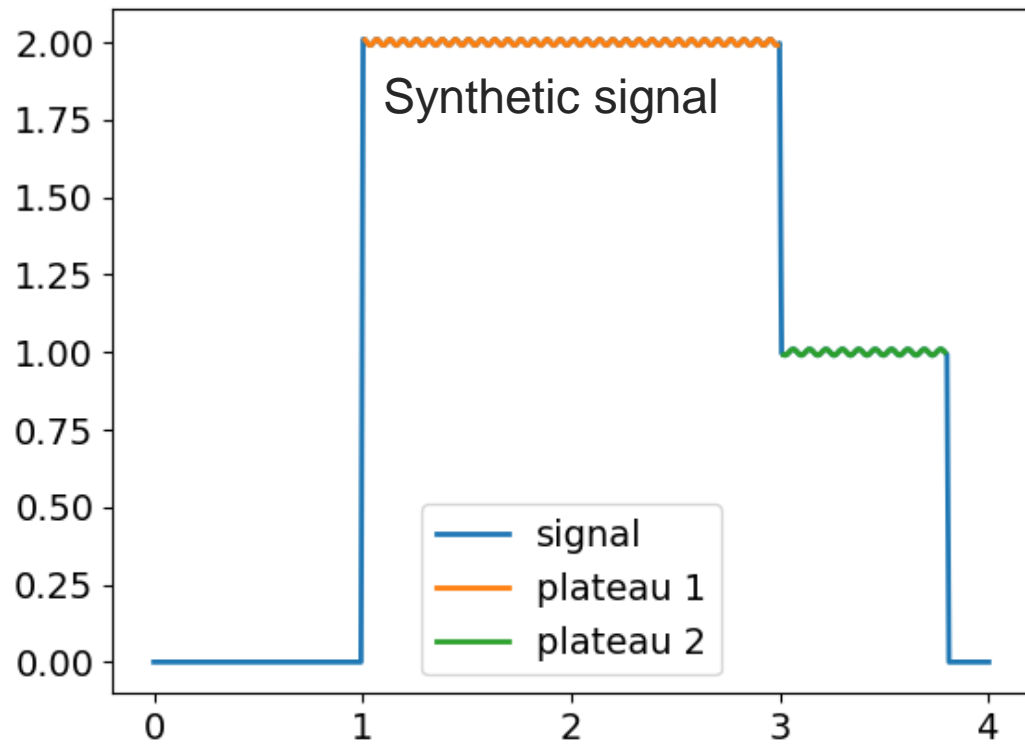
We extract data from IMAS
[Imbeaux, Nucl. Fusion, 2015]

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

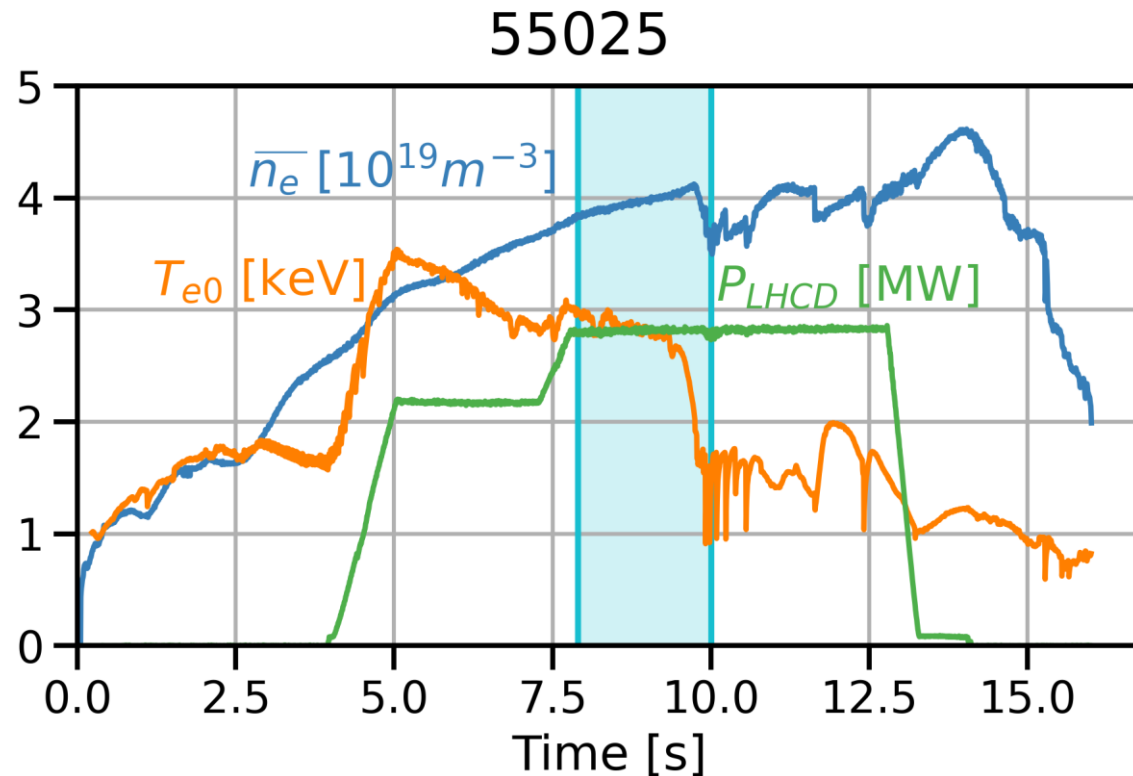
Histogram data: mean quantities in identified plateaus during WEST C4 to C7 campaigns (2019-2023)

Plateau detection

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



Collapse pulse example 55025



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

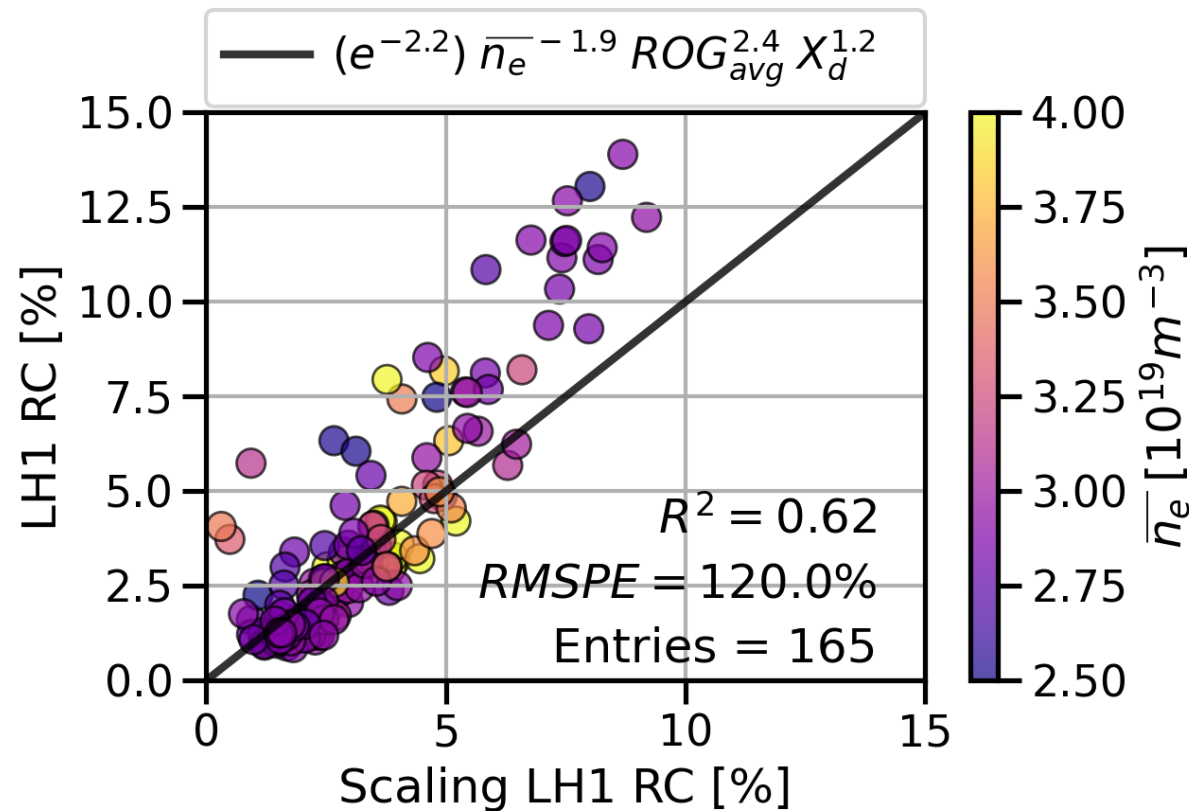
This pulse is interesting because LHCD power injection is constant during the whole collapse

[Ostuni, Nucl. Fusion, 2022]

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)



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

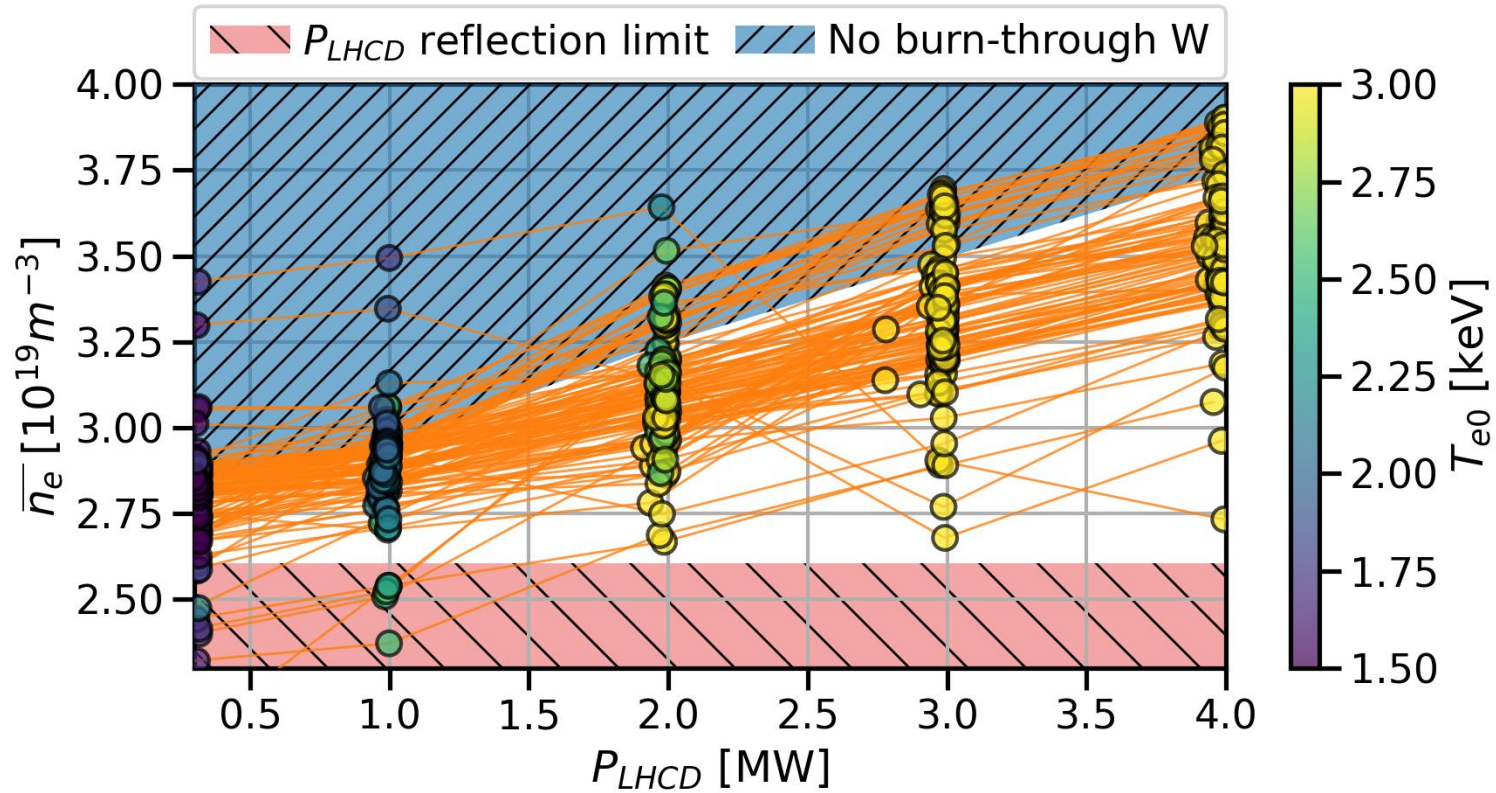
If we fix standard values for right hand side:

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

Then:

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

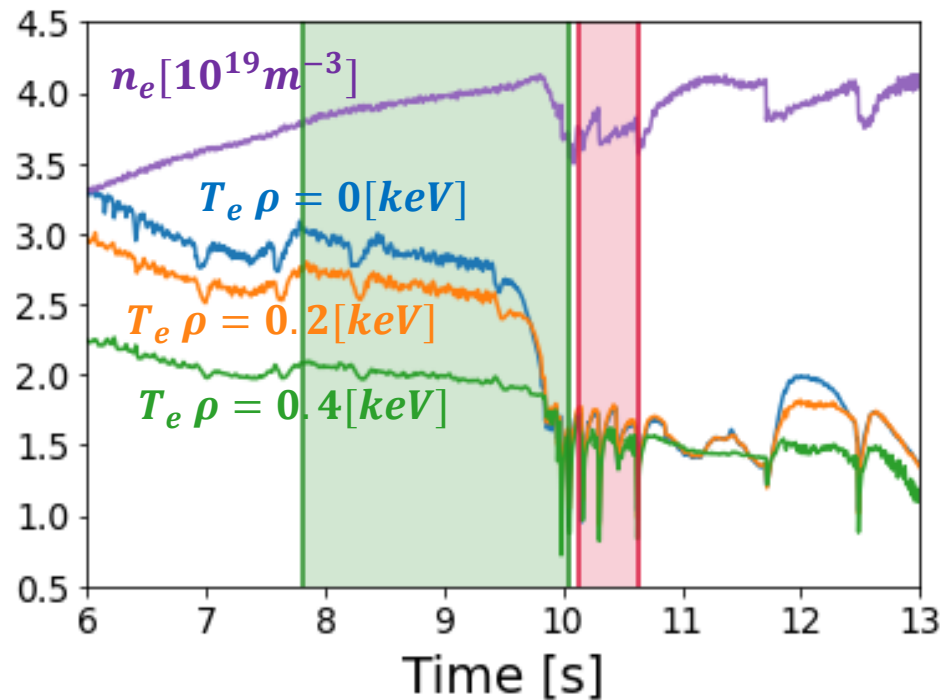
LHCD ramp-up operational space



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 $ROG_{avg} = 4cm$ and $X_d = 7cm$

Collapse pulse analysis 55025



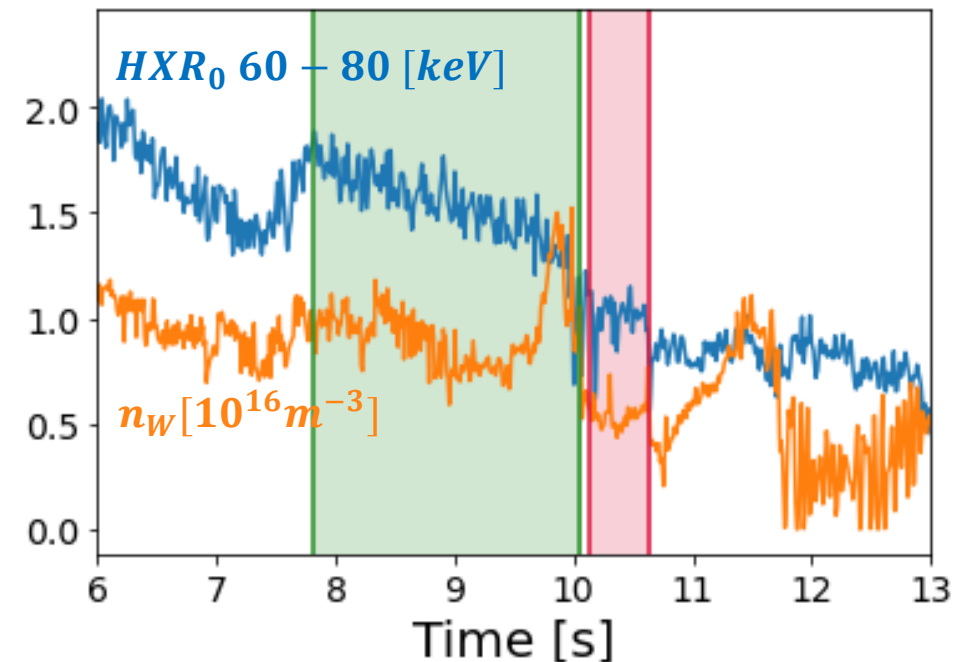
Prior to the collapse:

- 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

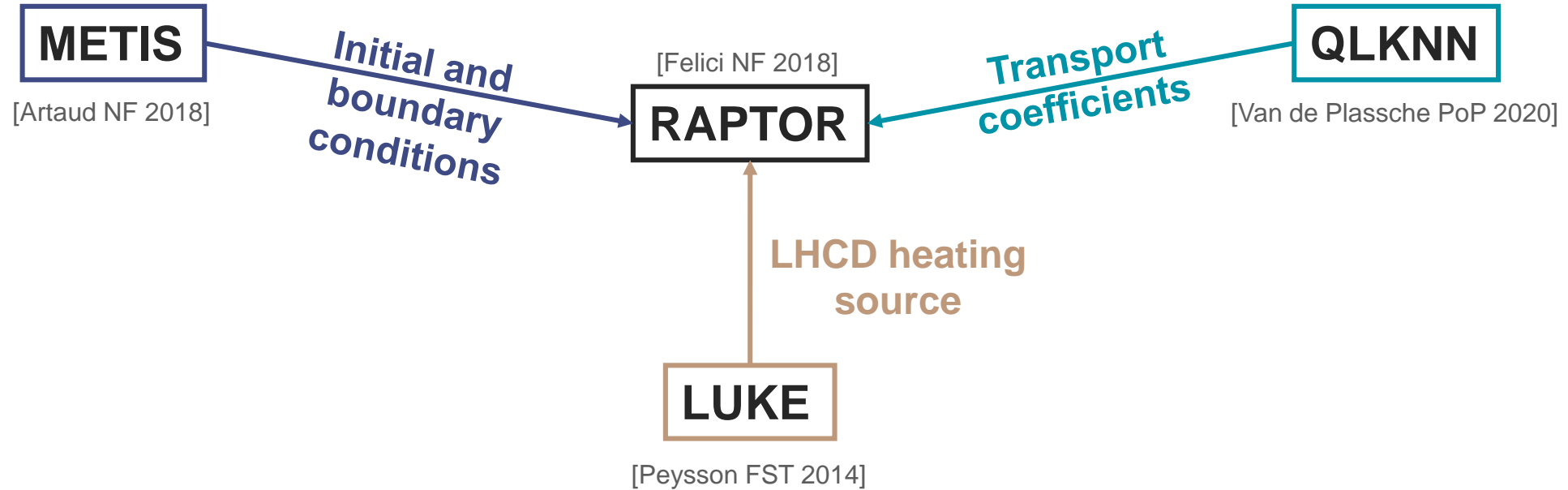
During the collapse:

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

This complex interplay requires integrated modelling

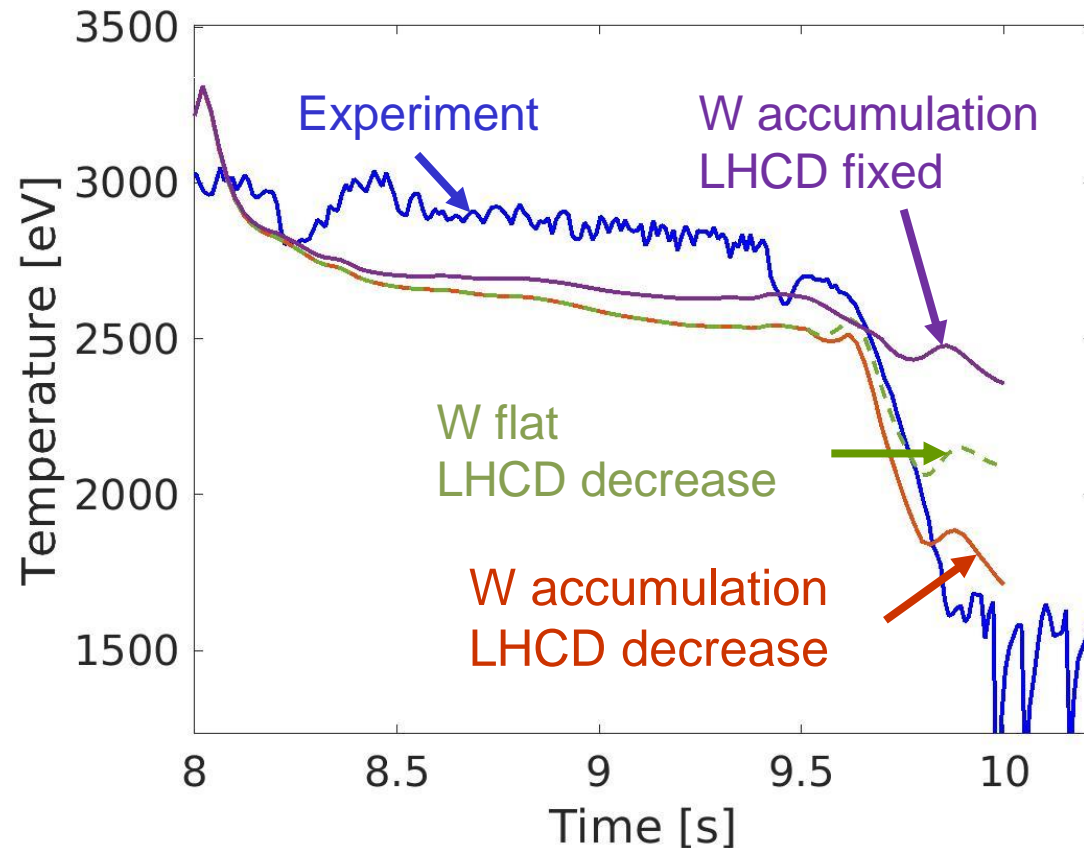


Simulation tools and settings



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:

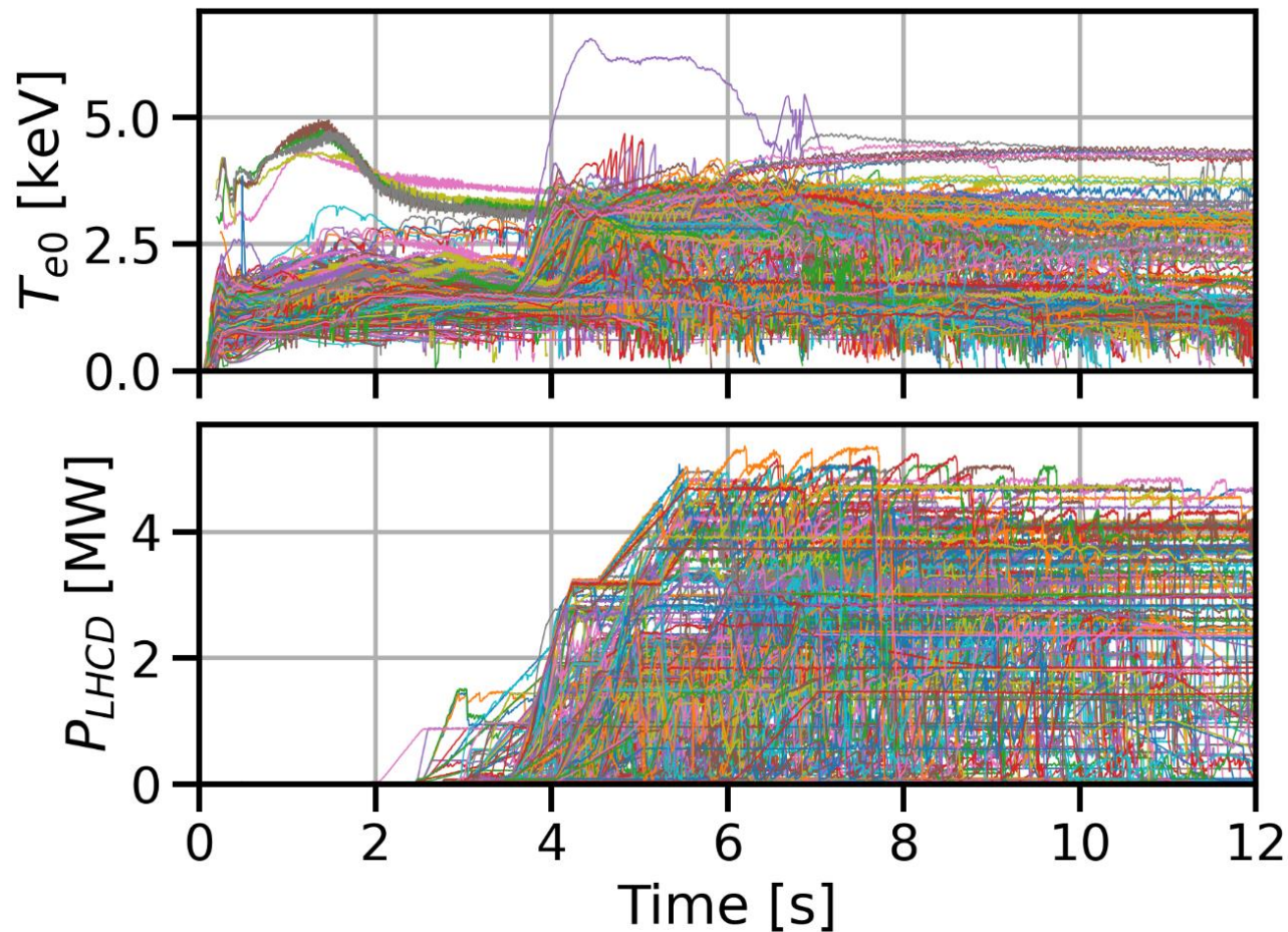
- Decrease of central LHCD power deposition
- Tungsten accumulation

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

How efficiently analyze entire experimental campaigns?

Example: 764 pulses from C4 campaign



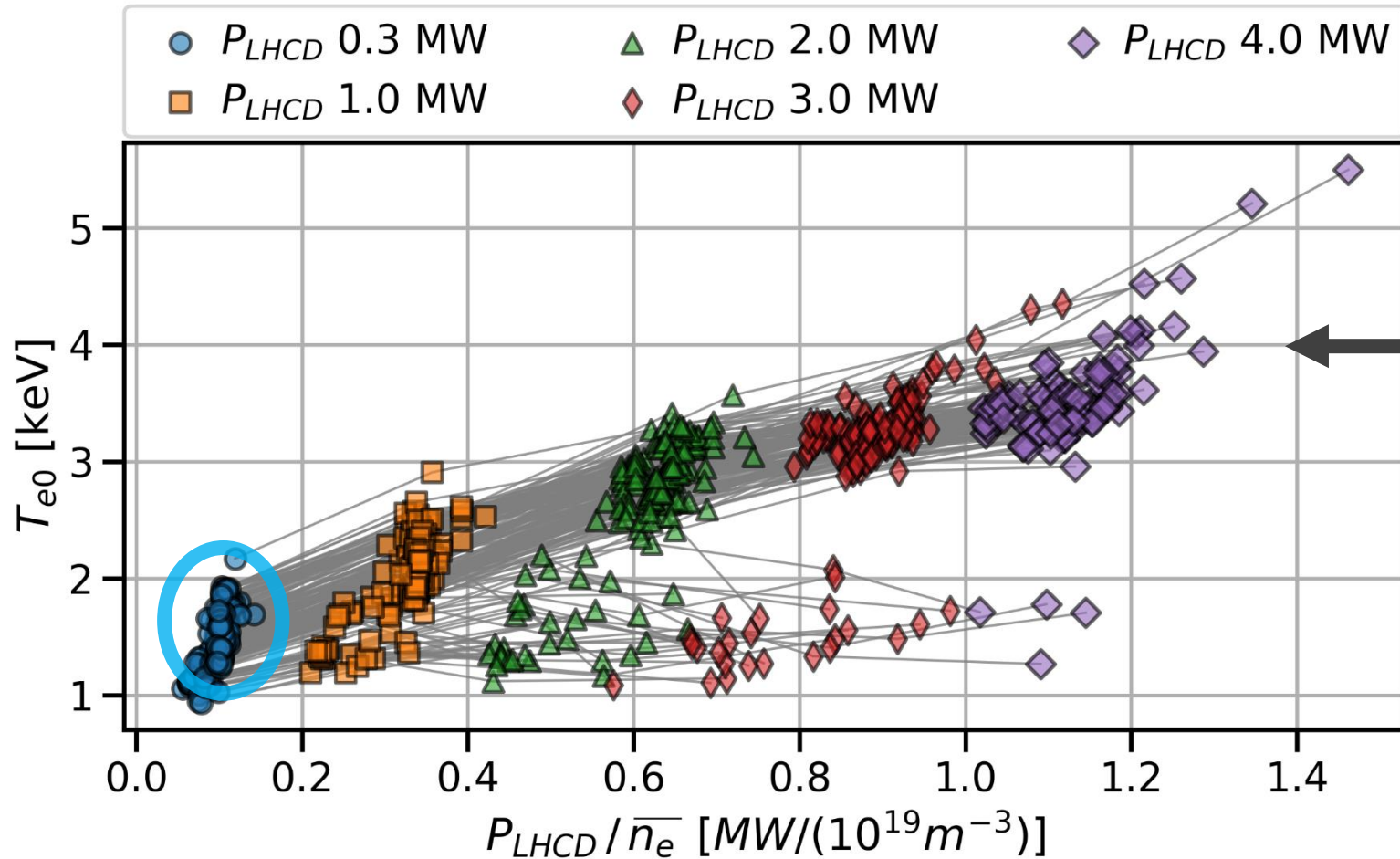
To efficiently characterize several campaigns: development of a numerical tool for **plateau detection on 1D signals**

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

1D signal

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

Pulse trajectories with increasing power (P_{LHCD})



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

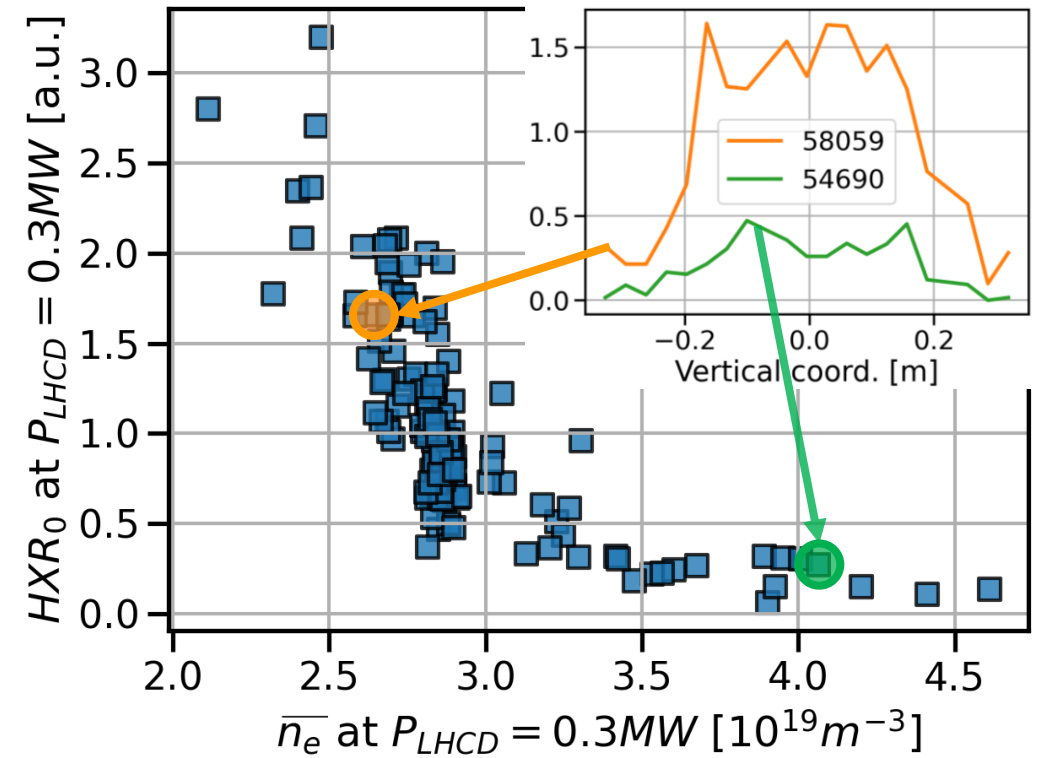
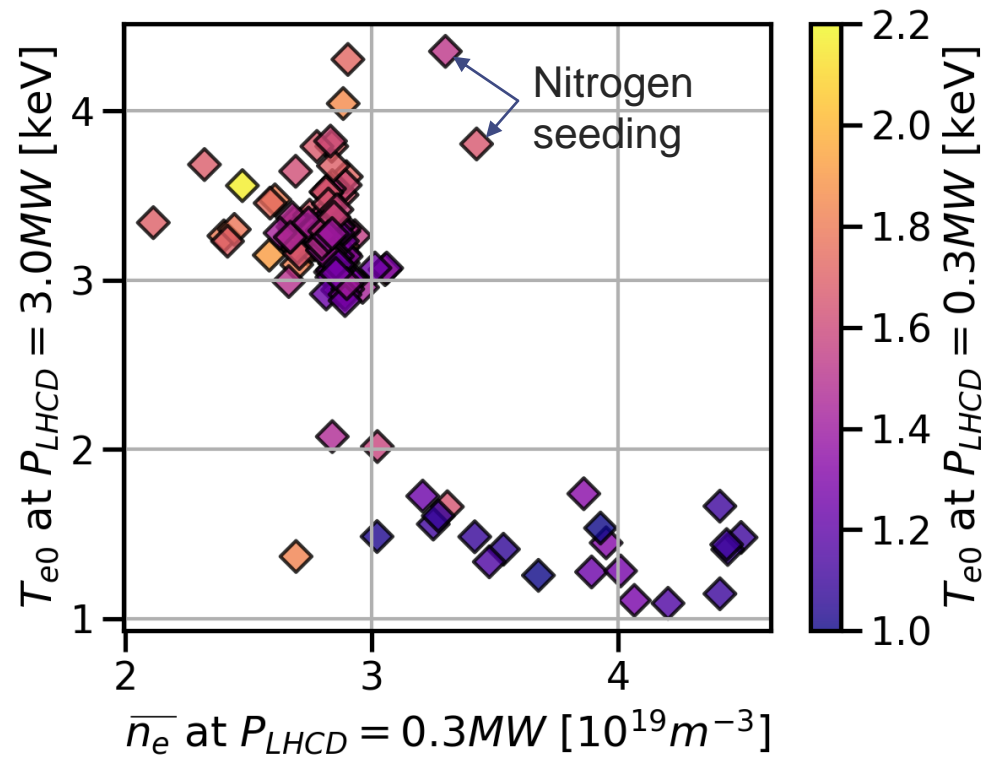
Two trajectories are observed:

- 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:

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

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)

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 r specified threshold,
 - 2. in order to burn-through tungsten, density upper limit during LHCD power ramp-up,**
 3. fast electron ripple losses must be limited (no)
- Physical understanding from integrated modelling

