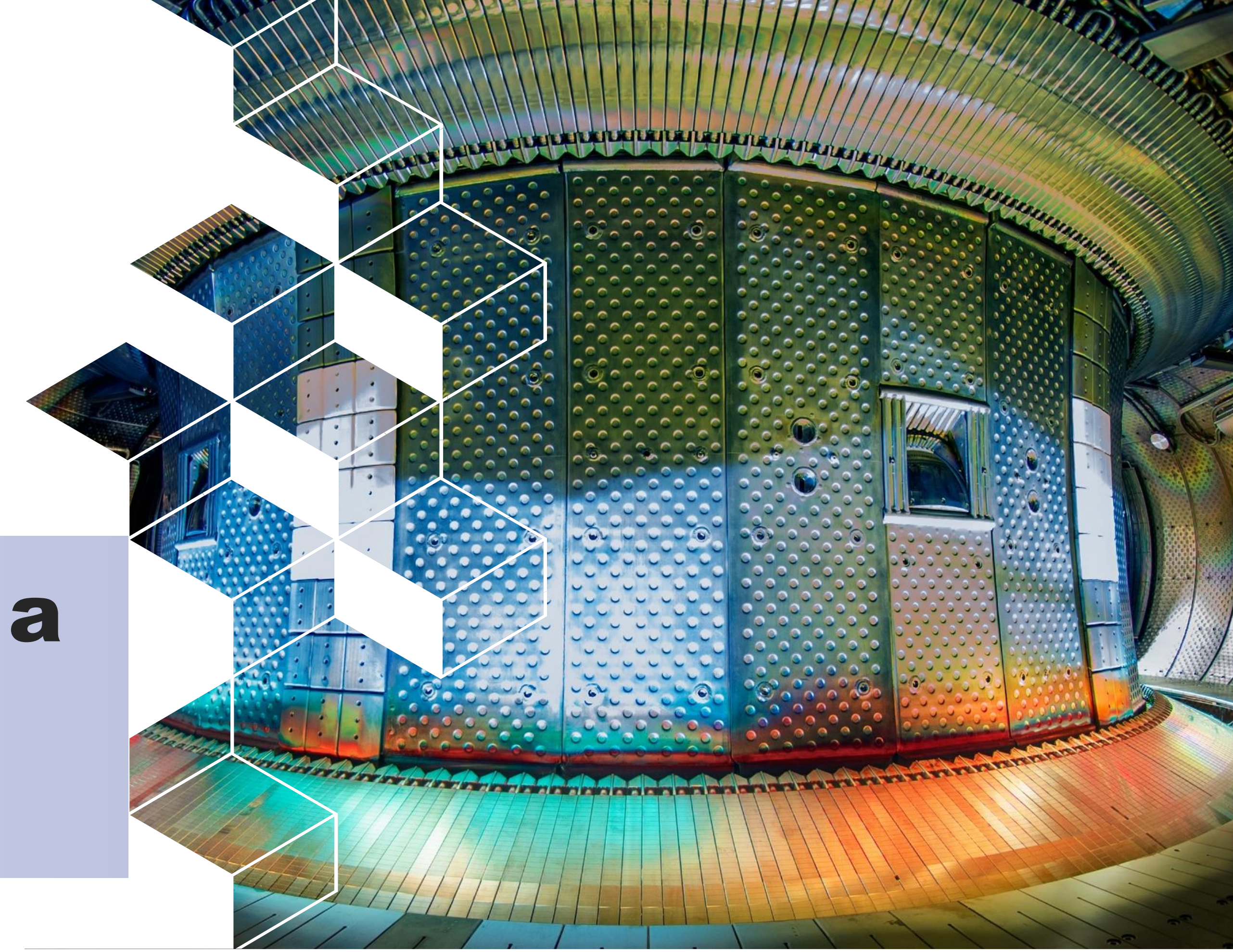
Long pulse operation in a tungsten environment: feedback from WEST



P. Manas, the WEST team[#] and the EUROfusion Tokamak Exploitation Team[§]
CEA, IRFM, F-13108 Saint Paul-lez-Durance, France

see http://west.cea.fr/WESTteam, § see author list E. Joffrin et al 2024 Nucl. Fusion https://doi.org/10.1088/1741-4326/ad2be4

Special thanks to P. Maget, J. Gaspar, A. Grosjean, J. Morales, K. Afonin, C. Bourdelle, Y. Corre, J. Dominski, R. Dumont, A. Ekedahl, N. Fedorczak, T. Fonghetti, A. Gallo, C. Guillemaut, J. Hillairet, E. Lerche, R. Lunsford, N. Rivals, E. Tsitrone, T. Wauters

WEST tokamak: a W-test bed for ITER operation

WEST: Long Pulse capability, dominant electron heating, no external momentum source

- Superconducting magnets, standard magnetic field 3.7 T
- LHCD power up to 7 MW – 1000 s [*X. Regal-Mezin Tuesday*]
- ICRH power up to 9 MW
- *ECRH 1 MW (2024), 3 MW from 2025*

[*J.M. Bernard Tuesday*]

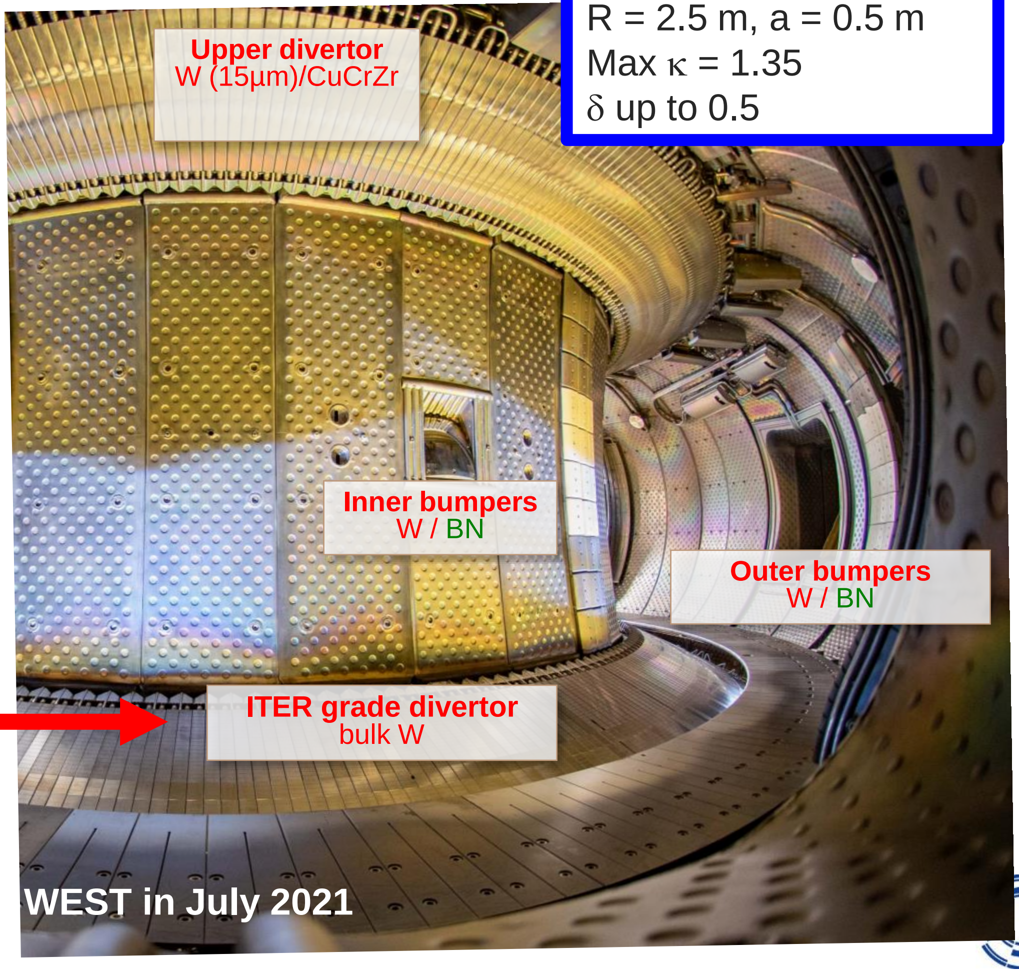
- Lower/Upper X-point, Double-Null configurations

Tungsten environment

- **Actively cooled ITER-grade tungsten divertor**
- Inner / outer bumpers
  - W coated until mid-2020,
  - BN at mid-plane until spring 2024,
  - *Bulk W from autumn 2024*

Unique test bed for adressing Long pulse operation in a W environment ⇨ PWI timescales

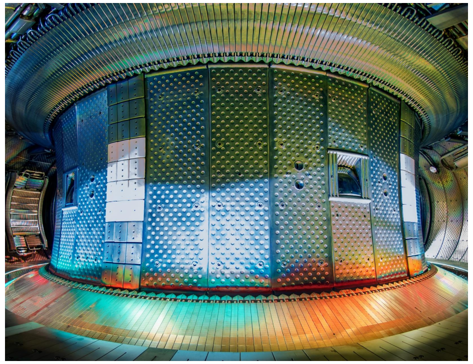
Plasma volume : 15 m^3
R = 2.5 m, a = 0.5 m
Max κ = 1.35
δ up to 0.5



WEST in July 2021

Content

1. Tungsten constraints on the operation



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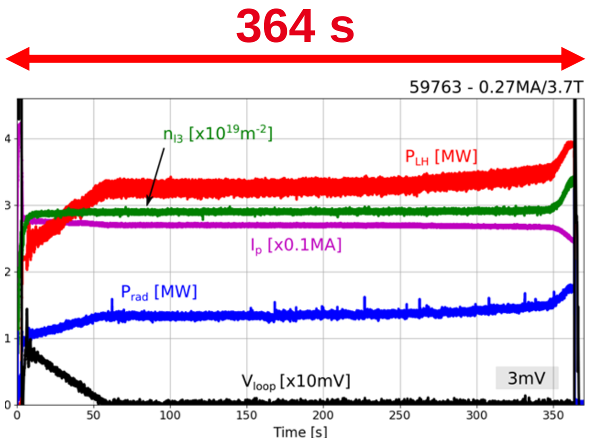

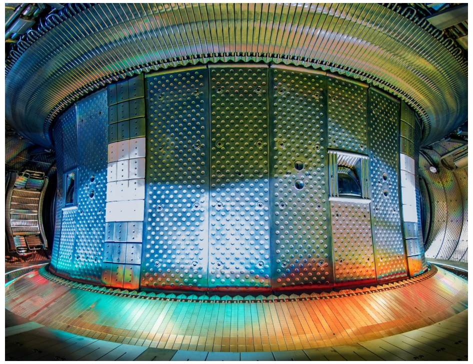

2. Long pulse scenario development and challenges

Content

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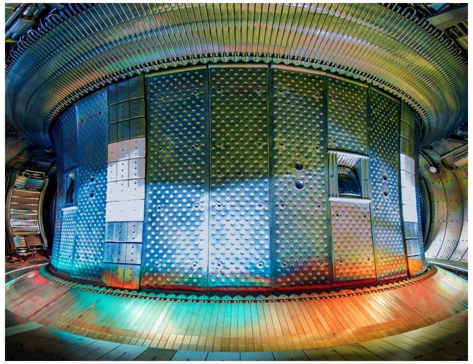
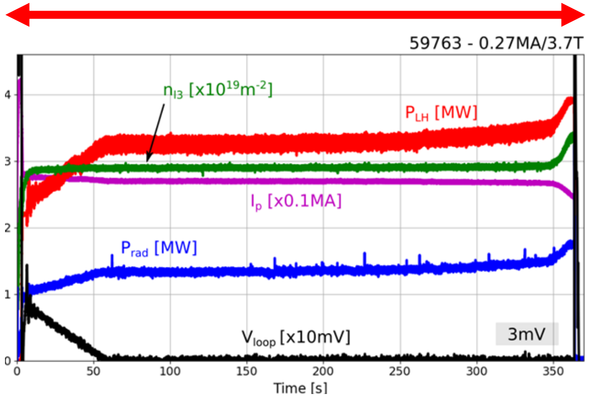


364 s



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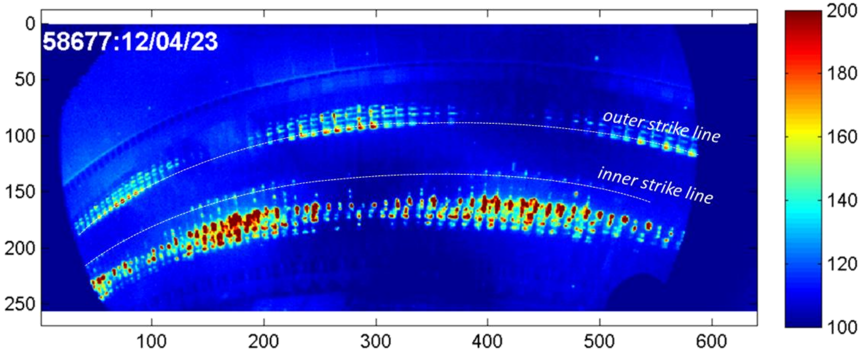
3. **High Fluence operation**



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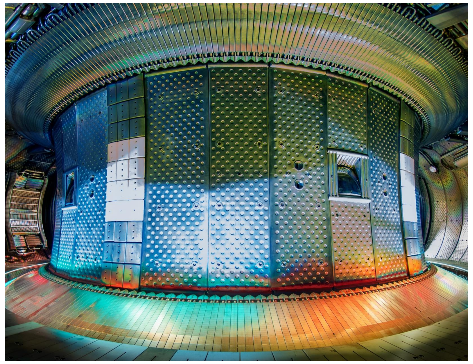

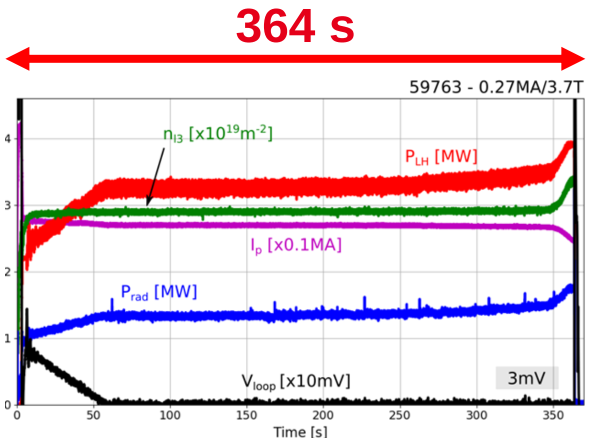

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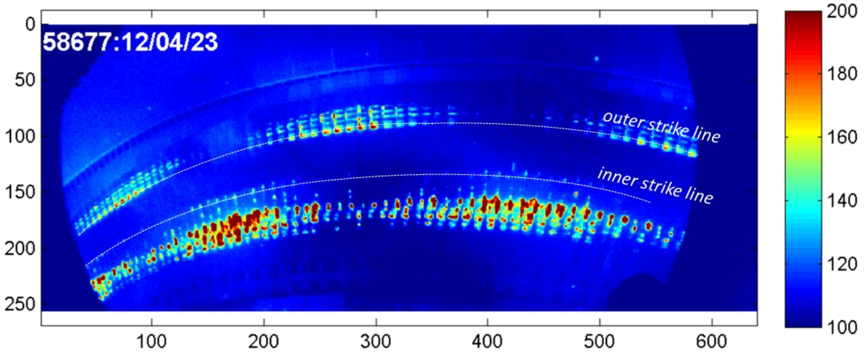

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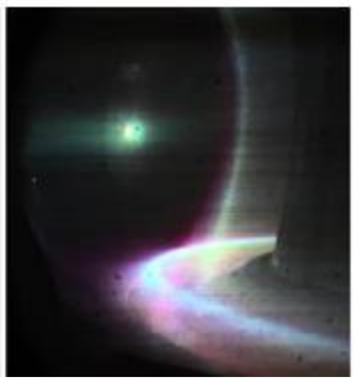

4. Low divertor temperature operation

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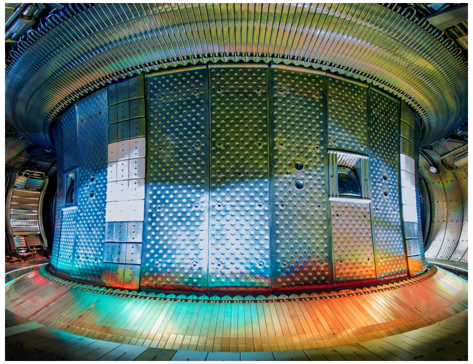

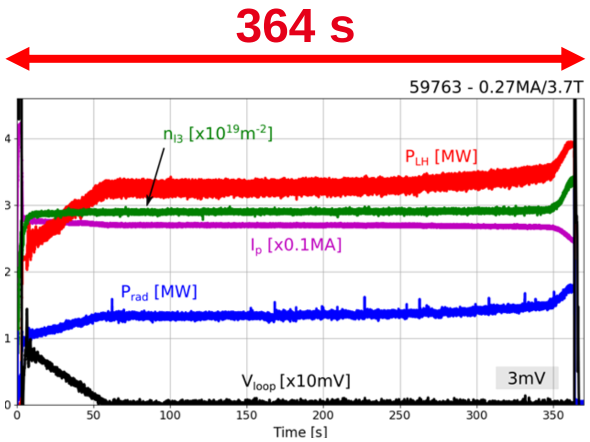

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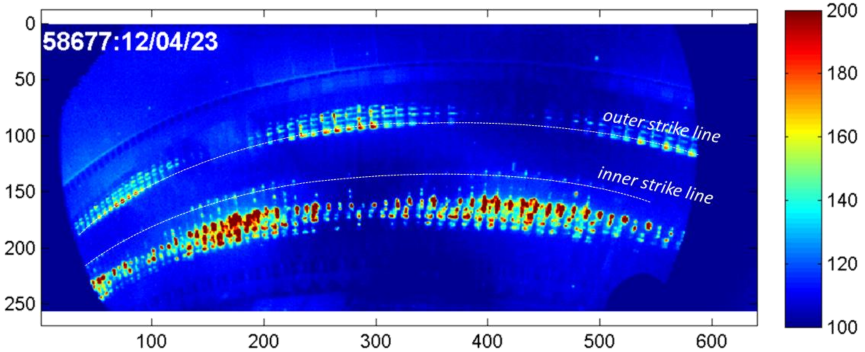

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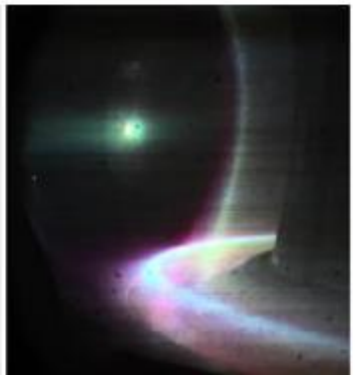
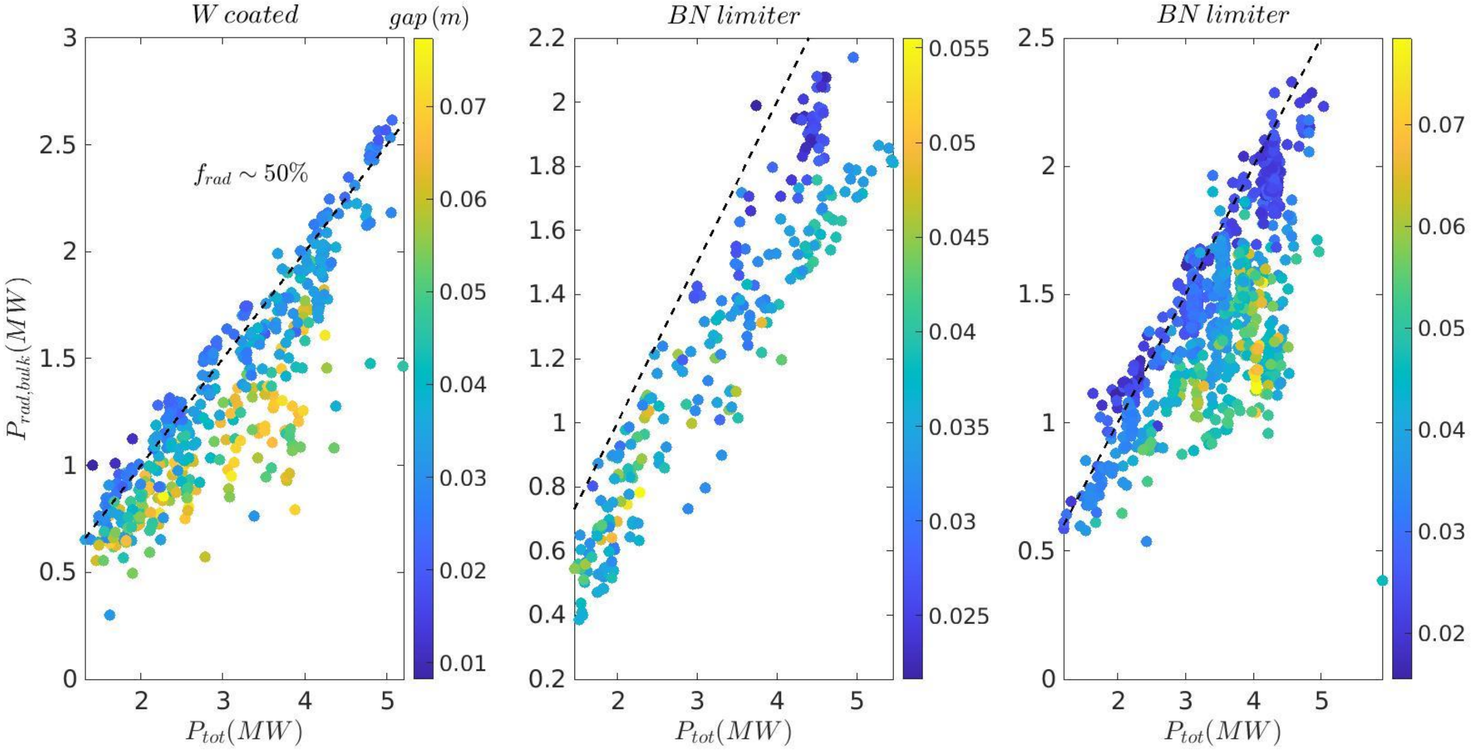


4. Low divertor temperature operation

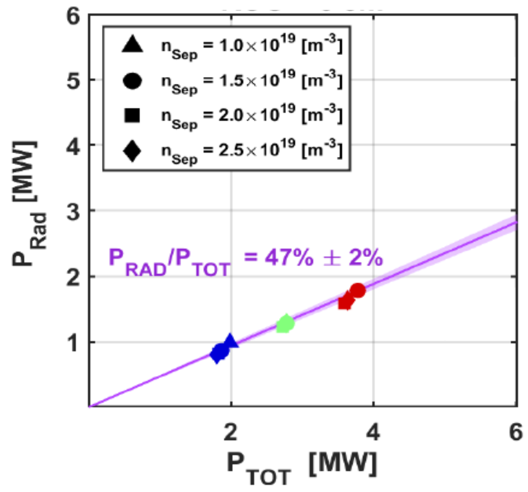
Tungsten contamination: a resilient radiative fraction

Radiative fraction is weakly dependent on injected power and density

- Radiative fraction centered around f_{rad}^{bulk} ~ 50 % - corresponding to c_W ~ 2-4x10^{-4}
- This resilience is recovered by SOLEDGE-ERO2.0 simulations [*Di Genova PFMC'23*]
  - More power to the SOL ↔ more radiation: strongly coupled core (radiation) / edge (erosion) system
  - Gaps with limiters (and magnetic configuration at upper divertor) are important players



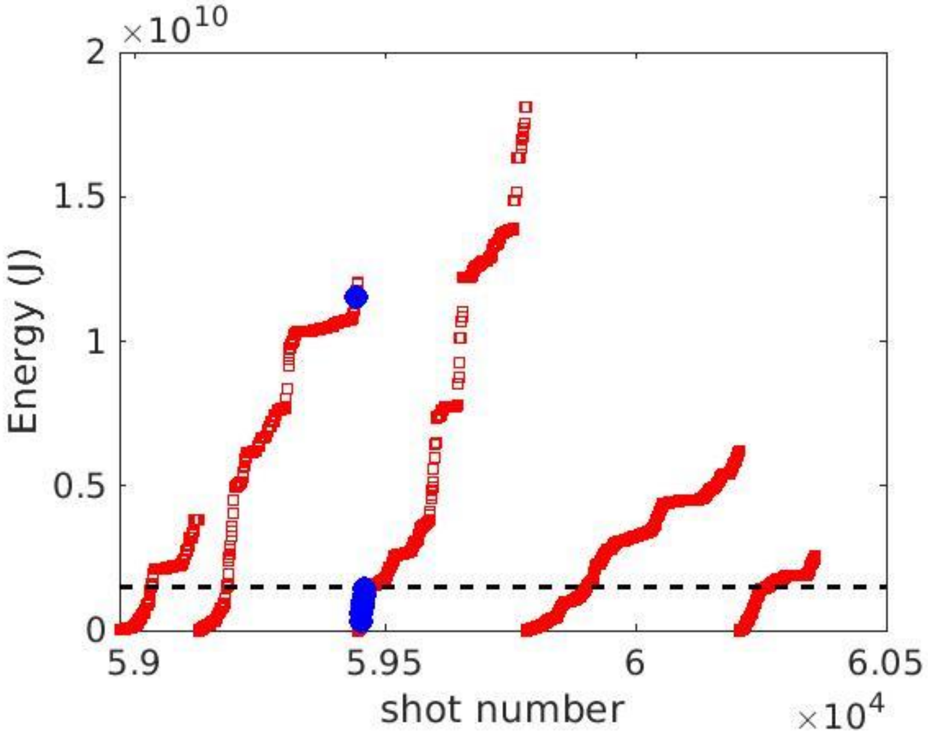
[*Di Genova PFMC'23*]



Tungsten contamination: boronization limited in time

Radiative fraction is reduced shortly after boronization

- Glow Discharge Boronization ($He+B_2D_6$) – typical boron mass 10g [A. *Gallo NME'24*]
- The time scale of the boronization effect is limited (**on average ~1 GJ vs ~40 GJ for a campaign**)



Tungsten contamination: boronization limited in time

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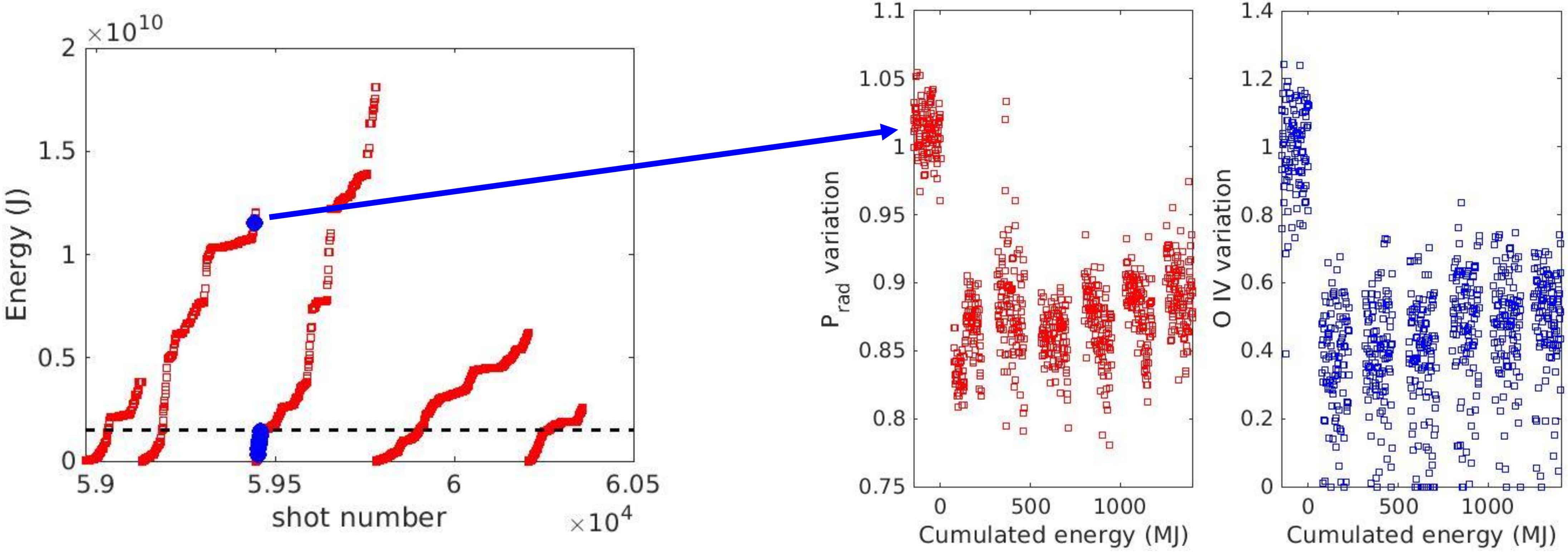
- The time scale of the boronization effect is limited (**on average ~1 GJ vs ~40 GJ for a campaign**)
- Analysis ongoing using identical pulses performed for fuel retention studies



Tungsten contamination: boronization limited in time

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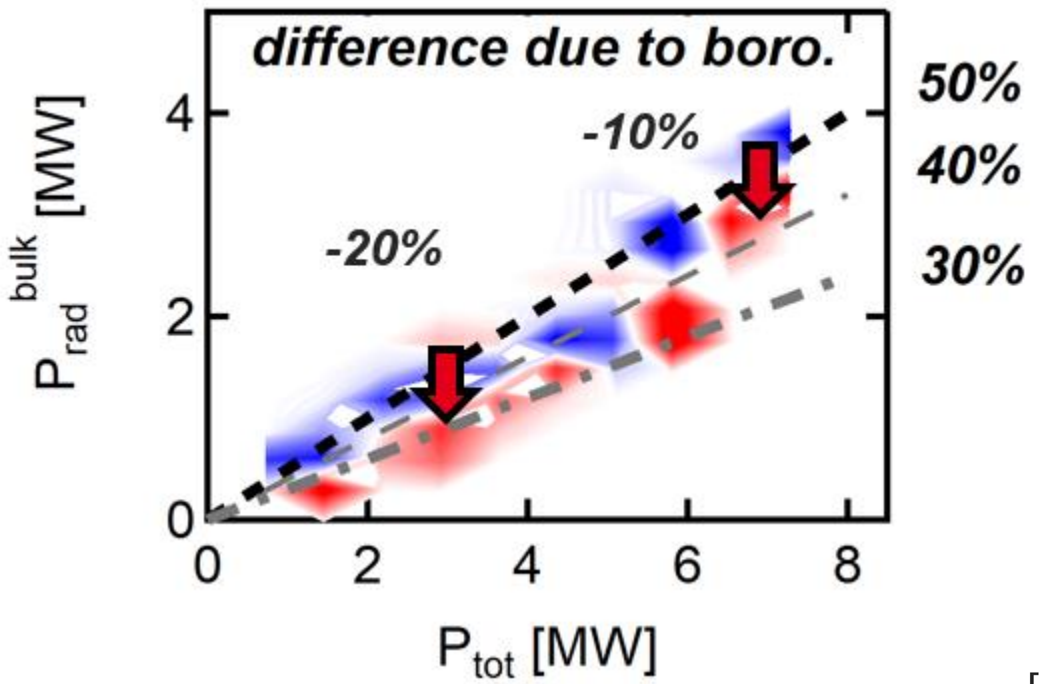
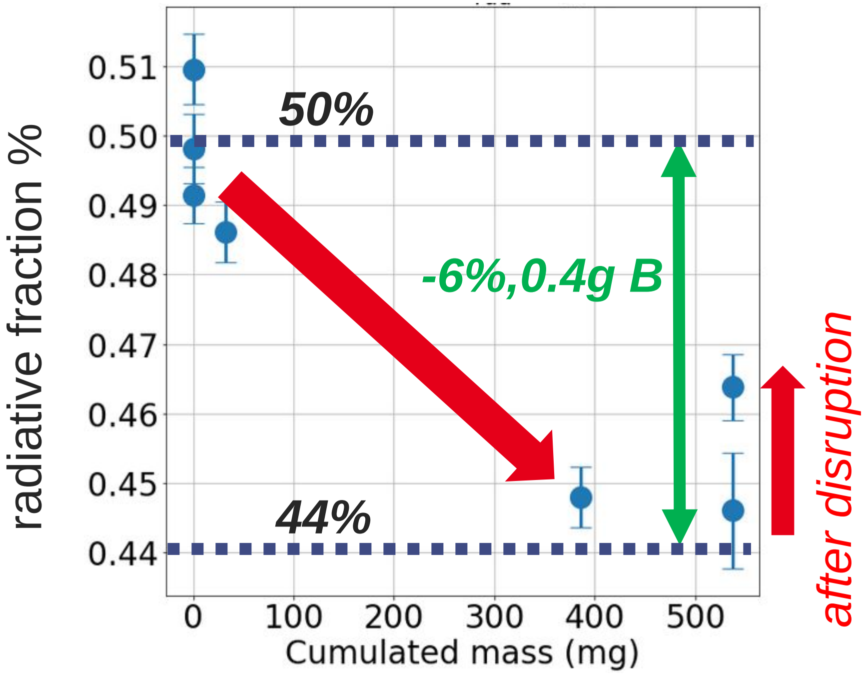
- The time scale of the boronization effect is limited (**on average ~1 GJ vs ~40 GJ for a campaign**)
- On the WEST database, for several shots after boronization, f_{rad} is reduced by 10 to 20% on average
- **Impurity Powder Dropper** (IPD) experiments shows cumulative effect on radiative fraction (**up to 35 s long injection**)

GDB



IPD – P_{add} = 5 MW

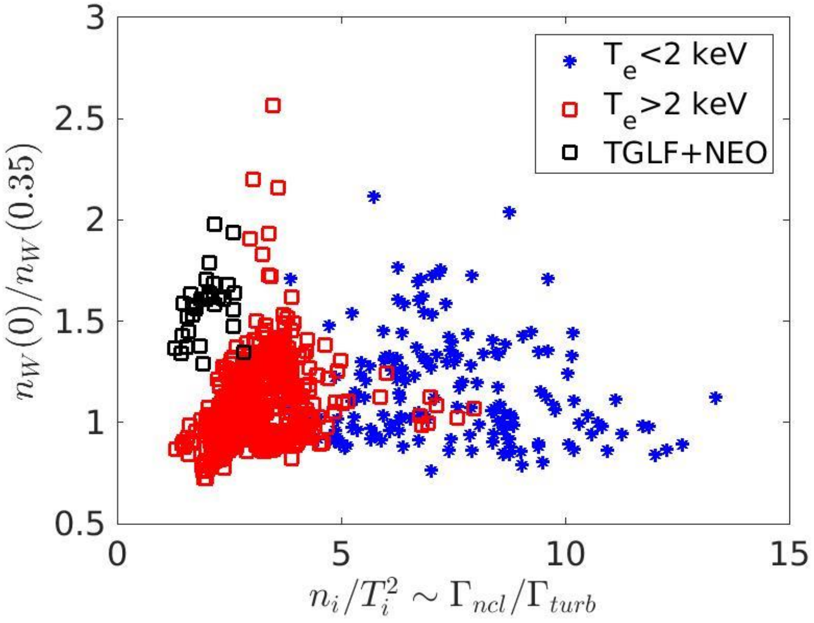


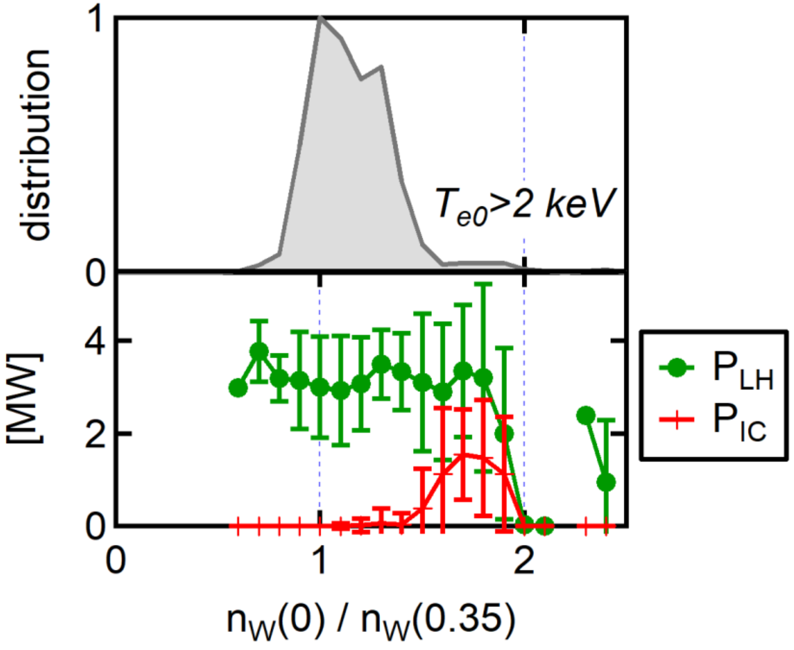
[K. *Afonin NME'24, R. Lunsford NME'24*]

Core tungsten transport: low central tungsten peaking

Core tungsten peaking is moderate due to limited neoclassical convection:

  - No external momentum input
  - No central particle source
- **Average peaking < 2** (mildly peaked to flat profiles) over the reduced WEST database and from the modelling (TGLF + NEO)
  - Highest peaking obtained from ICRH heated scenarios

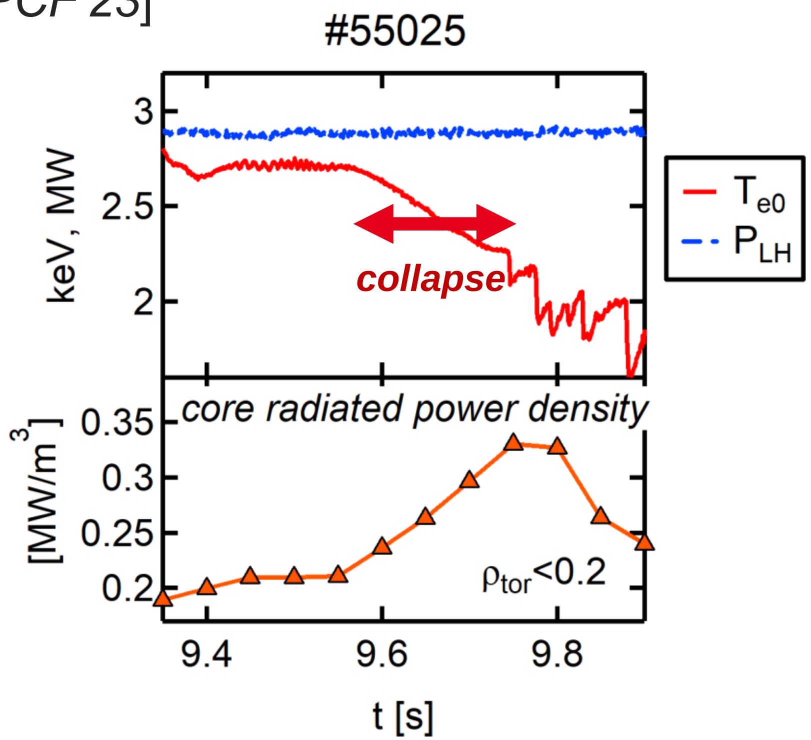


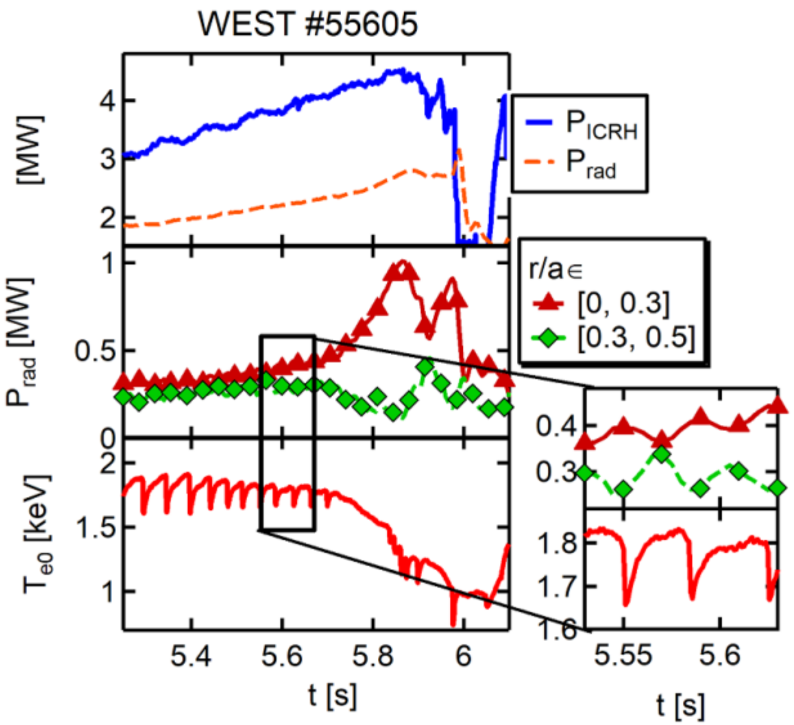


Central radiative collapse observed

However **radiative collapses** are observed due to lack of central heating as the starting point:

- **In LHCD heated plasmas**
  - Combination of off-axis LHCD power deposition and increased inward tungsten transport [*V. Ostuni NF'21*]
- **In ICRH heated plasmas**
  - Fast ions ripple losses reducing central electron heating + rotation induced mild tungsten peaking [*Maget PPCF'23*]





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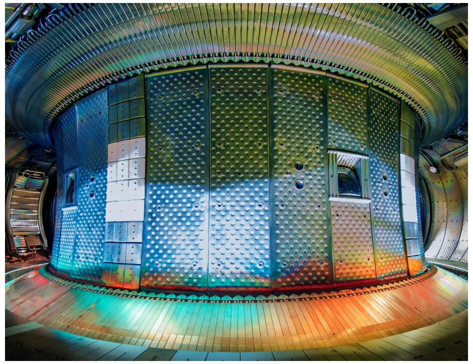

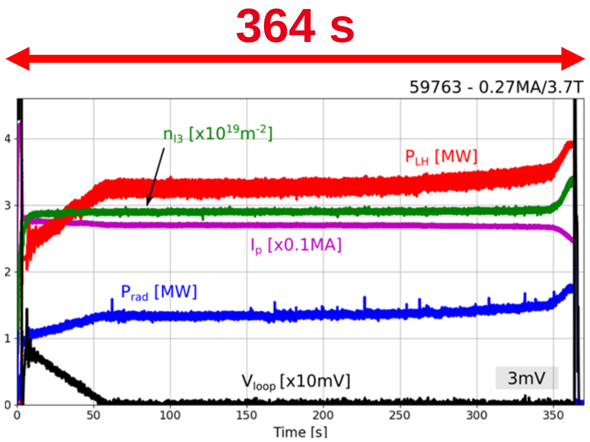

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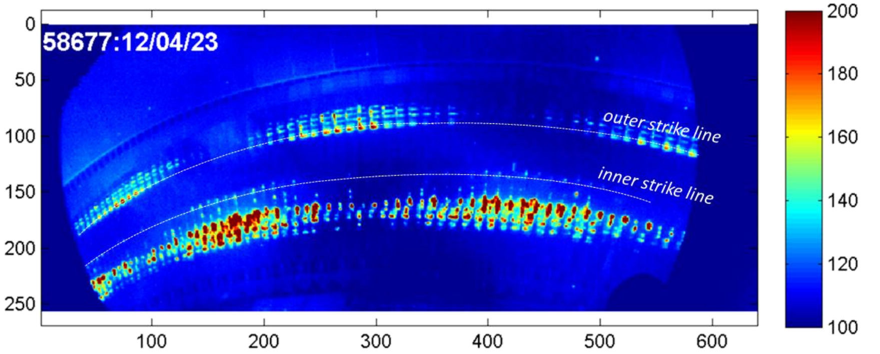

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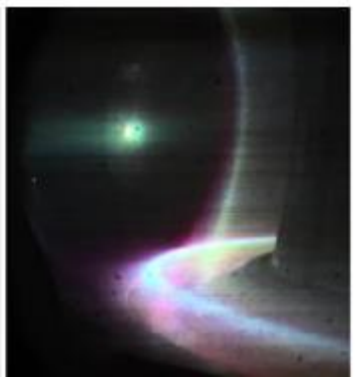


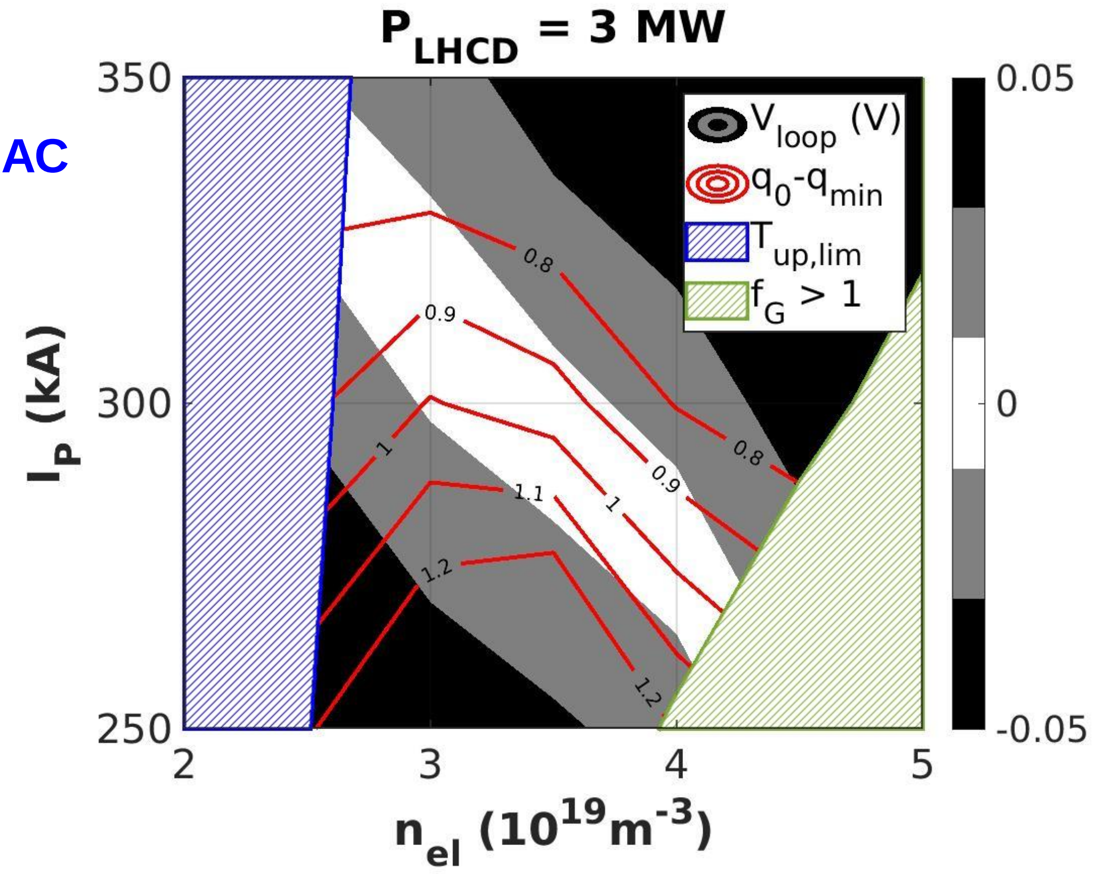
4. Low divertor temperature operation

Current drive efficiency and long pulse operational domain: predict first

Operational domain determined by current drive efficiency and machine specific constraints

- Integrated modelling to guide scenario development (0D METIS, JINTRAC [*T. Fonghetti Thursday*])

JINTRAC

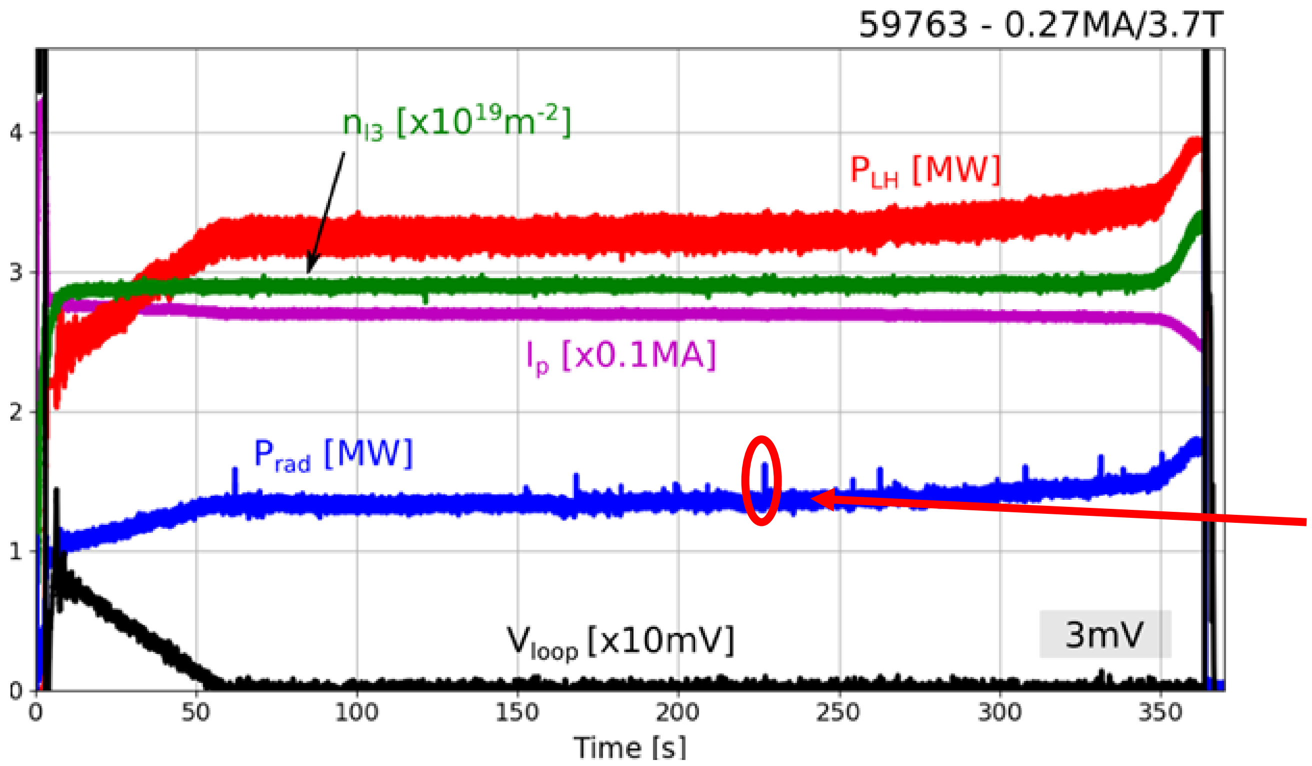


- Optimization of low V_{loop} operation
  - Temperature increase on upper elements impacted by fast electron ripple losses -> triggers safety limit
  - **Current drive efficiency** with **energy confinement time**
  - Greenwald fraction
  - Reversed q profiles triggering MHD
- Results in low plasma current and medium density/heating power (LHCD only)
- Long pulse operation involves much more than that *[V. Lamaison, L. Meunier Wednesday*]

Record duration pulse of 364 s

Record long pulse obtained for 364 s and 1.15 GJ of injected energy

- Double feedback control scheme developed on I_p and V_{loop} [*R. NouailletasThursday*]
- Stable discharge obtained at $\boldsymbol{V_{loop} = 3\ mV}$ **(1100 s can be achieved)** with $I_p = 0.27\ MA$, $P_{LH} = 3.2\ MW$ and $\bar{n} = 2.9\ 10^{19}\ m^{-3}$



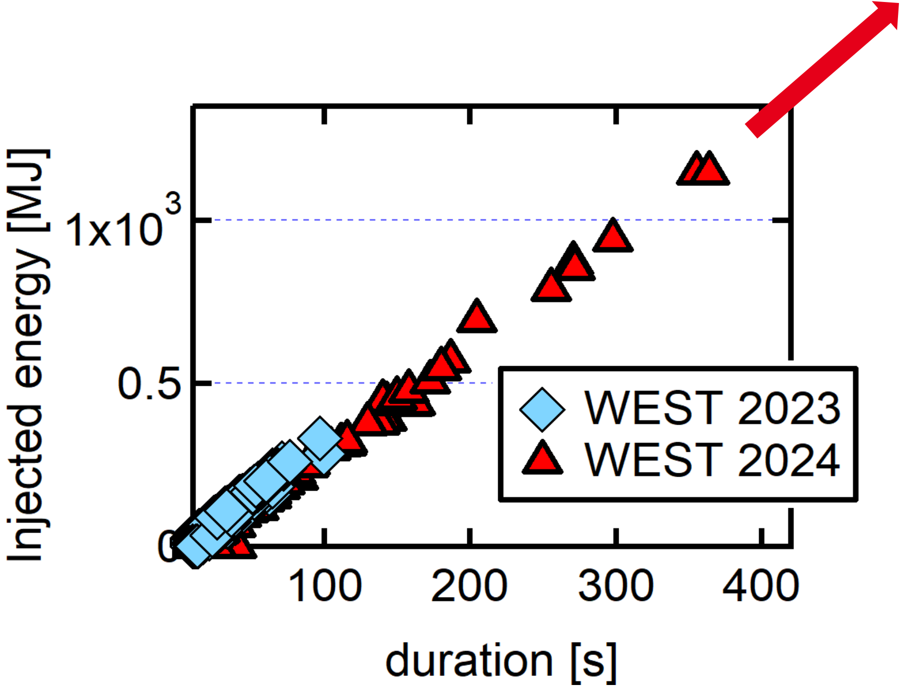
- Similar Lower Hybrid current drive efficiencies obtained compared to Tore Supra
- L-mode with central $T_e \sim 4-5\ keV$ [*L.F. Delgado-Aparicio Thursday*] and $L_{96} \sim 1.25$, $\beta_N \sim 0.7$, $\beta_p \sim 1.6$
- **No particular issue with W contamination but increase in Z_{eff}**
- **Sharp radiated power increase during operation: UFOs**
- **Increase in density t>300 s from outgassing of remote elements**

Long Pulse Operation and associated challenges

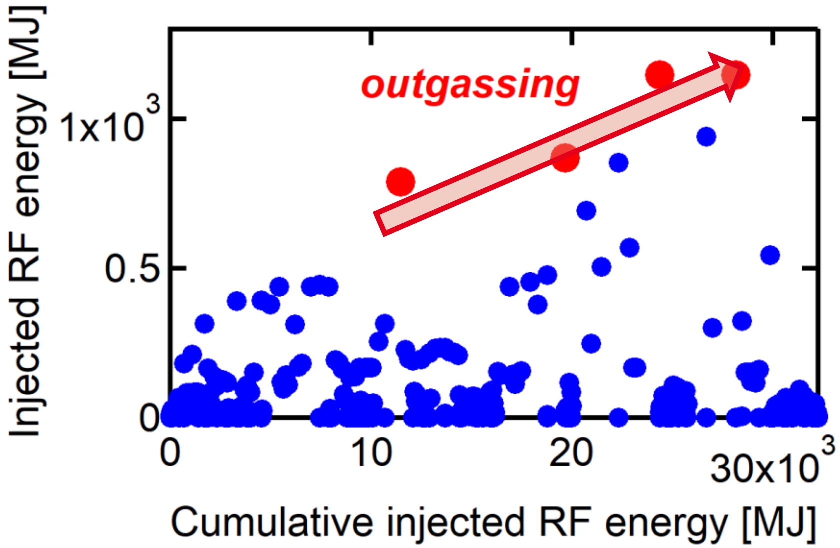
New challenges above the GJ range and towards 1000 s

- Outgassing of remaining far-off inertial elements
  - Evidence of progressive conditioning
- Increased probability of unforeseen events
  - UFOs, but also Internal Transport Barrier triggering ➪ *MHD*

➪ *actuator required (ECRH)*



Towards 1000 s

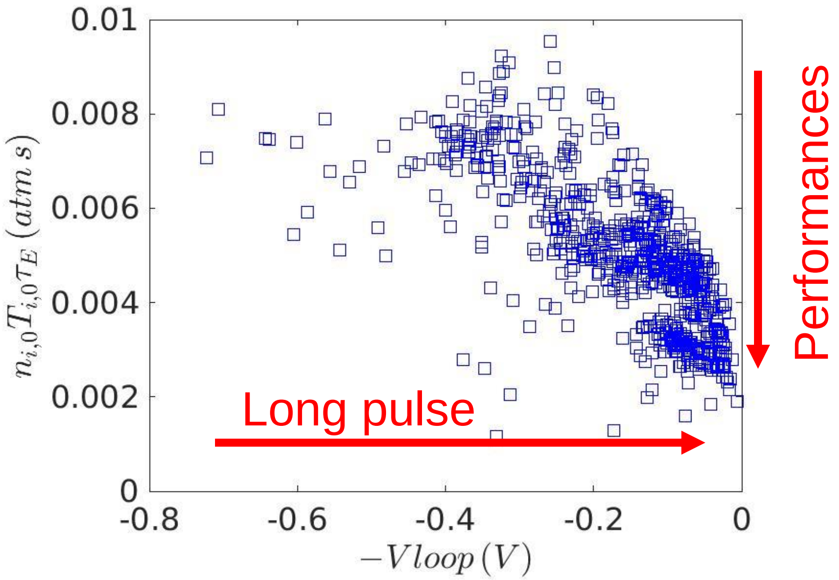


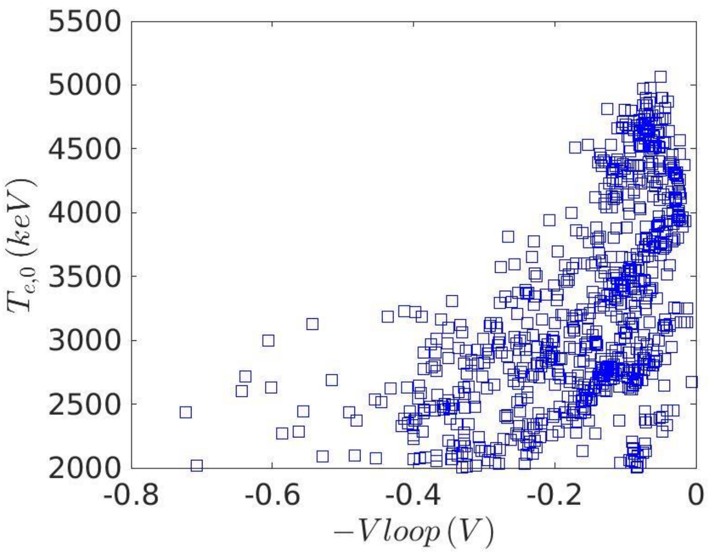
Limited performances of long pulses in current devices

Low performances in terms of triple product are obtained in long pulse tokamak plasmas [*X. Litaudon NF'23*]

  - Reduced confinement times at low plasma currents
  - Dominant electron heating with low densities results in limited ion temperature *[M. Beurskens NF'21]*

- **Linked to τ_{ei}/τ_E if dominant electron heating** *[P. Manas NF 2024]:*
  - Increasing density, provided sufficient CD efficiency and central heating (with the help of ECRH)
  - Direct ion heating (ICRH), radiative scenario…
  - **Problem arising in current machines but not expected for a reactor**





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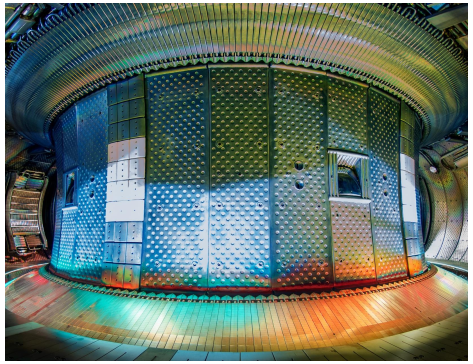

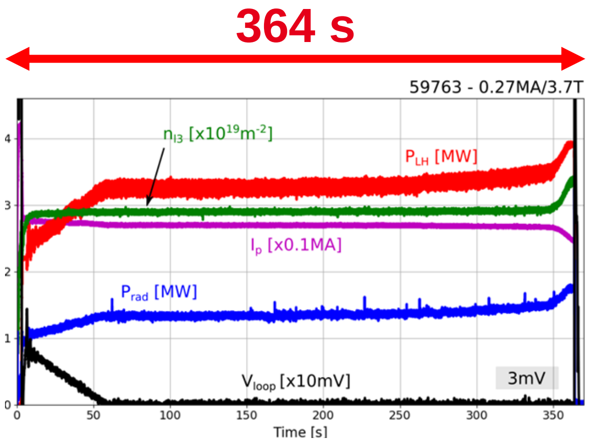

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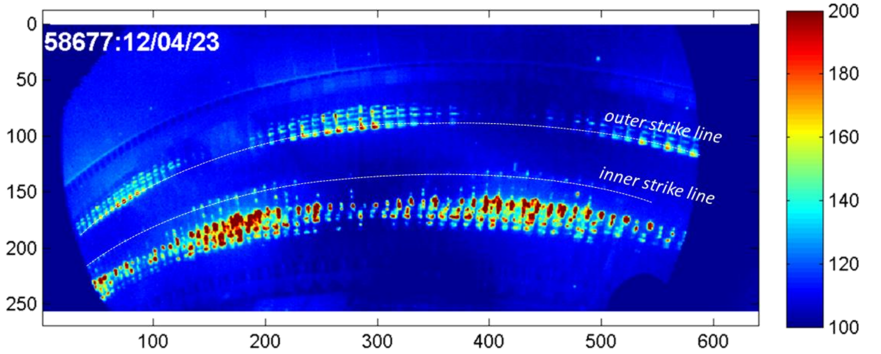
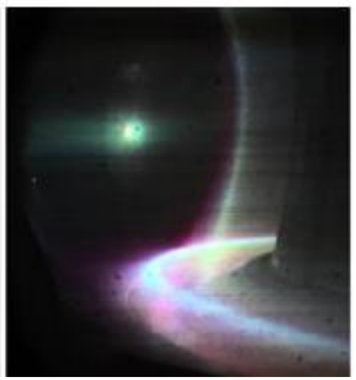
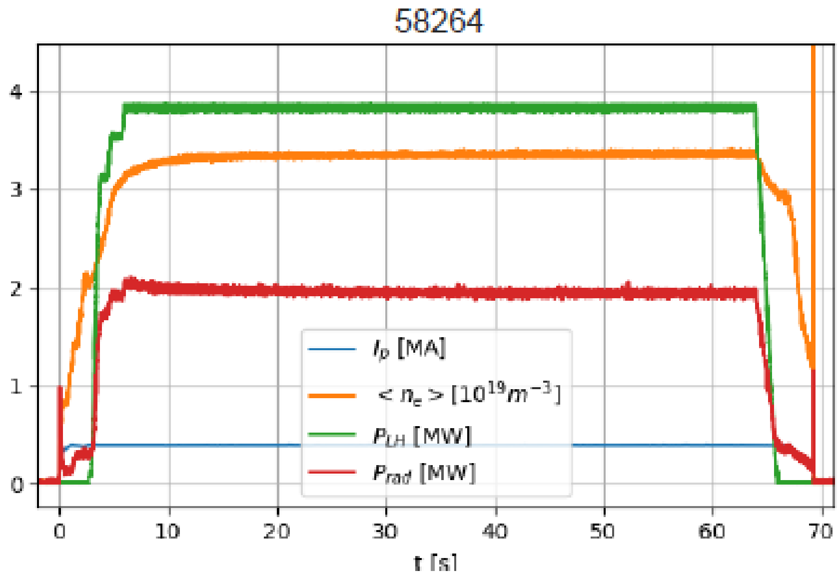


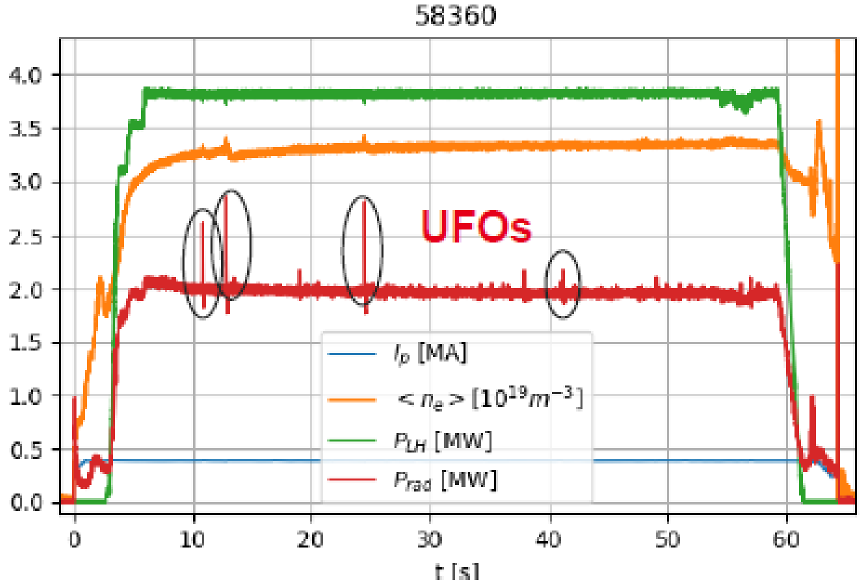


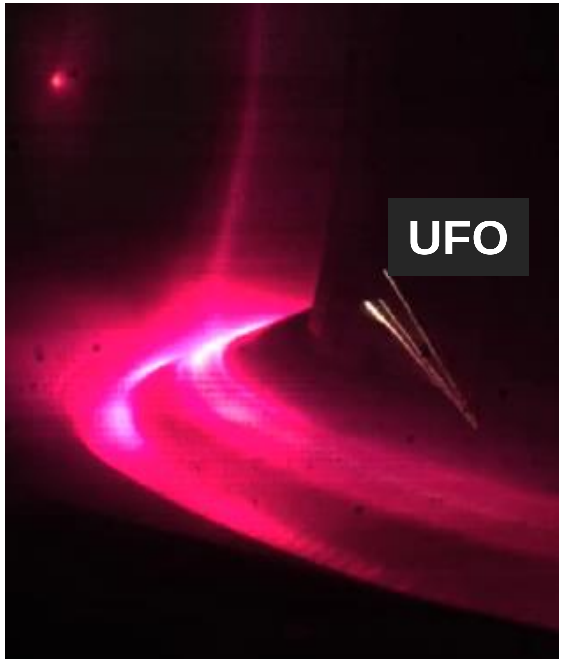
4. Low divertor temperature operation

High Fluence in attached divertor regime: UFO production

- **High Fluence campaign performed in 2023 in L-mode attached divertor regime**
  - Cumulated plasma time of about 3h in attached regime (T_e divertor ~20 eV), without boronisation
  - Cumulated fluence at lower divertor reached 5×10^{26} D/m^2 (more than an ITER PFPO pulse)
- **Divertor erosion generates deposits, flakes and UFOs**
  - Short peaks of radiated power, becoming more and more frequent ⇨ ***impact on plasma operation***
  - Extensive identification and analysis of UFOs [*Gaspar NME'24*]

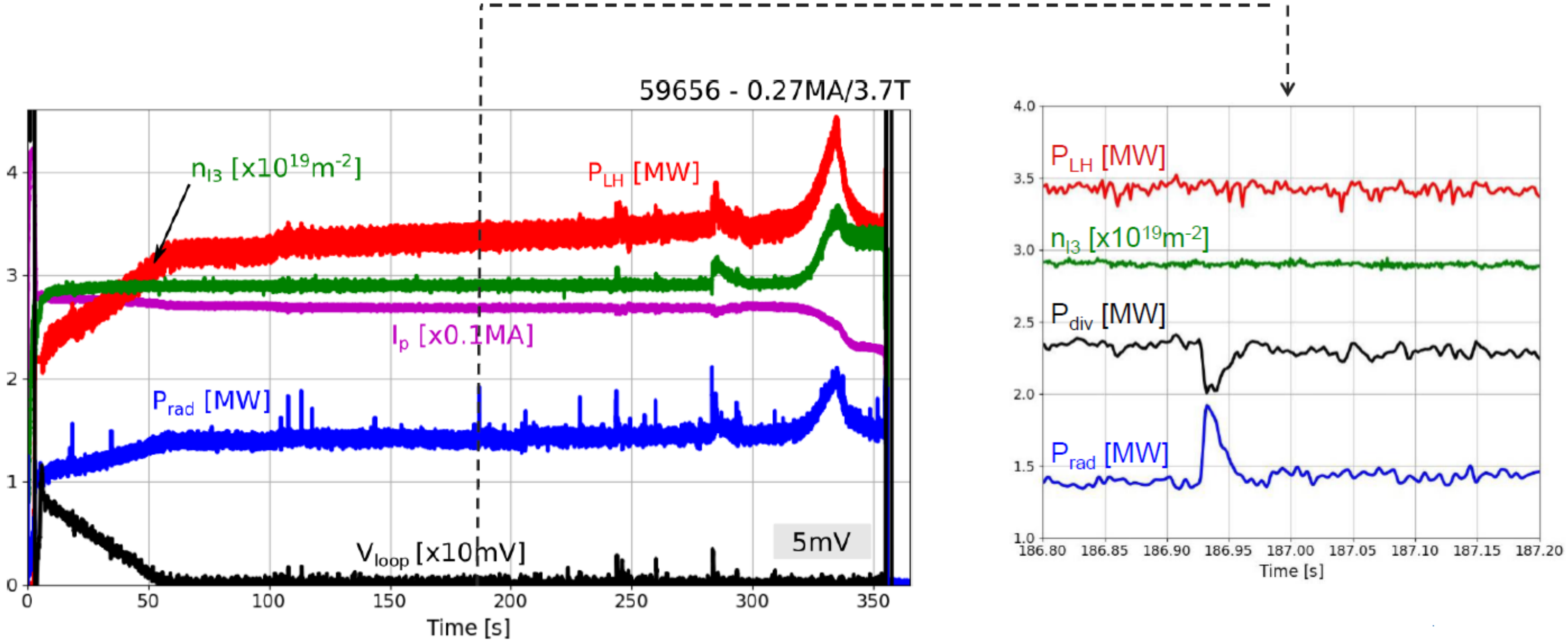






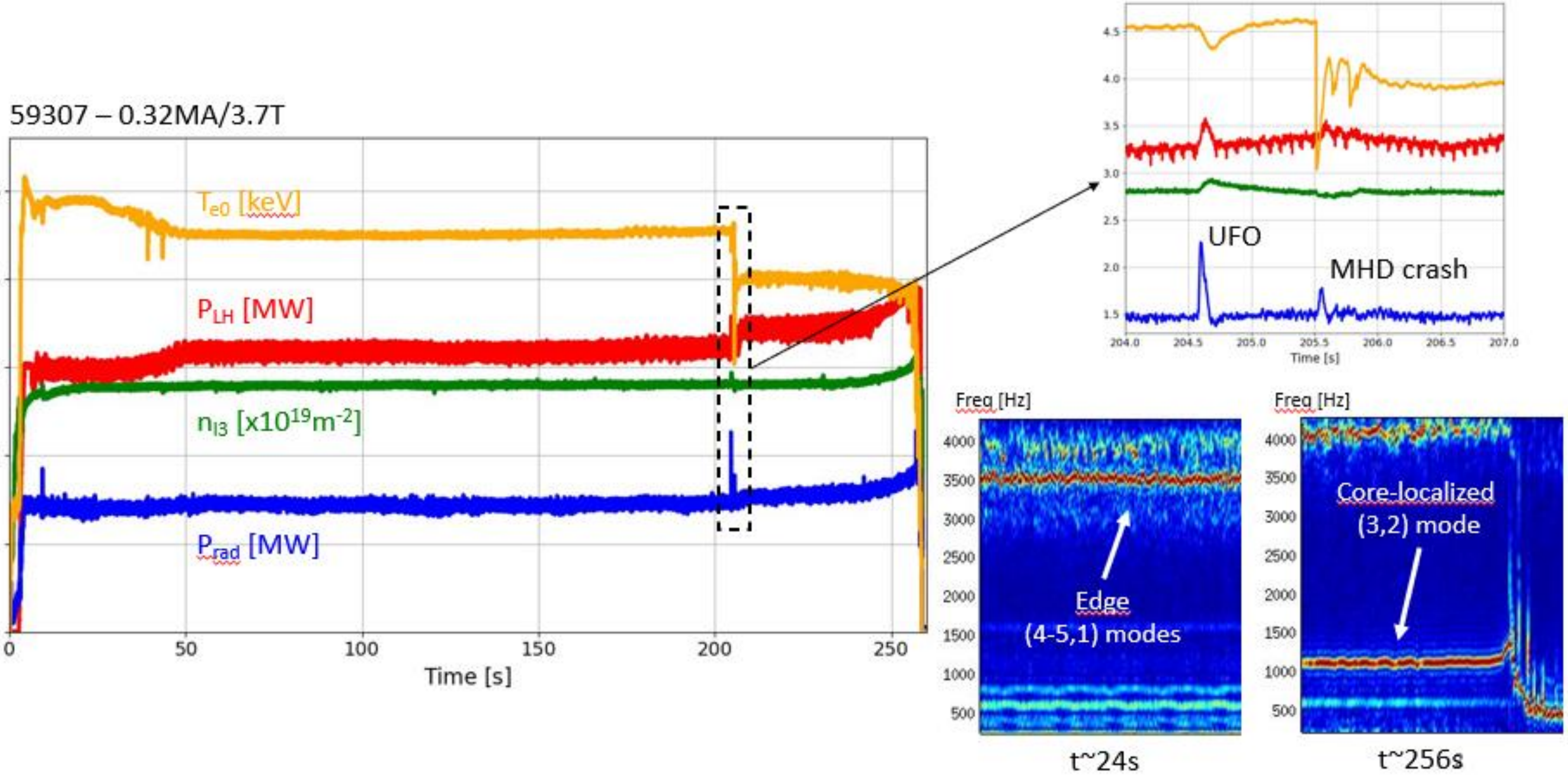
Different UFO classes and W mass mobilized

- **Formation / ejection of flakes**
  - 3 classes: **minor impact (1)**



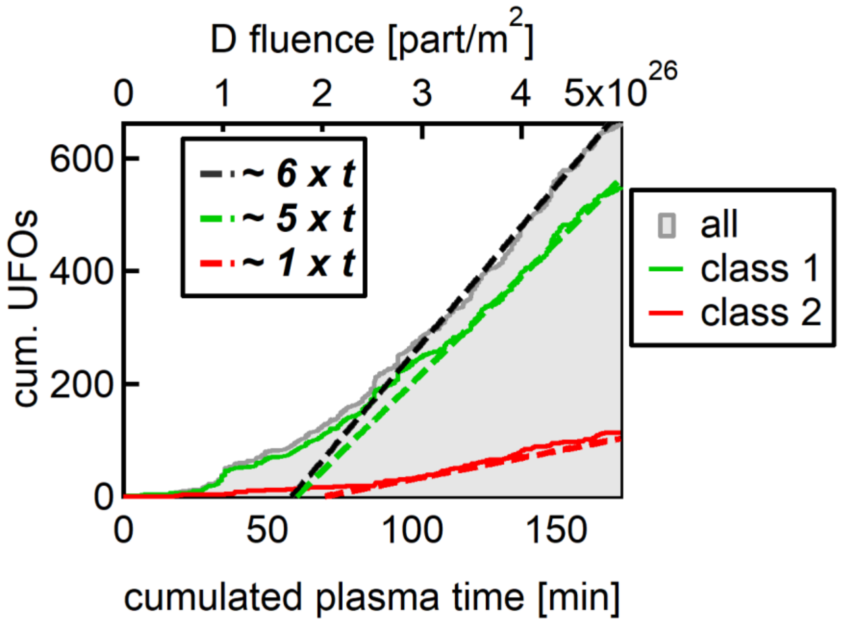
Different UFO classes and W mass mobilized

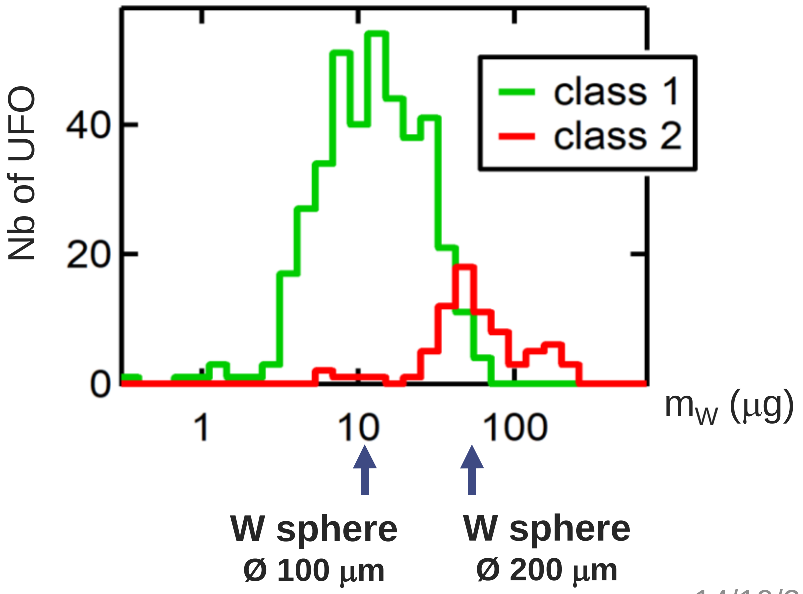
- **Formation / ejection of flakes**
  - 3 classes: **minor impact (1)** / **disruption after more than 0.2s (2)** / disruption after less than 0.2s (3)



Different UFO classes and W mass mobilized

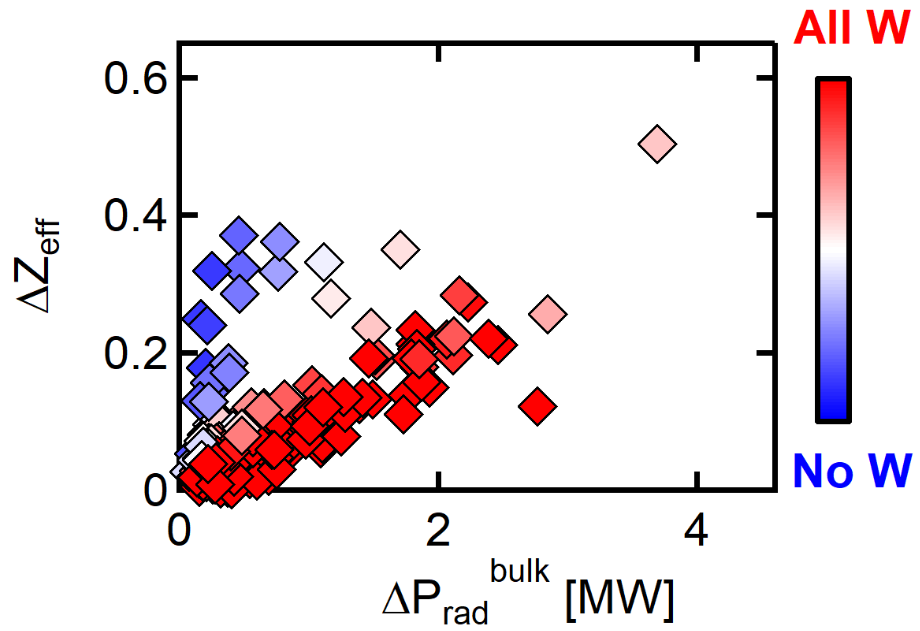
- **Formation / ejection of flakes**
  - 3 classes: **minor impact (1)** / **disruption after more than 0.2s (2)** / disruption after less than 0.2s (3)
  - Stationary regime after ~ 100 min of plasma for classes 1 and 2, but class 3 still growing
  - The W mass mobilized by the UFOs of class 1 and 2 is evaluated
    - *Average masses: 14 µg and 64 µg for classes 1 and 2 ⇨ ~140 µg/min of W mobilized in the UFOs*
      - *But no UFO issues reported on JET high fluence experiments [Brezinsek NF'19] → divertor geometry ?*

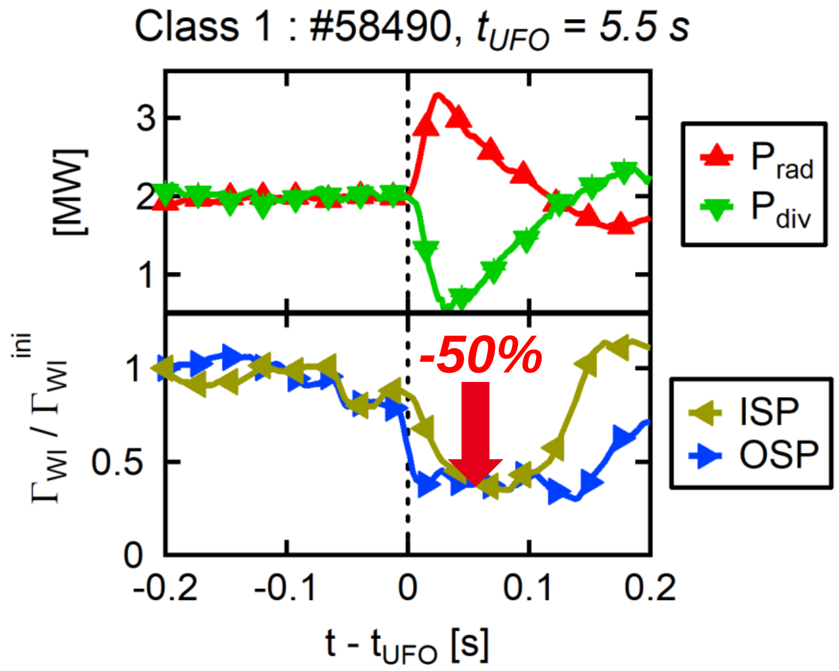




UFO composition and radiation resilience

- **Composition of the UFOs**
  - From Z_{eff} / bolometry measurements: mostly tungsten, but light impurities sometimes present
    - ➢ *In line with previous post-mortem results on deposits composition [Hakola NF'21, Balden PS'21, Martin PS'21]*
- **Consequences for plasma operation**
  - Class 1: reduction of incoming W flux after UFO ➩ ***fixed operation point in f_{rad} (resilience)***
  - Classes 2 & 3: radiation peak impacts safety factor profile ➩ ***MHD stability degraded***

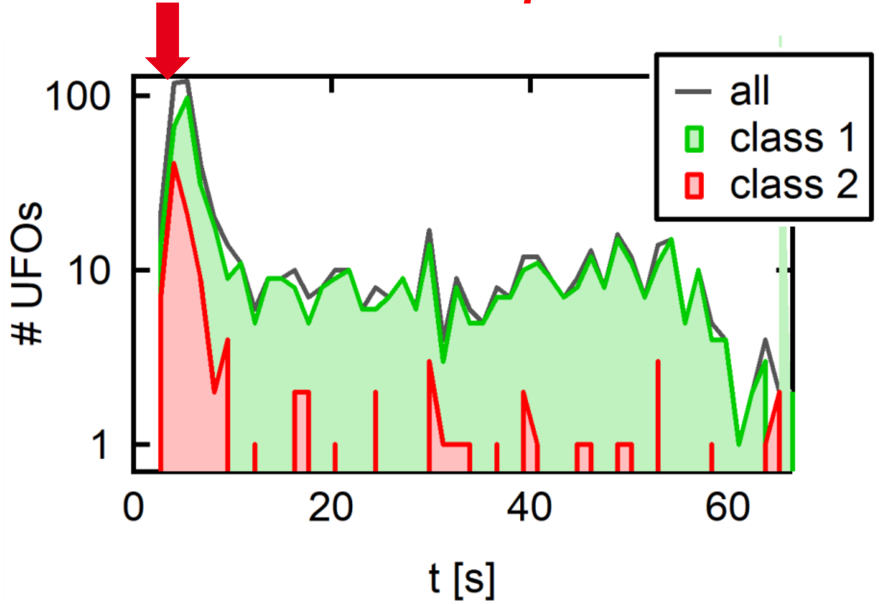




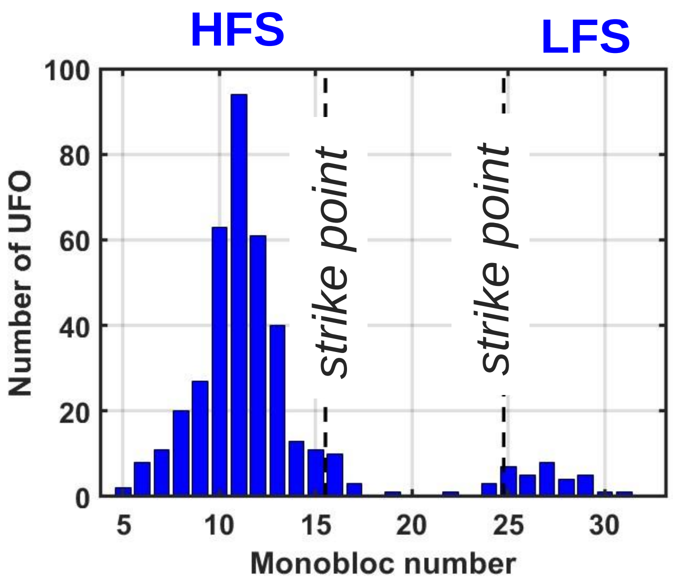
UFO origin: thermal stress, HFS, disruption flakes

- **Origin of the UFOs**
  - Temporal: mostly at the start of the additional power ⇨ ***thermal stress is the main trigger***
  - Spatial: mostly coming from the High Field Side (HFS) region [*Gaspar NME'24*]
    - ➢ *post-mortem: ~50µm thick deposits in HFS area [Martin NME'24]*
    - ➢ *Consistent with evaluation of cumulated W gross erosion [Fedorczak NME'24]*
  - Historical: most UFOs originate directly from the thick deposits
    - ➢ *~30% of disruptive UFOs are flakes from a preceding disruption*

Start of additional power

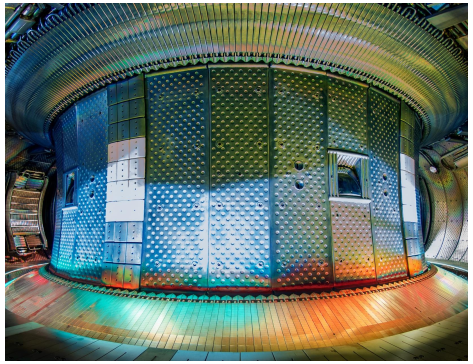


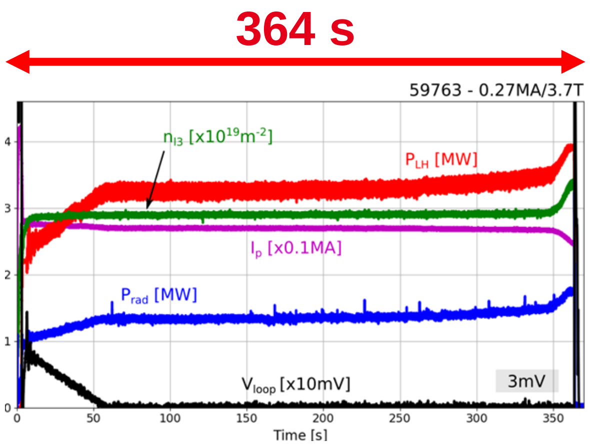
[*Gaspar PSI'24*]



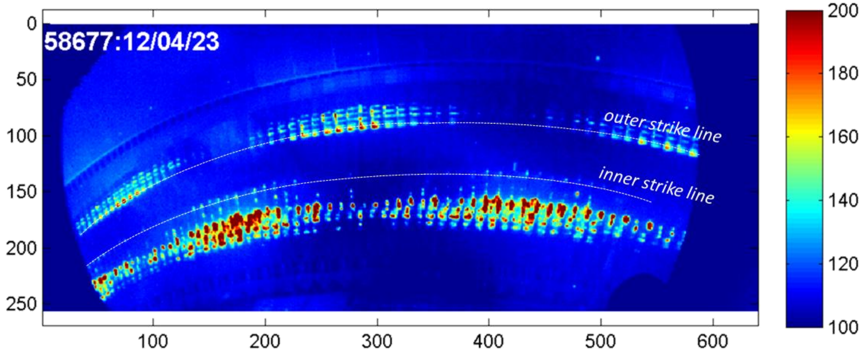
Content

1. Tungsten constraints on the operation

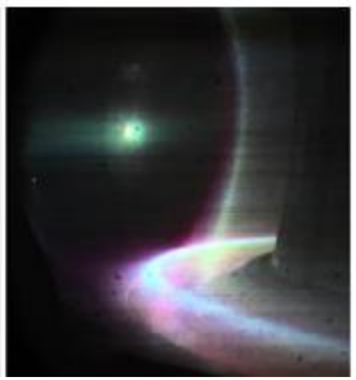




2. Long pulse scenario development and challenges



3. High Fluence operation



4. Low divertor temperature operation

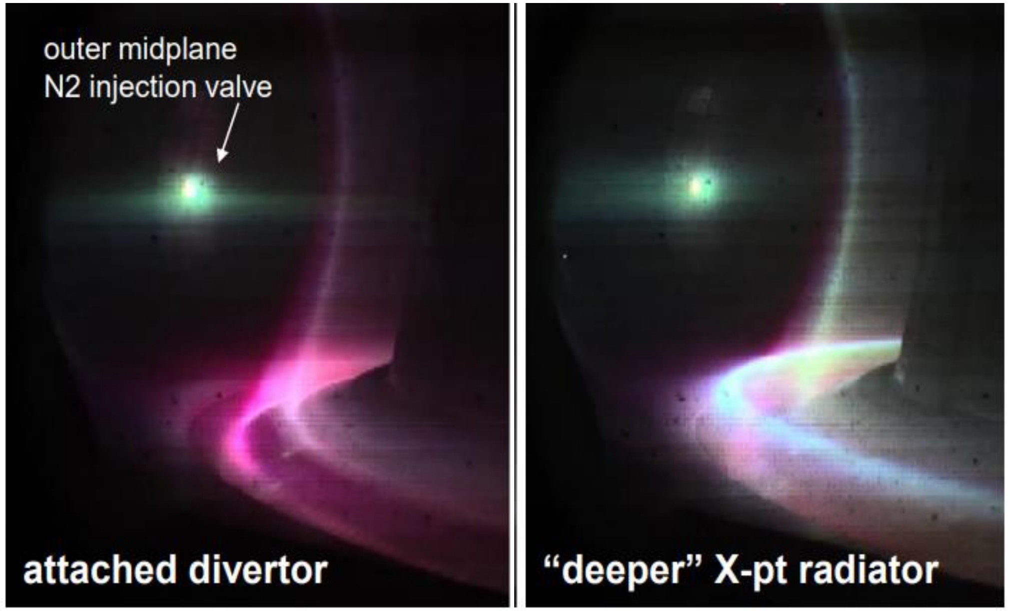
X-Point Radiator scenario

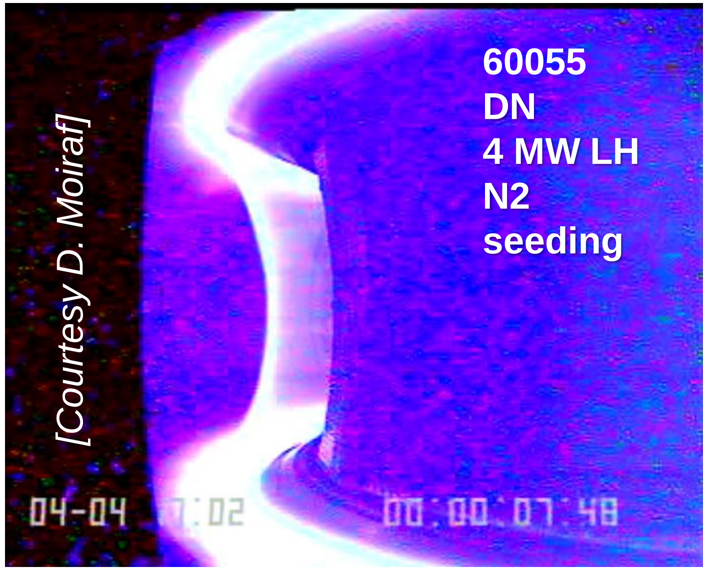
- **Preventing W contamination from divertor: a low temperature at the strike points is required**
  - Spontaneous transition to low divertor temperature obtained with light impurity seeding [*Bernert PS'24*]
    - ➢ *Radiative ring formation above the divertor, transition time scale ~ µs*
    - ➢ *In WEST : low temperature < 10 eV / attached plasma / weak upstream impact*

Similar in AUG, JET, TCV, KSTAR, …

- **XPR scenario in alternative configurations**
  - Double-Null configuration: alternative distribution of W sources
  - Compact configuration (X-point→target): gain in plasma volume

Analysis on-going

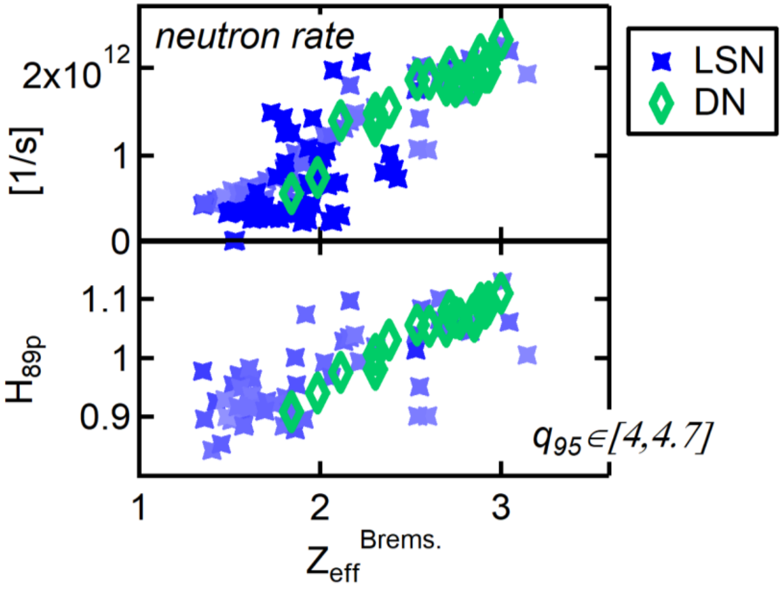


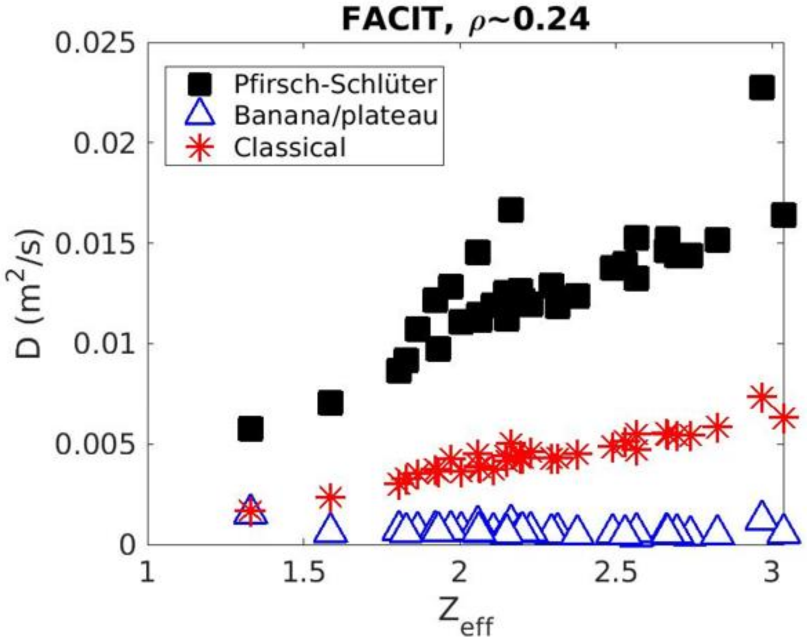


[Courtesy D. Moiraf]

X-Point Radiator scenario impact on performances and tungsten transport

- **Light impurity seeding impacts confinement, tungsten source and transport**
  - Increased neutron rate and H-factor with Z_{eff} -> increased triple product
  - Tungsten contamination reduced by only ~ 40% ⇨ ***other sources not negligible***
  - Tungsten peaking is reduced [*J. Dominski submitted to NF*]
    - **Increase neoclassical diffusion**
    - Reduced turbulent transport





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- **One-minute compatible XPR scenario achieved ($V_{loop} \sim 90\ mV$)**
  - **Adressing ITER-grad divertor ageing at low divertor temperature conditions**
    - Deposits formation?
    - UFOs generation from existing deposits?

Summary

Progress towards controlled LPO in full tungsten environment

- **Record long pulse duration of 364 s to be extended**
- Predict first integrated modelling intensively used for scenario development

Resilience of radiative fraction and tungsten transport

- **Stands around 50% in WEST** – *coupling between core radiation and erosion*
- Gaps with limiters *(and magnetic configuration at upper divertor)* are important players
- Wall conditioning by Glow Discharge Boronisations limited in time
- Impurity Powder Dropper conditioning possibilities explored

Challenges from Long pulse operation with an ITER-grade divertor

- ITER relevant fluences obtained: deposit formation and UFO generation in attached regime
  - Strong impact on WEST operation
  - Extrapolation to ITER uncertain (divertor geometry)
- **Low divertor temperature X-point radiator scenario:**
  - **Targeting ~1 min. discharges: for future characterization of PWI after high fluence campaign**
  - Higher performances (triple product)

WEST

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