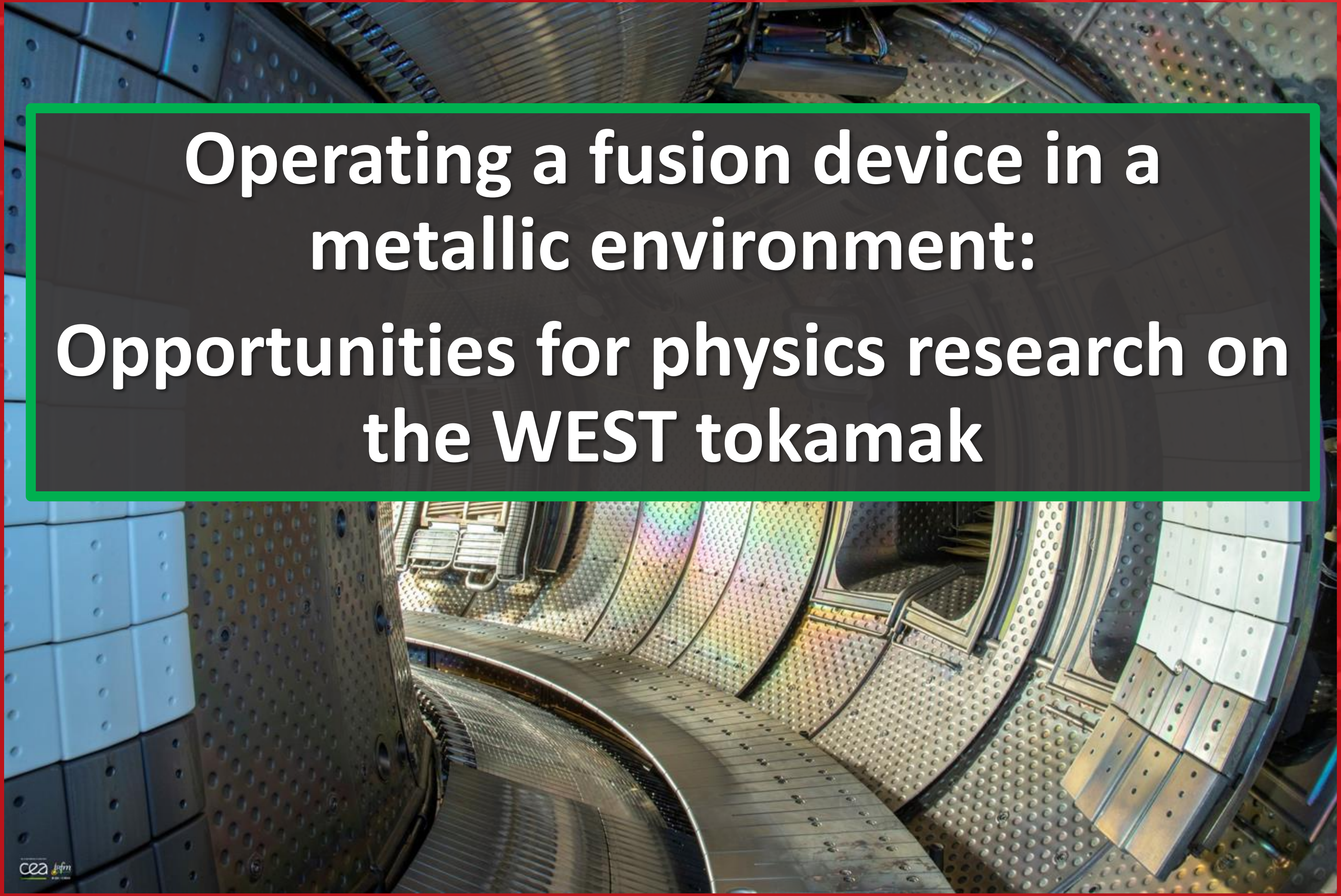
Operating a fusion device in a metallic environment:

Opportunities for physics research on the WEST tokamak



P. Maget
CEA/IRFM

Colloque Fédération de Recherche sur la Fusion par Confinement Magnétique
19/05/2022

FR FCM

Magnetic Fusion research on WEST

Specific issues for a fusion reactor operation

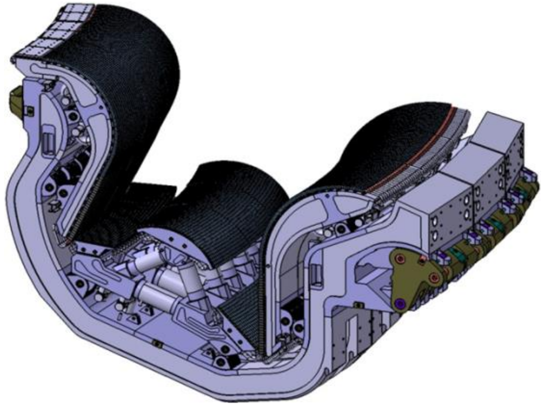
- Obtain high confinement plasma discharges in a metallic environment, on long duration
- Design components for the high heat flux region ; Qualify their tolerance to defaults
- Validate real-time safety survey for system integrity in a metallic environment

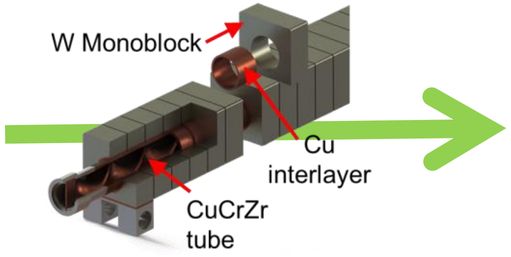
WEST
W Environment in
Steady-state **T**okamak

WEST : An actively cooled superconducting tokamak

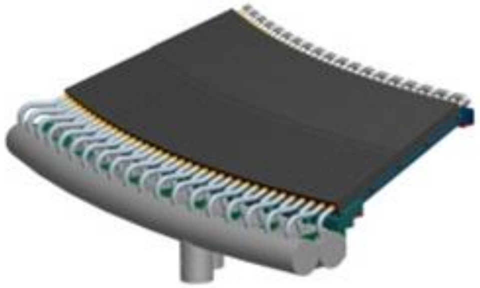
- Testing ITER divertor components : actively cooled tungsten monoblocks
- Flexible magnetic configuration (LSN, USN, DN)
- Large current drive capability : long pulse operation ➔ 1000 s
- High diagnostic coverage

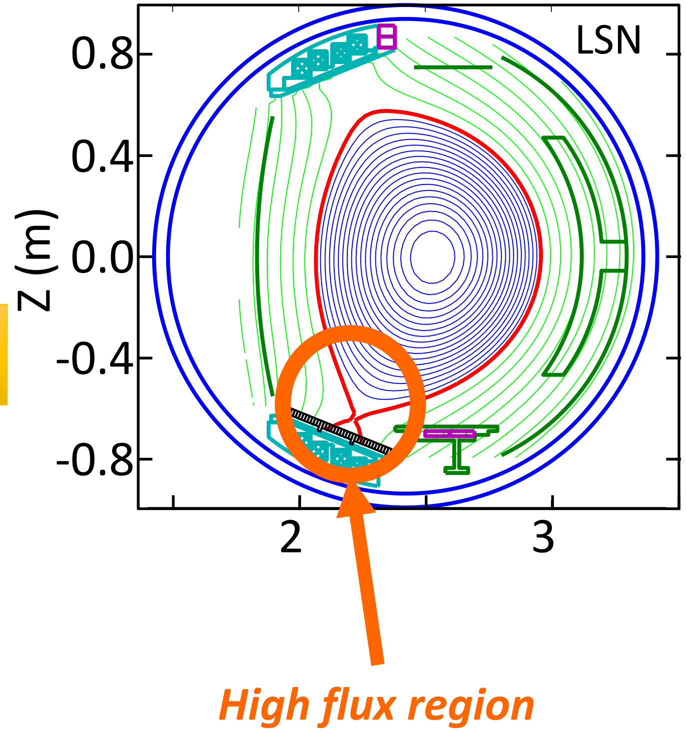
ITER divertor cassette





WEST ITER-like divertor





Extremely diverse physics topics of interest for fusion research

Confinement : from edge to core, different regimes and expectations

- Plasma edge: high power flux and the drive for improved confinement transitions
- Plasma core: turbulent transport channels, Electro-Magnetic and fast particle effects

Heating and Current Drive : the Radio-Frequency (RF) option adopted on WEST

- Ion and Electron Cyclotron Resonance Frequency (ICRF/ECRF), Lower Hybrid Current Drive (LHCD)
- Side effects in the confined region: Orbit Width (ICRH), Ripple losses (ICRH, LHCD), fast particles & turbulence
- Side effects in the open field line region: Sheath rectification (ICRH), electron acceleration in front of LH

Impurities : heavy and light ion species

- Tungsten ions can strongly radiate in the hot plasma core
  - Contamination issue: from erosion to contamination, mastering heat fluxes and screening
  - Transport issue : turbulence and collisional channels are influenced by the heat, particle and momentum sources
- Light impurities mitigate heat loads on tokamak walls (edge radiation and cooling)
  - Also improve confinement quality (dilution effect, current profile peaking)
  - But can contribute to tungsten sputtering

Unusual situations of major safety importance

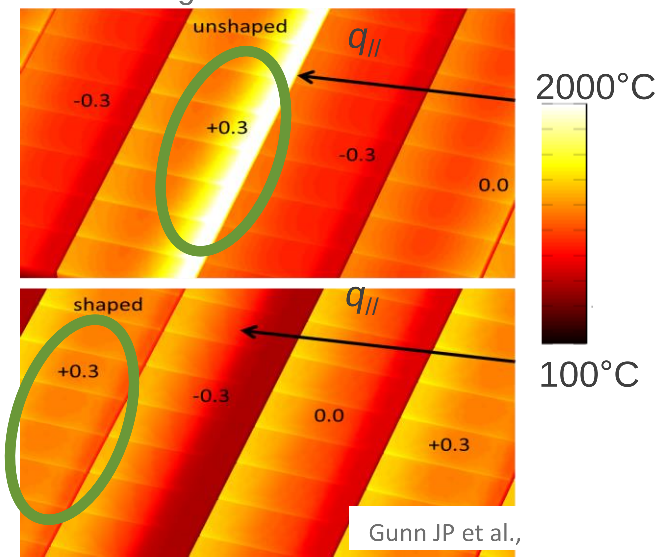
- Disruptions and runaway electron beams : avoidance, detection and mitigation

Key scientific achievements on WEST phase 1

Before 2022, WEST divertor is only partly equipped with cooled ITER-like components: phase 1

- Study of monoblock shaping impact and tungsten melting

Réponse « thermique » au désalignement des PFUs



Gunn JP et al.,

Exploration of WEST operating domain

- tungsten cycle, divertor erosion/redeposition
- real-time safety survey for component integrity
- confinement scaling, H-mode, tungsten transport
- Physics of RF heating and current drive

Two routes for scenario development

- **Test of ITER Plasma Facing Units (PFU):** high heat flux (10-20 MW/m^2), high fluence, ageing, …
- **Reactor compatible scenario:** heat flux mitigation on divertor, high edge radiation, …

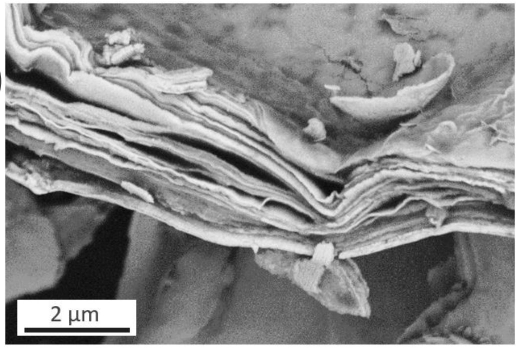
Increasing diagnostic coverage provides strong constraints to theory & modeling

- List of available diagnostics on the WEST Portal : https://westusers.partenaires.cea.fr/

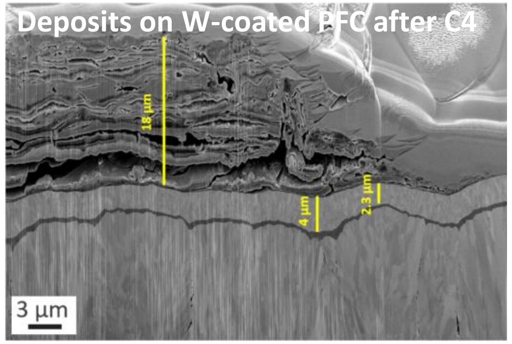
Key scientific achievements : material studies

Tungsten cycle : erosion, redeposition, structural changes and consequences for heat flux study

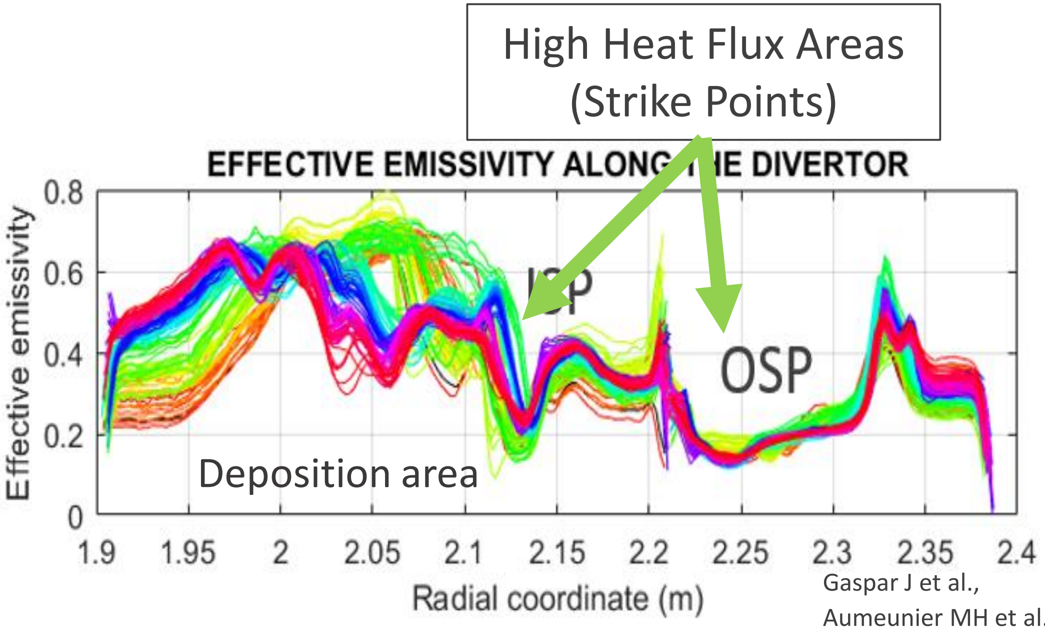
- **On the divertor, thick deposits & eroded areas**
  - Thick deposits can complicate long term operation (flake ejection)
- **Emissivity varies spatially and with time**
  - Quantification mandatory for temperature measurement using IR
- **Multiple reflections requires synthetic wall monitoring tools**
  - Complex deconvolution of reflected & direct patterns
  - Project for IA-based identification of thermal events



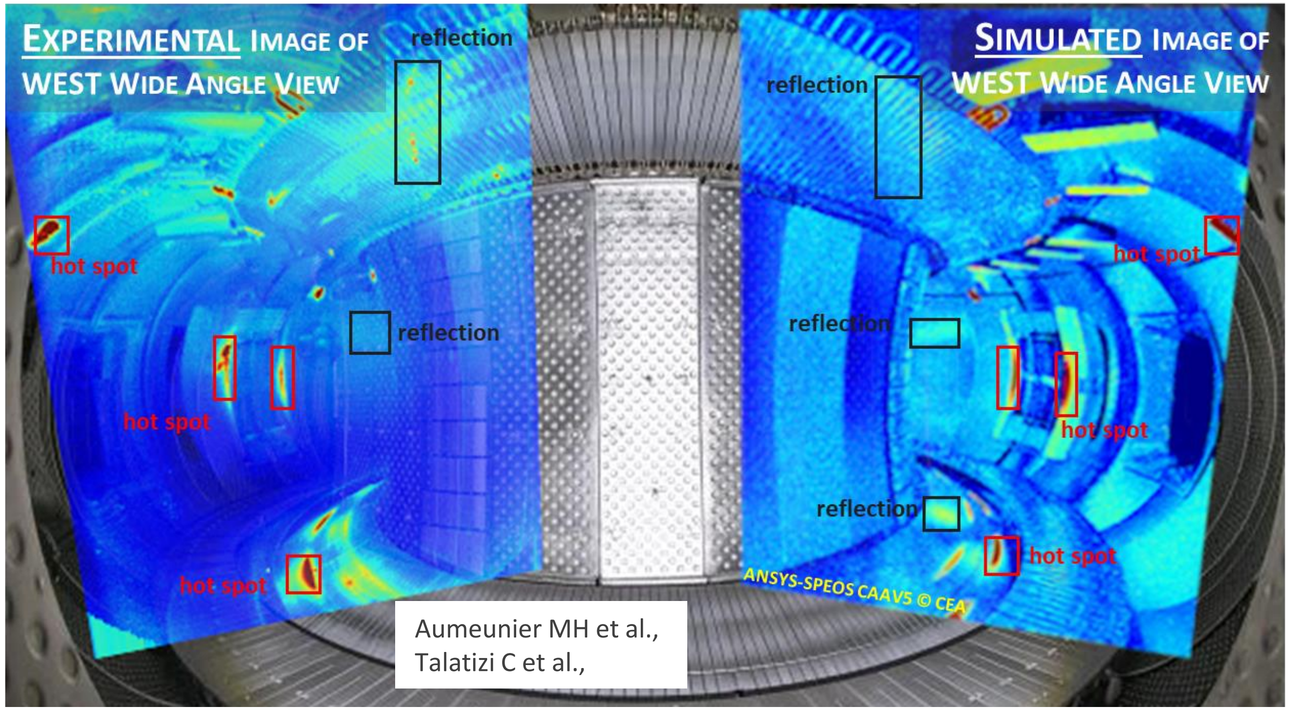
[C. Martin et al., Phy. Scr. 96, 2021]



[M. Balden et al., Phy. Scr. 96, 2021]



Gaspar J et al.,
Aumeunier MH et al.,



Aumeunier MH et al.,
Talatizi C et al.,

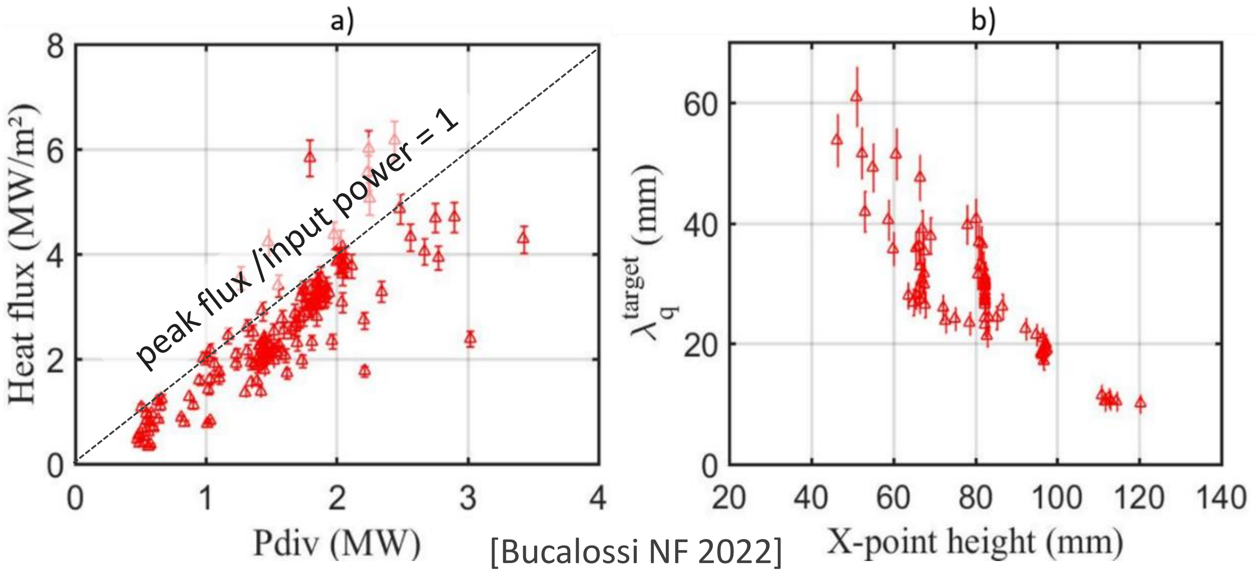
Key scientific achievements: tungsten sources & contamination

ITER divertor units needs to be tested at 10 MW/m² at least

- The physics of the heat flux on components is driven by transport in open field lines
- Decay length λ_q and divertor geometry sets the peak heat flux on divertor components
- Up to 6 MW/m² obtained so far, playing with X-point height and maximizing input power

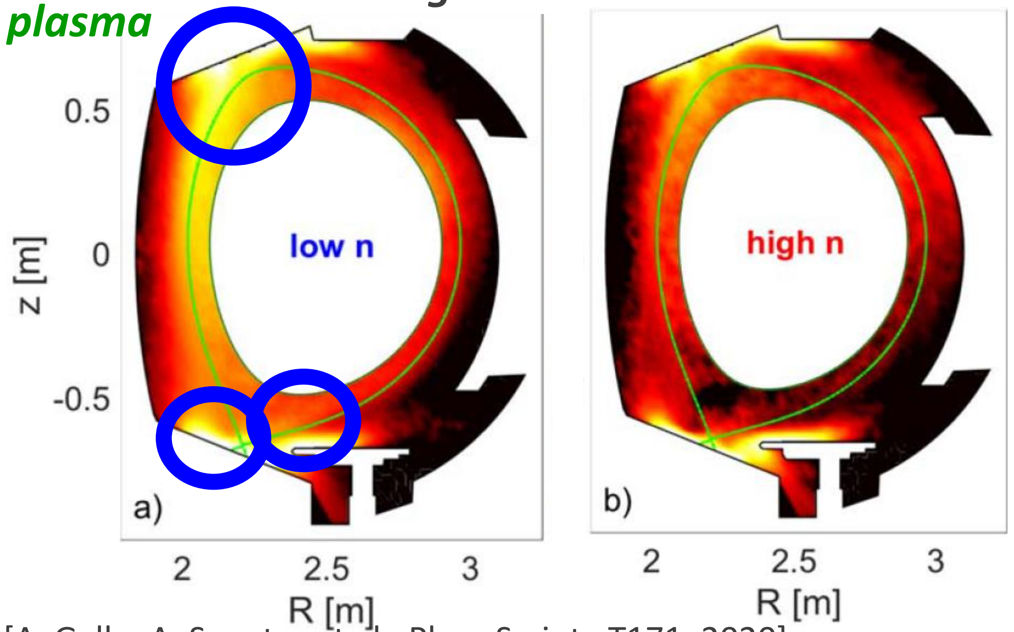
Tungsten access to confined plasma region : a key issue for limiting core radiation

- Erosion, redeposition, contamination : experiment vs model (SOLEDGE-ERO)
- Identification of W sources (O) & comparison with experimental data
    - *Modeling provides the origin of tungsten atoms reaching confined plasma*



[Bucalossi NF 2022]

Tungsten concentration



[A. Gallo, A. Sepetys et al., Phys. Scripta T171, 2020]

Key scientific achievements: confinement and turbulence

Confinement database

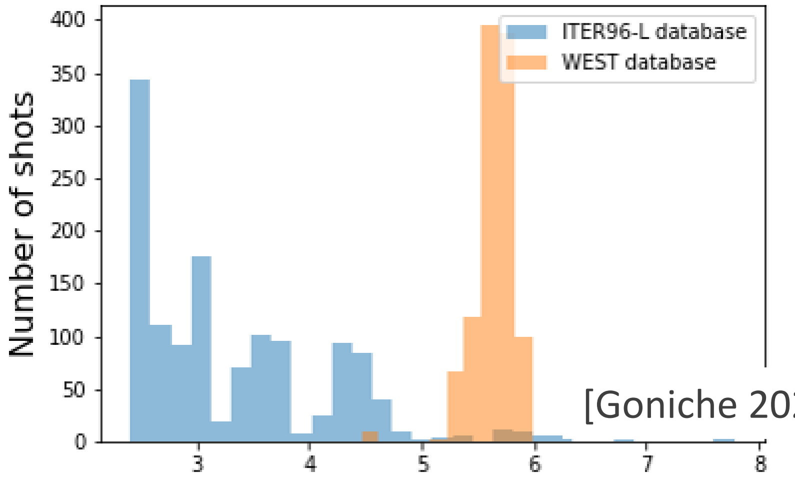
- A global overview on the WEST data confirms negligible impact of aspect ratio on confinement scaling

Turbulence measurement

- Evidence of Trapped Electron Mode (TEM) activity from reflectometry & theory in LH heated plasmas

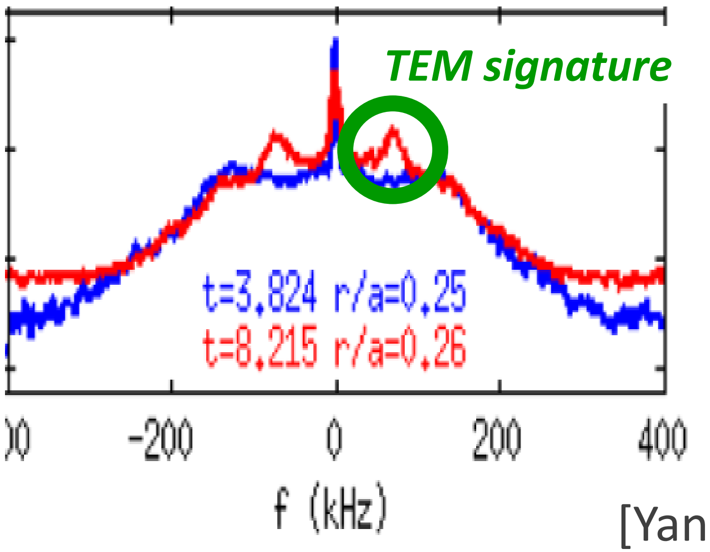
Integrated simulations needs for optimizing confinement in future experiments

- Density and temperature response to external sources crucial for impurity transport & MHD avoidance
- European effort on simulation tools (see Y. Camenen's talk on the TSVV-11 project)

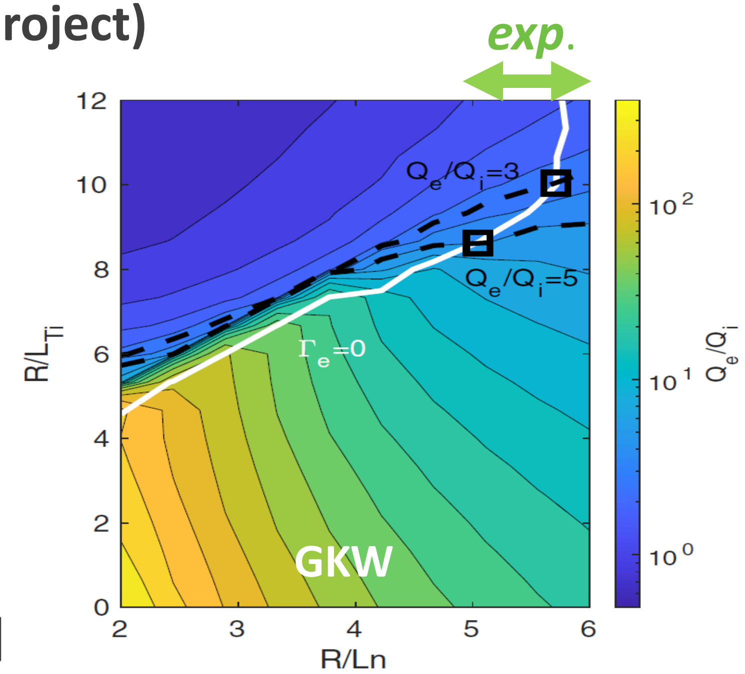


[Goniche 2021]

Rapport d'aspect : R / a



[Yang 2020]



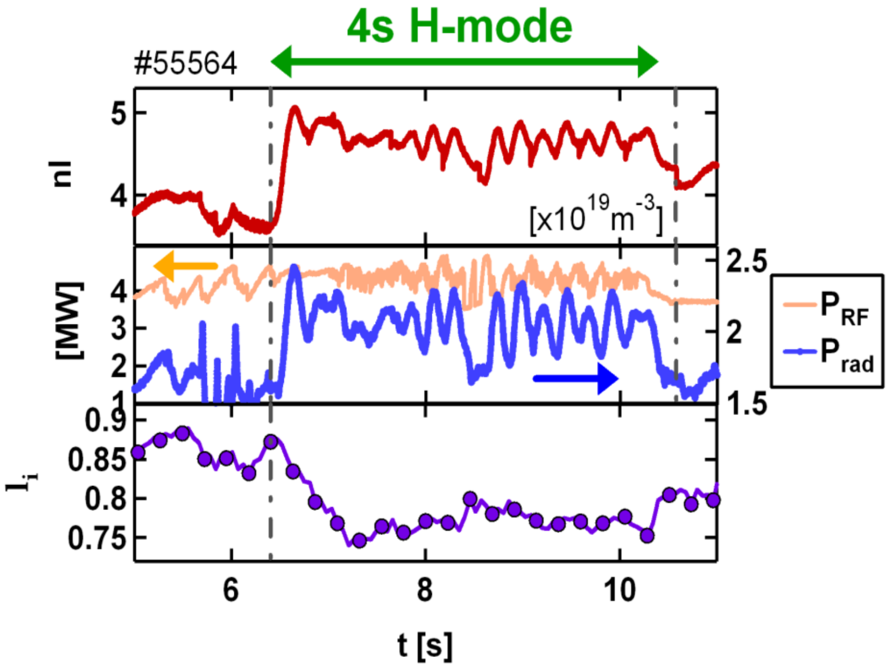
Key scientific achievements: improved confinement regimes

Access to typical H-mode transitions close to power threshold

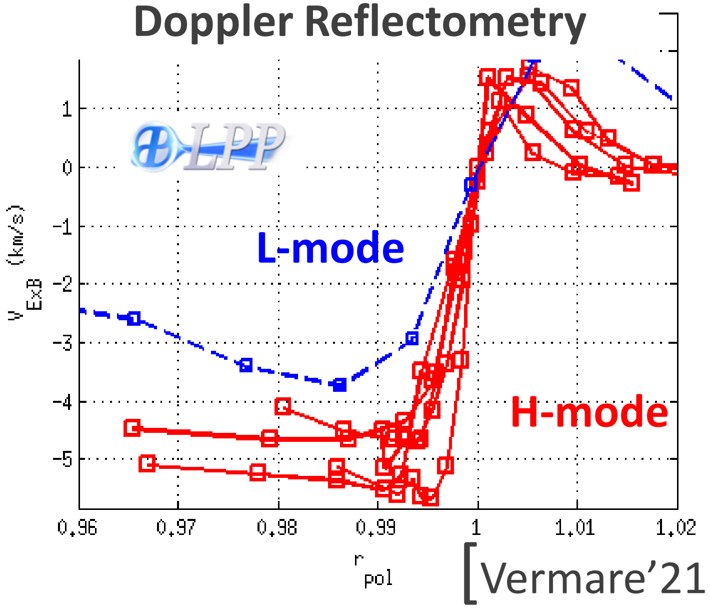
- Signature on density profile, radial electric field and internal inductance (broader current profile = lower l_i)
- Larger radiation leads to oscillating H-mode regime without Edge Localized Modes (ELMs)

Confinement improvement with light impurities

- Role of light impurities (N_2) in improved confinement by dilution & current profile peaking effects
  - Experiment consistent with turbulent transport computation using Qualikiz [Yang'20, Maget'22]

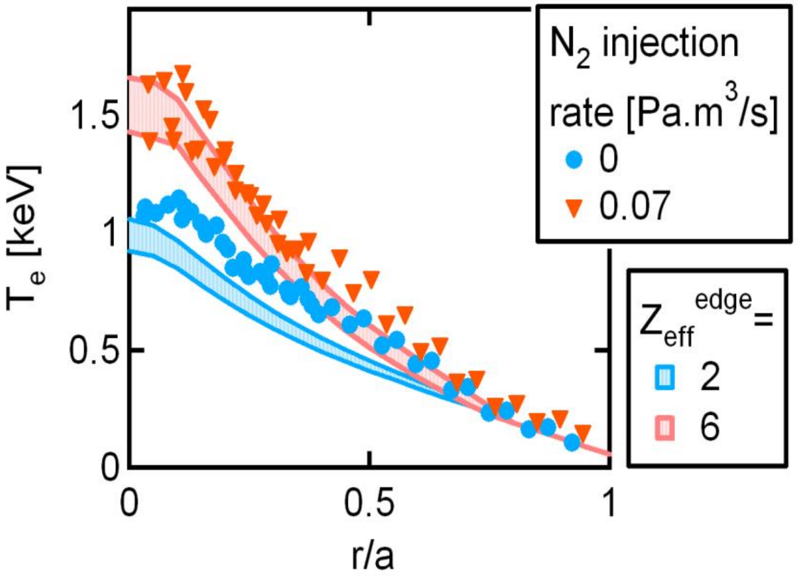


ExB velocity profiles from Doppler Reflectometry



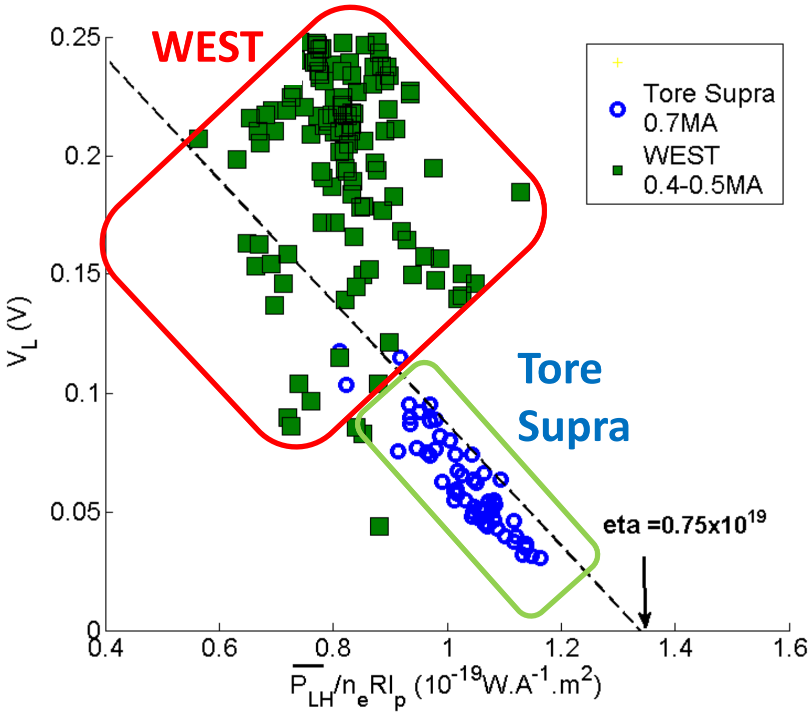
[Vermare'21]

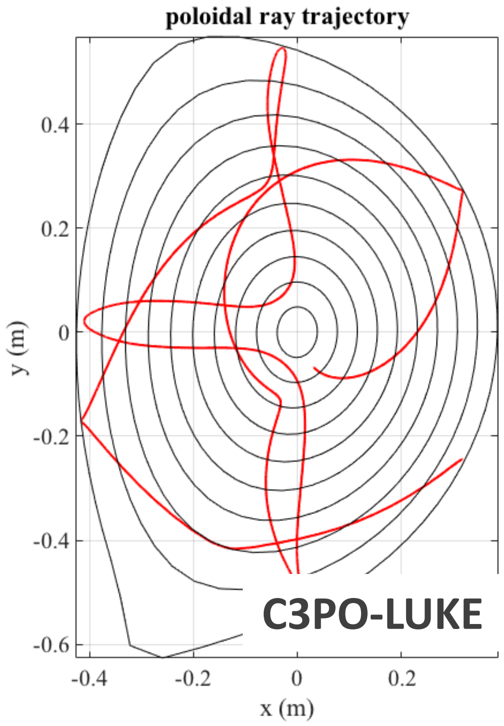
Electron temperature profiles from experiment (▼●) & Qualikiz

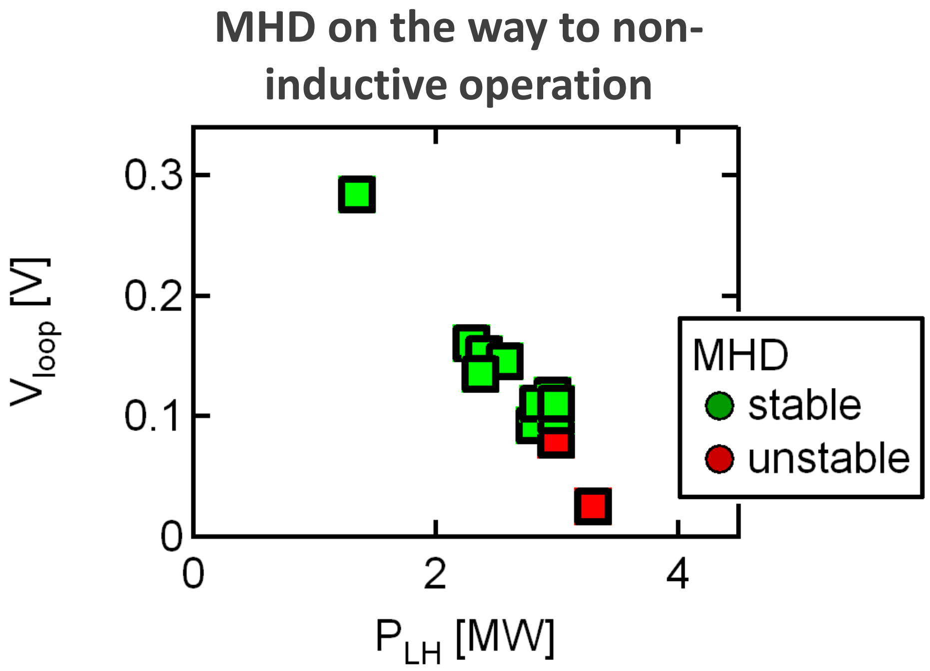


Lower Hybrid waves contribute to both electron heating & current drive

- **Large LH power gives access to non-inductive (unlimited) plasma discharges**
  - Current drive efficiency is a key issue: **LHCD code modeling** for WEST is essential
  - **Reconstructing LH heat deposition & current drive** from HXR measurement: tungsten enters into play
- **Non-inductive discharges are prone to MHD instabilities (Double-Tearing Mode)**
  - Hollow current profile leads to **fast magnetic reconnection**, core **confinement degradation** & **fast electron losses**





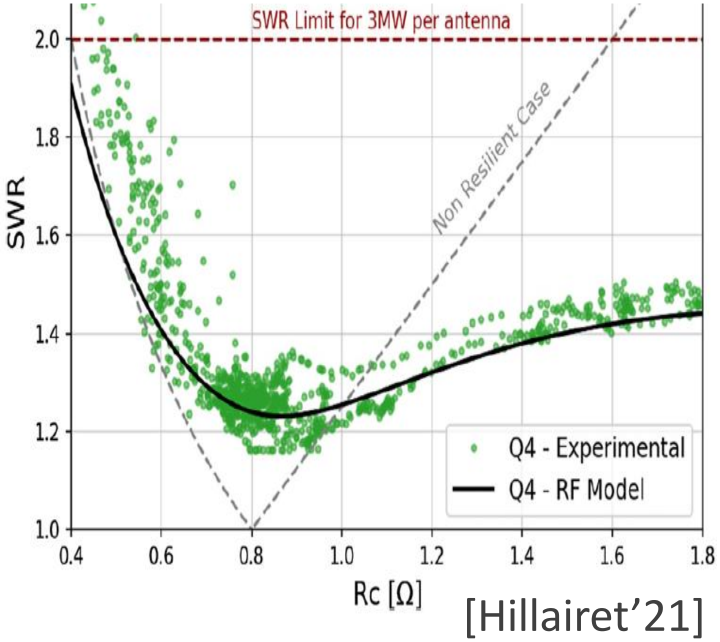


Key scientific achievements: RF heating – Ion Cyclotron Frequency

Ion Cyclotron Resonance Heating : load resilience, electron / ion heating & fast ion physics

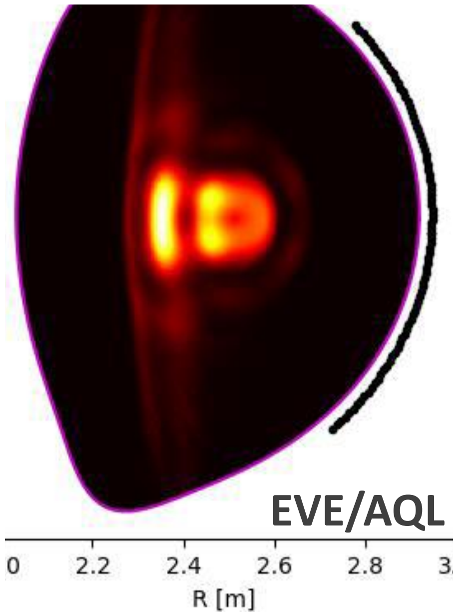
- **Load resilient antenna design : coupling still possible even during fast events (ELMs)**
- **Minority heating scheme tested so far: suprathermal hydrogen ions**
  - Wave coupling & Fokker-Planck codes: power deposition & ion/electron
  - Physics of **Finite Orbit Width** (FOW) and **ripple induced losses** are key to interpret experimental results
- **Observation of MHD modes driven by fast ions**

Load resilience of ICRH antennas



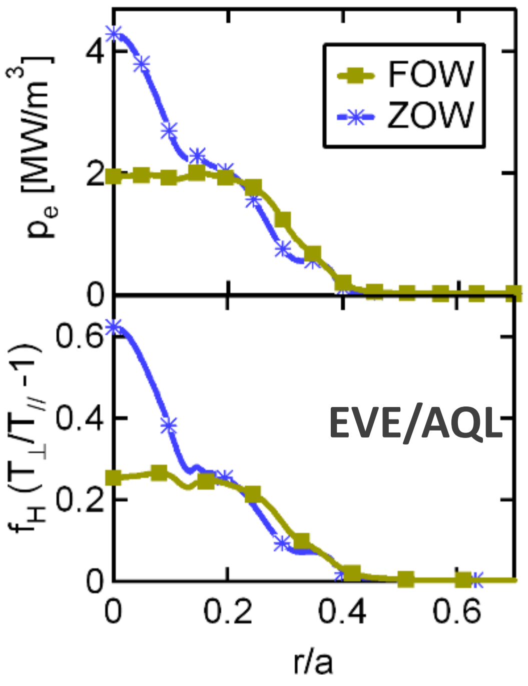
[Hillairet'21]

H damping [MW/m2]

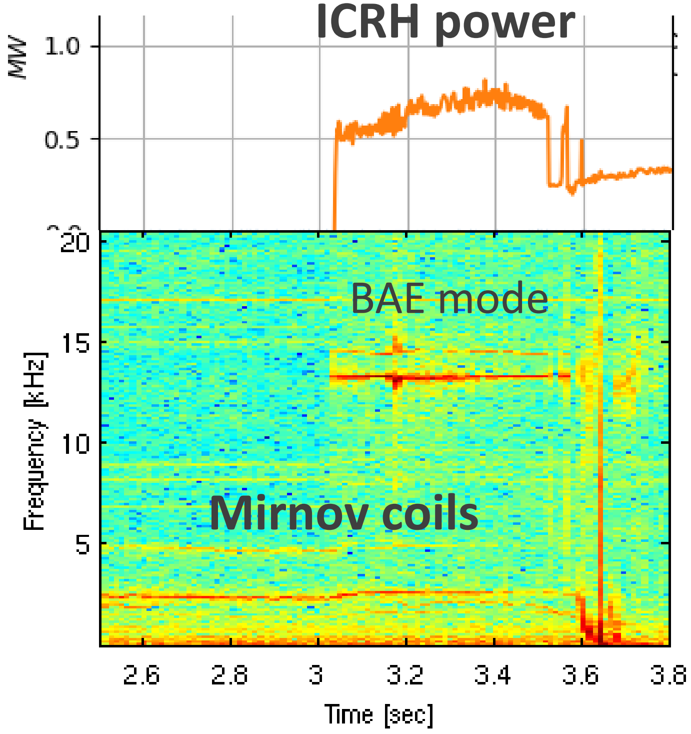


[Dumont'21]

Orbit Width effect



ICRH power



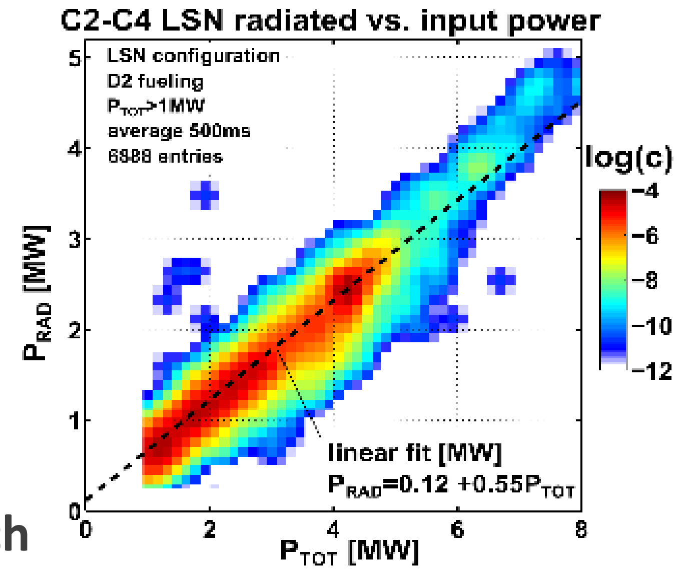
Key scientific achievements: tungsten identification & transport

Tungsten impurity is the main cause of radiative losses in the plasma core

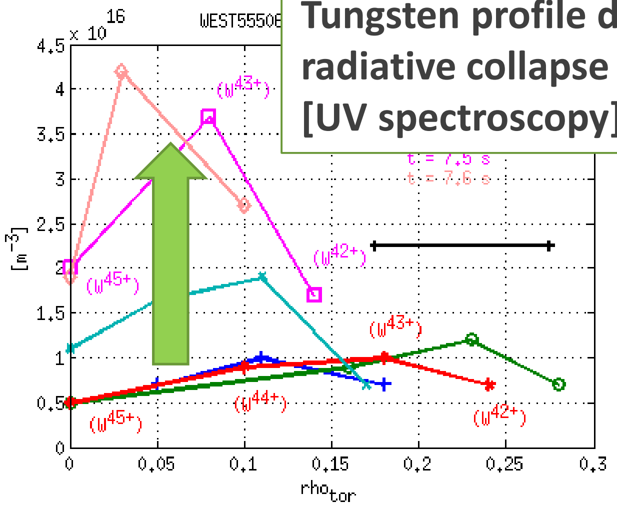
- The radiative fraction is typically around 50% of the heating power
  - Complex determination of the origin of tungsten atoms reaching confined plasma
- Bolometry, Soft X-ray and UV diagnostics used for profile determination

Tungsten transport has both turbulent and collisional components

- Collisional transport dominates in the core (and in the pedestal during H-mode)
  - Rotation and ICRH enhance collisional transport through poloidal asymmetries
- Tungsten peaking accelerates during radiative collapse through neoclassical pinch

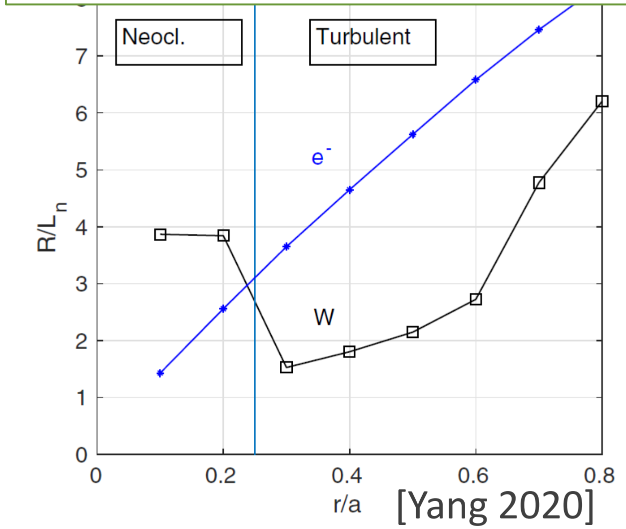


Tungsten profile during radiative collapse [UV spectroscopy]



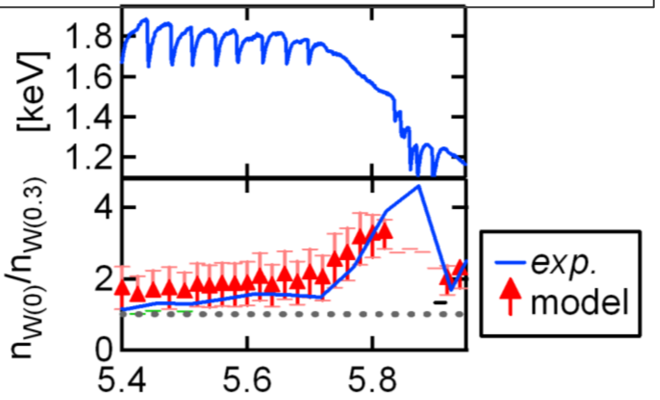
[Guirlet 2022]

Electron and tungsten peaking



[Yang 2020]

Radiative collapse during ICRH (FOW and ripple effects essential)



[Maget 2022]

Status of WEST enhancements

Next campaign with the complete ITER-like divertor (Phase 2 of WEST)

- 456 ITER-like actively cooled PFUs (400 new) : « New machine »
- Tungsten cycle (erosion, redeposition, contamination, structural evolution, …) in ITER-like conditions

Improved diagnostic coverage

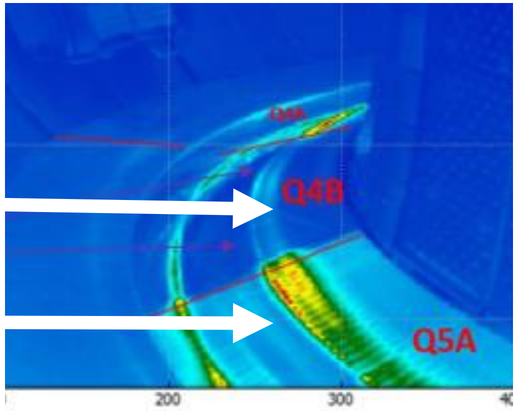
- With additional Multi-energy Soft X-ray & Hard X-ray (PPPL collaboration), and vertical bolometer
- First core Thomson scattering measurements next autumn

New actuator for wall conditioning & light impurity seeding : Impurity Powder Dropper (IPD)

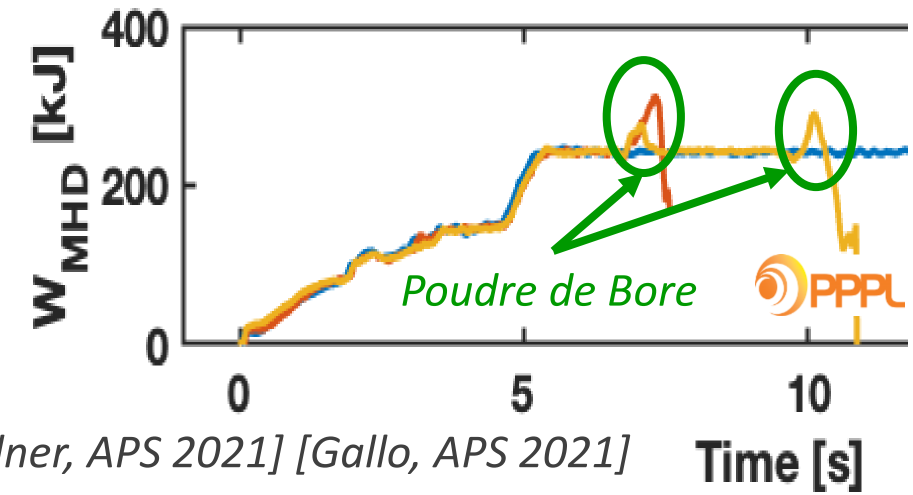
- First results in C5 campaign (2021): transient improved confinement
  - Evidence of wall conditioning as well

Cooled components

Inertial components



Expériences avec l'injecteur de poudre



[Bodner, APS 2021] [Gallo, APS 2021]

WEST timeline

Experimental campaign C6 in preparation

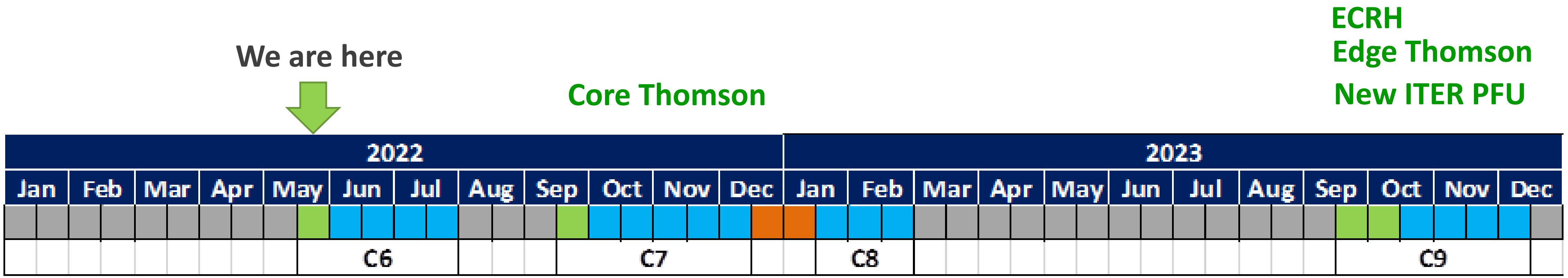
- Experiments planned until July 27th
- EUROfusion experiments (16 sessions)

C7 campaign will take place in autumn, C8 campaign early 2023

- Experimental program will include EUROfusion selected proposals submitted early May

Long shutdown in 2023 with major upgrades

- Electron Cyclotron Resonance Heating: key actuator for tungsten transport and MHD control
- Edge Thomson Scattering diagnostic : characterization of H-mode pedestal & transition between core & edge
- Installation of new ITER divertor units



Thanks for your attention

On-going works presented at regular Task Force Meetings – Thursdays 9h
Register to diffprogwest

https://westusers.partenaires.cea.fr

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