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UNDERSTANDING TUNGSTEN ACCUMULATION DURING ICRH OPERATION ON WEST



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[#] see <http://west.cea.fr/WESTteam>

48th EPS 2022 - Online
June 30th 2022
O4.114

The logo for the WEST tokamak project is shown in white on a red background. It features the word 'West' in a stylized font, with a yellow and orange flame-like graphic element above the 'e'.

Impurity peaking is a concern in tokamaks with metallic walls → core radiation

- ▶ Expected in presence of strong poloidal asymmetries [Angioni'14], mainly driven by :
 - Toroidal rotation (centrifugal force)
 - ICRH heating (electrostatic force)
- ▶ Operation on WEST : no external torque, no core particle source → ITER-relevant conditions
 - Several observations of radiative collapses
 - During LHCD [Ostuni, O4.113], LHCD+ICRH [Goniche'21], and *pure ICRH operation [this talk]*

ICRH impact tungsten profiles through 3 main channels

- ▶ Direct : electrostatic force
- ▶ Non-linear : effect of tungsten peaking on the electrostatic force (i.e. on the direct channel)
- ▶ Indirect : ICRH induced rotation

Modeling tungsten behavior in ICRH operation mobilizes a wide range of physics issues

- ▶ Finite Orbit Width (FOW) effects
- ▶ Fast Hydrogen Temperature Screening (HTS) effect [Casson'15,Casson'20]
- ▶ Ripple losses
- ▶ ... with consequences on the electrostatic force and electron heating

Context

A case of tungsten accumulation during ICRH operation on WEST

Physics of tungsten peaking with ICRH : the 3 channels

Tungsten peaking with ICRH and plasma rotation

Meeting the collapse condition

Summary and conclusion

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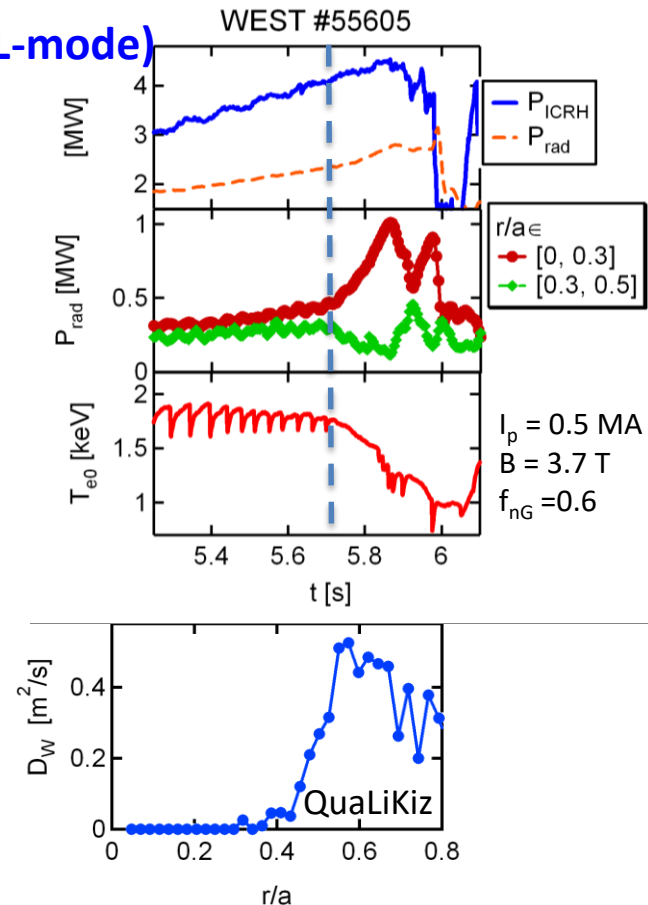
Summary and conclusion

Observation of tungsten accumulation & radiative collapse (L-mode)

- ▶ Core electron temperature falls above some ICRH power
- ▶ Bolometry inversion shows fast increase of core radiation
- ▶ Radiation peaking does not precede the collapse
 - Reversed temperature screening generates the large peaking

Modelling tools

- ▶ Equilibrium from **METIS** interpretative run [Artaud'18]
- ▶ ICRH deposition from **EVE/AQL** computations [Dumont'09 & '12]
- ▶ Turbulent transport computed with **QuaLiKiz** [Bourdelle'07]
 - Indicates nearly zero turbulent level inside $r/a=0.3$
- ▶ Collisional transport of tungsten → steady-state profile
 - **FACIT** [Maget'20&'22, Fajardo'22]: Fast tool, analytical
 - Includes neoclassical & classical transport
 - Does not cover Hydrogen Temperature Screening (HTS)
 - **NEO** [Bellì'08]: kinetic tool with accurate collision operator
 - Includes neoclassical transport only
 - Covers Hydrogen Temperature Screening (HTS)



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Direct channel : (horizontal) asymmetry of the electrostatic potential

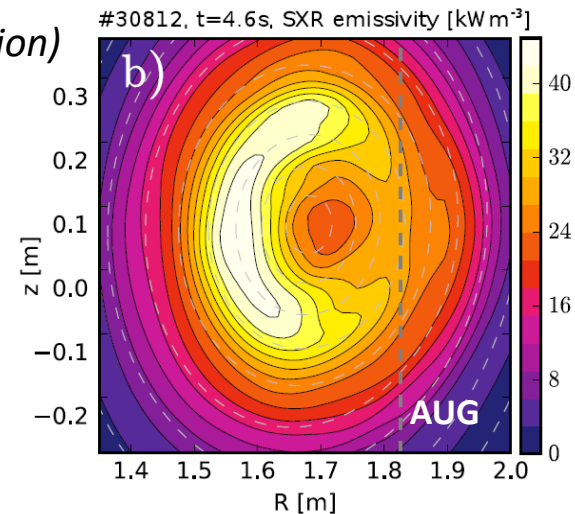
$$\delta\phi = \frac{\epsilon}{1 + Z_{eff}T_e/T_i} \left[f_H \left(\frac{T_{\perp}}{T_{\parallel}} - 1 \right) + m_i \frac{(R_0\Omega)^2}{T_i} \right]$$

ICRH drive

 $(f_H : \text{minority fraction})$

[Reinke'12]

- ▶ ICRH drives **High Field Side tungsten asymmetry**
- ▶ This direct drive is very sensitive to
 - **Finite Orbit Width (FOW)** effect
 - **Pitch angle scattering of hydrogen species on impurities**



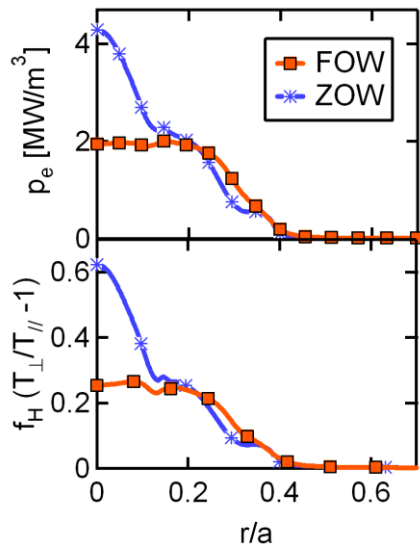
[Odstrcil'18]

Finite Orbit Width (FOW) effects reduce electron power source and temperature anisotropy

► Surrogate FOW model implemented in EVE

- Large orbits broaden the power deposition & temperature anisotropy profiles [Casson'20]
 - when compared to Zero Orbit Width (ZOW)

Finite Orbit Width (FOW) effect :



Less core electron heating

**Less temperature anisotropy
(reduction of the direct channel)**

Finite Orbit Width (FOW) effects reduce electron power source and temperature anisotropy

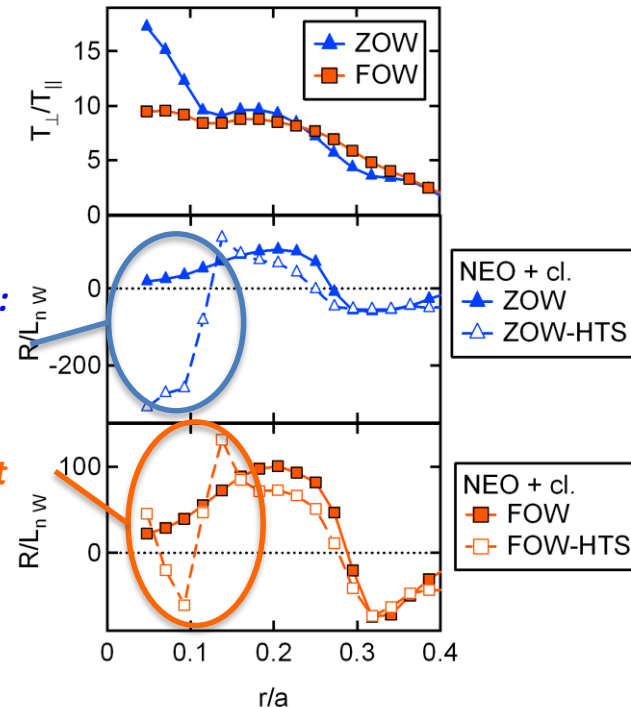
- ▶ Surrogate FOW model implemented in EVE: broad power & temperature anisotropy profiles

FOW effects reduce Hydrogen Temperature Screening (HTS)

- ▶ A negative radial gradient of T_{\perp} drives outward pinch [Casson'14]
- ▶ With FOW effect, reduced gradient \rightarrow reduced impact of HTS
- ▶ NEO computations confirms this
 - Large core tungsten removal in Zero Orbit Width (ZOW) limit
 - Not consistent with bolometry measurement
 - Small HTS effect in FOW limit
 - FACIT computation can be used

*Strong HTS effect:
Not consistent
with experiment*

Small HTS effect



Nonlinear channel: the parallel hydrogen temperature increases with Z_{eff}

- Pitch angle scattering of hydrogen species on impurities
- Parallel temperature increases with Z_{eff} [Stix'75]

$$T_{\parallel} \approx \frac{E_{\gamma}}{4}$$

$$E_{\gamma} \propto \left[\frac{2A_i^{1/2}}{n_e} \sum_{\beta} n_{\beta} Z_{\beta}^2 \right]^{2/3} T_e$$

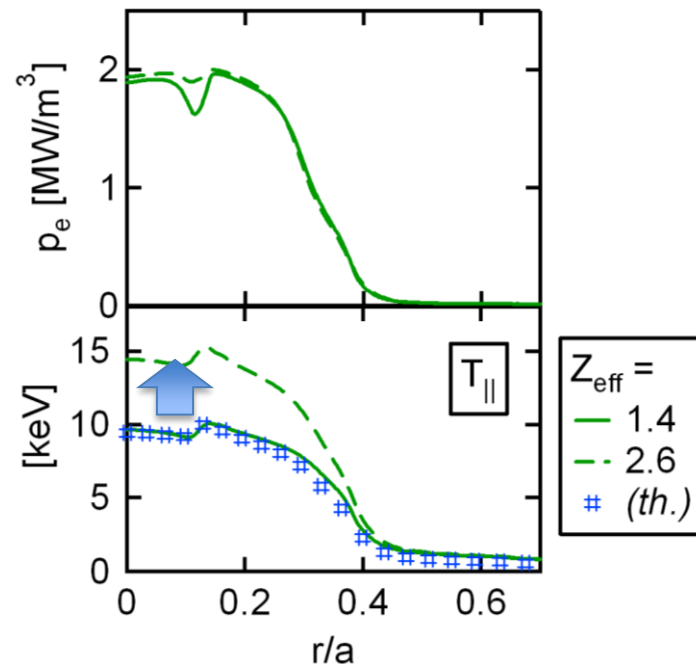
- EVE/AQL computations in good agreement with the formula :

$$T_{\parallel} = T_{\parallel}^0 [Z_{\text{eff}}]^{2/3}$$

- The electron heat source (p_e) is not modified
- *Tungsten accumulation reduces the direct ICRH drive*
- *Self-regulating mechanism*

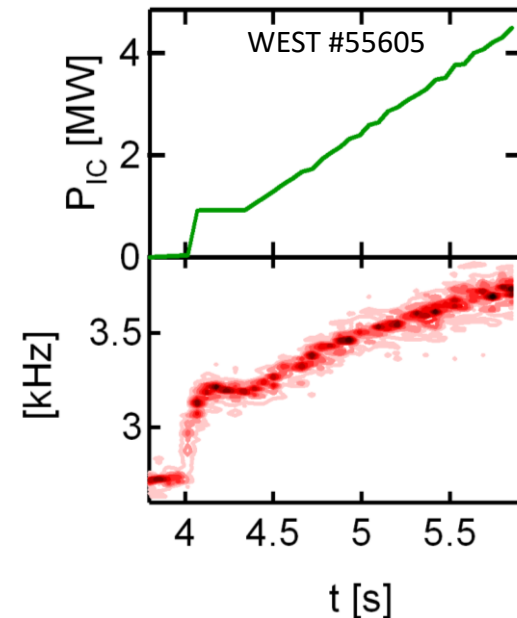
$$\frac{T_{\perp}}{T_{\parallel}}$$

- *This nonlinear channel has not been considered before*



Indirect channel : ICRH induced rotation

- ▶ WEST is a pure RF heated tokamak : no extrinsic momentum source
- ▶ ICRH induced rotation reported on tokamaks
 - Various physics mechanisms involved, difficult to disentangle [Rice'07]
 - **ICRH rotation spin up depends on the minority fraction** [Chouli'14]
 - Large counter rotation spin up at low f_H
 - Moderate co-rotation spin up at large f_H
- ▶ No core rotation measurement available for our experimental case
 - ICRH acceleration evidenced by MHD frequency measurement
 - located on $q=4$
 - Rotation measurements will be produced in future campaigns
 - *Here, toroidal rotation in the core is a free variable*
 - *Can be constrained indirectly by bolometry measurements*
 - *through P_{rad} and n_W at $r/a=0.3$*



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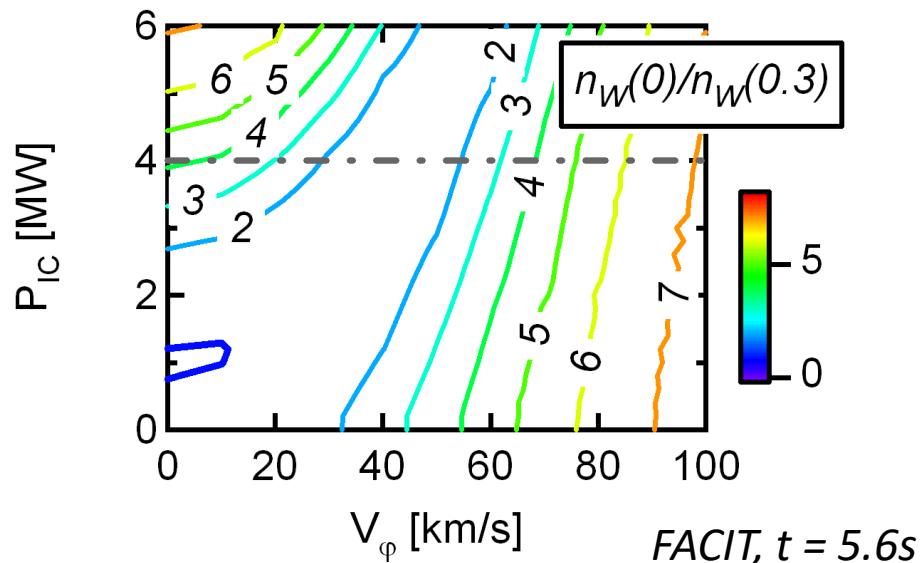
Tungsten peaking with ICRH and plasma rotation

Meeting the collapse condition

Summary and conclusion

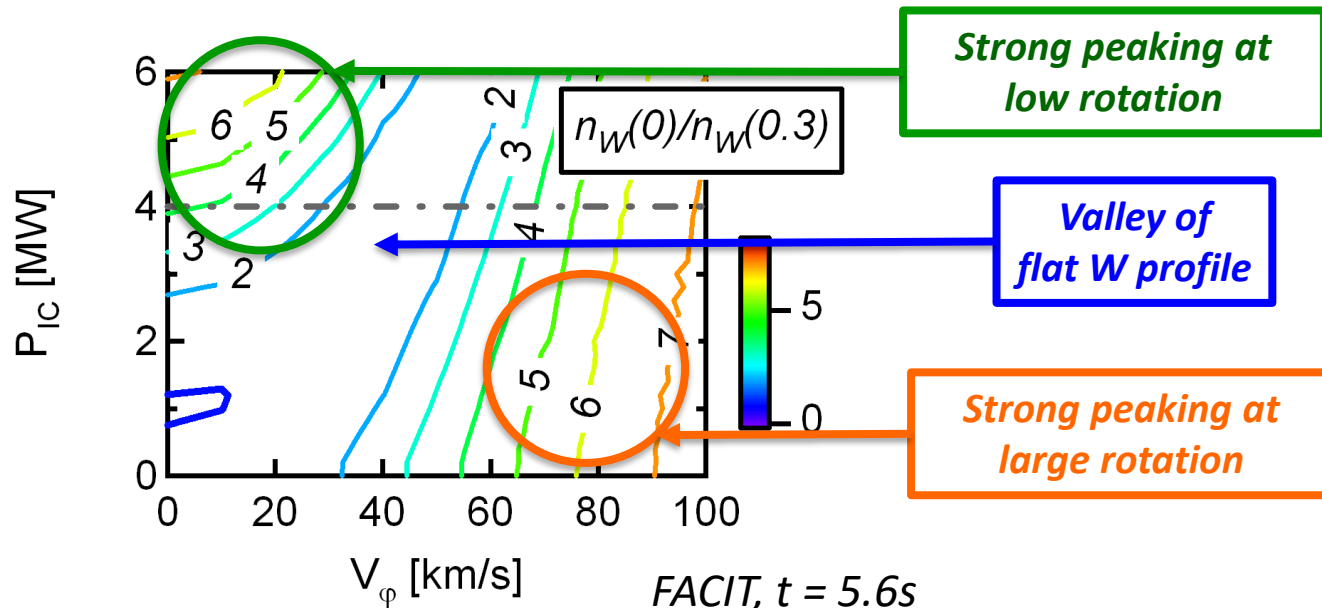
Map of tungsten peaking as a function of ICRH power and toroidal rotation (before collapse)

- Tungsten profile reconstructed in the collisional limit (no turbulence) with FACIT



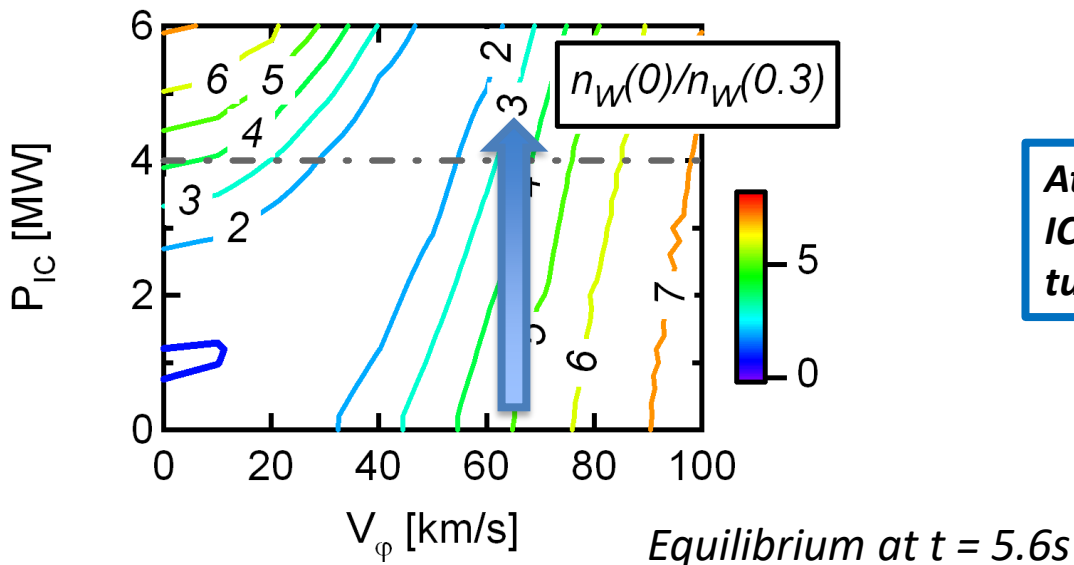
Map of tungsten peaking as a function of ICRH power and toroidal rotation (before collapse)

- ▶ Two regions of large tungsten peaking
 - At **low rotation** and **high ICRH power**
 - At **high rotation** and **moderate ICRH power**
- ▶ A valley of flat tungsten profile separates the two



Map of tungsten peaking as a function of ICRH power and toroidal rotation before collapse

- ▶ Two regions of large tungsten peaking
 - At **low rotation** and **high ICRH power**
 - At **high rotation** and **moderate ICRH power**
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*At high rotation,
ICRH reduces
tungsten peaking*

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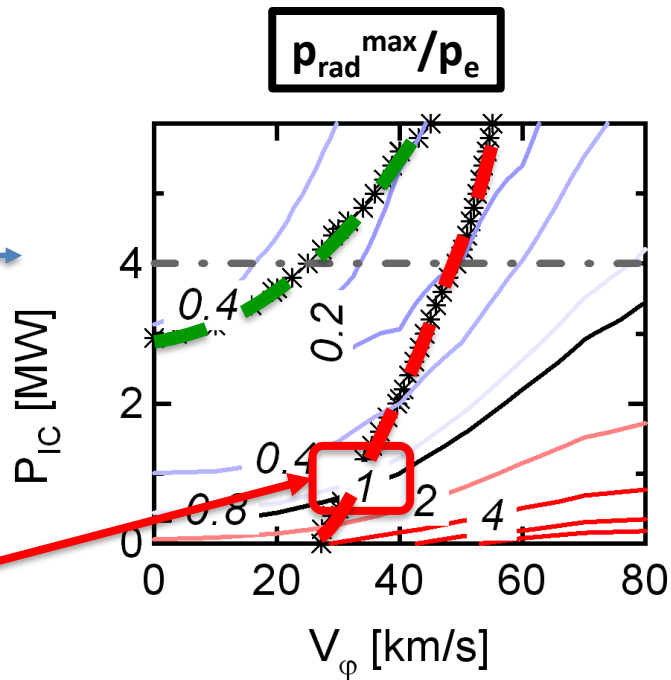
The collapse can be initiated if the electron heat source is balanced by radiation

- ▶ Tungsten profile → radiative power density, $P_{\text{rad}}(r/a=0.3)$, $p_{\text{rad}}^{\text{max}}$
- ▶ Electron heat source $p_e = p_e^{\Omega} + p_e^{\text{ICRH}}$
- ▶ Bolometry constraint on $P_{\text{rad}}(0.3)$: two branches (*)
 - **Low rotation**: tungsten peaking driven by ICRH
 - **Larger rotation**: tungsten peaking driven by centrifugal force
- ▶ Collapse condition is met on the **higher rotation branch only**
 - But **effective ICRH power must be lower than computed**
 - A reduction of p_e by more than 50% is required
 - The EVE/AQL results are then only indicative

Collapse criterion : $p_{\text{rad}}^{\text{max}}/p_e$

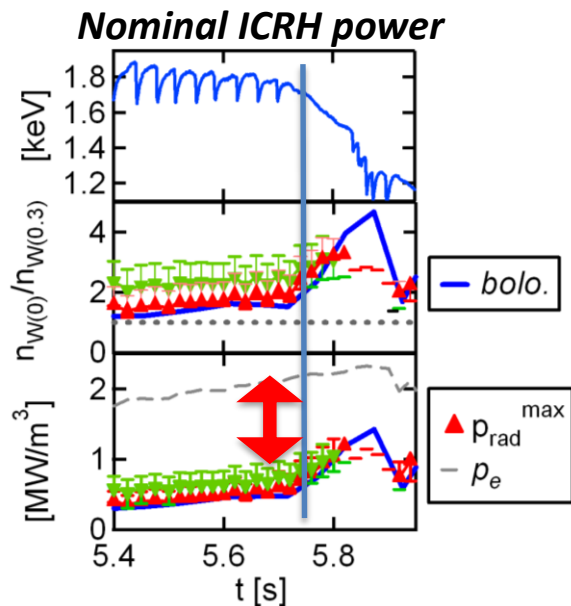
Injected ICRH power
4 MW

Area consistent with
imminent radiative
collapse

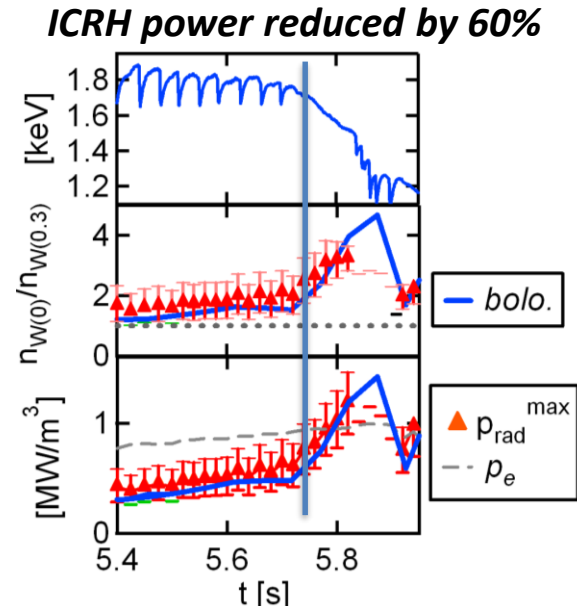


Collapse condition consistent with experiment if large reduction of effective ICRH power

- ▶ At nominal power the injected power on electrons is largely above the radiated power density
- ▶ With an artificial decrease by 60%, the collapse condition is met at $t = 5.75\text{s}$ as observed
 - Only the “high” velocity branch remains
- ▶ Large losses of fast minority ions in the ripple could explain this situation (on-going investigations)



∇ : low velocity branch
 \blacktriangle : high velocity branch



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Radiative collapse are key events for quantifying heat sources & sinks

- ▶ Of particular importance for developing robust heating schemes in tungsten environment

ICRH is a potential drive for tungsten accumulation

- ▶ Due to the induced poloidal asymmetry of the electrostatic potential

ICRH drive is modified by several effects

- ▶ Finite Orbit Widths : Reduced Hydrogen Temperature Screening & broader deposition
- ▶ Non-linear mitigation by the increase of the parallel hydrogen temperature (*new mechanism*)
- ▶ Induced toroidal rotation

ICRH impact on W transport in torque-free discharges, no core particle source

- ▶ Overall tungsten peaking is moderate (except in collapse phases)
 - on WEST, as well as on Alcator C-Mod [Loarte'15]
- ▶ The low rotation branch (ICRH-driven tungsten peaking) remains possibly unexplored
 - non-linear mitigation sufficient to prevent operational limitations ?



Thank you for your attention

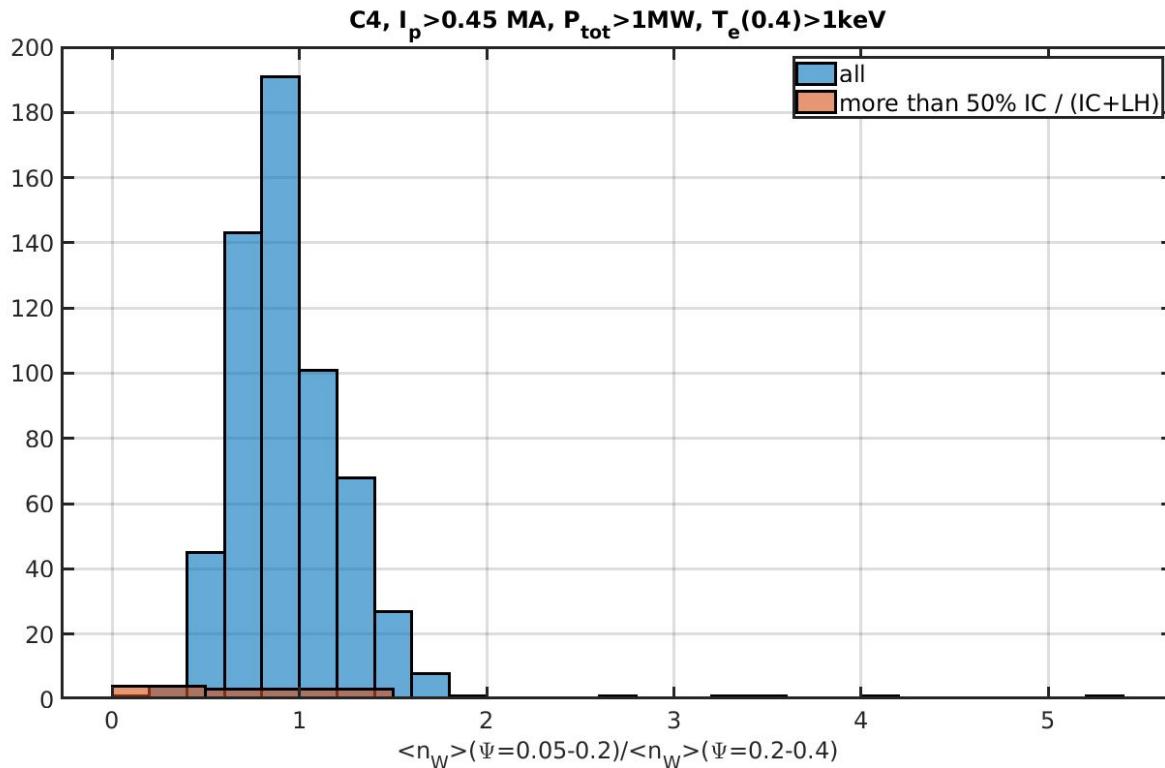
Contact: patrick.maget@cea.fr

<https://westusers.partenaires.cea.fr>



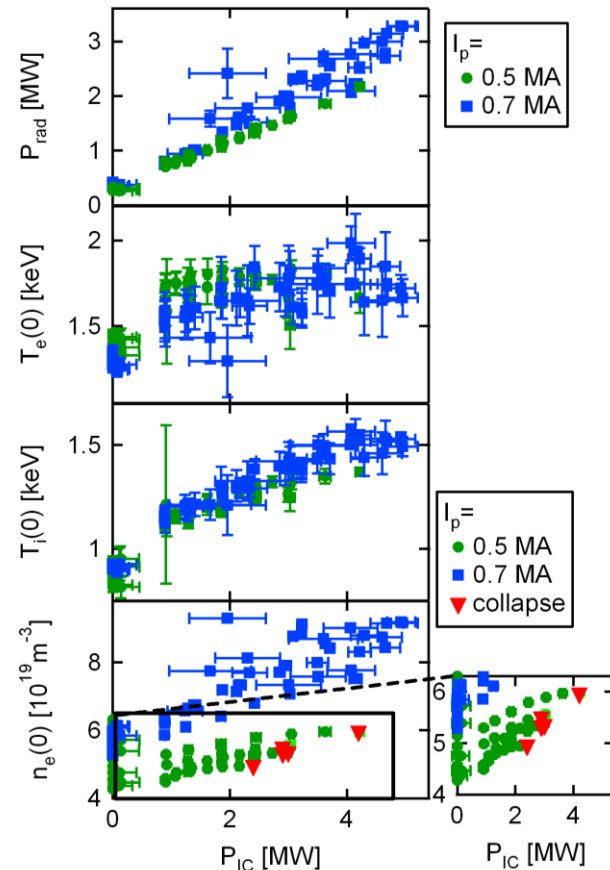
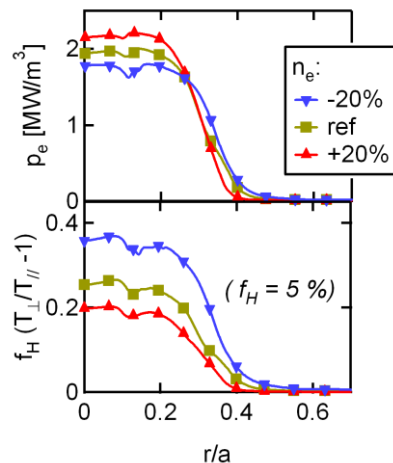
Histogram of tungsten peaking in WEST database

- Plateaus database (see Ostuni O4.113, this conference)



Mitigation of collapses at higher density & higher current

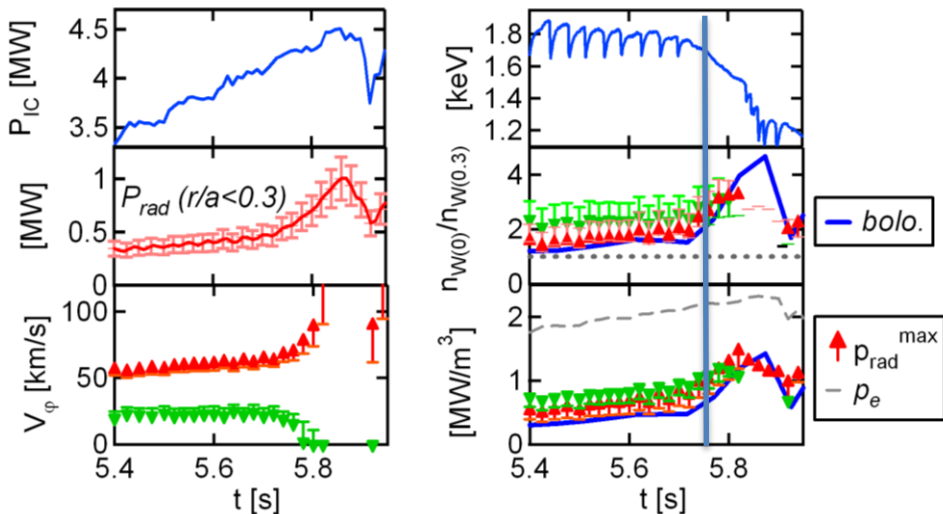
- ▶ Series of experiments at 0.5 and 0.7 MA
- ▶ Higher density allows operating at higher ICRH power without radiative collapse
 - EVE/AQL indicates larger core electron heating & lower ICRH drive
 - Qualitatively favorable for lowering ripple losses & tungsten sources
- ▶ Larger plasma current could also be favorable
 - Larger good confinement region with respect to ripple losses



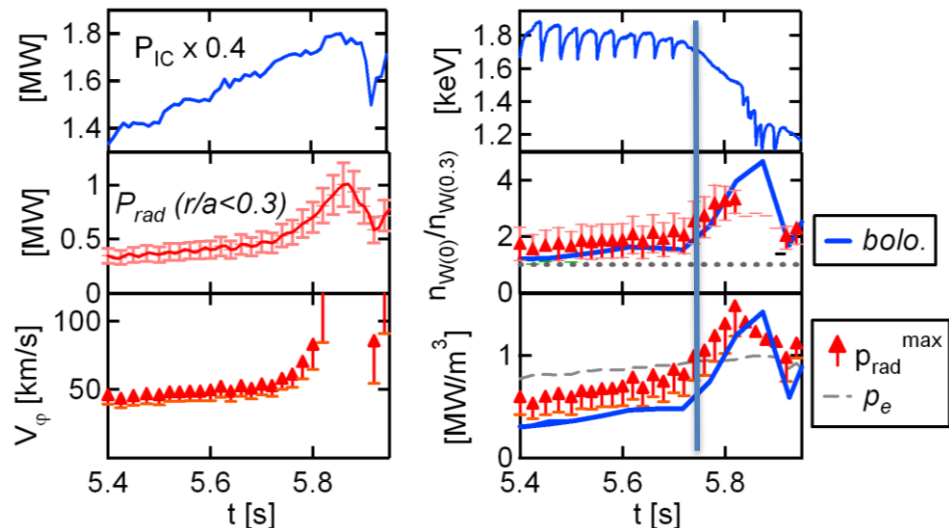
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Nominal ICRH power



ICRH power reduced by 60%



Mechanisms leading to an accelerated Tungsten accumulation

- ▶ Response of the Tungsten profile to a decrease of the ion temperature gradient
- ▶ Accelerated radiative collapse :
 - when a hollow temperature leads to a larger Tungsten peaking
 - Otherwise, the collapse is mitigated
- ▶ The collapse process is favored at low rotation

$$T_e(x) = T_e^{ref}(x) \times (1 - \gamma \exp(-30x^2))$$

$$T_i(x) = T_i^{ref}(x) \times (1 - (\gamma/2) \exp(-30x^2))$$

