

UNDERSTANDING TUNGSTEN ACCUMULATION DURING ICRH OPERATION ON WEST

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Patrick Maget, Pierre Manas, Rémi Dumont, Clemente Angioni, Jean François Artaud, et al.. UNDERSTANDING TUNGSTEN ACCUMULATION DURING ICRH OPERATION ON WEST. 48th EPS conference on plasma physics, Jun 2022, On line, France. cea-03736601

HAL Id: cea-03736601

https://cea.hal.science/cea-03736601

Submitted on 22 Jul 2022

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UNDERSTANDING TUNGSTEN ACCUMULATION DURING ICRH OPERATION ON WEST

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

Context

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**

Outline

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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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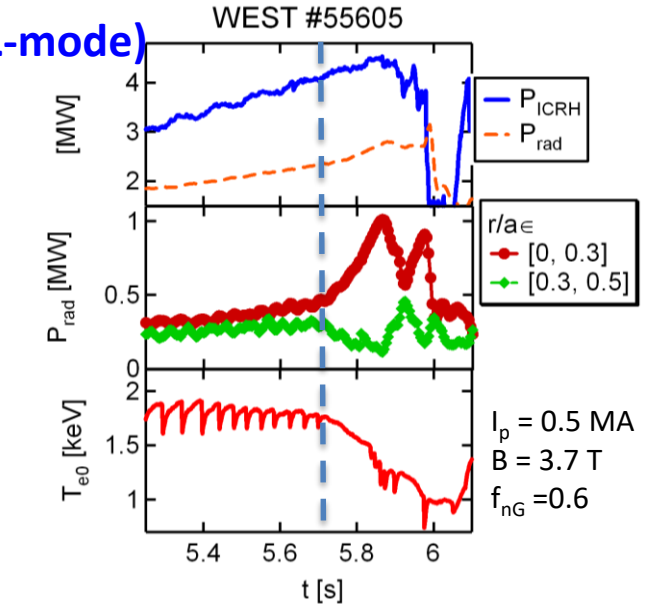
A case of tungsten accumulation during ICRH operation on WEST

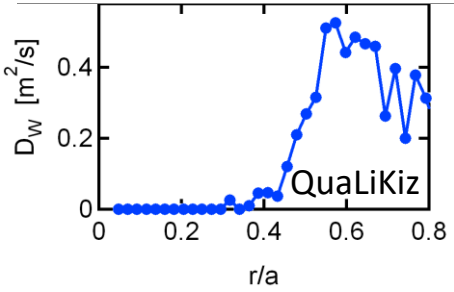
Observation of tungsten accumulation & radiative collapse (L-mode)

- **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** [Belli'08]: kinetic tool with accurate collision operator
    - Includes neoclassical transport only
    - Covers Hydrogen Temperature Screening (HTS)





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Physics of tungsten peaking with ICRH : the 3 channels (1/3: direct)

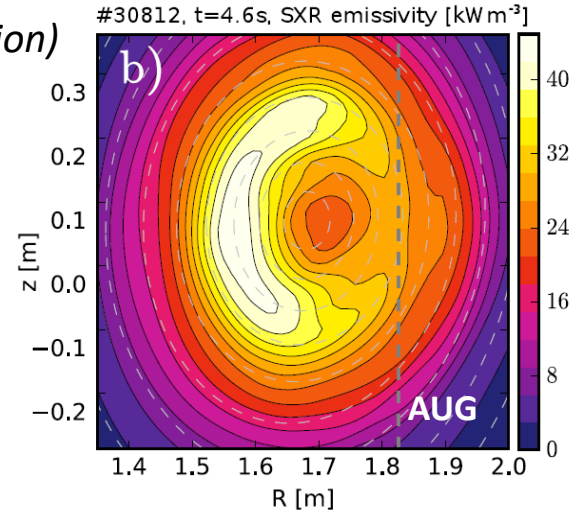
Direct channel : (horizontal) asymmetry of the electrostatic potential

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

ICRH drive

[Reinke'12]

(f_H : minority fraction)



[Odstrcil'18]

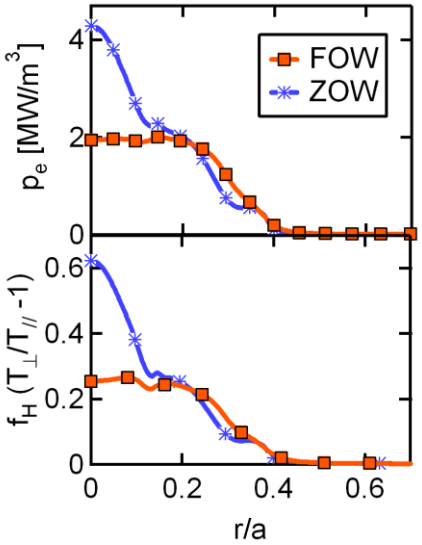
- **ICRH drives High Field Side tungsten asymmetry**
- **This direct drive is very sensitive to**
  - **Finite Orbit Width** (FOW) effect
  - **Pitch angle scattering of hydrogen species on impurities**

Physics of tungsten peaking with ICRH : the 3 channels (1/3: direct)

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)

Physics of tungsten peaking with ICRH : the 3 channels (1/3: direct)

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

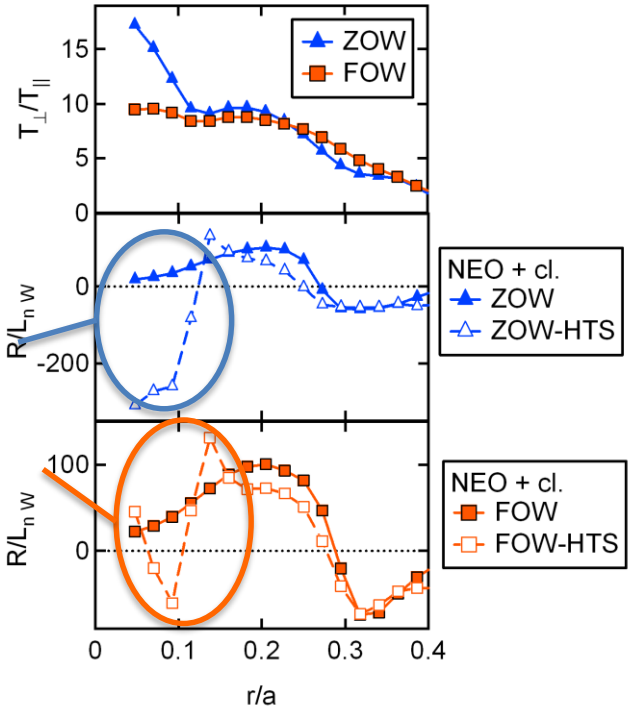
- **Surrogate FOW model implemented in EVE: broad power & temperature anisotropy profiles**

FOW effects reduce Hydrogen Temperature Screening (HTS)

- **A negative radial gradient of $T_\perp$ drives outward pinch [Casson'14]**
- **With FOW effect, reduced gradient → 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



Physics of tungsten peaking with ICRH : the 3 channels (2/3: nonlinear)

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]

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

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

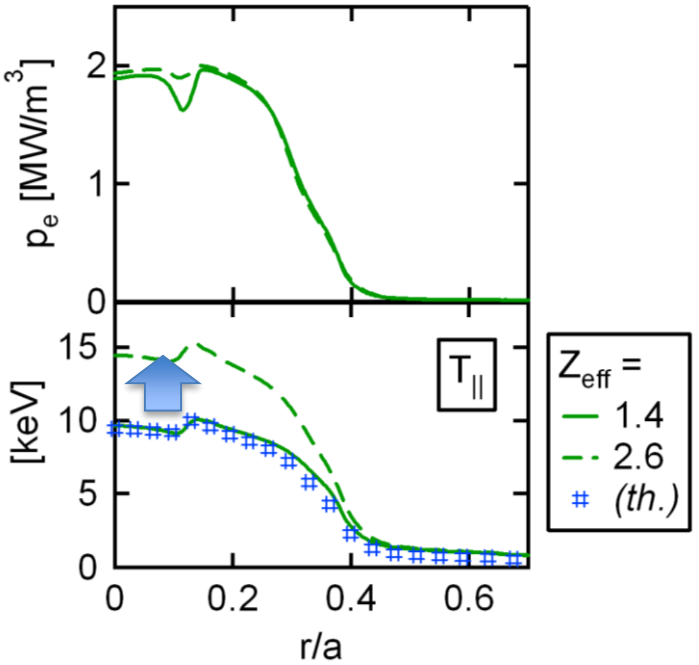
- EVE/AQL computations in good agreement with the formula :

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

- 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*

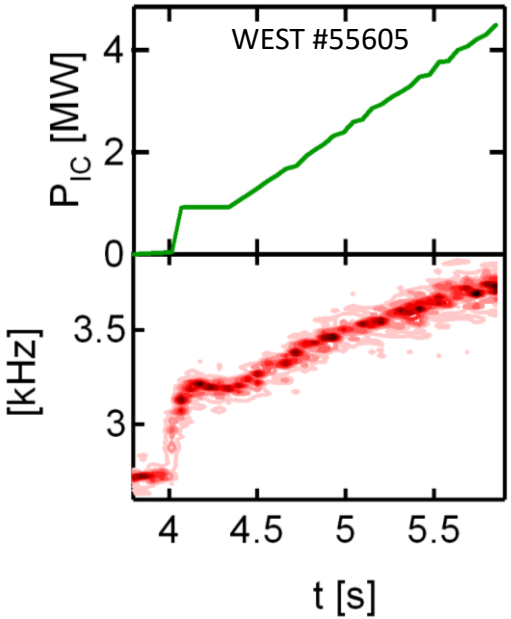


Physics of tungsten peaking with ICRH : the 3 channels (3/3 : indirect)

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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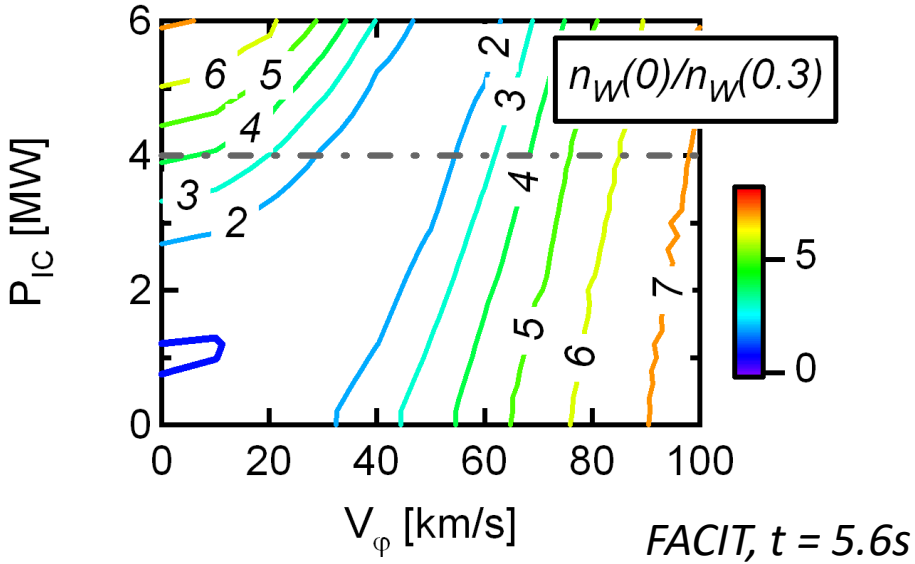
Meeting the collapse condition

Summary and conclusion

Tungsten peaking with ICRH and plasma rotation

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

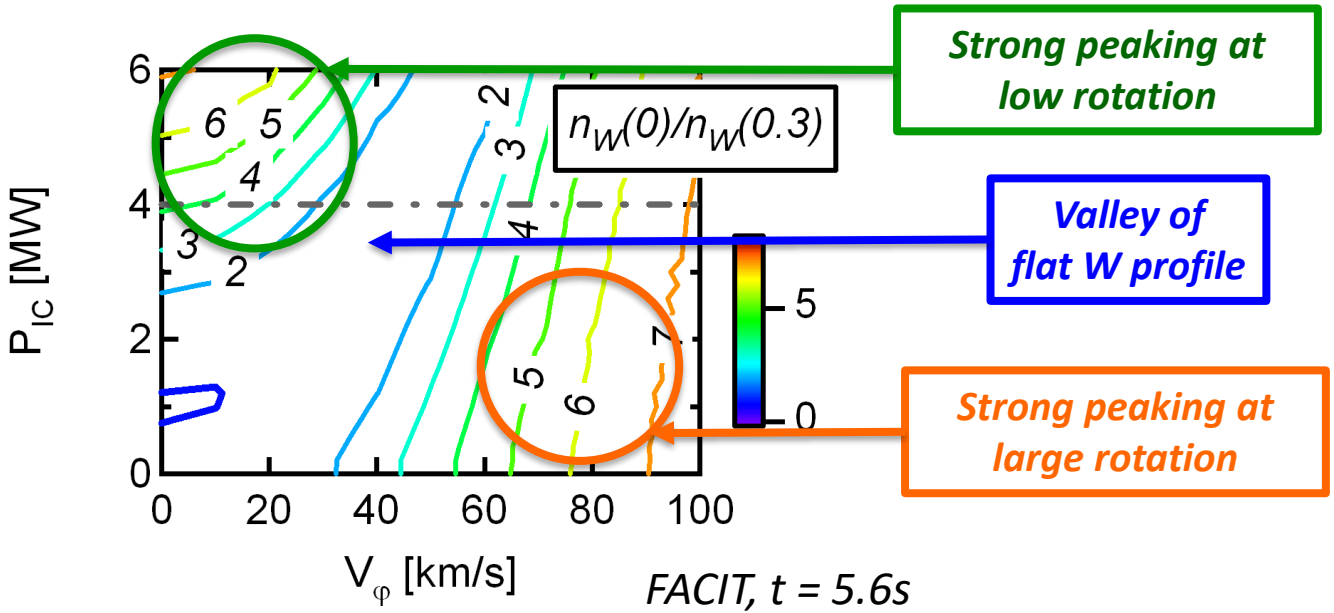
- **Tungsten profile reconstructed in the collisional limit (no turbulence) with FACIT**



Tungsten peaking with ICRH and plasma rotation

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

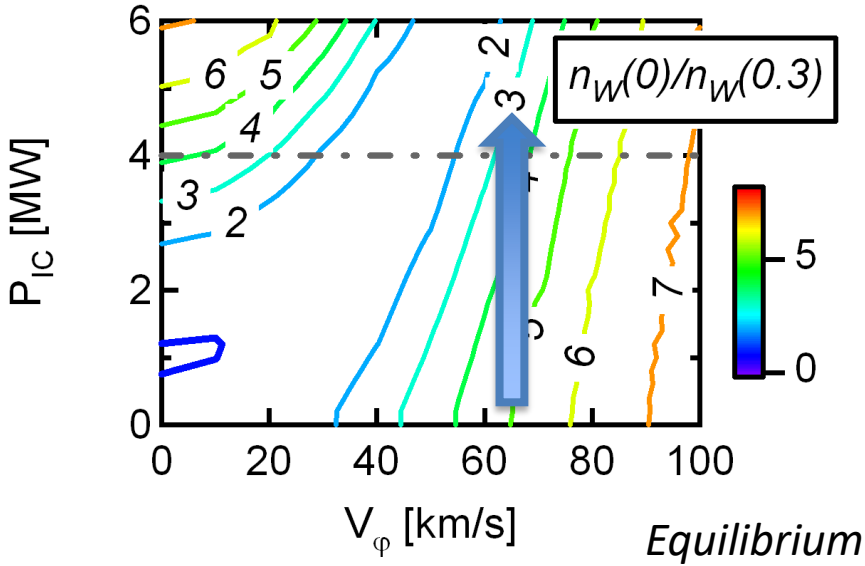
- **Two regions of large tungsten peaking**
  - At **low rotation** and **high ICRH power**
  - At **high rotation** and **moderate ICRH power**
- **A valley of flat tungsten profile separates the two**



Tungsten peaking with ICRH and plasma rotation

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**



At high rotation, ICRH reduces tungsten peaking

Equilibrium at t = 5.6s

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

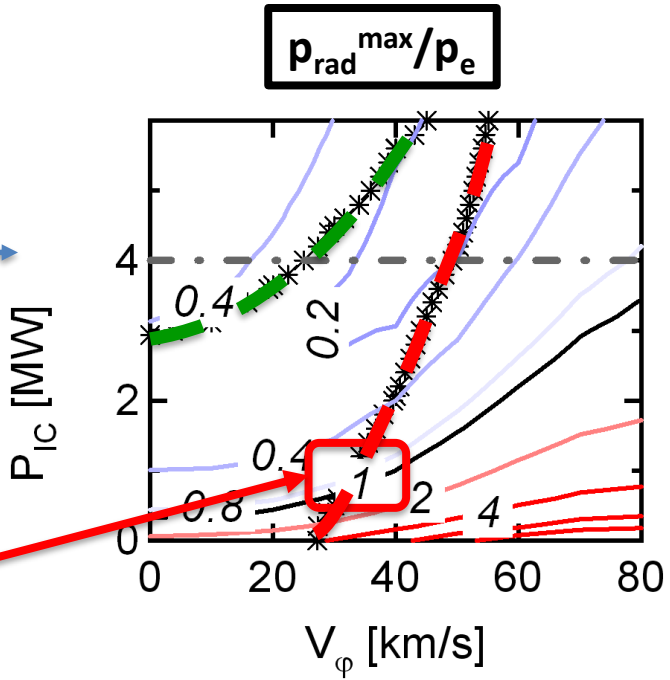
- **Tungsten profile → radiative power density, $P_{rad}(r/a=0.3)$, p_{rad}^{max}**
- **Electron heat source $p_e = p_e^{\Omega} + p_e^{ICRH}$**
- **Bolometry constraint on $P_{rad}(0.3)$: two branches (*)**
  - **Low rotation**: tungsten peaking driven by ICRH
  - **Larger rotation**: tungsten peaking driven by centrifugal force

Collapse criterion : p_{rad}^{max}/p_e

- **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

Injected ICRH power 4 MW

Area consistent with imminent radiative collapse

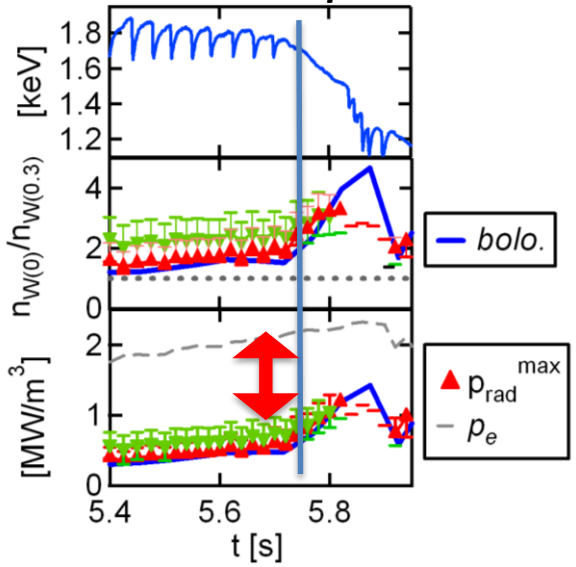


Meeting the collapse condition

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

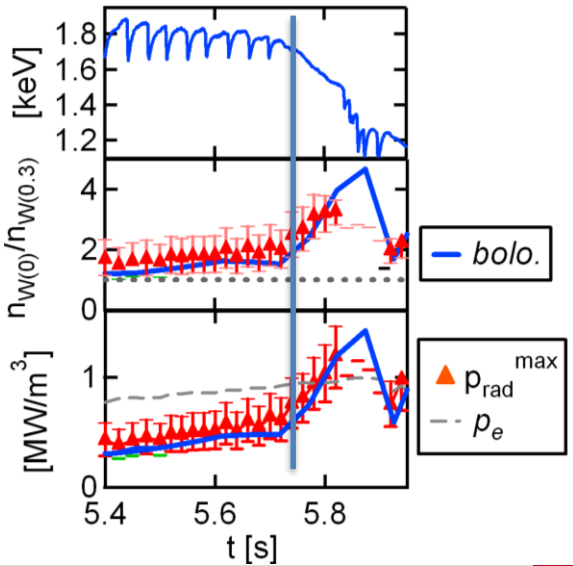
- **At nominal power the injected power on electrons is largely above the radiated power density**
- **With an artificial decrease by 60%, the collapse condition is met at t = 5.75s as observed**
  - Only the “high” velocity branch remains
- **Large losses of fast minority ions in the ripple could explain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

Nominal ICRH power



▼ : low velocity branch
▲ : high velocity branch

ICRH power reduced by 60%



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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

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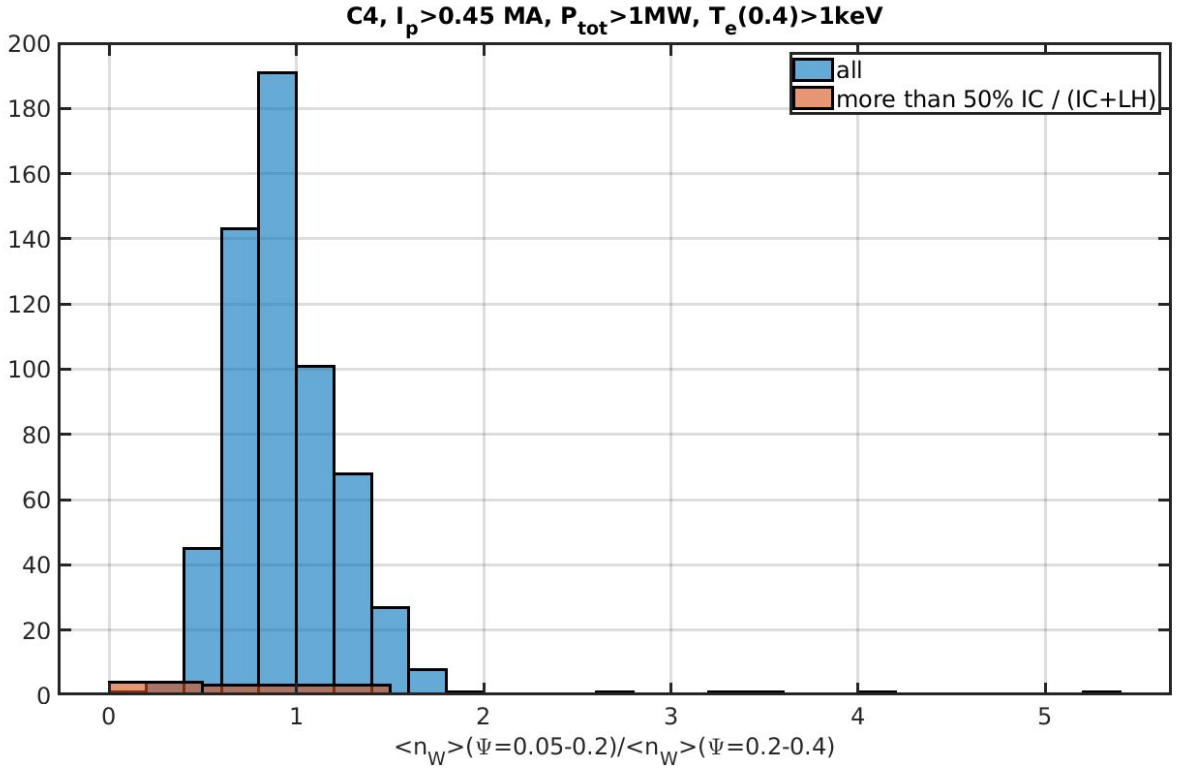






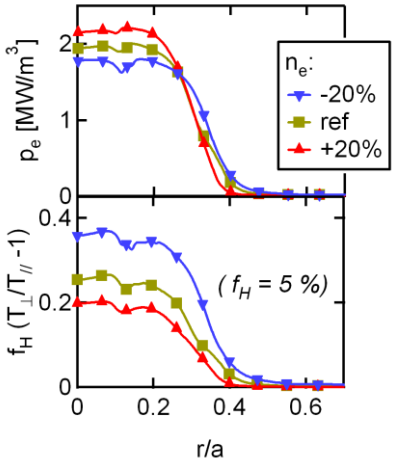
Histogram of tungsten peaking in WEST database

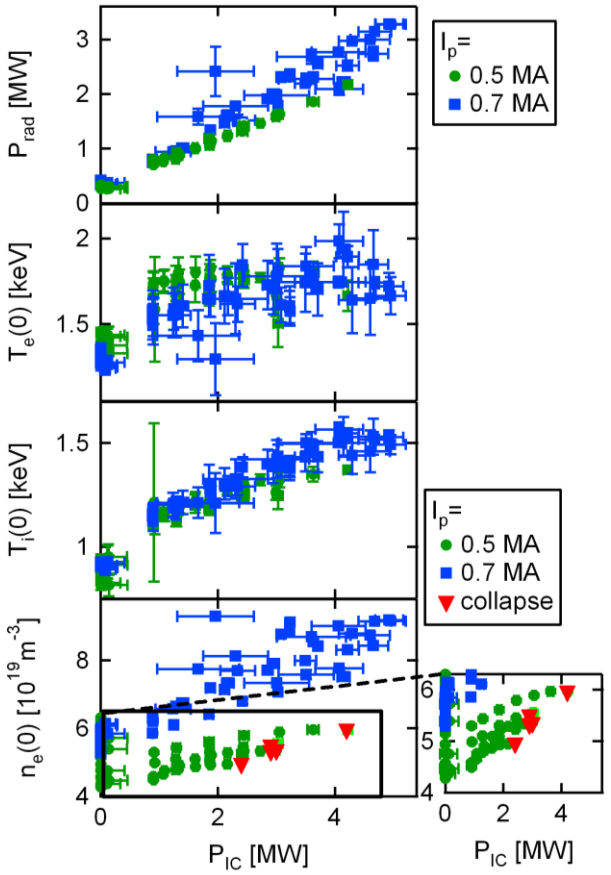
- **Plateaus database (see Ostuni O4.113, this conference)**



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



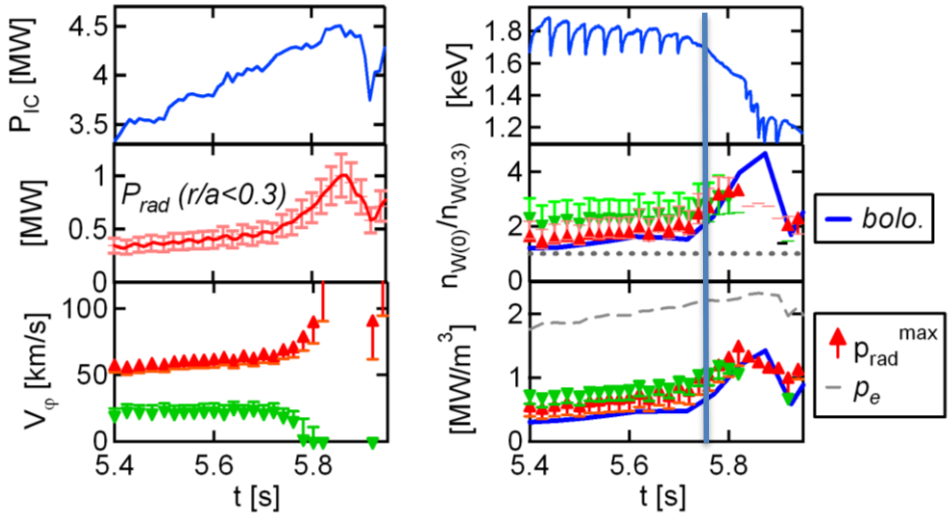


Meeting the collapse condition : reduced effective ICRH power

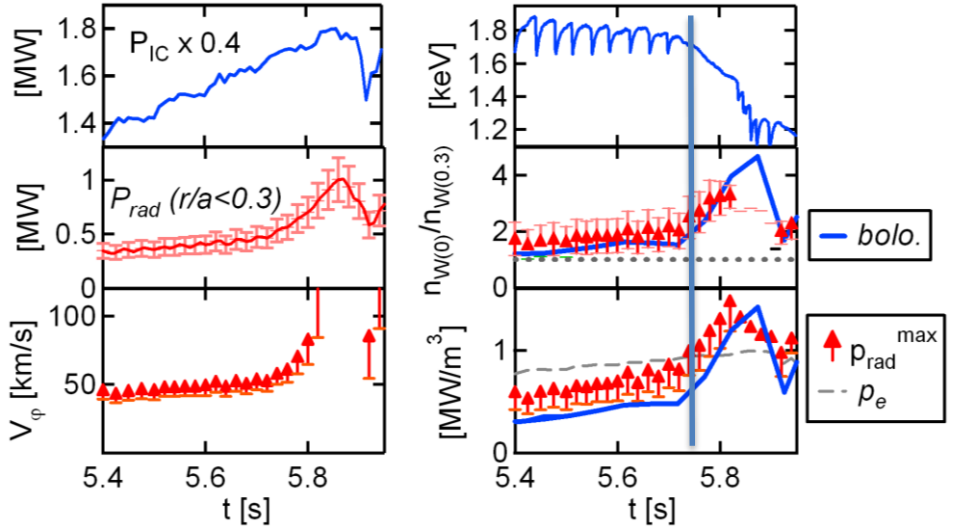
Collapse condition consistent with experiment if large reduction of effective ICRH power

- 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 = 5.75s as observed

Nominal ICRH power



ICRH power reduced by 60%



Understanding the temperature collapse

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**

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

