UNDERSTANDING TUNGSTEN ACCUMULATION DURING ICRH OPERATION ON WEST

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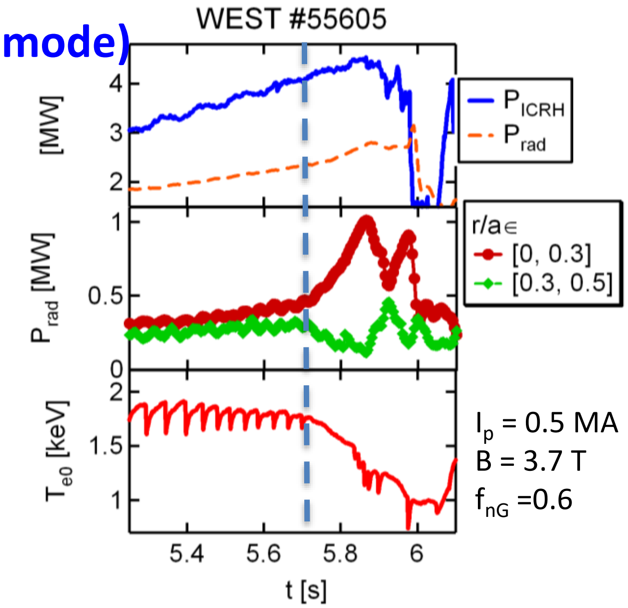
Observation of tungsten accumulation & radiative collapse (L-mode)

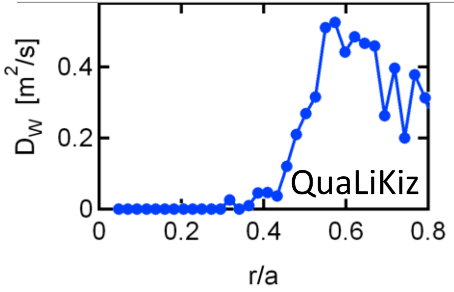
- **Core electron temperature falls above some ICRH power**
- **Bolometry inversion shows fast increase of core radiation**
- **Radiation peaking does not precede the collapse**
  - Reversed temperature screening generates the large peaking



I_p = 0.5 MA
B = 3.7 T
f_{nG} =0.6

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

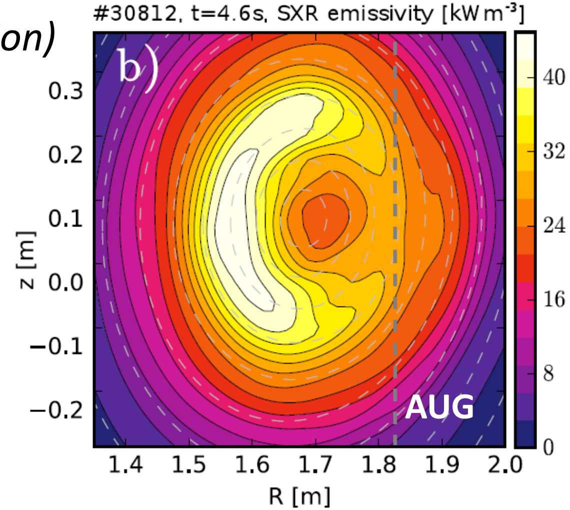
$$\delta_\phi = \frac{\epsilon}{1 + Z_{eff} T_e/T_i} \left[\boxed{f_H \left(\frac{T_\perp}{T_\parallel} - 1 \right)} + m_i \frac{(R_0 \Omega)^2}{T_i} \right]$$

[Reinke’12]

ICRH drive

(f_H : minority fraction)

- **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**



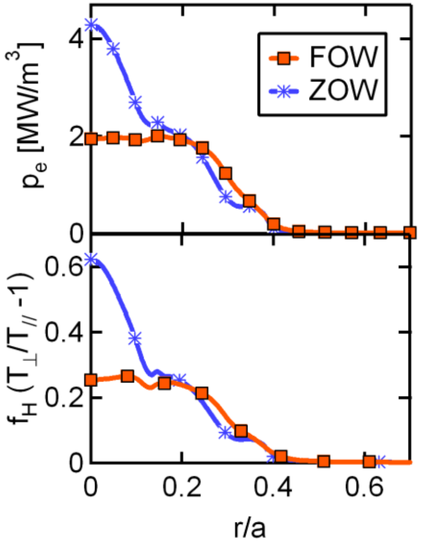
[Odstrcil’18]

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)

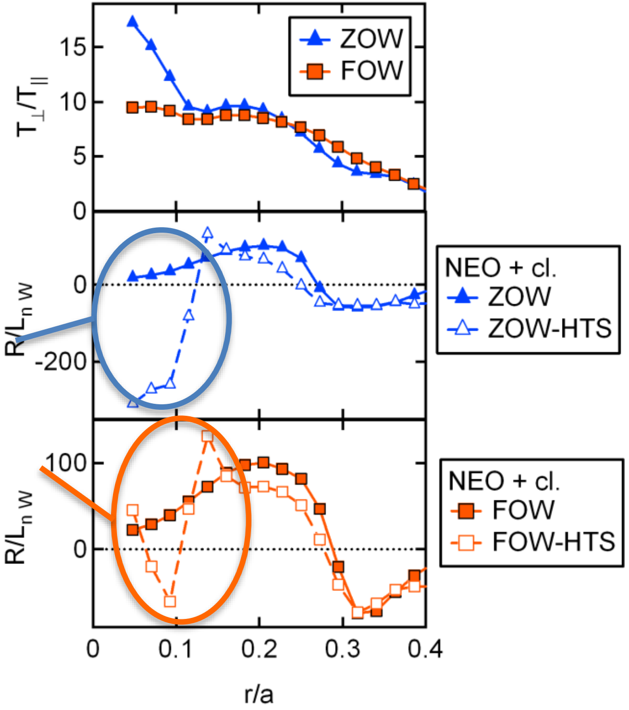
Physics of tungsten peaking with ICRH : the 3 channels (1/3: direct)

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]

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

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

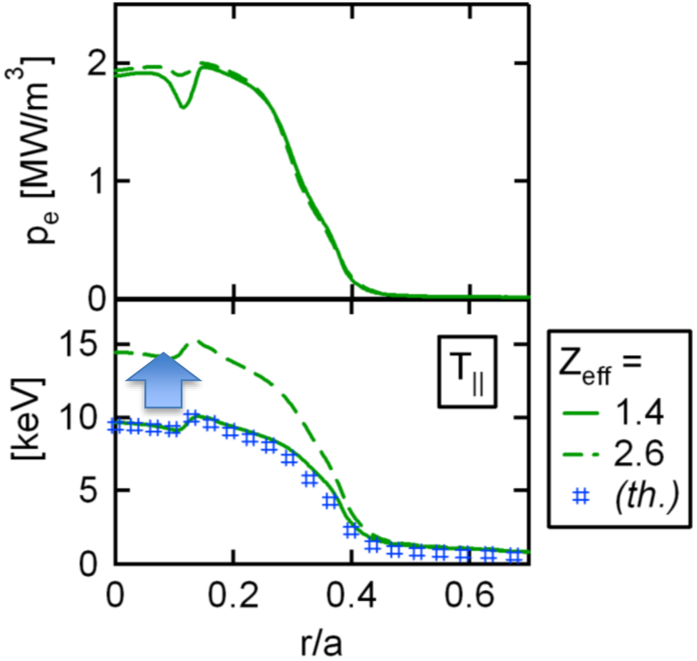
- EVE/AQL computations in good agreement with the formula :

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

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

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

- *This nonlinear channel has not been considered before*

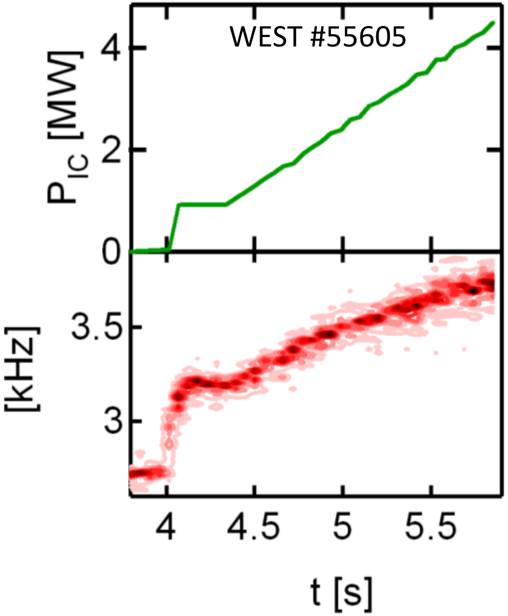


Physics of tungsten peaking with ICRH : the 3 channels (3/3 : indirect)

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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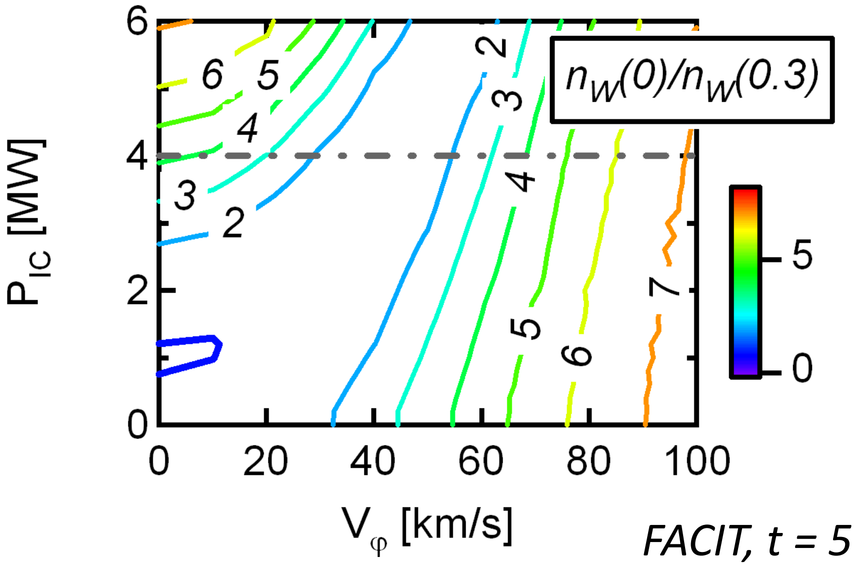
Tungsten peaking with ICRH and plasma rotation

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**

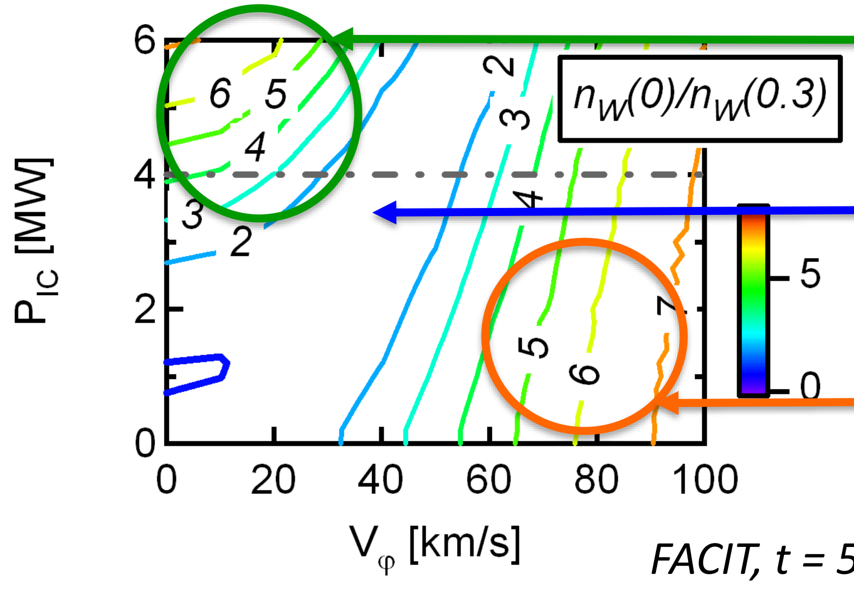


FACIT, t = 5.6s

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**



Strong peaking at low rotation

Valley of flat W profile

Strong peaking at large rotation

FACIT, t = 5.6s

Tungsten peaking with ICRH and plasma rotation

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

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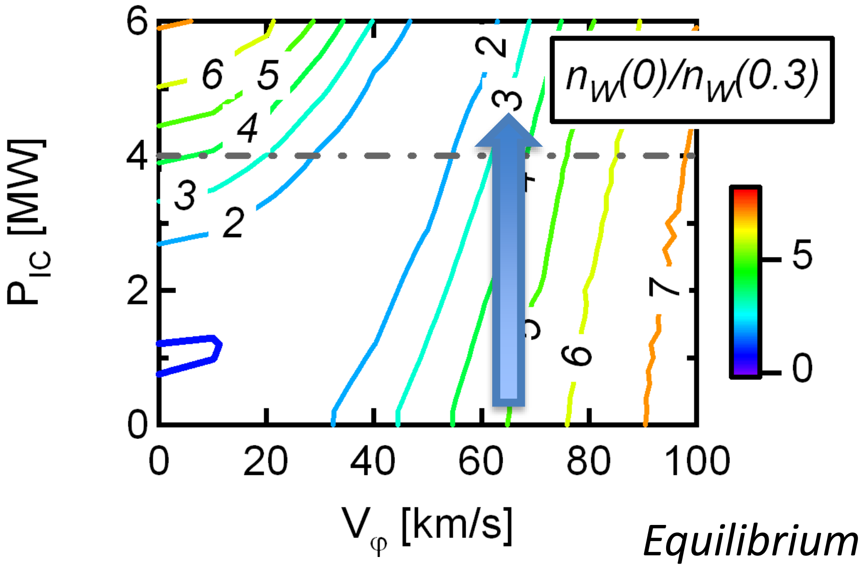

At high rotation, ICRH reduces tungsten peaking

Equilibrium at t = 5.6s

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

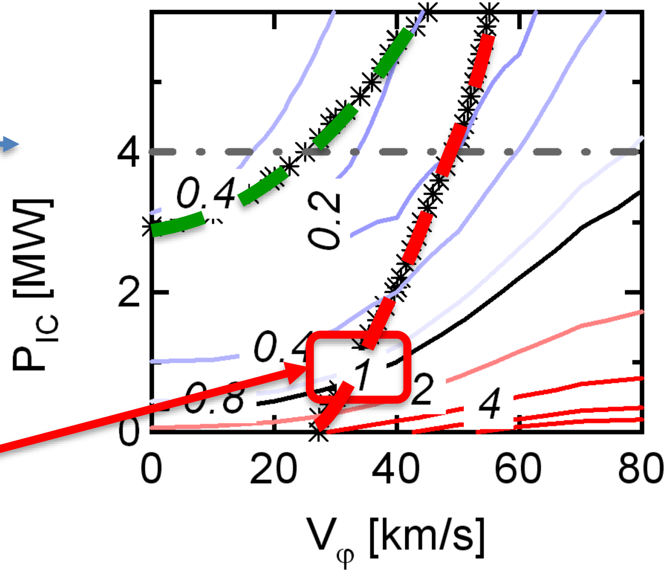
- **Tungsten profile → radiative power density, $P_{rad}(r/a=0.3)$, p_{rad}^{max}**
- **Electron heat source $p_e = p_e^{\Omega} + p_e^{ICRH}$**

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

- **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 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

p_{rad}^{max}/p_e



Injected ICRH power
4 MW

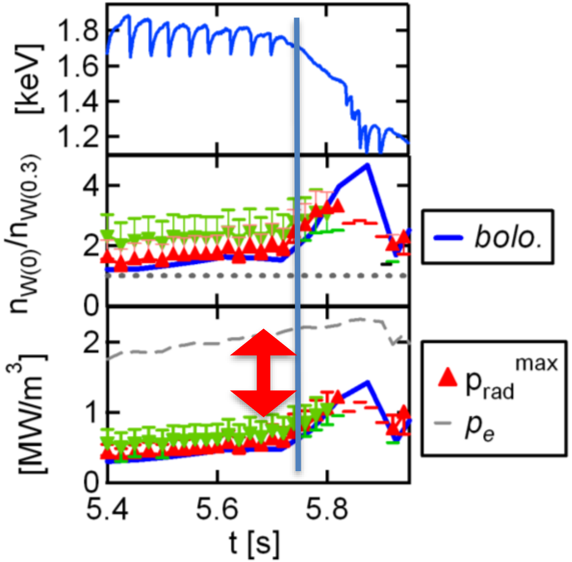
Area consistent with imminent radiative collapse

Meeting the collapse condition

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

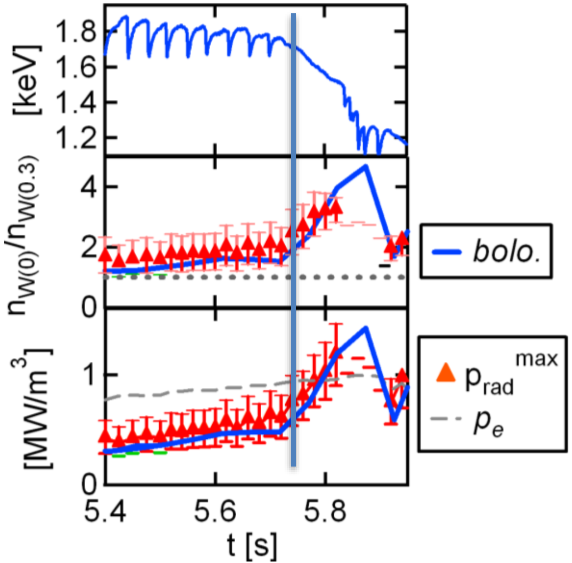
- **At nominal power the injected power on electrons is largely above the radiated power density**
- **With an artificial decrease by 60%, the collapse condition is met at t = 5.75s as observed**
  - Only the “high” velocity branch remains
- **Large losses of fast minority ions in the ripple could explain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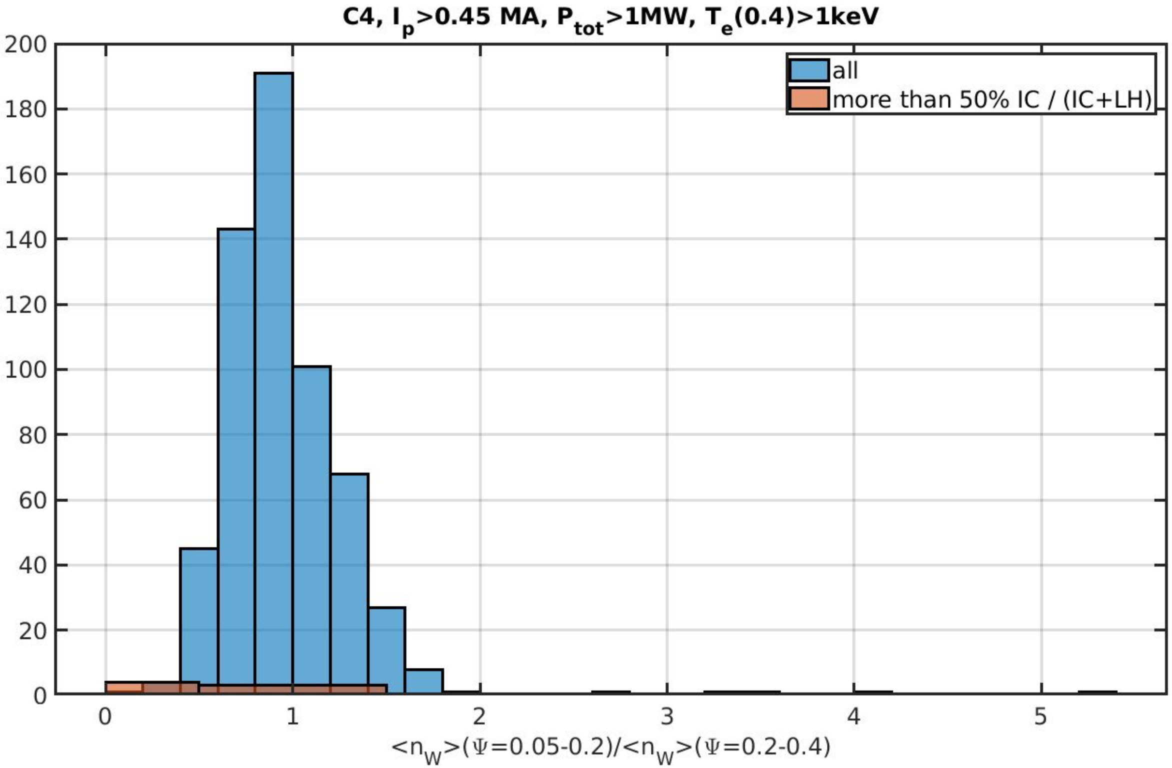
Tungsten peaking in WEST

Histogram of tungsten peaking in WEST database

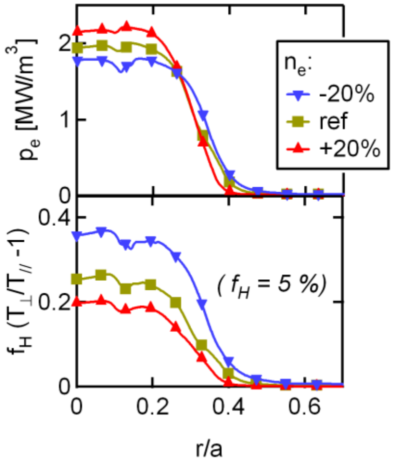
- Plateaus database (see Ostuni O4.113, this conference)

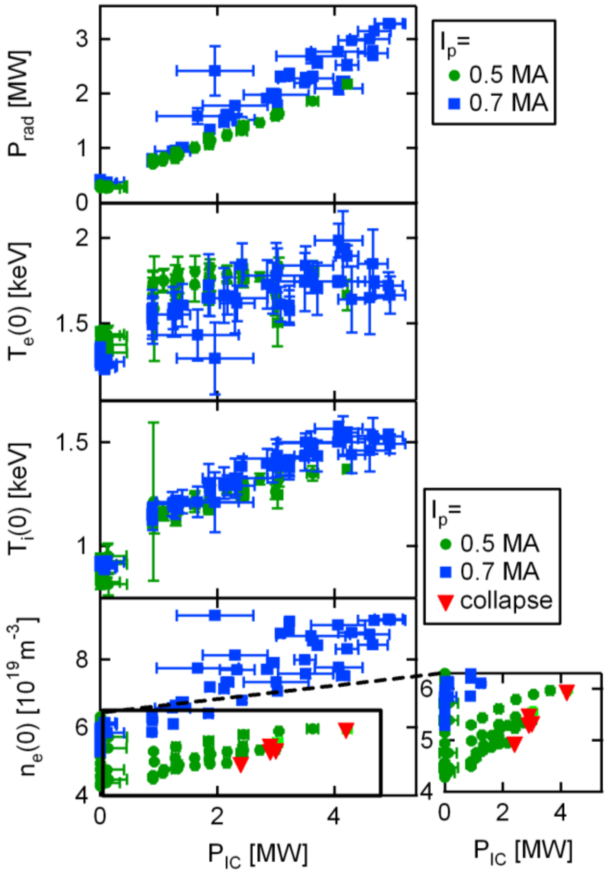


ICRH operation on WEST

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



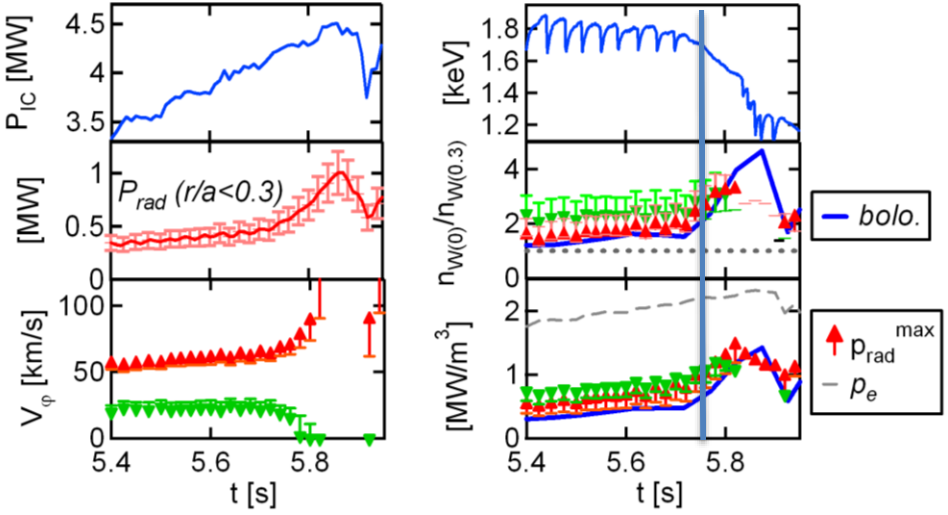


Meeting the collapse condition : reduced effective ICRH power

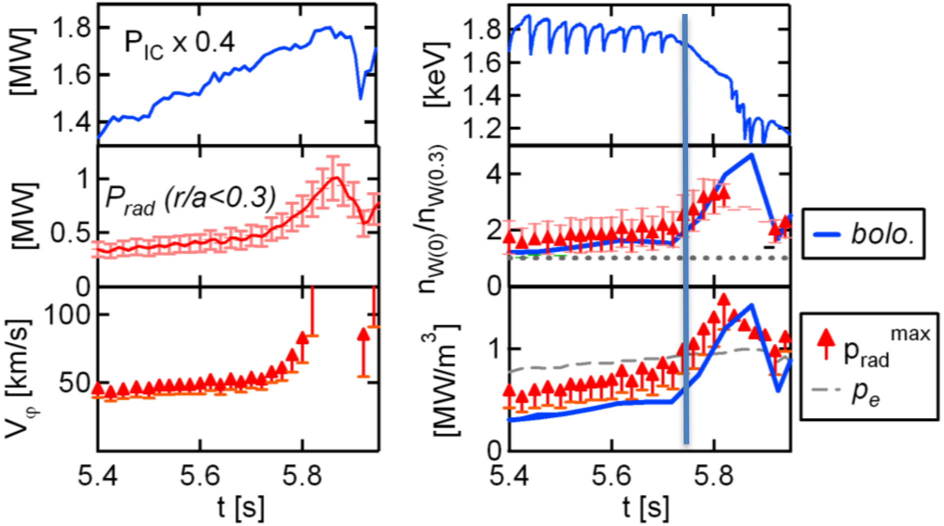
Collapse condition consistent with experiment if large reduction of effective ICRH power

- **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**

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