EUROfusion

Impact of ELM control in JET experiments on H-mode terminations with/without current rampdown and implications for ITER

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JET

Ciemat
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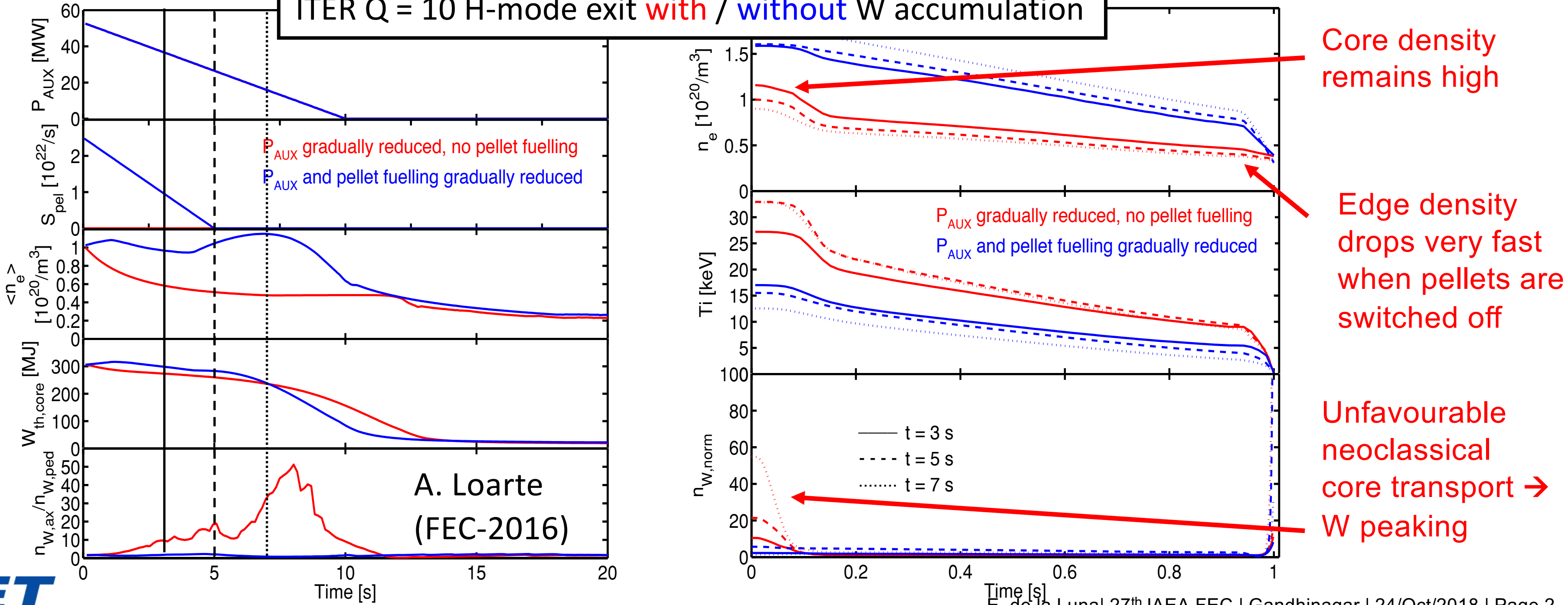
H-mode termination in ITER

- ITER Q = 10 H-mode termination should be controlled to keep dW/dt as low as possible (radial position and divertor power load control)→ keep H-mode as long as possible

➢ Optimization of heating and fuelling (pellets + gas) ramp-down required in ITER to avoid W accumulation during 'slow' H-mode termination

ITER Q = 10 H-mode exit with / without W accumulation



Content of the talk

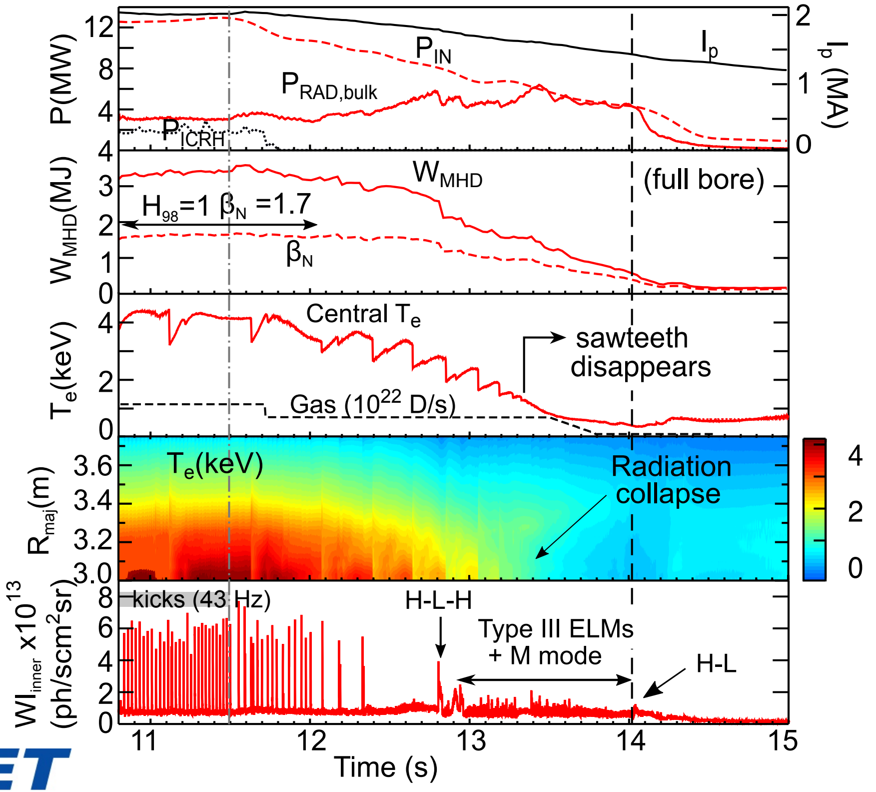
- Dedicated JET experiments using the ITER-like H-mode termination to investigate:
  - the conditions under which W accumulation develops
  - the effectiveness of foreseen W control strategies

- Examples of detailed validation studies to test the available transport models used for ITER predictions using JET-ILW experimental data (JINTRAC suite of codes)

W control: a challenge during H-mode exit

Core W accumulation can develop during the H-mode termination phase in JET-ILW, leading to a radiation collapse

#90652: 2MA, q_{95}=3.2 → 5, low δ (uncontrolled)



$$P_{sep} = P_{abs} - \mathrm{d}W/\mathrm{dt} - P_{RAD,bulk}$$

Core W accumulation leading to radiation collapse → fast decrease of W_{plasma}

↑

P_{sep} reduction results in an early H-L transition and/or transition to type III ELMs

↑

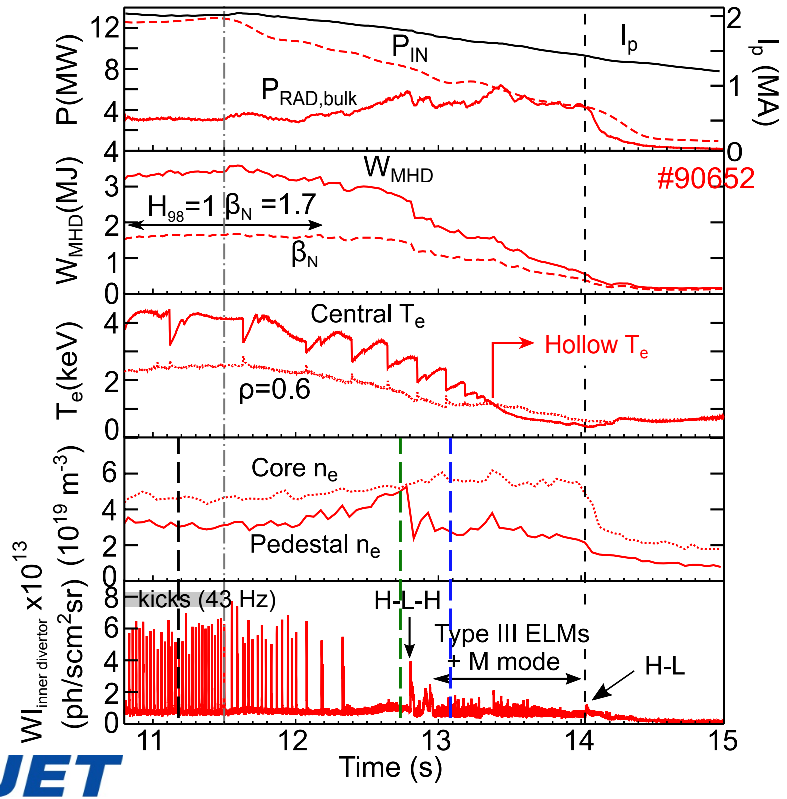
P_{rad} increases (reduced edge W outflux)

↑

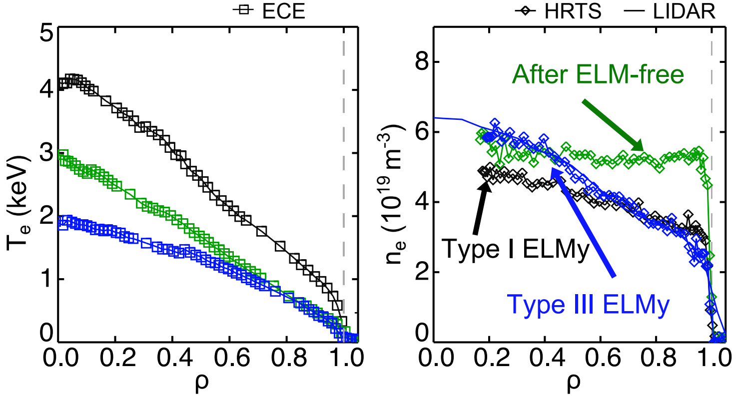
ELM frequency is reduced and long ELM-free phases develop as plasma approaches the H-L transition

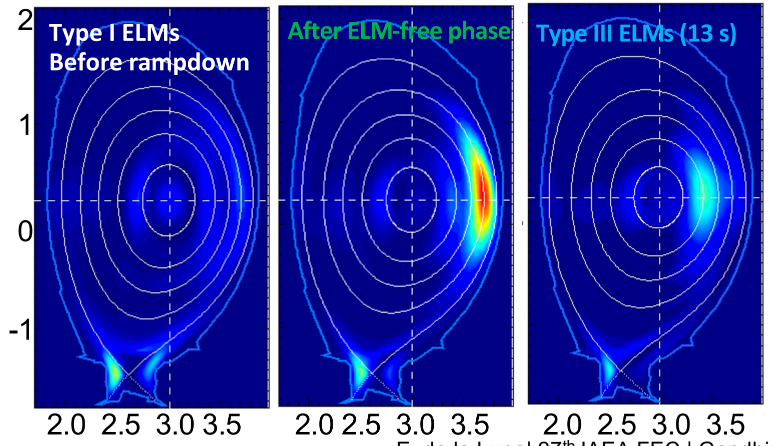
Slow H-mode termination in JET-ILW

Both edge W outflux reduction (at lower f_{ELM}) and unfavorable core transport involved in the W accumulation process



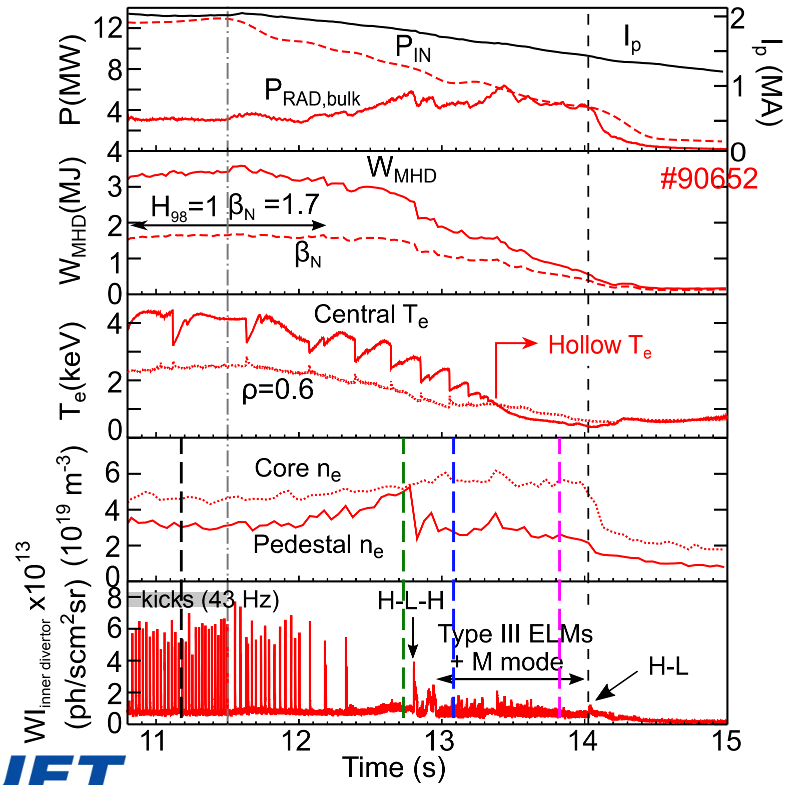
Self-accelerating W accumulation in central region ($|\nabla T_{core}|\downarrow$, $|\nabla n_{core}|\uparrow$)





Slow H-mode termination in JET-ILW

Both increase of edge W influx (at reduced f_{ELM}) and unfavorable core transport involved in the W accumulation process



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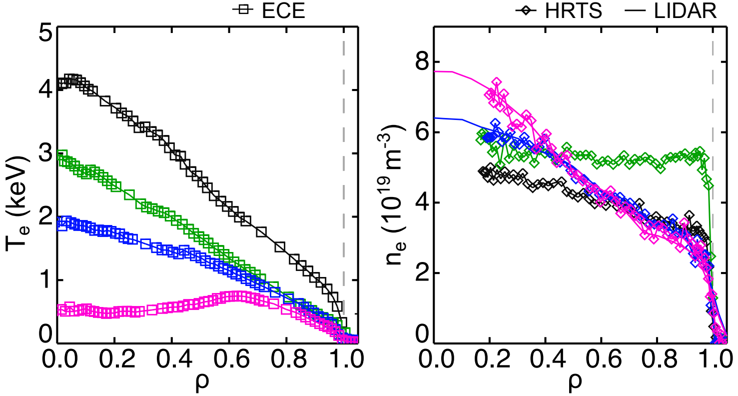
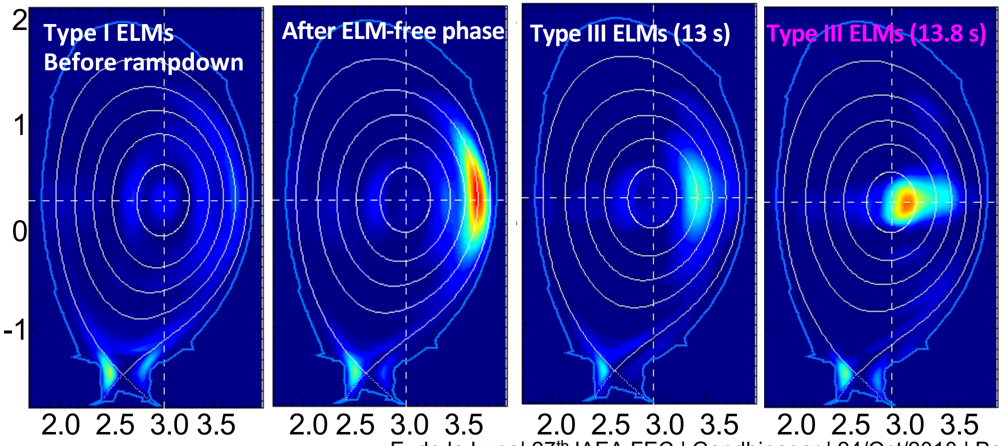
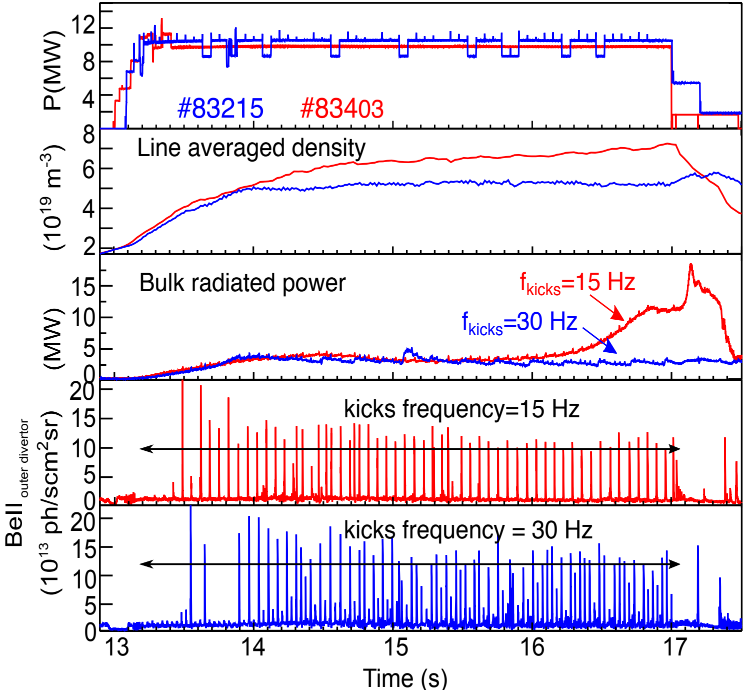
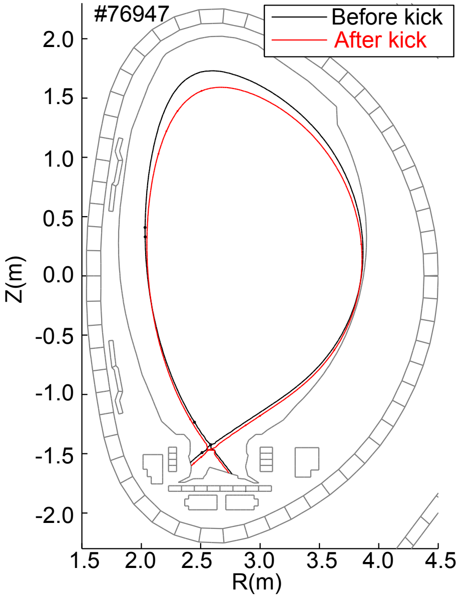




W control strategies in JET

- W transport can be controlled by :
  - operating at **high gas** to reduce the W source
  - increasing the ELM frequency using **ELM pacing** (kicks/pellets) to increase the edge W outflux
  - **central heating (ICRH)** to control core W transport (< 2 MW in these experiments, too small to be efficient)
    For application of ICRH for W control during the main heating phase see F. Casson, TH/3-2

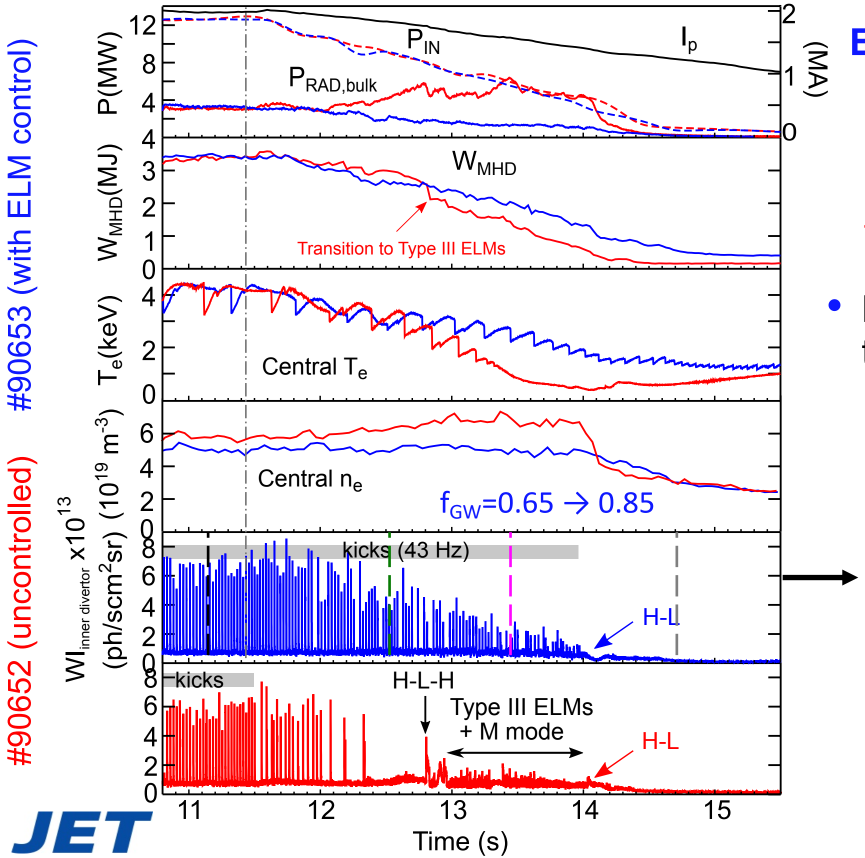




Example of edge W control using vertical kicks in JET

Impact of ELM control on H-mode termination

With ELM control (with kicks) the build-up of impurities in the core is prevented, resulting in a slower (lower dW/dt) H-mode termination



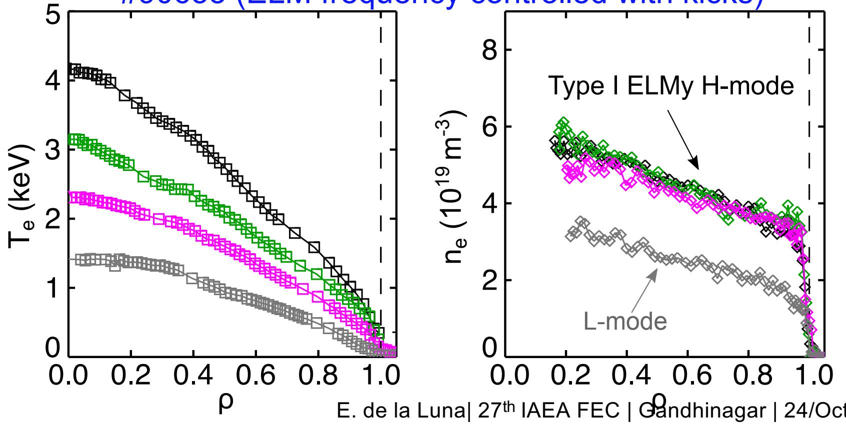
ELM control provides:

Edge W control: enhanced edge W outflux at higher f_{ELM}

Core W control: T_e profile remains peaked and density peaking is unchanged →ITER strategy to maintain favorable ∇n_{core} vs ∇T_{core} is demonstrated

- Density decays slower than Ip→ f_{GW} increases up to the HL transition→ this will limit the duration of the H-mode in ITER

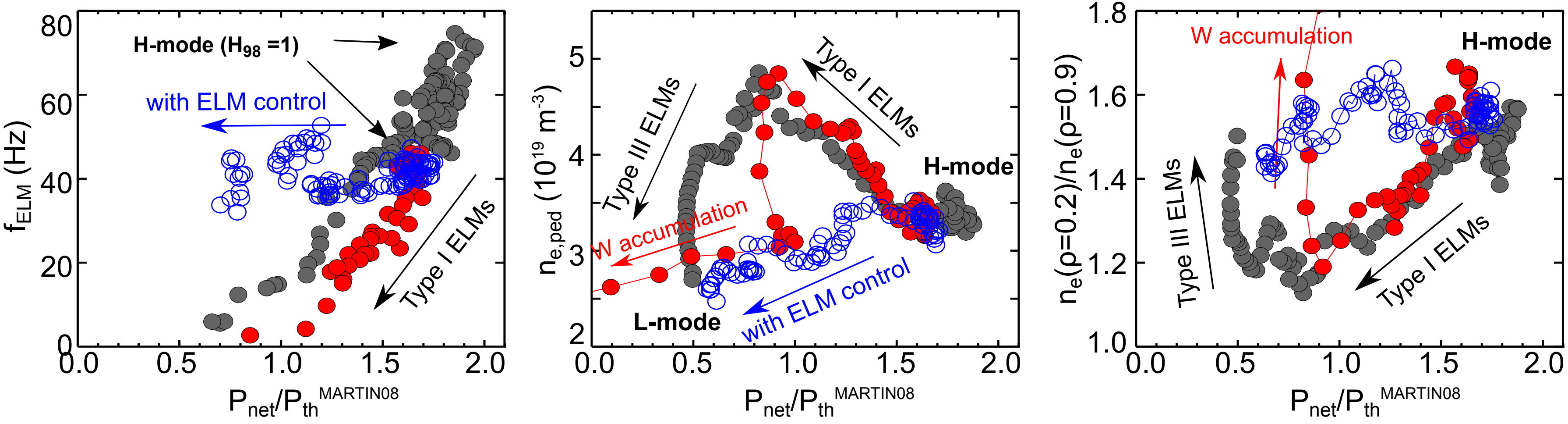
#90653 (ELM frequency controlled with kicks)



Impact of gas in slow H-mode termination

- Pedestal density strongly linked to ELM regime and associated confinement
- **With gas injection** W accumulation is prevented but density rises during H-mode termination → flatter n_e
- **With ELM control (with kicks),** both radiation and density control are achieved

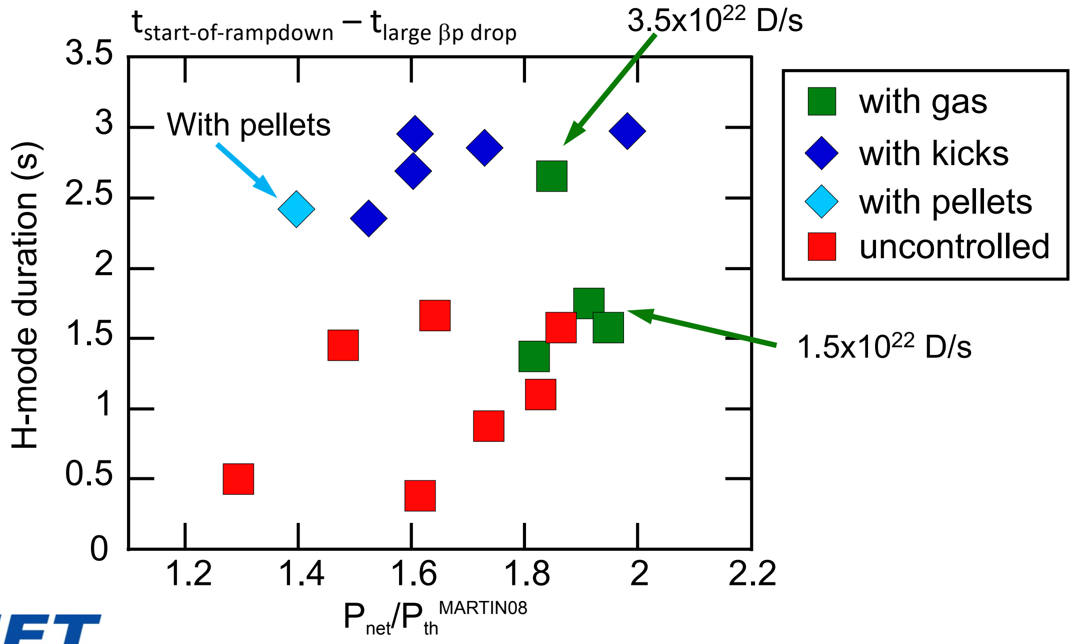
#90222 (high gas) #90223 (low gas)→ W accumulation #90224 (low gas + kicks)



Density behaviour in ITER probably different than in existing devices as the edge density will be controlled by pellets not gas (the penetration for recycling neutrals is modelled to be much less effective).

Slower H-mode termination with ELM control

- Experiments at JET have shown that the plasma dynamics up to the H-L transition strongly depends on the impurity and radiation levels
- The H-mode terminations are longer with ELM control (~ 10 energy confinement times of the initial H-mode with H_{98}=1) → dW/dt is slower, even at low P_{sep}/P_{th} (relevant for ITER since high Q_{DT} ITER plasmas are expected to operate at a relatively low P_{sep}/P_{th})



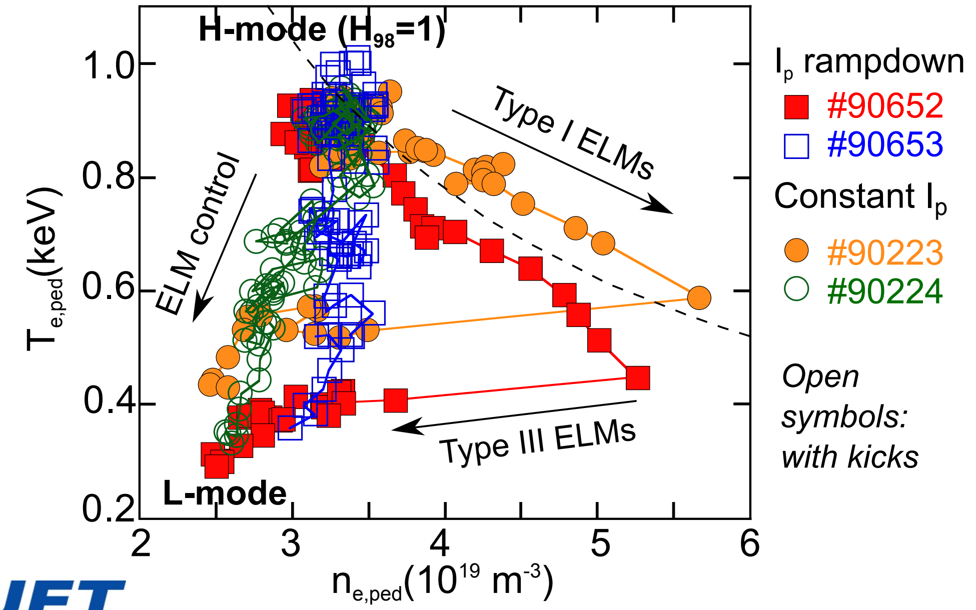
- Pellet injection (poor triggering efficiency) provides good impurity control but density increases during H-mode termination (similar to gas). Further optimization is required

NBI rampdown at I_p constant and with I_p rampdown

Two sets of discharges with slow ramp-down of NBI heating power: one at constant I_p and the other one with I_p ramped down together with the power

Without ELM control: $T_{e,ped}$ decreases at constant $P_{e,ped}$, as long as Type I ELMs are maintained, for both constant I_p and I_p ramp-down

With ELM control: $T_{e,ped}$ decreases at nearly constant $n_{e,ped}$



NBI rampdown at I_p constant and with I_p rampdown

Two sets of discharges with slow ramp-downs of NBI heating power: on at constant I_p and the other one with I_p ramped down together with the power

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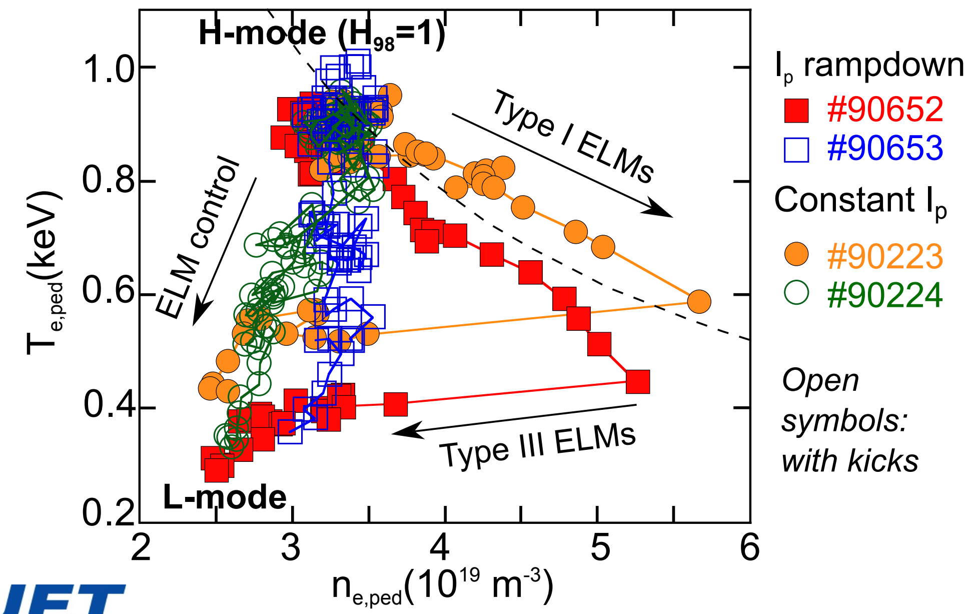
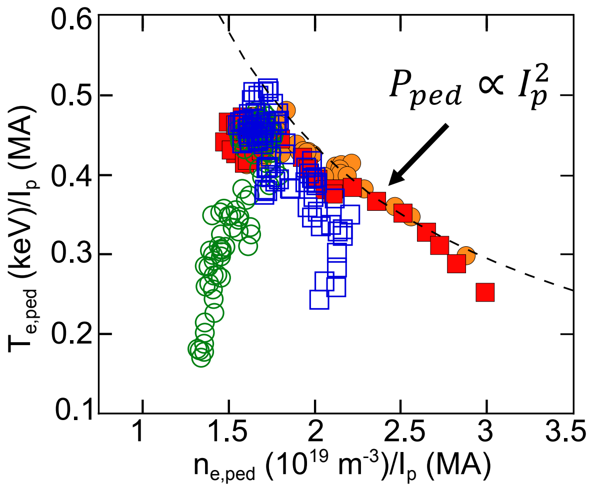


When I_p is rampdown, P_{ped} decreases with I_p^2 during the Type I ELMy H-mode phase (with no ELM control) → ballooning limit applies



Integrated core+edge+SOL transport modelling with JINTRAC

Integrated **fully predictive core+edge+SOL transport modelling** studies applying discrete models for the description of transients such as sawteeth and ELMs have been performed for the first time with the JINTRAC suite of codes for the entire transition **from stationary H-mode until the time when the plasma would return to L-mode focusing on the W transport behaviour.**

JINTRAC model assumptions

F. Koechl, NF 2018

Simulation mode:
Fully predictive: particle (D, Be, W), heat and momentum transport

W source:
Physical W sputtering + self-sputtering at target plates [Eckstein JNM 1997]

ETB transport:
Neoclassical + small anomalous contribution determined by empiric L-H transition model [Loarte NF 2014]

Discrete ELM model:
Gaussian $\Delta D = \Delta\chi$ applied in edge + near SOL region during ELM [Wiesen PPCF 2011]

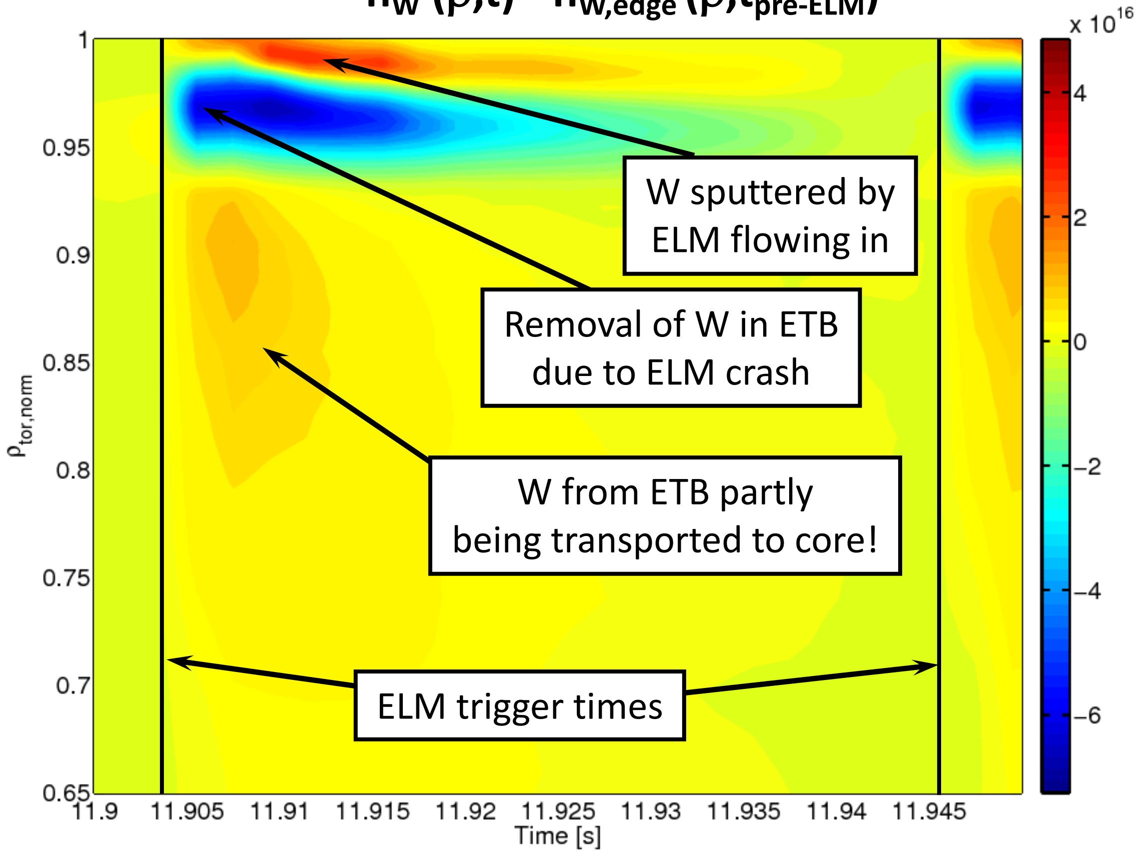
Core transport:
Neoclassical (NCLASS) including correction for rotation-induced high-Z poloidal asymmetry + anomalous (ITG/TEM) (L-mode: NCLASS + BgB) [Houlberg PoP 1997,Romanelli PPCF 1998, Waltz PoP 1997]

ELM-induced edge n_W evolution modelled by JINTRAC

ELM-induced edge n_W evolution:

JINTRAC calc.
f_{ELM} = 23.5 Hz

$n_W(\rho,t) - n_{W,edge}(\rho,t_{pre\text{-}ELM})$



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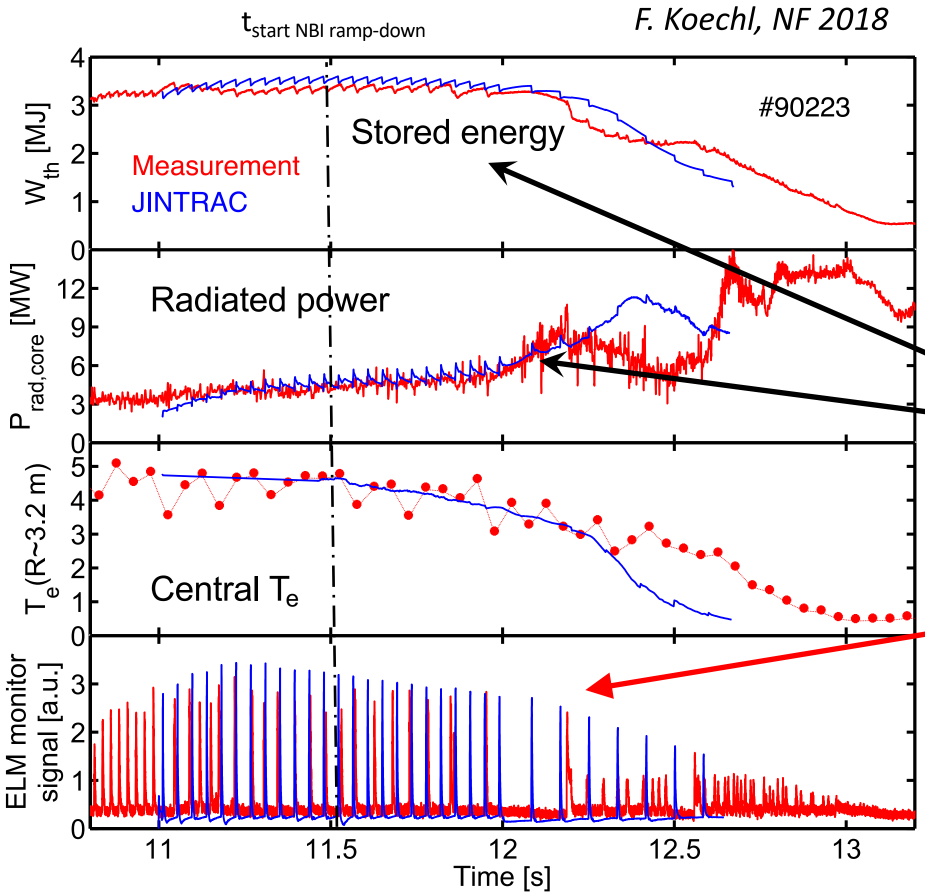
Transport model validation using JET data



Fully integrated modelling from the divertor to the core region

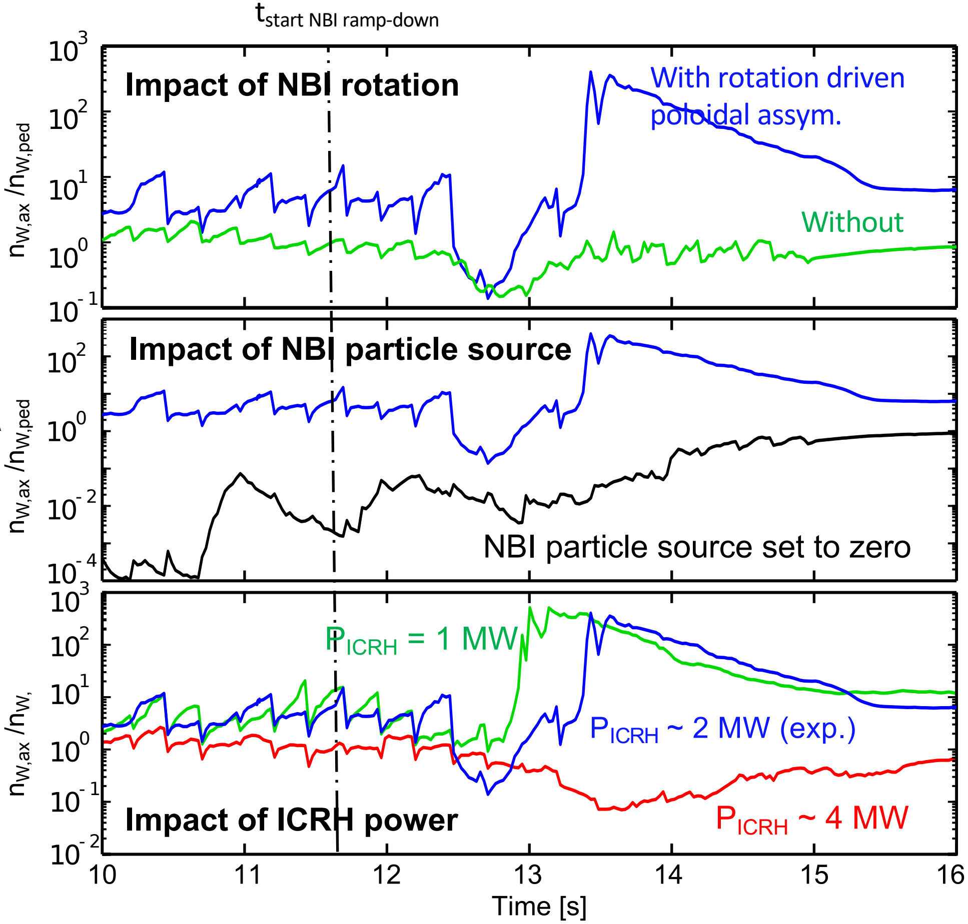
Good agreement in time evolution of core energy and radiation for t < ~12.25 s, faster predicted collapse later on

H-L-H transition and transition to Type III ELMs not included in the simulations

Scan in core W transport dependencies

JINTRAC modelling for #90223 (I_p constant, no ELM control, with radiation collapse)

Rotation and particle source from NBI play an important role in the W accumulation process in JET-ILW
(→ different in ITER with low torque and particle sources)



ICRH (≤ 2 MW) alone not efficient to prevent W accumulation in the experiments

Modelling predicts no core W accumulation with increased ICRH power in JET-ILW (to be confirmed during next JET campaign)

F. Koechl, NF 2018

Conclusions

- The use of ELM control is found to be essential to prevent W accumulation during ITER-like H-mode termination in JET-ILW:
  - avoids long ELM free phases and prevents early HL transitions (or transition to type III ELM)
  - provides edge W outflux and promote favourable neoclassical core transport conditions (∇n_{core} vs. ∇T_{core}) to avoid W accumulation
  - leads to slower H-mode terminations (lower dW/dt) → requirement for ITER to maintain radial position control and limit heats loads to the divertor

- Physics of core W accumulation seen during 'slow' H-mode terminations in JET is similar to that predicted in ITER. ITER strategy to control ∇n_{core} vs. ∇T_{core} to avoid W accumulation in H-mode exit is demonstrated, although in ITER edge density control is done using pellets fuelling while in JET it is obtained by controlling the edge recycling through ELM control

- Transport model validation: reasonable agreement with measurements achieved with available set of transport models (JINTRAC integrated modelling) → Observed trends favourable for extrapolation to ITER

Further validation work using experimental data is required to refine and gain confidence in the predictions for ITER's rampdown

Additional material

Radiation collapse does not always lead to disruption in JET-ILW

- Mode locking always present after radiation collapse in H-mode termination, but not all discharges terminate with a disruption
- **With P_{ICRH}< 2 MW during the L-mode phase,** peaked T_e profiles are recovered after the thermal quench (affecting only edge T_e), leading to a soft landing of the discharge