EUROfusion

Exploring the physics of a high-performance H-mode with small ELMs and zero gas dosing in JET-ILW

Presented by E. de la Luna

JET

Laboratorio Nacional de Fusión

Ciemat

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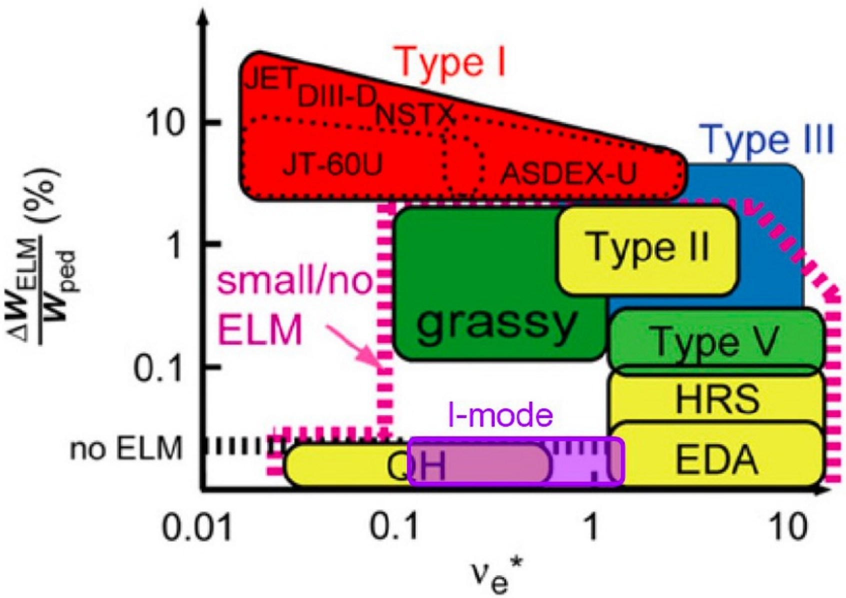
*See 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)

Introduction

K. Kamiya et al,
Plasma Phys. Control. Fusion 49 (2007) S43



- **ELM control** essential in ITER to avoid damage to PFCs:
  - operation with no-ELMs or small ELMs become attractive… but
  - operational space for small ELMs regimes (grassy, Type II, Type III ELMs) outside ITER requirements or plasma conditions lead to low thermal confinement

→ **Can good confinement be obtained with small ELMs at ITER relevant collisionality?**

Introduction

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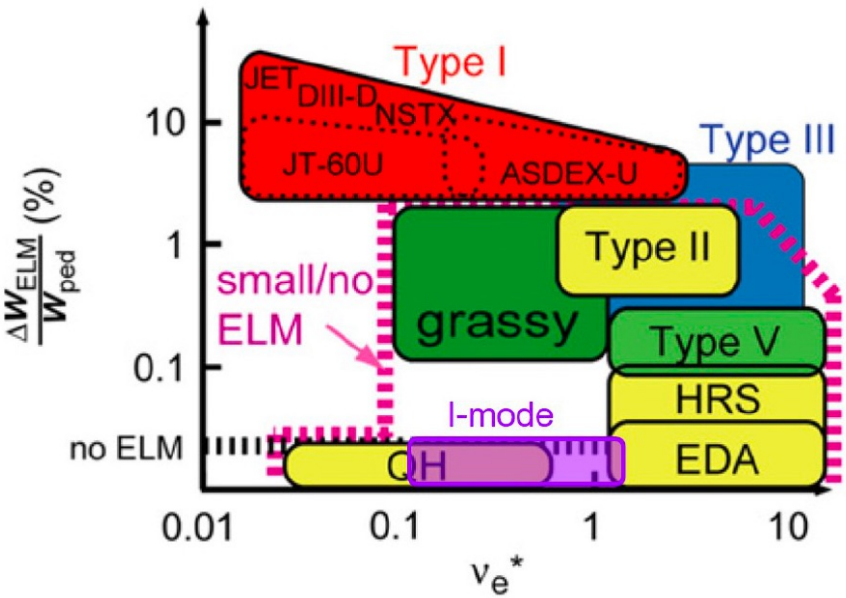

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  - operation with no-ELMs or small ELMs become attractive… but
  - operational space for small ELMs regimes (grassy, Type II, Type III ELMs) outside ITER requirements or plasma conditions lead to low thermal confinement

→ **Can good confinement be obtained with small ELMs at ITER relevant collisionality?**

- **Control of impurity concentration** also critical in ITER to achieve good confinement an maintain low disruptivity (avoiding W impurity accumulation)
  - Type I ELMs very effective in flushing out impurities from the pedestal region

→ **Can stationary conditions for plasma density and radiation be achieved in an H-mode with small ELMs?**

Outline

Results in JET-ILW have demonstrated a new H-mode operating regime that allows simultaneous access to good energy confinement and small ELMs, while maintaining plasma density and radiation in stationary conditions.

- Phenomenology of the small ELMs H-mode regime obtained by operating with very low gas dosing
- Experimental conditions for the onset of small ELMs at low collisionality
- Impurity accumulation
- Transport analysis: turbulent and neoclassical
- Comparison with other small ELMs regimes
- Summary

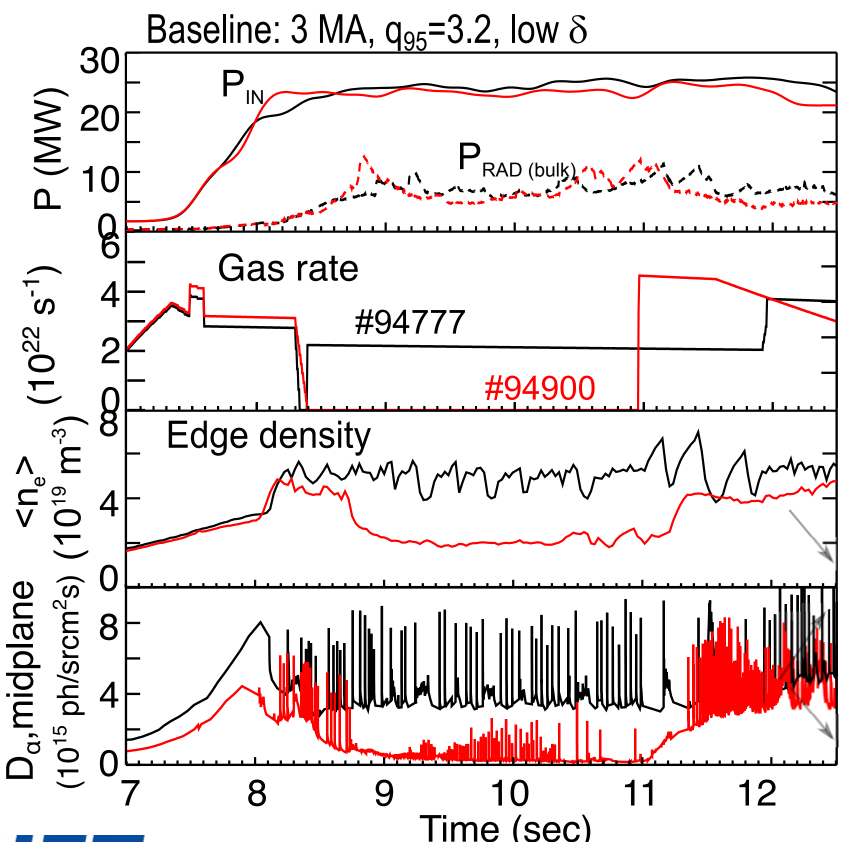
High performance H-mode plasmas obtained with very low gas dosing in JET-ILW

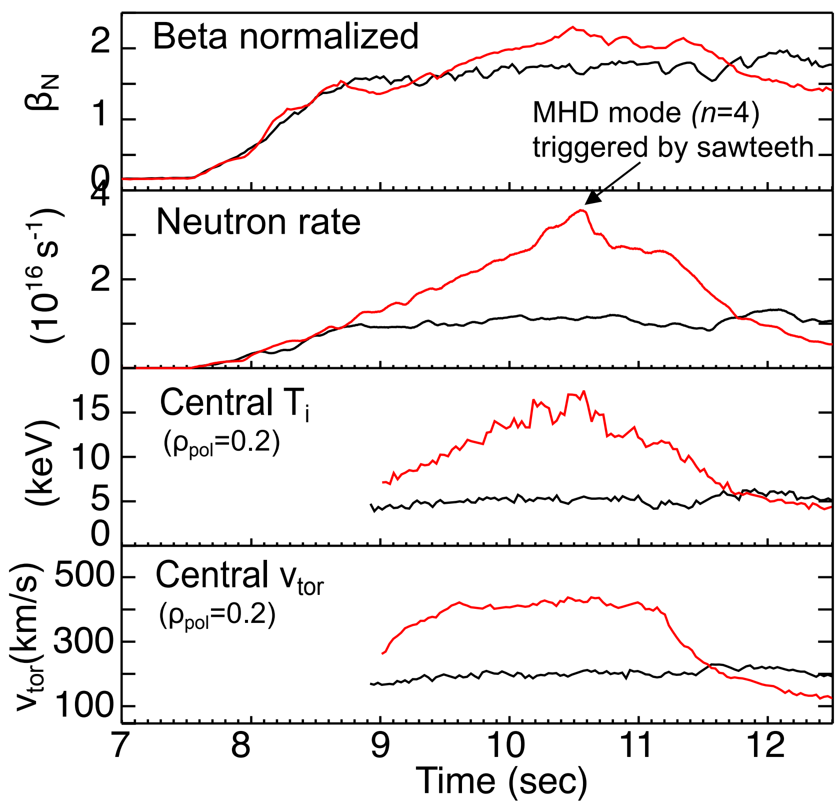
- Low plasma density ($0.40 x n_{GW}$)
- Stationary density and radiation levels
- ELMs smaller and faster than those found in discharges at higher gas dosing

Compared to conventional ELMy H-mode:

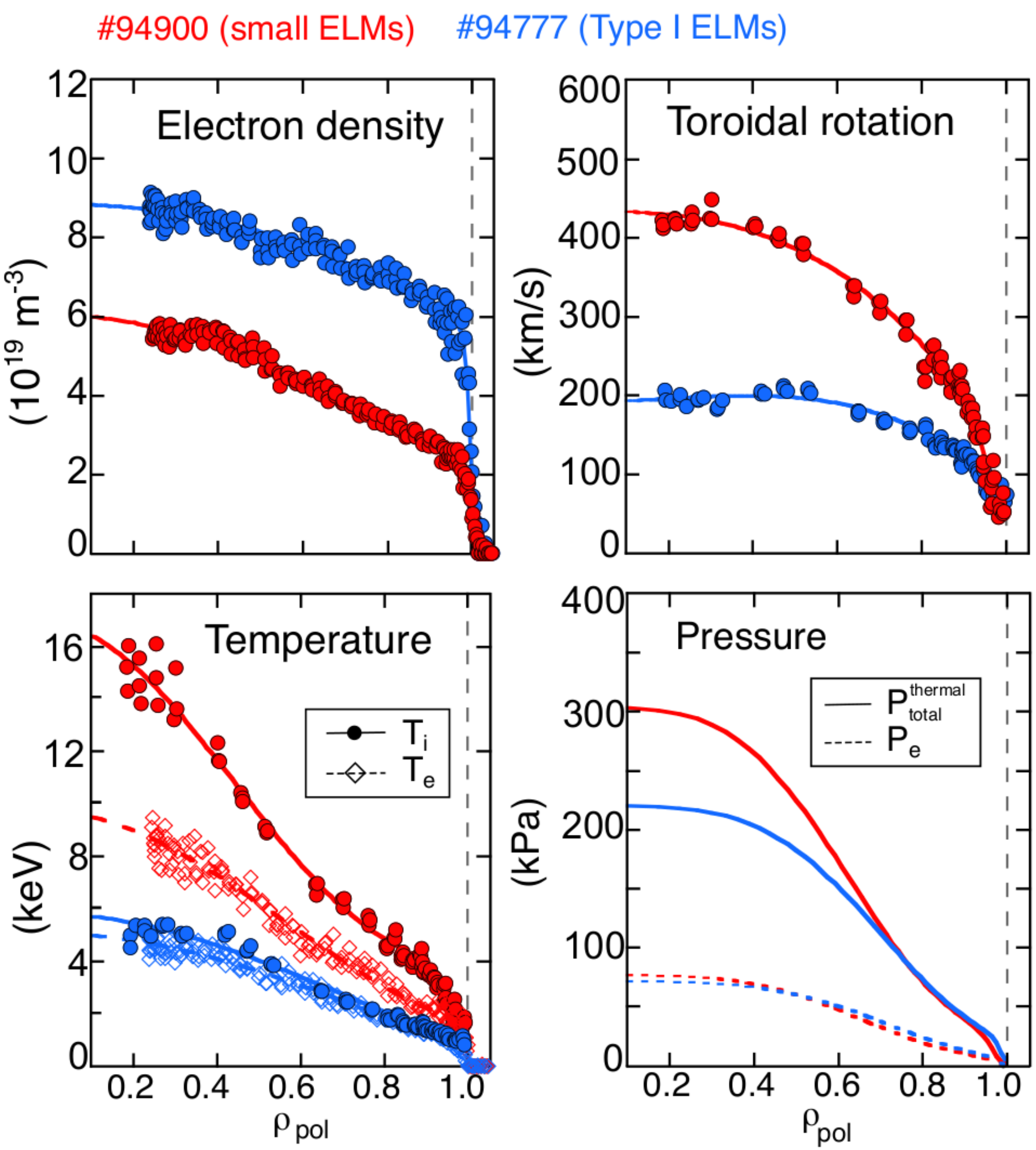
- better confinement and stronger rotation
- higher T_i (at pedestal and in core, with $T_i >> T_e$),
- higher DD neutron rates

→ Similarities with the 'hot-ion' H-mode in JET-C but also clear differences





High performance plasmas at low collisionality



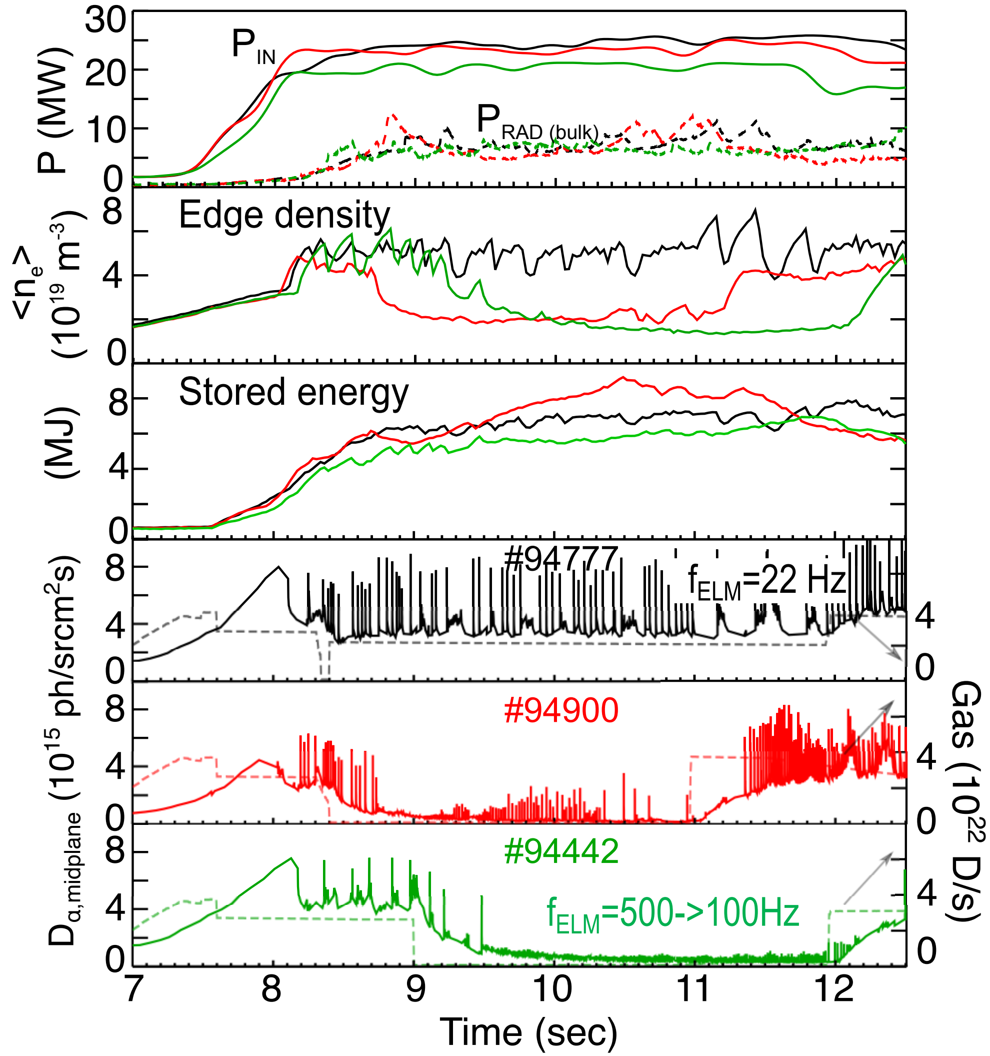
Small ELMs H-mode (no gas) compared with ELMy H-mode (gas fuelled):

- lower density and stronger density peaking
- higher T_i and T_e, starting from pedestal, with $T_i >> T_e$
- Higher rotation & rotation shear

→ Confinement above Type I ELMy H-mode, with similar pedestal pressure but higher core pressure

→ Low pedestal collisionality (ν_{ped}=0.1), as expected in ITER

Onset conditions for small ELMs in JET-ILW



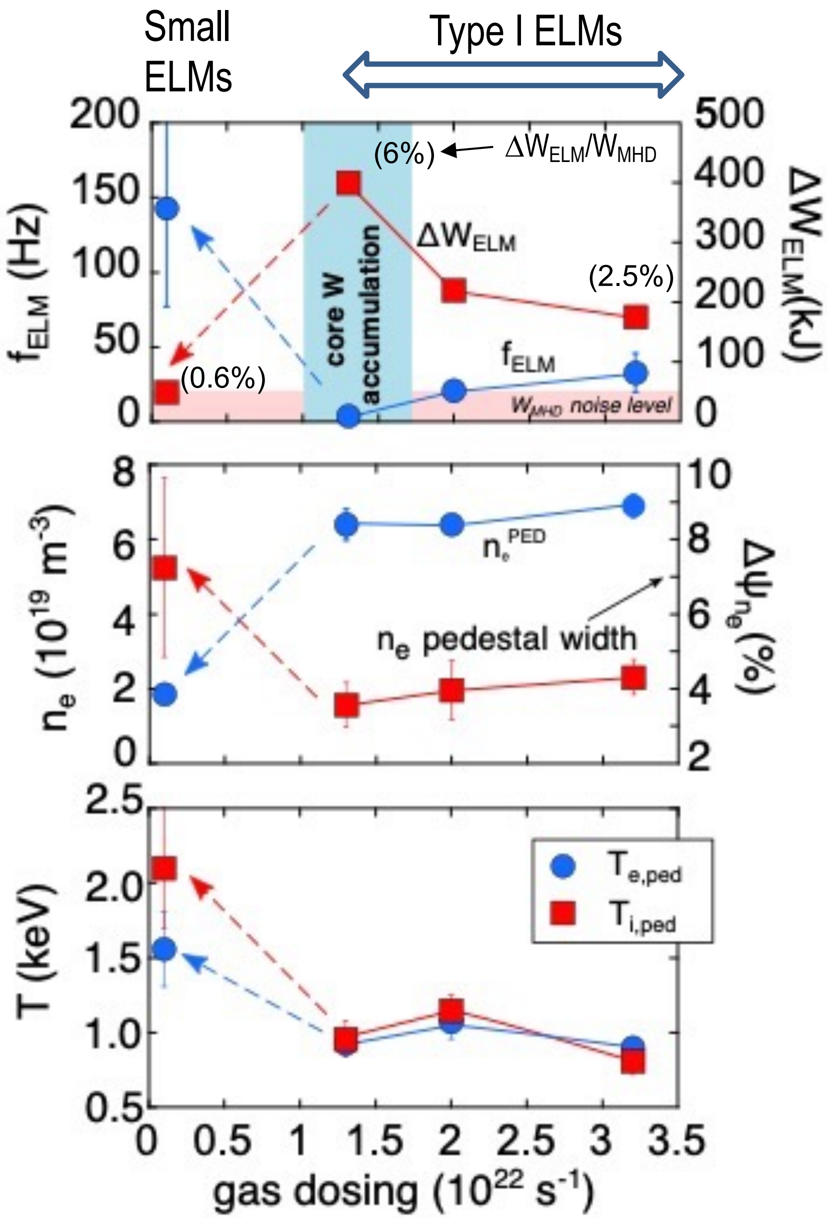
Low density key to access the 'small' ELM regime

Contrary to the Type I to Type III ELMs transition, the onset of small ELMs occurs with no degradation of confinement

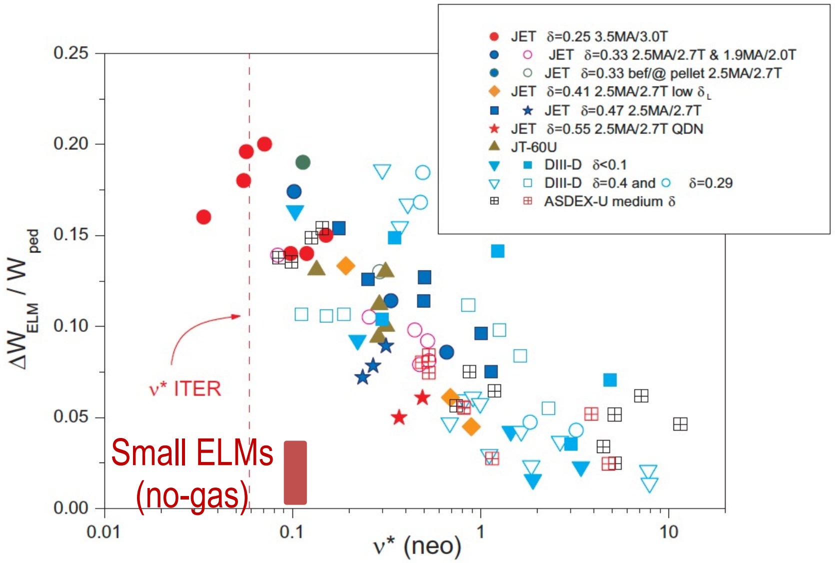
Stationary plasma density and radiation

→ contrary to QH-Mode (EHO) or I-mode (WCM), there is no evidence of edge MHD activity

Small ELMs found at low pedestal collisionality

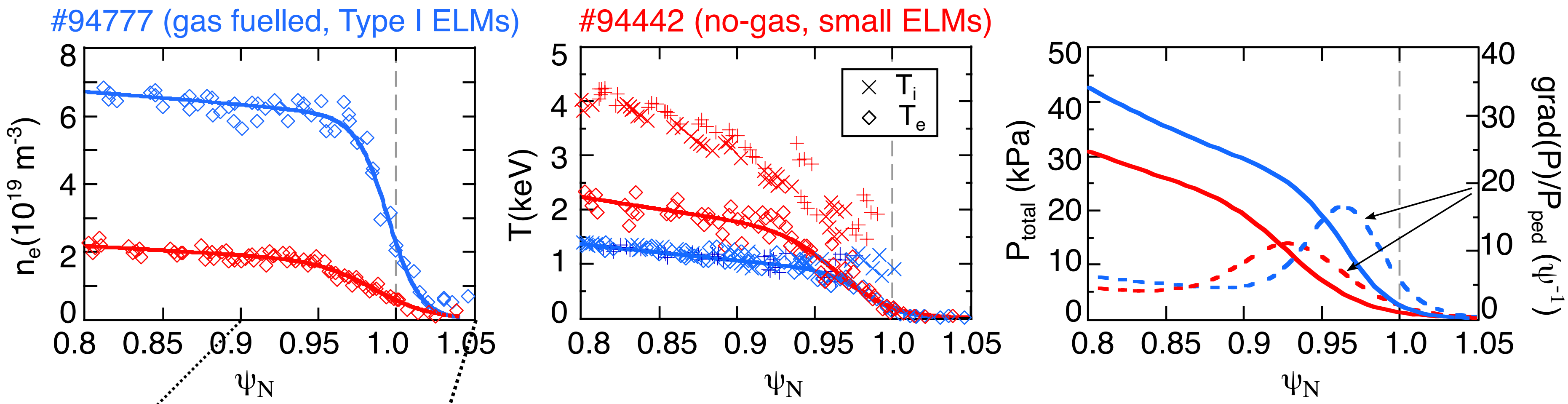


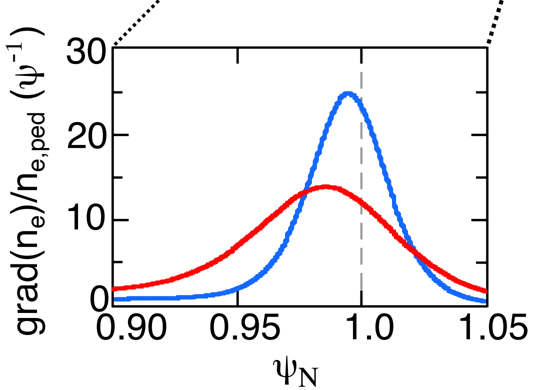
Small ELMs at low density/collisionality do not follow the usual trends found for Type I ELMs



A. Loarte et al. Plasma Phys. Control. Fusion 45 (2003) 1549

Wider density pedestal and high T_i^{PED} correlated with the onset of small ELMs





- Compared to the ELMy H-mode plasma, the discharge with small ELMs has:
  - similar P^{PED} (lower n_e^{PED}, but higher T_e^{PED}, T_i^{PED})
  - wider n_e and P_e pedestal width, significantly lower maximum ∇n_e & ∇p_e.
  - position of maximum gradient shifted inwards (due to wider width) → improved pedestal stability

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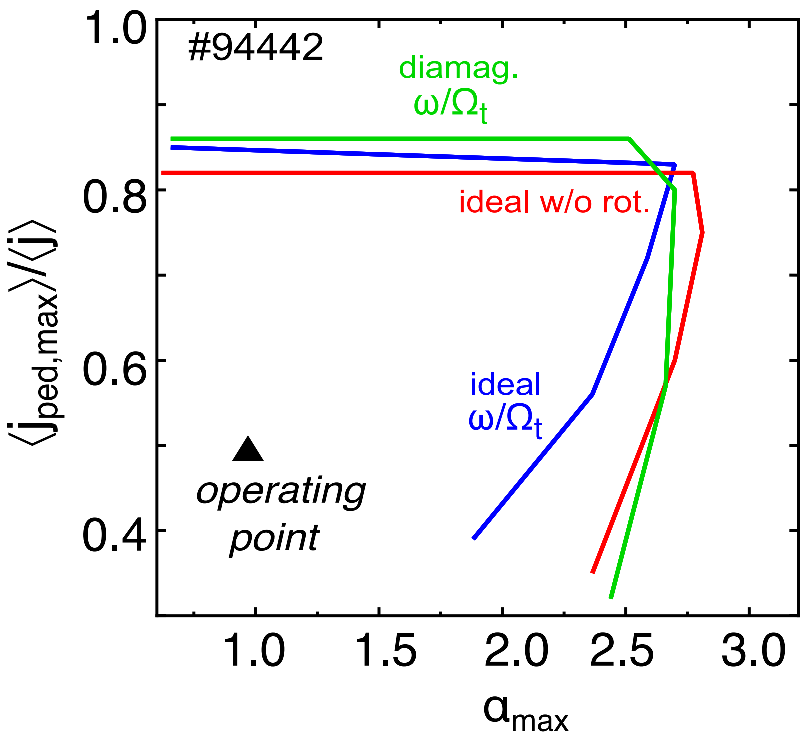
Ideal MHD stability



H-mode pedestals in the no-gas H-mode regime are MHD stable → explain the occurrence of small ELMs

Addition of rotation and diamagnetic effects does not significantly change the output

Physics mechanisms responsible for the onset of the small ELMs not yet identified

- BUT, in JET-ILW there are Type I ELMy H-mode discharges where pedestals are not limited by the P-B modes [1] :
  - typically found at high power, high gas (e.g. #94777), in plasmas with $n_{e,sep}/n_{e,\,ped}$ >0.4

→ missing physics for the ELM trigger ??? *(see L. Frassinetti, EX/2-2)*

[1] L. Frassinetti et al. Nucl. Fusion 61 (2021) 016001

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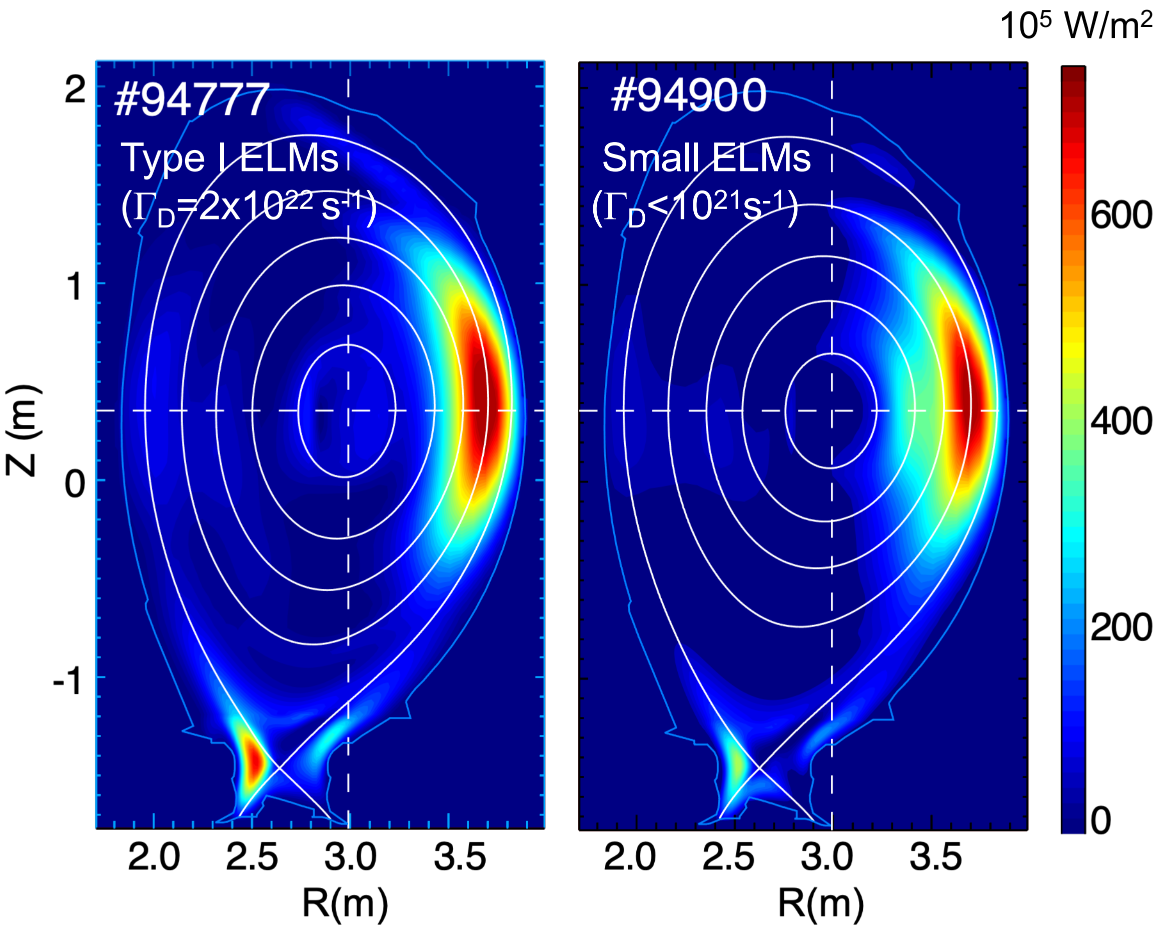
No core impurity accumulation despite operation with no-gas



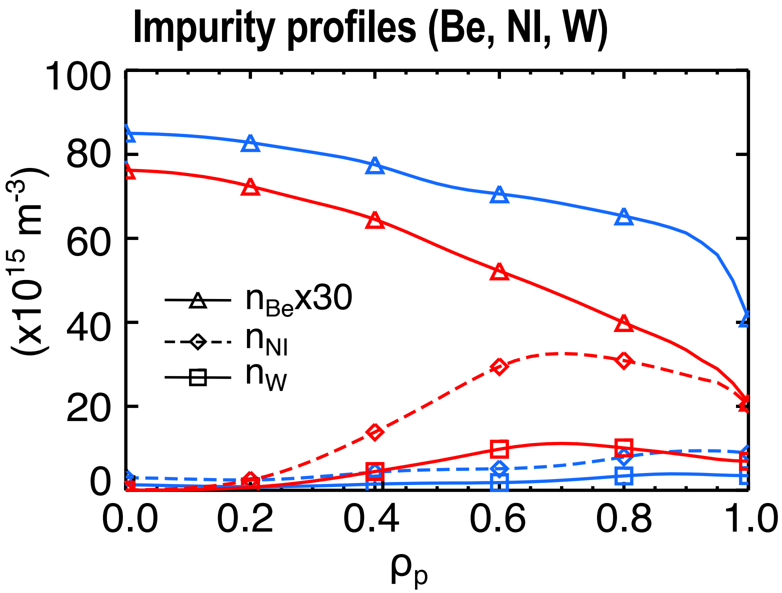
Operation with no-gas results in:

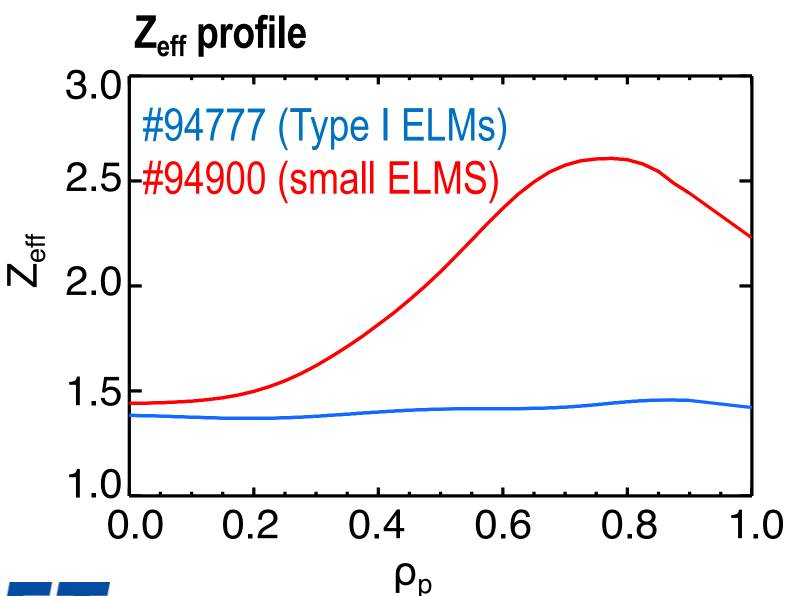
- low separatrix density and faster density decay length in the SOL
- stronger density peaking
- small ELMs (very small impact on pedestal profiles)

BUT no impurity accumulation

Impurities localized on the LFS (ρ_{pol}>0.7) due to neoclassical centrifugal effects → typical feature of high NBI power, highly rotating JET discharges

Impurity analysis



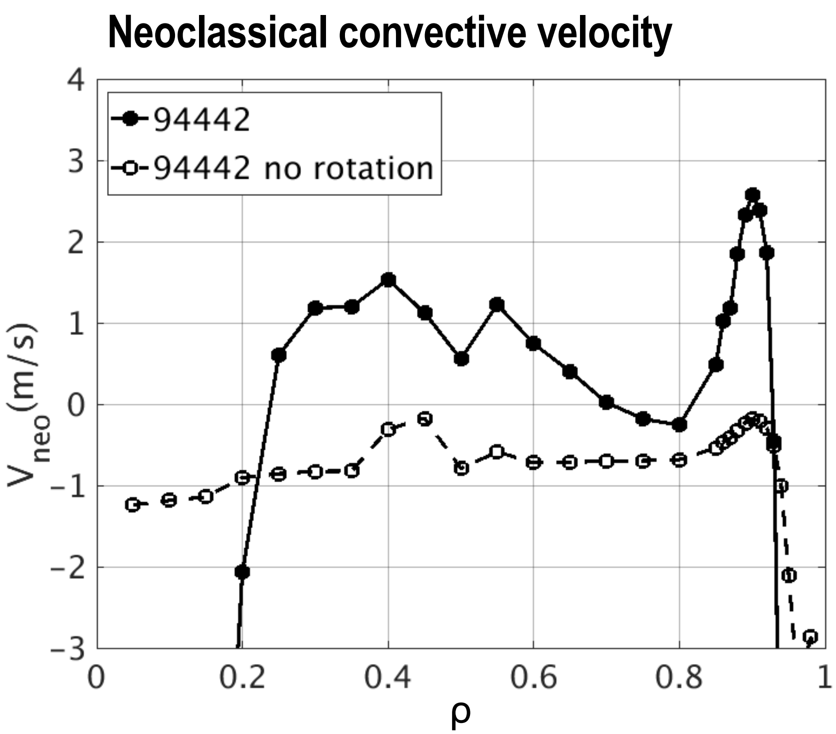


- Radiation trends confirmed by impurity concentration analysis
- For #94900 (no-gas, small ELMs)
  - Core impurity dominated by Be
  - W and Ni concentrations increase at the edge but profiles remain hollow
  - Z_{eff} increases but profile becomes hollow, no change in $Z_{eff}(0)$ → no core dilution

What is causing this good behaviour?

Impurity transport: W neoclassical pinch

Neoclassical convective flux modelled with NEO[1]

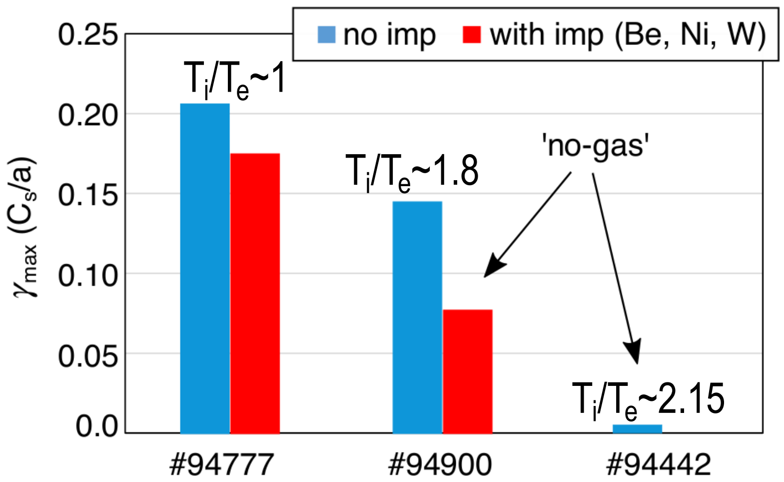


- Outward convective velocity for most of the plasma cross-section → Impurity screening → helps avoid W accumulation
- Toroidal rotation causes a sign reversal of the W pinch from negative (inward) to positive (outward) [2]
- Significant W pinch at the top of the pedestal → Edge screening at low collisionality as expected in ITER

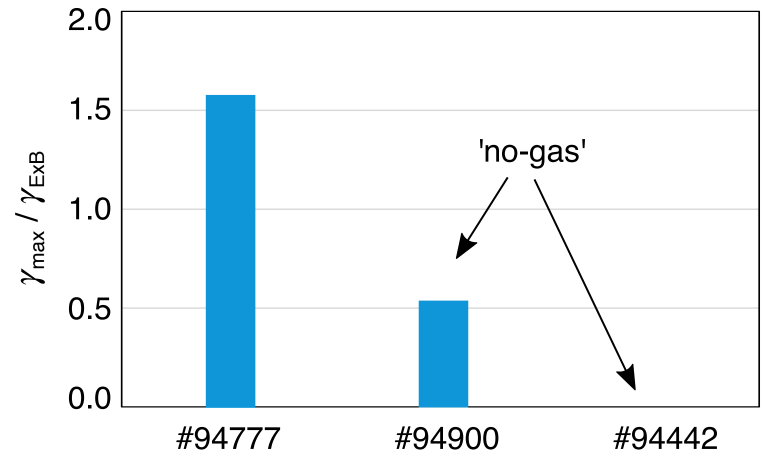
[1] E. A. Belli and J. Candy,
Plasma Physics and Controlled Fusion 50, 095010 (2008)
[2] J. Garcia et al, submitted to PRL

Linear turbulence analysis (GENE code[1])

Linear growth rates (at ρ_{tor}=0.8)



Linear growth & ExB shearing rate



Linear analysis provides a good proxy for the evaluation of different mechanisms on transport[2]: a) high T_i/T_e , b) impurities localized at the edge and c) sheared ExB flows

- Turbulence (ITG) growth rate reduction due to impurities stronger at higher T_i/T_e
- $\gamma_{max,ITG}/\gamma_{ExB}$ used for the evaluation of ExB shearing on transport → strong impact in the no-gas (small ELMs) H-mode, negligible for Type I ELMy H-modes
- transport for #94442 nearly supressed due to the high T_i/T_e from the pedestal

[1] F. Jenko et al, Phys. of Plasmas 7 (2000) 1904
[2] J. Garcia et al, submitted to PRL

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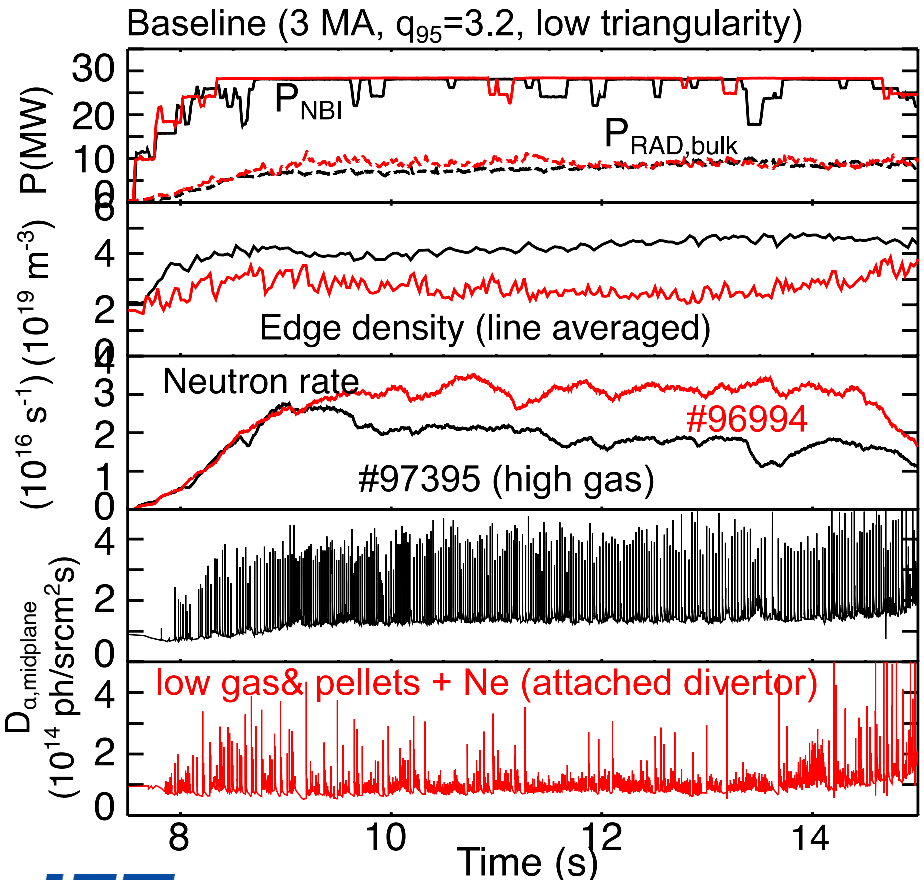
New plasma regime with small ELMs and high confinement (see J. Garcia [EX1-2] and J. Mailloux [OV1-2])

High H-mode performance also achieved by operation with low gas & pellet injection

→ Similar in character to the no-gas H-mode regime, including the small ELMs, but energy confinement is sustained in stationary conditions

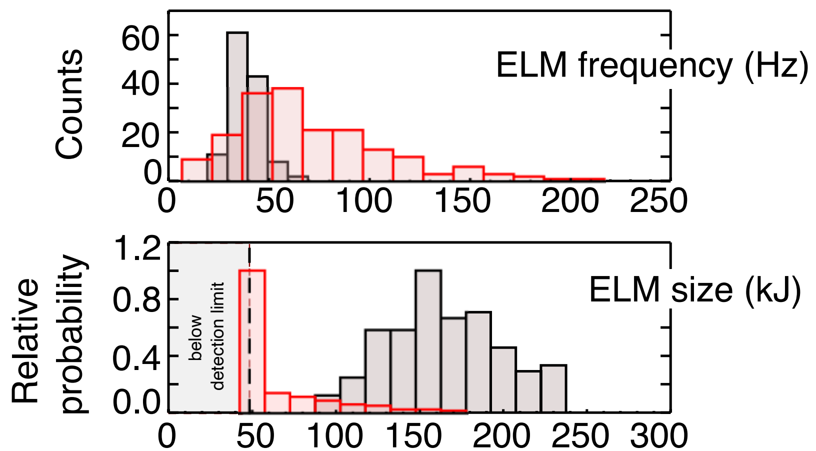
→ **best performance obtained so far in the JET-ILW baseline scenario**



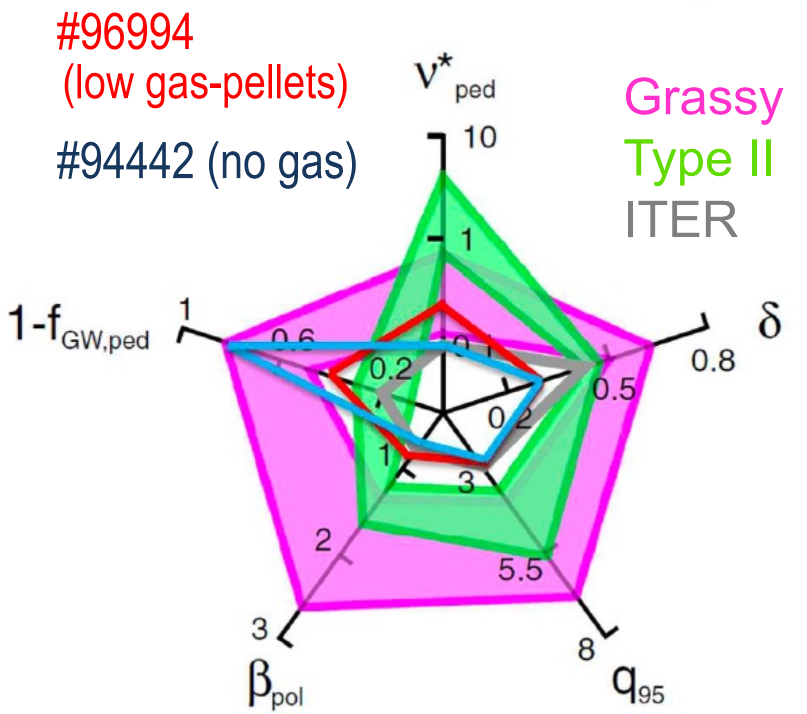
→ good confinement: H_{98}= 1.05, β_N = 2.2, n_e/n_{GW}=0.7

→ high DD fusion rates (in steady state)

→ mixed ELM regime, with long periods of small & faster ELMs → substantial reduction in ELM size



Comparison to other small ELM regimes



E. Viezzer et al. Nucl. Fusion 58 (2018) 115002

Small ELMs discharges obtained at JET cover a different operational space than other H-mode regimes with small ELMs:

→ Plasmas with low gas+pellets close to ITER conditions

Greenwald fraction requirement for ITER not clear as it depends on the density peaking

Summary

- **Results in JET-ILW have demonstrated a new H-mode operating regime that allows simultaneous access to good energy confinement, small ELMs and low core impurity content, and this is obtained at the low edge collisionality values expected in ITER**

- Access to low density/high temperature pedestals key to obtain high performance H-mode plasmas with small ELMs:
  - very low gas ($\sim 10^{21}$ s^{-1}): n_e/n_{GW}=0.35, T_i and neutron rate increases continuously during the high performance phase → useful platform to explore the physics of high perfomance plasmas
  - low gas ($\sim 10^{22}$ s^{-1}) + pellets: n_e/n_{GW}=0.7 → high performance sustained in stationary conditions

  → best performing baseline plasmas obtained in JET-ILW so far, which opens up an attractive path for high confinement, steady state H-mode operation with small ELMs in metal wall devices (see J. Garcia [EX1-2] and J. Mailloux [OV1-2])

- Parameters at the pedestal top play a key role in the enhanced ion confinement and the lack of W accumulation observed in the no-gas H-mode regime

- Pedestals with small ELMs are MHD stable. Physics mechanism responsible for the onset of the small ELMs not yet clear, correlated with high pedestal T_i and wide pedestal density