Pedestal structure and stability of high-performance scenarios with I-mode-like pedestals in JET with the Be/W wall

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† See the author list of "Progress on an exhaust solution for a reactor using EUROfusion multi-machines capabilities" by E. Joffrin et al., Nucl. Fusion 64 (2024) 112019

INTRODUCTION

Two very different high-performance scenarios at low density (and low $\upsilon^*_{e,ped}$) with no/small ELMs in stationary conditions for density and radiation have been recently achieved in JET.

A baseline scenario at low q_{95} (=3.2, 3 MA), with moderate NBI power (20-25 MW) and where the gas fuelling is completely removed (known as **'no-gas' Baseline Small ELMs** (BSE) regime)[1,2]

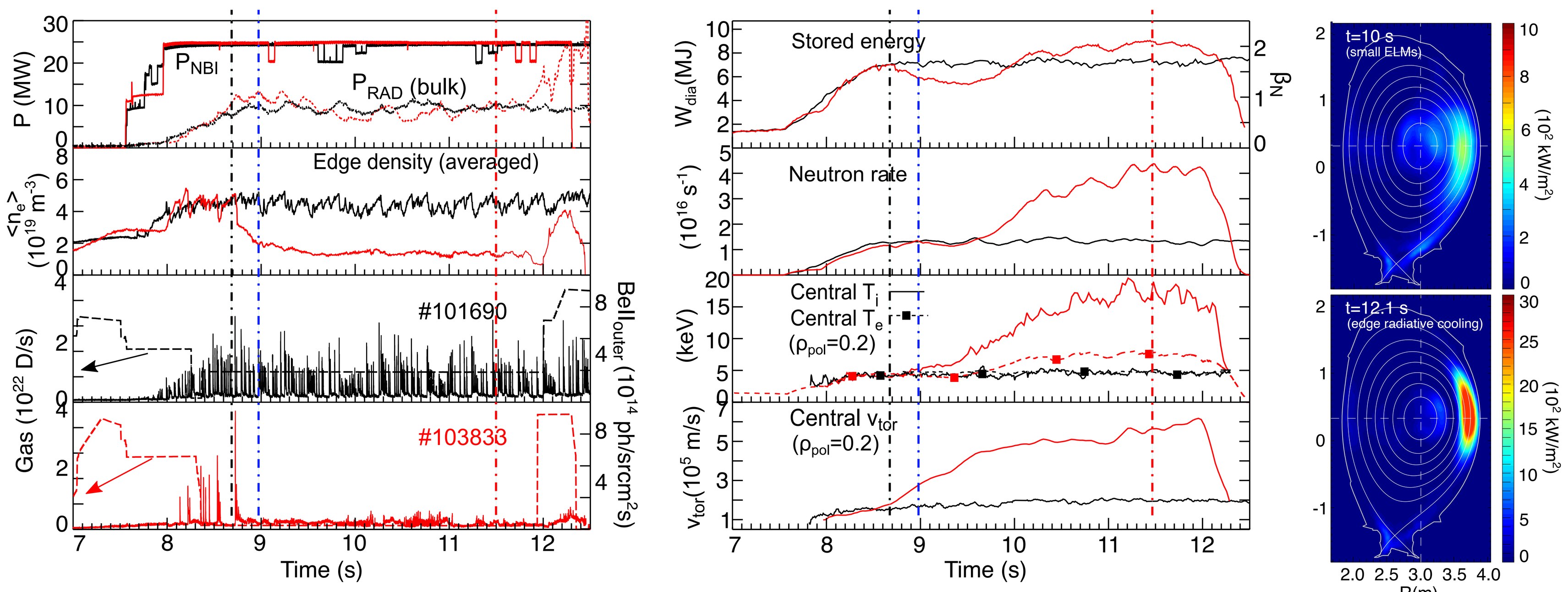
A high-performance scenario at lower I_p=1.9-2.5 MA with dominant electron heating by ICRH (minority heating), explored in D and D-T plasmas [3]

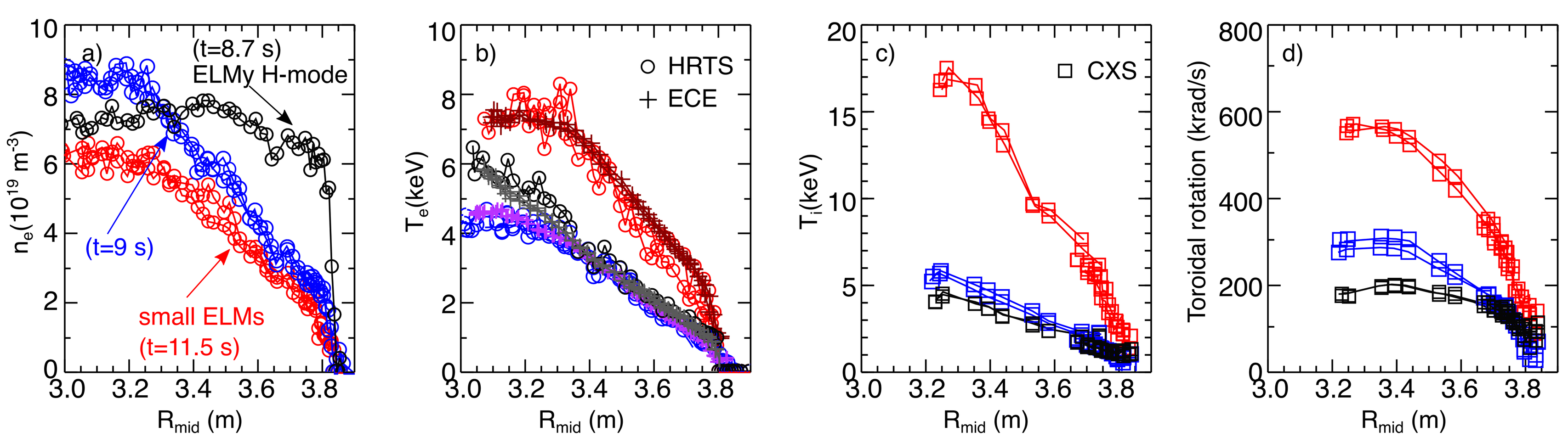
A common feature in both scenarios is the presence of an I-mode-like pedestal (also seen in low density L-H transitions experiments [5]). In contrast to observations of the I-mode in other devices, no edge coherent MHD activity (WCM)

HIGH PERFORMANCE PLASMAS WITH SMALL ELMS AT LOW $\nu^*_{e,ped}$ IN JET-IL

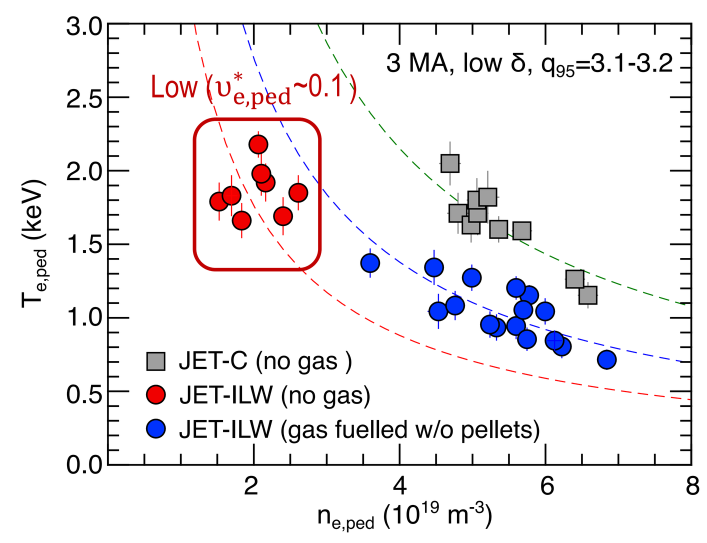
- **Discharges in the 'Baseline with small ELMs' (BSE) regime cover a different operational space than other H-mode regimes with small ELMs:**
  - 3 MA/2.8 T, q_{95} = 3.2, β_{pol}<1
  - good energy confinement, β_N=1.8-2.2
  - low pedestal collisionality ($\upsilon^*_{e,ped}$~0.1)
  - no impurity accumulation
  - low density Greenwald fraction (<0.3)
- Compared to conventional ELMy H-mode, they have:
  - better confinement and stronger rotation
  - higher T_i (at pedestal and in core, with T_i>>T_e)
  - higher DD neutron rates
  - → Similarities with 'hot-ion' in JET-C but also clear differences

Improved core energy confinement facilitated by favourable conditions for ITG driven turbulence stabilisation[1,2]

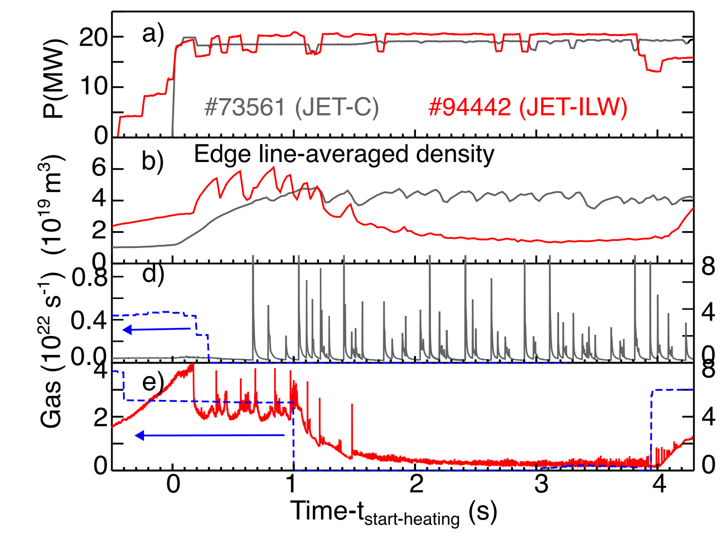




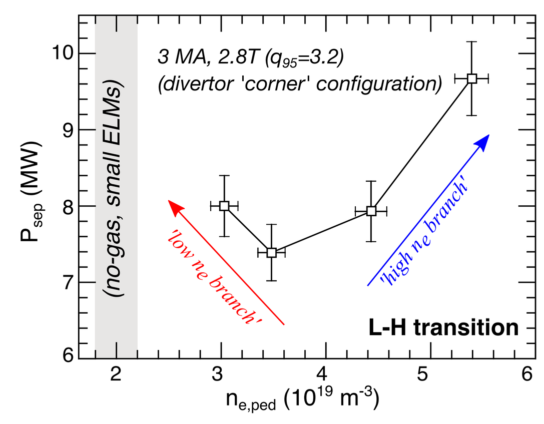
The lower recycling and wall retention of the Be wall allows access to a low-density regime that was not accessible with the C-wall



Low frequency type I ELMs typically observed in low δ, unfuelled plasmas in JET-C

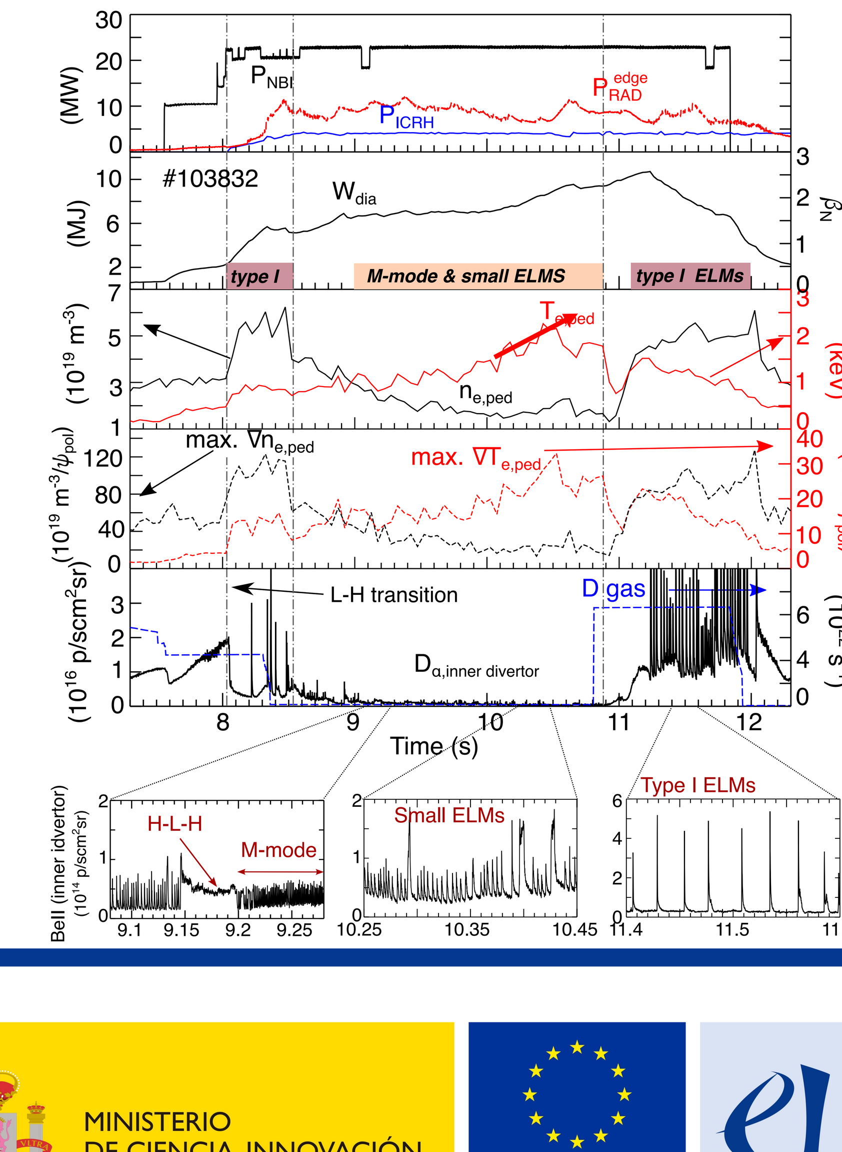


Operation at high P_{LH}: favourable ion ∇B drift for H-mode access but operating in the 'low density branch' of the P_{LH}



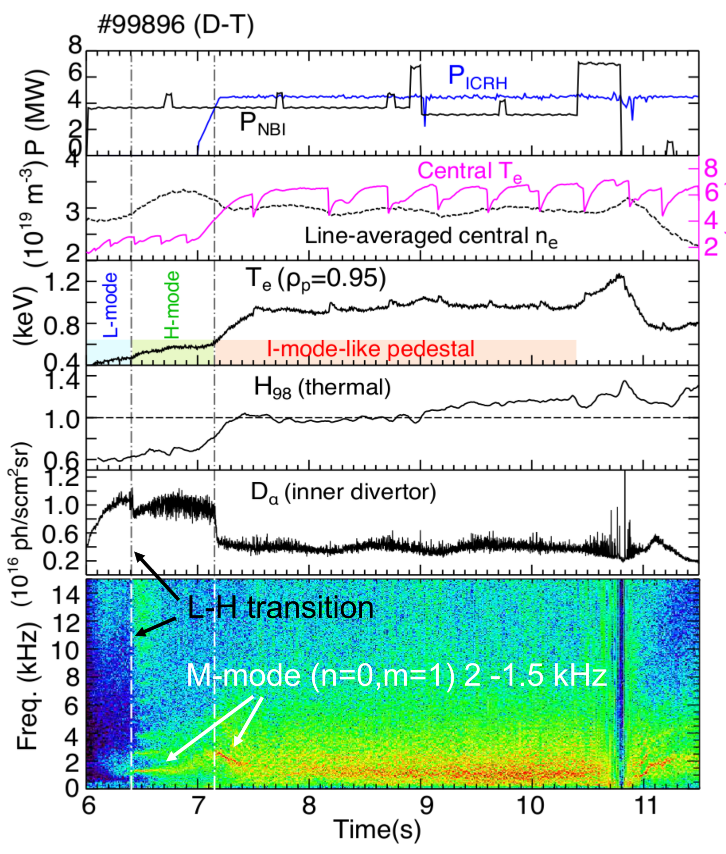
Operation close to the L-H transition, consistent with the behaviour of the divertor spectroscopy signals → high P_{LH}

Small ELMs maintained as $T_{e,ped}$ (& $T_{i,ped}$) increase at constant P_{IN} → **Edge pedestal gradients are not fixed by MHD stability limits**, as in the case of the ELMy H-mode, but **are most likely transport limited**

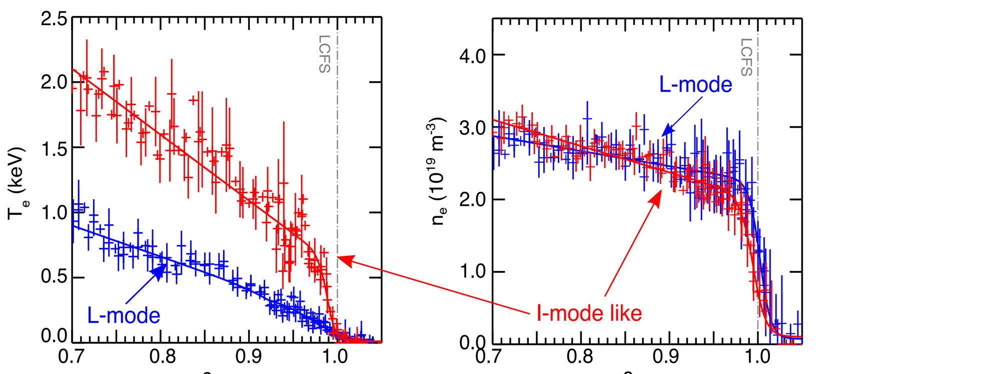


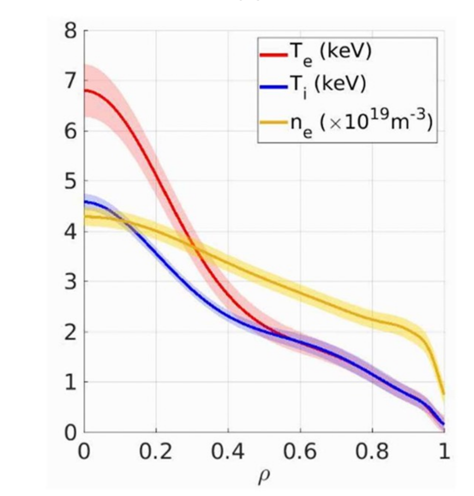
[1] J. García et al., Physics of Plasmas **29** (2022) 032505
[2] E. de la Luna et al., Nucl. Fusion **64** (2024) 096014
[3] J. García et al., Nature Communications **15** (2024) 7846
[4] E. Delabie et al, APS conference, 2016
[5] M. Dicoratto et al., submitted for publication

I-MODE LIKE PEDESTALS WITH NO ELMS ALSO OBSERVED IN PLASMAS WITH HIGH ELECTRON HEATING AND LOW TORQUE [5]



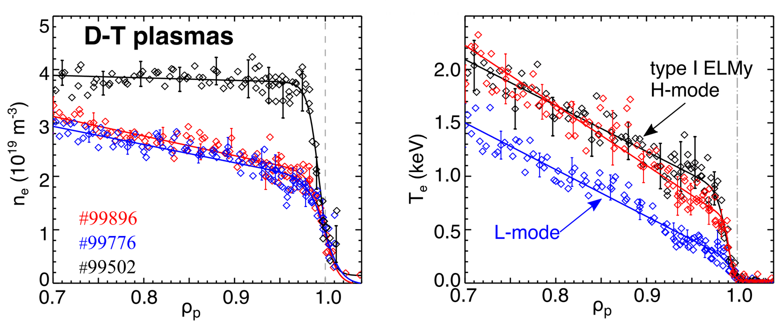
- D-T plasmas (1.9MA, 2.8 T, q_{95}=4.5) with f_{GW}=0.45 (also observed in D plasmas but it requires higher heating power)
- High electron heating and low torque (low NBI + ICRH): $T_{e,0}/T_{i,0}$~1.4
- Good impurity transport properties (no impurity accumulation)
- H-mode-like confinement ($H_{98,thermal}$=1-1.2) without a substantial change in density & pronounced increase in $T_{e,ped}$ → **I-mode-like**
- No ELMs (weak ∇n_e → low ∇P)

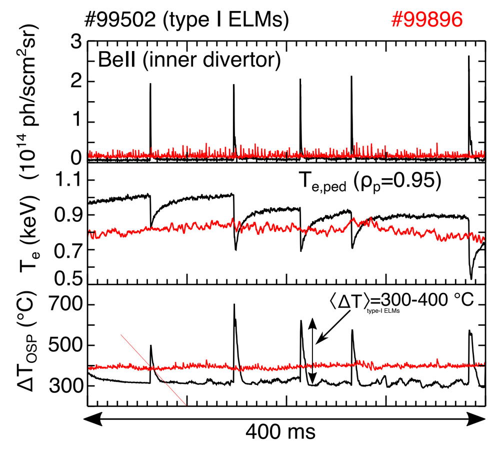




- **There are similarities with the I-mode:**
  - an H-mode-like pedestal is built up in the temperature profile, the density profile gradient resembles that found in L-mode

BUT some differences:
  - H-mode access with favourable ion ∇B drift for H-mode
  - operation close to the L-H transition, requiring low heating power
  - no edge MHD (WCM) observed in JET

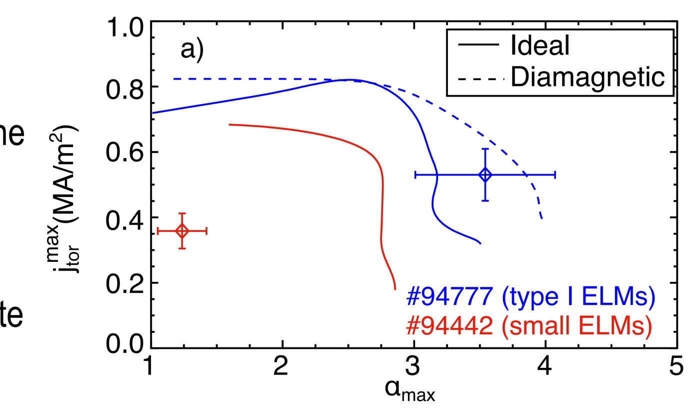




In the regime with an I-mode like pedestal:
- No ELMs
- Filaments observed in BeII/WI/D_α divertor signals but with no significant impact on pedestal or divertor IR signals

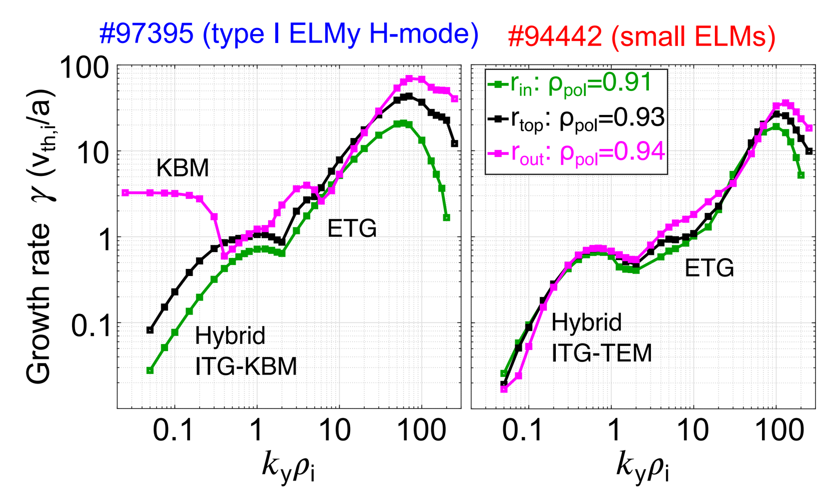
PEDESTAL STRUCTURE & EDGE STABILITY

- Compared to the ELMy H-mode plasma, the discharge with no-gas and small ELMs [2] has:
  - lower $n_{e,ped}$, larger $T_{e,ped}$ (and $T_{i,ped}$)
  - wider pedestals, significantly lower maximum ∇n_e & ∇P
  - comparable maximum ∇T_e → higher T_e^{ped} is due only to the wider width
  - maximum gradient position shifted inwards → improved pedestal stability
  - reduced edge current (due to the reduction in ∇n_e), despite the lower $\upsilon^*_{e,ped}$

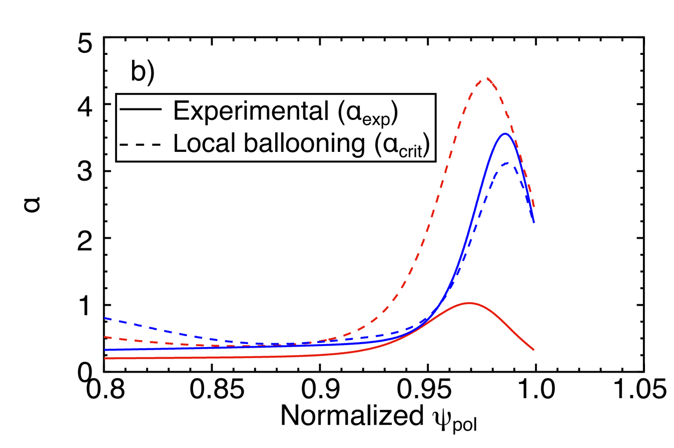


The edge plasma of the small ELMs discharges is very stable with respect to the P-B modes, consistent with the lack of ELMs [1,2]

- Local gyrokinetic simulations in the pedestal region [5]:
  - type-I ELMy H-mode: KBM unstable
  - small-ELMs: hybrid ITG-TEM (w/o KBM)



- α_{exp} is far from the local ballooning predictions across the entire pedestal profile → different from the QCE regime where α_{exp} = α_{crit} at the separatrix (higher $\upsilon^*_{e,ped}$, higher $n_{e,SOL}$) *[M. Dunne, EPS 2024 (invited)]*



CONCLUSIONS

- Recent experiments in JET have shown that operation at low density (and low $\upsilon^*_{e,ped}$) and high pedestal temperature opens a path for developing plasma regimes that allow simultaneous access to good energy confinement and very small ELMs, while maintaining plasma density and radiation in stationary conditions. Experimental evidence indicates that in both cases, plasma operates close to the L-H transition
- The access conditions with very small ELMs at low density in JET do not depend on the heating mix or the isotope plasma composition
- Similarities with Q=10 ITER pedestal: low $n_{e,ped}/n_{e,sep}$ (high $n_{e,sep}$ in ITER, low $n_{e,ped}$ in JET) with high $T_{e,ped}$, $T_{i,ped}$ →edge ∇P is primarily driven by temperature gradients rather than density gradients (as is the case in ELMy H-mode plasmas)
- Open questions: why is there a thermal but not particle barrier in the JET small/no ELM regimes? what keeps the plasma stationary in those conditions? What causes the small ELMs? what is the role of the Weakly Coherent Mode (WCM) in the I-mode regime? Is it an essential feature?

These regimes provide a valuable platform for further validation work using experimental data to refine and gain confidence in the predictions for ITER

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