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Non-linear simulations of small ELMs and bifurcation to type-I ELMs at low triangularity

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Introduction and Motivation

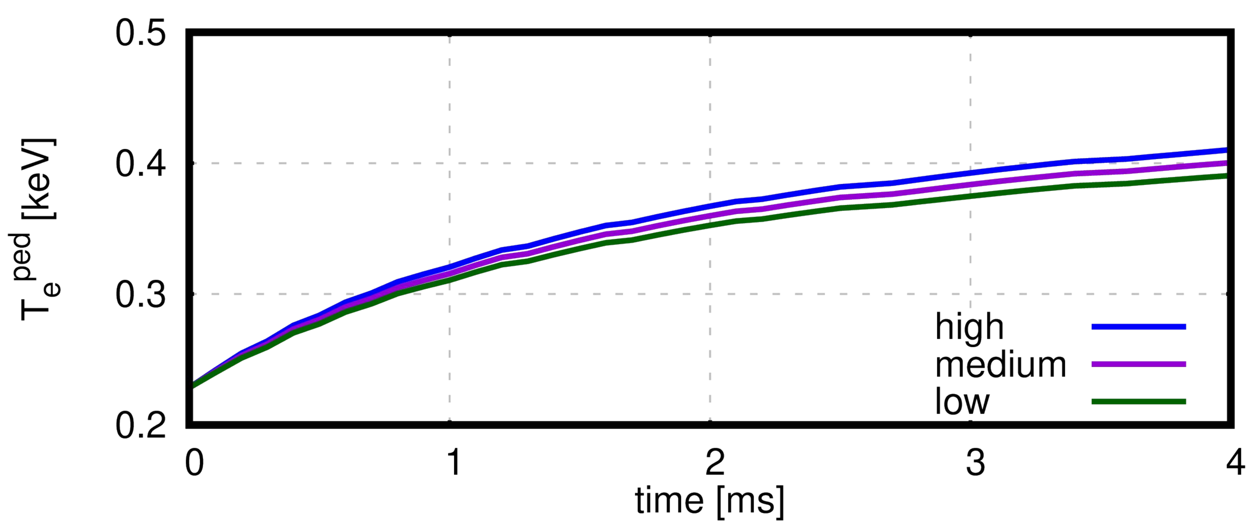
- Type-I **Edge localised modes** (ELMs) are thought to be intolerable for ITER [1]
- Small ELMs are potentially a good steady-state scenario [2-4]
- At low triangularity, small ELMs degrade confinement [3,5]
- From the experiment it is unclear if ITER could operate only with small ELMs [6], thus simulations are imperative
- JOREK is used to simulate small ELMs at low triangularity in ASDEX Upgrade and how they bifurcate to type-I ELMs

2. JOREK

- This work: single temperature reduced MHD plus extensions in X-point geometry [12]
- Toroidal Fourier decomposition
- 2D poloidal Bezier finite elements
- Fully implicit time discretization
- Neoclassical + diamagnetic drifts driven by $\nabla p_i/n$ [13]
- Consistent bootstrap current density evolution

3. Simulation set-up

- Start from **stable** post-ELM equilibrium at low triangularity
- Set $D_\perp$ and $K_\perp$ (fixed in time) to build-up pedestal ($K_{/\!/} \sim 10^8\, K_\perp$)
- High separatrix density $n_{sep} \sim 0.4\, n_{GW}$
- Use resistivity around 3x larger than experiment
- Toroidal resolution: n=0,2,4,...,12
  - Disclaimer: Higher toroidal modes also seen in experiment
- Three different total heating powers
- Double bootstrap current source to keep simulation time shorter



(3) Axisymmetric pedestal temperature recovery with different total heating power

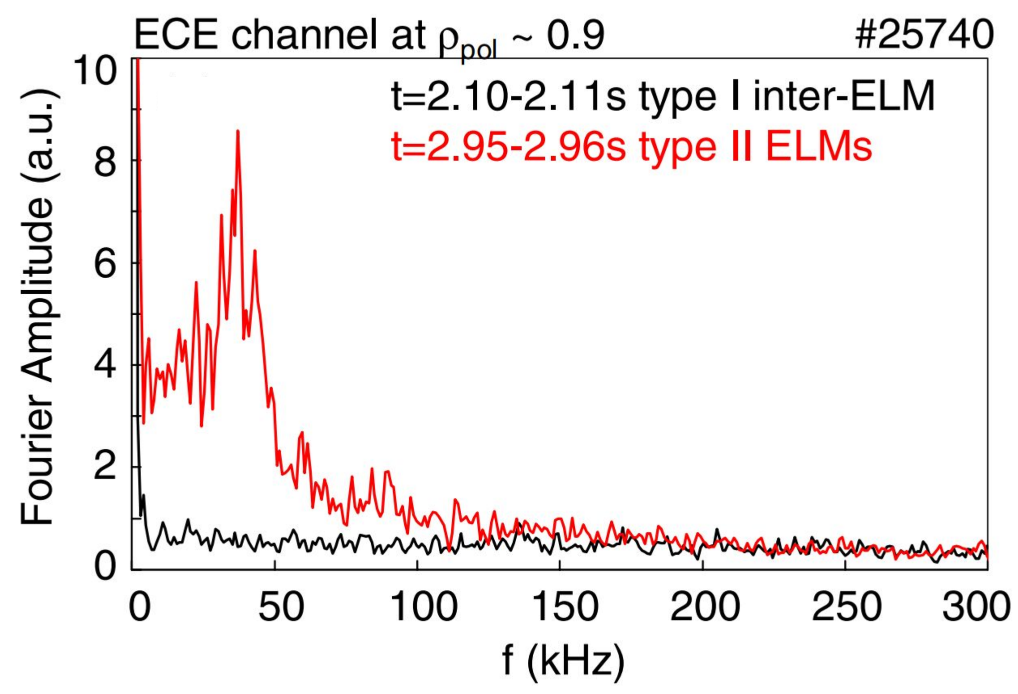
Conclusions

- We show simulations of edge localised instabilities during H-mode pedestal build-up with high separatrix density
- Diamagnetic stabilisation is studied by scanning the temperature recovery time scale
- At **low heating** power, and little diamagnetic stabilisation, small ELMs, which match several experimentally relevant observations, are simulated
- **High heating** (large diamagnetic stabilisation): a large type-I ELM is observed
- **Medium heating**: mixed small + type-I ELMs regime observed
- Next: multiple type-I ELMs, small ELMs at high triangularity, the stabilising effect of local magnetic shear, separation of ion and electron temperature, and type-III ELMs

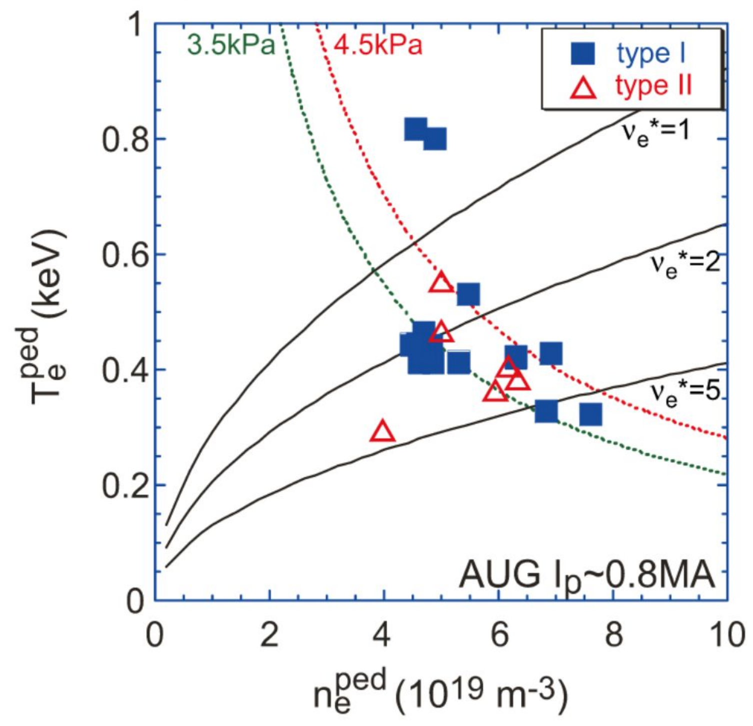
[1] G Federici, et al, *PPCF* 45.9 (2003) 1523
[2] J Stober, et al, *NF* 41.9 (2001) 1123
[3] B Labit, et al, *NF* 59 (2019) 086020
[4] N Oyama, et al, *PPCF* 48.5A (2006) A171
[5] T Eich, et al, *NF* 58.3 (2018) 034001
[6] GF Harrer, et al, *NF* 58.11 (2018) 112001
[7] EJ Doyle, et al, *Phys. Fluids* 3.8 (1991) 2300-2307
[8] H Zohm, *PPCF* 38.2 (1996) 105-128
[10] E Wolfrum, et al, *PPCF* 53.8 (2011) 085026
[11] G Saibene, et al, *NF* 45.5 (2005) 297
[12] GTA Huysmans, O Czarny. *NF* 47.7 (2007) 659
[13] F Orain, et al. *PPCF* 57.1 (2014) 014020

1. Experimental observations

- With $P_{sep} \gtrsim P_{LH}$: enter H mode with type-III ELMs, and increasing P_{sep} encounters a type-I ELM threshold
  - Type-III ELMs appear below the ideal MHD stability boundary, and $f_{ELM} \sim 1/P_{sep}$ [7,8]
- High $n_{e,sep}$ ($\gtrsim$0.4 n_{GW}) shows small ELMs which may degrade confinement, and increasing P_{sep} gets type-I ELMs [3,5]
  - BUT! At high triangularity, confinement stays good [2-4,6,10]!
  - Broadband fluctuations (30-50 [kHz]) observed across devices close to pedestal top (fig**1**) [10,2,11]
  - No clear crash + recovery dynamics in pedestal T or ∇p observed, but roughly constant fluctuations



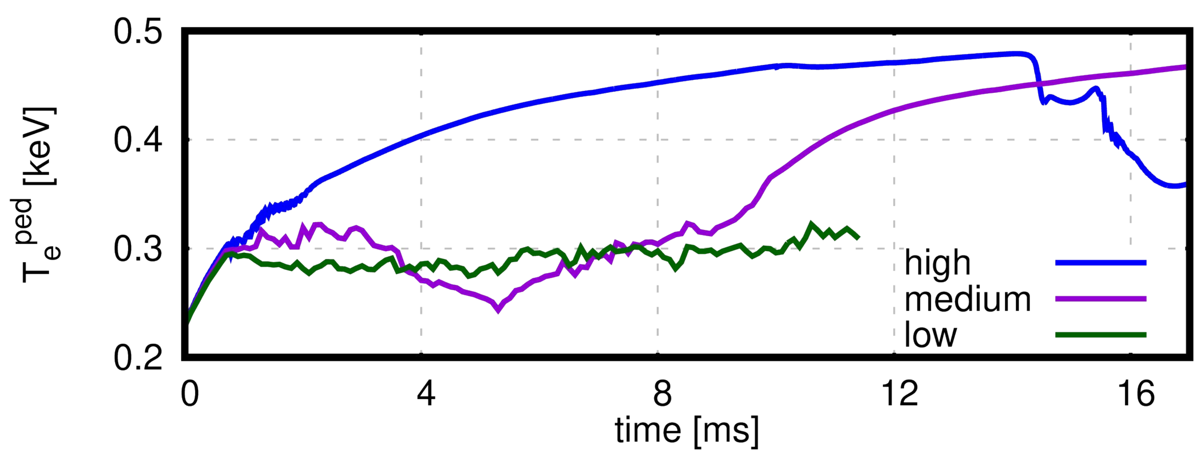
(1) Frequency spectrum of ΔT/T fluctuations in ASDEX Upgrade during type-I inter-ELM (in black) and small ELMs (in red) operation [10]



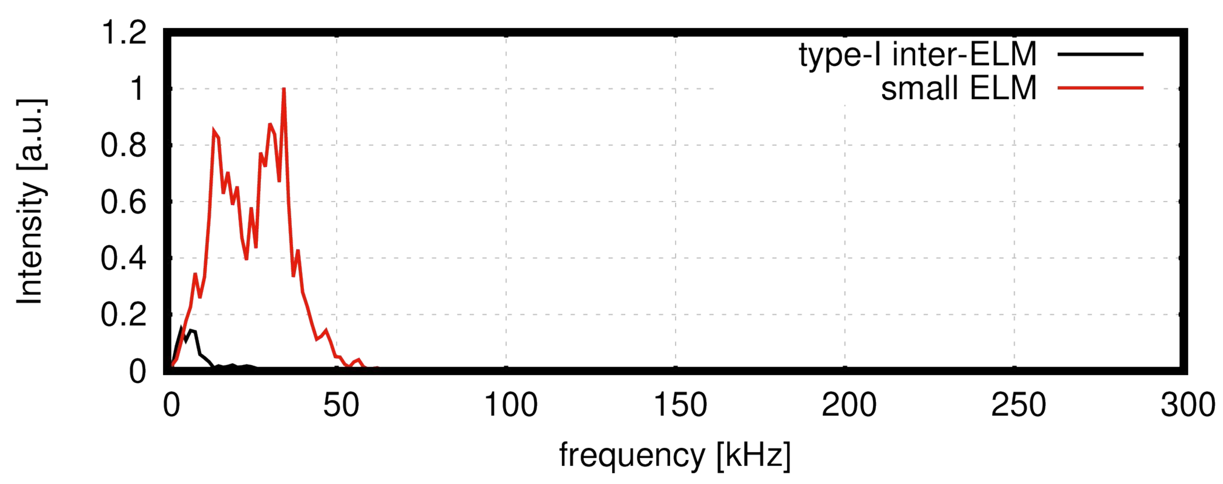
(2) AUG type-I and small ELMs in n vs. T space [4]

4. Simulation results and observations

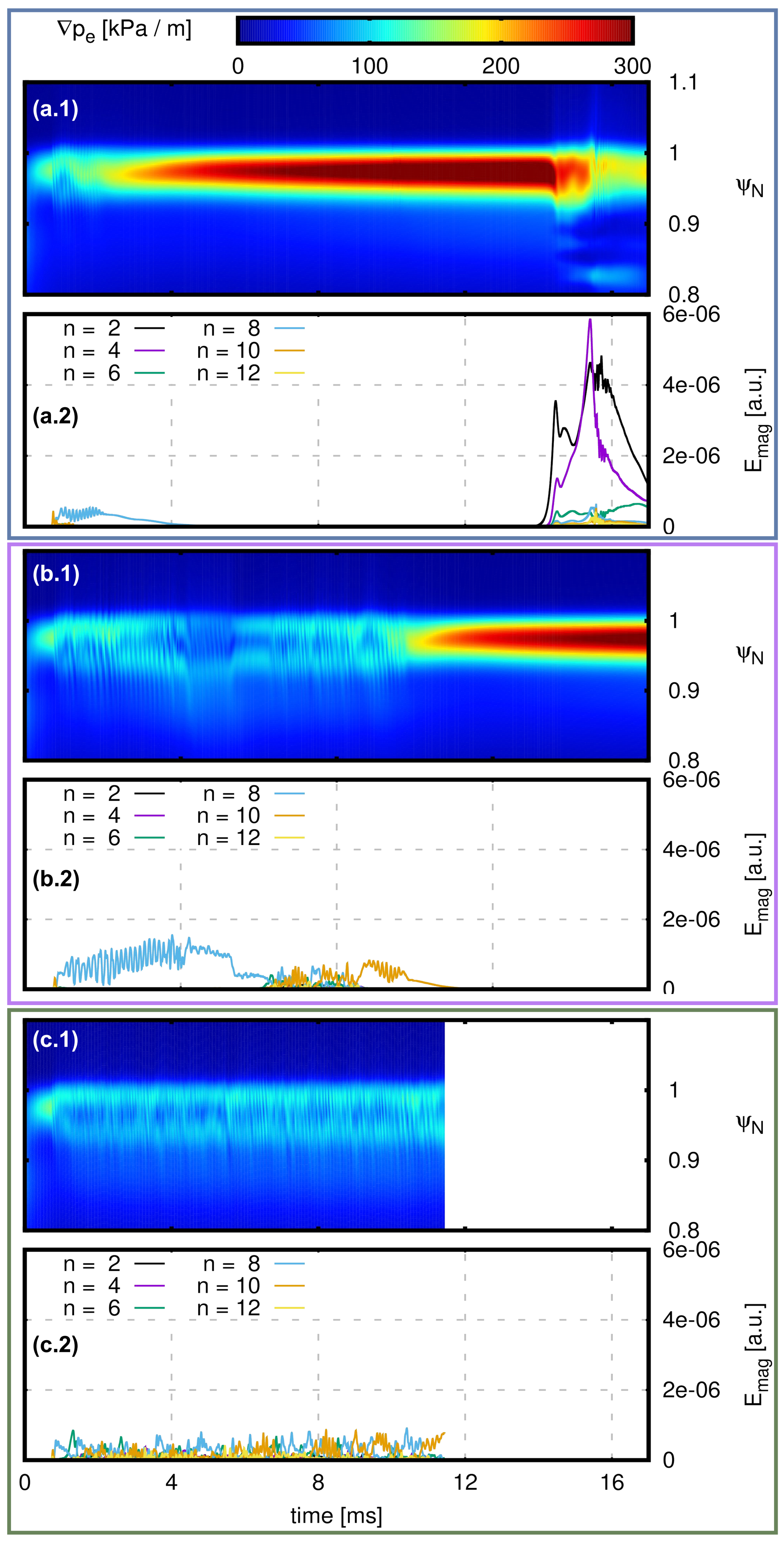
- **High heating:** strong type-I ELM (fig**4.a**, fig**5** and ■ in fig**7**)
  - n=2 precursor followed by n=2+4 dominated ELM crash
  - Outer (inner) divertor power loads during crash ~24(18) [MW]
  - $\Delta E/W_{MHD}$ ~ 10% in approx. 2 [ms]
- **Medium heating:** mixed small ELMs + type-I ELMs (fig**4.b**)
  - Type-I ELM crash not yet reached, but pedestal conditions show that it is approaching (fig**5**)
  - Small ELMs deposit between 5-7 (3-4) [MW] on the outer (inner) divertor until they give way to the type-I ELM
- **Low heating:** only small ELMs (fig**4.c** and △ in fig**7**)
  - max($-\nabla p$) remains low around ~ 120 [kPa/m] (fig**5**)
  - In [11], under similar conditions (AUG #25740), type-II ELMs kept max($-\nabla p$) at ~ 150 [kPa/m]
  - Freq. spectrum peaks at ~30 [kHz] (fig**6**), like small ELMs in AUG [10], TCV [3], and JET [11]
  - Outer (inner) divertor "constant" power loads 4-6 (3-4) [MW]
  - Separatrix ballooning turbulence, which sets in due to large n_{sep} (large α_{sep}), causes most losses
  - Suddenly increasing heating recovers type-I ELM behaviour
  - Lowering n_{sep} to 30% n_{GW} sees the small ELMs disappear



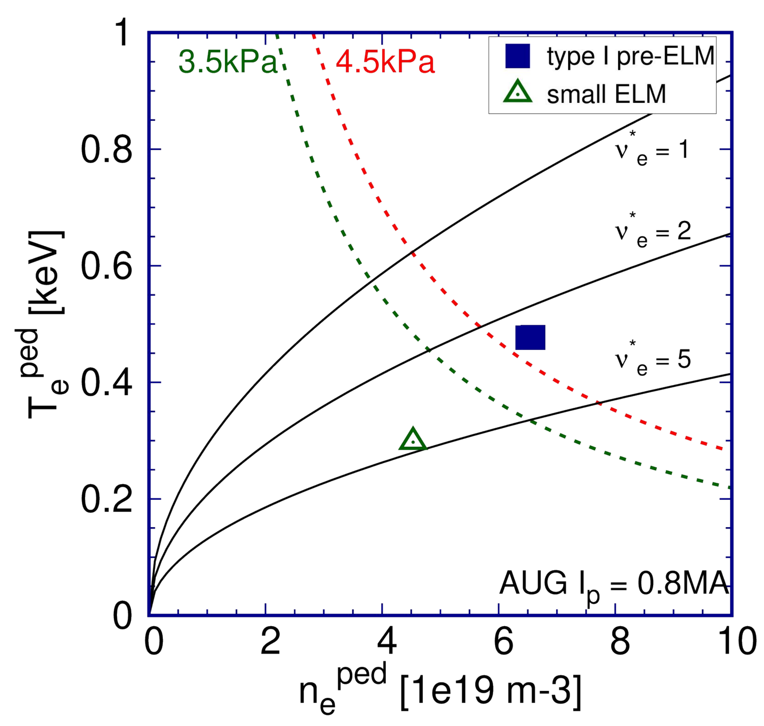
(5) Perturbed pedestal temperature for the three different heating powers



(6) Frequency of δn fluctuations averaged over 6 [ms] for two different cases



(4) **a**=high heating, **b**=medium heating, **c**=low heating
[a,b,c].1 outboard midplane pressure gradient in time, and **[a,b,c].2** magnetic energy of toroidal modes



(7) High and low heating scenarios in n vs. T space, seems to agree very well with fig2 (originally from [4])

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