Pedestal stability analysis of MAST-U H-mode plasmas and impact of plasma shaping parameters

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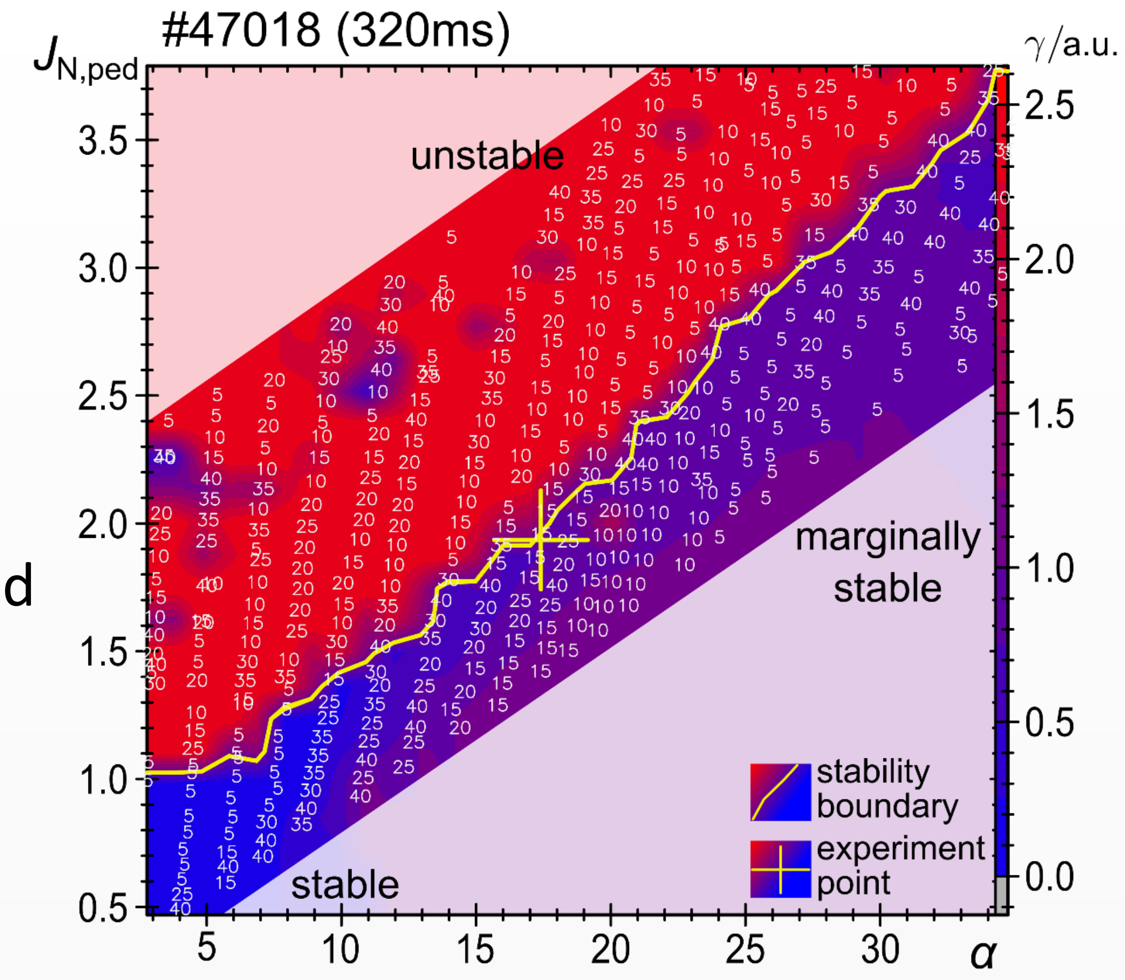
Outline

- "Headline news":
  - Peeling-limited pedestal phases observed in MAST-U H-mode scenario.
- Outline:
  - Peeling-ballooning theory for ELMs
    - Key parameters: "$J_{N,ped}$" and "α"
  - MAST-U pedestal stability
    - Extended stability region between peeling and ballooning branches (weakening coupling)
  - In high $T_{e,ped}$, low collisionality cases, stable against ballooning modes entirely.
  - Interesting high-triangularity case
  - Ongoing: more shaping parameter scans



Peeling-ballooning theory for ELM cycle

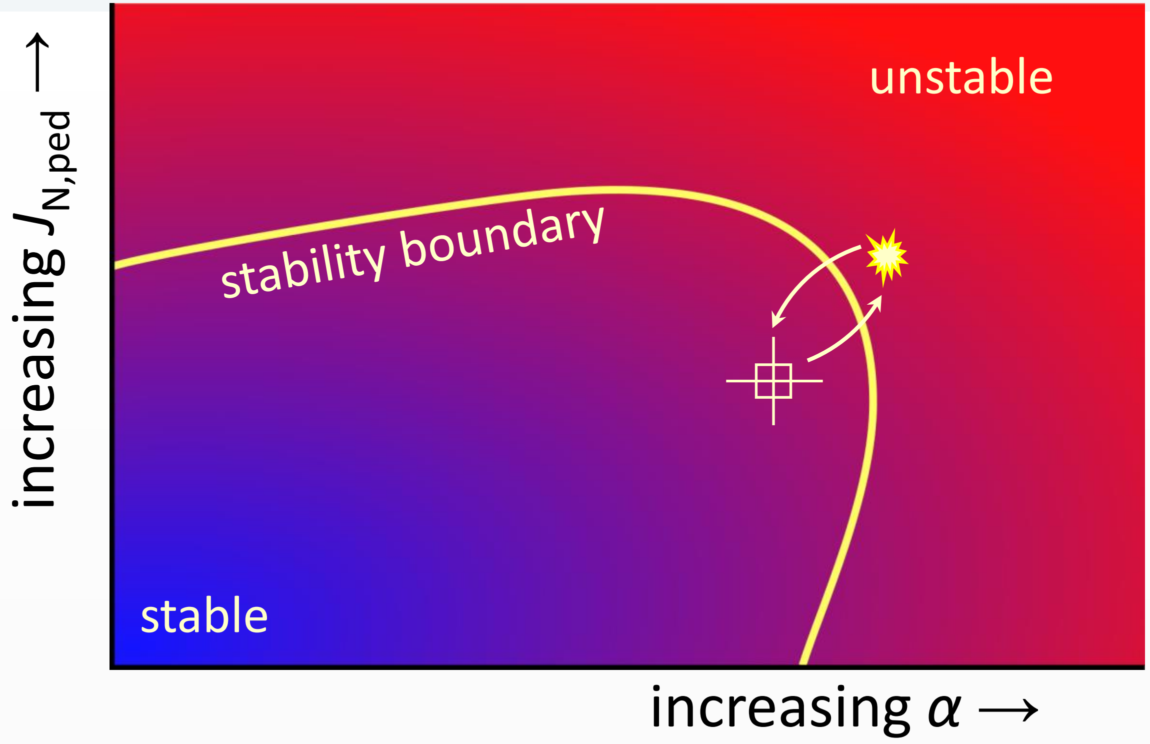
- According to the theory:[#1]
  - Pedestal stability in terms of pedestal current density, $J_{\mathrm{N,ped}}$ and normalised pedestal pressure gradient, α:

$$J_{\mathrm{N}} = \frac{J_{\mathrm{PB}}(\psi) + J_{\mathrm{PB}}(\psi_{\mathrm{separatrix}})}{2I(\psi)/A(\psi)}$$

$$J_{\mathrm{PB}} = (RB_T/R_0)\langle J_{||}/B\rangle$$

$$\alpha = \frac{\mu_0}{2\pi^2}\frac{\partial V}{\partial \psi}\left(\frac{V}{2\pi^2 R}\right)^{1/2}\frac{\partial p}{\partial \psi}$$

  - ELM triggered when stability boundary is crossed.
  - Crash brings $J_{\mathrm{N,ped}}$ and α back to the stable region again.

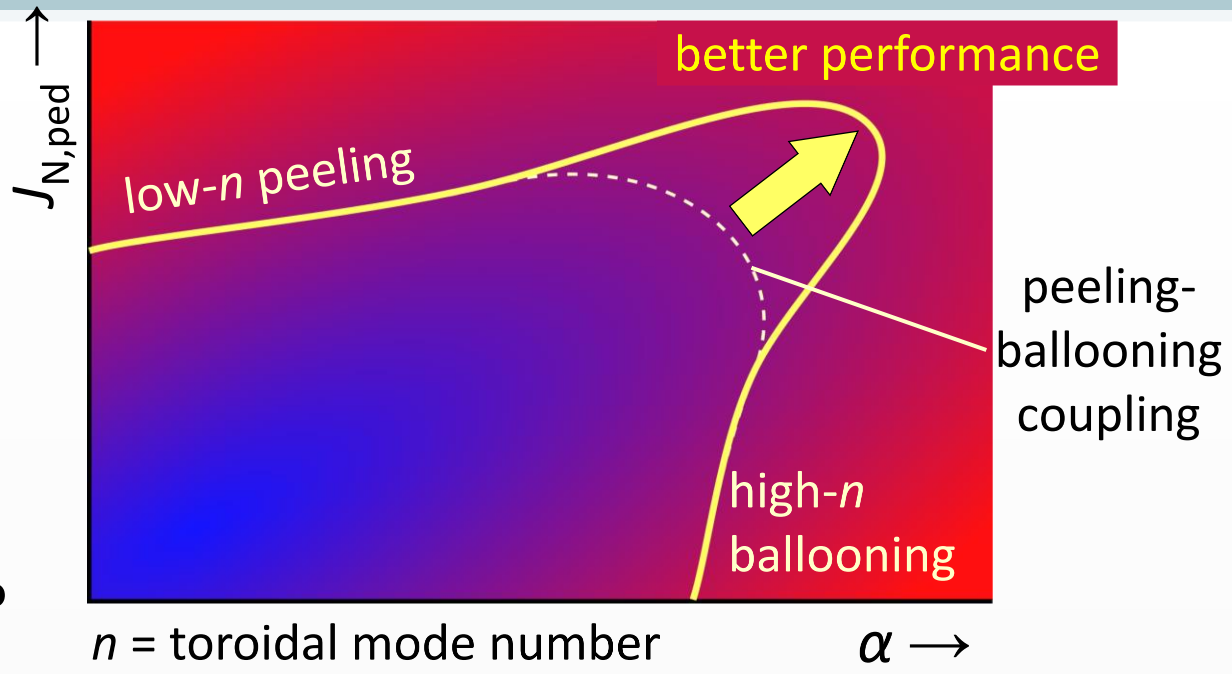


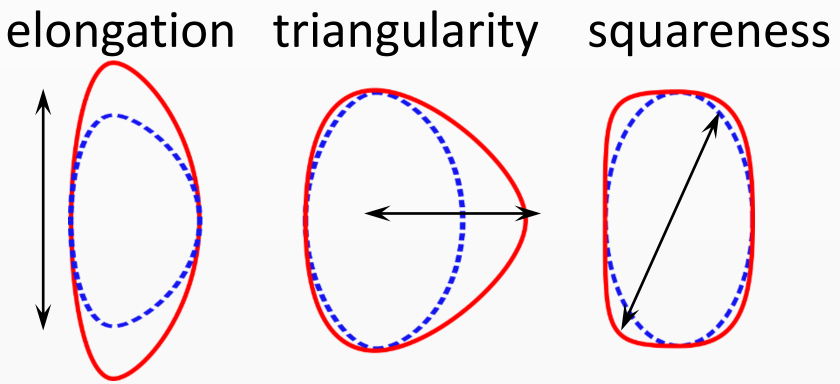
- How can we improve performance?
- How can we "move" the pedestal stability boundary?

#1: Connor et al, *Phys. Plasmas* **5** 2687 (1998), etc.

Research aim: optimise MAST-U pedestal stability

- Future fusion reactors, e.g. STEP, will operate in ELM-free* H-mode regimes.
  - Needs to avoid high-*n* ideal ballooning modes
  - Also stay clear of low-*n* peeling mode stability boundary
- Questions:
  - What affects the pedestal stability boundary?
    - pedestal T_e, collisionality ν_*, etc.
    - plasma shaping parameters:[#2,#3]
    - scrape-off layer & divertor config., etc. etc.
  - How do spherical tokamaks compare with conventional tokamaks?





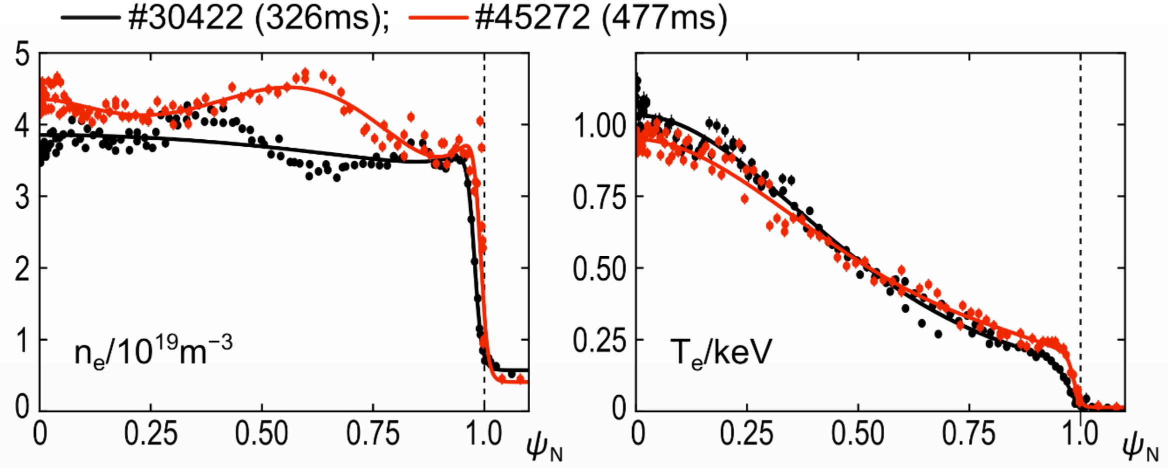
#2: Snyder et al, *Nucl. Fusion* **55** 083026 (2015), etc.
#3: Holcomb et al, *Phys. Plasmas* **16** 056116 (2009), etc.

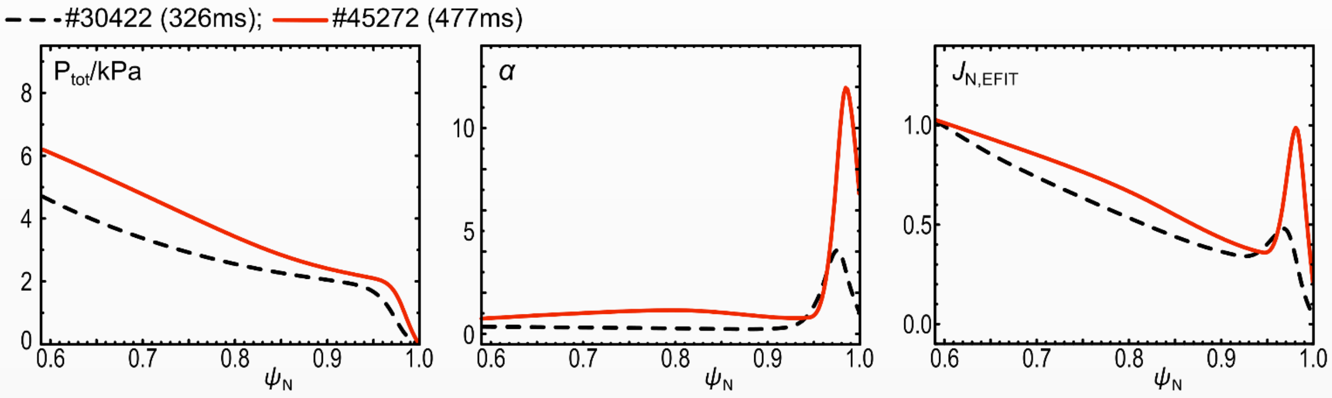
* Or possibly very small ELMs...

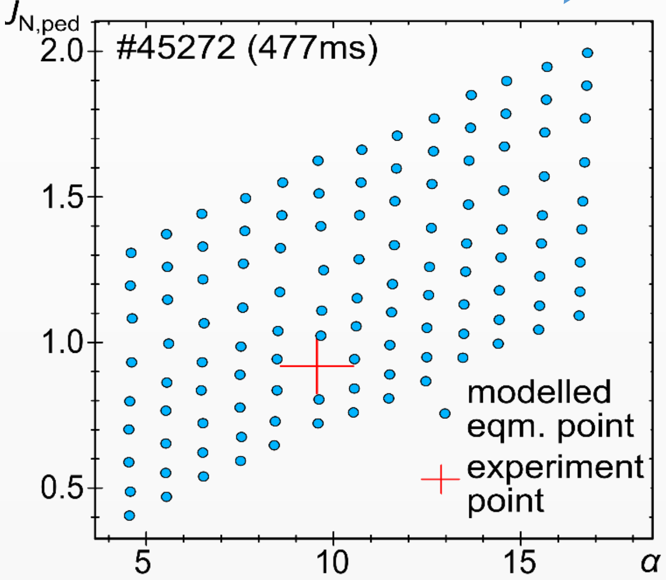
MAST-U H-mode analyses

- OMFIT kineticEFITtime[#4] for profile fitting
- TRANSP for fast ion density/pressure profiles
- Fixed-boundary EFIT with electron profiles for pedestal structure
- VARYPED[#5] to create modelled equilibria with varying $J_{N,ped}$ and α
- ELITE[#6] for MHD pedestal stability analysis

MAST vs. MAST-U:







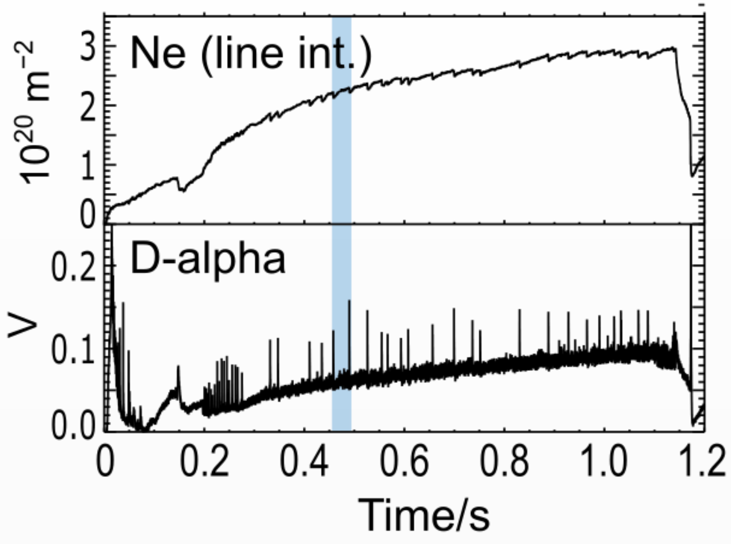
Comparison illustrates how MAST-U pedestal is significantly more developed than MAST ↗

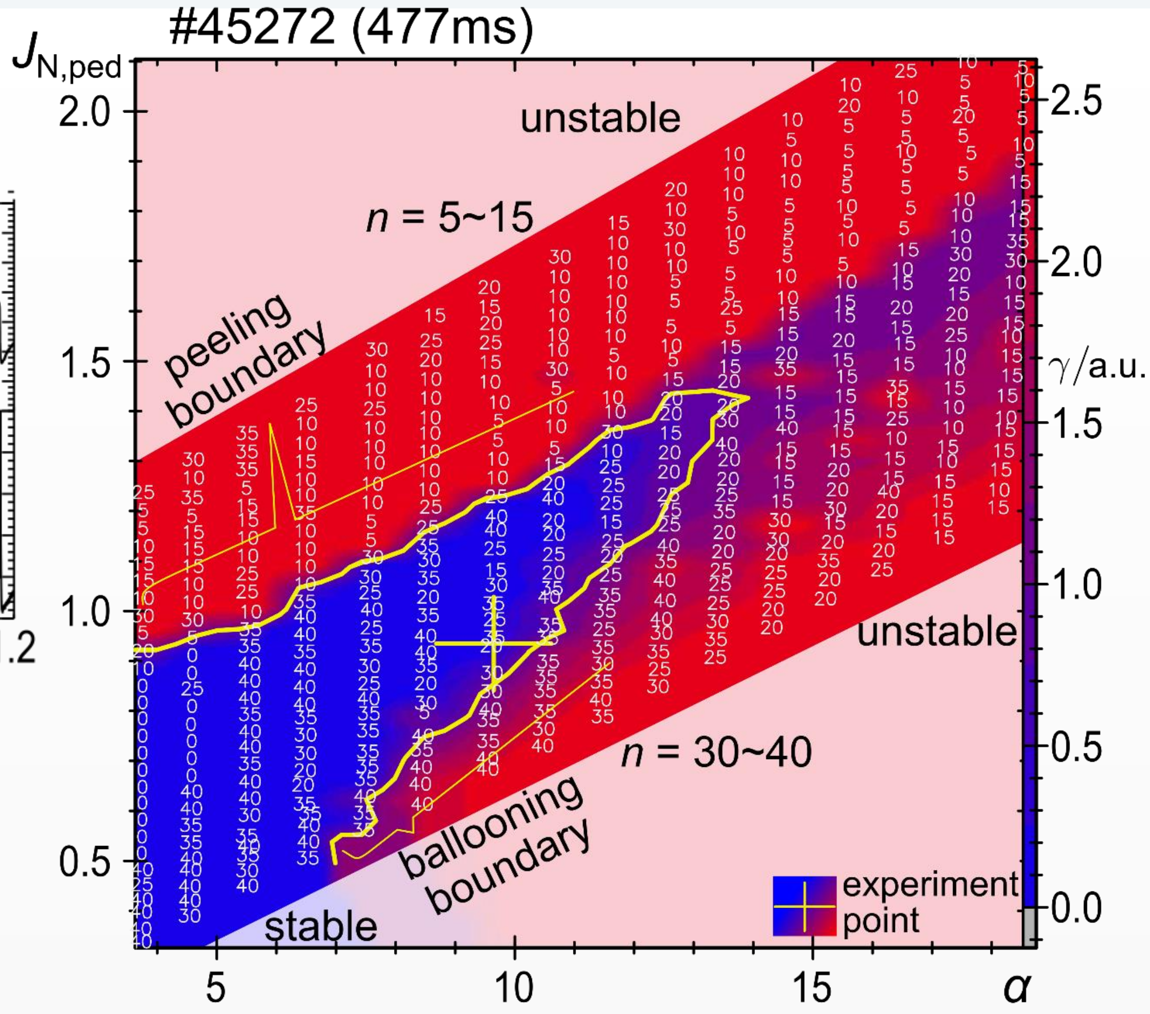
#4: Meneghini&Lao, *Plasma Fus. Res.* **8** 2403009 (2013)
#5: Osborne et al, *Nucl. Fusion* **55** 063018 (2015)
#6: Wilson et al/Snyder et al, *Phys. Plasmas* **9** 1277/2037 ('02)

Pedestal stability diagram for MAST-U[#7]

- Typical MAST-U H-mode, #45272:
  - Type-I ELMy from 400ms
  - Moderately shaped:

elongation	2.16
triangularity	0.48
squareness	0.38
$\nu_{*e,ped}$	1.66
$T_{e,ped}$/keV	0.19
α	9.57
$J_{N,ped}$	0.92





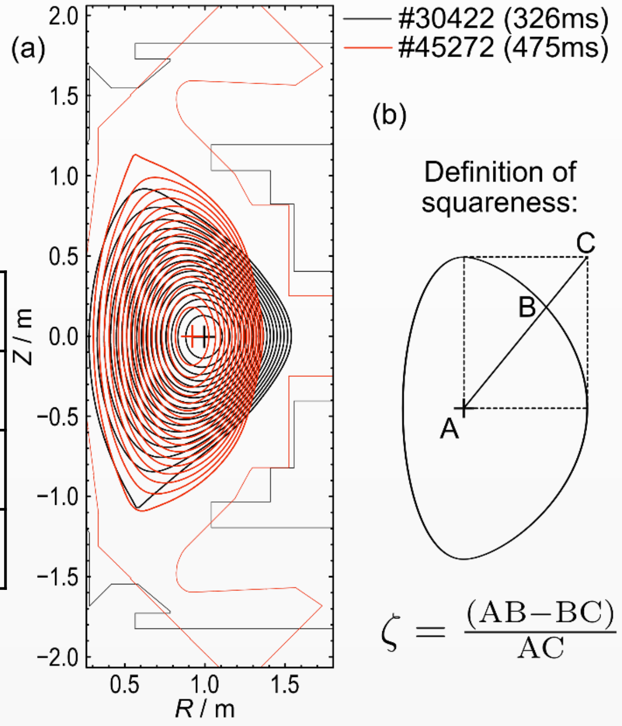
- Mixture of high-n (35 ~ 40) ballooning branch and low-n (5 ~ 15) peeling branch
- Extended region of stability!

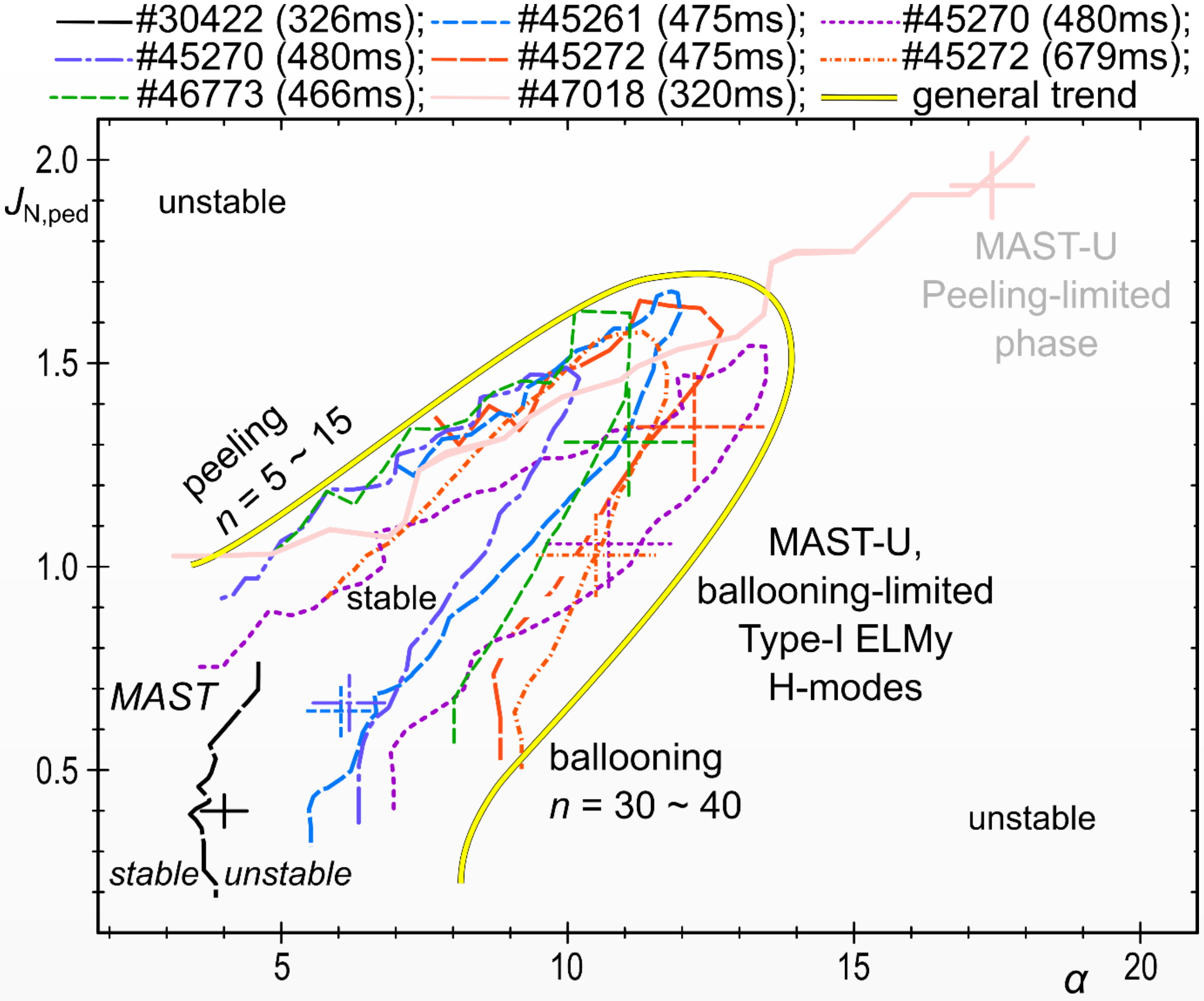
#7: Imada et al, *Nucl. Fusion* (submitted)

Pedestal stability diagram for MAST-U

- Extended stability region a general trend for MAST-U ELMy H-modes:
  - Weakening coupling between peeling and ballooning branches of stability boundary
  - Contributing to significantly higher $J_{N,ped}$ and α for MAST-U, compared to MAST
  - One (of many) explanation in terms of plasma shape:

	MAST	MAST-U
elongation	1.57	2.16
triangularity	0.50	0.48
squareness	0.19	0.38





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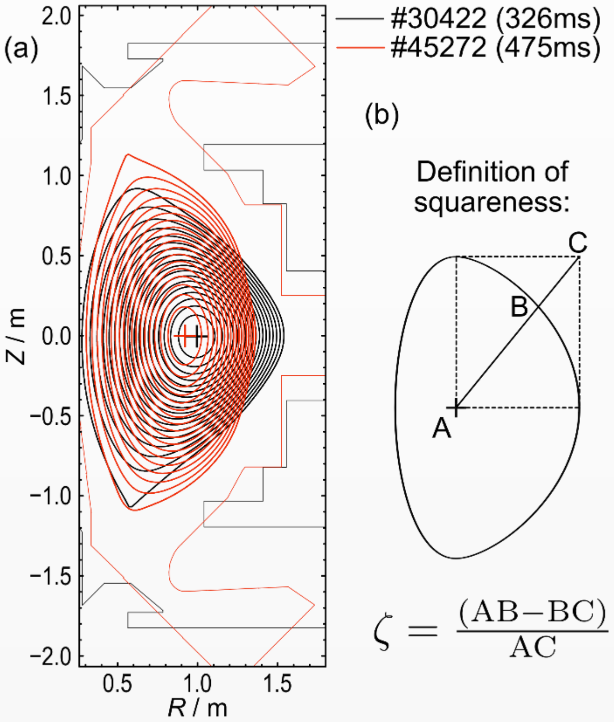
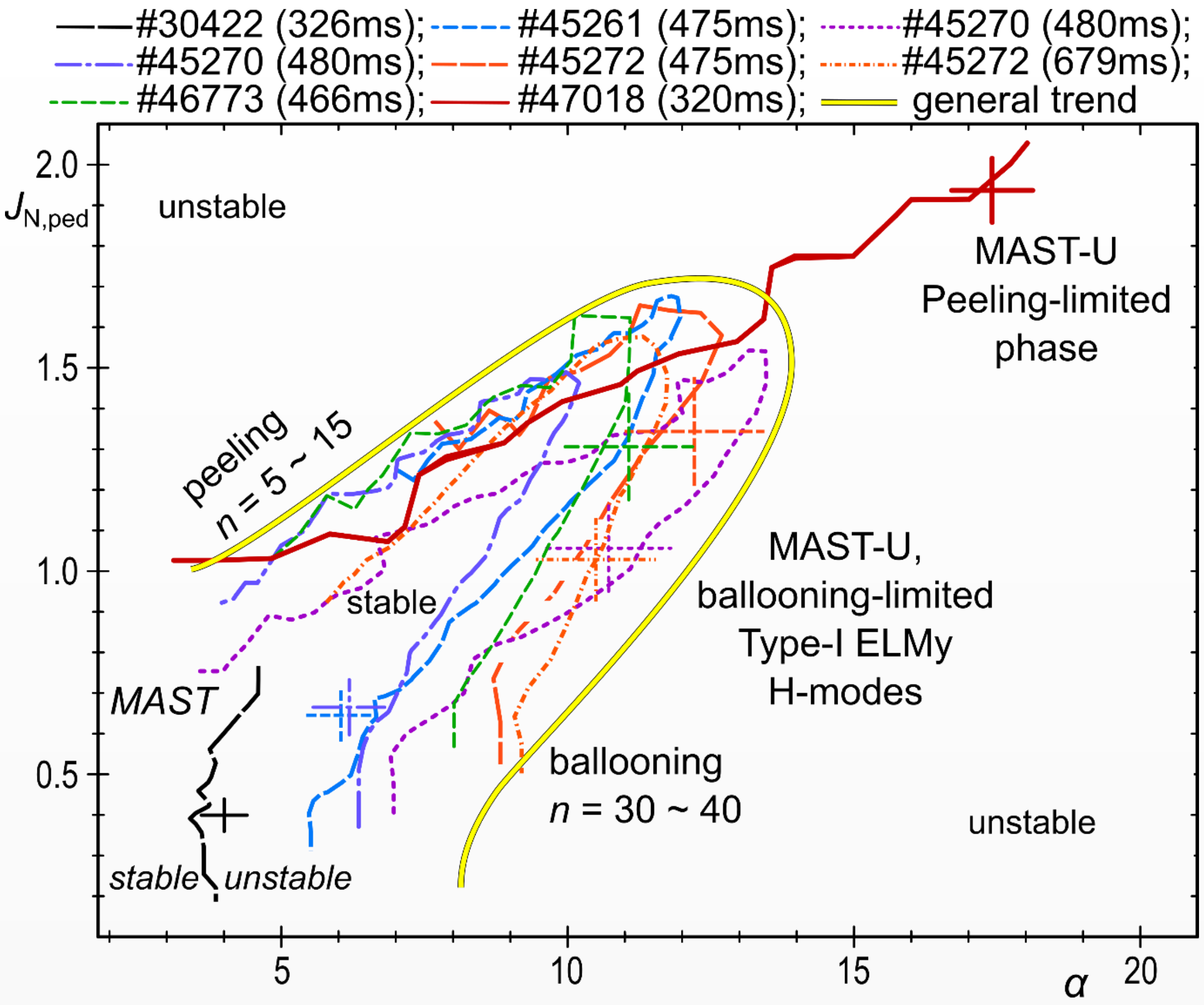
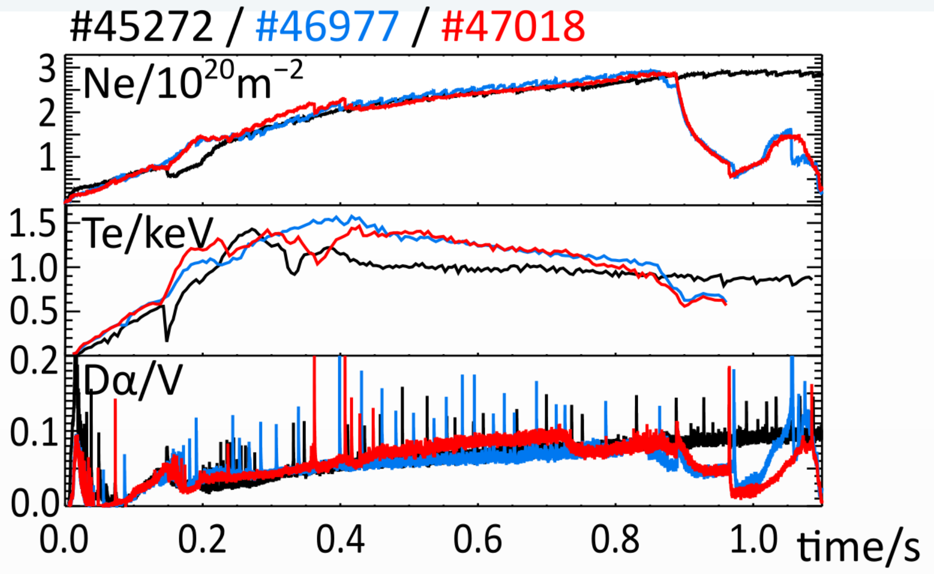


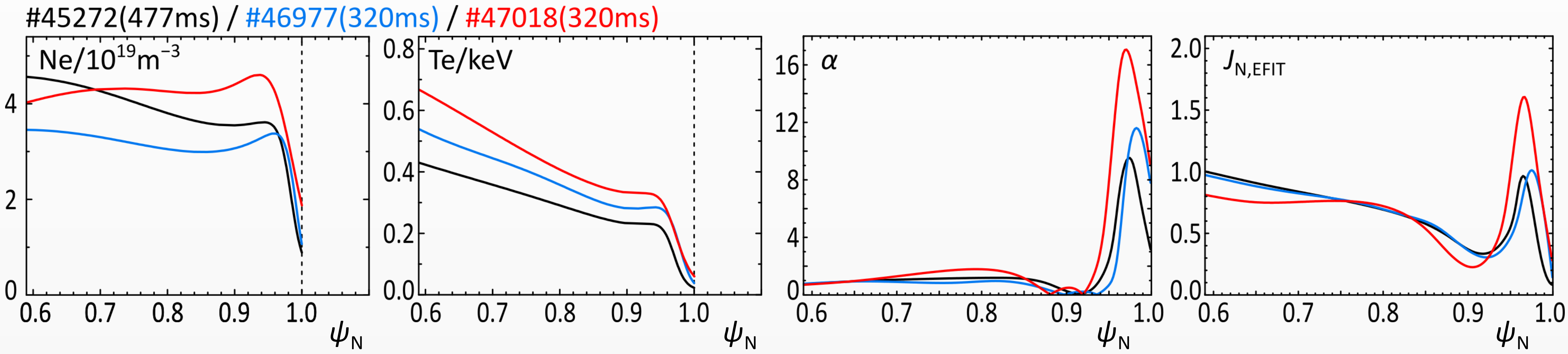


MAST-U high pedestal temperature case

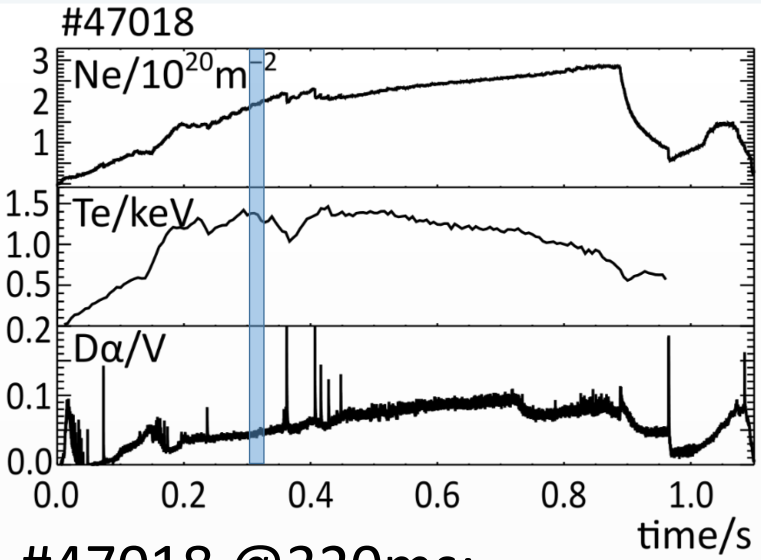
- #47018 has a notably high pedestal temperature:
- Results in low collisionality:
- 100ms of no-ELM phase results in high α (also high $N_{e,ped}$)
- High J_N in the pedestal region
- What about the P-B stability?

	45272	46977	47018
$\nu_{*e,ped}$	1.66	1.45	1.28
$T_{e,ped}$/keV	0.19	0.28	0.31
α	9.57	12.0	17.3
$J_{N,ped}$	0.92	1.15	1.91

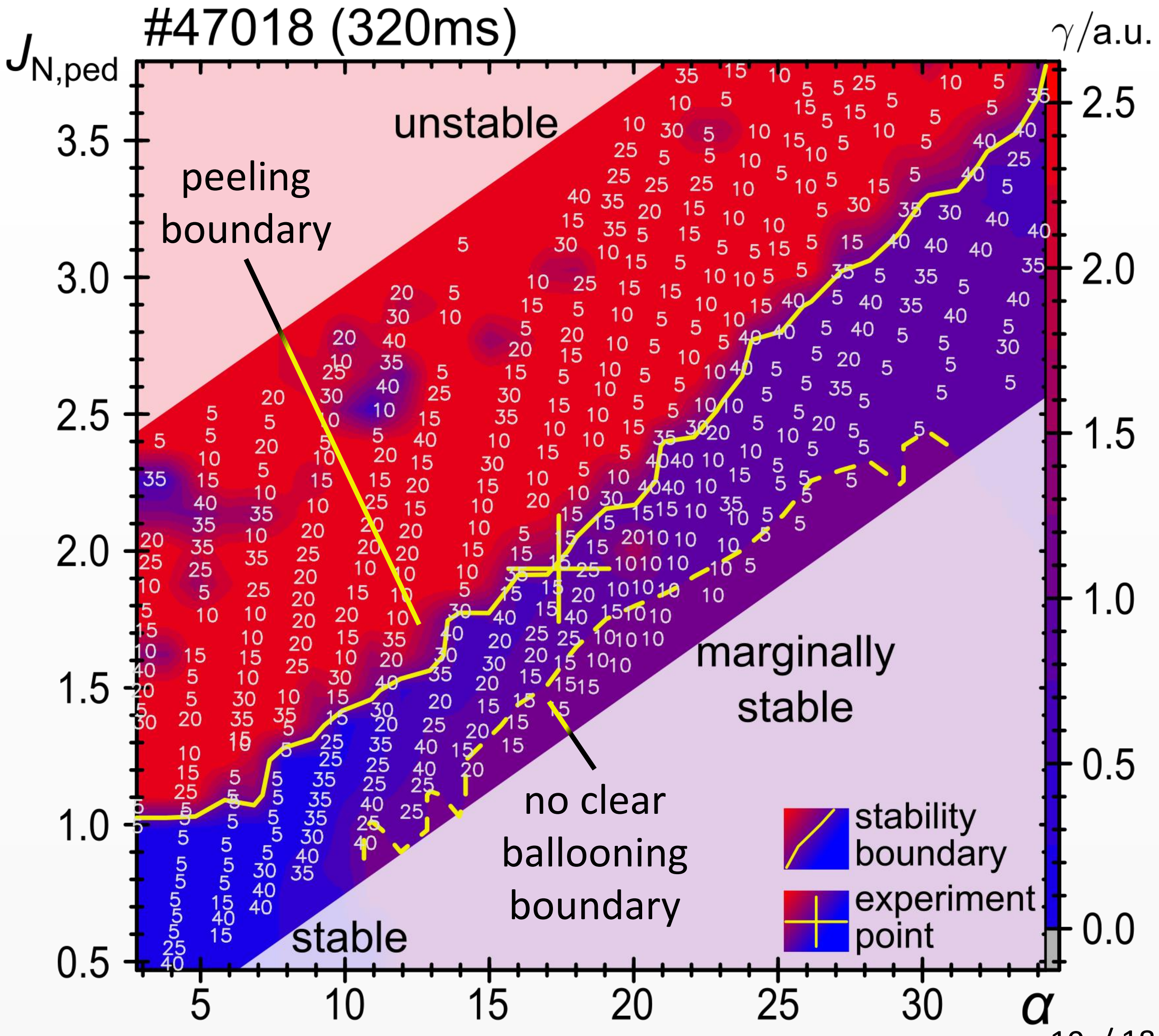




Peeling-limited phase with high Te,ped and low ν_*e,ped

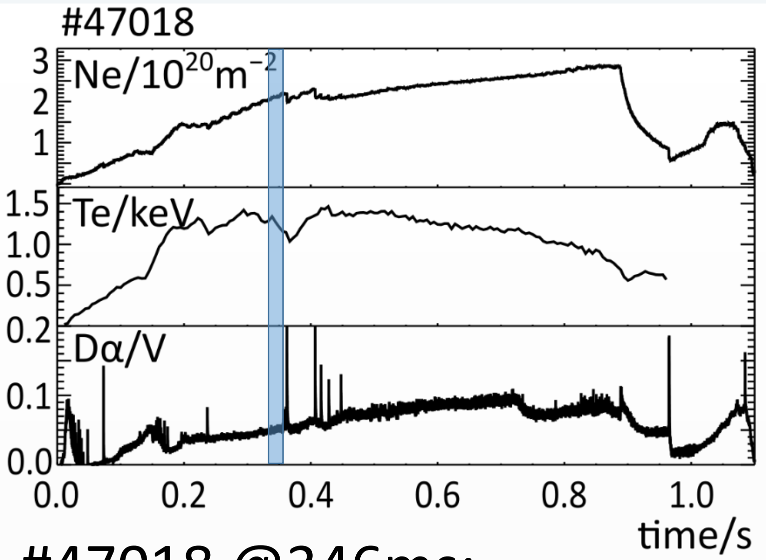


elongation	2.16
triangularity	0.42
squareness	0.38
$\nu_{*e,ped}$	1.28
$T_{e,ped}$/keV	0.31
α	17.3
$J_{N,ped}$	1.91



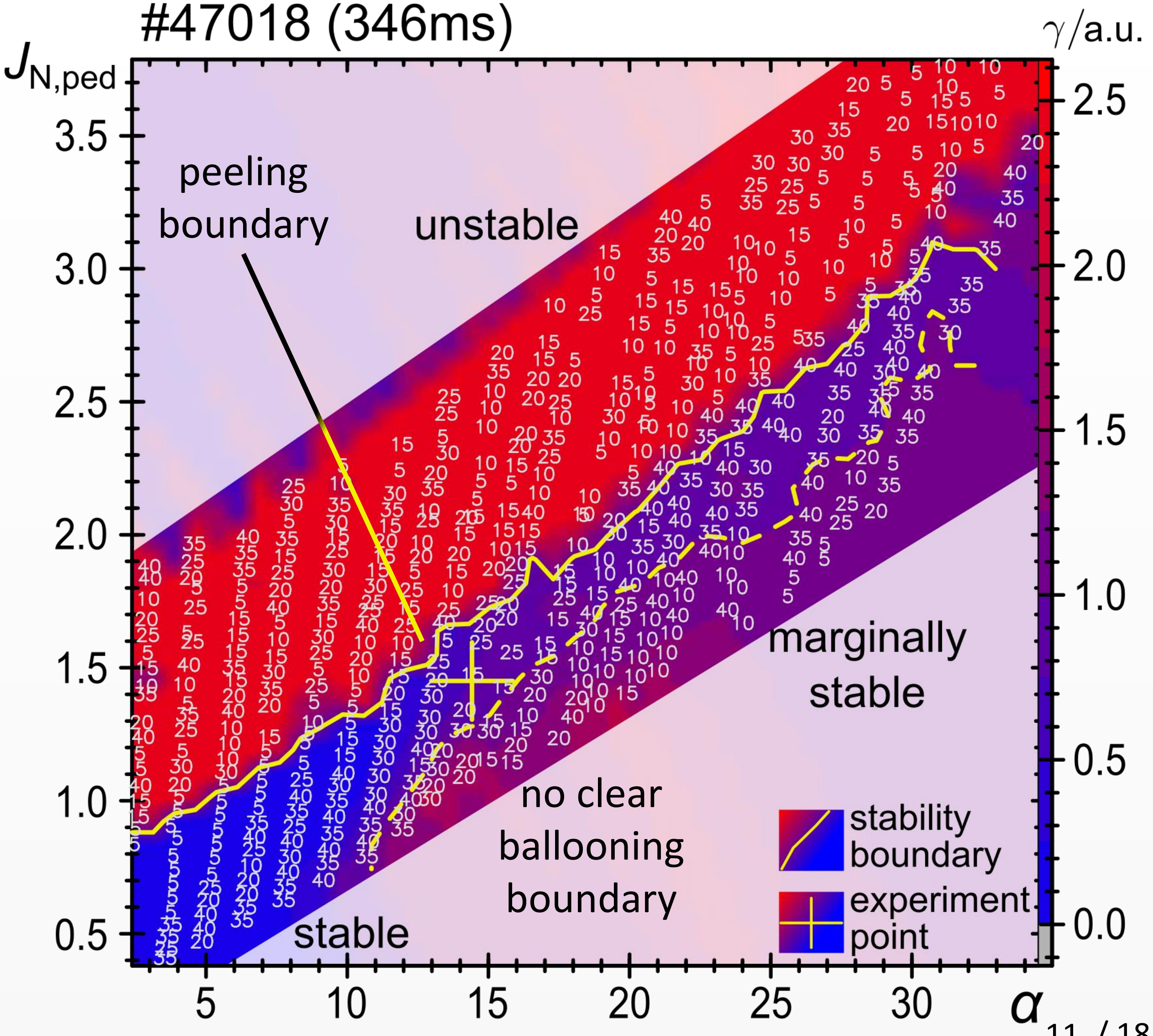
- #47018 @320ms:
  - Unlike "typical" MAST-U cases, no clear presence of ballooning stability boundary
  - (At least marginally) stable to ideal ballooning modes!
  - Lower mode numbers around expt. point: n = 5 ~ 15 (c.f. typically 30 ~ 40)
  - More "peeling-limited" than ballooning!

Peeling-limited phase with high *T*e,ped and low *ν*∗e,ped

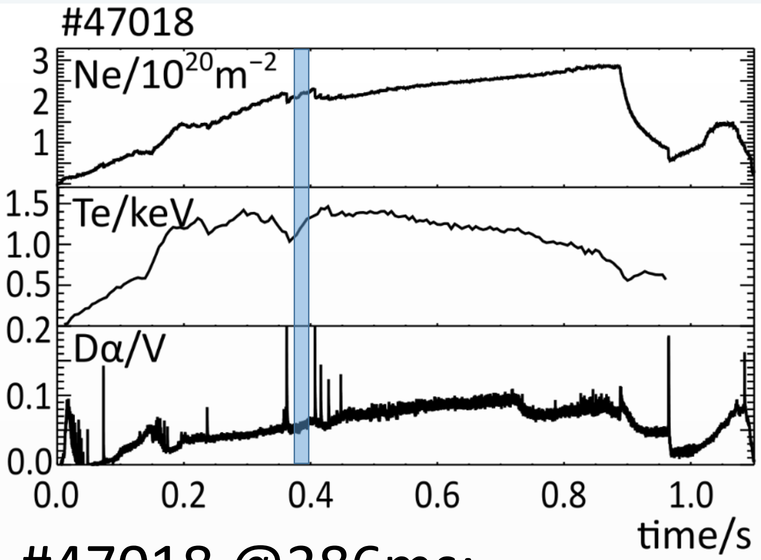


elongation	2.16
triangularity	0.43
squareness	0.38
$\nu_{*e,ped}$	1.29
$T_{e,ped}$/keV	0.31
α	14.5
$J_{N,ped}$	1.43

- #47018 @346ms:
  - Still lower mode numbers around expt. point: *n* = 5 ~ 15 (c.f. typically 30 ~ 40)
  - Still high $T_{e,ped}$ and low $\nu_{*e,ped}$
  - Expt. point drops in $J_{N,ped}$ and α (MHD modes starting to grow, prior to ELM?)

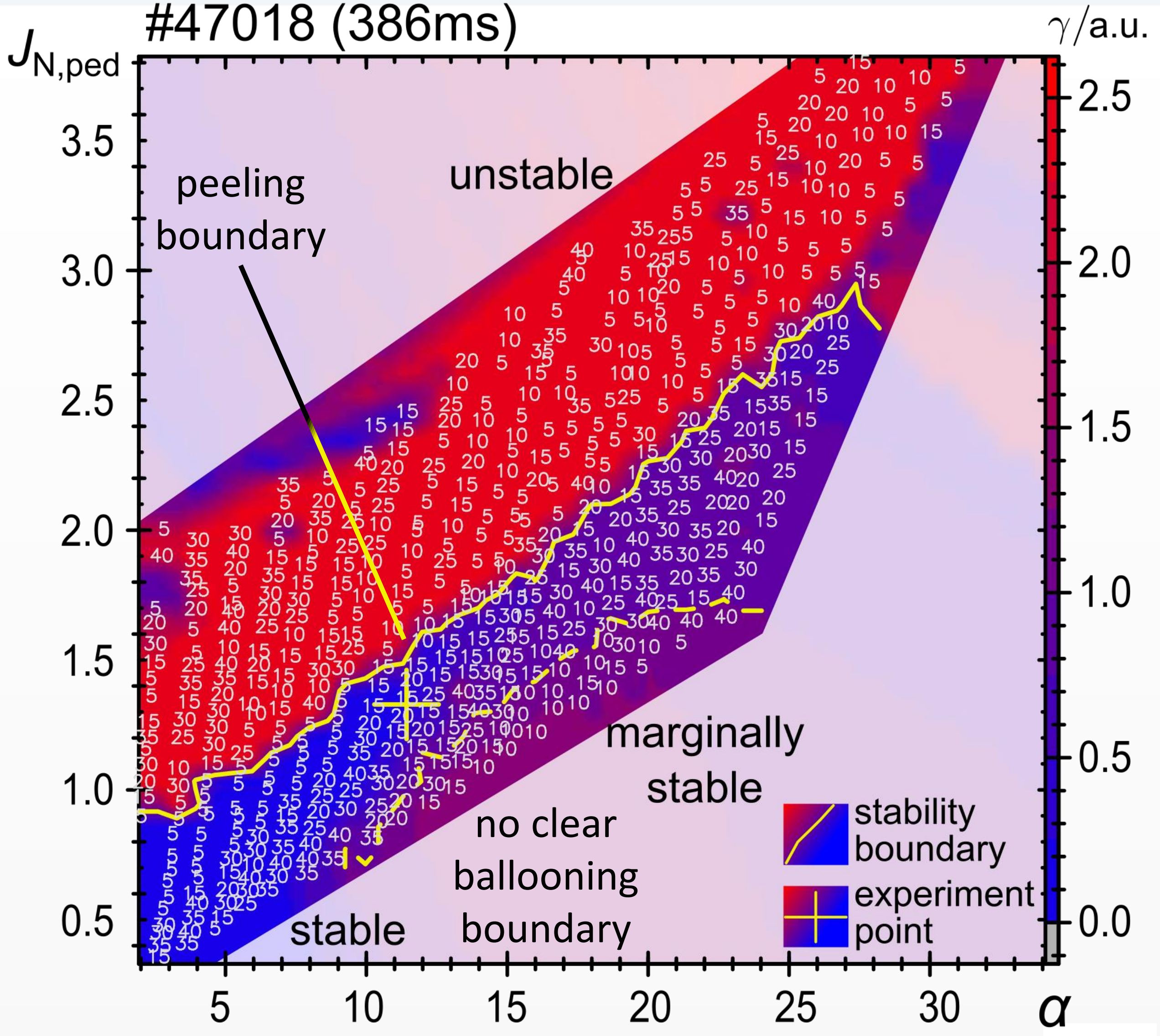


Peeling-limited phase with high Te,ped and low ν_*e,ped

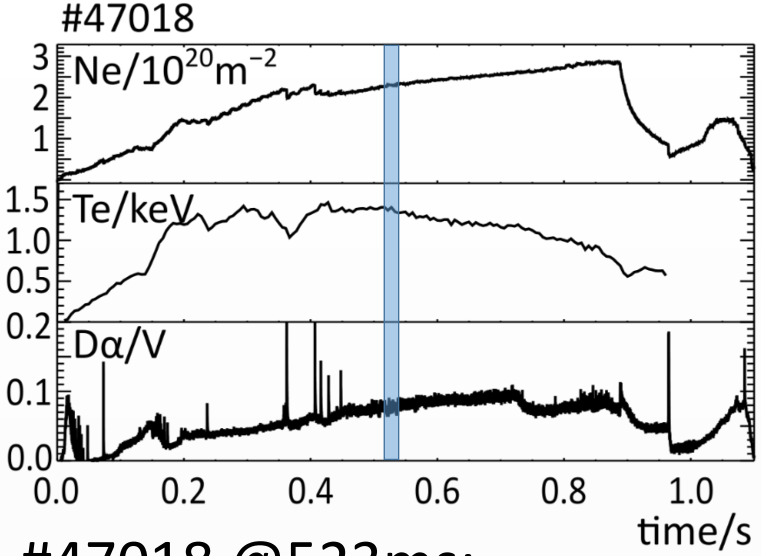


elongation	2.18
triangularity	0.48
squareness	0.38
$\nu_{*e,ped}$	0.97
$T_{e,ped}$/keV	0.35
α	11.4
$J_{N,ped}$	1.35

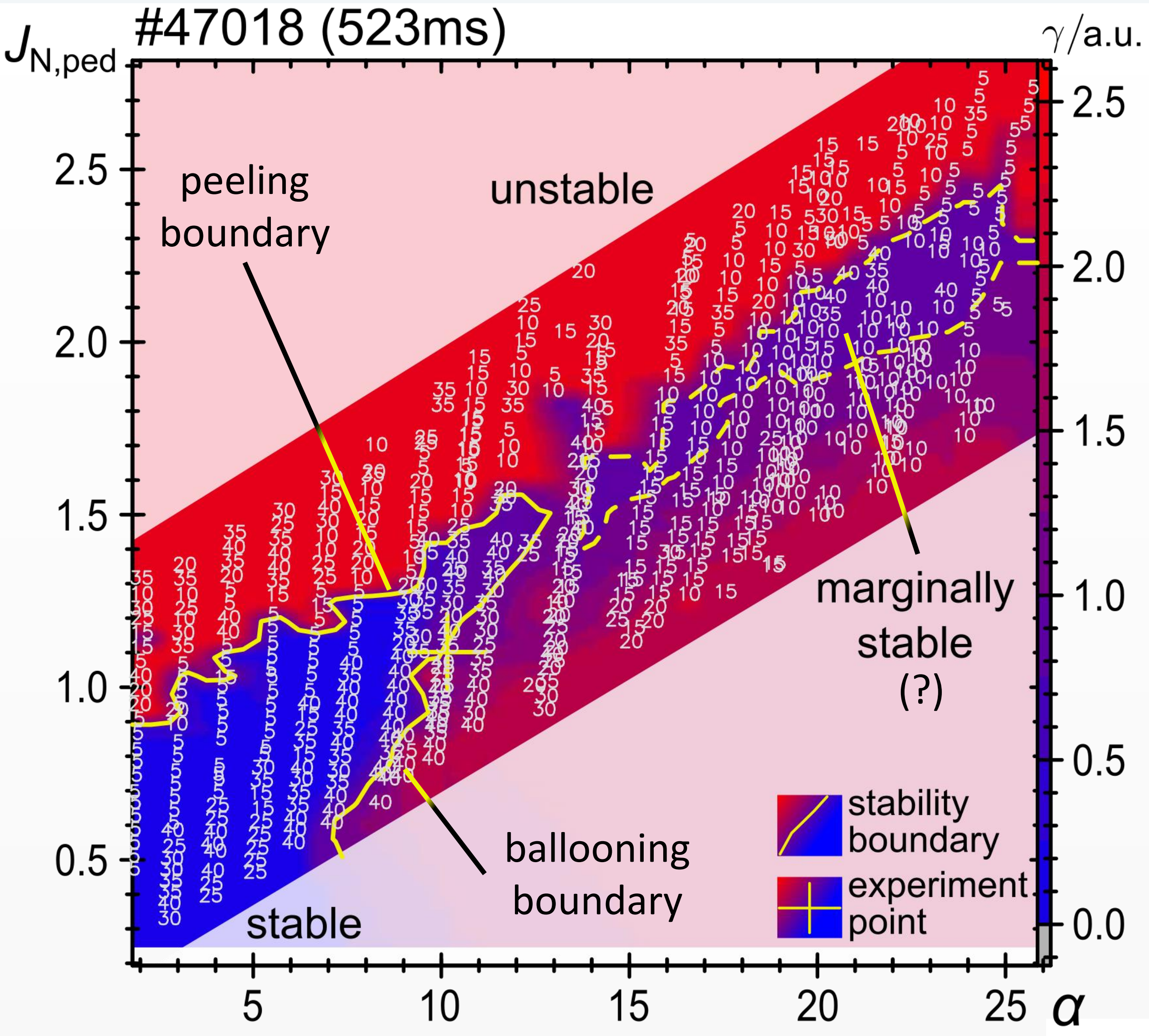
- #47018 @386ms:
  - Even after the ELM crash, still high $T_{e,ped}$ and low $\nu_{*e,ped}$
  - But pedestal is wider (~ 6.4%ψ_N compared to ~ 5.5%ψ_N before the ELM crash).
  - Still no clear ballooning boundary, and lower mode numbers around expt. point!



Not peeling-limited phase, but no ELMs either



elongation	2.13
triangularity	0.51
squareness	0.45
$\nu_{*e,ped}$	1.45
$T_{e,ped}$/keV	0.23
α	10.7
$J_{N,ped}$	1.08



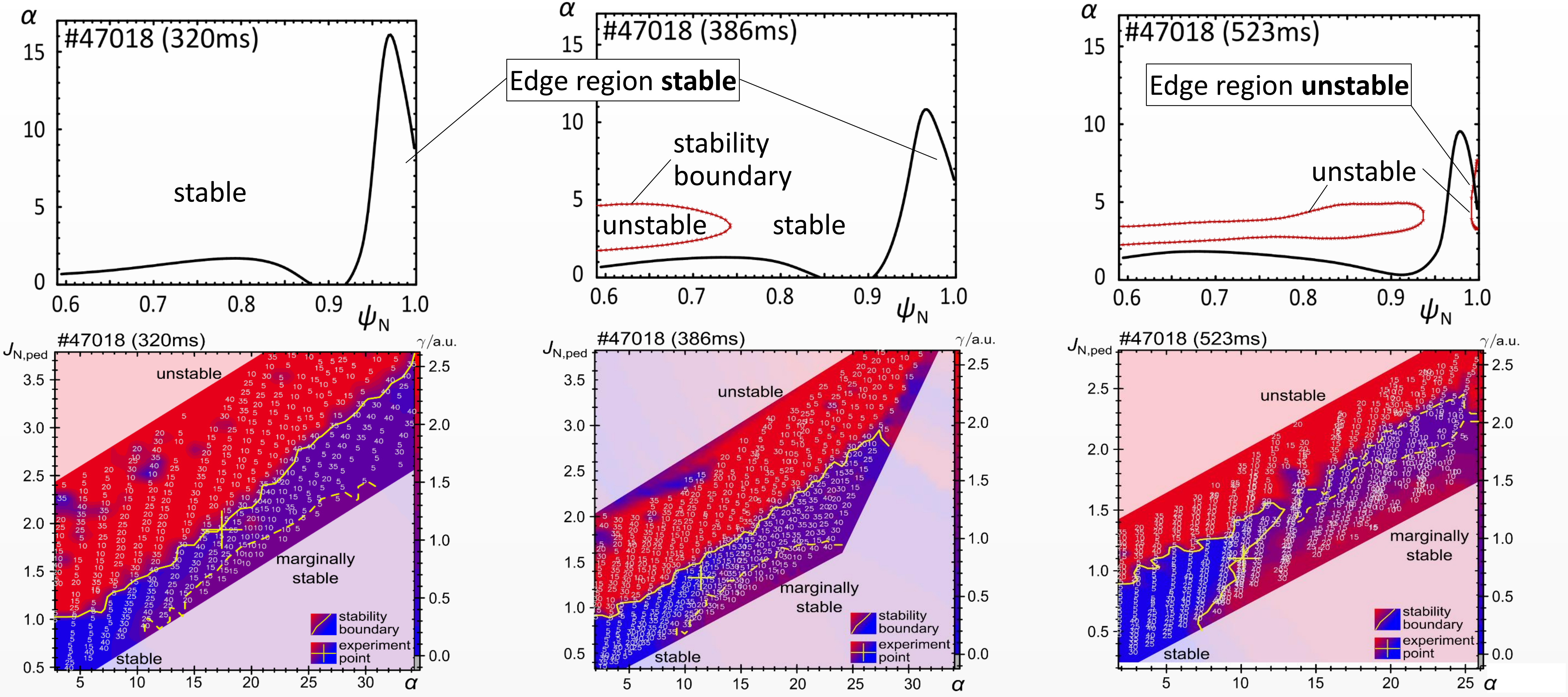
- #47018 @523ms:
  - After an increase in triangularity* (and squareness), pedestal performance drops
  - Parameters more typical of MAST-U
  - Ballooning boundary is back, with higher *n*
  - But no ELMs (reasons as yet unclear...)
    - (will return to this in a few slides time...)

* This was designed to be a triangularity shift experiment.

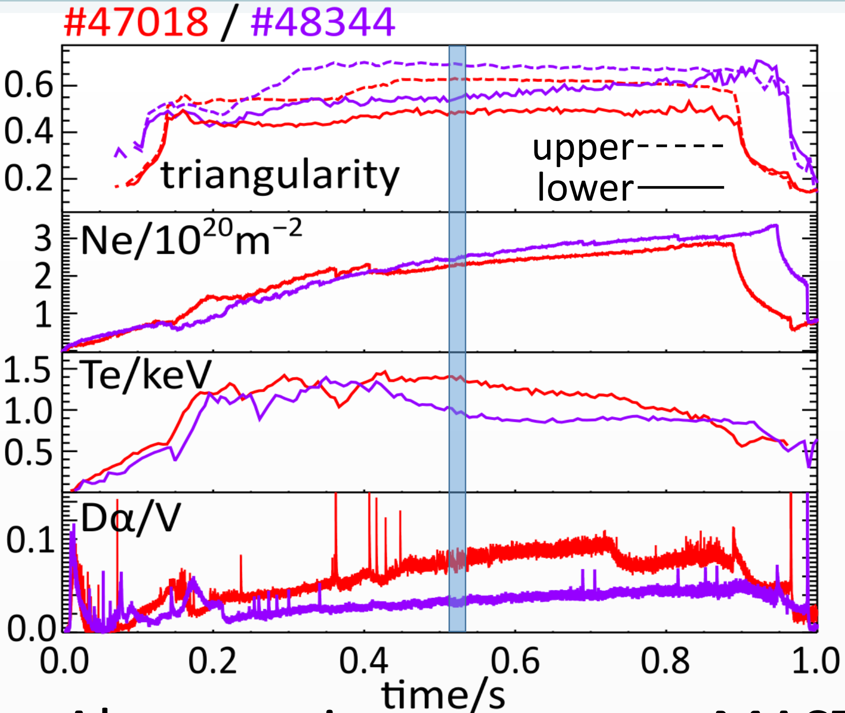
Peeling-limited phase with high Te,ped and low ν_*e,ped

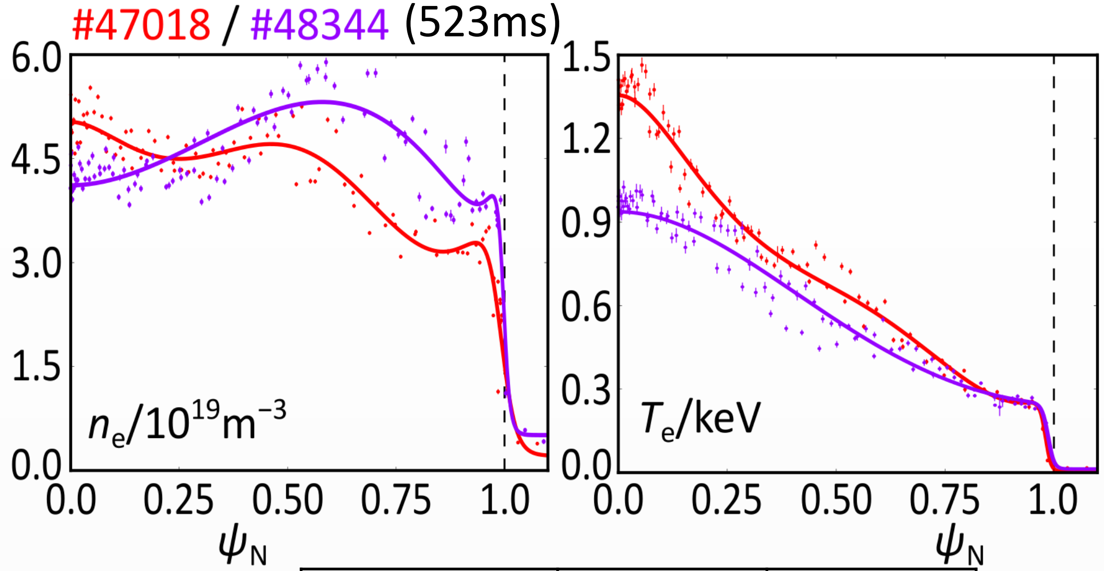
#8: Miller et al, *Nucl. Fusion* **27** 2101 (1987)

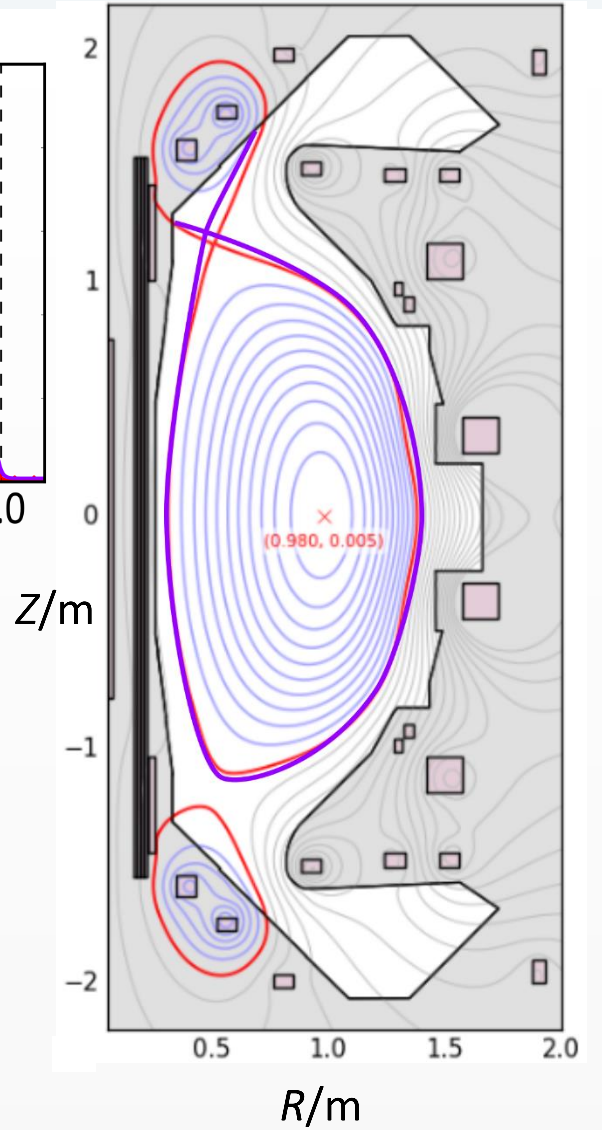
- BALOO[#8] analysis confirms stability against infinite-*n* ideal ballooning modes



No-ELM phase with high triangularity





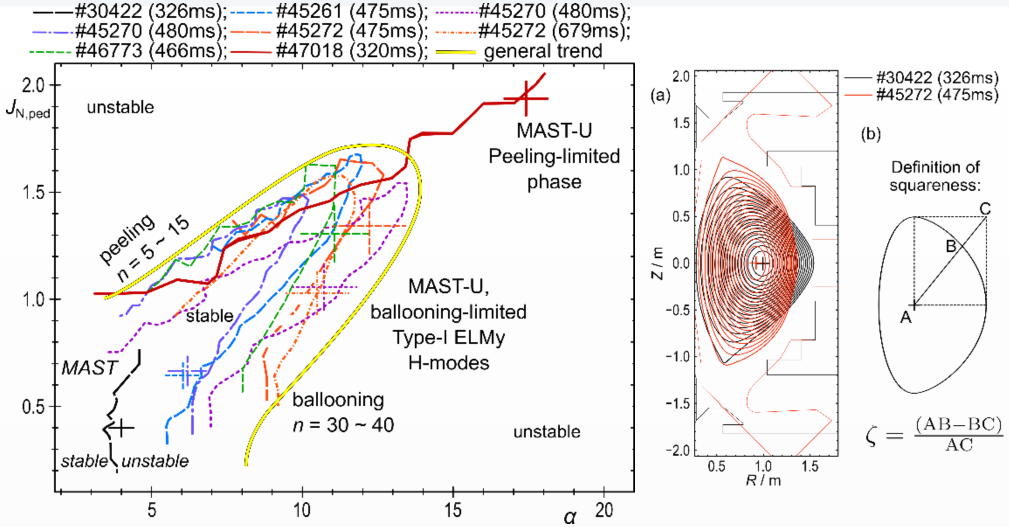


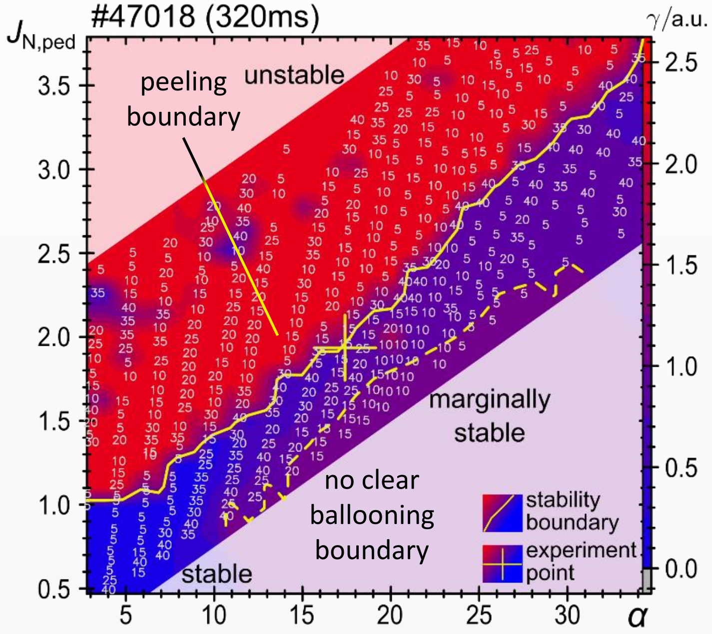
- Also seen in most recent MAST-U experiments (Aug. 2023: #48344):
  - After the increase in triangularity, ELMs disappear (but noisier Dα signal)
  - Still in H-mode, albeit little degraded
  - QCE? EDA? Further analysis needed!

	#47018	#48344
P_{NBI}/MW	3.20	3.22
elongation	2.13	2.2
triangularity	0.51	~0.6
squareness	0.45	~0.4
$\nu_{*e,ped}$	1.45	—
$T_{e,ped}$/keV	0.23	0.24
α, $J_{N,ped}$	10.7, 1.08	—

Summary

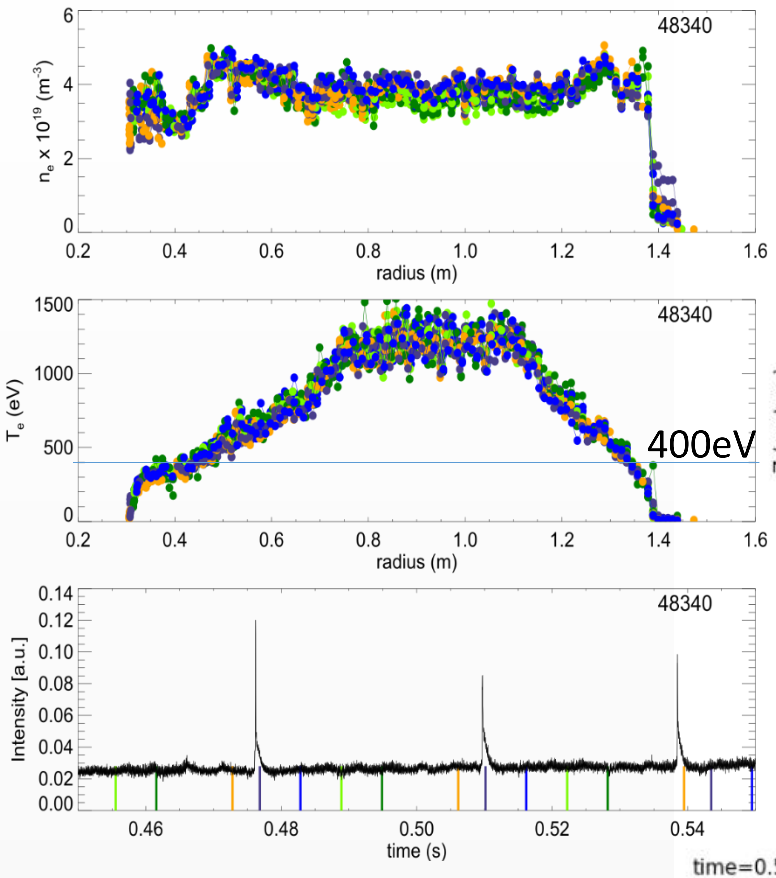
- Pedestal stability analysis on MAST-U ELMy H-modes
- High elongation (>2.0) , high squareness (~0.4) plasma
  → Seems to contribute to weaker peeling-ballooning coupling
- High pedestal temperature, low collisionality case:
  – Stable against high-*n* ideal ballooning modes
  – Longer inter-ELM period
  – Pedestal with much higher $J_{N,ped}$ and α.
- Next step: further shaping parameter scan:
  – Repeat experiments to verify impact of elongation, triangularity and squareness.
  – Compare with other tokamak data.

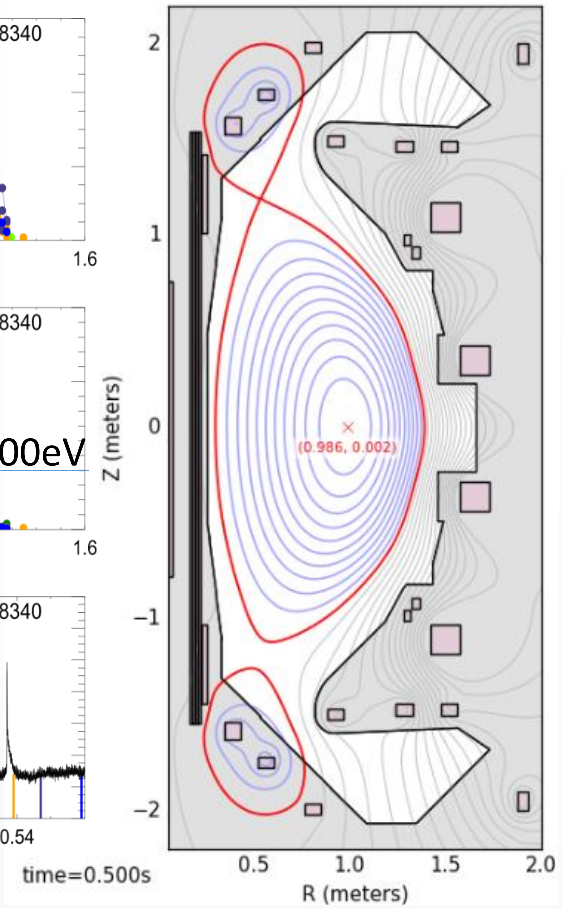




Ongoing: MAST-U pedestal stability experiments!

- Shaping parameter scans are ongoing, with high pedestal temperature cases:





  - e.g. #48340, with high elongation (2.1), low squareness (<0.35), moderate triangularity (~0.5)
  - c.f. #47018 →, with high squareness (>0.4) and triangularity (>0.55)
  - #48340 with high $T_{e,ped}$, moderate density – potentially low $\nu_{*e,ped}$
  - Full pedestal stability analysis ongoing!