Pedestal stability analysis of MAST-U H-modes using ELITE code

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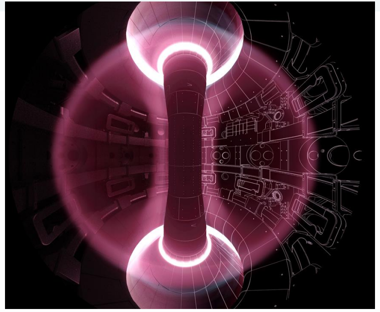
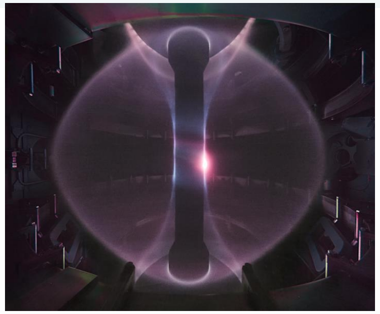
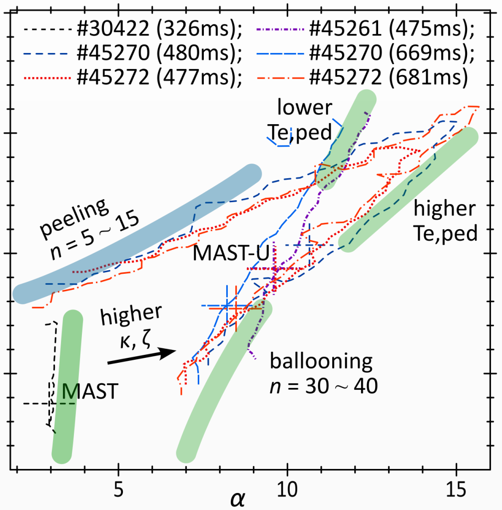
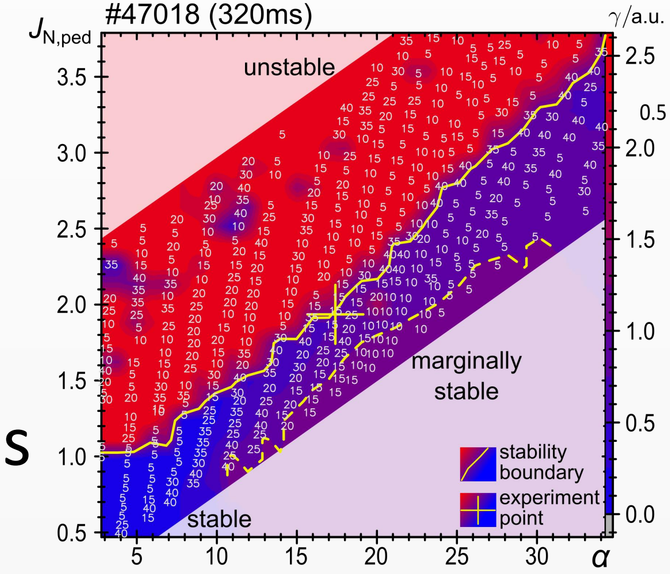
Outline

- Introduction to peeling-ballooning theory
  - H-modes, pedestal, ELMs, and "why study this"
- MAST/-U pedestal stability analysis
  - analysis method: EFIT, VARYPED, ELITE
- Case study 1: MAST vs. MAST-U
  - much improved pedestal stability in MAST-U
- Case study 2: ELM-free period in MAST-U H-mode
  - peeling-limited, ballooning stable(ish)!
- Summary and ongoing work
  - more on plasma shape, ELM-free periods



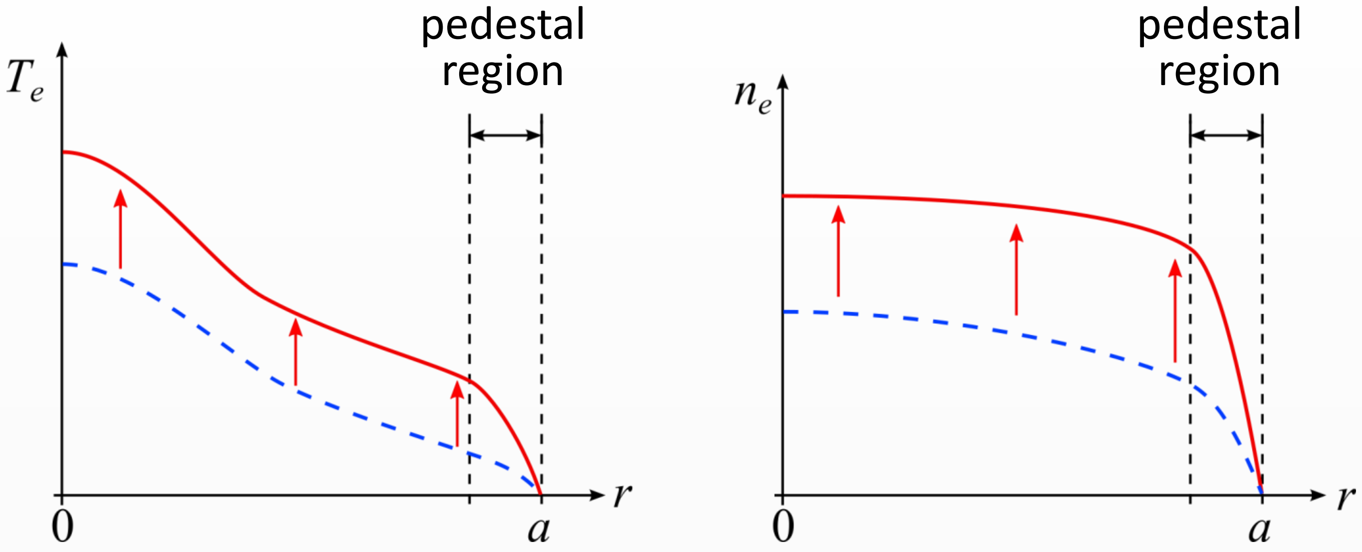




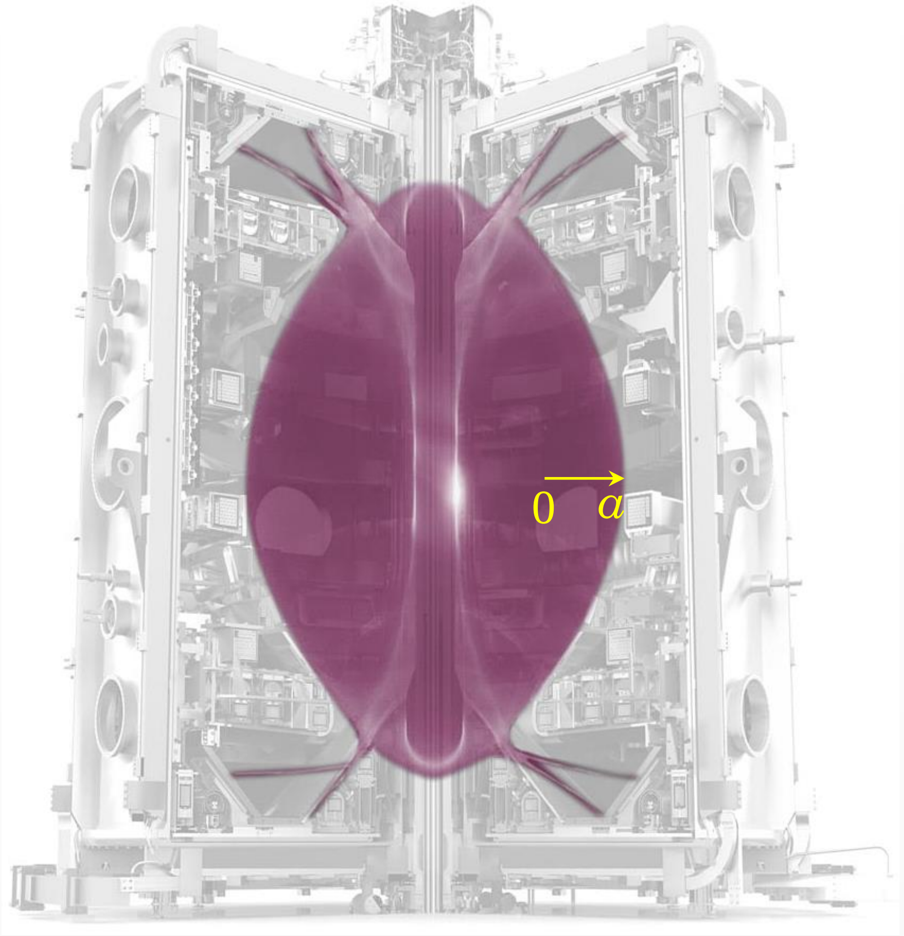


Background: H-modes in tokamak plasma

- Modern tokamaks operate in "**H**-modes":



  - Steep edge temperature/density gradients
  - Core profile is elevated (as if on a pedestal)
  - **H**igh confinement mode!



MAST-Upgrade at CCFE

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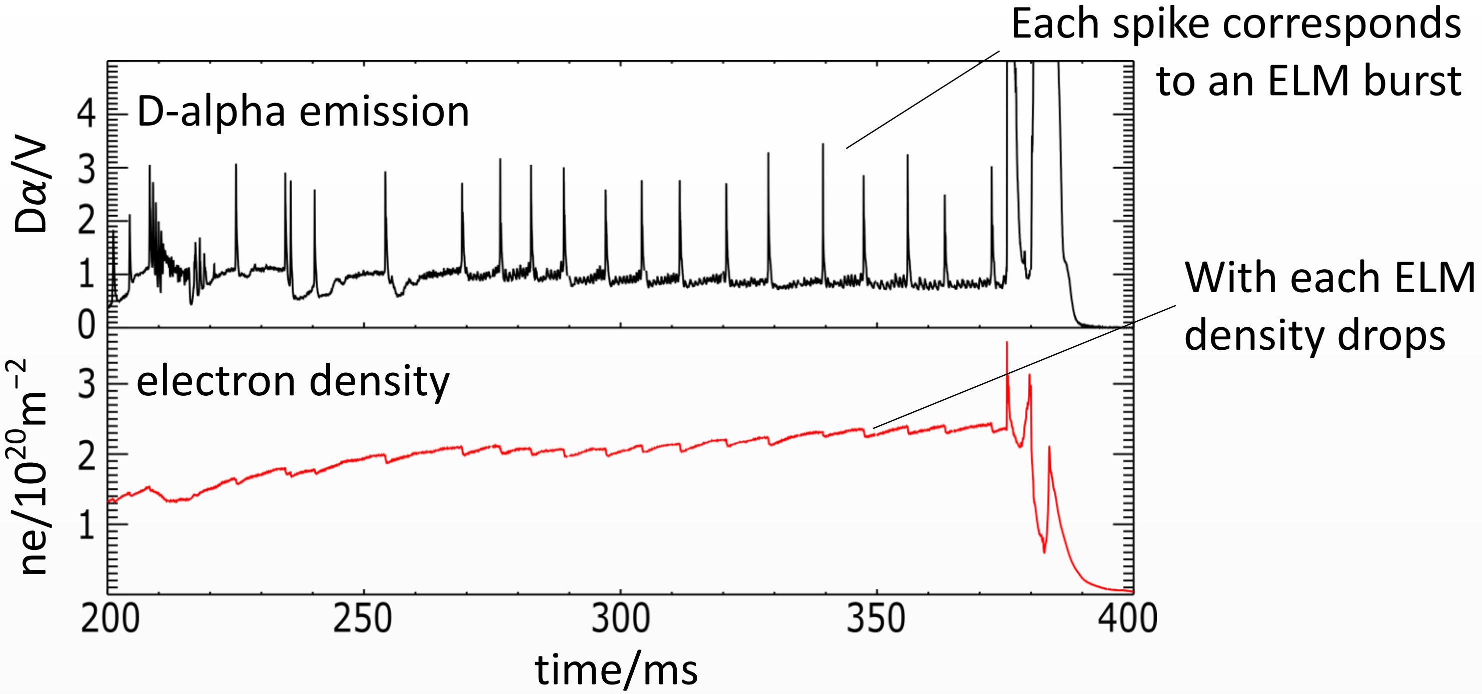
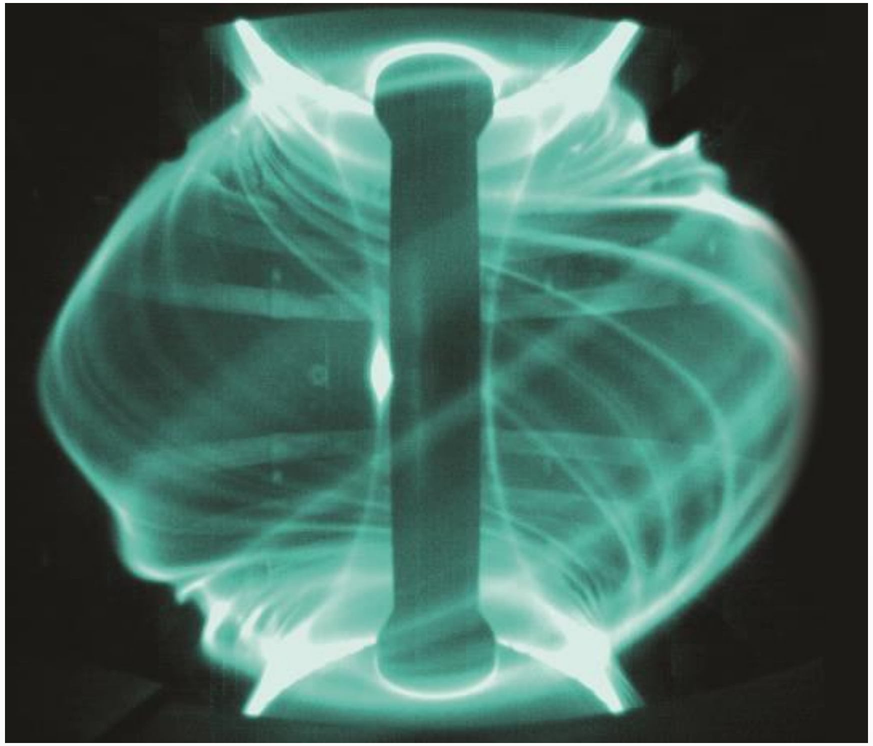
Background: ELMs – edge localised modes

- However...





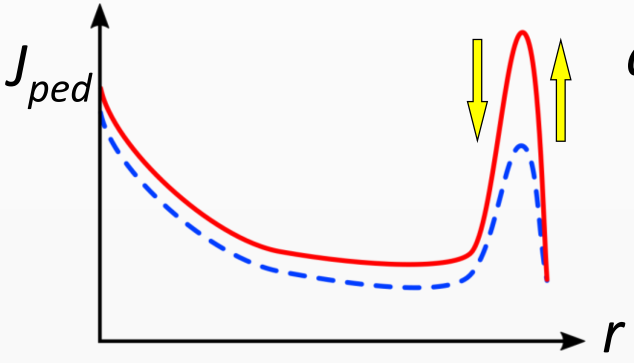
ELM eruption in MAST

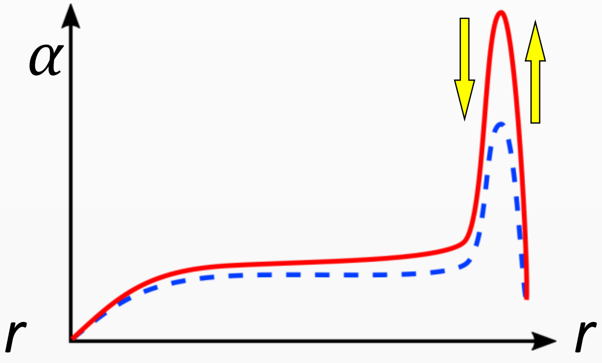
- Degrades confinement
- Can lead to a disruption – large ELMs must be mitigated/controlled!
- Or... is there an ELM-free H-mode?

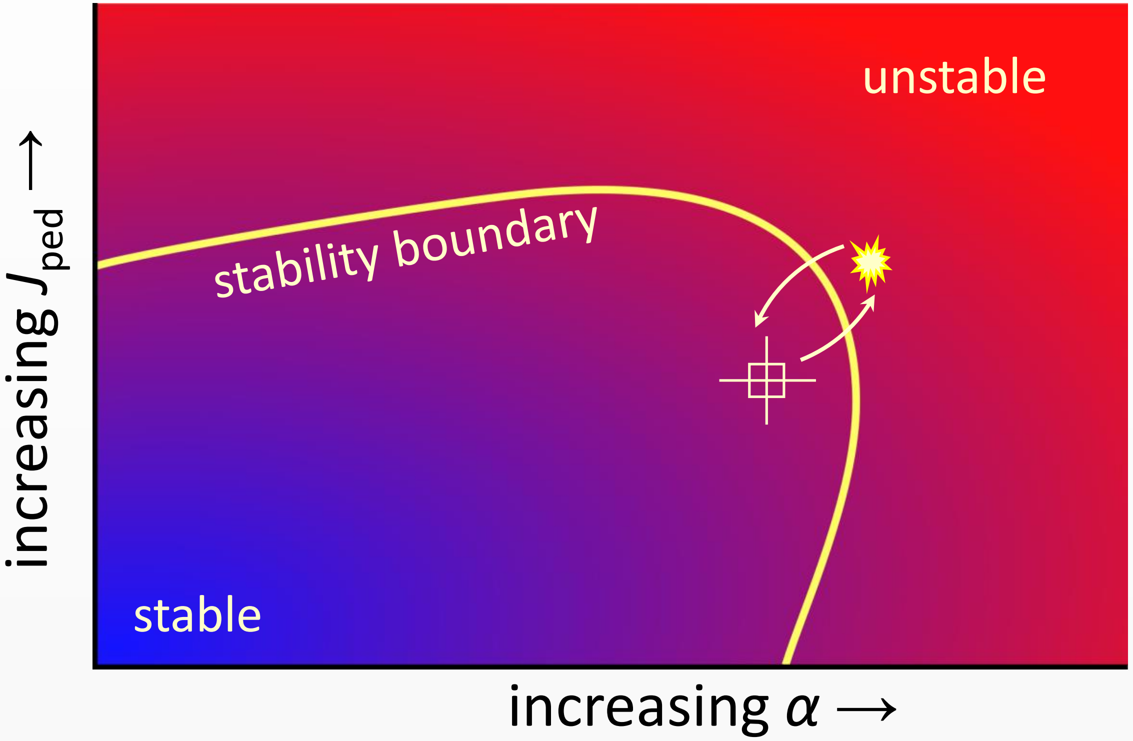
Image right (this version): fusion-cdt.ac.uk

Peeling-Ballooning theory for ELM cycle

- "Peeling-Ballooning theory" for ELM cycle:[#1]
  - Pedestal stability in terms of pedestal current, $J_{\mathrm{N,ped}}$ and pedestal pressure gradient, α ('alpha').
  - ELM triggered when stability boundary is crossed.
  - Crash brings J_{ped} and α back to the stable region again.







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

Peeling-ballooning theory for ELM cycle

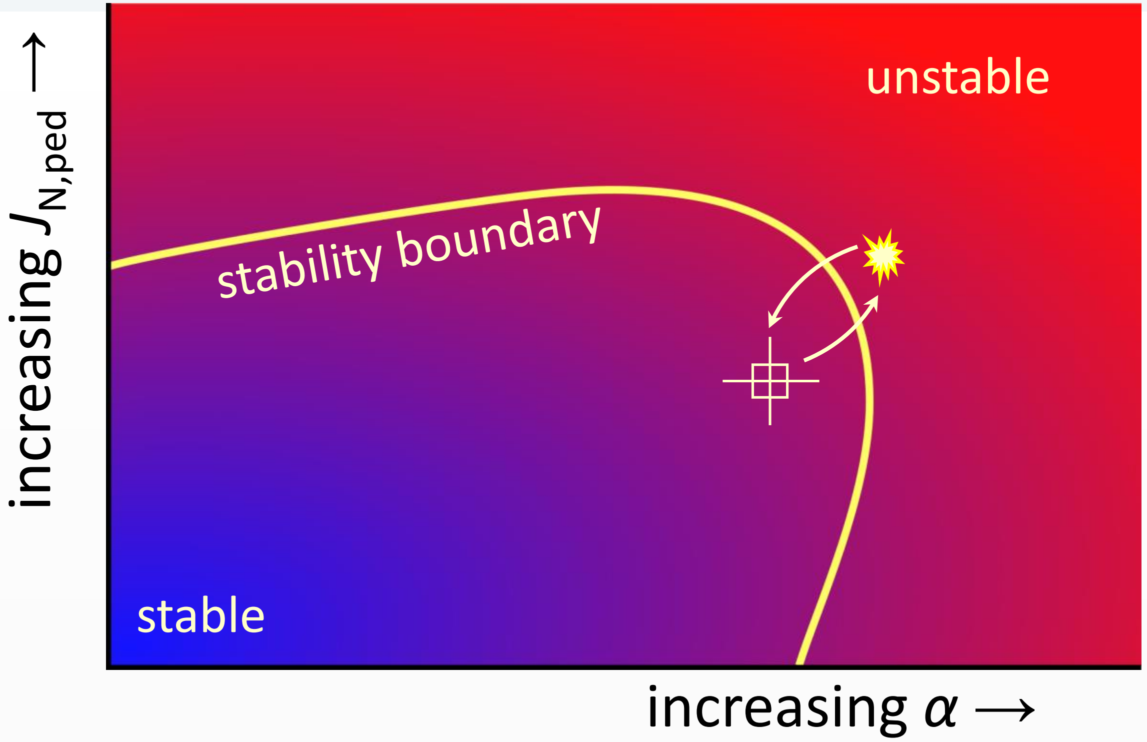
- According to the theory:[#1]
  - Pedestal stability in terms of pedestal current density, $J_{\mathrm{N,ped}}$ and normalised pedestal pressure gradient, α:

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

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

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

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



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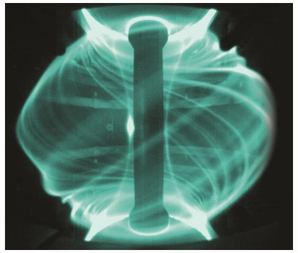
Peeling and ballooning modes



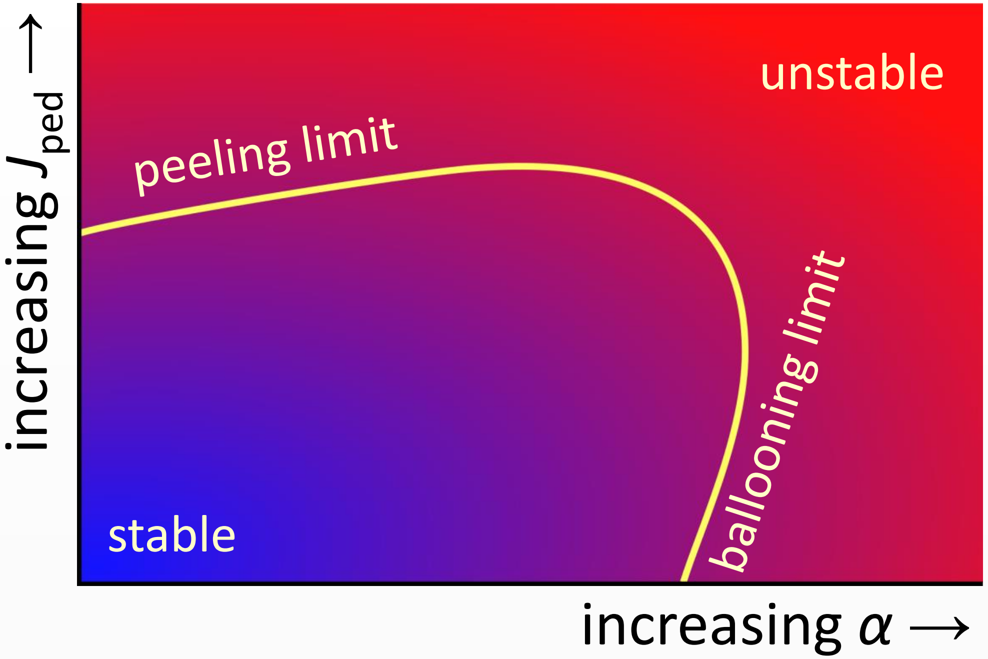
- Peeling modes:
  - large pedestal current, $\boldsymbol{J_{\mathrm{N,ped}}}$
  - typically *low* **mode number**:

$$n \lesssim 5 - 10$$

- Ballooning modes:
  - steep pedestal pressure gradient, $\boldsymbol{\alpha}$
  - typically *high* mode number:

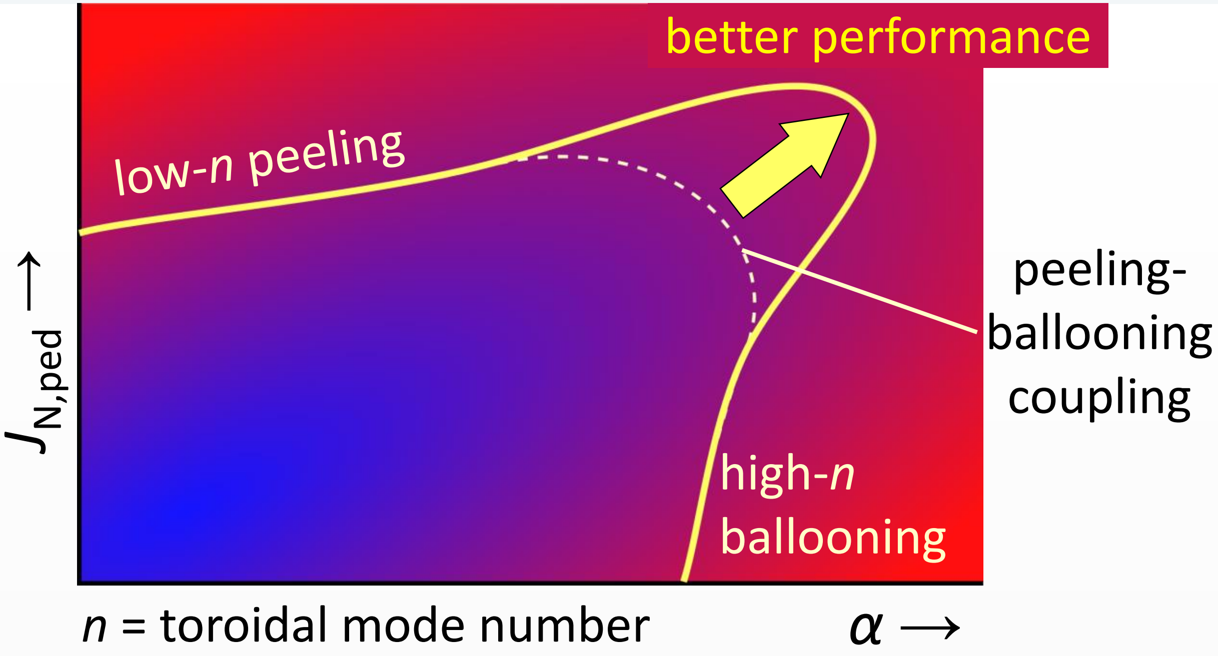
$$n \gtrsim 30 - 40$$

    - particularly high in spherical tokamaks, like MAST/-U

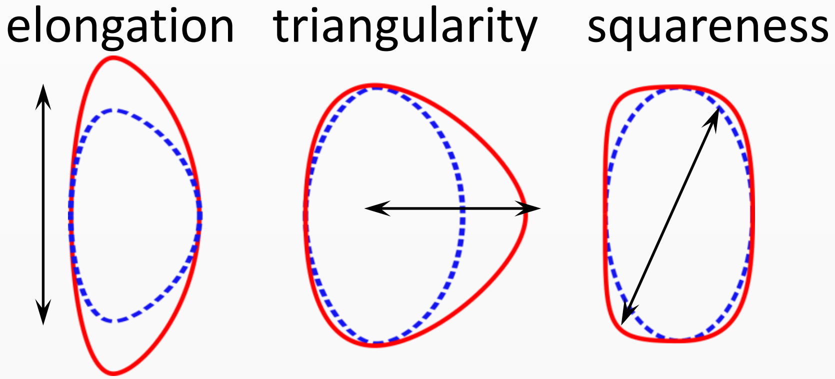


Research aim: MAST-U pedestal stability

- Future fusion reactors, e.g. STEP, will operate in ELM-free high confinement regimes.
  - Needs to avoid high-*n* ideal ballooning modes
  - Also stay clear of low-*n* peeling boundary
- What affects the pedestal stability boundary?
  - pedestal T_e, collisionality ν_*, etc.
  - clean ramp-up, without IRE, MHD instability
  - plasma shaping parameters:[#3,#4]
  - scrape-off layer & divertor config., etc. etc.
- Can we find pathways to ELM-free regimes?
  - Quiescent H (QH) modes with edge harmonic oscillations (EHO)
  - I-modes (possible in ST?), EDA modes?



n = toroidal mode number

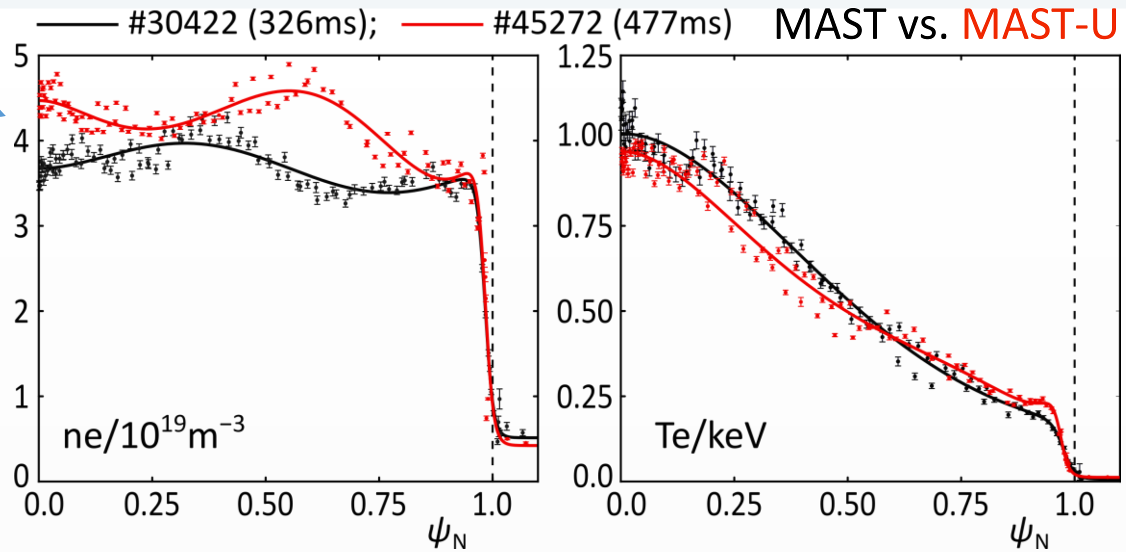


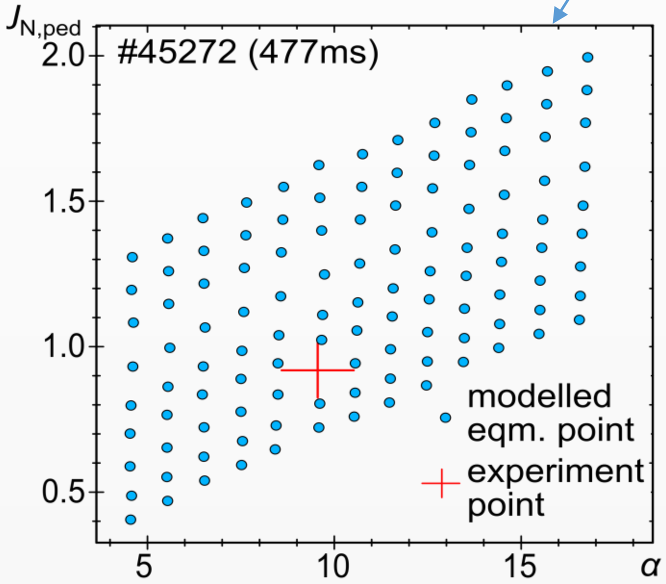
#3: Snyder et al, *Nucl. Fusion* **55** 083026 (2015), etc.

#4: Holcomb et al, *Phys. Plasmas* **16** 056116 (2009), etc.

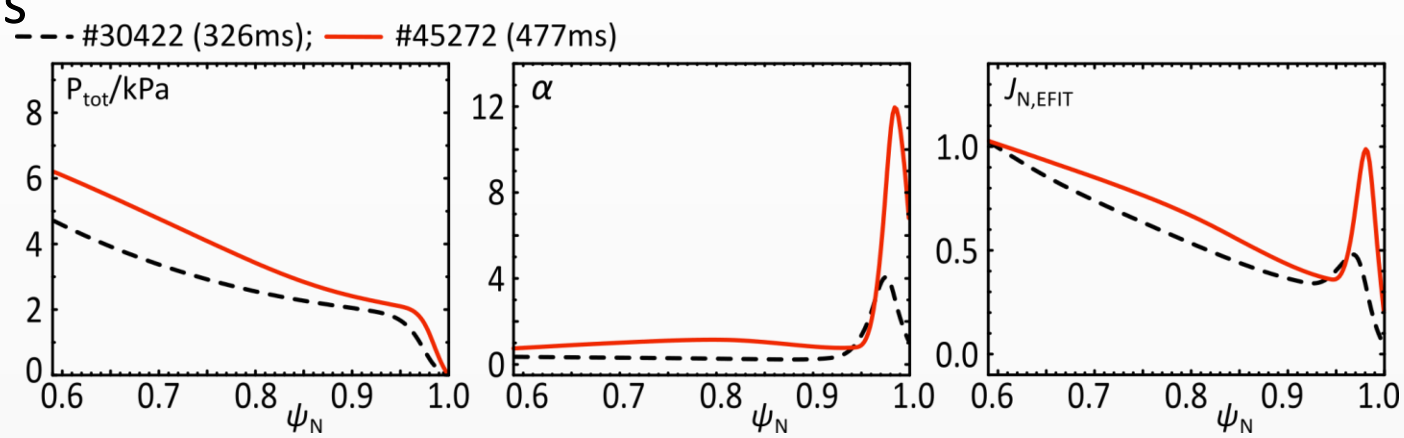
MAST-U H-mode analyses

- OMFIT kineticEFITtime#5 for profile fitting
- TRANSP#6 for fast ion density/pressure profiles
- Fixed-boundary EFIT with electron profiles for pedestal structure
- VARYPED#7 to create modelled equilibria with varying $J_{N,\mathrm{ped}}$ and α
- ELITE#8 for MHD pedestal stability analysis





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



#5: Meneghini&Lao, *Plasma Fus. Res.* **8** 2403009 (2013)

#6: Hawryluck (1981) & Grierson+, *FST* (2018)

#7: Osborne et al, *Nucl. Fusion* **55** 063018 (2015)

#8: Wilson et al/Snyder et al, *Phys. Plasmas* **9** 1277/2037 ('02)

ELITE ideal MHD pedestal stability analysis

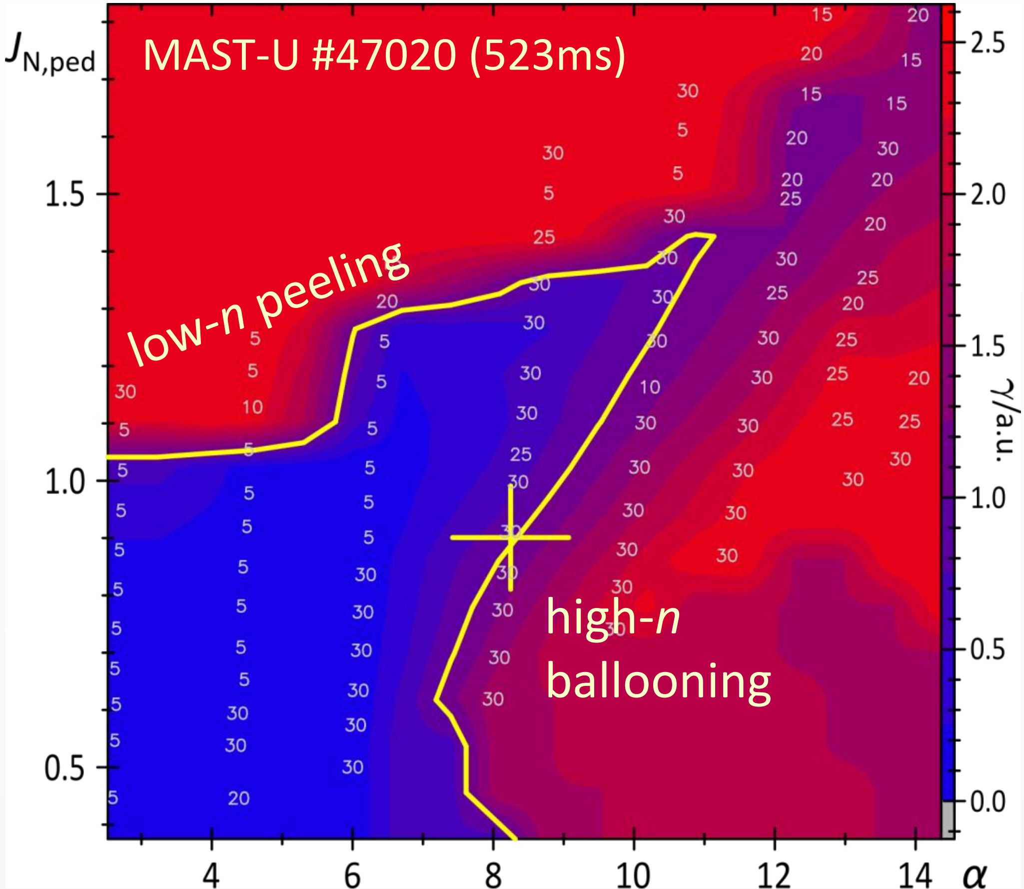
- ELITE uses the energy principle to determine the stability of ideal MHD peeling-ballooning modes, given perturbation in plasma displacement, $\boldsymbol{\xi}$:

$$\delta W = \frac{1}{2}\int \mathrm{d}\tau \left[\mathbf{Q}^2 - \mathbf{J}\cdot(\mathbf{Q}\times\boldsymbol{\xi}) + (\boldsymbol{\xi}\cdot\boldsymbol{\nabla}p)(\boldsymbol{\nabla}\cdot\boldsymbol{\xi}) + \gamma p(\boldsymbol{\nabla}\cdot\boldsymbol{\xi})^2\right]$$

hence depends on $J_{\mathrm{N,ped}}$ (**J**), α (∇p), q in **B**, etc.

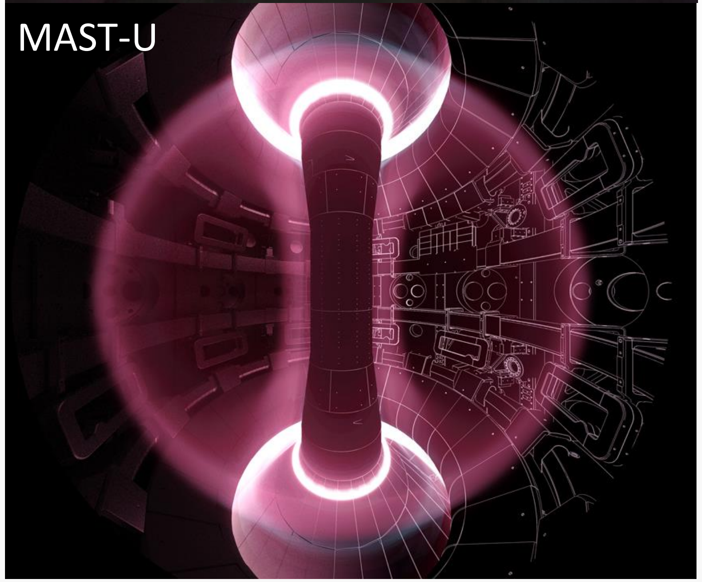
$$\mathbf{Q} = \boldsymbol{\nabla}\times(\boldsymbol{\xi}\times\mathbf{B})$$

- Outputs: the mode growth rate γ and eigenfunction describing radial mode structure for each toroidal mode number, *n*.
- For a given equilibrium input, there will be *n* with the highest growth rate.
- These are plotted to produce the "*J*-*α* stability diagram" →
- Stability boundary drawn for a threshold value of γ normalised to Alfvén frequency, ω_A (0.06 in this case).



Case study 1: MAST vs. MAST-U

- MAST-U plasma: compared to MAST, more strongly shaped, with higher elongation and squareness (comparable triangularity)
  - also new divertor chamber, higher B_T, etc. etc.
- Observations: MAST-U pedestal stability significantly different from MAST.
  - Higher $J_{\mathrm{N,ped}}$ and α; improved overall stability
  - extended region of stability; weaker coupling between peeling and ballooning branches
- Why so?? Likely the combination of plasma shape, new divertor configuration (+ other effects!)



Images right: ccfe.ukaea.uk

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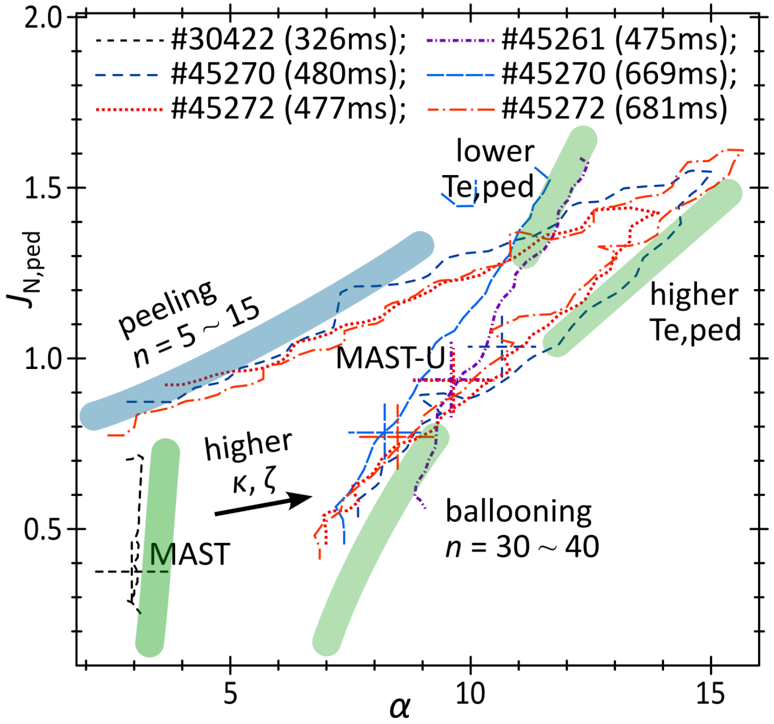

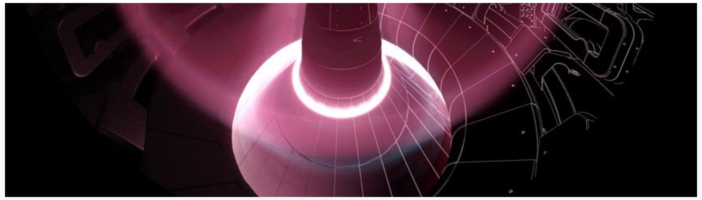

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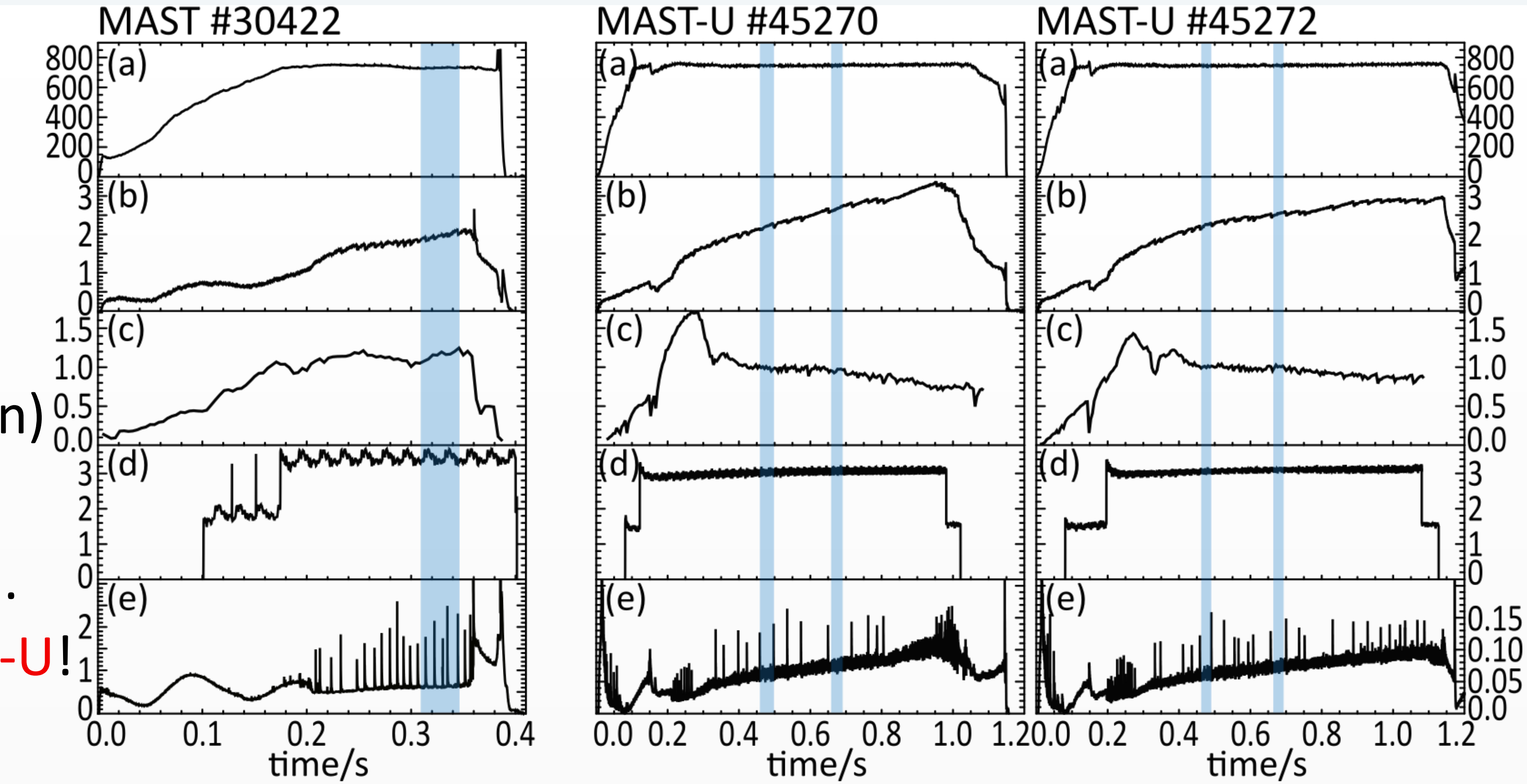
Case study 1: MAST vs. MAST-U

- Case study:
  - MAST-U #45270 and #45272 (Type-I ELMy H-mode with long "flat-top")
  - MAST #30422 (typical Type-I ELMy H-mode for comparison)
- Notable differences in shape:
  - $\kappa \sim 1.6$ for M, $\kappa > 2.1$ for M-U.
  - $\zeta \sim 0.19$ for M, $\zeta \sim 0.38$ for M-U!
- Higher q95 for M-U (~4.6 vs. 6.0~6.6)
- Similarities:
  - $B_T = 0.5\sim0.55$T, double-null config.



↑(a) = plasma current/kA; (b) = line-integrated electron density/10^{20}m^{-2}; (c) = core electron temperature/keV; (d) = total NBI heating power/MW; (e) = D-α signal (V), illustrating ELM events
Blue shades = time frames used for pedestal analysis

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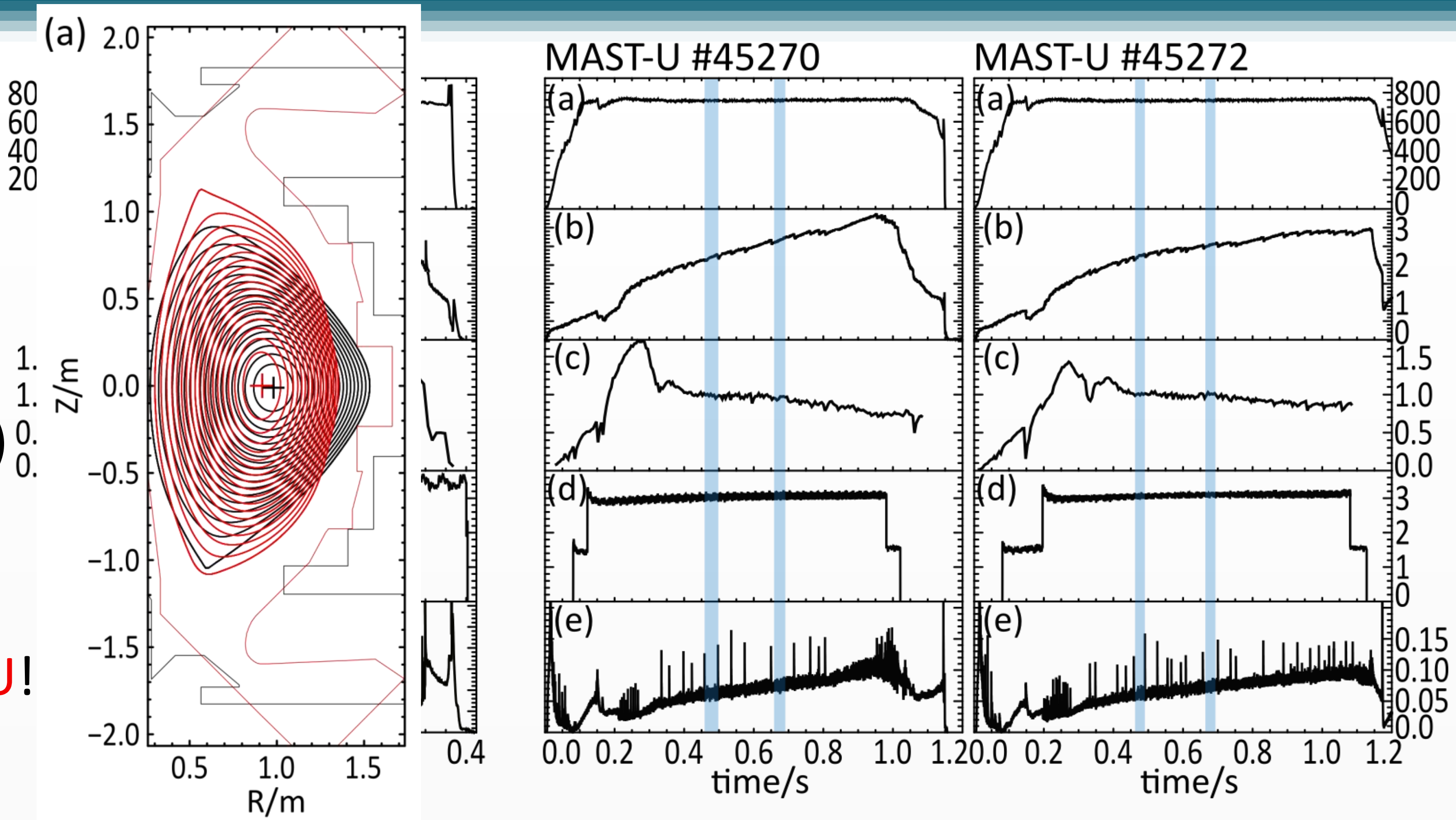

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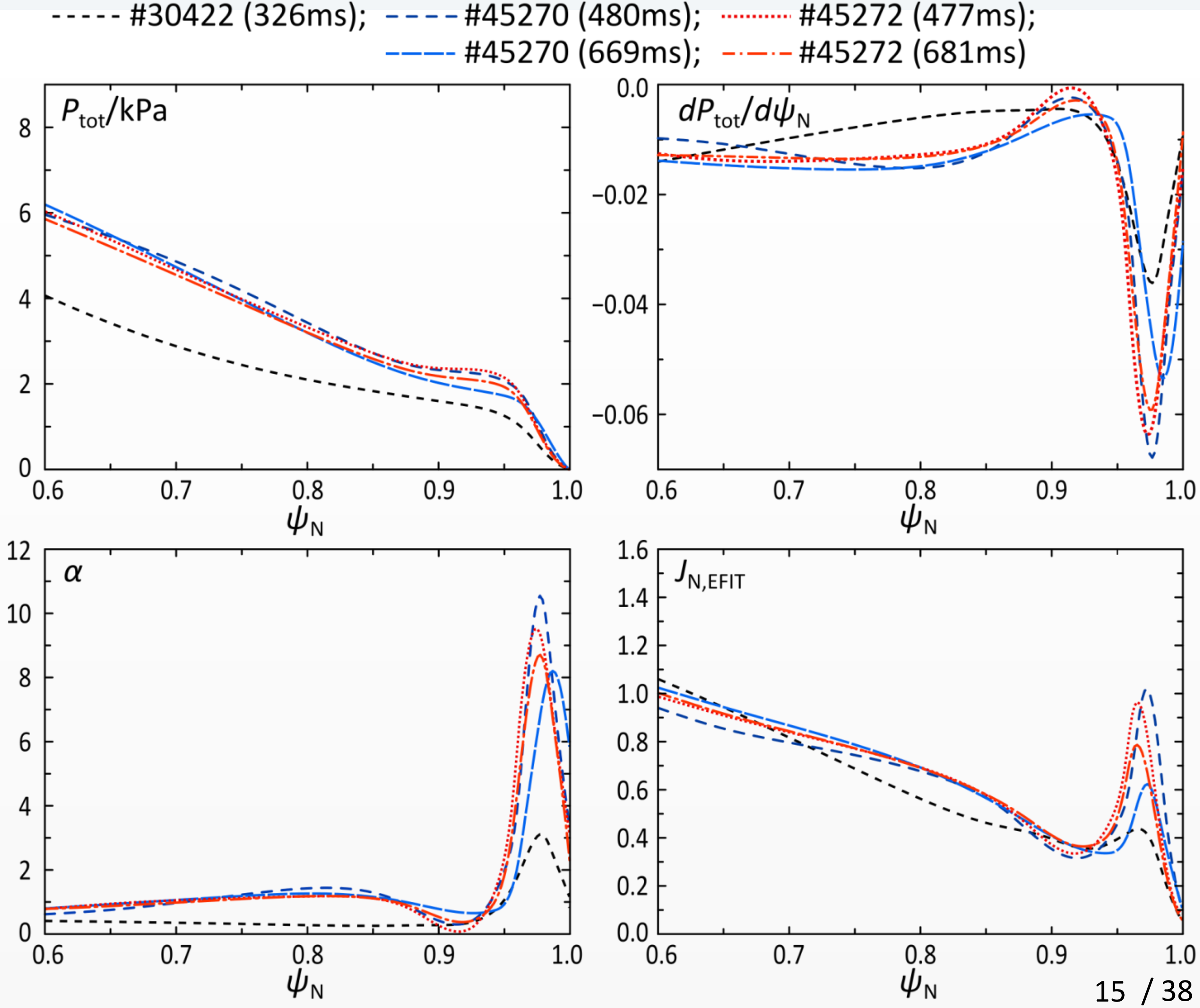
EFIT reconstruction comparison

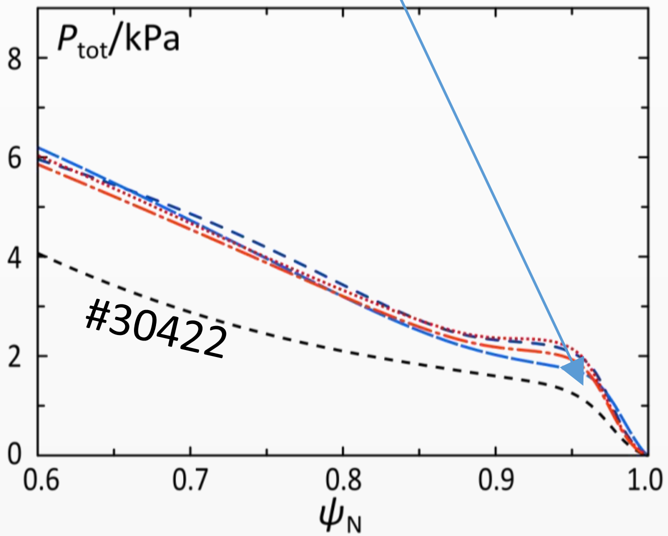
P_{tot} = Total pressure (and its gradient: $\mathrm{d}P_{\text{tot}}/\mathrm{d}\psi_N$);
α = normalised pressure gradient;
$J_{N,\text{EFIT}}$ = normalised current density
(all from EFIT reconstruction)

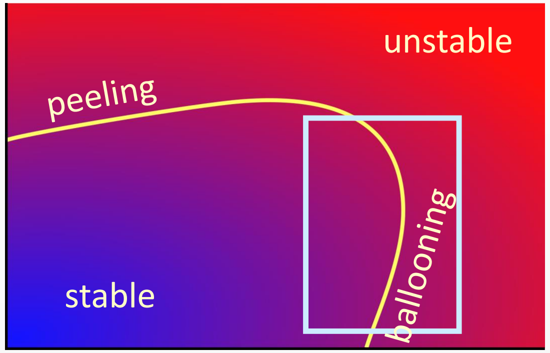
- Comparison between MAST/-U:
- Notably higher pedestals for MAST-U
- Definitely steeper and narrower pedestals for MAST-U (both #45270 and #45272) – hence significantly higher α
- Consequently, peak in pedestal current density also higher for MAST-U (i.e. bootstrap current contribution, $\propto \mathrm{d}p/\mathrm{d}\psi$)

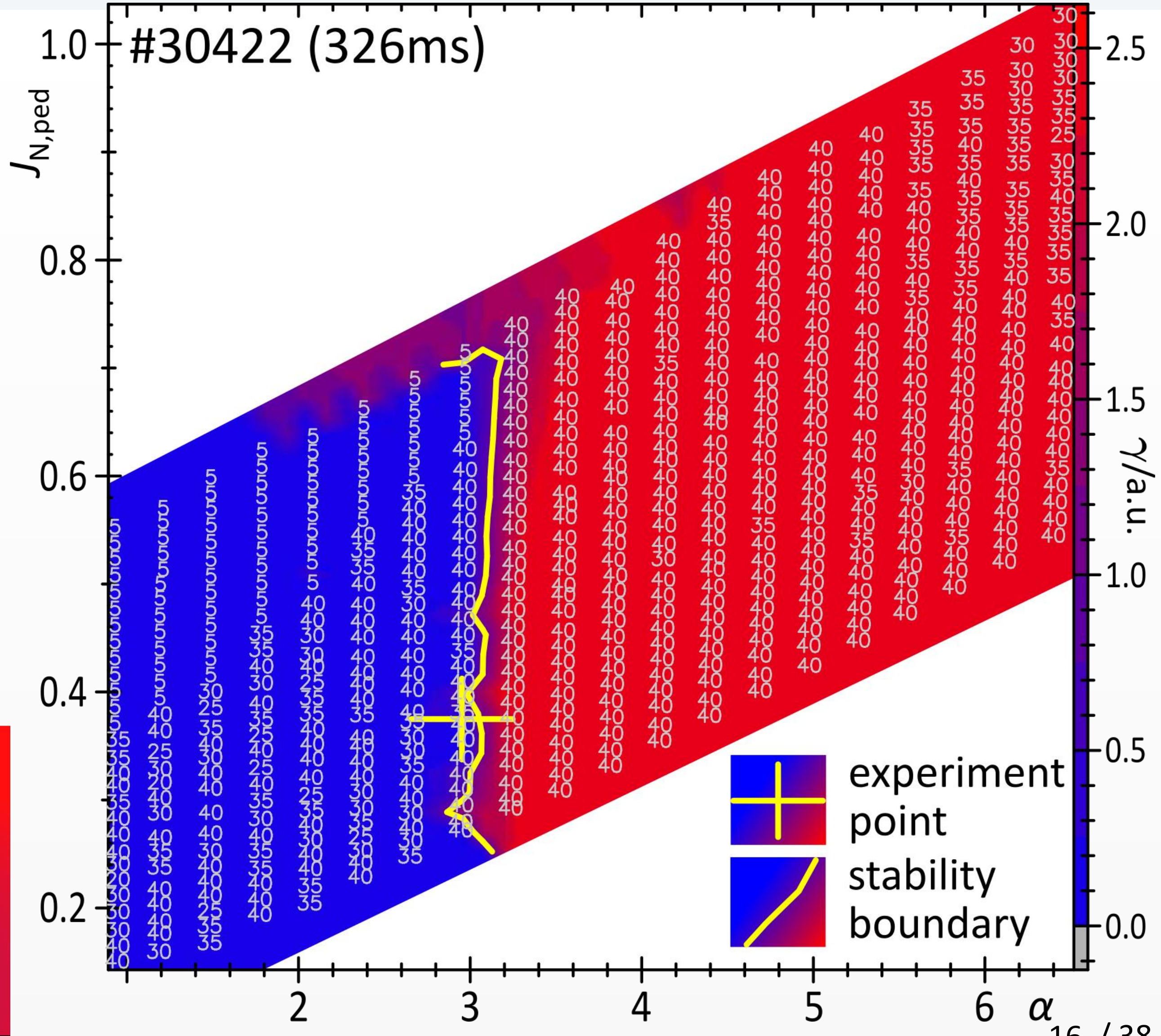


ELITE results for MAST #30422

- Strongly ballooning-limited pedestal, typical of MAST:
- High mode number: n = 35~40
- Stability boundary limiting access to higher values of α (only ~3), with "shallow" pedestal
- Region of lower n ~ 5; peeling boundary probably around $J_{\mathrm{N,ped}}$ ~ 0.7 – 0.8







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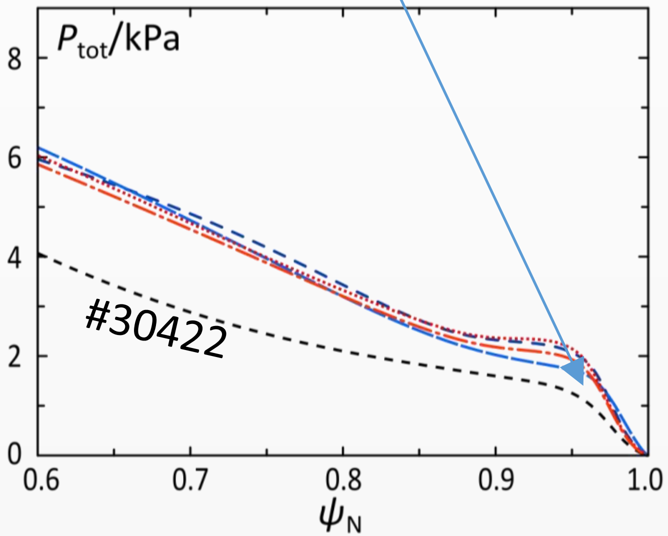
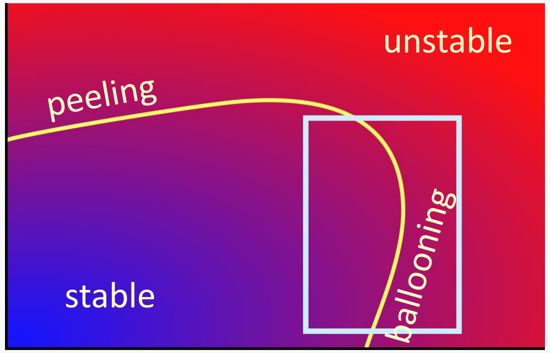
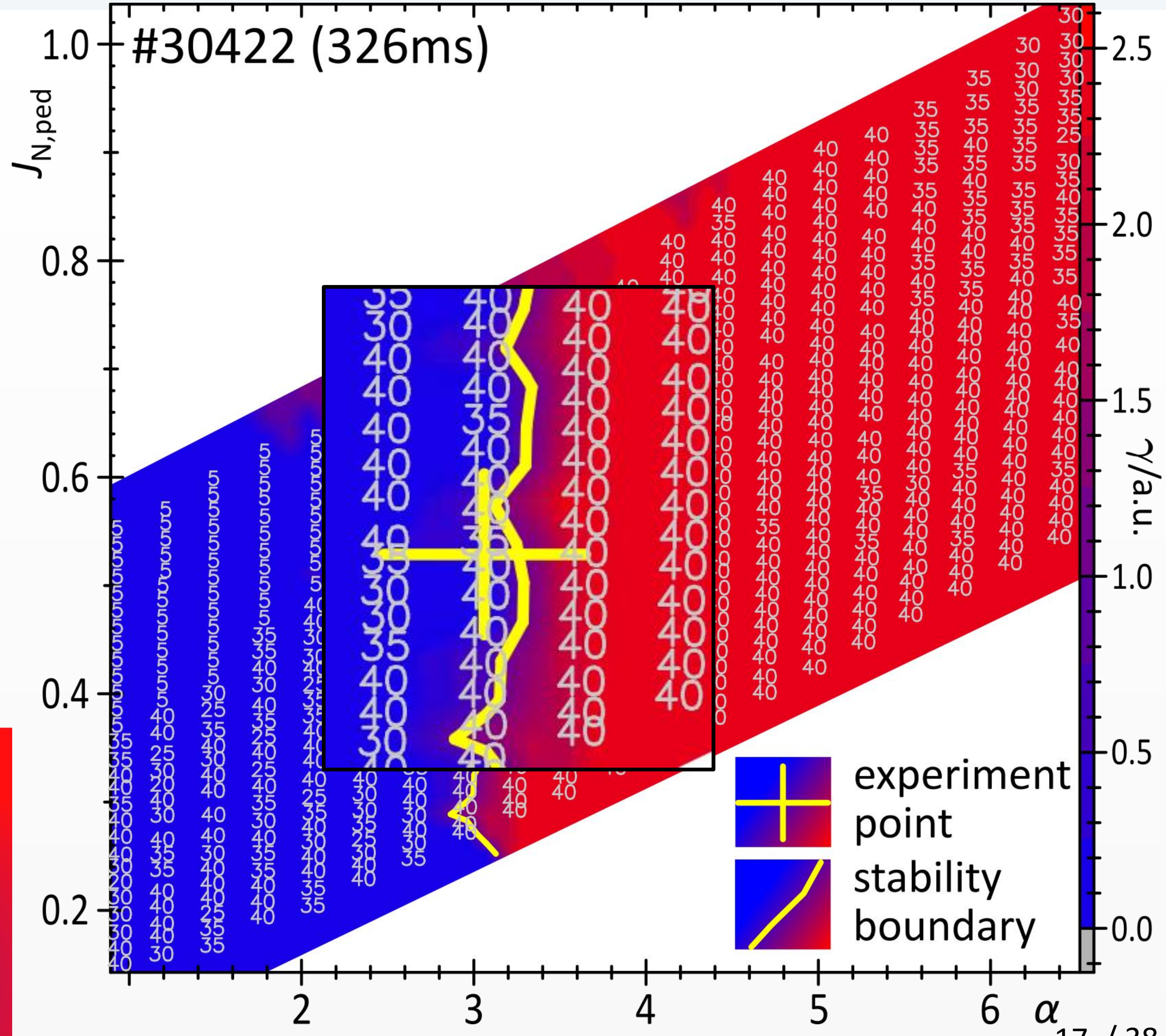
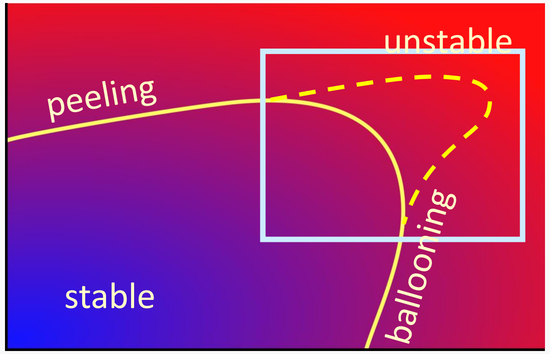


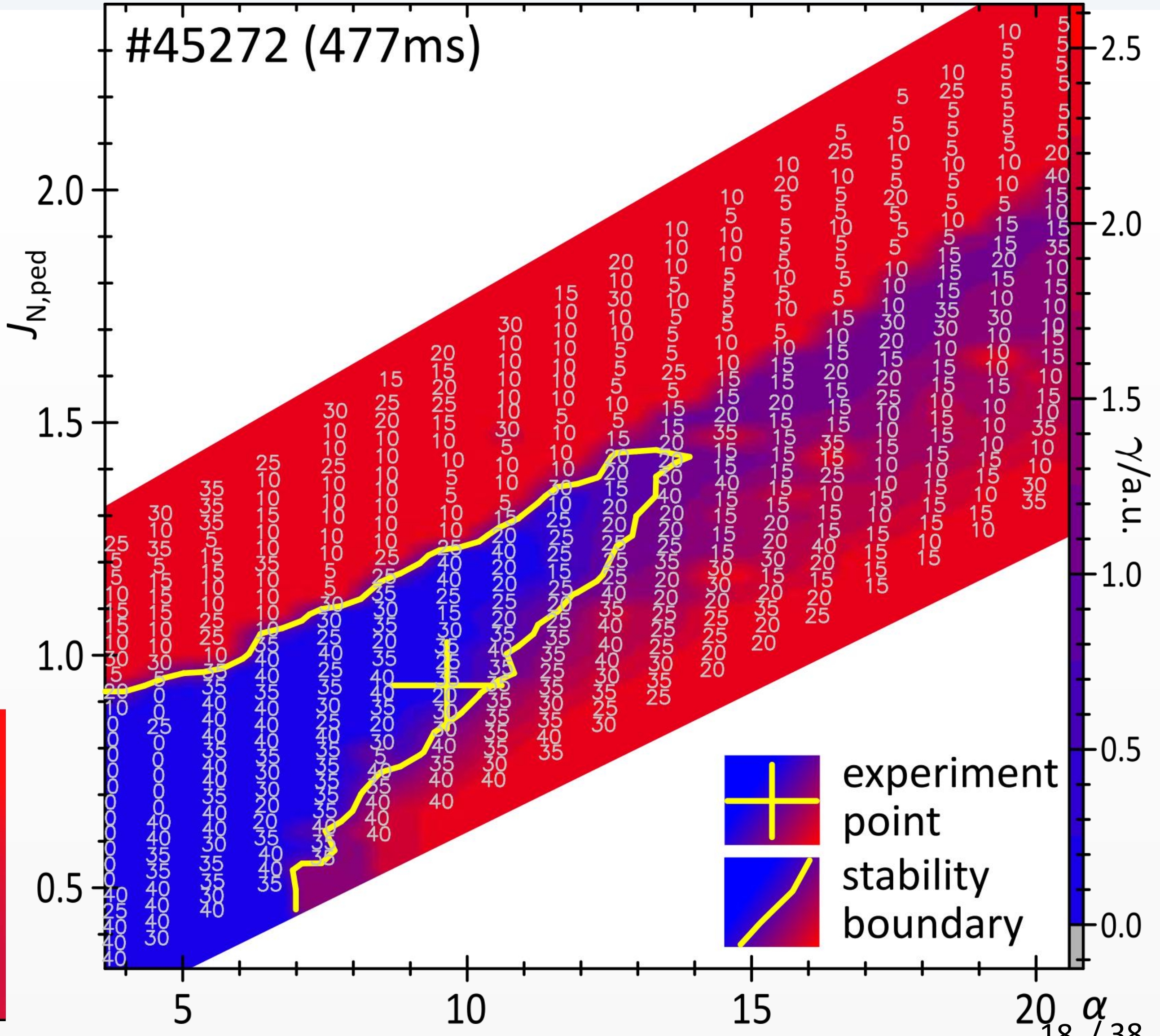




ELITE results for MAST-U #45272

- Radically different stability boundary
- Still moderately high n = 20~35 around the experiment point
- Considerably higher α and $J_{\mathrm{N,ped}}$, compared to MAST #30422
- Significantly extended "nose" of stability region between the boundary branches!
- Indicative of weaker coupling between peeling and ballooning modes





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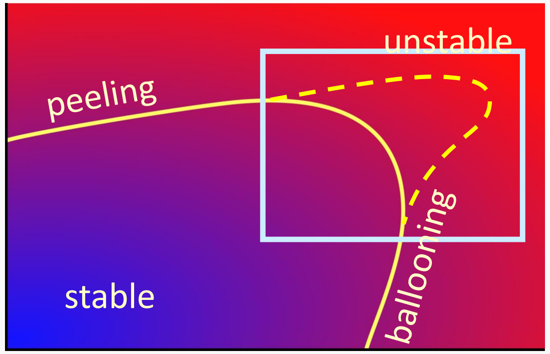
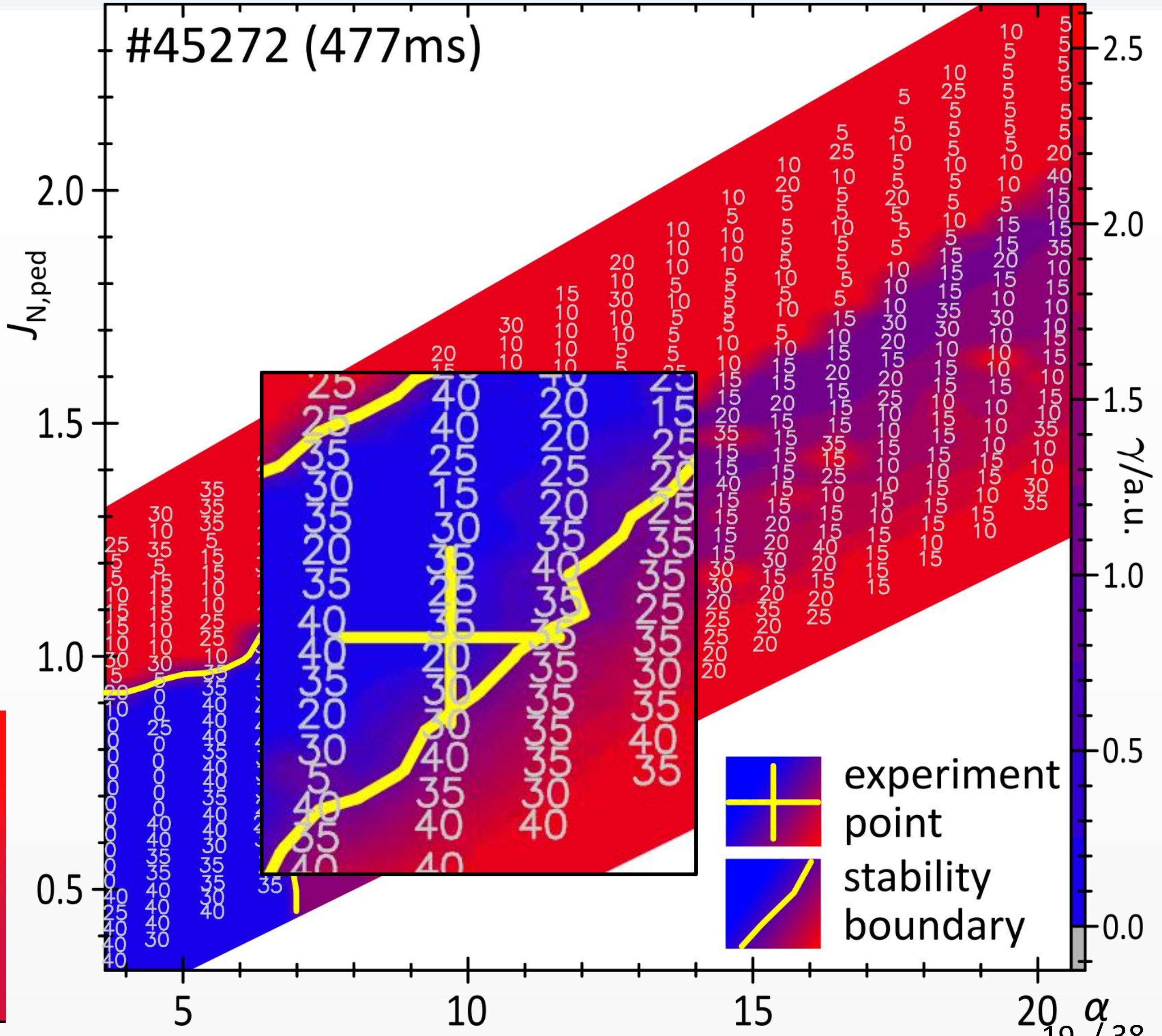


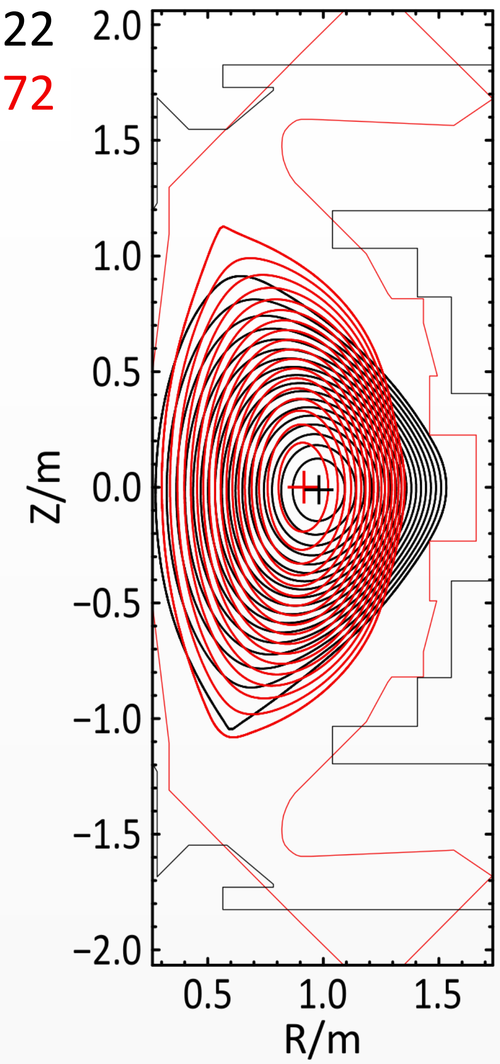


Effect of plasma shape?

- Many plausible reasons for the much improved pedestal stability in MAST-U.
- One contribution: shaping parameters (elongation *κ*, triangularity *δ*, squareness *ζ*)
- Try "swapping" the shapes and see what happens to the *J*-*α* stability diagram!
  - Keep triangularity the same, modify the other two:

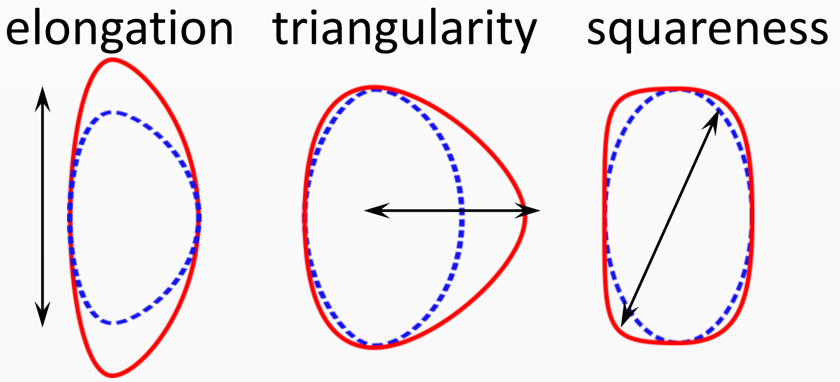
	MAST	MAST-U
κ	1.57	2.16
δ	0.50	0.48
ζ	0.19	0.38

MAST #30422
MAST-U #45272



	MAST′	MAST-U′
κ	*2.08*	*1.56*
δ	0.50	0.48
ζ	*0.29*	*0.28*

(squareness was modified as far as possible)



Effect of plasma shape

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original

	MAST	MAST-U
κ	1.57	2.16
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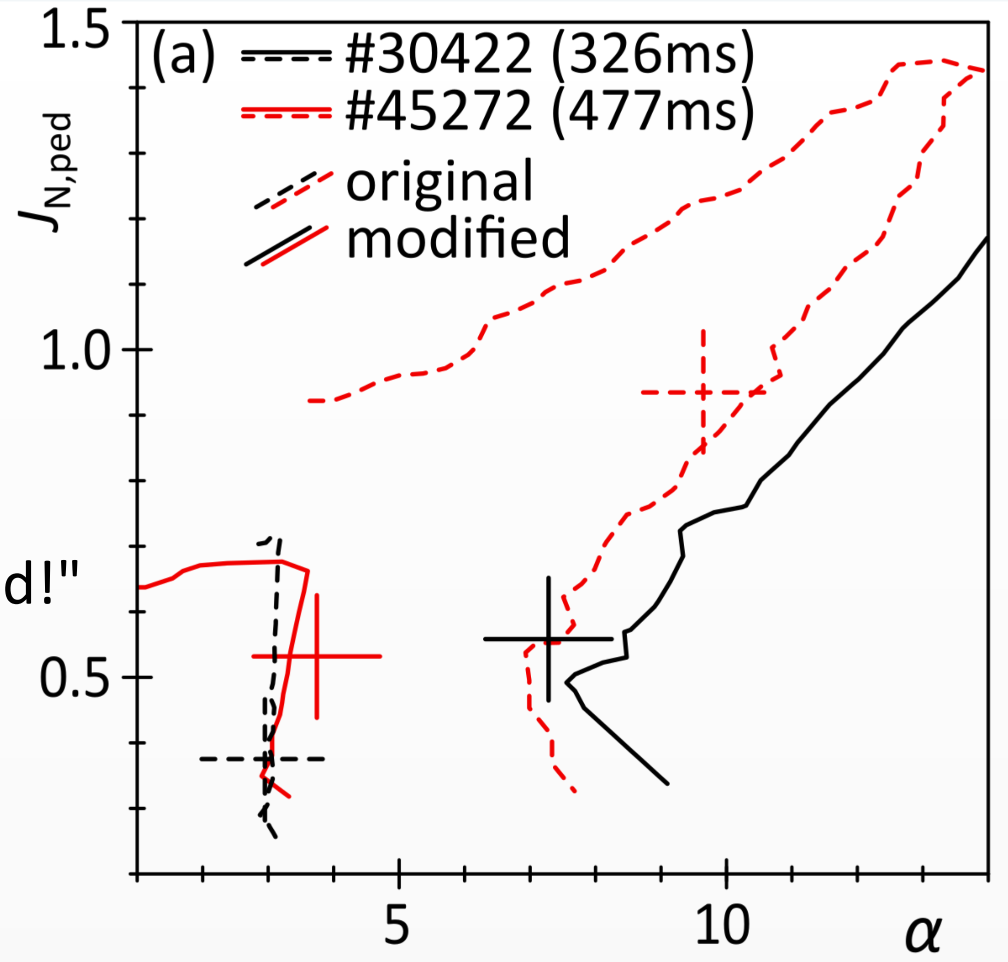
modified

	MAST’	MAST-U’
κ	*2.08*	*1.56*
δ	0.50	0.48
ζ	*0.29*	*0.28*

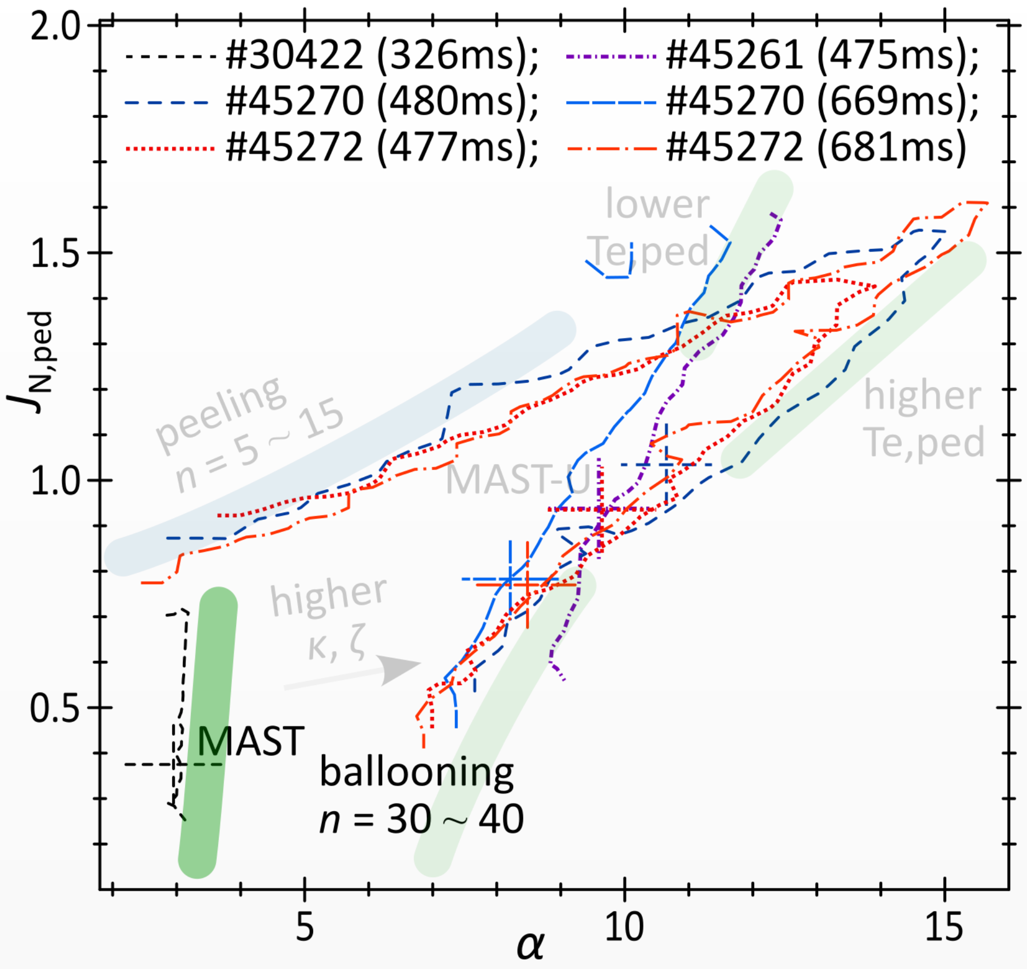
- Remarkably the stability boundaries are also "swapped!"
- MAST-U’ is now ballooning limited, whereas MAST’ has significantly extended region of stability.
- Significant changes in the shapes have impact also on α and $J_{N,ped}$.
- Higher elongation and squareness definitely play a part in MAST-U's improved pedestal stability.[#9]



#9: Imada et al, *Nuclear Fusion* (2024, in review)

Summary 1: *J*-*α* diagram for MAST vs. MAST-U

- MAST: definitely ballooning limited
  - peeling boundary probably around $J_{\mathrm{N,ped}} \sim 0.8$



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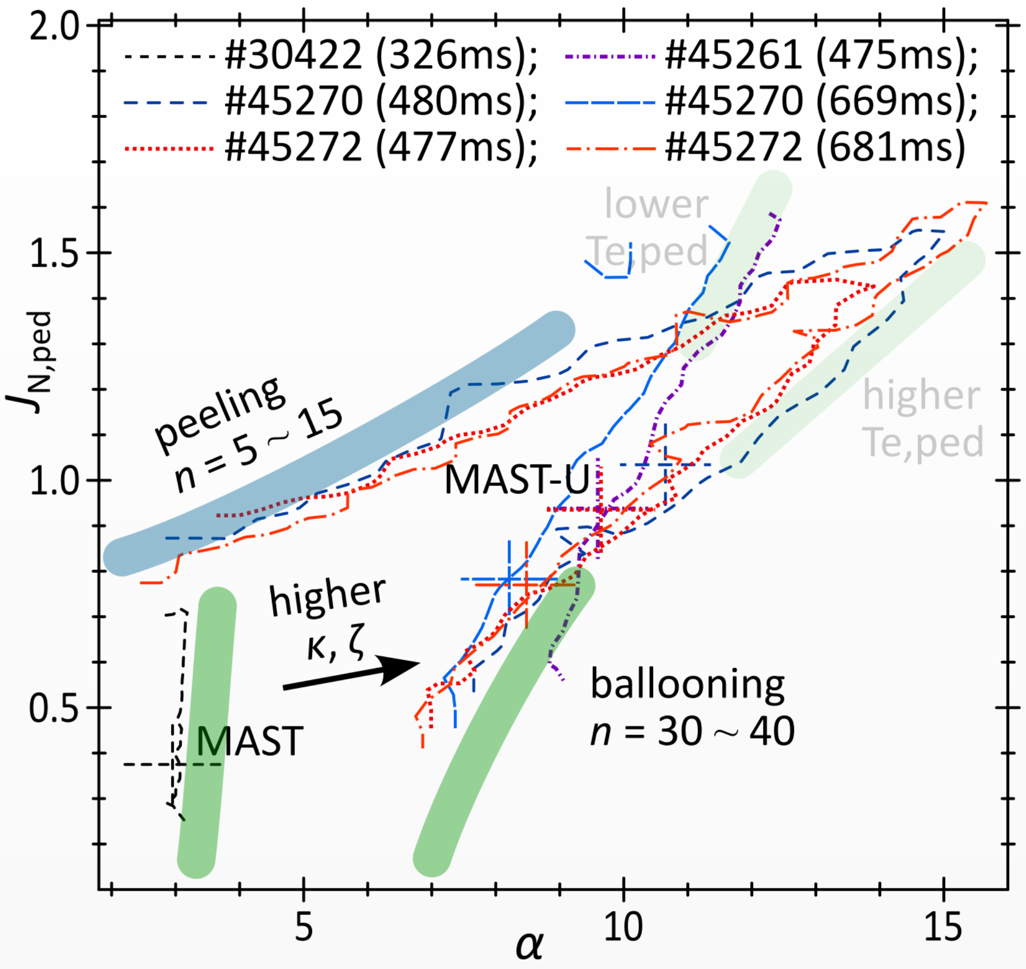
- MAST: definitely ballooning limited
  - peeling boundary probably around $J_{N,ped} \sim 0.8$
- MAST-U: boundaries at much higher $J_{N,ped}$ and α
  - Definite evidence of the peeling boundary, close to the experimental points
  - Stable region extends far into higher values of $J_{N,ped}$ and α; not seen to this extent before

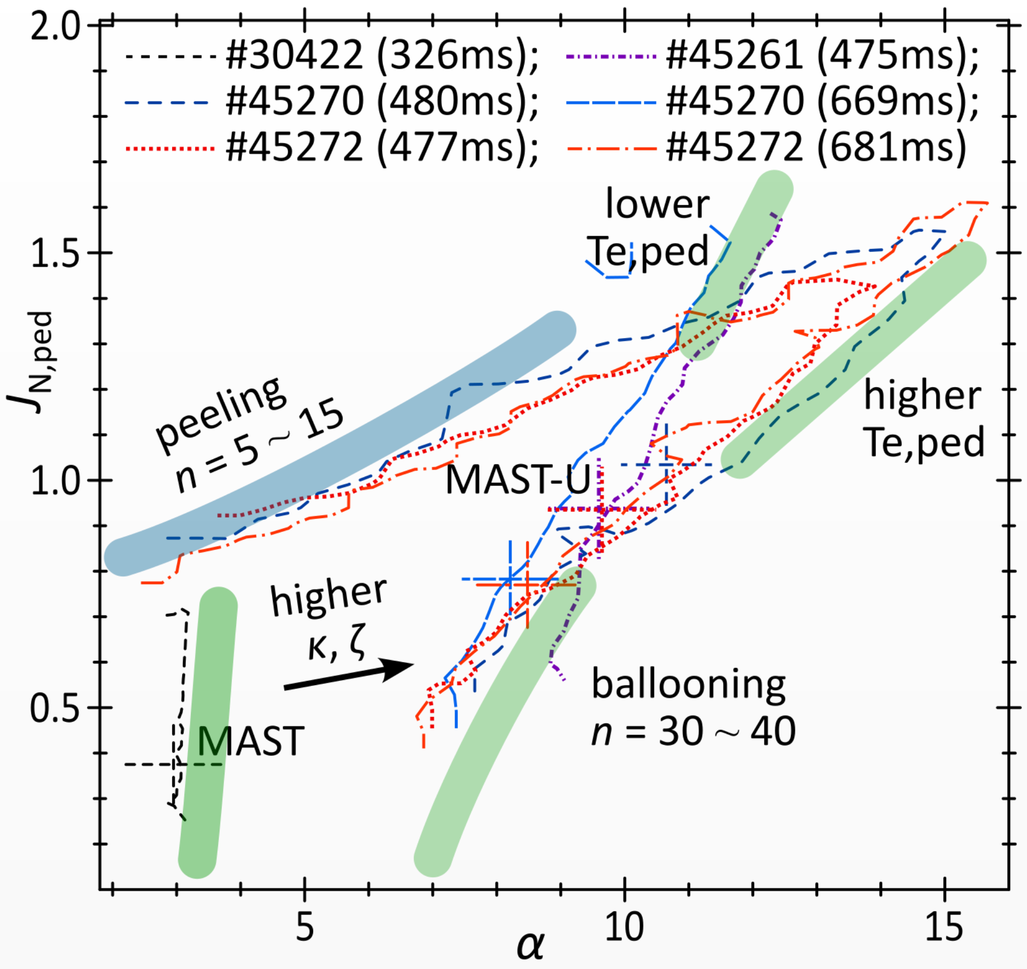


#9: Imada et al, *Nuclear Fusion* (2024, in review)

Summary 1: *J-α* diagram for MAST vs. MAST-U

- MAST: definitely ballooning limited
  - peeling boundary probably around $J_{\mathrm{N,ped}} \sim 0.8$
- MAST-U: boundaries at much higher $J_{\mathrm{N,ped}}$ and α
  - Definite evidence of the peeling boundary, close to the experimental points
  - Stable region extends far into higher values of $J_{\mathrm{N,ped}}$ and α; not seen to this extent before
  - Indicative of weaker coupling between peeling and ballooning branches (especially at higher Te,ped)
- Now, we could access peeling-limited pedestal regime (no Type-I ELMs there), if $J_{\mathrm{N,ped}}$ could be raised while keeping α fixed...

  → then QH / SH modes / other no-ELM regimes!(?)

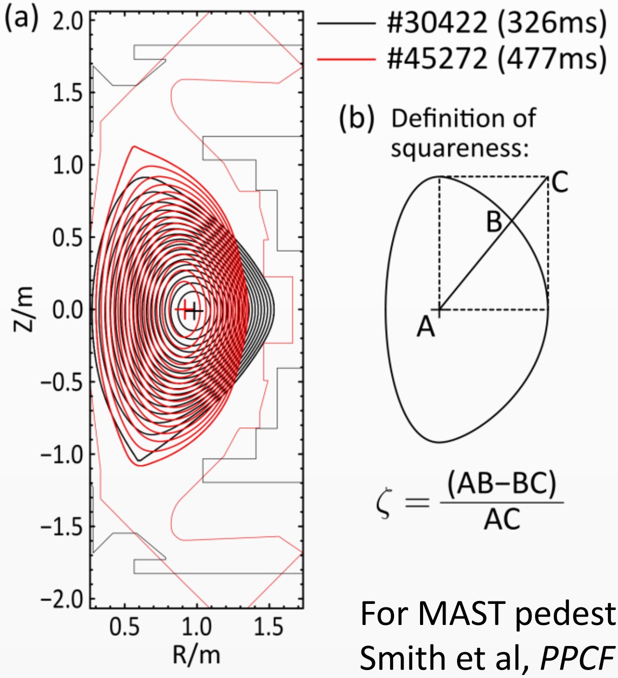


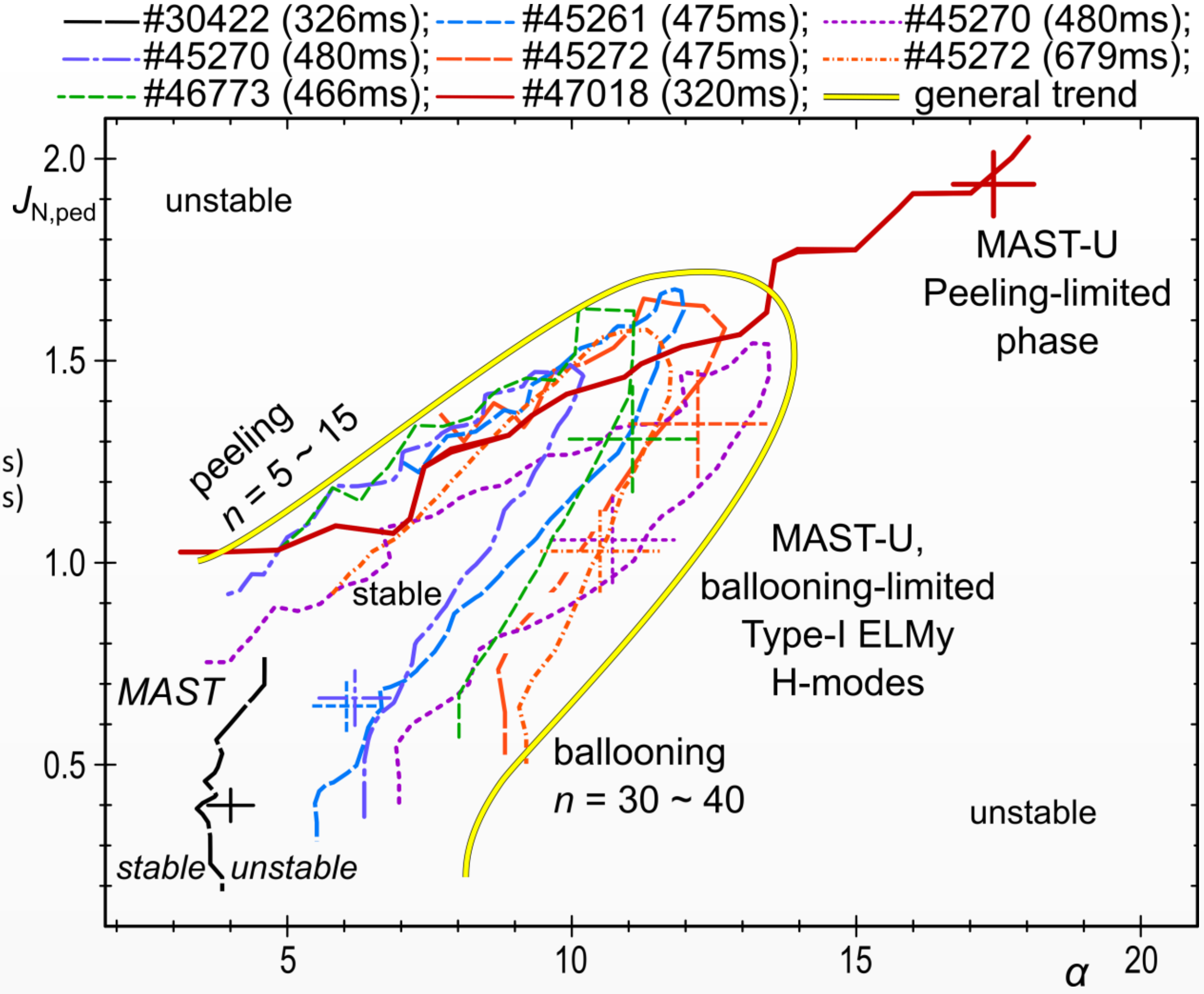
#9: Imada et al, *Nuclear Fusion* (2024, in review)

Case study 2: MAST-U ELM-free period

- 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



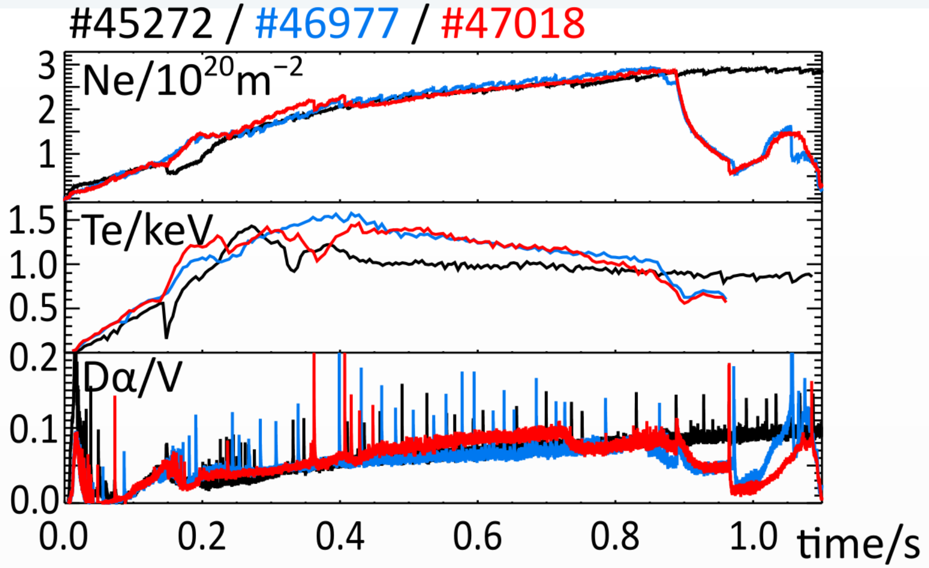


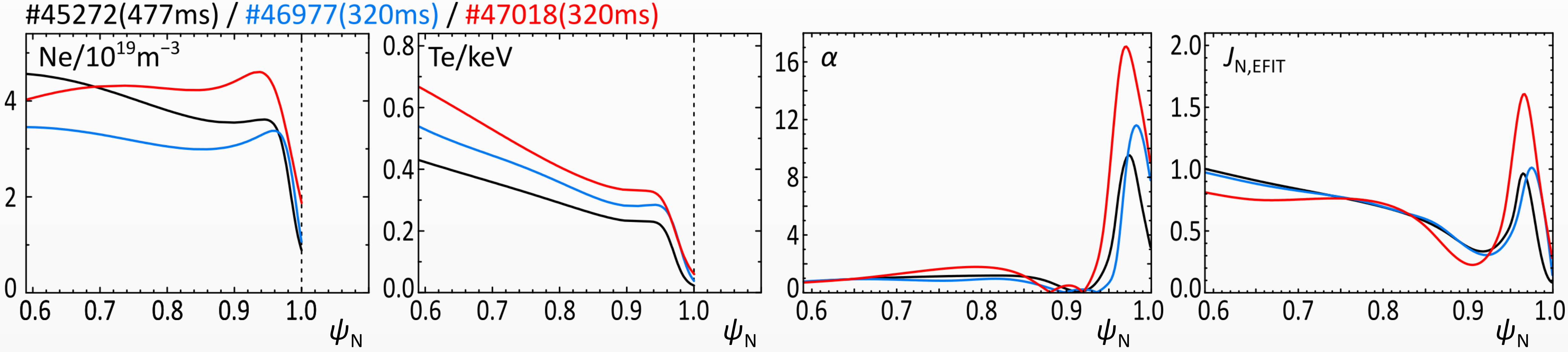
For MAST pedestal stability analysis, see e.g.:
Smith et al, *PPCF* **64**, 045024 (2022) / Knolker et al, *Nuclear Fusion* **61**, 046041 (2021)

MAST-U high Te,ped, ELM-free period

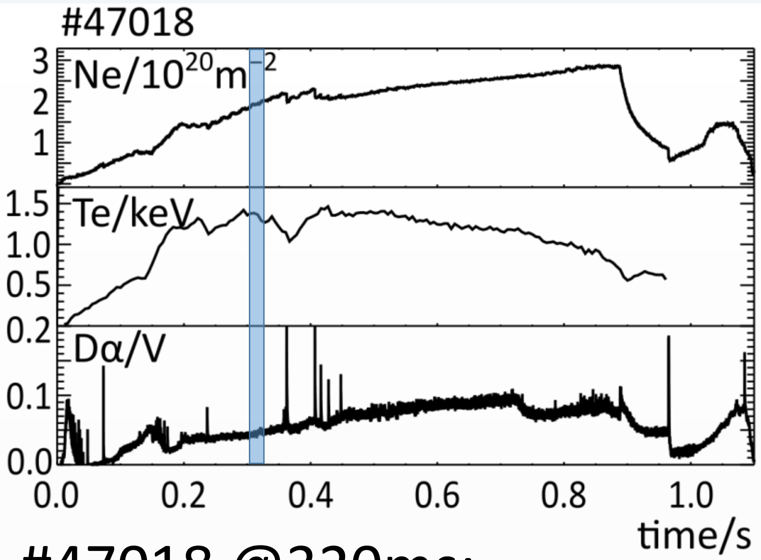
- #47018 has a notably high pedestal temperature:
- Results in low collisionality:
- 100ms of no-ELM phase results in high α (also high $N_{e,ped}$)
- High J_N in the pedestal region
- What about the P-B stability?

	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



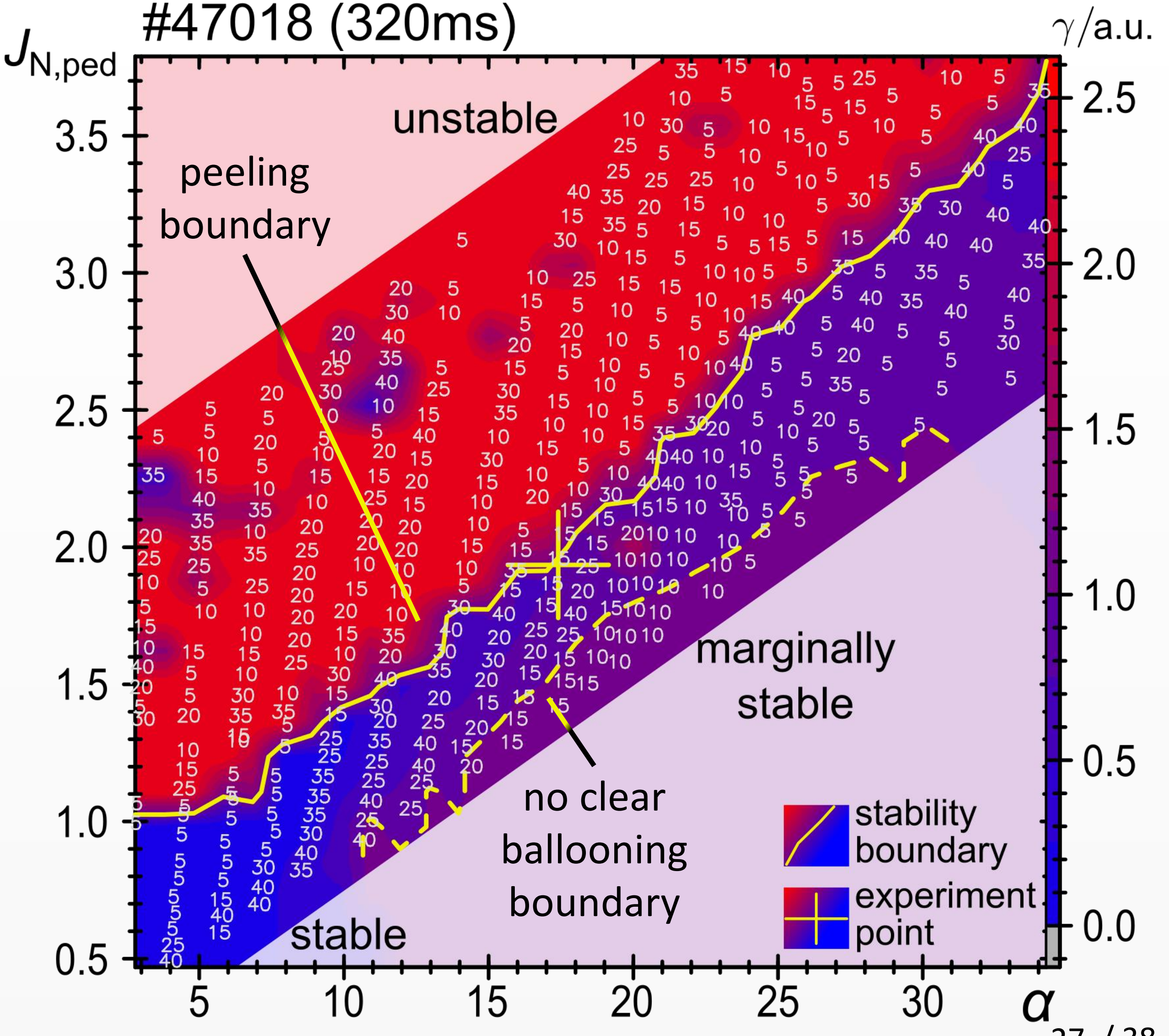


"Peeling-limited" period with high *T*e,ped and low ν_*e,ped[#10]



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

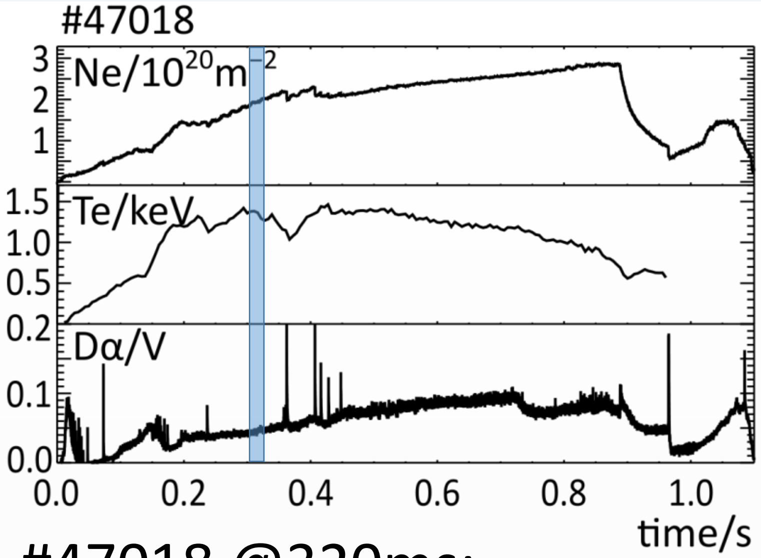
- #47018 @320ms:
  - Unlike "typical" MAST-U cases, no clear presence of ballooning stability boundary
  - (At least marginally) stable to ideal ballooning modes!
  - Lower mode numbers around expt. point: $n = 5 \sim 15$ (c.f. typically $30 \sim 40$)
  - More "peeling-limited" than ballooning!



#10: Imada et al, *PPCF* (in preparation)

"Peeling-limited" period with high T_e,ped and low ν_*e,ped[10]

[10]: Imada et al, *PPCF* (in preparation)



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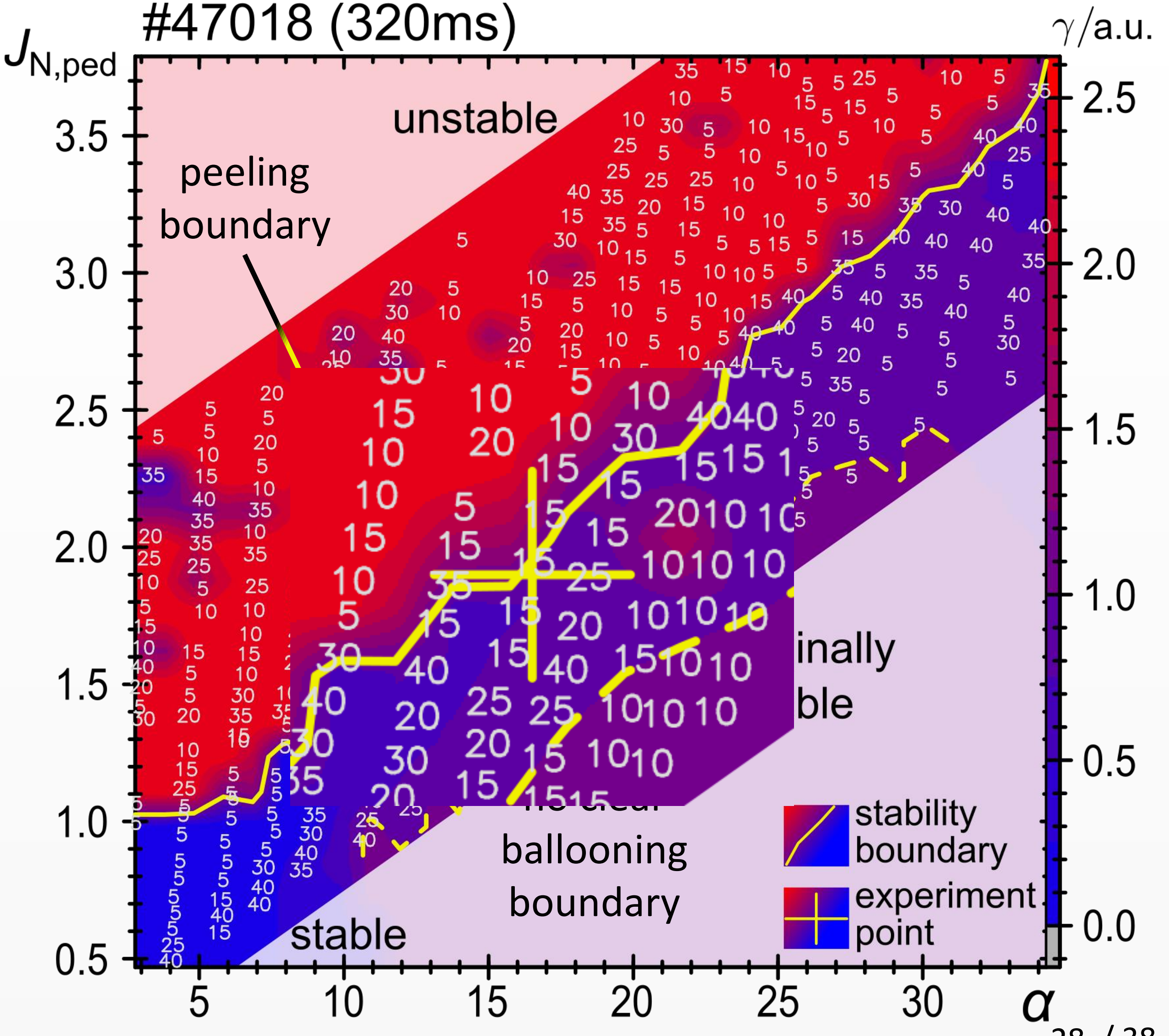
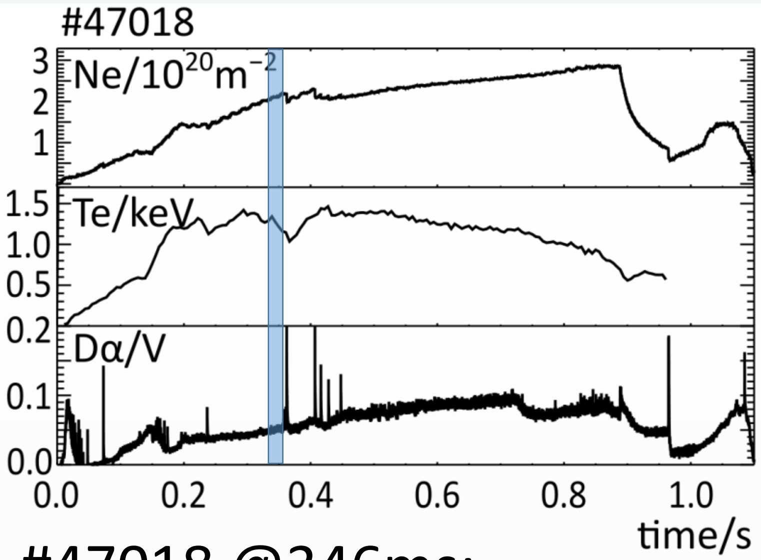


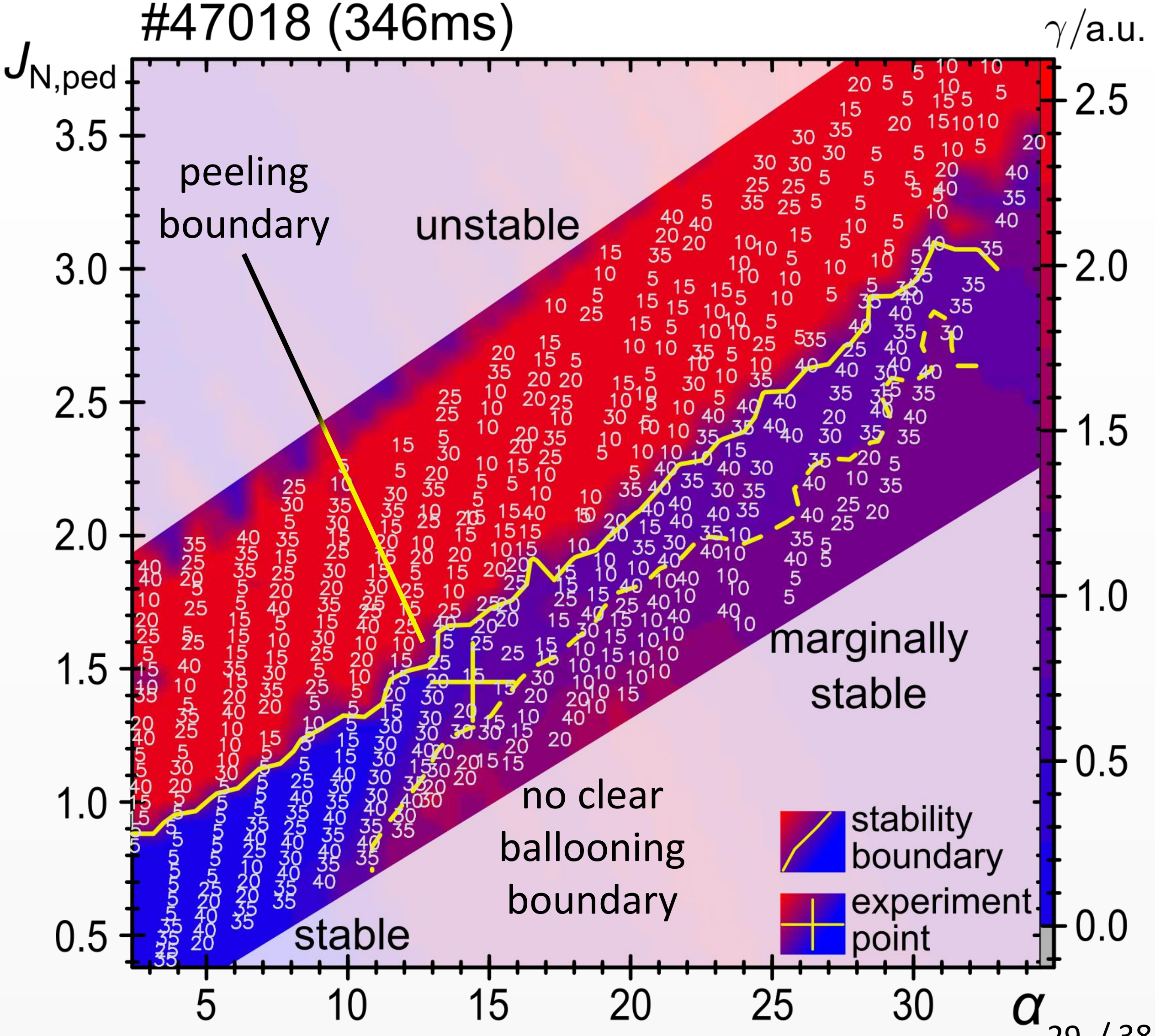
"Peeling-limited" period with high *T*e,ped and low ν_*e,ped[#10]

#10: Imada et al, *PPCF* (in preparation)



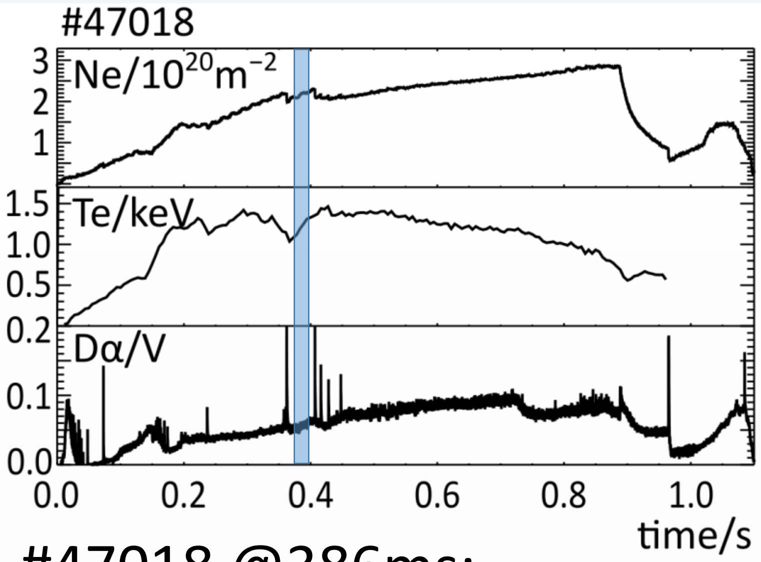
elongation	2.16
triangularity	0.43
squareness	0.38
$\nu_{*e,ped}$	1.29
$T_{e,ped}$/keV	0.31
α	14.5
$J_{N,ped}$	1.43

- #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?)



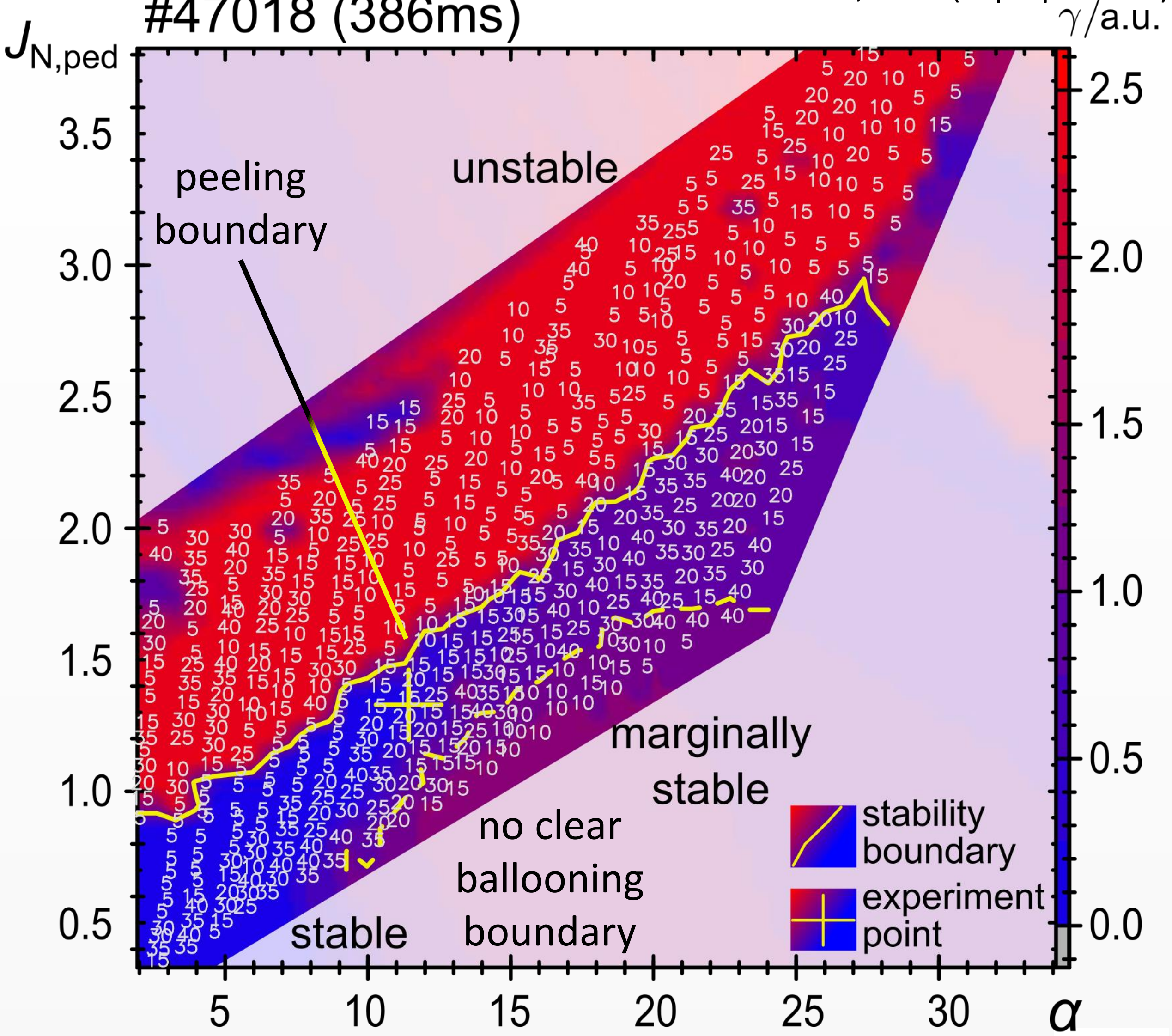
"Peeling-limited" period with high Te,ped and low ν_*e,ped[10]

#10: Imada et al, *PPCF* (in preparation)

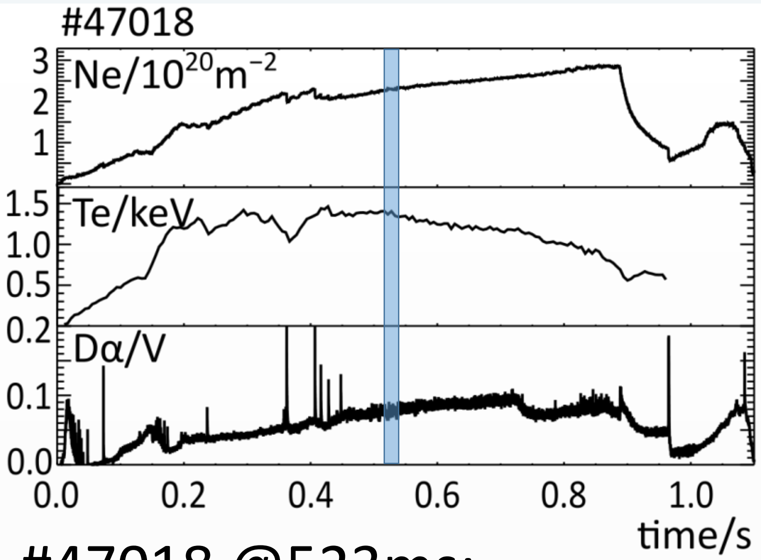


elongation	2.18
triangularity	0.48
squareness	0.38
$\nu_{*\mathrm{e,ped}}$	0.97
$T_{\mathrm{e,ped}}$/keV	0.35
α	11.4
$J_{\mathrm{N,ped}}$	1.35

- #47018 @386ms:
  - Even after the ELM crash, still high $T_{\mathrm{e,ped}}$ and low $\nu_{*\mathrm{e,ped}}$
  - 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!

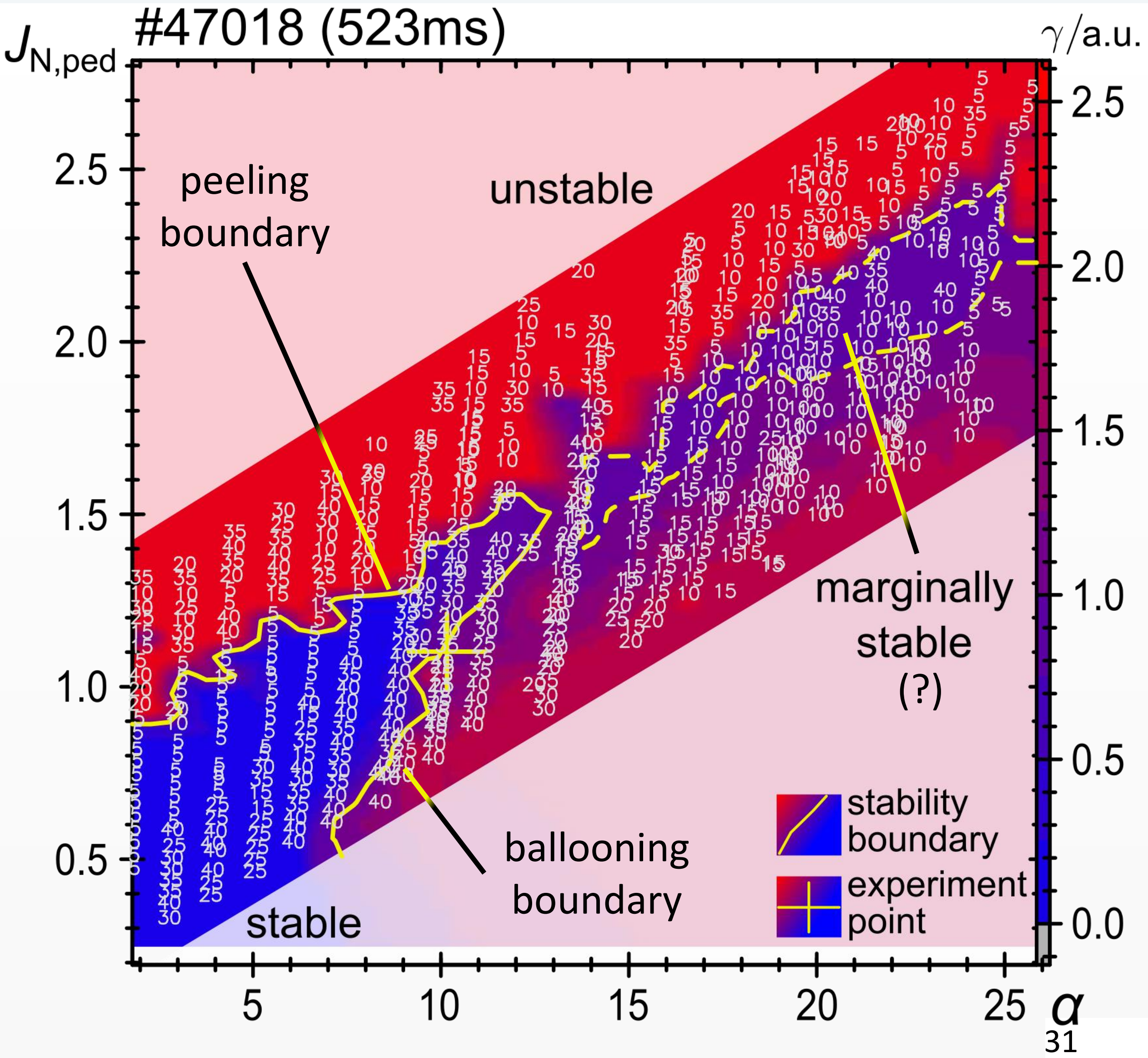


Not peeling-limited period, but no ELMs either



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 later...)



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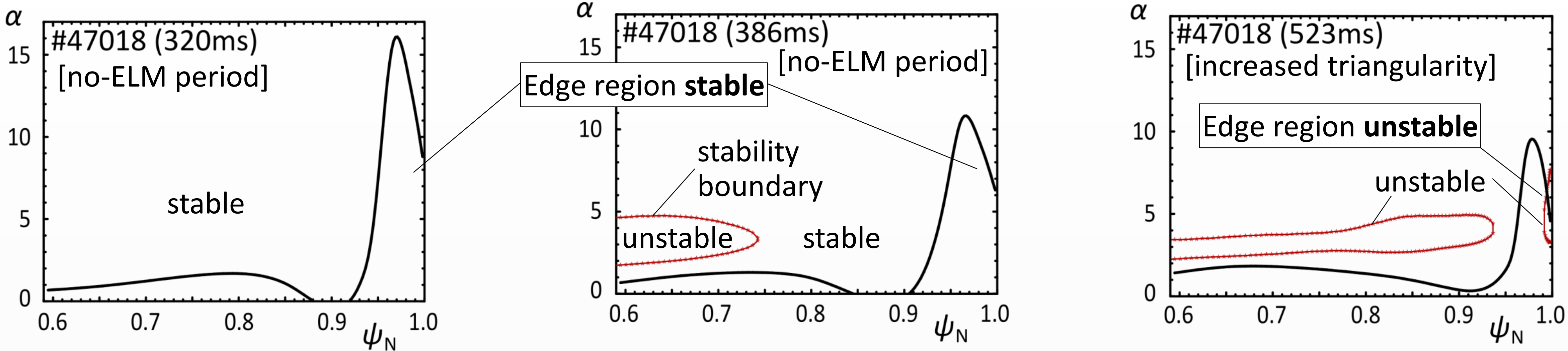
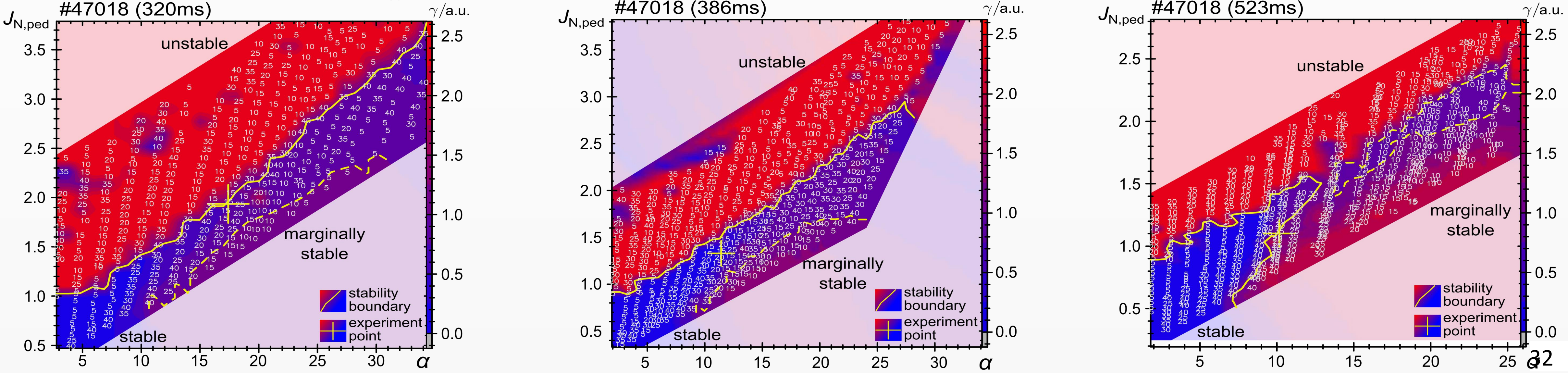
* This was designed to be a triangularity shift experiment.

Peeling-limited phase with high T_e,ped and low ν_{*}e,ped

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

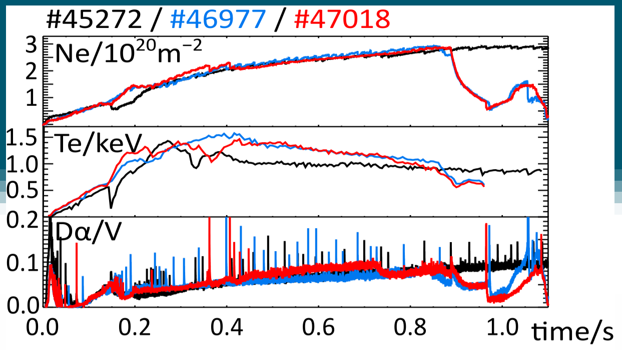
- BALOO[#11] analysis confirms stability against infinite-*n* ideal ballooning modes



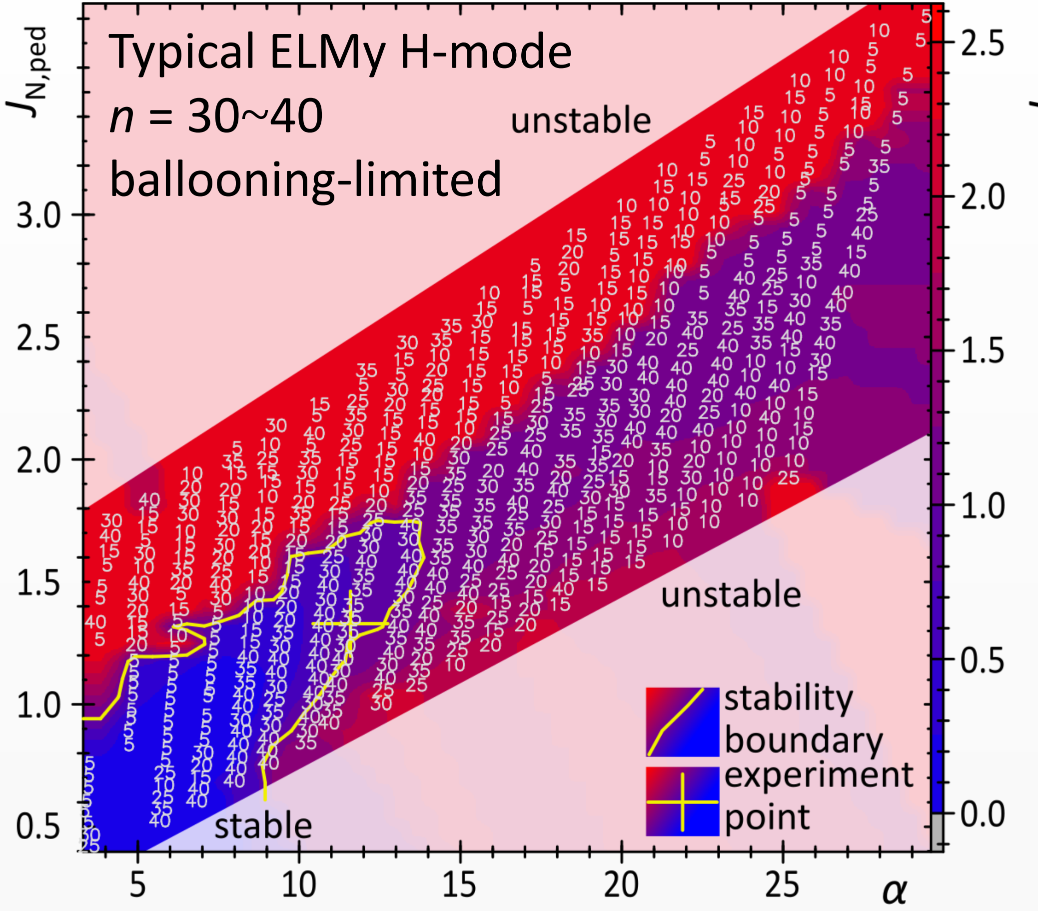


#47018: Why ballooning stable?

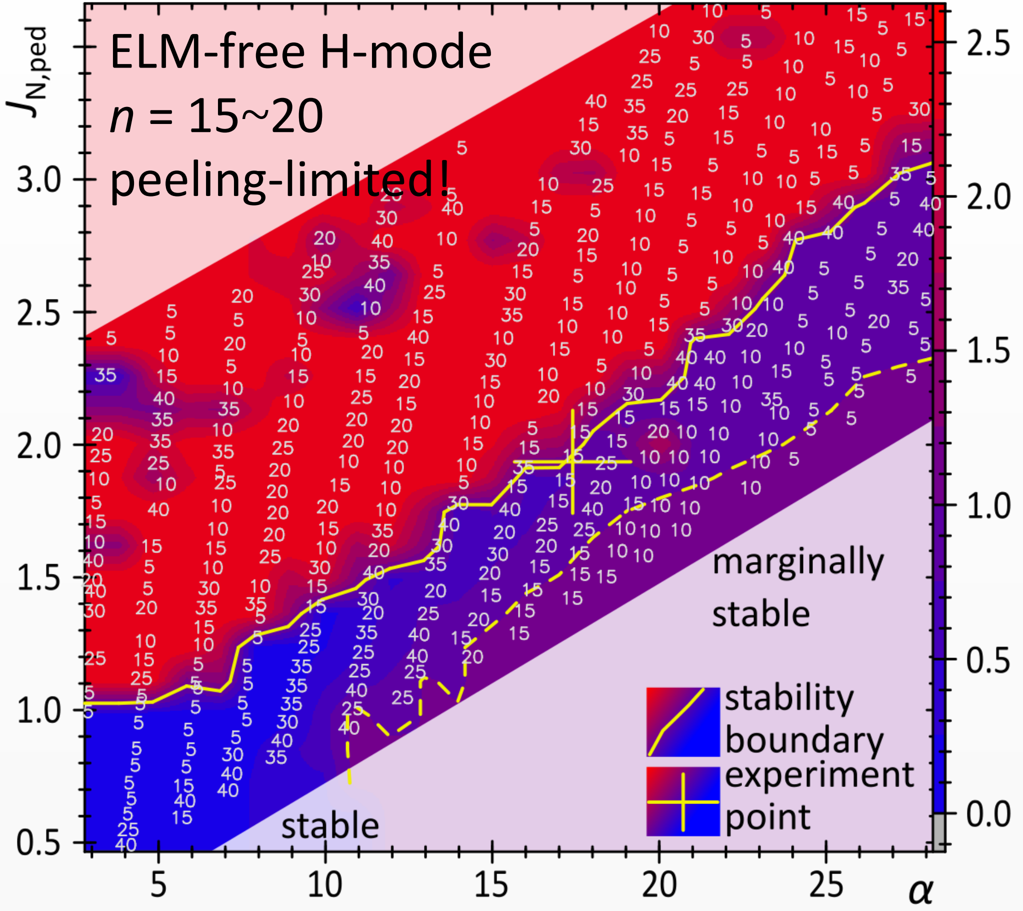
- Is this an exception? Compare with #46977 again:



#46977 (320ms)

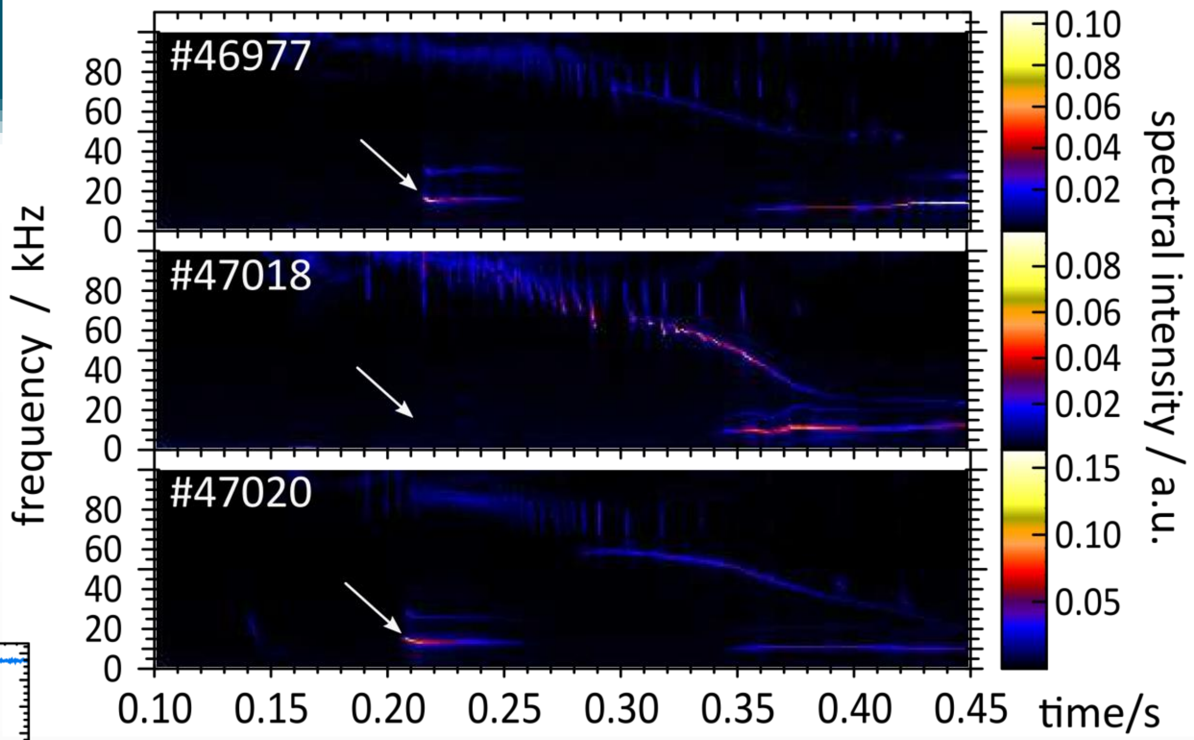


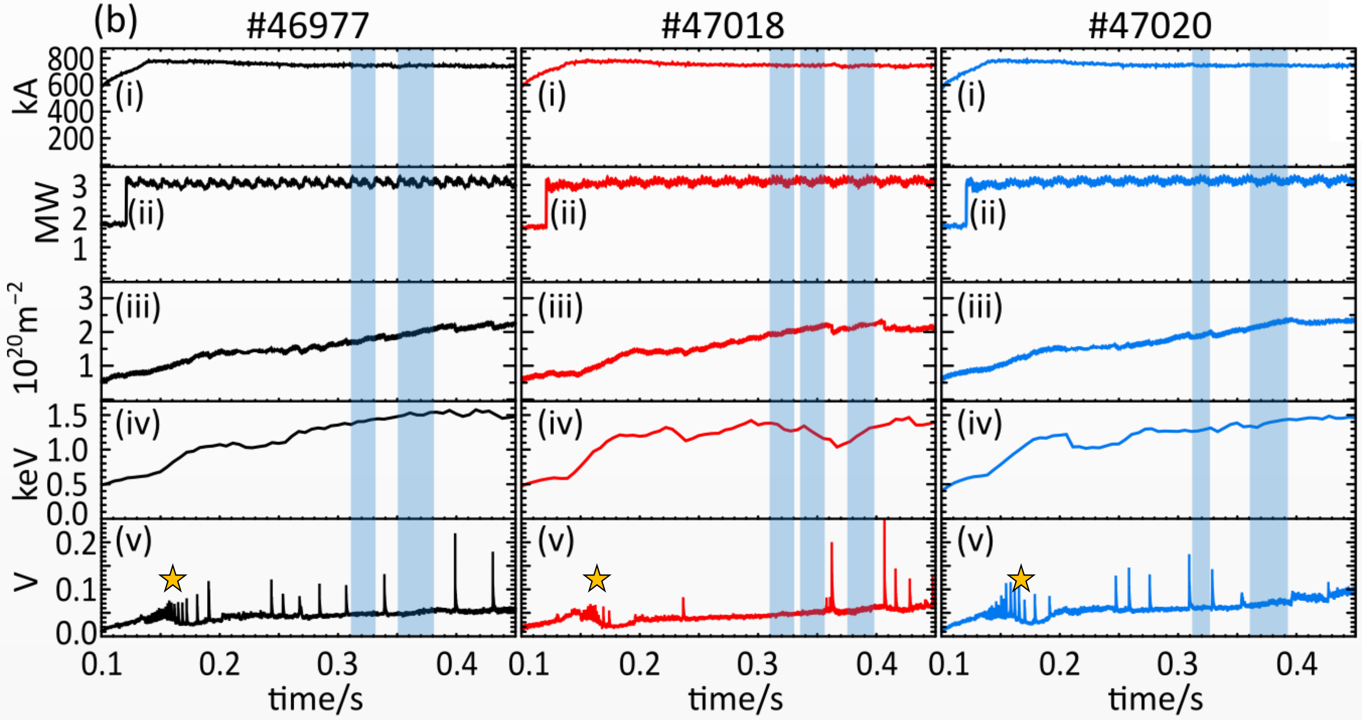
#47018 (320ms)



#47018: Why ballooning stable?

- #46977 and #47018 (also #47020) were identical in setup, except for triangularity increase later (350ms+) in the latter two.
- Clean ramp-up, no "IREs" – internal reconnection events, which typically upsets plasma (with dips in current / temp. evolution)





- However, difference in the onset of q=2 MHD modes...! (prevalent in MAST-U)
- No modes appearing for #47018
- Also, shorter Type-III ELM period (←☆)

(i) plasma current; (ii) NBI power;
(iii) line int. electron density;
(iv) core electron temperature;
(v) Dα signal (ELMs)

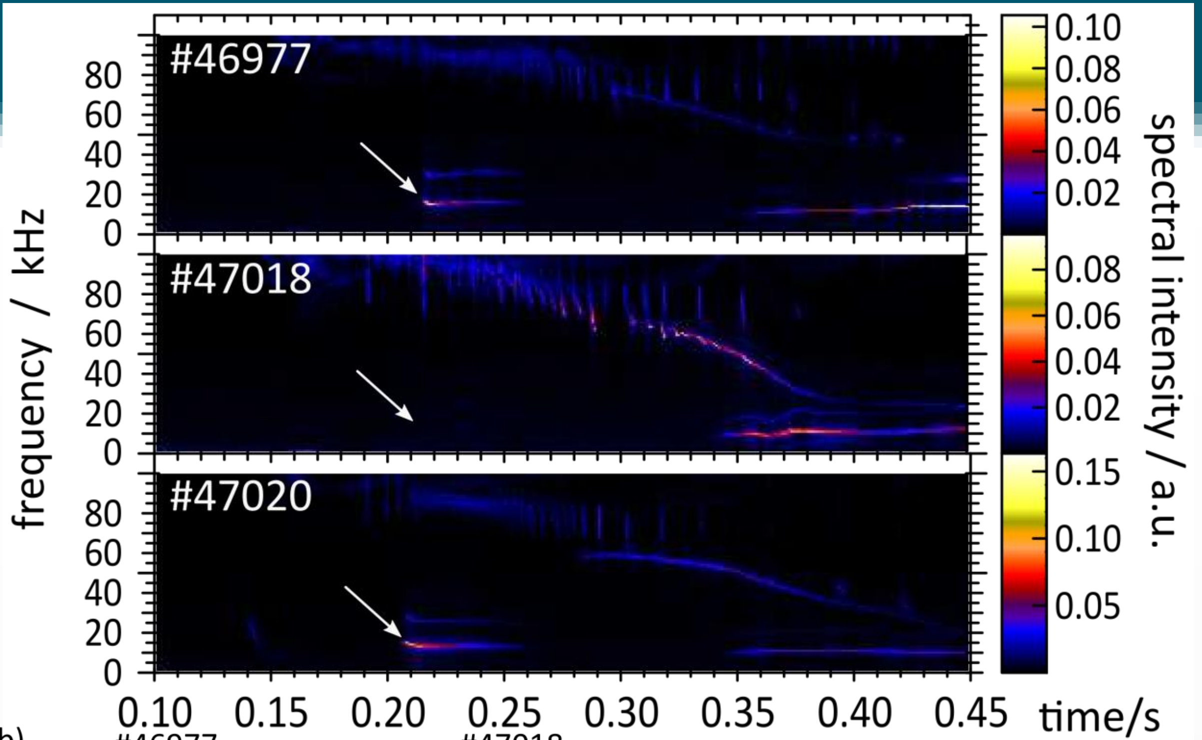
#47018: Why ballooning stable?

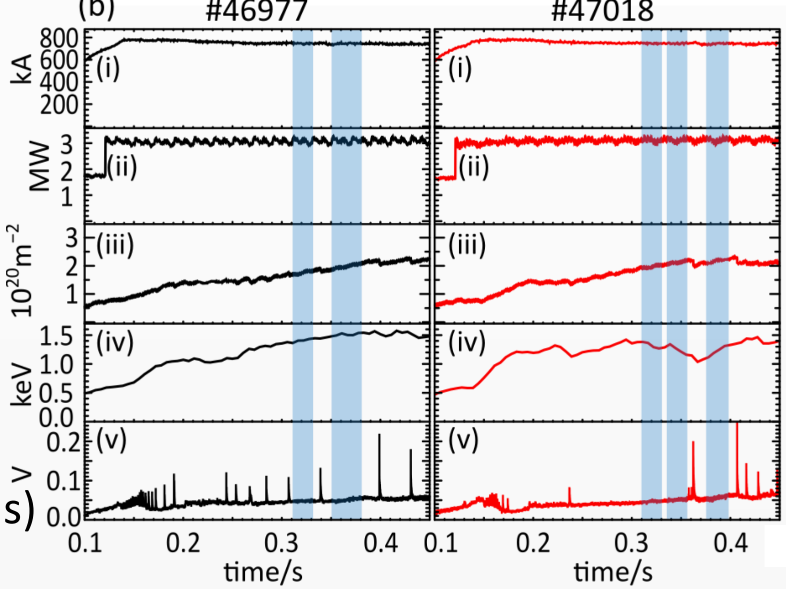
- No q=2 core MHD mode appearing for #47018.
- Also shorter Type-III ELM period.
- And comparatively high q95 (8~9 instead of 7~8)

resulting in...:

- Initially high pedestal temperature
- Low collisionality as a result ($\nu^* \propto n/T^2$)
- Allowing for higher peak in current density
- Hence higher $J_{\mathrm{N,ped}}$ for given α, and more stable plasma edge
- ∴ plasma far away from the ballooning boundary, pedestal is peeling-limited, and no ELMs triggered!

(ELMs do return, as MHD mode eventually appears after 350ms)

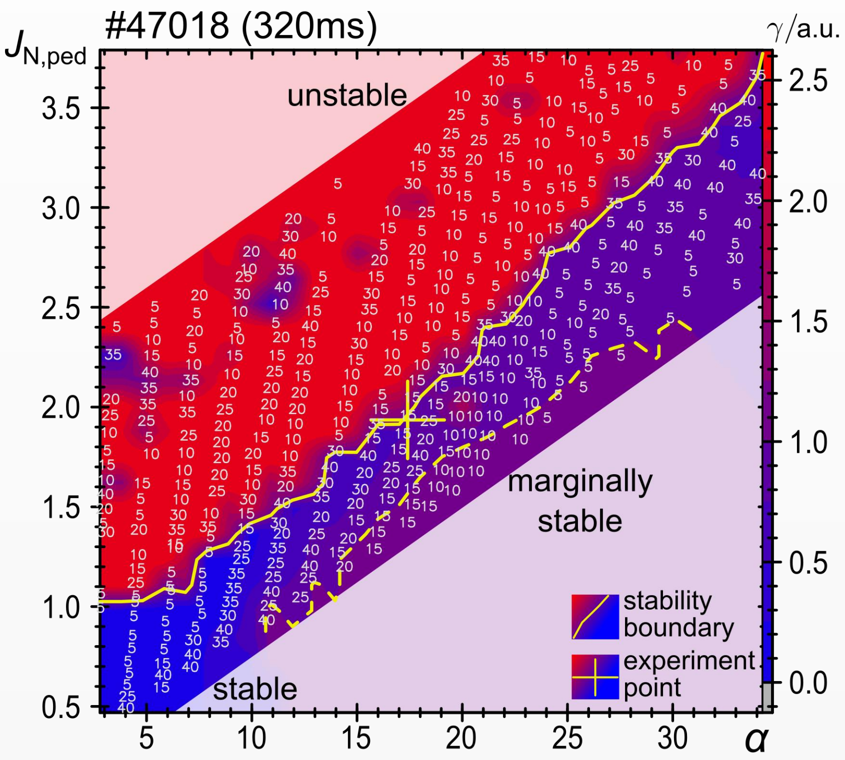


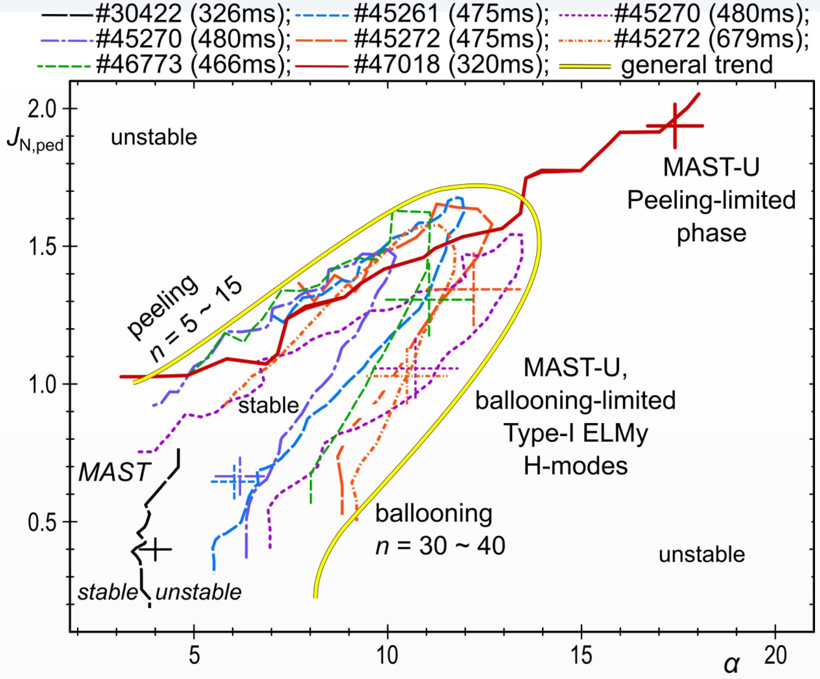


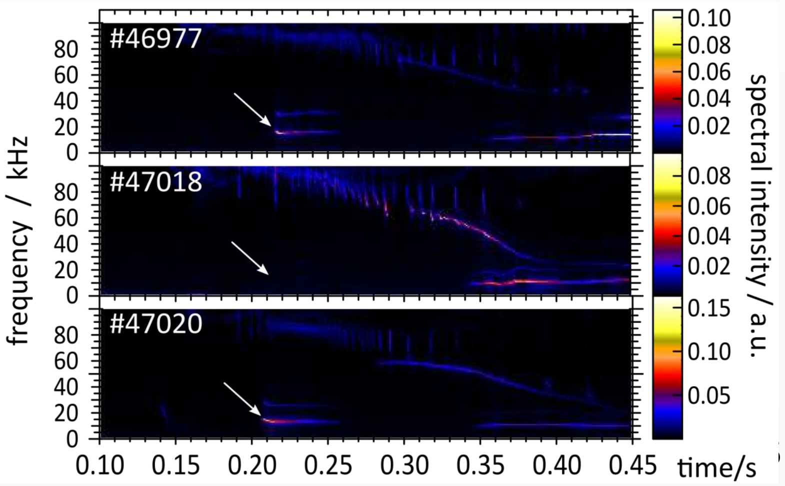
	46977	47018
$\nu_{*\mathrm{e,ped}}$	1.45	1.28
$T_{\mathrm{e,ped}}$/keV	0.28	0.32
α	12.0	17.3
$J_{\mathrm{N,ped}}$	1.15	1.91

Summary 2: ELM-free period in MAST-U

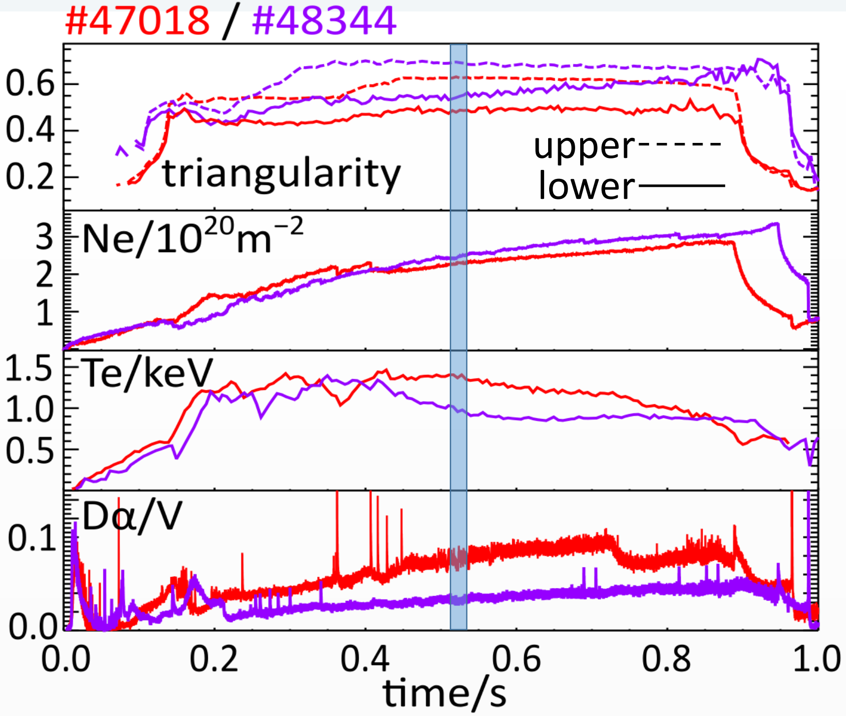
- High pedestal temperature, low collisionality case:
  - Stable against high-*n* ideal ballooning modes
  - Peeling-limited with much higher $J_{N,ped}$ and α
  - Longer inter-ELM period
- Key ingredients:
  - clean, smooth ramp-up
  - avoid q=2 MHD mode
  - achieve high pedestal temperature, low collisionality
  - others?
    - (work ongoing!)

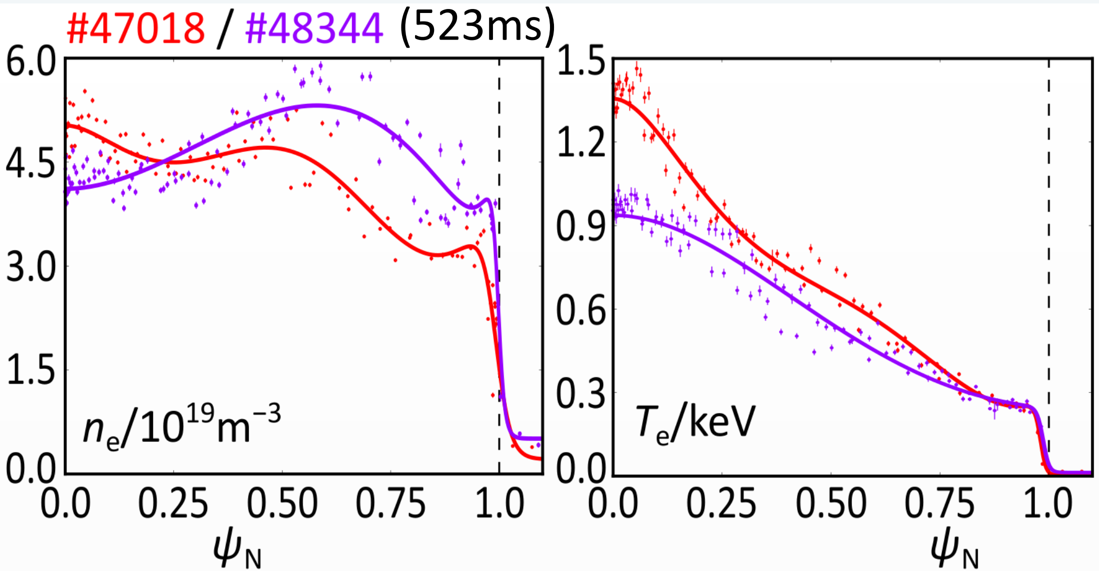


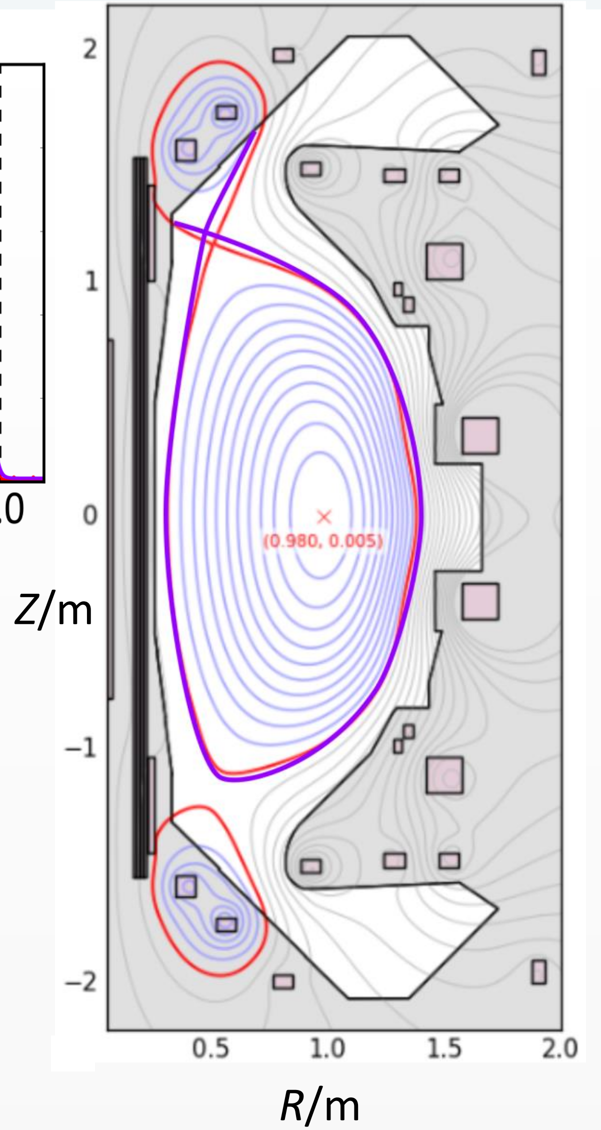




(mini) Case study 3: No-ELM period with high triangularity







- Also seen in more recent MAST-U experiments (08/'23: #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
$\nu_{*\mathrm{e,ped}}$	1.45	—
$T_{\mathrm{e,ped}}$/keV	0.23	0.24
α, $J_{\mathrm{N,ped}}$	10.7, 1.08	~20, 1.3

Summary

- Improved pedestal stability in MAST-U
  - Plasma shape plays an important role
- ELM-free periods in some MAST-U shots
  - Ballooning-stable, peeling-limited
  - #47018, also seen in Jan. 2024!: #49360
  - Need high $T_{e,ped}$, low $v^*_{e,ped}$
  - Or, EDA mode with very high triangularity..?
- More expts + analyses to come!