Impact of elongation on peeling–ballooning stability in TCV H-mode pedestals

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1 Motivation & Goal

Background

- ITER pedestals are expected to be limited by low-n peeling modes, motivating studies of peeling-limited regimes [1,2,3]
- Most existing tokamaks operate in ballooning-limited regimes [4,5]
- However, previous TCV experiments reached peeling-limited pedestals close to the nose of the peeling–ballooning boundary [3]
- Studies in KSTAR [6] and MAST-U [7] show that increasing plasma elongation can stabilize high-n ballooning modes and shift the limiting instability toward lower n

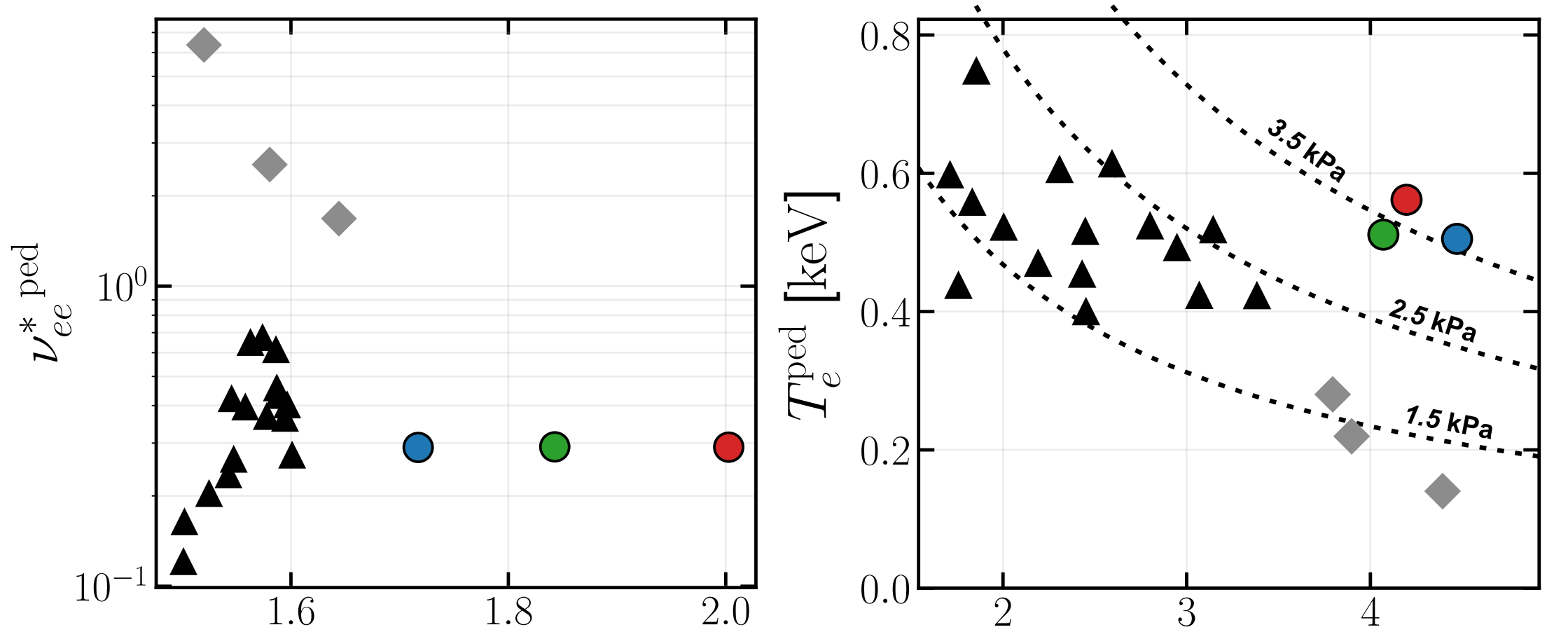
Goals of the study

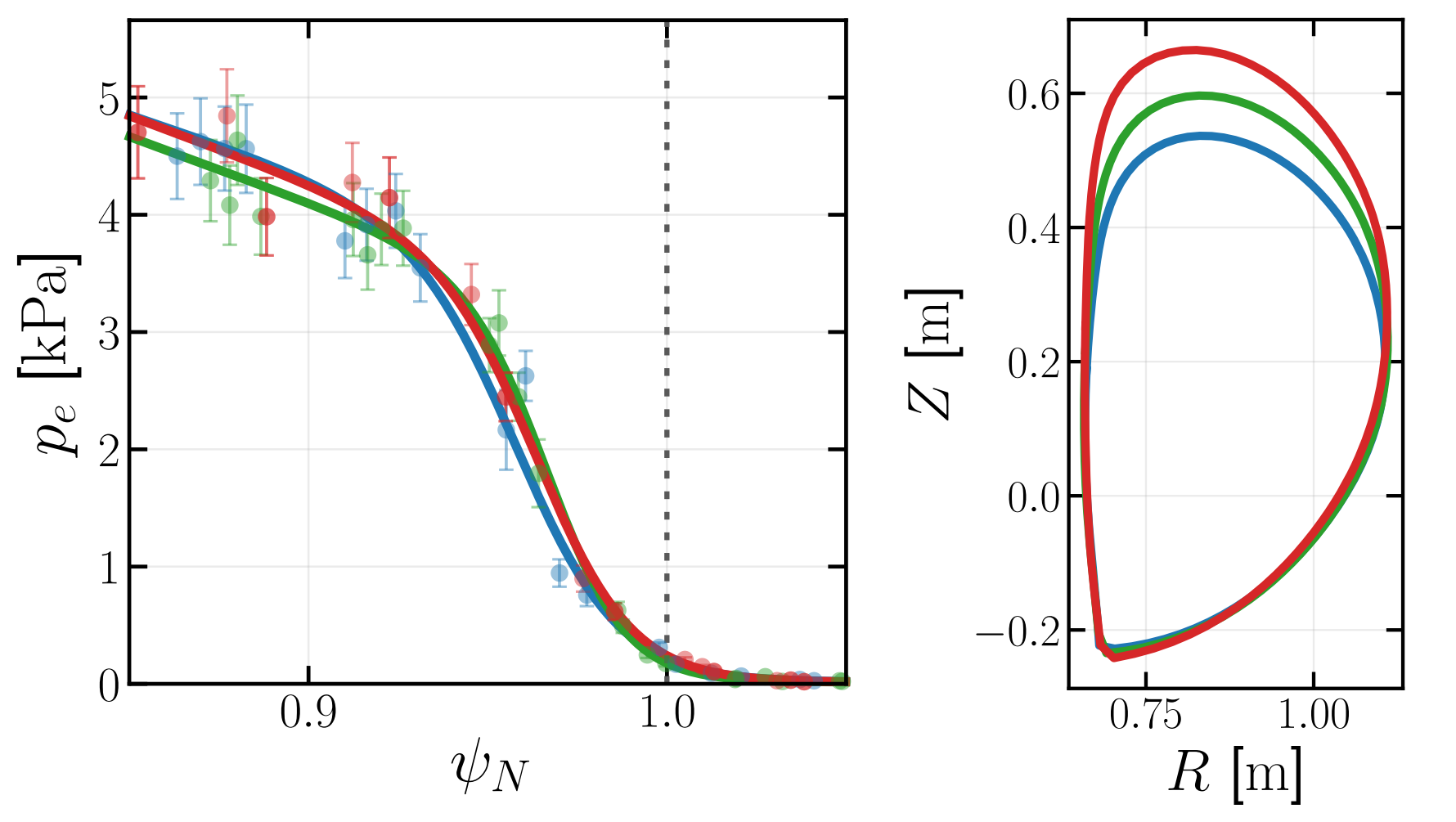
- Determine how κ affects the peeling-ballooning stability and the limiting mode number in TCV.
- Assess whether increasing κ can move TCV pedestals closer to the low-n peeling-branch, rather than near the nose

2 The Dataset

Two TCV H-mode discharges were analysed: #81545 and #81586

- $430\ \mathrm{kA} / 1.43\ \mathrm{T}$, $P_{\mathrm{ECRH}} \approx 1.8$ MW, $\beta_N \approx 1.48\text{-}1.65$, $Z_{\mathrm{eff}} \approx 2.4$
- Three time intervals were selected: $\kappa = 1.71$, 1.84, and 2.01
- The κ scan dataset reaches relatively low $\nu_{ee}^{*\,\mathrm{ped}} \sim 0.3$





Plasma elongation colour code:

- 🟦 $\boldsymbol{\kappa = 1.71}$
- 🟩 $\boldsymbol{\kappa = 1.84}$
- 🟥 $\boldsymbol{\kappa = 2.01}$

No large variation of the p_e profile with κ is observed

- Variations are small compared to the scatter of the data
- κ is increased mainly through the upper elongation

3 Peeling-Ballooning Stability

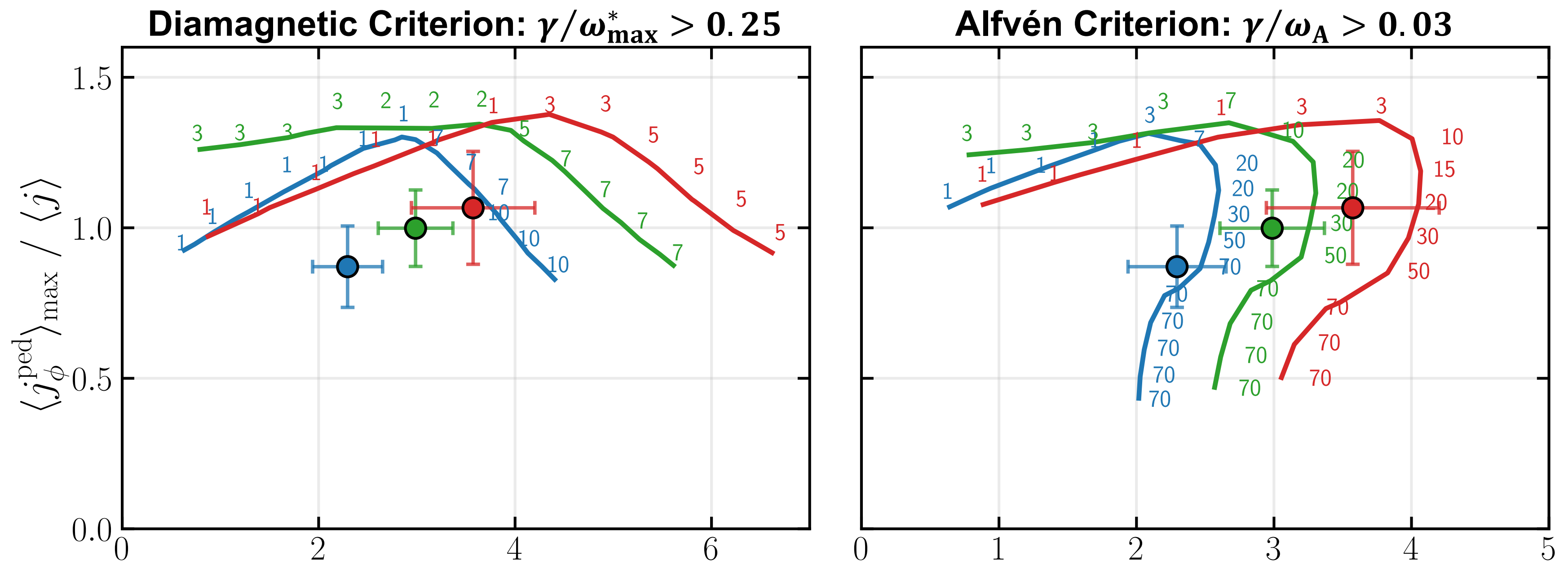
The following assumptions were used in the analysis:

- $T_i = T_e$ was assumed, since no CXRS measurements were available
- $T_e^{\mathrm{sep}} = 81$ eV was calculated for the $\kappa = 1.84$ case using the two-point model [9], and the same value was assumed for all κ (sensitivity scans of $\pm 20\%$ did not change the conclusions)
- $q_0 \sim 1$ was used to avoid unrealistically low $q_0 < 1$

Results:

- The peeling-ballooning stability was calculated using a HELENA-MISHKA workflow [1,10,11]
- Both the diamagnetic and Alfvén criterion show a shift of the stability boundary toward higher $\alpha_{\max}$ with increasing κ, caused by a stabilization of the higher-n ballooning modes
- With the Alfvén criterion, n_{crit} decreases from $n = 50\text{-}70$ at $\kappa = 1.71$ to $n = 15\text{-}30$ at $\kappa = 2.01$
- With the diamagnetic criterion, the $\kappa = 2.01$ case approaches the low-n peeling-branch

Increasing κ shifts the pedestal toward higher $\alpha_{\max}$ and lower n_{crit}

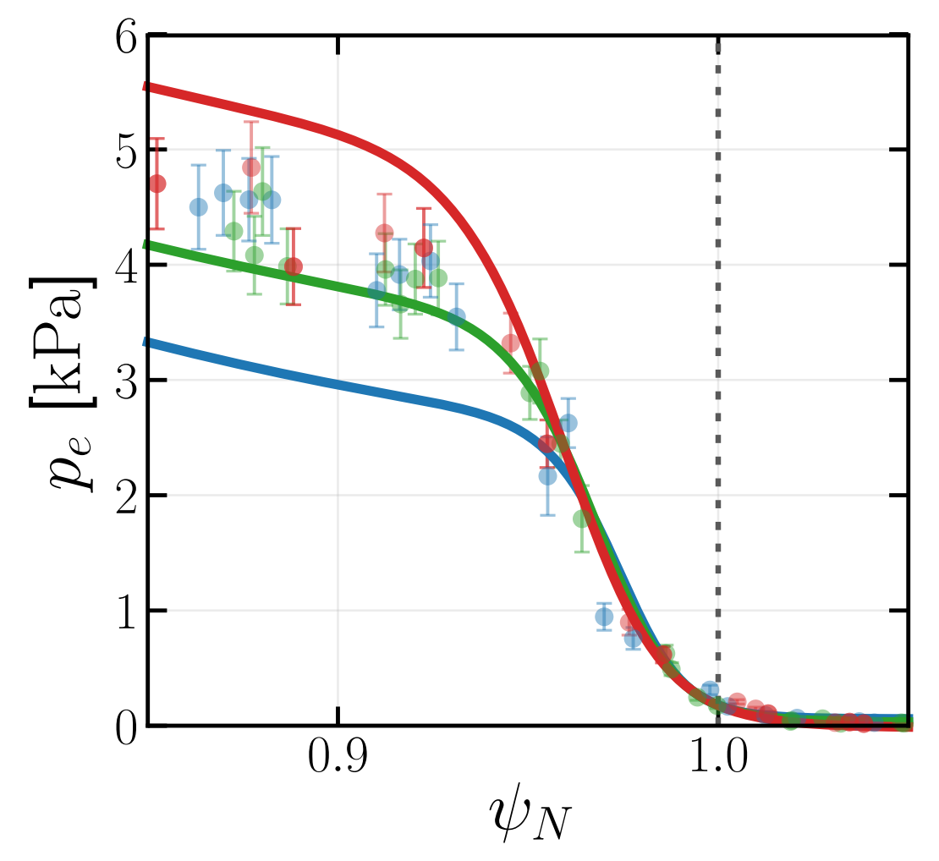


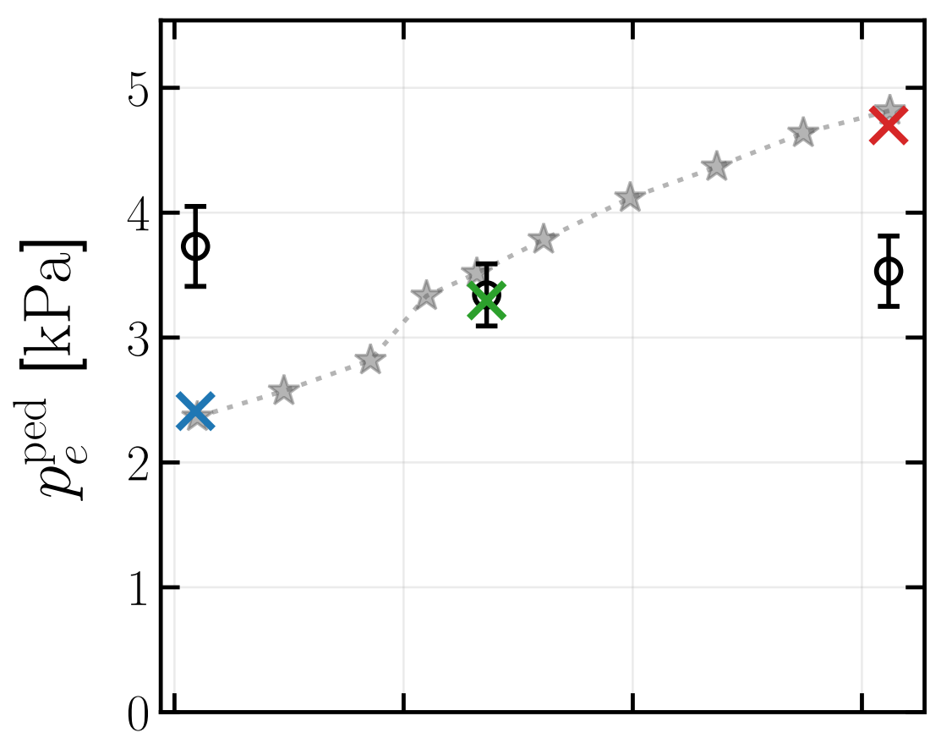
$$\alpha = -\frac{2\partial_\psi V}{(2\pi)^2}\left(\frac{V}{2\pi^2 R_0}\right)^{\frac{1}{2}} \mu_0 \partial_\psi p \Longrightarrow$$

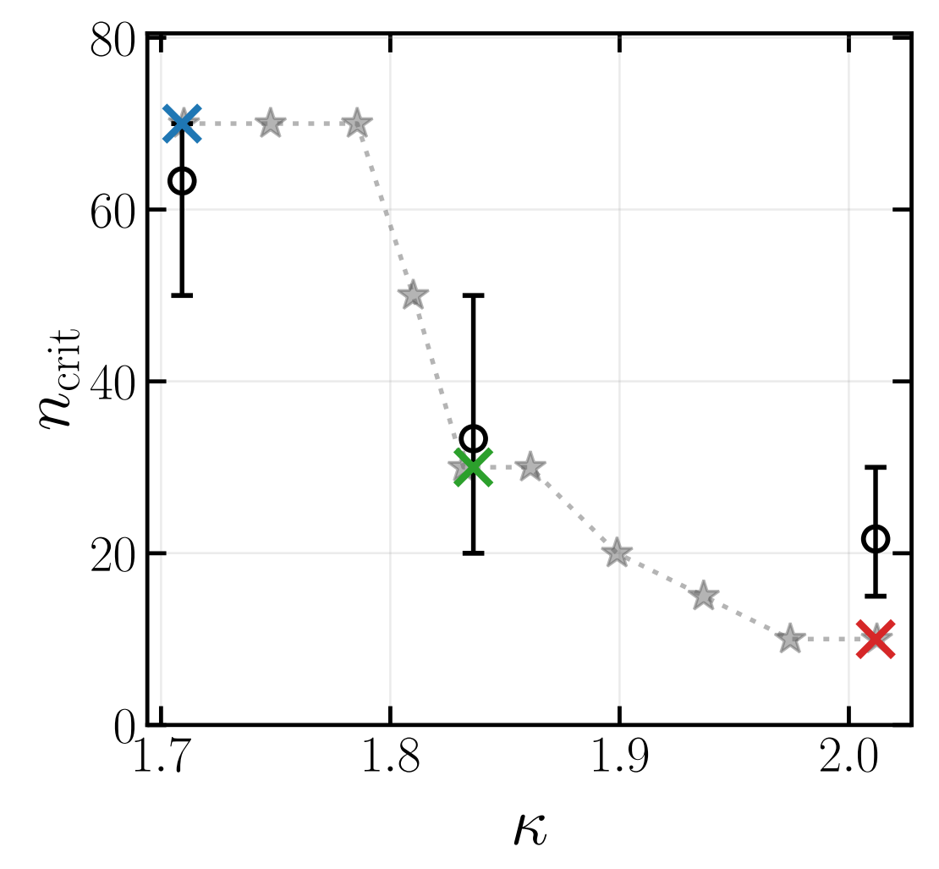
α can be affected by changes in shape, $V(\psi_N)$, even for similar p

- This can explain the increase in $\alpha_{\exp}$ with increasing κ

4 Europed Predictions







The predictive pedestal code Europed [12] was used to assess whether the experimental trends could be reproduced

- Europed is based on the EPED model [13], using the relation:

$$w = c_{\mathrm{KBM}} \sqrt{\beta_\theta^{\mathrm{ped}}}$$

- The $\kappa = 1.84$ case was used as a reference, with the experimental n_e^{ped}, n_e^{sep}, and β_N as inputs
- Calibration of the KBM width constant resulted in: $c_{\mathrm{KBM}} = 0.11$

The plasma elongation was changed through two methods, while keeping all other input parameters fixed:

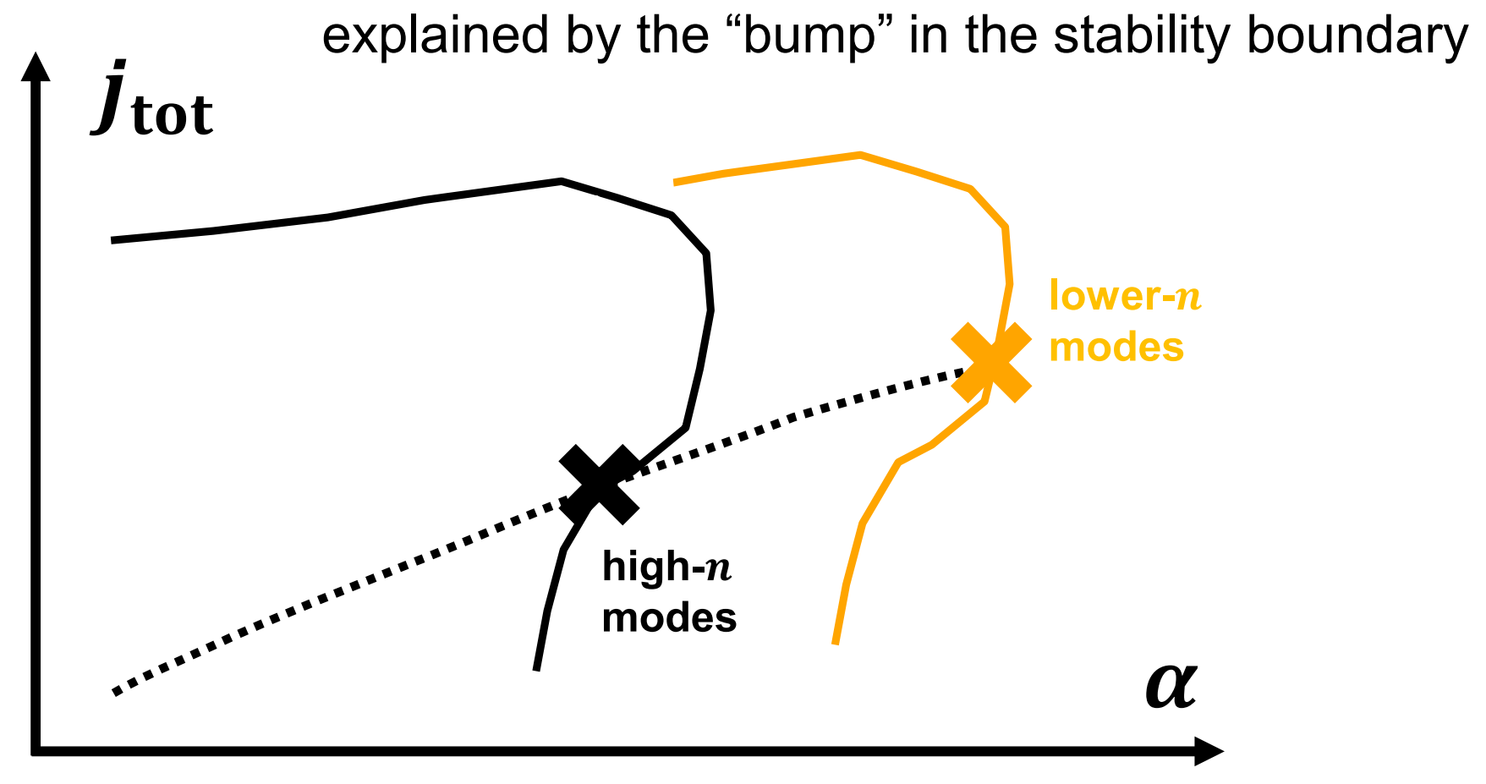
- ✕ Using the experimental boundaries
- ★ Using a fitted κ scan, where the upper elongation is varied within the experimental range ($\kappa = 1.84$ was fitted using the parametrization in [14])

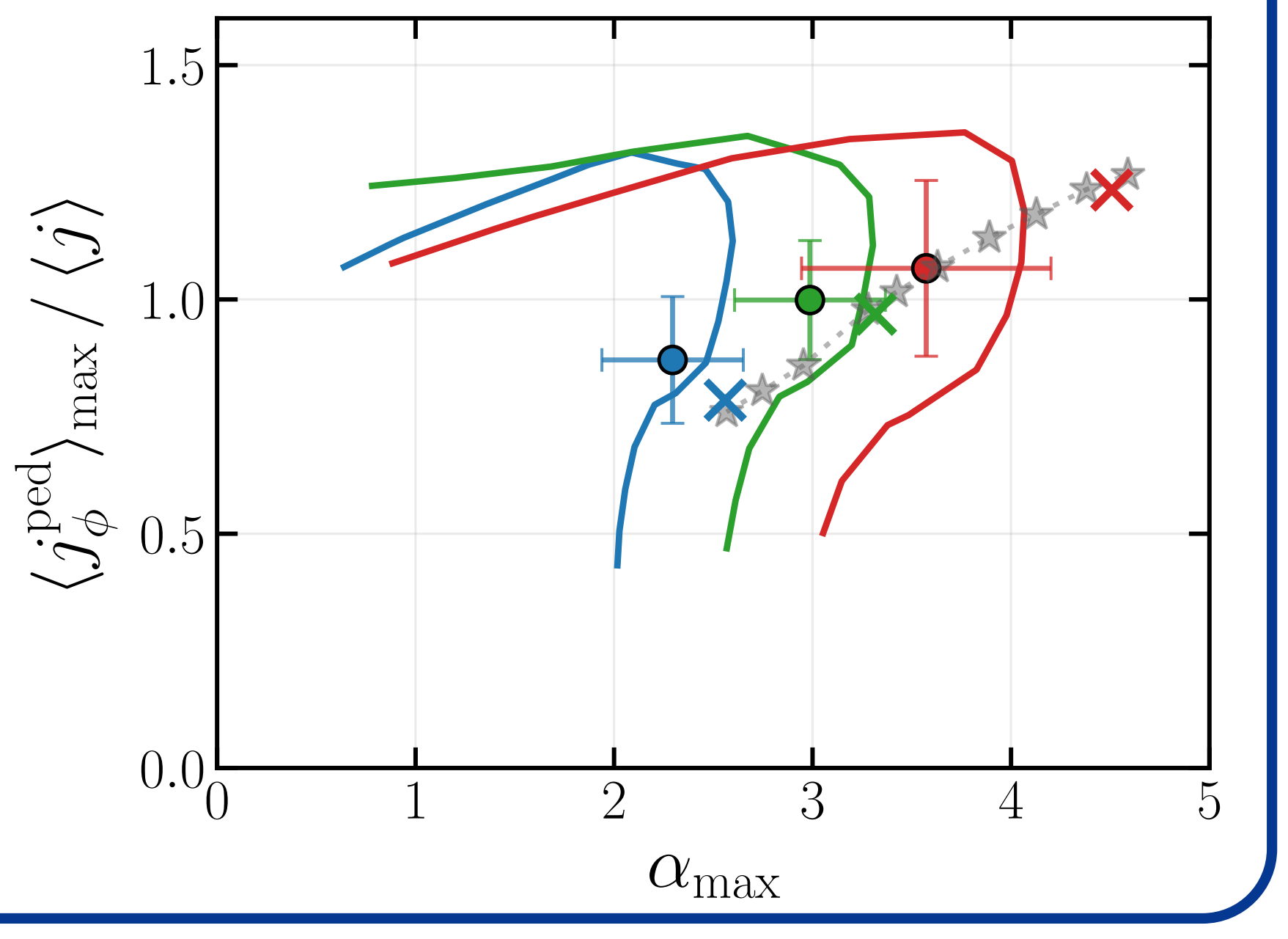
Results:

- The fitted κ scan and the experimental boundaries give similar results, indicating that κ is the dominant shaping effect
- With $c_{\mathrm{KBM}} = 0.11$, Europed underestimates p_e^{ped} at $\kappa = 1.71$ and overestimates it at $\kappa = 2.01$
- Despite this, Europed reproduces the decrease in n_{crit} and increase in $\alpha_{\max}$ with increasing κ
- In $j{-}\alpha$ space, Europed captures the stability trend reasonably well, with a slight overprediction for $\kappa = 2.01$

With $c_{\mathrm{KBM}} = 0.11$, Europed captures the qualitative κ-dependence of the stability

The strong decrease in n_{crit} at $\kappa \approx 1.8$ can be explained by the "bump" in the stability boundary





5 Sensitivity to c_{KBM}

To test why a fixed $c_{\mathrm{KBM}} = 0.11$ does not give quantitative agreement, Europed was calibrated separately for each κ

- Experimental n_e^{ped}, n_e^{sep}, and β_N were used for each κ, while c_{KBM} was varied to obtain good experimental agreement
- The variations in n_e^{ped}, n_e^{sep}, and β_N had only a minor impact; the main improvement comes from changing c_{KBM}
- The individual calibrations reproduce p_e^{ped}, w_{p_e}, and ∇p_e, with slightly weaker agreement for $\kappa = 2.01$
- The decrease in n_{crit} with increasing κ is preserved

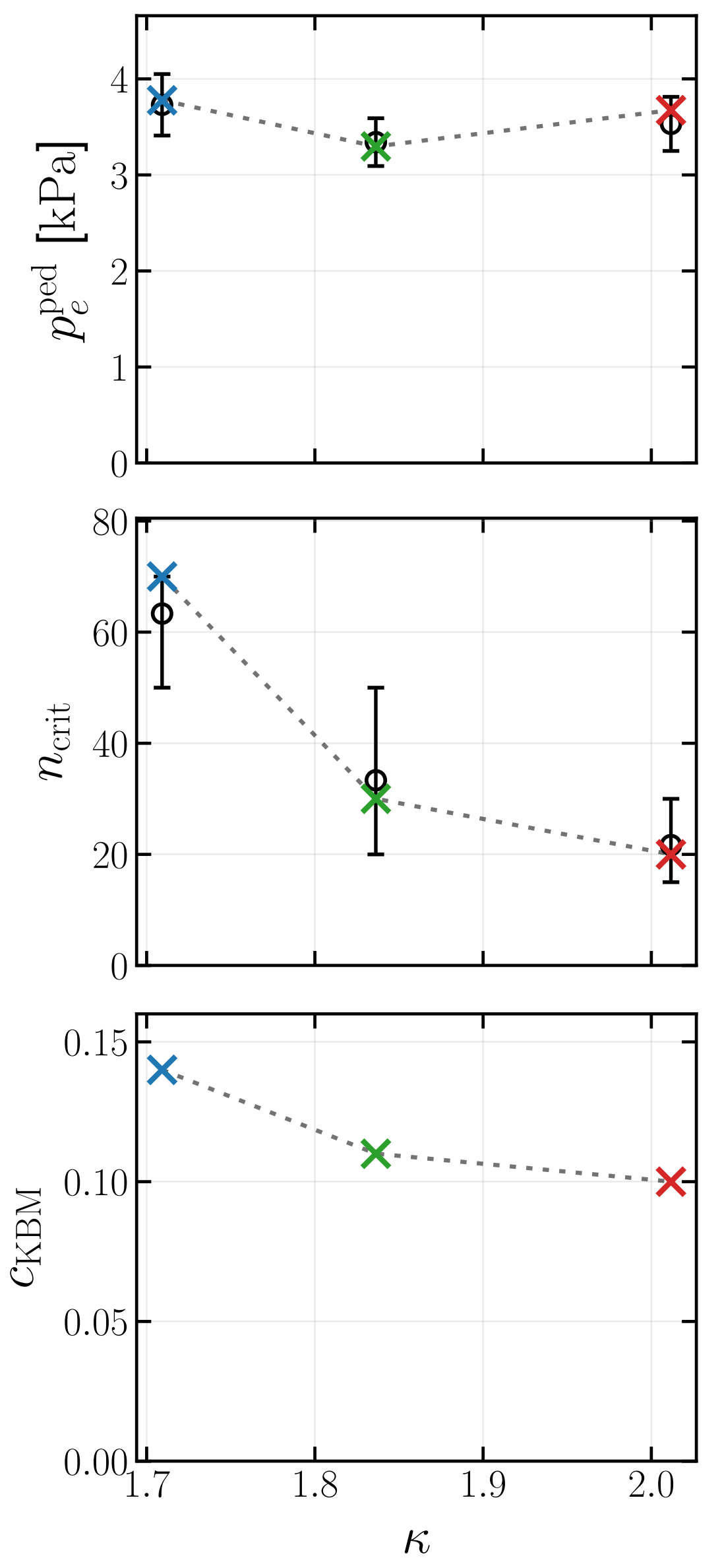
The calibrated c_{KBM} decreases with increasing κ:

- $c_{\mathrm{KBM}} = 0.14$ at $\kappa = 1.71$, decreasing to $c_{\mathrm{KBM}} = 0.10$ at $\kappa = 2.01$
- This suggests a possible shape dependence of c_{KBM}, and may indicate that the pedestal turbulent transport changes with κ

Confirming these results and justifying the use of a shape-dependent c_{KBM} requires additional work:

- Gyrokinetic transport analysis and experimental edge turbulence measurements are needed to assess the impact of κ on pedestal turbulent transport

Separate c_{KBM} calibration suggests a decrease with κ, which needs to be confirmed



6 Conclusion & Future Work

Experimental results:

- Increasing κ shifts the pedestal stability toward higher $\alpha_{\max}$ and lower n_{crit}, moving the pedestal closer to a peeling-limited regime

Europed results:

- Europed captures the qualitative elongation dependence of the stability
- Quantitative agreement may require a shape-dependent c_{KBM}

Future work:

- Dedicated high-κ H-mode experiments with stationary high-κ and ELMy phases
- T_i measurements to test the $T_i = T_e$ assumption
- Experimental and gyrokinetic analysis to study how pedestal turbulent transport changes with κ

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