Pedestal stability studies on tokamaks

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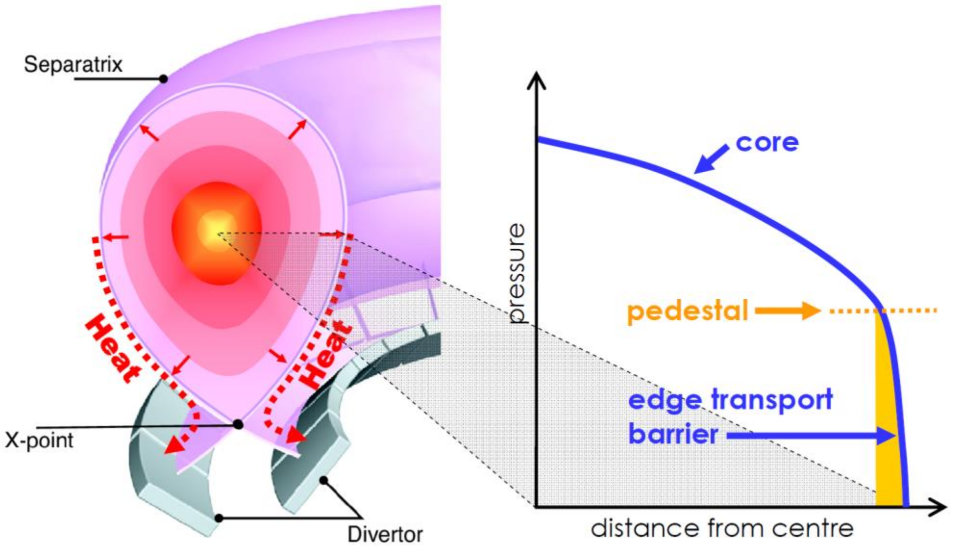
1.7. 2021

Outline

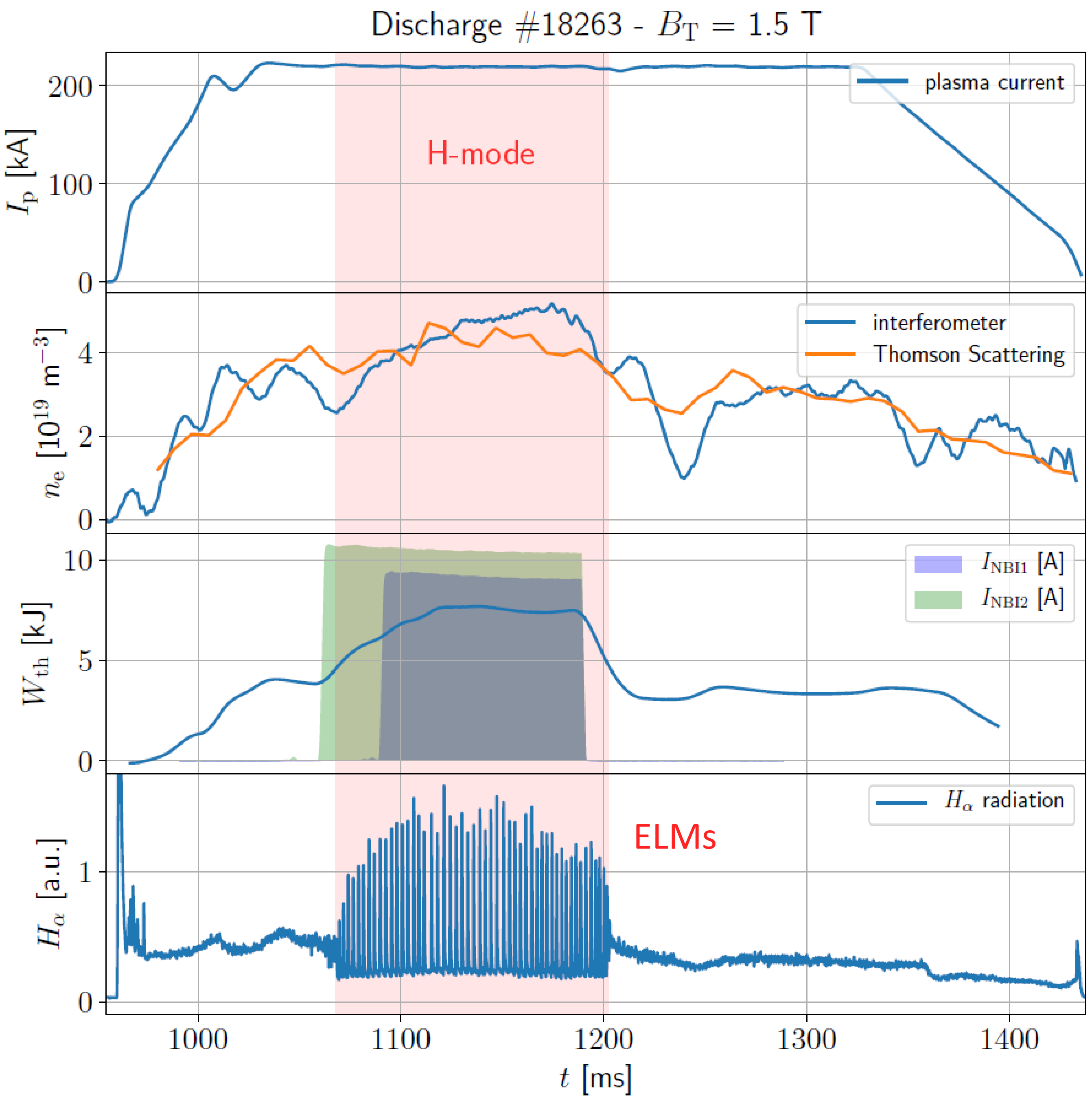
- Introduction to H-mode and ELMs
- Peeling-ballooning model and pedestal stability
- Pedestal stability research
  - COMPASS
  - JET
- Summary and outlook

H-mode regime

- Proposed baseline scenario for ITER
- Energy confinement time increased by a factor of 2
- Edge transport barrier (pedestal) formation
- New type of instabilities (ELMs)

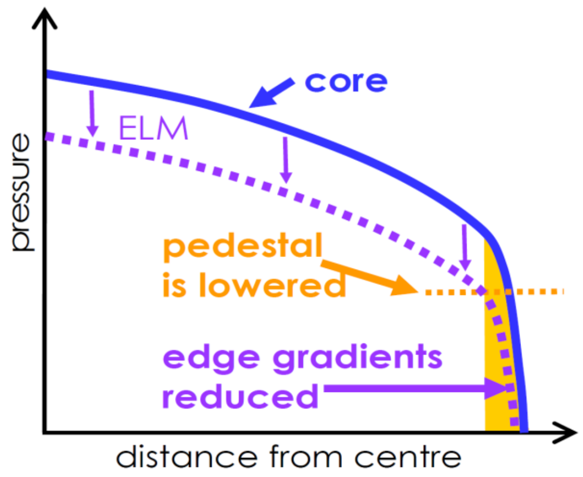


J. W. Connor *et al*, AIP Conference Proceedings 1013, 174-190 (2008)



Pedestal stability and ELMs

- Cyclic pedestal degradation by ELMs
- Transient high heat fluxes
- Peeling-ballooning model



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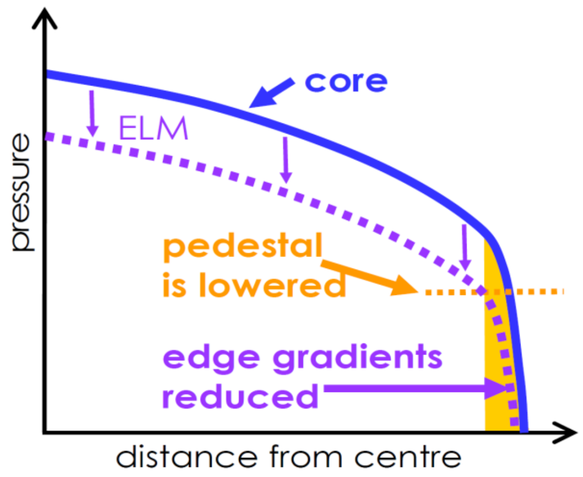

[J. W. Connor *et al*, 2008]

- MHD equations

$$\frac{d\vec{B}}{dt} = \frac{1}{\sigma\mu}\nabla^2\vec{B} + (\vec{B}\cdot\nabla)\,\vec{u} - \vec{B}\,\mathrm{div}\,\vec{u} \qquad \frac{d}{dt}\left(p\rho^{-\gamma}\right) = 0$$

$$\frac{d\rho}{dt} + \rho\,\mathrm{div}\,\vec{u} = 0$$

$$\rho\frac{d\vec{u}}{dt} = -\nabla p - \nabla p_M + \frac{1}{\mu}(\vec{B}\cdot\nabla)\vec{B} + \eta\nabla^2\vec{u} + (\zeta + \eta/3)\nabla(\mathrm{div}\vec{u})$$

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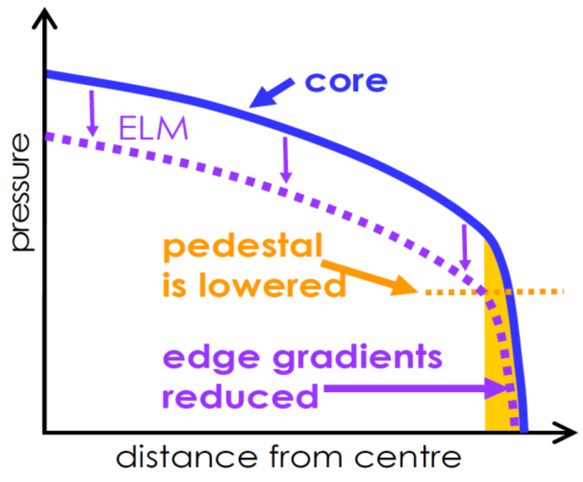

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- Perturbation theory

$$\rho\frac{\mathrm{d}^2\vec{\xi}}{\mathrm{d}t^2} = -\omega^2\rho\vec{\xi} = \vec{F}(\vec{\xi})$$

$$\vec{F}(\vec{\xi}) = \frac{1}{\mu_0}\left(\nabla\times\vec{B}\right)\times\vec{Q} + \frac{1}{\mu_0}\left(\nabla\times\vec{Q}\right)\times\vec{B} + \nabla\left(\vec{\xi}\cdot\nabla p + \gamma p\nabla\cdot\vec{\xi}\right)$$

$$\vec{Q} = \nabla\times\left(\vec{\xi}\times\vec{B}\right),$$

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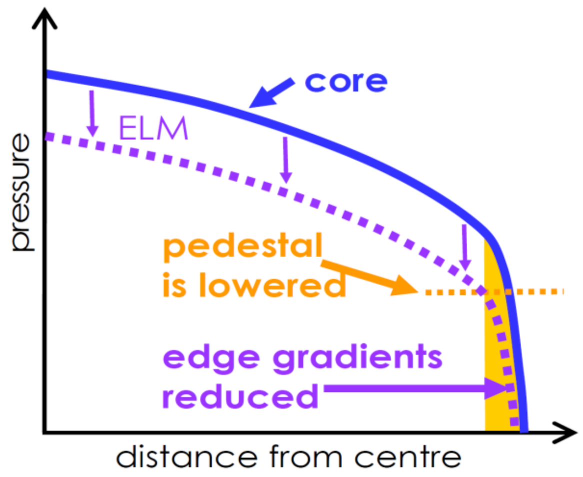

[J. W. Connor *et al*, 2008]

- MHD equations + perturbation theory + variation principle

$$\delta W = \delta W_{\mathrm{F}} + \delta W_{\mathrm{S}} + \delta W_{\mathrm{V}}$$

$$\delta W_{\mathrm{F}} = \frac{1}{2}\int_{\mathrm{P}} \left[\frac{\vec{Q}^2}{\mu_0} + \frac{B^2}{\mu_0}\left|\nabla\cdot\vec{\xi}_\perp + 2\vec{\xi}_\perp\cdot\vec{\kappa}\right|^2 + \gamma p\left|\nabla\cdot\vec{\xi}\right|^2 - \right.$$

$$\left. -2\left(\vec{\xi}_\perp\cdot\nabla p\right)\left(\vec{\kappa}\cdot\vec{\xi}_\perp^{*}\right) - j_\parallel\left(\vec{\xi}_\perp^{*}\times\frac{\vec{B}}{B}\right)\cdot\vec{Q}_\perp \right] \mathrm{d}^3\vec{r}$$

$$\delta W_{\mathrm{F}} = \frac{1}{2}\int_{\mathrm{S}} \left|\vec{n}\cdot\vec{\xi}_\perp\right|^2 \vec{n}\cdot\left[\nabla\left(p + \frac{B^2}{2\mu_0}\right)\right] \mathrm{d}S$$

$$\delta W_{\mathrm{V}} = \frac{1}{2}\int_{\mathrm{V}} \frac{\left|B_1\right|^2}{\mu_0}\mathrm{d}^3\vec{r}$$

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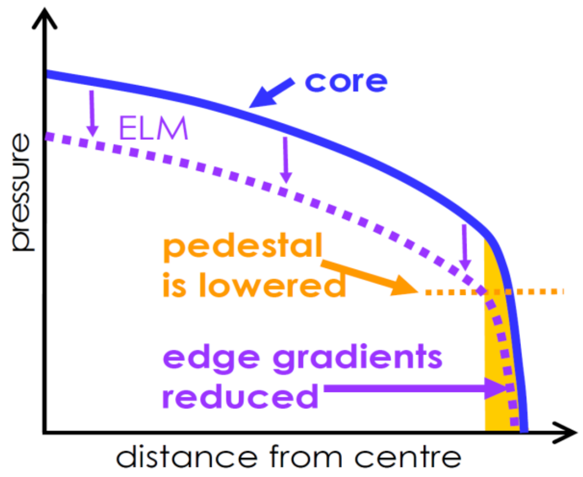

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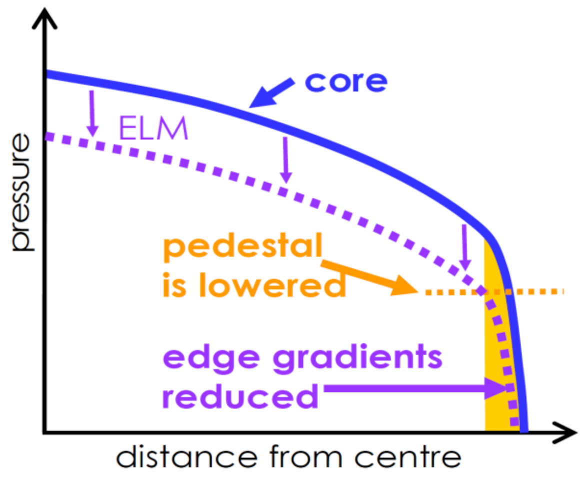

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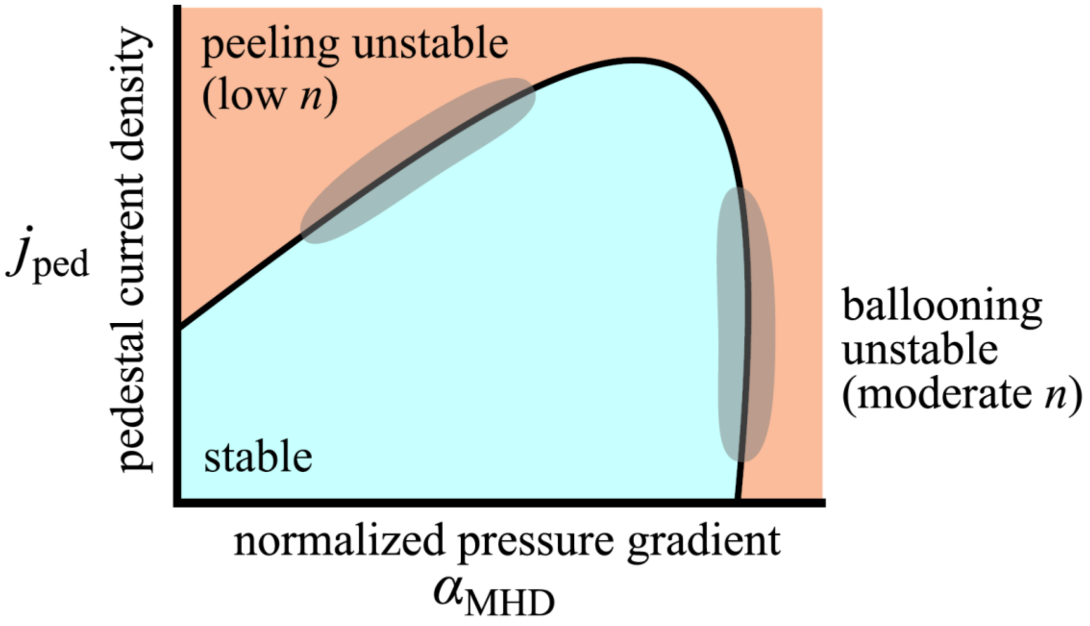

Adapted from [J. R. Walk, PhD thesis, MIT 2014]

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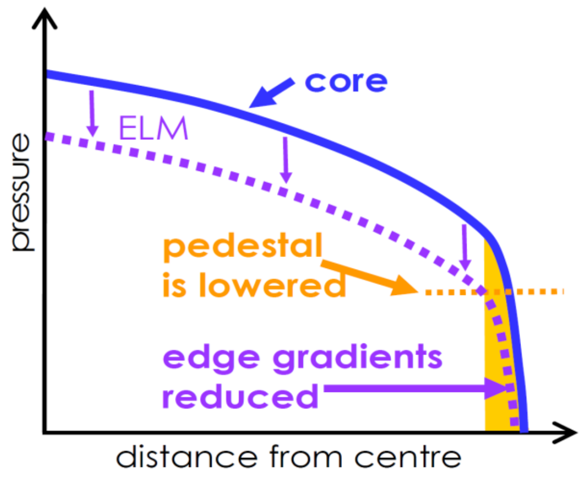

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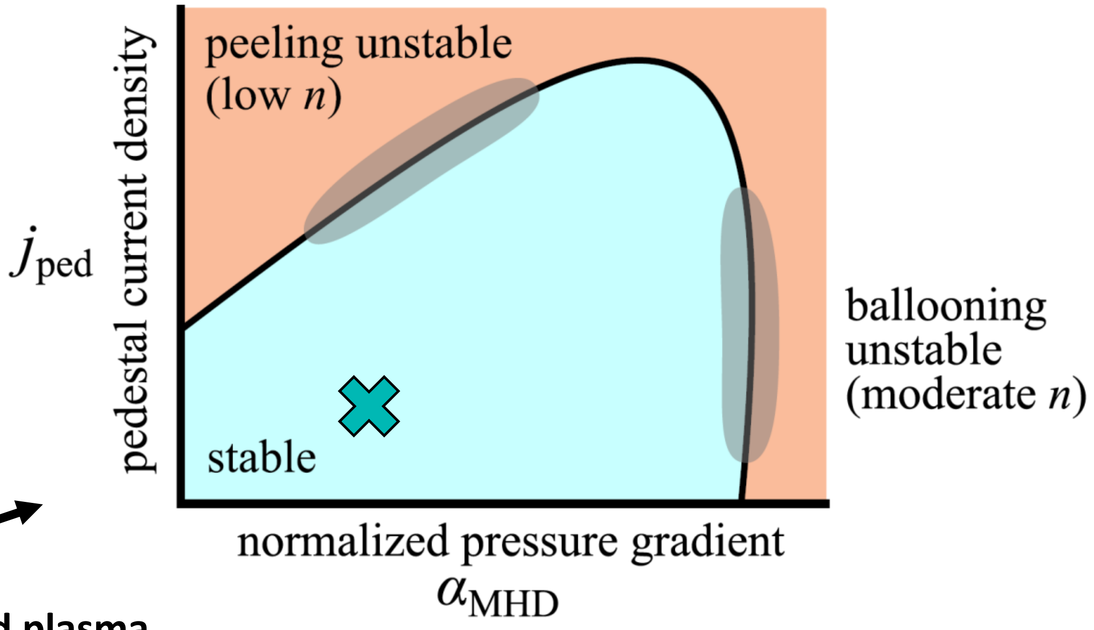
Pedestal and plasma properties



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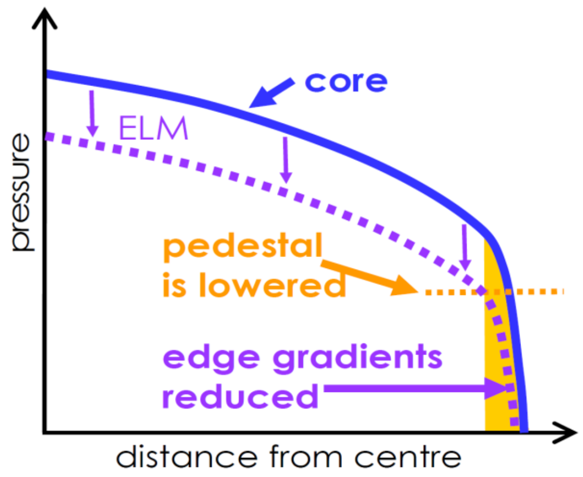

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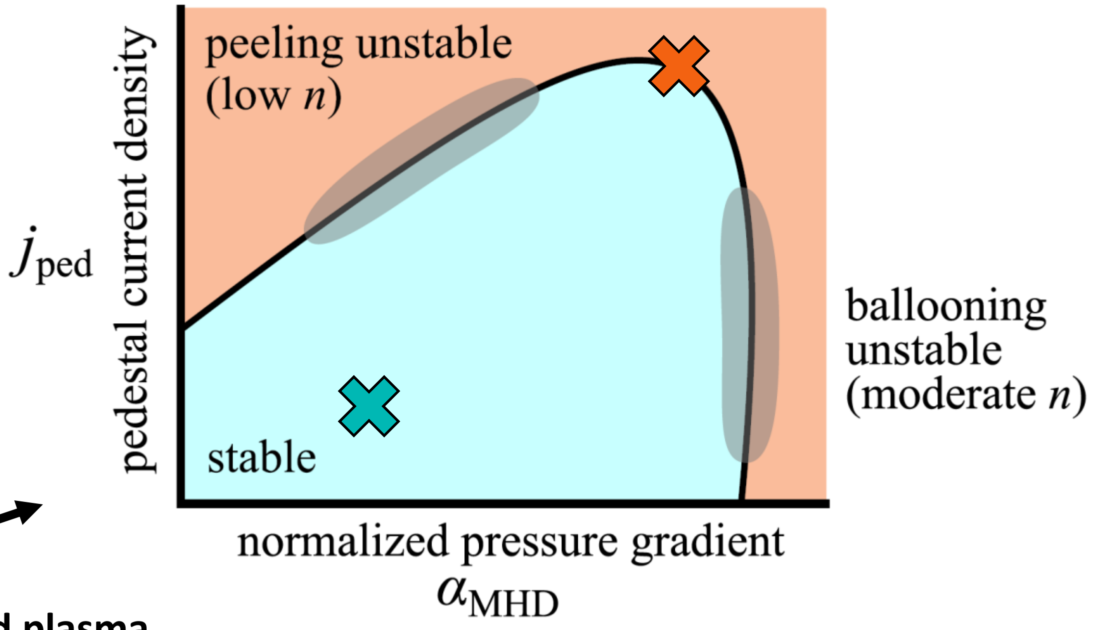

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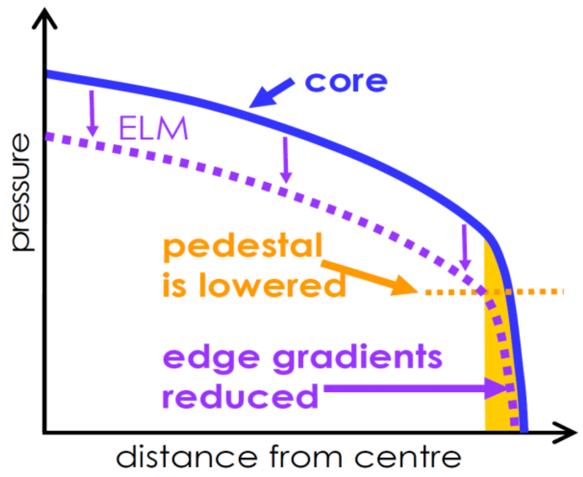
Pedestal stability and ELMs

- Cyclic pedestal degradation by ELMs
- Transient high heat fluxes
- Peeling-ballooning model
  - Different ELM types distinguished



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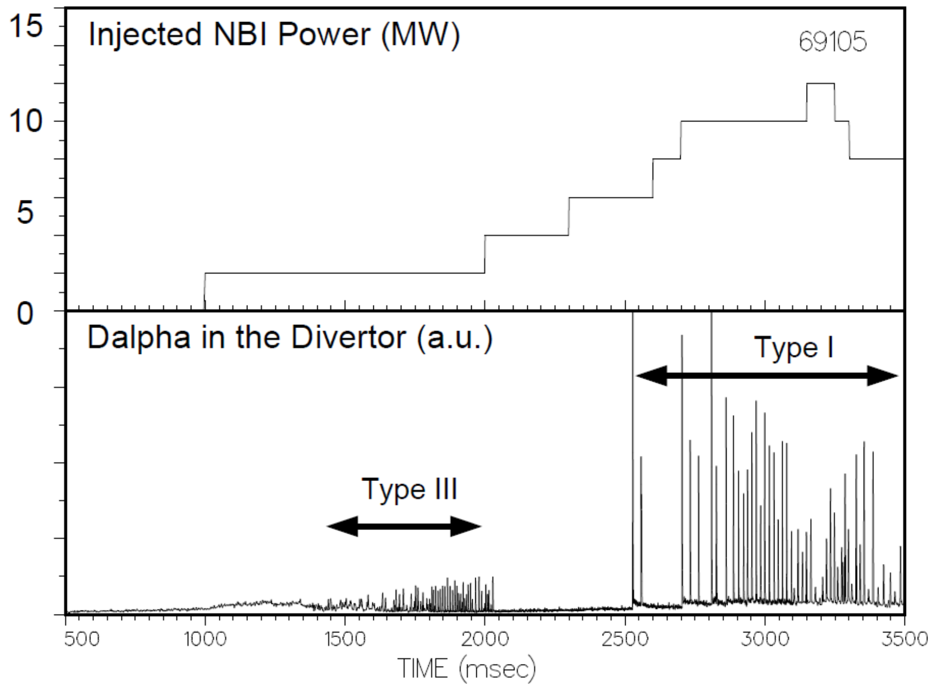
- ELM types:

Type I – Large, low frequency, inc. with P_{input}

Type II – Smaller, higher freq., unaffected by P_{input} („grassy“)

Type III – Small, decrease frequency with P_{input}



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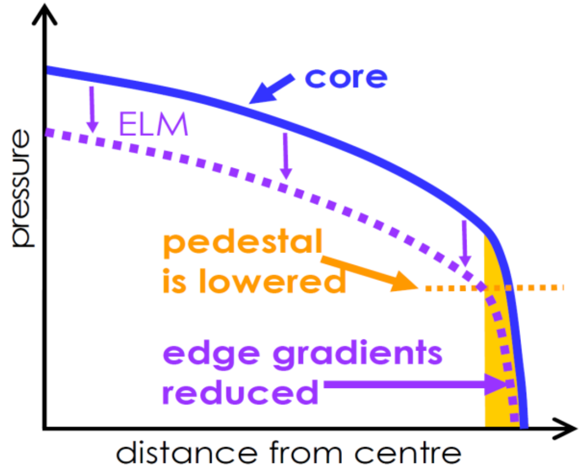

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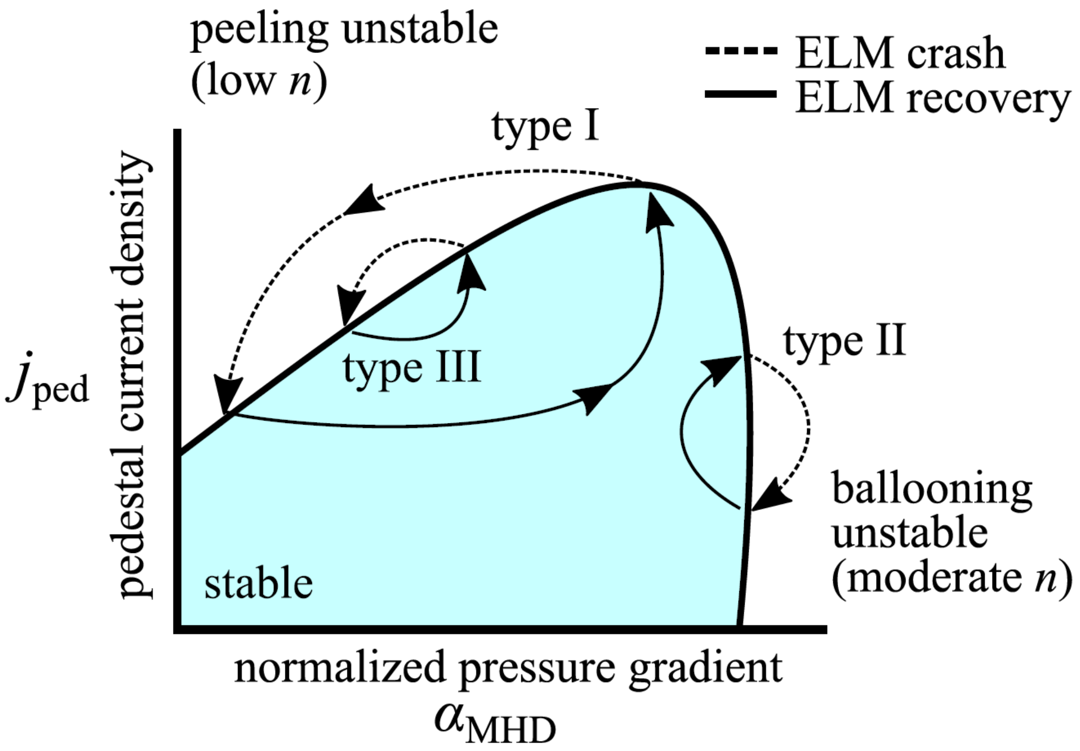

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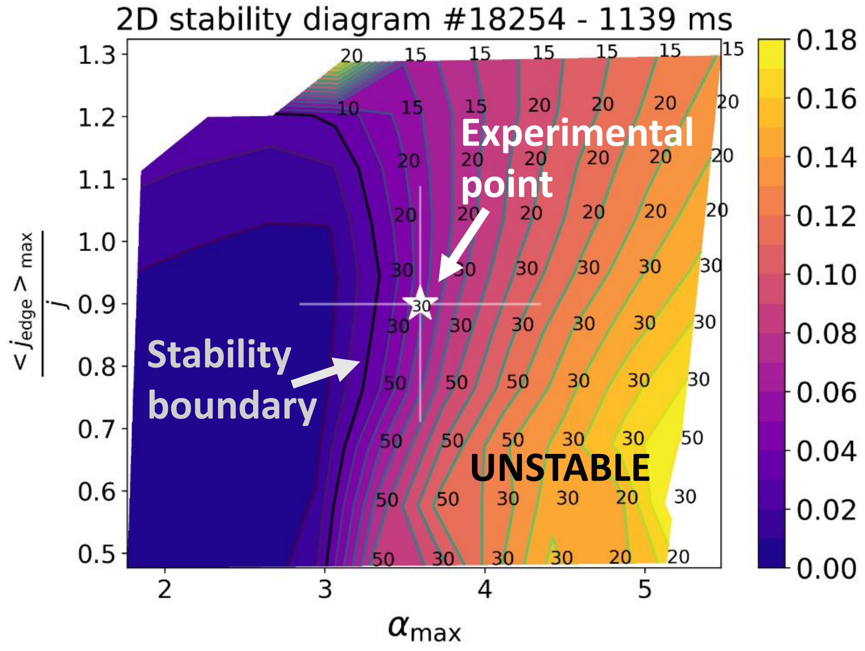
Pedestal stability at COMPASS

- Initial results of pedestal stability on COMPASS using ELITE/MISHKA codes
- ELMy H-mode – higher triangularity (RMPs)
- Mostly peeling-ballooning (PB) stable



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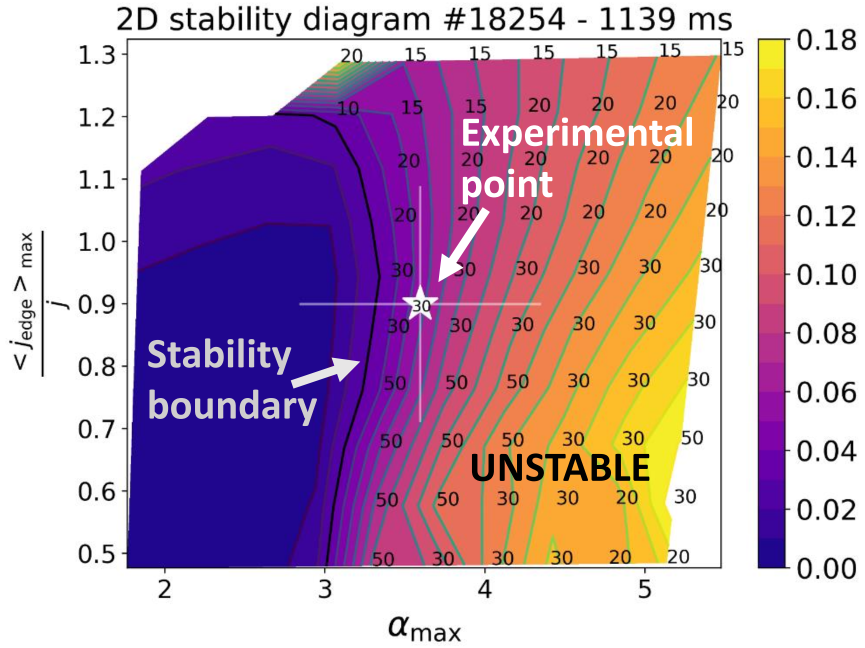
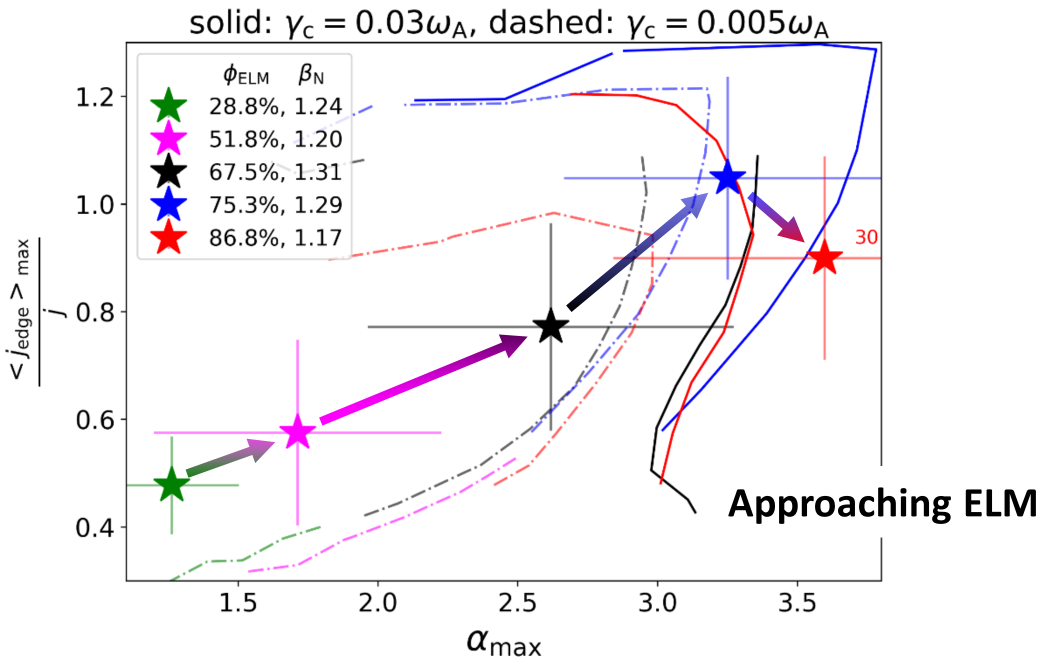
- Mostly peeling-ballooning (PB) stable
- ELM cycle analysis
  - Gradual approach to PB unstable
- Changing discharge performance





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Summary

- H-mode is indispensable for future tokamak operation
- ELMs are ugly and have to be dealt with!
- Pedestal stability analysis can help