Snowmass Preview

Edge Stability/Pedestal Constraints

Preliminary Results

P.B. Snyder

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GENERAL ATOMICS

Pedestal Height and ELM behavior are key issues for Next Step

- Core transport modeling indicates profiles are quite stiff, $P_{fus} \sim \beta_{ped}^{1.8}$, pedestal conditions essentially determine performance *[Kinsey,Waltz]*
- Large ELMs pose risk of severe divertor erosion

- Begin Uniform Technical Assessment of pedestal constraints due to MHD stability, and predictions of ELM behavior for ITER-FEAT, FIRE, Ignitor
  - "Uniform" is a challenge as Ignitor plans to operate in L-mode. For now, ignore this and calculate constraints that would exist if it did have an H-mode-like pedestal.
- Uncertainty in pedestal transport, particularly in physics setting the pedestal width, leaves gaps in our predictive capability
- Suggestions for how to proceed welcomed

Procedure for evaluating ELM/pedestal stability

- Construct model equilibria, match design B_t, I_p, R, a, □, □, $<n_e>$
- Density and Temperature Profiles have tanh pedestal profiles and polynomial profiles in the core (where $\square < \square_{ped}$)

  $$n_e(\square) = n_{sep} + a_{n0}\{\tanh[2(1\square\square_{mid})/\square]\square\tanh[2(\square\ \square\square_{mid})/\square]\} + a_{n1}[1\square(\square/\square_{ped})^{\square_{n1}}]^{\square_{n2}}$$

  $$T(\square) = T_{sep} + a_{T0}\{\tanh[2(1\square\square_{mid})/\square]\square\tanh[2(\square\ \square\square_{mid})/\square]\} + a_{T1}[1\square(\square/\square_{ped})^{\square_{T1}}]^{\square_{T2}}$$

  - a_0 & a_1 chosen to give desired pedestal and axis values
  - $\square_0$ & $\square_1$ chosen to match expected core profiles from transport codes
  - Note that these instabilities are relatively insensitive to details of core profiles
- Current profile aligned to Sauter collisional bootstrap model in the edge, core profile chosen to give $q_0=1.05$
- Width (□) and height (T_{ped}) of pedestal are varied, and MHD stability boundaries for n=8,10,15,20,30 are evaluated with ELITE (requires hundreds of full equilibrium constructions and thousands of MHD stability calculations)

- "Baseline" case: $n_{ped}=0.71<n_e>$, $n_0=1.1<n_e>$, $n_{sep}=0.3<n_e>$, $\square_{n0}=1$, $\square_{n1}=0.5$, $\square_{T0}=1$, $\square_{T1}=2$
- ITER: $B_t=5.3T$, $I_p=15MA$, R=6.2m, a=2.0m, □=1.85, □=0.49, $<n_e>=10^{20}m^{-3}$
- FIRE: $B_t=10T$, $I_p=7.7MA$, R=2.14m, a=0.595m, □=2.0, □=0.7, $<n_e>=3.6\ 10^{20}m^{-3}$
- Ignitor: $B_t=13T$, $I_p=11MA$, R=1.33m, a=0.455m, □=1.8, □=0.4, $<n_e>=9.5\ 10^{20}m^{-3}$
- Some caveats: no separatrix, up-down symmetric model equilibria, ideal MHD

ELITE is a highly efficient 2D MHD code for n>~5

- Expect that most unstable mode will often be coupled peeling-ballooning mode at intermediate wavelength (5<~n<~50)
- Need to scan real equilibria in several parameters simultaneously and explore stability constraints over a wide range of n -> Need a fast code
- ELITE is a 2D eigenvalue code, based on ideal MHD (amenable to extensions, includes simple model of diamagnetic stabilization):
    - Generalization of ballooning theory to incorporate surface terms which drive peeling modes, and retain first two orders in 1/n (treats intermediate n>~5)
    - Plasma displacement, X, expanded in polodial Fourier harmonics:

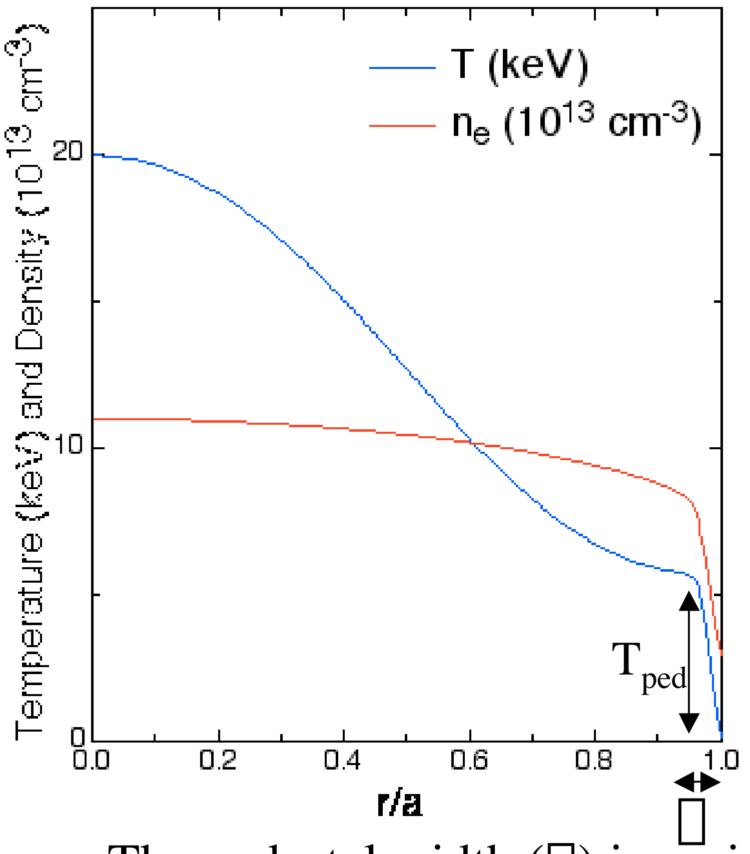
$$X = \sum_{m=m_{\min}}^{m=m_{\max}} u_m(x)\, e^{-im\theta}$$

    - Makes use of fact that each $u_m(x)$ is localized about its own mode rational surface where $m=nq$ => ***fast and efficient code***
    - Study coupled peeling/ballooning modes and quantitative constraints on edge gradients and pedestal height. Growth rates and mode structures generated.
    - Successfully benchmarked against GATO and MISHKA
    - *[P.B. Snyder, H.R. Wilson et al Phys Plas **9** 2037 (2002); H.R. Wilson, P.B. Snyder et al Phys Plas **9** 1277 (2002)]*

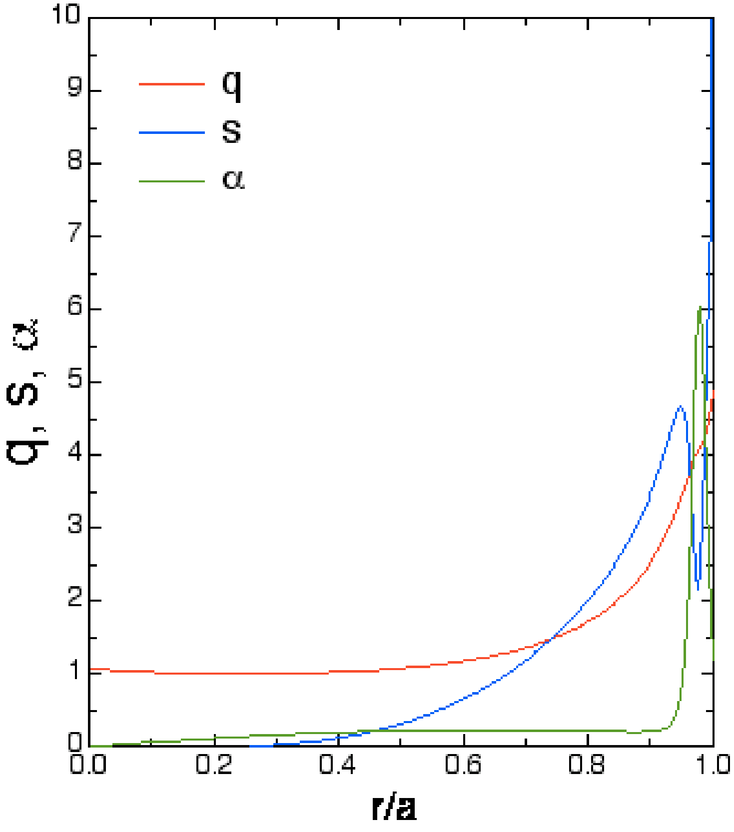
Sample Model Equilibrium Profiles

ITER-FEAT model profiles for □/a~0.03, T_{ped}~5keV case

Sample ITER-FEAT profiles



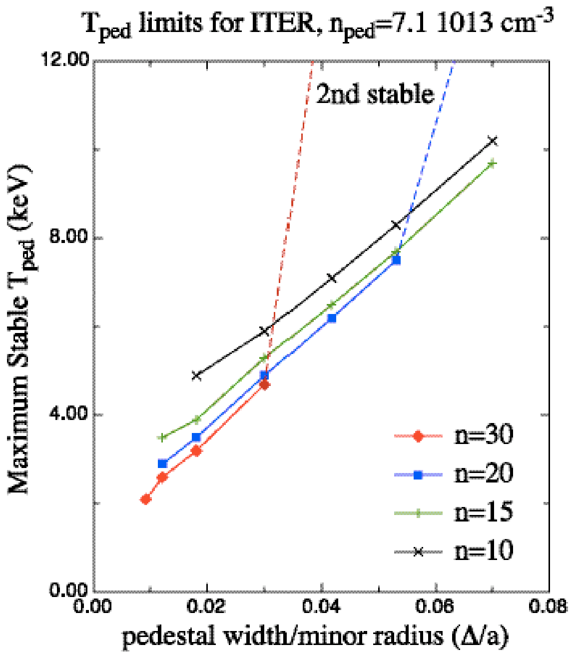
Sample ITER-FEAT profiles



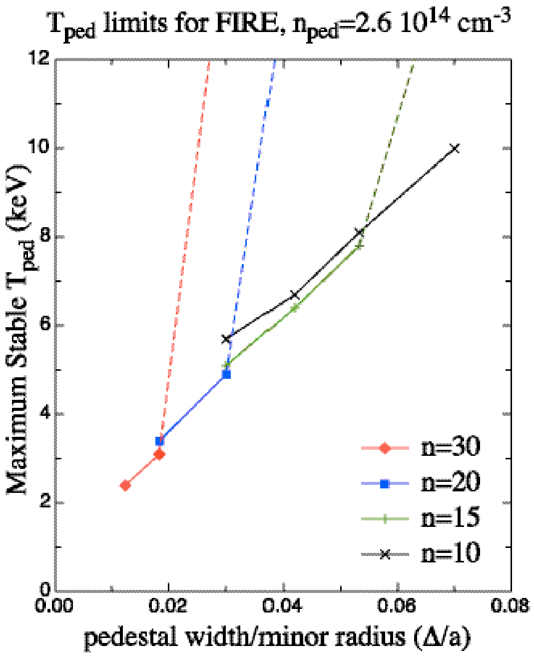
- The pedestal width (□) is varied from ~1% to 12% of the poloidal flux (□/a~0.005-0.07)
- At each value of □, T_{ped} is increased (with J_{bs} calculated consistently) until instabilities are triggered

GENERAL ATOMICS

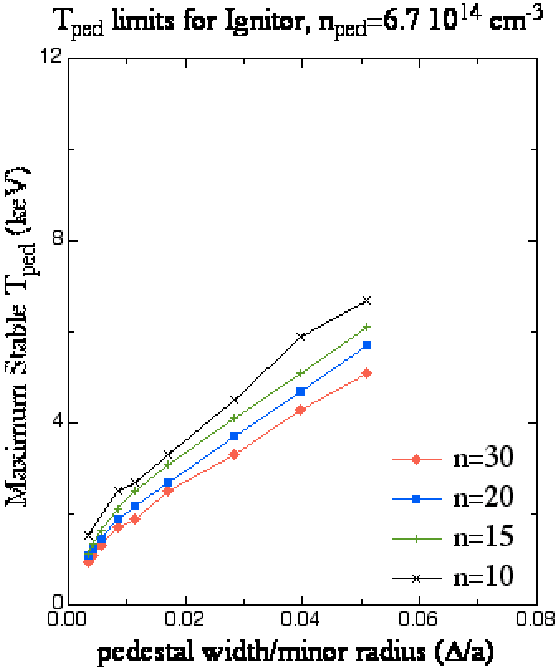
Pedestal Stability Constraints on T_{ped}



T_{ped} limits for ITER, n_{ped}=7.1 1013 cm^{-3}



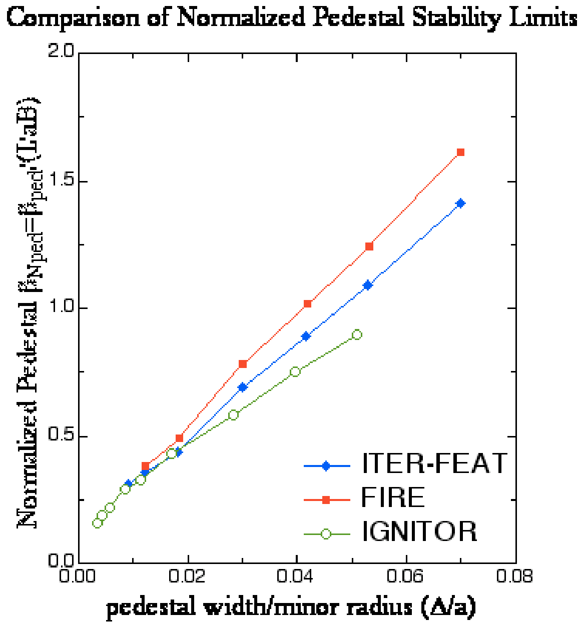
T_{ped} limits for FIRE, n_{ped}=2.6 10^{14} cm^{-3}

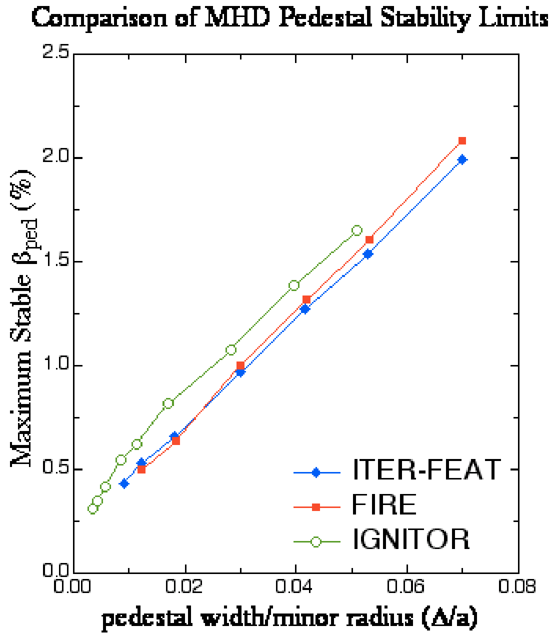


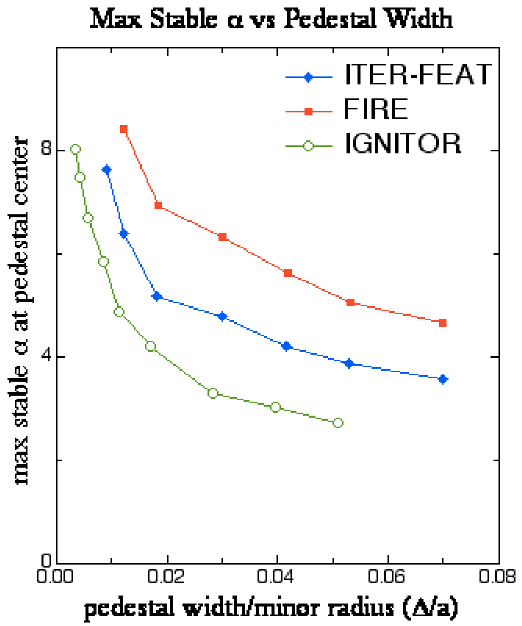
T_{ped} limits for Ignitor, n_{ped}=6.7 10^{14} cm^{-3}

- T_{ped} limit is a strong function of pedestal width, but notably sub-linear, particularly at narrow width ($\sim\Delta^{2/3}$)
- Intermediate to high-n peeling-ballooning modes are most unstable. ITER & FIRE show significant second stability to high-n modes at larger widths.
- Useful metric for comparing machines is β_{ped} or β_{Nped} (see following)
- Δ/a=0.03 provides a useful reference point, similar to present observations. At this width or larger, T_{ped} is in range needed for good performance. *[J. Kinsey transport talk Wednesday morning]*

Stability constraints on $\square_{Nped}$, $\square_{ped}$, $\square_{c}$

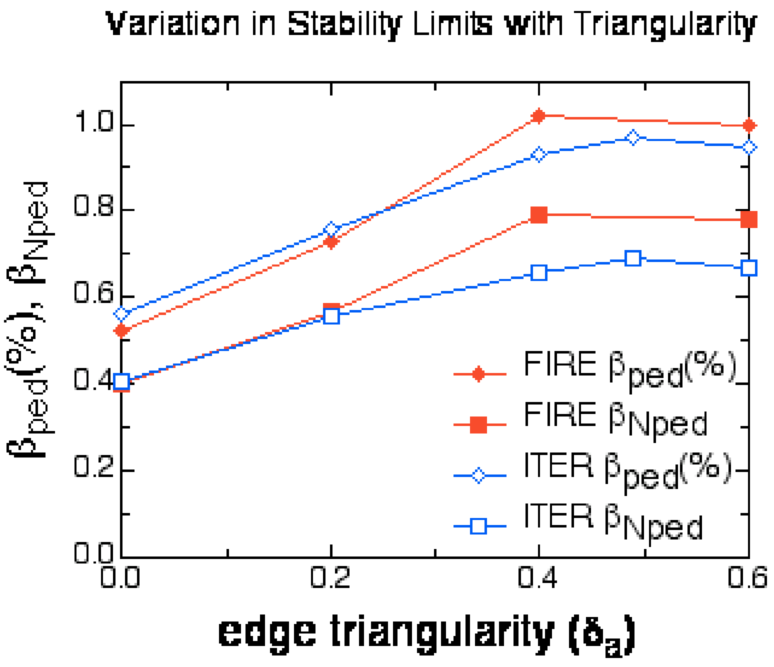

Comparison of Normalized Pedestal Stability Limits

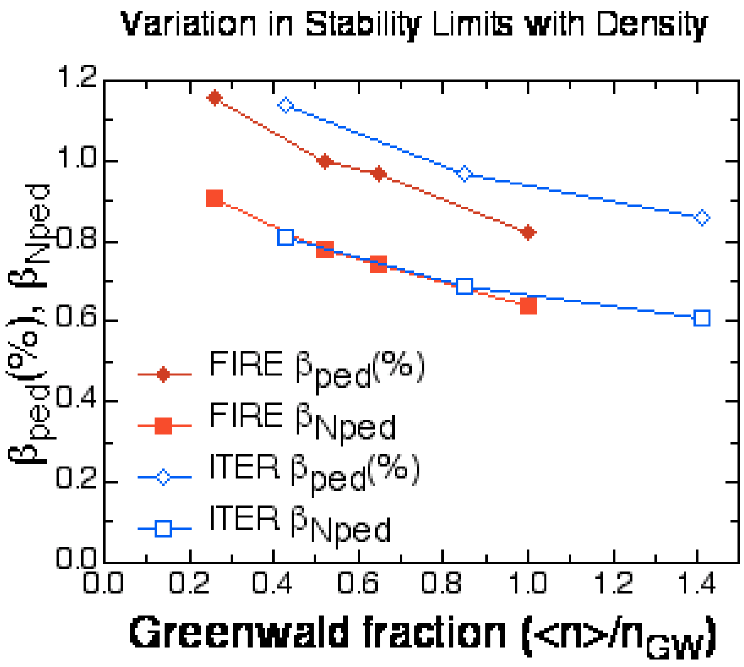

Comparison of MHD Pedestal Stability Limits


Max Stable α vs Pedestal Width

- $\square_{Nped}$ provides a useful figure of merit for inter-machine comparisons
- Stronger shaping □ higher $\square_{Nped}$ & $\square_{cped}$
- Ignitor has largest I/aB=1.86, ITER=1.42, FIRE=1.29
- Maximum stable $\square_{ped}$ important for core transport, remarkably similar between machines
- $\square_{crit}$ decreases strongly with width
- [note: these figures contain the same data as the previous page, selecting the most unstable *n* and re-plotting the stability threshold in terms of other vars]

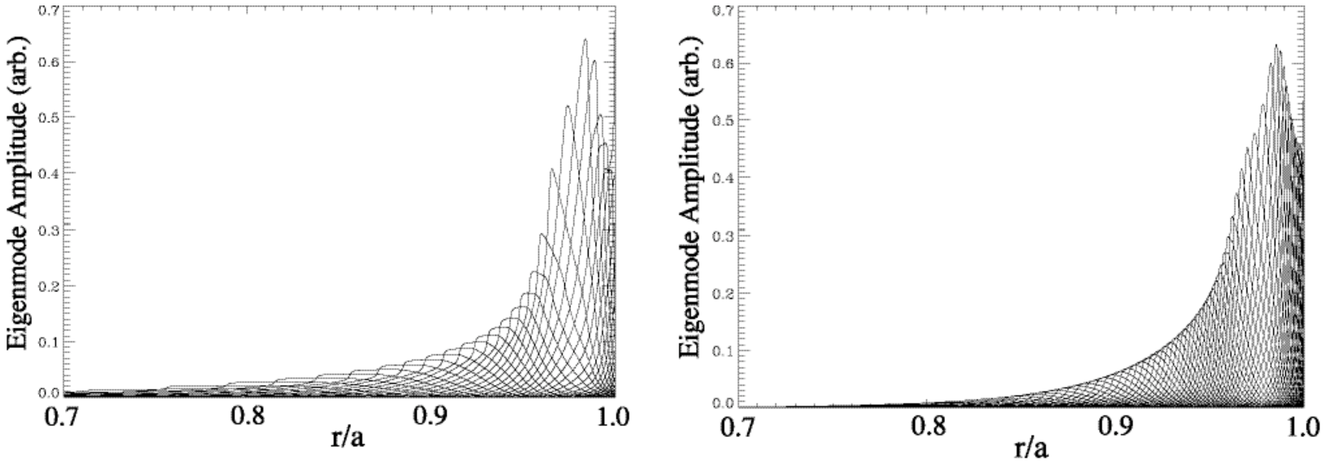
Variation with triangularity and density


Variation in Stability Limits with Triangularity

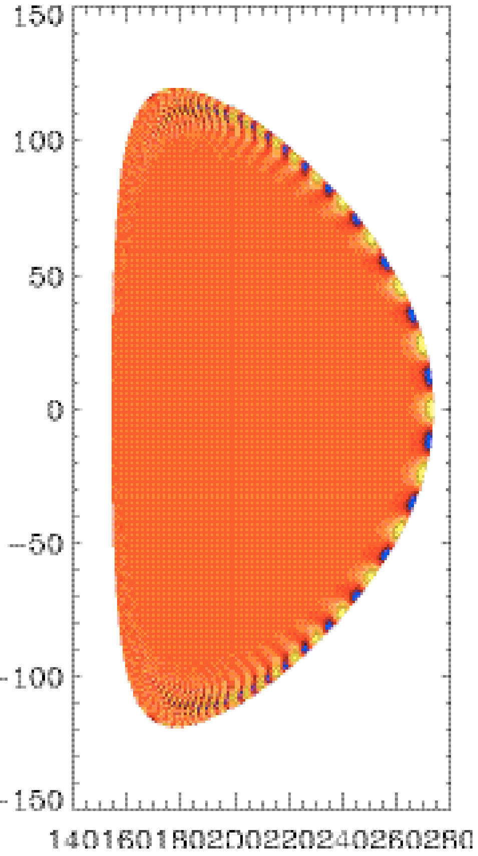

Variation in Stability Limits with Density

- Calculated at fixed width □/a~0.03 (5% of flux) and reference parameters except the one varied
- Increasing triangularity ($□_a$) is stabilizing, levels off around $□_a$~0.5
- Increasing density lowers edge bootstrap current, restricts 2nd stability access. Appears possible to increase performance by operating at lower density; tradeoffs with divertor, ELM size?

Unstable Mode Structure and ELM size



Comparison of radial eigenmode structures for *n*=8 & 20 in ITER-FEAT model equilibrium with □/a=0.03, T_{ped}=6.2keV. Lower n modes are slightly more extended



2D Structure of *n*=20 mode in FIRE model equilibrium with □/a=0.03, T_{ped}=5keV

- ELM size expected to be related to unstable mode width, but details of this relationship are complex and uncertain.
- Calculated mode structures extend beyond pedestal. Some dependence on *n*.
- ITER & FIRE appear able to access 2nd stable edge regime and explore tradeoffs between higher pedestal and possible larger ELMs due to lower *n* instabilities.

GENERAL ATOMICS

Summary/Plans

- MHD stability imposes constraints on pedestal height, which are strong functions of pedestal width (but ***not*** linear with width) and plasma shape. Constraints are ~similar between machines.
- Limiting instability is intermediate to high-*n* peeling-ballooning mode. Strong shaping opens 2nd stability, and leads to lower *n* for limiting mode. Mode width extends somewhat beyond the pedestal.
- Uncertainty about the pedestal width makes precise prediction difficult. Observed correlations ($\square\sim\square_p^{1/2}$, $\square\sim\square^x$) are ~expected from the stability constraints and may provide limited information on physics setting the width. Finite-*n* stability constrains the width as well as the gradient, but understanding of transport likely needed as well to accurately predict width. (power dependence of width is a key question)
- For $\square/a$ in observed range, constraints allow $\square_{ped}$ in vicinity of what's predicted to be needed for good performance (GLF23 Kinsey, Waltz). Optimizing shaping & density may increase it further.
- These are preliminary results with ideal MHD. Non-ideal effects such as diamagnetic stabilization will be considered - expected to increase stability threshold somewhat and move most unstable mode toward lower *n*
- Plan to parameterize stability constraints, and try to use better understanding of pedestal stability to "back out" behavior of width from the database