MHD stability constraints on divertor heat flux width in DIII-D

by
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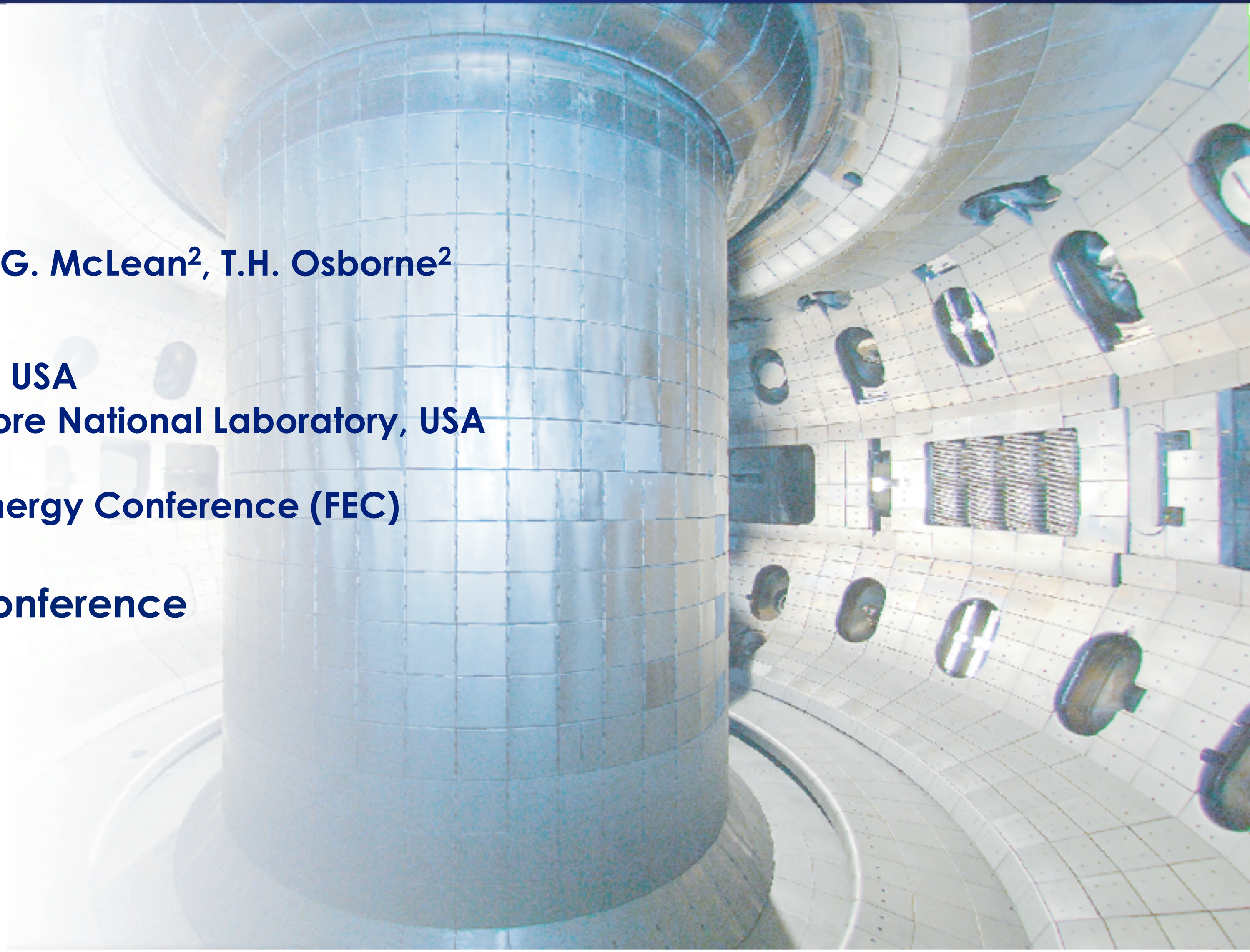
28th IAEA Fusion Energy Conference (FEC)

Virtual Online Conference
10-15 May, 2021



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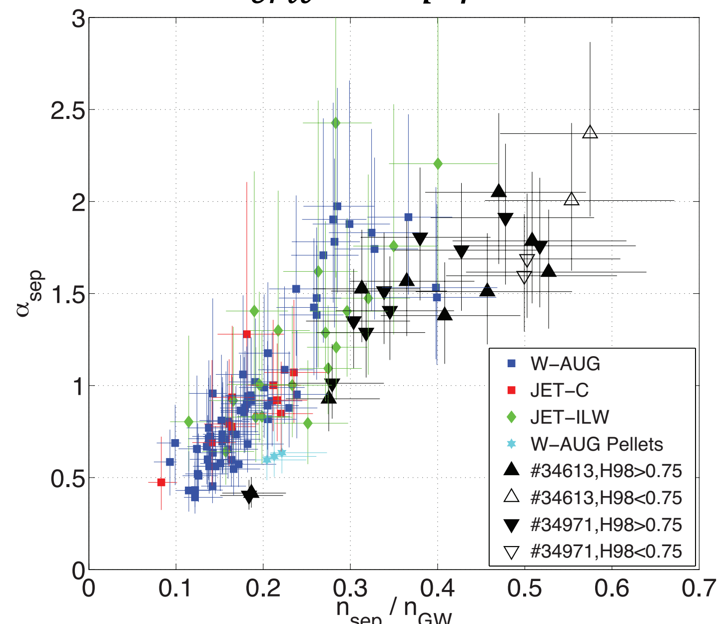
GENERAL ATOMICS

Recent analysis suggests MHD stability limits the density range of ITPA heat flux width scaling

- **Eich[1] finds separatrix pressure gradient limit in JET and ASDEX-U**
  - Derive MHD limit for ITPA heat flux width scaling at n_{sep}/n_{GW}~0.5
  - SOL broadens at high pressure gradient and/or collisionality
- **Goal: Examine DIII-D data for similar trends and implications**
  - Vary power and density for scanning separatrix pressure and its gradient
  - Correlate high separatrix gradients with SOL, divertor and pedestal behavior
- **SOL broadening observed in DIII-D**
  - SOL width increases with high density and power
  - Detached divertor plasma broadens at high power
  - Pedestal pressure does not inherently degrade for high density SOL and detached divertor operation

$$\alpha_{crit} = Rq^2\beta' \sim 2.5$$



[1]Eich, NF 2018

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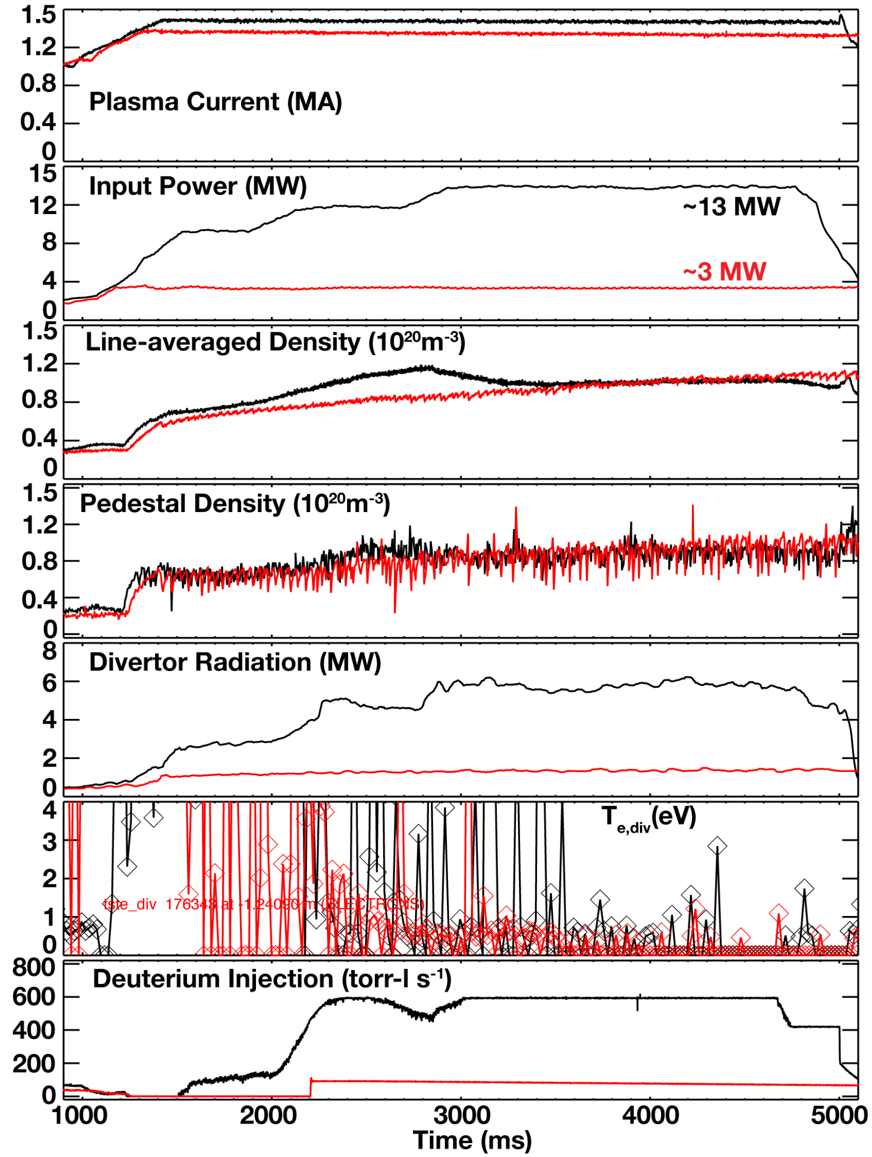
Density and input power scans provide a wide range of separatrix pressure

- **LSN configuration**
  - Modest triangularity, δ_L~ 0.5, δ_U~ 0.2
- **Vary injected power by 4x**
  - 3 MW, 5 MW and 13 MW
- **Vary D_2 gas injection from natural H-mode density to divertor detachment, $T_{e,div}$~ 1eV**
- **Pressure gradient measurements:**
  - Profiles of n_e and T_e from Thomson in last half of ELM phase
  - T_i profile from CER of CVI
- **Edge MHD stability from:**
  - Magnetic reconstruction (EFIT) with current and pressure constraints
  - Baloo calculation of infinite-n ideal ballooning stability



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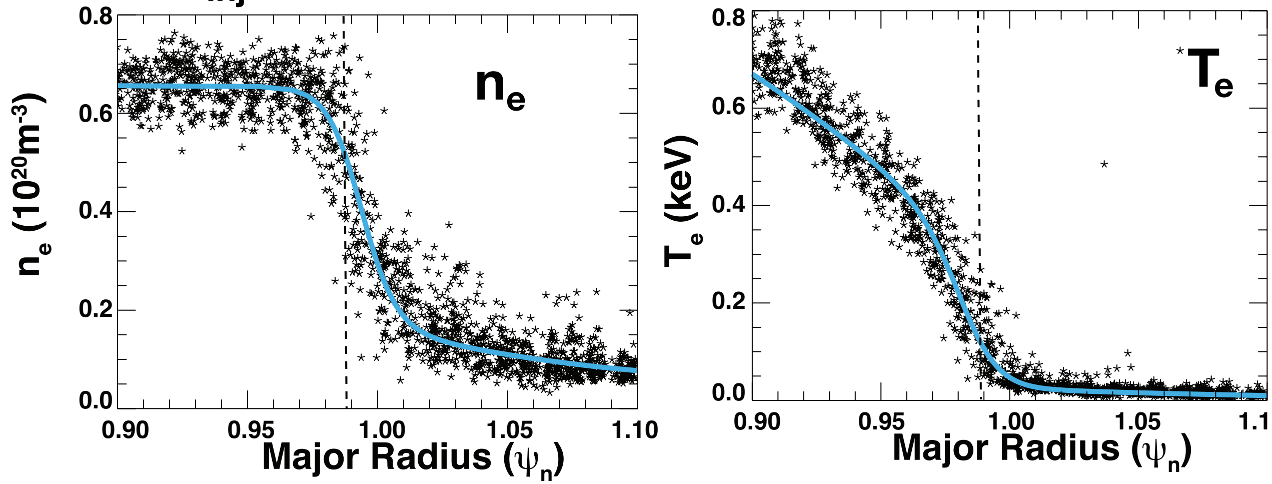
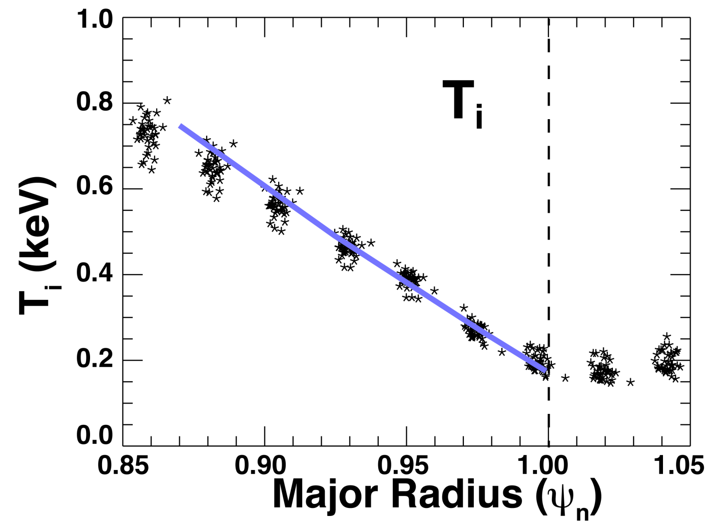
Separatrix pressure gradients examined by scanning power and density

- **Separatrix pressure scan**
  - Density scan to detachment onset
  - Power scan; 3-13 MW
  - High power required to support high SOL density

P_{inj}=13 MW; Detached Divertor Onset



- **Midplane profiles collected**
  - Thomson data between ELMs fit with tanh function
  - Separatrix location; T_{sep}~70-90 eV from power balance
  - T_i from CER CVI



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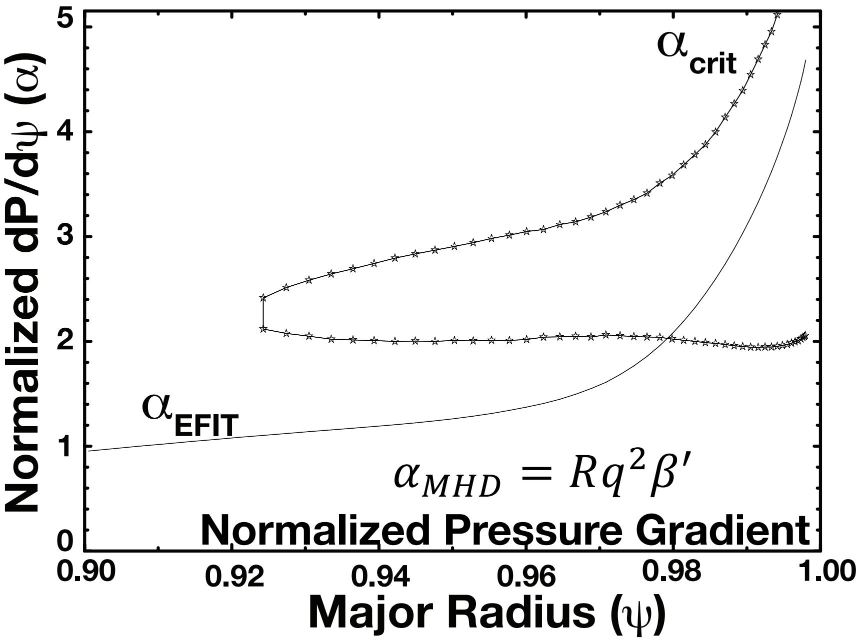
For ITPA λ_q scaling MHD limit is reached at high density

- **∇p_{sep} increases with density**
  - Fixed λ_{Te}, λ_{ne}(ITPA scaling)
  - Little variation in $T_{e,sep}$, 70-90 eV, $T_{e,sep} \propto q_{\parallel}^{2/7}$
  - High power required to support high SOL density at detachment onset, $n_{sep} \propto q_{\parallel}^{5/7}$

MHD stability limit from BALOO

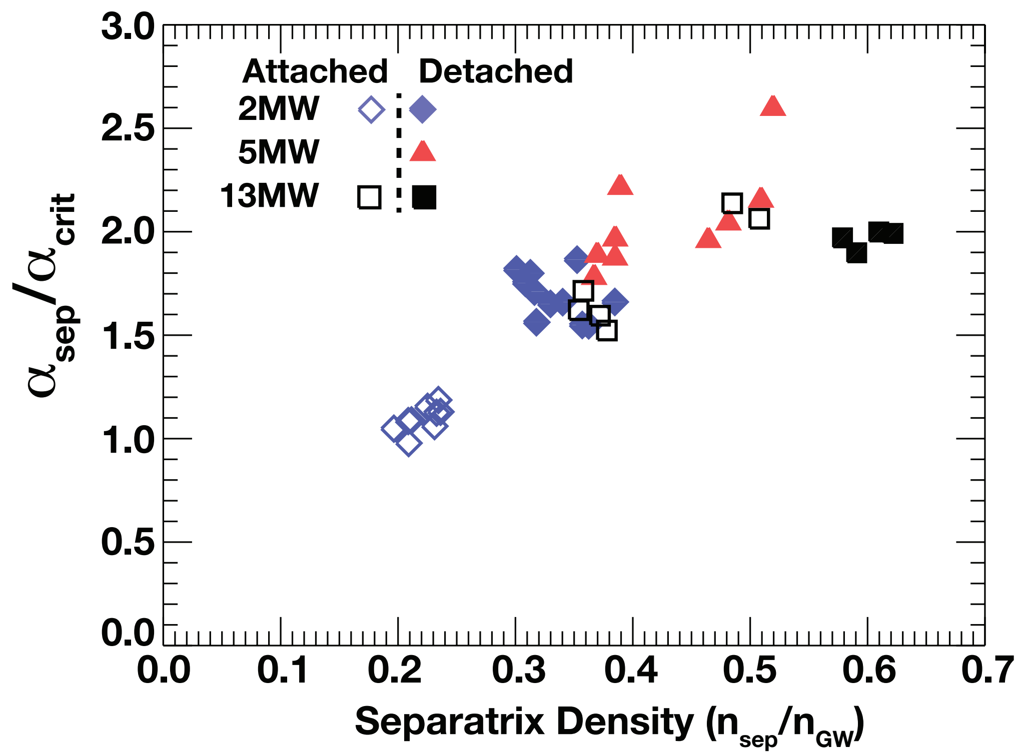


- **Magnetic equilibria reconstructed with measured pressure and edge bootstrap current model**
- **Baloo calculates 2D ideal MHD ballooning limit**
  - Across dataset; α_{crit} ~ 2.2-2.7

Separatrix pressure gradient increases with density until saturating at $n_{e,sep}/n_{GW} \geq 0.4$

- **∇p_{sep} ($\alpha_{sep}/\alpha_{crit}$) saturates vs. density at twice the MHD limit**
- **∇p_{sep} consistently above stability limit**
  - Result not sensitive to SOL transport assumption
  - Potential stabilization due to FLR and flow shear effects

Normalized Separatrix Pressure Gradient
($\nabla p_{e,sep}$ + $\nabla p_{i,sep}$)/ ∇p_{crit}



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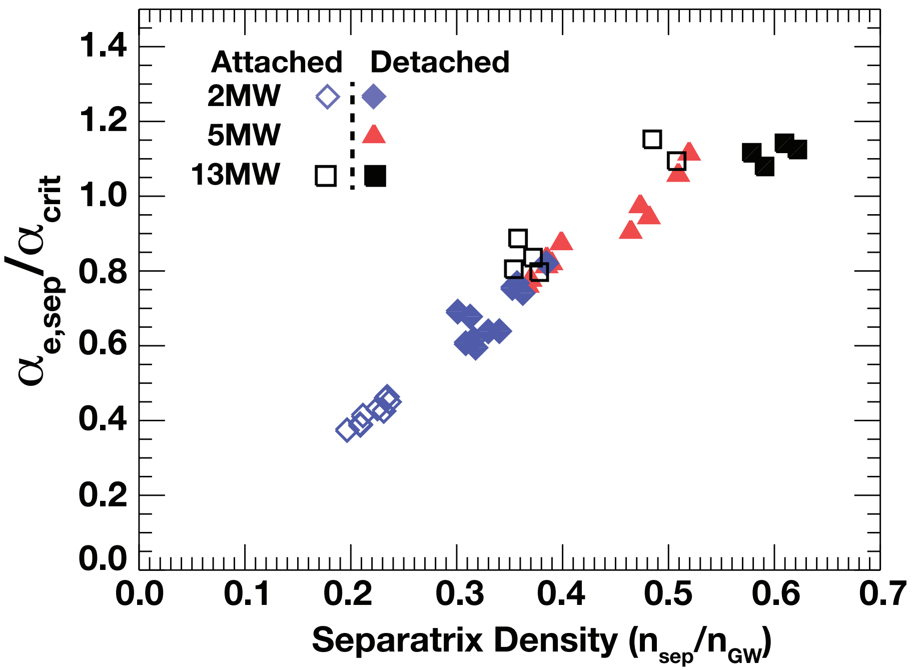
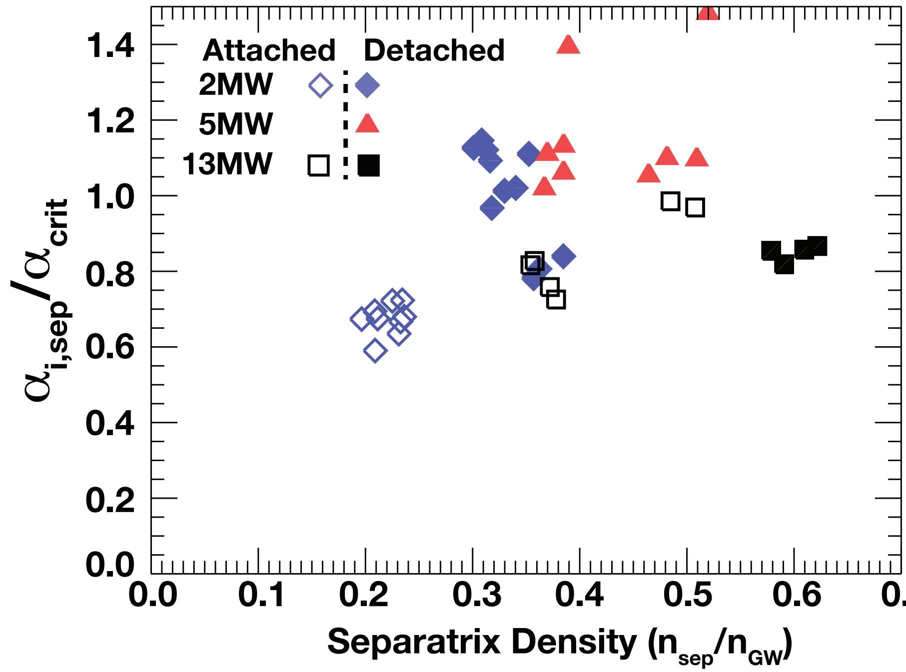
Electron pressure gradient increases linearly with density

Electron Pressure Gradient; $\nabla p_{e,sep}$



Ion Pressure Gradient; $\nabla p_{i,sep}$



- $\nabla p_{e,sep}$ increases linearly with $n_{e,sep}$ until $n_{e,sep}/n_{GW} \sim \geq 0.5$
- $\nabla p_{i,sep}$ inherently more uncertain due CVI CER challenges
  - Initial main ion CER analysis reduces $T_{i,sep}$, but increases $\nabla T_{i,sep}$

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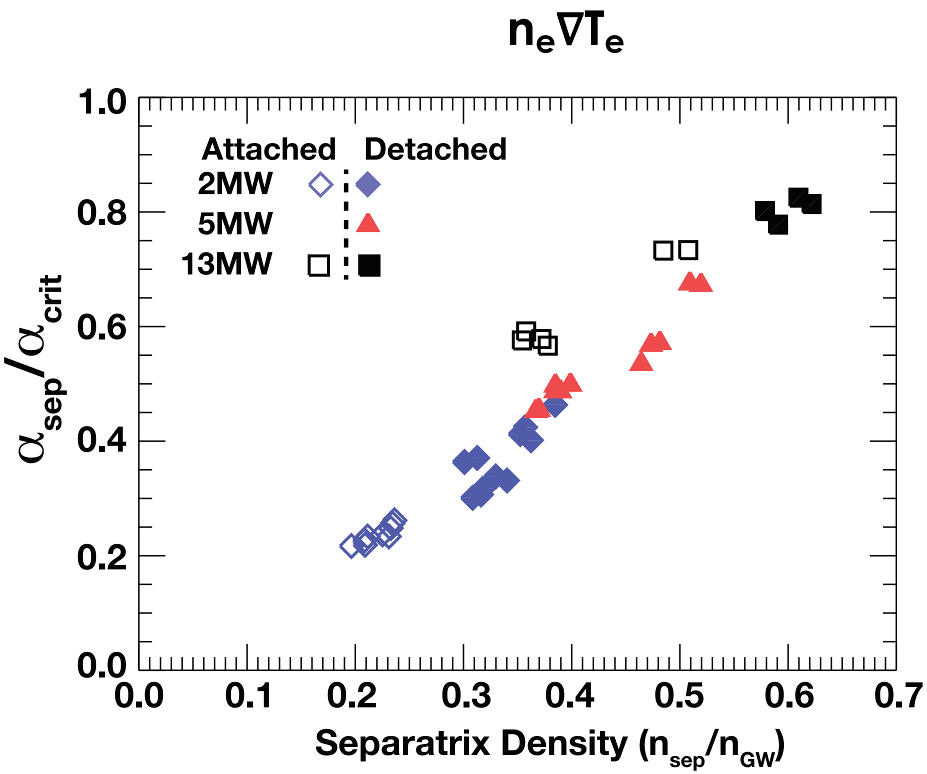
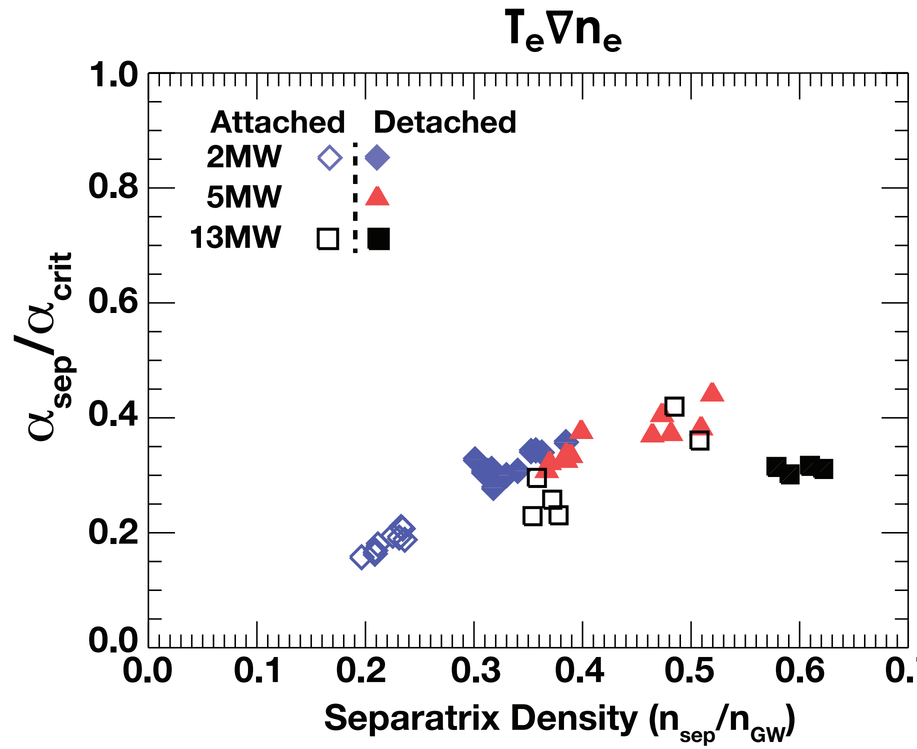
Electron pressure gradient driven by both temperature and density profiles





- **$n_e \nabla T_e$:**
  - Linear increase with n_{sep} indicates constant ∇T_e
  - Little change in scaling with divertor detachment
- **$T_e \nabla n_e$:**
  - Saturation with n_{sep} indicates broadening of SOL density
  - $T_{e,sep}$ insensitive to density and power in this analysis

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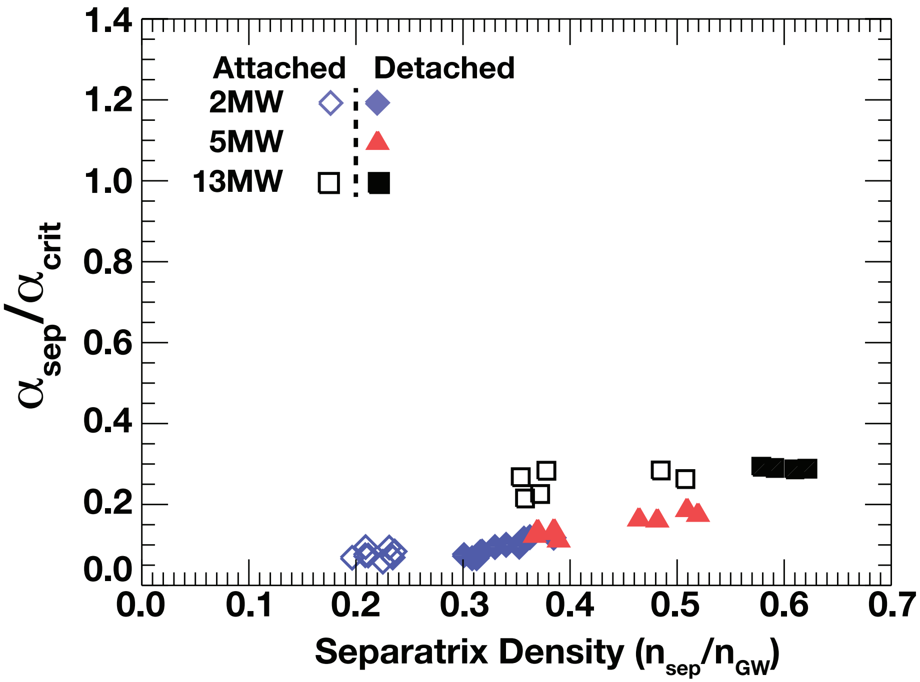
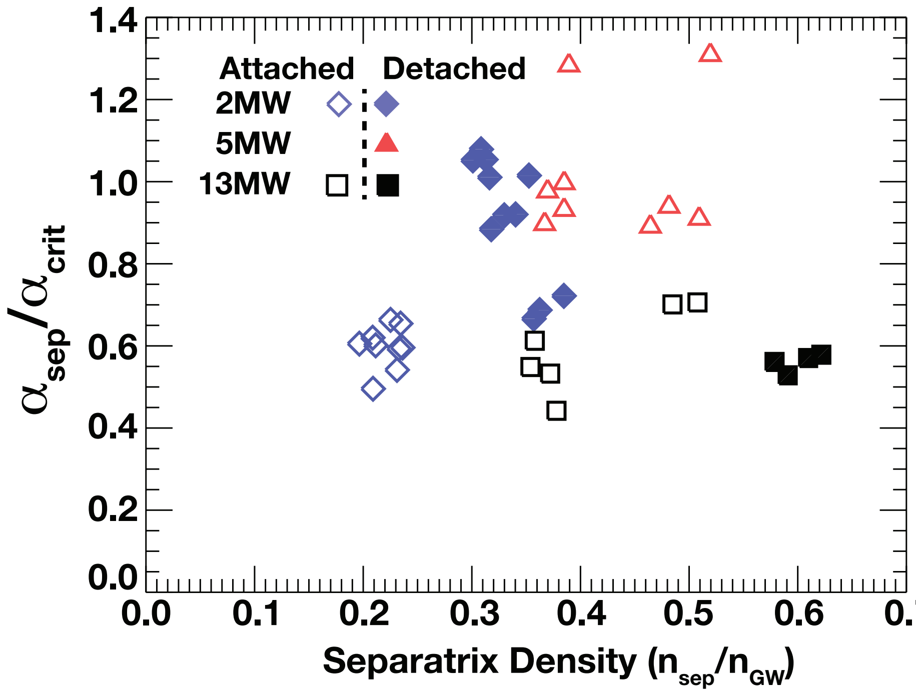
Ion pressure gradient dominated by ∇n_i



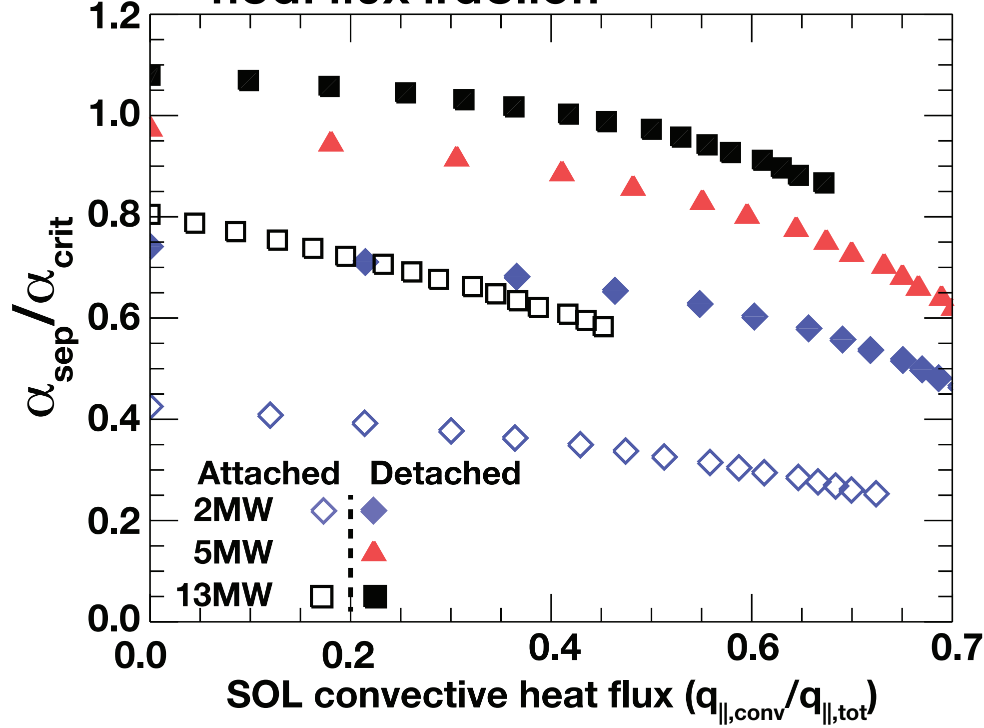


- **$n_i \nabla T_i$:**
  - Low values due to high $T_{i,sep}$ and low T_i gradient
  - Main ion CER expected to decrease $T_{i,sep}$ but increase $\nabla T_{i,sep}$
- **$n_i \nabla T_i$:**
  - Large value due to high $T_{i,sep}$ with n_i profile similar to n_e
  - Large scatter in data set due to challenging CVI CER measurement

Low sensitivity of pressure gradient to analysis assumption of conduction dominated SOL heat flux

- **Sensitivity of $\nabla p_{e,sep}$ to analysis assumption**
  - Vary convected fraction of SOL heat flux by varying Mach # of parallel flow of SOL profiles
  - Convections shifts separatrix location to slightly lower T_e
- **Sensitivity of $\nabla p_{e,sep}$ to separatrix location is not strong enough to qualitatively affect conclusions**

$\nabla p_{e,sep}$ vs. SOL convected heat flux fraction



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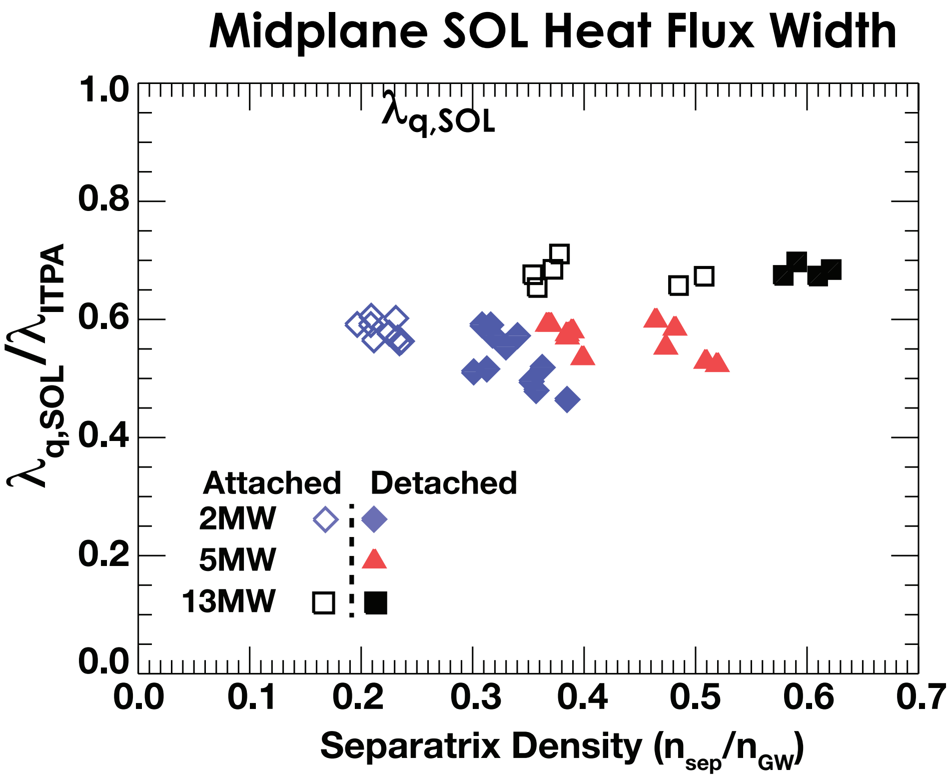
SOL heat flux width broadens marginally at high power

- **Midplane SOL λ_q obtained from Thomson profiles**
  - $\lambda_q \sim \frac{2}{7}\lambda_{T_e}$ (flux-limited Spitzer)
  - λ_q ~ 60−70% of ITPA scaling
- **No SOL broadening with density at low power**
  - $\lambda_{q,SOL}$ constant vs. density up through divertor detachment
- **SOL λ_q at detachment onset broadens with increasing power**
  - $\lambda_{q,SOL}$ increases ~30% from low to high power



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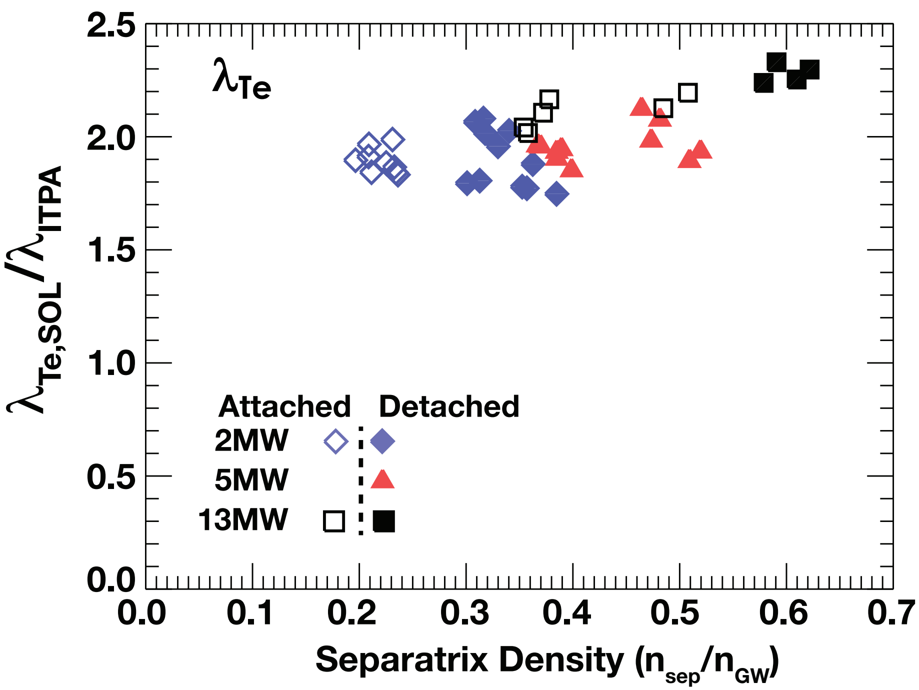
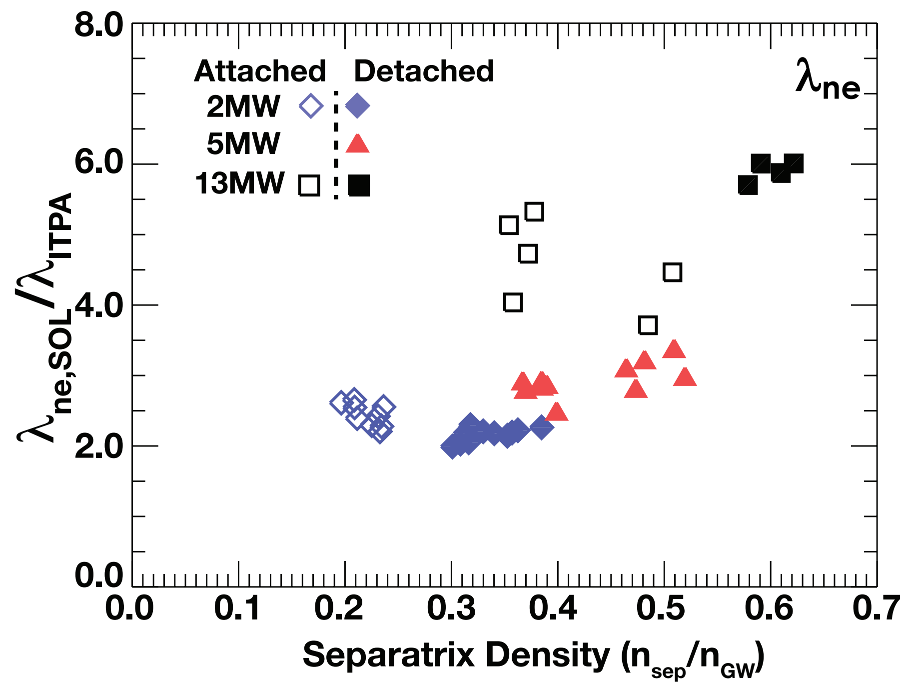
λ_{ne} increases more than λ_{Te} at high power and density





- **SOL λ_{Te} scaling similar to $\lambda_{q,SOL}$**
  - $\lambda_q \sim \frac{2}{7}\lambda_{T_e}$ (flux-limited Spitzer)
- **SOL λ_{ne} 3x broader at high power**
  - $n_{e,sep}$ at detachment onset only 2x higher for 5x higher power

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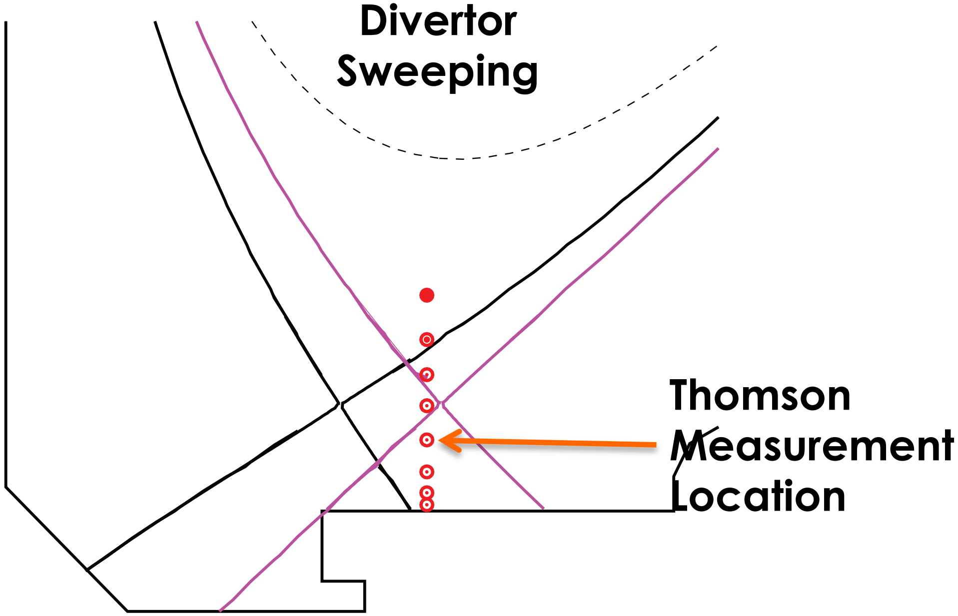
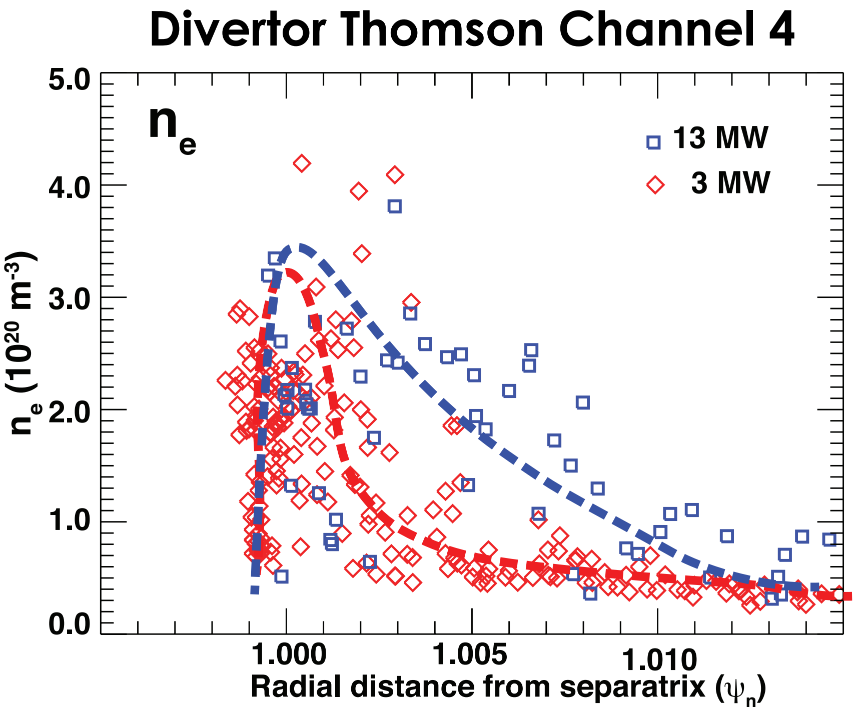
At high power detached divertor broadens similar to $\lambda_{ne,SOL}$



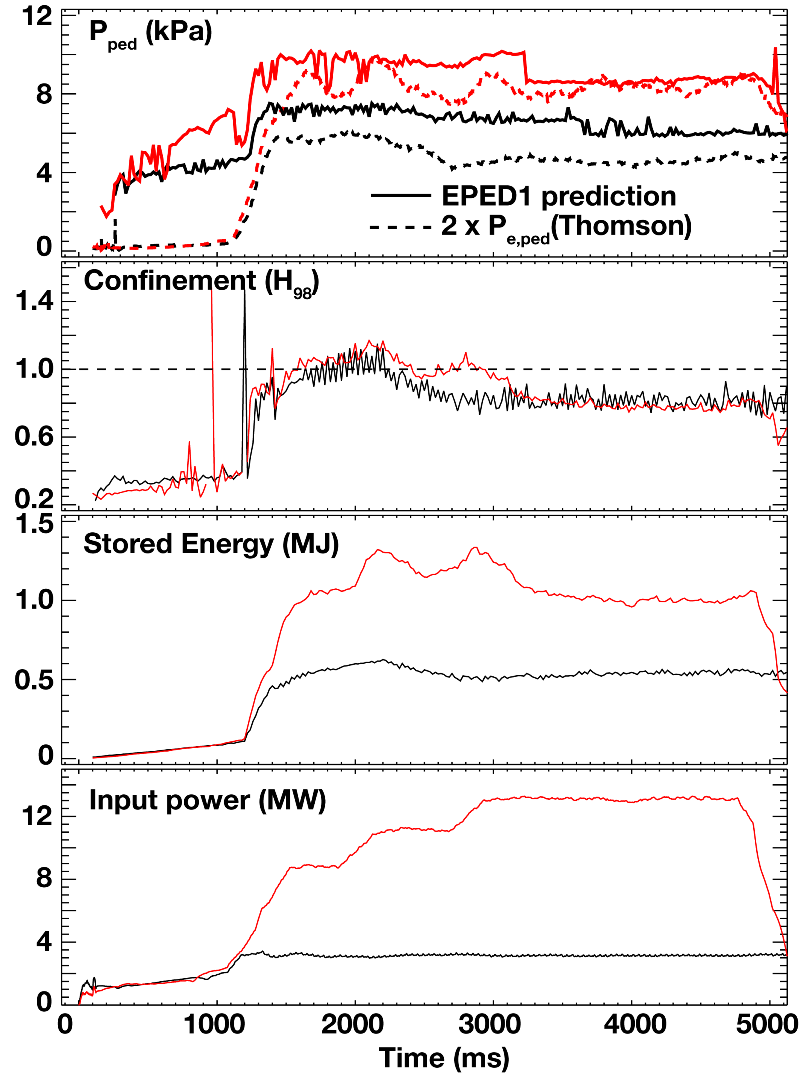


- **During divertor detachment**
  - T_e ~1 eV at target and ~5 eV at midpoint for both low and high power
  - Divertor plasma 2-3 x broader at high power, similar to midplane density
  - Peak divertor density does not increase significantly with power
  - Divertor power width, ~$\lambda_{ne,div}$ correlated with $\lambda_{ne,SOL}$ rather than $\lambda_{Te,SOL}$

Pedestal degradation during detachment is evaluated with EPED

- **EPED based on known pedestal physics**
  - Dependence on collisionality (density)
  - Plasma β_{pol} (input power)
  - Other inputs; Shape, I_p, B_t, Z_{eff}, etc.
- **Effect of detachment and SOL broadening on confinement not directly extrapolatable due to other physics**
  - Internal MHD (NTMs), core profile peaking with collisionality, dependence of confinement on rotation, etc.

Detached Divertor Discharges



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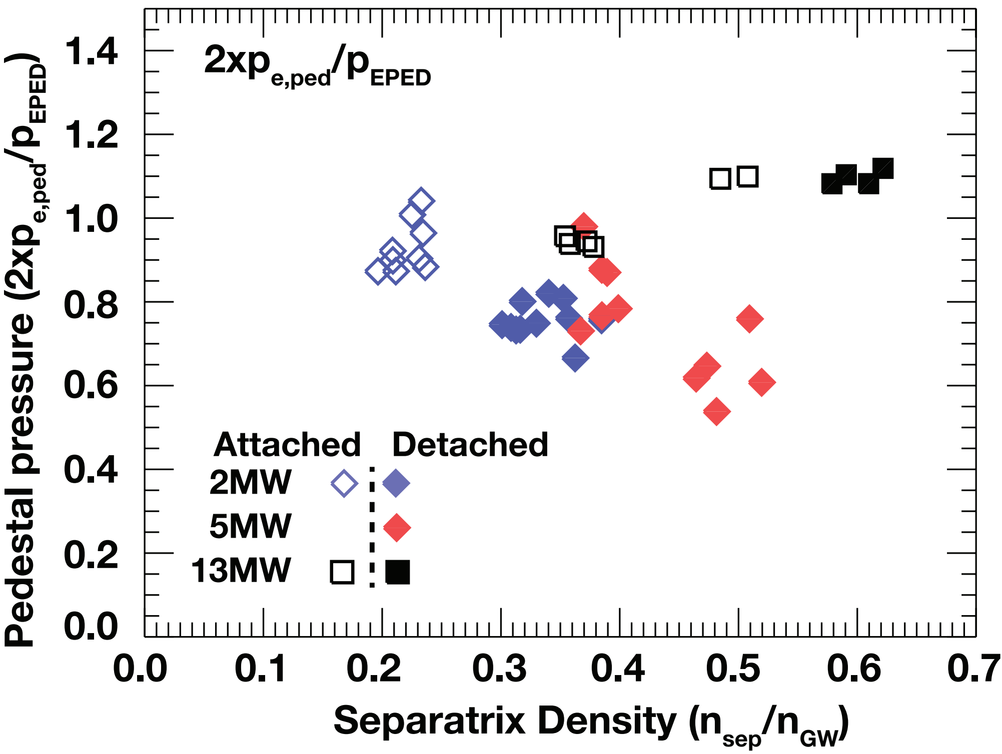
Pedestal can be maintained during detachment with high power

- **Pedestal degrades ~20% below EPED expectation for low power detached conditions**
  - High collisionality?
  - Narrow density pedestal due to edge fueling?
- **Detached plasmas can maintain high pedestal at high power**
  - Higher P_{LH} margin required at high collisionality?
- **Pedestal degradation is not an inherent feature of a detached divertor or broadened SOL**

Pedestal Pressure Normalized by EPED expectation



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Summary and future work

- **Experimental observations**
  - SOL broadens, n_e more than T_e, at high power and density
  - Divertor plasma also broadens similarly to the upstream SOL density
  - Pedestal does not degrade below EPED predictions at high power
- **Implications**
  - Divertor detachment in future tokamaks may be possible at lower densities than implied by ITPA λ_q scaling
  - Divertor test tokamaks may require similar field strengths to simulate reactor divertor conditions
- **Future work**
  - Test SOL profiles with realistic stability models; BOUT++
  - Examine ion pressure with main ion CER measurements