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

by
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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 \(n_{\text{sep}}/n_{\text{GW}} \sim 0.5\)
  - 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

\[ \alpha_{\text{crit}} = R q^2 \beta' \sim 2.5 \]
Density and input power scans provide a wide range of separatrix pressure

- **LSN configuration**
  - Modest triangularity, $\delta_L \sim 0.5$, $\delta_U \sim 0.2$

- **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, $T_{e,\text{div}} \sim 1\text{eV}$**

- **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
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

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

$P_{inj}=13$ MW; Detached Divertor Onset

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*Figure*: Major Radius ($\psi_n$) vs. $n_e$ (left), $T_e$ (middle), and $T_i$ (right) profiles with data points and fitted curves.

*Footnote*: Midplane profiles collected

- Thomson data between ELMs fit with tanh function
- Separatrix location; $T_{sep} \sim 70-90$ eV from power balance
- $T_i$ from CER CVI
For ITPA $\lambda_q$ scaling MHD limit is reached at high density

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

- Magnetic equilibria reconstructed with measured pressure and edge bootstrap current model
- Baloo calculates 2D ideal MHD ballooning limit
  - Across dataset; $\alpha_{crit} \sim 2.2-2.7$
Separatrix pressure gradient increases with density until saturating at $n_{e,\text{sep}}/n_{GW} \geq 0.4$

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

Normalized Separatrix Pressure Gradient

\[
\frac{(\nabla p_{e,\text{sep}} + \nabla p_{i,\text{sep}})}{\nabla p_{\text{crit}}}
\]

Separatrix Density ($n_{\text{sep}}/n_{GW}$) vs. $\alpha_{\text{sep}}/\alpha_{\text{crit}}$
Electron pressure gradient increases linearly with density

- $\nabla p_{e,sep}$ 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 $\nabla T_{i,sep}$
Electron pressure gradient driven by both temperature and density profiles

- $n_e \nabla T_e$:
  - Linear increase with $n_{sep}$ indicates constant $\nabla T_e$
  - 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
Ion pressure gradient dominated by $\nabla n_i$

- $n_i \nabla T_i$:
  - Low values due to high $T_{i,\text{sep}}$ and low $T_i$ gradient
  - Main ion CER expected to decrease $T_{i,\text{sep}}$ but increase $\nabla T_{i,\text{sep}}$

- $n_i \nabla T_i$:
  - Large value due to high $T_{i,\text{sep}}$ 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 $\nabla p_{e,\text{sep}}$ 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 $\nabla p_{e,\text{sep}}$ to separatrix location** is not strong enough to qualitatively affect conclusions
SOL heat flux width broadens marginally at high power

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

- **SOL \( \lambda_{Te} \) scaling similar to \( \lambda_{q,SOL} \)**
  - \( \lambda_{q} \sim \frac{2}{7} \lambda_{Te} \) (flux-limited Spitzer)

- **SOL \( \lambda_{ne} \) 3x broader at high power**
  - \( n_{e,sep} \) at detachment onset only 2x higher for 5x higher power
At high power detached divertor broadens similar to $\lambda_{ne,SOL}$

- During divertor detachment
  - $T_e \sim 1$ eV at target and $\sim 5$ 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, $\sim \lambda_{ne,div}$ 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 $\beta_{pol}$ (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.
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 $P_{\text{LH}}$ margin required at high collisionality?
- Pedestal degradation is not an inherent feature of a detached divertor or broadened SOL
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 $\lambda_q$ 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