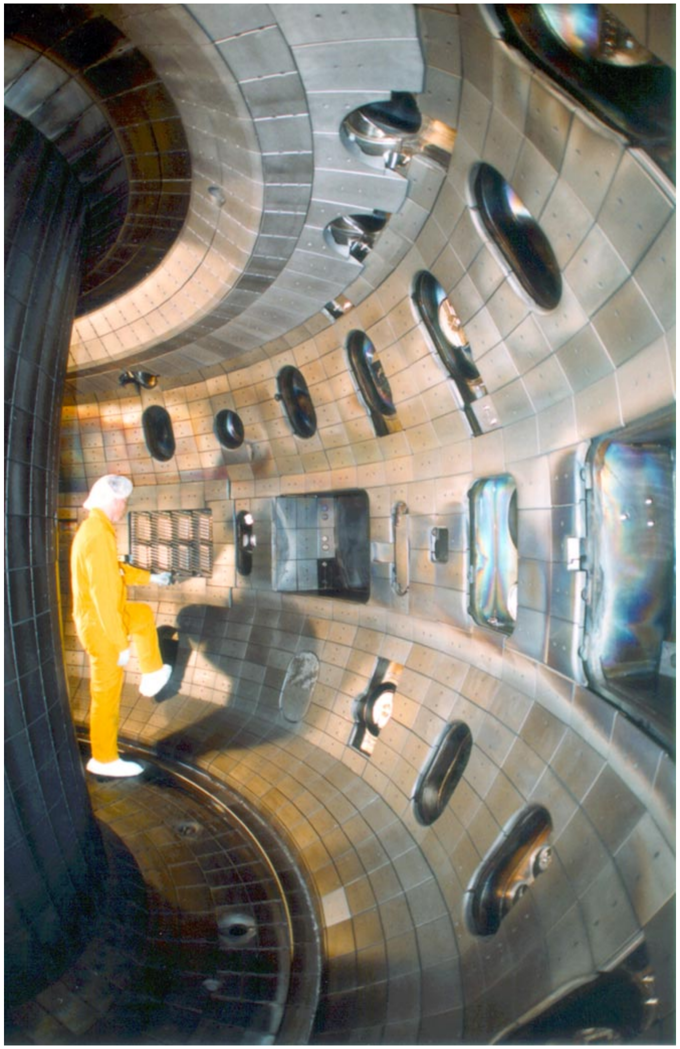

Effect of Variation in Equilibrium Shape on ELMing H-mode Performance in DIII-D Diverted Plasmas

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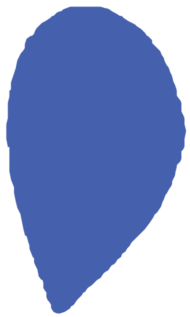
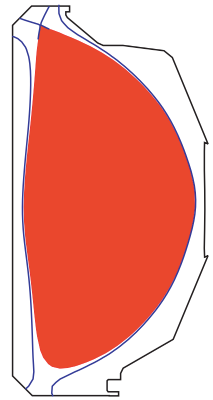
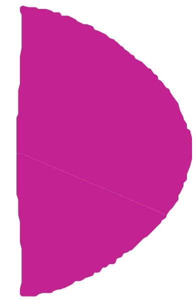
Motivation: Many desirable characteristics of tokamak operation may be enhanced by plasma shaping.



Low Triangularity
Single Null



High Triangularity
Unbalanced
Double Null



Very High
Triangularity
Balanced
Double Null

- Engineering simplicity
  - Single divertor
  - Vertical access
  - Vertically stable
- Disadvantages
  - Modest confinement
  - Low beta limit
  - High Peak Heat Flux

- Shape Optimization
  - Good confinement
  - Good beta limit
  - Reduced Peak Heat Flux
  - High I_p at fixed q_{95}
  - Specialized divertors

- Physics Advantages
  - High confinement
  - High normalized beta
  - Reduced Peak Heat Flux
- Disadvantages
  - Large ELMs
  - Reduced core volume
  - Shape control

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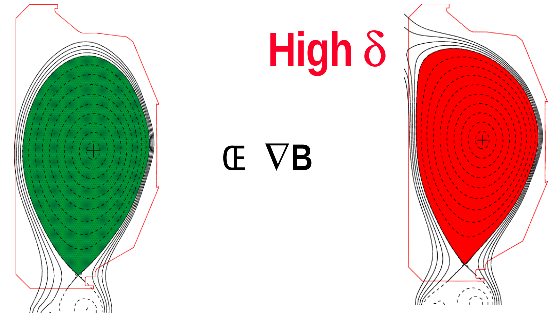
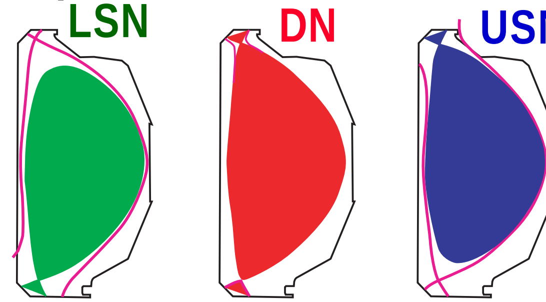
Outline: ELMing H-mode plasmas, shape changes between and density ramps within discharges.

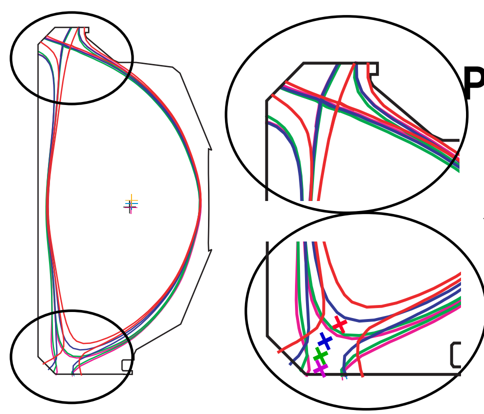
- **Triangularity (δ) Variations**
  - **Pedestal and core performance**



- **Up/down Magnetic Balance (dRsep) Variations**
  - **Divertor sharing**



- **Secondary Divertor Volume (Z_x^s) Variations**
  - **Determine minimum**



- **Conclusions**

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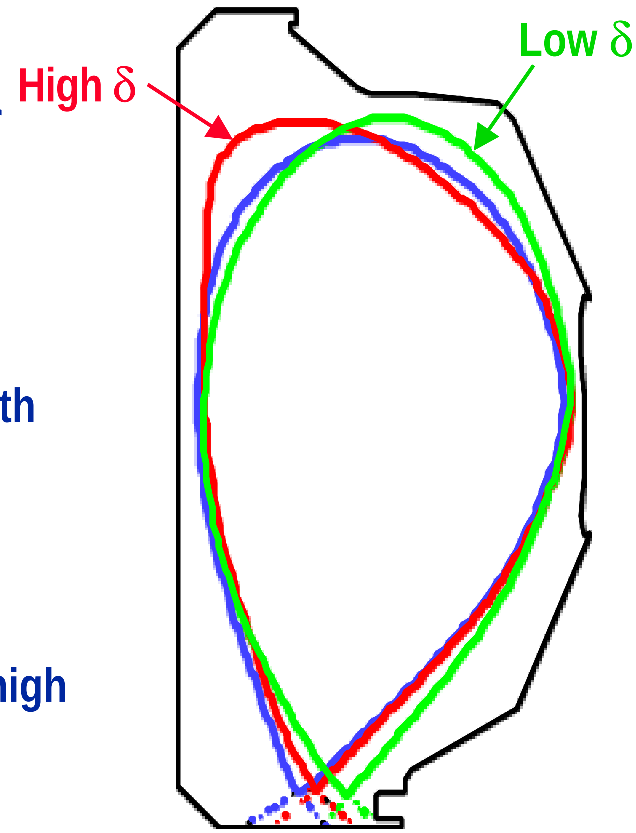
Summary: Triangularity advantageous at moderate density but dependence weaker at high density

<u>RESULTS</u> - Pedestal vs. δ

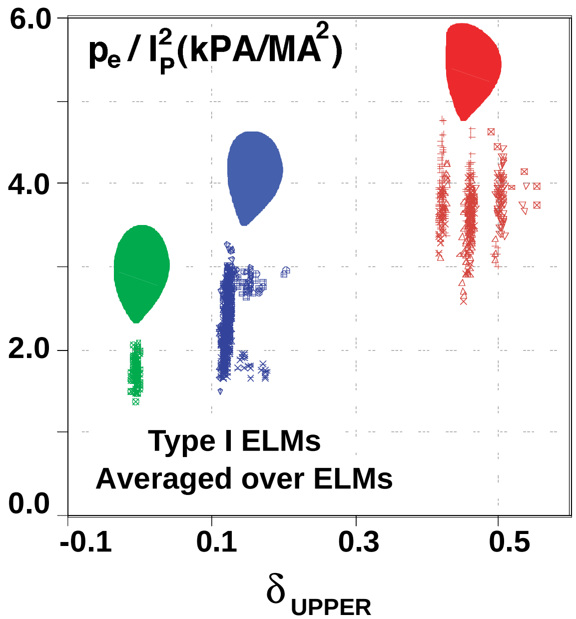
- Pedestal pressure and confinement increase with δ for $n_e/n_{Gr} \leq 0.7$
  - Pedestal pressure gradient increased
- At high density the degradation of pedestal stronger with density at high δ
  - Temperature profile stiff at high ne
- $\Delta W_{ELM}/p_e^{ped}$ reduced and ELM frequency increased at high density, $n_e/n_{Gr} > 0.7$

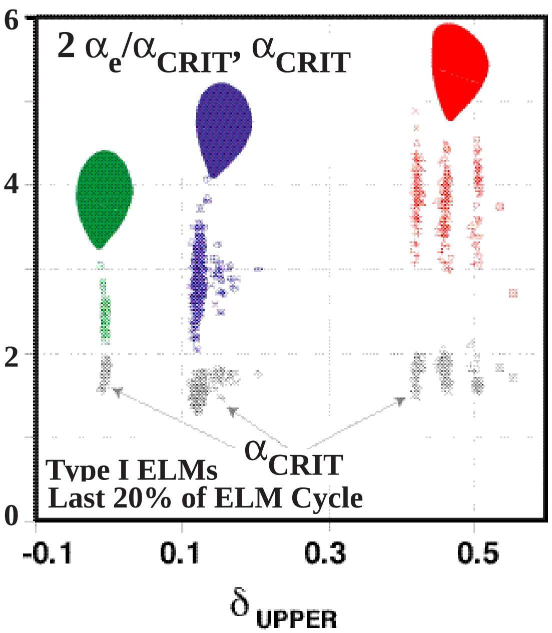


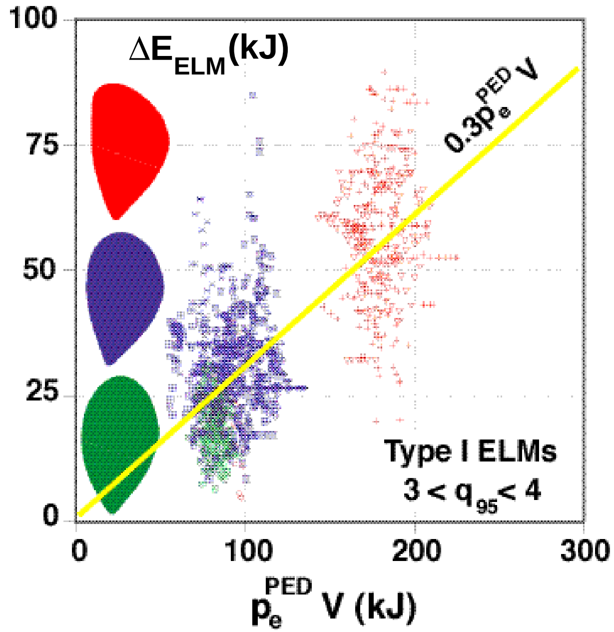
Increased triangularity increases pedestal pressure and core confinement.

δ Study, $n_e/n_{Gr} \leq 0.7$

- Edge electron pedestal pressure p_e^{ped} and confinement increase with triangularity δ.
  - ELM energy loss also increases
- Gradient of p_e^{ped} higher than ideal ballooning critical gradient and increases with δ.
  - Width of p_e^{ped} remains nearly constant with δ.
- At low density ELM energy loss is fixed fraction of pedestal energy independent of δ.



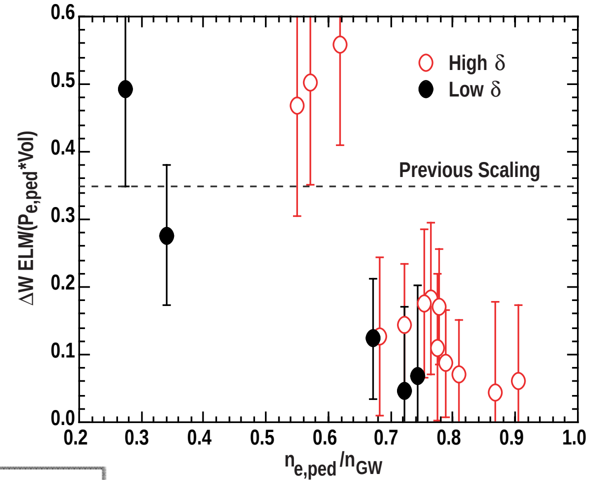


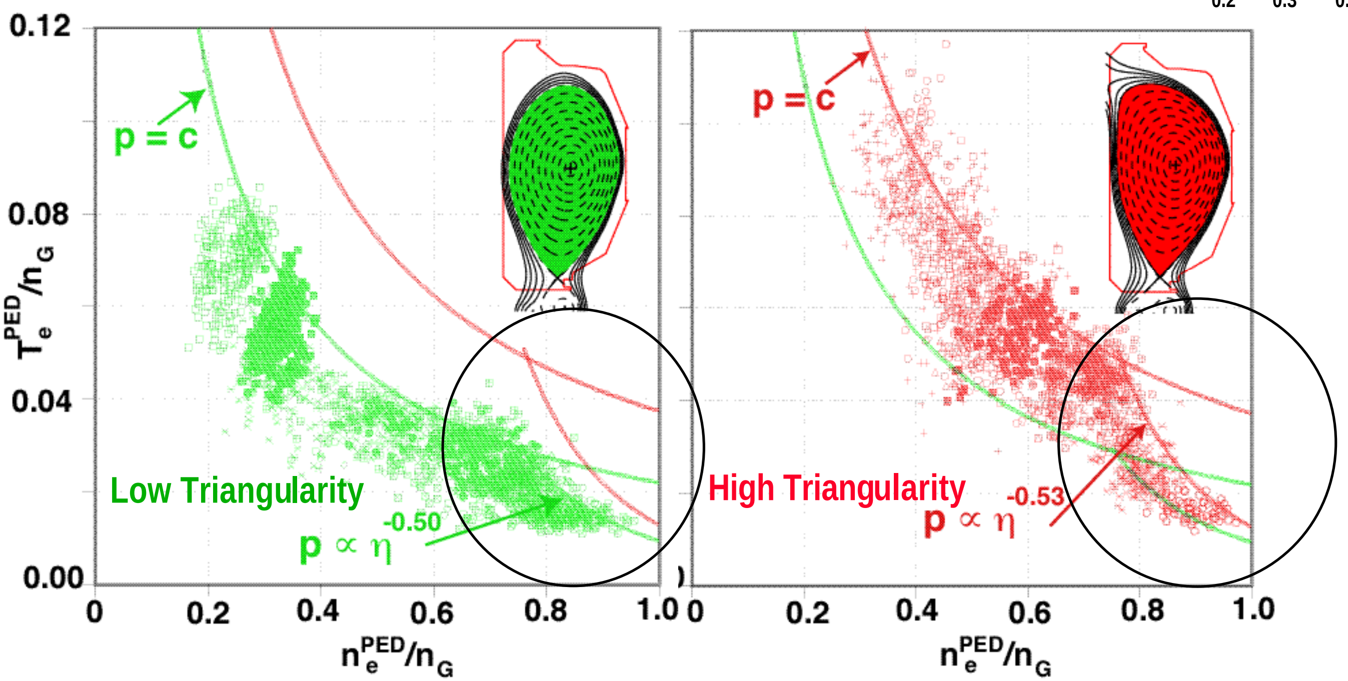


Reduced p_e^{ped} and stiff temperature profiles can produce confinement reduction independent of δ at high n_e.

δ Study, $n_e/n_{Gr} > 0.7$

- Degradation occurs at the same $n_e^{ped}/n_{Gr} \sim 0.75$ independent of δ.
  - Stronger reduction of p_e^{ped} vs. n_e^{ped} at high δ.
- Stiff profiles at high n_e (low T_e) give reduced confinement.
- As n_e increased ELM fraction of pedestal energy decreases independent of δ.



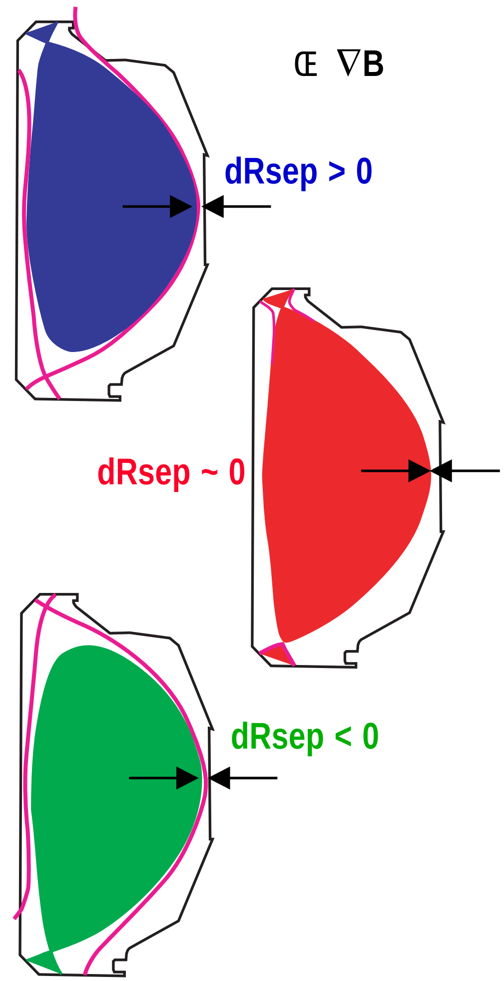


Summary: Magnetic balance optimization of unbalanced DN operation is predictable.

dRsep Study

RESULTS - Divertor Sharing vs. dRsep (LSN - DN - USN)

- Moderate density $n_e/n_{Gr} \leq 0.7$ - ***Attached***:
  - Target heat flux sharing determined by conduction
  - ELM energy sharing determined by broad SOL profile
  - Particle flux sharing affected by divertor neutral recycling.
- High density, $n_e/n_{Gr} > 0.7$ - ***Detached***:
  - Detachment physics determines heat flux sharing
  - $n_{eH\text{-}L}$ higher for magnetic balance toward ion ∇B drift divertor.

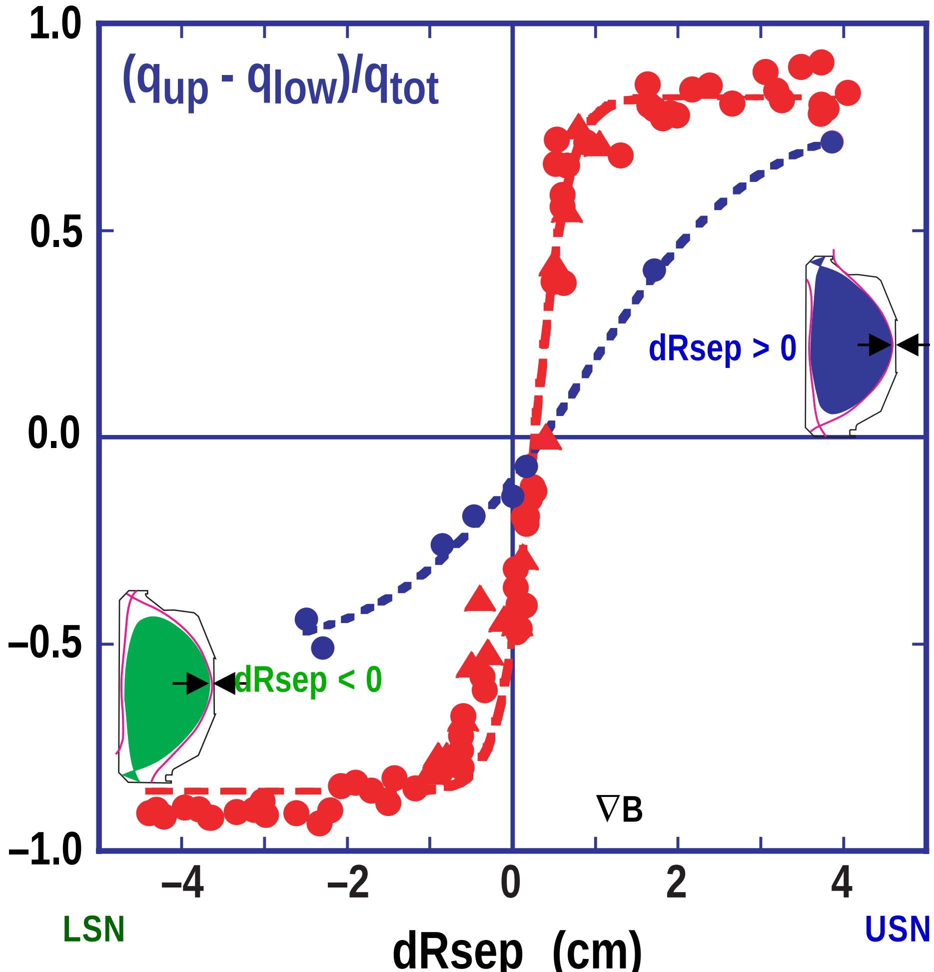


Variation in heat flux sharing is large near DN for ne/nGr ≤ 0.7; less sensitive for high density.

dRsep Study, $n_e/n_{Gr} \leq 0.7$ and > 0.7

- Peak heat flux sharing for ne/nGr ≤ 0.7:
  - Switches divertors within dRsep ± 0.4 cm
  - Balance at dRsep = +0.3 cm
  - Consistent with SOL energy conduction and ExB drifts.
- At higher density:
  - Less sensitive to dRsep variation
  - Broader than implied by SOL conduction
  - Divertor detachment important
    - Upstream radiation
    - Convection

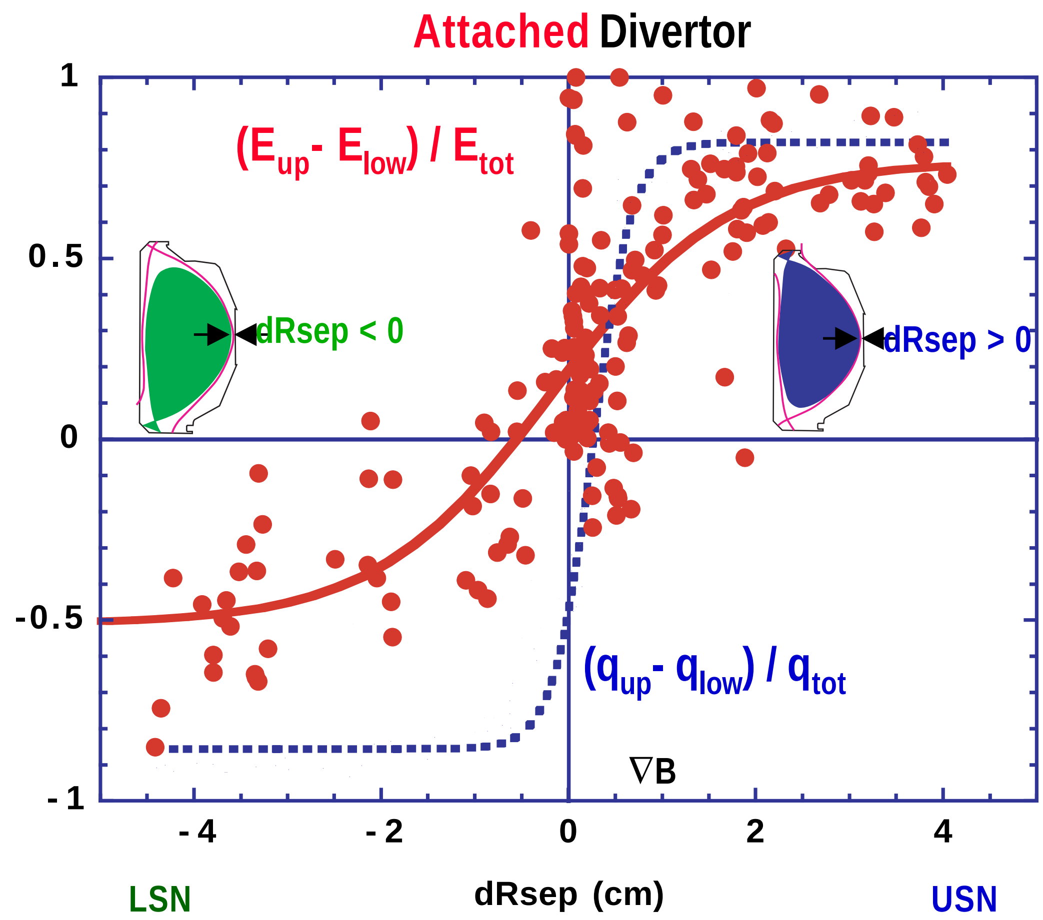
Attached vs Detached Divertor



ELM energy profile broad in SOL; divertor sharing weakly dependent on dRsep

dRsep Study, $n_e/n_{Gr} \leq 0.7$

- ELM energy sharing less sensitive than time averaged peak q_{div}.
- Assuming conduction dominates:
  - ELM energy radial profile in SOL up to 4x broader than time averaged q_{div} profile
  - ELM energy will strike conformal divertor structures.

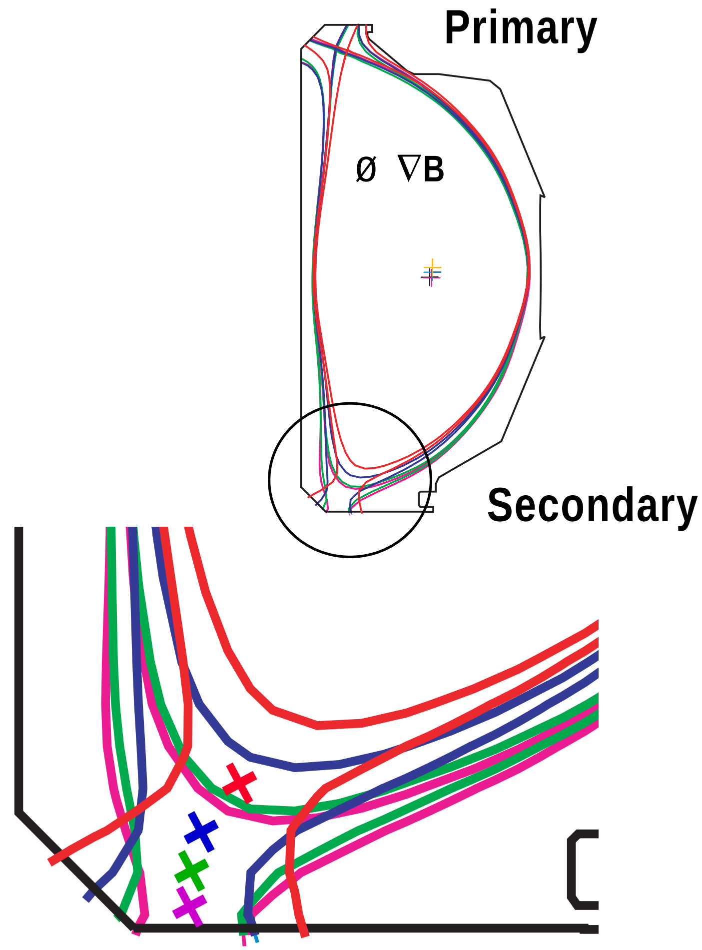


Summary: Reducing secondary divertor volume lowers peak heat flux but also reduces density operating window.

Z_x^s Study

<u>RESULTS</u> - Divertor and Edge as Z_x^s reduced

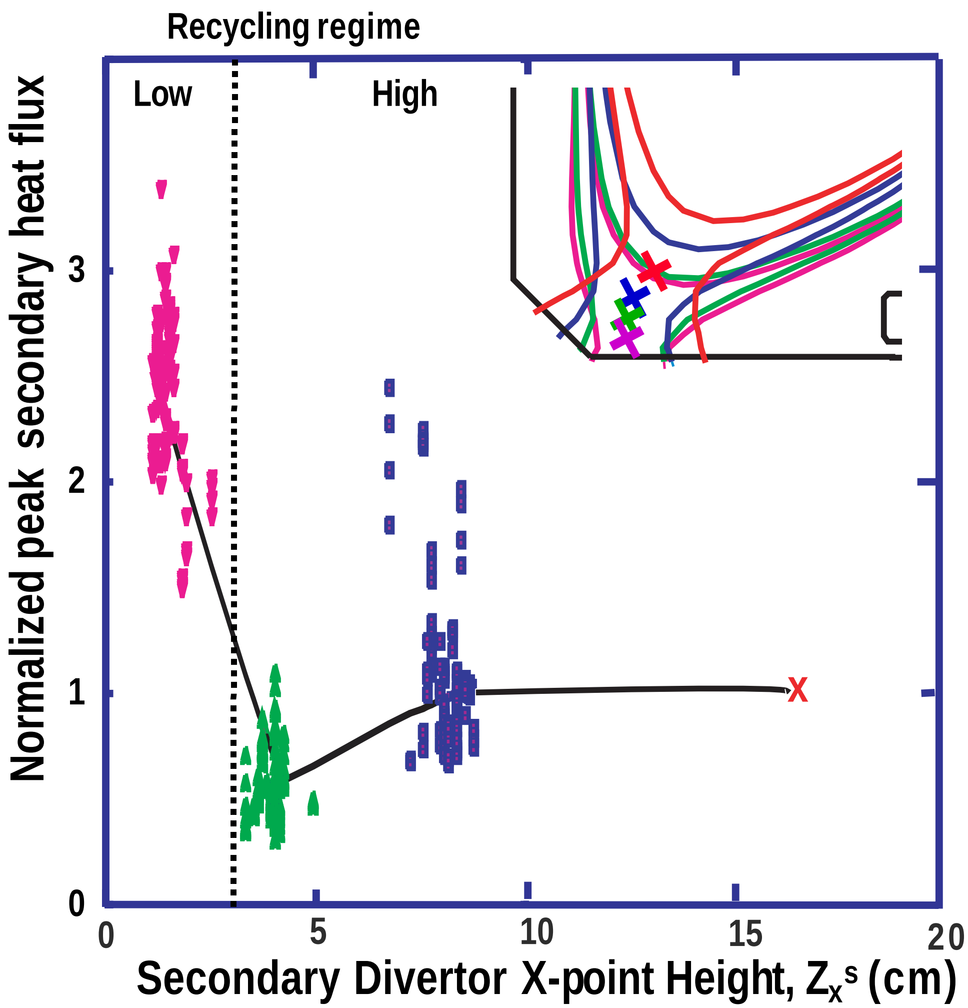
- Moderate density $n_e/n_{Gr} \leq 0.7$:
  - Secondary divertor peak heat flux
    - Reduced initially due to flux expansion
    - Increased when high recycling lost in secondary.
  - Core fuelling rate increases.
- High density, $n_e/n_{Gr} > 0.7$:
  - Density limit at H-L back transition decreases.
- Increase in neutral penetration to LCFS as Z_x^s reduced explains observations.



Minimum in secondary divertor peak heat flux vs. $Z_X{}^s$ shows limit to volume optimization.

$Z_X{}^s$ Study, $n_e/n_{Gr} \leq 0.7$

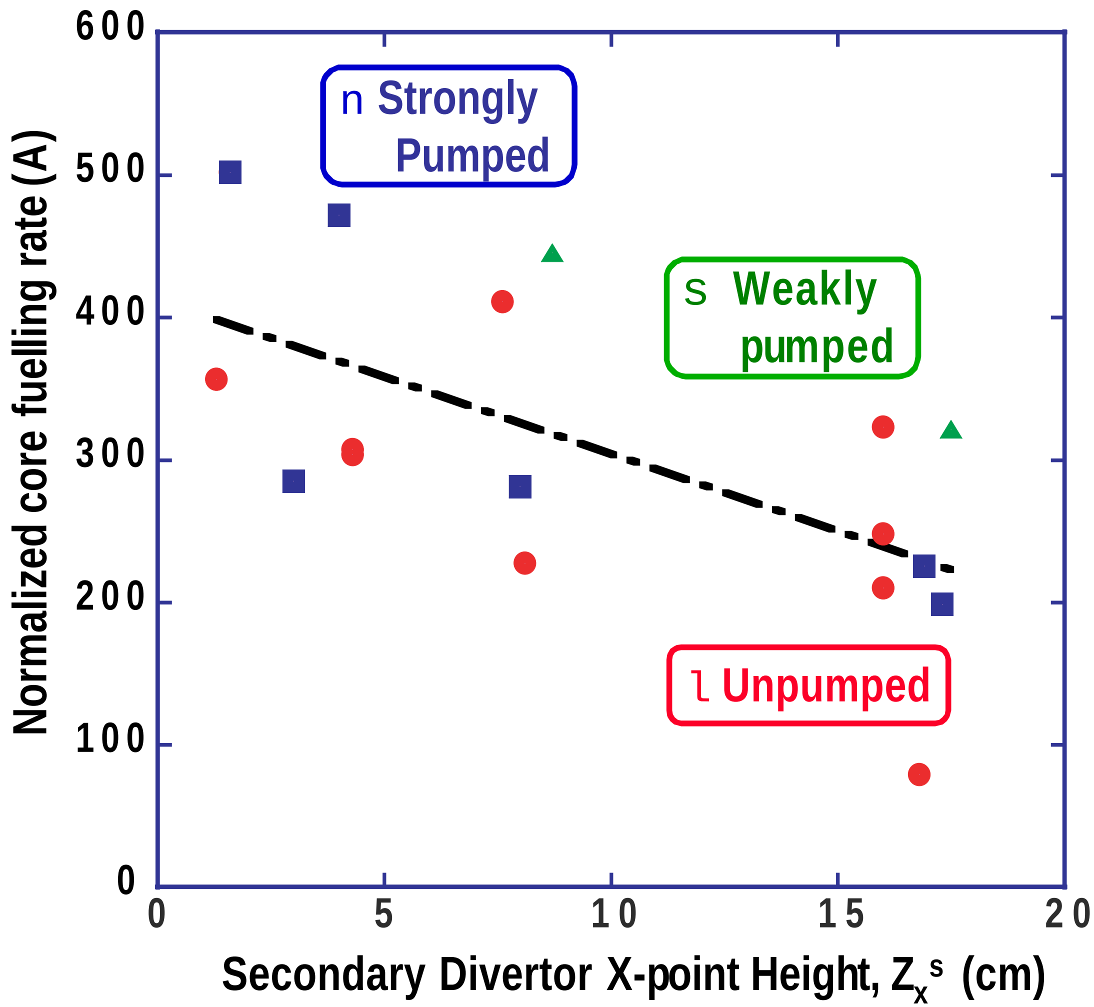
- Peak secondary q_{div} normalized to $Z_X{}^s$ = 16 cm case.
- Reduction of $Z_X{}^s$:
  - q_{div} reduced initially due to flux expansion
    - Engineering advantage
  - q_{div} increased at low $Z_X{}^s$ when high recycling divertor lost
- Neutral penetration physics limits $Z_X{}^s$ reduction.



Fuelling increase at L-H transition and lower n_e^{H-L} as Z_x^s reduced may shrink density operating window.

Z_x^s Study, $n_e/n_{Gr} \leq 0.7$

- Density rise at L - H normalized to n_e^{ped} and midplane gas pressure
- As Z_x^s reduced:
  - Fueling increased 2X
  - Independent of primary pumping
  - Density limit at H-L transition reduced
- Increased neutral penetration to core explains results.



Conclusion: Quantitative understanding from these systematic studies can guide optimization of ELMing H-mode tokamaks.

- Triangularity Variations - δ
  - Increased δ improves confinement of core but ELM size increases.
  - At n_e/n_{GR} > 0.7 dependence on δ is weaker; ELMs can be smaller.
- Up/Down Magnetic Balance - dRsep
  - Peak heat flux sharing very sensitive to dRsep near DN for $n_e/n_{GR} \leq 0.7$
  - Less sensitivity for $n_e/n_{GR} > 0.7$.
  - ELM energy flux profile in the SOL broader than time averaged q_{div}.
  - Density limit reduced if dRsep shifted away from divertor in ion ∇B drift direction.
- Secondary Divertor Volume Minimization - Z_x^s
  - Secondary peak heat flux is predictable.
  - Density operating window reduced as Z_x^s reduced.
  - Neutral penetration physics explains observations.
- High triangularity unbalanced DN shapes have confinement and reduced target heat flux advantages for ELMing H-mode operation. Shape optimization necessarily involves compromises.

Related DIII-D papers at this conference

- High density with good confinement
  - M.A. Mahdavi, paper EXP1/04, Thursday afternoon
- H-mode Pedestal Physics
  - R. J. Groebner, paper EXP5/21, Tuesday morning
- Dependence of Edge Stability on Plasma Shape
  - L. L. Lao et al, paper EXP3/06, Monday morning