Diverted Negative Triangularity plasmas on DIII-D: The benefit of high confinement without the liability of an edge pedestal

The Route to High Performance, DEMO relevant, Negative Triangularity Tokamak Operation on TCV

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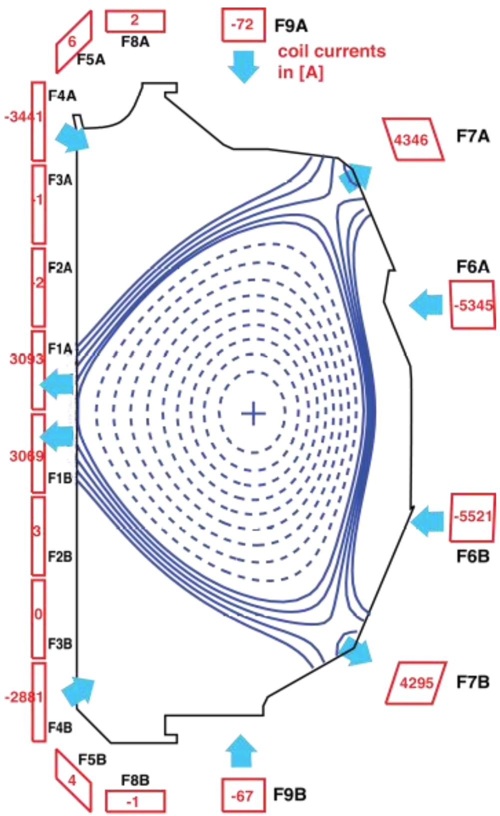
DIII-D NATIONAL FUSION FACILITY | Swiss Plasma Center | MIT PSFC | The University of Texas at Austin | UW | University of California San Diego

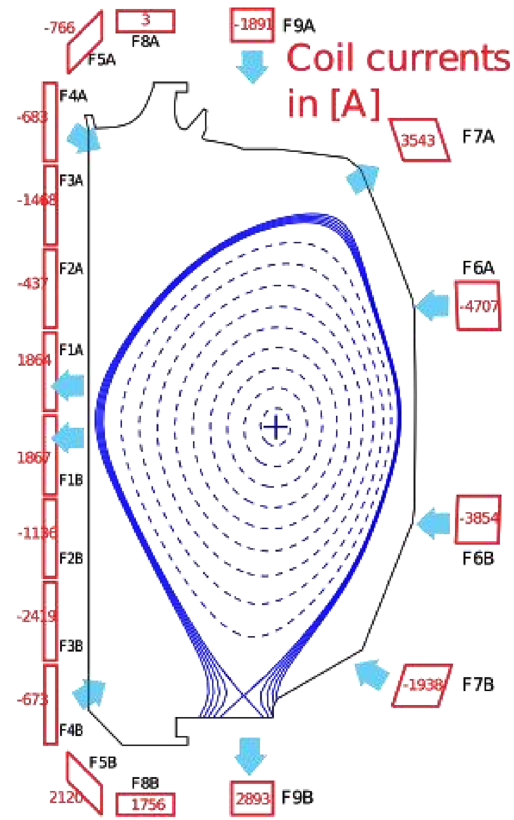
DIII-D OVERVIEW. High confinement L-mode plasmas extended to a diverted configuration

Limited shape



- A novel LSN equilibrium at NegD was created
- L-mode edge plasmas sustain H-mode grade confinement and pressure levels
- L->H power threshold drastically increases as NegD increases
- SOL power fall-off length significantly widens

Diverted shape



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TCV OVERVIEW. Pioneered NegD in the '90s Extensive campaign just concluded

Diverted L-mode operation with strike-points on outer wall

- High normalized confinement ($H_{98} \sim 1$)
- High normalized pressure ($\beta_N \sim 3$)
- Stable operation at $q_{95} < 3$
- L-mode edge maintained at high auxiliary power
- Reduced edge fluctuations compared to PosD L-mode

Other explored topics not covered in this presentation

- Dependence of confinement on upper/lower δ, T_e/T_i
- Density and current limits
- Vertical stability
- Energetic particles
- Exhaust: detachment, λ_q

Outline

- **Motivation for Negative Triangularity (NegD)**
- **New (diverted) experiments**
  - Core confinement
  - Edge pedestal
  - Edge-SOL fluctuations
- **Conclusions and future work**

Positive Triangularity H-mode relies on edge pedestal: High confinement but congenital issues

- ⚠ Edge localized modes
- ⚠ Narrow heat flux width in scrape-off layer
- ⚠ Impurity retention
- ⚠ Power flow across LCFS must exceed LH threshold
- ⚠ Must dissipate power in small region outside separatrix
- ⚠ Must insulate pedestal from detachment front

Pedestals => core-edge tension

Will L-mode edge plasmas at Negative Triangularity yield High Confinement while easing the tension ?

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Negative Triangularity relies on core turbulence reduction: issues are easier to overcome

- ⚠ Edge localized modes
  - ✓ Intrinsically stable
- ⚠ Narrow heat flux width in scrape-off layer
  - ✓ Relaxed edge profiles widen heat flux
- ⚠ Impurity retention
  - ✓ Weaker due to absence of edge barrier
- ⚠ Power flow across LCFS must exceed LH threshold
  - ✓ No lower limit required
- ⚠ Must dissipate power in small region outside separatrix
  - ✓ Compatible with large mantle radiation
- ⚠ Must insulate pedestal from detachment front
  - ✓ No pedestal to insulate

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ENGINEERING BENEFITS: Negative Triangularity simplifies actuators and controllers in reactors

NegD automatically sets strike points on the low field-side:

- ✓ wider SOL wetted area ($R_{strike\text{-}out}/R_{strike\text{-}in} \sim 1+2a/R_0 \sim 170\%$)
- ✓ more room to install and maintain divertor components
- ✓ internal polidal field coils benefit from being on the low field side of the machine

S.Yu. Medvedev et al, NF 2015
M. Kikuchi et al, NF 2019

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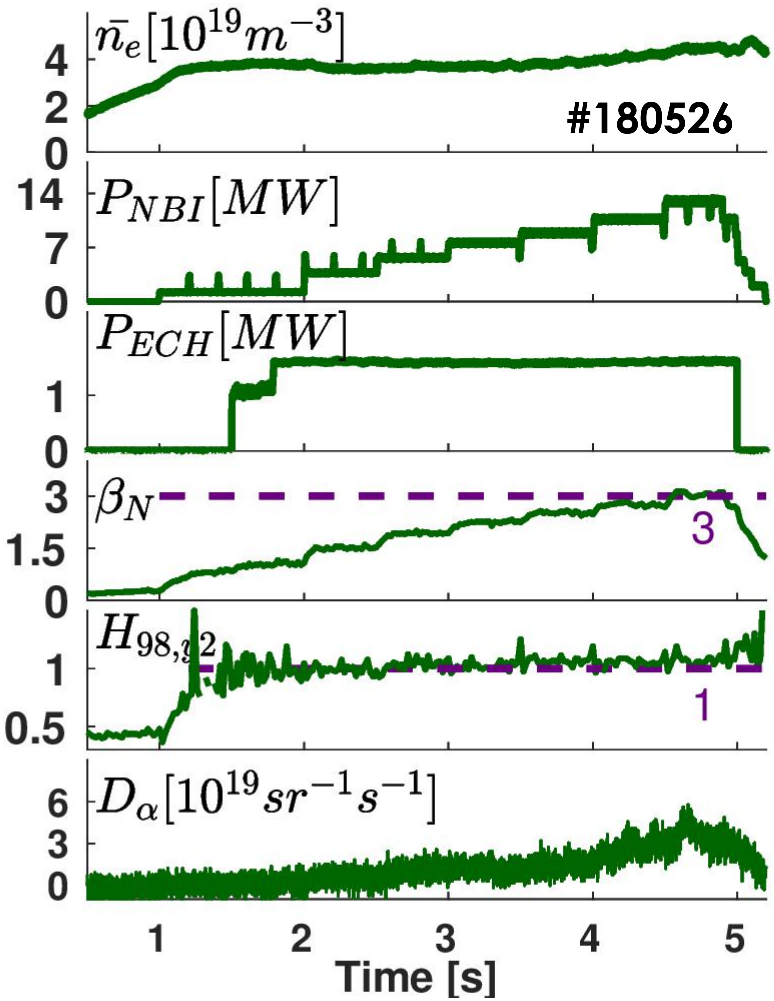
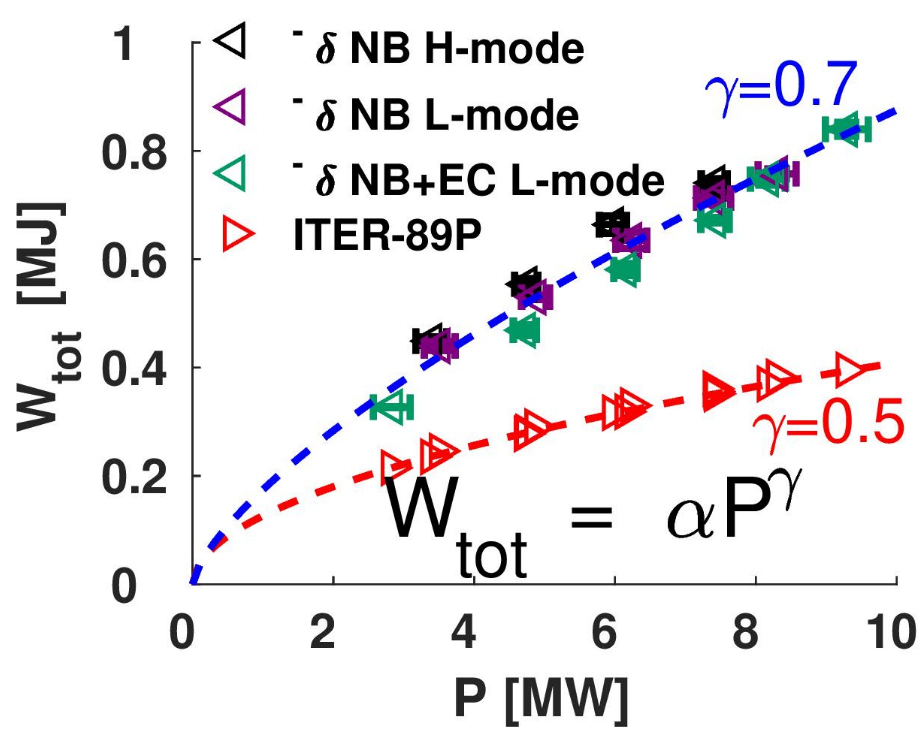
DIII-D CORE. L-mode edge diverted plasmas sustain high confinement with 20% bootstrap fraction



Compared to previous IWL experiments

- Density not increasing with NBI fueling
- Lower Zeff (1.5 vs 3)
- ITG at low k (vs TEM in IWL)
- Weak but finite power degradation



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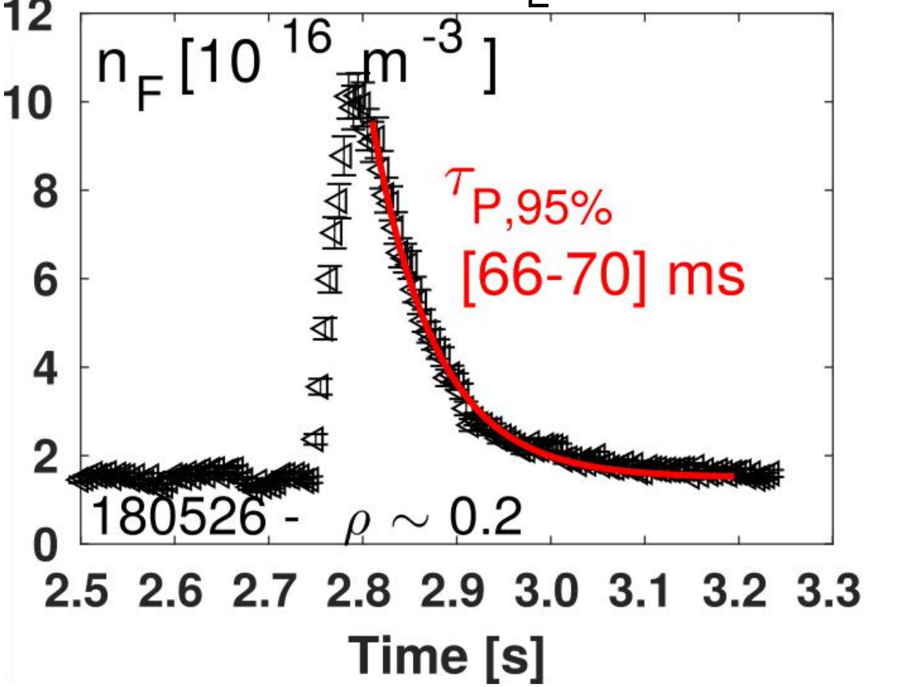
DIII-D CORE. Particle to energy confinement time ratio measured of order unity by laser blow-off

L-mode case τ_E = 85 ms



Standard H-mode scenarios typically feature τ_P/τ_E~[2-4]

Impurity retention is less problematic when edge density profile is relaxed, viz. NegD IWL *[A. Marinoni, PoP 2018]*
I-mode *[D. Whyte, NF 2010]*

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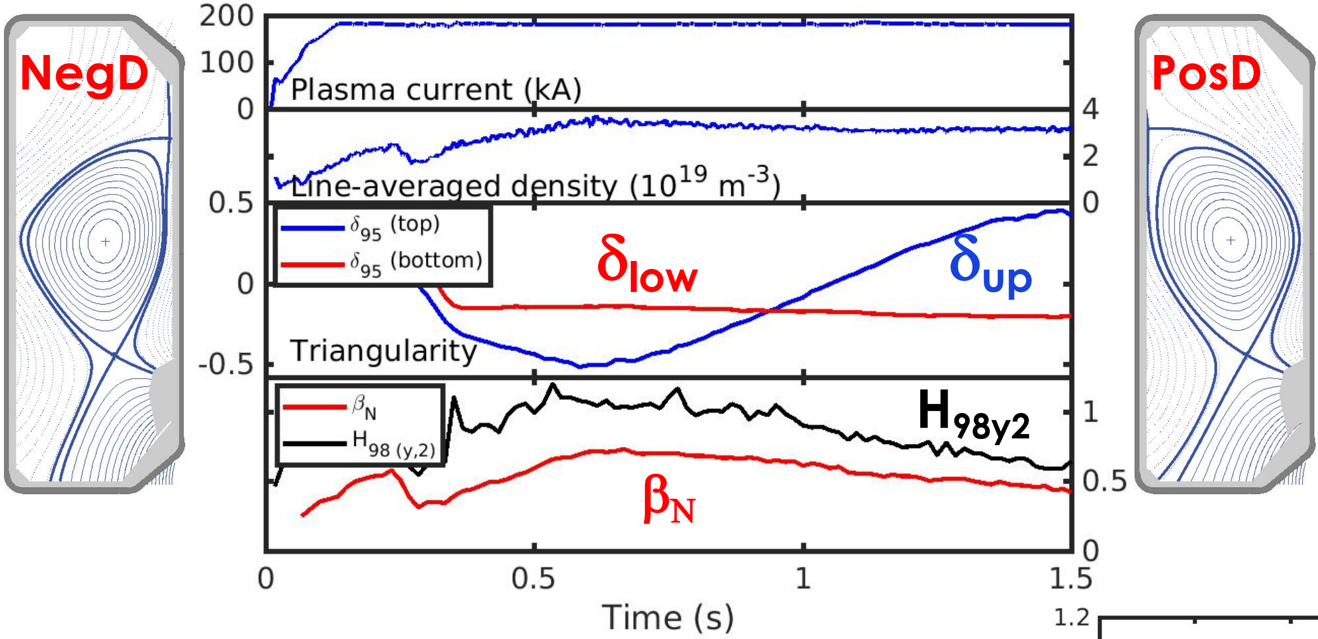
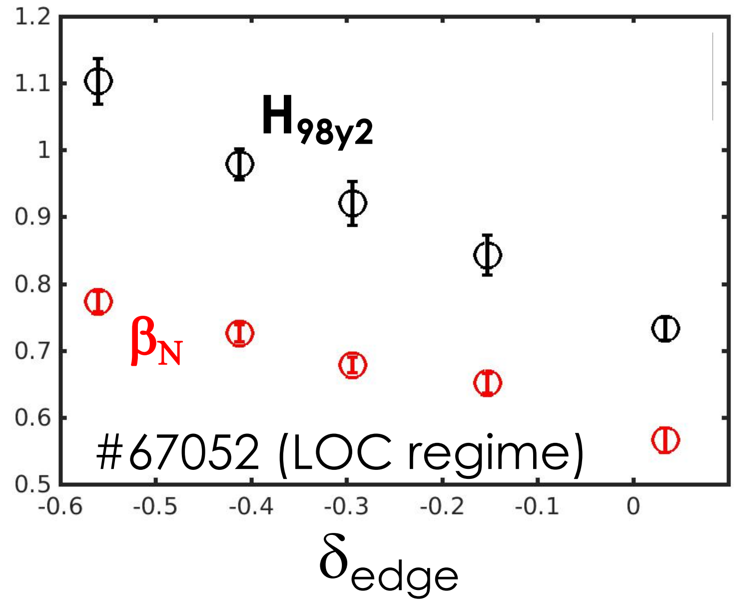
TCV CORE. Confinement monotonically improves with NegD at fixed conditions





Energy confinement enhancement factor does not saturate with decreasing triangularity

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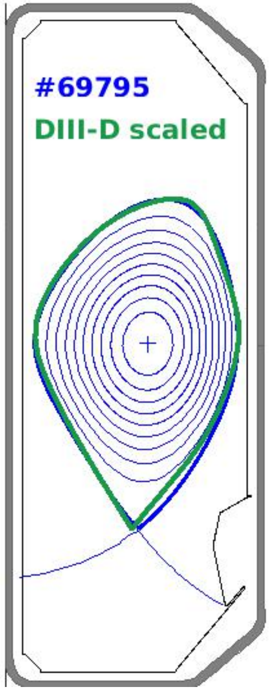
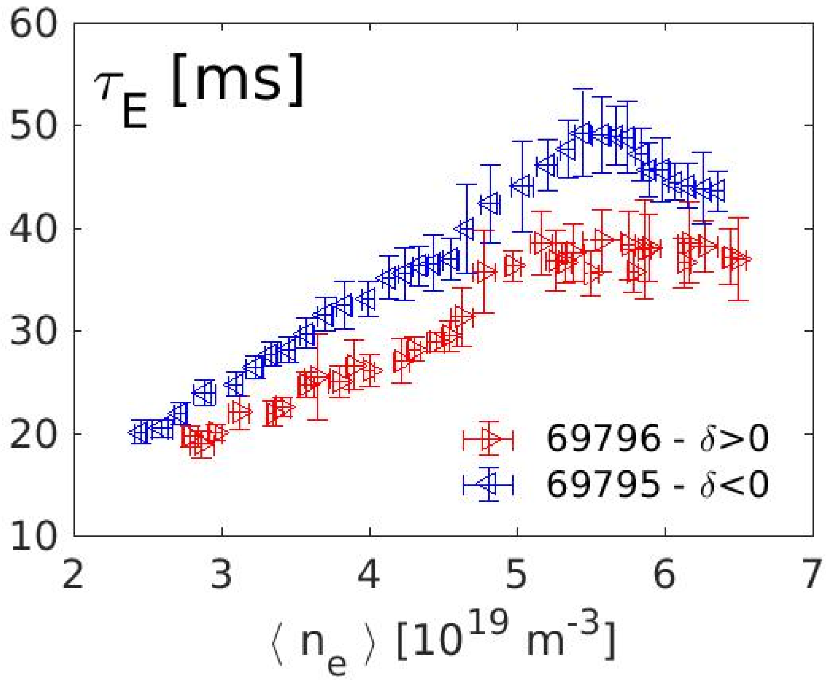
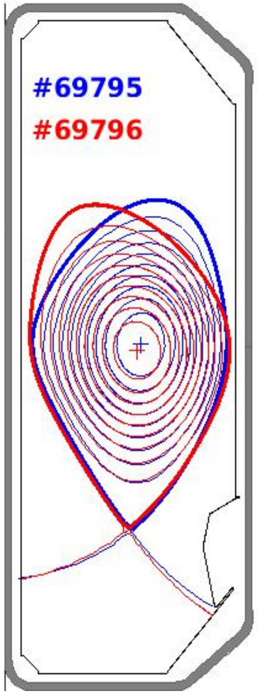
TCV CORE. TCV & DIII-D closely collaborated by executing similarity experiments



LOC-SOC transition does not strongly depend on triangularity





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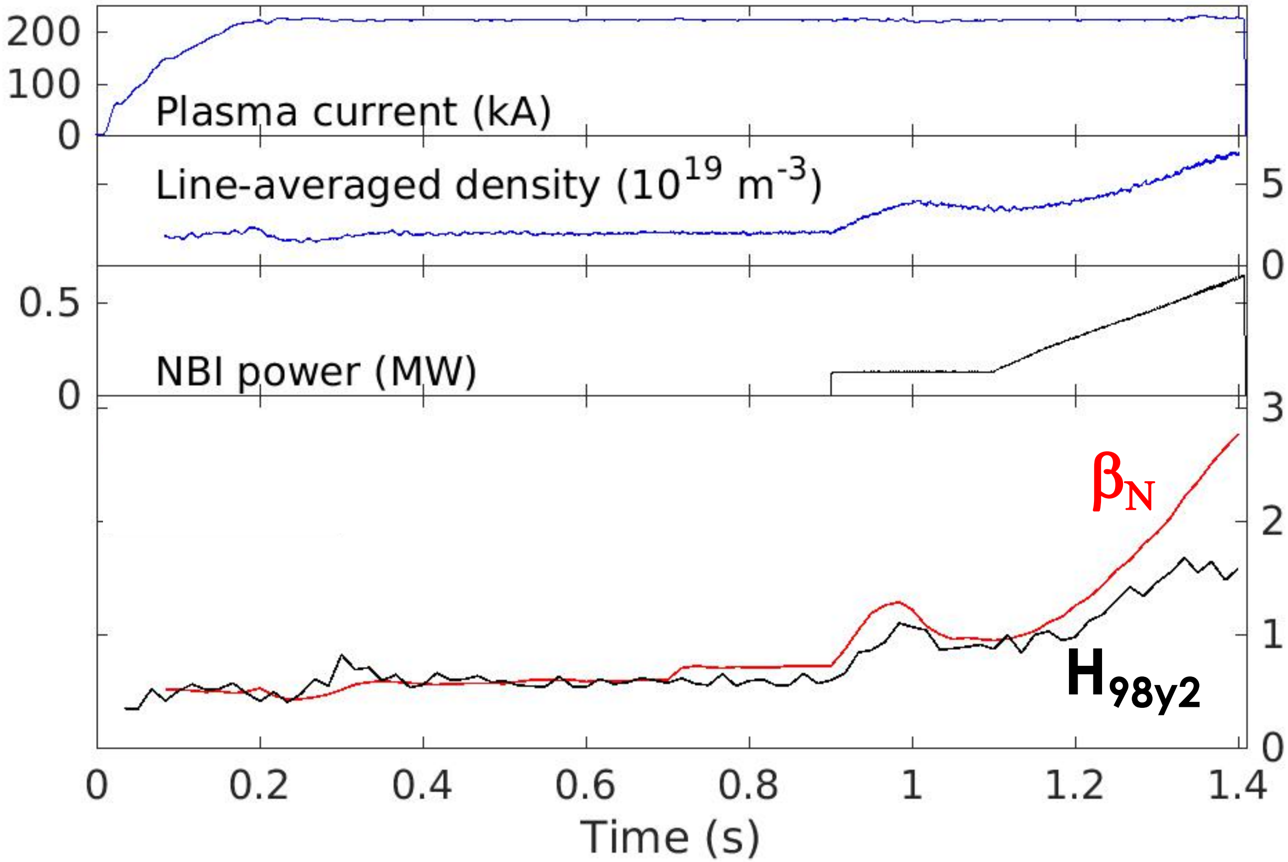
TCV CORE. High confinement and pressure levels routinely sustained in L-mode at $q_{95} < 3$



Confinement enhancement factor increases with increasing auxiliary power

L-mode edge maintained even up to $P_{aux} > 1$ MW in spite of favorable ∇ B drift

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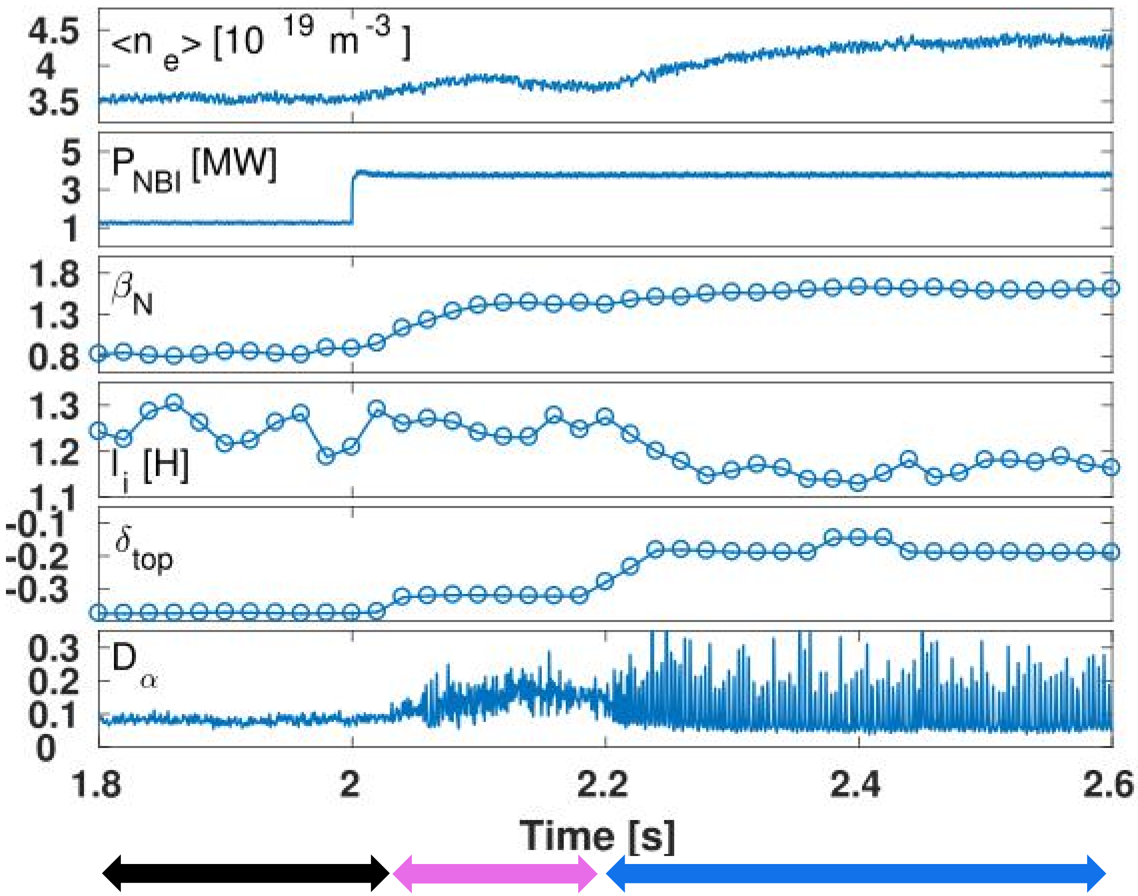
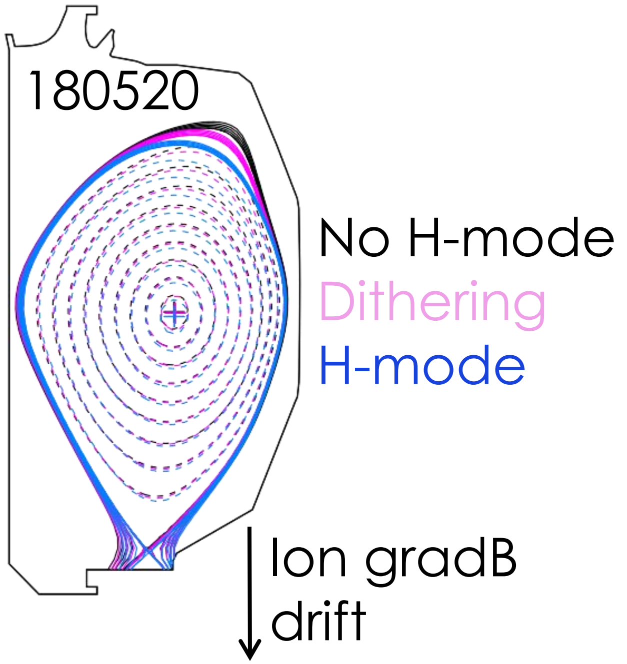
DIII-D EDGE. H-mode power threshold is postulated to increase at Negative Triangularity



IWL plasmas never transitioned to H-mode

Plasmas at δ_{top}= -0.4 maintain L-mode edge despite net heating exceeds **5x** the expected

LH power threshold



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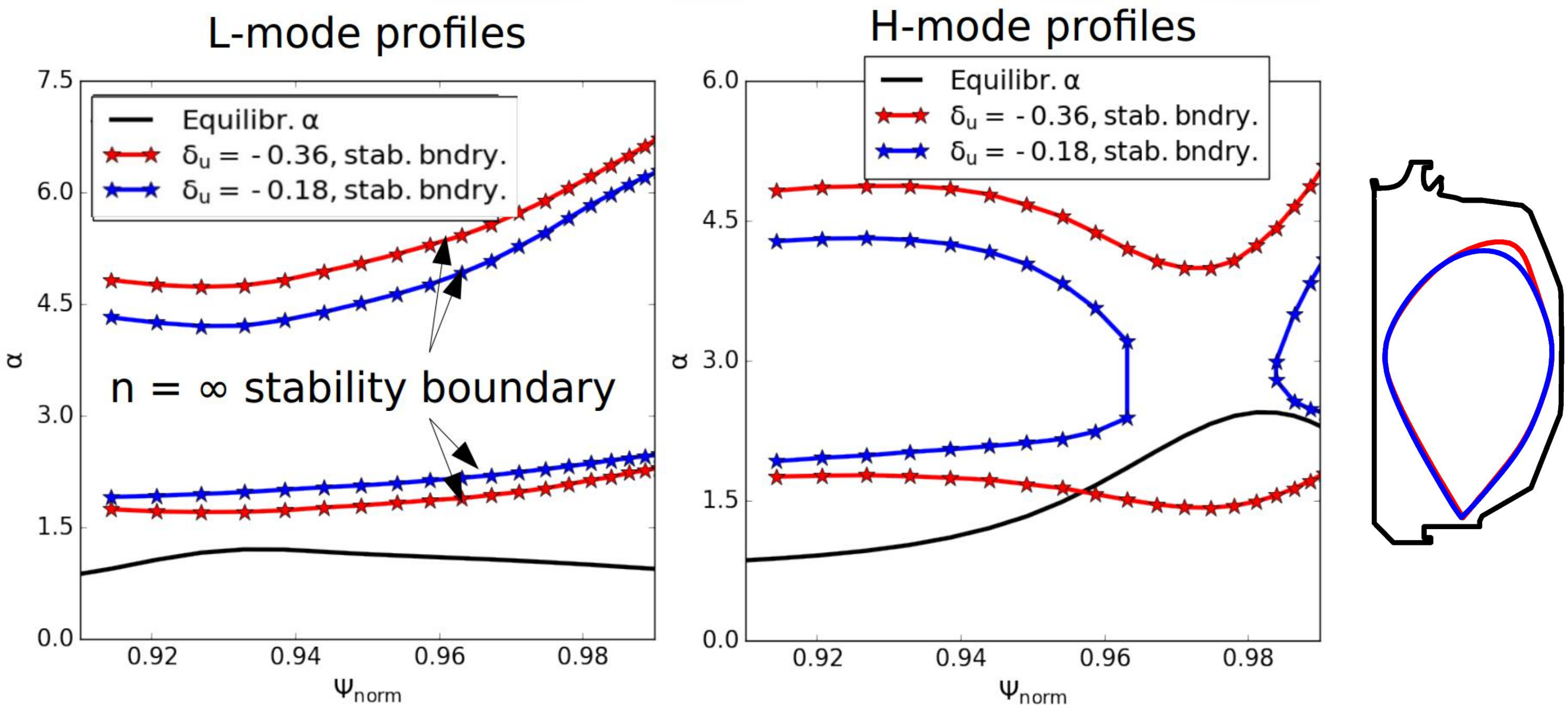
DIII-D EDGE. Small difference in shape has large impact on edge stability and may prevent H-mode



n=∞ ballooning modes limit gradients in strongly NegD

Bootstrap current opens 2nd stability at relaxed NegD

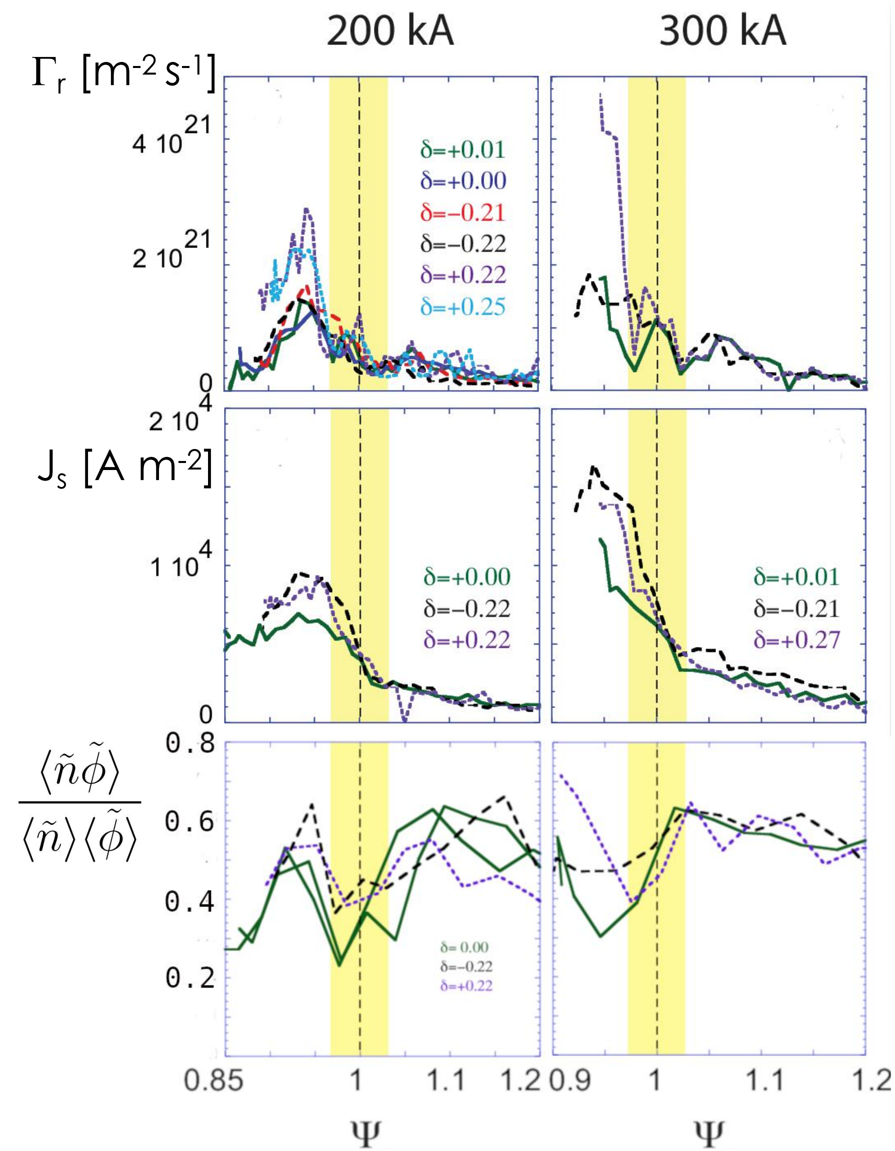
S. Saarelma, PPCF submitted

TCV EDGE. Particle flux inside LCFS reduced at zero and negative triangularity

Flux reduction observed by reciprocating probe is related to

- reduced fluctuation level
- modified phase shift between density and potential fluctuations

J. Boedo et al, in preparation



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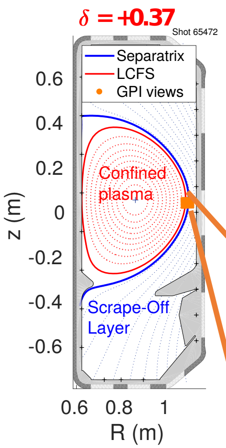
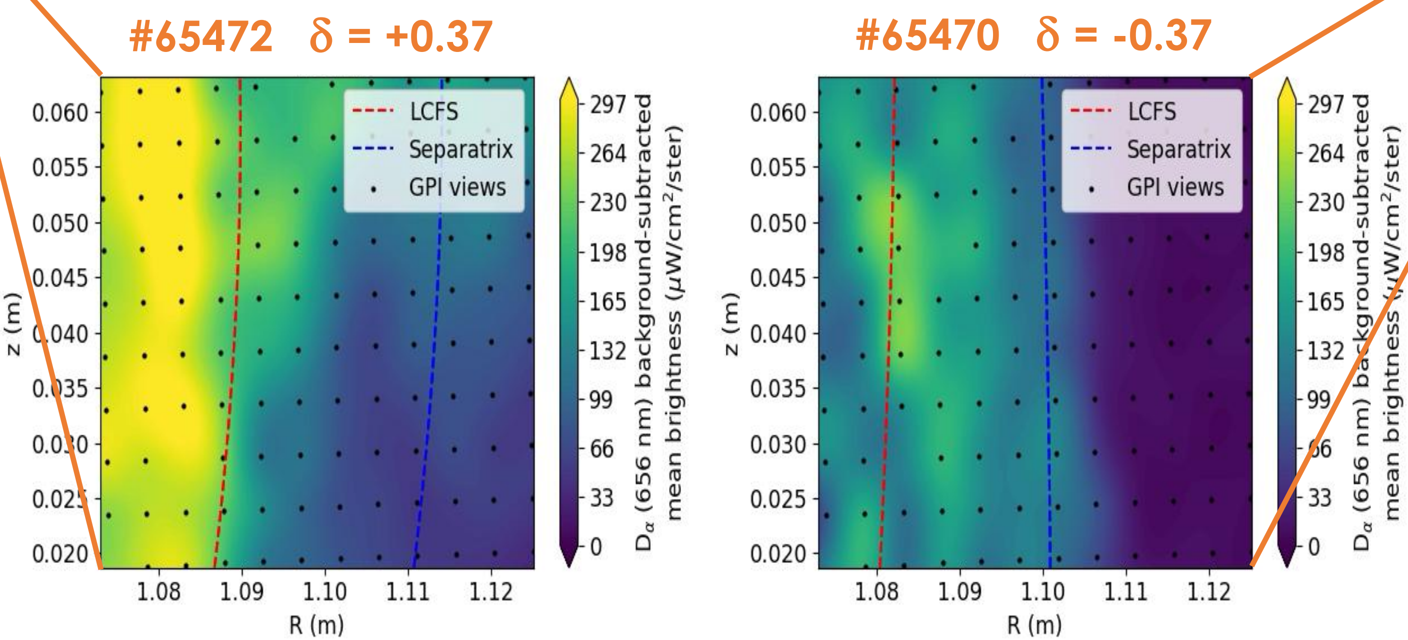
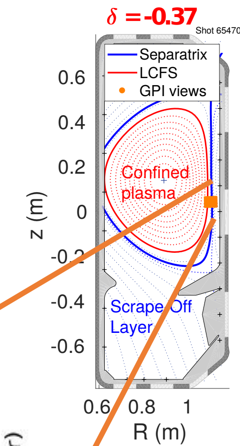
A. Marinoni IAEA-FEC 2020

TCV EDGE/WALL. Fluctuations in Near and Far SOL weakened at strong NegD



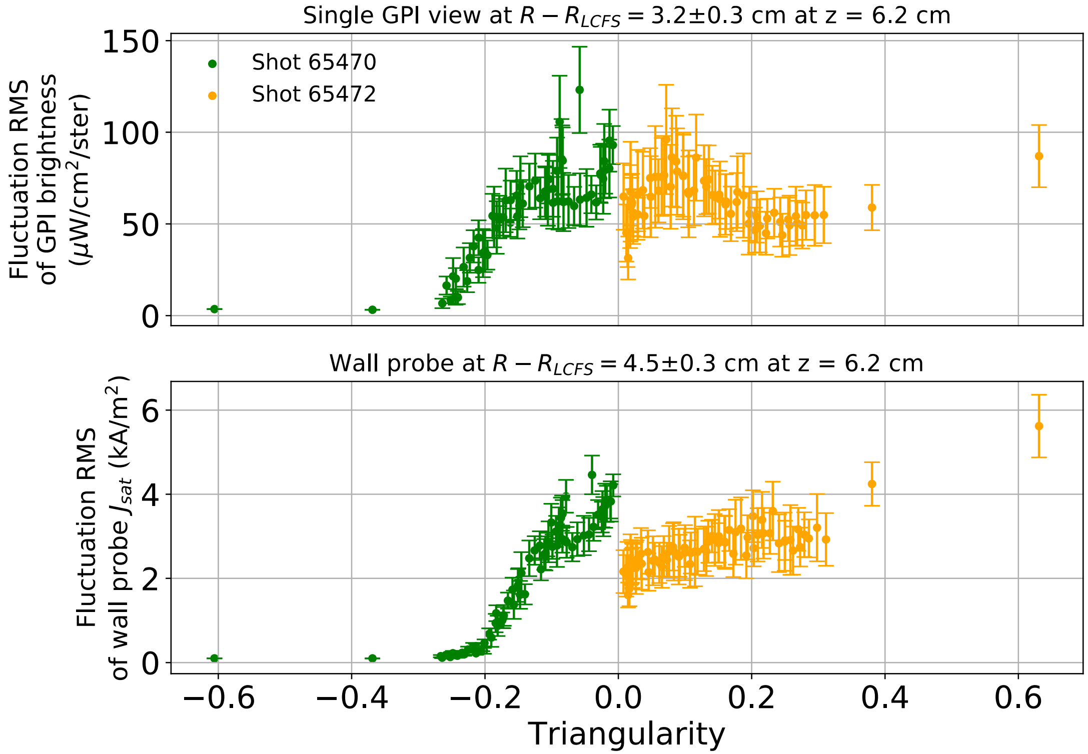
Recently installed Gas Puff Imaging system detects decreased fluctuations in IWL and diverted plasmas





W. Han et al, NF 2021

TCV EDGE/WALL. Plasma-Wall interactions strongly reduced for critical value of NegD



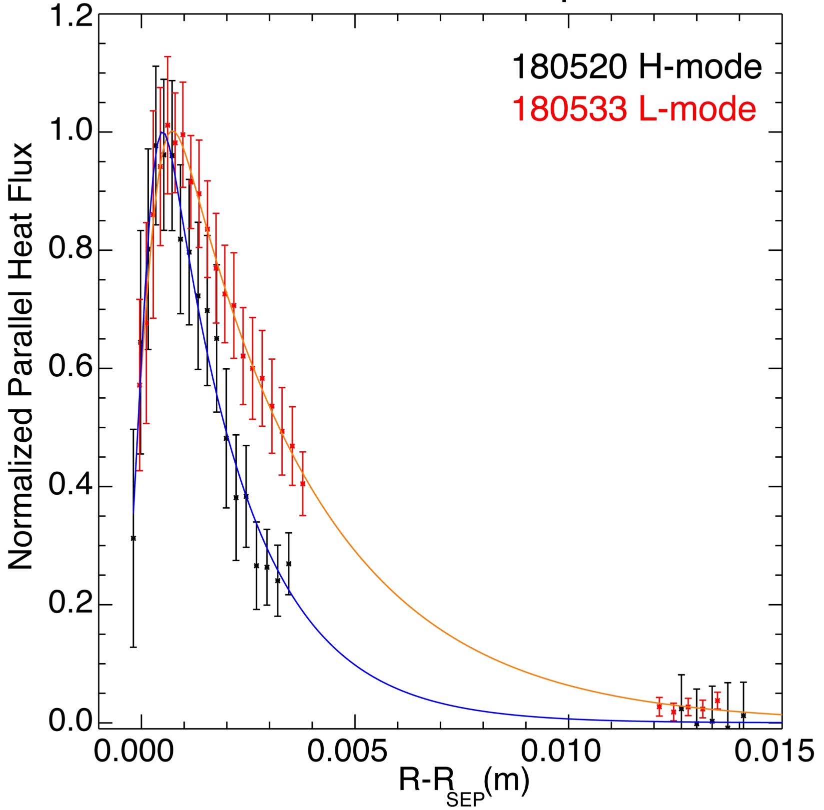
Reduced wall interaction correlates with shorter connection length

W. Han et al, NF 2021

DIII-D WALL. SOL heat flux width widens by 50% in high-confinement L-mode phase vs H-mode

- Scrape-off layer power fall-off length (λ_q) inferred from IR thermography and direct profiles near separatrix
- In the only H-mode discharge inter-ELM λ_q consistent with ITPA scaling and discharges with similar lower-half plasma shaping
- In all L-mode discharges, wider λ_q (~50-60%) with respect to the NegD H-mode case

Heat flux radial profile



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Conclusions and future work

- L-mode plasmas at NegD maintain high-confinement also in diverted configurations (**DIII-D** & **TCV**)
- High confinement routinely obtained at $q_{95} < 3$ (**TCV**)
- Impurity confinement time shorter than in H-mode (**DIII-D**)
- H-mode transition is elusive, likely due to much higher LH-power threshold (**DIII-D** & **TCV**)
- Edge fluctuations reduced compared to PosD L-mode (**TCV**)
- SOL heat flux width is larger than in H-mode (**DIII-D**)

NegD L-mode may be a viable solution for future reactors
further research & cross-validation needed

scalings for: LH power threshold, core confinement, low-torque, λ_q, detachment

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