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

Alessandro Marinoni

with

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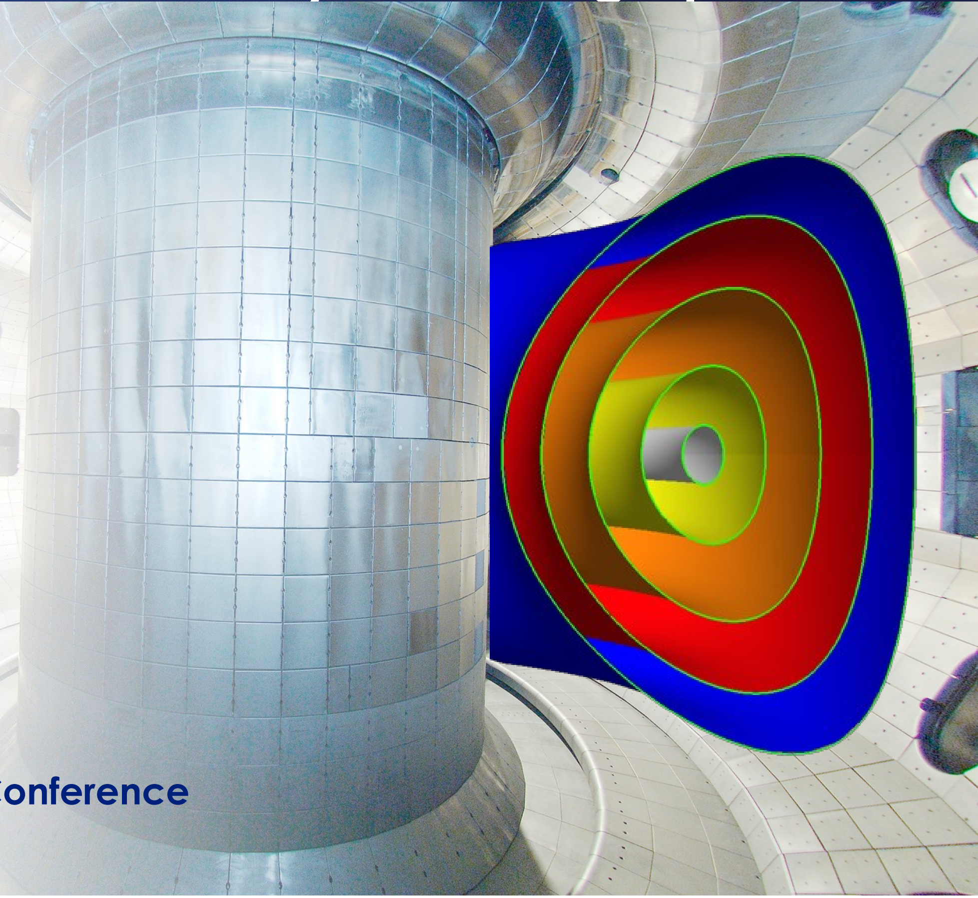

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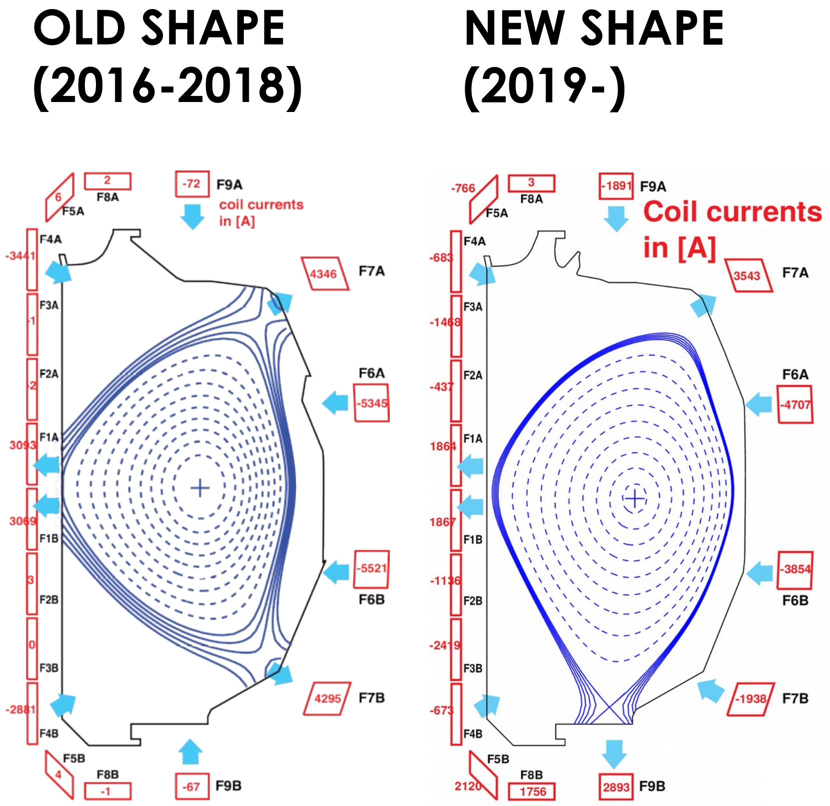
MIT PSFC

High confinement L-mode plasmas at Negative Triangularity extended to diverted configuration

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



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Outline

- Introduction
- Previous inner wall limited experiments
  - TCV
  - DIII-D
- New diverted experiments on DIII-D
- Conclusions

Why do we study Negative Triangularity ?

- Nuclear fusion needs high confinement *[D. Lawson, Technical report 1955]*
  - H_{98} is largest leverage for capital cost of power plant *[M. Wade, 2019]*
  - H-mode offers a solution *[F. Wagner, PRL 1982]*
- Standard H-mode is enabled by pedestal (=> drawbacks)
  - Edge Localized Modes
    - I-mode, QH-mode, RMP, Pellet pacing
  - Impurity retention (helium ash)
  - Narrow heat flux width in Scrape-Off layer
    - Unfavorable scaling with B_{pol} *[R.J. Goldston, NF 2012]*
  - Detachment cliff worsens as λ_q narrows *[H. Du, NF 2020]*
    - ExB poloidal flows driven by steep gradients near separatrix
  - Need to stay above LH power threshold and dissipate all in SOL

Why do we study Negative Triangularity ?

N

Pedestals => core-edge tension

Is H-mode the (only) way to go?

- ExB poloidal flows driven by pressure pedestal

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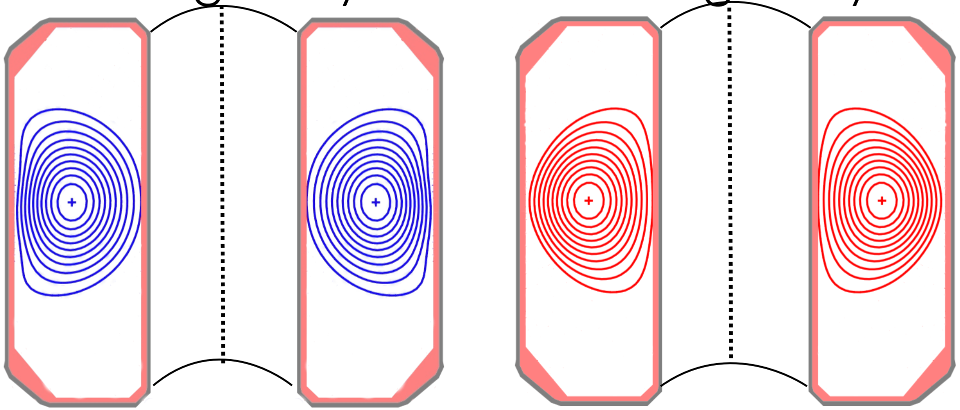
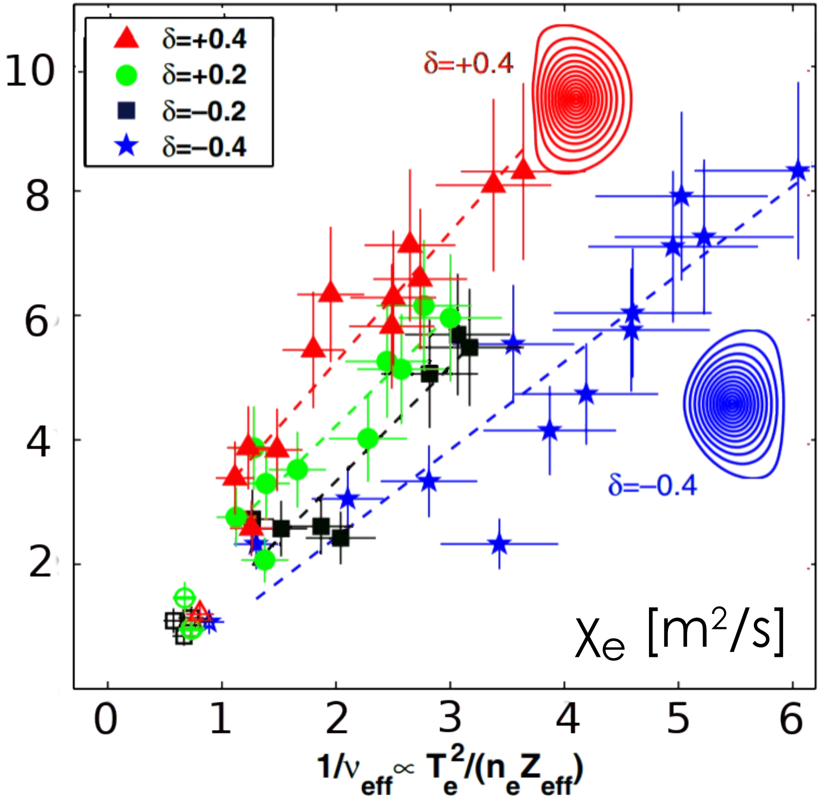
EC heated Negative Triangularity L-mode plasmas obtained H-mode-like energy confinement on TCV



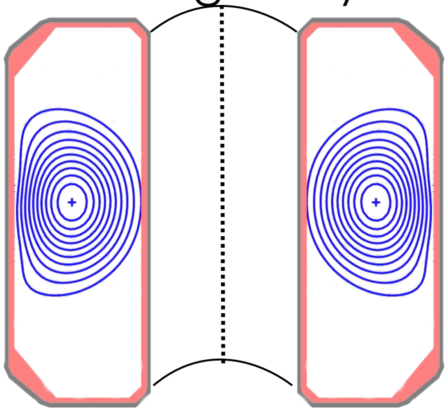
[Y. Camenen, NF 2007]



- Inner wall limited L-mode
- Pure electron heating (ECH) – $T_e >> T_i$
- -δ lowers χ_e only at low collisionality
- TEM dominated

EC heated Negative Triangularity L-mode plasmas obtained H-mode-like energy confinement on TCV

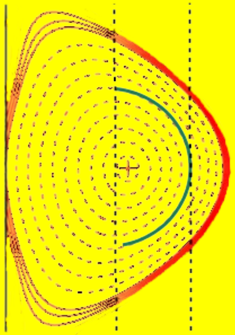
Negative triangularity



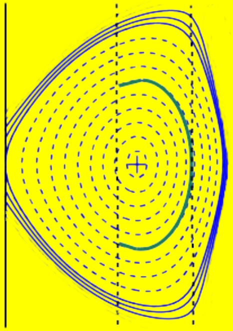
- Inner wall limited L-m
- Pure electron heatin
- -δ lowers χ_e only at lo
- TEM dominated

Heuristic explanation

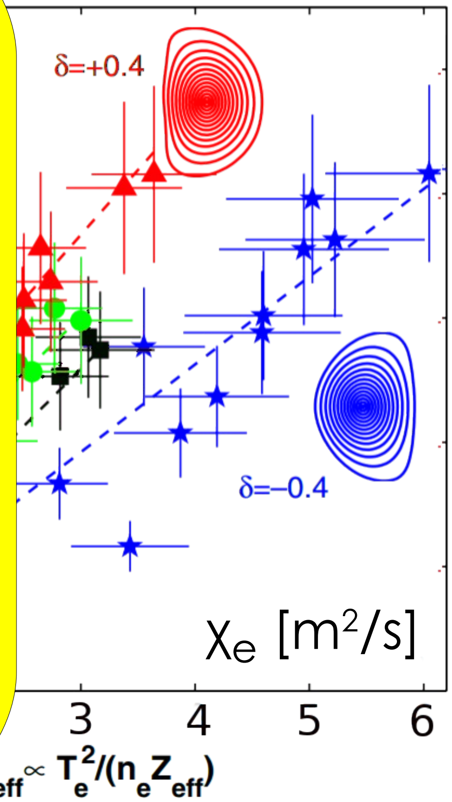
Trapped electron is always in **bad** curvature region



The same trapped electron spends time in **good** curvature region



[Y. Camenen, NF 2007]



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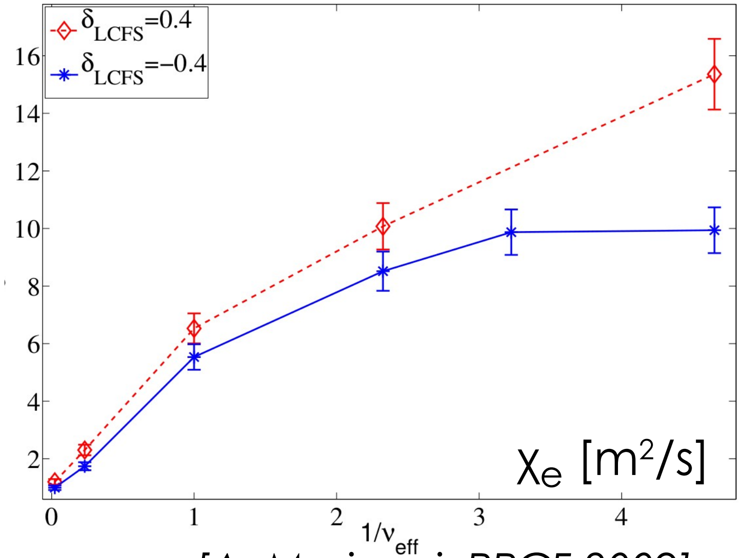
SWISS PLA
CENTER

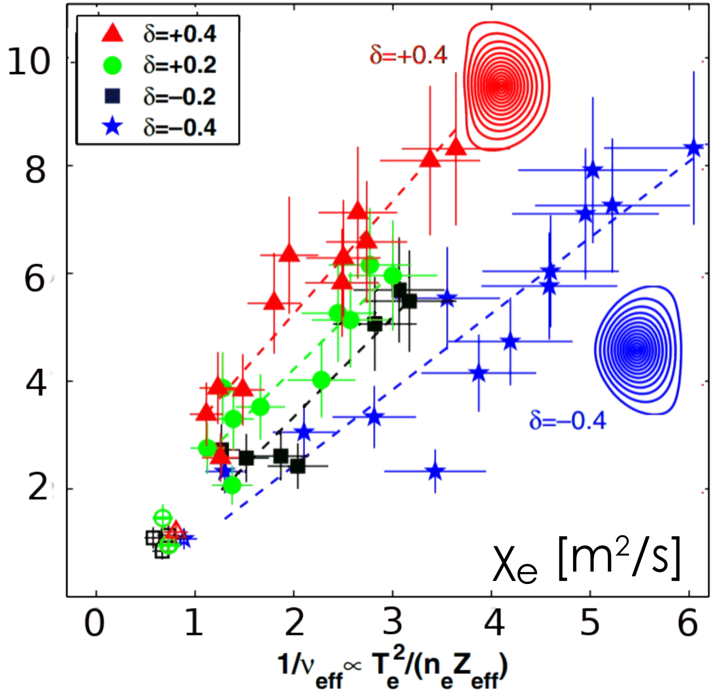
Non-linear GK modeling fairly reproduce collisionality and δ dependence of heat diffusivity

Non linear Gyro-kinetic (GS2)



[A. Marinoni, PPCF 2009]

Experiment



[Y. Camenen, NF 2007]

Radial dependence not reproduced

Global effects?

[G. Merlo EPFL Ph.D Thesis 2016]

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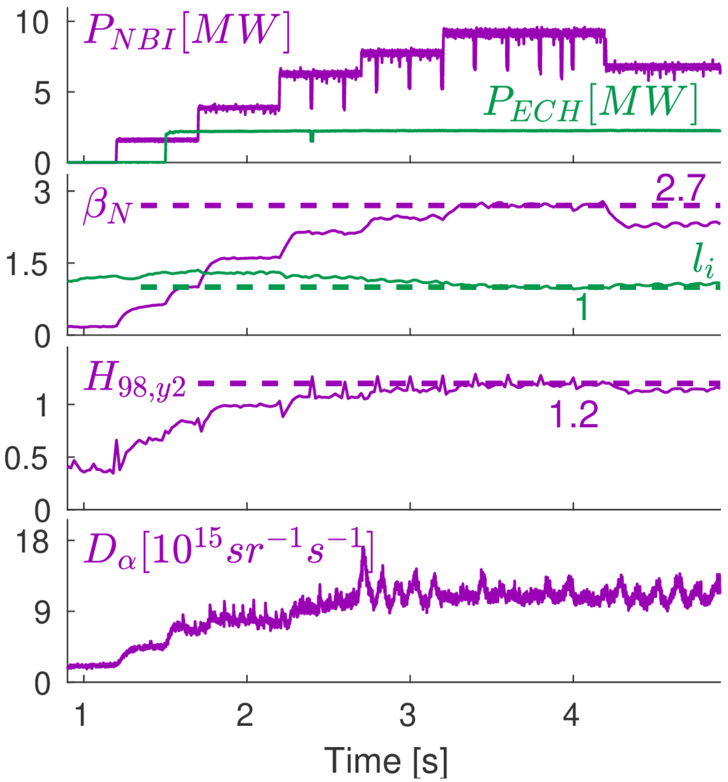
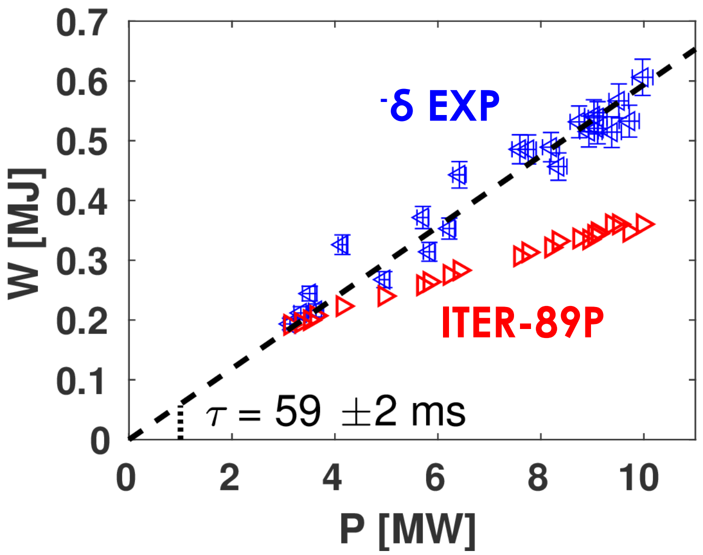
DIII-D demonstrated high confinement L-mode plasmas at reactor grade pressure level



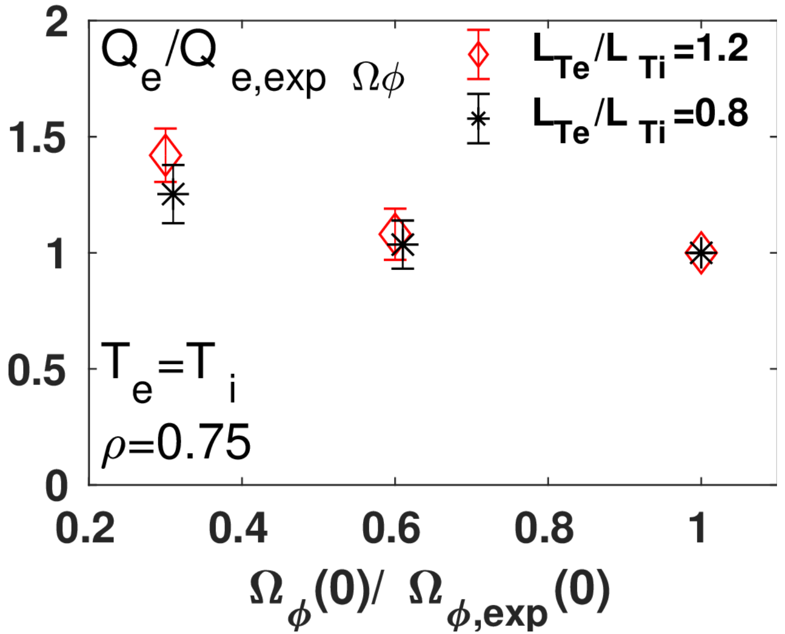
[M.E. Austin, PRL 2019]
[A. Marinoni, PoP 2019]



- ELM free
- Near zero power degradation
- T_i~T_e
- No major MHD event
- Low impurity confinement time
- Expected ideal limit at β_N~3-3.2

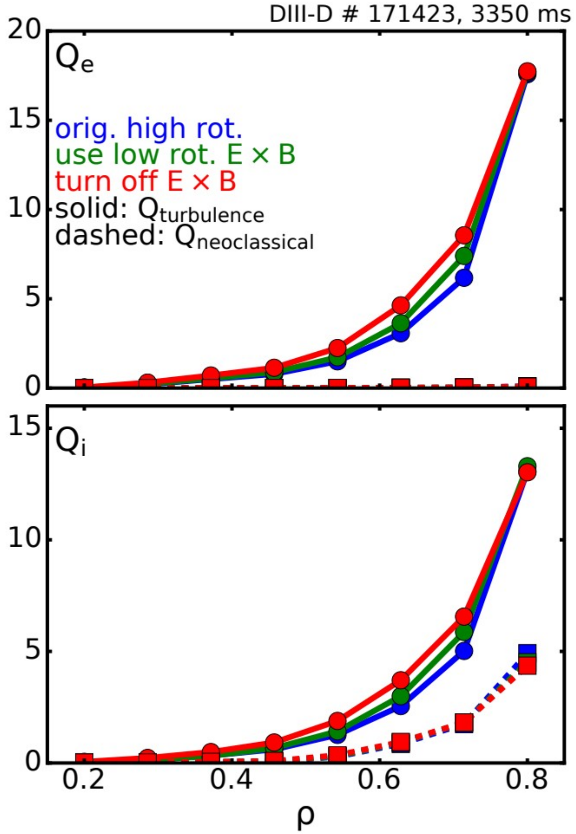
Low torque is not expected to significantly deteriorate confinement (preliminary modeling)

NON LINEAR CGYRO



For fixed profiles, heat flux increases by 30%-40% at low rotation (similar behavior for Q_i and Γ)

TGLF (fixed density)



30% increase in heat fluxes at zero ExB

Exp H_{98}=1.2

No ExB H_{98} = 1.05

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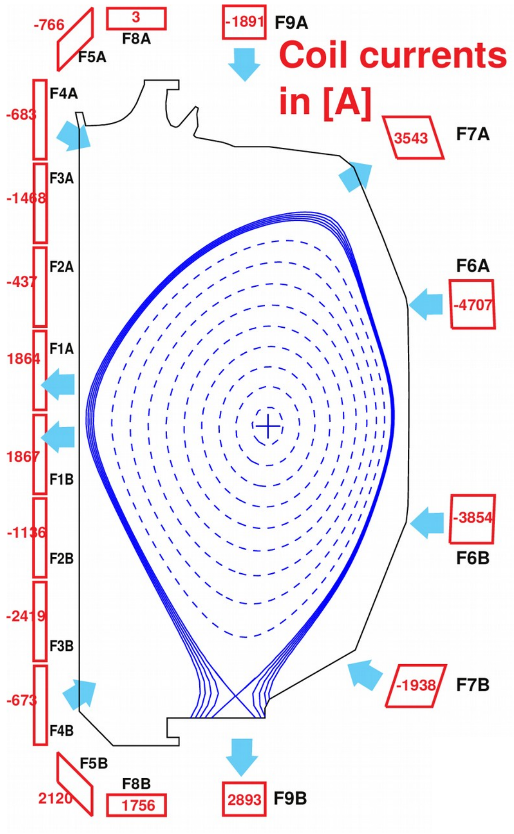
Diverted experiments were executed to extrapolate this scenario to reactors

Existing Inner wall limited experiments on DIII-D **do not** inform on:

- **CORE:** Does confinement degrade at low Z_{eff} ?
  - Transition between ITG/TEM dominated regimes
- **CORE/EDGE:** Power scans at constant density
  - Field lines far away from cryo-pumps
- **EDGE:** What is the H-mode power threshold ?
  - LH power threshold above max auxiliary power allowed
- **SOL:** How wide is λ_q ?
- **SOL:** Do plasmas detach ?
  - Is it easy to control detachment ?

Will core-edge tension be eased in NT plasmas?



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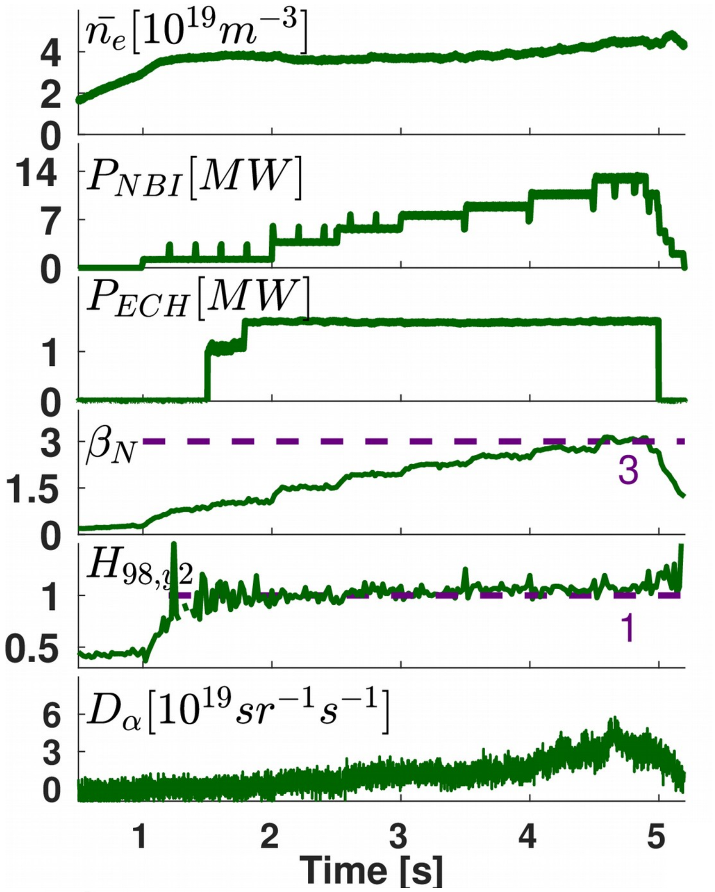
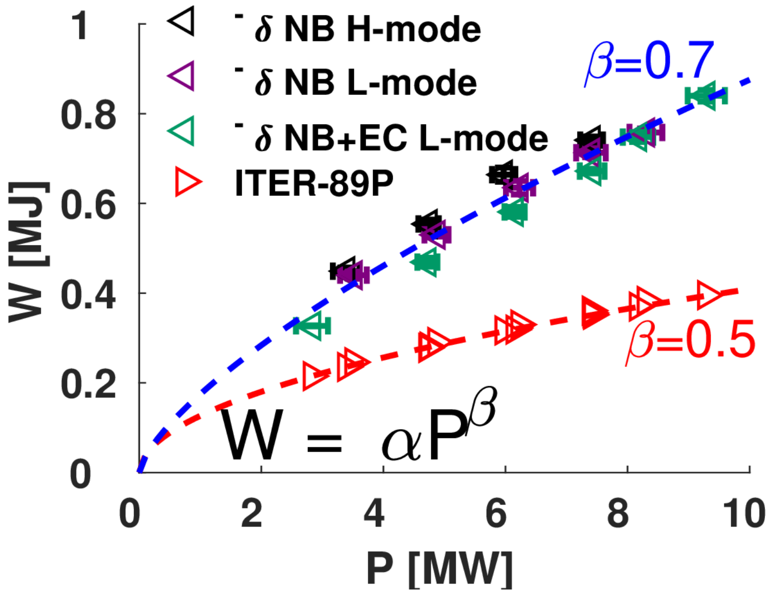
Core. L-mode edge diverted plasmas sustain high-confinement with 20% bootstrap fraction



<u>Differences wrt previous IWL experiments</u>

- Density does not increase with NBI fueling
- Lower Z_{eff} (1.5 vs 3)
- ITG at low k (vs TEM in IWL)
- Weak but finite power degradation



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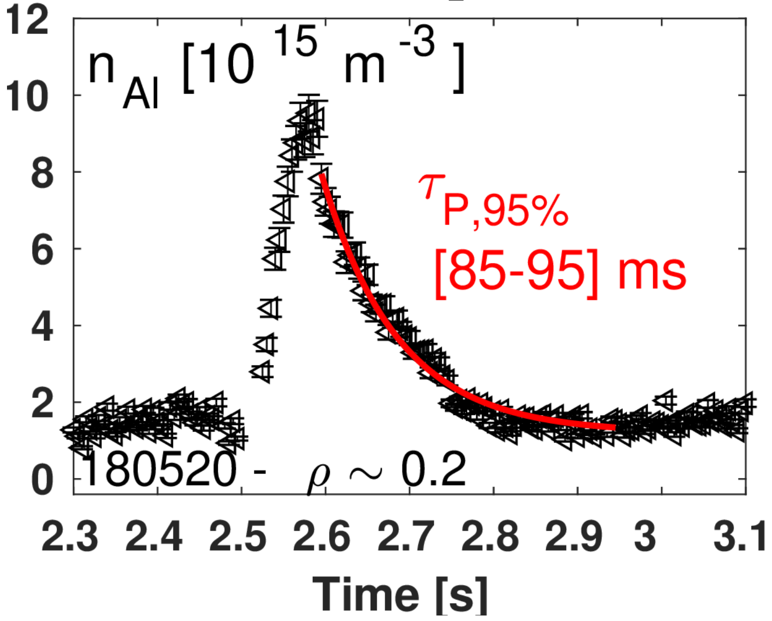
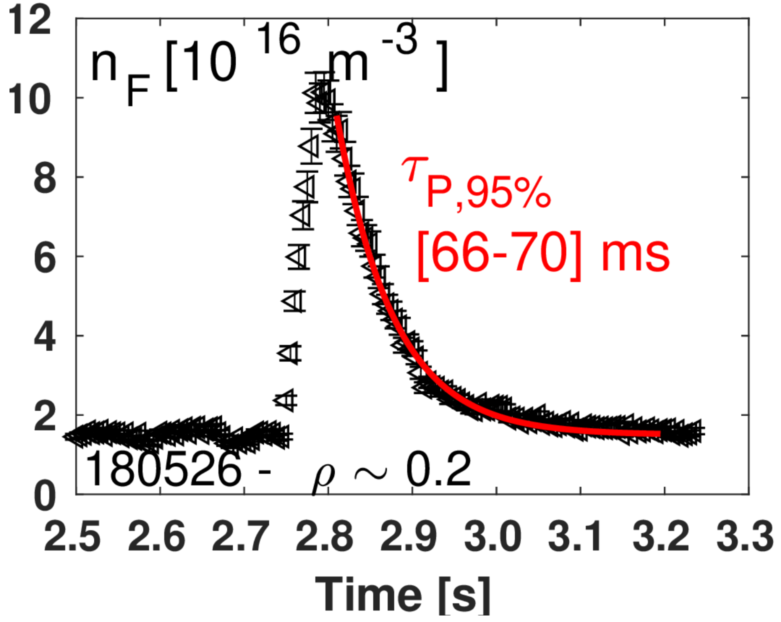
Core. Particle to energy confinement time ratio measured to be of order unity by Laser Blow-Off

H-mode case $\tau_E \sim 100$ ms



L-mode case $\tau_E \sim 85$ ms



Standard H-mode plasmas typically measure $\tau_P/\tau_E \sim [2\text{-}4]$

Impurity retention is less problematic but
it might be harder to fuel reactors

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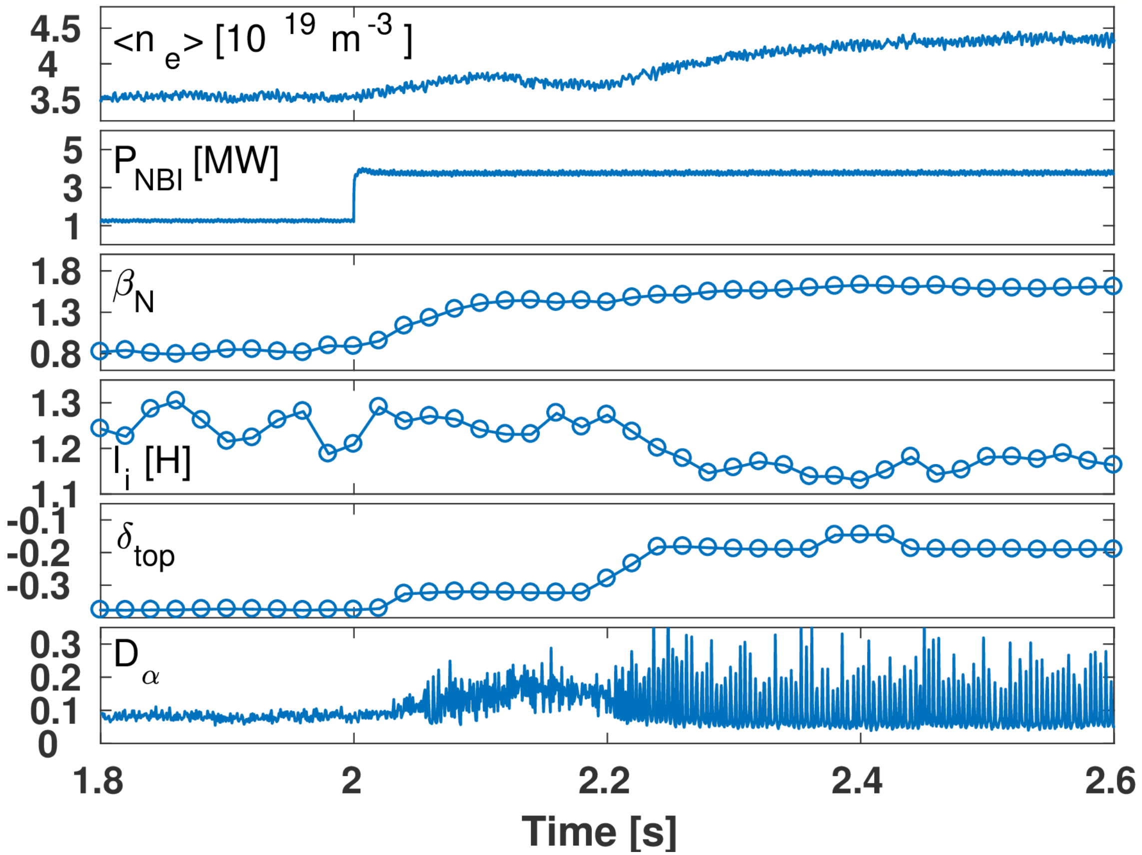
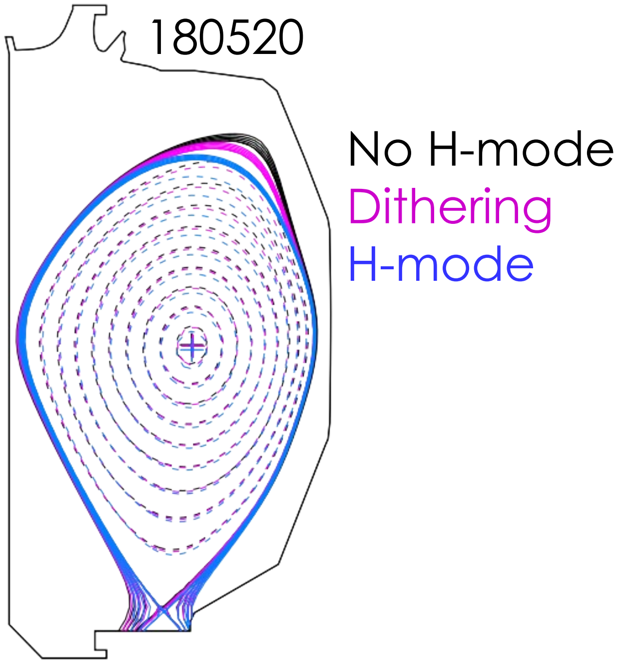
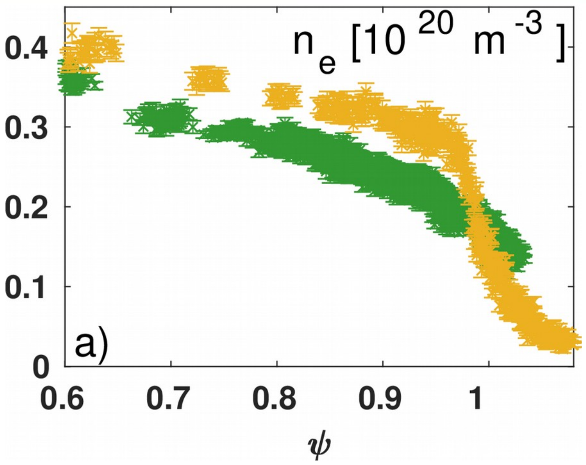
Edge. H-mode transition obtained only at relaxed triangularity

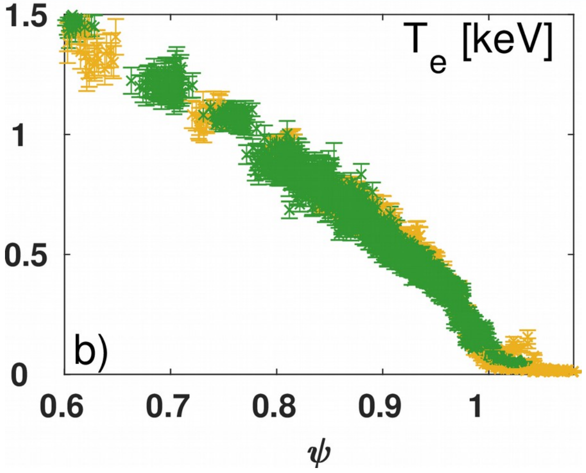




Plasmas at δ_{top}= -0.4 maintain L-mode edge despite net heating exceeds 5x the expected LH power threshold

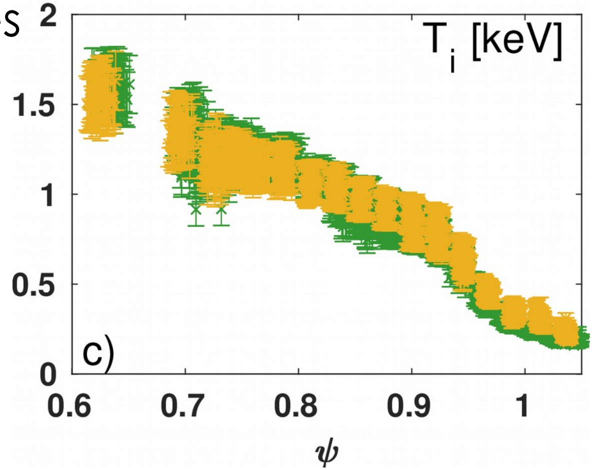
Edge. H-mode case develops shallow density pedestal

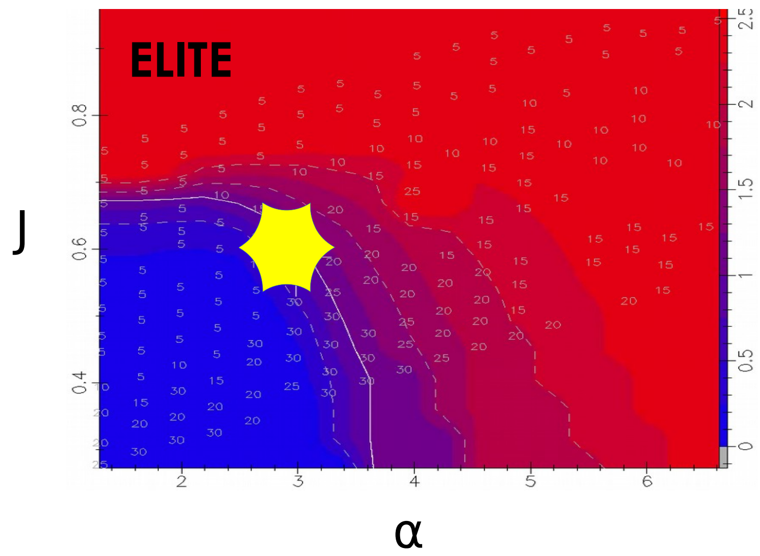




L-mode and H-mode cases differ only in density

similar, shallow, edge temperature gradients





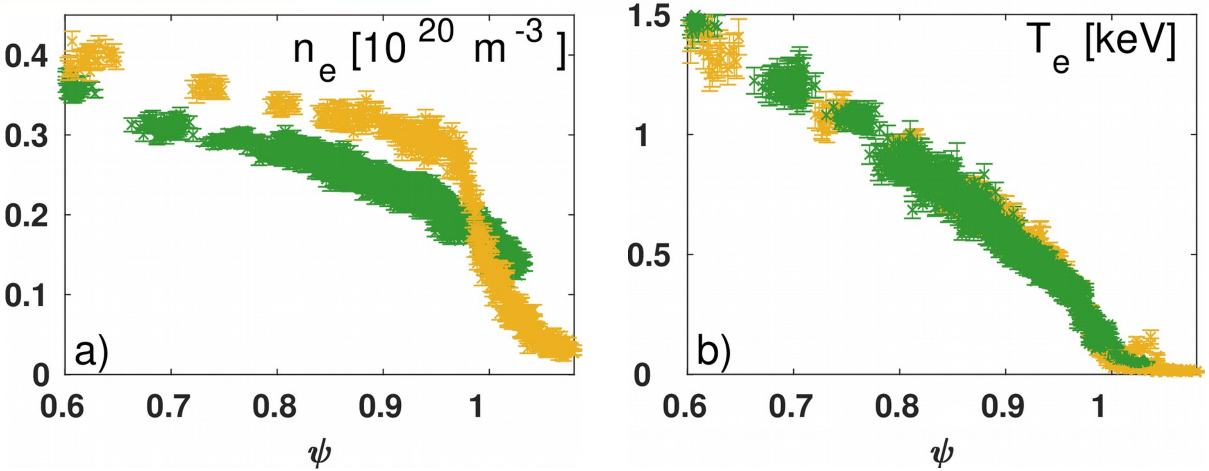
Narrow stability region at negative triangularity

[conjectured in '80s]

[S. Medvedev, NF 2015]

[A. Merle, PPCF 2017]

Edge. H-mode case develops shallow density pedestal with type-I ELMs



L-mode and H-mode cases differ only in density

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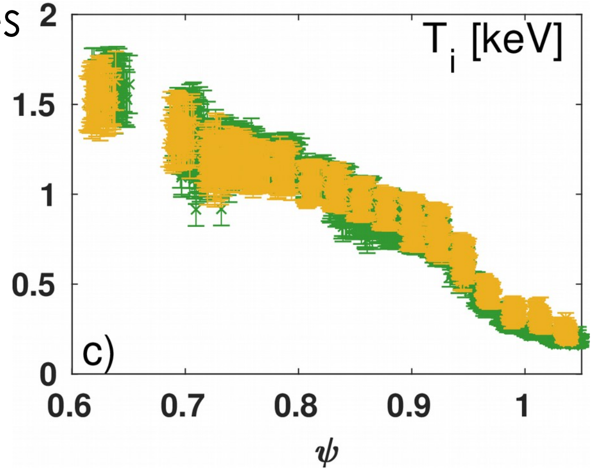

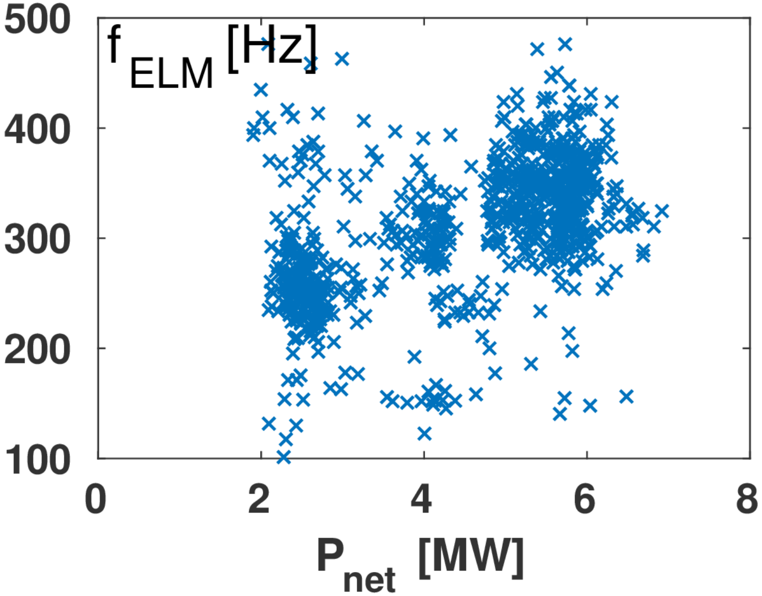

$W_{ELM}/W_{DIA} \sim 0.01\text{-}0.04$

Consistent with previous results from TCV

[A. Pochelon PFR 2012]

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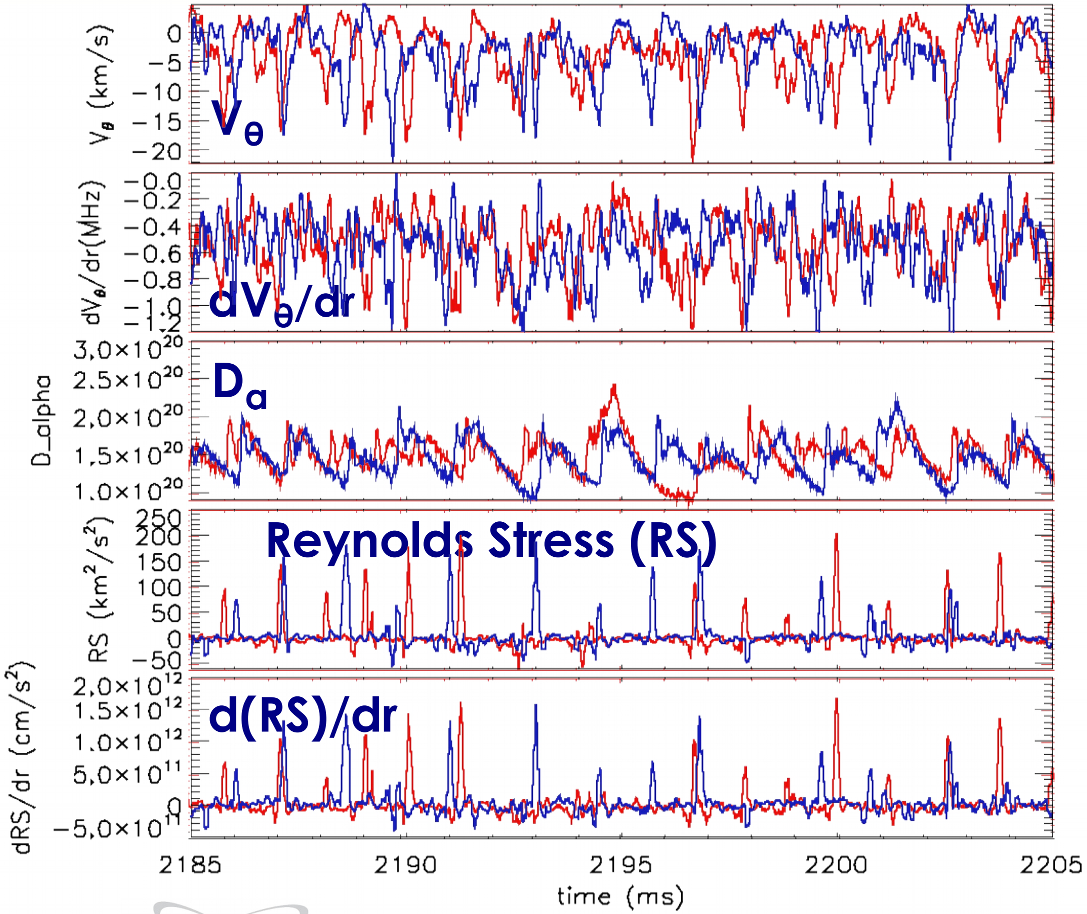
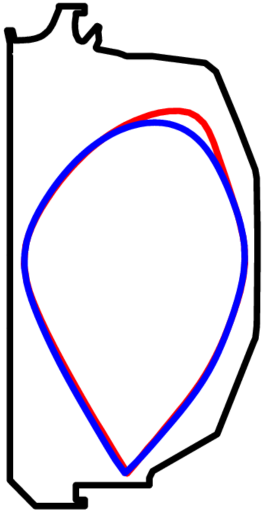
Edge. LH power threshold dependence on δ does not appear to be due to Reynolds stress



180519 (δ_{top}=-0.4)
L-mode throughout

180520 (δ_{top}=-0.2)
H-mode at 2205 ms



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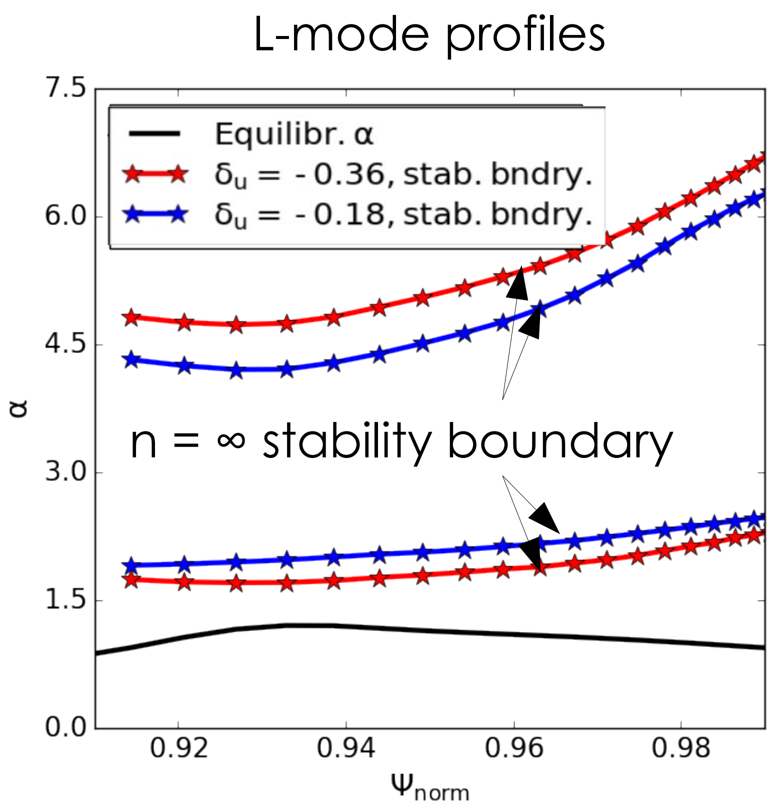
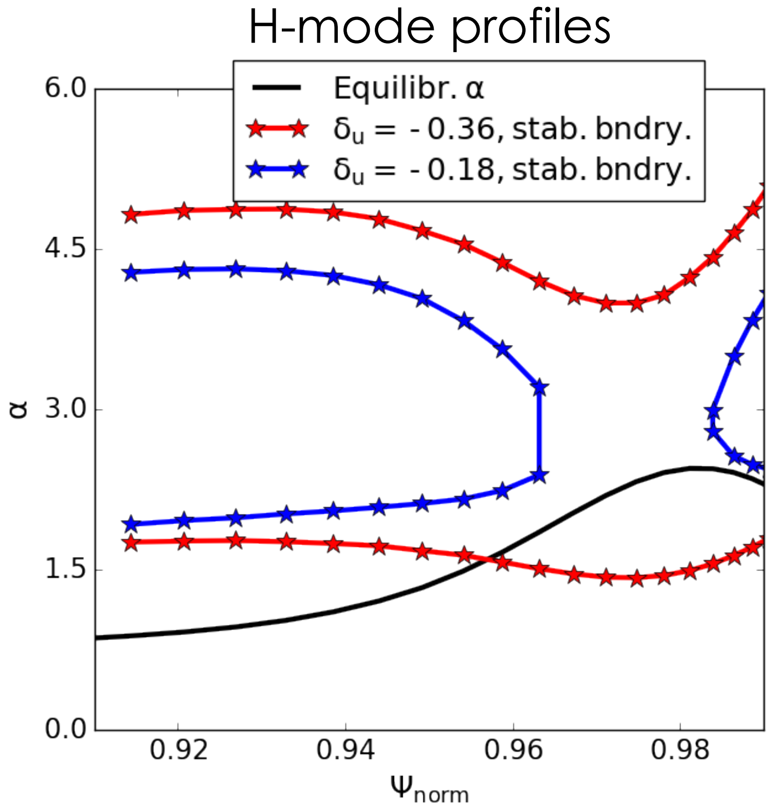
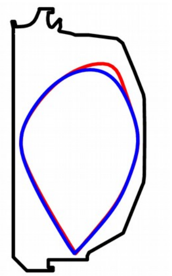
Edge. Reduced ballooning stability limit may prevent H-mode pedestal growth







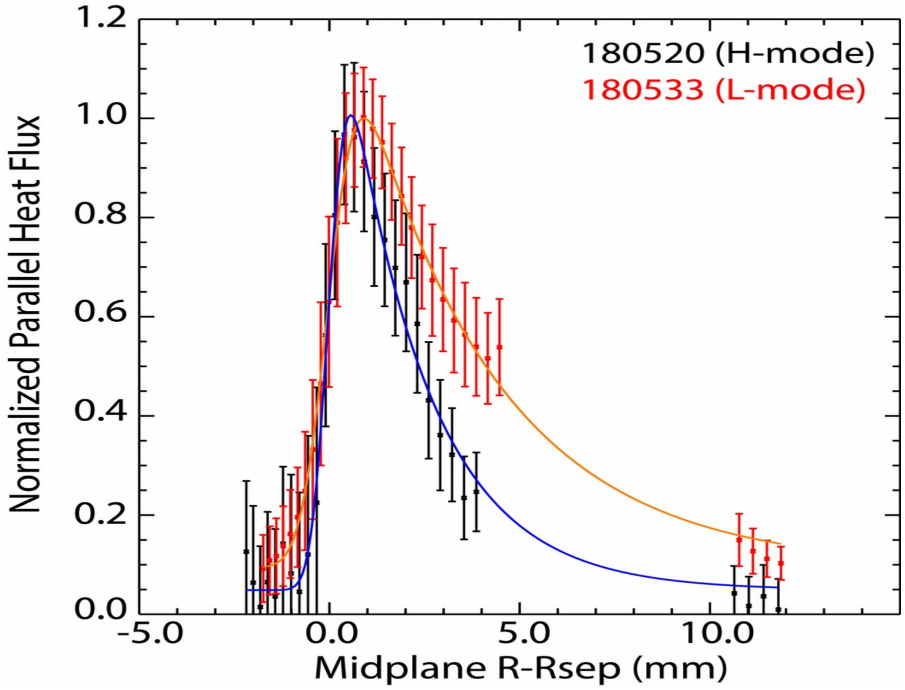
n=∞ ballooning modes limit gradients in strongly negative triangularity

If shape is relaxed, bootstrap current opens 2[nd] stability

[S. Saarelma, PPCF submitted]

SOL. Heat flux widens by 50% in high-confinement L-mode phase

- Scrape-off layer power fall-off length (λ_q) inferred from IR thermography
- 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 H-mode case



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Conclusions and outlook

- High confinement L-mode discharges at Negative Triangularity have been recently extended to a diverted LSN configuration
  - The L→H power threshold strongly increases at negative triangularity
  - Plasmas maintain L-mode profiles and routinely achieve β_N~3 and H_{98y2}~1
  - Impurity to energy confinement time is measured to be of order unity
  - 50% wider λ_q in L-mode cases compared to H-mode
  - Wider λ_q, resilience to impurities, no need to stay above LH power threshold offer considerable advantages in future reactors

- Core-edge tension may be eased but need further research & cross-validation
  - Scalings for LH power threshold, confinement, λ_q, detachment