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

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with
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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

OLD SHAPE (2016-2018)

NEW SHAPE (2019-)

Coil currents
in [A]
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 $\lambda_q$ 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?

Pedestals => core-edge tension

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

ExB poloidal flows driven by pressure pedestal

Pedestals, core-edge tension, and ExB poloidal flows are key in understanding fusion reactor design and operation.
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EC heated Negative Triangularity L-mode plasmas obtained H-mode-like energy confinement on TCV

- Inner wall limited L-mode
- Pure electron heating (ECH) – $T_e \gg T_i$
- $\delta$ lowers $\chi_e$ only at low collisionality
- TEM dominated

$\chi_e \left[ m^2/s \right]$

$1/\nu_{eff} \propto T_e^2/(n Z_e)$

[Y. Camenen, NF 2007]
EC heated Negative Triangularity L-mode plasmas obtained H-mode-like energy confinement on TCV

- Inner wall limited L-mode
- Pure electron heating (ECH) \( T_e > T_i - \delta \) lowers \( \chi_e \) only at low collisionality
- 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]
Non-linear GK modeling fairly reproduce collisionality and δ dependence of heat diffusivity.

Non linear Gyro-kinetic (GS2)

Radial dependence not reproduced
Global effects?

[Y. Camenen, NF 2007]

[A. Marinoni, PPCF 2009]

[1/νeff ∝ T_e/(n_e Z_eff)]

Experiment

[G. Merlo EPFL Ph.D Thesis 2016]

[Δ = 0.4, 0.2, -0.2, -0.4]

[Δ = 0.4, 0.2, -0.2, -0.4]
DIII-D demonstrated high confinement L-mode plasmas at reactor grade pressure level

\[ P_{NBi}[MW] \]

\[ \beta_N \]

\[ l_i \]

\[ H_{98.92} \]

\[ D_\alpha[10^{15} s^{-1} s^{-1}] \]

Time [s]

EML free
Near zero power degradation
\( T_i \sim T_e \)
No major MHD event
Low impurity confinement time
Expected ideal limit at \( \beta_N \sim 3-3.2 \)

[\text{M.E. Austin, PRL 2019}]
[A. Marinoni, PoP 2019]
Low torque is not expected to significantly deteriorate confinement (preliminary modeling)

For fixed profiles, heat flux increases by 30%-40% at low rotation (similar behavior for $Q_i$ and $\Gamma$)
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A Marinoni IAEA-FEC 2020
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 $Z_{\text{eff}}$?
  - 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 $\lambda_q$?
- **SOL:** Do plasmas detach?
  - Is it easy to control detachment?

Will core-edge tension be eased in NT plasmas?
Core. L-mode edge diverted plasmas sustain high-confinement with 20% bootstrap fraction

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

\[ \bar{n}_e [10^{19} \text{m}^{-3}] \]

\[ P_{\text{NBI}} [\text{MW}] \]

\[ P_{\text{ECH}} [\text{MW}] \]

\[ \beta_N \]

\[ H_{98.2} \]

\[ D_\alpha [10^{19} \text{sr}^{-1} \text{s}^{-1}] \]

\[ W [\text{MJ}] = \alpha P^\beta \]
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 $\tau_P/\tau_E \sim [2-4]$

Impurity retention is less problematic but it might be harder to fuel reactors
Edge. H-mode transition obtained only at relaxed triangularity

Plasmas at $\delta_{top} = -0.4$ 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

Consistent with previous results from TCV [A. Pochelon PFR 2012]

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

Identical, shallow, edge temperature gradients

\[ W_{\text{ELM}}/W_{\text{DIA}} \sim 0.01-0.04 \]
Edge. LH power threshold dependence on $\delta$ does not appear to be due to Reynolds stress.

180519 ($\delta_{\text{top}}=-0.4$) 
L-mode throughout

180520 ($\delta_{\text{top}}=-0.2$) 
H-mode at 2205 ms
Edge. Reduced ballooning stability limit may prevent H-mode pedestal growth

If shape is relaxed, bootstrap current opens 2\textsuperscript{nd} stability

\[ n = \infty \text{ ballooning modes limit gradients in strongly negative triangularity} \]

[S. Saarelma, PPCF submitted]
SOL. Heat flux widens by 50% in high-confinement L-mode phase

- Scrape-off layer power fall-off length ($\lambda_q$) inferred from IR thermography
- In the only H-mode discharge inter-ELM $\lambda_q$ consistent with ITPA scaling and discharges with similar lower-half plasma shaping
- In all L-mode discharges, wider $\lambda_q$ (~50-60%) with respect to the H-mode case
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 $\beta_N \sim 3$ and $H_{98y2} \sim 1$
  - Impurity to energy confinement time is measured to be of order unity
  - 50% wider $\lambda_q$ in L-mode cases compared to H-mode
  - Wider $\lambda_q$, 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, $\lambda_q$, detachment