Viability of Wide Pedestal QH-Mode for Burning Plasma Operation

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Oral 11:05 AM  EX/2-2 Pedestal & ELM Optimization (24 Oct 2018, 10:45-12:30)
Poster (24 Oct 2018, 14:00-18:45)
Rapid Progress Suggests Wide Pedestal QH-Mode is Attractive Scenario for Burning Plasma Operation in ITER

- New stationary ELM-stable regime in DIII-D
- QH-Mode transitions to Wide Pedestal at low $E_r$ shear
  - Pedestal pressure $\uparrow$60%
  - Pedestal width $\uparrow$65%
  - Global confinement time $\uparrow$40%
  - $H_{98y2} \uparrow$45%
- Zero injected torque throughout discharge
- Sustained with up to 77% ECH power
  - Confinement improves with electron heating
  - Promising for burning plasma: $\alpha$-particles heat electrons

- Wide Pedestal QH-Mode in LSN Shape
  - Lower $Z_{eff}$ implicates sources
Transition to Wide Pedestal QH-Mode First Discovered While Ramping Counter-NBI Torque Toward Zero

- Reduced Pedestal $E_r$ shear
- Less drive for Edge Harmonic Oscillations (EHO) which regulate standard QH-Mode
  - EHO replaced by shorter wavelength broadband fluctuations
  - Transition to 60% higher and 65% wider pedestal
  - Transport-limited pedestal – no ELMs
- Core confinement improves with higher pedestal

Chen et al., Nucl. Fusion (2017)
Creation of
Wide Pedestal QH-Mode does not
Require Injected NBI Torque
NBI Torque to Initiate and Sustain Wide Pedestal QH-Mode now Reduced to ~Zero Net Torque Injected Throughout

- New zero torque startup

- Replace NBI counter torque with Neoclassical Toroidal Viscous (NTV) torque
  - Use n=3 non-axisymmetric magnetic fields
  - NTV torque prevents early locked modes, tailor to avoid n=2 NTM

- Same or better wide pedestal QH-Mode performance with zero injected NBI torque

Burrell et al. (2018)
Measured Intrinsic Torque Dominates and Matches Direction of Rotation

With ~zero injected NBI torque

- Measured both carbon and deuterium toroidal rotation profiles
- Intrinsic torque density measured using beam torque modulation in similar discharge
  - Includes thermal ion loss (co-)
  - Edge NTV not yet included (counter-)
- Local beam torque density opposite rotation over most of profile
Wide-Pedestal QH-mode Operation has been Extended to LSN and USN Shapes and a Wide Range of NBI Torque

- Wide pedestal transition seen in range of discharge shapes over wide range of NBI torque
  - Transition not seen yet for USN with \( d\text{Rsep} \geq 2 \text{ cm} \)

- Shape and torque ramps in wide pedestal conditions used to broaden parameter space further

- Range of wide pedestal accessible torques exceeds ITER equivalent range
Approaching Dominant Electron Heated Wide Pedestal QH-Mode using Off-Axis ECH
In Wide Pedestal QH-Mode, Confinement Improves further with Increasing Auxiliary Power

- $H_{98y2} \sim 1.6$ increases with power

- Global energy confinement time $\tau_E$ does not degrade with power as in usual H-Mode scaling

- These scans utilize NBI heating at zero injected torque
Electron Heating Improves Wide Pedestal QH-Mode Confinement, Unlike any Other DIII-D Regime — as $T_e/T_i \to 1$ at ITER Collisionality

Off-axis ECH at $\rho=0.4$

- $\tau_E$ increased 60% with 1/3 ECH power
  - Pedestal $E_r$ well widens/deepens
- With more ECH, $T_e$ fluctuations intensify for $\rho=0.5$-0.7
  - $T_e$ profile stiffens
  - Ion channel degrades
- Suggests $T_e/T_i$ threshold crossed
With ECH off-axis, Confinement Initially Improves but Shows Less Improvement at Higher ECH Power Fractions

Off-axis ECH at $\rho=0.4$

- $\tau_E$ increased 60% with 1/3 ECH power
- Encounter “stiff” response as increase ECH power further
- $\tau_E$ still 19% higher with equal ECH and NBI powers
Fourier Analysis of Modulated ECH Shows Electron Thermal Diffusivity Increases Monotonically with Electron Temperature Gradient $R/L_{Te}$

Off-axis ECH at $\rho=0.4$

- At highest ECH power fraction, stiffness with respect to $R/L_{Te}$ decreases
- Consistent with crossing threshold in $T_e/T_i$ or collisionality

\[
\chi_e^\text{HP} = \chi_e^\text{PB} + \frac{\partial \chi_e^\text{PB}}{\partial \nabla T_e} \nabla T_e
\]

(heat pulse diffusivity\(^2\))

\[
S = \frac{\partial \ln Q_e^\text{PB}}{\partial \ln \nabla T_e} = \frac{\chi_e^\text{HP}}{\chi_e^\text{PB}}
\]

(stiffness\(^2\))

Dominant Electron Heated Wide Pedestal QH-Mode using On-Axis ECH
Low Torque, Wide-Pedestal QH-mode Sustained with 77% ECH Power

- Recovers from loss of beam core fueling
- New core $T_e$ ITB forms without reverse shear

On-axis ECH replacing beam power

- Confinement not degraded with ECH

Central Temperatures
- $T_{e0}$ (keV)
- $T_{i0}$ (keV)

Energy Confinement Time (ms)

- Electron Pedestal Width (cm)
- Electron Pedestal Pressure (kPa)
- Divertor $D\alpha$ Light
With ECH on-axis, New ITB Forms in Electron Temperature Despite Monotonic q-profile, Further Improving Confinement with ECH

ECH location scan

- Move one gyrotron per discharge from $\rho=0.4 \rightarrow \rho=0.1$
- Carbon toroidal velocity hollows in ITB
  - Connected to $e^-$ channel
  - $n = 3$ NTV torque; electron root?

- $T_e$ profile inside ITB controlled by ECH location
Role of Electron Heat Pinch Identified in $T_e$ ITB Formation through ECH Location Scan and Fourier Analysis of Modulated ECH

ECH location scan

Electron Thermal Diffusivity (Power Balance)

$$\chi_{e}^{PB} \text{ (m}^2/\text{s)}$$

Electron Convective Velocity (Power Balance)

$$V_{e}^{PB} \text{ (m/s)}$$

Contributions to Electron Temperature Gradient

$$\frac{R}{L_{Te}} = \frac{Q_{e} R}{n_{e} T_{e} \chi_{e}^{PB}} - \frac{R V_{e}^{PB}}{\chi_{e}^{PB}}$$

- Electron Heat Pinch increases $R/L_{Te}$ by factor 2.4
# Current Status of Wide Pedestal QH-Mode as Candidate Burning Plasma Regime for ITER Baseline Scenario

<table>
<thead>
<tr>
<th>Demonstrated</th>
<th>Work in Progress</th>
<th>Not Yet Addressed</th>
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<tbody>
<tr>
<td>No ELMS</td>
<td>Reduce $q_{95}$</td>
<td>Radiative divertor</td>
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<tr>
<td>No reliance on NBI torque, fueling; zero torque throughout, torques spanning ITER equiv. range</td>
<td>Reduce high $Z_{\text{eff}}$ (DIII-D specific sources)</td>
<td>Wall conditioning requirements</td>
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<tr>
<td>Dominant Electron Heating (77%) with Improved $\tau_E$</td>
<td>Impurity confinement studies</td>
<td></td>
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<tr>
<td>$H_{98y2} \approx 1.6$ with power, $\beta_N \sim 2.3$</td>
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<tr>
<td>LSN Shape</td>
<td></td>
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<tr>
<td>$T_e \sim T_i$</td>
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<tr>
<td>Very low core MHD</td>
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<td>ITER collisionality</td>
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- **Wide pedestal QH-Mode:** low $ExB$ shear – turbulence limited pedestal
- **ITER at low $\rho_*^+$, where** $E_r \simeq \nabla p/en$:

$$\frac{\omega_{E\times B}}{\gamma} \propto \left( \frac{a}{w_{\text{ped}}} \right) \rho_*^+$$

+$^t$ Kotschenreuther et al. NF (2017)
Backup slides
Preliminary Results for Impurity Transport in Wide-pedestal QH-Mode

- Impurity transport studied by injecting pulses of Aluminum using laser blow-off system
- WP QH has typical H-Mode ratio of particle to energy confinement time $\tau_p/\tau_E \sim 2-3$
- Unlike ELMy H-mode, Wide-pedestal QH-mode does not have inward impurity pinch

![Graph showing impurity confinement time](image)

WP QH-Mode 175539 (DN Shape) $\tau_E = 150$ ms
ELMy H-Mode 175849 80 Hz ELMs (LSN Shape) $\tau_E = 100$ ms

Xi Chen, C. C. Petty et al., APS (2018)
Impurity Concentrations Due (in part) to Stronger Sources of Carbon

- Balanced double null (DN) configurations tend to have higher $Z_{\text{eff}}$
- Counter NBI orbit losses also increase carbon influx, but counter NBI is not needed
- Expect lower $Z_{\text{eff}}$ Wide Pedestal QH-Mode without NBI and with ITER-relevant Lower Single Null (LSN) shape
- ECH does not appear to lower $Z_{\text{eff}}$

**Wide Pedestal QH-Mode in LSN Shape**
- $Z_{\text{eff}}$ reduced by 23% going from Double Null to Lower Single Null
Use Beam Torque Modulation at Constant Power to Measure Intrinsic Torque

- Vary torque by exchanging co- and counter- beams, keeping total power constant
- Mean counter-current NBI torque 0.9 Nm
  - Modulated in 400 ms duration steps ±0.2 Nm
- TRANSIP with 250,000 particles to compute beam torque
  - Use reflectometer density profile with high time resolution
- Determine momentum confinement time at each radius; “peel the onion” to infer “intrinsic” torque density profile

\[ \text{Intrinsic Torque Density (Modulation)} \]

\[ 0 \text{ Nm/m}^3 \]

\[ 0.1 \]

\[ -0.2 \]

\[ \rho \]

\[ \text{N.m/m}^3 \]

\[ 0 \]

\[ 0.5 \]

\[ 0.75 \]

\[ 1.0 \]

\[ \text{DIII-D NATIONAL FUSION FACILITY} \]

\[ \text{C. Chrystal, B. A. Grierson et al., Phys. Plasmas 24, 056113 (2017)} \]