Favorable Transport Properties of the Wide Pedestal QH-Mode Regime

by

D. R. Ernst¹

with K.H. Burrell², C. C. Petty², K. Barada³, T. L. Rhodes³, G. Wang³, S. Haskey⁴, C. Chrystal², B. A. Grierson⁴, N. Logan⁴, T. Odstrcil¹, C. Paz-Soldan², Xi Chen², Q. Pan¹, P. C. Crandall³, T. M. Wilks¹, M. E. Austin⁶, L. Bardoczí², T. Carlstrom², M. Yoshida⁵, T. Osborne², L. Zeng³ and the DIII-D Team

¹MIT Plasma Science and Fusion Center, Cambridge, MA 02139, USA
²General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA
³University of California Los Angeles, PO Box 957099, Los Angeles, CA 90095-7099, USA
⁴Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543-0451, USA
⁵National Institutes for Quantum and Radiological Science and Technology, Naka, Ibaraki 311-0193, Japan
⁶Institute for Fusion Studies, University of Texas, Austin, TX, 78712, USA

Presented at the
2019 US Transport Task Force Workshop
Austin, Texas
March 18-21, 2019

Email: dernst@psfc.mit.edu
Favorable Confinement Properties of Wide Pedestal QH-Mode are Attractive for Burning Plasma Operation in ITER

- New stationary ELM-stable regime in DIII-D with turbulence regulated pedestal\(^1,2\)
- QH-Mode transitions to Wide Pedestal at low \(E_r\) shear with increased confinement
  - 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 \(Z_{\text{eff}}\) may implicate sources

\(^1\)Burrell et al., Phys. Plasmas (2016)
\(^2\)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 to prevent early locked modes, avoid NTMs
- Same or better wide pedestal QH-Mode performance with zero injected NBI torque
- But still have counter NBI Loss torque at edge … is it required?
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-)

D. R. Ernst et al. IAEA EX/2-2 (2018)
Approaching Dominant Electron Heated Wide Pedestal QH-Mode using Off-Axis ECH
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 due to ion channel improvement
- Encounter “stiff” response as increase ECH power further
- $\tau_E$ still 19% higher with equal ECH and NBI powers

- $n_e$ (independent of beam fueling)
- $175602$ 0% ECH
- $175610$ 32% ECH
- $175606$ 55% ECH

(ECH)

$(Z_{eff} \sim 4.5$ shows little change)
With ECH off-axis, Confinement Initially Improves 60% but Shows Less Improvement at Higher ECH Power Fractions Due to Stiff Response

Off-axis ECH at $\rho=0.4$

- $\tau_E$ increased 60% with 1/3 ECH power
  - Pedestal $E_r$ well widens/deepens (DBS)
- 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

$R/I_{T_e} > 1$ (0.50 - 0.65)

$<I_{T_e}/I_T>$ (0.50 - 0.94)

$\frac{P_{ECH}}{P_{ECH} + P_{NBI}}$

$\tilde{n}_e (a.u.)$

$\tilde{T}_e (eV)$

Electron Temperature Fluctuation Level (CECE)

Density Fluctuation Level (DBS)
Dominant Electron Heated
Wide Pedestal QH-Mode using On-Axis ECH
Low Torque, Wide-Pedestal QH-mode Sustained with 77% ECH Power

- Recover 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)

Divertor $D_\alpha$ Light

Energy Confinement Time (ms)

174675
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: \( E_r \) well forms
- \( n = 3 \) NTV torque: Is it the electron root?
- \( T_e > T_i \) & \( T_e \) peaked but \( T_i \) flat: \( \Gamma_{\text{e neo}} > \Gamma_{\text{i neo}}(E_r) \) [W7-AS: MaaBberg et al., Phys. Plasmas 7(1) 298 (2000)].
- \( E_r \) more positive in well so that \( \Gamma_{\text{e neo}} = \Gamma_{\text{i neo}}(E_r) \)

- \( T_e \) profile inside ITB controlled by ECH location
- \( \alpha \) stabilization, high \( q_{\text{min}} \) may contribute to ITB formation
Role of Electron Heat Pinch Identified in $T_e$ ITB Formation through ECH Location Scan and Fourier Analysis of Modulated ECH

**ECH location scan**
- GENE shows $\nabla T_e$ TEM is dominant in ITB ($k_y\rho_s < 15$) and ETG is stable
- Nonlinear simulations in poster with model collisions and LES

**Electron Thermal Diffusivity (Power Balance)**

$\chi_e^{PB}$ (m$^2$/s)

$R/L_{Te}$

$\rho = 0.3$

**Electron Convective Velocity (Power Balance)**

$V_e^{PB}$ (m/s)

$R/L_{Te}$

**Contributions to Electron Temperature Gradient**

\[
\frac{R}{L_{Te}} = \frac{Q_e}{n_e T_e \chi_e^{PB}} - \frac{RV_e^{PB}}{\chi_e^{PB}}
\]

**Electron Heat Pinch increases $R/L_{Te}$ by factor 2.4 in ITB**
Nonlinear GENE Simulations in ITB

- GENE shows $\nabla T_e$ TEM is dominant in ITB ($k_y \rho_s < 15$) and ETG is stable
  - Nonlinear simulations with model collisions
  - Large Eddy Simulation essential to prevent pileup at high $k_y$
  - $\chi_{em} = 0.68 +/- 0.32 \text{ m}^2/\text{s}$
  - $\chi_{es} = 0.04 +/- 0.06 \text{ m}^2/\text{s}$

- (See Poster by Qingjiang Pan for first implementation of exact GK Landau collisions and comparison with Sugama ZF Damping)


(Using shorter averaging window free of large numerical instabilities)
Unique Transport Properties of Wide Pedestal QH-Mode Relevant to Burning Plasmas

- Low Pedestal ExB shear regime with higher and wider pedestal, no ELMs
- Initiated and sustained with net zero NBI torque
  - Measured intrinsic torque balances NBI orbit loss torque
- \( H_{98y2} \sim 1.6 \) increases with NBI power
- Ion, Electron thermal confinement improves strongly with electron heating
- Dominant Electron Heating (77\%) achieved with Improved \( \tau_E \)
- Strong electron thermal pinch in core with strong electron heating forms ITB
- Impurity transport shows outward convection in core despite higher \( Z_{\text{eff}} \)
- ITER at low \( \rho_*^\dagger \), where \( E_r \sim \nabla p/en \): low pedestal ExB shear expected
  \[
  \frac{\omega_{E \times B}}{\gamma} \propto \left( \frac{a}{w_{\text{ped}}} \right) \rho_*^\dagger
  \]
  \( \dagger \) Kotschenreuther et al. NF (2017)

- Will Wide Pedestal QH-Mode be the de-facto H-Mode in ITER?
Backup slides
Preliminary Results for Impurity Transport in Wide-pedestal QH-Mode Suggest Favorable Properties Relative to ELMy H-Mode, Despite $Z_{\text{eff}}$

- $Z_{\text{eff}}$ is lower in Lower Single Null than Double Null, suggesting upper divertor source
- Impurity transport studied by injecting pulses of Aluminum using laser blow-off system
- Initial LBO studies in WPQH-Mode show $\tau_p \sim 2-4 \tau_E$ for Aluminum, typical of ELMy H-Mode
- Unlike ELMy H-mode, Wide-pedestal QH-mode has outward core impurity convection

<table>
<thead>
<tr>
<th>Demonstrated</th>
<th>Exp. in Progress</th>
<th>Not Yet Addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>No ELMS</td>
<td>Reduce high $Z_{\text{eff}}$ (sources or xport?)</td>
<td>Radiative divertor</td>
</tr>
<tr>
<td>Zero torque throughout, torques spanning ITER equiv. range</td>
<td>Impurity confinement studies</td>
<td>Wall conditioning requirements</td>
</tr>
<tr>
<td>Dominant Electron Heating (77%) with Improved $\tau_E$ and $T_e \sim T_i$</td>
<td></td>
<td>Initiate with ITER shape</td>
</tr>
<tr>
<td>$H_{98y2} \sim 1.6$ with power, $\beta_N \sim 2.3$</td>
<td></td>
<td>Reduce $q_{95}$</td>
</tr>
<tr>
<td>Sustained in ITER Shape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very low core MHD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ITER collisionality</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 \( dR_{sep} \geq 2 \) 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

\[ T_{\text{inj}} \ (\text{Nm}) \]

\[ dR_{sep} \ (\text{cm}) \]

\[ \text{Counter } I_p \]

\[ \text{ITER torque range} \]

Burrell APS (2017)
Use Beam Torque Modulation to Measure Intrinsic Torque in Same Cond.

- Average NBI torque 0.9 Nm (counter $I_p$)
  - Modulated in 400 ms duration steps ±0.2 Nm
- TRANSP 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

\[^{1}\text{C. Chrystal, B. A. Grierson et al., Phys. Plasmas 24, 056113 (2017)}\]
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
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

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

(heat pulse diffusivity$^2$)

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

(stiffness$^2$)

\[\begin{align*}
\chi_e^{PB} & = \chi_e^{PB} \\
\frac{\partial \chi_e^{PB}}{\partial \nabla T_e} & = \chi_e^{PB}
\end{align*}\]

\[\begin{align*}
\chi_e & = \chi_e^{PB} + \frac{\partial \chi_e^{PB}}{\partial \nabla T_e} \nabla T_e
\end{align*}\]

(heat pulse diffusivity$^2$)

\[\begin{align*}
S & = \frac{\partial \ln Q_e^{PB}}{\partial \ln \nabla T_e} = \frac{\chi_e^{HP}}{\chi_e^{PB}}
\end{align*}\]

(stiffness$^2$)

\[\begin{align*}
\chi_e^{BP} & = \chi_e^{BP} \\
\frac{\partial \chi_e^{BP}}{\partial \nabla T_e} & = \chi_e^{BP}
\end{align*}\]

In Wide Pedestal QH-Mode, Confinement Does not Degrade with 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

Burrell et al. APS (2017)
Transition to Wide Pedestal QH-Mode First Discovered While Ramping Counter-NBI Torque Toward Zero

- Reduced Pedestal $E_r$ shear, Increased $E_r$ shear inward of Pedestal Top
- 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)