Bifurcation of Quiescent H-mode to a Wide Pedestal Regime in DIII-D and Advances in the Understanding of Edge Harmonic Oscillations

by Xi Chen¹, K.H. Burrell¹, T.H. Osborne¹, W.M. Solomon¹, K. Barada², N.M. Ferraro³, A.M. Garofalo¹, B.A. Grierson³, R.J. Groebner¹, G.J. Kramer³, N.C. Luhmann⁴, G.R. McKee⁵, C.M. Muscatello¹, R. Nazikian³, M. Ono⁶, C.C. Petty¹, M. Porkolab⁷, T.L. Rhodes², J. Rost⁷, M. Shafer⁸, P.B. Snyder¹, B. Tobias³, Z. Yan⁵, L. Zeng² and the DIII-D team

¹General Atomics, San Diego, CA, USA
²University of California, Los Angeles, CA, USA
³Princeton Plasma Physics Laboratory, Princeton, NJ, USA
⁴University of California, Davis, CA, USA
⁵University of Wisconsin, Madison, WI, USA
⁶Graduate University for Advanced Studies, Toki, Japan
⁷Massachusetts Institute of Technology, Cambridge, MA, USA
⁸Oak Ridge National Laboratory, Oak Ridge, TN, USA

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Quiescent H-mode is a Good Candidate for ELM-stable, High Performance Operation Regime in ITER and Beyond

- QH-modes operate at ITER-like low collisionality with H-mode confinement but without ELMs

- Two approaches to run QH at ITER-like low-torque:

1. Apply 3D fields to provide the strong edge $E \times B$ rotation shear ($\omega_{E \times B}$) required for edge harmonic oscillations (EHO) that regulate standard QH edge
   - New modeling finds linear eigenmode structure closely matches the measurements, confirms the importance of $\omega_{E \times B}$ in destabilizing low-$n$ EHO

2. New wide-pedestal QH-mode at low rotation with edge regulated by broadband MHD
   - Increased edge turbulent transport at low torque (thus low $\omega_{E \times B}$) reduces pedestal gradients and allows higher pressure

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1 Xi Chen, et al., NF 56, 076011 (2016)
Strong Edge Rotation Shear is Required to Excite and Sustain EHO in Experiments

- Theory and previous data analysis suggest EHO is a low-n kink/peeling mode destabilized by ExB rotation shear$^{1,2}$

- A series of NBI torque ramp QH-mode experiments were carried out to investigate the critical ExB shear ($\omega_{\text{ExB}}$)

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1. P.B. Snyder, et al., NF 47, 961 (2007)
2. A.M. Garofalo, et al., NF 51, 083018 (2011)
Positive Correlation between Critical ExB Shear and Pedestal Electron Collisionality Observed

- Preliminary analyses of 15 EHO $\rightarrow$ ELM or ELM $\rightarrow$ EHO data points from 10 discharges

- $\omega_{\text{ExB}}^{\text{crit}}$ decreases with pedestal $v_e^*$
  - No clear dependence on $n_{e,\text{ped}}$ seen
  - $v^*$ effects on $J_{BS}$ might be related

- Favorable scaling for exciting EHO in machines where low edge collisionality and rotation are expected, such as ITER

Linear least-square fit considering uncertainties in both axes:

$$\omega_{\text{ExB}}^{\text{crit}} = 0.038 + (0.22 \pm 0.06) v_e^*$$
Sheared Mode Structure Observed in M3D-C1 Simulation with Rotation in Line with Experiments

- **M3D-C1** is 3D resistive initial-value extended fluid MHD code\(^1\)
  - Real X-point geometry
  - Low-n (n\(\leq\)5)
  - Rotation shear effects (experimental rotation profile)

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\(^+\) Xi Chen, *et al.*, NF 56, 076011 (2016)
Calculated Edge Magnetic Perturbations Match Well with External Magnetics Measurements

- Calculated perturbation amplitudes are scaled to measurements by least-squares fit
- Stochastic edge appears in modeling with experimental perturbation amplitude ($\delta B/B \sim 2 \times 10^{-4}$ at midplane vessel wall)
  - Similar to nonlinear simulation results of JOREK [Liu TH/P1-9] and NIMROD [King TH/1-542]
Calculated Mode Structures Closely Match Internal Density and Temperature Fluctuation Measurements

- **General features:**
  - Extends over the whole pedestal (~2.5cm radial width)
  - Peaks in the steep gradient region

- **Agreement is found in the more stringent test of modeling: comparison of wavenumber**
  - $k_{pol}$ of EHO (0.02-0.2cm$^{-1}$) increases linearly with toroidal mode number
M3D-C1 Modeling Shows $ExB$ Rotation Shear Destabilizing Low-$n$ Modes while Stabilizing Higher-$n$ Modes

- $ExB$ rotation shear ($\omega_{ExB}$) profile was scanned in a series of linear M3D-C1 modelings of QH plasma # 153440 ($n=2$ EHO dominates)

- Linear growth rates of low-$n$ modes increase with $\omega_{ExB}$ while that of higher-$n$ modes decrease
  - Consistent with the loss of low-$n$ EHO and onset of higher-$n$ ELMs at too low $\omega_{ExB}$

- $n=2$ is the least stable mode at the experimental $\omega_{ExB}$ level
  - Consistent with detected dominant EHO component

* Xi Chen, et al., NF 56, 076011(2016)
Discovery of Wide-Pedestal QH-mode in NBI Torque Ramp Experiments In Double-null Plasma Shape

- EHO is lost and ELMs onset at too low torque in USN plasmas

- EHO ceases and broadband MHD rises at low torque in DN plasmas

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\[ \text{K.H. Burrell, et al., POP 23, 056103 (2016); Xi Chen, et al., NF 57, 022007 (2017)} \]

\[ \text{1 K.H. Burrell, et al., POP 23, 056103 (2016); Xi Chen, et al., NF 57, 022007 (2017)} \]
Bifurcates to Wide-Pedestal State and Stationary High Confinement Operation with Net-zero Injected Torque

- Rapid transition to improved pedestal conditions as neutral beam torque is reduced to zero
  - $P_e^{\text{PED}} \uparrow 60\%, \quad \text{Width}_e^{\text{PED}} \uparrow 50\%, \quad \tau_E \uparrow 40\%$

- Improved pedestal achieved with reactor-relevant plasma parameters
  - $\beta_N = 1.5-2.3, \quad H_{98y2} = 1.2-1.6, \quad \nu_e^* (\text{PED}) = 0.2-0.4$

- Transition is associated with
  - Changes in $E_r$ well and ExB shear profiles
  - Increased edge density and broadband MHD fluctuations

- Working hypothesis: Wider pedestal is due to changes in turbulent transport caused by altered $E \times B$ shear

Substantial Increase in Pedestal Height and Width and Decrease in Pedestal Gradients and Edge ExB Shear

Pedestal pressure gradient decreases and peak $P'$ moves away from the separatrix.

$E_r$ well becomes shallower and ExB shear decreases outside $\Psi_N \sim 0.9$.
Torque Needs to be Reduced Sufficiently to Access the Wide-Pedestal QH

- Torque was ramped down and held at 0, 1, 2, 2.7 Nm (ctr-Iₚ)

- Transition into wide-pedestal occurred except in 2.7 Nm case
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- 2.7 Nm case: discharge stays in std. QH-mode with EHO
Edge ExB Shear Seems to be the Key

- Torque was ramped down and held at 0, 1, 2, 2.7 Nm (ctr-$I_p$)
- Transition into wide-pedestal occurred except in 2.7 Nm case
- 2.7 Nm case: discharge stays in std. QH-mode with EHO
- 2 Nm case: the transition occurs in flat torque phase when the edge ExB shear decreased sufficiently
Magnetic and Low-k Broadband Fluctuations Increase after Transition

- Edge magnetics reveal two counter-propagating spectrally overlapping branches
- Low-k ($k_\rho_s \leq 0.5$) density fluctuation spectra detected by BES and MIR in wide-pedestal QH are superposition of two counter-propagating branches
  - Mode amplitudes peak at different locations
Intermediate-\(k\) Turbulence in the Pedestal after Transition is also Enhanced

- Phase Contrast Imaging (PCI) system detects high frequency (\(f > 500\text{kHz, lab frame}\)) intermediate-\(k\) (\(0.3 < k \rho_s < 1.2\)) turbulence in the pedestal of wide-pedestal QH
  - Absent in L-mode and high-torque QH
  - Similar to that in standard ELM-free H-mode
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- Doppler Back-Scattering (DBS) system detects broadband lab-frame electron-directed mode (\( k_\theta \rho_s \sim 1 \)) peaking near the pedestal top
  - Significantly weaker at \( k_\theta \rho_s \sim 2 \) or when the EHO is present
Operating Point of QH-mode with EHO is Near but Below the ELM Limit

- Intersection of PBM and KBM constraints determines pedestal height and width in EPED\(^1\)
  - PBM: \(P' \propto W^{-0.25}\)
  - KBM: \(P' \propto W\)

- ELITE\(^2\) calculations statistically show std. QH edge sits just below the no-rotation PBM boundary

- Pedestal width well described by EPED-KBM limit

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1. P.B. Snyder, et al., NF 51, 103016 (2011)
2. P.B. Snyder, et al., POP 9, 2037 (2002); H.R. Wilson, et al., POP 9, 1277 (2002)
Higher Pedestal Pressure Expected at Reduced $P'$

- Additional transport can reduce $P'$
- PBM and KBM intersect at higher $P_{\text{ped}}$ at reduced $P'$ due to the weaker width dependence of PBM
- Higher $P_{\text{ped}}$ is allowed within ELM limit when peak $P'(\alpha_{\text{max}})$ moves away from separatrix
  - Seen in lithium induced pedestal bifurcation on DIII-D\(^1\)

\(^1\) T.H. Osborne, et al., NF 55, 063018(2015)
Increased Edge Transport in Wide-Pedestal QH Reduces $P'$ Allowing Higher $P_{ped}$ while Remaining Below ELM Limit

- ELITE calculations consistently show wide-pedestal QH edge sits far below the PBM boundary
- Pedestal width exceeds (by 50%) the EPED-KBM scaling
Transport Improvement in Outer-Core Region Consistent with Global Confinement Improvement

- In outer-core region, ExB shearing rate increases and transport is reduced.
- Similar to previous finding of reduced outer-core transport in low rotation QH-mode using NTV torque from applied 3D fields\(^1\)

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\(^1\) A.M. Garofalo, et al., NF 51, 083018 (2011)
We are Developing Predictive Confidence in QH-mode as Low Rotation ELM Free Regime for Future Reactors

• M3D-C1 modeling predicts $E \times B$ rotation shear ($\omega_{E \times B}$) destabilizes EHO
  – Consistent with theory and experiment, including measured eigenmode structure
  – Experimentally, lower $\omega_{E \times B}$ for exciting EHO correlates with lower pedestal $v_e$

• New wide-pedestal QH state discovered at low torque where Increased edge turbulence reduces pedestal gradients allowing higher pressure
  – Stationary ELM-free operation at net-zero torque with excellent confinement ($H_{98y2} \sim 1.5$, $\beta_N \sim 2$) for 12 $\tau_E$

• Standard QH with EHO (assisted by NTV at low torque) and new wide-pedestal QH are exciting candidates for high confinement ELM-stable operating modes for ITER and future machines where torque, rotation and collisionality are expected to be low
Plasma Shape, Diagnostics Coverage and ‘Directions’

Low-\(k\) \(\tilde{n}_e\) diagnostics
Beam Emission Spectroscopy (BES)
Microwave Imaging Reflectometry (MIR)

Intermediate-\(k\) \(\tilde{n}_e\) diagnostics
Doppler-Back Scatter (DBS)

Low-to-high-\(k\) \(\tilde{n}_e\) diagnostics
Phase Contrast Imaging (PCI)

Low-\(k\) \(\tilde{T}_e\) diagnostics
Correlation Electron Cyclotron Emission (CECE)
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