Edge Pedestal Control in Quiescent H-Mode Discharges in DIII-D Using Co Plus Counter Neutral Beam Injection

by

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for

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Quiescent H-Modes are the Ideal H-mode Plasmas

- Quiescent H-modes (QH-mode) exhibit H-mode confinement and operate ELM-free with
  - Constant density and radiated power
  - Long duration (> 4 s or 30 $\tau_E$) limited only by hardware constraints

- No ELMs means no pulsed divertor heat loads
  - Quite important for next step device such as ITER

- Time-averaged edge particle transport is faster than in ELMing H-mode
  - Facilitates He ash exhaust

- QH-mode seen from 3 MW to over 15 MW
  - Maximum power limited by core beta limit
QH-Mode Operation Achieved Over Substantially Broader Parameter Range

- Achieved QH-mode operation over a continuous torque range, from all counter-injection to near balanced injection
- Demonstrated QH-mode operation with all co-injection
- Discovered that edge particle transport can be continuously adjusted by varying edge rotation
  - Achieved maximum pedestal density and pressure possible without ELMs
- Peeling-ballooning mode stability theory has been used to guide experiments
  - Theory provides ELM stability limits; shape dependence is quite important
  - Provides basis for theory of edge harmonic oscillation, which controls edge particle transport in QH-mode
Edge Peeling-Ballooning Mode Stability Theory Guides QH-Mode Experiments

- Peeling-ballooning mode stability theory is embodied in codes such as ELITE [P.B. Snyder, Phys. Plasmas (2002)]

- Modes are driven unstable by edge pressure gradient and by edge current
  - Simplified, 2D stability diagram can be plotted using these parameters

- As density and collisionality increase, most unstable modes move from low toroidal mode number $n < 5$ on peeling boundary to high $n > 25$ on ballooning boundary
Stable Region is Much Broader in More Highly Shaped (Triangular) Plasmas

- Experimental results show QH-mode exists along peeling boundary

![Graph showing normalized pressure gradient vs. pedestal current for different triangularities and plasma densities](image-url)
Edge Harmonic Oscillation (EHO) is Key to QH-Mode Operation

- **Edge harmonic oscillation (EHO) is an edge localized, electromagnetic oscillation**
  - Waveform is typically nonsinusoidal with multiple toroidal harmonics n

- **Previous work showed the EHO enhances edge particle transport**

- **Edge transport enhancement allows transport equilibrium at edge parameters just below peeling-ballooning mode limit**
Theory posits that EHO is low-n peeling-balloonning mode destabilized by rotational shear just before edge plasma reaches the zero-rotation stability boundary [P.B. Snyder, Nucl. Fusion(2007)]

- At finite amplitude, EHO saturates because mode drags on vessel wall, reducing sheared rotation while enhanced transport also reduces edge pressure gradient, edge bootstrap current, and rotation

- Theory predicts that rotational shear effect is independent of direction of plasma current — QH-mode should be possible with both co and counter injection
In 2006, DIII-D was equipped with simultaneous co plus counter NBI capability.

QH-mode pedestal density increases as input torque is reduced at constant input power.
• In 2006, DIII-D was equipped with simultaneous co plus counter NBI capability

• QH-mode pedestal density increases as input torque is reduced at constant input power

• ELMs return at lower rotation and higher density

• Speculation: EHO-induced particle transport changes with changing rotation
Operating Points of Shots at Various Torques Are Consistent with Edge Peeling-Ballooning Stability Theory

- Stability calculations performed with ELITE code
- QH-mode plasma with EHO operates near but below peeling stability boundary
- ELMing shots are closer to peeling boundary
Higher Triangularity Allows QH–Mode Operation At Significantly Higher Pedestal Density
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\( n_e^{\text{PED}} \) up to 0.5 \( n_GW \)

![Diagram showing neutron density (nePED), NBI power, and torque over time.](image)
Plasma Shape With Improved Edge Stability Developed for 2007 Campaign
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![Diagram showing normalized pressure gradient and edge current](image)

128513 t=3750 $\gamma/(\omega_\ast/2)$ contours

Edge Current [(jmax+jsep)/2] vs. Normalized Pressure Gradient ($\alpha$)

- **UNSTABLE**
- **STABLE**

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Plasma Shape With Improved Edge Stability Developed for 2007 Campaign

128513 \( t = 3750 \) \( \gamma / (\omega_{ce}/2) \) contours

Normalized Pressure Gradient (\( \alpha \))

Edge Current \( [j_{max} + j_{sep}/2] \)

UNSTABLE

STABLE

Normalized Pressure Gradient (\( \alpha \))
Rotation Control of Density and Improved Shape Allow QH-Mode Operation at Higher Pedestal Pressure and Higher Stored Energy
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- Compared to upper single null shape, optimal shape allows QH-mode at a factor 2.5 lower input torque
Edge Density Increases as Toroidal Rotation Decreases

- Global stored energy and energy confinement time increase 35% at lower rotation

\[
\begin{align*}
\rho \quad (\text{m}^{-3}) & \quad \text{High Torque} & \quad \text{Low Torque} \\
0 & 2 & 4 & 6 & 8 \\
0.0 & 0.2 & 0.4 & 0.6 & 0.8 & 1.0 & 1.2 \\
\end{align*}
\]

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QH-Mode Operation with All Co-Injection Confirms Theoretical Prediction that Co-NBI QH-Mode is Possible

- QH-mode created with 100% co-injection using
  - Low target density
  - Feedback control of beam power to regulate stored energy

- In preliminary experiments, see all usual features of QH-mode for periods up to 1 second long
  - H-mode edge pedestal
  - Constant density and radiated power
  - EHO providing extra edge particle transport
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- Termination of QH-mode may be due to slow decay of edge rotation shear
  - Input power and torque are at low end of what has been used in counter-NBI QH-mode
Edge Rotation Shear is Similar in Co-NBI and Counter-NBI QH-Modes at Similar Input Torque

- Theory predicts that magnitude of edge rotation shear is important but sign is not.

- Both co-NBI and counter-NBI QH-mode are predicted to exist if magnitude of rotation shear is large enough.
QH-Mode is Lost if Edge Rotation Shear is too Small

- Balanced beam injection results in low edge rotation shear
- EHO is absent and plasma is standard ELM-free H-mode in shot with low rotation shear
  - Standard ELM-free has monotonically rising density and radiated power
Peeling-Ballooning Stability Analysis Shows Excellent Edge Stability in Co-NBI QH-Mode Shots

- Co-NBI QH-mode also operates near peeling stability boundary

Edge Current $\left[\left(\frac{j_{\max} + j_{sep}}{2}\right)\right]$

$\gamma/\left(\omega_p/2\right)$ Contours

Normalized Pressure Gradient ($\alpha$)

Stable

Unstable

KH Burrell/IAEA/Oct2008
Conclusions

• Demonstrated QH-mode operation with all co-injection and strong edge co-rotation
  – Counter-NBI and counter rotation of plasma edge are not essential for QH-mode

• Achieved QH-mode operation over a continuous torque range, from all counter-injection to near balanced injection
  – More highly shaped plasmas allow QH-mode operation at lower input torque and lower edge rotation

• Discovered that EHO-induced transport can be continuously adjusted by varying edge rotation
  – Allows optimization of H-mode pedestal density and pressure

• Peeling-ballooning mode theory used to guide experiments
  – Effect of rotational shear on edge modes provides basis for theory of the EHO
  – Theory predicted existence of co-NBI QH-mode prior to experiments