Active Control of ELMs and Small ELM/ELM-less Regimes

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My Thanks to: A. Bortolon\textsuperscript{1}, L. Baylor\textsuperscript{2} (Pellet ELM Pacing)  
A. Hubbard\textsuperscript{3}, T. Happel\textsuperscript{4} (I-mode)  
K. Burrell\textsuperscript{5}, Xi Chen\textsuperscript{5}, T. Wilks\textsuperscript{3} (QH and WPQH-mode)

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Title Covers Full Day of Material – Had to Make Choice to Focus on Physics of 4 Leading Candidate Techniques

- This will be a PRIMER with REFERENCES, not a REVIEW or a TUTORIAL
  - Will not cover all work in each area
    - Focus on experimental data – refs to theory/modeling
    - Will assume basic pedestal physics knowledge (Diallo’s talk)
    - Will be a combination of brief discovery history and confirmed results
      - All data herein are published in fusion journals

- Dominantly work by DIII-D and CMOD colleagues – Limited time to prepare, had to go to most accessible sources for examples
  - Apologies in advance to colleagues if their work is not presented
  - Hopefully additional work covered in the references and citations therein

- Material “borrowed” from many presentations by many authors
  - Credit for brilliant insights and physics understanding goes to them
  - All errors in this version are my responsibility not those of the previous authors or their institutions!
Talk Will Take Medium Level Dive into the Physics Basis of 4 Candidate ELM Control Techniques

- Talk will cover:
  - Pellet ELM Pacing
  - I-mode
  - QH-mode
  - Wide-Pedestal QH

- Note: I am not an expert in any of these (I’m an RMP guy!)
  - Organizers apparently thought I had access to detailed info on all of these
  - This may limit my ability to answer questions!

- Talk will not cover other ELM Control Techniques:
  - Type-II, III, IV and V small ELM regimes
  - Grassy ELMs at high q95 or EDA H-mode
  - Vertical plasma kicks
  - Supersonic Molecular Beam Injection (SMBI)
  - LHCD SOL current filaments for 3D field control
  - Biased divertor target plates for SOL current filaments

Most Recent Comprehensive ELM Control Overviews:
R. Maingi, NF, 53, 043004 (2013) [43 Figs, 187 Refs]
and
E. Viezzer, NF, 58, 115002 (2018) [12 Figs, 122 Refs.]
Motivation: ELM Erosion of the Divertor is a Serious Issue for ITER and Future Fusion Reactors

• ITER SOL projection on divertor plates is 0.6 – 3.0 m²

• ITER ELM losses at 15 MA are projected to be ~ 15MJ

• Tungsten surface damaged at >0.6 MJ/m² due to local melting/resolidification

• \( \rightarrow \) To avoid monoblock damage ELM size must be reduced ~40x

• W accumulation must be prevented during ELM control
  – Sufficient \( f_{\text{ELM}} \)
  – Sufficient W transport without ELMs

Loarte 2012 IAEA s3 2014 NF f5
Makhlai 2016 NME f5a
In Addition to RMPs Leading Candidates for ITER ELM Control Include Pellet ELM Pacing or Operation in I- Mode or QH-mode

- **Pellet ELM Pacing** – Mitigate transient ELM heat fluxes by increasing $f_{ELM}$ and decreasing ELM size (particle and energy content)
  - Hardware Actuators: Pellet size, Velocity, Injection location, Material
  - Issues: Hardware, Triggering physics and ELM size mitigation

- **I-mode** – Eliminate ELMs by separating energy transport (barrier) from particle transport (no barrier) to operate “between L- and H-mode” with pedestal MHD
  - Operation Actuators: Unfavorable $B_T$ direction, High $B_T$
  - Issues: Needs high $B_T$, Avoid H-mode at high power

- **QH-mode** – Eliminate ELMs by plasma self organization to pedestal with MHD activity (coherent multi-harmonic EHO or broadband) to prevent pedestal growth to ELM instability thresholds
  - Operation Actuators: Sufficient edge $ExB$ velocity shear, low collisionality kink-peeling pedestal
  - Issues: $ExB$ velocity shear generation at low input torque, Control of saturated edge instabilities (eg. Wide Pedestal variant)
Basic Requirements of Any ELM Control Technique for ITER and Future Reactors (adapted from Loarte IAEA12/NF14)

Requirements for H-mode without ELMs or small ELM regimes (either natural or actively mitigated eg via pellets, RMP) include:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Pellet ELM Pacing</th>
<th>I-mode</th>
<th>QH-mode</th>
<th>WPQH-mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>High $\tau_E$ (H98~1), Low-$q_{95}$~3</td>
<td>Marginal</td>
<td>Yes/Yes</td>
<td>Yes/??</td>
<td>Yes/??</td>
</tr>
<tr>
<td>Sufficient particle flux for stationary $n_e$, low impurities</td>
<td>Marginal</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Accessible in BP conditions - low torque</td>
<td>??</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Accessible in BP conditions - low $v^*$</td>
<td>??</td>
<td>??</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Compatible with radiative divertor</td>
<td>??</td>
<td>??</td>
<td>??</td>
<td>??</td>
</tr>
<tr>
<td>Compatible with fueling/pumping sys</td>
<td>Marginal</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Compatible with low $P_{L-H}$</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Compatible with Pinj~$P_{L-H}$</td>
<td>Yes</td>
<td>Yes</td>
<td>??</td>
<td>??</td>
</tr>
<tr>
<td>Compatible with ICRF and Fast Ions</td>
<td>Marginal</td>
<td>Yes</td>
<td>??</td>
<td>??</td>
</tr>
<tr>
<td>Compatible with High-Z PFCs</td>
<td>Yes</td>
<td>Yes</td>
<td>??</td>
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</table>
Theory Framework for Remainder of Talk Will Rely Heavily on Linear Stability in Pressure Gradient, Edge Current Space

- “Kink-Peeling”, “Peeling-Ballooning” and “Ballooning” boundaries
- Plasma shaping (e.g. triangularity) opens up stable pedestal operating space

Most examples in this talk from analysis with ELITE code - P.B. Snyder, Phys Plasmas (2002)

See Viezzer 2018 NF, 58, 115002, Fig.1
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ELM Size Control by Pellet ELM Pacing Originated at ASDEX-U and JET

• Both HFS near vertical and LFS horizontal injection tested

• Experiments originally focused on pellet fueling
ASDEX-U Configuration to Minimize \( \text{D}_2 \) Pellet Breakup by Maximizing Guide Tube Radius of Curvature

- ASDEX-U Pellet Injector Setup for HFS 45 degree Injection
JET Pellet Injector Setup for Both HFS Near Vertical and LFS Midplane Injection

- Sketch of the experimental setup at JET in 2011-12
- Designed 50ms change time for different injection locations
Fast IRTV Data in AUG Showed Transient Heat Fluxes from Triggered and Intrinsic ELMs Were Very Similar

- Discovered with large pellets injected from HFS for core fueling
- Hypothesis: If \( f_{\text{pellet}} \) increased, \( f_{\text{ELM}} \) could be increased, and \( \Delta W_{\text{ELM}} \) decreased
DIII-D Pellet ELM Pacing Experiment Performed with D$_2$ Pellets Injected from Low Field Side Midplane and X-point

- New ITER like LFS X-point injection line installed on DIII-D.
- All 1.3mm pellets from X-point and Midplane reliably trigger ELMs – no fueling.
- HFS 1.3mm pellets trigger ELMs, but provide fueling.

1.3mm pellets
~100-150 m/s
(2 mbar-L, 1x10$^{20}$ atoms per pellet)

HFS

Mid

ORNL 3 barrel injector
20 Hz per gun

X-pt

New ITER like X-point Injection line added in 2011

Baylor 2012 IAEA s4

[S. Maruyama, ITR/P5-24]
Divertor Heat Deposition Per Pellet Triggered ELM Smaller Than Natural ELMs and Decreases With Pellet Frequency

- Average ELM energy and peak heat flux deposited in the divertor scales as $1/f_{ELM}$
  - Peak heat flux in outer divertor > inner divertor

Baylor 2012 IAEA s10
Heat Flux Mitigation Obtained with D\textsubscript{2} Pellets in ITER Baseline Scenario (IBS) at Zero Input Torque

- \( \beta_N = 1.7 \), \( q_{95} = 3.2 \), \( T_{\text{inj}} = 0 \) Nm, \( f_{\text{ELM}} \sim 10 \) Hz, \( q_{\text{peak}} \sim 350 \) W/cm\textsuperscript{2}

- D\textsubscript{2}P at 60 Hz \( \rightarrow f_{\text{ELM}} \sim 60 \) Hz, \( q_{\text{peak}} \sim 50-100 \) W/cm\textsuperscript{2}

- D\textsubscript{2}P at 90 Hz \( \rightarrow f_{\text{ELM}} \sim 90 \) Hz, \( q_{\text{peak}} \sim 30 \) W/cm\textsuperscript{2}

- No Nickel accumulation with D\textsubscript{2}P
Approximate $1/f_{ELM}$ Scaling of $q_{peak}$ and $\Delta W_{MHD}$ Observed

- 60 Hz injection $\rightarrow q_{peak}, \Delta W_{MHD} \sim 1/f_{ELM}$ 
  \[ f_{ELM} = 1/\Delta t_{ELM} \]
- 90 Hz injection $\rightarrow q_{peak}$ strongly reduced at all frequencies
Reduction of Impurities Observed with Pellet ELM Pacing – A Function of the Pellet Frequency

- Reduced high-Z and lower Z impurities during pellet ELM pacing.
- STRAHL calculations indicate a reduced Ni density explains reduced emission.
- Higher frequency pellets reduce impurity levels.
- Impurities and natural ELMs return within $\tau_E$.

Ni 26 Intensity Plasma Center

O VIII Intensity Plasma Edge

Divertor Dα Inner Strike Point

Time (s)
High Frequency D$_2$ Injection Reduces Pedestal Pressure and Modifies Edge Profiles

- Divertor conditions modified by D$_2$P
  - Increase of D$_{\alpha}$ baseline from OSP
  - Higher neutral density in divertor
- At 90 Hz, $p_{e,ped}$ ~20-30% lower than pre-ELM
  - $v^*_{e,ped}$ increased ~2x
Pellet ELM Pacing Produces a Narrower Pedestal Width - Stable to Peeling Ballooning Modes

- The boundary for peeling and ballooning stability in this plasma configuration is calculated by ELITE (P. Snyder, NF 2007).
- Pellet case is far in stable region, ELMs likely triggered by local effect.

\[
\gamma = 1.0 \omega / 2 \text{ contours}
\]

- **Natural ELMing Case**
  - Stable
  - Pre-ELM
  - Post-ELM

- **Pellet ELMing Case**

\[
\beta_N^{\text{ped}} / \Delta^{3/4}
\]

Baylor 2012 IAEA s15, 2013 PRL f4
Fast Camera Images of Pellets Triggering ELMs Show Individual Filaments Being Perturbed

- X-point pellet exciting a filament as it enters the plasma. ELM is subsequently triggered.
- Midplane pellet triggers ELM while X-point pellet fragment enters plasma.

Images consistent with hypothesis of a local ballooning mode triggered by pressure gradient in pellet cloud.
Hypothesis: Pellets Trigger ELMs by Local Pressure Perturbation on Flux Tube and Ballooning Instability

- Pellet cloud releases from pellet and expands along a flux tube at the sound speed \( c_s \).
- Temperature ‘cold wave’ travels along the flux tube at the thermal speed. Heat is absorbed in the cloud resulting in a local pressure increase in the cloud.
- Strong local cross field pressure gradients produced along the flux tube in \( \mu s \).
- The pellet ablates with a rate given by:
  \[
  \frac{dN}{dt} \propto r_p^{4/3} T_e^{11/6} n_e^{1/3}
  \]
- The local \( \nabla P \) is proportional to the ablation rate. Once sufficient ablation occurs, the local \( \nabla P \) can trigger a ballooning instability at that location.

Suggests a minimum pellets sized required.
Experiments in Both JET and DIII-D Showed Pellets of Insufficient Size / Speed Do Not Trigger ELMs

- Contours by fitting data from 855 pellets, 216 triggered ELMs
  
  Lang 2013 NF f7

- Black dots selected for detailed analysis
  
  Baylor 2012 IAEA paper f3
Energy Loss of Pellet Triggered ELMs Depends on Proximity to Previous ELM \(\rightarrow\) Limit to Maximum Mitigation Frequency?

- Triggering small rapid ELMs is complicated balance of perturbation size, location and pedestal evolution state
- Pellet size, velocity and freq all important
Low-Z, Non-Recycling Solid Granules Investigated as Possible ELM Pacing Material Without Plasma Fueling

- Solid granules injected by slapping with high frequency impeller

- Pellet size, velocity and frequency controlled by combination of granules used, impeller frequency, paddle radius, and dropping frequency
Impurity Granule Injector (IGI) Hardware on Midplane Port of DIII-D Capable of Injecting Several Granule Species

- Advanced IGIs Use Multiple Chambers to Supply Different Kinds of Granules

Dropper housing

Impeller chamber

Bortolon 2016 NF f2
Granule Penetration Depth in DIII-D ITER Baseline Scenario
Plasmas Varied By More Than 5x For Different Materials

- B$_4$C tends to shatter at LCFS due to thermal stresses on sharp edges

- C deepest penetration (5-12 cm)
  - From measured ablation times and injection velocity, assumed constant

Bortolon 2016 IAEA s11
ELM pacing and mitigation demonstrated with Li granules

- **0.4 mm granules ~20% trig efficiency**
  - Hybrid-like scenario (not IBS)
    - $\beta_N=1.4$, $q_{95}=4.6$
    - $P_{inj}=4$ MW, $T_{inj}=3$ Nm
    - Natural $f_{ELM} \sim 12$ Hz
  - On full-shot: $<f_{ELM}>\sim 38$ Hz (3X)
  - Reduced $q_{peak}$ at higher $f_{ELM}$
    - Data scatter at const. $f_{ELM}$
  - Outer Strike point
    - $q_{peak} < 1/f$
  - Inner Strike Point
    - $q_{peak} > 1/f$ (for 0.4 mm)

- **0.7 mm granules ~100% trig efficiency**
  - Inner
  - Outer
  - Bortolon 2017A ITPA York s8
Li Pellets Typically Decrease Pedestal Collisionality \( \rightarrow \) ELM Size Increases

- **Li injection changes pedestal structure**
  - Lower \( n_{e,\text{ped}} \), higher \( T_{e,\text{ped}} \) (dilution)
  - Collisionality \( \nu^*_{\text{ped}} \sim 3.5 \rightarrow 1.3 \)

- **Multi-machine scaling indicates**
  larger ELM size at lower \( \nu^*_{\text{ped}} \)

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Bortolon 2016 IAEA s18
Pedestal widens during Li injection – Operating Point Deep in Stable Regime

- With increasing injection frequency (0→70Hz→130Hz)
- $n_{e,ped}$ reduced (-30%)
  - Effect of ELM flushing
- $T_e, T_i$ increase
  - Lower radiative losses
- $\nu_{e,ped}$ reduced (5-6→1)
- Pressure pedestal 2X wider
  - $p_{ped}$ unchanged (or higher)
Pellet ELM Pacing Effectiveness Depends on Pellet Size, Freq, Velocity, Injection Location, Material and Pedestal Dynamics

- Actuators (size, frequency, material) require sophisticated hardware (high frequency extruders or slappers), and injection location requires design decisions prior to construction.

- ELM *triggering physics* delicate balance of ablation rate and radial location, poloidal location, perturbation size and background edge plasma dynamics.

- ELM *size mitigation* at high frequency sensitive to pedestal recovery dynamics and effect of pellets on pedestal collisionality.

- Simulations with JOREK code in progress (see references).
## Selected Experimental, **Simulation/Modeling** and Hardware References

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<td>Lang et al., NF, 47, 754 (2007)</td>
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<td>Lang et al., NF, 51, 033011 (2011)</td>
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I-mode of Interest Both For Reactor Operation and As A Challenge to Transport Barrier Understanding

1. As a potential regime for fusion reactors:

   - **No Type I ELMs, avoiding damaging heat pulses.** Pedestals are MHD stable.
   - **Good energy confinement close to H-mode and may have more favorable power scaling**
     - Many ELM-mitigated H-modes have reduced confinement vs ELMy H-modes.
   - **L-mode-like density pedestal and low particle confinement.**
     - Stationary, controlled densities, allows efficient current drive.
     - Avoids accumulation of high or low Z impurities (a big problem with high Z PFCs eg on JET, AUG), and the need to boronize (today’s conditioning method, which does not extrapolate to steady state reactors).

2. **Challenges our simple understanding of transport barriers.**
   - How and why are particle and energy barriers decoupled?
   - What happens to turbulence to decrease thermal transport, allow particle transport?
I-mode is a high energy confinement regime, *without* a particle barrier

- Temperature pedestal and high energy confinement.
  - On C-Mod, usually *stationary*.

- L-mode-like density pedestal and low particle confinement.

- Usually formed with ion Grad-B drift out of the divertor (all data in this talk)

*Obligatory clarification: This is NOT the same as the Limit Cycle Oscillation phase between L and H-mode, sometimes known as “I-phase”.*
At L-I transition, pedestal develops in $T_e$ and $T_i$ Density remains nearly unchanged

- Increasing $T_e$, $T_i$, $\nabla T$, at similar input power implies lower thermal transport than L-mode.

- Constant $n_e$, $D_\alpha$ imply ~same main species particle transport as L-mode.

- More quantitative estimates support this.
I-mode is now established on Alcator C-Mod, ASDEX Upgrade and DIII-D

- Figures from multi-device study through ITPA, presented at IAEA 2014 (Hubbard, Ryter, Osborne et al). Ranges have increased since then.

- Wide ranges of dimensional and dimensionless parameters: including $T_{\text{ped}}$ 0.2 - 1 keV, $\nu^* 0.17 - 4$, $q_{95} 2.4 - 5.3$, $n/n_G 0.1 - 0.8$.

- I-mode is usually formed with ion $B \times \text{grad-}B$ drift out of the divertor (unfavorable direction) in all devices (all results in this talk—more on this later).
I-mode has low global impurity confinement, high global energy confinement $\tau_E$

$\tau_E$ is normalized to H-mode scaling

$$\tau_{E,98y2} = 0.0562 \rho^{0.93} B_T^{0.15} \kappa^{0.78} R^{1.97} (R/a)^{0.58} n_e^{0.41} M_{eff}^{0.19} P^{-0.69}$$

Rice
NF 2015
\[ \tau_E \text{ in I-mode has weak power degradation.} \]

- Weaker power degradation in I-mode:
  \[ \tau_{E,I\text{-mode}} \sim P_I^{-0.3} \text{ vs } \tau_{\text{ITER98p}} \sim P_I^{-0.69} \]

- Range of \( H_{98,y2} \sim 0.6-1.2 \), correlating well with pedestal pressure (i.e., stiff core profiles).
  - Need power well above \( P_{I-I} \) to get maximum \( H_{98} \)
  - Upper limit in power is usually set by I-H transitions.
    - How high could we go in power?
    - Will pedestals and stored energy saturate at some point?
I-modes are well below pedestal linear MHD limits - Consistent with lack of ELMs

- Pedestals in ELMy H-modes generally lie at boundary set by peeling-ballooning (ELITE) and expected Kinetic Ballooning Mode thresholds.
- I-mode pedestals lie well away from these limits – explaining lack of ELMs, and consistent with pedestals not predicted by EPED.
- I-mode pedestal height must be limited by turbulence and heating power, which in turn are related to thresholds – room to increase.
Several characteristic changes in edge fluctuations, flows observed at L-I, I-H transitions

At **L-I transition**, as T pedestal forms, see

1. **DECREASE** in edge broadband turbulence (n and B) in mid-f range (~60-150 kHz)

2. Usually a **PEAK** in turbulence at higher f **"Weakly Coherent Mode"** (~200-400 kHz on C-Mod)

3. Fluctuating flow at **GAM frequency**. (10’s of kHz)

At the **I-H-mode** (particle barrier) transition, remaining turbulence drops suddenly, density and impurities rise.
Density fluctuations are strongly intermittent during I-mode

- AUG data show I-mode has lower base-level of fluctuations than L-mode, but exhibits strong irregularly spaced ‘solitary’ bursts (intermittency).

- At all measured structure sizes ($k_\perp = 5$-12 cm$^{-1}$): **Low fluctuation amplitudes decrease, while large fluctuation amplitudes increase (PDF broadens).**
  - Note bursts extend to larger $k$ than WCM ($k_\perp \sim 15$ cm$^{-1}$).

- Intermittency increases with $\nabla T$.

T. Happel et al, NF 56 064004 (2016)
T. Happel et al, PPCF 59 014004 (2017)
P. Manz et al, NF 57 086022 (2017)
Density ‘bursts’ are connected to WCM, and to radiation at divertor.

- Intermittent events (5 kHz) are preceded by smaller density perturbations.
- $\Delta t$ of precursor events corresponds to $1/f_{WCM} \sim 100$ kHz
- Bolometry signal in divertor is correlated with fluctuation amplitude, with a time delay $\sim 50 \mu$s
  - Suggests a particle flux from inside separatrix.

T. Happel et al, PPCF 59 014004 (2017)

Hubbard 2018 UTK Lecture
$E_r$ well develops during I-modes

- Builds up gradually along with $T_{\text{ped}}$
- ExB shear greatest in outer region.
- Steeper, deeper well than L-mode.

Hubbard 2018 UTK Lecture
Decrease in edge thermal conductivity correlates with reduction in mid-f turbulence

- At transition from L to I-mode, edge $\nabla T$ steepens, at near-constant $P_{\text{net}}$ and edge $n_e \Rightarrow \text{Edge } \chi_{\text{eff}} \text{ is decreasing}$
  - Edge power balance: $\chi_{\text{eff}}$ 0.6->0.2 m²/s

- Edge $\chi_{\text{eff}}$ correlates well to the drop in mid-f turbulence. ($\sim$60-150 kHz) from reflectometry

- Fast drops are seen in both turbulence and $\chi_{\text{eff}}$ at I-H transitions.

- Consistent with (but does not prove) this mid-freq turbulence playing a key role in thermal transport.
Edge particle flux correlates with amplitude of Weakly Coherent Mode

- Relative amplitude of WCM from edge reflectometer.
- Edge particle flux $\Gamma_{\text{LCFS}}$ derived from calibrated $D_\alpha$ imaging near the outboard midplane.

- Correlation with $\Gamma_{\text{LCFS}}$ is consistent with (does not prove) the WCM playing a role in driving particle transport, perhaps helping avoid transition to H-mode.

**Caveats**: $\Gamma_{\text{LCFS}}$ analysis was only done for a few discharges. Have not tried similar correlations for recently observed turbulence features (eg GAM, bursts)

- We don’t yet have a full picture of what is causing particle and energy transport.
I-mode is accessed by slowly increasing input power with ion $\mathbf{B} \times \nabla \mathbf{B}$ drift away from X-pt.

Most I-Modes have been obtained with unfavorable $\mathbf{B} \times \nabla \mathbf{B}$ drift (Rev B LSN or normal B USN), which has increased L-H threshold power.

- Some cases with “favourable” drift towards X-pt, with atypical shaping, but these are limited to low power (near usual L-H threshold).
L-I power threshold well characterized

For comparison, **L-H threshold**, for favourable \( B_x \nabla B \) drift, above \( n_{\text{min}} \):

\[
P_{L-H,\text{ITPA08}} = 0.0488 \, n_e^{0.717} \, B_T^{0.8} \, S^{0.941} \quad \text{(Martin 2008)}
\]

- **L-I threshold**, for \( B_x \nabla B \) drift away from X-pt:
  - **Increases with density** (linear C-Mod, offset linear AUG).
  - **Increases with S** (at most linear, ITPA IAEA 2014, NF 2016)

What about magnetic field \( B_T \)?
C-Mod experiments showed more robust I-mode at $B_T > 5$ T vs 2.8 T.

- In contrast to L-H transition, L-I power threshold did not increase with $B_T$.
- But, I-H power does $\rightarrow$ possibility of even higher $B_T$ ($\sim 8$ T) I-modes
  - At 7.8T, 1.35 MA $T_{e0} = 7.3$ keV, $T_{e,ped} = 1.0$ keV
Power range for I-mode widens with increasing magnetic field

- In contrast to $P(L-H)$, **L-I power threshold has at most a weak dependence on $B_T$**
  
  \[ P(L-I)/n_e \sim B_T^{0.26} \]

  - Uncertainties in $P_{\text{loss}}$ at 8 T
  - ASDEX Upgrade has consistent results, over a smaller window 1.8-2.5 T (Ryter NF 2016)

- **Maximum power for I-mode increases with $B_T$.**
  
  - NO discharges at 7.8-8 T had I-H transitions, up to 5 MW available ICRF power ($P_{\text{tot}}/S \leq 0.63 \text{ MW/m}^2$)

**More range to stay robustly in I-mode at higher $B_T$, avoiding H-mode. BUT, we still don’t have a good understanding and scaling for I-H thresholds.**

Hubbard 2018 UTK Lecture
I-mode has both advantages and challenges for boundary solutions

Advantages over H-mode:

- **No Type 1 ELMs with large transient heat pulses.**
  - Heat flux is usually quite stationary. Sometimes observe isolated, small pedestal drops, or rapid spikes.

- **Low impurity confinement, compatible with uncoated high Z PFCs (Mo, W) and high power ICRH.**
  - C-Mod required frequent (few days) boronization of Mo PFCs to maintain high confinement H-modes. But ran I-mode campaigns of up to 6 weeks with no boron.

Challenges include:

- Narrow inner and outer SOL heat flux $\lambda_q$ (similar to H-mode).
- More power to the inner divertor leg than in typical configuration. (due to $B_x\nabla B$ away from x-point, SOL drifts).
- Typically lower density or detachment more difficult than H-mode.
Outer Divertor $\lambda_q$ in I-mode $> 0.6$ mm in CMOD, scales as H-mode

- Outer $\lambda_q$ decreases at higher $B_{pol}$, as in Eich ITPA scaling.

- Lower bound very similar to H-mode
  Observed range is up to 2x scaling
  \[ q_{//} \sim PB/R \] (up to 2 GW/m$^2$ on C-Mod)
  - I-mode is neither an advantage nor disadvantage in this regard.
  - Still very challenging!
\( \lambda_q \) in I-mode > 0.6 mm in CMOD, scales as H-mode

- Outer \( \lambda_q \) decreases at higher \( B_{pol} \), as in Eich ITPA scaling.
- Lower bound very similar to H-mode, range is up to 2x scaling.
  \[ q_{/\!\!/} \sim PB/R \] (up to 2 GW/m\(^2\) on C-Mod)
  - I-mode is neither an advantage nor disadvantage in this regard.
  - Still very challenging!
- Simple scaling rule: \( \lambda_q \) [mm] = \( 1/(p[\text{atm}])^{0.5} \) implies high confinement and performance linked to narrow SOL width
  - Not good news for divertor
- Inner divertor \( \lambda_q \) is also consistent with \( 1/B_{pol} \) scaling and trends inversely with core pressure
\( \lambda_q \) in I-mode > 0.6 mm in CMOD, scales as H-mode

- Outer \( \lambda_q \) decreases at higher \( B_{\text{pol}} \), as in Eich ITPA scaling.
- Lower bound very similar to H-mode, range is up to 2x scaling.
  \[ q_{//} \sim \frac{PB}{R} \] (up to 2 GW/m\(^2\) on C-Mod)
  - I-mode is neither an advantage nor disadvantage in this regard.
  - Still very challenging!

- Simple scaling rule: \( lq \ [\text{mm}] = \frac{1}{(p[\text{atm}])^{0.5}} \)
  implies high confinement and performance linked to narrow SOL width
  - Not good news for divertor

- Inner divertor \( \lambda_q \) is also consistent with \( 1/ B_{\text{pol}} \) scaling and trends inversely with core pressure
  - Substantial heat flux with \( B \times \nabla B \) drift away from the X-point

Seeding reduces peak heat flux in I-mode, but detachment not yet achieved

- Modest Neon impurity seeding is often used to reduce divertor temperatures and Mo influx in I-modes with high ICRF power.
  - No Ne accumulation
  - High energy confinement maintained

- Higher Neon seeding levels, or N\textsubscript{2} seeding resulted in I-L back transitions before detachment.

- Surprisingly, higher power and stored energy plasmas have I-L even sooner after N\textsubscript{2} reaches the divertor
  - Seems to be an issue of transition/pedestal physics, vs a net power threshold.
Extrapolation of I-mode regime to fusion devices is promising, especially for compact, high B

- Strong increase of H-mode threshold with $B$, combined with weak dependence of $P(L-I)$ on $B$, lead to robust I-mode at high $B$
- Simple projections indicate **I-mode could be accessible in ITER, SPARC, ARC**, and be maintained to full fusion power by increasing $n_e$
- But, multi-device scalings of thresholds, $\tau_E$, density range are needed for confident extrapolation
  - New ITPA database set up, aims at ‘I-mode $\tau_E$ scaling’
  - Experiments are active on AUG, planned on WEST, other tokamaks
  - Data at larger size (JET, JT60-SA) are needed to clarify scalings of $\tau_E$ and $P(L-I)$ with $R, S$
  - Need an I-H scaling or theory!

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* pre-conceptual design point

Hubbard 2018 UTK Lecture
Key to I-mode is Window Between L- and H-mode for Power Crossing Separatrix $\Rightarrow$ Need High BT

• Weaker scaling of L-I power threshold scaling than L-H scaling with BT opens I-mode window at high BT

• Physics: New WCM (intermittent bursts) at high frequency keeps particle transport high while thermal transport decreases to H-mode like levels

• High particle transport prevents density pedestal formation and pressure evolution to an ELM

• Selected remaining issues:
  – Staying in I-mode at high fusion power – burn control
  – Ion GradB out of the divertor requires design decision before construction
    • Also means larger ISP heat flux
  – SOL power width $\sim 1/I_p$ means narrow target heat flux at high BT for fixed $q_{95}$
  – $I \rightarrow L$ sensitivity to radiative divertor attempts so far
### Selected Experimental and Simulation/Modeling References

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<thead>
<tr>
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<th>Simulation/Modeling Reference</th>
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<tr>
<td>Happel et al., NF, 56, 064004 (2016)</td>
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In Addition to RMPs Leading Candidates for ITER ELM Control Include Pellet ELM Pacing or Operation in I- Mode or QH-mode

- **Pellet ELM Pacing** – Mitigate transient ELM heat fluxes by increasing $f_{\text{ELM}}$ and decreasing ELM size (particle and energy content)
  - Hardware Actuators: Pellet size, Velocity, Injection location, Material
  - Issues: Hardware, Triggering physics and ELM size mitigation

- **I-mode** – Eliminate ELMs by separating energy transport (barrier) from particle transport (no barrier) to operate “between L- and H-mode” with pedestal MHD
  - Operation Actuators: Unfavorable $B_T$ direction, High $B_T$
  - Issues: Needs high $B_T$, Avoid H-mode at high power

- **QH-mode** – Eliminate ELMs by plasma self organization to pedestal with MHD activity (coherent multi-harmonic EHO or broadband) to prevent pedestal growth to ELM instability thresholds
  - Operation Actuators: Sufficient edge $ExB$ velocity shear, low collisionality kink-peeling pedestal
  - Issues: $ExB$ velocity shear generation at low input torque, Control of saturated edge instabilities (eg. Wide Pedestal variant)
In 1999 there was little experience operating DIII-D with NBI counter to IP
- Required wiring to reverse Ip direction – rarely done

One special Rev-Ip day with good, low recycling wall conditions and low density operation, Phil West (spectroscopist supporting the experiment) noticed that the large Type-I ELMs typical of H-mode disappeared mid-shot
- Control actuators had not been changed

Curious, he checked indicators of whether plasma had spontaneously transitioned back to L-mode
- Stored energy had not decreased; Pedestal pressure had not decreased → Plasma was still in H-mode
- Magnetics activity had increased – MHD mode of some sort had started when ELMs disappeared

This moment of following one’s curiosity has led to 2 decades of research into one of the most attractive regimes of plasma self-organization known as Quiescent H-mode (QH-mode)
QH-mode Operating Regime Without ELMs Sustained for Long Pulse With Density and Radiated Power Control

- DIII-D USN plasma with NBI counter to $I_p$
- Maintains quiescent edge without ELMs for >3.5s, $\sim 25\tau_E$ limited only by hardware

![Graphs showing plasma current, density, NBI power, radiated power, and ELM-free edge control](image-url)
THE PLASMA EDGE DURING THE QUIESCENT PHASE IS AN H–MODE EDGE

- Edge gradients in quiescent phase are comparable to those in ELMing phase
  - Note high $T_i$ pedestal
- QH–mode edge also has other standard H–mode signatures
  - Edge $E_r$ well
  - Reduced turbulence

**Graphs:**
- $n_e (10^{19} \text{ m}^{-3})$
- $T_e (\text{keV})$
- $P_e (\text{kPa})$
- $T_i (\text{keV})$

**Legend:**
- **ELMing**
  - 106919.01323
- **Quiescent**
  - 106919.03050

**Footnote:**
- Burrell 2001 APS s6
QH–MODE EDGE HAS LOWER PEDESTAL DENSITY AND HIGHER TEMPERATURE THAN CONVENTIONAL ELMING H–MODE

- QH–mode
- ELM Phase in QH–mode Shot, Last 20% of ELM Cycle
- Type I, Last 20% of ELM Cycle
- $\delta > 0.3$
- Type III

Burrell 2001 APS s9
EDGE RADIAL ELECTRIC FIELD WELL IS DEEPER IN QUIESCENT PHASE

- CER data show much deeper $E_r$ well in counter-injected quiescent H-mode than in co-injected ELM-free shot

- CER data show much deeper $E_r$ well in quiescent phase than in ELMing phase of same discharge

**CER Data**

- ELM-free (co-NBI)
- QH-mode (counter-NBI)

Shot 106919

**ELMing (985 ms)**

- Quiescent (3055 ms)

Separatrix

Burrell 2003 APS s6
QUIESCENT OPERATION IS USUALLY ASSOCIATED WITH THE PRESENCE OF AN EDGE HARMONIC OSCILLATION (EHO)

- EHO is seen on magnetic, density and electron temperature fluctuation diagnostics during QH-mode operation - Significant electromagnetic component
  - Quiescent operation also obtained with a global 1/1 mode (single example)
- Toroidal mode mixture (amplitude and harmonic content) can change spontaneously
  - Edge profiles, density and impurity control not sensitive to mode mixture

![Color contour plot of $\dot{B}_\theta$ signal](image.png)

- Frequency (kHz) vs. Time (s)
- Waves with different $n$ values ($n=1, 2, 3, 4$) are shown
Maximum in Density Fluctuations Located Closest to Maximum Gradients in $E_r$ and $V_{phi}$

Burrell 2001 APS s17
THE EHO CAUSES PARTICLE TRANSPORT — EHO MODULATES BOTH PARTICLE FLUX TO DIVERTOR AND SOL DENSITY PROFILE

- Divertor Langmuir probe Isat signal shows particle flux is modulated at EHO frequencies
  - EHO harmonics account for ~100% of the total flux to the probe

- High resolution profile reflectometer system shows scrape-off layer (SOL) density profile is modulated at EHO frequency
  - $\tilde{n}_e$ (a.u.) from $2.8 \times 10^{18} \text{ m}^{-3}$ density layer

Contour plot of divertor Langmuir probe Isat:

- Frequency vs. Time (s)
- Intensity scale (a.u.)

Contour plot of location of SOL density layers as function of time:

- Major Radius (m)
- Time (ms)

Burrell 2001 APS s15
IMPURITIES AT THE PLASMA EDGE ARE EXHAUSTED FASTER IN THE QH–MODE PHASE THAN IN THE ELMING PHASE

- The impurity particle confinement time at the plasma edge increases with the pedestal density
- EHO exhausts impurities faster than ELMs
QH-mode Operation Has Moderate Heat Flux to the Divertor Target Plates

- Heat flux in QH-mode lower than for H-mode at comparable power and density
  - QH heat flux higher than high density, low power H-mode
  - Raises question of coupling QH-mode to radiative divertor

![Diagram showing heat flux comparison between QH-mode and H-mode](chart.png)

Burrell 2001 APS s11
Quiescent H-mode in ASDEX Upgrade

- Extended ELM-free period with stationary (low) density and radiation
- Confinement (here: poloidal beta) at or above ELMy H-mode
- High ion temperature at pedestal and in core often higher than in ELMy H-mode (but same R/Lₜ)
- Strong core toroidal rotation (ctr-ᵣ) in the absence of sawteeth
Hallmark of QH-mode: “Edge Harmonic Oscillation” (EHO)

AUG, JET: n=1 fundamental m for resonance in steep gradient region
ECE: $\xi$ in phase outside/inside resonant surface – i.e. no island – kink (?)
Si laser blow-off demonstrates impurity transport

Si XIII line (He-like)
λ=0.665 nm
Flat crystal Bragg spectrometer

Intensity decays despite electron density increases:
Radial transport of Si in between ELMs

QH decay time of several hundred ms comparable to ELMing plasma at similar parameters

IAEA Fusion Energy Conference 2004, Vilamoura

Suttrop, 2004 IAEA s12

Wolfgang Suttrop, Studies of Quiescent H-mode
Large radial electrical field exists in barrier region

Doppler reflectometry: \( v_{\perp} \sim v_{\text{ExB}} \)

QH-mode: peak \( E_r \) \(~ -60 \text{ kV/m, twice as large as in ELMy phase} \)

Significant IERl found in DIII-D (charge exchange recombination spectroscopy)

This large IERl can reverse the precession drift from ion- to electron-direction: Resonance with EHO

G D Conway et. al. PPCF 46 (2004) 951

Suttrop, 2004 IAEA s17
Wolfgang Suttrop, Studies of Quiescent H-mode
Quiescent H-mode in JET

Low recycling conditions:
- long He glow + pumping
- Be evaporation

Various combinations of $I_p$, $B_t$ ($q_{95} = 3.3-4.9$)

Quiescent H-mode phases observed with up to 1.5 s duration

Longest phases after fresh wall treatment.

IAEA Fusion Energy Conference 2004, Vilamoura

Suttrop, 2004 IAEA s6
Wolfgang Suttrop, Studies of Quiescent H-mode
Pedestal pressure in QH phase is smaller than in ELMy phase

- Pedestal parameters were almost constant during QH phase.

$T_e$, ECE

$3.4s (18\tau_E)$

$41\% n_{GW}$

$T_i^{\text{ped}}$ was also smaller in QH phase

Oyama 2004 IAEA s9
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
Edge Operating Points of QH-mode Discharges are Near but Below Peeling-ballooning Mode Stability Boundary

- Stability is calculated with ELITE code [P.B. Snyder et al., Phys Plasmas (2002)]
- Modes are driven unstable by edge pressure gradient and edge current
- QH-mode plasma with EHO operates near but below peeling stability boundary
- ELMing cases are closer to peeling boundary

Burrell, 2012 IAEA poster s7
Increased Edge Stability Motivates Work At High Triangularity

• New divertor configuration allows stronger pumping of high triangularity plasma

• ELITE calculations for previous experimental results show high triangularity plasma allows ELM-free operation at higher edge pressure

Burrell 2006 APS s8
Stronger Plasma Shaping Allows QH-mode Operation with Higher Pedestal Pressure

- Higher triangularity gives higher stable $p'$ and broader pedestal width
  - Doubled $n_e^{\text{ped}}$ to 0.25 $n_{GW}$

Improved operating point and broader stable region seen for double null shape
Higher Pedestal Density in Strongly Shaped DN Consistent With Peeling-Ballooning Stability

- Theoretical prediction consistent with experimental observation of higher pedestal density in double null plasma

Snyder, NF, 2007, 47, 961 (2007)

Burrell 2008 APS Inv s19
For ITER: Stability Calculations Predict ITER Pedestal will Operate on Peeling Boundary Where QH-mode can Exist

- Theoretical calculations [Snyder et al., NF (2007)] show that ITER edge will be on the peeling stability boundary for pedestal densities up to $1.2 \times 10^{20}$ m$^{-3}$
  - Pedestal density of $1.2 \times 10^{20}$ m$^{-3}$ is well above ITER design value

- ITER’s pedestal will be in the QH-mode parameter range of collisionality and beta

Burrell, 2012 IAEA poster s32
EHO CAN SPONTANEOUSLY CHANGE TOROIDAL MODE NUMBER

- Edge harmonic oscillations directly measured in $B_{pol}$, $n_e$ and $T_e$

![Graph showing edge harmonic oscillations](image)

- Frequency (kHz) vs. Time (ms)
- Modes: $n=1, 2, 3, 4, 5$

Burrell 2004 APS Inv s19
EDGE $E_r$ WELL CHANGES LITTLE WHEN EHO SWITCHES FROM $n = 1, 2$ DOMINATED TO $n = 3$ DOMINATED

**Shot 106999 at Times 3550.0 – 3750.0 ms**

$E_r$ during $n = 1, 2$ dominated EHO

**Shot 106999 at Times 3790.0 – 4000.0 ms**

$E_r$ during $n = 3$ dominated EHO

$E_r$ (kV/m)

$R - R_{sep}$ (cm)

$E_r$ (kV/m)

$R - R_{sep}$ (cm)

$I_p = 1.3$ MA

$B_T = 2.0$ T

$P_B = 9.1$ MW

Burrell 2003 APS s27
Theory of Edge Harmonic Oscillation Based on Effect of Rotational Shear on Peeling-Ballooning Stability

- **Theory**¹: EHO is low-n Kink-Peeling mode destabilized by rotational shear just before edge plasma reaches zero-rotation stability boundary (ELM)

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

- **Prediction**: Rotational shear effect independent of direction of plasma current → QH-mode should be possible with both co- and counter-NBI

ELITE calculations show low-n = 3, 4 kink-peeling modes destabilized by sufficient edge rotation shear

1. Snyder, NF 2007

Burrell 2008 IAEA s7
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

- 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

Burrell 2008 APS Inv s31
Peeling-Ballooning Stability Analysis Shows Excellent Edge Stability in Co-NBI QH-Mode Shots

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

Diagram showing contours and stability regions in the context of edge current and normalized pressure gradient.
QH-mode Obtained with Strong Edge Rotation Shear Magnitude, But Lost If Too Small, Consistent With Stability Theory

- QH-mode can be accessed both with co-lp and counter-lp rotation
- Minimum pedestal velocity shear necessary for QH-mode consistent with theory predictions

Burrell 2008 IAEA s23
Counter Plus Co- NBI Allows Toroidal Rotation Control

⇒ Rotation control

Burrell 2006 APS s3
QH-mode is lost if rotation velocity shear is too small, consistent with stability theory.

- QH-mode can be accessed both with co-Ip and counter-Ip rotation.
- Minimum pedestal velocity shear necessary for QH-mode consistent with theory predictions.
- Balanced beam injection results in low edge rotation shear:
  - EHO absent and plasma is standard ELM-free H-mode
  - Rising density and radiated power

Burrell 2008 IAEA s23
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 $E \times B$ rotation. (Xi Chen, 2016 IAEA s3)

- A series of NBI torque ramp QH-mode experiments were carried out to investigate the critical $E \times B$ shear ($\omega_{EB}$).

The graphs show:

- NBI torque
- Hahm-Burrell $\omega_{EB}$ ($\rho \approx 0.945$)

EHO appears when $\omega_{EB} > \omega_{crit}$

EHO disappears, ELMs appear when $\omega_{EB} < \omega_{crit}$
Shear in Edge Rotation Driven by Radial Electric Field Is Important Quantity in Maintaining QH-mode Edge

- $\Omega = \text{Carbon impurity ion rotation}$
- $\omega_E = \frac{E_r}{\left( R B_\theta \right)} = \text{Toroidal rotation driven by ExB drift}$
- $\Delta$ evaluated across the outer half of the edge pedestal

![Graph showing shear in edge rotation](image-url)

Garofalo 2010 IAEA s17
Shear in Edge Rotation Driven by Radial Electric Field Is Important Quantity in Maintaining QH-mode Edge

- Threshold near $\Delta \omega_E/\omega_A \sim 0.7\%$ emerges for QH-mode operation
QH-mode Critical Rotation Shear in $\omega_E = E_r/RB_\theta$; Shear on Inside of Er Well Larger in QH-mode Than in ELMing, Outside Similar

- Shear is evaluated across outer half of H-mode edge pedestal

![Graph showing shear comparison between QH-mode and ELMing H-mode](image)

Garofalo 2010 IAEA

Burrell 2014 APS
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 \((\omega_{\text{ExB}})\).

\[ \text{EHO appears when } \omega_{\text{ExB}} > \omega_{\text{crit}} \]

\[ \text{EHO disappears, ELMs appear when } \omega_{\text{ExB}} < \omega_{\text{crit}} \]

Xi Chen, 2016 IAEA s3
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

- $\omega_{ExB}^{\text{crit}}$ decreases with pedestal $v_e^*$
  - No clear dependence on $n_e^{\text{ped}}$ seen
  - $v^*$ effects on $J_{ES}$ 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:

$$\omega_{ExB}^{\text{crit}} = 0.038 + (0.22 \pm 0.06)v_e^*$$
Addition of Rotational Shear Modifies Pedestal Instability Boundaries Differently for Peeling vs Ballooning Modes

- Rotational shear is destabilizing for low $n$ modes along peeling boundary
- Rotational shear is stabilizing for medium $n$ ballooning modes

Burrell 2014 APS poster s3
Addition of Rotational Shear Modifies Pedestal Instability Boundaries Differently for Peeling vs Ballooning Modes

- Rotational shear is destabilizing for low \( n \) modes along peeling boundary
  - Rotational shear is stabilizing for medium \( n \) ballooning modes
- After L-H transition at low density operating point moves up toward peeling boundary
- EHO destabilized before pedestal reaches hard, current driven ELM
- Finite amplitude EHO enhances transport to produce pedestal equilibrium w/o ELMs
- Multiple feedback loops allow EHO to reach steady state
  - Rotation shear driving EHO saturates by drag on the wall
  - Bootstrap current drive reduced by transport

Burrell 2014 APS poster s4
EHO and QH-mode Lost For Heating Without Torque Injection Because Edge Rotation Shear is Too Small

- Brilliant idea (Garofalo) from core error field/locked mode research:
  - Neoclassical Toroidal Viscosity (NTV) from applied non-resonant 3D magnetic perturbation fields can produce torque on plasma
  - If NTV could be made strong in the pedestal this might yield ExB velocity shear needed for EHO
  - Need to optimize applied 3D field spectrum

Burrell 2008 IAEA s23
Non-axisymmetric Fields can Generate Significant Torques through Neoclassical Toroidal Viscosity

- Small ($\delta B/B_0 \sim 10^{-3}$) non-resonant magnetic fields (NRMF) generate neoclassical toroidal viscous torque on bulk plasma of the form

$$\frac{\partial \left\langle \rho_m R^2 \Omega \right\rangle}{\partial t} \bigg|_{NTV} = -\rho_m \mu_{||} (\Omega, \nu) \left( \frac{\delta B_{3D}}{B_0} \right)^2 \left( \left\langle R^2 \Omega \right\rangle - \left\langle R^2 \Omega \right\rangle_{NTV} \right)$$

which is absent in perfect axisymmetry

- Neoclassical offset velocity $V_{\phi}^{NTV} = R^3 \Omega^{NTV}$ is in the counter $I_p$ direction
  - Nonzero offset has been seen experimentally [A.M. Garofalo et al., Phys. Rev. Lett. (2008)]

- NTV torque is in the counter-$I_p$ direction for $V_{\phi} > V_{\phi}^{NTV}$

- $\mu_{||} (\Omega, \nu)$ has a strong local peak near $\Omega = 0$
  - Peak has been seen experimentally [A.J. Cole et al., Phys. Rev. Lett. (2011)]

- In counter-rotation, NRMF maintains rotation shielding $T_{NRMF} \propto -(V_{\phi} - V_{\phi}^{NC})$
Non-axisymmetric Coils on DIII-D Allow Creation Of Non-Resonant Magnetic Perturbations (NRMFs)

- Two sets non-axisymmetric coils can be used to correct intrinsic n=1 error fields and apply n=3 magnetic perturbations

- Several configurations used for NTV experiments in QH-mode

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Burrell, 2012 IAEA poster s10
Mostly Nonresonant Magnetic Fields (NRMFs) Applied Using the I-coil

- Toroidal mode number $n=3$
- Odd-parity (up-down anti-symmetric) configuration

- C-coil can augment $n=3$ field, but adds more resonant components

Garofalo 2010 IAEA s7
External 3D Fields Sustain Low Collisionality QH-mode Plasma With No ELMs and Zero-Net NBI Torque

- ELMs a serious challenge for acceptable edge conditions in ITER
- ELM-stable regime of quiescent H-mode (QH-mode) seen in many low-collisionality tokamaks
  - Previously required significant NBI torque
- Application of nonresonant magnetic fields enables QH-mode operation in plasmas with zero-net NBI torque
  - Path toward QH-mode in self-heated burning plasma regime
- We propose this as a new regime to be investigated for ITER

Pedestal collisionality $\nu^*_{ped} \sim 0.07$

- $\beta_N \geq 2$
- $n=3$ I-coil (kA)
- $n=3$ C-coil (kA)
- $H_{89P} \geq 2$
- $D_\alpha (10^{14} \text{ ph/cm}^2/\text{sr/s})$ No ELMs
- $T_{NBI} (\text{Nm})$ Zero-net NBI torque

Garofalo 2010 IAEA s2
Radial Profiles of Rotation with and Without Torque from NRMF Show Clear Effect of n=3 Field

- With NRMF, counter-$I_p$ rotation and strong edge rotational shear maintained even for co-$I_p$ NBI torque
  - QH-mode needs edge rotational shear
- Without NRMF, co-$I_p$ NBI torque yields co-$I_p$ rotation
- Comparison made at similar NBI torque ($\sim 1.4$ Nm) and density ($\sim 3.6 \times 10^{19} m^{-3}$)
Larger Counter-Ip Rotation with n=3 NRMF from External C-coil Qualitatively Consistent with Prediction from NTV Theory

- Shots have zero net NBI torque and similar density
- Shot with larger counter-IP rotation uses C-coil for dominant NRMF
  - Other shot uses I-coil
- Larger counter-Ip rotation for same NBI torque implies larger counter-Ip NTV torque with C-coil
  - Consistent with IPEC-NTV code predictions
- This scenario pushed to low q95 (high Ip) yields fusion gain product $\beta_N H_{98}/q_{95}^2 = 0.4$ needed for ITER $Q=10$

Burrell 2011 APS Inv s31
With Zero NBI Torque Input, Shear in Edge ExB Rotation Needed To Maintain QH-mode Provided by NTV from NRMFs

- With NRMF: large shear in edge velocity of impurity C ions not required to sustain QH-mode
- Large shear in edge $\omega_E$ rotation (toroidal rotation driven by ExB drift) better correlates with QH-mode

Garofalo 2010 IAEA s16
QH-modes with NRMFs From Either Internal or External Coils Operate Near Peeling Stability Boundary

- Operating point near peeling boundary is similar with and without NRMF
- $n=3$ NRMF from I+C-coils

![Graph showing NRMFs from internal + external coils](image)

- $n=3$ NRMF from C-coil only (7.1 kA)

![Graph showing normalized pressure gradient vs. edge current](image)

Burrell, 2012 IAEA poster s17
Surprise: QH-mode Shows Improvement in Confinement at Low NBI Torque and Rotation

- Confinement quality of other H-mode plasmas in DIII-D generally reduced with lower NBI torque and rotation rate
  - Standard type-I ELMing
  - ELM suppressed
  - Advanced inductive
  - ITER baseline ($q_{95} \sim 3.1$, shape, beta...)

1. Solomon et al., TTF (2012)

Burrell, 2012 IAEA poster s26
QH-mode Critical Rotation Shear in $\omega_E = E_r/R\theta$; Shear on Inside of Er Well Larger in QH-mode Than in ELMing, Outside Similar

- Shear is evaluated across outer half of H-mode edge pedestal

Normalized $\omega_E$ shear

$\frac{\Delta \omega_E/\Delta r}{\omega_A}$ (m$^{-1}$)

Normalized carbon rotation shear

QH-mode
Std. ELM-free H-mode
ELMing H-mode

Garofalo 2010 IAEA

Burrell 2014 APS
Coherent EHO Disappears at Small Rotation - Only Broadband MHD Remains

\[ \beta_N \sim 1.5-1.7, \quad q_{95} = 5.5 \]

Burrell 2014 APS poster s?
EHO Character Correlated With Shear on Inner Side of Er Well Not With Shear on Outer Side

- **ExB Shear on inner side of Er well may be key to EHO**

Burrell 2014 APS, MEF 2014 PEP
<table>
<thead>
<tr>
<th>Selected Experimental References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen, Xi et al., NF, 56, 076011 (2016)</td>
</tr>
</tbody>
</table>
Rapid Transition to Improved Pedestal Pressure First Seen in Double Null Shots with Neutral Beam Torque Ramp Down

- Pedestal height and width rapidly increase in high $\delta$, DN QH-mode plasmas without ELMs during injected torque ramp down
  - $P_e^{PED} \uparrow 60\%$, $W_e^{PED} \uparrow 50\%$, $\tau_E \uparrow 40\%$

- Improved pedestal with reactor-relevant plasma parameters
  - $\beta_N = 1.5-2.3$, $H_{98y2} = 1.2-1.3$, $v^{*e}_e (PED) = 0.3-0.4$

- Transition associated with
  - Changes in structure of edge Er well – Less Er shear, Less EHO drive
  - Increased density and shorter $\lambda$ broadband MHD fluctuations

- Improved pedestal collapses when torque is increased again

M.E. Fenstermacher - 2019 IIS Lecture
Chen et al., Nucl. Fusion (2017)
Burrell, 2015 PD APS Inv s6
Torque Needs to be Reduced Sufficiently to Access the Wide-Pedestal QH Regime

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

- Transition into wide-pedestal occurred in 0, 1, and 2 Nm cases
  - 2.7 Nm case stayed in standard QH with EHO

- Post transition plasma has pedestal width greater than standard H- or QH-modes

- Working Hypothesis: Wider pedestal due to changes in turbulent transport caused by altered ExB shear

Chen 2016 IAEA s12
Both Pedestal Density and Temperature Profiles Increase in Height and Width

Steep gradients move away from separatrix

ExB shear decreases outside $\rho=0.9$ and increases inside.
WPQH Operating Point Also Near Kink-Peeling Boundary, But Further From Instability than QH-mode

**Standard QH:**
- Narrow pedestal
- High rotation
- Coherent EHO
- On peeling boundary

**WPQH-mode:**
- Wide pedestal
- Low rotation
- Broadband MHD
- Below peeling boundary

Burrell, 2015 PD APS Inv s20
Magnetic Probes Show Increased Broadband MHD Always Occurs at Transition to Wide Pedestal

- Coherent EHO does not inhibit wide pedestal

Burrell, 2015 PD APS Inv s11
Magnetic and Edge Density Fluctuations Both Increase at Transition to Wide Pedestal QH-mode

- Density fluctuations with $k_\theta \rho_s \approx 1$ measured using Doppler Back Scattering (DBS)
- Magnetic fluctuations measured with magnetic probes
- In this case, magnetic fluctuations from coherent EHO cease at transition
Increased Edge Transport Reduces $P'$ Allowing Higher Pedestal Pressure While Remaining Below PBM Limit

- Additional edge transport allows higher pedestal without ELMs

**Graphical Representation**

1. **Edge transport increases**

2. **1.5X wider than EPED KBM constraint at measured pedestal height**
   - EPED* scaling: $\Delta \psi_N = \beta_{p, ped}^{1/2} G$

3. **Additional edge transport allows higher pedestal without ELMs**

---

* Xi Chen, 2015 HMWS s4

* P.B. Snyder, *et al.*, NF 51, 103C

* Xi Chen, NF, 57, (2017) 086008
TRANSP Analysis Shows Transport Improvement in Outer Core ($\Psi_N \sim 0.75-0.9$) Consistent with Global Confinement Improvement

- Outer-core region ($Y_n \sim 0.8-0.9$): ExB rotation, ExB shear, ne fluctuations, transport, confinement
  - Similar to previous findings of improved outer core transport\(^1\)


M.E. Fenstermacher - 2019 IIS Lecture
NBI Torque to Initiate and Sustain Wide Pedestal QH-Mode 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
Low Torque, Wide-Pedestal QH-mode Sustained with 77% ECH Power – Electron Heating

On-axis ECH replacing beam power

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

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

Electron Pedestal Width (cm)

Electron Pedestal Pressure (kPa)

Divertor $D_\alpha$ Light

Energy Confinement Time (ms)

Ernst, 2018 IAEA s14
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

Burrell APS (2017)

Ernst, 2018 IAEA s7
Preliminary Results Suggest Impurity Transport in Wide-Pedestal QH-Mode Similar to Standard H-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

Soft X-ray Emission
Wide Pedestal QH-Mode 175539
$\tau \sim 296 \text{ ms}$

Impurity Confinement Time: CER (Al)

WP QH-Mode 175539
(DN Shape)
$\tau_E = 150 \text{ ms}$

ELMy H-Mode 175849
80 Hz ELMs
(LSN Shape)
$\tau_E = 100 \text{ ms}$

Ernst, 2018 IAEA s19

Xi Chen, C. C. Petty et al., APS (2018)
So Far Wide Pedestal QH-Mode Is An Attractive Candidate Burning Plasma Regime for ITER Baseline Scenario

<table>
<thead>
<tr>
<th>Demonstrated</th>
<th>Work in Progress</th>
<th>Not Yet Addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>No ELMS</td>
<td>Reduce $q_{95}$</td>
<td>Radiative divertor</td>
</tr>
<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>
</tr>
<tr>
<td>Dominant Electron Heating (77%) with Improved $\tau_E$</td>
<td>Impurity confinement studies</td>
<td></td>
</tr>
<tr>
<td>$H_{98y} \approx 1.6$ up with power, $\beta_N \approx 2.3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sustained in LSN Shape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_e \approx T_i$</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>

Ernst, 2018 IAEA s17
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 $\text{ExB}$ 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

---

Xi Chen, 2016 IAEA s2
## Selected Experimental References

<table>
<thead>
<tr>
<th>Reference</th>
<th>Journal</th>
<th>Volume</th>
<th>Issue</th>
<th>Page</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burrell et al.</td>
<td>PoP</td>
<td>23</td>
<td>056103</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Xi Chen et al.</td>
<td>NF</td>
<td>57</td>
<td>022007</td>
<td>2017</td>
<td></td>
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<tr>
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<td>NF</td>
<td>57</td>
<td>086008</td>
<td>2017</td>
<td></td>
</tr>
<tr>
<td>Ernst et al.</td>
<td>NF</td>
<td>58</td>
<td>submitted</td>
<td>2018</td>
<td></td>
</tr>
</tbody>
</table>
Basic Requirements of Any ELM Control Technique for ITER and Future Reactors (adapted from Loarte IAEA12/NF14)

Requirements for H-mode without ELMs or small ELM regimes (either natural or actively mitigated eg via pellets, RMP) include:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Pellet ELM Pacing</th>
<th>I-mode</th>
<th>QH-mode</th>
<th>WPQH-mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>High $\tau_E$ (H98~1), Low-$q_{95}$~3</td>
<td>Marginal</td>
<td>Yes/Yes</td>
<td>Yes/??</td>
<td>Yes/??</td>
</tr>
<tr>
<td>Sufficient particle flux for stationary $n_e$, low impurities</td>
<td>Marginal</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Accessible in BP conditions - low torque</td>
<td>??</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Accessible in BP conditions - low $\nu^*$</td>
<td>??</td>
<td>??</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Compatible with radiative divertor</td>
<td>??</td>
<td>??</td>
<td>??</td>
<td>??</td>
</tr>
<tr>
<td>Compatible with fueling/pumping sys</td>
<td>Marginal</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Compatible with low $P_{L-H}$</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Compatible with Pinj~$P_{L-H}$</td>
<td>Yes</td>
<td>Yes</td>
<td>??</td>
<td>??</td>
</tr>
<tr>
<td>Compatible with ICRF and Fast Ions</td>
<td>Marginal</td>
<td>Yes</td>
<td>??</td>
<td>??</td>
</tr>
<tr>
<td>Compatible with High-Z PFCs</td>
<td>Yes</td>
<td>Yes</td>
<td>??</td>
<td>??</td>
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</tbody>
</table>