DEPENDENCE OF THE L- TO H-MODE POWER THRESHOLD ON TOROIDAL ROTATION AND THE LINK TO EDGE TURBULENCE DYNAMICS

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DEPENDENCE OF EDGE TURBULENCE DYNAMICS
AND THE L-H POWER THRESHOLD ON TOROIDAL ROTATION

- Power flux required to trigger an L-H transition increases rapidly with injected torque and toroidal rotation

- Edge turbulence characteristics change dramatically and consistently with toroidal rotation

- Radial electric field shear increases more rapidly at low rotation

- Connection between toroidal rotation and ion $\nabla B$ drift dependence

- Mechanism appears to depend on complex interplay of radial electric field, turbulence and zonal flow dynamics in edge region of plasma
**CO-ROTATING DISCHARGE REQUIRES TWICE THE INJECTED POWER OF BALANCED INJECTION DISCHARGE TO UNDERGO L-H TRANSITION**

- Upper-Single-Null plasmas: ion $\nabla B$ drift away from X-point
  - Higher L-H power threshold than with ion $\nabla B$ drift towards X-point

- Beam power ramped gradually

- Co and counter NBI sources control torque and power

- Fluctuating $D_\alpha$ phase determined to be L-mode

- $P_{\text{LH}, \text{co}} = 6$ MW
  $P_{\text{LH}, \text{balanced}} = 3$ MW

**Graphs and Data**

- $I_p = 1$ MA
- $B_T = -2$ T

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*International Atomic Energy Agency Fusion Energy Conference, Geneva, Switzerland - G. McKee- October, 2008*
**PLH Increases Significantly with Increasing Neutral Beam Torque**

- Factor of 4 increase in $P_{ LH}$ with rotation and $\nabla B$ away from X-Point
- Factor of 2 increase with $\nabla B$ towards X-Point
- Difference in $P_{ LH}$ between $\nabla B$ drift directions increases with rotation
**$P_{LH}$ Increases Significantly with Increasing Neutral Beam Torque**

- Factor of 4 increase in $P_{LH}$ with rotation and $\nabla B$ away from X-Point
- Factor of 2 increase with $\nabla B$ towards X-Point
- Difference in $P_{LH}$ between $\nabla B$ drift directions increases with rotation

**Graph:**
- Red dots: $\nabla B$ away from X-point
- Blue squares: $\nabla B$ towards X-point

**Legend:**
- Lower Single Null: $\nabla B$ towards X-Point
- Upper Single Null: $\nabla B$ away from X-Point

**Axes:**
- Torque (N-m)
- $P_{LH}$ (MW)

**Diagram:**
- Shows ion drift and $\nabla B$ directions for different nulls.
$P_{LH}$ INCREASES SIGNIFICANTLY WITH INCREASING NEUTRAL BEAM TORQUE

- ECH used in conjunction with NBI to examine importance of neutral beam ion orbit effects
- Density is 25% higher in ECH shots for operational reasons
- Similar trend with torque is observed:

No significant beam-orbit effect
$P_{\text{LH}}$ INCREASES SIGNIFICANTLY WITH INCREASING NEUTRAL BEAM TORQUE

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ROTATIONAL DEPENDENCE MAY EXPLAIN SIGNIFICANT UNCERTAINTY IN $P_{LH}$ SCALING RELATION

- L-H Threshold scaling relation (red band)
  
  $P_{LH}^{Scaling} = 0.042 n_{20}^{0.73} B_T^{0.74} S^{0.98} (MW)$

- $P_{LH}$ values in range of scaling relation, but large variation suggests a “hidden variable,” such as rotation
LH TRANSITION INDUCED VIA TORQUE-SCAN AT CONSTANT POWER

- $P_{LH} = 3$ MW
- Consistent with previous measurements
- Slowly evolving turbulence characteristics

$\nabla B$ away from X-point

Total Beam Power (MW)

Co-Injected Power (MW)  CTR-Injected Power (MW)

Toroidal Rotation (km/s)

$\rho = 0.7$

$D_\alpha$ Divertor Recycling

Visualizations of edge turbulence demonstrate significant variation in flow patterns and mode structure with rotation.
**SIGNIFICANT DIFFERENCE IN EDGE TURBULENCE & FLOWS BETWEEN CO-INJECTION & BALANCED INJECTION ($\nabla B$ AWAY FROM X-POINT)**

- For $\rho = 0.9$:
  - Power Spectra (a.u.)
  - Temperature
  - Phase Shift (rad)
  - Frequency (kHz)
  - Ion Direction
  - Electron Direction
  - $\Delta Z = 1.2$ cm

- For $\rho = 0.98$:
  - Power Spectra (a.u.)
  - Temperature
  - Phase Shift (rad)
  - Frequency (kHz)
  - Ion Direction
  - Electron Direction
  - Edge $v_\theta$ Reversal
  - $129125(2050-2150 \text{ ms})$
  - $129127(1375-1475 \text{ ms})$
Plasmas with ion $\nabla B$ towards X-point exhibit similar flows as well as multiple turbulence modes.

**$\rho = 0.9$**

Power Spectra (a.u.)

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Power (a.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10^-9</td>
</tr>
<tr>
<td>50</td>
<td>10^-7</td>
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<tr>
<td>250</td>
<td>10^0</td>
</tr>
<tr>
<td>300</td>
<td>10^1</td>
</tr>
</tbody>
</table>

**Phase Shift (rad)**

Ion Direction

Electron Direction

**$\rho = 0.98$**

2 Counter Propagating Modes

1) low-f e-mode
2) high-f i-mode

Frequency (kHz)

Multi-Mode Structure Observed in Balanced-Injection Plasmas with $\nabla B$ Away from X-Point

- Dual-mode structure observed in both balanced injection discharges with $\nabla B$ away from X-point,
  
  $\textit{AND}$
  
  Co-injected discharge with $\nabla B$ towards the X-point
- Two conditions have similar $P_{\text{LH}}$
- Correlation with dual-mode structure and lower LH power threshold

![Graph](image)

$$\rho = 0.98$$
Radially-sheared poloidal turbulence flows evolve differently for co- and balanced-injection plasmas.

- Turbulence poloidal velocity obtained via cross-correlation analysis
- Gradual evolution and increasing shear in Co-injection discharge
- Sudden “reversal” of poloidal flow in balanced prior to LH
RADIA L Y-SHEARED POLOIDAL TUR B UL E N CE FLOWS EVOLVE DIFFERENTLY FOR CO- AND BALANCED-INJECTION PLASMAS

- Turbulence poloidal velocity obtained via cross-correlation analysis
- Gradual evolution and increasing shear in Co-injection discharge
- Sudden “reversal” of poloidal flow in balanced prior to LH
LH Transition Occurs as Shearing Rates Increase and Exceed Turbulence Decorrelation Rates

- BES data allow for independent measurement of poloidal velocity, velocity shear, and turbulence decorrelation rates.

**Co-Injection, ∇B away from X-point**

\[ \omega_s \sim (\tau_c)^{-1} \]

**Decor. Rate / Shear Rate**

- Decor. Rate
- Shear Rate

\[ \omega_s = dv_\theta/dr \]

**Velocity Shearing Rate**

**Turbulence Decorrelation Rate**

LH Transition occurs as shearing rates increase and exceed turbulence decorrelation rates.

- BES data allow for independent measurement of poloidal velocity, velocity shear, and turbulence decorrelation rates.

Co-Injection, \( \nabla B \) away from X-point

\[ \omega_s > (\tau_C)^{-1} \]

\[ \omega_s = \frac{d v_\theta}{dr} \]

D. Schlossberg et al., submitted to PRL (2007)
LH Transition Induced Via Torque-Scan at Constant Power

- $P_{LH} = 3$ MW
- Consistent with previous measurements
- Slowly evolving turbulence characteristics

$\nabla B$ away from X-point

Total Beam Power (MW)

Co-Injected Power (MW)

CTR-Injected Power (MW)

Toroidal Rotation (km/s)

$D_\alpha$ Divertor Recycling

**Edge Turbulence Poloidal Flow Reverses During Constant-Power Torque Scan**

- Reversed $v_\theta$ during balanced injection, shortly before LH-transition.
- Shear increases as rotation varied from co- to balanced.

**Power Spectra (a.u.)**

- Co-Injection
- 3/4 Co
- Balanced

**Phase Shift (rad.)**

- Ion Direction
- Electron Direction

Break in phase reflects dual modes

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**Poloidal Velocity Spectrum Evolves From GAM-Dominated to Low-Frequency Zonal Flow as Plasma Rotation Slows**

- Time-Delay-Estimation (TDE) methods applied to poloidally-separated BES measurements to determine $v_\theta(t)$ ($t = 20 \mu s$ resolution, 25 kHz)

- GAM oscillation identified in $v_\theta(t)$ spectra ($E_r$ oscillation $\Rightarrow v_\theta(t)$)

- GAM dominates ZF spectrum at high rotation
  - gradually decays in amplitude and disappears as plasma slows

**Geodesic Acoustic Mode:**
- coherent
- $m=0$, $n=0$
- finite $k_r$
- $f=15$ kHz
  $\approx c_s/2\pi R$
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  - *gradually decays in amplitude and disappears as plasma slows*

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**Geodesic Acoustic Mode:**
- coherent
- $m=0$, $n=0$
- finite $k_r$
- $f \approx 15 \text{ kHz}$
  - $c_s/2\pi R$

**GAM decays with time**
POLIODAL VELOCITY SPECTRUM EVOLVES FROM GAM-DOMINATED TO LOW-FREQUENCY ZONAL FLOW AS PLASMA ROTATION SLOWS

- Time-Delay-Estimation (TDE) methods applied to poloidally-separated BES measurements to determine $v_\theta(t)$ ($t = 20 \mu s$ resolution, 25 kHz)

- GAM oscillation identified in $v_\theta(t)$ spectra ($E_r$ oscillation $\Rightarrow v_\theta(t)$)

- GAM dominates ZF spectrum at high rotation
  - gradually decays in amplitude and disappears as plasma slows

- Zero-Mean-Frequency Zonal Flow arises and dominates spectra
  - ZMF-ZF power significantly higher than GAM power
  - Lower frequency shears more effectively (Hahm-1999)
  - More likely to trigger transition?


Geodesic Acoustic Mode:
- coherent
- $m=0$, $n=0$
- finite $k_r$
- $f = 15$ kHz $\approx c_s/2\pi R$

GAM decays with time

ZMF-ZF signature arises at low-frequency prior to LH
CONCLUSIONS

- Power flux required to trigger an L-Mode to H-mode transition increases with applied torque and toroidal rotation
  - Affects plasmas with ion $\nabla B$ drift towards and away-from $X$-point
  - ECH+NBI exhibit similar trend as NBI-only (not a beam ion effect)

- Edge turbulence characteristics change dramatically and consistently with toroidal rotation:
  - Radially sheared poloidal turbulence flows
  - Shear exceeds turbulence decorrelation rates prior to transition (all cases)
  - Zonal flow behavior strongly dependent on rotation: candidate trigger mechanism

- Connection between toroidal rotation and ion $\nabla B$ drift dependence

- Mechanism appears to depend on radial electric field, turbulence, flows, and zonal flow dynamics in edge region of plasma

- Beneficial implications for accessing H-mode in slowly rotating plasmas
  - Presently $P_{LH}$ scaling does not consider rotation
Radial Electric Field Terms Favor Higher Edge $E_R$ Shear in Balanced Injection Plasma, Facilitating L-H Transition

- Consider model of ExB shear suppression of turbulence
- $\nabla P$ term dominates $E_r$ and $E_r'$ near the plasma edge in balanced-INJ discharges

Radial Electric Field:

$$E_r = \frac{\nabla P}{Z I e n_i} + v_{\phi,i} B_\theta - v_{\theta,i} B_\phi$$

Eddy

Pressure Gradient

Rotation

$E_r$ prior to LH Transition

Co-INJ $P_{INJ} = 5.9$ MW

Bal-INJ $P_{INJ} = 2.9$ MW

Radial Electric Field Terms Favor Higher Edge $E_R$ Shear in Balanced Injection Plasma, Facilitating L-H Transition

- Consider model of ExB shear suppression of turbulence
- $\nabla P$ term dominates $E_r$ and $E_r'$ near the plasma edge in balanced-INJ discharges

Radial Electric Field:

$$E_r = \frac{\nabla P}{\nabla T} + v_{\phi,i}B_\theta - v_{\theta,i}B_\phi$$

$E_r$ prior to LH Transition

$P_{\text{INJ}} = 5.9$ MW

$P_{\text{INJ}} = 2.9$ MW

$E_r, \nabla P$

$E_r, vxB$

Radial Electric Field Terms Favor Higher Edge $E_R$ Shear in Balanced Injection Plasma, Facilitating L-H Transition

- Consider model of $E_xB$ shear suppression of turbulence
- $\nabla P$ term dominates $E_r$ and $E_r'$ near the plasma edge in balanced-INJ discharges

Radial Electric Field:

$$E_r = \frac{\nabla P_I}{Z_I en_I} + v_{\phi,i} B_\theta - v_{\theta,i} B_{\phi}$$

Eddy

$\nabla B$ away from X-point

Graphs showing $E_r$ for Co-INJ and Bal-INJ injection with different injection powers:

- Co-INJ $P_{INJ} = 5.9$ MW
- Bal-INJ $P_{INJ} = 2.9$ MW


Co-Current and Counter-Current NBI Injection and Array of Fluctuation Diagnostics Facilitate Detailed Examination

Plan View of the DIII-D Tokamak

Doppler Reflectometer
\((v_\theta(t), \tilde{n}_e)\)

CER
\((T_i, v_{tor}, E_r)\)

BES
\((\tilde{n}(r,Z), \tilde{V}(r,Z))\)

Reciprocating Langmuir Probe
\((M, \phi, n)\)
Rapid Fluctuation Suppression Observed in Edge at LH Transition

BES Measurements of density fluctuation spectra

\[ r/a = 0.95 \]

Fluctuation Power Spectrum \( (V^2/\text{kHz}) \)

\[ 129143, \text{ ST: 1600/1700} \]
\[ \text{NP:1k/NB:75, ALT-CP} \]

L-H transition

L-mode

H-mode

Fluctuation Level (a.u.)

Minor Radius \( (r/a) \)

\[ 129143, \text{ Ch-1} \]
\[ r/a = 0.90 \]

\[ 129143, \text{ Ch-25} \]
\[ r/a = 1.02 \]

\( \nabla B \) away from X-Point

Beam ion prompt losses appear not to have a significant impact on LH transition power threshold.

- Similar discharges: (USN - Net Balanced NB Injection)
  1) More tangential beams
  2) More radial beams
- Beam ion confinement changes significantly between conditions
- LH power nearly identical: \( P_{\text{INJ}} \approx 2.9 \, \text{MW} \)

**Graphs:**
- \( I_p \) (MA)
- \( T_e(0) \) (keV)
- \( D_\alpha \)
- \( n_e \)

**Time (ms):**
Visualizations of edge turbulence demonstrate significant evolution in flow patterns and mode structure.

- 200 \( \mu \)s segments at 5 intervals

Doppler Reflectometer shows localized increase in \( v_\theta \) during torque scan

Mach Probe shows little change in SOL toroidal flow

DIIID National Fusion Facility