Role of stationary zonal flows and momentum transport for L-H transitions in JET

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Presented by

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• Work on L-H transition physics in JET-ILW:

• Factors known to impact threshold not included in scaling law include
  • Rotation, divertor configuration, X-point height, connection length, low density branch, and others

\[
P_L = P_{OHM} + P_{abs} - \frac{dW}{dt} - P_{Floss}
\]

\[
P_{Thresh} = 0.0488 e^{0.057 n_{e20}^{0.717 \pm 0.035} B_T^{0.803 \pm 0.032} S^{0.941 \pm 0.019}}
\]

<table>
<thead>
<tr>
<th>Density [10^{20} m^{-3}]</th>
<th>Predicted threshold power [MW]</th>
<th>95% confidence interval [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>52</td>
<td>28 - 96</td>
</tr>
<tr>
<td>1</td>
<td>86</td>
<td>46 - 160</td>
</tr>
</tbody>
</table>
Outline

• L-H transition power threshold results at high magnetic field and plasma current in JET

• Scaling of zonal flow properties and comparison to width of edge radial electric field well

• Momentum transport during L-H transitions
  • Comparison to linear and non-linear gyrokinetic simulations

• Recent results in hydrogen/deuterium mixtures
• L-H transition power threshold results at high magnetic field and plasma current in JET

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• Recent results in hydrogen/deuterium mixtures
Same divertor configuration used for baseline and hybrid scenarios
Slow power ramp to identify L-H transitions
Excellent density control in plasma current and magnetic field scans
Scans of $B_t$ (3-3.4 T) and $I_p$ (2.2-3.2 MA) covering $q_{95} \approx 2.7 - 4.0$ at low ($\sim 2.0 - 2.3 \times 10^{19} \text{ m}^{-3}$) and high density ($\sim 3.2 - 3.3 \times 10^{19} \text{ m}^{-3}$)
Dependence on plasma current characterized

- No Ip dependence in 2008 scaling law
  - Weak dependence, $\sim I_p^{0.2}$, found in Maggi NF 2014
- Plasma current can impact power threshold in low density branch
  - Seen also in other cases in JET-ILW
- Highest threshold cases fall above scaling law prediction

Arrows indicate lower or upper bounds.
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Doppler backscattering measures the radially-localized lab frame velocity and density fluctuation level

- Doppler backscattering (DBS):
  - A refraction-localized scattering region is created near the cutoff
  - Amplitude of backscattered signal related to fluctuation level of density fluctuations
  - Doppler shift in backscattered signal induced by lab frame velocity of the turbulence
    \[ \omega_D \approx k_\perp v_{Lab} \]
    \[ v_{Lab} = u_{E \times B} + \tilde{v} \]
  - TORBEAM used to determine scattering position and wavenumber
    - \( k_\perp \approx 3 - 5 \, cm^{-1} \)

Starting during 2015 campaign, DBS measurements now routine in JET
Comparison between DBS and CXRS in L-mode

- DBS profiles built up with 2 tunable channels over ~200 ms
- Spline fits performed to CXRS components from carbon impurity to calculate $E_r$
- Comparison between CXRS and DBS implies $0 < v_{ph} < v_{dia,e}$ in L-mode well region
  - Later linear gyrokinetic calculations consistent with modes propagating in electron direction
- All later DBS profiles assume $v_{ph} = 0$
Fine-scale structure in $E_r$ profile consistent with zonal flows observed at bottom of edge well

- Wavelength of zonal flow structures varies with density
- Zonal flows stationary in time
- Small experiments at larger $\rho^*$ have observed variety of oscillatory ZF, but not stationary ZF
Simultaneous collapse of density fluctuation levels, turbulence phase velocity, and zonal flows across transition in high density branch, but not low density branch

- Hillesheim PRL 2016
- No clear ‘smoking gun’ relating stationary ZF to transition ‘trigger’
ZF wavelength correlates with radial correlation length of turbulence
\[ k_{ZF} l_r \approx 2.3 \]

Radial correlation length much smaller than well width
\[ w_{Er} \sim 5-8 \text{ cm} \]

When stationary ZF are observed, \[ \frac{\ell_r}{w_{Er}} \ll 1 \]

Data with periodic zonal flow structures used to characterize local parameter dependencies
Width of radial electric field well varies in plasma current scan

- Plasma current increased ~50% and edge temperature approximately doubles in Ip scan at 3 T, such that banana orbit width changes only marginally
  - $T_e = T_i$ within uncertainties in similar conditions where CXRS available

- Independent variation of $E_r$ well width and radial correlation length may play role as effective $\rho^*$ development of the edge transport barrier
  - May explain why stationary zonal flows observed in JET, but not in smaller experiments
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• Recent results in hydrogen/deuterium mixtures
In region where $E_r$ dominated by toroidal rotation, flow builds into core at constant gradient value

- Dashed lines at same constant slope
- Critical gradient behavior expected for temperature gradients, but surprising for rotation
Linear GS2 growth rate calculations performed in edge

- Propagation direction in electron diamagnetic direction at bottom of well, consistent with DBS vs CXRS comparisons
- Large growth rates across broad wavenumber range
  - Multi-scale effects could be important
- Growth rates insensitive to flow shear, no linear critical gradient

\[
\gamma' = \frac{R}{\rho_i} \frac{\partial \Omega_{tor}}{\partial r} \frac{a}{v_{ti}}
\]

\[u'_{exp} = 1.3\]
Non-linear gyrokinetic simulations used to investigate momentum transport close to plasma edge

- Momentum transport effects could explain apparent critical gradient behavior
  - Ratio of momentum to heat flux set by NBI input
  - Temperature held at critical gradient
  - Prandtl number constant
    - If above conditions are met, rotation gradient also held constant

- Long wavelengths only, with hyperviscosity
  - $0.02 < k_\theta \rho_i < 0.94$
- Kinetic ions and electrons
  - Electrostatic, full GS2 collision operator
- For radius $\sqrt{\psi} = 0.93$, shot 86470, where rotation gradient builds up
Non-linear consistency relation can explain apparent critical gradient behavior

\[ Pr \left( \frac{a}{L_{T_i}}, \gamma_E \right) \sim \frac{\partial T_i / \partial n}{\partial \Omega / \partial n} \Pi / Q_i \]

- **Ion heat transport stiff**, GS2 over-predicts experimental values of Qi, \( \Pi \)
  - Multi-scale effects could be important
- Flux ratio set by **NBI** & well matched by simulation
- Prandtl number varies systematically over range ~0.5-0.8

Shaded regions from TRANSP +/- 100 ms from simulation time
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Mass scaling of L-H transition

- Empirically $P_{\text{LH}} \sim 1/m_i$
  - Consistent with results from multiple experiments
    - Righi NF 1999, Gohil IAEA 2012, Ryter NF 2013

- Very little existing results in mixed species plasmas
  - Results in 50/50 D-T plasmas were consistent with $\sim 1/m_i$

- Zonal flows have been suggested as being responsible for mass dependence through ion collisions
Power threshold studied in hydrogen-deuterium mixtures in JET

- Slow, ~8 s, power ramps used to identify transition
- Same shape used for extensive mixture and isotope data set
- $Z_{\text{eff}} \approx 1.0 - 1.2$
- Minimum threshold moves to higher density due to stronger dependence in low density branch
Non-linear dependence of power threshold observed in mixed species plasmas

- Largest variations observed at high and low \( \frac{H}{H+D} \)
- Little variation in range \( 0.2 < \frac{H}{H+D} < 0.8 \)
- Experiments at end of campaign with \( H-^4He \) mixtures show drop of power threshold with helium seeding in hydrogen plasmas
  - Effect could be used during non-active phase of ITER operation

\[
P_{scal} = 0.0488 < n_e >^{0.717} B_T^{0.803} S^{0.941}
\]
Summary

- Fine-scale structure in edge flows consistent with stationary zonal flows observed during L-H transitions in JET & can vary independently of well width

- Radial correlation length of turbulence much smaller than well width, $\frac{\ell_r}{w_{Er}} \ll 1$, which may be important effective $\rho^*$ for development of edge transport barrier
  - Planned diagnostic upgrades at JET will allow DBS measurements at lower magnetic field in future, enabling this to be tested

- Momentum transport limits development of inner shear layer of well
  - Non-linear gyrokinetic simulations show consistency relation between momentum and heat flux can explain apparent critical gradient
  - Implies in strongly driven regime that $\Pi/Q_i$ (e.g. NBI voltage) can act as control knob for rotation shear

- Non-linear dependence of $P_{LH}$ in mixed species plasmas
  - Reduction of $P_{LH}$ in H-4He mixture shows potential path to access H-mode in hydrogen during non-active phase of ITER operation
L-H transition time traces

Bt=3 T, Ip=3.2 MA, q95=2.7

NBI

$10^7$ Watt

$10^4$ Joule

$10^8$ m$^{-2}$

$10^6$ W

$s$

$10^8$ Joule

$10^9$ Joule

$10^10$ Joule

ICRH/PTOT (MW)

EFIT/POHM (MW)

H/(H+D) - KS3D

H/(H+D) - KS3B

SCAL/PLTH (MW)

EDG8/TDAO

EDG8/TDAE

KG1V/LID

EDG8/TBEO

EFIT/WP (MJ)

BOLO/TOBU (MW)
L-H threshold on density characterized in three divertor configurations

- 3 T/2.5 MA in C/C and VT; 3 T/2.5-2.75 MA in HT
  - C/C shape used for hybrid and baseline scenario development
- Power threshold lowest in horizontal target
- Threshold similar in C/C and VT, even though pumping and X-point height very different
- Note: Core $P_{rad}$ estimated from weighted bolometer chord average; tomographic inversions may modify results
• Edge well shallower in C/C in Ohmic conditions
• Fine-scale zonal flow structure in $E_r$ profile coincident with steeper density gradient in C/C
• Small experiments have observed variety of oscillatory ZF, but not stationary
  • e.g. Conway PRL 2011, Estrada PRL 2011, Xu PRL 2011, Schmitz PRL 2012
Strong dependence on heating source in hydrogen, but not deuterium

- Similar to Gohil NF 2010, threshold much higher in hydrogen with more input torque
- Power threshold so low in deuterium that NBI provides little momentum input
Dependence on divertor configuration

- VT and corner, with different X-point height and pumping efficiency have similar threshold
- V5OH has lower threshold
Edge temperatures within uncertainties for ions and electrons

- 90742: 3.4 T/ 3.2 T
  - \(<n_e>=2.2 \text{ m}^{-3}\)

- High field, high current, low density
  - Extreme case where one might expect separation of temperatures

- \(T_e=T_i\) within uncertainties during time leading up to L-H transition
Hydrogen-deuterium mixture scan performed in high density branch

- Multiple $\text{H}/(\text{H}+\text{D})$ ratio measurements consistent
- Neutron rate consistent with square of thermal deuterium density over broad range
H/(H+D) measurements

![Graph showing H/(H+D) measurements at time of L-H transition.](image-url)