EX/3-3: Pedestal Confinement and Stability in JET-ILW ELMy H-modes

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25th IAEA FEC Conference, St Petersburg, Russian Federation, 2014
Acknowledgements

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*See the Appendix of F. Romanelli et al., Proc. 25\textsuperscript{th} IAEA FEC 2014, St Petersburg, Russian Federation
In JET-ILW, H-mode operation needs to be compatible with W control

- Lower $T_{e,\text{PED}}$ in initial phase of JET-ILW at all densities
- → Confinement loss is dominantly in pedestal
- $N_2$ seeding in high $\delta$ H-modes allows recovery of $T_{e,\text{PED}}$ to values approaching JET-C

(2.4-2.6 MA / 2.3-2.7 T, $P_{\text{NBI}} = 12-16$ MW), $\beta_N \sim 1.2$

Similar $p_{\text{PED}}$ at low and high $\delta$ in JET-ILW at low $\beta_N$ ($\sim 1.2$)

[Beurskens, PPCF 2013]
[Giroud, Nucl. Fusion 2013]
Experiments in 2013-2014 with the JET-ILW have investigated the pedestal confinement and stability with respect to:

- Triangularity
- Beta
- Neutrals (D and low-Z impurities)
• Lower $T_{e,PED}$ $\rightarrow$ Higher $\nu_{*P Pedro}$ $\rightarrow$ lower bootstrap current
• $\rightarrow$ plasma shaping barely affects the achievable pedestal height
• Similar $p_{PED}$ at low and high $\delta$

Triangularity alone does not recover pedestal height
Pedestal pressure and beta

- high-δ, high $\beta_p$
- high-δ
- low-δ

• Increasing power/beta increases $p_{PED}$ both at low and high $\delta$
• At low beta similar pedestal pressures
• At high $\delta$, stronger increase in $p_{PED}$ with power at constant density

Challis, EX/9-3

Low $D_2$ gas injection
Pedestal stability consistent with P-B

- Increasing core pressure stabilises ballooning modes due to Shafranov shift, which raises P-B boundary

- Pedestals limited by intermediate-\(n\) P-B instabilities before type I ELM crash, both at low and high \(\delta\)

*Low \(D_2\) gas injection*

*Challis, EX/9-3*
Power scans at higher gas rates

- Higher $D_2$ gas rate, typical of JET-ILW steady H-modes

$1.4\text{MA}/1.7\text{T}$, Low triangularity

- Lower $\beta_N$ at higher $D_2$ gas rate
- Type I ELMs
- Lower $p_{\text{PED}}$ at larger gas rate

$P_{\text{sep}} = P_{\text{heat}} - P_{\text{rad,bulk}}$
Peeling-Ballooning stability

- At low gas rates, pedestals are at P-B boundary
- At high gas rates, pedestals are stable to P-B modes at higher beta
- All type I ELMy H-modes

Weaker increase of pedestal pressure with power at high D$_2$ gas rates is not consistent with peeling-balloonning model
Varying the plasma neutral content

Neutral D content increases when

- $D_2$ injection rate is increased $\leftrightarrow$ W control tool
- Divertor configuration is varied from C/C or V/H $\rightarrow$ C/V (pumping efficiency + neutrals recirculation to main chamber)

[Tamain, PSI 2014], [Frassinetti, EPS 2014]

Joffrin, EX/P5-40
Pedestal pressure and neutrals

- **C/C**: good pumping + lower neutral content $\rightarrow n_{e,PED} \downarrow$, $T_{e,i,PED} \uparrow$
- **C/V**: good pumping + higher neutral content $\rightarrow n_{e,PED} \downarrow$, low $T_{e,i,PED}$

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<th>Major Radius [m]</th>
<th>Height [m]</th>
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**Cryopump**

**de la Luna, EX/P5-29**

**Joffrin, EX/P5-40**
In C/C, $H_{98} \sim 1$ and $\beta_N \sim 1.8$ at 2.5MA

$V/H \rightarrow C/C$

Increase of $W_{th}$ at similar $p_{PED}$ but lower collisionality

[Frassinetti, EPS 2014]
In C/C, $H_{98} \sim 1$ and $\beta_N \sim 1.8$ at 2.5MA

**V/H $\rightarrow$ C/C**

Increase of $W_{th}$ at similar $p_{\text{PED}}$ but lower collisionality

**V/H $\rightarrow$ C/V**

Low pedestal and core pressure

[Frassinetti, EPS 2014]
At high $\delta$ $N_2$ seeding increases $T_{e,\text{PED}}$

- Increase of $T_{e,\text{ped}}$ is independent of divertor configuration
- Effect on density depends on divertor configuration
- Increase of $T_{e,\text{PED}}$ with $N_2$ is weaker at low $\delta$
- The underlying physics process is not yet understood

**Giroud, EX/P5-25**
2.5MA/2.7T, High Triangularity, V/H Configuration

- With increasing $D_2$ rate, pressure gradient decreases and width increases at constant $\beta_{pol}$
- With increasing $N_2$, temperature pedestal widens and peak density gradient increases

At high gas rates, challenge for KBM based EPED model

[Leyland, Nucl. Fusion, accepted]
Conclusions

• The changeover from JET-C to JET-ILW has forced us to re-optimize pedestal confinement and stability

• What we understand within the P-B framework and EPED model:
  – Stabilizing effects of beta and plasma shaping at low $D_2$ gas rates

• What we still need to understand in order to advance our predictive capability of the pedestal height:
  – Physics process through which D neutrals degrade $T_{e,PED}$ (inter-ELM transport?...)
  – Physics process through which $N_2$ impurities increase $T_{e,PED}$
Back-up slides
Distance of operational point to P-B boundary is length of arrow, calculated at fixed pedestal width and increasing $T_{e,PED}$. 

SOLID: Experiment
OPEN: P-B Stability Boundary
Gyrokinetic analysis of the pedestal

Local flux tube simulation (GS2) indicates that JET pedestal is stable to KBMs due to high bootstrap current

[JET-C, #79498, 2.5MA /2.7T]

[Saarelma, Nucl. Fusion 2013]
Pedestal prediction

- EPED predicts fully developed pedestal before an ELM at crossing of KBM and P-B stability limits.
- EPED has predicted the pedestal height in several devices within ±20%.

[Snyder et al., NF 2009]
[Snyder et al., NF 2011]
High-n ballooning:
• Inclusion of higher toroidal mode numbers reduces the critical pressure gradient at which ballooning modes become unstable, changing the stability boundary

Diamagnetic stabilization:
• BOUT++ simulations indicate that $\gamma > \omega^*_{\text{max}}/2$ at low $n$ and $\gamma > C * \omega_A$ at high $n$ is more appropriate