Introduction to H-mode plasmas: L-H transition, pedestal, ELMs

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Acknowledgements: R. Maingi, P. Snyder, F. Laggner, and Max Fenstermacher

Material extracted from:
W. Suttrop Advanced PhD course 2010
H. Wilson Lectures on Transport and stability of pedestals in tokamaks 2014
E. Wolfrum Introduction to the physics of the pedestal in between ELMs =‘inter-ELM’ 2017
P. Snyder APS-DPP Review talk 2018
Fundamental Challenge: Fusion Conditions in Core Compatible with Edge/Materials

Core:
T\sim 10-30 \text{ keV}
P\sim 200-2000 \text{ kPa}

Separatrix:
T\sim 0.1 \text{ keV}
P\sim 0.3-2 \text{ kPa}

Materials:
T\sim 0.0001 \text{ keV}
Background: What is H-Mode?

As plasma is increasingly heated past a threshold, there is bifurcation to an improved confinement state.

H-mode = high confinement mode

*Plasma state with increased ratio of stored kinetic energy vs heating power*

H-mode pedestal = Edge transport barrier

*Region of reduced radial transport at the plasma boundary*
The critical region of interaction (also known as the H-mode pedestal) mediates the tension between core and edge, and plays a defining role in the performance of both.
Outline

- L-H transition phenomenology
  - Turbulence suppression
  - Access condition dependencies
  - Radial electric field shear

- Formation of the Pedestal
  - Brief overview
  - Importance of pedestal
  - Challenge in diagnosing pedestals

- Edge localized modes
  - How do we arrive at theses ELMs?
  - ELM types survey

- The type I ELM cycle
  - Stability: Description
  - Pedestal evolution during ELM cycle
  - What control the pedestal?

- EPED model a predictive model for the pedestal pressure
  - Mechanics
  - Other dependencies

- Small ELM regimes as a viable option for ITER

- Summary
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Suppression of Turbulence: characteristic of the H-mode transition

Phenomenology is akin to a phase transition!

GPI provides edge turbulence images
Views neutral Da light emission

Reduction of density fluctuations

Fluctuation levels [std/mean]

R - R_{sep} = -1 cm

Time rel. to L-H transition [ms]

25 %

15 %
Suppression of Turbulence: characteristic of the H-mode transition

Phenomenology is akin to a phase transition!

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Reduction of density fluctuations

Fluctuation levels [std/mean]

\[ R - R_{\text{sep}} = -1 \text{ cm} \]

Time rel. to L-H transition [ms]

-3 -2 -1 0 1

25 %
15 %

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Suppression of turbulence - emergence of a transport barrier

Increased pressure gradient

Fluctuation levels [std/mean]

$R - R_{sep} = -1$ cm

Time rel. to L-H transition [ms]

25%

15%

[Courtesy T.H. Osborne]
What limits the rise of the edge pressure gradient?

Steep gradient drives instability (Edge localized Modes)

Cycle consists of: ELM - Loss of density and temperature - reheat - new ELM
Minimum heating power access condition?

- H-mode transition occurs if loss power $P_L$ across plasma surface is above a threshold power ($P_{\text{thresh}}$)

- $P_{\text{thresh}}$ is proportional to surface

- $P_{\text{thresh}}$ depends on plasma density and toroidal field

- Hysteresis: $P_{L-H} > P_{H-L}$

\[
P_L = P_{\text{heat}} - \frac{dW}{dt} - P_{\text{rad,core}}
\]

Stored energy

\[
P_{\text{Thresh}} = 0.0488 \, e^{\pm 0.057} \, n_{e20}^{0.717 \pm 0.035} \, B_T^{0.803 \pm 0.032} \, S^{0.941 \pm 0.019}
\]
E_r shear and radial correlation lengths

H-mode exhibits:

Much larger E_r' than L-mode

Smaller radial correlation length

J Schirmer PPCF 49 (2007) 1019
Final $E_r$ profile has two shear layers

$$3k_B \nabla T_e = \frac{e}{}$$

$E_r$ vs $\rho$

Inner Shear Layer

$=\text{Neo Class.} + \text{Zonal Flows} + \text{Ion Losses} + ...$

Outer Shear Layer

2 0 0.5 [cm]
How do we get to the transport barrier?

Radial electric field produces $E \times B$ drift: $\mathbf{V} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$

Radial force balance:

$$E_r = \frac{\nabla p_i}{Z_i e n_i} - v_{\theta i} B_\phi + v_{\phi i} B_\theta$$

Sheared $E_r \times B$ velocity decorrelates the turbulent eddies which leads to reduced transport

Hypothesis condition: Shear rate > instability growth rate

$$\gamma E \times B = v'_{E \times B} > \gamma$$
Summary of L-H transition

Gradient drive \rightarrow \text{Instabilities} \rightarrow \text{Turbulence} \rightarrow \text{Reynolds work} \rightarrow \text{Zonal flow} \rightarrow \text{Damping}

\downarrow \downarrow \downarrow \downarrow \downarrow

Equilibrium shear flow \rightarrow \text{shearing} \rightarrow \text{Turbulent dissipation} \rightarrow \text{shearing} \rightarrow \text{Damping}
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The improvement in confinement is due to a region of steep pressure gradient at the plasma edge: At the plasma edge, this is referred to as the pedestal region.

- The pressure in the plasma core is proportional to the pedestal pressure.
- Pedestal physics is very important for tokamaks.

Connor et al., AIP Conf. Proc. 2008
Basic pedestal structure: the modified tanh profile

\[ Y(X) = A \times \text{MTANH}(\alpha, z) + B \]

\[ \text{MTANH}(\alpha, z) = \frac{[1 + \alpha^z \exp(z) - \exp(-z)]}{[\exp(z) + \exp(-z)]} \]

\[ z = \frac{(X_{\text{SYM}} - X)}{\text{HWID}} \]

Pedestal = A + B
Offset = B - A
Width = 2 \times \text{HWID}

R J Groebner,
NF 41 (2001) 1789
Resulting edge Bootstrap current

- Pressure gradient gives rise to toroidal bootstrap current

\[ j_b \propto \frac{dp/dr}{B_\theta \left(1 + 0.9 \sqrt{v_e^*}\right)} \]

[H. Stoschus, 2012]
The pedestal: so narrow but impactful

- H-mode pedestal stores additional kinetic energy
- High pressure core rests on the edge pedestal
- Can have >10x increase in T, and >40x increased P across this layer
  - Typically larger relative increase than core
- Overall, it is paramount to understand how the pedestal forms and what sets its width.
Future burning plasmas rely on maintaining high pedestal pressure.
Challenges in diagnosing the pedestal

- Profiles & fluctuations required for good interpretation
- Uncertainties are associated with every measurement
- Awareness necessary when interpreting
- Understand and to consider the fundamental limitations of the utilized diagnostics
- Some examples:
  - ECE: shine through
  - BES: radial widening of emission profile
  - CER: assumption of equilibrium temperature

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Lagnner 2018
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Large pressure and current gradients in pedestal drive MHD instabilities

- **Potential Energy with stabilizing and destabilizing terms**
  - Negative energy implies MHD instability
  - $\xi = \text{displacement of plasma fluid, } B_1 = \text{magnetic field perturbation}$

\[
\delta W = \frac{1}{2} \int dV \left( |B_{1,\perp}|^2 + B_0^2 |\nabla \cdot \xi\perp + 2 \xi\perp \cdot \kappa|^2 + \lambda p_0 |\nabla \cdot \xi|^2 \right) - \int dV \left( 2 (\xi\perp \cdot \nabla p_0) (\kappa \cdot \xi\perp) + J_{0,\parallel} (\xi\perp \times B_0 / B_0 \cdot B_{1,\perp}) \right)
\]

Compression of the magnetic field, (Fast, magneto-acoustic waves)

magnetic field line bending (Alfven waves)

pressure gradient destabilizing ($\kappa=\text{field curvature}$) **ballooning** drive

parallel current destabilizing **kink/peeling** drive

compression (Slow, magneto-acoustic waves)
Large “Type I” ELMs are thought to be triggered by coupled peeling-balloonning modes:

- Ballooning mode is destabilized by pressure gradient, but stabilized by current density
- Peeling mode is destabilized by current density, but stabilized by pressure gradient
- The modes can couple, leading to a somewhat complicated stability boundary
Range of Edge-localized modes: Type I ELMs

- Type I ELMs are the most prevalent, over a wide range of parameters
  - Good confinement, but large ELMs
  - Cannot be tolerated on ITER
  - Well-explained by the peeling-ballooning modes
Type III ELMs: More benign, but degrade confinement

- **Type III ELMs** typically occur close to the L-H transition
  - Small ELMs, but reduced confinement
  - Confinement degradation not desirable for ITER
  - A high collisionality and low collisionality branch
Type II ELMs: Small ELMs with good confinement

- **Type II ELMs** occur at high collisionality in plasmas with **strong shaping**
  - Small ELMs, and good confinement
  - They can co-exist with Type I ELMs
  - Is high collisionality inconsistent with ITER?

*Oyama, et al PPCF (2006)*
Grassy ELMs: Small ELMs with good confinement

- **Grassy ELMs** occur at low collisionality, strong shaping
  - High $\beta_p$ and $q_{95}$ required (low current?)
  - Small ELMs, and good confinement
  - Could be a viable regime for ITER (if accessible to ITER)

# Summary

<table>
<thead>
<tr>
<th>ELM Type</th>
<th>Access criteria</th>
<th>Confinement</th>
<th>Size</th>
<th>ITER implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>High power; wide parameter regime</td>
<td>Good</td>
<td>Large</td>
<td>Excessive erosion</td>
</tr>
<tr>
<td>Type II</td>
<td>Strong shaping; high collisionality; high q95</td>
<td>Good</td>
<td>Small</td>
<td>Collisionality too high for ITER?</td>
</tr>
<tr>
<td>Type III</td>
<td>Lower power; high and low collisionality branches</td>
<td>Poor</td>
<td>Small</td>
<td>Confinement unacceptable; inaccessible at high power?</td>
</tr>
<tr>
<td>Grassy</td>
<td>Strong shaping; high $\beta_p$; low collisionality</td>
<td>Good</td>
<td>Small</td>
<td>Possible tolerable ELM regime</td>
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Let’s revert to the type I ELM cycle

- The coupled peeling-balloon-ballooning mode stability diagram provides a model for Type I ELM cycle.

- Big drop in pressure large ELM (Type I)

- Stable region

- Unstable region

- Coupled Peeling-Ballooning modes (medium n)

- Peeling modes (low n)

- Ballooning modes (high n)

- Pressure gradient and current rise between ELMs

- ELM crash triggered as current reaches peeling-balloon-ballooning limit
Experiments on all tokamaks consistent with peeling-ballooning trigger

- Validated on all major international tokamaks

- ELM crash within 20% of calculated pedestal stability limit

Observed ELM Spatial Structure Similar to Calculated Peeling-Ballooning Modes

- Complicated structure but mode number similar to that calculated from linear stability

Simulating a full ELM cycle with multi-scale physics is a grand computational challenge.
Pedestal gradient recoveries during the ELM cycle

- ELM cycle studies reveal different recovery timescales of $T_e$ and $n_e$.

- $\nabla T_e$ recovery shows three phases:
  1. $\nabla T_e$ recovery is delayed and $\nabla n_e$ snaps back quickly.
  2. $\nabla T_e$ continues to recover while $\nabla n_e$ is saturated.
  3. $\nabla T_e$ slowly evolves to saturation.

A. Burckhart et al., PPCF 2010; Diallo PoP 2015; F. Laggner et al., PPCF 2016
Measurements on DIII-D reveal the existence of pedestal localized mode during the ELM cycle: Quasi-Coherent Frequency (QCF)

- QCF Onsets at Given Temperature Gradient and its Evolution Tracks the Gradient Evolution

Diallo, Physics of Plasma 2015
Measurements on DIII-D reveal the existence of pedestal localized mode during the ELM cycle: Quasi-Coherent Frequency (QCF)

- QCF Onsets at Given Temperature Gradient and its Evolution Tracks the Gradient Evolution
Summary of possible inter-ELM transport mechanisms

- Transport processes in the pedestal can be explored by considering the pedestal evolution between ELMs

<table>
<thead>
<tr>
<th>Instability</th>
<th>Drive</th>
<th>Prop.</th>
<th>Scale</th>
<th>$\alpha_{\phi, \tilde{p}}$</th>
<th>$\alpha_{\phi, \tilde{T}_e}$</th>
<th>$\omega(L_{\perp}/c_s)$</th>
<th>Parity</th>
</tr>
</thead>
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<tr>
<td>IPM</td>
<td>$J_\parallel$</td>
<td>n.p.</td>
<td>$k_\theta \rho_s \ll 0.1$</td>
<td></td>
<td></td>
<td></td>
<td>Global</td>
</tr>
<tr>
<td>(I–R)BM</td>
<td>$\nabla p$</td>
<td>n.p.</td>
<td>$k_\theta \rho_s &lt; 0.1$</td>
<td>$\pi/2$</td>
<td></td>
<td></td>
<td>Ball.</td>
</tr>
<tr>
<td>KBM</td>
<td>$\nabla T_{e,i}$</td>
<td>i dia.</td>
<td>$k_\theta \rho_s \sim 0.1$</td>
<td>$\pi/2$</td>
<td></td>
<td></td>
<td>Ball.</td>
</tr>
<tr>
<td>KPBM</td>
<td>$\nabla p_{e,i}$</td>
<td>e dia.</td>
<td>$k_\theta \rho_s \ll 0.1$</td>
<td></td>
<td></td>
<td></td>
<td>Ball.</td>
</tr>
<tr>
<td>MTM</td>
<td>$\nabla T_e$</td>
<td>e dia.</td>
<td>$k_\theta \rho_s \sim 0.1$</td>
<td>0</td>
<td></td>
<td>$0.1–1$</td>
<td>Tear.</td>
</tr>
<tr>
<td>ITG</td>
<td>$\nabla T_i$</td>
<td>i dia.</td>
<td>$0.1 \leq k_\theta \rho_s \leq 1$</td>
<td>$\pi/2$</td>
<td>$\pi$</td>
<td>$0.1–1$</td>
<td>Ball.</td>
</tr>
<tr>
<td>TEM</td>
<td>$\nabla T_{e,n}$</td>
<td>e dia.</td>
<td>$0.1 &lt; k_\theta \rho_s &lt; 1$</td>
<td>0</td>
<td>$\pi/2$</td>
<td></td>
<td>Ball.</td>
</tr>
<tr>
<td>ETG</td>
<td>$\nabla T_e$</td>
<td>e dia.</td>
<td>$k_\theta \rho_s &gt; 1$</td>
<td>$\pi/2$</td>
<td>$0 - \pi/2$</td>
<td>$0.5–100$</td>
<td>Ball.</td>
</tr>
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</table>
Micro-instabilities in the pedestal appears to set its structure

- Gyrokinetic simulations of the MAST pedestal show:
  - At low density gradient, the micro-tearing mode is unstable
  - At higher density gradient this mode is stabilized, but the kinetic ballooning mode is instead destabilized as the pressure gradient rises
A model for pedestal formation

- Simulations suggest the following model:
  - The pedestal gradients are initially held low by the micro-tearing mode
  - This mode is initially stabilized close to the plasma edge, allowing the pressure gradient to build until the KBM is destabilized
  - As the MTM is progressively stabilized, the pedestal widens into the core
What limits the extent of the pedestal penetration?

- The more the pedestal penetrates, the greater the pedestal width and the higher the core pressure
  - So what limits the pedestal width?
- It is actually the peeling-ballooning stability limit
  - A wider pedestal has a lower threshold for instability

![Graph showing the relationship between pedestal width and pressure gradient](image)
What limits the extent of the pedestal penetration?

- The more the pedestal penetrates, the greater the pedestal width and the higher the core pressure
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EPED model: a predictive model for the pedestal pressure

• EPED divides the instabilities that impact transport & stability in the pedestal into 2 categories:
  – “Global” modes: extend across edge barrier including significant impact at top
  – “Nearly-local” modes within the edge barrier

Conjecture: while neoclassical and electron microinstabilities drive transport, KBM commonly provides the final constraint on the pressure gradient.

• Key elements: neoclassical bootstrap current, nearly local KBM, global peeling ballooning
• Density is taken as key input
Mechanics of the EPED Predictive Model

- **Input**: $B_t, I_p, R, \alpha, \kappa, \delta, n_{ped}, m_i, [\beta_{global}, Z_{eff}]$

- **Output**: Pedestal height and width (no free of fit parameters)

**A.** P-B stability calculated via a series of model equilibria with increasing pedestal height

ELITE, n=5-30 nonlocal diamagnetic model from BOUT++ calcs

**B.** KBM onset: $\Delta \sim \beta_p^{1/2}$

P-B stability and KBM constraints are tightly coupled: If either physics model (A or B) is incorrect, predictions for both height and width will be systematically incorrect

Effect of KBM constraint is counter-intuitive: Making KBM stability worse increases pedestal height and width

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P. Snyder APS-DPP Review talk 2018
Numerous Experimental Tests of EPED Conducted

>800 Cases on 6 tokamaks
Broad range of density (~1-24 $10^{19}\text{m}^{-3}$), collisionality (~0.01-4), $f_{GW,ped}$ (~0.1-1.0), shape (6~0.05-0.65), q~2.8-15, pressure (1.7 - 35 kPa), $\beta_N$~0.6-4, $B_t$=0.7-8T
Typical $\sigma$~20-25%
EPED model: A major advance, but not the full picture

- While EPED broadly predicts pedestal width, there are differences in trends
- Recent analysis from JET, for example:

![EPED prediction graph](image)

Also on JET, the pedestal appears to narrow into the ELM cycle, rather than broaden – a challenge for the model (but there are ideas)

M Leyland, et al. Nucl Fusion 2013
Dependence on $\rho^*$ Important for Predictions of ITER

- Key dimensionless parameters for ITER or DEMO reactor matched on existing machines ($\nu^*, \beta, q, \varepsilon$) except $\rho^*$

Important to continue testing and developing understanding at very small $\rho^*$
Fueling and impurity seeding can alter density profiles, and can decrease or increase the pedestal height.

- Density profile can be altered by fueling and seeding, changing collisionality and bootstrap current profile.
- At high collisionality (p-limited pedestal), high gas puff unfavorable for pedestal height.

Predictive capability for effects of fueling and seeding on density and impurity profiles.
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Could this be an ingredient to achieve small ELM regimes?

JT-60U Oyama 2005

Large ELMs

Increase flow shear

Small ELMs
Flow shear provides a control knob: Transition between isolated and general modes

H. Wilson Lectures on Transport and stability of pedestals in tokamaks 2014

D Dickinson, et al, Phys Plas 2014
Towards a model for small (Grassy?) ELMs

- Return to our pedestal evolution model
- Assume at some point the conditions are right for the isolated mode
- Large ELM situation beyond ideal MHD boundary
Towards a model for small (Grassy?) ELMs

- Return to our pedestal evolution model
- Assume at some point \( \heartsuit \) the conditions are right for the isolated mode
- Small ELM situation \( \heartsuit \) is encountered before large scale MHD event

If conditions for isolated mode are satisfied at \( \star \) (as flow evolves), plasma suddenly unstable \( \Rightarrow \) small ELM crash
Summary

• The pedestal region is key for confinement in ITER and the requirements of the plasma exhaust system

• The pedestal properties are a consequence of an interaction between turbulence and stability

• Plasma eruptions called ELMs are potentially very damaging for ITER
  – The largest “Type I” ELMs are well-understood in terms of peeling-ballooning modes, and cannot be tolerated on ITER
  – A range of possible ELM control techniques will be available on ITER
  – Ideal MHD stability properties indicate that the no-ELM QH Mode may be accessible for ITER (edge flow shear may be key) [See Max’s Lecture]
  – Small ELM regimes are more of a challenge – we have some ideas, but still great uncertainty whether they can be accessed on ITER

• Despite being a very small region, the pedestal is key to ITER performance and operation
The critical region of interaction is the edge transport barrier (also known as the H-mode pedestal), which mediates the tension between core and edge, and plays a defining role in the performance of both.

Exciting New Discoveries in Pedestal Physics will lead to Improvements in Fusion Performance!