PEDESTAL PHYSICS
a phenomenological introduction

L. Frassinetti
H-mode plasma

- When the input power to the plasma is above a specific threshold, the plasma has a transition from a low confinement regime (L-mode) to a high confinement regimes (H-mode).

- The H-mode is characterized by:
  - steep gradients in the pressure "near" the edge of the plasma. This region is named "pedestal".
  - sudden releases of energy and particles from the pedestal region to the SOL and the divertor. These events are triggered by MHD instabilities and are named edge localized modes (ELMs)
OUTLINE

- L-H transition
- Pedestal structure
- Edge localized modes (ELMs)
  - ELM energy losses
  - ELM types
- MHD stability of the pedestal
  - Role of MHD stability (and few words on transport)
  - The peeling-ballooning (PB) model
  - The ELM cycle within the PB model
  - Parameters that influences the pedestal
- Pedestal predictions
  - The EPED model:
    - The PB constraint
    - The KBM constraint
  - Non-linear MHD modelling
- Some of the most active research areas in pedestal physics
L-H transition

- Above a specific threshold in power ($P_{\text{LH}}$), the plasma enters the H-mode.
- The $P_{\text{LH}}$ threshold depends on several parameters.
- A scaling law based on results from several machines produces:
  $$P_{\text{LH}} = 0.049 n_e^{0.72} B^{0.8} S^{0.94}$$  
  [Martin JPC2008]

- However, the links between engineering/plasma parameters and $P_{\text{LH}}$ is more complex. Some of the main parameters that affects $P_{\text{LH}}$ are:
  - Magnetic field
  - Isotope mass ($P_{\text{LH}}$ decreases with isotope mass)  
    [Righi NF1999]
  - Divertor geometry  
    [Delabie EPS2015]
  - Wall material ($P_{\text{LH}}$ reduced from carbon to metal walls)  
    [Neu JNM2013]
  - Plasma density  
    [Martin JPC2008]
    - Minimum around 0.2-0.4$n_{\text{GW}}$
    - Non-monotonic behavior seem related to edge ion heating  
      [Ryter NF2014]
L-H transition

- The physics of L-H transition is not yet fully understood
  - several models have been proposed to explain the experimental results
  - but a physics based model of the L-H transition with full predictive capabilities has not been developed yet.

- Some key experimental and theoretical concepts to explain the L-H transition are well established:
  - The L-H transition is due to stabilization of the turbulence near the plasma edge [Burrel PoP1997], [Terry RMP2000]
  - \( \mathbf{E} \times \mathbf{B} \) shear stabilization plays a key role
    - higher \( \mathbf{E} \times \mathbf{B} \) in L-mode \( \rightarrow \) lower \( P_{\text{LH}} \).
    - The formation of a \( E_r \) well, just inside the separatrix, occurs as the plasma enters H-mode
    - The well has to reach a certain depth to allow the transition
L-H transition

- Many of the theoretical works are based on the interplay between the L-mode turbulence and $E_r$ shearing. [Connor PPCF2000]
- A large part of other theoretical works are based on the stabilization of RBM via increased pressure gradient. [Rogers PRL1997]
- An example: [Bourdelle NF2015]
  - $\gamma_{\text{turb}}$ (growth rate of the turbulence) can be modeled from theory (either analytically or numerically)
  - $\gamma_E$ ($E_r$ shear) can be obtained by modelling the $E_r$ profiles.
  - $\gamma_{\text{turb}}/\gamma_E$ can be used to identify at which temperature the transition occurs
  → Qualitative trends can be tested

- For a recent review on L-H transition: [Bourdelle NF2020]
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Pedestal structure

- To study the pedestal, it is necessary to quantify the parameters that identify its structure.

- The key parameters are
  - pedestal height
  - pedestal width
  - pedestal position (often defined as the position of the maximum gradient).
  - maximum gradient

- The pedestal parameters are determined for:
  - pressure
  - temperature
  - density

- These parameters are determined by fitting an analytical function (typically, a modified hyperbolic tangent) to the experimental data.
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Edge Localized Modes (ELMs)

- The pedestal is characterized by sudden events, triggered by MHD instabilities, called edge localized modes (ELMs).
- The ELM triggers the collapse of the pedestal temperature and density, which in turn leads to the release of energy and particles to the divertor.

[Frassinetti NF2013]
Edge Localized Modes (ELMs)

- The pedestal is characterized by sudden events, triggered by MHD instabilities, called edge localized modes (ELMs).
- The ELM triggers the collapse of the pedestal temperature and density, which in turn leads to the release of energy and particles to the divertor.
- The ELM collapse affects the kinetic profiles only in the pedestal region.
- The ELM losses can be calculated by integrating the profiles just before and soon after the ELMs:

\[
\Delta W_{ELM} = W_{pre} - W_{post} = \frac{3}{2} k \int \left( n_{pre} T_{pre} - n_{post} T_{post} \right) dv \\
\approx \frac{3}{2} k \int \Delta n \ T \ dv + \frac{3}{2} k \int n \Delta T \ dv
\]

[Beurskens NF2009]
ELM types: definitions

- H-mode plasma can be characterized by several types of ELMs. The ELM frequency \( f_{\text{ELM}} \) is often used to identify the most common ELMs.
- The most common are:
  - **Type I ELMs.**
    - \( f_{\text{ELM}} \) increases with \( P_{\text{sep}} = P_{\text{in}} - P_{\text{rad}} - \frac{dW}{dt} \).
    - Typically occurs at \( P_{\text{sep}} \gg P_{\text{LH}} \).
    - They are triggered by ideal MHD.
    - They appear as sharp burst on the D\(_{\alpha}\).
  - **Type III ELMs.**
    - \( f_{\text{ELM}} \) decreases with \( P_{\text{sep}} \).
    - Typically occurs \( P_{\text{sep}} \approx P_{\text{LH}} \).
    - They are not triggered by ideal MHD.
  - **Type II (or ”grassy” ELMs).**
    - Not achieved in all machines.
    - Occurs at high confinement and high triangularity.
    - They lead to small but frequent energy losses.
ELM types: examples

- **Type I ELMs.**
  - $f_{\text{ELM}}$ increases with $P_{\text{sep}} = P_{\text{in}} - P_{\text{rad}} - dW/dt$.
  - Typically occurs at $P_{\text{sep}} \gg P_{\text{LH}}$.

- **Type III ELMs.**
  - $f_{\text{ELM}}$ decreases with $P_{\text{sep}}$.
  - Typically occurs $P_{\text{sep}} \approx P_{\text{LH}}$.

For reviews of ELM types:
- [Zohm PPCF1996]
- [Leonard PoP2014]
**ELMs: energy losses and heat loads**

- ELM losses tend to increase with decreasing collisionality.
- At ITER collisionalities, the ELM energy losses might be 15%-20% of the pedestal stored energy.
- ELMs lead to fluxes of energy and particles to the divertor.
- The divertor can be damaged or could even melt. This could pose a problem for ITER. [Pitts JNM2013]

→ It is essential to understand ELM pedestal physics to:
  - Minimize ELM energy losses
  - Develop techniques for ELM mitigation/suppressions. Some of the most developed techniques are:
    - RMPs [for a review: Evans JNM2013]
    - ELM pacing with pellets [Baylor NF2009]
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MHD stability and transport

- What are the physical mechanisms that determines the pedestal structure and trigger the ELMs?

- Two main concepts
  - MHD stability
  - Heat and particle transport

- The time evolution is set by transport
  - Transport determines time evolution of
    - pedestal gradients
    - pedestal heights

- The pedestal grows till a critical threshold in pressure. Then, the MHD stability triggers an ELM.
  - MHD stability determines:
    - pedestal height
    - the maximum gradient.
  - In the pedestal, the main MHD instabilities are:
    - ballooning (B) modes
    - peeling (P) modes
    - coupled PB modes
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The ballooning modes

- The ballooning instabilities are pressure driven: they are triggered when the pressure gradient exceeds a critical threshold.
- They arise from toroidicity
- B has an unfavourable curvature low field side → balloning modes develop mainly on the LFS

- Two key parameters define the ballooning stability
  - the normalized pressure gradient $\alpha$
    \[
    \alpha = -\frac{2\mu_0 R q^2 dp}{B^2 dr}
    \]
    has a destabilizing effect.
  - the magnetic shear
    \[
    s = -\frac{r dq}{q dr}
    \]
    $s$ has a stabilizing effect.
The ballooning modes

- **The normalized pressure gradient $\alpha**
  
  \[ \alpha = -\frac{2\mu_0 R q^2 dp}{B^2 dr} \]
  
  - the increase of $\alpha$ destabilizes ballooning modes
  - at a certain threshold in $\alpha$ ($\alpha_{\text{crit}}$), the mode is unstable

- **The magnetic shear**
  
  \[ s = -\frac{r dq}{q dr} \]
  
  - the shear has a stabilizing effect
  - Increasing the shear leads to an increase in $\alpha_{\text{crit}}$

- Most of the machines have a pedestal in region (1): the first stability region

- However, theory predicts a second stability region, at high $\alpha$ and low shear

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[Wesson “tokamaks”]
The ballooning modes

- **The normalized pressure gradient $\alpha**
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- Most of the machines have a pedestal in region (1): the first stability region
- However, theory predicts a second stability region, at high $\alpha$ and low shear
- Finite Larmor radius effects have a stabilizing effects and reduce the unstable region
The bootstrap current

- Due to the steep gradients in the pedestal region, the bootstrap current ($j_{bs}$) can give a significant contribution to the total current density.
- For an expression of $j_{bs}$: [Sauter PoP1999]
- The increase in the current density affects the shear [Miller PoP1999]

$\rightarrow j_{bs}$ has an effect on the ballooning stability. [Snyder PoP2002]

$\rightarrow$ the parameters that affects $j_{bs}$ will affect also the balloning stability:
  - collisionality
  - plasma shape

- It is common to use $j_{tot}$ instead of the shear in the stability diagram
The bootstrap current

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[Horvath PPCF2018]

[Miller PoP1999]

[Snyder PoP2002]
The external kink / peeling mode

- The external kink mode is current driven
- The kink mode \((m, n)\) is destabilized when \(q\) at the plasma edge is low enough that \(q_{\text{edge}} < m/n\) and the resonance is very close to the plasma
  - the kink mode is resonant outside the plasma
  - the kink mode is strongly localized at the plasma edge.
- For comparison, the ballooning modes have a more global structure.
- The kink mode depends on the edge current \(\rightarrow j_{bs}\) has a strong role

\[ j_{bs} \]

\[ kink/peeling \text{ unstable} \]

\[ \alpha \]
The peeling-ballooning (PB) modes

- Toroidicity and shaping effects can couple peeling and ballooning (PB) modes.
- The coupled PB modes can be destabilized even if the single peeling mode and ballooning are stable. [Connor PoP1998]
- The PB stability are driven by both pressure gradient and current density.
- The PB stability is the leading theory to explain the pedestal behavior in type I ELMy H-modes. [Snyder PoP2002]
  [Wilson PoP2002]
- The PB modes strongly limit the stable region.
- The access to the 2nd stability region is closed (most of the times).
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The PB model for the ELM cycle

1. Just after an ELM, the pedestal has low gradient and low $j_{bs}$.
2. During the ELM cycle, the pressure gradient (and hence $j_{bs}$) increases.
3. The process continues till the PB boundary is reached.
4. Then an ELM is triggered:
   - the pressure gradient and the $j_{bs}$ collapse.
   - the process starts again.
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Parameters that affect the pedestal: $\beta$

- $\beta = \frac{\langle p \rangle}{B^2/(2\mu_0)}$
- The increase of $\beta$ leads to the increases of the Shafranov shift.
  - The Shafranov shift has a stabilizing effect on the ballooning modes.
  - The ballooning modes boundary moves to higher $\alpha$.
  - The pre-ELM pedestal pressure gradient increases.
- $p^{\text{ped}}$ increases with increasing $\beta$. 
Parameters that affect the pedestal: $\beta$

- $\beta = \frac{\langle p \rangle}{B^2/(2\mu_0)}$

- the increase of $\beta$ leads to the increases of the Shafranov shift.
  - the Shafranov shift has a stabilizing effect on the ballooning modes.
  - the ballooning modes boundary moves to higher $\alpha$
  - the pre-ELM pedestal pressure gradient increases

$\Rightarrow p_{\text{ped}}$ increases with increasing $\beta$. 

[Saarelma PoP2015]
Parameters that affect the pedestal: $\nu$

- **Collisionality**
  \[ \nu^* = c ln \Lambda \frac{R q n_e}{\varepsilon^{3/2} (T_e)^2} \]

  the collisionality has a major effect on $j_{bs}$.
  \[\text{[Sauter PoP1999]}\]

- **Approximately:**
  \[ j_{bs} \approx \nu^*^{-1} \]

- The reduction of collisionality tends to increase $\nabla p$, if the pedestal is near the ballooning boundary
- \( \delta \): plasma triangularity
- the increase of \( \delta \) stabilizes part of the ballooning modes.
- the PB is strongly shaped at high \( \delta \) and a so called "nose" is formed:
  - high \( j_{bs} \) \( \rightarrow \) \( \nabla p \) increases with increasing \( \delta \).
  - low \( j_{bs} \) \( \rightarrow \) \( \nabla p \) does not change much with \( \delta \).

Parameters that affect the pedestal: \( \delta \)

[Saibene PPCF2002]
[Beurskens NF2013]
[Urano NF2014]
Parameters that affect the pedestal

- Other parameters that affect the pedestal stability are:
  - **Impurities.** $Z_{\text{eff}}$ affects collisionality and $j_{bs}$. It affects the electron pressure via the dilution effect.  
    - [Saarelma PoP2015]
  - **q-profile.** A change in q-profiles affects the shear.  
    - [Snyder PoP2002]
  - **Pedestal width.** A wider pedestal can contain more ballooning modes, so it is more unstable  
    - [Snyder PoP2002]
  - **Plasma rotation.**  
    - [Aiba NF2018]
  - **Density at the pedestal top.** Not trivial effects, see later  
    - [Snyder NF2011]
  - **Position of the pedestal.** An outward shift of the pedestal destabilizes the ballooning modes $\rightarrow$ pedestal reduction  
    - [Dunne PPCF2007]
  - **Density at the separatrix.** Only partially understood.  
    - [Snyder IAEA2018]
  - **Isotope mass.** Origin of the effect still unclear.  
    - [Maggi NF2019]
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Pedestal predictions: the PB constraint

- Can we use the PB model to predict the pedestal pressure height before the ELM?

- The PB model identify the critical normalized pressure gradient ($\alpha_{\text{crit}}$) above which the PB modes are destabilized.
  - It can be used to determine $\nabla p$.

- For a specific pedestal width, the PB model can determine the critical $\nabla p$ at which the PB modes are destabilized.
  - for this specific width, the critical pressure height can determined from ($\nabla p_{\text{crit}}$).
  - A correlation between width and critical pressure can be obtained. This is often called ”PB constraint”

- More information is necessary to predict pedestal height and width.
Pedestal predictions: the KBM constraint

- The other constraint can come from pedestal transport
- The problem is that the pedestal transport is (often) driven by turbulence. Turbulence studies are not trivial and very time consuming
- The most successful approach, so far, has been developed in DIII-D [Snyder PoP2009]
  - Experimental results suggest that DIII-D pedestal transport is driven by kinetic ballooning modes (KBMs)
  - From the theoretical arguments, it can be derived that for pedestals limited by the KBM turbulence:
    \[ w_{ped} = c \sqrt{\beta_{\theta}^{ped}} \]
  - An experimental fit from DIII-D data gives:
    \[ w_{ped} = 0.076 \sqrt{\beta_{\theta}^{ped}} \]
The EPED1 model

- The EPED1 model predicts pedestal pressure height and pedestal pressure width using the
  - KBM constraint: local KBM stability $\rightarrow$ "clamps" $\nabla p$
  - PB constraint: global PB stability $\rightarrow$ triggers the ELM

THE ELM CYCLE ACCORDING TO EPED1:

1. $\nabla p$ grows unconstrained
2. KBM boundary is reached:
   - $\nabla p$ is "clamped"
   - The pedestal height grows via the increase of the pedestal width:
     $$w_{ped} = 0.076 \sqrt{\beta_{\theta}^{ped}}$$
3. PB boundary is reached
   - ELM triggered

[Snyder PoP2009]
[Snyder NF2011]
The EPED1 model

- EPED1 tends to predicts the pedestal pressure height rather well, for a large of parameters and in many machines. [Snyder NF2019]

- EPED1 is a useful tool to test the PB model.

- EPED1 is widely used to predict the pedestal height (also in ITER).

- Example: prediction of pedestal pressure dependence with:
  - density
  - $\beta$

[Snyder IAEA2012]
Non-linear MHD modelling

- EPED1 works relatively well, but it is a linear model:
  - it does not predict time evolutions
  - cannot predict ELM energy losses
- Non-linear codes are necessary for modelling the details of the ELMs.
- Recent results with the JOREK code are very promising:
  - type I ELMs start to be modeled rather accurately
  - ELMs similar to type III have also been modelled.
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Some active research areas

- Discrepancies between EPED1 and experimental results, especially in JET-ILW, have been observed.
  - what physics is missing in EPED?
- Super H-mode: DIII-D results show that at high $\delta$ the 2nd stability region can be accessed.
  - can other experiments reach this region?
- Isotope effect
  - What is the physical mechanism that explains the effect of isotope mass on the pedestal?
- Small ELMs
  - will operation with good pedestals and small ELMs be possible in ITER?
- ELM mitigation
  - develop and test ELM mitigation techniques that can be used in ITER

[Frassinetti NF2019], [Saarelma PoP2019], [Frassinetti NF2021]

[Snyder NF2015]
Some useful references

The choice of the following papers is based on two criteria:
- overview papers, when possible.
- most recent papers.

This list does not necessarily cite the original papers on the topic. Many excellent papers have not been included.

- Pedestal physics: [Urano NF2014]
  [Leonard PoP2014]
- LH transition: [Bourdelle NF2020]
- Pedestal structure: [Frassinetti NF2021]
- Isotope effect: [Maggi PPCF2018]
- ELMs: [Zohm PPCF1996]
  [Leonard PoP2014]
- PB model: [Wilson PoP1999]
  [Snyder PoP2002]
  [Snyder NF2004]
- EPED model: [Snyder PoP2009]
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