Overview of H-mode Pedestal Research on DIII-D


28th EPS Conference on Controlled Fusion and Plasma Physics
Maderia, Portugal, 18 - 22 June 2001
Motivation and Goals for H-mode Pedestal Studies

♦ Motivation
  - As a boundary condition for core kinetic profiles, H-mode transport barrier characteristics can strongly influence energy transport and $\beta$ limit.
  - The ELM instability can negatively impact core performance and result in unmanageable divertor power loads.

♦ Goals
  - Develop a physics based predictive capability for the H-mode pedestal characteristics in the Type I ELM regime to be used as boundary conditions in core transport models, and for possible control of the pedestal parameters.
  - Develop a physics based predictive capability for the effects of Type I ELMs in the core and divertor, for possible mitigation of the negative effects of ELMs.
  - Explore alternatives to the Type I ELM regime that may provide a path to high core performance without the negative ELM effects.
H-mode pedestal may impact H-mode based tokamak reactor performance through temperature profile stiffness.

- Maximum $P_F$ and $Q$ are obtained at min $<T>$ for stable operation $\Rightarrow P_F / P_{\text{LOSS}} \sim H^2$.

Effect of H-mode pedestal on H factor varies with tokamak possibly due to changes in turbulent transport process [2].

Turbulent transport simulations that predict stiff temperature profiles (ITG) show strong dependence of core on edge [1].

H-mode pedestal pressure loss with stiff temperature profiles contribute to H reduction at high density on DIII-D

\[ T(\rho) = T^{PED} f(\rho) \Rightarrow W_{Total} \propto p^{PED} g(n^0 / n^{PED}) \]

- Stored energy loss at high density associated with loss of \( p^{PED} \) and stiff T profiles.
- Density profile peaking can compensate for reduced \( p^{PED} \).

GLF23 SIMULATION FOR \( n/n_{GW} = 1.4 \) Shot

\( \rho = 0.4 \)

GLF23 SIMULATION

\( 2.3^*T(\rho = 0.75) \)

DIII-D

H-ITER89P

\( 1.00 < \bar{n}_e/n_{PED} < 1.15 \)
\( 1.15 < \bar{n}_e/n_{PED} < 1.30 \)
\( 1.30 < \bar{n}_e/n_{PED} < 1.45 \)
\( 1.45 < \bar{n}_e/n_{PED} < 1.60 \)
\( 1.60 < \bar{n}_e/n_{PED} < 1.75 \)

H-ITER89P

\( \beta_n \)

\( D_2 \) Puff

\( p_e^{PED} (kPa) \)

Density Peaking

\( \bar{n}_e/n_{GW} \)

\( \bar{n}_e/n_{GW} \)

\( 0.5 1.3 \)

\( 0.9 1.3 \)

\( 0.5 1.3 \)

\( 0.9 1.3 \)

\( 0.5 1.3 \)

\( 0.9 1.3 \)

\( 0.5 1.3 \)

\( 0.9 1.3 \)

\( 0.5 1.3 \)

\( 0.9 1.3 \)

\( 0.5 1.3 \)

\( 0.9 1.3 \)

\( 0.5 1.3 \)

\( 0.9 1.3 \)

\( 0.5 1.3 \)

\( 0.9 1.3 \)
H-mode pedestal can impact core stability

Global $\beta$ limit increases with $p^{\text{PED}}$

Unstable $n=1$ Ideal Mode

JET Optimized Shear Discharge\[^1\]

$\beta_n = 2.1$

$\beta_n = 1.15$

NTM can be triggered by ELM

$\beta_0 = 1.27 > \beta_{\text{min}} = 1.05$

$W = 0$ curve at onset

$\Delta r = -5.8$

Type I ELM energy loss increases with H-mode pedestal energy. ELM divertor heat loads can be a problem for reactor scale device.

\[ \Delta W \approx \frac{1}{3} E_{\text{ped}} \text{ for DIII-D and } \frac{1}{4} E_{\text{ped}} \text{ for JET.} \]

Assuming \( \Delta W_{\text{ELM}}/p_{\text{PED}} \) is the same for DIII-D and ITER gives for ITER:

\[ \Delta W_{\text{ELM}} = 8 T_{\text{PED}}^2 \text{MJ/keV} \]
Edge Stability

- Determining a scaling for $p_{\text{PED}}$ or $T_{\text{PED}}$ is separated into a study of the H-mode transport barrier width, $\Delta$, and pressure gradient, $p'$.
- $p'$ may be set by the ELM instability.
- $\Delta$ may be set by the physics of turbulence suppression.
- Stability work has concentrated on Type I ELM regime which has high energy confinement over a wide range of conditions.
- Comparison of conditions just before an ELM with theory:
  - GATO, $1<n<11$ ideal modes in real geometry with wall
  - BALOO, $n=\infty$ ideal ballooning modes
  - ELITE, intermediate $n$ pealing/ballooning modes

Pedestal Parameter Evolution in Type I ELM Discharge

![Graph showing evolution of $p_{\text{PED}}$, $p'_{\text{PED}}$, and $\Delta_{\text{PED}}$ over time.](image)
Future work on edge stability: Li Beam Diagnostic

- Lithium Beam Diagnostic (D.M. Thomas[1]): high spatial resolution Zeeman effect measurement of edge magnetic field
  - Diagnostic is installed on DIII-D and taking preliminary data.
  - Will allow quantitative comparison between theory and experiment

Ballooning mode model for ELM cannot account for edge $p'$; second stability plays a role.

Ballooning mode model for ELM is inconsistent with high $p'$ value and variation of $p'$ value with triangularity.

Qualitative change in ELM behavior is consistent with loss of second stable access at high and low squareness.
Observations are consistent with low n, ideal, edge localized, kink/ballooning as mode associated with the Type I ELM.

\[ p' \text{ variation with shape is consistent with low n edge localize kink/ballooning stability} \]

Fast growing low \((1 < n < 10)\) toroidal mode number mode is observed as Type I ELM precursor.
H-mode transport barrier width and stability limit are coupled for lower n modes.

- Improved Stability for narrow H-mode barrier width predicted in GATO runs for n=5 and by Rodgers, Drake, Zeiler theory.
- Effect of barrier width for higher n modes (no SS access to ballooning) predicted by RDZ theory does not appear to be present.
ELM mode may be the highest n ideal mode without access to second stability and consistent with FLR stabilization

- $p'$ limit decreases with increasing n (GATO calculation for wall=1.5a, self consistent $j_{BOOT}$)
- First mode without second stable access may be responsible for ELM


H-mode Transport Barrier Width

♦ Derivation of barrier width scaling form data base of discharges.
♦ Testing of derived scaling with specific experiments.
♦ Dimensionally similar comparison with CMOD discharges.
♦ Role of neutrals model for in determining the density pedestal.
♦ Future Work
  o Hopefully more direct inter-machine comparisons
  o Development of a coupled turbulent transport and stability code for the edge (underway).
H-mode transport barrier width scaling

- Empirical scaling: only $I_p$, $p_{e_{ PED}}$, $T_{e_{ PED}}$ are strongly correlated with $\Delta$:
  $\Delta \propto (p_{e_{ PED}})^{0.52}/B_P^{0.94} \approx (\beta_{P_{ PED}})^{1/2}$ or $\Delta \propto (T_{e_{ PED}})^{0.36}/B_P^{0.44} \approx (\rho_{P_{ PED}})^{1/2}$

- Shaing[1]: Ion orbit loss $\Rightarrow E_R$, $\omega_{EXB}$ $\Rightarrow$ turbulence suppression
  $\Delta/R \approx (\varepsilon/s)^{1/2}\rho_p/R$, where $s=$orbit squeezing.
  $s=|1-dE_R/dR/(B_P\Omega_P)| \approx |1+(\rho_p^2/(\delta_{LT_i})| \approx 1 \Rightarrow \delta_{SHAING}/R \approx 0.6\rho_p/R$

- IFS-PPPL[2]: ITG and TEM turbulence, nonlinear simulations indicate turbulence is suppressed when $\omega_{EXB} > \gamma_L \Rightarrow \Delta_{IFS-PPPL}/R \approx 4\rho_i/R(T_i/T_e)(1+f(q))/(1+f(e)) [\times S^x][3]$

Divertor pumping experiment appears to rule out the $T^{\text{PED}}$ as a controlling parameter for H-mode transport barrier width

- To match the variation of $\Delta$ just before the ELM (or for time average) with divertor pumping requires $\Delta \propto (T_e^{\text{PED}})^{0.2}$ while to match the variation of $\Delta$ between ELMs requires $\Delta \propto (T_e^{\text{PED}})^{1.0}$
- $\Delta \propto (p_e^{\text{PED}})^{0.5}$ is a better match to the overall and between ELM $\Delta$ variation.
Pedestal dimensionless scaling experiment in collaboration with Alcator-CMOD Group

♦ Can dimensionless scaling be applied to H-mode transport barrier width (or is atomic physics important)?
♦ Match plasma shape, q; scale $T_e^{PED}$, $n_e^{PED}$ to maintain $\nu^*$, $\rho^*$, $\beta$ fixed
♦ Data still being analyzed but possible quasi-coherent mode observed in DIII-D
♦ Future direct comparisons between machines of this type could be very helpful.

$T_e^{PED}$ and $n_e^{PED}$ were scaled to keep dimensionless quantities fixed.

Shapes were well matched
Density pedestal may be determined by charge exchange penetration of neutrals


$$D_f f(\theta)^2 d^2 n_e / d\xi^2 = \int n_e n_e \sigma V_e d\theta \quad (1)$$

$$V_H / f(\theta) \partial n_e / \partial \xi = -n_e n_e \sigma V_e \quad (2)$$

where $\xi = 1 - \rho$ is the flux coordinate and

$$f(\theta) = 1/d\xi/dx$$

In scrape-off layer ($\xi > 0$) $n_e(\xi) = n_{sep} \exp[-\xi/\sqrt{D_{\parallel}}]$

Inside the separatrix ($\xi \leq 0$),

$$n_e(\xi) = n_{ped} \tanh[C - (\sigma V_e / 2 V_H) f(\theta_0) n_{ped} \xi]$$

where $C \equiv 0.5 \sinh^{-1}(U)$, $U \equiv [(\sqrt{D_{\parallel}}) \sigma V_e / 2 V_H] f(\theta_0) n_{ped}$, and $\tau_\parallel$ is particle confinement time in SOL

For $U \leq 1$, $n_{ped} / n_{sep} \propto 2 / U$ ⇒

$$n_{ped}^2 \propto n_{sep} / f(\theta_0)$$

$$\Delta_{ne} \propto 1/ n_{ped}$$

Although neutral penetration may set the $\Delta_{ne}$ the transport barrier may be controlled by other physics

ELM effects

- Radial extent of the ELM instability eigenmode correlated with ELM size.

- **Quiescent H-mode**: high energy confinement ELM free regime without the problems of ELM free H-mode (density and impurity accumulation, large edge current and resulting instability).

- Future work.
  - Other models for the Type I ELM energy loss mechanism?
    - Coupling of edge kink/ballooning to core?
    - Response of stiff temperature profile?
    - Inward propagation of the instability?

![Pedestal Parameter Evolution in Type I ELM Discharge](image-url)
Change in ELM size with shape and q may be related to change in radial mode width of associated instability (JT-60U discharges[1]).

- Giant ELMs ~ 100 Hz, small amplitude “grassy” ELMs ~ 500-1000 Hz
- At intermediate δ and q95 mixtures of giant and grassy ELMs
- Unstable edge modes in grassy elm discharges have narrow radial mode width (ELITE Code).
- Changes in radial width related to difference in q profiles

**JT-60U Results**

![Graphs showing ELM behavior and q profiles](image)

Reduction in ELM size at high density may be due to reduced mode number at higher collisionality

With increasing \( n_e^{\text{PED}} \) or \( \nu^* \propto n/T^2 \):

- \( \Delta W_{\text{ELM}}/W_{\text{PED}} \) decreases
- ELM mode increases in \( n \)
- Calculated \( j_{\text{BOOT}} \) decreases \( \Rightarrow \) edge magnetic shear increases \( \Rightarrow \) SS access lost
- \( \nabla p \) is reduced from calculated \( n=5 \) limit (GATO) to ideal nigh \( n \) ballooning mode limit (BALOO).

n number of ELM mode increases with \( n_e \) perhaps due to loss of second stability

Mode width decreases with increasing \( n \).
ELM free H-mode with edge harmonic oscillation (EHO) has high H and no density accumulation.

- Counter Injection
- Low density with divertor pumping
- Large outer gap
- H89P to 2.4
- $\beta_N$ to 2.9
- $\beta_N H$ to 7
Conclusions

♦ Edge Stability
  o Low - medium n edge localized kink/ballooning mode is good candidate for Type I ELM instability
    – Quantitative comparison between theory and experiment will be possible with Li-Beam edge current density diagnostic.
    – Extension of intermediate n theory
  o MHD associated with QH-mode still not understood

♦ Transport barrier width
  o DIII-D - CMOD comparison may indicate dimensionless scaling applies to the edge but need more inter-machine comparisons to settle this and to derive the scaling laws.
  o Need to develop a model for the edge including both transport and stability since these effects are coupled

♦ ELM Effects
  o ELM size may be related to low-medium n mode radial extent
  o Other possibilities (e.g stiff profiles) should be tested