Pedestal Stability Constraints and ELM Dynamics in ITER

P.B. Snyder


1General Atomics, San Diego, USA
2U. of York, York, UK
3LLNL, Livermore, CA USA
4IPP Garching, Germany

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Motivation: The Pedestal and ELMs

- **ITER and most BP devices to operate in H-mode**
  - Edge barrier dramatically improves confinement
  - Broadens profiles, leads to high MHD $\beta$ limit

- **ELMs and the edge pedestal are key fusion plasma issues**
  - “Pedestal Height” strongly impacts core confinement and therefore fusion performance ($Q$)
  - ELM heat pulses impact plasma facing materials
    - Large ELMs not tolerable in ITER

**Predicted Impact of Pedestal Height**

**Observed Impact of Pedestal Height**
The Peeling-Ballooning Model

- Peeling-Ballooning model offers explanation for ELM onset and constraints on pedestal
- ELMs caused by intermediate wavelength (n~3-30) MHD instabilities
  - Both current and pressure gradient driven
  - Complex dependencies on $\nu_*$, shape etc. due to bootstrap current and “2nd stability”, nonlocality and variation in limiting $n$

The Peeling-Ballooning Model: Code Verification

  - Extended ballooning expansion + peeling
  - Validated against GATO, MISHKA, CASTOR, MARS, BAL-MSC
    - infinite-n ballooning only valid at very high-n
    - Non-locality and kink terms essential
  - Validated with toroidal flow (MARS, CASTOR)
**The Peeling-Ballooning Model: Verification against Experiment**

DIII-D Shot 119748, Pedestal Stability just before ELM

![Graph showing Kink/Peeling Unstable, Stable, and Ballooning Unstable regions.](image)

- **Successful comparisons to multiple tokamaks both directly and in database studies**
  - Onset of Type I ELMs corresponds to crossing P-B threshold
    - Role of bootstrap current largely confirmed
  - Edge stability analysis becoming routine on some devices
  - MHD physics, taking into account two fluid effects, does a remarkably good job accounting for ELM onset and observed pedestal constraints (as function of width)

Effect of Density (Collisionality) on Peeling-Ballooning Stability

**Effect of Density**

- **The pedestal current is dominated by bootstrap current**
  - Roughly proportional to $p'$
  - Decreases with collisionality
- **Lower density means more current at a given $p'$**
  - Moderate to high density discharges limited by P-B or ballooning modes
  - Very low density discharges may hit kink/peeling boundary
- **Typically:**
  - High-n ballooning -> small Type I ELMs
  - Intermediate n peeling-ballooning -> normal Type I
  - Low n kink/peeling -> QH mode
Theory: QH Mode Exists in Low-n Kink/Peeling Limited Regime

- Detailed Study Using Model Equilibria to Explore Stability Bounds in QH-like discharges

- Weak Shaping (left): QH Regime accessible only at very low density \( n_{\text{ped}}<\sim1.5 \times 10^{13} \text{ cm}^{-3} \)
- Stronger Shaping (right): QH regime can be accessed at higher density (here up to \( n_{\text{ped}}<\sim3 \times 10^{13} \text{ cm}^{-3} \)), more robust
- Low-n modes experience some wall stabilization, despite localization
Experiment: QH Discharges Exist Near Kink/Peeling Boundary

- Stability Studies Perturbing around reconstructed QH Discharges on DIII-D

Moderate Shaping (left): QH operating point near kink/peeling bound, low density $n_{ped} \sim 1.5 \times 10^{13}$ cm$^{-3}$

Strong Shaping (right): QH operating point near kink/peeling bound, higher density QH operation possible, $n_{ped} \sim 3 \times 10^{13}$ cm$^{-3}$

Observed EHO during QH mode has poloidal magnetic signal qualitatively consistent with low-$n$ kink/peeling mode
RMP ELM-free Discharges in Similar Regime

- n=3 Resonant Magnetic Perturbations used to suppress ELMs in low density discharges
- ELM-suppressed shots in stable region, nearest kink/peeling boundary
  - Increasing density causes ELMs to return
- Propose that RMP plays the role of the EHO here
  - Particle, Te, rotation steady state
- While EHO grows only to amplitude needed for steady state, RMP amplitude can be controlled
  - Able to operate a factor of 2 below stability boundaries
Model ITER Equilibria Constructed to Calculate Pedestal Stability Bounds

- Match design $B_t$, $I_p$, $R$, $a$, $\kappa$, $\delta$, $<n_e>$
- Tanh pedestals, polynomial in core, bootstrap aligned current in pedestal
- The pedestal width ($\Delta$) is varied from $\sim$1% to 12% of the poloidal flux ($\Delta/a\sim0.005-0.07$)
- At each value of $\Delta$, $T_{\text{ped}}$ is increased (with $J_{bs}$ calculated consistently) until instabilities ($n=8,10,15,20,30$ tested with ELITE) are triggered

ITER model profiles for $\Delta/a\sim0.03$, $T_{\text{ped}}\sim5$keV case
Pedestal Stability Constraints on $T_{\text{ped}}$, $\beta_{\text{Nped}}$, $\alpha_{\text{cped}}$

- $T_{\text{ped}}$ limit is a strong function of pedestal width, but notably sub-linear, particularly at narrow width ($\sim \Delta^{2/3}$)
- Intermediate to high-$n$ peeling-ballooning modes ($n\sim 20$) are most unstable. Significant second stability to high-$n$ modes at larger widths.
- Stronger shaping $\Rightarrow$ higher $\beta_{\text{Nped}}$ & $\alpha_{\text{cped}}$
- $\alpha_{\text{crit}}$ decreases strongly with width (stability is non-local)
• Increasing triangularity ($\delta_a$) is stabilizing, levels off around $\delta_a \sim 0.5$
• Increasing density lowers edge bootstrap current, restricts 2nd stability access. Appears possible to increase performance by operating at lower density; tradeoffs with divertor, ELM size?
• Rotation and non-ideal effects expected to have significant impact
• Simple models give indication of the impact of diamagnetic effects
  – Local $\gamma_{\text{MHD}} > \omega_{\text{pi}}/2$
  – Rogers & Drake suggested modification: $1/(1+1/k_\theta L_p)$
• Simple models suggest significant diamagnetic stabilization, shift of most unstable mode to longer wavelengths ($n \sim 8-20$)
ITER Study Shows QH Regime May be Accessible at Low Density

- **ITER base case**, $R=6.2\,\text{m}$, $a=2\,\text{m}$, $B_t=5.3\,\text{T}$, $I_p=15\,\text{MA}$, 5% pedestal width
- **Reference density** $<n_e>=10.1\times10^{19}\,\text{cm}^{-3}$, $n_{\text{ped}}\approx7\times10^{19}\,\text{cm}^{-3}$
  - High $n\sim20$ ballooning limited at Ref density
- **QH region for $n_{\text{ped}}<\sim4\times10^{19}\,\text{cm}^{-3}$**
  - Worth exploring low density operation (divertor impacts?)
The Peeling-Ballooning Model: Nonlinear Dynamics

- **Nonlinear**: 3D BOUT simulations (reduced Braginskii), include equilibrium scale MHD drives as well as small scale diamagnetic terms in collisional limit

- **Expected P-B linear growth and structure in early phase, followed by explosive burst of one or many filaments into the SOL**
  - Leads to two-prong model of ELM losses (conduits and barrier collapse)
    
    \[ P.B. \ Snyder, \ Phys \ Plasmas \ 2005, \ H.R. \ Wilson, \ PRL \ 2004 \]

- **Nonlinear simulations carried out for DIII-D equilibria in the same range of parameters as ITER (n~20 limited), in region where small Type I ELMs observed**
  
  - Bursts of one or many filaments
  - Direct ITER simulations more challenging because of smaller \( \rho^* \), but planned
Filamentary structures observed during early ELM evolution (multiple filaments, n~18)
ELITE linear P-B calculations show peak 15<n<25; mode in this range predicted to be first to go unstable
Calculated n=18 structure qualitatively similar to observations
Nonlinear simulations show symmetric structure in early phase, extended uneven filaments later
Summary

- Peeling-ballooning model has achieved a degree of success in explaining pedestal constraints, ELM onset and a number of ELM characteristics
  - Nonlinear explosive growth of one or many filaments, similar to observations
  - Two prong model (conduits and barrier collapse) for ELM losses
  - Low density, strong flow key to Quiescent operation

- Calculations for ITER suggest it can achieve sufficiently high pedestal for good performance, with pedestal width in observed range ($\Delta/a$)
  - Pedestal width physics remains key uncertainty (varies little in existing expts)
  - Some improvement possible at lower density, increased shaping (good design)

- ITER study suggests base operation is in small Type I ELM regime, $n \sim 20$ limited
  - Marginally tolerable for materials (pending detailed understanding of deposition)
  - Need further (direct) nonlinear studies to confirm

- Predicted QH operation in ITER possible at significantly reduced density $n_{\text{ped}} \sim 4 \times 10^{19}$ cm$^{-3}$
  - This low density regime has also been best for RMP ELM suppression
  - Need to consider divertor and other implications of low density operation
References

Hypothesis for QH Mode Mechanism

Avoiding ELMs requires a mechanism to make confinement in the edge regions worse, and must do so robustly and self-consistently across all transport channels.

- QH Mode exists in regime where low-n kink/peeling is limiting, due to low density, high bootstrap current.
- Strong flow can stabilize “ELRWM” branch, leave rotationally destabilized low-n “ideal” (with kinetic and diamagnetic corrections) rotating kink/peeling mode most unstable.
  - This rotating mode is postulated to be the EHO.
- As EHO grows to significant amplitude it couples to wall, damping rotation and damping its own drive.
  - A) Presence of the mode breaks axisymmetry, spreads strike point and stochasticizes surfaces.
  - B) Small scale ballooning instabilities can grow inside low-n EHO structure.
    - -> more particle transport and more efficient pumping, allowing steady state density profile.
    - $T_e$ profile is able to reach a transport steady state in low $n_e$ regime.
- EHO saturates at finite amplitude, resulting in near steady-state in all key transport channels in the pedestal region.
Filaments Observed During ELMs

DIII-D Observation  [E Strait, Phys Plas 1997]
- Filament observed in fast magnetics during ELM (left)
- Finger-like structure from simulation (right) is extended along the magnetic field
- Qualitatively similar (rotation rate consistent with toroidal extent)