Stability and Dynamics of the Edge Pedestal in the Low Collisionality Regime

Physics Mechanisms for Steady State ELM-Free Operation

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Outline

Physics of ELMs and Pedestal Constraints

- The Peeling-Ballooning Model and ELITE
  - Successfully explains observed ELM onset and pedestal constraints
  - Impact of sheared toroidal flow

- Nonlinear Dynamics of ELMs
  - Direct 3D nonlinear simulation results: bursts of filaments
  - Proposals for dynamics of full ELM crash, and particle & energy losses

Physics of ELM-free Discharges

- Quiescent H-Mode (QH) Theory and Observation
  - QH Theory explains observed density, rotation, mode structure
  - Application to ELM-suppressed RMP discharges
The Peeling-Ballooning Model Predicts ELM Onset, Pedestal Constraints

- **Pedestal Height and ELM heat impulses key issues for tokamaks/ITER**
  - Peeling-Ballooning model developed to explain ELM onset and pedestal constraints

- **ELMs caused by intermediate wavelength (n~3-30) MHD instabilities**
  - Both current and pressure gradient driven, non-local
  - Complex dependencies on $v_*$, shape etc. due to bootstrap current and “2nd stability”

- **ELITE code developed to efficiently evaluate P-B stability, compare to observation**
  - Extensively benchmarked against other MHD codes, includes non-locality, rotation

The Peeling-Ballooning Model: Code Verification

  - Extended ballooning expansion + peeling
  - Validated against GATO, MISHKA, CASTOR, MARS, MARG 2D, 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: Extensive Validation against Experiment

- **Successful comparisons to multiple tokamaks both directly and in database studies**
  - Over 100 discharges directly studied with ELITE
  - Onset of Type I ELMs corresponds to crossing P-B threshold
  - **MHD physics, taking into account diamagnetic effects, does a remarkably good job accounting for ELM onset and observed pedestal constraints**
  - Power scaling understood via Shafranov shift, dynamic effects
  - Predictions for ITER pedestal height (as function of width)


See also Leonard EX/P8-3
**Effect of Strong Toroidal Flow Shear in the Edge Region**

- **Eigenvalue formulation with rotation and compression derived and included in ELITE**
  - Sheared rotation strongly damps high $n$
  - weaker impact intermediate $n$, can be destabilizing at low $n$
  - Small change in instability threshold, limiting mode moves to lower $n$
  - radial narrowing of mode structure
Calculated Mode Rotation AGREES with Observation during ELM

- Measured rotation profile flattens at ELM onset
  - Value matches eigenfrequency of most unstable mode
- Suggests "locking" of pedestal region to the mode during initial phase of ELM crash ⇒ edge barrier collapse
Nonlinear ELM Dynamics
Direct Numerical Simulation of Nonlinear Peeling-Ballooning Finds Radially Propagating Filaments


- **Nonlinear**: 3D BOUT simulations (EM two-fluid), 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**
  - Successful comparisons of structure, radial velocity to observations
    - Nonlinear ELM simulations and theory predicted filaments before fast camera observations
  - Leads to two-prong model of ELM losses (conduits and barrier collapse)
    [P.B. Snyder, Phys Plasmas 2005, H.R. Wilson, PRL 2004]
- **Picture developing to explain ELM onset and dynamics in the usual moderate to high density ELMing regime**
Simulations Compared to DIII-D Fast Camera Images of ELMs

- Use reconstructed equilibrium just before fast camera image of ELM
  - Most unstable mode n~18
- Nonlinear simulations find good agreement in filamentary structure, wavelength, and qualitative radial propagation speed
  - Filaments were predicted by simulation and theory before fast camera images
Physics of ELM-free Regimes
Quiescent H-mode (QH): ELM-free regime seen on multiple machines, wide range of parameters, usually with saturated edge mode (EHO)
- Operation generally requires low density and strong counter rotation in the pedestal region

Effect of Low 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’
  \( (\nu \sim n_e^3 \text{ at given } p) \)
  - Moderate to high density discharges limited by P-B or ballooning modes
  - Very low density discharges may hit kink/peeling boundary
Theory: QH Mode Exists in Low-n Kink/Peeling Limited Regime

- Can quantitatively predict density range over which QH operation possible

Weak Shaping (left): QH Regime accessible only at very low density \( n_{\text{ped}} < \sim 1.5 \times 10^{13} \text{ cm}^{-3} \)

Stronger Shaping (right): QH regime can be accessed at higher density (here up to \( n_{\text{ped}} < \sim 3 \times 10^{13} \text{ cm}^{-3} \)), more robust

Low-n modes experience some wall stabilization, despite localization
Observation: 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 $n_{ped} \approx 1.5 \times 10^{13} \text{ cm}^{-3}$
- **Strong Shaping (right):** QH operating point near kink/peeling bound, higher density QH operation possible, $n_{ped} \approx 3 \times 10^{13} \text{ cm}^{-3}$
  - Good quantitative agreement with predictions, confirmed by 2006 expts
- **Observed EHO during QH mode has poloidal magnetic signal qualitatively consistent with low-n kink/peeling mode**
ITER Model Shows QH Regime May be Accessible at Low Density

- **ITER base case**, \( R=6.2\, \text{m}, \, a=2\, \text{m}, \, B_t=5.3\, \text{T}, \, I_p=15\, \text{MA} \)
- **Reference density** \(<n_e>=10.1 \times 10^{19} \, \text{cm}^{-3}, \, n_{\text{eped}} \approx 7 \times 10^{19} \, \text{cm}^{-3} \)
  - High \( n \) ballooning limited at Ref density
- **QH region for** \( n_{\text{eped}} \sim 4 \times 10^{19} \, \text{cm}^{-3} \)
  - Worth exploring low or peaked density operation
Rotation Plays an Important Role in QH Mode

- Flow stabilizes "edge localized RWM" (and high-n ballooning modes)
  - Allows plasma to reach ideal boundary, triggering rotating low-n mode

- Limiting modes are rotationally destabilized
  - As mode grows and damps rotation, it is stabilized (unlike ELM)

- Rotation requirements quantified in DIII-D experiments
  - Density rises then ELMs return when net beam torque is reduced
Theory for QH Mode Mechanism

- QH Mode exists in regime where low-n kink/peeling is limiting, due to low density, high bootstrap current
- Strong flow shear stabilizes “ELRWM” branch, leaves 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
  - Presence of the mode breaks axisymmetry, spreads strike point and stochasticizes surface -> more current/particle transport and more efficient pumping, allowing steady state profiles
- EHO saturates at finite amplitude, resulting in near steady-state in all key transport channels in the pedestal region

Predicted density requirement agrees quantitatively with experiment. Predicted mode structure, rotation, and wall coupling requirements agree qualitatively
RMP ELM-free Discharges in Similar Regime to QH

- $n=3$ 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, $T_e$, j, 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
Summary

- Peeling-ballooning model has achieved significant success in explaining pedestal constraints, ELM onset and a number of ELM characteristics
- Toroidal flow shear stabilizing at high-n, study suggests edge flow locks to mode
- Dynamics studied via direct, 3D nonlinear two-fluid ELM simulations (BOUT)
  - Expected peeling-ballooning behavior in linear phase followed by rapid burst of one or many filaments
  - Successful comparisons with observations

⇒ Two prong model (conduits and barrier collapse) for ELM losses

- QH Theory: ELM-free QH exists in low-n kink/peeling limited regime
  - Successfully predicts observed density requirements for QH mode: increase with stronger shaping
    - ITER study suggests QH for $n_{\text{ped}} \leq 4 \times 10^{19}$ m$^{-3}$
  - Flow shear stabilizes ELRWM (and higher n), leaves low-n rotationally destabilized kink/peeling mode most unstable (EHO)
  - Saturates by damping rotation and providing current/particle transport

- Low density RMP ELM free discharges in similar regime to QH
  - RMP plays the role of the EHO, but actively controlled
References