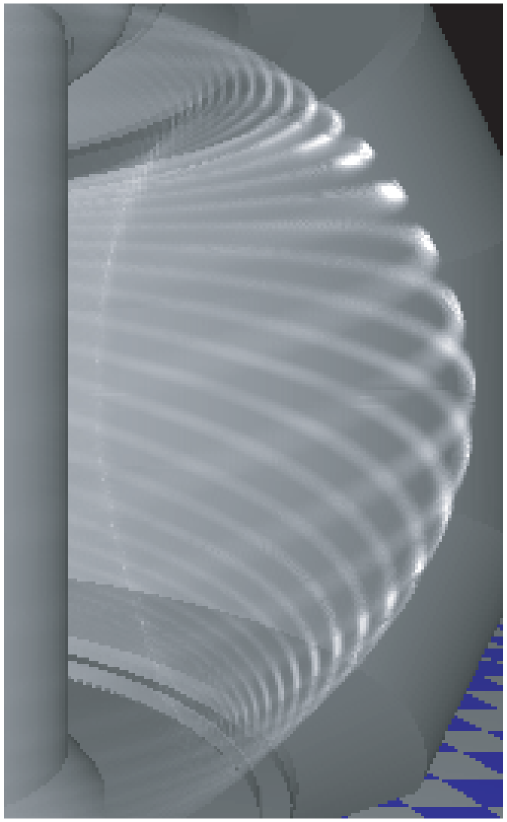
Stability and Dynamics of the Edge Pedestal in the Low Collisionality Regime

Physics Mechanisms for Steady State ELM-Free Operation



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Outline

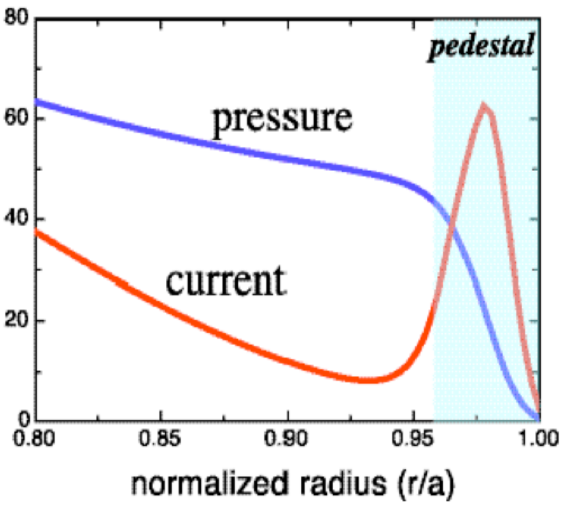
Physics of ELMs and Pedestal Constraints

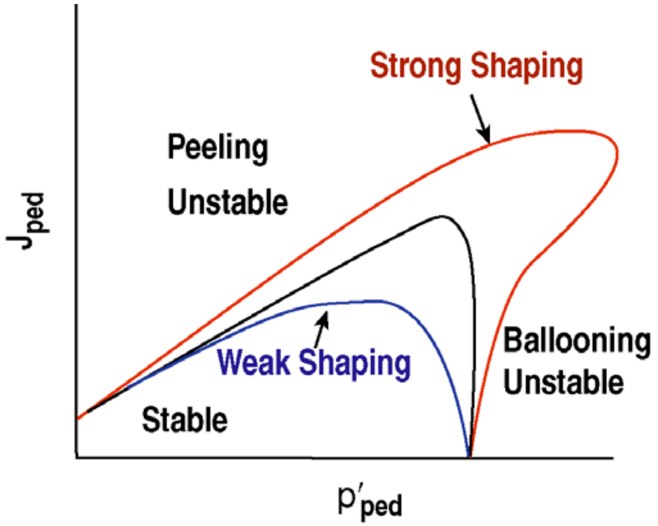
- **The Peeling-Ballooning Model and ELITE**
  - Successfully explains observed ELM onset and pedestal constraints
  - Impact of sheared toroidal flow
- **Nonlinear Dynamics of ELMs**
  - Direct 3D nonlinear simulation results: bursts of filaments
  - Proposals for dynamics of full ELM crash, and particle & energy losses

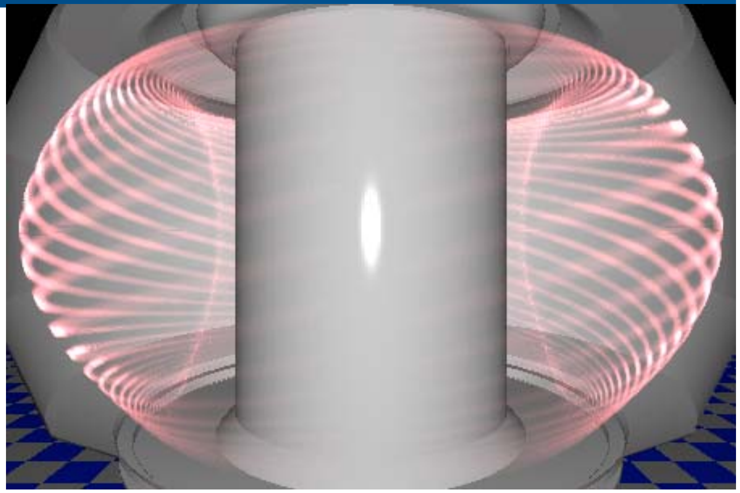
Physics of ELM-free Discharges

- **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





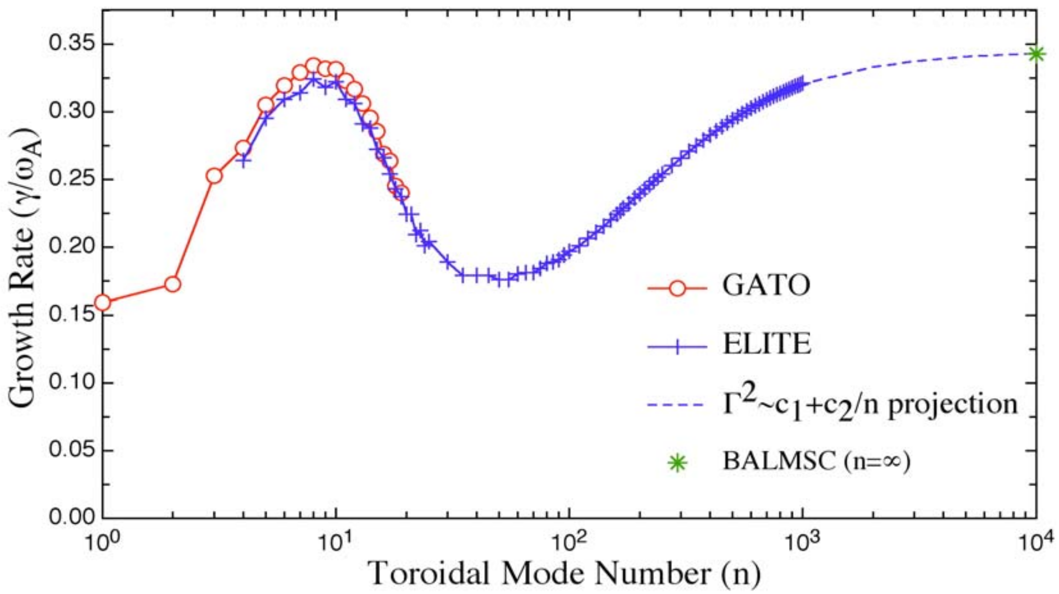


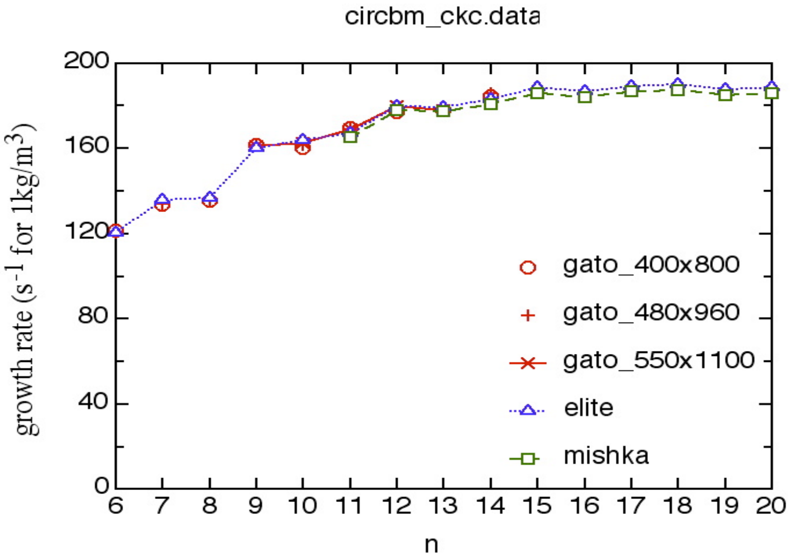
ELITE, n=18 mode structure

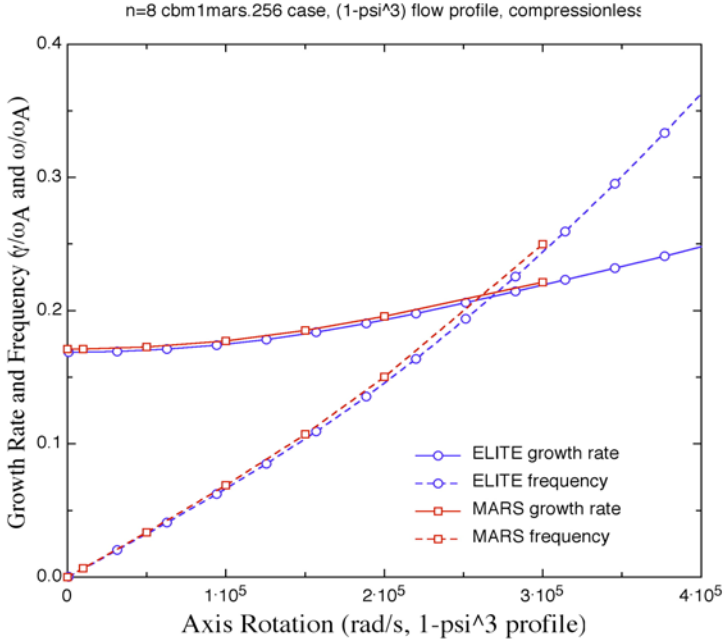
- **Pedestal Height and ELM heat impulses key issues for tokamaks/ITER**
  - Peeling-Ballooning model developed to explain ELM onset and pedestal constraints
- **ELMs caused by intermediate wavelength (n~3-30) MHD instabilities**
  - Both current and pressure gradient driven, non-local
  - Complex dependencies on ν_*, 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

[P.B. Snyder, H.R. Wilson, et al., Phys. Plasmas ***9*** *(2002) 2037, Phys. Plasmas* ***9*** *(2002) 1277 & Nucl. Fusion* ***44*** *(2004) 320.]*

The Peeling-Ballooning Model: Code Verification

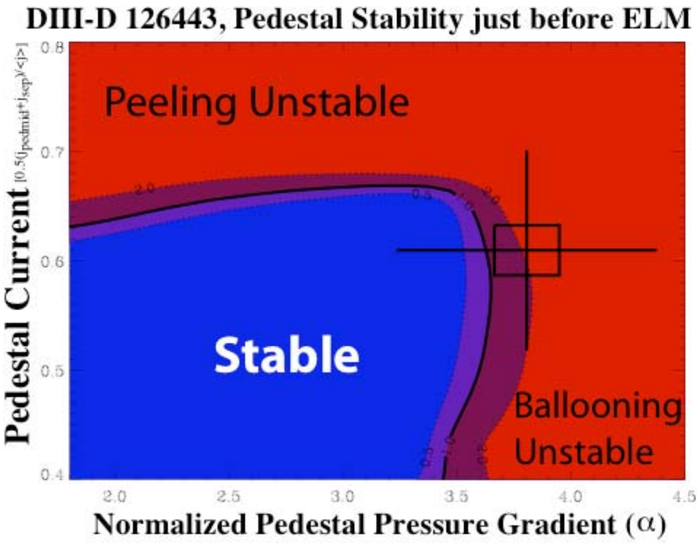


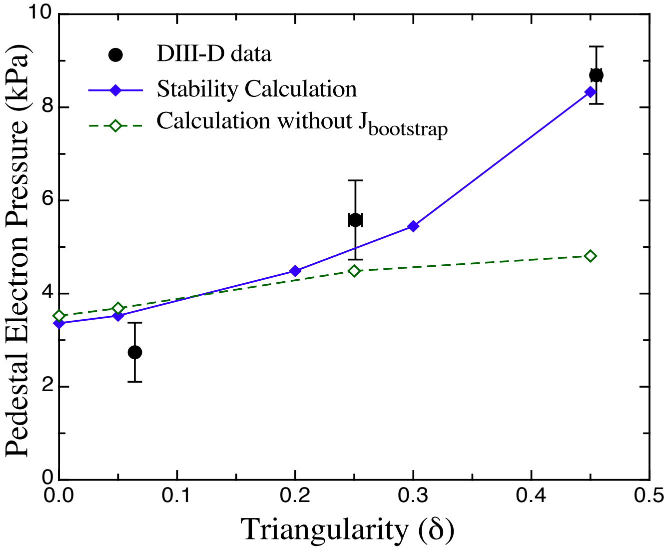


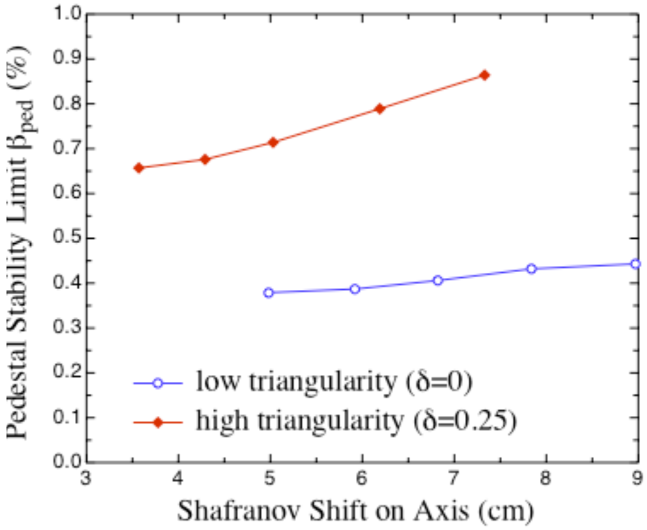


- **ELITE code developed to efficiently treat P-B stability across wide spectrum, realistic geometry** *[H.R. Wilson, P.B. Snyder et al Phys Plasmas 9 (2002) 1277; P.B. Snyder, H.R. Wilson, et al., Phys. Plasmas **9** (2002) 2037]*
  - Extended ballooning expansion + peeling
  - Validated against GATO, MISHKA, CASTOR, MARS, MARG2D, 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


DIII-D 126443, Pedestal Stability just before ELM





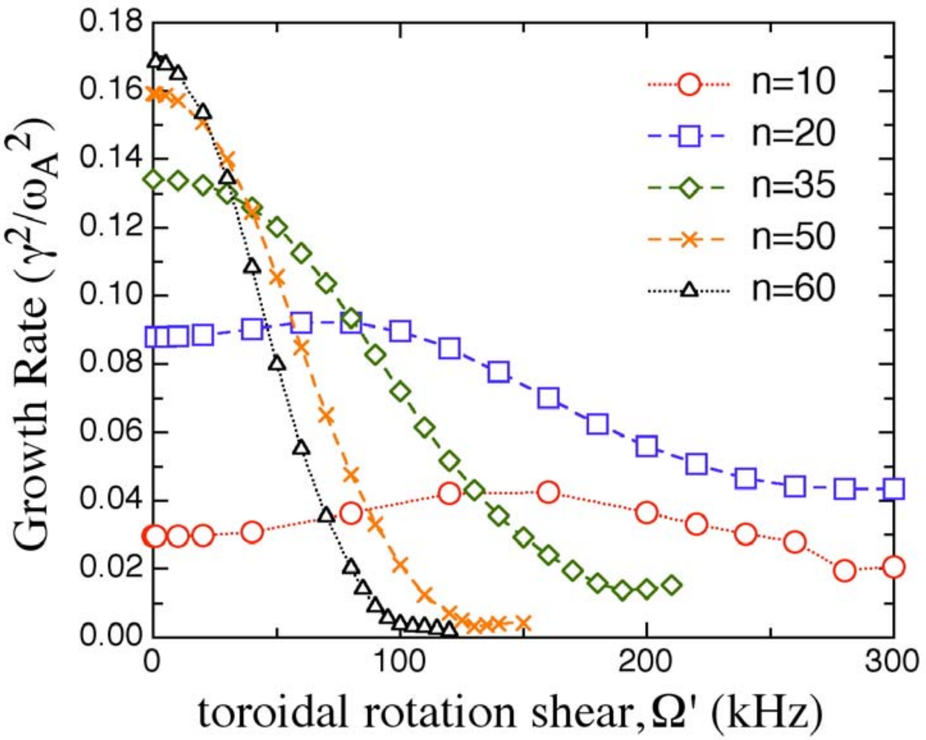
- **Successful comparisons to multiple tokamaks both directly and in database studies**
  - Over 100 discharges directly studied with ELITE
  - Onset of Type I ELMs corresponds to crossing P-B threshold
  - **MHD physics, taking into account diamagnetic effects, does a remarkably good job accounting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

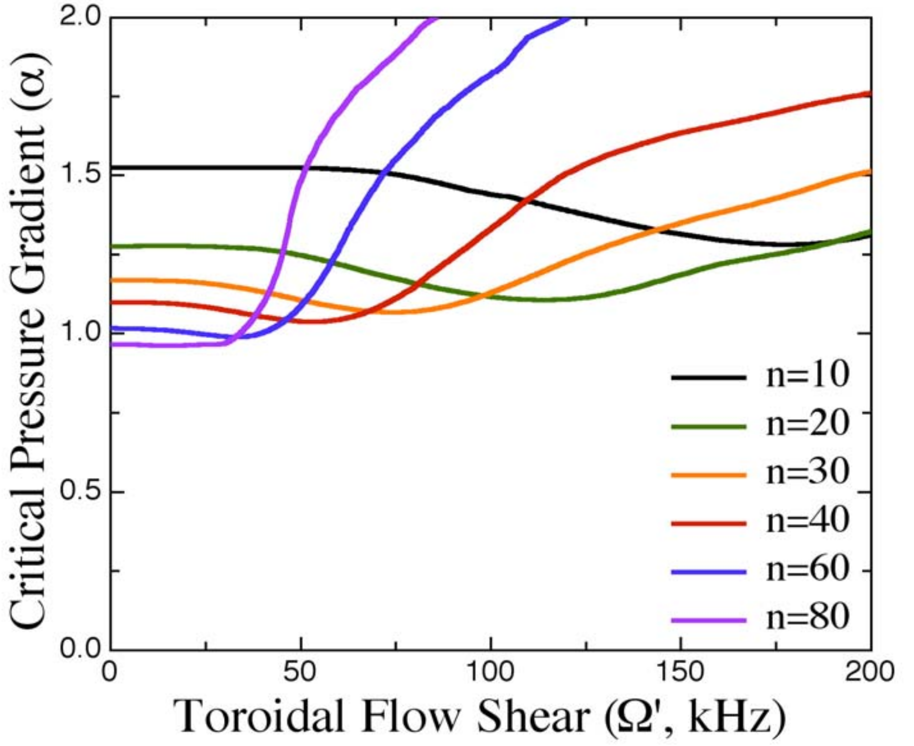
[P.B. Snyder, H.R. Wilson, et al., Phys. Plasmas ***9*** *(2002) 2037; D. Mossessian, P.B. Snyder et al., Phys. Plasmas* ***10*** *(2003) 1720; P.B. Snyder, H.R. Wilson, et al., Nucl. Fusion* ***44*** *(2004) 320.]*

See also Leonard EX/P8-3

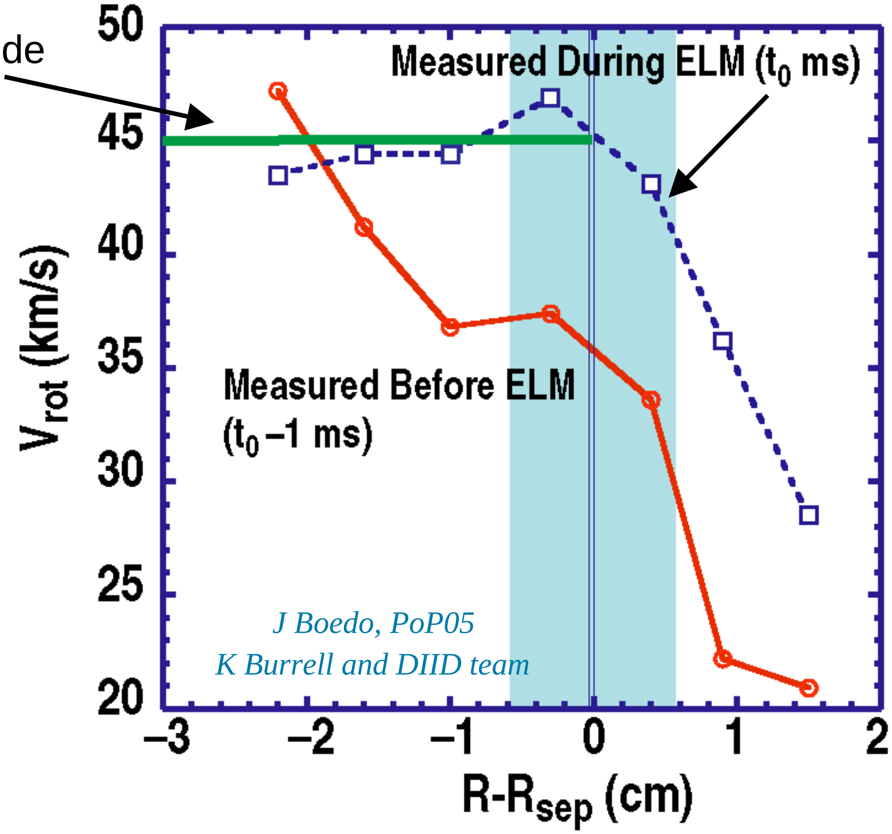
Effect of Strong Toroidal Flow Shear in the Edge Region

- **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





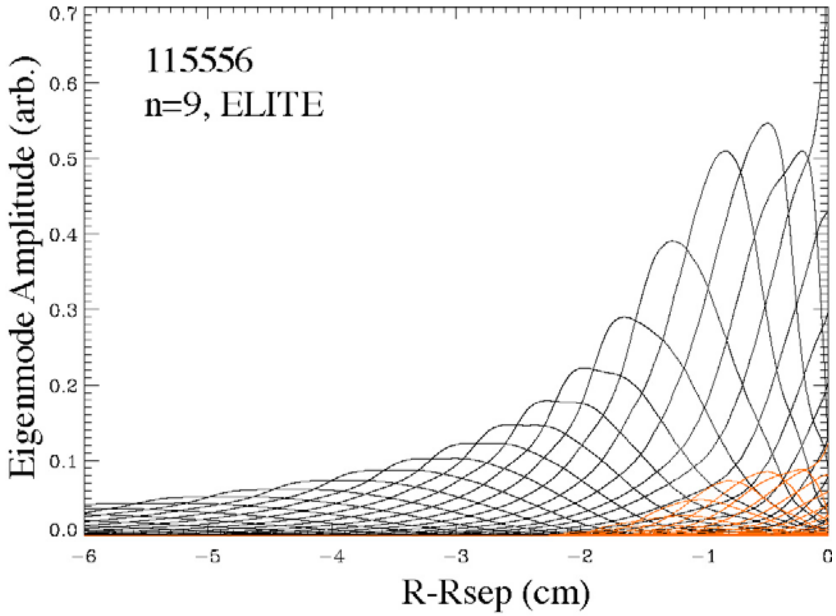
Calculated Mode Rotation Agrees with Observation during ELM



Predicted Mode Rotation

J Boedo, PoP05
K Burrell and DIID team

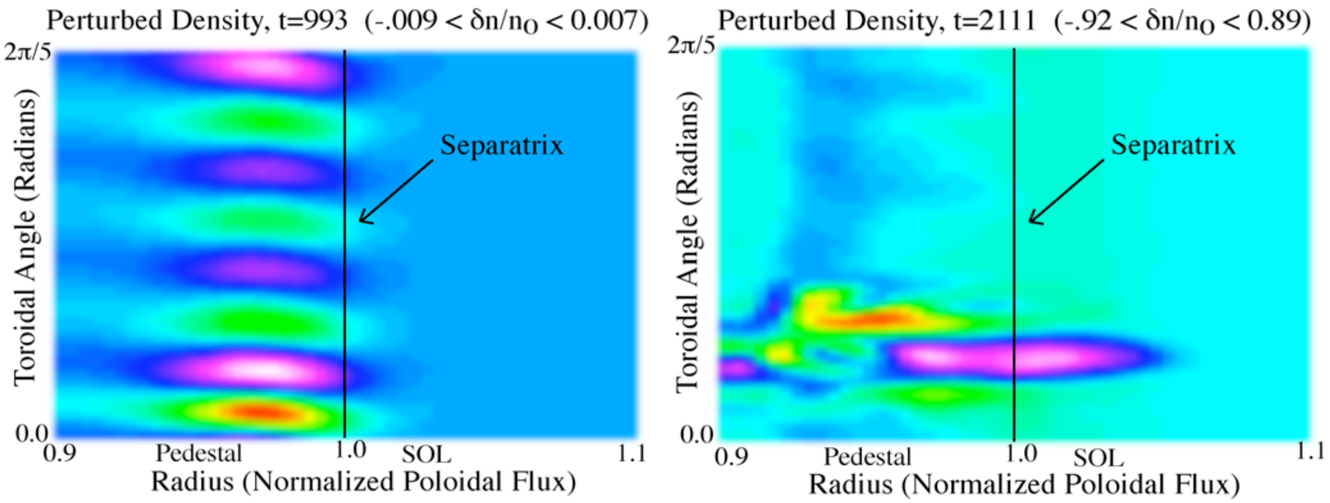
Calculated Structure of Most Unstable Mode

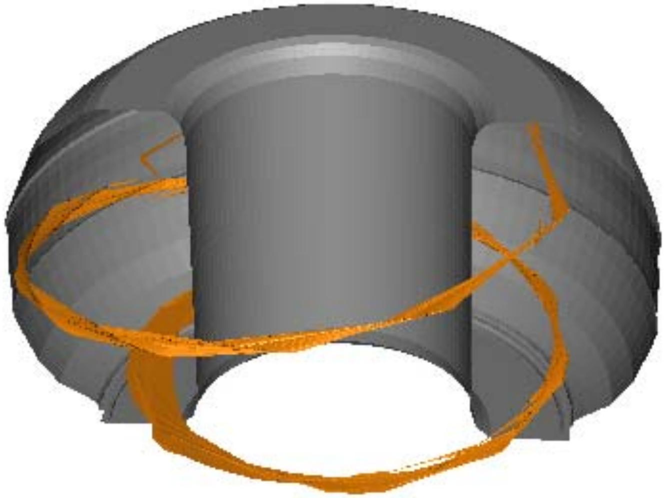


- **Measured rotation profile flattens at ELM onset**
  - Value matches eigenfrequency of most unstable mode
- **Suggests “locking” of pedestal region to the mode during initial phase of ELM crash ⇒ edge barrier collapse**

Nonlinear ELM Dynamics

Direct Numerical Simulation of Nonlinear Peeling-Ballooning Finds Radially Propagating Filaments

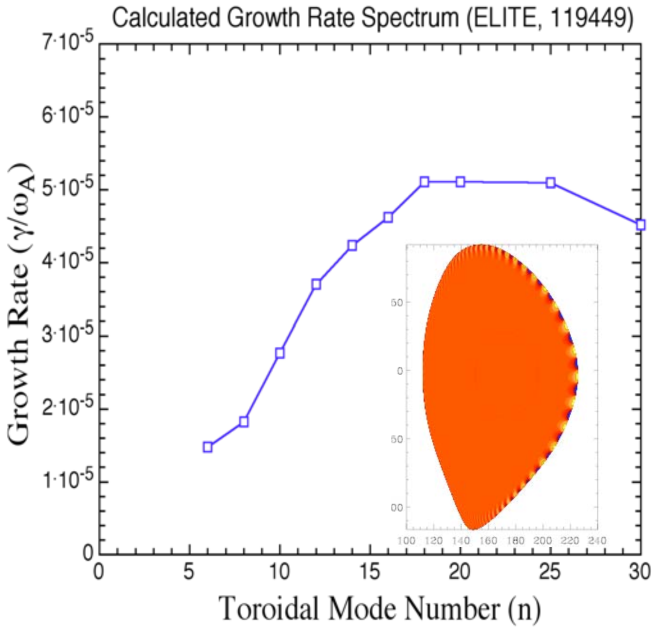




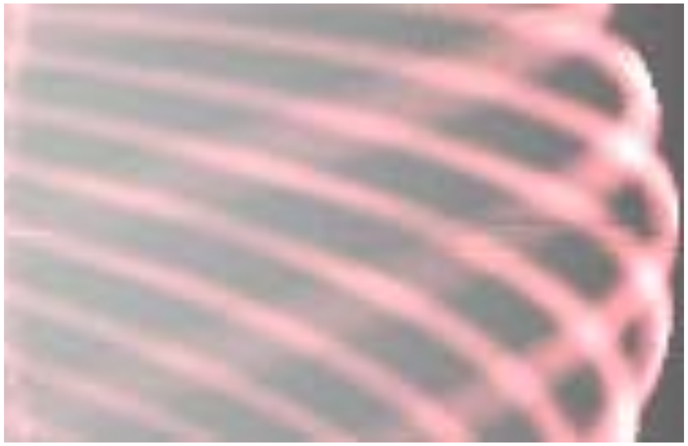
P.B. Snyder et al, Phys. Plasmas **12** *056115 (2005).*

- **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

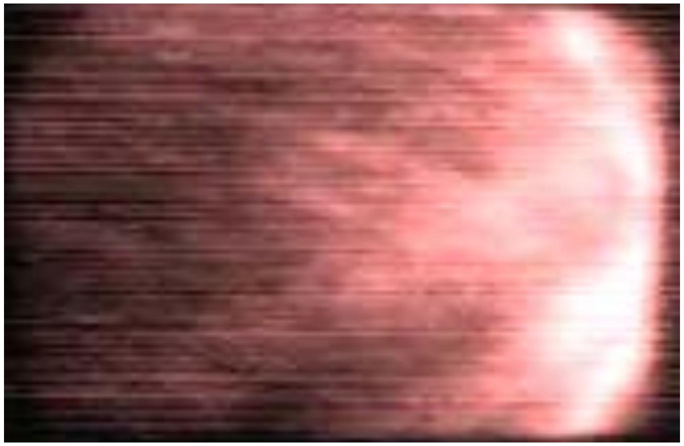


ELITE, n=18



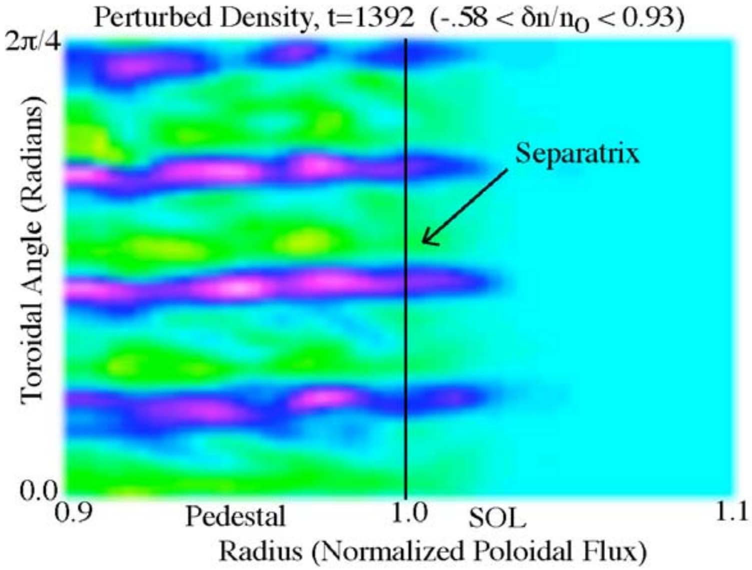
Fast CIII Image, DIII-D 119449

M. Fenstermacher, DIII-D/LLNL



- **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

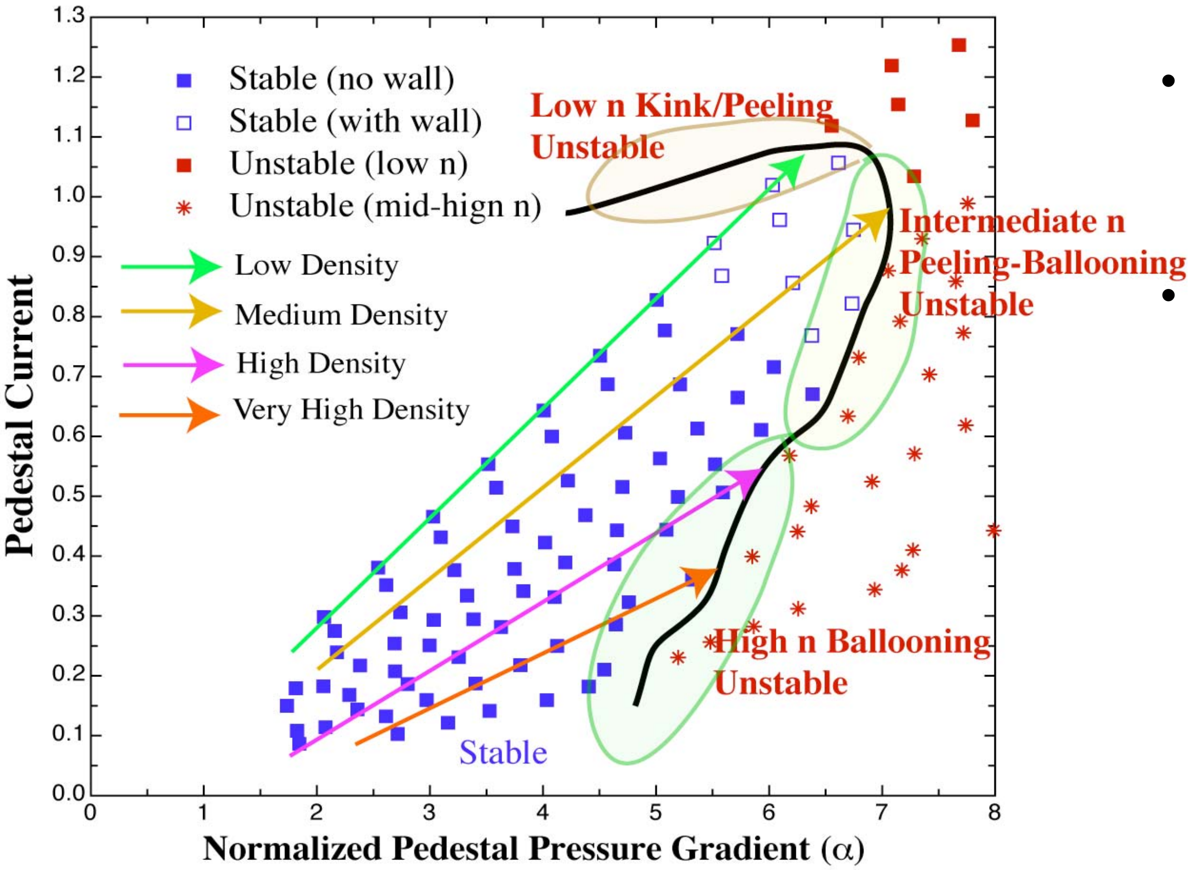
BOUT, nonlinear burst phase



Physics of ELM-free Regimes

QH Modes Exist at Low Density, High Rotation

- **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



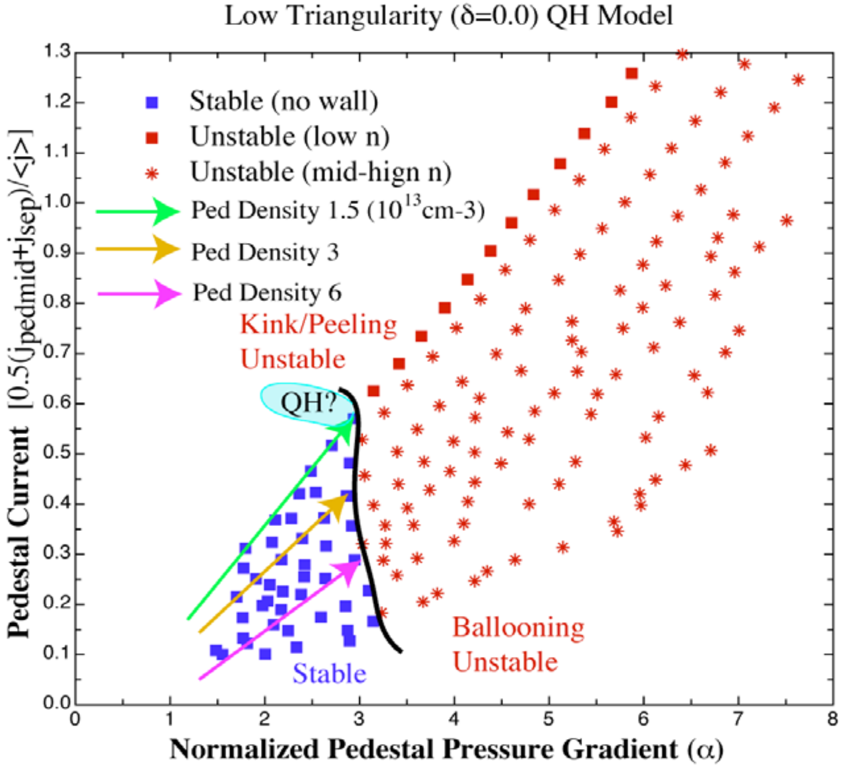
Effect of Low Density

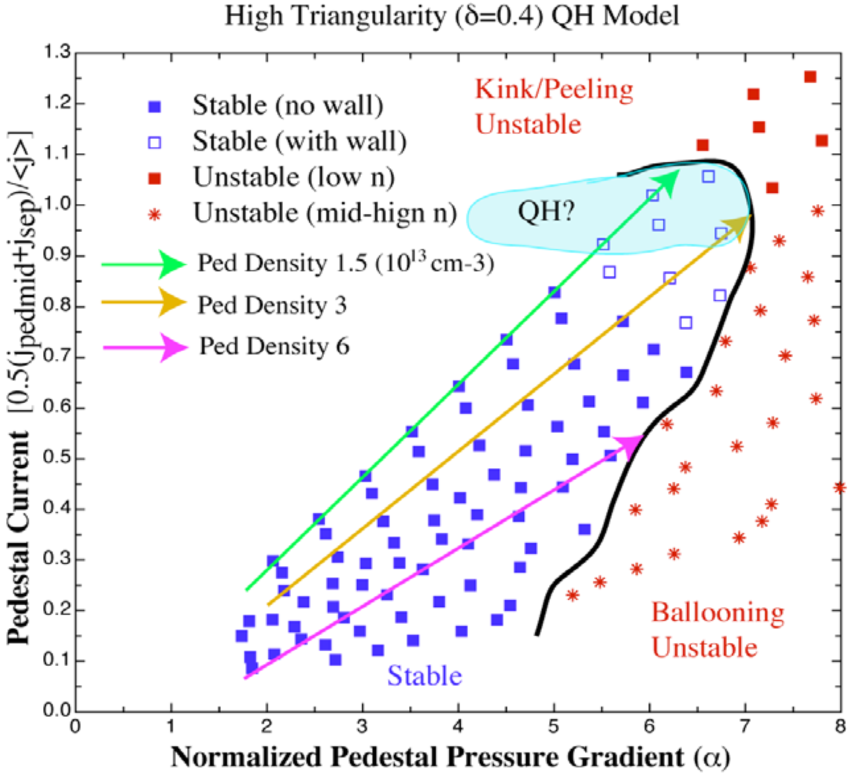
- **The pedestal current is dominated by bootstrap current**
  - Roughly proportional to p’
  - Decreases with collisionality
- **Lower density means more current at a given p’**

  $(\nu_* \sim n_e^3$ *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**

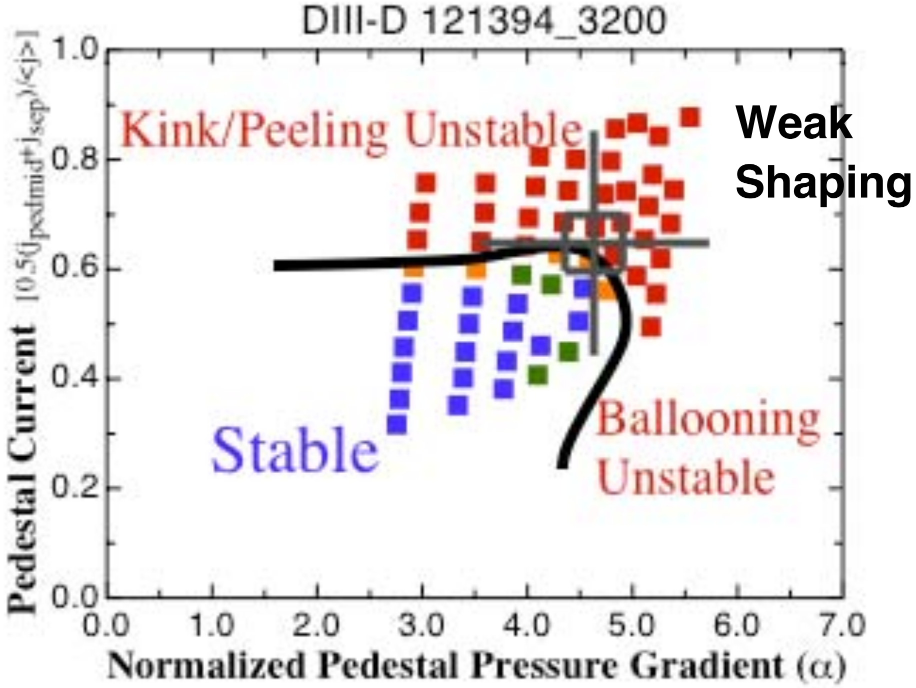

Low Triangularity (δ=0.0) QH Model

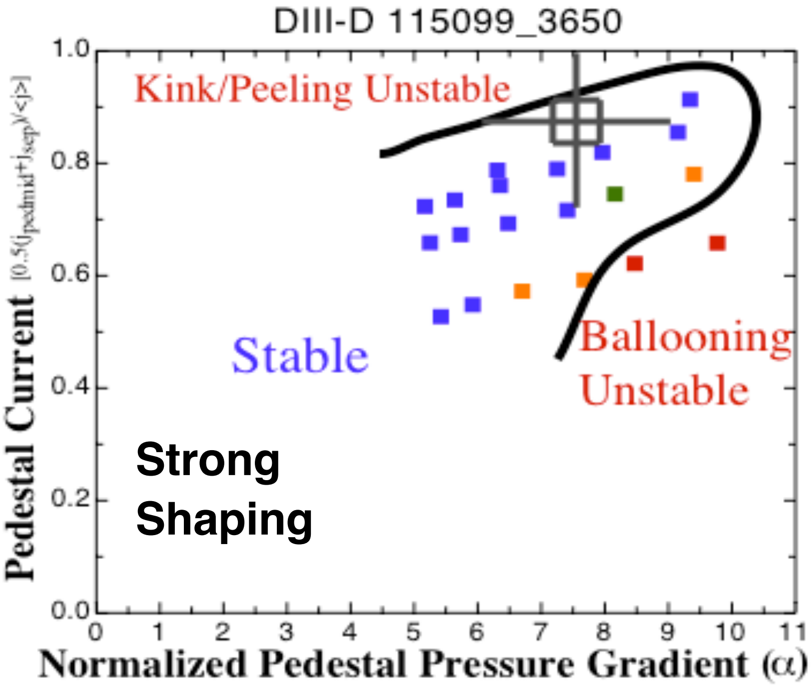

High Triangularity (δ=0.4) QH Model

- **Weak Shaping (left): QH Regime accessible only at very low density (n_{ped}<~1.5 10^{13} cm^{-3})**
- **Stronger Shaping (right): QH regime can be accessed at higher density (here up to n_{ped}<~3 10^{13} cm^{-3}), more robust**
- **Low-n modes experience some wall stabilization, despite localization**

Observation: QH Discharges Exist Near Kink/Peeling Boundary

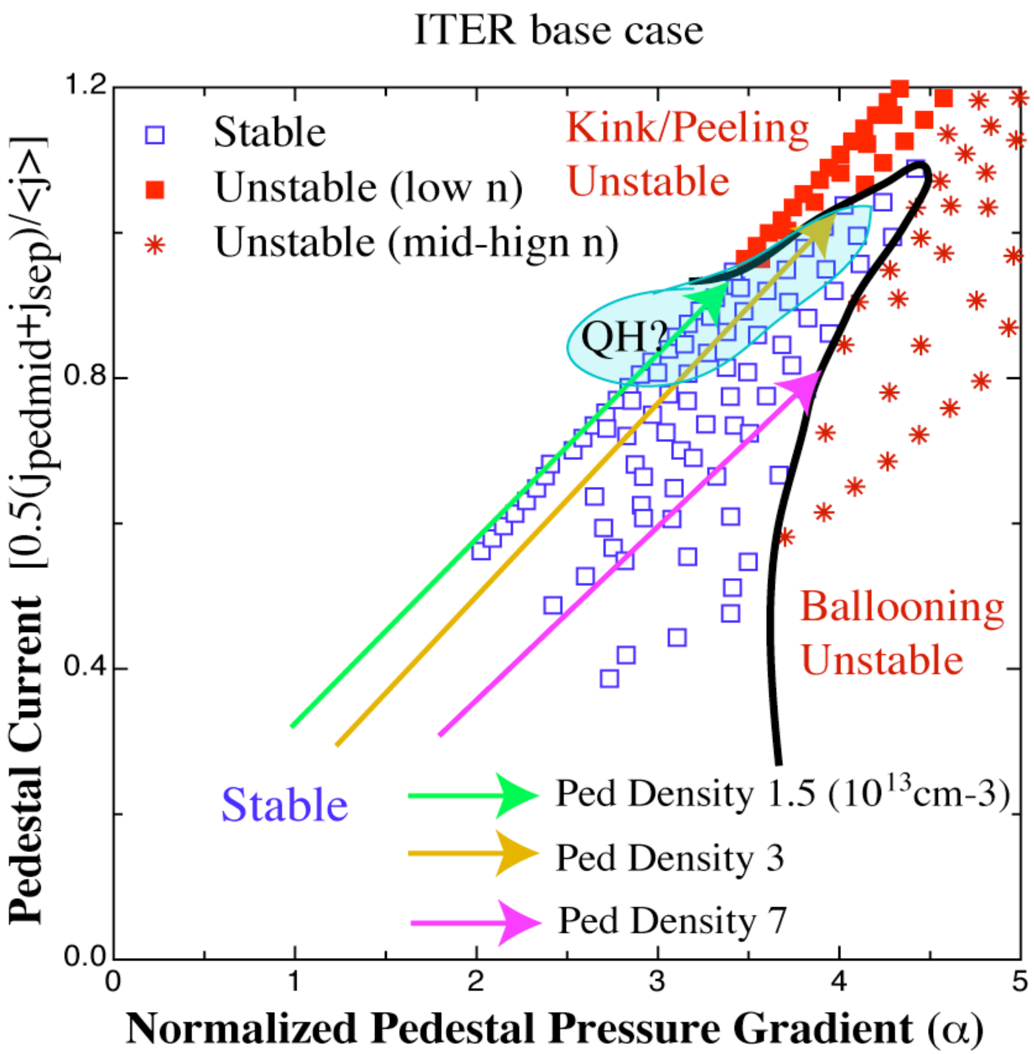
- **Stability Studies Perturbing around reconstructed QH Discharges on DIII-D**





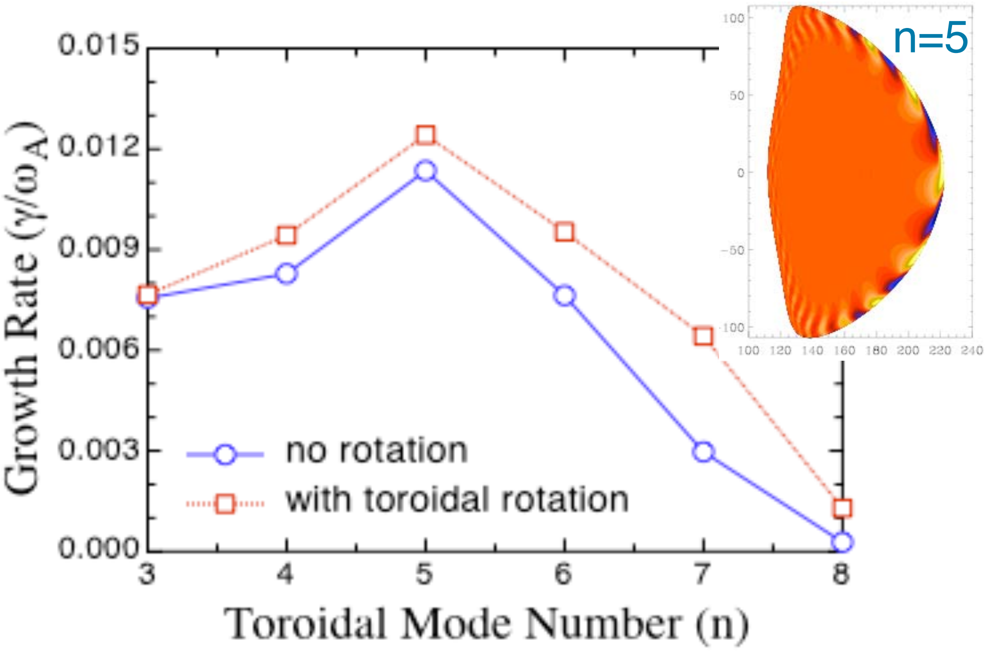
- **Moderate Shaping (left): QH operating point near kink/peeling bound, low density n_{ped}~1.5 10^{13} cm^{-3}**
- **Strong Shaping (right): QH operating point near kink/peeling bound, higher density QH operation possible, n_{ped}~3 10^{13} cm^{-3}**
  - **Good quantitative agreement with predictions, confirmed by 2006 expts**
- **Observed EHO during QH mode has poloidal magnetic signal qualitatively consistent with low-n kink/peeling mode**

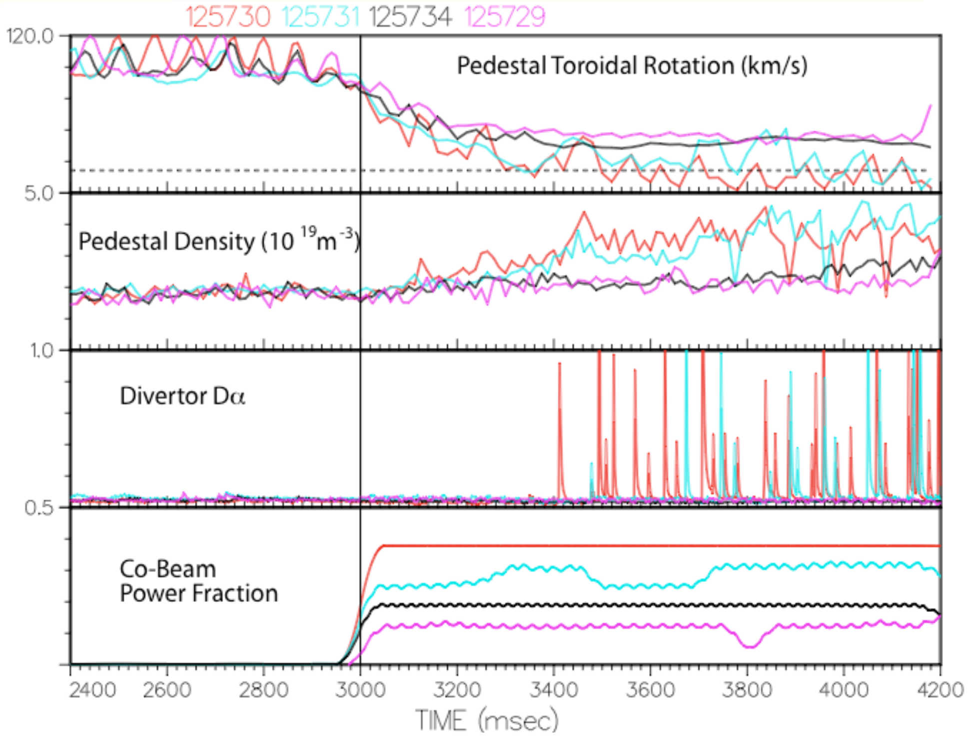
ITER Model Shows QH Regime May be Accessible at Low Density



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

Rotation Plays an Important Role in QH Mode





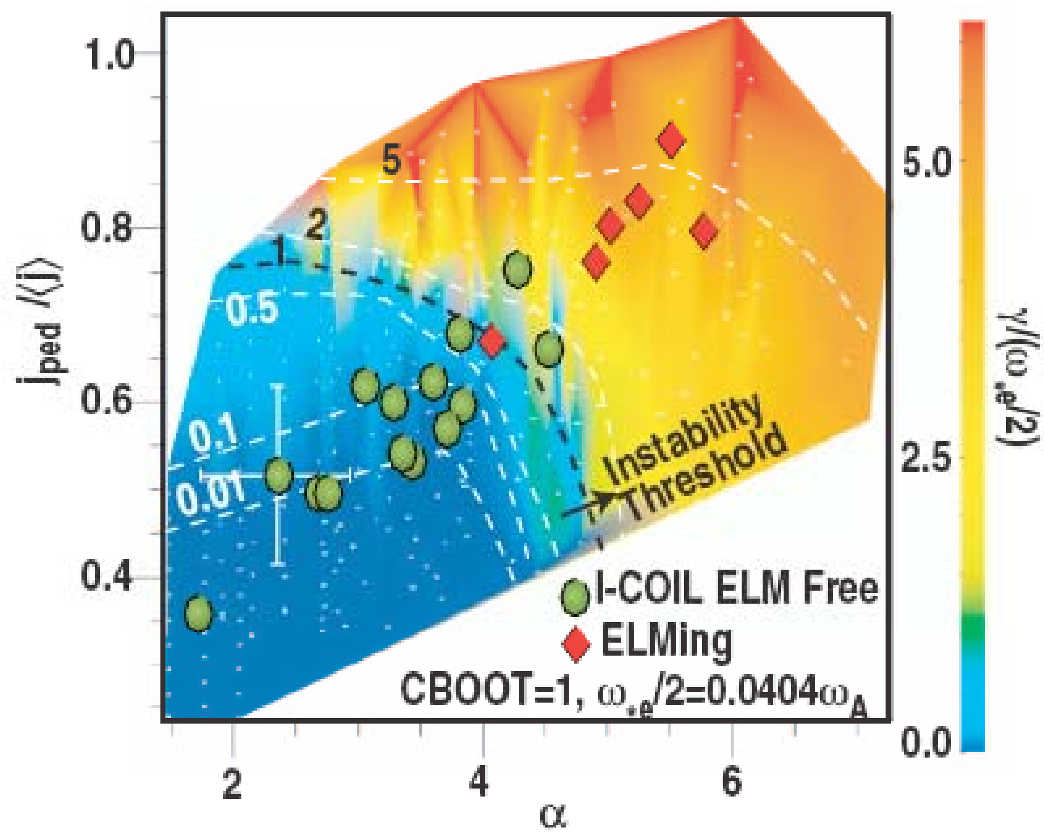
- **Flow stabilizes “edge localized RWM” (and hign-n ballooning modes)**
  - Allows plasma to reach ideal boundary, triggering rotating low-n mode
- **Limiting modes are rotationally *de*stabilized**
  - As mode grows and damps rotation, it is stabilized (unlike ELM)
- **Rotation requirements quantified 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_{eped}<~4 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

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