MHD Analysis of the Tokamak Edge Pedestal in the Low Collisionality Regime

Thoughts on the Physics of ELM-free QH and RMP Discharges

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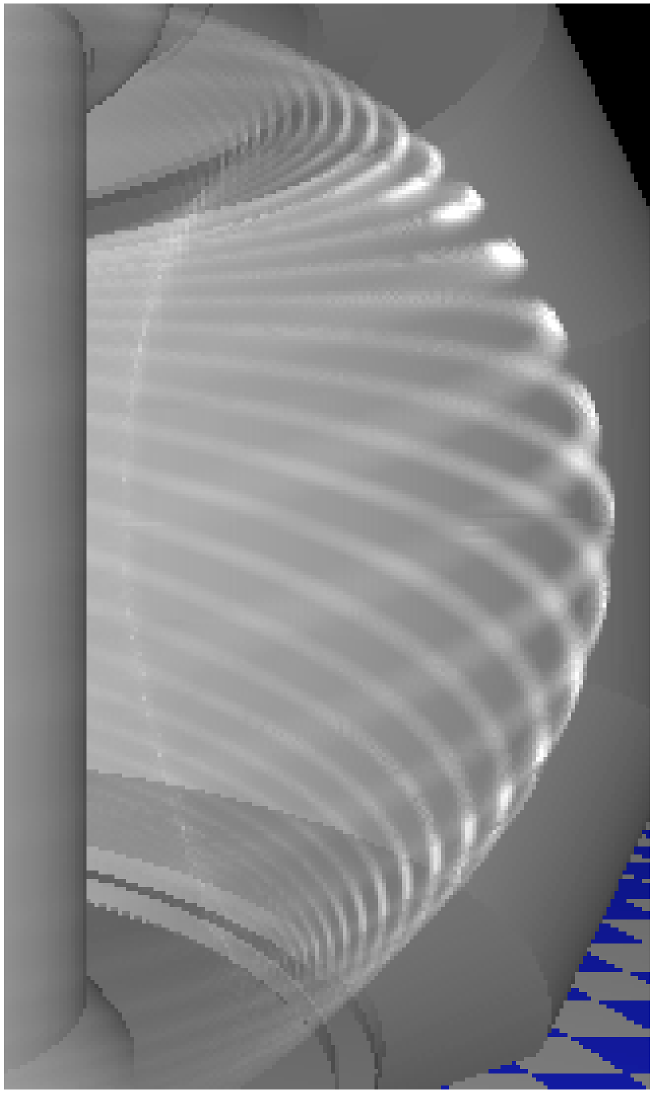

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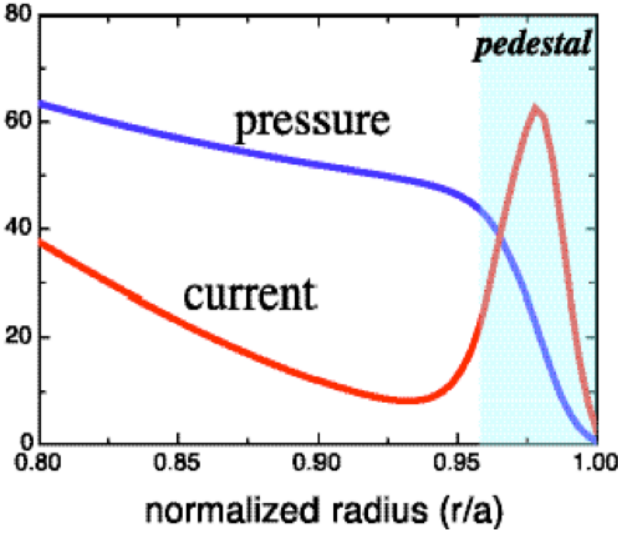
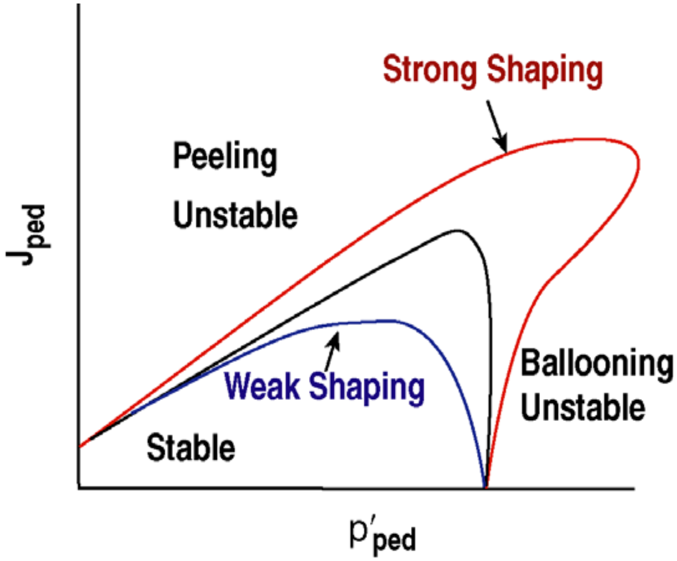
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

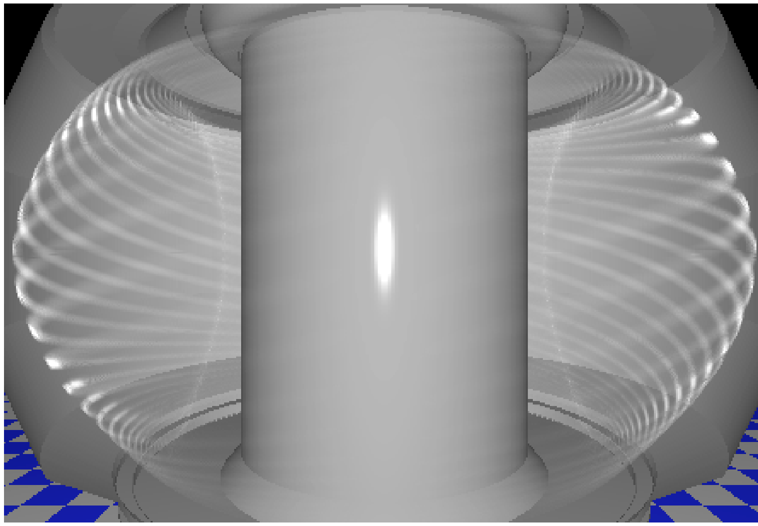
EFDA JET

GENERAL ATOMICS

The Peeling-Ballooning Model





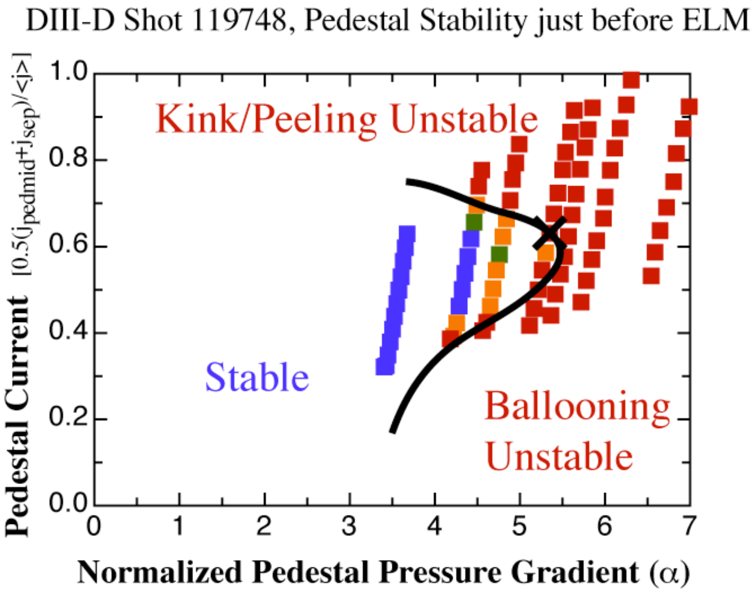


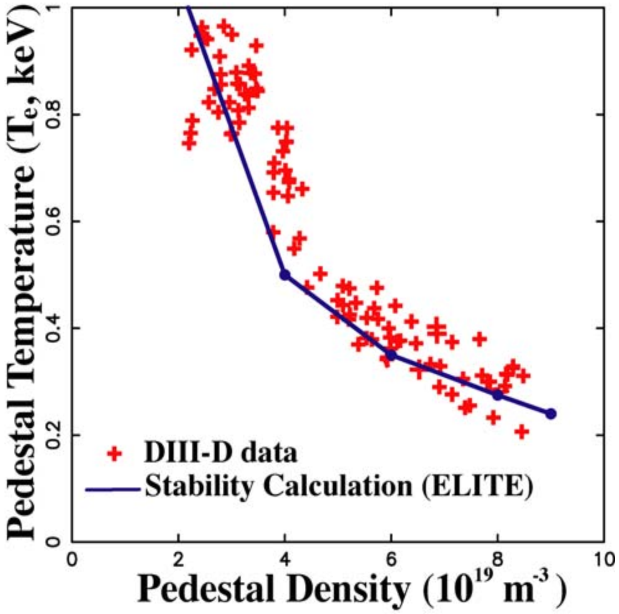
ELITE, n=18 mode structure

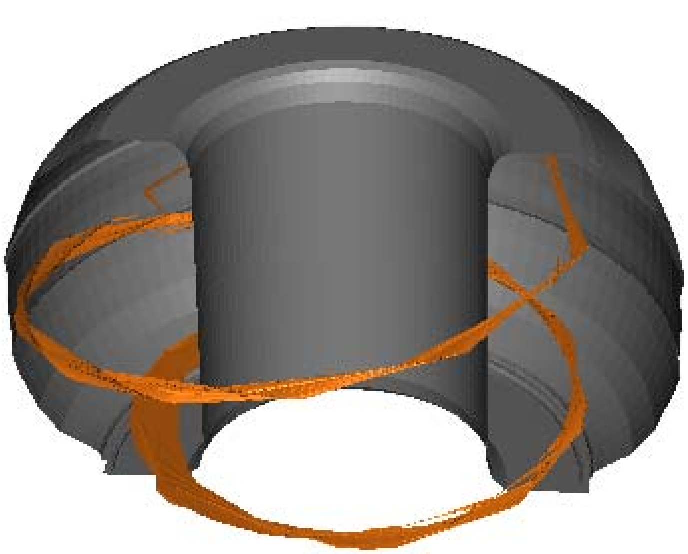
- **Pedestal Height and ELM heat impulses key issues for tokamaks/ITER**
  - Peeling-Ballooning model offers explanation for ELM onset and constraints on pedestal
- **ELMs caused by intermediate wavelength (n~3-30) MHD instabilities**
  - Both current and pressure gradient driven
  - Complex dependencies on ν_*, shape etc. due to bootstrap current and “2nd stability”

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

The Peeling-Ballooning Model: Validation and Nonlinear Dynamics





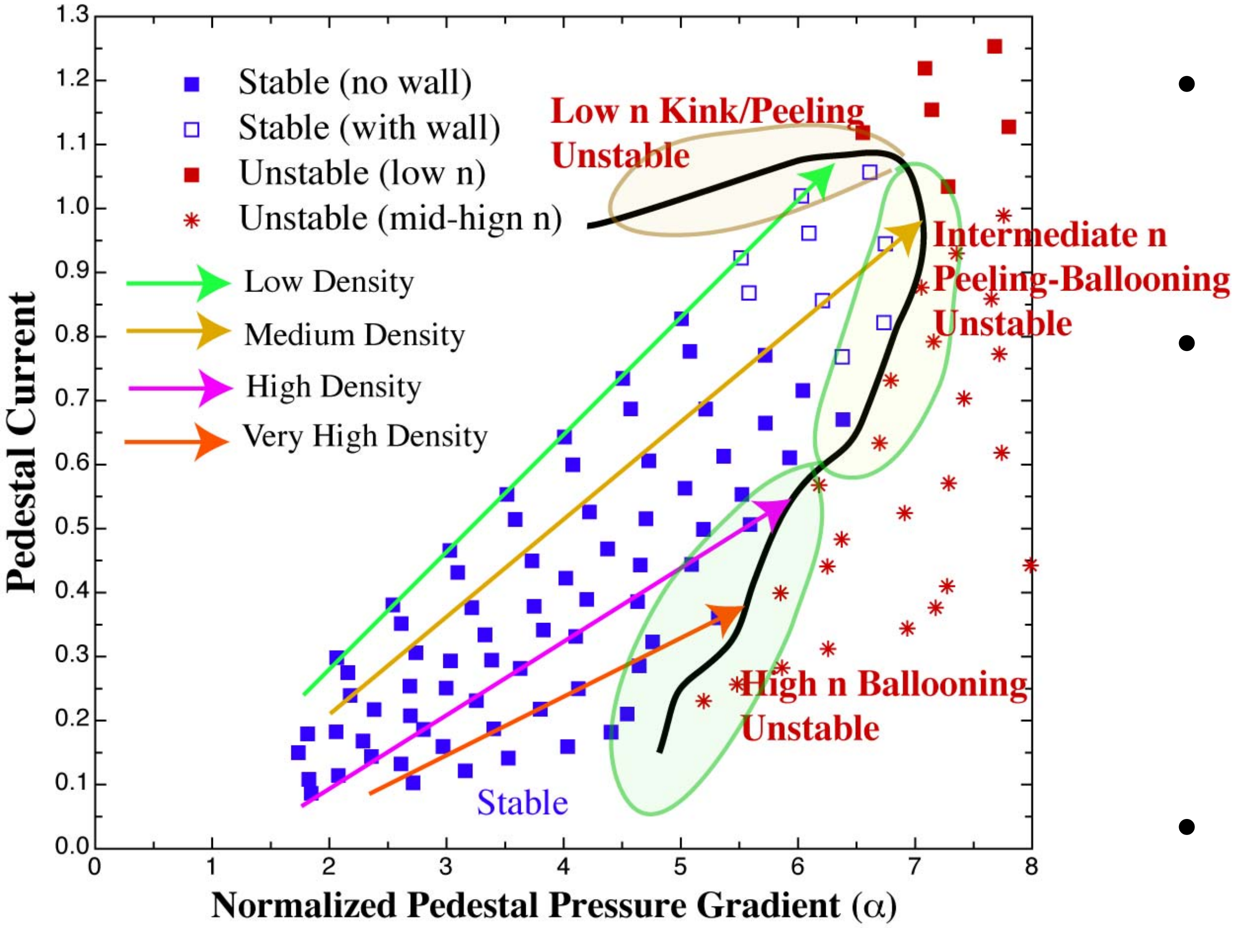


- **Successful comparisons to expt both directly and in database studies**
  *[P.B. Snyder, H.R. Wilson, et al., Phys. Plasmas **9** (2002) 2037; D. Mossessian, P.B. Snyder et al., Phys. Plasmas **10** (2003) 1720; P.B. Snyder, H.R. Wilson, et al., Nucl. Fusion **44** (2004) 320.]*
- **Nonlinear: Expected 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] *[See also DP Brennan oral]*
- **Picture developing to explain ELM onset and dynamics in the usual moderate to high density ELMing regime - initial comparisons of structure, radial velocity**
- ***Much less focus on exciting new regimes, QH and RMP, which occur at low density and can be ELM-free***

QH Modes Exist at Low Density, High Rotation

- **QH mode operation generally requires *strong counter rotation* in the pedestal region and *low density***



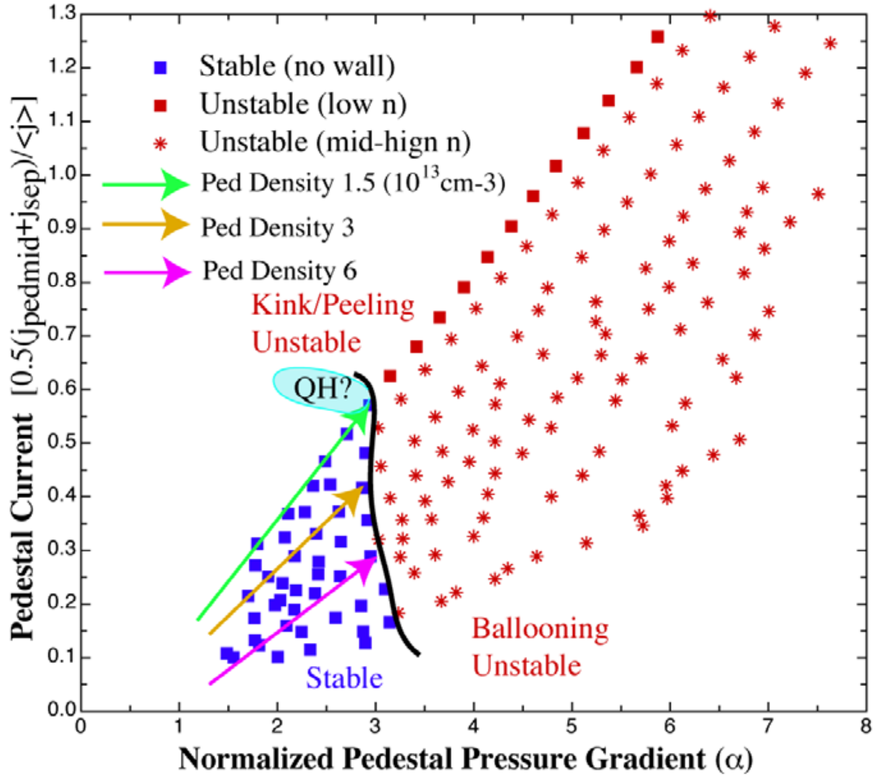
Effect of Low Density

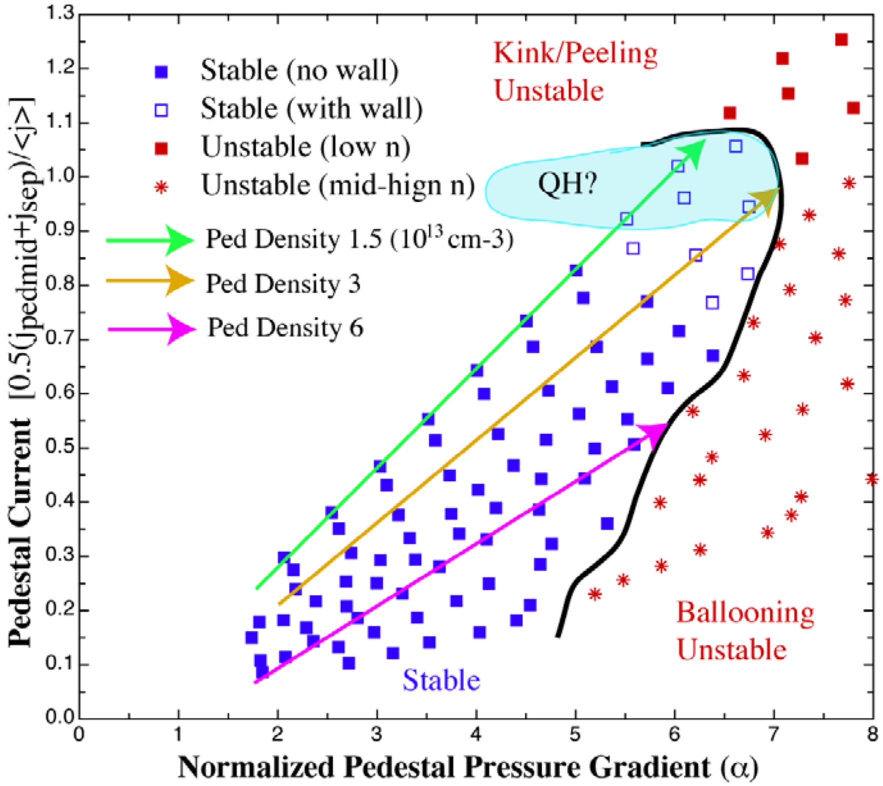
- **The pedestal current is dominated by bootstrap current**
  - Roughly proportional to p’
  - Decreases with collisionality
- **Lower density means more current at a given p’**

  (ν_*~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
- **Stability Analysis more complex at low density: uncertainty in current profile, resonant conditions**

Theory: QH Mode Exists in Low-n Kink/Peeling Limited Regime

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

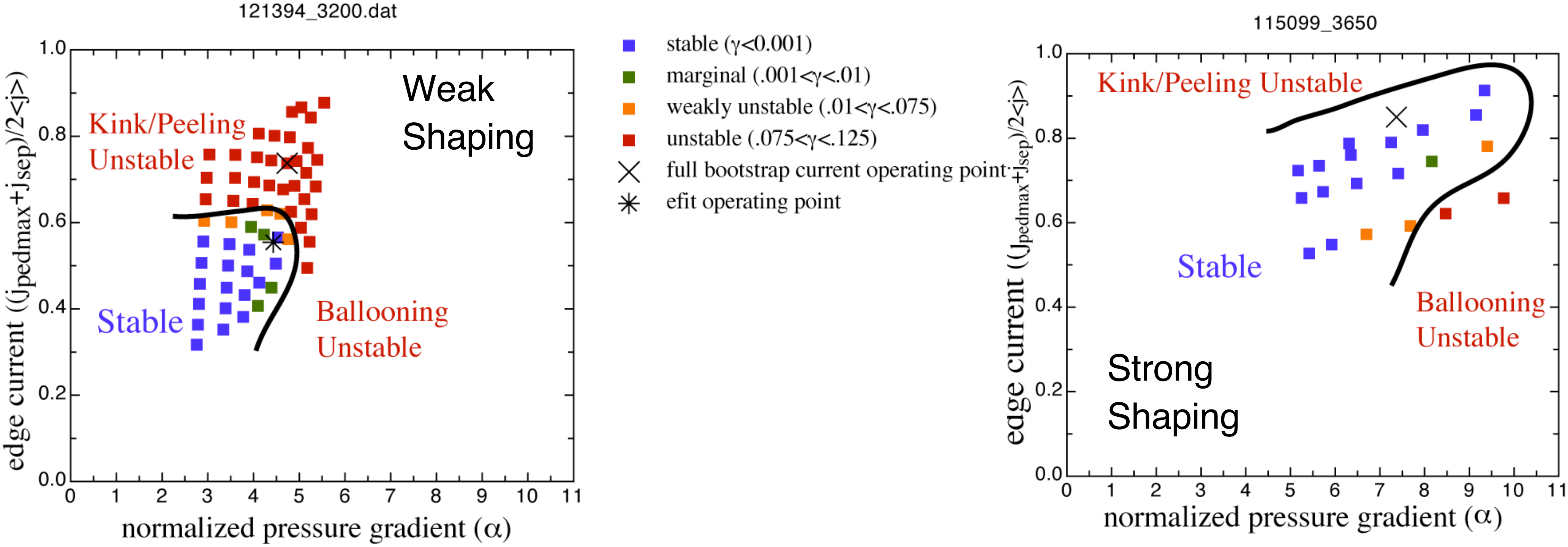

Low Triangularity (δ=0.0) QH Model


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**

Experiment: QH Discharges Exist Near Kink/Peeling Boundary

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

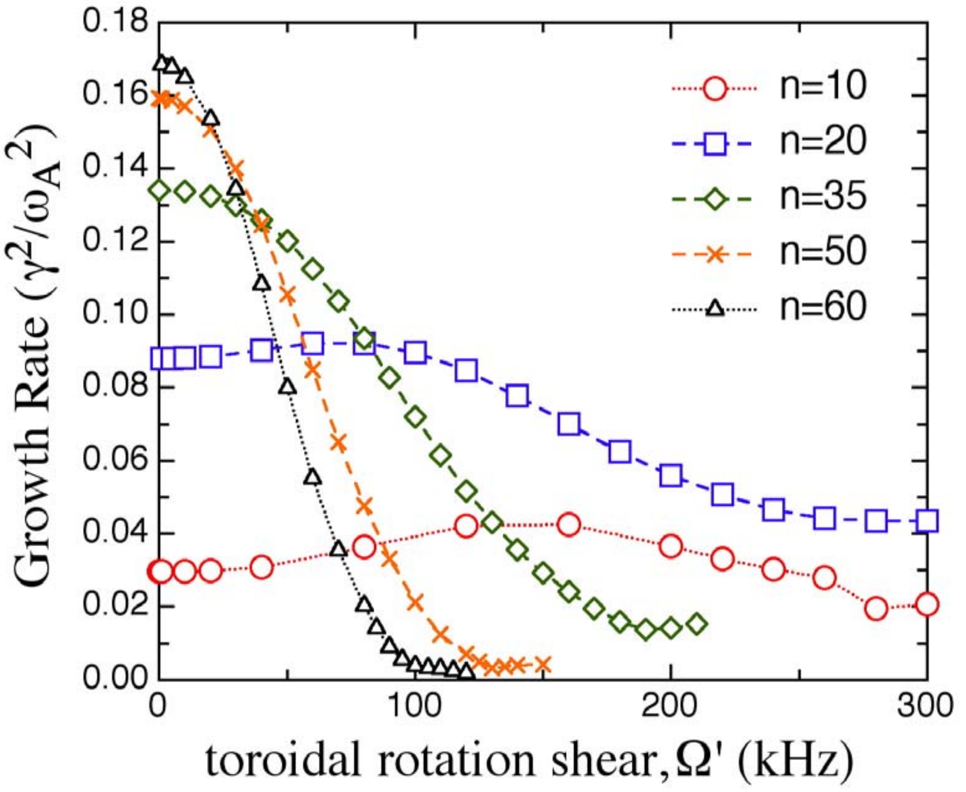


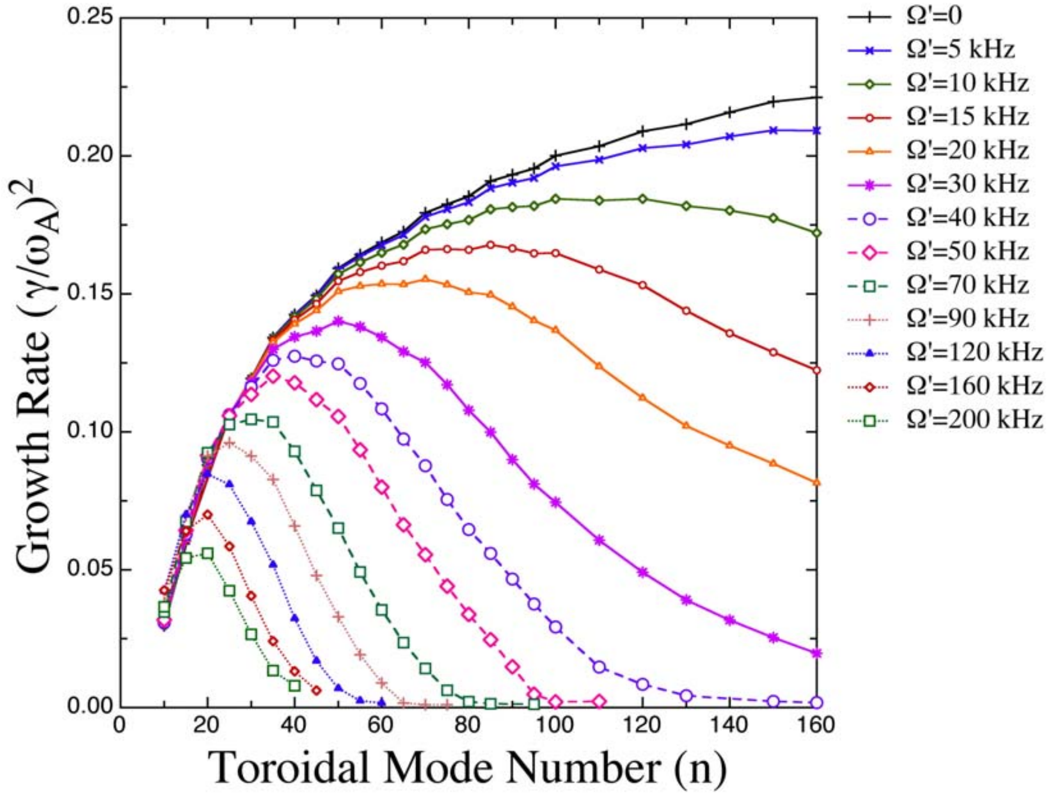
[See WP West poster this afternoon for further details]

- **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}**
- **Observed EHO during QH mode has poloidal magnetic signal qualitatively consistent with low-n kink/peeling mode**

Effect of Strong Toroidal Flow Shear in the Edge Region

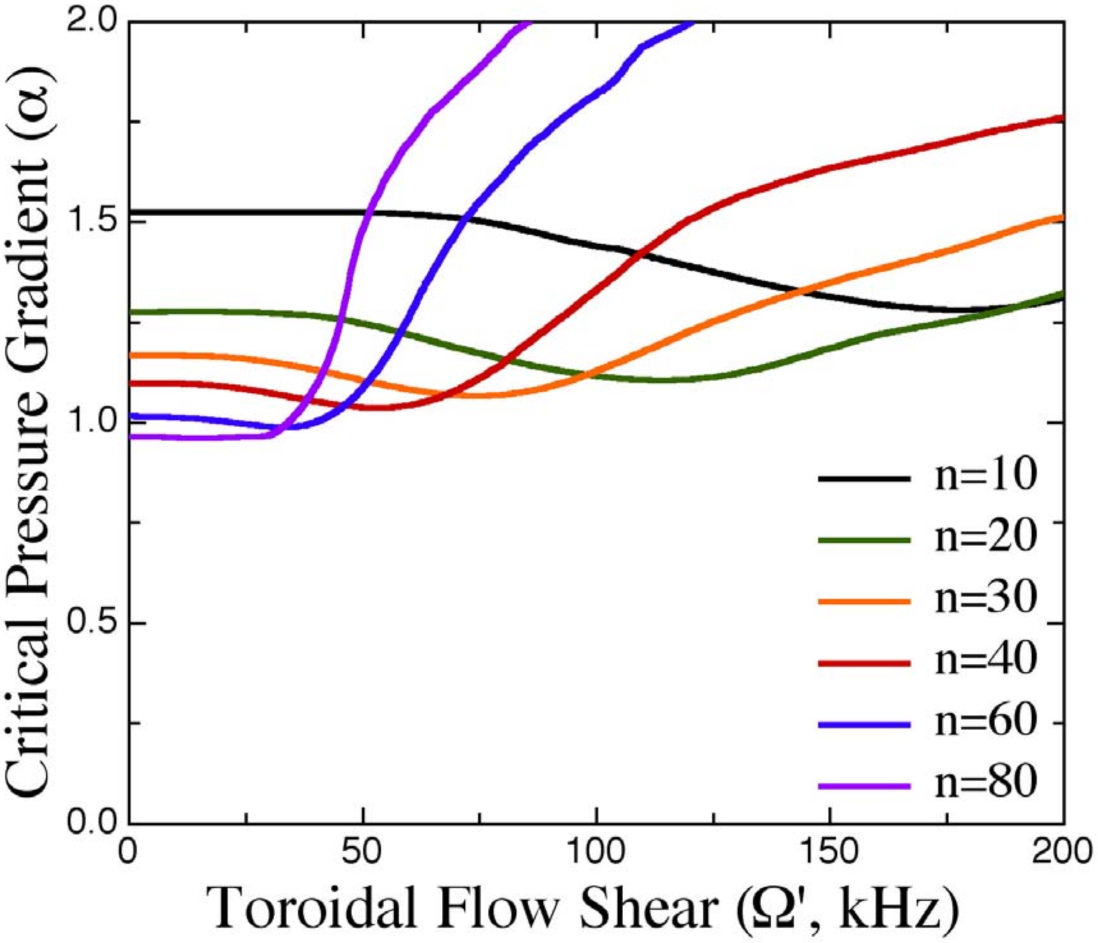
- **Eigenvalue formulation with rotation and compression derived and included in ELITE**
  - **Sheared rotation strongly damps high n**
  - weaker impact intermediate n, **can be destabilizing at low n**
  - radial narrowing of mode structure
- **Sheared flow stabilizes "ELRWM"**
  - Allows plasma to reach ~ideal boundary, trigger rotating low-n mode





Effect of Strong Toroidal Flow Shear in the Edge Region

- **Flow Shear Does Not Dramatically Impact Critical Gradient**

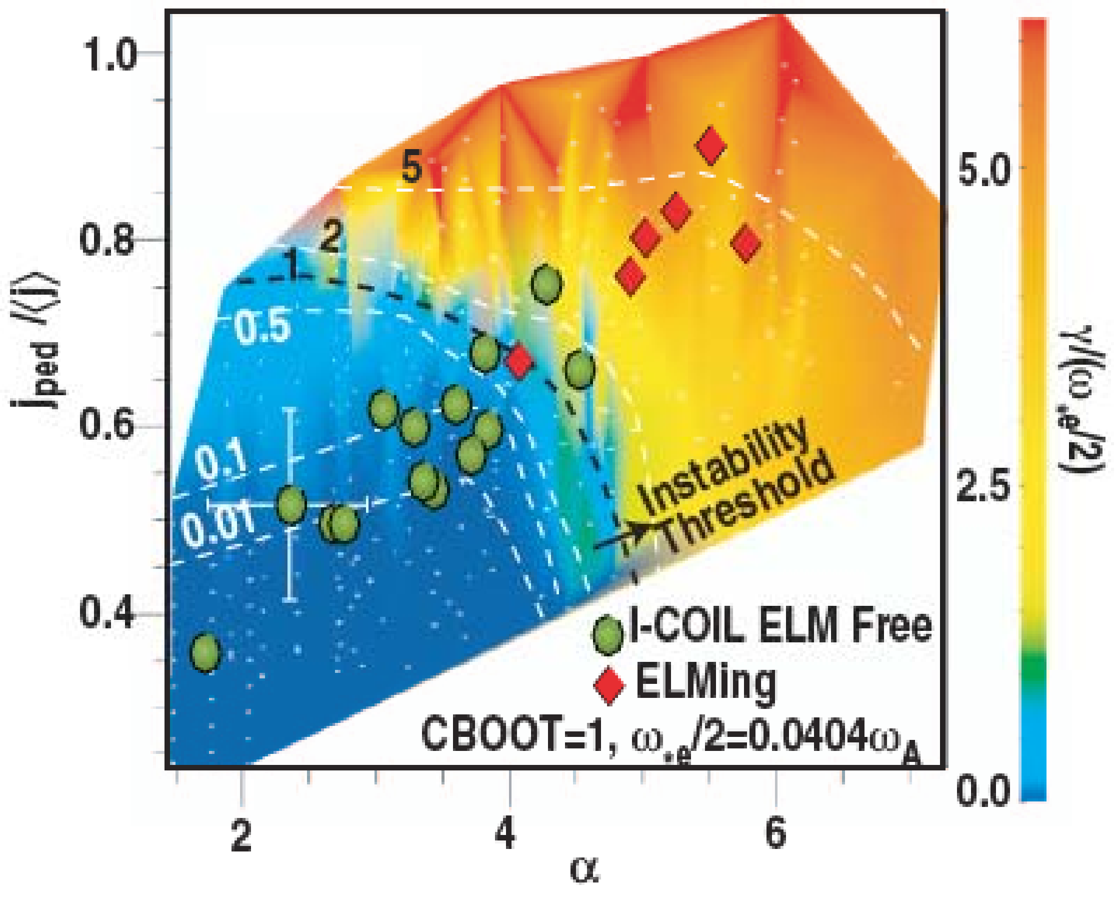


- **Most unstable-n decreases with flow shear (QH~50-120kHz)**
- ***Rotationally de-stabilized low-n modes are limiting in QH regime***

Hypothesis 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 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**

RMP ELM-free Discharges in Similar Regime



See T. Evans invited talk this afternoon

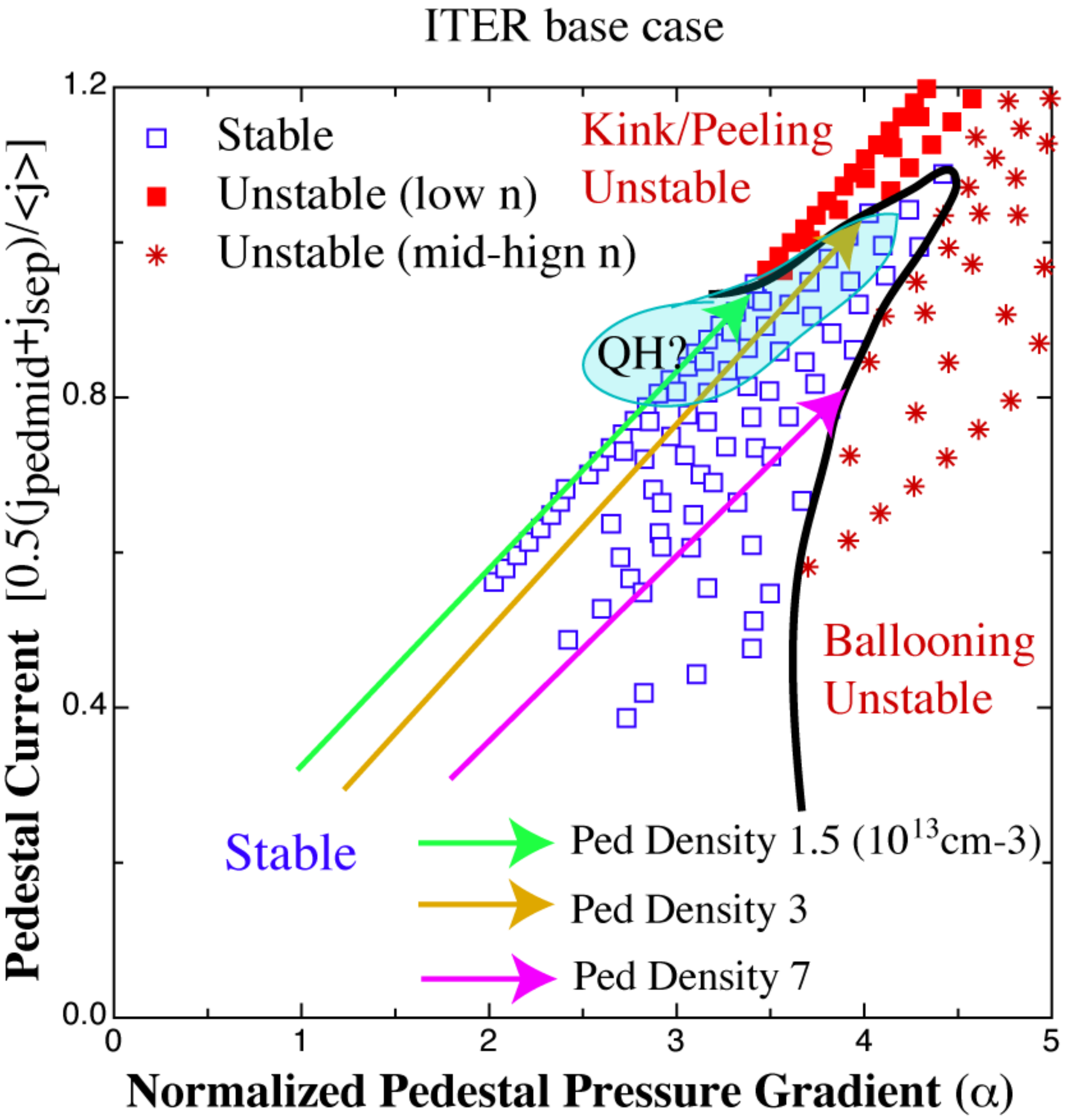
- **n=3 Resonant Magnetic Perturbations used to suppress ELMs in low density discharges**
- **ELM-suppressed shots in stable region, nearest kink/peeling boundary**
  - Increasing density causes ELMs to return
- **Propose that RMP plays the role of the EHO here**
  - Particle, Te, rotation steady state
- **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

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
- **Use same approach to study low density, ELM free, regimes**
- **Propose: QH exists in low-n kink/peeling limited regime**
  - Very low density required with moderate shaping, higher density and pressure possible with strong shaping
    - Agreement with observed QH density range
    - ITER study suggests QH regime for n_{eped}<~4 10^{19} cm^{-3}
- **Flow shear stabilizes ELRWM (and higher n), leaves low-n rotationally destabilized kink/peeling mode most unstable**
  - With kinetic corrections, this is the EHO
  - Saturates by damping rotation and providing particle transport
    - Essentially steady state operation in the key edge transport channels
- **Low density RMP ELM free discharges in similar regime**
  - Propose that RMP is playing the role of the EHO -> Controllable, can exist near or well below stability bound

Extra Slides

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 density operation

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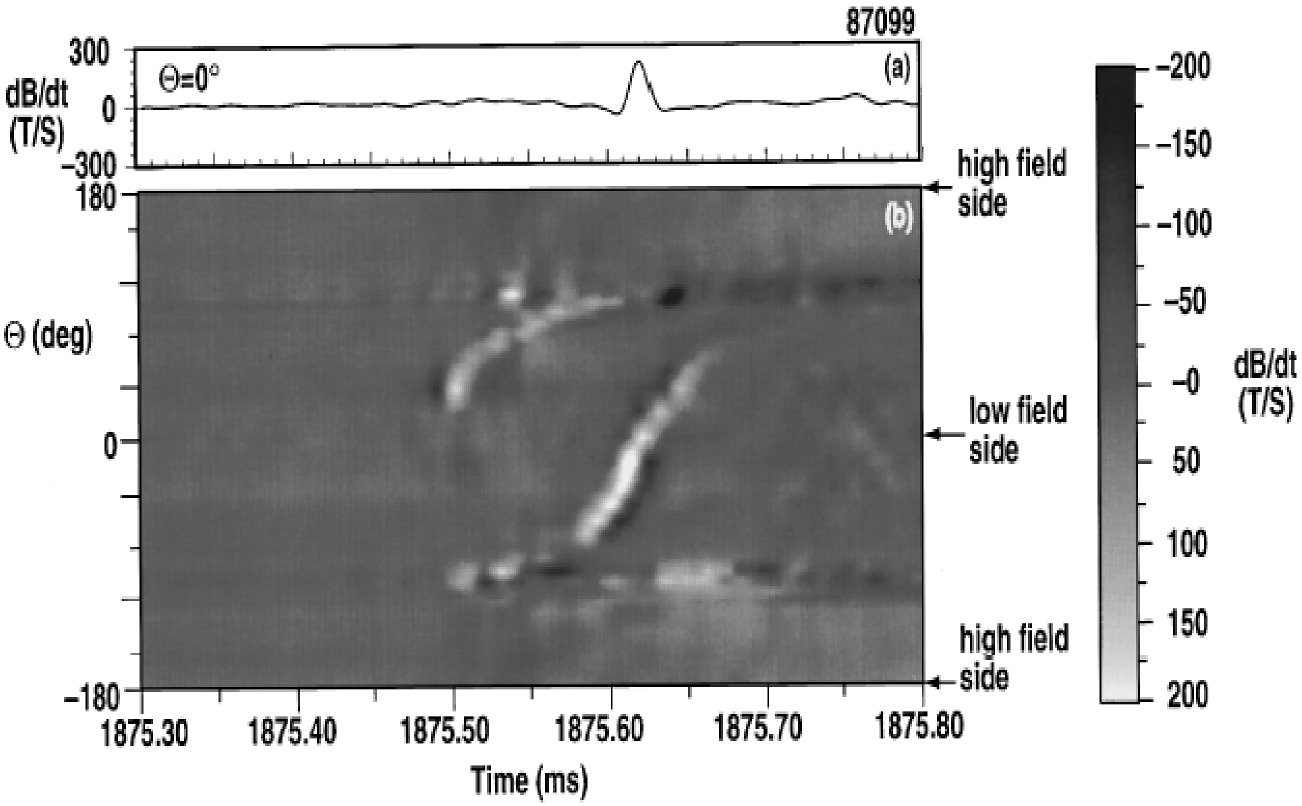
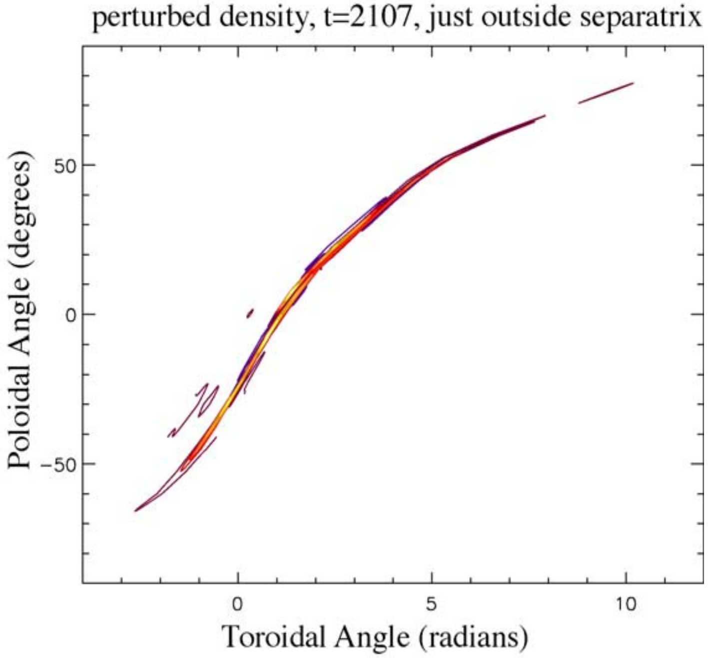
Filaments Observed During ELMs



DIII-D Observation *[E Strait, Phys Plas 1997]*



3D Simulation

- 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)