Stability and Nonlinear Dynamics of ELMs and ELM-Free Regimes

TH/4-1Ra: Stability and Dynamics of the Edge Pedestal in the Low Collisionality Regime — Physics Mechanisms for Steady State ELM-Free Operation

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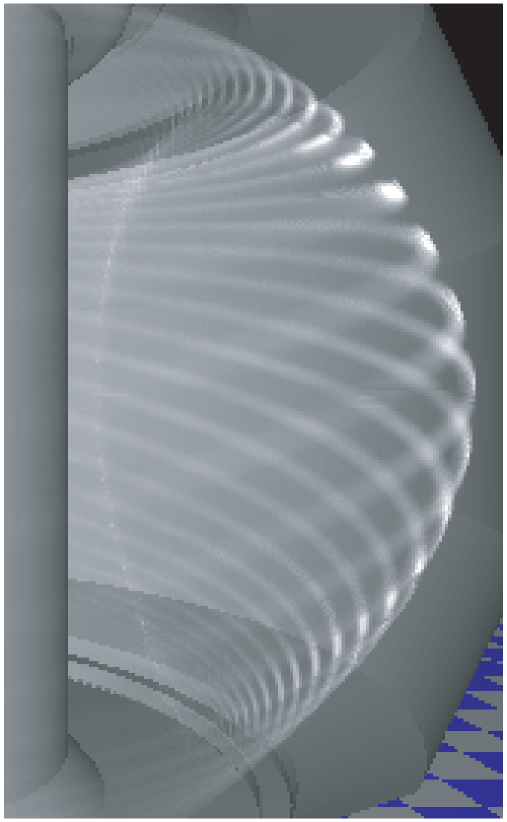

TH/4-1Rb: ELM Crash Theory — Relaxation, Filamentation, Explosions and Implosions

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Outline

Physics of ELMs and Pedestal Constraints

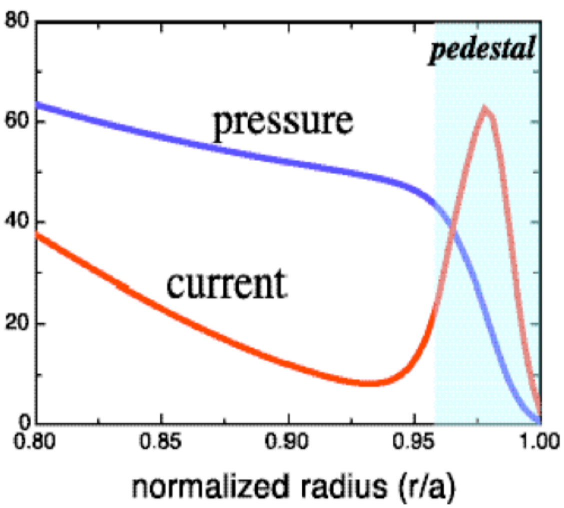
- **The Peeling-Ballooning Model and ELITE**
  - Successfully explains observed ELM onset and pedestal constraints

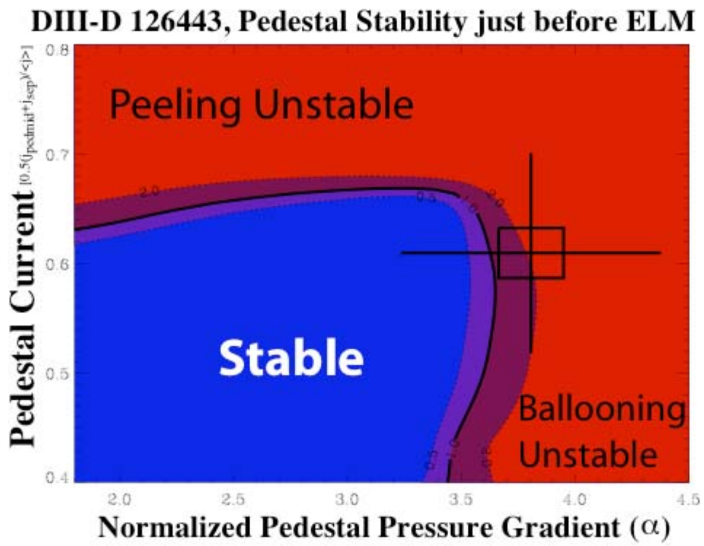
- **Nonlinear Dynamics of ELMs**
  - Relaxation theory for peeling modes: small variable ELMs
  - Theory of nonlinear ballooning modes: explosive filaments
  - Direct 3D nonlinear simulation results: bursts of filaments
  - Proposals for dynamics of full ELM crash, and particle & energy losses

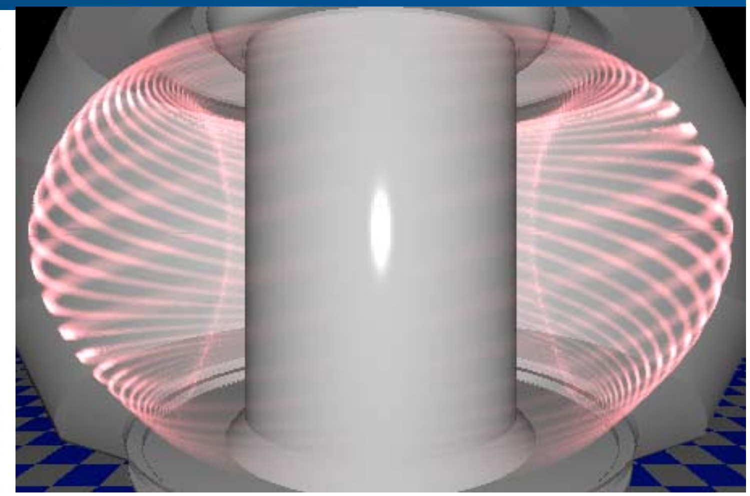
Physics of ELM-free Discharges

- **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: Extensive Validation against Experiment







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
  - >100 successful comparisons with observation, value and parametric dependence

MHD physics, taking into account diamagnetic effects, does a remarkably good job accounting for (T1&T2) ELM onset and observed pedestal constraints

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

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Nonlinear ELM Dynamics

- Relaxation theory for peeling modes [TH4/1Rb]

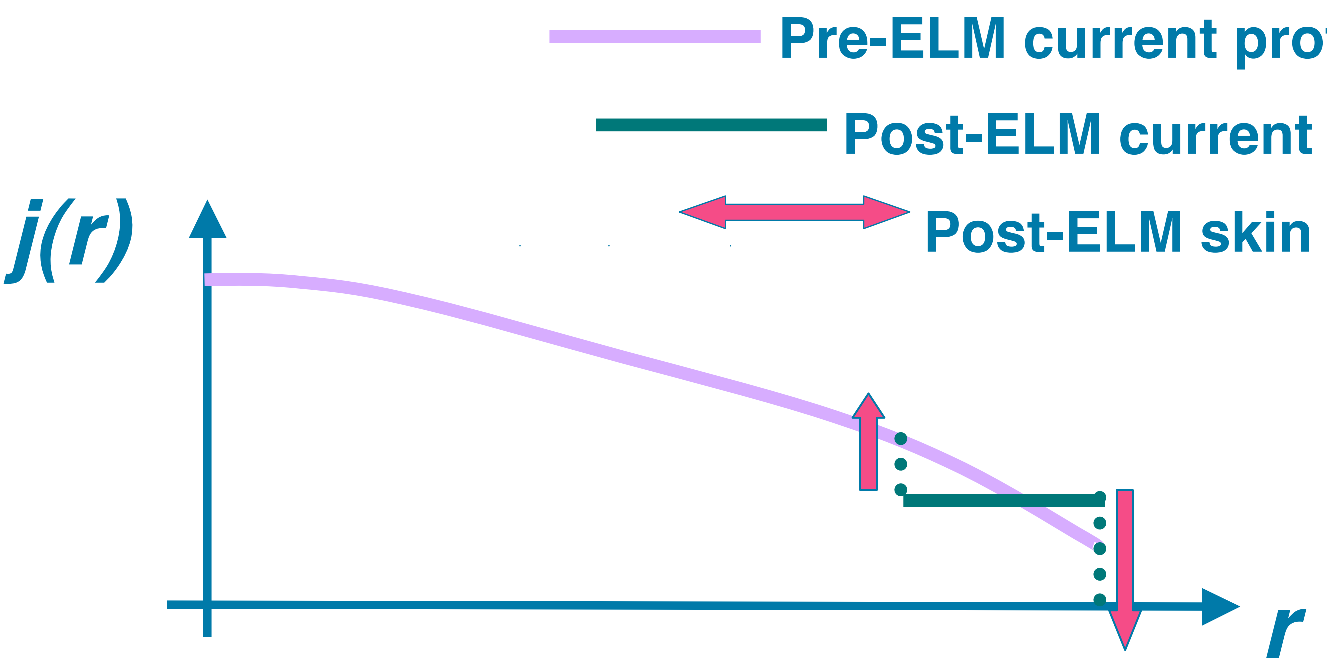
The Peeling Mode/Relaxation ELM Model

- **Toroidal peeling mode initiates an edge Taylor relaxation**
- **Flattening of the current further destabilises peeling**

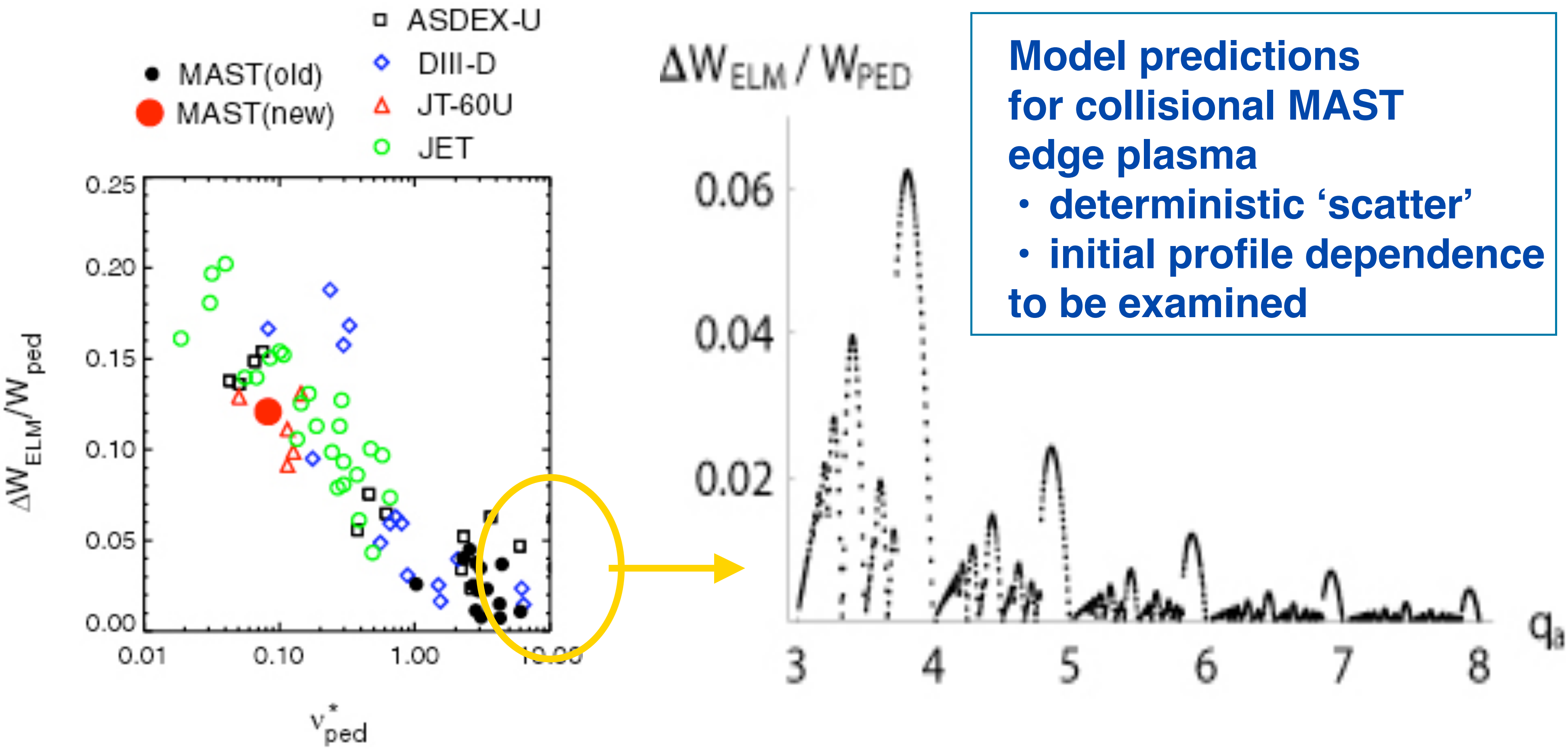
BUT

- **Formation of a negative edge skin current is stabilising**
- **The balance between the two predicts an annular width**

C. Gimblett et al., Phys. Rev. Lett. ***96****, 035006 (2006)*



Relaxation Model: ELM Width Predictions Plus Critical Pressure Gradient Gives Energy Loss



A. Kirk *et al., PPCF 46, A187 (2004).*

Model predictions for collisional MAST edge plasma

- **deterministic 'scatter'**
- **initial profile dependence to be examined**

- **Predicted ELM energy loss comparable to small, high collisionality ELMs**
  - **-A collisionality dependence may enter through the bootstrap current**

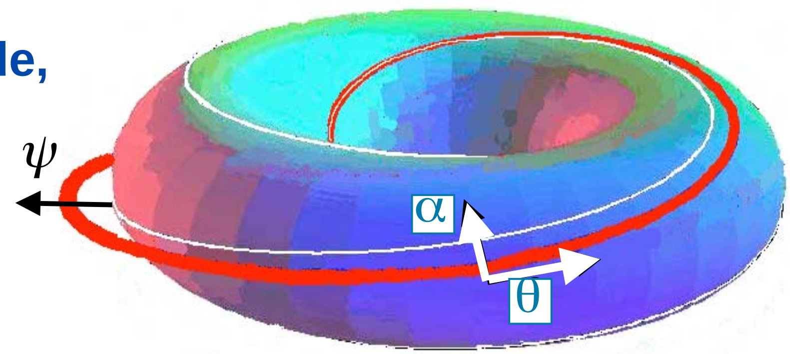
Nonlinear ELM Dynamics

-Theory of nonlinear ballooning modes [TH4/1Rb]

Derivation of the Nonlinear Ballooning Theory

In the early nonlinear evolution of the ballooning mode, the ideal MHD equations can be reduced analytically:

H.R. Wilson and S.C. Cowley, Phys. Rev. Lett. ***92*** *(2004) 175006.*



- **Leading order provides variation of displacement, ξ, along field line:**
  - standard linear ballooning equation, with solution $H(\theta,\varepsilon\psi)$ ($\varepsilon \ll 1$)

$$\xi(\psi,\alpha,\theta;t) = F(\psi,\alpha;t)H(\theta,\varepsilon\psi)$$

- **The variation across field lines and the time dependence is determined by a nonlinear equation for the amplitude, F:**

$$C_I \frac{\partial}{\partial\alpha}\frac{\partial^2}{\partial t^2}\left[\int_0^t dt' \frac{F(t')}{(t-t')^{\lambda_S-\lambda_L-1}}\right] + \rho C \frac{\partial}{\partial\alpha}\left(\frac{\partial^2 F}{\partial t^2}\right) = C_1\left[2(1-\mu)\frac{\partial F}{\partial\alpha} - C_0\frac{\partial^2 u}{\partial\psi^2}\right] + C_2\frac{\partial F^2}{\partial\alpha} + C_4\frac{\partial F}{\partial\alpha}\frac{\partial^2\overline{F^2}}{\partial\psi^2}$$

Nonlinear drive term

A representation of a fractional derivative

Linear instability drive

"Finite n" linear term (stabilising)

Cubic nonlinearity determines radial structure

$$F = \frac{\partial u}{\partial\alpha}$$

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Solution to Envelope Equation => Filaments Erupt from Surface

$$C_I \frac{\partial}{\partial\alpha}\frac{\partial^2}{\partial t^2}\left[\int_0^t dt' \frac{F(t')}{(t-t')^{\lambda_S-\lambda_L-1}}\right] + \rho C \frac{\partial}{\partial\alpha}\left(\frac{\partial^2 F}{\partial t^2}\right) = C_1\left[2(1-\mu)\frac{\partial F}{\partial\alpha} - C_0\frac{\partial^2 u}{\partial\psi^2}\right] + C_2\frac{\partial F^2}{\partial\alpha} + C_4\frac{\partial F}{\partial\alpha}\frac{\partial^2 \overline{F^2}}{\partial\psi^2}$$

- **In nonlinear regime, balance quadratic nonlinearity with inertia (left hand side)**

$$F \sim \frac{1}{C_2}\frac{1}{\left[t_0(\psi,\alpha)-t\right]^{\lambda}}$$

$\Rightarrow$ Explosive growth near $t=t_0$

$$\lambda = \begin{cases} 2 & D_M < -3/4 \\ \sqrt{1-4D_M} & D_M > -3/4 \end{cases}$$

- **Balance quadratic and cubic nonlinearities:**

$$\frac{(\Delta\psi)^2}{\Delta\alpha} \sim \frac{1}{\left[t_0(\psi,\alpha)-t\right]^{\lambda}}$$

$\Rightarrow$ Broadens in ψ, narrows in α

- **Combine with slow variation along field line**
  - $\Rightarrow$ Filamentary structure erupts from the surface
  - $\Rightarrow$ Coefficient C_2 determines direction of filament propagation
    - **Highly challenging calculation, two length scale expansions + expansion about a JET-like equilibrium surface**

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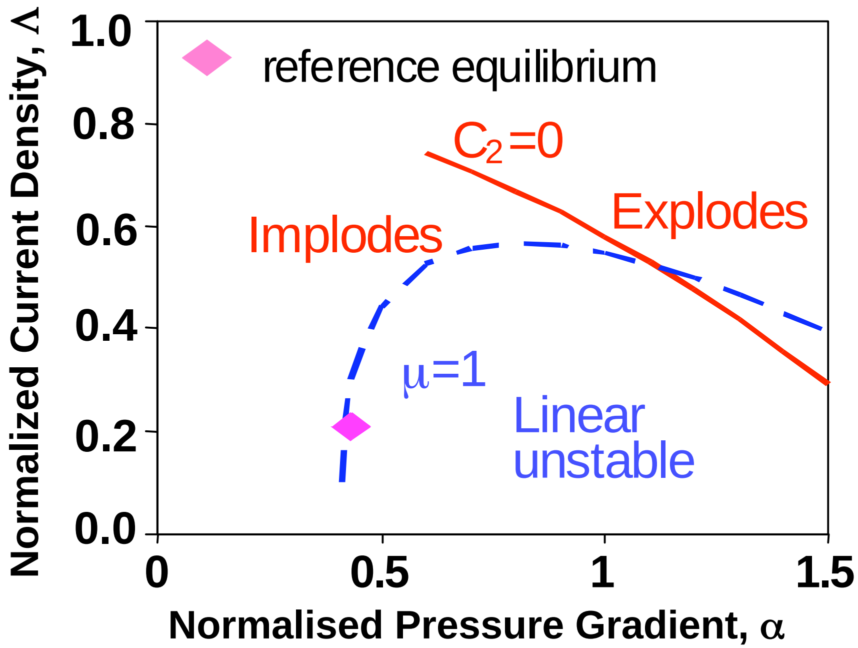
Filaments Explode Outward at High Edge Current

- **We can scan pressure gradient and current density on the reference flux surface to map out**
  1. The marginal ballooning stability boundary (calculation only accurate near here)
  2. The contour C_2=0, separating explosive and implosive behaviour



$C_2>0 \Rightarrow$ filaments explode out towards SOL

$C_2<0 \Rightarrow$ filaments implode in towards core

- **The filaments explode outward if there is sufficient current density**
  – At lower current density, the filaments "implode" towards the core
- **More work is required to understand the impact of non-ideal effects**

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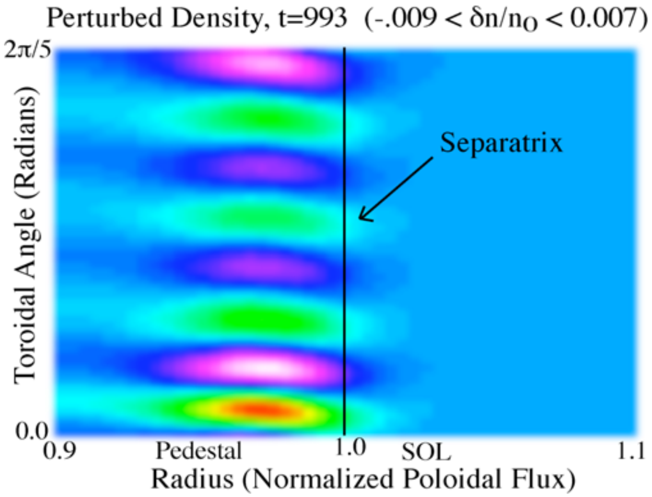
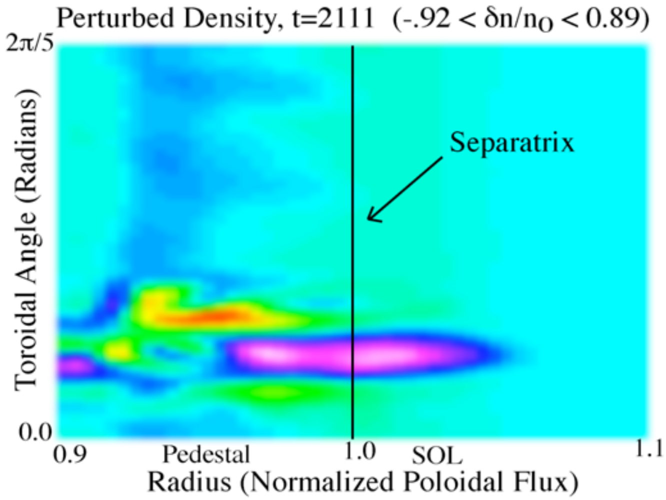
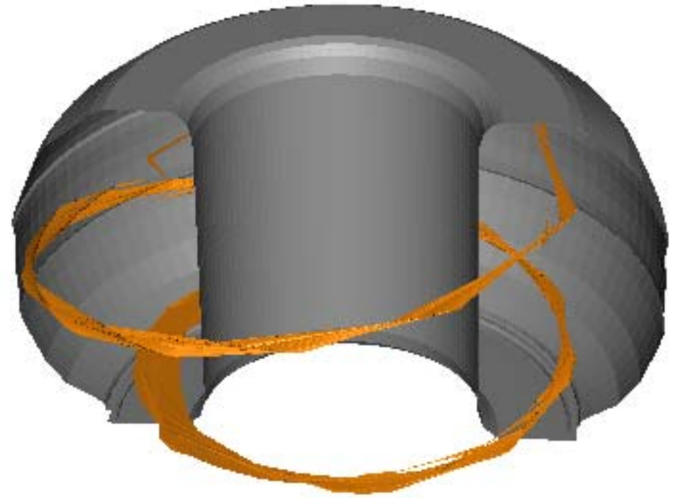
Nonlinear ELM Dynamics

- Direct 3D nonlinear simulation results [TH4/1Ra]

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







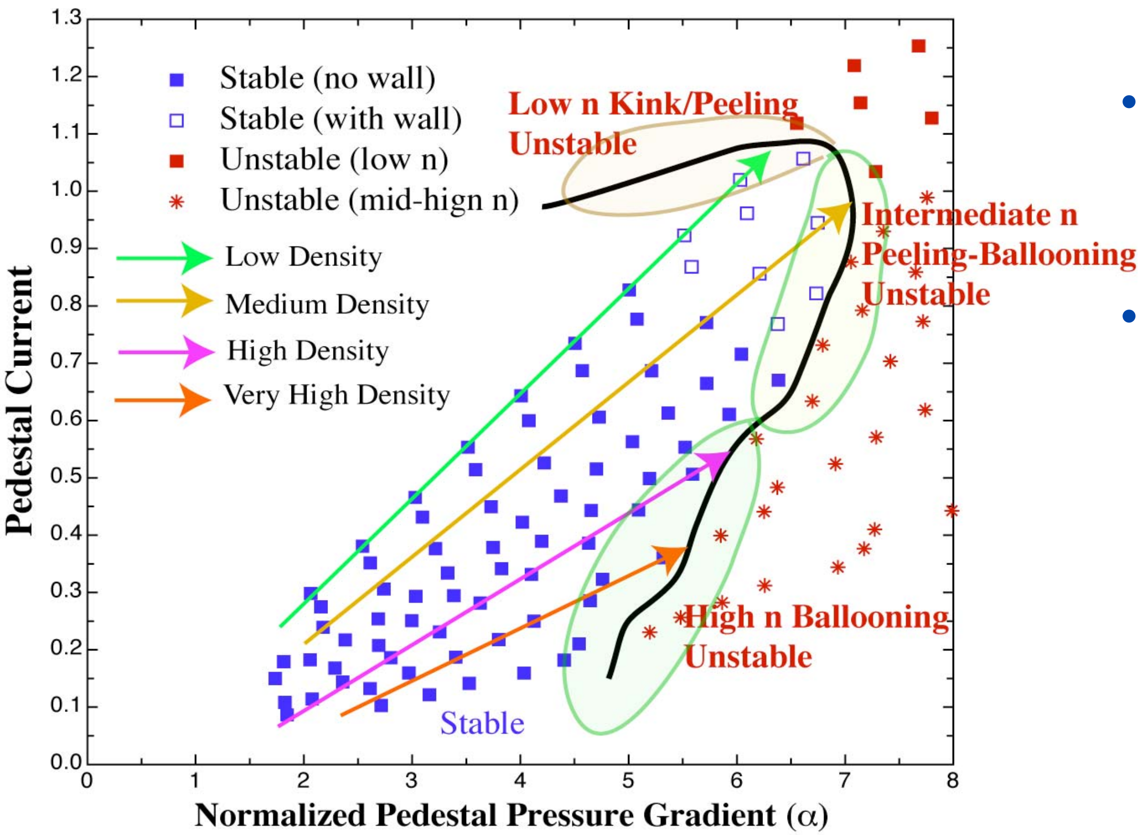
P.B. Snyder et al, Phys. Plasmas ***12*** *056115 (2005).*

- **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**

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'**

  (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

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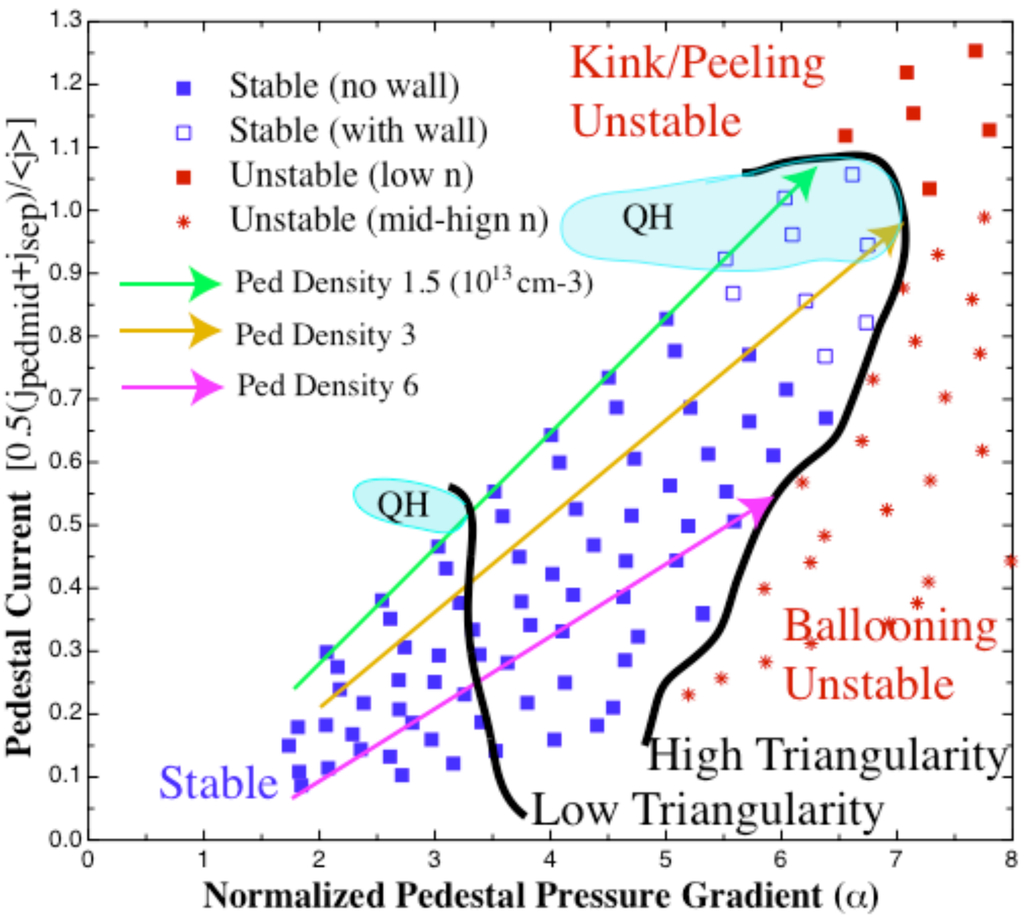

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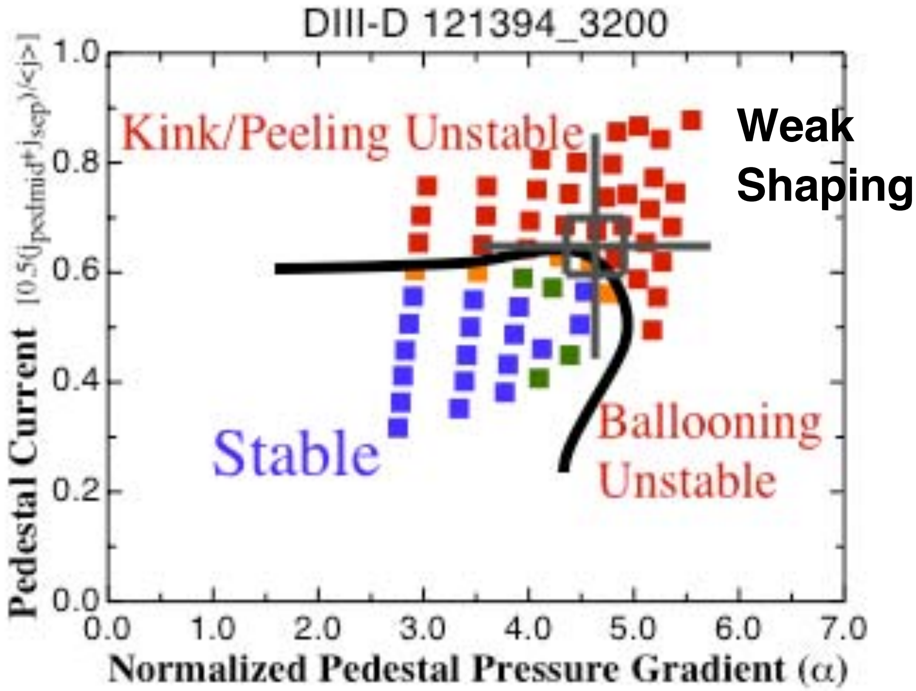
Theory: QH Mode exists in Low-n Kink/Peeling Limited Regime

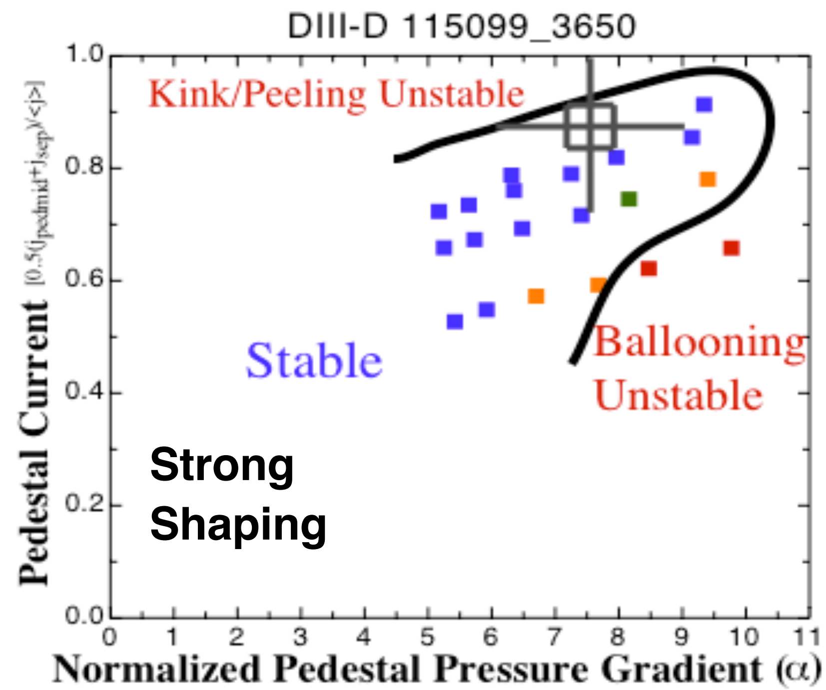
-Allows quantitative density predictions

-Density limit varies with triangularity

Observation: QH Discharges Exist Near Kink/Peeling Boundary

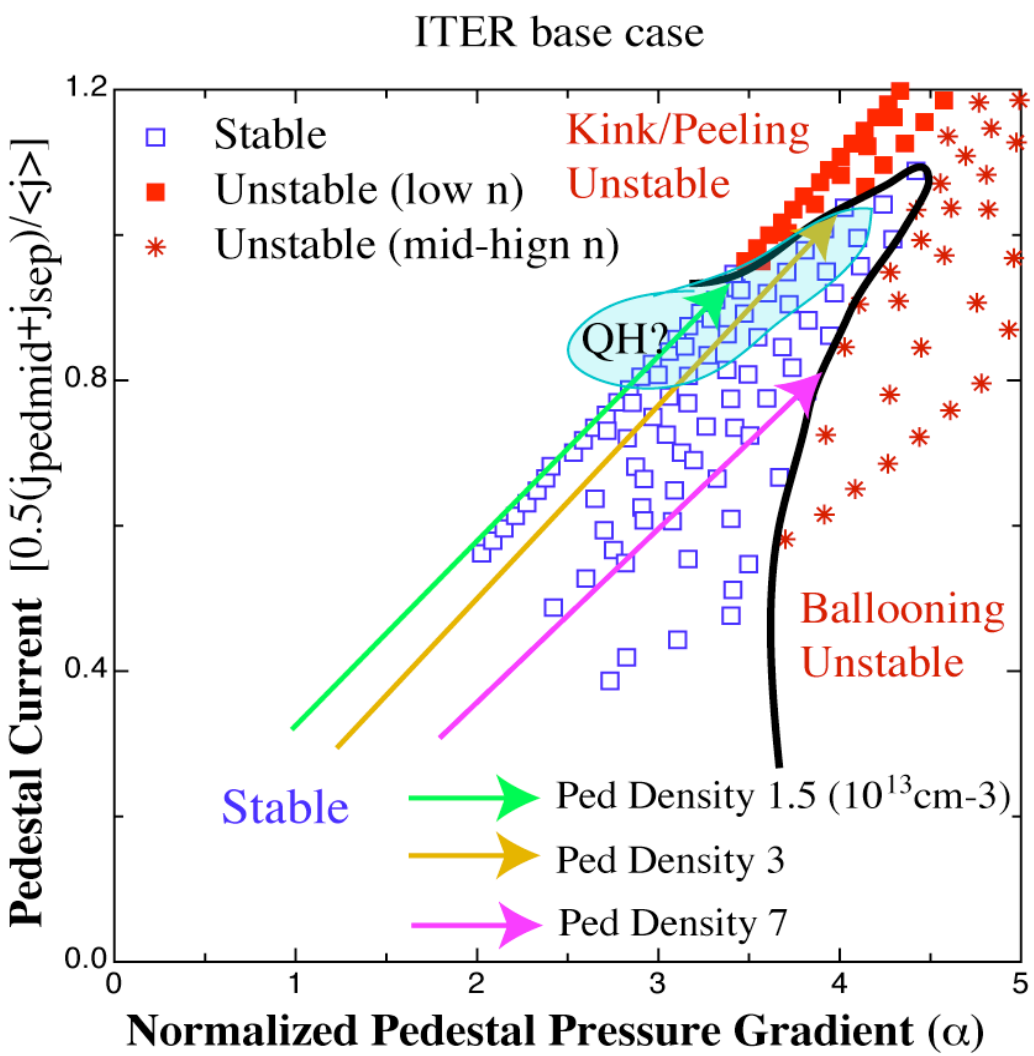
- Stability Studies Perturbing around reconstructed QH discharges on DIII-D





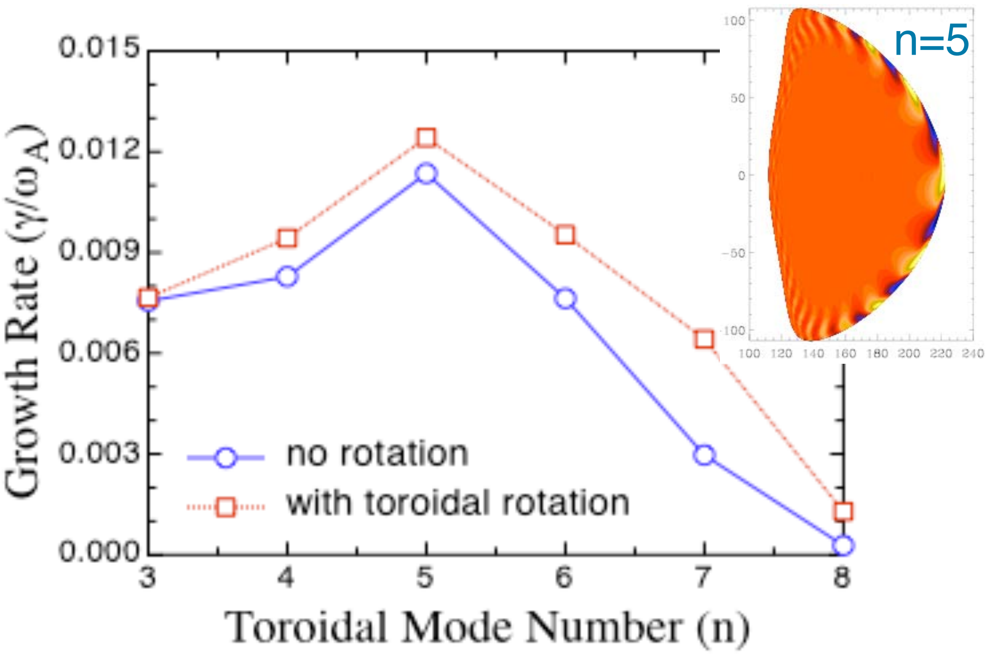
- Moderate Shaping (left): QH operating point near kink/peeling bound, low density n_{ped}~1.5 10^{13} cm^{-3}
- Strong Shaping (right): QH operating point near kink/peeling bound, higher density QH operation possible, n_{ped}~3 10^{13} cm^{-3}
  - Good quantitative agreement with predictions, confirmed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

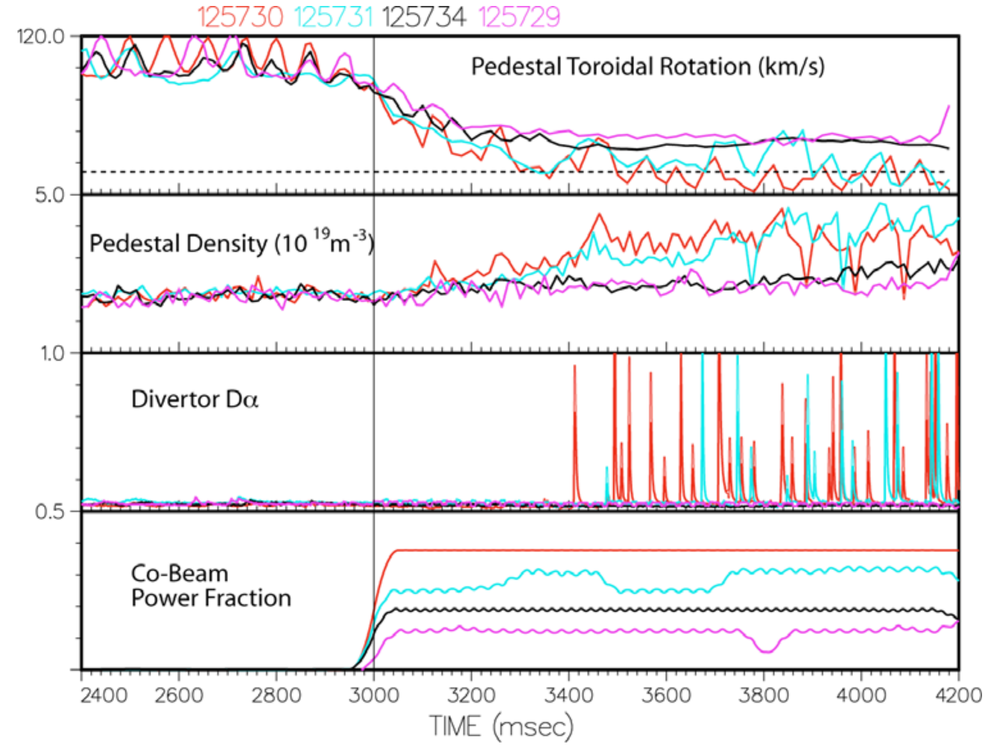
ITER Model Shows QH Regime May be Accessible at Low Density



- **ITER base case, R = 6.2 m, a = 2 m, B_t = 5.3T, I_p = 15 MA**
- **Reference density $\langle n_e \rangle = 10.1\times10^{19}\text{cm}^{-3}$, $n_{eped}\sim7\times10^{19}\text{cm}^{-3}$**
  - High *n* ballooning limited at Ref density
- **QH region for $n_{eped}<\sim4\ 10^{19}\text{cm}^{-3}$**
  - Worth exploring low or peaked density operation

Rotation Plays an Important Role in QH Mode





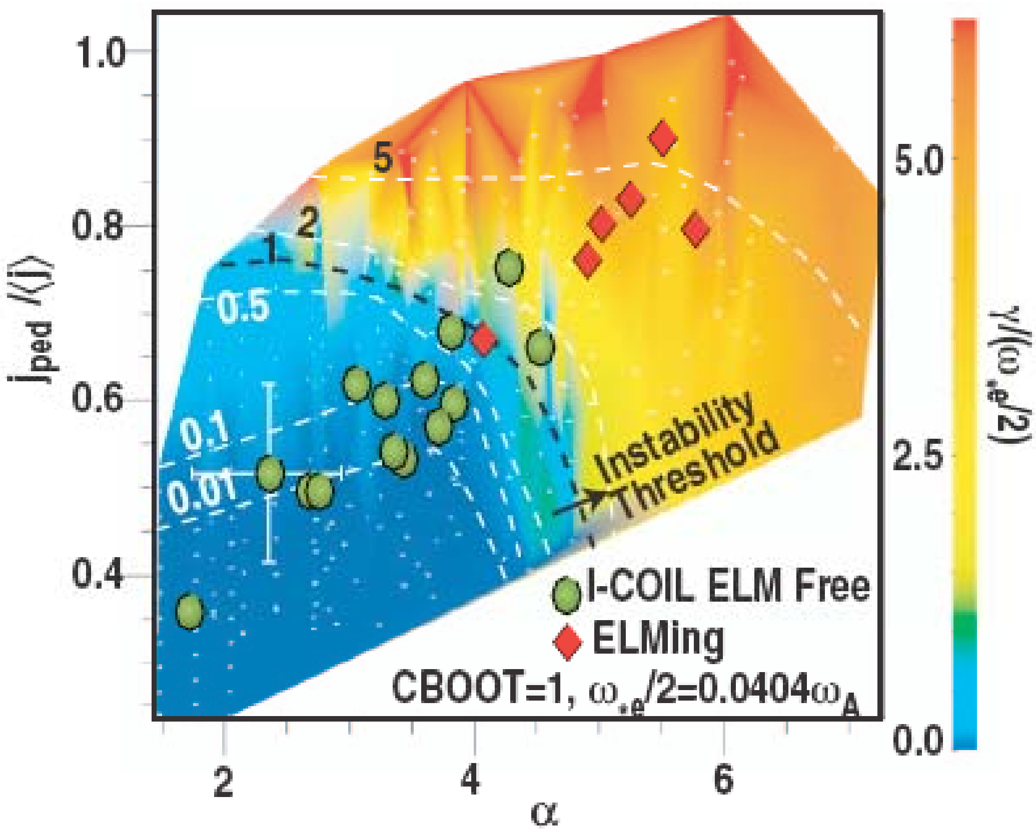
- **Flow stabilizes "edge localized RWM" (and hign-n ballooning modes)**
  - Allows plasma to reach ideal boundary, triggering rotating low-n mode
- **Limiting modes are rotationally *de*stabilized**
  - As mode grows and damps rotation, it is stabilized (unlike ELM)
- **Rotation requirements quantified 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**
- **Nonlinear dynamics studied with a variety of approaches**
  - Relaxation theory applied to peeling modes: small, variable ELMs
  - Nonlinear ballooning theory: Explosive filaments, critical current density
  - Direct 3D electromagnetic, two-fluid nonlinear 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 finds 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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