

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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 **GENERAL ATOMICS**
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Outline

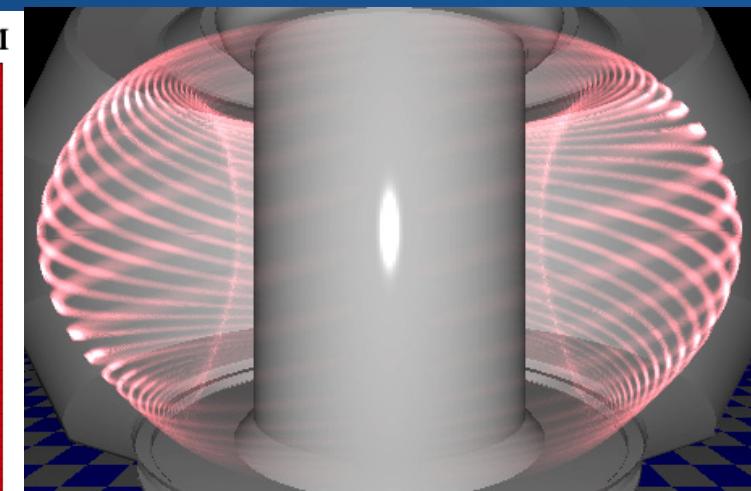
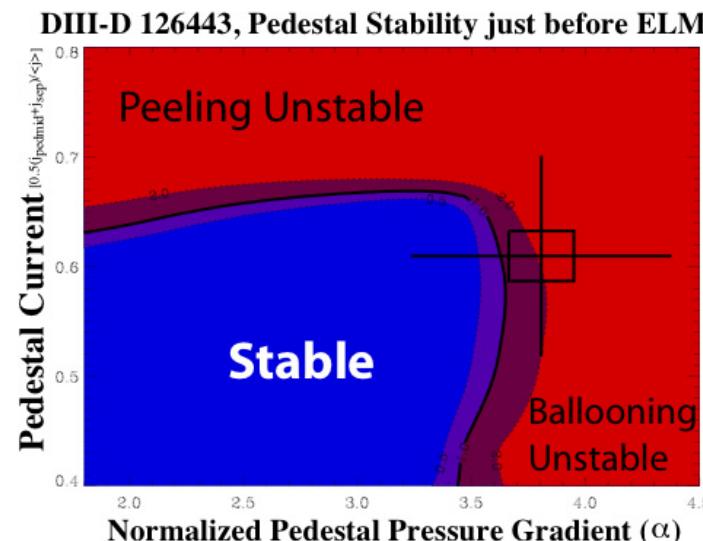
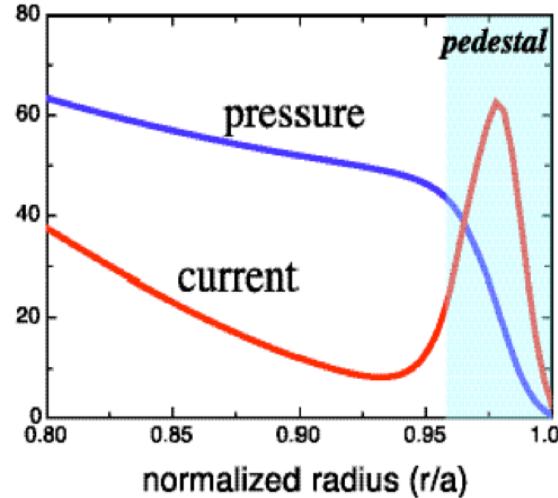
Physics of ELMs and Pedestal Constraints

- **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 ($n \sim 3-30$) 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
 - >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.]

Nonlinear ELM Dynamics

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

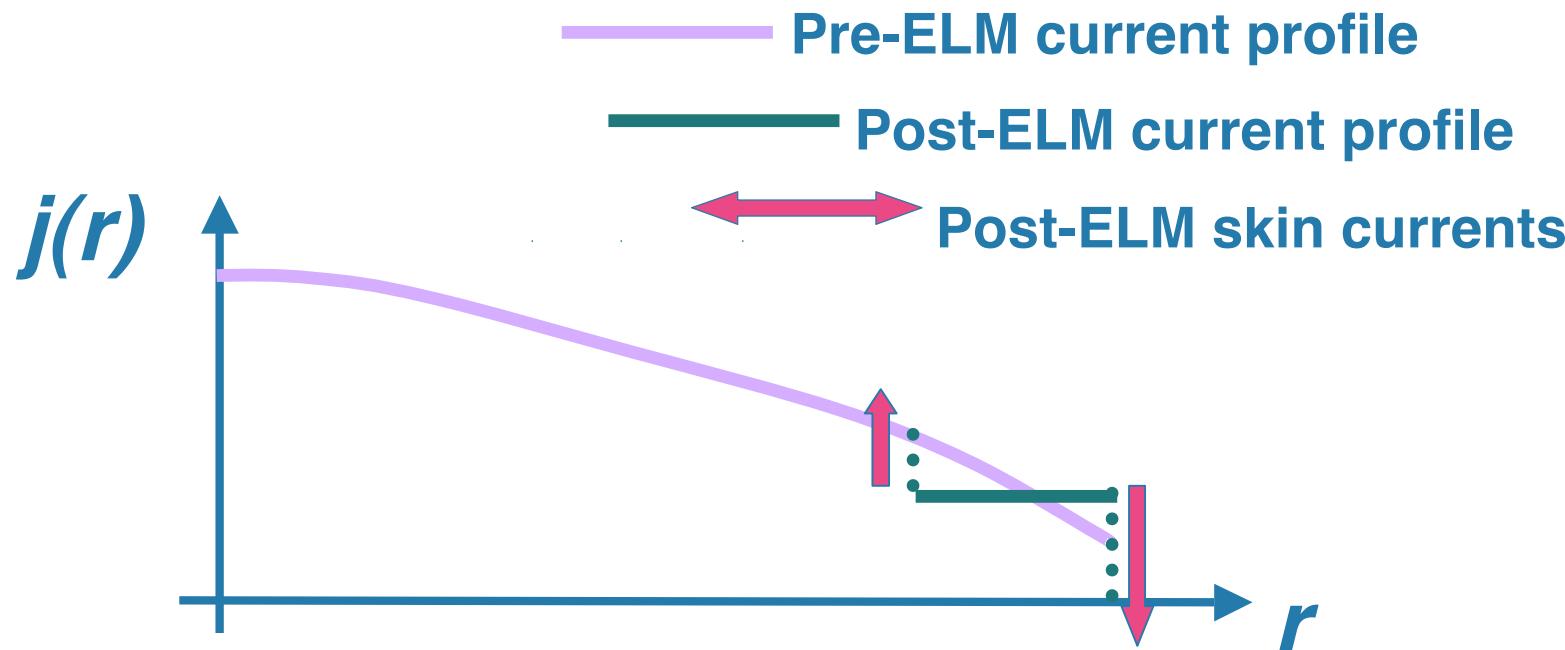
The Peeling Mode/Relaxation ELM Model

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

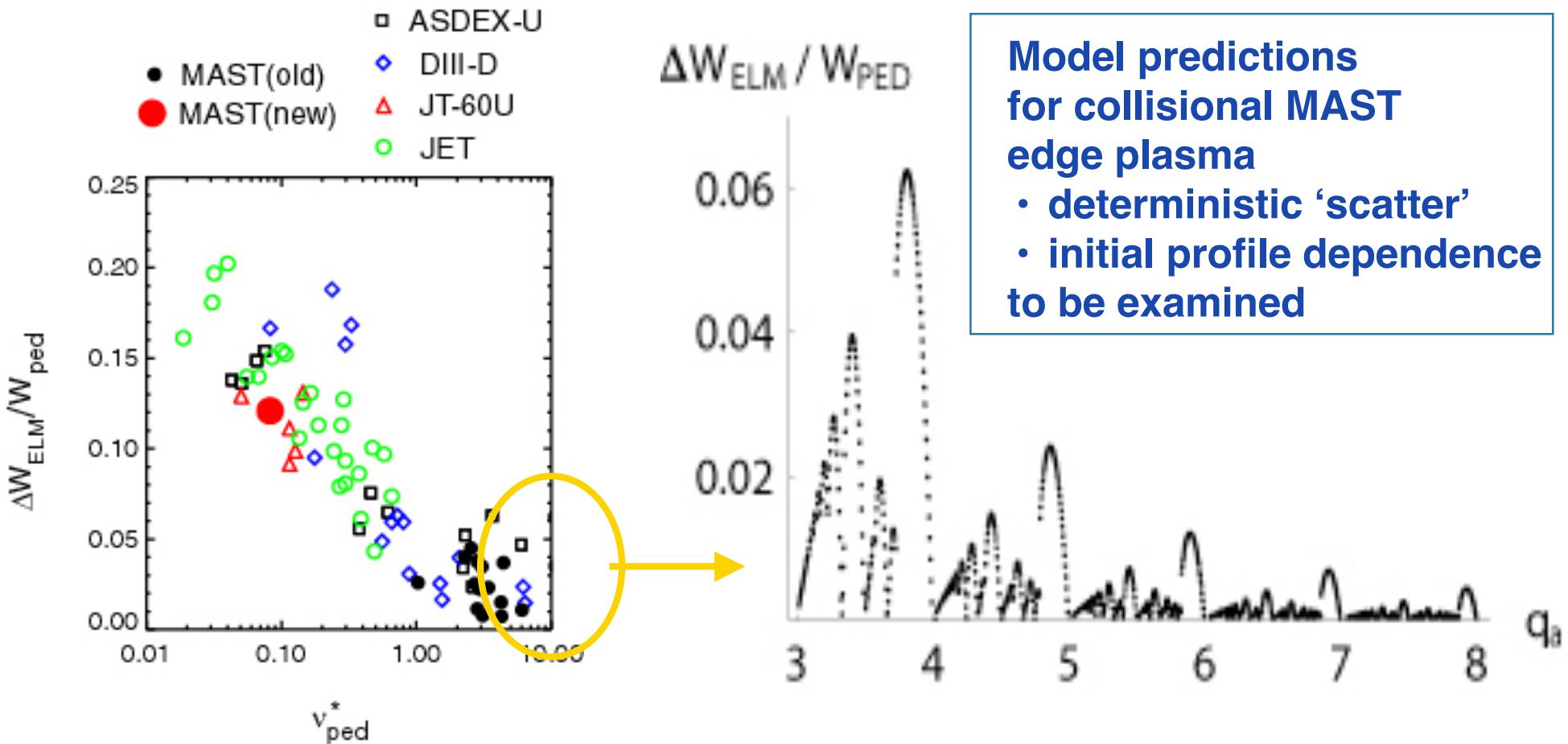
BUT

- 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).

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

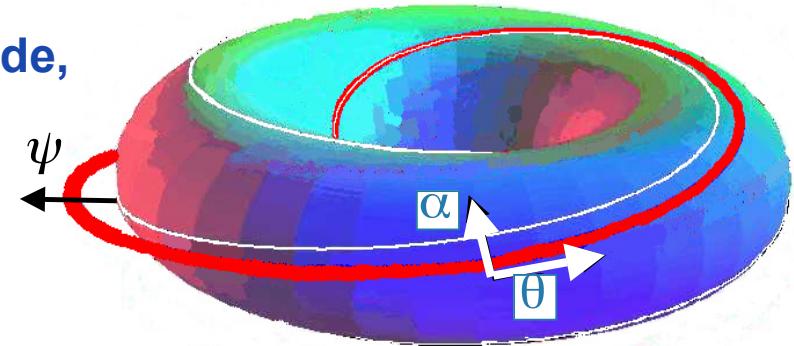
Nonlinear ELM Dynamics

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

Derivation of the Nonlinear Ballooning Theory

In the early non-linear 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 non-linear equation for the amplitude, F :

$$C_I \frac{\partial}{\partial \alpha} \frac{\partial^2}{\partial t^2} \left[\int_0^t dt' \frac{F(t')}{(t-t')^{\lambda_s - \lambda_L - 1}} \right] + \rho C \frac{\partial}{\partial \alpha} \left(\frac{\partial^2 F}{\partial t^2} \right) =$$

A representation of a fractional derivative

Linear instability drive

$$C_1 \left[2(1-\mu) \frac{\partial F}{\partial \alpha} - C_0 \frac{\partial^2 u}{\partial \psi^2} \right] + C_2 \frac{\partial F^2}{\partial \alpha} + C_4 \frac{\partial F}{\partial \alpha} \frac{\partial^2 \bar{F}^2}{\partial \psi^2}$$

Cubic non-linearity determines radial structure

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

Non-linear drive term

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 non-linear regime, balance quadratic non-linearity with inertia (left hand side)

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

⇒ 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 non-linearities:

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

⇒ Broadens in ψ , narrows in α

- Combine with slow variation along field line

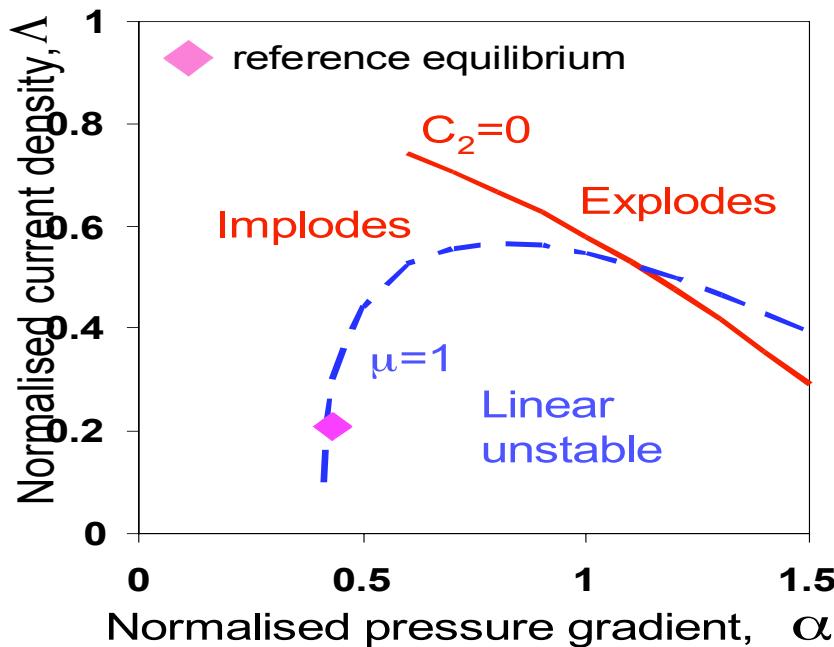
⇒ filamentary structure erupts from the surface

⇒ coefficient C_2 determines direction of filament propagation

- Highly challenging calculation, two length scale expansions + expansion about a JET-like equilibrium surface

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



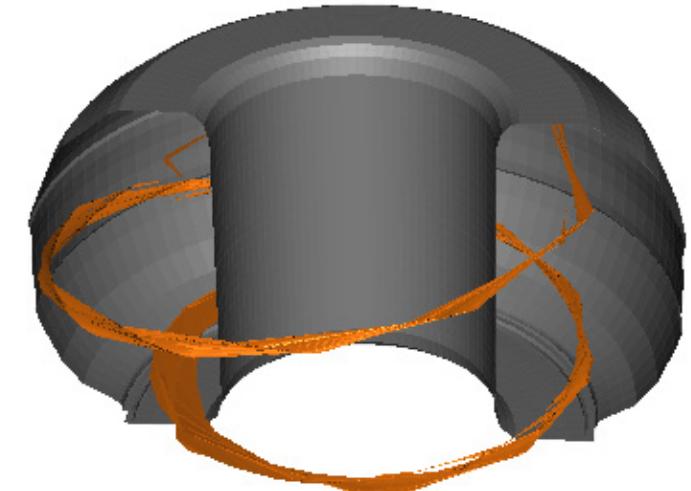
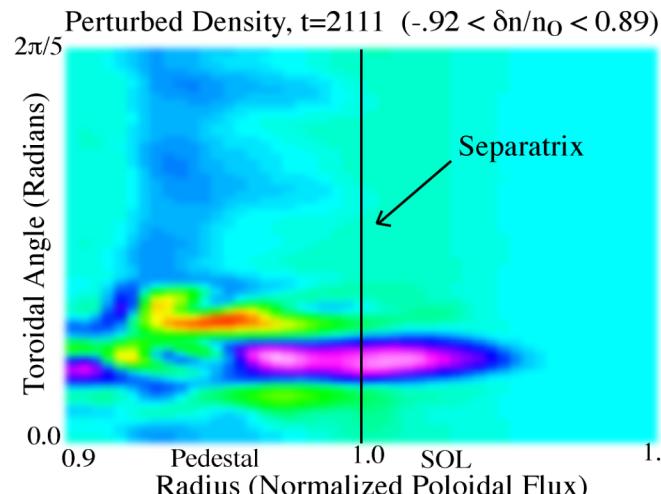
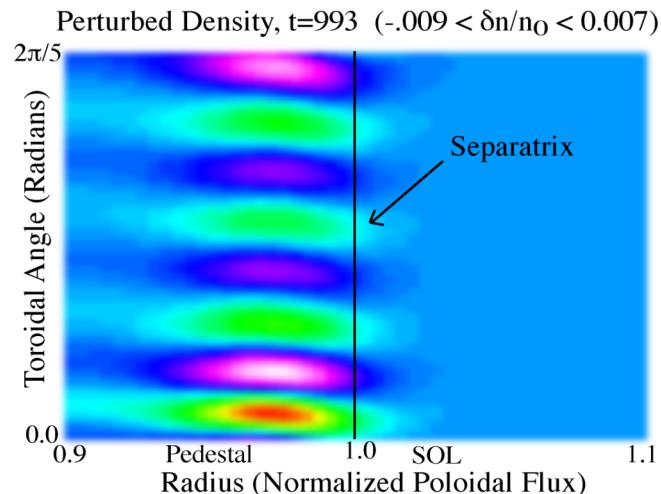
$C_2 > 0 \Rightarrow$ filaments explode out towards SOL
 $C_2 < 0 \Rightarrow$ filaments implode in towards core

- 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

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).

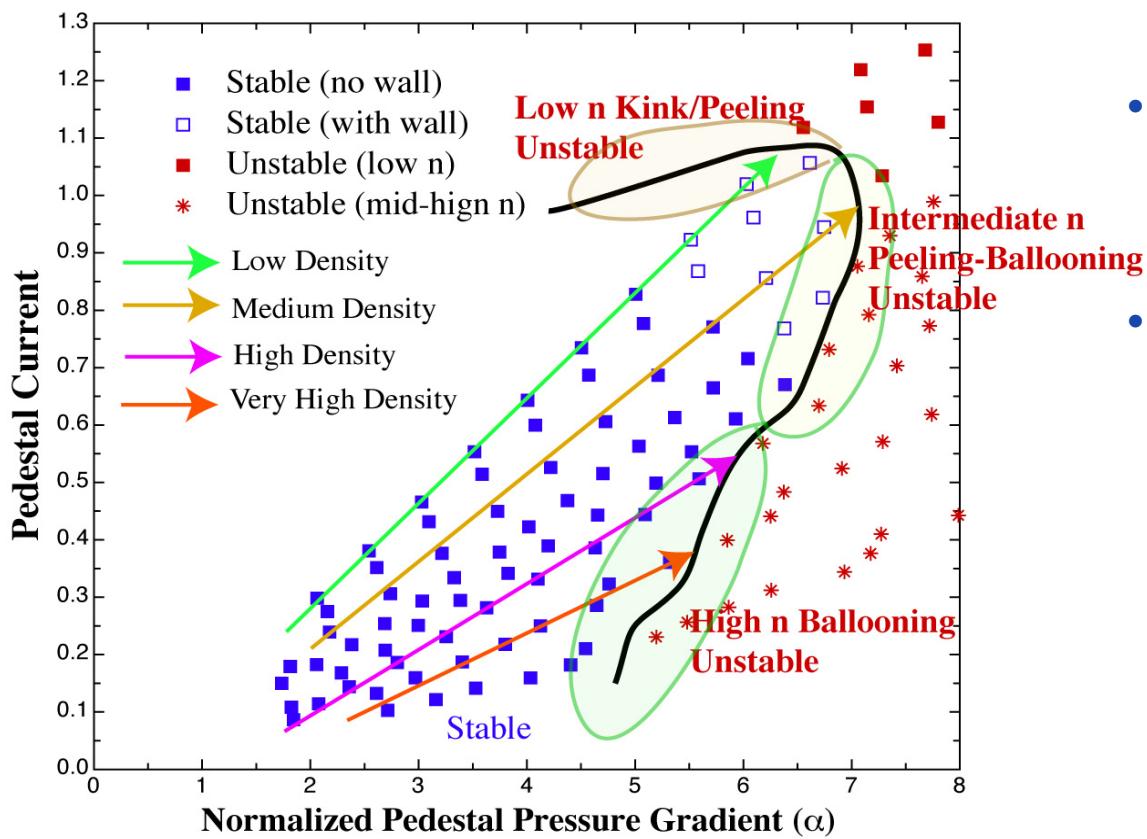
- **Nonlinear: 3D BOUT simulations (EM two-fluid), include equilibrium scale MHD drives as well as small scale diamagnetic terms in collisional limit**
- **Expected P-B linear growth and structure in early phase, followed by explosive burst of one or many filaments into the SOL**
 - Successful comparisons 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

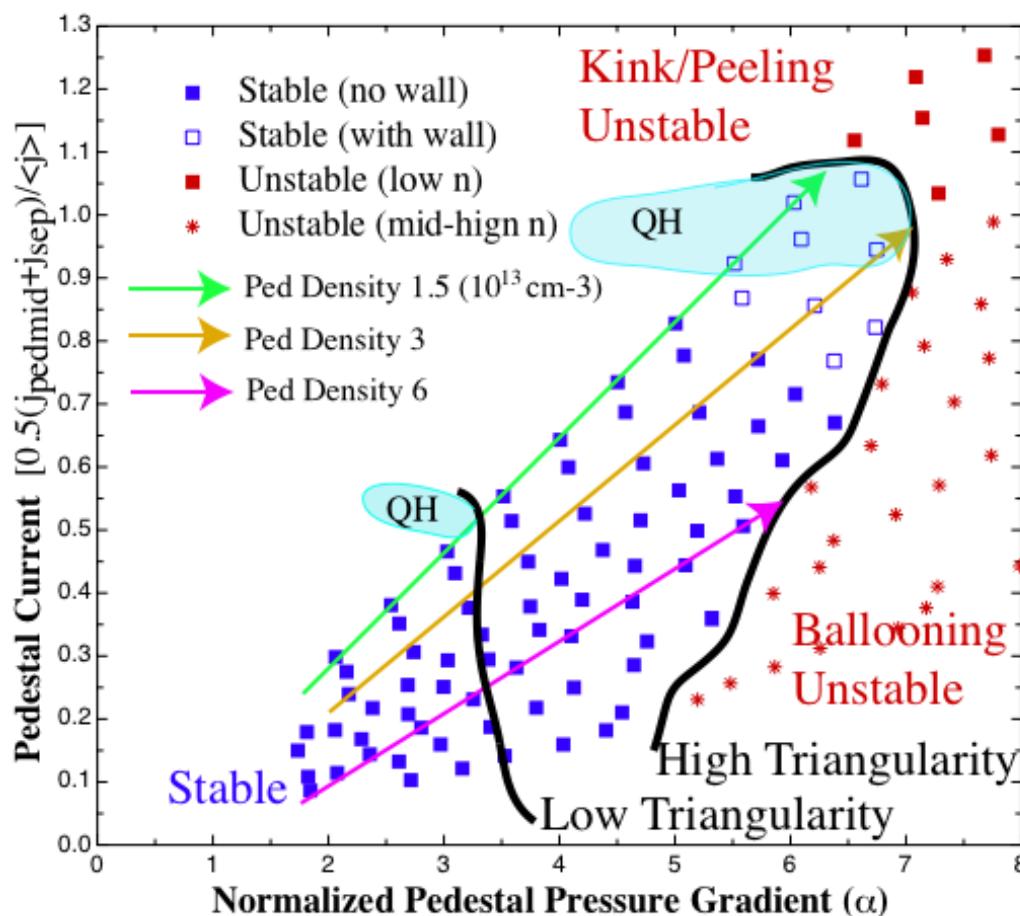


Effect of Low Density

- The pedestal current is dominated by bootstrap current
 - Roughly proportional to p'
 - Decreases with collisionality
- Lower density means more current at a given p'
 - ($v_* \sim n_e^{-3}$ at given p')
 - Moderate to high density discharges limited by P-B or ballooning modes
 - Very low density discharges may hit kink/peeling boundary

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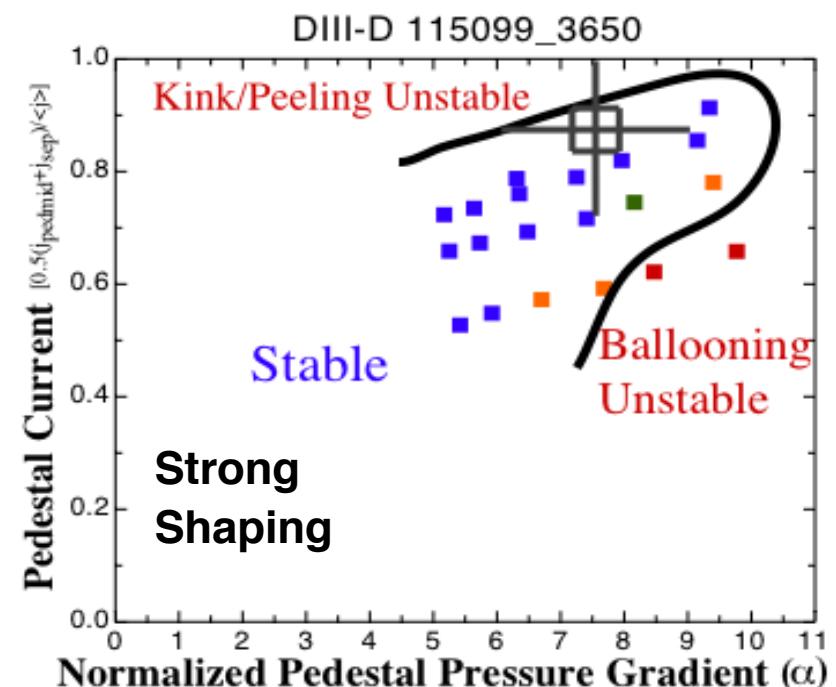
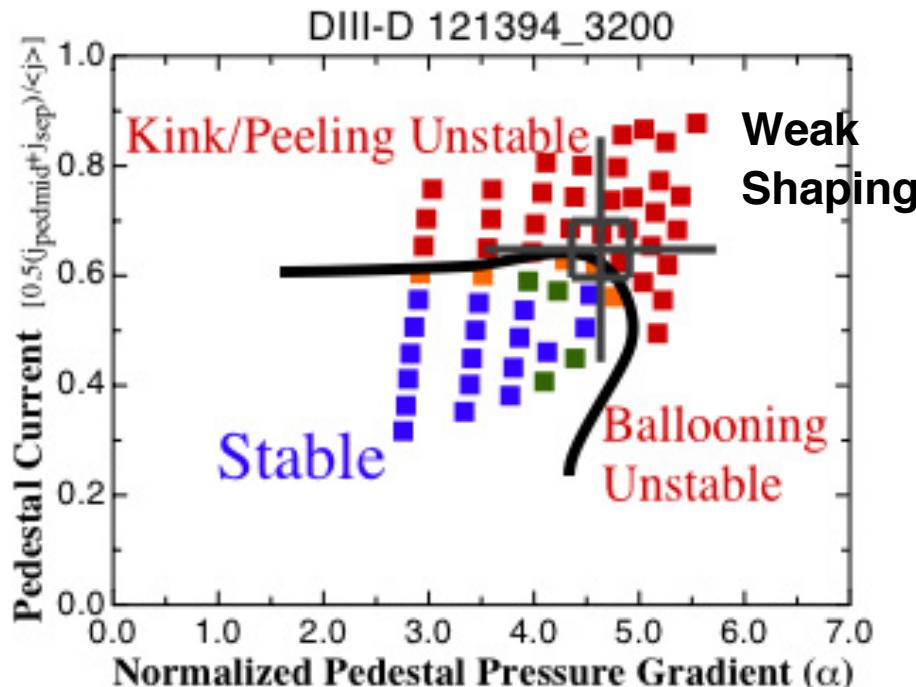
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Theory: QH Mode exists in Low-n Kink/Peeling Limited Regime

- Allows quantitative density predictions
- Density limit varies with triangularity

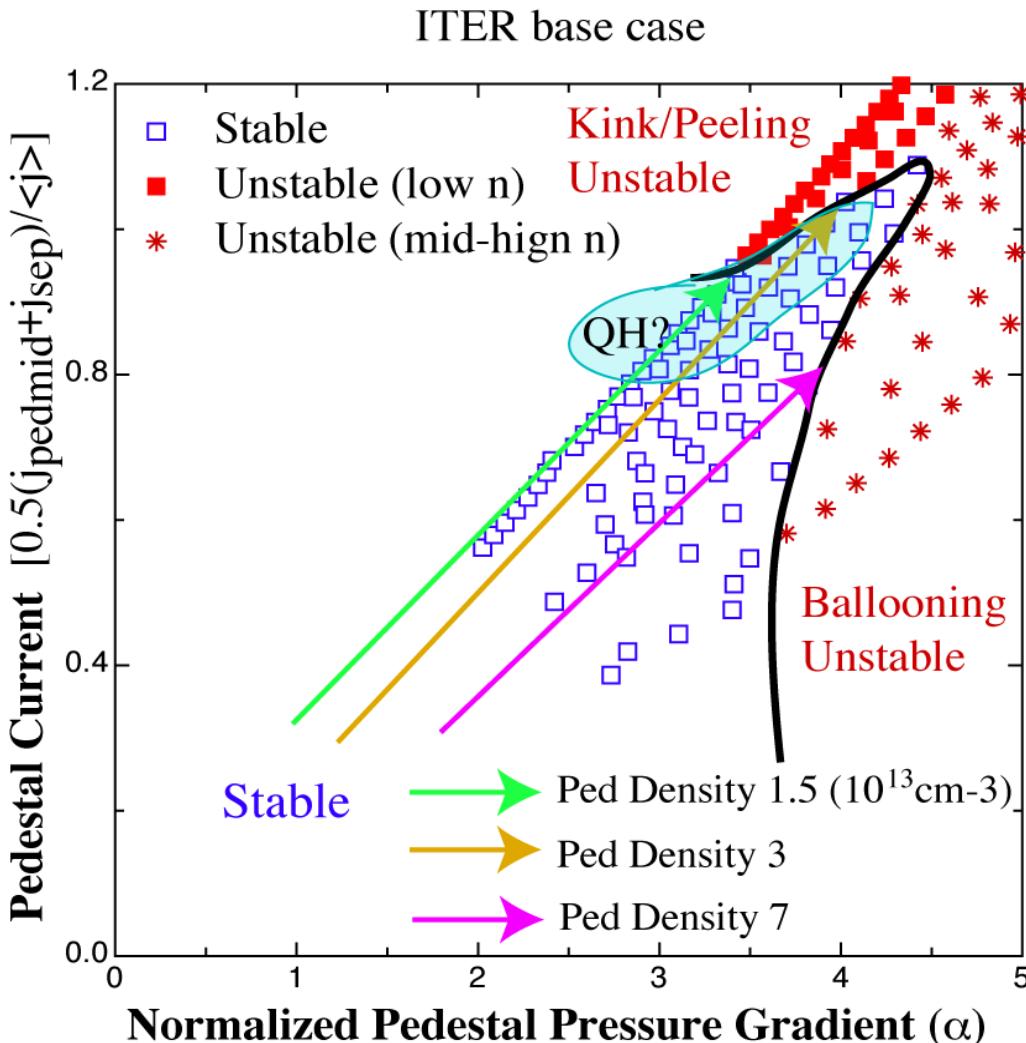
Observation: QH Discharges Exist Near Kink/Peeling Boundary

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



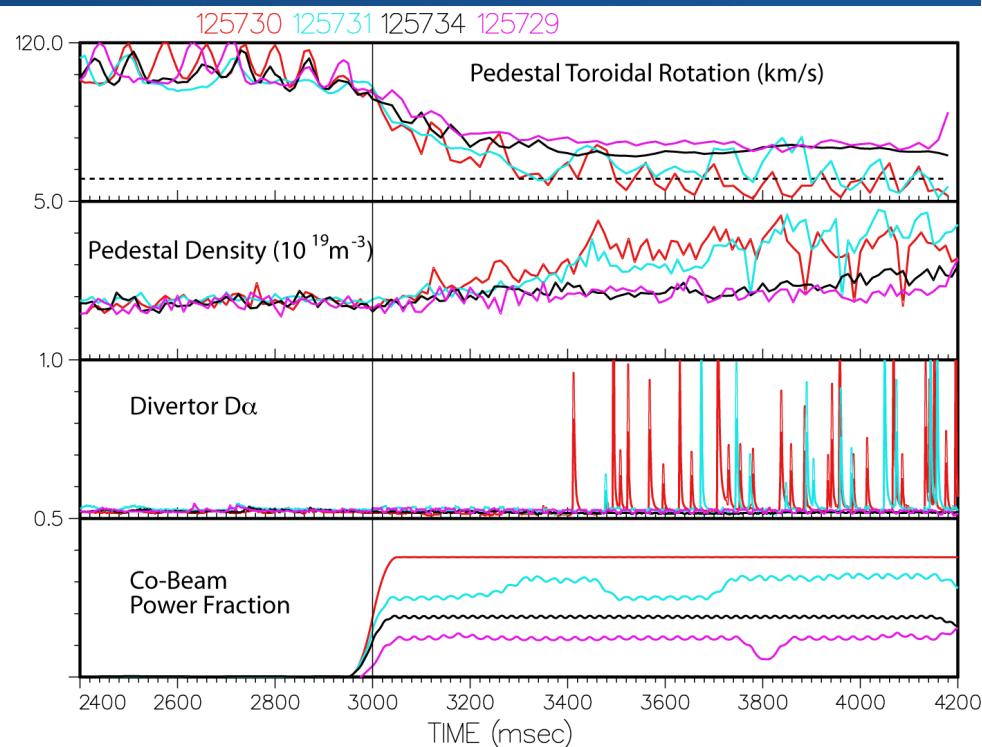
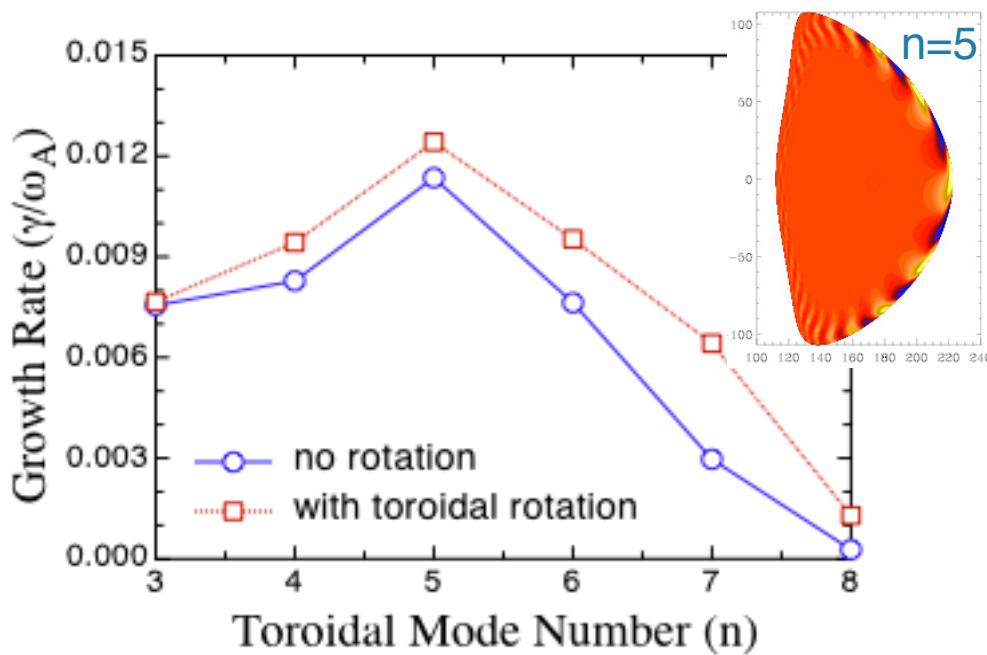
- Moderate Shaping (left): QH operating point near kink/peeling bound, low density $n_{\text{ped}} \sim 1.5 \cdot 10^{13} \text{ cm}^{-3}$
- Strong Shaping (right): QH operating point near kink/peeling bound, higher density QH operation possible, $n_{\text{ped}} \sim 3 \cdot 10^{13} \text{ cm}^{-3}$
 - 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 $\langle n_e \rangle = 10.1 \cdot 10^{19} \text{ cm}^{-3}$, $n_{\text{eped}} \sim 7 \cdot 10^{19} \text{ cm}^{-3}$
 - High n ballooning limited at Ref density
- QH region for $n_{\text{eped}} < \sim 4 \cdot 10^{19} \text{ cm}^{-3}$
 - Worth exploring low or peaked density operation

Rotation Plays an Important Role in QH Mode



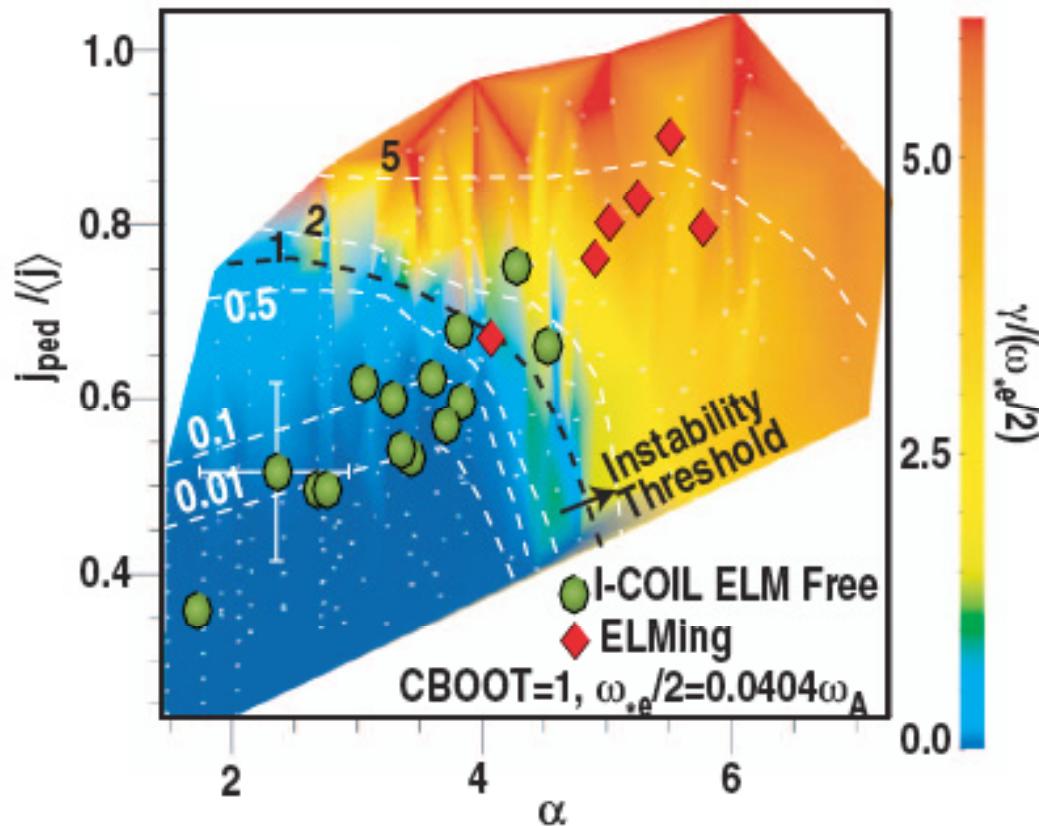
- **Flow stabilizes “edge localized RWM” (and high-n ballooning modes)**
 - Allows plasma to reach ideal boundary, triggering rotating low-n mode
- **Limiting modes are rotationally destabilized**
 - As mode grows and damps rotation, it is stabilized (unlike ELM)
- **Rotation requirements quantified 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-balloonning 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-balloonning 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 $n_{eped} < \sim 4 \cdot 10^{19} \text{ m}^{-3}$)
 - 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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