Stabilizing Effects of Edge Current Density on Peeling-Ballooning Instability [1]

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Abstract

Resistive MHD computations using the NIMROD code find a strong dependence of low-n edge instabilities on the edge parallel current density distribution. Here n is the toroidal mode number. The low-n edge-localized-modes can be driven unstable by increasing the edge current density across the peeling-ballooning stability boundary. When edge peak current density is sufficiently large, the corresponding safety factor q profile obtains an edge region with zero or reversed magnetic shear, and the low-n edge instabilities are partially or fully stabilized. These results are consistent with previous analytic theory on peeling modes which indicates that zero or reversed magnetic shear can be stabilizing. Nonlinear simulations indicate that the stabilizing effects of edge current density on the low-n peeling-dominant modes through zero and reversed shear can persist throughout the nonlinear exponential growth phase. Near the end of this nonlinear phase, the radial extent of the filament exceeds the pedestal width, and disconnected blob-like substructures start to develop within the filaments. Relative pedestal energy loss from these radially extending filaments can reach $20-30\%$. Both filament size and pedestal energy loss from the nonlinear low-n peeling-dominant instabilities can be reduced and regulated by the equilibrium edge current density distribution.

Outline

1. Introduction
    - ELM power loss scaling not understood
    - Tokamak edge instability sensitive to current current density
2. TOQ equilibriums with different edge current profiles
3. Linear edge instabilities with different edge current density profiles
4. What is the range of achievable edge current density?
    - Contribution from bootstrap current
5. Does the stabilizing effect persist in nonlinear stage?
    - Blob formation
    - Pedestal energy loss
6. Summary and Discussion

Empirical scaling of type-I ELM energy loss on collisionality suggests possible role of edge bootstrap current in pedestal instability [Loarte *et al.* 2003]

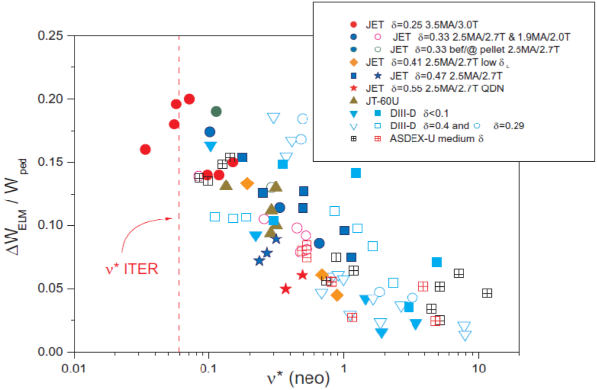
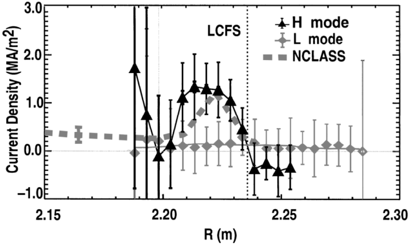
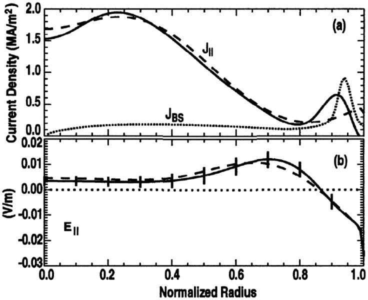


Figure 11. Normalized ELM energy loss ($\Delta W_{\mathrm{ELM}}/W_{\mathrm{ped}}$) versus pedestal plasma collisionality for a large range of Type I ELMy H-mode plasmas in ASDEX Upgrade, DIII-D, JT-60U and JET including various plasma triangularities, ratios of $P_{\mathrm{INPUT}}/P_{\mathrm{L-H}}$ and pellet triggered ELMs.

Edge current profiles in H-mode experiments are less certain from direct measurement or equilibrium reconstruction



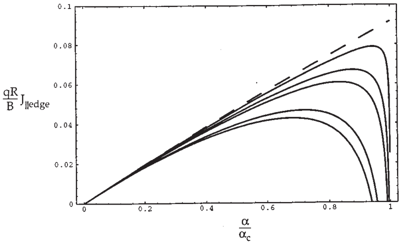
[Thomas *et al.* 2004]



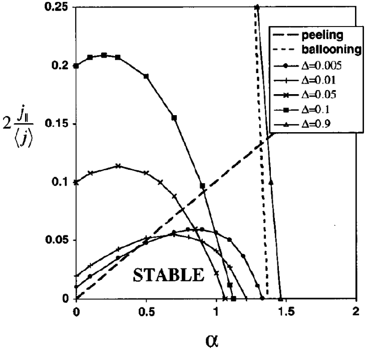
[Wade *et al.* 2004]

- Direct measurement of edge current density in experiment difficult and less accurate.
- Reconstruction of edge current density profile involves considerable uncertainty.

Peeling-ballooning instability boundary from theory is sensitive to edge current density location



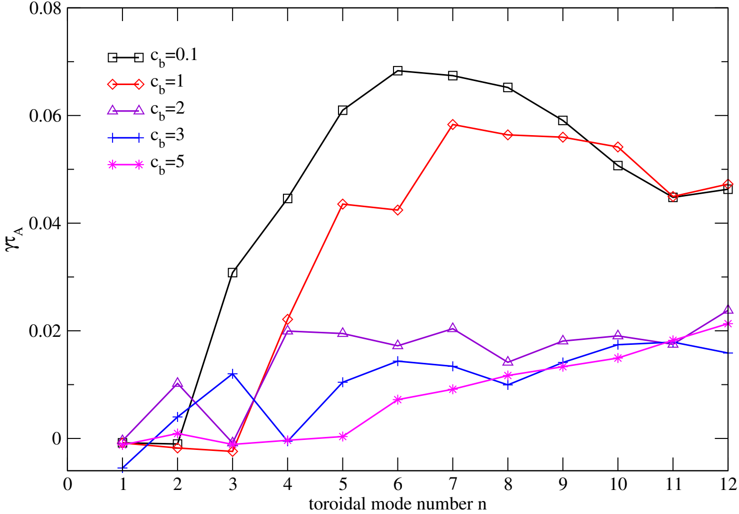
[Hegna *et al.* 1996]



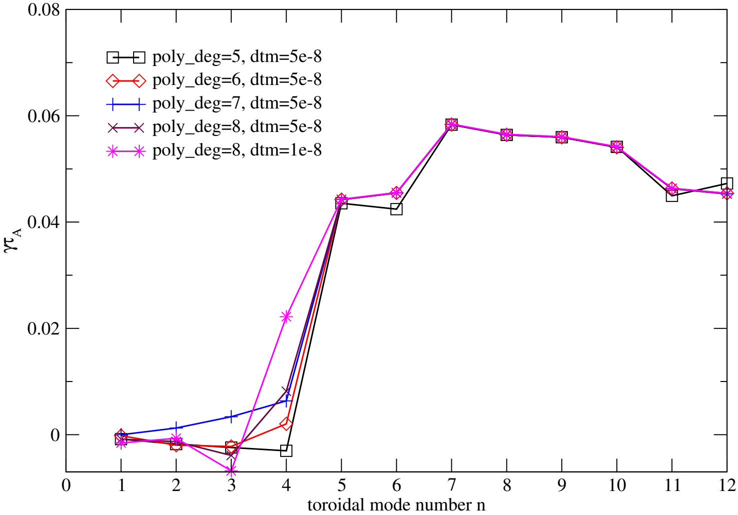
[Connor *et al.* 1998]

- Marginal stability bounary closer to peeling as plasma edge approaches 1st external rational surface.
- Marginal stability boundary closer to ballooning as plasma edge moves away from 1st external rational

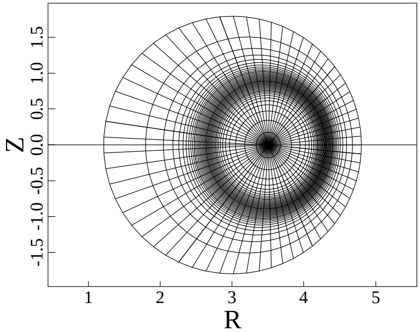
NIMROD calculations show low-n ($n < 10$) mode linear growth rate can decrease with edge current density [Zhu, Hegna, and Sovinec 2011]

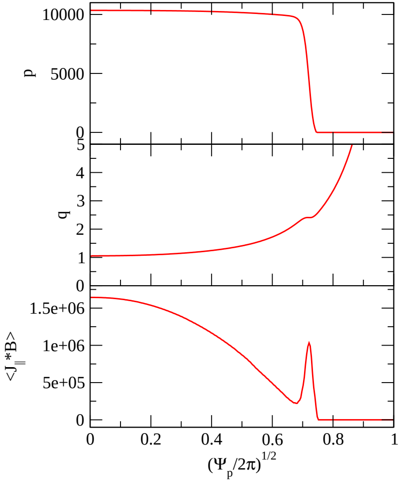


Linear growth rates of low-n modes spatially converge in NIMROD calculations



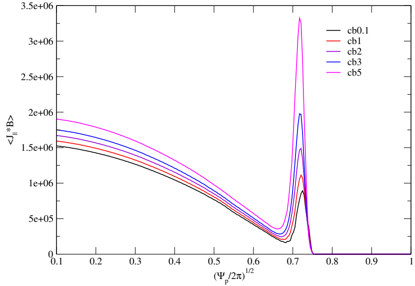
Circular-shaped tokamak equilibrium is used

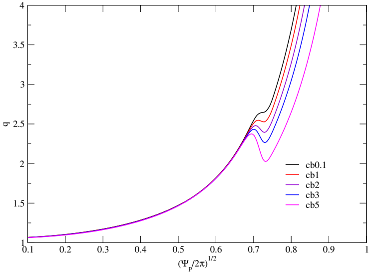




- Equilibrium from TOQ solver
- Finite element mesh used in NIMROD simulation.

A set of equilibria prepared with different edge localized current profile and same pressure profile





- Peak location slightly shifts inward as peak value increases
- A reverse shear region appears as peak current increases.

Theory suggests zero or reverse shear can be stabilizing for peeling mode

- Leading order necessary stability condition for peeling mode [Connor *et al.* 1998]

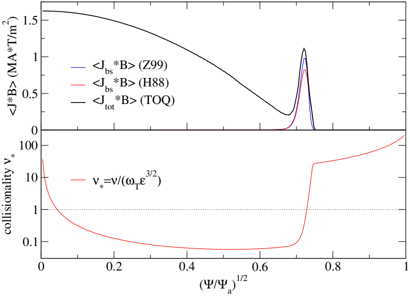
$$\alpha\left\{\frac{r}{R}\left(1-\frac{1}{q^2}\right)+s\Delta'-f_t\frac{Rs}{2r}\right\}>Rqs\left(\frac{J_\parallel^{\text{driven}}}{B}\right)_{\text{edge}}$$

  where $\alpha=-2\frac{Rq^2}{B^2}p'$ and shaping effects ignored.
- Shafranov shift Δ' term from Pfirsch-Schlüter current contribution.
- Trapped particle fraction f_t term from bootstrap current contribution.
- Zero or reverse shear yields less restrictive criterion, suggesting stabilizing effects.

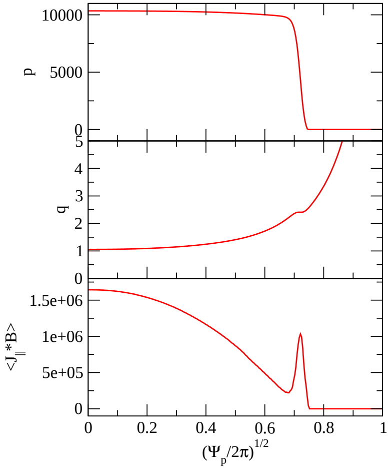
Neoclassical theory is used to evaluate the range of bootstrap current density in pedestal region

- Models on tokamak bootstrap current calculations, e.g.
  - Multi-ion species, full matrix numerical [Hirshman and Sigmar 1981]
  - Single ion species, analytical [Hirshman 1988; Harris 1991; Kessel 1994]
  - Single ion species, CQL fitted [Sauter *et al.* 1999]
- Full matrix based method has been used here [Zhu *et al.* 1999]. Similar to and benmarked with NCLASS [Houlberg *et al.* 1997] but with approximations
  - Collisionless regime
  - Model equilibrium $B = B_0(1 + r\cos\theta/R)^{-1}$
  - Large aspect ratio
- For single ion species, basically recover [Hirshman 1988] formula.

For the given equilibrium the calculated bootstrap currents are consistent with total equilibrium current

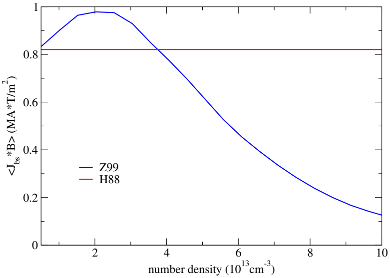


- Major part of inner pedestal region is in banana transport regime ($\nu_* < 1$).

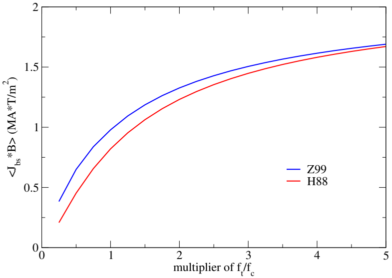


- MHD equilibrium profiles.

For the given equilibrium there is a moderate range of variation for the peak value of bootstrap current density



- Bootstrap current density maximizes at certain number density.

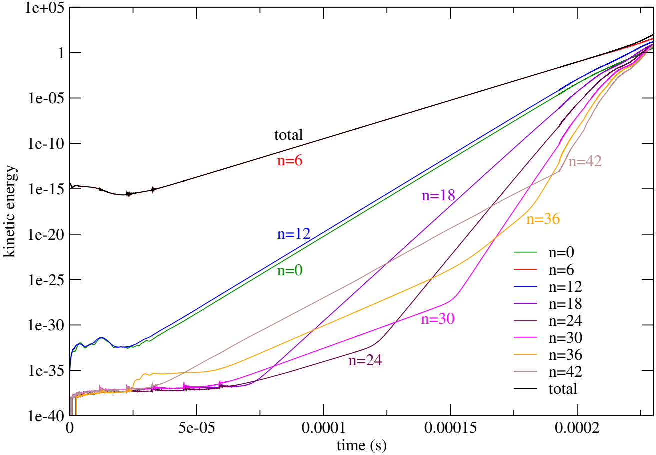


- Increasing trapped particle fraction is most effective at increasing bootstrap current density.

Several other factors can affect edge current density in pedestal region

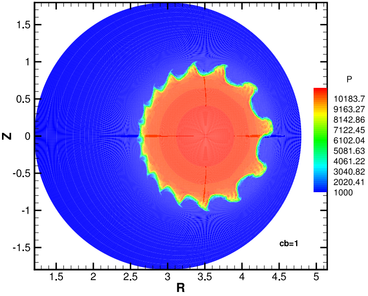
- $J_{||} = \sigma_{\text{neo}} E_{||} + J_{\text{NBI}} + J_{\text{rf}} + J_{\text{PS}} + J_{\text{bs}}$.
- Finite aspect ratio and full geometry effects.
- Varing collisionality from collisionless to collisional regimes; can lower bootstrap current at edge [e.g. Houlberg *et al.* 1997].
- Impurity ion species effects.
- Pedestal width comparable to ion drift orbit size (nonlocal).
- Ion orbit squeezing effects due to E_r in pedestal region.
- Strong E_r may enhance bootstrap current in banana regime [e.g. Kagan and Catto 2010].
- Ion orbit loss effects [Shaing 1992].
- Nonaxisymmetric magnetic field effects.
- ......

Exponential growth persists well into nonlinear stage when higher toroidal harmonics become same order of magnitude

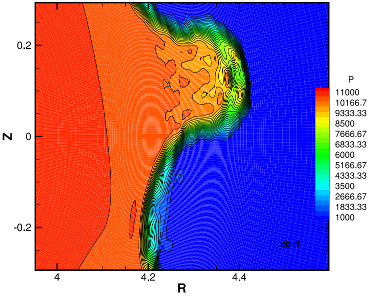


- Initialized with $n = 6$ component; spatially converged with 5th order 40×195 elements and 43 Fourier components.

Blob-like structure starts to develop near the end of nonlinear exponential growth phase

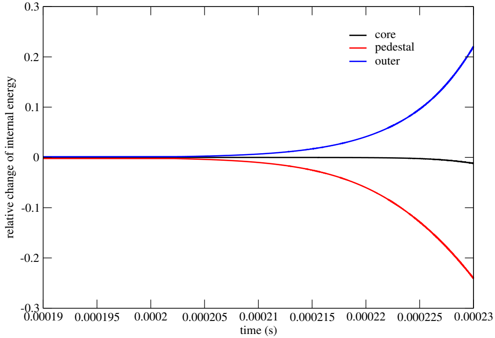


- Radial extent of nonlinear structure reaches and exceeds pedestal scale length.



- Disconnected segments of radially extending structure can be source of blobs.

Relative pedestal energy loss reaches experimental level near the end of nonlinear exponential growth phase



$$\frac{\Delta W_{\mathrm{ped}}(t)}{W_{\mathrm{ped}}} = \frac{\int_{\mathrm{ped}} [p(\mathbf{r},t) - p_0(\mathbf{r})] d\mathbf{r}}{\int_{\mathrm{ped}} p_0(\mathbf{r}) d\mathbf{r}}, \quad \left\{ \begin{array}{ll} \text{core region:} & p_0 \geq p_{\mathrm{ped}}^{\mathrm{top}}, \\ \text{pedestal region:} & p_{\mathrm{ped}}^{\mathrm{out}} \leq p_0 < p_{\mathrm{ped}}^{\mathrm{top}}, \\ \text{outer region:} & p_0 < p_{\mathrm{ped}}^{\mathrm{out}}. \end{array} \right.$$

Discussion

- Reversed magnetic shear is known to stabilize not only peeling but also internal ballooning instability. Which stabilization is dominant?
- What is the self-consistent maximum and minimum (noninductive) edge current density for a given pressure pedestal?
- Full saturation phase needed for evaluation of pedestal energy loss per pedestal crash.
  - Nonlinear time advance becomes challenging as blob front steepens and moves to less resolved domain.
  - What additional nonideal and dissipation physics needed?

Summary

- Marginal peeling-ballooning stability boundary is known to be sensitive to edge current density.
- NIMROD calculations indicate increasing edge current density can reduce and stabilize linear growth of low-n edge instability.
- NIMROD simulations show such a stabilization effect can persist in exponential nonlinear growth phase.
- Neoclassical calculation suggests it's possible for edge bootstrap current to provide the necessary edge current density required for the stabilization.
- Future work
    - Mechanism of edge current stabilization effects.
    - More accurate evaluation of edge bootstrap current density.
    - Full saturation and relaxation phase.