Edge Current Effects on Peeling-Ballooning Instability

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Outline

1. Introduction
   - ELM power loss scaling
   - Peeling dominant vs ballooning dominant edge instability
2. TOQ equilibriums with different edge current profiles
3. Linear peeling-ballooning properties vs edge current
   - Dispersion relation
   - Mode structures
4. Nonlinear peeling dominant simulations
   - Blob formation
   - Pedestal energy loss
5. 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]

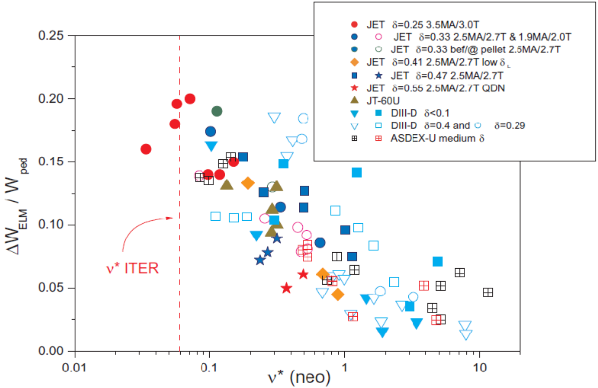
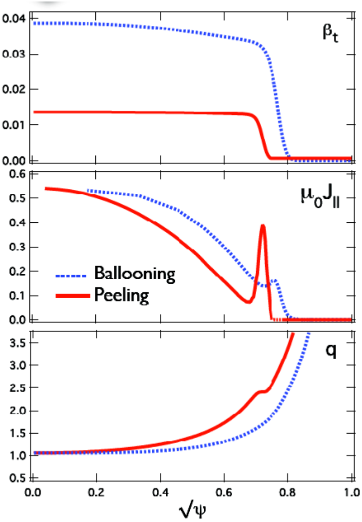
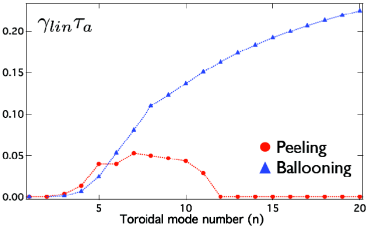


Figure 11. Normalized ELM energy loss ($\Delta W_{ELM}/W_{ped}$) versus pedestal plasma collisionality for a large range of Type I ELMy H-mode plasmas in ASDEX Upgrade, DIII-D, JT-60U and JET including various plasma triangularities, ratios of P_{INPUT}/P_{L-H} and pellet triggered ELMs.

Both low-n peeling and high-n ballooning instabilities are studied in late nonlinear stage

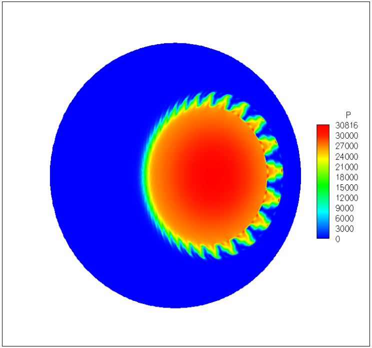
[Burke *et al.* , 2010]



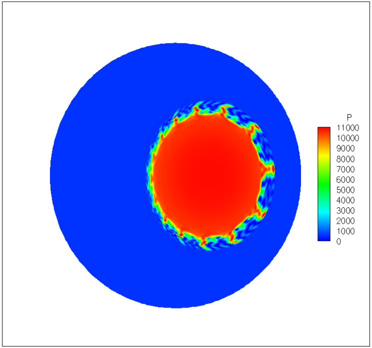


- Ballooning dominant (`dens8`): monotonic growth *vs n*
- Peeling dominant (`pbs07`): low *n* bump in growth

Dynamics of blob-like structure during late nonlinear phase appears different for high-n ballooning and low-n peeling dominant edge instability

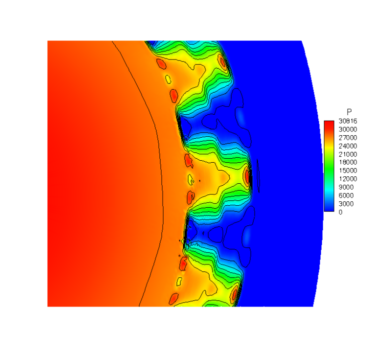


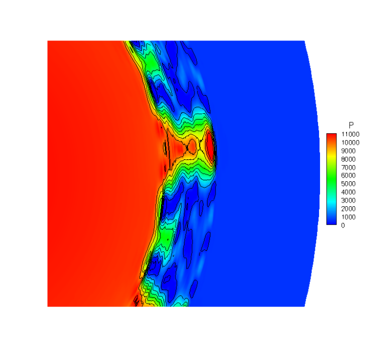
- `dens8` equilibrium, n=15 i.c.



- `pbs07` equilibrium, n=6 i.c.

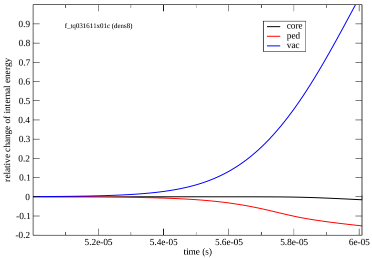
Dynamics of blob-like structure during late nonlinear phase appears different for high-n ballooning and low-n peeling dominant edge instability

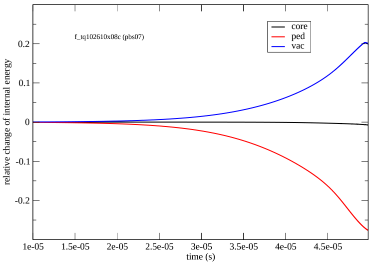




- `dens8` equilibrium, n=15 i.c.
- `pbs07` equilibrium, n=6 i.c.

Pedestal energy loss during late nonlinear phase also different for high-n ballooning and low-n peeling dominant edge instability

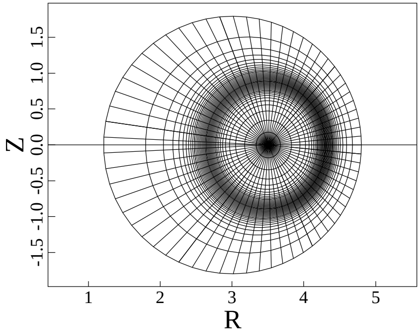


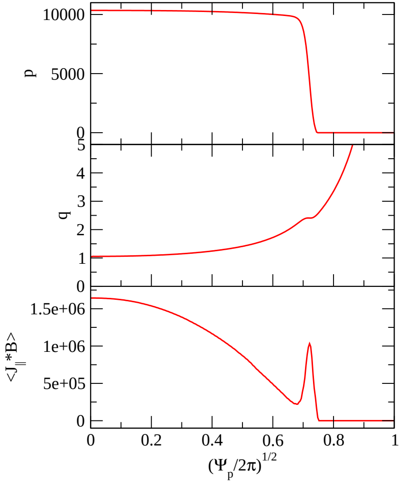


- `dens8` equilibrium, n=15 i.c.
- `pbs07` equilibrium, n=6 i.c.

core: $p > p_{\rm ped}^{\rm top}$; ped: $p_{\rm ped}^{\rm mid} < p < p_{\rm ped}^{\rm top}$; vac: $p < p_{\rm ped}^{\rm mid}$

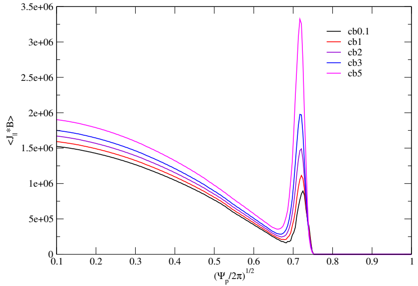
Circular-shaped tokamak equilibrium is used

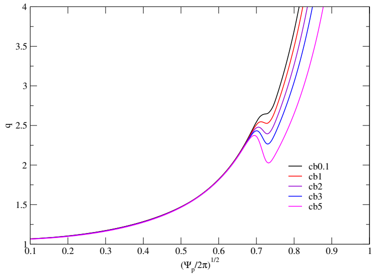




- Equilibrium from TOQ solver
- Finite element mesh used in NIMROD simulation.

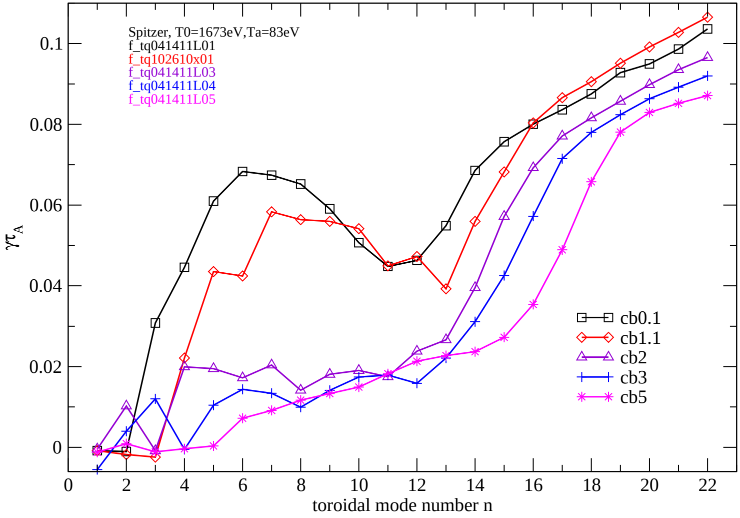
A set of equilibria prepared with different edge localized current profile and same pressure profile



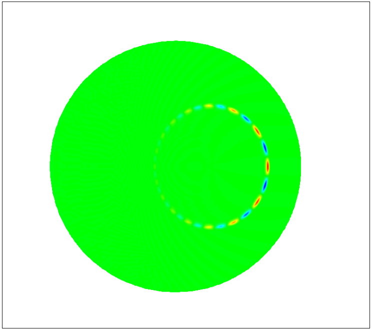


- Peak location slightly shifts inward as peak value increases
- A reverse shear region appears as peak current increases.

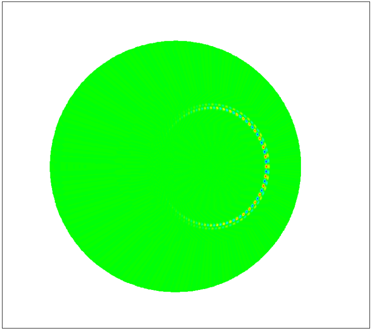
Low-n ($n < 10$) linear dispersion structure sensitive to edge current density



For smaller edge current both low-n and high-n components show stronger ballooning structure in $\tilde{p}$

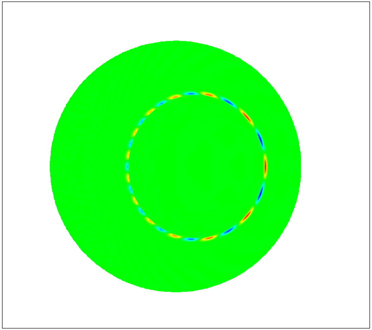


- `cb0.1`, n=6

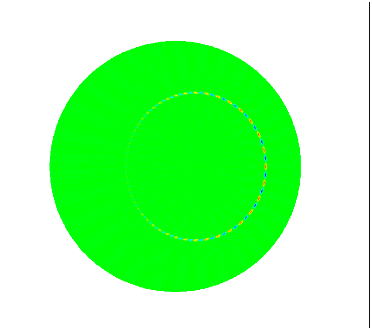


- `cb0.1`, n=22

For larger edge current both low-n and high-n components show weaker ballooning structure in $\tilde{p}$

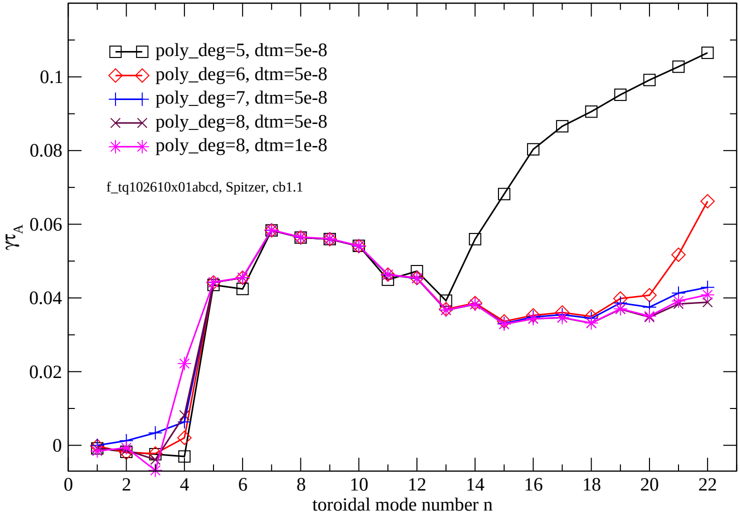


- `cb5`, n=6



- `cb5`, n=22

Linear growth rates of low-n modes spatially converge faster than high-n modes



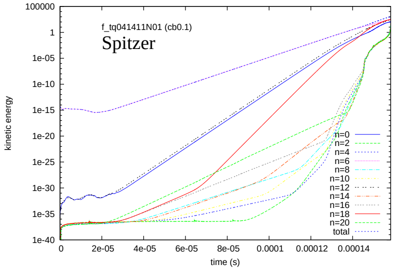
Theory suggests zero or reverse shear can be stabilizing for peeling mode

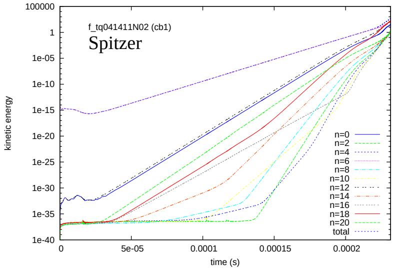
- Leading order necessary stability condition for peeling mode [Connor *et al.* 1998]

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

  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.

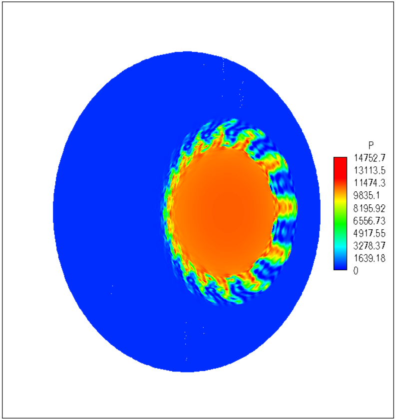
Late nonlinear peeling growth depends on nonlinear growth of coupled high-n components

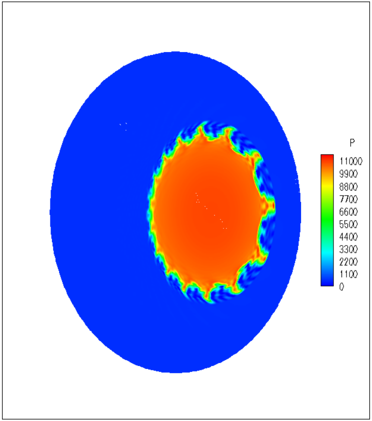




- Initialized with $n = 6$ component; nonlinear simulations include 22 toroidal components.
- Left (`cb0.1`): Smaller edge current, higher linear growth ($n = 6$), nonlinear growth weaker (from $n = 18$)
- Right (`cb1`): Larger edge current, lower linear growth ($n = 6$), nonlinear growth stronger (from $n = 18$)

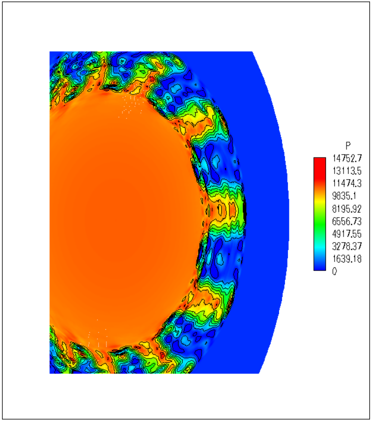
Blob structure during late nonlinear phase appears more pronounced for smaller edge current with larger linear peeling growth

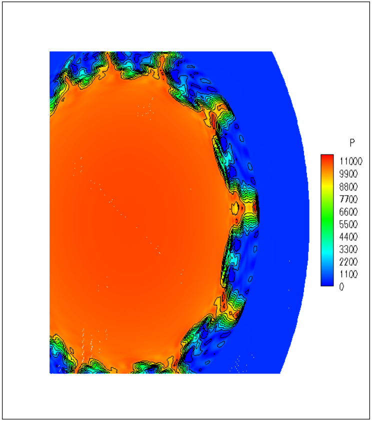




- `cb0.1` smaller peak edge current, n=6 i.c.
- `cb1` larger peak edge current, n=6 i.c.

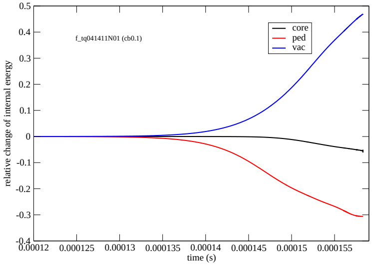
Blob structure during late nonlinear phase appears more pronounced for smaller edge current with larger linear peeling growth

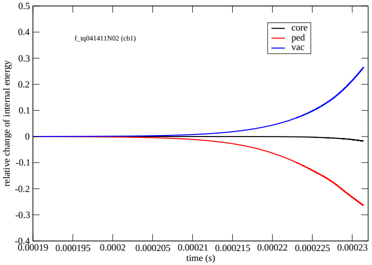




- `cb0.1` smaller peak edge current, n=6 i.c.
- `cb1` larger peak edge current, n=6 i.c.

Pedestal energy loss during late nonlinear peeling phase correlates with its linear growth rate





- `cb0.1` edge peak current lower, n=6 linear growth larger.
- `cb1` edge peak current larger, n=6 linear growth slower.

core: $p > p_{\mathrm{ped}}^{\mathrm{top}}$; ped: $p_{\mathrm{ped}}^{\mathrm{mid}} < p < p_{\mathrm{ped}}^{\mathrm{top}}$; vac: $p < p_{\mathrm{ped}}^{\mathrm{mid}}$

Discussion

- Is reversed shear responsible for stabilization effect?
- Does an optimal peak value of edge current exist that maximizes peeling growth?
- 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.
  - Additional nonideal and dissipation physics needed?

Summary

- Simulations indicate strong dependence of low-n peeling components of edge instability on edge current distribution.
- Increasing edge current density does not always increase linear growth rate of low-n peeling components.
- In certain regime, edge current density with higher peak value can actually reduce linear growth rate of low-n peeling components.
- Blob size and pedestal power loss due to nonlinear low-n peeling instability appear to be proportional to linear growth rate instead of edge current density.
- Future work
  - Mechanism of edge current stabilization effects.
  - Full saturation and relaxation phase.
  - Two-fluid effects.