Comparisons of Peeling and Ballooning Mode Growth in the Intermediate Nonlinear Regime for Shifted-Circle Tokamak Equilibria

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General Outline

• Analytical Ideal MHD description of dominant edge-localized nonlinear dynamics in a cylindrical geometry

• Comparison of nonlinear ideal peeling-dominated and ballooning-dominated mode evolution using the extended MHD code NIMROD

• Comparison of temperature dependent profiles using Spitzer resistivity with ideal evolution and parameters used in a JOREK study

• Summary
Progress toward understanding ELMs has been made using NL ballooning theory

- Edge localized filamentary structures in the bad curvature region suggests a strong connection between ideal ballooning modes and ELMs.

- Ballooning analysis employs a double-expansion in perturbation size and cross-field wave number.
  - The perturbation is small.
  - A large wave number perpendicular to the dominant magnetic field is assumed.

- Original work explained early nonlinear regime.
  - Predicted explosive growth rate at finite time.
  - Promising explanation for fast ELM behavior.
Recently, ballooning theory has been extended to describe the intermediate NL regime

- Ballooning filament growth satisfies the following,

\[
\rho B^2 \partial_t^2 \xi_{1/2}^\parallel - \mathcal{L}_{\parallel}(\xi_{1/2}^\Psi, \xi^\parallel) = 0
\]

\[
[\Psi + \xi_{1/2}^\Psi, \rho|e_\perp|^2 \partial_t^2 \xi_{1/2}^\xi - \mathcal{L}_{\perp}(\xi_{1/2}^\Psi, \xi_{1/2}^\parallel) = 0
\]

- Where \(\xi\) = the global perturbation vector, \(\mathcal{L}_{\parallel}\) & \(\mathcal{L}_{\perp}\) are the linear parallel and perpendicular ballooning operators & \([A, B] \equiv \partial_\psi A \partial_\alpha B - \partial_\alpha A \partial_\psi B\).

- **Linear eigenfunction a solution to governing intermediate-NL equations.**
  - Instability continues to grow at the linear growth rate in the int. NL regime.

- **P. Zhu is working to extend theory into late nonlinear regime.**
  - Ballooning analysis has been well developed.

- **To understand peeling-ballooning coupling and nonlinear peeling contributions a description of nonlinear peeling modes is needed.**
Nonlinear ideal MHD analytic description is obtained using Lagrangian formalism

- The ideal MHD equation (Lagrangian formalism)

\[
\frac{\rho_0}{\mathcal{I}} \nabla_0 \mathbf{R} \cdot \frac{\partial^2 \vec{\xi}}{\partial t^2} = -\nabla_0 \left[ \frac{p_0}{\mathcal{I} \gamma} + \frac{\left( \vec{B}_0 \cdot \nabla_0 \mathbf{R} \right)^2}{2 \mathcal{I}^2} \right] + \nabla_0 \mathbf{R} \cdot \left[ \frac{\vec{B}_0}{\mathcal{I}} \cdot \nabla_0 \left( \frac{\vec{B}_0}{\mathcal{I}} \cdot \nabla_0 \mathbf{R} \right) \right]
\]

- where,

\[
\mathbf{R}(\vec{r}_0, t) = \vec{r}_0 + \vec{\xi}(\vec{r}_0, t) \quad \nabla_0 = \frac{\partial}{\partial \vec{r}_0} \quad \mathcal{I}(\vec{r}_0, t) = |\nabla_0 \mathbf{R}|
\]

\[
\vec{B}_0 = B^\theta(r) \vec{e}_\theta + B^z(r) \vec{e}_z
\]

- and the plasma displacement \(\vec{\xi}\) is small compared to the equilibrium scale length and is expanded for a cylindrical geometry,

\[
\frac{|\vec{\xi}|}{L_{eq}} \ll 1
\]
ELM’s are radially localized

- ELM-relevant:
  - The system is expanded about a radially localized mode width.

\[
\hat{r} \cdot \nabla = \frac{\partial}{\partial r} \sim \frac{1}{\delta}
\]

\[
\hat{b} \cdot \nabla = \frac{\partial}{\partial l} \sim \delta
\]

\[
\hat{b} \times \hat{r} \cdot \nabla = \frac{\partial}{\partial \eta} \sim 1
\]

\[
\frac{\partial}{\partial l} = \frac{iF}{B_0} \sim \delta \quad F = m_h B^\theta + k_{\|} B^z
\]

\[
\frac{\partial}{\partial \eta} = \frac{iG}{B_0} \sim 1 \quad G = \frac{m_h}{r} B^z - k_{\|} B^\theta
\]

- This differs from the intermediate nonlinear ballooning ordering analytics

The perturbation is expanded using a cylindrical geometry

- Here $\vec{\xi}$ is expressed in cylindrical coordinates,

$$\vec{\xi}_h(r, \theta, z) = \sum_{h=-\infty}^{\infty} \sum_{\eta=\infty}^{\infty} \vec{\xi}_h(r) e^{im_h \theta + i\eta_h z}$$

- and can be expanded by order of perturbation size,

$$\vec{\xi}_h(r) = \sum_{j=1}^{\infty} \delta^j \left[ \delta \xi_{h(j+1)} \hat{r} + \eta_{h(j)} \hat{\eta} + \xi_{||h(j)} \hat{b} \right]$$

- The Jacobian $\mathcal{J}$ is also expanded, 

$$\mathcal{J} = 1 + \sum_{j=0}^{\infty} \delta^j \mathcal{J}(j)$$
NL parallel equation is described by combining force balance projections

- The nonlinear parallel evolution is determined with a combination of parallel and cross field force balance at $O(\delta^3)$.

$$\frac{iG_h}{B_0} \rho \partial_t^2 \xi_{||h(1)} = \mathcal{L}(\xi, \xi_{\|}) + \text{NL}(\xi, \xi_{\|})$$

$$\mathcal{L}(\xi, \xi_{\|}) \left\{ -\frac{\gamma P_0}{(\gamma P_0 + B_0^2)} F_h G_h \frac{iF_h}{B_0} \xi_{||h(1)} + 2 \frac{\gamma P_0}{(\gamma P_0 + B_0^2)} \frac{iG_h}{B_0} \frac{iF_h}{B_0} \xi_{h(2)} B^{\theta 2} r \right\}$$

$$\text{NL}(\xi, \xi_{\|}) \left\{ +2 \frac{\gamma P_0}{(\gamma P_0 + B_0^2)} B^{\theta 2} \frac{iF_k}{B_0} \frac{iG_k}{B_0} r^2 \xi_k \xi_\theta + 2 \frac{\gamma P_0}{(\gamma P_0 + B_0^2)} B^{\theta 2} \frac{iF_j}{B_0} \frac{iG_k}{B_0} r^2 \xi_k \xi_\theta \right\}$$
A closed set of NL equations for $\vec{\xi}$ are described by combining parallel vorticity and force balance.

- The $O(\delta^2)$ the vorticity equation can be expressed as,

$$-\rho \partial_t^2 \eta'_{h(1)} = \mathcal{L}(\xi) + NL(\xi, \xi|)$$

\[
\mathcal{L}(\xi) \begin{cases} 
-2 \frac{\dot{G}_h}{B_0} \mathcal{J}_h \hat{r} \cdot \mathcal{B}_0 \cdot \nabla \mathcal{B}_0 + \frac{B^z}{B_0 r} \left( \left( \mathcal{B}_0 \cdot \nabla \mathcal{J}_h \right) \partial_r (B^\theta r^2) \right) - \frac{B^\theta r}{B_0} \left( \left( \mathcal{B}_0 \cdot \nabla \mathcal{J}_h \right) \partial_r (B^z) \right) \\
+ \frac{B^z}{B_0 r} \left[ \tilde{R} : \mathcal{B}_0 \cdot \nabla \tilde{B}_{1h} \right]_{r,\theta} - \frac{B^\theta r}{B_0} \left[ \tilde{R} : \mathcal{B}_0 \cdot \nabla \tilde{B}_{1h} \right]_{r,z}
\end{cases}
\]

\[
NL(\xi, \xi|) \begin{cases} 
+ \frac{B^z}{B_0 r} \left[ \xi'_k : \mathcal{B}_0 \cdot \nabla (\mathcal{B}_0 + \mathcal{B}_{1t}) \right]_{r,\theta} - \frac{B^\theta r}{B_0} \left[ \xi'_k : \mathcal{B}_0 \cdot \nabla (\mathcal{B}_0 + \mathcal{B}_{1t}) \right]_{r,z}
\end{cases}
\]

\[
NL= 2 \frac{B^\theta r}{B_0} \left( i k_i \xi^\theta_k \xi^\theta_l \left[ \mu_0 P' - 2 \mathcal{B}_0 \cdot \nabla \mathcal{B}_0 \right] - \nu F_k B^z \xi^\theta_k \xi^\theta_l - \nu F_k B^z \xi^\theta_l \xi^\theta_k \right) \quad \& \quad r \xi^\theta = \left[ \eta_k \frac{B^z}{B_0} + \xi| \frac{B^\theta r}{B_0} \right]
\]

- Where $\eta_{h(1)}$ can be related to the radial perturbation using $\mathcal{J}(1) = 0$.  

Dominant nonlinear dynamics generates a cross field \((\hat{b} \times \hat{r})\) shear flow

- Simplify, for \(\gamma = 0\) the nonlinear shear rate equation reduces to,

\[
- \rho \partial_t^2 \eta'_{h(1)} = \partial_r \left( F_h^2 \eta_{h(1)} \right) - \frac{\nu G_h}{B_0} \left( B^{\theta 2} \right)' r \xi_{h(2)} - 2 \nu B^{\theta} B_0 k_h \xi_{h(2)} - 4 \nu B^{\theta} B_0' k_h \xi_{h(2)} - 2 \nu G'_{h} B^{\theta 2} r \xi_{h(2)} - 2 \frac{\nu G_{h}}{B_0} B^{\theta 2} \xi_{h(2)} + 4 \frac{\nu G_{h}}{B_0} \frac{B^{\theta 4} r^2}{B_0^2} \xi_{h(2)} - 2 \frac{\nu F_k}{B_0} \frac{B^3 B^{\theta 3} r^2}{B_0^2} \left( \eta_{k(1)} \eta'_{l(1)} + \eta_{l(1)} \eta'_{k(1)} \right)
\]

- Note the nonlinear contribution is 0 for \((m_h, k_h) = (0, 0)\)
Quasi-linear approximation used to assess nonlinear impact on marginal stability

- The linear eigenfunction for marginal stability can be written as,

\[ \xi_j = C_j \left( \frac{1}{r_s} + \frac{1}{r - r_s} \right) \quad & \quad \xi(0) = 0 \]

- Examine \( k=0, m \neq 0 \).
- Toroidally symmetric nonlinear effects.

- Nonlinear \( k=0 \) terms become,
  - vary inversely with \( m \).

\[ -\rho \partial_t^2 \eta'_{k(1)} \approx 8 \frac{iF_l}{B_0} B^3 B^{1/2} r^2 \left( \frac{C_l C_j}{G_l G_j (r - r_s)^2} \right) \rightarrow -16 \frac{B^z B^{1/4} r^4}{B_0} \left( \frac{b_{l,j}}{|m_j| (r - r_s)^5} \right) \]

\[ C_l C_j = (a_{l,j} + i b_{l,j}) \]

\( l \neq -j \), \( l = [1, \infty) \)
\( j = (-\infty, -1] [1, \infty) \)
Nonlinear contribution generates an n=0 edge localized shear flow

• Can compare predictions with intermediate NL ballooning mode equations.
  - Local linear ballooning mode structure is a general solution to the nonlinear equations.
  - Perturbations evolving from a linear ballooning instability
    - continue to grow exponentially.
    - maintain a filamentary spatial structure.

• For peeling dominated modes, a nonlinearly driven shear flow plays an important role in the intermediate nonlinear regime.
  - NIMROD simulations help to determine how flow effects the stability.
  - Unlike ballooning ordering the local linear solution is not a solution to the nonlinear equations.
    - Perturbations evolving from a linear unstable mode will not continue to grow exponentially.
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• Summary
Two model equilibria are evolved nonlinearly in NIMROD

- Equilibria generated with a modified TOQ code.
  - dens8: Ballooning-dominated spectrum (P. Snyder)
  - PBS07: Peeling-dominated spectrum (B. Burke)
  - dens8:
    - mx: 25-45
    - my: 45-115
    - polydegree: 5, 6
    - S=\infty
    - nd_diff, kperp=0
    - divbd\approx 1e5
  - PBS07:
    - mx: 45-60
    - my: 45-75
    - polydegree: 5, 6
    - S=\infty
    - nd_diff, kperp=0
    - divbd\approx 1e5
Ideal linear toroidal mode spectrum shows dominant drive of each equilibrium

- Ballooning: \( n_{\text{peak}} > 20 \)
- Kink: low-\( n \) growth dominates. \( n_{\text{peak}} = 7 \)
Examine range of low-n modes in peeling-dominated equilibrium

- Low-n dominated linear toroidal spectrum.
- Initialize with linear eigenmodes.
  - $n=5 \rightarrow NL: n = 0, 10, 15, 20$
  - $n=6 \rightarrow NL: n = 0, 12, 18$
  - $n=7 \rightarrow NL: n = 0, 14, 21$

- Multiple mode analysis.
  - $n=1-10$ modes

- How do nonlinear dynamics compare to that of ballooning dominant system?
- Does the $n=7$ dominate the nonlinear growth spectrum when multiple modes are present?
The perturbation is stabilized in the intermediate NL regime at low-$n$.

- Unlike high-$n$ ballooning where perturbation continues to grow linearly.
- $n=5$, $6$ & $7$: high-$n$ modes grow slower than initial linear mode.
  - For example:
    \[
    \gamma_{n=6} \gg \gamma_{n=12} \quad \gamma_{n=7} \gg \gamma_{n=14}
    \]
The \( n=6 \) eigenmode structure mainly in the pedestal region, grows self similarly in time.

- Re \( P \) vs. \( i \)
- Re \( Vn \) vs. \( i \)
- Re \( V\gamma \) vs. \( i \)
- Re \( V\tau \) vs. \( i \)

- \( \gamma_{\tau a} \)
- \( n = 6 \)
- \( |\xi_{max}| \)
- Etot

\( \xi_{max} \)
The n=0 cross field shear rate $> \gamma_{\text{Lin}}$ in the intermediate nonlinear regime

- In the intermediate nonlinear regime the cross field shear rate $\mathcal{O}(\gamma_{\text{Lin}})$.
  - Late into nonlinear regime shear rate is double the nonlinear growth rate.
  - $V_{\text{avg}}$ uses 3 largest shear values in pedestal region.
  - $V_{\text{max}}$ is largest shear rate measured in pedestal region.

![Graph showing shear rate vs. radius and time](image-url)
The n=0, m=1 mode is dominant which is consistent with analytical predictions

- Nonzero growth of shear rate predicted in the analytical cylinder for n=0 mode.
  - varies inversely with m.
  - consistent with analytical results

- The shear rate quickly becomes the order of the linear growth rate.
  - Nonlinear shearing grows steadily in time.
  - Mode is stabilized in the nonlinear regime as the shear rate $\sim \gamma_{\text{Lin}}$.

\[ \begin{align*}
Z(m) & \quad \text{Vn} \quad \text{Vphi} \quad \text{Vtan} \\
2.5 & \quad 3.0 \quad 3.5 \quad 4.0 \quad 4.5 \\
2.5 & \quad 3.0 \quad 3.5 \quad 4.0 \quad 4.5
\end{align*} \]
Multiple mode $n=(1-10)$ initialization show that the $n=7$ dynamics dominate.
Multiple mode $n=(1-10)$ initialization show that the $n=7$ dynamics dominate.
Examine ballooning unstable equilibrium at various mode numbers

- Initialize with a single linear eigenfunction.
  - \( n = 15 \rightarrow \text{NL: } n = 0, 30 \)
  - \( n = 10 \rightarrow \text{NL: } n = 0, 20, 30, 40 \)
  - \( n = 7 \rightarrow \text{NL: } n = 0, 14, 21 \)

- Examine nonlinear evolution of,
  - Total growth rate.
  - Initialized mode growth.
  - Mode coupling.
The dominant NL dynamics is governed by the most unstable linear mode

- **n=15**: mode continues to grow at linear rate nonlinearly.
- **n=10**: nonlinear growth of perturbation approximately linear.
- **n=7**: high toroidal mode coupling dominates nonlinear growth rate.
For ballooning dominant equilibrium shear rate $\ll \gamma_{Lin}$ through intmed NL regime

- Self-similar growth of shear rate occurs in nonlinear regime.
  - Localized to pedestal region.
- The $n=0$, $m=1$ is dominant mode structure.
- Shear rate $\ll \gamma_{Lin}$ throughout evolution and beyond the intermediate nonlinear regime.
  - Global perturbation is not stabilized.
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• Summary
Toroidal spectrum is sensitive to temperatures at the plasmas edge.

PBS07

$\gamma/\tau_A$

Toroidal mode number (n)

1603 (eV) .... 12 (eV)
1615 (eV) .... 25 (eV)
1640 (eV) .... 49 (eV)
1673 (eV) .... 83 (eV)
1704 (eV) .... 114 (eV)
DIII-D-like parameters used to evolve the peeling-dominated equilbrium into late NL regime

- **Plasma Parameters**
  - $T_{\text{core}} = 1.6\text{keV}$, $T_{\text{edge}} = 83\text{eV}$
  - Constant density: $n = 2.03 \times 10^{19}\text{(m}^{-3})$
  - Diffusivities
    - $k_{\parallel} = 1\text{(m}^2/\text{s})$
    - $k_{\perp} = 1\text{(m}^2/\text{s})$
    - $k_{\parallel} = 1 \times 10^6\text{ (m}^2/\text{s})$
  - Spitzer resistivity
    - $\eta_{\text{elecd}} = 1.931 \times 10^{-2}\text{(m}^2/\text{s})$
    - $\eta_{\text{plasma}} \sim 10^8\text{, }\eta_{\text{sedge}} \sim 10^6$

- **Computational Parameters**
  - $\text{nd} \_ \text{diff} = 0\text{ (m}^2/\text{s})$
  - $m_x = 65$, $m_y = 65$, polydegree = 5
  - Broad radial packing around mode for nonlinear resolution
  - $d_{\text{tm}} = 5 \times 10^{-8}\text{(s)}$
• Overall the system behavior is similar to the ideal evolution
  ♦ The mode growth slows in the intermediate NL regime

• 21 modes included nonlinearly
  ♦ $n=6$ beats to generate $n=0,12,18$

• Beyond the intermediate NL regime the higher-$n$ coupled modes begin to dominate the mode growth and the growth rate increases
Eigenmode structure remains mostly linear into the intermediate NL regime

- Contours of pressure perturbation
  - Spatial structure is similar to linear regime
In the late NL regime localized pressure filaments form

- Several pressure filaments form on the low field side
  - Radial extent is largest on outboard midplane (as measured from equilibrium pedestal edge)
    - \( \sim 12.5 \text{(cm)} \)
  - Vertical width
    - measured as fwhm of pressure and temperature contours
    - \( \sim 14 \text{(cm)} \)
  - Isolated filaments are separated by approximately 45-60(cm)
  - As pressure elongates multiple mushroom structures are created
    - radial width of each structure \( \sim 6-8 \text{(cm)} \)
The filamentary structures are localized poloidally and toroidally

- 6 toroidally-localized structures.
  - toroidal localization observed in experiment.
  - higher modes required for localized toroidal structure.

- In general filaments follow magnetic field line structure.
  - also similar to experimental observations.

- Radial extent of modes decreases to very small values on inboard side.
Multiple mushroom structures form with regions of increased pressure.

- Pressure and temp increase in time for outer most structure nearing pedestal values.
  - Radial filamentary hotspots are observed in which the pressure increases to the order of the pedestal value.
  - Filaments accelerate radially outward
    - Expansion duration $\sim 100\,\mu s$
    - $V_R$ ranges from $\sim 0.5$-11.2 (km/s)
      * can compare to experiment:
        * DIII-D: $V_R \sim 0.5$-1.0 (km/s),
        * MAST: $V_R \sim 1.0$-9.0 (km/s)
    - Acceleration ranges from $\sim (4.0 \times 10^7$-$1.5 \times 10^9$ m/s$^2$)
Compare evolution of experimental-like parameters with previous JOREK work

- Parameters approximate work from,
    - X-point geometry
    - $n=5 \times 10^{19} \text{m}^{-3}$ *decreases by factor of 10 at edge
    - temp:~20eV

- Nonlinear saturation is observed
- NIMROD parameters
  - shifted-circle equilibrium (no X-point)
  - $m_x:50$, $m_y:65$, polydegree:5
  - temp:~18eV
  - $n(\text{constant})=2.4 \times 10^{21} \text{m}^{-3}$
    - high value used to match temp param
  - Diffusivities
    - $k_v=13.8 \text{m}^2/\text{s}$
    - $k_{\perp}=26.7 \text{m}^2/\text{s}$
    - $k_{||}=1 \times 10^6 \text{m}^2/\text{s}$

Mode structure and contours show xpoint geometry of Huysmans06 work
Linear pressure contours differ

- Linear mode structure for the Huysmann case is broader and has more structure on the inboard side.

**Perturbed Pressure Contours**

- **Huysmans-like parameters**
- **DIII-D-like parameters**
Nonlinear evolution and structure differs significantly from experimental case

- Much broader mode evolution.
- Filaments are less localized both poloidally and toroidally
- Average radial velocity much slower (~1-2 km/s)
Pressure forms a single mushroom structure in late NL regime

- Large mushroom-like pressure fingers are physically close to one another.
- Filament experiences heating, but temperature is 1/3 of pedestal (~5eV)
- Two radial filamentary hotspots are observed (subtle secondary structure)
Nonlinearly mode growth saturates

- This is different from experimentally relevant case in which no saturation was observed.
- Mode structure doesn’t evolve when saturated.
  - Sharp localized filaments never occur.

![Graph showing kinetic energy over time](image)
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Summary

- Evidence of distinctly different nonlinear behavior in ballooning dominated vs. peeling dominated equilibria.
  - **Ballooning**: Linear growth persists into the intermediate nonlinear regime as predicted by (*P. Zhu, C. C. Hegna, and C. R. Sovinec, Phys. Rev. Letters 102, 235003 (2009)).
  - **Peeling**: growth stabilized in intermediate nonlinear regime.
  - Nonlinearly driven $n=0, m=1$ flow structure appears to grow steadily and maintains a self-similar flow pattern.
    - Numerical calculations support cylindrical analytics.
  - Perturbation is stabilized when nonlinear shearing rate is on the order of $\gamma_{\text{Lin}}$.
    - Ballooning modes: $n=0$ shear rate $\ll \gamma_{\text{Lin}}$.
    - Peeling modes: $n=0$ shear rate $O(\gamma_{\text{Lin}})$.
- Computationally nonlinear dynamics are governed by the most unstable linear mode.
Summary

• Nonideal simulations using experimentally relevant values of resistivity produce ideal-like evolution.
  ✦ Linear analysis shows that toroidal spectrum using Spitzer resistivity is very sensitive to the edge temperature.
  ✦ Experimentally relevant edge temperatures produce “ideal-like” spectra and dynamics.

• Nonideal comparisons with JOREK parameters from Huysmann ‘06 points to the importance of using experimentally relevant parameters.
  ✦ Different linear and nonlinear spatial structures are observed.
    - Cold, viscous plasma is broader and less filamentary.
  ✦ Nonlinearly the system dynamics are also different.
    - No mode saturation occurs when using experimental parameters.
    - Filament heating is stronger and filaments have a much larger radial velocity for experimental conditions.
  ✦ Motivates simulations with an X-point equilibrium using NIMROD