MHD Ballooning Instability with RMP

Ping Zhu

University of Wisconsin-Madison
Collaborators: C. R. Sovinec, C. C. Hegna, and J. O'Bryan

CEMM Meeting
Chicago, IL
November 7, 2010

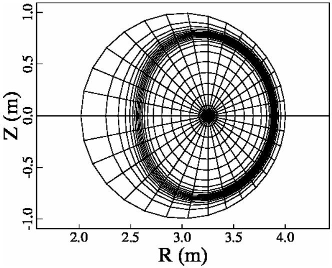
Motivation

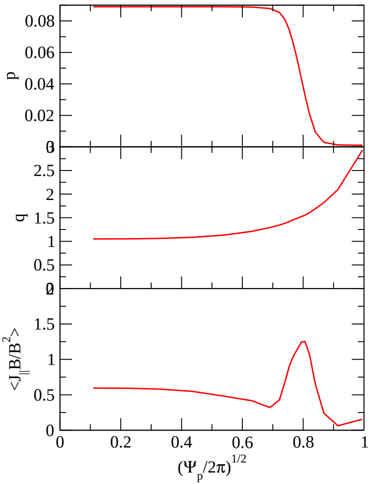
- Resonant magnetic perturbation (RMP) can suppress ELM activities in DIII-D experiments; plasma response to RMP remains current topics of research
  - Response at equilibrium or vacuum scale (superposition)
  - Response at MHD instability scale
  - Response at transport scale
- Previous and other work, e.g.
  - NIMROD RMP simulations [Kruger *et al.* 2007; Kruger and Held 2008; Izzo and Joseph 2008]
  - M3D RMP simulatons [Strauss *et al.* 2008; Sugiyama *et al.* 2008; Ferraro *et al.* 2010]
  - Local equilibrium and 3D ballooning theory [Hegna and Bird 2010]
- This study
  - Simulates nonlinear plasma response to RMP at peeling-ballooning scale in global 3D configuration
  - Starts with non-rotating plasma and static RMP

RMP is modeled as a boundary condition on the simulation domain surface

- $B_n(\theta, \zeta) = B_{na} * cos(m\theta - n\zeta)$ is prescribed at $r = a$ for a circular-shaped tokamak [Yu and Günter 2009].
- A quasi-single helicity RMP is considered $m/n = 2/1$ (or 4/2, 6/3, ...) first (where $\theta \simeq \Theta$).
- An RMP configuration is prepared in simulation by applying a static RMP to an tokamak equilibrium.
- Potential interaction between ballooning instability and RMP is studied by following high-n perturbations in pedestal region under RMP conditions.
- $\eta = 25$ ($S \sim 10^5$), $D = 25$, $\mu_{\rm kin} = 25$, $\chi_\perp = 1$, $\chi_\| = 10^8$.
- `20x32, poly=5`, 22 Fourier modes

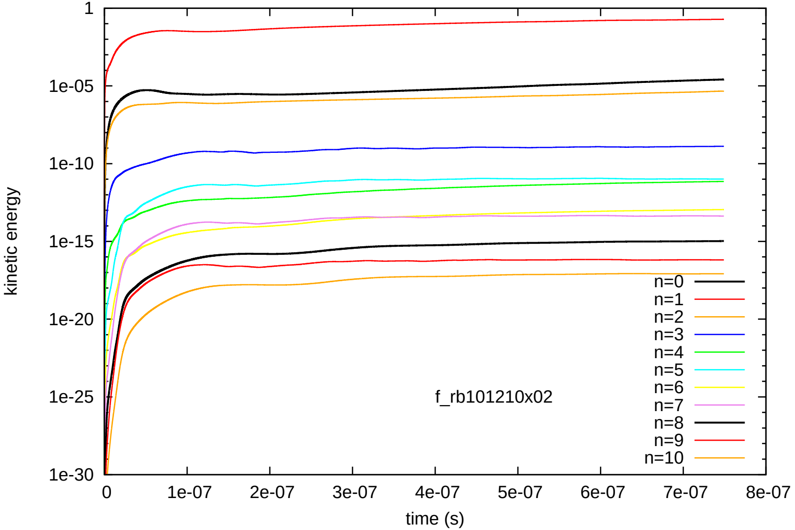
Simuluation uses a circular-shaped limiter equilibrium unstable to peeling-ballooning



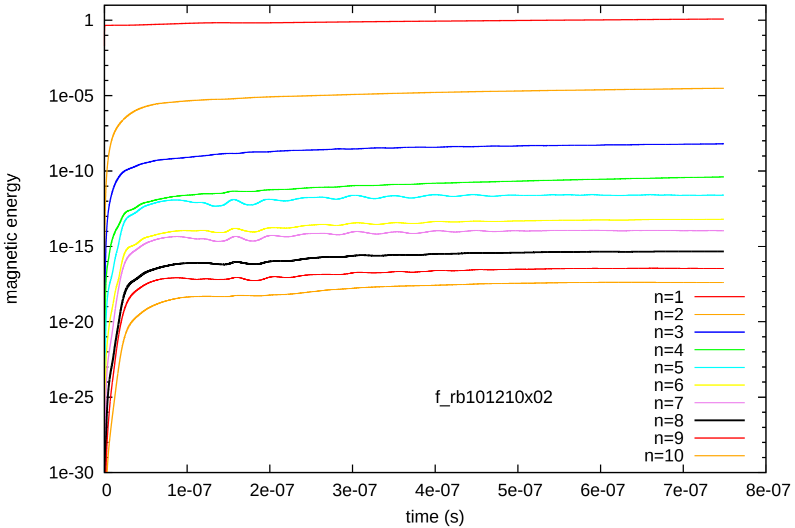


- Unstable to peeling-ballooning for $n \gtrsim 3$
- $q = 2$ surface is located near pedestal foot.

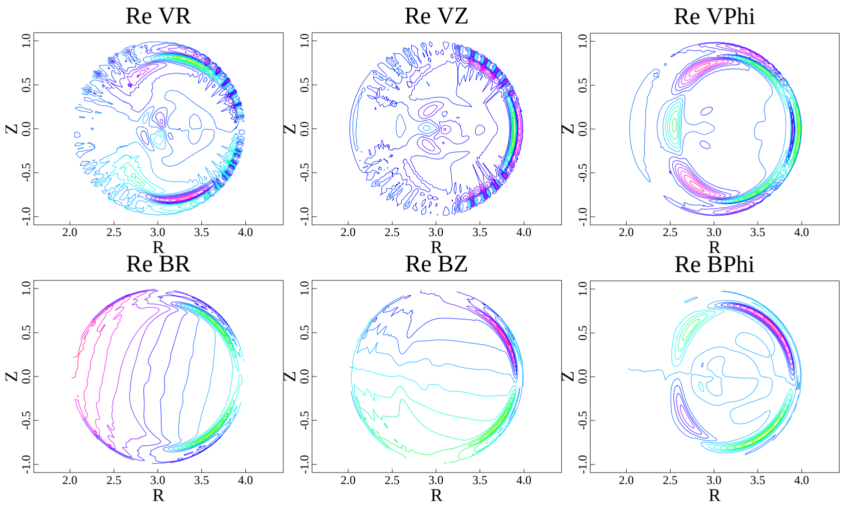
Initial response (first 1 μs): all Fourier components are driven to quasi-steady states



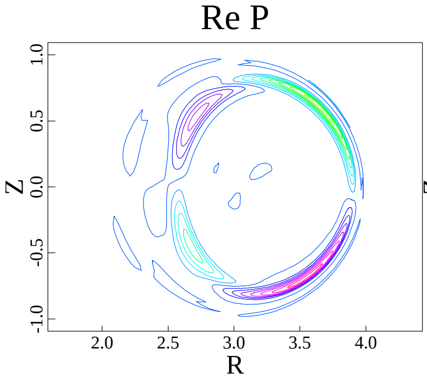
Magnetic perturation energy growth pattern similar to kinetic energy growth

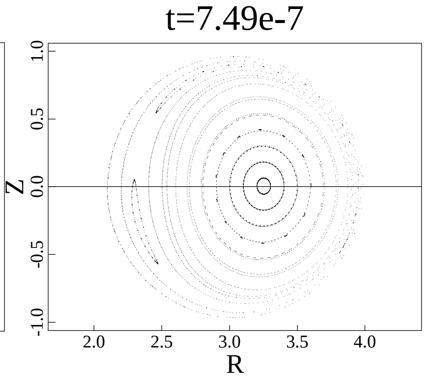


$t = 0.75\mu s$: Perturbation localized near boundary; $m = 2$ structure seen in $\tilde{u}_\zeta$ and $\tilde{B}_\zeta$

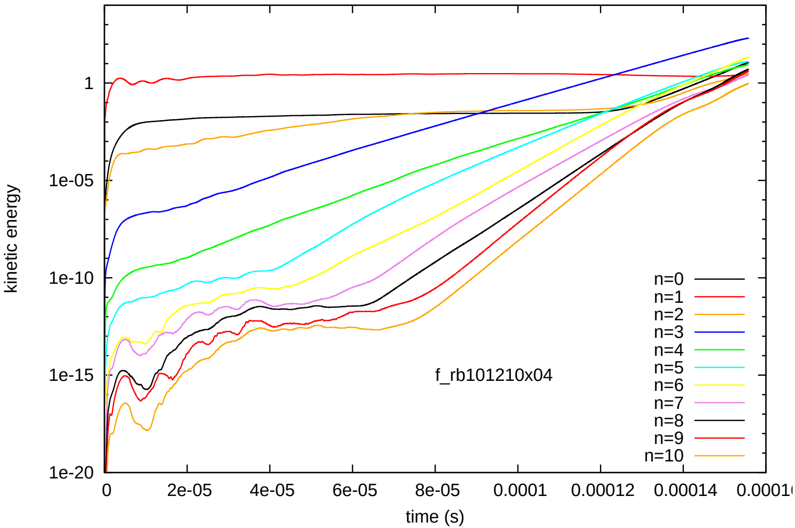


$t = 0.75\mu s$: Narrow islands form outside $m = 2$ mode structure; most flux surfaces remain intact





$t \lesssim 0.15ms$: $n = 1$ mode mostly steady; $n = 3$ mode dominates growth; all $n \gtrsim 2$ modes eventually grow



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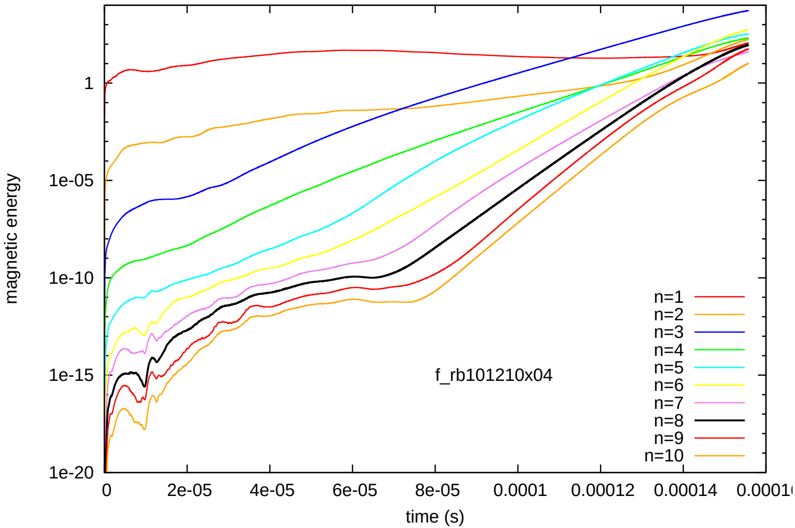
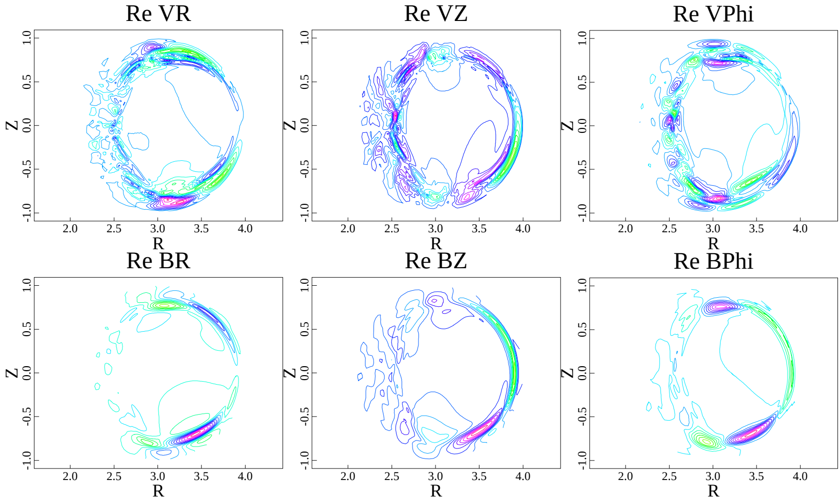
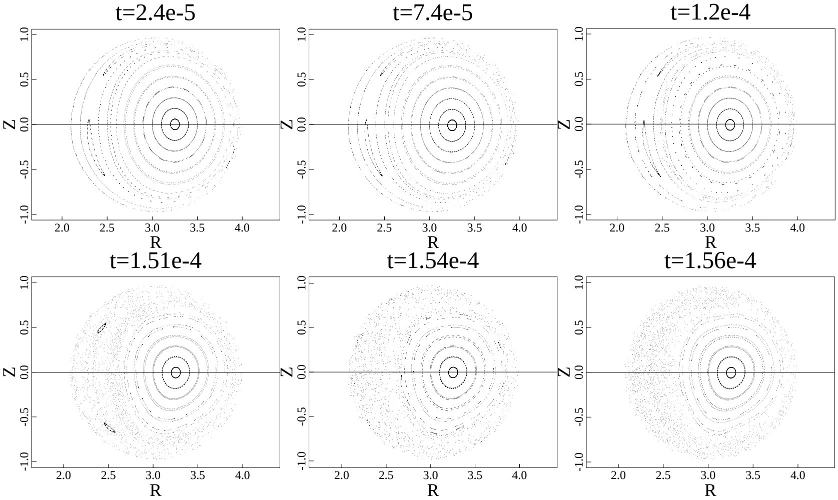


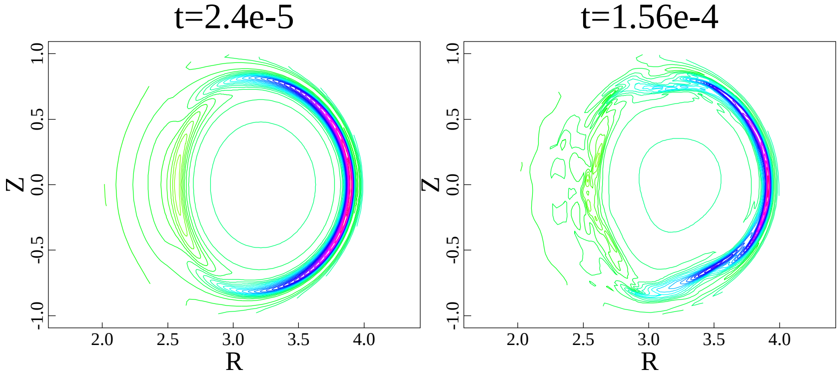
$t = 0.155ms$: Perturbation is dominated mostly by low m structures in pedestal region



Island structures remain unchanged for $t \lesssim 0.15ms$; then suddenly disappear into stochastic edge region; inner good flux surface distorts shape

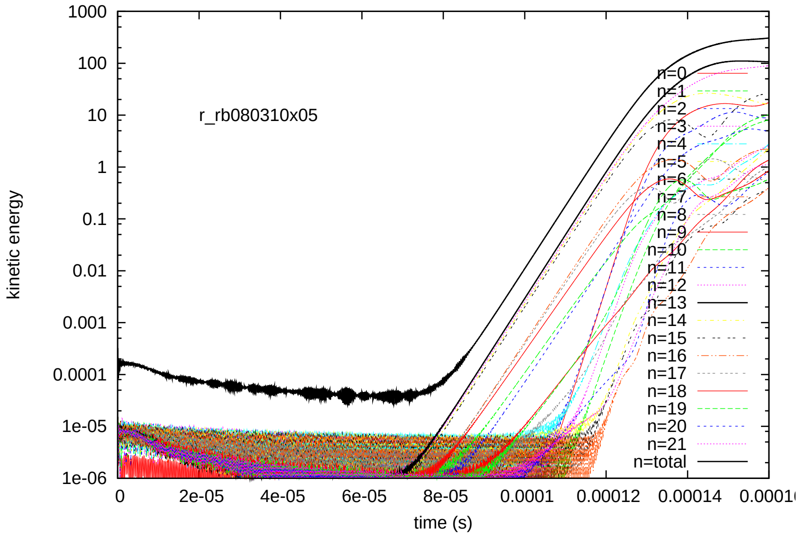


Parallel current structure in poloidal plane changes in response to RMP



- May result in change of pedestal (peeling-ballooning) stability

Multi-n non-eigenmode initial perturbation with Zero-RMP: $n = 10 - 20$ modes growth dominant, low-n nonlinearly driven by high-n modes



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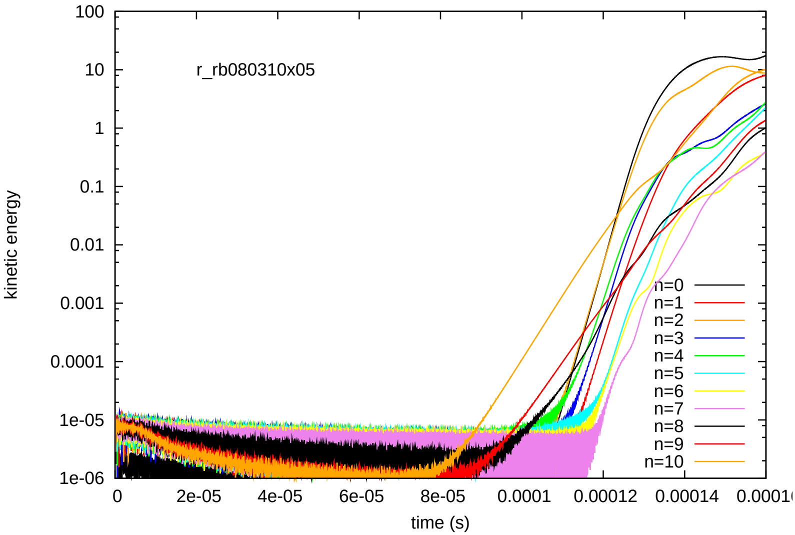
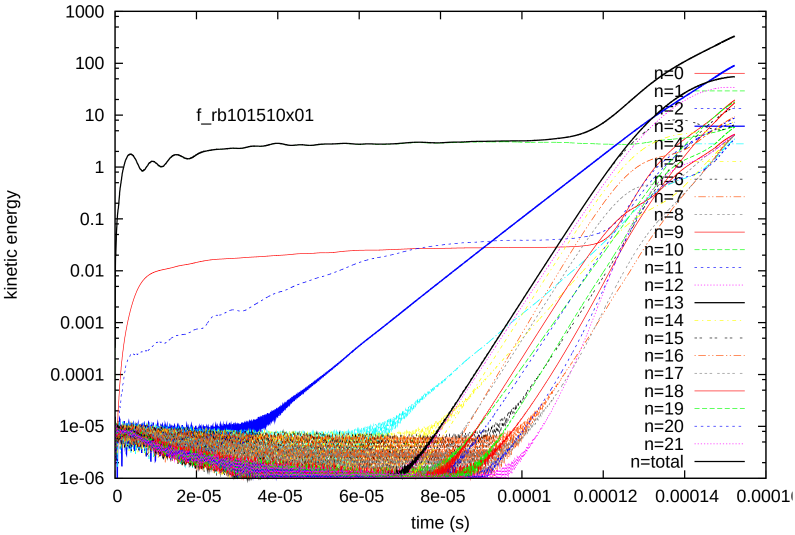


Multi-n non-eigenmode initial perturbation with RMP: $n = 3$ growth dominant; low-n $n \lesssim 10$ modes driven by RMP; high-n modes growth not affected



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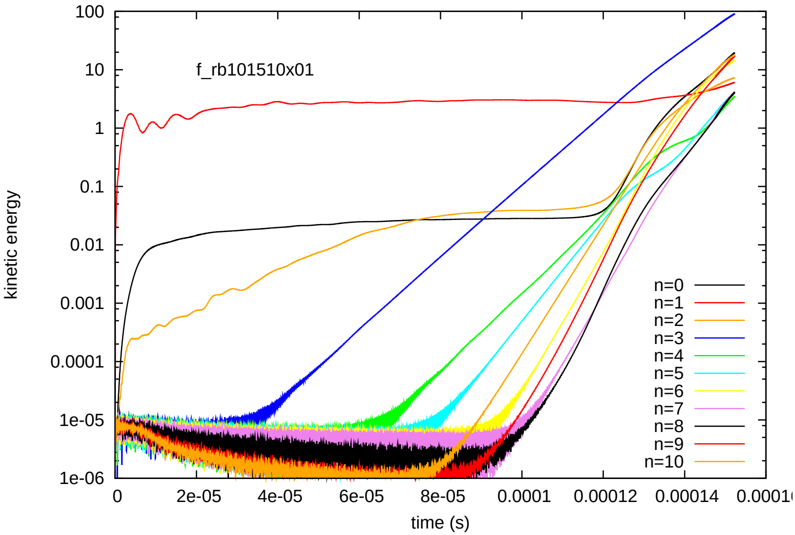
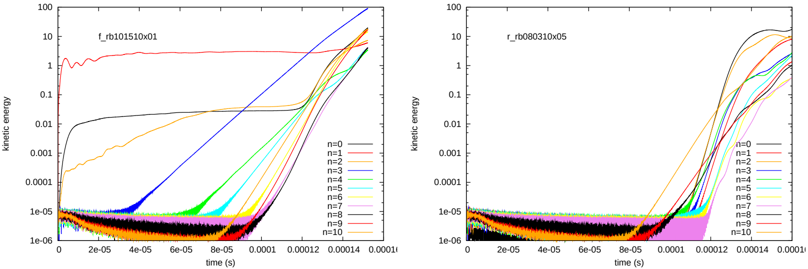
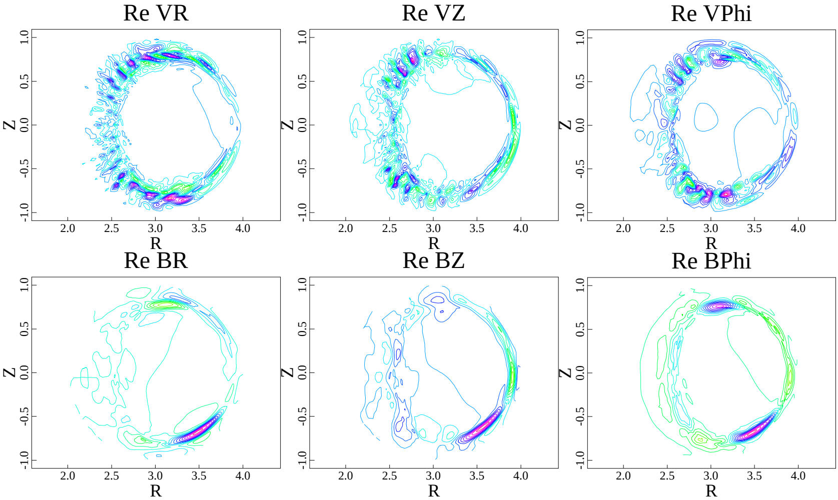


Multi-n non-eigenmode initial perturbation: RMP may directly and effectively influence low-n, peeling components of peeling-ballooning instability at 0.1*ms* scale

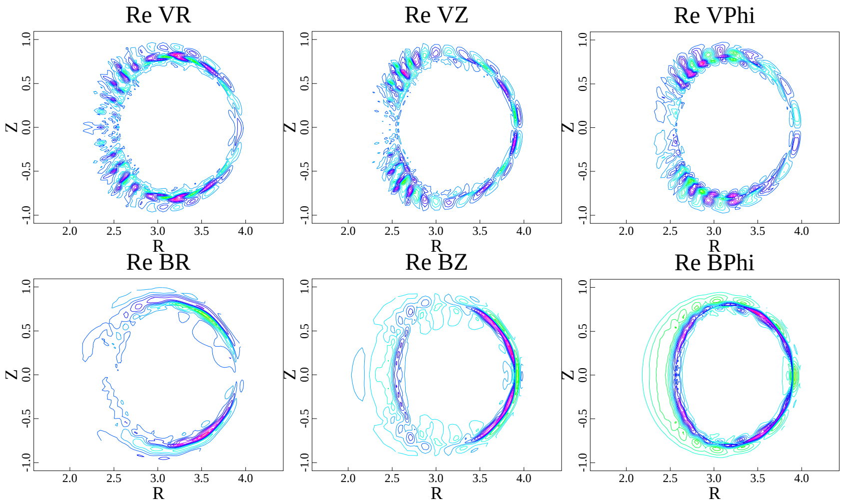


Left: with RMP; Right: no RMP

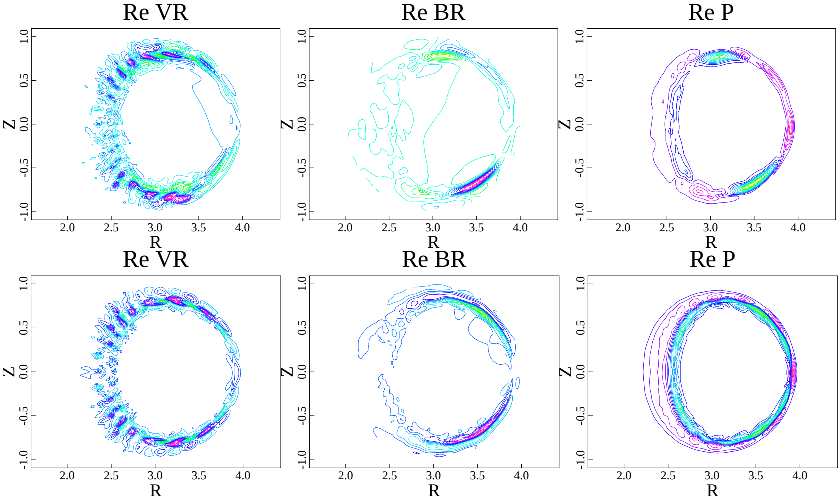
Multi-n non-eigenmode initial perturbation with RMP ($t = 0.15ms$): $\tilde{u}$ ($\tilde{B}$) structures are dominated by high-n (low-n) components



Multi-n non-eigenmode initial perturbation with zero-RMP ($t = 0.15ms$): $\tilde{u}$ ($\tilde{B}$) structures are dominated by high-n (low-n) components

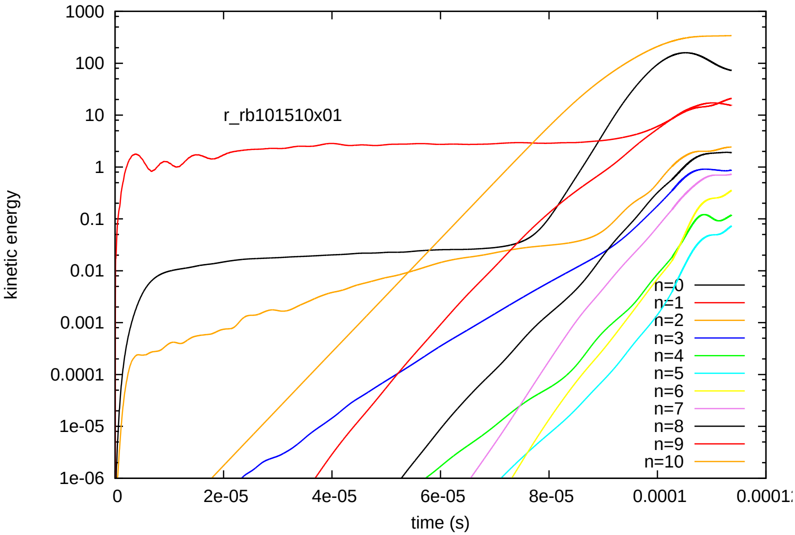


Multi-n non-eigenmode initial perturbation: RMP mostly affects low-n components of P-B instability

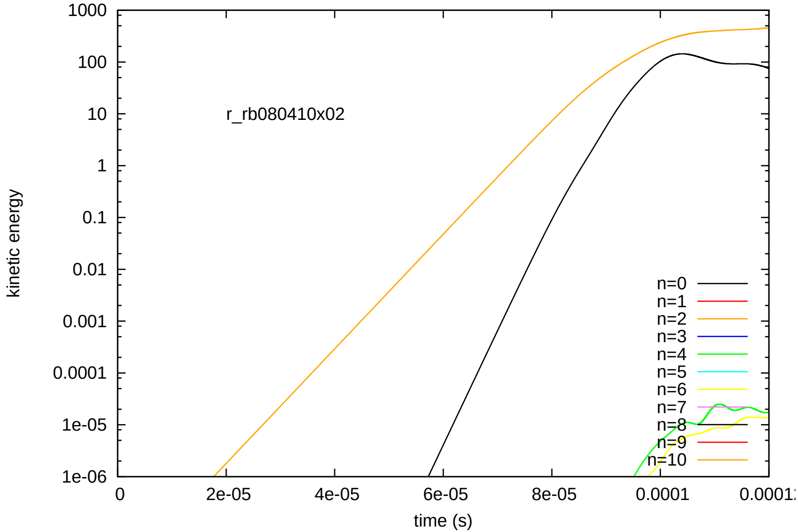


Upper: with RMP field; Lower: no RMP field

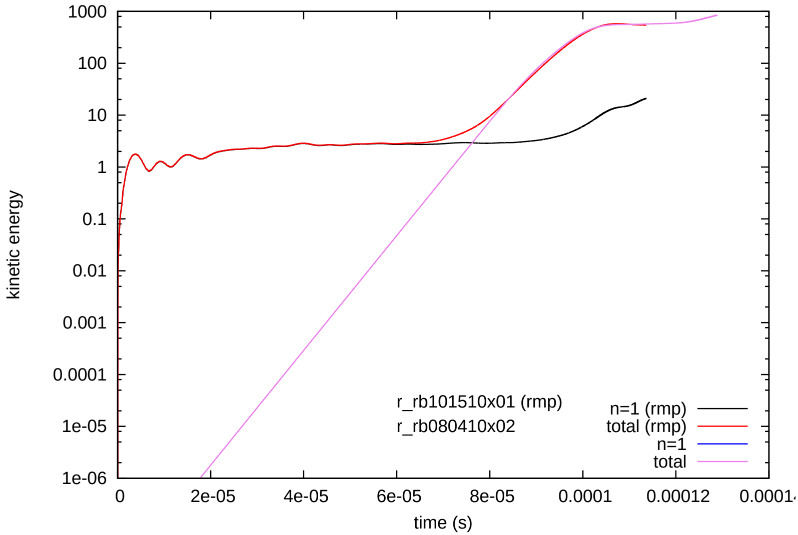
$n = 10$ ballooning mode initial perturbation with RMP: $n = 10$ component dominant; RMP mostly drives lower n-components



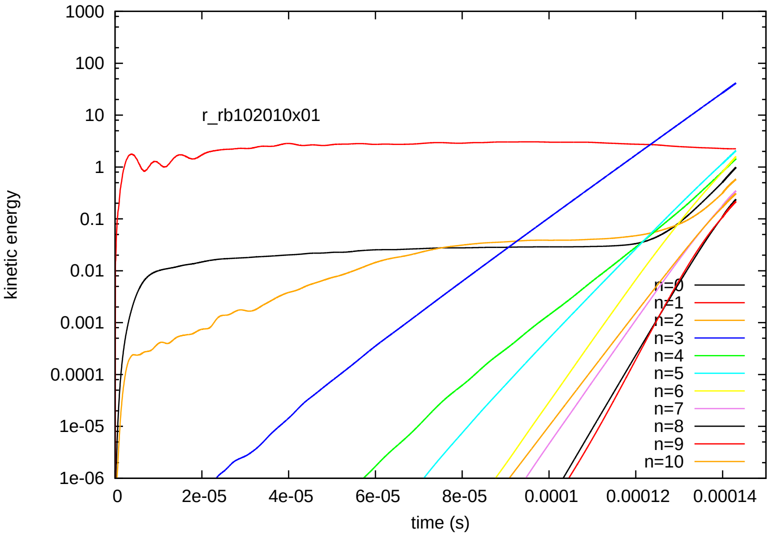
$n = 10$ ballooning mode initial perturbation with zero-RMP: Few lower n-components are excited



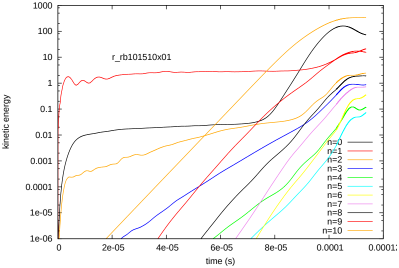
$n = 10$ ballooning mode initial perturbation: RMP has almost no effect on $n = 10$ and total perturbation in nonlinear and saturation phase



For weaker $n = 10$ ballooning mode initial perturbation, the RMP-driven $n = 3$ component dominates nonlinear phase



$n = 10$ ballooning mode development can influence RMP-driven $n = 3$ and low-n components growth



Left: larger $n = 10$ i.c.; Right: weaker $n = 10$ i.c.

Summary and Discussion

- A model static quasi-2/1 RMP configuration in time scale of $0.1ms$ is generated in NIMROD simulations.
- RMP may directly affect the low-n, peeling component of edge localized instability.
  - RMP can modify edge localized parallel current profile at MHD scale.
  - RMP-driven low-n modes can be affected by high-n ballooning development.
- In nonlinear stage, time step drops below 10^{-9}, T_i iteration near 200, difficult to further advance.
- Future work
  - Off-diagonal coupling preconditioner for T_i equation
  - Rotational screening effects
  - Experiment relevant collisional regimes
  - Dynamics RMP ramping and interaction