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# Nonlinear dynamics and stability surveys of energetic particle instabilities

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## ABSTRACT

- **Energetic particle (EP) populations are inherent to fusion plasmas. Understanding EP driven instabilities is crucial since they can lead to degraded heating efficiency and damage to plasma-facing components. Global nonlinear MHD-kinetic simulations using the FAR3d model are used here to address 3 important aspects of energetic particle (EP) transport:**
  - Dynamical critical gradient fast ion profiles in the presence of zonal flows/currents + energy exchanges between multiple toroidal modes
  - Time interval required for evolution from unstable fast ion profile to relaxed sub-marginal profiles – profile stiffness effect
  - Instability-driven intermittency effects - zonal flow generation/relaxation (predator-prey) + dynamic energy transfers within coupled multiple toroidal mode system

## BACKGROUND

- One of several Landau closure models in use for energetic particle physics
  - FAR3d, TGLF-EP, TAEFL
- Computationally ready for large extended nonlinear problems
  - Uses hybrid parallelism (MPI, OpenMP)
  - 3rd order accurate time stepper for numerical stability
  - Only evolves continuum fields – no particle noise
- Treats multi-physics effects consistently
  - Profile relaxation; Zonal flows/currents
  - Nonlinear energy transfers between coupled modes
  - Collective transport effects related to temporal/spatial phase alignment between fast ion density perturbations and potential/magnetic field fluctuations:

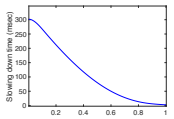
$$\Gamma_\rho = \tilde{v}_\rho \tilde{n}_{fastion} = \left( \tilde{v}_{\rho,ExB} + v_\parallel \frac{\delta B_\rho}{B_0} \right) \tilde{n}_{fastion}$$

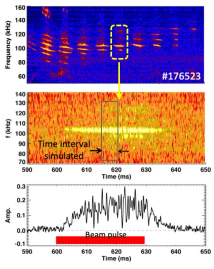
## METHODS / IMPLEMENTATION

**Pulsed beam DIII-D experiments provide good test case for EP instability enhanced transport studies**

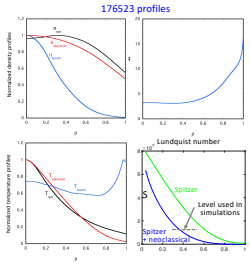
Expt. beam decay time is 8 to 10 msec << $\tau_{SD}$
- from fluctuation and INPA decay rates

Beam decay time ~ 7000$\tau_{Alfvén}$ >> $\tau_{Alfvén}$

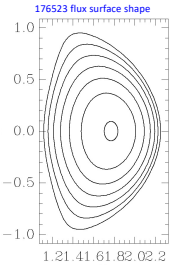



176523 profiles




176523 flux surface shape




$T_{beam}(0)$ = 35 keV to match avg. energy of slowing-down distribution

*Reduced MHD/gyro-Landau closure equations used in FAR3d model with nonlinear and diffusive terms color-coded*

The nonlinear FAR3d six-field model includes convective and magnetic nonlinearities (these are indicated in magenta, diffusive terms in blue). These induce zonal flows, zonal currents, and $n_{fast}$ profile flattening.

$$\frac{\partial \Psi}{\partial t} = \frac{R}{B_0}\left(\mathbf{B}_{\nu\zeta}\cdot\nabla\phi + \tilde{\mathbf{B}}\cdot\nabla\tilde{\phi}\right) + \eta J_\zeta + \text{Thermal Ion FLR terms}$$

Generates zonal (n = 0) currents

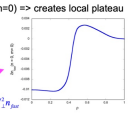
Generates zonal (n = 0) flows

$$\frac{1}{\sqrt{g}}\frac{\partial U_\zeta}{\partial t} = \frac{\partial}{\partial t}\left[\nabla\times\left(\rho_{\nu\zeta}\sqrt{g}\,\mathbf{v}\cdot\nabla\mathbf{v}\right)\right]^\zeta = -\left[\nabla\times\left(\rho_{\nu\zeta}\sqrt{g}\,\mathbf{v}\cdot\nabla\mathbf{v}\right)\right]^\zeta + \left[\nabla\times\sqrt{g}\left(\tilde{\mathbf{J}}\times\mathbf{B}_{\nu\zeta} + \mathbf{J}_{\nu\zeta}\times\tilde{\mathbf{B}} + \tilde{\mathbf{J}}\times\tilde{\mathbf{B}}\right)\right]^\zeta$$

$$-\left[\nabla\sqrt{g}\times\nabla\left(P_{i\nu\zeta} + T_{i\nu\zeta}\tilde{n}_{fast}\right)\right]^\zeta + D_U\nabla_\perp^2 U_\zeta + \text{Ion/electron Landau damping terms}$$

$\delta n_{fast}(m=0,n=0)$ => creates local plateau

$$\frac{\partial \tilde{p}_{ih}}{\partial t} = -\mathbf{v}\cdot\nabla\tilde{p}_{ih} - \mathbf{v}\cdot\nabla p_{ih\nu\zeta} + T p_{ih\nu\zeta}\nabla\cdot\mathbf{v} + D_{ih}\nabla_\perp^2\tilde{p}_{ih}$$



$$\rho_{i\nu\zeta}\frac{\partial \mathbf{v}_{i,ih}}{\partial t} = -\rho_{i\nu\zeta}\mathbf{v}\cdot\nabla\mathbf{v}_{i,ih} - \hat{\mathbf{b}}_{\nu\zeta}\times\nabla\tilde{p}_{ih} - \frac{\tilde{\mathbf{B}}}{B_{0\nu\zeta}}\cdot\nabla p_{ih\nu\zeta} + D_{i\nu\zeta}\nabla_\perp^2\mathbf{v}_{i,ih}$$

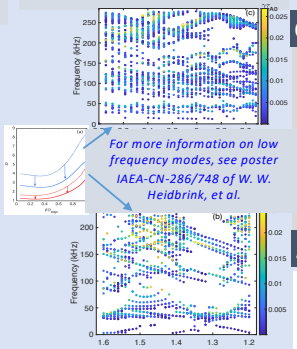
Generates local flattening (n = 0) in fast ion density, by cancelling part of drive term

$$\frac{\partial n_{fast}}{\partial t} = -\mathbf{v}\cdot\nabla n_{fast} - \mathbf{v}_d\cdot\nabla n_{fast} - n_{f0}\nabla_\parallel\mathbf{v}_{i,fast} - n_{f0}\left(\mathbf{v}_d\cdot\nabla - \Omega_*\right)\left(\frac{e\phi}{T_{fast}}\right) + D_{fast}\nabla_\perp^2 n_{fast}$$

$$\frac{\partial \mathbf{v}_{i,fast}}{\partial t} = -\mathbf{v}\cdot\nabla\mathbf{v}_{i,fast} - \mathbf{v}_d\cdot\nabla\mathbf{v}_{i,fast} - \left(\frac{\pi}{2}\right)^{1/2}\bar{v}_{fast}\left|\nabla_\parallel\mathbf{v}_{i,fast} - T_{fast}\nabla_\parallel n_{fast} - en_{f0}\Omega_*\left(\frac{\Psi}{R}\right) + D_{i,fast}\nabla_\perp^2\mathbf{v}_{i,fast}\right.$$

where $\mathbf{v} = \frac{\hat{\mathbf{b}}_{\nu\zeta}\times\nabla\phi}{B}$ $\quad \nabla_\parallel = \left(\hat{\mathbf{b}}_{\nu\zeta}\cdot\nabla\right)$ $\quad \hat{\mathbf{b}}_{\nu\zeta} = \frac{\mathbf{B}_{\nu\zeta}}{B}$ $\quad \bar{v}_{fast} = \sqrt{\frac{T_{fast}}{M_{fast}}}$ $\quad \Omega_* = \frac{T_{fast}}{eBn_{f0}}\nabla n_{f0}\cdot\hat{\mathbf{b}}_{\nu\zeta}\times\nabla$

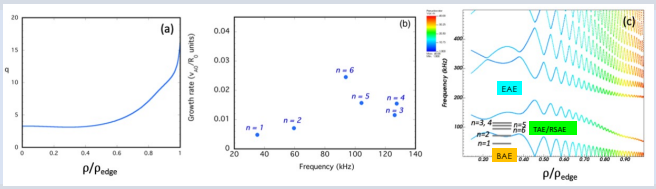
*Use of FAR3d eigensolver option to survey all unstable modes as q-profile changes*



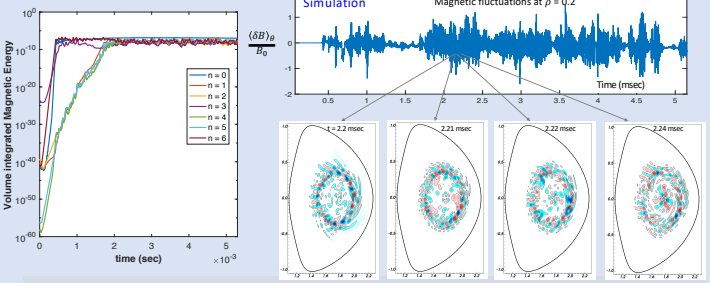

*For more information on low frequency modes, see poster IAEA-CN-286/748 of W. W. Heidbrink, et al.*

## RESULTS

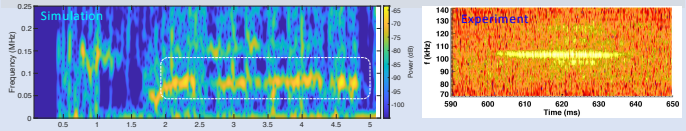
*Linear growth rates and continuum plot showing frequency locations; 277 m,n pairs retained with n = 0, 1, 2, 3, 4, 5, 6*



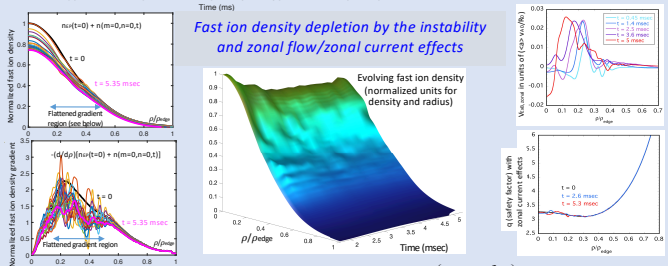

*Nonlinear growth/saturation of magnetic energy; nonlinear saturated poloidal magnetic field fluctuations with mode structures – predator prey cycle: coherent structure => shearing => radial collapse => reform coherent structure,…*



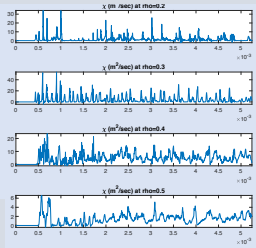

*Spectrogram of magnetic field fluctuations shows similar dominant frequency (~100 kHz) as expt.*



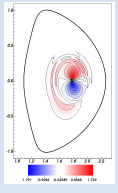

*Fast ion density depletion by the instability and zonal flow/zonal current effects*




*Collectively-driven fast ion radial transport coefficients and 2D flows*

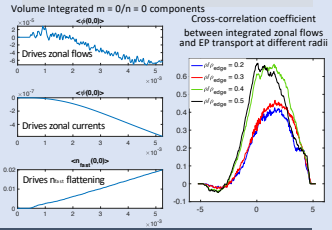



Taking into account m > 0 terms, the 2D variation of $\Gamma_\rho$ can be constructed



$$\Gamma_\rho = \tilde{v}_\rho \tilde{n}_{fastion} = \left( \tilde{v}_{\rho,ExB} + v_\parallel \frac{\delta B_\rho}{B_0} \right) \tilde{n}_{fastion} \qquad \chi = \Gamma_\rho / (-dn_{fast}/dr)$$

*Zonal flow fluctuations correlate most directly with EP transport intermittency*




## CONCLUSION

- The feasibility of long-time scale nonlinear simulations using the FAR3d model has been demonstrated => predicts similar frequency spectra and can address experimentally relevant time-scales
- Beam pulse experiments provide a good test-bed for EP transport analysis
- This model predicts strong intermittency from nonlinear energy transfers and zonal flow predator-prey phenomena

## ACKNOWLEDGEMENTS

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