Validation of critical gradient model for fast ion relaxation in NSTX

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October 27-31, 2014

Abstract

Confinement of energetic particles (EP) is essential to achieve burning plasma conditions in future fusion devices. EP interact resonantly with Toroidal Alfvén Eigenmodes (TAEs), resulting in enhanced radial transport and particle loss. A reduced 1.5D quasilinear "critical gradient model" (CGM) has been developed by Ghantous to account for this interaction, and was previously validated against DIII-D demonstrating surprising agreement in some cases. CGM combines linear stability theory with the kinetic NOVA-K code to calculate the fast ion pressure gradient corresponding to marginal TAE stability. Integration of this gradient determines the relaxed fast ion profile and losses. This work focuses on applying CGM to an NSTX plasma, using neutral beam injection for its validation. Comparison between the measured neutron flux and the TRANSP prediction determines the neutron deficit attributed to TAE-EP interaction. Satisfactory agreement is found between CGM and the investigated NSTX shot, motivating future development of a more robust 2D quasilinear model for EP pressure relaxation.

Work supported by U.S. DOE Contracts DE-AC02-09CH11466 and DE-AC02-09CH11466

Motivation

- Important to confine energetic particles (EP) to achieve burning plasma conditions
- Spatial gradient of super-Alfvènic particles destabilize Toroidal Alfvèn Eigenmodes (TAE)
- TAE-EP interactions may lead to undesirable EP redistribution or loss
- Reduced 1.5D quasilinear "critical gradient model" (CGM) should approximately describe this interaction for large number of small amplitude TAE modes[1]
- If successfully validated, CGM may be used for predictive modeling of EP profiles

[1] K. Ghantous et al., Phys. Plasmas **19**, 092511 (2012)

Critical Gradient Model, Ghantous (CGM)

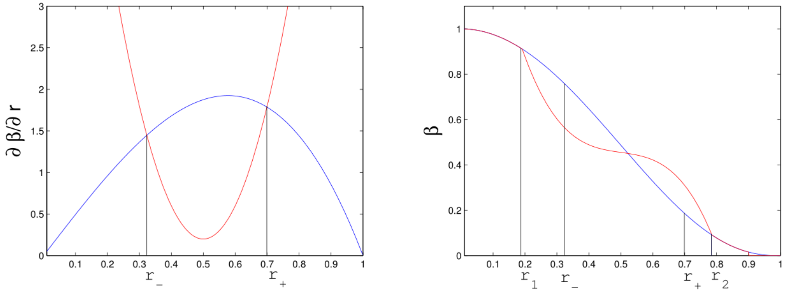
- Radial transport (1D) + simple velocity resonance (0.5D)
- TAE drive $\gamma_L = \Gamma_L \frac{\partial \beta_{EP}}{\partial r}$
  - Γ_L depends on background plasma only, not EP profile
- Sources of damping (γ_D): continuum, radiative, ion Landau, electron Landau, electron collisional
  - radiative, electron Landau negligible on NSTX shot of interest
- If $\gamma_L > \gamma_D$, EP pressure profile flattens through stochastic diffusion until marginal stability ($\gamma_L \approxeq \gamma_D$) is achieved

Critical EP Pressure Gradient

$$\left.\frac{\partial \beta_{EP}}{\partial r}\right|_{\text{crt}} = \frac{\gamma_d}{\Gamma_L}$$

EP Pressure Relaxation

- Integrating critical gradient yields relaxed EP pressure profile
- Region of instability expanded iteratively to impose continuity of β_{EP} and conserve particles
- Below: relaxation of example β_{EP} profile due to quadratic critical gradient
  - Left: initial $\partial\beta_{EP}/\partial r$ (blue) and critical gradient (red)
  - Right: initial β_{EP} (blue) relaxes to final state (red)



EP and Neutron Loss

- EP loss when region of instability extends beyond plasma boundary

$$L_{EP} = 1 - \frac{\int_0^a \beta_{\mathsf{rlx}} dr}{\int_0^a \beta_{\mathsf{ini}} dr}$$

- Neutron deficit may result from EP redistribution or loss

$$L_n = 1 - \frac{\int_0^a \langle \sigma \nu \rangle \beta_{\mathsf{ion}} \beta_{\mathsf{rlx}} dr}{\int_0^a \langle \sigma \nu \rangle \beta_{\mathsf{ion}} \beta_{\mathsf{ini}} dr}$$

CGM Assumptions

- Best for large number of small amplitude TAE modes
  - expected to be unsuitable for few large, bursty modes
- Local, linear theory for analytic growth/damping rates, normalized by NOVA-K code
- Instant radial transport – no transition time.
- $\omega_{*EP} \gg \omega_{TAE}$
  - radial diffusion dominates diffusion in velocity
- η fraction of particles in resonance[2]
  - Simple resonance assumption $v_{\parallel} \sim V_A$

[2] Y. Kolesnichenko, Nucl. Fusion **20**, 727 (1980)

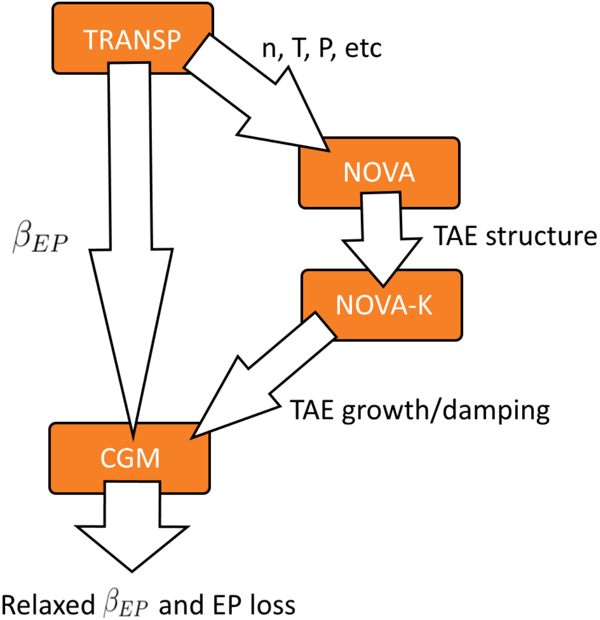
CGM Input Procedure

1. TRANSP with NUBEAM generates $n, T, P, f_{EP}, \beta_{EP}$ profiles
2. NOVA ideal MHD code solves for the equilibrium, TAE mode structures for $n = 2 - 6$
3. NOVA-K kinetic code calculates growth and damping rates.
4. Choose most unstable mode at 5 spatial locations
   - $\sqrt{\Psi_{\text{pol}}} \approx 0.1, 0.3, 0.5, 0.7, 0.9$

Normalized Critical Gradient

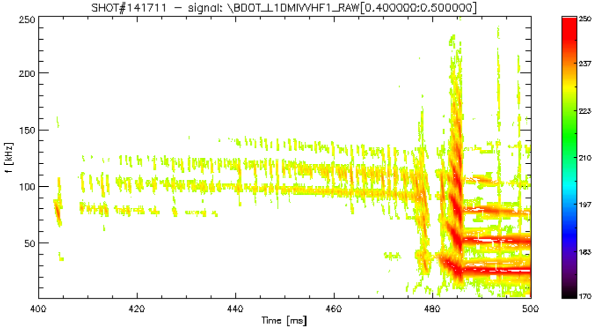
- Interpolate between NOVA-K points
- Extrapolate with analytic expressions

CGM Input Procedure



NSTX shot 141711 TAE Activity

- Investigated 10 times from $400 - 500$ ms
- Relatively small activity until ≈ 480 ms
  - $400 - 475$ ms: good match with CGM assumptions
  - $475 - 500$ ms: less suitable, will test model



Effective Diffusion Rates

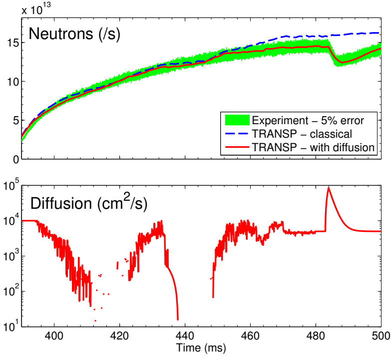
- Comparing TRANSP prediction to measured neutron flux determines neutron deficit due to TAE-EP interaction
- Experimental neutron flux can be matched in TRANSP by including fine-tuned artificial radial diffusion

$t < 475$ ms

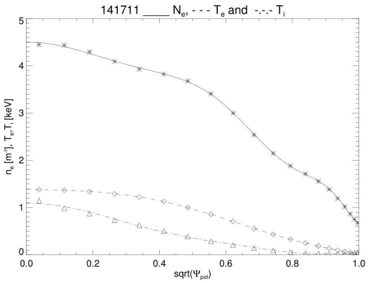
- $\lesssim 10\%$ neutron deficit
- Typical diffusion ≈ 1 m^2/s

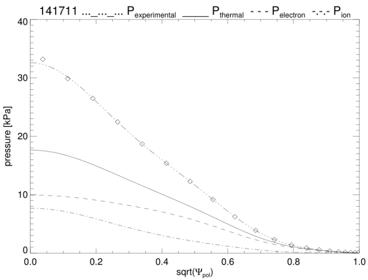
$t > 475$ ms

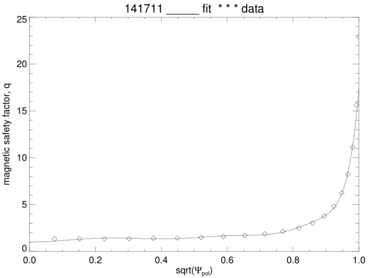
- $10 - 20\%$ neutron deficit
- Transient peak diffusion ≈ 8 m^2/s

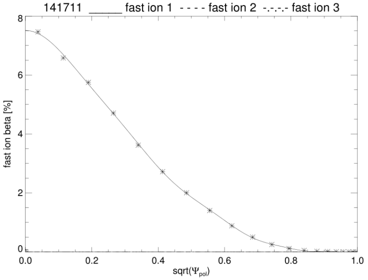


TRANSP profiles, $t = 470$ ms

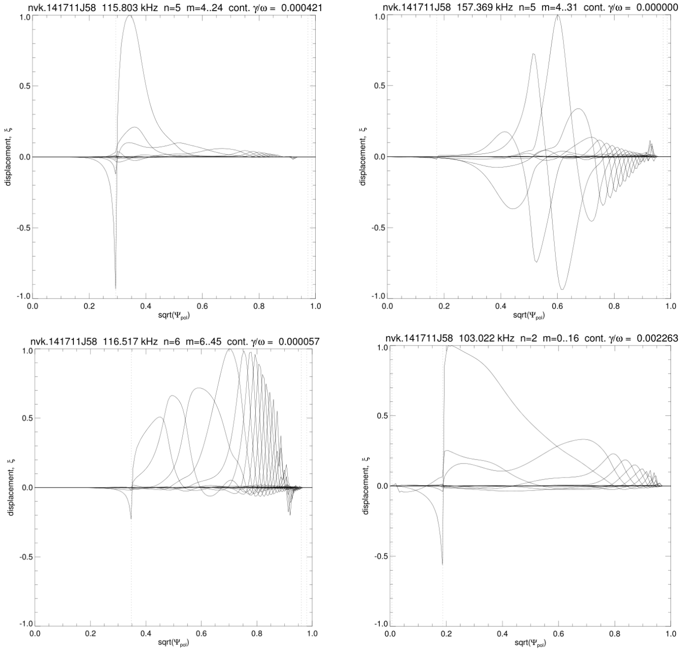






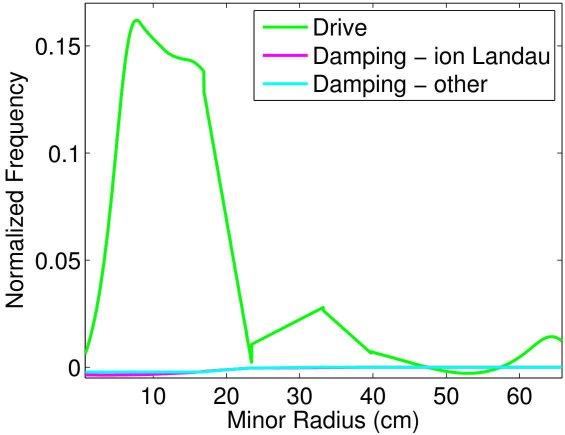


NOVA-K most unstable modes $t = 470$ ms



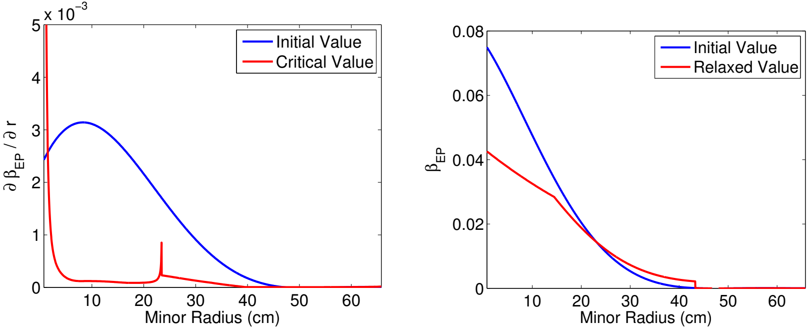
NOVA-K/CGM Calculated Rates, $t = 470$ ms

- Interpolation between NOVA-K points at $\sqrt{\Psi_{\text{pol}}} = .25, .35, .50, .60, .75$
- Analytic expressions used for $r < 18$ cm and $r > 40$ cm.

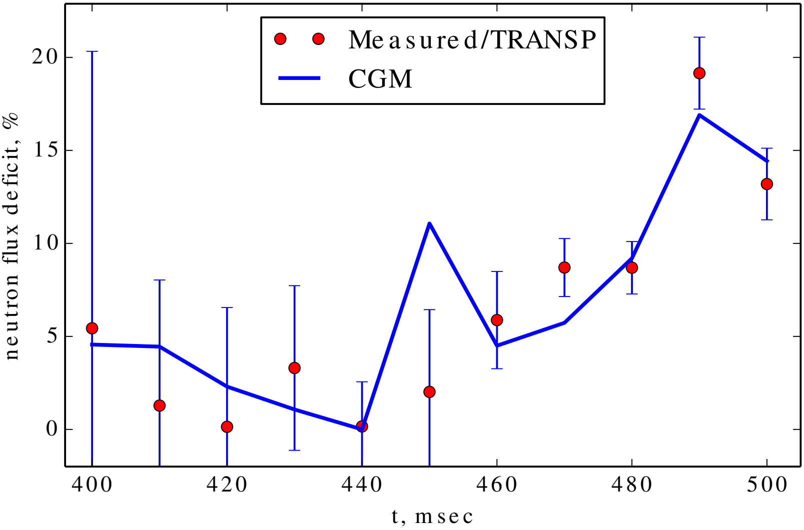


CGM β_{EP} relaxation, $t = 470$ ms

- Initial gradient relaxes to critical gradient wherever $\frac{\partial \beta_{EP}}{\partial r} > \left.\frac{\partial \beta_{EP}}{\partial r}\right|_{\text{crt}}$
- 6.5% EP loss, 5.7% neutron loss



CGM Neutron Deficit Prediction – reasonable match!



Summary and Future Plans

- 1.5D Quasilinear Critical Gradient Model provides fast evaluation of EP pressure relaxation and loss
- Successfully validated for predictive modeling in non-virulent TAE regimes
- Surprisingly satisfactory agreement found with NSTX for such a simple model. Why???
- Requires further validation against more bursty TAE activity to test its limits
  - Gorelenkov, et al, DPP56 Poster BP8.00041, Monday 9:30 AM
- Motivates development of more robust 2D quasilinear model

References

1. K. Ghantous, N.N. Gorelenkov, H.L. Berk, W.W. Heidbrink, and A. Van Zeeland, *Physics of Plasmas* **19**, 092511 (2012)
2. Ya.I. Kolesnichenko, *Nuclear Fusion* **20**, 727 (1980)