Validating predictive models for fast ion profile relaxation in burning plasmas

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Motivations
Perturbative CGM/1.5D
Non-perturbative CGM
Validation via “kick model”/ORBIT
CGM validation in NSTX

Nonlinear Scenarios and Predictive Models

Various groups proposed Critical Gradient Model (CGM) concept independently: IFS’95, PPPL & IFS’05, GA & UCSD’12 ...

- Nonlinear scenarios vary from sub-critical to metastable distribution
- Full nonlinear computations are expensive and not always required
- Predictive models should capture main plasma parametric dependencies

- Predictions should be on (slightly) a pessimistic side of plasma performance for future devices.

CGM concept should be well understood and validated!!

Breizman & Sharapov, PPCF, 2011
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Critical Gradient Model (CGM) is Getting Ready for Predictions

Earlier applications of CGM showed consistency with DIII-D data

(K. Ghantous et al., PoP12) (W. Heidbrink et al., NF’13)

- CGM predicted neutron deficit of the same order with experiments
- The time evolution of neutron source is recovered
- Efficient computations
- More V&V is required to:
  - verify against established codes – ORBIT
  - systematically validate against tokamak experiments

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   - nCGM is consistent with CGM in DIII-D

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   - High $\beta$ plasma, low-$n$ modes
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Model Outline
validating CGM on DIII-D

1.5D QL/crit. gradient model OUTLINE [K.Ghantous et.al.PoP’12]

• assume: large number of unstable localized modes
  • or overlapped resonances of a few modes
  ⇒ strong collisionality is an ultimate condition for CGM

• assume: fast EP diffusion within velocity/phase island

• fixed background dampings, thermal plasma profiles
  (DIII-D XP on critical gradient model)

• compute: critical gradient \( \partial \beta_{EP}/\partial r \) due to AE instabilities
  • perturbative CGM uses NOVA-K growth/dampings: ion Landau, trapped electron are key in used conditions - should include rotation, realistic continuum;
  • non-perturbative CGM is based on H1gh-n STability fully kinetic local ballooning code HINST;

• compute: 1.5D post-processor integrates critical EP beta gradient for
  (i) relaxed profiles; (ii) losses;
  • \( V \)-space distribution in a simple form [Kolesnichenko NF’80], i.e. dominant resonance \( v_{\parallel} \sim v_A \) (\( \rightarrow 0.5D \)) (too optimistic?)

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N. N. Gorelenkov et al. Validating predictive models
CGM main equation:

$$\frac{\partial \beta_{EPc}}{\partial r} = -\frac{\gamma_i L + \gamma_{ecoll} + \gamma_{rad}}{\gamma'_{EP}}, \quad \gamma_{EP} = \frac{\gamma_{EP}}{(\partial \beta_{EP}/\partial r)}$$

Dominant dampings in DIII-D, NSTX and ITER: thermal ion Landau, electron collisional, radiative (high-n’s) → nonlocal (local) in (non-) perturbative regimes!!

Fixed AE damping shapes EP profiles

Condition $|\beta'_{EP}| \leq |\beta'_{EPcrit}|$ is used to compute the relaxed EP profile. It is broadened from initially unstable: $r_{\pm} \rightarrow r_{1,2}$
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Schematic of EP CGM application for *AE instabilities

CGM main equation:
\[
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Validate CGM against high-$q_{\text{min}}$ shot #153072 (Heidbrink et al. PPCF’14)

- Validate CGM against high-$q_{\text{min}}$ shot #153072 (Heidbrink et al. PPCF’14)
- rely on TRANSP for neutron loss predictions
- use NOVA-K (perturbative) for CGM normalization
- compare neutron loss vs time
- Mirnov spectrum indicates virulent (nonperturbative?) AEs; some other low-$f$ modes, Alfvén-acoustic?

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validating CGM on DIII-D

Apply CGM to high-\( q_{\text{min}} \) #153072 DIII-D shot systematically

- apply ideal MHD Q-solver for plasma equilibrium
- choose NOVA-K normalization for EP CGM
- to account for discretness of TAE mode, each time \( t = t_0 \) is subdivided by \( \delta t = 20 \text{msec} \ll \tau_{se} \), i.e. \( t_0^- = t_0 - \delta t \) and \( t_0^+ = t_0 + \delta t \).
  - this helps to make the study systematic
- ideal NOVA finds following modes

\begin{align*}
  n = 4 \text{ red) (blue) AEs} & \quad \text{DIII-D pulse 153072} \\
  \text{Frequency (kHz)} & \quad 100 \quad 200 \quad 300 \\
  n = 4 \quad n = 6 \quad n = 7 \quad n = 8 \quad 1 \text{AEs} \\
  \text{Frequency (kHz)} & \quad 100 \quad 149 \quad 1 \text{AEs}
\end{align*}

\( n = 5 \) TAEs from NOVA normalization
For each TAE vary \( n/z_h \) to find the plateau of the growth rate vs. particle charge for normalization
Most unstable case out of 3 closest times gives lowest critical gradient

- CGM assumes fast diffusion
- TRANSP computed fast ion distribution function is used in NOVA-K
- Neutron flux deficit is compared with classic TRANSP predictions
- CGM finds critical gradient using TRANSP run with matched neutron rate

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Compare CGM with TRANSP classic predictions

CJM under-predicts the neutron loss by a factor of $\sim 2$.

Linear stability theory suggests: either drive is too weak or the damping is too strong. Why?

Motivates further comparison with Podesta’s “kick” model (see below).

$\Rightarrow$ conjecture:
nonlinear regime drives non-perturbative modes, EPMs, rTAEs
nonperturbative modes are more unstable & localized (Z. Wang, PRL’13 and Yang Cheng et al., PoP’10).
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**Compare CGM with TRANSP classic predictions**

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Make use of local High-n STability code - HINST

Solves vorticity equation in ballooning variable with fast ion terms:

\[
\frac{c^2}{4\pi \omega} B \nabla \frac{k^2}{B^2} B \nabla (\Phi - \Psi) - \sum_{j=i,e,h} \int d^3 v Z_j e \left\{ \omega_d j_0 g_j + \frac{Z_j e}{M_j} \frac{\partial F_j}{\partial \epsilon} \left(1 - \frac{\omega_{*j}^T}{\omega}\right) \left[ \omega \Phi \left(1 - J_0^2\right) - \omega_d j_0 - \frac{\omega_{\epsilon_\perp}}{c\omega_c} \int \delta B_\parallel \right] \right\} = 0
\]

and Quasi-neutrality and Perpendicular Ampere’s law expressions for \( \Psi \) and \( \delta B_\parallel \)

\( (C.Z.Cheng, N.N.Gorelenkov, PoP’04) \).

Physics included:

- Ballooning variable: \( \theta \rightarrow \eta_\parallel \rightarrow \text{infinite} \eta_\parallel \rightarrow \Phi \) is periodic in \( \theta \);
- Drive from beam ions with FLR, FOW and slowing down distribution;
- Ion, electron Landau damping;
- Realistic geometry, ESC equilibrium (Zakharov’99);
- Recovers TAEs, EAEs, (K)BMs, BAEs.
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HINST in realistic DIII-D geometry finds AEs

ESC equilibrium is provided by TRANSFP (Zakharov et al. PoP’99)

example of TAE $n = -7$ solutions at $\theta_k = 0$: $\sqrt{\psi/\psi_0} = 0.2$

$\sqrt{\psi/\psi_0} = 0.5$

broad AE structure in $\eta$:
$\Rightarrow$ radiative/cont. damping

narrow AE in $\eta$
no cont. damping

$\Rightarrow$ Critical gradient computations via HINST:

use AE total damping ($\Leftrightarrow$ growth rate at $\beta_h = 0$)
and the drive with fast ions, finite $\beta_h = \beta_h_{\text{TRANSFP}}$. 
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Critical gradient is computed to relax EP profiles at each time

Three times are compared with the perturbative CGM treatment below:

- \( t = 2.7 \text{ sec} \)
- \( t = 3.2 \text{ sec} \)
- \( t = 3.7 \text{ sec} \)

Both perturbative and non-perturbative variations of CGM give similar profiles:

- the models are consistent to each other; three regions are important for losses:
  1) core region - dominant by ion Landau damping
  2) zero shear region at \( r/a \sim 0.5 \), almost zero crit. gradient, and
  3) edge with strong trapped electron collisional damping.
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   - High $\beta$ plasma, low-$n$ modes
Non-perturbative and perturbative models are consistent

Each of chosen times was analyzed in details and compared with the perturbative treatment:

Main reasons for agreement of CGM and nCGM models
weak drive (growth rate) near the center and at the edge.
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“Kick model” validation (M. Podesta morning talk)

“Kick model” resolves phase space for EP-*AE interactions

Prob.Dens.Funct. is computed by ORBIT ⇒ accuracy, details for redistribution
kicks are proportional to amplitude $A(t)$

ORBIT computes random walk for EP given the (measured) amplitude.
Implement “kick model” via NUBEAM package.
M. Podesta PPCF ’14, NF’15.

Kick model relies on measurements of the unstable *AEs
needs “seed” mode structures to compute PDEs: rely on NOVA+measurements

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Alfvén-acoustic polarization of the modes is needed for better agreement with the neutron deficit from DIII-D
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NSTX provides a weakly chirping TAE validation case

- Special exercise within TRANSP/NUBEAM codes infers diffusion coefficient up to $<1m^2/sec$.
- Use CGM method as NOVA/TRANSP postprocessor to compute neutron losses.
- Relatively “non-virulent” instability case is chosen, but still chirping modes.

<table>
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<th>Time (ms)</th>
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<tr>
<td>480</td>
<td>2.8</td>
</tr>
<tr>
<td>490</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Diffusion (cm$^2$/s)

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CGM analysis shows good agreement for #141711 neutron deficit predictions

- NOVA improved stability calculations account for plasma rotation, thermal ion drift orbit effects
- NOVA-K finds strong effects on growth/damping rates prediction from rotation
- Near threshold conditions are appropriate for linear theory applications.

CGM (linear theory) is consistent with considered NSTX plasma. Low aspect ratio, more coupling for harmonics? Avalanches are present even near threshold!
Summary and Future plans

- 1.5D/Critical Gradient Model validations showed consistency with the neutron deficit from experiments on DIII-D and NSTX.
- Non-perturbative and perturbative CGM have similar predictions for neutron deficit in DIII-D shots.
- “Kick model” mediates CGM concept validation for TAE frequency range spectrum in DIII-D.
- Some applications do not require details of fast ion distribution function and can rely on CGM predictions:
  - EP density profile knowledge is often sufficient for TRANSP analysis.
  - Calculations are fast, but may need proper normalization and should be done with appropriate time resolution.
- Further (another) model(s) development in order to include the pitch angle diffusion is required.
  - Line broadening Quasi-linear model is being developed with velocity space resolution of EP distribution - IFS/PPPL work in progress.
BACKUP SLIDES
Backup: NUBEAM computes broad distribution function in $\chi = v_\parallel / v$.

#152932 DIII-D shot

$\frac{v_\parallel}{v}$

$E$ (eV)

#153072 DIII-D shot

$\frac{v_\parallel}{v}$

$E$ (eV)

Finite anisotropy is local, due to orbit width effects

HINST approximation of isotropic DF is justified since near the TAE resonances

$v^2_A / v^2_\alpha \sim 0.5$. 

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High $\beta$ plasma, low-$n$ modes

Promising initial applications of CGM were done on DIII-D

On-axis $\uparrow$ On+Off-axis $\uparrow$ (W. Heidbrink et al., NF’13)

- Linear instability theory should be robust
- 1.5D model motivates more accurate 2D quasi-linear (QL) theory development

How accurate/robust 1.5D model is? Is there a need for systematic validation?
“Kick model” resolves discrepancy if the mode amplitude x4 – 6 times !!!

- Amplitude increased by 4-8x for TAEs, BAEs
- Neutron deficit recovered…
  - ... but amplitude seems unusually large
High $\beta$ plasma, low-$n$ modes

Pure Alfvénic modes lead to weaker EP relaxation

- HINST + CGM reduces the fast-ion pressure gradient
- Predicted neutron deficit: too high at low beam power, correct at high beam power
Some indications of non-perturbative characteristics of the spectra

BES indicates some low-\(f\) modes which are not seen by ideal MHD

NOVA finds only core BAAEs but not at the measured edge location

Virulent, non steady state signal evolution

Critical Gradient model for strong Alfvénic turbulence is justified:

but the lack of phase space details motivates the development of the diffusive approach for appropriate resolution in the velocity space.