FAST ION RELAXATION IN ITER MEDIATED BY ALFVÉN INSTABILITIES USING REDUCED MODELS

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in collaboration with

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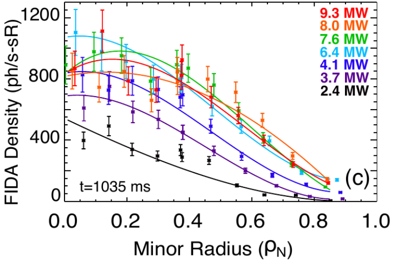
PPPL PRINCETON PLASMA PHYSICS LABORATORY UCIrvine University of California, Irvine iter china eu india japan korea russia usa Office of Fusion Energy Sciences Excellent Science Attractive Energy

Classical α-particle confinement & Coulomb collisions may result in weak Alfvénic mode driven α-transport in burning plasmas

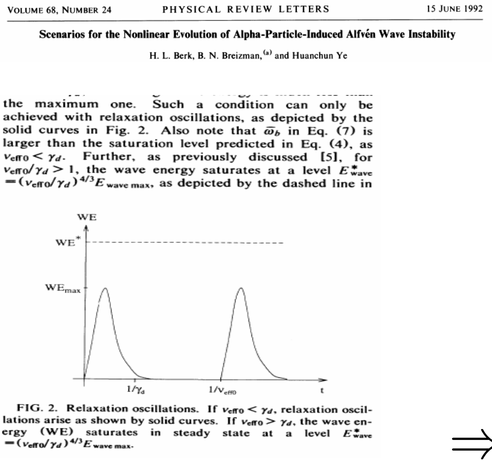
- Recent Critical Gradient DIII-D XPs imply stiff EP transport with resilient EP profiles (Collins et al., PRL'16) ⟶
- Fitzgerald, NF'16 (and Schneller, PPCF'16) predicted n=1-35 unstable AEs at $\delta B_r/B \lesssim 3\times 10^{-4}$ driven by fusion alphas in ITER ***baseline*** scenarios where $\beta_{\alpha 0} \simeq 10\beta_{b0} \simeq 1.2\%$ *(Pinches, PoP'15)*.



- Recent ITER Physics Basis and US DOE FY22 Theory Performance Target milestone studies indicate that classically confined α-particles & $1MeV$ NBI ions will not lead to appreciable losses. Self consistent QL approach (Gorelenkov et al., PLA'21, Duarte et al., PRL'23) is underappreciated for future fusion devices planning.

Our studies show that anomalous pitch angle scattering due to microturbulence (i) is required to drive AEs to high amplitudes for dangerous losses (ii) is compatible with QL approach.

Berk-Breizman-Ye nonlinear scenarios envisioned 3 decades ago are (QL) confirmed now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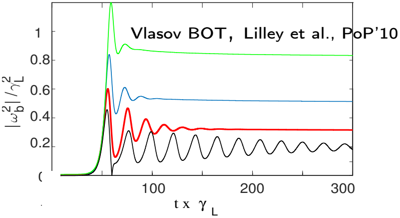
Scenarios for the Nonlinear Evolution of Alpha-Particle-Induced Alfvén Wave Instability

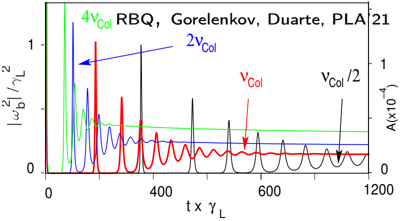
H. L. Berk, B. N. Breizman,[a] and Huanchun Ye

the maximum one. Such a condition can only be achieved with relaxation oscillations, as depicted by the solid curves in Fig. 2. Also note that $\bar{\omega}_b$ in Eq. (7) is larger than the saturation level predicted in Eq. (4), as $\nu_{\rm eff0} < \gamma_d$. Further, as previously discussed [5], for $\nu_{\rm eff0}/\gamma_d > 1$, the wave energy saturates at a level $E^*_{\rm wave} = (\nu_{\rm eff0}/\gamma_d)^{4/3} E_{\rm wave\,max}$, as depicted by the dashed line in

FIG. 2. Relaxation oscillations. If $\nu_{\rm eff0} < \gamma_d$, relaxation oscillations arise as shown by solid curves. If $\nu_{\rm eff0} > \gamma_d$, the wave energy (WE) saturates in steady state at a level $E^*_{\rm wave} = (\nu_{\rm eff0}/\gamma_d)^{4/3} E_{\rm wave\,max}$.

$\Longrightarrow$





Interplay of 3 time scales envisioned in 1992.
QL model is applicable to a SINGLE AE!: ion motion near the island is diffusive due to pitch angle scattering
⇒ multiple broadened resonances justify QL theory.

Resonance-Broadened Quasi-Linear code (RBQ) is built

RBQ is a post- (NOVA/NOVA-C) processor to compute EP dynamics in the presence of Alfvénic modes.

- RBQ includes:
  - (slow varying) eigenmode structures (NOVA or other solvers);
  - finds AE amplitude evolution and EP distribution function in time;
  - QL model is based on diffusion in Constants of Motion space ⇒ oscillations/intermittences!!
- RBQ is connected with TRANSP WDM to compute EP diffusion and EP distribution function *(Gorelenkov et al., NF'18, PoP'19, Gorelenkova et al., APS'22).*
- Extensively verified and validated against ***developed analytic*** cases *(Gorelenkov et al., APS'18, PoP'19, Duarte et al. NF'19,'17).*
- Verified against kick model & BOT Vlasov solver *(Gorelenkov & Duarte PLA 21).*
- RBQ2D is build with selfconsistent model for EP diffusion near the resonance region *(Duarte AAPPS, APS'20).*

RBQ aims at single/multiple AE instabilities in BP conditions & is numerically efficient.

Quasi-Linear equations include 3 time scales: γ_L, γ_d, and ν_{eff}

Action-angle formalism using flux variables include γ_L^{-1}, γ_d^{-1}, *and* ν_{eff}^{-1} in equations for EP DF: (Kaufman,PhFl'72, Berk NF'95, adapted for RBQ Duarte PhD'17, Gorelenkov NF'18, APS'18, Duarte PRL'23)

$$\frac{\partial}{\partial t} f = \pi \sum_{l,k} \frac{\partial}{\partial P_\varphi} C_k^2 \mathscr{E}^2 \frac{G^*_{m'p} G_{mp}}{\left|\partial\Omega_l / \partial P_\varphi\right|_{res}} \mathscr{F}_l[\Omega] \frac{\partial}{\partial P_\varphi} f + \nu_{eff}^3 \left|\frac{\partial \Omega_l}{\partial P_\varphi}\right|^{-2} \frac{\partial^2}{\partial P_\varphi^2}(f - f_0),$$

where distribution f is evolved due to scattering terms on the RHS and AE driven Constant Of Motion (COM) diffusion.

AE amplitudes evolve due to explicit equations involving $\gamma_L(t;f)$, γ_d damping is fixed:

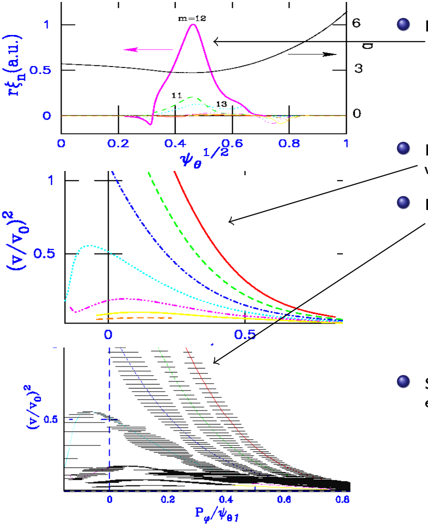
$$C_k(t) \sim e^{(\gamma_L + \gamma_d)t} \Rightarrow \frac{dC_k^2}{dt} = 2\left[\gamma_L(t;f) + \gamma_d\right] C_k^2.$$

Critical for RBQ *multi-mode cases (Dupree'66, Berk'95, White'18) is*
the resonant frequency and its broadening (nonlinear bounce ω_{bNL} and effective scattering ν_{eff}):
(V. Duarte APS'20 inv. talk, PRL'23)

$$\delta\left(\Omega = \omega + n\dot{\varphi} - m\dot{\theta} - l\omega_b\right) \rightarrow window\ \ function, \mathscr{F}_l[\Omega]$$

RBQ computes EP diffusion rates for TRANSP/NUBEAM whole device modeling to evolve EP distribution function & evolve it during the run within the code.
Self-consistent diffusion near the resonance region (Duarte AAPPS, APS'20, PRL'23) is critical.

RBQ workflow for $n=4$ Reversed Shear Alfvén Eigenmode (near q_{min})

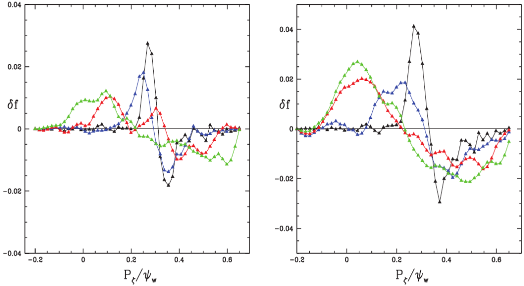


Shown is the broadening at measured amplitude $\delta B_\theta/B = 7\times10^{-3}$.

- Ideal MHD code NOVA finds RSAE structure $f = 84kHz$ *(Collins, PRL'16)*.
  - This mode provides a channel for ion diffusion and hollow fast ion pressure profiles: resonant particles are close to the injected pitch angle.
- NOVA-K code computes resonances for particle interactions with the mode and $\langle v\cdot E\rangle$ matrices.
- RBQ1D broadens those resonances along P_φ direction using QL prescriptions for each mode.
- Similarity with spectral light line broadening due to various effects:
  - natural line broadening,
  - thermal Doppler broadening etc,
  - non-local broadening and so on,
  - FIDA line broadening.

ORBIT on importance of χ-scattering for WPI resonances (White et al., PoP'19)

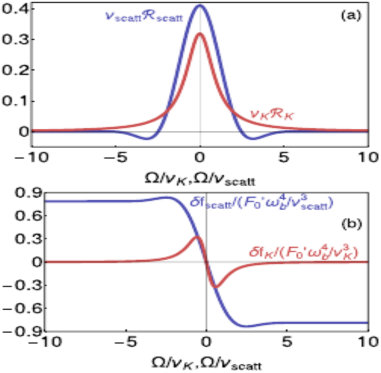
$\delta B_\theta / B = 10^{-4}$ vs. $\delta B_\theta / B = 2 \times 10^{-4}$



- vary collisionality from 0 to 22Hz; δf saturates at strong collisionality;
- the broader the resonance $\Rightarrow$ more free energy is available for instability;
- both examples demonstrate that χ-scattering dominates the broadening in P_φ at small AE amplitudes;
- near threshold island vanishes, but broadened region remains *(analytic broadening is formulated Duarte et al., PoP'19).*

RBQ 2D upgrade involves more sophisticated wind. function (Duarte PoP'19)

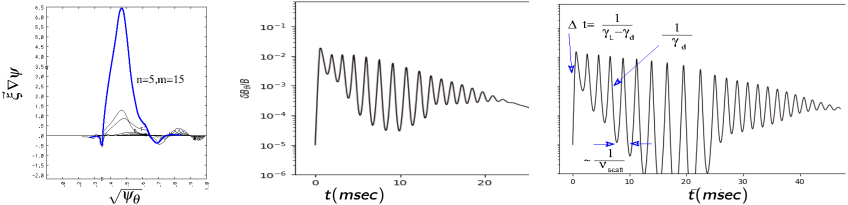
A QL theory is revisited for near threshold regimes basing on **near threshold** WF: $0.3 \lesssim \nu_{eff}/(\gamma_L - \gamma_d) < 1$, $\gamma_d/\gamma_L > 0.35$.



- QL methodology accounts for resonant dynamics *selfconsistently*.
- Measurable interplay of growth/damping rate scales is important for experiments.
- Energy slowing down is weak and is included in recent work: *Duarte et al., PRL'23.*

RBQ captures interplay of three time scales for one mode

RSAE structure *constant radius* $v_{scatt} = 5msec^{-1}$ & $2.5msec^{-1}$

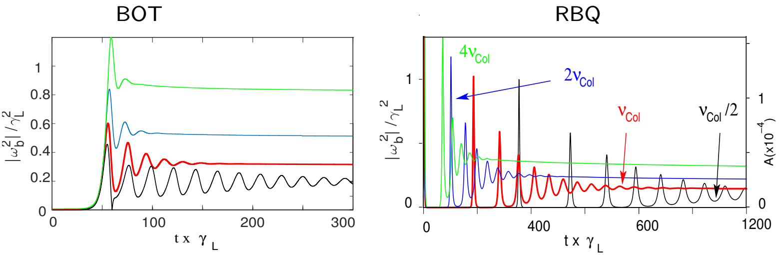


- Interplay between 3 time scales explains amplitude oscillations with the flat top broadening:
  - Linear growing phase: $1/(\gamma_L + \gamma_d)$, Damped phase, γ_d^{-1} & Recovering phase, ν_{scatt}^{-1}.
- Periodicity (or oscillatory time evolution) is due to Coulomb scattering - effective source of resonance ions.

- Coulomb collisions are insufficient for periodic, intermittent oscillations.
  Theory requires additional scattering, expected to be $\gg$ Coulomb collisions.

RBQ+near threshold window function & Bump-on-tail (BOT) agree qualitatively

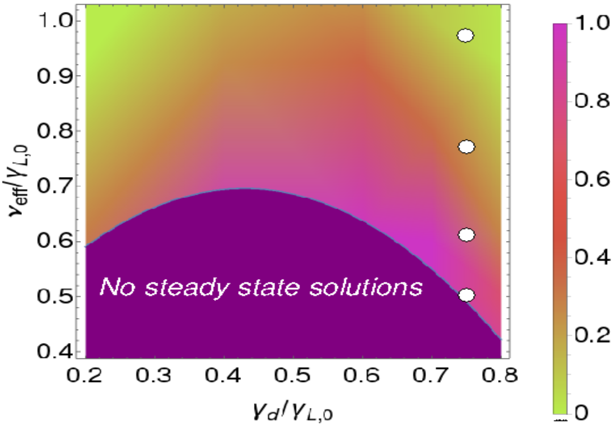
RBQ (Quasi-linear): fixed boundary conditions (BC) at the axis, fixed (zero) at the edge. BOT (fully nonlinear Vlasov kinetic equation solver): Ω, γ_L, γ_d, ν_{eff}, fixed BC at infinity.



Nominal case for $n = 3$, $f = 75kHz$: $\gamma_d = -0.75\gamma_L = -2.075\%$ at $\nu_{Coul} = 8.9sec^{-1}$ or $\nu_{eff} = 8.017 \times 10^3 sec^{-1}$.

In RBQ the recovery time (repetition rate) scales for nominal DIII-D case *(Collins et al., PRL'16)* as $\Delta t (\simeq \nu_{eff}^{-1}) = 19msec$. In BOT it has close value $\sim 30msec$.
(Gorelenkov & Duarte, PLA'21)

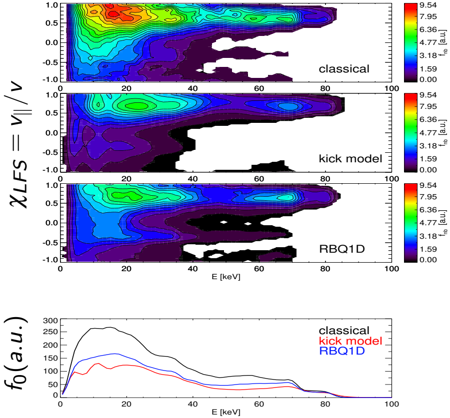
Contour map of oscillatory behavior: RBQ vs BOT - fully nonlinear Vlasov solver



RBQ does a good job near marginality, $0.35 < \gamma_d/\gamma_{L0} < 1$ at wider range of ν_{eff}/γ_{L0}.

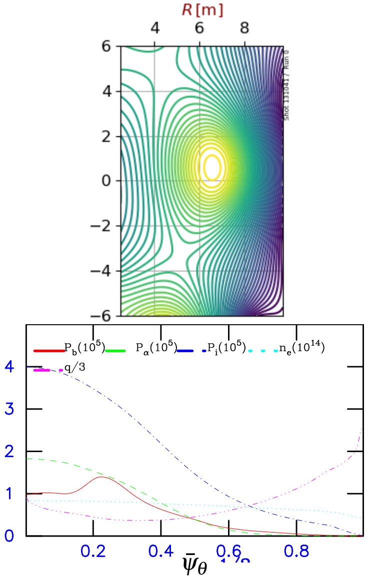
Theory is presented at AAPPS'20 and APS'20 invited talks by Duarte & PRL'23, IAEA'20 and IAEA'23 by Gorelenkov on ITER EP relaxation.

TRANSP/NUBEAM with RBQ diffusion result in similar DF as kick model's



- Co-going passing beam ions are strongly redistributed (Collins et al., PRL'16, Heidbrink et al., NF'17).
- Within kick, RBQ models amplitudes are kept constant throughout observed times (Gorelenkov et al., APS'18, PoP'19).
- Neutron rate includes radial and energy dependence within TRANSP simulations.
- Rotation is ignored!!
  It can be significant and could lead to EP energy shift $\sim E_0/2$ in DIII-D.

ITER Steady-State plasma #131041 is analyzed



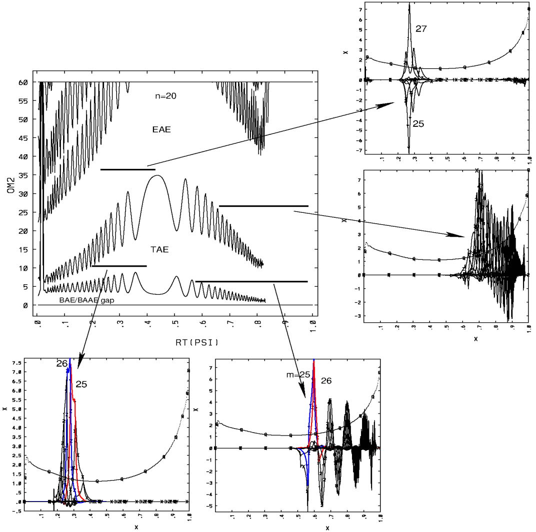
3.52MeV α-particles with $v_{\alpha 0}/v_A = 1.86$ and 1MeV NBI D fast ions at $v_{b0}/v_A = 1.43$ are investigated.

AE linear stability properties of US theory FY2022 milestone are favorably compared with Pinches et al., PoP'15 of baseline scenario.

Steady-State plasma dampings shape EP profile relaxation

Comparison of linear stability properties with earlier studies by Pinches et al., PoP'15 of baseline scenario.

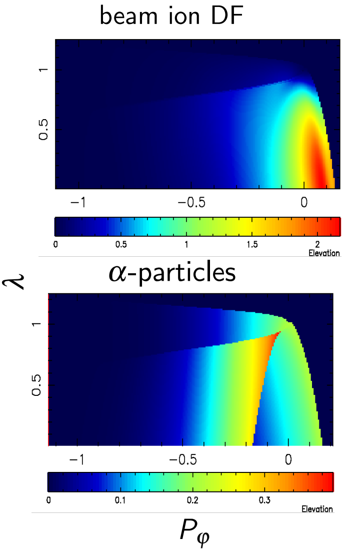
- Damping mechanisms (NOVA-C):
  - thermal ion Landau damping - core
  - trapped electron collisional damping - edge
  - radiative damping is also important.
  - continuum damping is ignored near the center and q_{min} region where most unstable TAE/EAE are found (Rosenbluth et al.,PRL'92, PhFl.'92).



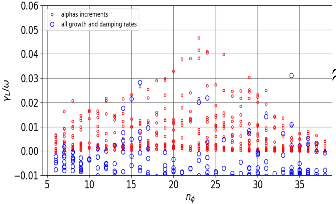
Beam ion and α-particle distribution functions include finite orbit width

Realistic EP distribution use TRANSP pressure profiles, injection/birth energy are used.

- Beam ions are injected into the most unstable COM location.
- *D*-ions are injected copassing.
- Fusion α-particle isotropically born have natural anisotropy which is captured by NOVA-C code.



comprehensive linear AE stability has been assessed using NOVA-C



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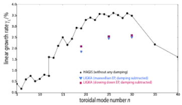
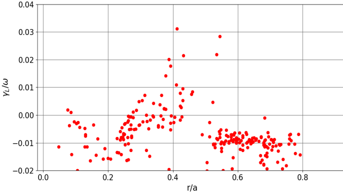


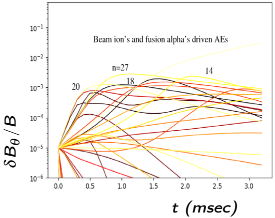
Fig. 9: Linear growth rates (due to α particle drive) γ_L (without damping) calculated by HAGIS *(black dots) and* LIGKA *(squares and triangles).* HAGIS *results are around 1% higher, due to the missing FLR effects.*



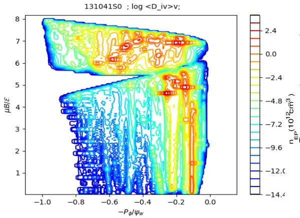
- AEs with n spanning from 0 to 40 are in focus.
- But unlike Pinches et al., PoP'15 (baseline $\beta_{0beam} = 0.08\%,\ \beta_{0\alpha} = 1.2\%$), steady state NBI ions ($\beta_{0beam} = 1.35\%,\ \beta_{0\alpha} = 2.2\%$) are dominant for AE excitation.
    - 42 unstable/marginally stable AEs were found.
    - WPI $\{v_{dr} \cdot E_\perp\}$ matrices in COM, $\{P_\varphi, \mathscr{E}, \lambda = \mu B_0/\mathscr{E}\}$, space are prepared for subsequent RBQ calculations.
    - TRANSP projects $\chi_{i,e}$ matrices to help RBQ evaluate effective pitch angle scattering rate.

RBQ2D is applied with Coulomb EP scattering

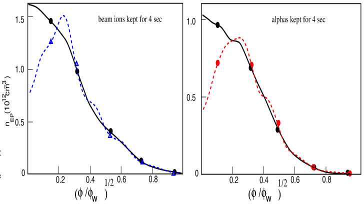
AE amplitude



AE diffusions



Prelim. RBQ relaxation of beam ions & alphas



- No anomalous pitch angle scattering used in RBQ simulations
- Passing and trapped ions have strong diffusion near q_{min} location, $D_{rr} \lesssim 10^2 m^2/sec$.
- Microturbulence in ITER BL & SS leads to little EP redistribution, but could drive large thermal transport and affect AE & fishbones, which can drive larger EP transport.
- Integrated simulation of cross-scale coupling of MHD mode, AE, and microturbulence is needed to reliably predict EP confinement in ITER. Or reliable reduced models for ZF, ZS.

Summary

- Various AE saturates with $n = 1 \div 42$ and frequencies in BAE-TAE-EAE gaps, expected to be unstable in ITER steady state scenario. A strong but local EP transport is driven by AEs $\Rightarrow$ modest flattening of EP profiles.
  - ~ 42 unstable, marginally stable AE modes could oscillate in time.
  - effective pitch-angle scattering could be important to determine the limit of tolerance for the BP devices $\Rightarrow$ additional quantities need to be provided.
- Interface of SciDAC codes with WDM IMAS-like frameworks and efficient reduced EP models ready for integration for ITER/FPP predictions are needed.
- At the moment 2D version of RBQ is developed within ISEP SciDAC
  - Integration into WDM frameworks is planned.
  - needs to be numerically optimized.
- NOVA-C needs further upgrades: rotation, EP anisotropy & orbit width effects through equilibrium; ESC (HPE) already includes those effects.