Microturbulence-mediated route for stronger energetic ion transport and Alfvénic mode intermittency in ITER-like tokamaks

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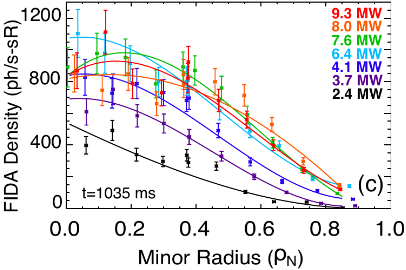
62^{nd} APS DPP Virtual Meeting, November 9-13^{th}, 2020

This work is supported in parts by ISEP SciDAC, and DoE contract No. DE-AC02-09CH11466

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

αs, beam confinement is crucial for selfsustained plasma with current drive and auxiliary heating.

- Recent Critical Gradient DIIID XPs imply stiff EP transport with resilient EP profiles (Collins et al., PRL'16) ⟶



- M. Fitzgerald et al., NF'16 (see also M. Schneller et al., PPCF'16) predicted n=1-35 unstable Alfvénic eigenmodes (AEs) at $\delta B_r/B \lesssim 3\times 10^{-4}$ driven by fusion alphas in ITER. HAGIS was used to assess α-particle relaxation in the presence AEs.
- Amplitudes are too low to produce a noticeable α-transport in ITER (5% of all alphas: Fasoli, TPB, NF'07).
- $1MeV$ NBI ion drive was ignored.
- AE amplitude increase by a factor ~ 50 is required to see appreciable alpha losses.

We are showing that the anomalous pitch angle scattering such as due to the micro-turbulence is required for higher AE amplitudes.

Resonance Broadened Quasi-linear (RBQ) model computes time dependent EP dynamics

Action-angle formalism using flux variables results in a set of equations for fast ion DF:

(Kaufman,PhFl'72, Berk,Breizman, NF'95, adapted for RBQ Duarte, PhD'17, Gorelenkov, NF'18, APS'18)

RBQ quasilinear equations include 3 time scales: γ_L^{-1}, γ_d^{-1}, and ν_{eff}^{-1}

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

where distribution f is evolved due to scattering terms on the RHS and AE growth rate.

AE amplitudes evolve due to explicit equation

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

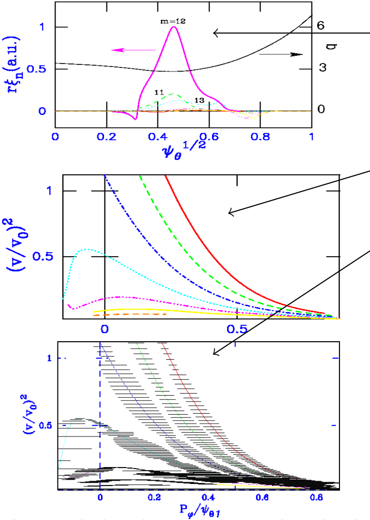
*AE growth rates γ_L are evolved due to $f\left(t\right)$; γ_d are fixed.

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)

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

RBQ provides EP diffusion to TRANSP whole device modeling code to evolve EP distribution function.
Extensive V&V are undertaken within ISEP SciDAC. Self-consistent diffusion near the resonance region (Duarte AAPPS, APS'20 on Friday).

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

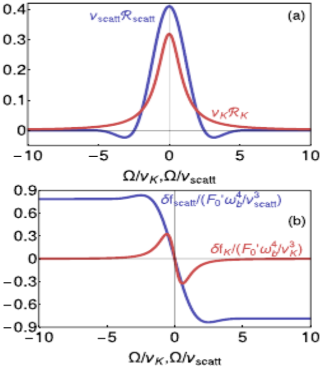


Shown is the broadening at measured amplitude $\delta B_\theta / B = 7 \times 10^{-\mathbf{3}}$.

- Ideal MHD code NOVA finds RSAE structure $f = 84 kHz$ *(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 $\langle \boldsymbol{v} \cdot \boldsymbol{E} \rangle$ matrices.
- RBQ broadens those resonances along P_φ direction using QL prescriptions for each mode.
- Quasi-linear methodology is adopted for its numerical efficiency.
  - Rigorous V&V is implied through ISEP SciDAC.

Selfconsistent wind. function accounts for radial (or P_φ) diffusion (Duarte PoP'19)

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

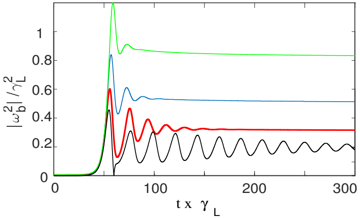


- QL methodology accounts for resonant dynamics *selfconsistently*.
- Measurable interplay of growth/damping rate scales is important for experiments.
- Energy slowing down is weak and is included in recent work: *Duarte, Lestz et al., in preparation (see J. Lestz poster, Wed. PP12).*
- Window function is required for ITER for efficient and (yet) realistic simulations to account for α-particle dynamics near the resonances with AEs.

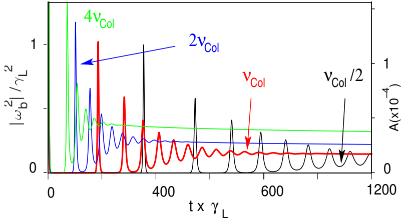
RBQ+near threshold window function & Bump-on-tail (BOT) agree qualitatively

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

BOT



RBQ



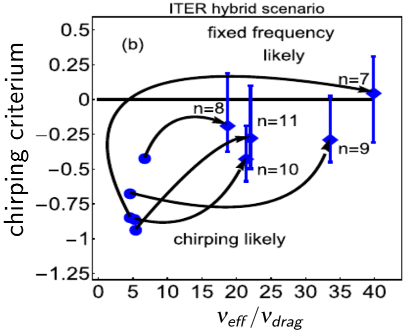
Nominal case for $n=3$, $f=75kHz$: $\gamma_d=-0.75\gamma_L=-2.075\%$ at $\nu_{Coul}=8.9sec^{-1}$ or $\nu_{eff}=8.017\times10^3 sec^{-1}$.

In RBQ the recovery time (repetition rate) scales for nominal DIIID case *(Collins et al., PRL'16)* as $\Delta t(\simeq\nu_{eff}^{-1})=19msec$. In BOT it is $\sim30msec$.

(Gorelenkov & Duarte, PLA'20 in press)

Expectations for ITER plasmas are based on earlier chirping studies

Coulomb scattering can be enhanced by the microturbulence in ITER



V.Duarte, N.Gorelenkov et al., NF'18

- Projections of microturbulence from $E_\alpha = T_i$ to $E_\alpha = 3.52 MeV$ are made with the help of Zhang et al., PRL'08.
- Pitch angle scattering is increased by the factor 4 to 10. Expected AE amplitude can grow to $A \sim \nu_{eff}^2 = (16 \div 100)\, \nu_{Coul}^2$.
- Fitzgerald et al., NF'16 cite ~ 50 times required AE amplitude increase to see appreciable α losses.
- No NBIs were included.

- Gyrokinetic simulations are needed to compute robustly pitch angle scattering in ITER experimental conditions to make reliable predictions.

Summary

1. AE instabilities can lead to losses and significant redistribution of alphas and beam ions in ITER if mediated by microturbulence.
   1. Coulomb scattering alone is not strong enough for strong losses.
   2. Microturbulence needs to be accounted for.

2. At the moment 2D version of RBQ is being developed within ISEP SciDAC for realistic simulations:
   1. RBQ is to be used for burning plasma applications, ITER, where multiple instabilities are expected.