Building 1D Resonance Broadening Quasi-linear (RBQ) code for fast ion Alfvénic relaxation

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This work supported in part by DoE contract No. DE-AC02-09CH11466

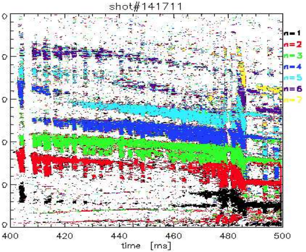
PPPL PRINCETON PLASMA PHYSICS LABORATORY
Office of Fusion Energy Sciences — Excellent Science Attractive Energy

2016 NSTX-U Results Review, September 21-22, 2016, PPPL

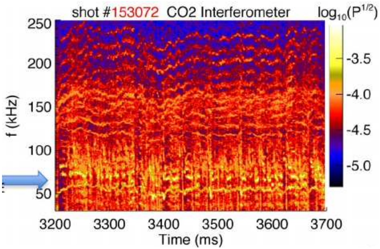
Perturbative AE theory/computations to help understand EP transport

1. PIC or continuum codes provide good resolution but are very expensive to run, need efficient **reduced models** such as QL (RBQ) with velocity space resolution: CD, EP losses etc.
2. **Steady-state** (**this talk**) and **chirping** frequency regimes (Duarte talk) are both required - which to expect in BPs?
3. Linear perturbative AE theory is well established, understood, V&V => should be used
   - Linear codes are available, used to explain AE instabilities
   - Realistic RBQ formalism is targeted with RBQ1D + NOVA-K codes within Scidac CSEP

NSTX - chirping



DIII-D - "steady state"



N.N. Gorelenkov, IAEA'15 on CGM

RBQ includes pitch angle scattering in its core

Action-angle formalism (Kaufman'72) - cf. diffusion operator in CQL3D by Harvey

Set of equations for RBQ for particle DF follows from Vlasov kinetic equation as per H.L.Berk, B.N.Breizman et al. NF'95

$$\frac{\partial f}{\partial t} = \frac{\pi}{2} \sum_{l,M} \frac{\partial}{\partial \chi} C_M^2 \mathscr{F}_{lM} \frac{\partial}{\partial \chi} f_{lM} + \nu_{eff}^3 \sum_{l,M} \frac{\partial^2}{\partial \chi^2} \left(f_{lM} - f_0 \right), \qquad (1)$$

where the amplitude satisfies

$$\frac{dC_M^2}{dt} = 2\left(\gamma_L - \gamma_d\right) C_M^2.$$

Realistic RBQ is a long term project with staged approaches leading to 2D version.

It can resolve EP distribution in the phase space: CD etc.
Can be time efficient.

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WPI resonances are broadened: amplitude ω_{bWPI} + growth γ_L + scattering ν_{scatt}

Inherited from Dupree'66: broadening is the platform for momentum and energy exchange between particles and waves:

$$\delta(\Omega) \to \mathscr{F}(\Delta P_\varphi),$$

where $\Delta P_\varphi \Omega'_{P\varphi} = c_\omega \omega_{bWPI} + c_\gamma \gamma_L + c_\nu \nu_{scatt}$. $c_{\omega,\gamma,\nu}$ are chosen following *Berk&Breizman'95.*

RBQ1D assumptions for ion diffusion due to TAEs for all broadened terms in case of $\omega_{bWPI}\&\gamma_L\&\nu_{scatt}$:

$$\Delta\mathscr{E} = \frac{\omega}{n}\Delta P_\varphi.$$

But should be different depending on the process. For RBQ1D propose a recipe:

- ω_{bWPI}: $\Delta\mathscr{E} = \frac{\omega}{n}\Delta P_\varphi$; $\Delta\mu = 0$.
- γ_L: $\Delta\mathscr{E} = \frac{\omega}{n}\Delta P_\varphi$; $\Delta\mu = 0$.
- ν_{scatt}: $\Delta\mathscr{E} = 0$; $\Delta P_\varphi \neq 0$; $\Delta\mu \neq / = 0$.

Is true in 1D case $\Delta P_\varphi \neq 0$, $\Delta\mathscr{E} = 0$ and should be true for strong collisional plasmas. Need to engage ORBIT into quantitative estimates of EP single particle dynamics.

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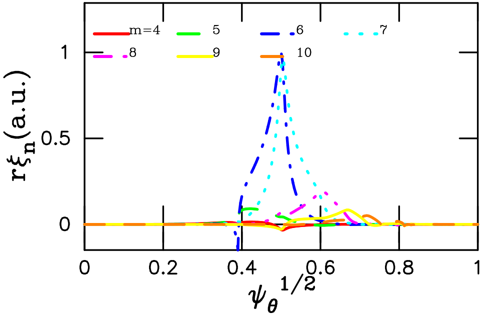
NBI heated plasma by 80keV ions

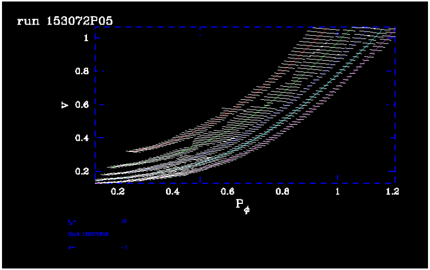
Take localized TAE at half of the minor radius ($f = 132kHz$) for test calculations.



What are EP COM trajectories, resonances in RBQ1D?

NOVA-K TAE resonances in COM, fixed μ

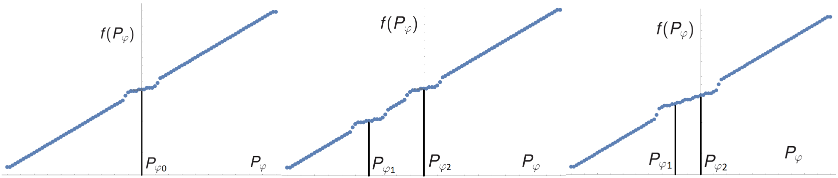
Resonances exist throughout the plasma even though the TAE is localized $0.4 < \sqrt{\psi_\theta \left\{ , P_\varphi \right\}} < 0.6$.
counter- passing



Here 7 drift-bounce harmonics are kept.
Only collisional scattering is allowed and yet the resonances almost overlap.

Module for particle diffusion scattering is being developed

Single, two isolated to two overlapped modes are shown to evolve in a separate module



- The module is optimized for parallel computing
- Multiple resonance overlapping Is being targeted

Future plans

- Broadening technique is offered for non-slanted 1D mesh
- Diffusion solver is being prepared for single and multiple resonance problem
- Apply to NSTX and DIII-D cases which are available.

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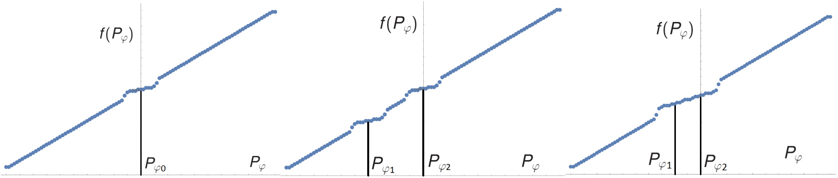

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