

Quasilinear Simulation of Energetic-Particle-Driven Alfvén Modes using M3D-C1

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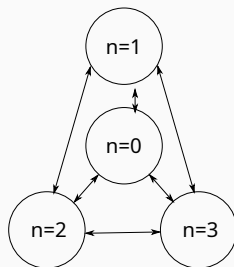
- Alfvén Modes can be driven by energetic particles in tokamak and stellarators.
 - Alfvén modes has very large frequency (10 ~ 100 kHz) and its growth rate depends on EPs.
 - n number of Alfvén Modes are typically large (4 ~ 7)
- It is found that the split θ -implicit method (imp_mod=0) used in M3D-C1 gives a smaller growth rate of Alfvén modes compared to fully implicit or Caramana method (imp_mod=1).
 - Split θ -implicit method calculate the second order time derivative of \mathbf{V} using the field equation. However, the contribution of particle pressure or current is not taken into account.
 - For nonlinear simulation, fully implicit method using a direct solver is very memory-consuming, and Caramana method can lead to numerical instabilities.

Quasilinear MHD simulation with self-interaction and zonal fields

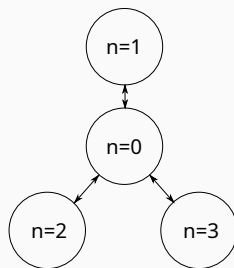
- The dominant MHD nonlinear effect comes from the “zonal fields”, which is the $n = 0$ components.
 - Zonal fields are generated by “self-interaction”, modes interacting with themselves ($1 + 1 \rightarrow 0$)
 - Perturbed fields are damped through interaction with zonal fields ($1 + 0 \rightarrow 1$)
- Inspired by this, we can do a quasilinear MHD simulation by only including the nonlinear MHD effects of self interaction and interaction between zonal and perturbed fields.
 - Zonal fields, unlike the perturbed fields (dominated by AEs), does not have real frequency and has weak direct interactions with EPs, thus can be evolved using split θ -implicit method with a large timestep
 - Perturbed fields (Alfvén modes) are calculated using Caramana method following linear MHD equations, avoiding numerical instabilities.
 - $n = 0$ components of nonlinear terms, calculated explicitly, are filtered and feed into the zonal fields.

Nonlinear vs. Quasilinear

Nonlinear:



Quasilinear:

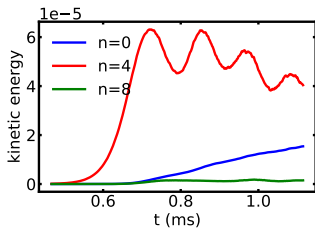


Steps of quasilinear simulation

1. Calculate the oscillation of Alfvén mode following linear MHD equations for N steps, with $dt = \tau_A$.
 - (V_0, B_0) includes the equilibrium fields and zonal fields. (V_1, B_1) includes Alfvén mode.
 - Linear calculation can be very fast as there is no need to assemble factorize the matrix in later steps.
 - Nonlinear terms are calculated using explicit method, the low- n component are picked and added to (V'_0, B'_0)
2. (V'_0, B'_0) is added to (V_0, B_0) , and then evolved following nonlinear MHD equations with $dt = N\tau_A$.

Evolution of mode energy

Nonlinear:



Quasilinear:

