August 2020

Efficient Simulations of Energetic Ion Relaxation in Burning Plasmas

The resonance-broadened quasi-linear model couples with Alfvénic modes to compute energetic particle diffusion.

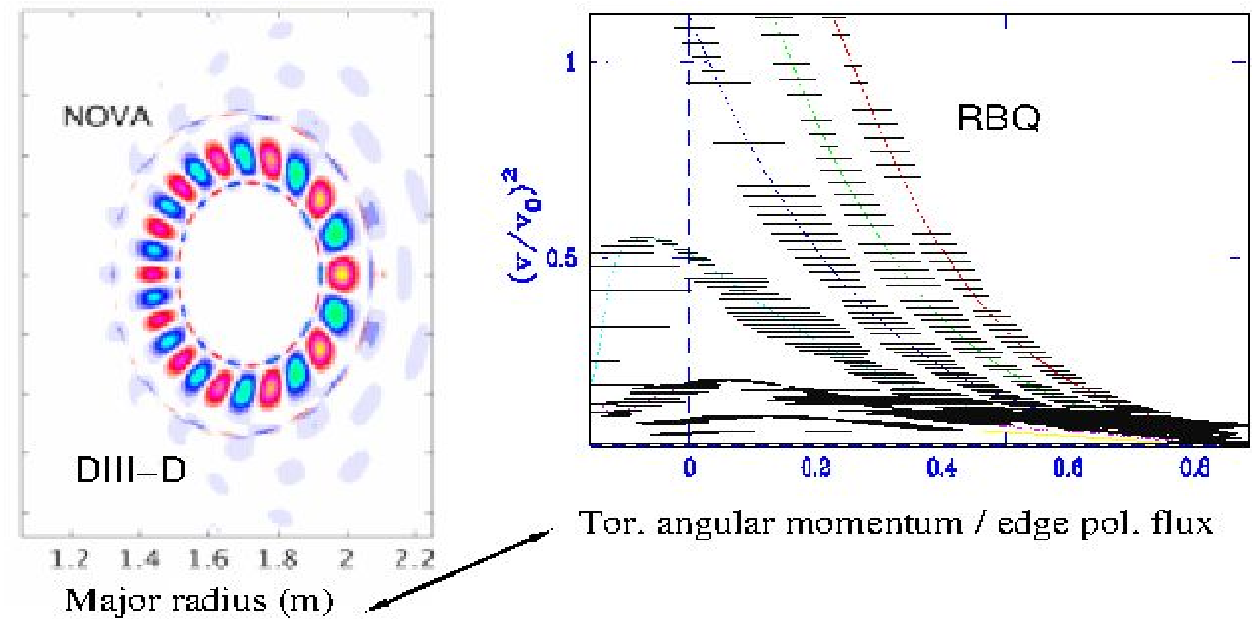

Image courtesy of N.N. Gorelenkov, PPPL.
The ideal MHD code NOVA computes a reversed shear Alfvén eigenmode (RSAE) structure (n=4 is shown on the left) and is being used by the quasi-linear code, RBQ. Resonance locations of fast ions interacting with RSAE and their resonance broadening (right) are computed by RBQ code in COM space.

The Science

In future fusion reactors, highly energetic particles are produced by fusion reactions. How these and other energetic particles used to heat the plasma transfer their energy to the background “gas” of charged particles known as a plasma is crucial for creating so-called burning plasmas and sustained fusion energy. Energetic particles can resonate with vibrations in the magnetic field known as Alfvén waves, which can lead to losses and degraded current drive. In our work, a self-consistent “quasi-linear” model of the energetic-particle slowing down process is developed. The resonance broadened quasi-linear (RBQ) model broadens the phase space resonances self-consistently in near-threshold regimes. The formulation shapes the vicinity of the resonant region, which was verified by the guiding center code ORBIT. Mode structures and their wave-particle interaction matrices are precomputed by the ideal MHD code NOVA and its kinetic extension NOVA-K in realistic toroidal plasma geometry.

The Impact

Reliable whole-device modeling of present and future burning plasmas critically depends on the correct treatment of energetic particles. The new numerical tool is required when there are multiple Alfvén modes and a dense spectrum of resonances, as will be the case in ITER. These energetic “super-thermal” ions can effectively resonate with Alfvénic plasma oscillations, leading to losses and degraded current drive. The RBQ code is critically important for accurate planning of operational scenarios in burning plasma conditions.

Summary

A self-consistent quasi-linear theory in the presence of multiple unstable Alfvénic modes has been developed from first principles and implemented numerically for instabilities in the near-threshold regimes. The resonances between the energetic particles and Alfvénic modes are broadened to the specific shape and width prescribed by analytic theory which was also developed. The formulation includes the discrete-resonance collisional functions to broaden the resonances for both Krook and Fokker-Planck scattering collisions. It was verified by the guiding center code ORBIT that the resonances are indeed broadened by the amount determined by the pitch angle scattering frequency.

The RBQ simulations find the diffusion rates in the space of the constant of the unperturbed motion for subsequent computation by WDM TRANSP's NUBEAM package using the probability density functions. The EP diffusion dependence across the resonance regions allows the RBQ code to compute the amplitude evolution which can exhibit oscillating, intermittent and saturated state behavior depending on the pitch angle scattering rate. This can be clearly observed in experiments when only a few Alfvénic modes are excited such as in DIII-D and TFTR.

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Funding

The research was funded by Department of Energy (DOE) Office of Science, Fusion Energy Sciences; Scientific Discovery Through Advanced Computing (SciDAC),

Publications

N.N. Gorelenkov, V.N.Duarte, C.S. Collins, *et al.*, " Verification and application of resonance broadened quasi-linear (RBQ) model with multiple Alfvenic instabilities" Physics of Plasmas **26,** 072507 (2019). [DOI: 10.1063/1.5087252]
V.N. Duarte, N.N. Gorelenkov, R.B. White, H.L. Berk, "Collisional resonance function in discrete resonance quasilinear plasma systems", Physics of Plasmas **26** 120701 (2019).