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Multi-Time-Scale Energetic Particle Dynamics in JT-60U Simulated with MHD Activity, Sources and Collisions

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Recent advances in high-performance computing allow to carry out long-time simulations of energetic ion dynamics subject to MHD activity, sources and collisions in a self-consistent manner, by combining these processes in a single code. In this paper, the model and methods are introduced, and first results are reported, focusing on the simulation and analysis of intermittent bursts of chirping Alfvén modes in beam-driven JT-60U plasmas. The results are relevant for the validation of the model and methods used, for the interpretation of experimental observations, and for our understanding of meso-time-scale physics.

1. Introduction

Energetic ions will play an important role in fusion power plants based on toroidal magnetic confinement. Their dynamics are being studied intensively in present-day experiments, supported by theory and simulation. On short time scales (μs-ms), energetic ion dynamics are governed by interactions with MHD modes; in particular, shear Alfvén waves. On long time scales (ms-s), sources and collisions are also important. Due to recent advances in high-performance computing, it became possible to simulate these processes side-by-side in a single code, without artificial interfaces, in realistic geometry and with realistic sources. The self-consistent integration of fast and slow processes allows to study meso-time-scale dynamics, such as intermittent bursts of MHD activity and energetic ion transport. Self-consistency combined with realism also facilitates direct comparisons of simulations with experimental measurements for the purpose of model validation and interpretation of experiments.

2. Model and methods

The dynamics of the bulk plasma, which serves primarily as a medium that supports MHD waves, is described by full MHD equations, which are solved with a finite-difference scheme in cylinder (R,φ,Z) coordinates. A full-f particle-in-cell method is used to represent the energetic ions, and a gyrokinetic model describes their motion in the fluctuating $\boldsymbol{E}$ and $\boldsymbol{B}$ fields. A 4-point average is used to account for finite Larmor radii (FLR). The perturbed energetic ion current enters the MHD momentum equation. Implemented in the code MEGA [1,2], this global nonlinear hybrid model has served as an initial-value instability code to study wave-particle interactions between Alfvén waves and energetic ions in simplified and realistic tokamak geometry. Such simulations start from a small perturbation and an unstable particle distribution (e.g., [1-3]).

Recently, MEGA was extended with collision models and sources, allowing it to be used for long-time simulations, where the energetic ion distribution builds up self-consistently under the influence of MHD activity. Two versions of MEGA with this capability exist at present.

The implementation by Y. Todo (NIFS) uses an extended MHD model and a collision operator as described in [4]. It is presently used to simulate toroidal Alfvén eigenmodes (TAE) with toroidal mode numbers n=1-5 in a DIII-D tokamak plasma driven by 80 keV neutral beams. The numerical prediction for the energetic ion density profile was improved [4] and a good agreement of temperature fluctuation profiles (amplitudes and phases) with experimental measurements was obtained [5].

In the implementation by A. Bierwage (JAEA), MEGA is combined with the collision and source models from the orbit-following Monte-Carlo code F3D-OFMC [6]. It is presently used to simulate energetic particle modes (EPM) with toroidal mode number n=1, which are held responsible for so-called fast Frequency-Sweeping (fast FS) modes observed in JT-60U plasmas driven by 400 keV negative-ion-based neutral beams (N-NB) [7]. In the present paper, first results of these simulations for JT-60U plasmas are presented and discussed.

3. Results

3.1 *Reproduced multiple bursts of chirping modes*

Fig.1(a) shows power spectra of magnetic fluctuations in a JT-60U experiment. After a quiet period following an Abrupt Large Event (ALE), intermittent bursts of fast FS modes are seen. The simulation results in Fig.1(b) reproduce salient features of these bursts: the frequency range (40-60 kHz), duration (1-2 ms) and intervals (3-10 ms).

When the form of the shear Alfvén continuum is altered relative to the energetic ion drive, evidence is found showing that the chirps are preferentially directed towards decreasing continuum damping. This may explain why experiments carried out under similar conditions but uncertain safety factor profile can exhibit up- or down-chirping, or both.

When gyro-averaging is turned off (drift-kinetic limit), the quiet periods between the bursts disappear and the fluctuation base line energy rises. This shows that the large Larmor radii of N-NB ions (10% of the plasma minor radius) are important for short-time instability dynamics and for reproducing meso-time-scale phenomenology.

3.2 *Analysis of chirping burst dynamics*

The burst around t = 22.5-26.5 ms is analyzed in detail. A smooth down- and up-chirp is only seen with FFT windows of size 0.5-1 ms, as used in the analyses of experimental data. For the analysis of simulation results with n=1 fluctuations only, FFT window sizes down to 0.04 ms can be used. The results in Fig.2 reveal that the apparent chirps are composed of series of pulses, possibly with successively decreasing/increasing frequencies. The “frequency spikes” seen between successive pulses are caused by phase slippages. The direction of the spikes seems to determine the direction of the apparent chirping seen with larger FFT windows.

When sources and collisions are turned off just before the burst at t = 22.5 ms, the burst amplitude is attenuated by a factor 2-3. Nevertheless, similar chirps are still seen, which indicates a certain robustness in the way the waves and particles interact.

3.3 *Evolution of energetic ion profiles*

Some of the above findings raise the question how much detail is required to reproduce products of long-time dynamics; in particular, the steady-state distribution of energetic ions. Results obtained so far indicate that the detailed evolution of the modes is not important: the relaxed energetic ion beta profile of the long-time gyrokinetic simulation is reproduced by the drift-kinetic simulation and by a simulation using a multi-phase method [4], where MHD is alternately turned on (1 ms) and off (4 ms).

5. Conclusion

Multi-time-scale simulations of energetic ion dynamics in neutral-beam-driven tokamak plasmas, including MHD activity, sources and sinks, have produced first results. The results are found to be useful for model validation, interpretation of experimental observations and physics studies. In particular, the new tools promise to improve our understanding of meso-time-scale phenomena.

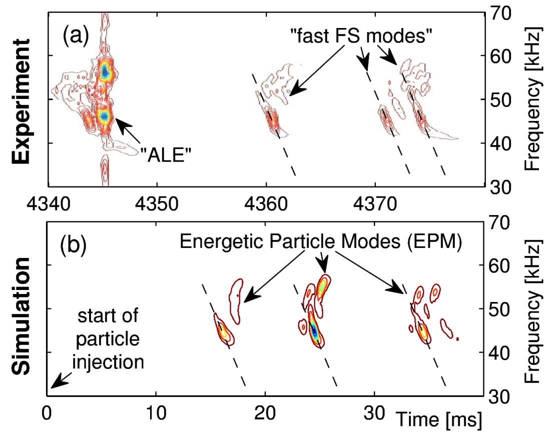

Fig.1. Power spectra of magnetic fluctuations.

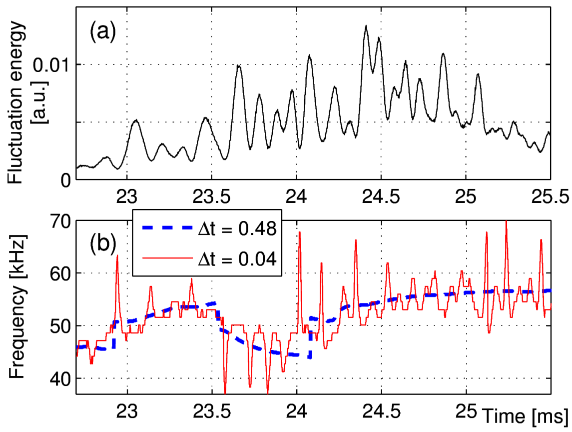

Fig.2. Detailed view of a chirping n=1 EPM burst.

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