Verification of gyrokinetic particle simulation of Alfven eigenmodes excited by external antenna and by fast ions

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Here we report an important step in developing the gyrokinetic capability for the Alfven wave physics in magnetic fusion plasmas: verification of the global gyrokinetic toroidal code (GTC) simulations of the toroidal Alfven eigenmode (TAE), reversed shear Alfven eigenmode (RSAE), beta-induced Alfven eigenmode (BAE), and ideal ballooning mode. A novel approach is that GTC utilizes an antenna to excite a damped eigenmode for accurately measuring the real frequency, damping rate, and mode structure, which provides a reliable verification of the gyrokinetic simulation of fast ion excitation of TAE, RSAE, and BAE. The GTC gyrokinetic simulation is also benchmarked with established hybrid MHD codes HMGC and TAEFL by suppressing kinetic effects of thermal ions.

I. Introduction

It is crucial to include kinetic effects of thermal ions and trapped electrons in order to properly account for the damping and, thereby, the instability thresholds for Alfven eigenmodes and energetic particle modes in tokamaks. Therefore, the simulation code must have the capability to resolve the micro-scale thermal ion Larmor radius and finite parallel electric field, i.e., a paradigm shift to the global gyrokinetic simulation is necessary for energetic particle physics in burning plasmas. However, a doubt has been raised whether it is feasible to use the fully kinetic approach for simulating magnetohydrodynamic modes. Here we report an important step in developing the gyrokinetic capability for the Alfven wave physics in magnetic fusion plasmas: verification of the global gyrokinetic toroidal code (GTC) simulations of toroidal Alfven eigenmode (TAE), reversed shear Alfven eigenmode (RSAE) [1], beta-induced Alfven eigenmode (BAE) [2], and ideal ballooning mode. A novel approach is that GTC utilizes an antenna to excite a damped eigenmode for accurately measuring the real frequency, damping rate, and mode structure, which provides a reliable verification of the gyrokinetic simulation of fast ion excitation of TAE, RSAE, and BAE. The GTC [3] gyrokinetic simulation is also benchmarked with established hybrid-MHD and gyro-fluid codes XHMGC [4], TAEFL [5], and BOUT++ [6].

In the GTC simulation, the RSAE excited by fast ions shows an exponential growth. With kinetic thermal ions and electron pressure, the RSAE frequency increases due to the elevation of the Alfven continuum by the geodesic compressibility. In the BAE simulation, the frequency at small safety factor q is slightly higher than the BAE accumulation point frequency. Comparisons between the antenna excitation and the energetic particle excitation show that the BAE frequency excited by the energetic particles has a small downshift. The non-perturbative contributions from the fast ions and kinetic thermal ions modify the RSAE and BAE mode structures relative to the ideal MHD theory. The finite Larmor radius effects of the fast ions are found to significantly reduce the RSAE and BAE growth rate.

II. RSAE

Although many linear properties of the RSAE have been reported, understanding the linear and nonlinear kinetic effects of background plasmas [7] on the RSAE remains inadequate. Recent gyrokinetic simulations [8-11] have focused more on the TAE than the RSAE. Here, we would like to study the linear and nonlinear properties of the RSAE with the thermal particle kinetic effects by using the global gyrokinetic particle code GTC [3]. The current GTC version [12] has new features such as full-f and δf simulation, general geometry using experimental equilibrium data, kinetic electrons and electromagnetic simulation [13, 14]. In the current work, we have successfully excited the RSAE by initial perturbations, by antenna, and by fast ion drives. The RSAE excitation by antenna provides verification of the frequency, damping rate, and the mode structure (Fig. 1). When the kinetic effects of the background plasma are artificially suppressed, the mode amplitude shows a near-linear growth. With kinetic thermal ions, the mode amplitude eventually saturates due to the thermal ion damping as shown in Fig. 2. The damping rates measured from the antenna excitation and from the initial perturbation simulation agree very well. Such a damping rate measurement technique has been used in JET [15, 16]. In Fig. 3 The RSAE excited by fast ions shows an exponential growth. The finite Larmor radius effects of the fast ions are found to significantly reduce the growth rate. With kinetic thermal ions and electron pressure, the mode frequency increases due to the elevation of the Alfven continuum by the geodesic compressibility (Fig. 2). The non-perturbative contributions from the fast ions and kinetic thermal ions modify the mode structure relative to the ideal MHD theory, as seen in Figs. 1 and 3. The gyrokinetic simulations have been benchmarked with extended hybrid MHD-gyrokinetic (XHMGC) [4] simulations as shown in Figs. 1 and 3.

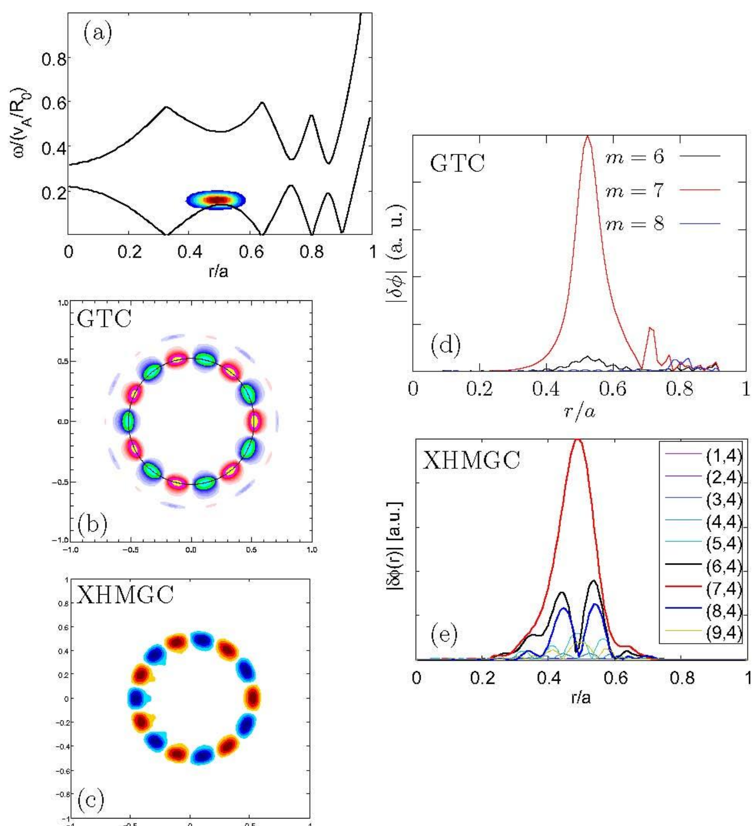

FIG. 1. Antenna excitation of n = 4, m = 7 RSAE without kinetic thermal ion, using GTC and XHMGC. (a) Alfven continua and frequency spectrum from XHMGC. (b)(c) Poloidal contour plots of electrostatic potential δϕ from GTC and XHMGC, respectively. (d)(e) Radial profiles of δϕ m-harmonics from GTC and XHMGC, respectively.

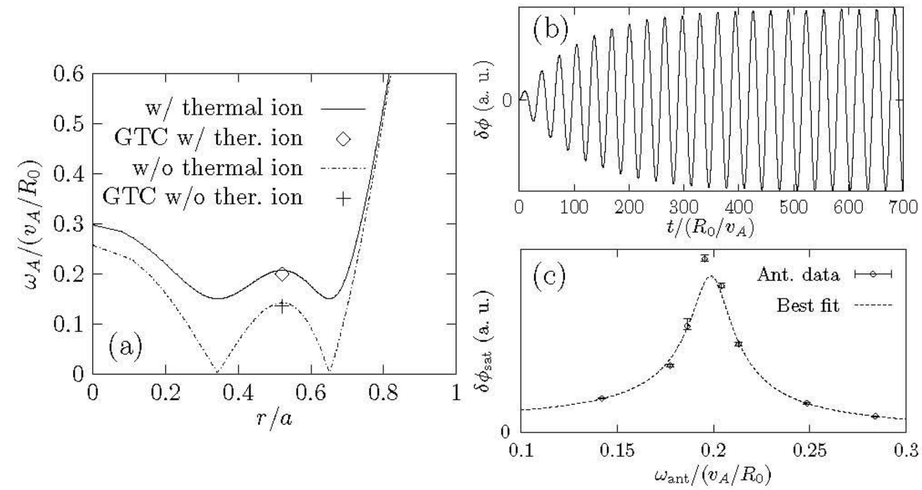

FIG. 2. Antenna excitation of n = 4, m = 7 RSAE with kinetic thermal ions using GTC. (a) m = 7 Alfven continua and eigen-frequencies obtained from GTC simulations, with and without thermal ions. (b) Time history of electrostatic potential δϕ for antenna frequency $\omega_{ant} = 0.195 v_A/R_0$ showing saturation of the mode. (c) Saturated δϕ amplitude versus antenna frequency and best fit to estimate the RSAE damping rate.

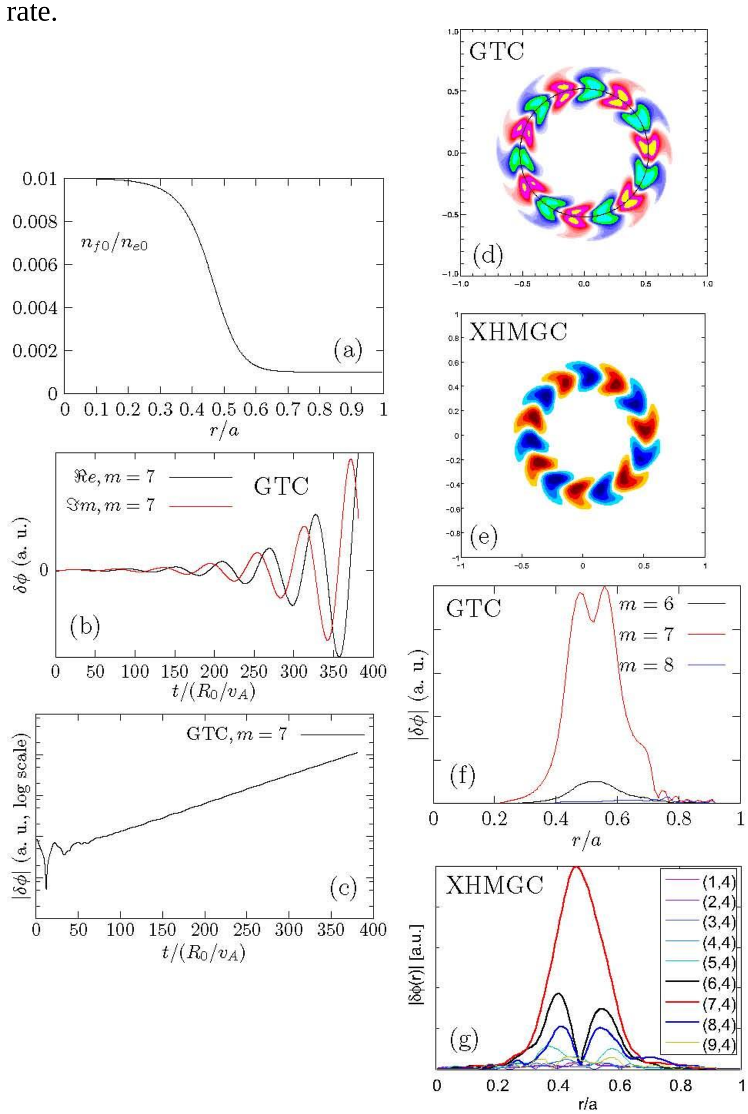

FIG. 3. Fast ion excitation of n = 4, m = 7 RSAE without kinetic thermal ions, using GTC and XHMGC. (a) Fast ion density profile. (b) Time history of electrostatic potential δϕ. (c) Time history of |δϕ| in log-linear plot. (d)(e) Poloidal contour plots of δϕ from GTC and XHMGC, respectively. (f)(g) Radial profiles of δϕ m-harmonics from GTC and XHMGC, respectively.

III. BAE

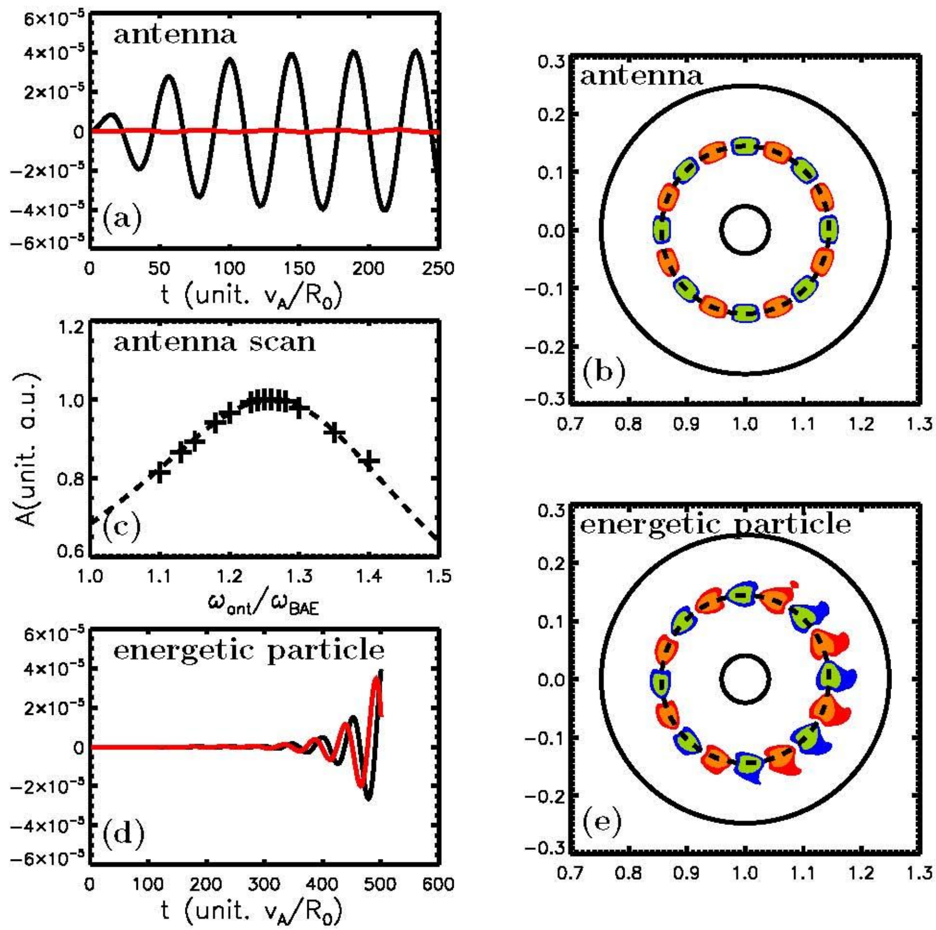

Fig. 4. Time evolution (panel (a)) and poloidal mode structure (panel (b)) of the BAE excited by antenna with $\omega_{ant} = 1.67 v_i/R_0$. Panel (c): saturated amplitude vs. antenna frequency. The dashed line is the numerical fit. Panels (d) and (e) are the time evolution and poloidal mode structure of the BAE excited by energetic particles. In panels (a) and (d), the black line is the real part and the red line is the imaginary part. In panels (b) and (e), the dash circle is the q = 2 surface.

The BAE frequency is due to the finite compressibility induced by the geodesic curvature of the equilibrium magnetic field, together with the plasma pressure [17]. The BAE is observed in various tokamaks with energetic particles [18], strong tearing mode activity [19], and ion cyclotron resonant heating [20]. Although there has been extensive experimental and theoretical work on the BAE, little has been reported on BAE simulations [4] and nonlinear studies. In this work, using the electromagnetic gyrokinetic toroidal code (GTC) [3], we carry out gyrokinetic particle simulation of the BAE for the first time. GTC has been successfully applied to the simulations of magnetohydrodynamic (MHD) Alfven eigenmodes [1, 2, 9] and geodesic acoustic modes (GAM) [21, 22]. Here, we successfully excite the BAE in GTC simulations both by an antenna and by energetic particle density gradients as shown in Fig. 4. The antenna excitation method enables us to measure the BAE frequency, damping rate, and mode structure accurately for verifying GTC simulation of the BAE excited by the energetic particles. We find that the BAE frequency at small safety factor *q* is slightly higher than the BAE accumulation point frequency, and also higher than the theoretical prediction. The energetic particle excitation shows an exponential growth of the BAE (Fig. 4). Comparisons between the antenna excitation and the energetic particle excitation show that the BAE frequency excited by the energetic particles has a small downshift. The BAE frequency in both antenna and energetic particle excitation varies slightly with the plasma β and $k_\theta \rho_i$ (β is the ratio between plasma pressure and magnetic pressure, k_θ and ρ_i are the poloidal wave number and thermal ion Larmor radius, respectively.). The BAE growth rate in the energetic particle excitation is sensitive to the energetic particle temperature and density. Furthermore, we find that non-perturbative contributions by the energetic particles modify the BAE mode structure and frequency relative to the ideal MHD theory as shown in Fig. 4. The finite Larmor radius effects of the energetic particles reduce the BAE growth rate. Benchmarks between GTC and a hybrid MHD-gyrokinetic code XHMGC [4] show that the results of the two codes agree well on the frequency and mode structure, which provides a further verification of the gyrokinetic particle simulation of the BAE.

IV. TAE

The simulation of the linear n=1 TAE instability used the same parameters of a TAE theory [23]. The linear eigenmode structure, linear frequency, growth rates, and the ratio of the growth rate to the real frequency from the GTC simulation agree well with the theory [9]. The GTC simulation has been benchmarked with an MHD-gyrofluid hybrid code TAEFL [5], using the toroidal mode numbers, $n=3\text{-}10$, and the central fast ion $\beta_{EP}(0)$=0.01-0.04. GTC and TAEFL find unstable TAE modes with real frequencies in the gap and growth rates that are close (±20%). GTC simulations of the n=5 TAE driven by both antenna and by fast ions have been performed. Fig.5 shows good agreement in mode structure (and frequency) between antenna and fast ion excitation.

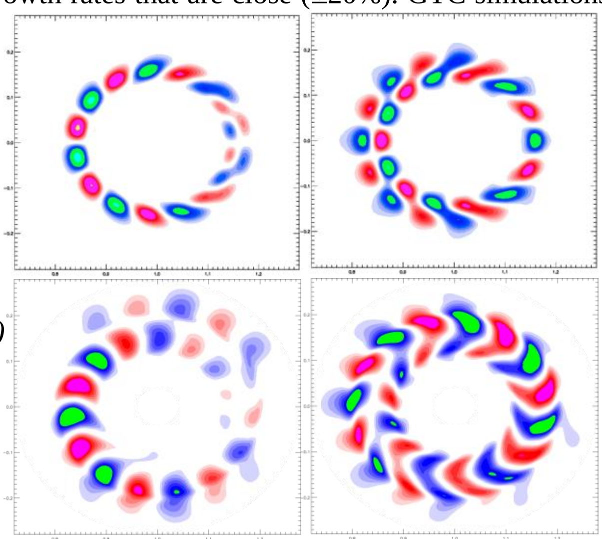

Fig. 5 *GTC simulation of n=5 TAE excitation by an antenna (upper panels) and fast ions (lower panels). Left column is the contour plots of vector potential ($A_{||}$) and right column is electrostatic potential (ϕ).*

V. Ideal Ballooning Mode

Although the understanding of edge turbulence and ELM dynamics has made significant progress during the last decade, a quantitative model of the complete ELM cycle is still elusive. Traditionally MHD, extended MHD and various fluid codes are used for simulating ELM dynamics. With the large driving gradients, transport is likely dominated by nonlinear physics. For example, linear theory cannot explain the slow inward propagation of the pedestal (mainly density) in the ELM precursor. The nonlinear transport during various times of the pedestal recovery period could be driven not only by the KBM or resistive ballooning mode, but also by other microinstabilities, involving wave-particle resonance that is best simulated by kinetic codes. In addition, coupling between different scales could contribute to the crash of the pedestal and the complex nature of the ELM cycle. Therefore, it is desirable to have a kinetic code that deals simultaneously with the longer wavelength, fast time scale MHD modes and the shorter wavelength, slow time scale drift wave modes simultaneously. To this end, we have verified the GTC simulations of the ideal ballooning mode and KBM [24]. In Fig. 7, GTC simulation of the ideal ballooning mode has successfully demonstrated the predicted mode structure and the existence of the instability threshold, and found the linear growth rate in Fig. 8 close to the results [25] of a fluid code BOUT++ [6] and other fluid codes in Ref. 25 when the kinetic effects is artificially suppressed in GTC simulations.

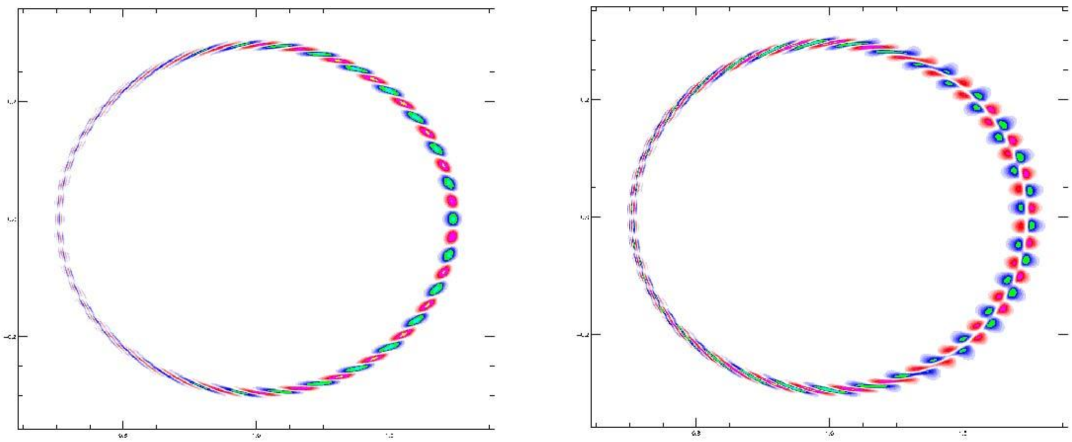

Fig. 6: GTC simulation of ideal ballooning mode: poloidal contour plot of electrostatic potential (left) and vector potential (right).

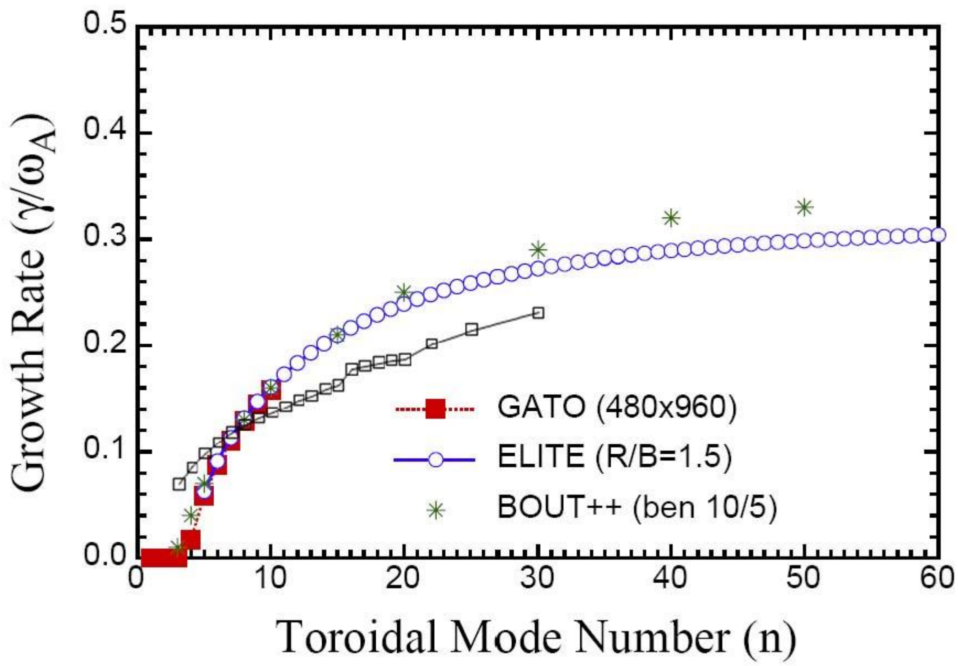

Fig. 8: GTC simulation of ideal ballooning mode: linear growth rate as a function of n, compared to the results from several fluid codes in Ref. [25].

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