Verification and Validation of Global Gyrokinetic Simulations of Alfvén Eigenmodes in Spherical Tokamaks

H.H. Wong,[1] H. Huang,[2] P. Liu,[2] Y. Yu,[2] X. Wei,[2] G. Brochard,[3] N.N. Gorelenkov,[5] N. Fil,[4] Z. Lin,[2] M. Podesta,[5,6] P.J. Bonofiglo,[5] K.G. McClements,[4] C.A. Michael,[1] N.A. Crocker,[1] L. Garzotti,[4] and T.A. Carter[1,7]

1)University of California, Los Angeles, Los Angeles, CA 90095, USA

2)University of California, Irvine, Irvine, CA 92697, USA

3)ITER organization, St. Paul Lez Durance, France

4)United Kingdom Atomic Energy Authority, Culham Campus, Abingdon, Oxfordshire OX14 3DB, UK

5)Princeton Plasma Physics Laboratory, Princeton, NJ 08543,USA

6)École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

7)Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA

Energetic particles (EPs) from neutral beam injection (NBI) can induce instabilities in fusion plasmas leading to significant transport or losses of the EPs, threatening both heating efficiency and the integrity of plasma-facing components. Hence, the development of simulations capable of accurately modeling these instabilities and their associated EP transport is essential for the success of future fusion reactors. It is important to use a kinetic description for both the thermal plasma and the beam fast ions to assess the stability of these NBI-induced modes. Global gyrokinetic (GK) codes. The design of spherical tokamaks (STs) offers many advantages as a promising fusion reactor but also brings challenges when attempting to use global gyrokinetic code GTC [1] to simulate NBI-induced Alfven eigenmodes in STs. STs have a smaller aspect ratio compared to conventional tokamaks, offering higher plasma pressure and improved plasma stability. However, some unique features in STs, such as the strong field gradient on the high-field side and the high fast-ion-to-thermal-ion beta ratio compared to conventional tokamaks, have not been thoroughly tested in gyrokinetic simulations. The works presented here aim to bridge this gap by validating the first global gyrokinetic simulations of the Toroidicity-driven Alfvén Eigenmodes (TAEs) in the Mega-Amp Spherical Tokamak (MAST) and beam-driven low-frequency modes (LFMs) in ST-40.

Verification and Validation of Linear GTC Simulations of TAEs in MAST

This work compares the measured characteristics of TAE in MAST plasma discharge 26887 to various simulations using GTC, as well as an ideal MHD simulation from NOVA [2]. The targeted TAE-like mode has a toroidal mode number $n = 1$, frequency starting at ~90 kHz (in the lab frame with a rotational Doppler shift) and down-chirped to ~60 kHz in ~2 ms, and a radial mode structure peaking near the $|q| = 1.5$ surface, inferred from various diagnostics [3]. These results are compared with the NOVA calculations and show good agreement. The TAE from NOVA has the dominant $m = 1, 2$ located near the $|q| = 1.5$ surface with a frequency at 88 kHz, which is at the bottom of the $n = 1$ Alfvén continuum gap. These results match the expected properties of an $n = 1$ TAE in an ST.

The NOVA results serve as a baseline for GTC simulations, which can calculate properties and physical mechanisms excluded in linear MHD simulations. Various GTC simulations using an analytic antenna module are performed to study the damping mechanisms of the TAE. Antenna-excited TAE runs in single-, two-fluid, and GK thermal ions reveal that ion Landau damping is responsible for most of the damping, with the total damping rate at -11.0% [3]. This highlights the importance of using simulations with the kinetic descriptions of the thermal ions, as linear MHD codes like NOVA only include continuum damping and do not account for other damping mechanisms.

The capabilities of exciting TAE in GTC using fast-ion distributions are also tested. Maxwellian fast-ion distributions containing analytic fast-ion density profiles that mimic the NUBEAM/TRANSP [4] fast-ion density profiles are employed to excite TAEs in the linear GK regime in GTC, revealing the instability threshold of the mode. The total growth rate of the TAE is roughly linearly proportional to the fast-ion density scaling factor. The result also reveals that TAE has a stability threshold with fast-ion beta slightly below the value from

NUBEAM/TRANSP. Apart from Maxwellian distributions, analytic fast-ion slowing-down distributions are also utilized to excite the TAE in GTC, which is the first time this has been done in a gyrokinetic simulation for an instability in an ST. The use of anisotropic fast-ion distributions alters the mode spatial structure slightly and increases the mode growth rate significantly. This is most likely the result of the increased number of trapped fast ions excited by the anisotropic fast-ion distribution compared to the Maxwellian fast-ion distribution. These results showcase and test the capabilities of incorporating fast-ion distributions and fast-ion kinetic models in GTC, which are absent in ideal MHD codes.

Verification and Validation of GTC Simulations of LFMs in ST-40

A similar approach is applied to compare characteristics of LFMs in ST-40. A mode from the ST-40 discharge 09894 is selected as the target because of its distinct transition from a steady phase to pronounced chirping behavior. The targeted mode has a toroidal mode number $n = 1$, poloidal mode number $m = 1$, and dominant frequency ranging from 100–150 kHz, starting at around 0.075 s, with the transition from fixed frequency to chirping occurring at around 0.090 s. A NOVA run was conducted in previous work [5], showing a dominant $m = 1$ structure located near the magnetic axis with a frequency at around 128 kHz (in the lab frame with rotational Doppler shift). This led to an identification of the mode as a Beta-induced Alfvén-Acoustic Eigenmode (BAAE) in earlier work, as the NOVA run result is within the BAAE gap in the Alfvén-acoustic continuum.

GTC simulations of the targeted Alfven eignmode in the ST-40 exhibit differences from NOVA results, indicating that the mode might have been misidentified previously. In linear GTC simulation using antenna, the damped mode structure, frequency, and continuum from the ideal MHD GTC simulations are similar to those from NOVA calculations. However, the mode frequencies from ideal MHD simulations of both codes differ significantly from the measurements, suggesting that the mode might not be in the BAAE gap. Instead, a low frequency mode (LFM) arises in GTC simulations using the gyrokinetic model, exhibiting characteristics closer to the measured mode. GTC gyrokinetic simulations with fast ions present are also conducted. However, the mode damping rate increases as fast-ion density rises. Together with the phase-space resonances and wave-particle energy exchange analyses (shown in Figure 1), these results from gyrokinetic simulations in GTC suggest the LFM is primarily driven by thermal species rather than fast ions. These findings showcase the importance of using global gyrokinetic models like GTC to correctly identify the Alfven eigenmode and provide insights into the driving mechanisms of the instability.

Conclusion

Global gyrokinetic simulations using GTC are conducted to investigate a TAE in MAST and an LFM in ST-40 spherical tokamaks. In the MAST case, fast-ion distributions are used in GK simulations to excite TAEs, marking a first global gyrokinetic simulation of the Alfven eigenmode in an ST equilibrium. In the ST-40 case, an LFM and its driving mechanisms are identified using gyrokinetic simulations in GTC, demonstrating the importance of using global gyrokinetic models for simulating Alfven eigenmodes in ST.

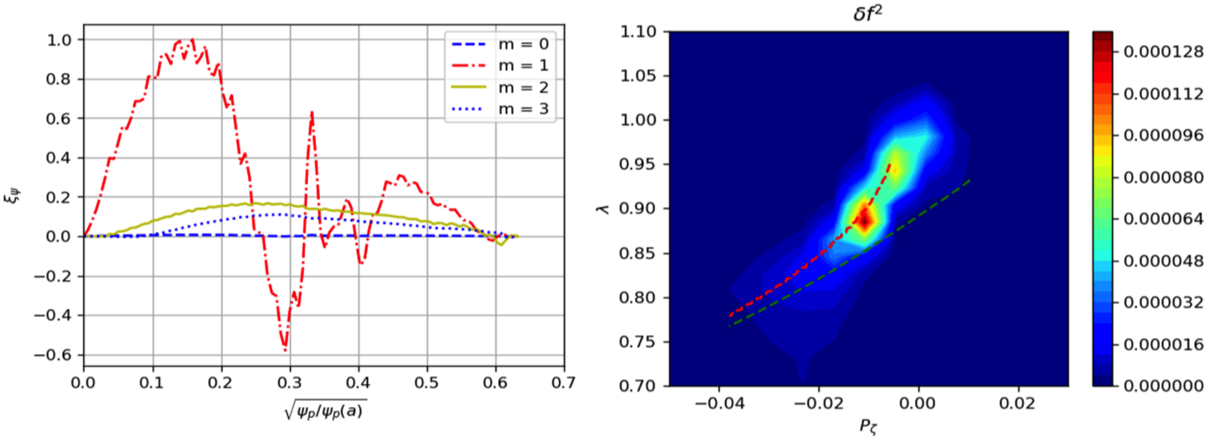

Figure 1 (a) Radial mode structure of LFM in ST40 spherical tokamak from GTC gyrokinetic simulation. (b) The entropy distribution in (P_ζ, λ) space for particles with μ value ranging from 1.1 E_0/B_a to 1.85 E_0/B_a. The red dashed line is the boundary between passing particles and trapped particles, while the green dashed line is where the transit frequency of ion coincides with the low frequency wave.

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