The drift kinetic and rotational effects on determining and predicting the macroscopic magnetohydrodynamic instability

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Many advanced tokamaks, e.g. ITER towards the steady state operation, will require the high plasma current to maintain the plasma confine and the high normalized pressure to generate efficiently high fusion energy. One of most prominent obstacles to achieve such high plasma performance is the macroscopic magnetohydrodynamic (MHD) instabilities such as resistive wall mode (RWM), and ideal wall mode (IWM) which can cause the severe plasma disruption. The reliable prediction base on the modelling of MHD theory is crucial to avoid these instabilities. Therefore, carrying out the quantitative validation of MHD model with the experiments in high pressure plasma becomes important. The activity can verify the present MHD model and indicate what physics is essential to be included in MHD theory.

For instance, the drift kinetic and flow rotational effects have been extensively studied and compared with the experiments. It has shown the necessity of including these effects on determining MHD instability. The MARS-K code, having the capability to solve MHD equations with the kinetic effects and plasma flow self-consistently, predicts the consistent ideal wall β_N limit and the mode frequency with NSTX experimental measurements [1]. In Fig.1(a), β_N limit predicted by fluid MHD (no kinetic effects) is reduced from 5.6 (black) to 4.2 (red) due to the destabilizing effects of flow rotation while including the experimental Ω_ϕ. However, the hybrid kinetic-MHD, solved by MARS-K, predicts the rotation-destabilized IWM is substantially re-stabilized by the kinetic effect as indicated by the three γ curves (green, blue, orange) for the varied fast-ion pressure profiles shown in the inset of Fig.1(a). The predicted kinetic marginal β_N from 5.3 to 5.5 is more consistent with the experimental marginal β_N range than the fluid predication. The more frequency of kinetic IWM also is more consistent with experiments. This IWM study clearly shows the importance of self-consistently solving MHD instability with kinetic and rotational effects in high β plasmas. Especially, MARS-K simulation shows the kinetic effects can largely change the structure of fluid mode eigenfunction resulting in the kinetic IWM eigenfunction.

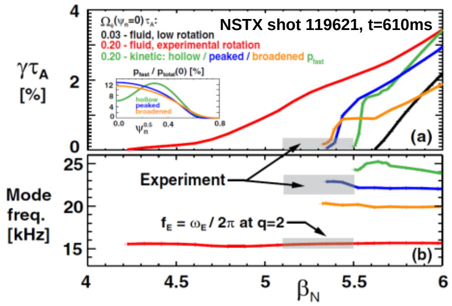

Figure 1. (a) Fluid and kinetic IWM growth rate (γ) vs β_N and flow rotating frequency (Ω_ϕ), and (b) predicted and measured mode frequency vs β_N.

The further quantitative validation of the self-consistent computation of hybrid kinetic-MHD theory was the application of MARS-K to study DIII-D n=1 plasma response experiments in the presence of external nonaxisymmetric magnetic perturbations [2]. This work resolves an long-standing issue, where ideal MHD theory finds a singular amplification of plasma response near no-wall β_N limit, denoted as $\beta_N^{\text{no wall}}$. In contrast, the experiments show the plasma response increases almost linearly along with β_N across$\beta_N^{\text{no wall}}$. This disagreement between ideal MHD theory and experiments is shown by the blue and black curves in Fig 2(a). Due to the dissipative kinetic energy, the plasma response (red curve), computed by hybrid kinetic-MHD theory with MARS-K, shows a much better agreement with experiments. The simulated internal structures of response is also compared with experimental measurement at β_N= 0.87$\beta_N^{\text{no wall}}$ in Fig 2(b). It is noted that only the kinetic response shows very good agreement with experiments. This eventually indicates the validation of kinetic modification on response structure and mode eigenfunction. Moreover, only the hybrid kinetic-MHD theory, consistent with the experimental observation, predicts that RWMs are stable while β_N>= 1.12$\beta_N^{\text{no wall}}$.

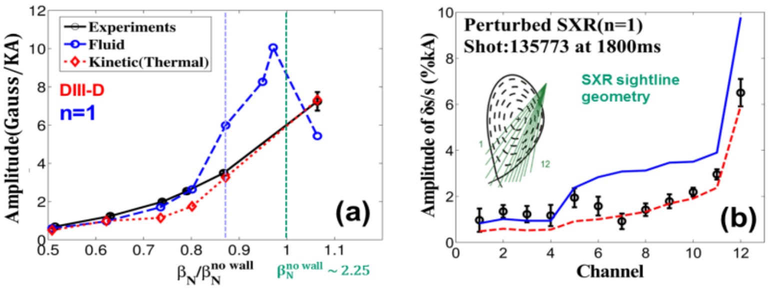

Figure 2. (a) The amplitude of plasma response measured at the magnetic sensor is plotted as the function of β_N for fluid (blue) and kinetic (red) response. (b) Comparison of amplitude between the measured (black) and computed soft x-ray structure of response at $\beta_N = 0.87\beta_N^{NW}$. The inset in (b) shows x-ray sightline geometry of each channel. Here, β_N^{NW} is around 2.25.

Recently the first order correction of finite orbit width (FOW) has been implemented into the kinetic-MHD model in MARS-K and applied to predict the RWM stability for 9 MA steady state ITER plasma [3]. The results show that the FOW correction of the energetic particles (EPs, e.g. α particles) can significantly reduce the mode growth rate but also decrease the no-wall β_N limit. It indicates that the careful investigation of FOW effect on MHD instability should be taken while EPs is included in the high performance plasmas.

Though the hybrid kinetic-MHD theory has been successfully validated and used to predict the experiments, the more sophisticated experimental validation and the more complete kinetic model development still need to be carried out for better predicting the plasma behavior. Therefore, we list the following subjects which can be important to the future study of kinetic and rotational effects on MHD instabilities.

(1) Scanning the rotating frequency of magnetic perturbation in a wide range and plot the measured plasma response in the complex plane can form the Nyquist contour. Comparing the measured and simulated contours will give more clear information about how the kinetic effects change MHD instability. The contour will also provide the direct evidence about the multi-mode response and even infer the damping rate of stable MHD modes. The plasma transfer function, which can be very useful to the design of feedback system, will also be obtained from the experimentally measured contour.

(2) It will be important to study how tearing modes are triggered by RWM and IWM in NSTX/NSTX-U. The damping of fluid rotation at q=2 surface due to NTV torque, which is caused by unstable RWM/IWM, may destabilize the tearing mode. Since MARS-K can compute the neoclassical toroidal viscosity (NTV), the interaction among NTV, ideal MHD instability and tearing instability can be studied by the code.

(3) Including more complete kinetic effects, such as the perturbed electrostatic potential and the experimental distribution function of EPs, will be important to MARS-K for more reliable experimental prediction and get deeper understanding of kinetic effects on MHD instabilities.

(4) Presently, the computation of kinetic effects in MARS-K has been parallelized. If the parallelization could be made for the finite element solver, the efficiency of code will be largely improved. With the future much more powerful high performance computer, MARS-K might have the chance to perform the real-time computation to predict stability limits and guide actuators to avoid the MHD limits.

(5) The semi-analytic treatment of kinetic effects as developed in MARS-K maybe a good candidate for the incorporation of the kinetic effects in the non-linear code e.g. M3D-C1. It will enlarge our capability to study how the kinetic effects affect RWM/IWM, tearing instabilities etc. while the modes develop in the non-linear phase.

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