Simulation study of magnetohydrodynamic instabilities in Variable Symmetry Torus

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Variable Symmetry Torus (VAST) shown in Fig. 1 is a device currently being considered as one of the candidates for the successor to the Large Helical Device (LHD) at the National Institute for Fusion Science [1, 2]. By adjusting the coil currents, it can realize different types of quasi-symmetric magnetic configurations, such as quasi-axisymmetric (QA) and quasi-isodynamic (QI)-like configurations, within a single device. This study presents the current status of the investigation on VAST from the perspective of magnetohydrodynamic (MHD) stability based on simulation studies.
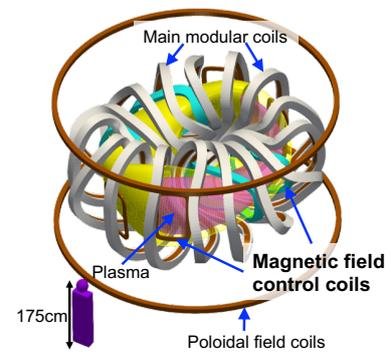

Fig. 1 Conceptual illustration of VAST.

In this analysis, the MHD equilibrium was constructed using the HINT code [3], a three-dimensional MHD equilibrium code that does not assume the existence of magnetic surfaces. The MHD stability was then evaluated using the MIPS [4] and MEGA [5] codes. The MIPS code is a nonlinear MHD simulation code capable of solving either the single-fluid MHD model or the Hazeltine-Meiss (HM) model, which incorporates diamagnetic drift effects. The code is based on cylindrical coordinates (R,ϕ,Z), with spatial discretization performed using a fourth-order finite difference method and time integration carried out using a fourth-order Runge-Kutta method. On the other hand, the MEGA code is a kinetic MHD simulation code that incorporates ion kinetic effects by treating ions using a drift-kinetic model. In this study, only the kinetic effects of thermal ions are considered; fast ions are neglected. In the simulations, the number of grid points is $256 \times 512 \times 256$ and the number of marker particles is $256\times512\times256\times64\approx2\times10^9$.

Figures 2 and 3 show the magnetic field strength distribution, Poincaré plots of magnetic field lines on poloidal cross-sections, and rotational transform profiles for the QA and QI-like configurations obtained by the HINT code, respectively. The pressure profile is assumed to follow $(1-s)^{1.5}$, with a central beta value of 2%. Here, s is the normalized toroidal flux. In the QA configuration, similar to a tokamak, the low magnetic field region is located on the outer side of the torus. In contrast, in the QI-like configuration, the weak
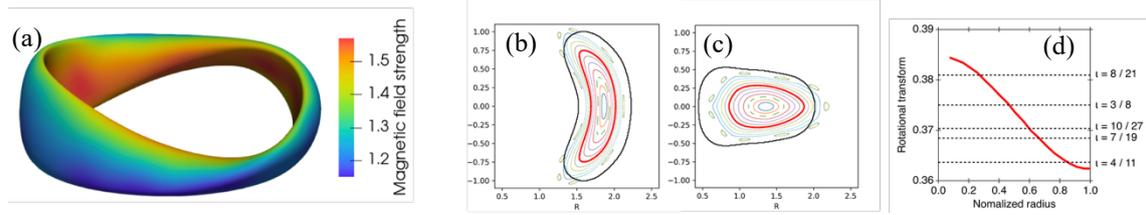
Fig. 2 The magnetic field strength distribution, Poincaré plots of magnetic field lines on poloidal cross-sections, and rotational transform profiles for the QA configuration. In (b) and (c), the red curve and black curves shows the plasma-vacuum boundary and the vacuum vessel, respectively.
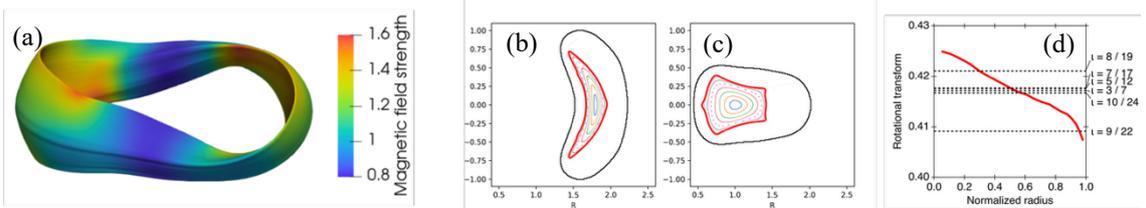

Fig. 3 The magnetic field strength distribution, Poincaré plots of magnetic field lines on poloidal cross-sections, and rotational transform profiles for the QI-like configuration. In (b) and (c), the red curve and black curves shows the plasma-vacuum boundary and the vacuum vessel, respectively.

field region is localized near the horizontally elongated cross-section. As a result, in the QI-like configuration, trapped ions confined in this weak field region cannot circulate toroidally. As shown in Figs. 2(d) and 3(d), the magnetic shear is weak for both QA and QI-like configurations, and rational surfaces corresponding to n=1, 2 are not present within the plasma.
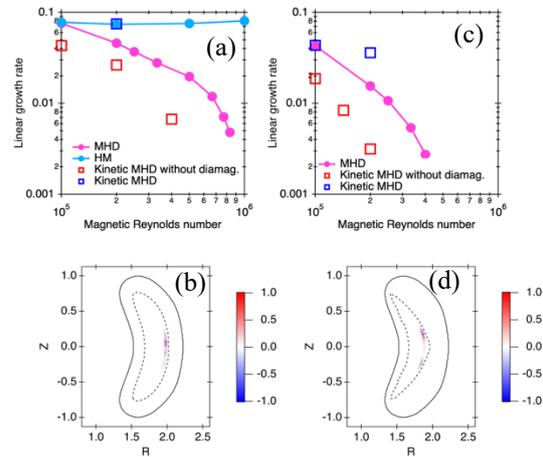

Fig. 4 Dependence of the linear growth rate of the most unstable mode on the magnetic Reynolds number, and the profile of the perturbed pressure for $S=10^5$, in the QA (a, b) and QI-like (c, d) configurations.

Figures 4(a) and 4(c) show the dependence of the linear growth rate of the most unstable mode on the magnetic Reynolds number S, as obtained from both the MIPS and MEGA code depends on S, indicating that the instability is resistive in nature. Figures 4(b) and 4(d) present the profile of the perturbed pressure for $S=10^5$. In both QA and QI-like configurations, the mode structures are localized on the outboard side of the torus and exhibit ballooning-like characteristics. In the QA configuration, results using the HM model are also shown; the linear growth rate is larger than in the standard MHD model and is independent of S. This suggests that the diamagnetic drift effect has a destabilizing influence on the mode. The results obtained with the MEGA code for the kinetic MHD model include both cases—with and without diamagnetic drift effects. Compared to the

MHD model, the growth rate decreases when only kinetic effects are included, but increases when diamagnetic drift effects are also considered. In the QA configuration, the growth rate becomes comparable to that obtained with the HM model. These results suggest that while the kinetic effects of thermal ions have a stabilizing effect on the mode, the destabilizing effect of the diamagnetic drift dominates.

Fig. 5 Time evolution of the kinetic energy and radial profile of the (m,n)=(0,0) component of pressure at the saturated state for the QA (a, b) and QI-like (c, d) configurations. In (b) and (d), the black curve corresponds to the initial equilibrium profile. The saturated-state pressure profiles in the horizontally elongated poloidal cross section are also shown.

Figures 5(a) and 5(c) compare the time evolution of the kinetic energy for different models at $S=10^5$. In the QA configuration, although the linear growth rates in the HM and kinetic MHD models are higher than in the MHD model, the saturation levels are lower. As shown in Fig. 5(b), the radial profiles of the (m,n)= (0,0) component of the pressure in the saturated state show that in the MHD model, the pressure decreases significantly from the initial profile. In contrast, the deviation from the initial profile is small in both the HM and kinetic MHD models. For the QI-like configuration, the saturation levels of the MHD and kinetic MHD models are similar, and in both cases, the (m,n) =(0,0) component does not show significant deviation from the initial profile. These results indicate that while the diamagnetic drift effect increases the linear growth rate, it does not necessarily lead to an increase in the saturation level.

Figure 6 shows the profile of pressure fluctuations on a horizontally elongated poloidal cross-section in the saturated state, obtained from the kinetic MHD model. In the QA configuration, no significant difference is observed in pressure fluctuations parallel or perpendicular to the magnetic field. In contrast, in the QI-like configuration, although the
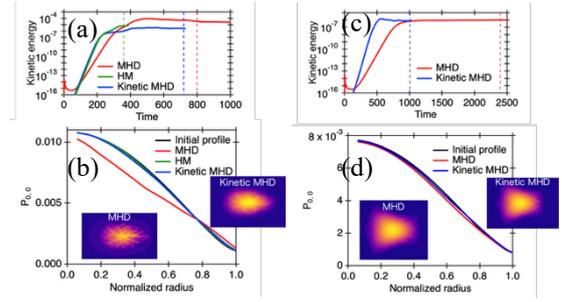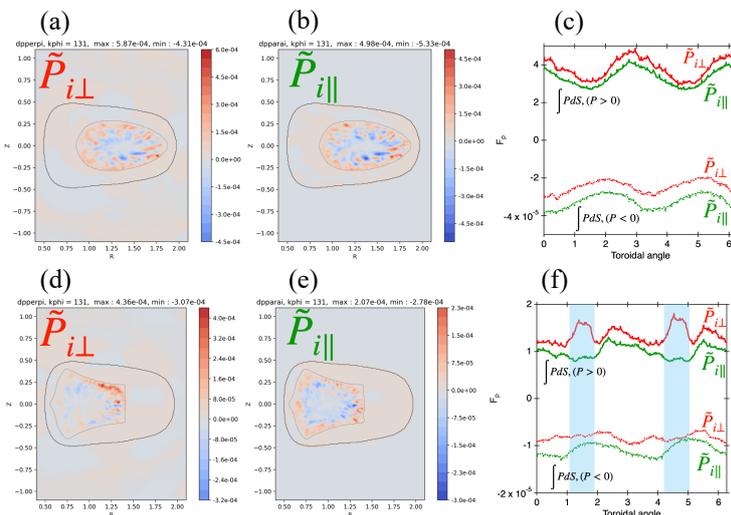

Fig. 6 Ion fluctuating pressure profile in the horizontally elongated cross section and the toroidal-angle dependence of the fluctuation amplitude at each poloidal cross section in the saturated state obtained from the kinetic MHD model for QA (a-c) and QI-like (d-f) configurations.

vertically elongated cross-section shows little difference, the horizontally elongated cross-section exhibits a clear distinction in the fluctuation distribution. Figures 6(c) and 6(f) show the toroidal angle dependence of the positive and negative amplitudes of pressure fluctuations. Here the positive (negative) amplitude is defined as $\int P dS$ where the area integration is performed on each poloidal cross section, and dS denotes the surface element. Only positive (negative) values of P are considered. In the QA configuration, the toroidal dependence of the fluctuations parallel and perpendicular to the magnetic field is similar. However, in the QI-like configuration, a significant increase in the perpendicular component of positive pressure fluctuations is observed near the weak field region around the horizontally elongated cross-section. This is considered to be a consequence of the trapped ions localized in this weak field region.

In this study, we investigated the MHD stability of the Variable Symmetry Torus (VAST) configuration at a central plasma beta of $\beta_0 = 2\%$. The identified linear instability is a three-dimensional, resistive, pressure-driven mode characterized by strong toroidal mode coupling. Despite the presence of this instability, no significant degradation in plasma confinement is observed in the nonlinear saturated state. When kinetic effects are incorporated through the kinetic MHD model, the linear growth rate increases compared to the ideal MHD model. Nevertheless, the saturated confinement performance remains largely unaffected. Furthermore, in the quasi-isodynamic (QI) configuration, the kinetic model reveals strong anisotropy in the pressure fluctuation mode structure in the saturated state, particularly in regions of weak magnetic field.

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