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Stabilization of kink/peeling modes by coupled rotation and ion diamagnetic drift effects in QH-mode plasmas in DIII-D and JT-60U

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MHD stability at edge pedestal in QH-mode plasmas in DIII-D and JT-60U was analyzed by considering plasma rotation and ion diamagnetic drift effects. It was found for the first time the coupled rotation and ion diamagnetic drift effects can stabilize a kink/peeling mode in both experiments in case the rotation direction is counter to the plasma current direction although it has been recognized the rotation alone destabilizes the mode regardless of its direction. The stabilizing mechanism was identified as reduction of the destabilizing energy flow from rotation to the mode due to the coupling between rotation and ion diamagnetic drift. The coupling can be harnessed to both stabilize and destabilize the kink/peeling mode by switching the rotation direction. This trend could be the reason QH-mode plasmas in DIII-D and JT-60U favor toroidal rotation counter to the plasma current direction.

In H-mode regime in tokamaks, edge localized modes (ELMs) often appear and induce large heat load to divertors. Since the heat load is unacceptable for future large reactors like ITER and DEMO, it is necessary to suppress or mitigate the ELMs. Quiescent H-mode (QH-mode) is one of the promising candidates realizing ELM suppression and high confinement performance with reactor-relevant plasma parameters [1]. One of the characteristics of QH-mode is the appearance of edge harmonics oscillations (EHOs) although ELMs disappear. Since QH-mode can be obtained experimentally when plasma current I_p and sheared rotation counter to the I_p direction (counter-I_p direction) are large near plasma surface, current-driven MHD (kink/peeling) mode destabilized by rotation has been recognized as the trigger of the EHOs. In the plasmas, the ion diamagnetic drift frequency ω_{*i} can be comparable to the plasma rotation frequency $\Omega_{v\times B}$, hence, the E×B rotation frequency $\Omega_{E\times B} = \Omega_{v\times B} + \omega_{*i}$ has been considered as a strong candidate of the rotation responsible for QH-mode. However, it has not been identified numerically the importance of $\Omega_{E\times B}$ for realizing QH-mode even in nonlinear MHD simulations [2].

In this study, to identify the key mechanism explaining the role of rotation for triggering the EHOs, we analyze the impact of plasma rotation on kink/peeling mode stability in QH-mode plasmas in DIII-D and JT-60U by considering $\Omega_{v\times B}$ and ω_{*i} simultaneously with the linear extended MHD stability code MINERVA-DI [3]. The analyzed DIII-D plasma is #153440/1.725sec., and the JT-60U plasma is E42868/6.5sec.; in both plasmas,

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the EHOs were observed with the dominant $j_{ped,max}, \alpha_{max}$ harmonic in DIII-D and ω_{*i} and ω_{*i} harmonics in JT-60U, where ω_{*i} is the toroidal mode number. The $\Omega_{v\times B,C}$ profile is determined with the measured rotation of carbon $j_{ped,max}$, where the toroidal component of this rotation is in the counter-ω_{*i} direction. In both plasmas, when analyzing the MHD stability without the $n = 2$ effect, the stability boundary on the ($n = 2$) stability diagram indicates the kink/peeling mode is slightly destabilized by 4 rotation because the mode can be unstable with a small amount of n as shown in Fig. 1 (a) (DIII-D), where $\Omega_{v\times B}$ is the maximum flux averaged current density at pedestal, and $\Omega_{v\times B,C}$ is the maximum normalized pressure gradient. The trend is consistent with the previous results discussing the impact of sheared rotation on the ideal kink/peeling mode stability I_p. However, when considering the ω_{*i} effect, the kink/peeling mode in rotating plasmas requires a larger amount of $j_{ped,max}, \alpha_{max}$ for destabilization as shown in Figs. 1 (b) (DIII-D) and (c) (JT-60U); namely, rotation stabilizes the MHD mode in both plasmas. Note that the operation points exist near the stability boundary of the kink/peeling modes whose $\Omega_{v\times B,C}$ number is $j_{ped,max}$ in DIII-D and $j_{ped,max}$ in JT-60U when analyzing the stability with the rotation and α_{max} effects, and the [4] numbers correspond to the dominant harmonics of the EHOs in both plasmas; the error bars on the point are determined to be ω_{*i} of $j_{ped,max}$ and n.

The physics mechanism stabilizing the kink/peeling mode by the coupled 2 and 4 effects was investigated with the energetics established in ω_{*i}. In ideal MHD case, an MHD mode can be destabilized due to energy flow from a fast-rotating equilibrium to a slow-rotating mode; this is called as dynamic pressure. When including the n effect, it was identified a part of the energy flow from an equilibrium to a mode is proportional to the product of $\pm 20\%$ and $j_{ped,max}$, and the modulation of dynamic pressure through the coupling between α_{max} and $\Omega_{v\times B,C}$ can stabilize the kink/peeling mode. The result also clarifies the coupling can be harnessed to both stabilize and destabilize the mode by switching the rotation direction, because the sign of the energy flow due to the coupling depends on the direction. In fact, when inverting the direction from ω_{*i} to [3] in the DIII-D plasma, the stability boundary on the stability diagram moves downward as shown in Fig. 2.

Based on the result, it is possible to make a hypothesis explaining the reason why QH-mode discharges in DIII-D and JT-60U favor toroidal rotation in the counter-ω_{*i} direction. A plasma can be assumed as axisymmetric before the transition to QH-mode, but when a kink/peeling mode becomes unstable, the plasma has non-axisymmetric distortion. Such distortion can accelerate plasma rotation in the counter-$\Omega_{v\times B,C}$ direction near plasma surface, the rotation which is induced by neoclassical toroidal viscosity as observed in DIII-D ω_{*i}. The kink/peeling mode will stop growing due to the stabilization by the rotation, and as the result, the plasma with non-axisymmetric distortion will be sustained to keep the rotation, the distortion which could be observed as EHOs. In this case, the operation point will be between the stability boundaries with and without rotation effect. The results in Figs. 1 (b) and (c) show the condition can be satisfied, because the error bar of the point is in the area.

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