EFFECT OF DECREASING ASPECT RATIO ON ION-SCALE ELECTROSTATIC DRIFT-TYPE MODES AND PEDESTAL STABILITY IN H-MODE PLASMAS

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Spherical tokamak (ST) with a low aspect ratio (*A*) is receiving strong interest as a compact ignition device for economic fusion reactors. A particular feature of the ST is that the ion-scale electrostatic drift-type modes, such as the ion temperature gradient (ITG) or trapped electron mode (TEM), are often stabilized, with turbulent transport then dominated by the electron-scale mode or the electromagnetic modes, such as the kinetic ballooning mode (KBM) or micro-tearing mode (for example, see Ref. 1-2). This change of the dominant turbulence mode is significant in that, in the conventional tokamak with high *A*, turbulent transport is typically governed by the ion-scale electrostatic modes so the suppression of such modes will facilitate the achievement of high beta plasma with improved confinement. It seems, however, still less certain how such a change or stabilization occurs, even though several mechanisms have been proposed. Closely related to this issue, it looks also important to check further how pedestal stability varies when tokamak type changes from the conventional to the ST one. This is because the overall performance of ST H-mode plasmas closely depends on pedestal height as well as core transport through the profile stiffness. As an effort to understand such global effects of the decreasing *A*, we here give a modelling study on the above two issues related to the core and pedestal regions, respectively.

On the stabilization of ion-scale electrostatic drift-type modes: For this study, we analyse the linear stability the ITG and TEM using some well-known analytic stability theory and kinetic simulation codes. For simplicity, most of these studies are conducted in the s-α equilibrium model. Even though this model becomes less accurate as *A* decreases, it can still provide useful information or insight as long as *A* is not too low or near 1 (note that for the future ST devices, like STEP [3] or STAR [4], *A* has the design value of around 2 which is not so low). Meanwhile, to concentrate on the effects directly coming from decreasing *A* through the major radius (*R*) or minor radius (a), we here fix the safety-factor (q) and thus magnetic shear (s) profiles. Noting that in typical H-mode plasmas core density has a broad profile, we also mainly consider the ITG and the electron temperature gradient driven TEM (T-TEM), while a brief check also given on the density gradient driven TEM (D-TEM).

It is shown that, when *A* decreases, the linear stabilization of the ITG and TEM can occur through the following two new mechanisms [5]. One is the increase of threshold temperature gradient, which is particularly strong for the ITG and occurs clearly when *A* is reduced through *R*. To see this, note first that in the broad density profile condition the threshold ion temperature gradient roughly has the form, $\left(\frac{R}{L_{Ti}}\right)_c \simeq 2(1+\tau)$ for the ITG, while $\left(\frac{R}{L_{Te}}\right)_c \simeq \frac{2}{f_t}\left(1+\frac{1}{\tau}\right)$ for the T-TEM, where $\tau = T_i/T_e$ and $f_t \sim (\frac{2\varepsilon}{1+\varepsilon})^{1/2}$ with $\varepsilon = r/R$ (see Ref. 5-6 for the detailed derivation of them). These forms show clearly that the threshold temperature gradients become smaller [$(L_{Ti})_c \propto R$ and $(L_{Te})_c \propto R^{1/2}$] so the marginal temperature profiles become steeper as *R* decreases. To check these analytic results we have also performed numerical calculations using the local kinetic code [7]. As shown in Fig. 1, the threshold temperature gradients for the ITG and T-TEM (and also the threshold density gradient for the D-TEM) have substantial enhancement when *R* decrease from 1.8→0.9m, in qualitative agreements with the above analytic estimates. These increases of the threshold gradients are mainly attributed to the enhancement of magnetic

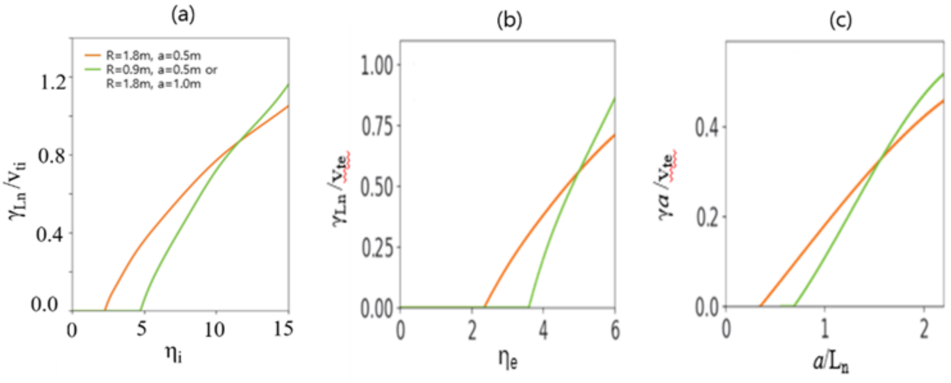

Figure 1. Variation in the normalized growth rate as a function of temperature or density gradient when $A=R/a$ decrease from 3.6 to 1.8 through R=1.8→0.9m or a=0.5→1.0m. Note that (a), (b), (c) represent the ITG, T-TEM, D-TEM cases, respectively, with $\eta_i = L_n/L_{Ti}$ and $\eta_i = L_n/L_{Te}$ when τ=1, k_y=0.5 and L_n=0.9m [in (a) and (b)].

curvature drift resonance with decreasing *R*. When *A* decreases through *a*, unlike the above decreasing *R* case there is no change in the actual threshold temperature gradient. However, the effective one defined in terms of the normalized minor radius still has an increase, resulting in similar enhancement of core temperature at the plasma center. The other important stabilization by the decreasing *A* arises through the increment of the ballooning force parameter α, which roughly varies in proportion to $1/A^2$ when we assume a fixed *q*-profile. This increase of α then enhances the linear electromagnetic and Shafranov-shift effects, which are known to give a strong stabilization on the ITG and TEM, respectively. It should be noted that the above two new stabilization mechanisms found here will be particularly effective in the relator-relevant condition where temperature profiles are expected to have a strong profile stiffness and the ExB flow shear suppression to be less significant due to the low toroidal rotation. Finally, we note that, with the increment of α, the standard KBM can be excited at a smaller pressure gradient, but it is expected to have the 2nd stability regime access over most core region if plasma shape is strong, as typically taken in the low *A* ST devices. As shown in the recent simulation work by Kennedy et al. [2], however, the hybrid KBM may be excited even when the standard KBM is stable, and a brief discussion is given about its possible origin based on the present modeling results.

On the change of pedestal stability: For the study of this issue, we use the well-known HELENA-MISHKA1 code package. Noting that the ST devices typically have a very large elongation (for example, with κ=3 in STEP [3]) to utilize its inherent stability against the vertical instability, the present study is mainly focused on such a strong shape plasma. With the usual high sensitivity of pedestal stability to the edge safety-factor q(a), we also consider both the two cases where q(a) is fixed or allowed to vary when *R* or *a* changes.

It is first shown that, when the elongation is very large (roughly, with κ>2.0), the eigenvalue spectrum of the peeling ballooning mode (PBM) completely shifts to the *n*=1 limit, unlike the usual one peaked in the intermediate-*n* range (here, *n* is the toroidal mode number). This makes the mode sensitive to the distance between the last closed flux-surface and adjacent outer rational surface, as expected for the peeling-type mode. In addition, it allows the PBM to couple to the n=1 external kink mode (EKM) as the normalized plasma beta (β_N) approaches the no or ideal wall limit, as also observed in the high poloidal-beta discharge case [8]. When *A* decreases these mode characteristics are well maintained, while the threshold pedestal height (P_{ped}) has a different behaviour, depending on whether q(a) is fixed or not. When q(a) is fixed, P_{ped} has a non-negligible increment with decreasing *R* or *A*, as shown in Fig. 2(a). This increment occurs even when B_T decreases with *A* (like $B_T \propto R$ or $1/a$), mainly due to the increase of plasma current (I_P) by the enhanced toroidicity effect. Meanwhile, when I_P is fixed so q(a) varies with *A*, P_{ped} has an oscillating behaviour, as expected for the n=1 peeling-type mode. As shown in Fig. 2(b)-(c), in this case the peaks of P_{ped} occur at the integer q(a) points with the oscillation amplitude or width being reduced as q(a) becomes larger. From Fig. 2(a)-(b), it is also notable that β_N easily approaches the no or ideal wall limit (around 4-5) if B_T decreases rapidly with *A*, which can then induce a sudden drop of P_{ped} through the coupling to the n=1 EKM. Finally, we note that some discrepancies are observed between these modelling results based on the ideal MHD and experimental measurements in the contemporary ST devices, and a brief discussion will be given on its possible origins, including the resistive effect which was recognized in a recent work [9].

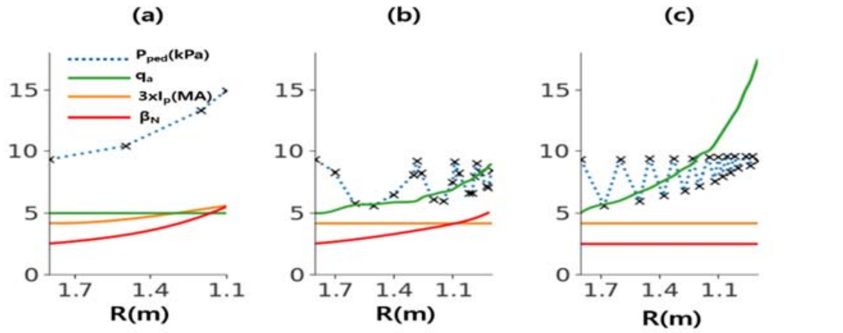

Figure 2. Variation in various plasma parameters, including P_{ped}, when *R* decreases at a fixed *a*(=0.5m) in the three cases where (a) q(a) is fixed to 5.0 or (b) I_P is fixed to 1.4MA with $B_T \propto R$, and (c) I_P and B_T are fixed to 1.4MA and 2.0T, respectively. Plasma elongation and triangularity are assumed to be κ=2.3 and δ=0.5, with poloidal plasma beta of β_P~1.0 in most cases.

[1] Kaye S.M. *et al* 2021 *Plasma Phys. Control. Fusion* 6**3** 123001
[2] Kennedy D. *et al* 2023 *Nucl. Fusion* **63** 126061, and also 2024 *Nucl. Fusion* **64**, 086049
[3] Tholerus E. *et al* 2024 *Nucl. Fusion* **64** 106030
[4] Brown T.G. and Menard J.E. 2023 *Fusion Engineering and Design* **192** 113583
[5] Kim J.Y. *et al* 2025 *Nucl. Fusion* **65** 036019
[6] Romanelli F. 1989 *Phys. Fluids* B **1** 1018
[7] Kim J.Y. *et al* 2019 *Nucl. Fusion* **59** 056021
[8] Kim J.Y. *et al* 2023 *Phys. Plasmas* **30** 050702
[9] Kleiner A. *et al* 2021 *Nucl. Fusion* **61** 064002