On Stability of ITER-like Plasma with High Fraction of Fast Ions.

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1. Type-I ELMy H-mode Operational Space in H/He ITER operation

Initial ITER operation in the H/He plasmas is foreseen to start with an auxilliary heating power of $P_{aux} = 63$ MW, lower than the level foreseen for DT operation [1,2]. Thus, the access to the Type I ELMy H-mode in in this phase will require operation with reduced magnetic field, $B \leq 2.65$ T, plasma density, $n \leq 3.5\ 10^{19}\mathrm{m}^{-3}$ and, possibly, reduced plasma surface, $S \leq 680\ \mathrm{m}^2$ to keep the edge power flux $P_{SOL} \sim P_{aux}$, well above the L-H threshold, $P_{SOL}/P_{L\text{-}H,D} > \alpha_{HP}= 2\text{-}2.8$. (Here $P_{L\text{-}H,D} \sim B^{0.8}S^{0.94}n^{0.7}$ [3] is the power threshold deuterium, and $\alpha_{HP} = 2$ for He and $\alpha_{HP} = 2.8$ for H are assumed). The reduction of $B < 2.65$ T shifts the EC and IC resonances toward the edge. It is restricted to $B \geq 2.3$ T by the need to access the q=1.5, q=2 flux surfaces for NTMs stabilization by the ECCD at 170 GHz. To keep the safety factor at $q_{95} \geq 3$, plasma current should be reduced to $I_p \sim 7$ MA. The maximum electron density for Type I ELMy H-mode operation (n_{max}) is determined by $P_{SOL}/P_{L\text{-}H,D}(n_{max}) = \alpha_{HP}$. It should be higher than the edge plasma density (n_s) predicted by the SOLPS [4]. To keep the shine-through losses under the engineering limit of 4 MW/m^2, the plasma density must be larger than n_{shth}. For the H^0-NBIs at full power (E_{NB}=870 keV, P_{NBI} = 33 MW) in pure hydrogen plasma $n_{shth} > n_{max}$ for $P_{SOL} \sim 60$ MW. In order to have a viable operational space, $n_{max} > n > n_{shth}$ for H plasmas it is advisable to dilute it with He to a level of $n_{He}/(n_{He} + n_H) \sim 0.6$, with $n_{shth} \sim 2.8\ 10^{19}\ \mathrm{m}^{-3}$.

2. Transport Model

The plasma parameters of H/He H-modes have been simulated in the frame of ASTRA [5] with free boundary SPIDER equilibrium solver [6] and the scaling based model [1] fitted to provide $\tau_E = 0.7\ \tau_{98y2,D}$ as expected from experimental results in He/H H-mode plasmas [7]. Separatrix boundary conditions and particle sources in the core for ASTRA modelling are derived by the SOLPS for the ITER fuelling scheme [4]. The effect of density value and peaking ($n(0)/n_{ped} = 1 - 1.5$) with the SOLPS boundary conditions are assessed by variation of the core diffusivity, $D = C_D\ (\chi_i+\chi_e)$, and pinch, $V = 2\ C_V\ D\ r/a^2$, with C_D =0.1-1.3, C_V =0-0.5. The values of the transport coefficients at the pedestal were adjusted to provide a normalised pressure gradient, α, and maximal current density at the peeling-ballooning limit predicted with the KINX code [8] (Fig.2). The saw-tooth (ST) crashes are simulated by current mixing in the area $r_s = 1.4\ r(q=1)$. Predicted period of the STs is, $\Delta t_{ST} \sim 30$ s.

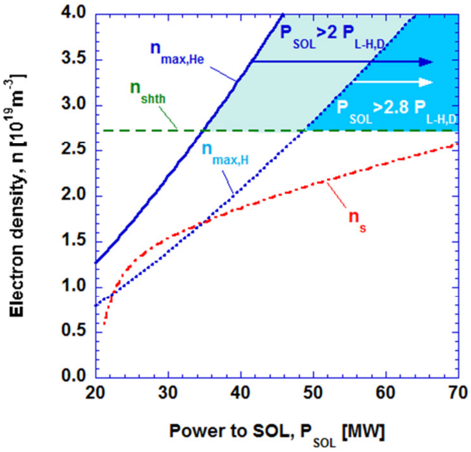


Fig. 1 Operational space for Type-I ELMy H-mode in 100% He (blue arrow), 100% H (white arrow).

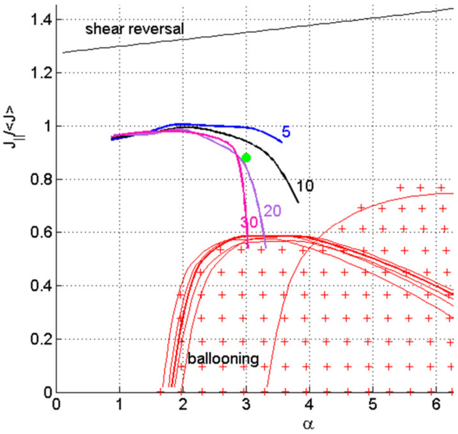


Fig. 2 Stability diagram for ITER pedestal. Operational point is shown by green dot.

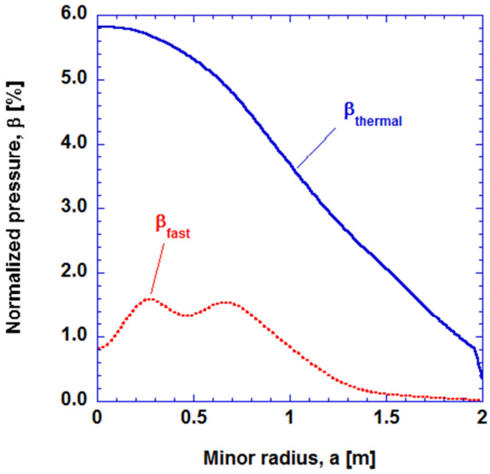


Fig. 3 Pressure profiles for fast and thermal components for <n>= 3.5 $10^{19}m^{-3}$.

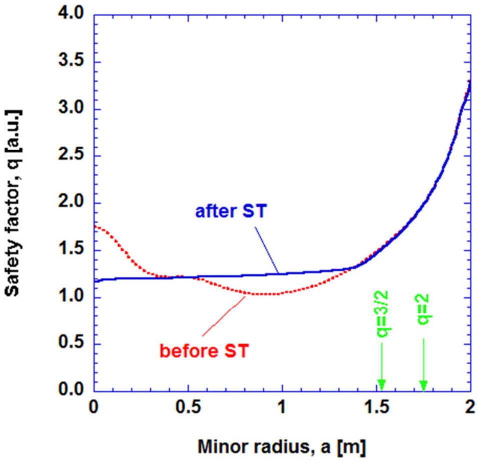


Fig. 4 Safety factor profile before and after the saw-tooth crash.

3. Stability Analysis

The edge stability diagram (Fig.2) shows a moderate pedestal pressure limit which is caused by the strong coupling to the current driven external modes [9] due to the high pressure gradient and current density at the separatrix.

For the plasma conditions required in H/He H-modes in ITER (P_{NBI} = 33 MW, n ~ 2.75 - 3.5 $10^{19}m^{-3}$, B = 2.3 MW, I_p = 7 MW) the modelled plasma pressure profiles are quite peaked, $p_0/<p> \sim 3\text{-}4$, and there is a significant contribution from NBI fast ions to the total plasma energy, $\beta_{fast}/\beta_{th} \sim 20$ - 25% as shown in Fig. 3. The fast ion contribution to the total plasma pressure creates a reversed pressure gradient region near the magnetic axis, which make potentially unstable the severe infernal modes. After the ST, the current diffuses back into the central plasma region creating a reversed shear configuration with the q_{min} at zero shear location very close to the region of the strongest fast ion pressure gradient. (Fig. 4) and, therefore, TAEs and Kink Modes are potentially unstable. Since the normalized pressure of this plasmas is sizeable, $\beta_N \sim 1.9$ (similar to that expected for 15 MA $Q_{DT} = 10$ conditions in ITER) it is expected that these plasmas will require stabilisation of the NTMs by the ECCD.

The existence of a broad region of reversed shear between sawteeth with the q_{min} location at $r/a = 0.5$ and reversed pressure gradient near the axis results in the destabilization of the ideal MHD internal m=1 mode before q_{min} reaches 1, but quite close to it: $q_{min}<1.05$. Fortunately the pressure gradient is not sufficient to drive the infernal modes unstable.

The stabilization of the NTMs for the He/H H-modes considered was simulated with the OGRAY code [10] for the EC extraordinary wave injection from the upper launcher (UL) with toroidal angle, ϕ = 18°-20° and variable poloidal angle, θ, assumed in present design. Similar to Q_{DT}=10 operation we assume that to avoid plasma performance degradation [11] the NTM stabilization [13] is required and it could be achieved if the EC driven current at the q=1.5, 2 surfaces exceeds the value of the local bootstrap current density, $j_{ECCD} \geq j_{bs}$. For P_{EC} = 4-6 MW focused at each of the q = 1.5 and 2 surfaces, the predicted ECCD currents are sufficient, for NTM stabilisation (Fig. 5). Reduction of currents $I_p < 7$ MA requires the increase of the toroidal launch angle ϕ.

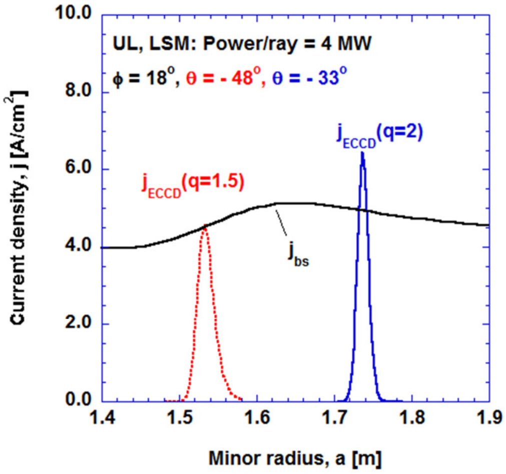
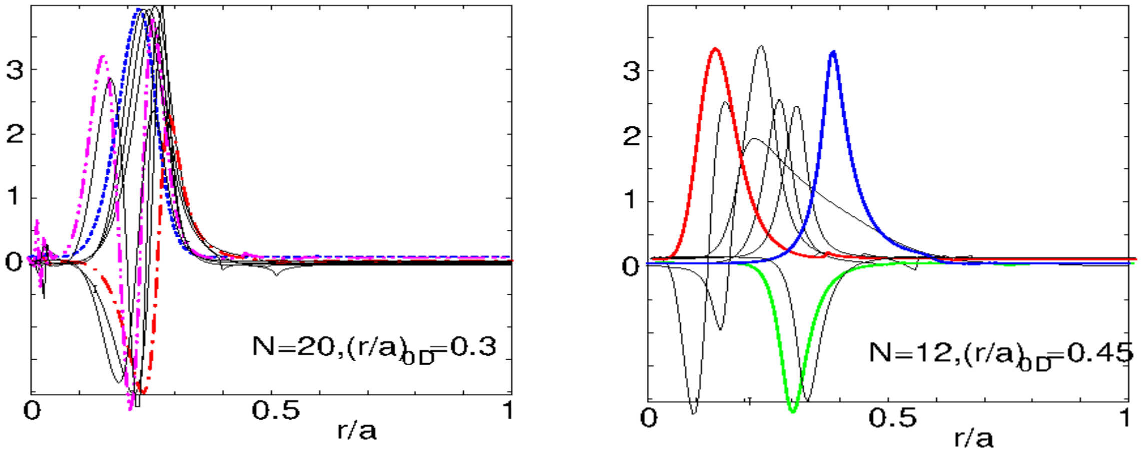


Fig. 5 Bootstrap current density j_{bs}, and EC driven currents, j_{ECCD}, for P_{EC} = 4 MW per ray.



a **b**

Fig. 6 Radial structure of unstable TAE modes. Predicted number of the unstable TAEs and radial flattening range are indicated a) r/a = 0.3 for flat q, b) r/a = 0.45 before the ST crash (Fig.4).

The TAE stability analysis has been carried out by the application of a quasilinear 0D-model based on experimentally validated ideal MHD TAE structure calculations and their stability properties by NOVA-K code [14,15]. The 0D model produces the expected region for the flattening of the fast ion distribution function evaluated from the spatial structure of the linear modes and their growth and dumping rates [16,17]. This analysis predicts that for the flat q profile after the ST crash all unstable modes are localized within r/a=0.3 due to the small shear and low radiative damping. Before the ST this area spreads to r/a = 0.45 (Fig.6 a,b), remaining within the region of flat fast ion pressure, so that fast ion redistribution within this area is not expected to lead to a significant additional fast ion loss (Fig.3).

4. Discussion and Conclusions

Type I ELMy H-modes in the non-active phase of ITER (H/He plasmas) operation will have a large fraction of fast ions due to required high power P_{aux} ~ 63 MW (P_{NBI} = 33 MW) and the reduced magnetic field, B~2.3T, current, I_p ~ 7MA and densities, n ~ 2.75 - 3.5 $10^{19}m^{-3}$. In such conditions, the large fast particle population and the strong current drive from the NBIs leads to the formation of a reversed shear region between the STs which reaches up to r/a = 0.5. The internal kink modes are expected to become unstable in such conditions and may affect triggering of saw-teeth before q_{min} reaches q=1. The TAEs are expected to be unstable in the core plasma region with r/a = 0.3-0.45 with rather flat fast ion pressure profile. Thus, the TAE instability is not expected to lead to a major effect on fast ion redistribution/losses nor plasma performance deterioration. The required power for NTM stabilization for modes on the q=1.5 and 2 surfaces is moderate (P_{EC} ~ 10 MW).

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

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