Operational Limits of ITER Helium-4 Plasmas with ELM Pace-making.

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Abstract. The possibility of stationary Type-I ELMy H-mode operation in helium plasma is studied with hydrogen NBI and ELM pacing with hydrogen pellets. A possible extension of the operational domain is also discussed.

1. Introduction

The first Type-I ELMy H-mode operation in ITER pre-DT phase is expected to be in helium plasma [1] at half field, B_0=2.65 T (I_p=7.5 MA). In helium plasma it is possible to use full power for heating, $P_{aux} = P_{NB}+P_{EC}+P_{IC}$ = 73 MW, once it is installed. Moreover, the L-H power threshold in helium, $P_{LH,He}$ is 1.4-2 times lower than in hydrogen, $P_{LH,H}$. Two approaches to testing ELM control are foreseen in ITER: the RMP coils (in pure helium plasmas) and the use of hydrogen pellets in helium target plasmas. Here we assess the Type-I ELMy H-mode operational space (OS) in ITER helium plasmas with ELM pacing by hydrogen pellets. Hydrogen throughput from the low field side (LFS) pellets required for ELM pacing can be as large as helium puffing. The main issue is the dilution of helium plasma by hydrogen which may reduce the Type-I ELMy H-mode OS, defined by power loss to the SOL, $P_{SOL}/P_{LH} \geq 1.4$, by increasing the L-H power threshold since $P_{LH,H}$~1.4-2 $P_{LH,He}$ ~ 2 $P_{LH,D}$. This effect was analyzed in [2]. It was found that for low separatrix density and auxiliary heating power, $n_{e,s} \sim 2\ 10^{19}\text{m}^{-3}$, P_{aux}< 60 MW, the Type-I ELMy H-mode operation is possible only transiently. To find the OS for stationary operation we extend here our considerations to higher separatrix densities and to the full power, $n_{e,s} \sim 2.5\ 10^{19}\text{m}^{-3}$, P_{aux}= 73 MW, and we also consider a case with reduced plasma surface, S and current (fig.1). Residual fuelling from the LFS hydrogen pellets for ELM pacing is calculated taking into account the outwards particle drift [3].

2. Plasma Model

For core transport we use the scaling based model [4]. For boundary conditions and particle sources in the core we use the parameterization of [2]. At the Edge Transport Barrier (ETB) the heat diffusivities, χ_i, χ_e are fitted to provide the pedestal pressure according to [5], $T_{ped}n_{ped}/I_p^2 \sim \beta_{p,ped} \sim A_i^{0.48}(P_{SOL}/P_{LH,D})^{0.144}/n_{ped}^{1/3}$, taking A_i = 1, as for hydrogen with the ETB width from [6], $\Delta_{ped} = 0.076\ \beta_{p,ped}^{1/2}$. For all plasma species we assume the same diffusivities, $D = 0.1\ (\chi_i+\chi_e)$. To assess the effect of density peaking, $F_n = n(0)/n_{ped} = 1 - 1.5$ we vary particle pinch, $V = 2\ C\ D\ r/a^2$, C=0-0.6. The heat diffusivities, $\chi_i = 2\chi_e$, at the core are fitted to provide $\tau_E = 0.7\ \tau_{98y2,D}$, from the scaling prediction for deuterium $\tau_{98y2,D}$, which is valid both for hydrogen and He plasmas [7]. Our modeling shows that, for the pedestal parameters considered, the residual core fuelling from pellets is negligible due to the outward drift. Thus, this source of hydrogen is counted only in total throughput, G_H. The pellet frequency required to keep the ELM energy loss at the acceptable level, $\Delta W_{ELM} < \Delta W_{max}$ is determined from the scaling, $f_{pel} = 0.2\ P_{SOL}/\Delta W_{max}$. We assume the conservative value, $\Delta W_{max} = 0.6$ MJ, required for $I_p = 15$ MA. Hydrogen throughput, $G_H = f_{pel}\ N_{pel}$ is calculated for the minimal foreseen pellet size, $N_{pel} \sim 1.5$ Pa m^3. Helium throughput, given by $G_{He} = 0.027\ \mu^{1.61} P_{SOL}^{1.69} S_n - 0.2\ G_H$ [2], is fitted to avoid plasma detachment: $\mu \leq 1$, where μ is the normalized gas pressure in the divertor. Here we choose the maximal possible pumping speed, $S_{eng} = 75$ m^3/s, which corresponds to $S_n = 1.27$ [2]. Operation with higher power enables higher edge densities, $n_{He,s} \sim P_{SOL}^{0.66}$. Operation with maximal pumping speed, $S_n = 1.27$ close to detachment, $\mu \sim 1$, reduces edge hydrogen density, $n_{H,s} \sim (G_H/S_n\mu)^{0.86}$, reduces the hydrogen core source, $G_{H,core} \sim G_H/S_n\mu^{1.13}$ and increases the He core source, $G_{He,core} \sim \mu^{0.8}$. Thus, it is favorable for minimization of undesirable helium dilution by hydrogen (fig.2).

3. Type-I ELMy H-mode Operational Space

The OS is assessed for the maximal pumping speed, $S_{eng} = 75$ m^3/s at the detachment limit, $\mu = 1$ with the plasma model described above. This model provides the boundary and pedestal parameters and core fuelling as functions of P_{SOL}. We scan the plasma density by varying the pinch velocity and the input power P_{aux}. In real experiments the pinch velocity is not a controllable parameter. Thus, the operational point should be chosen to provide the Type-I ELMy H-mode conditions, $P_{SOL} > \alpha\gamma_k P_{LH,D} \sim B^{0.8} S^{0.94} n^{0.7}$ [8] for any density peaking expected in ITER. In our analysis we assume $\alpha = 1.4$, and $\gamma_H = 2$, $\gamma_{He} = 1.4$. The OS is limited by $n \leq n_{max,k} \sim (\alpha\gamma_k P_{SOL}/S)^{1.4}$ and the NBI shine through limit, $n \geq n_{e,in,NBI}$ (shown in fig. 3 for full bore plasma for pure hydrogen and pure helium cases). As follows from the scaling [8], with assumed α and γ_k, such operation will be possible even in pure hydrogen for $P_{SOL} > 58$ MW for $F_n = 1$. For low densities one can also expect shrinking of the OS (fig.3b) due to changes of the power threshold dependence on density, $P_{LH} \geq P_{LH,D}(n_{crit})$, observed in experiments. We assume $n_{crit} \sim 3.5\ 10^{19}$m^{-3}. With such changes the lower boundary of the Type-I ELMy H-mode operation in He plasma diluted by hydrogen varies between 45 MW for pure helium (fig.3a) and 65 MW for pure hydrogen limit (fig.3b). Therefore, the OS where the stationary Type-I ELMy H-mode can be expected for any contamination by hydrogen exists and corresponds to high power operation. It is shown in blue in figures 3 and 4. This part of the OS in full bore plasma exists for density peaking in the range F_n= 1 - 1.3. The OS can be extended by reduction of plasma surface, S. In practice the possibility of such reduction is limited by variation of plasma elongation (fig. 1). In the case of the reduced elongation, the part of the OS where the stationary Type-I ELMy H-mode is expected for arbitrary dilution extends from $P_{SOL}\sim 60$ MW for the range of moderate peaking, F_n= 1 - 1.2 to $P_{SOL}\sim 70$ MW for the range with high peaking F_n=1 - 1.7 (fig.4b). It is worth noting that, for high power operation, the predicted separatrix density is rather high [2], $n_{e,s}\sim 2.5\text{-}2.6\ 10^{19}m^{-3}$. For $D = 0.1\ (\chi_i+\chi_e)$, this $n_{e,s}$ is sufficient to keep plasma density above the NBI shine-through limit, $n \geq n_{ped}\sim 3\ 10^{19}m^{-3} > n_{e,min,NBI}$ even without an anomalous pinch. This is important because for helium operation, the achievable density is limited by the detachment condition, $\mu \leq 1$ for He puffing, and by the dilution for hydrogen pellet fuelling if the pinch is not sufficient. The core plasma radiation, predicted for low B_0, n and T, expected in He plasmas without the impurity injection, is a factor of 10 smaller than predicted for Q = 10 DT operation, $P_{rad,He} < 4$ MW. In the high power case, $P_{aux} - P_{rad} = P_{SOL} > 60$ MW our modeling predicts rather moderate fraction of hydrogen, $n_H/(n_H + n_{He})\sim 38\%$, ($n_H/n_e\sim 24\%$). In general it is possible to reduce the shine-through loss at high contamination by hydrogen by reducing the NBI energy (- 15%), $P_{NB}\sim E_b^{2.5}$, provided the OS enables operation with reduced power.

4. Conclusions and discussion

It is shown that for B_0=2.65 T, $I_p \leq 7.5$ MA the operational space for the stationary Type-I ELMy H-mode in Helium plasmas with substantial dilution by hydrogen can exist for a range of density peaking, F_n= 1-1.7, if the power coupled to the plasma is sufficient to provide $P_{SOL}\sim 60\text{-}70$ MW. Predicted stationary contamination by hydrogen remains moderate, $n_H/(n_H+n_{He})\sim 38\%$, ($n_H/n_e\sim 24\%$). Thus, if the P_{LH} dependence on the dilution is weak, the OS can spread on a wider range of n and P_{aux}.

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

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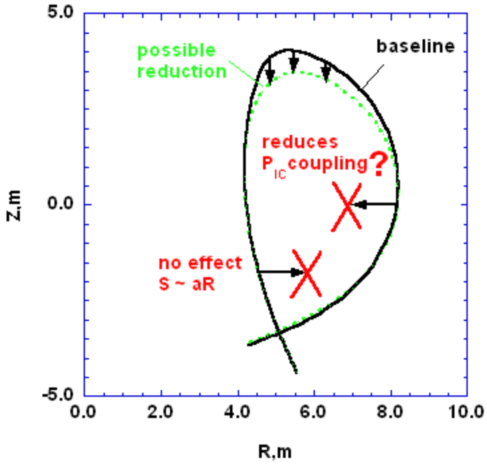

Fig. 1 Possible reduction of power threshold by shaping from CORSICA. Current is reduced from I_p=7.5 MA to I_p=6.5 MA to keep q_{95}>3 at B_0=2.65 T.

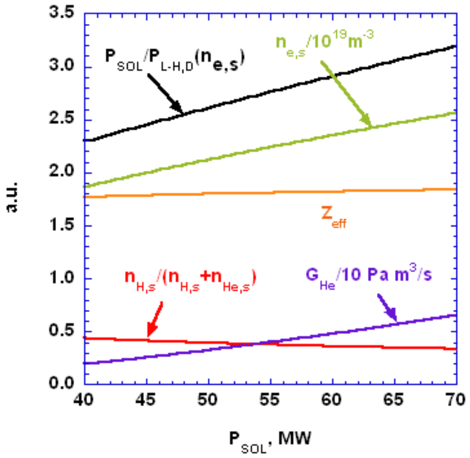

Fig. 2 Separatrix densities, $n_{e,s}$, $n_{He,s}$ $n_{H,s}$, helium source in the core at μ=1 with G_H=30 Pa m^3/s and pumping speed, S_{eng}=75 m^3/s according to ref. [2].

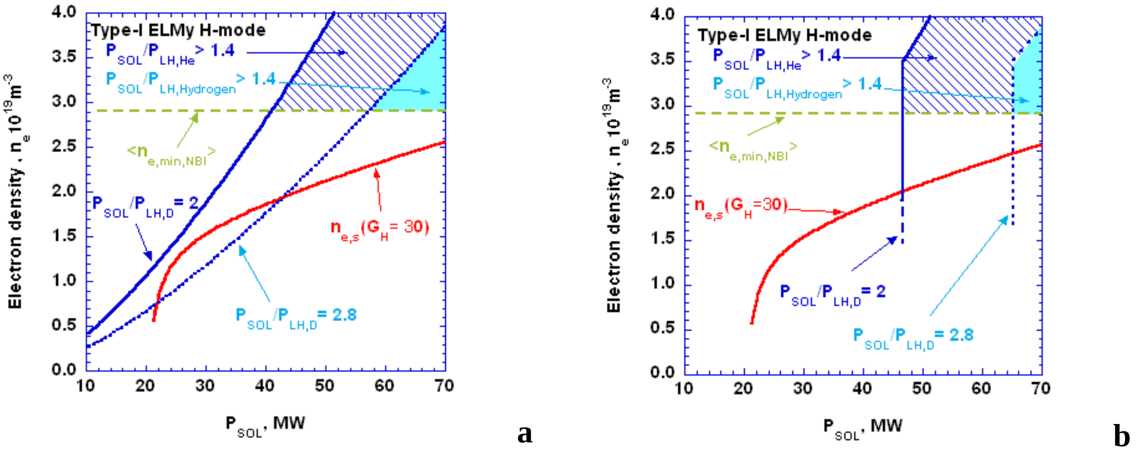

Fig. 3 OS for Type-I ELMy H-mode in He+H full-bore plasmas for parameters from fig.2: a) from scaling [8], P_{LH}~ $B^{0.8}S^{0.94}n^{0.7}$, b) for $P_{LH} \geq P_{LH,D}$(n = 3.5 $10^{19}m^{-3}$) in pure helium (P_{LH} > 1.4 $P_{LH,He}$= 2 $P_{LH,D}$) and in pure hydrogen (P_{LH} > 1.4 $P_{LH,H}$= 2.8 $P_{LH,D}$). <$n_{e,min,NBI}$> is shown for hydrogen NBI with E_b = 870 keV.

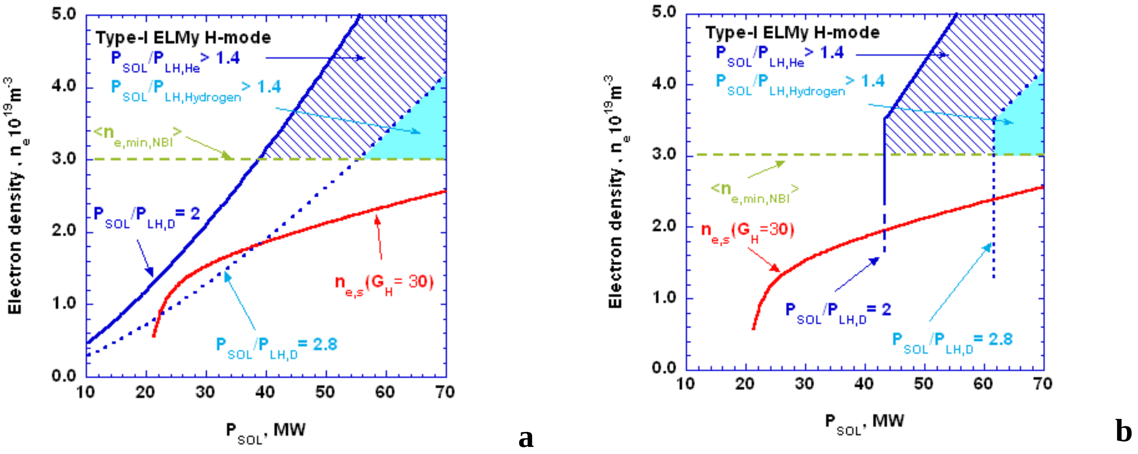

Fig. 4 The same as figure 3, but for reduced elongation case shown in figure 1.