

ITER tungsten divertor: initial operation at low power

A.S. Kukushkin¹, H.D. Pacher², R.A. Pitts¹,

V. Kotov³, G.W. Pacher⁴, D. Reiter³

¹ITER Organization, Route de Vinon sur Verdon, 13115 St Paul Lez Durance,

France; ²INRS-EMT, Varennes, Québec, Canada;

³FZ Jülich, Jülich, Germany; ⁴St. Bruno, Québec, Canada;

According to the ITER Research Plan [1], operation of the machine will develop in three stages, using first H-He plasmas in the non-active phase, then switching to pure D and finally to D-T fuel in the nuclear campaigns. The first two phases are necessary for commissioning different systems and gaining operational experience before the device becomes highly activated. The heating power absorbed by the plasma in the first two phases of operation can reach 60 MW [1]. Instead of using carbon in the high heat flux areas in the first phase (the original strategy) the ITER Organization is now proposing [2] to use W there from the beginning. In this paper we apply the SOLPS4.3 code package [3] to study the operational space of a carbon-free divertor during the initial phases of ITER operation – in particular, the extent to which impurity seeding is required to control target power loads, separatrix density, and W impurity levels in the core.

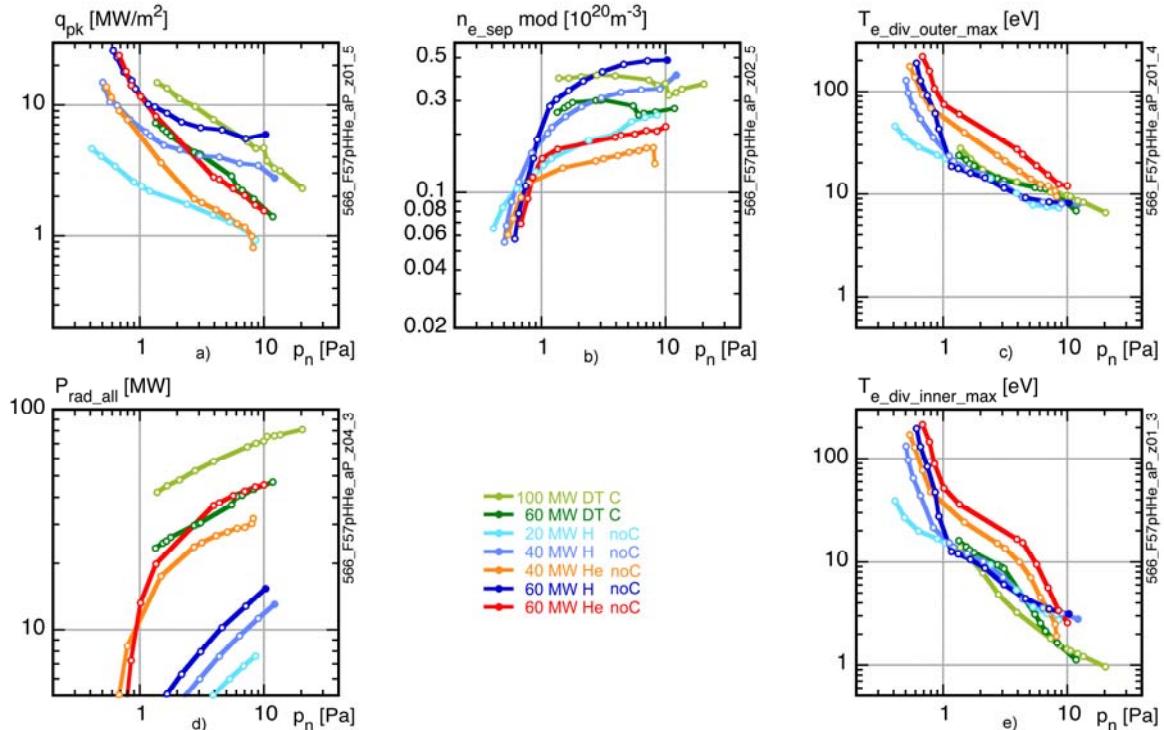


Fig. 1. Variation of q_{pk} (a), $n_{e,sep}$ (b) maximum electron temperature at the outer and inner targets (c,e) and total power radiated from the divertor (d) vs. p_n for pure H and pure He plasma with various values of P_{SOL} . Data for DT operation with C targets [4] are also shown for comparison.

The computational model is the same as that of [5], except that all C surfaces of [5] are now metal. We include neither W erosion (which is not expected to modify the divertor characteristics for levels consistent with acceptable core confinement) nor Be erosion for the moment (previous studies [6] have shown only minor effects except at low throughput). Therefore, the plasma in our runs consists of either pure H or of He with 5% H (described as

“pure He” below; H at this level does not affect the results [5] and is kept for computational reasons), or the same with addition of Ne puffed from the top. To explore the operational space of the ITER divertor in the non-active phase, we vary the gas puffing rate, and hence the gas pressure, p_n , in the private flux region (PFR), as in [5], the plasma composition and the power input to the SOL (P_{SOL}).

The maximum peak power at the targets, q_{pk} , for various P_{SOL} in the pure H and He plasmas is shown in Fig. 1a. Whereas the He scans are qualitatively similar to those for DT with carbon, the pure H plasma behaves differently. He plasma radiates even more strongly than D-T plasma with C, whereas radiation from H is much lower, Fig. 1d. The decrease of q_{pk} with p_n is much smaller at high p_n in H, Fig. 1a, which illustrates the importance of radiation for the detachment. For both H and He plasmas, at $p_n > 1 \text{ Pa}$, the values of q_{pk} are well below the engineering limit of 10 MW/m^2 [2]. Impurity seeding is therefore not required to mitigate q_{pk} for H and He plasmas for any reasonable p_n and for the heating power to be used during non-active operation.

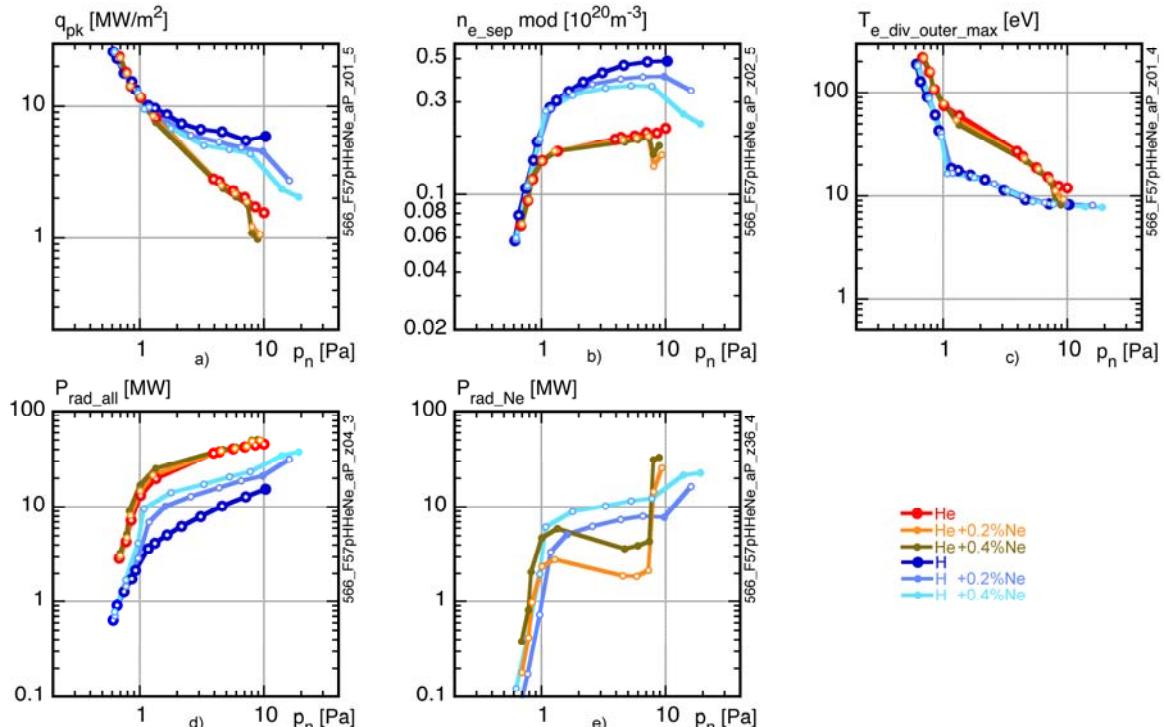


Fig. 2. Effect of Ne seeding on q_{pk} (a), $n_{e,\text{sep}}$ (b), maximum temperature at the outer target (c), total radiated power (d) and power radiated by Ne in H and He plasmas (e). $P_{\text{SOL}} = 60 \text{ MW}$

The separatrix density $n_{e,\text{sep}}$, Fig. 1b, is rather high in the pure H case, and this can hinder the H-mode transition [5]. It is lower in He plasmas, but if a test of ELM pace-making (H pellets) is considered, the He plasma will be strongly contaminated by H, leading to problems with the H-mode transition also in He [5]. The maximum temperature at the targets, Fig. 1c and Fig. 1e, is high with He plasma, with consequences to be discussed below.

The effect of Ne seeding on these parameters is shown in Fig 2. It was found in [6] that the Ne concentration at the separatrix, $c_{\text{Ne}} > 0.5\%$ leads to a deterioration of the core performance in the DT plasma. Therefore here the Ne puff from the top is adjusted so that c_{Ne} is kept constant at the level of 0.2% or 0.4% in a density scan. At this level, the Ne seeding effects are minor for most parameters – q_{pk} is slightly lower for H and unchanged for He, Fig. 2a, plasma target temperatures are unchanged, Fig. 2c, $n_{e,\text{sep}}$ is unchanged for He, Fig. 2b. The exception is $n_{e,\text{sep}}$ for H plasma, Fig. 2b, which is significantly reduced by Ne seeding at the highest p_n because less power is then available for ionising H and He, [6]. Ne seeding thus alleviates one of the obstacles to H-mode operation in H plasma [5].

To evaluate the gross eroded W flux, a special post-processing run was performed for which the particle fluxes and energies obtained in the calculations without W were used. The results are shown in Fig. 3. As expected, the pure H plasma practically does not sputter W for $P_{\text{SOL}} \leq 60$ MW except at very low p_n . Introducing the Ne seeding in the 60 MW series, where the erosion starts to be visible, increases the erosion at $p_n > 1$ Pa to $> 10^{20} \text{ s}^{-1}$, dropping to 10^{19} s^{-1} at 10 Pa, Fig. 3a. The increased erosion is due to the lower energy threshold and higher charge state for Ne ions compared to H; its level remains low. Significant contamination of the H plasma by W can therefore occur only during ELM phases, and will thus be less than for He plasmas which release W also during inter-ELM phases, see below.

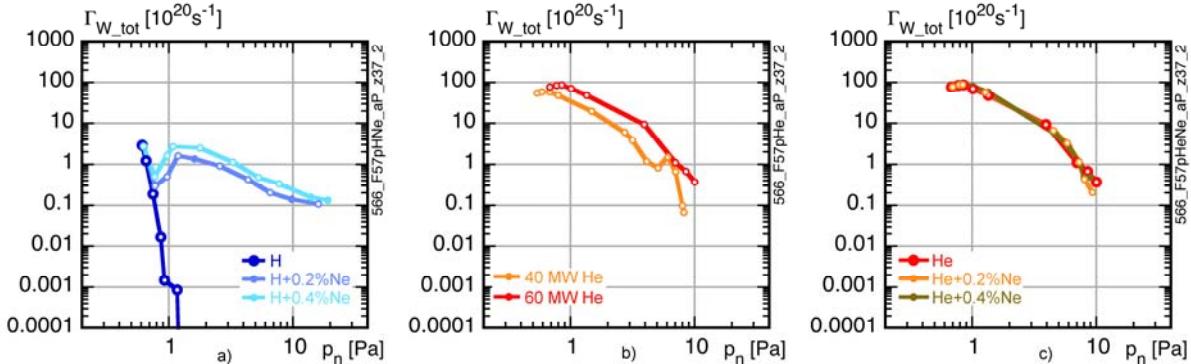


Fig. 3. Total gross flux of W sputtered from the targets vs. p_n for (a) H plasma, 60 MW, various c_{Ne} ; (b) pure He plasma, various P_{SOL} ; (c) He plasma, 60 MW, various c_{Ne}

In the pure He plasma, both the temperature at the targets and the charge state are higher than for H plasmas. The sputtering threshold for W ($E_{\text{th}} \sim 100$ eV for He on W) is easily reached for He at most p_n at some points along the target. Although the peak values for electron temperature and ion target flux do not coincide, Fig. 4, the ion flux profile is rather broad, Fig. 4b, so even at high p_n (7 Pa, moderate $T_{\text{e,max}} \sim 15$ eV, $q_{\text{pk}} \sim 2 \text{ MW/m}^2$, Fig. 1a,c), W sputtering at the target is not negligible. It is much higher than for H, Fig. 3b, since the mean energy of impinging ions exceeds the threshold. Seeding such a plasma with Ne at the level up to $c_{\text{Ne}} = 0.4\%$ has no effect, Fig. 3c. This is natural since T_{e} does not change and the contribution of the tiny fraction of Ne in the ion flux to the target is negligible compared to that of the He ions which already sputter significantly.

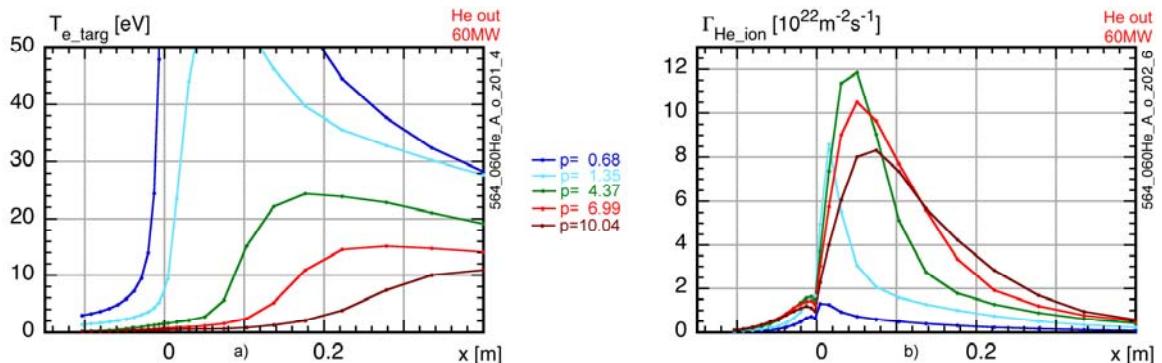


Fig. 4. Profiles (zoomed) of T_{e} and He ion flux along the outer target for various p_n . Pure He plasma, $P_{\text{SOL}} = 60$ MW, $x < 0$ in PFR

How dangerous is this level of W erosion for the core plasma? To provide a rough idea, the total line radiation from W can be estimated as $Q_W = \int n_e n_w R(T) dV \cong \langle n_e \rangle \langle n_w \rangle \langle R(T) \rangle V$, where V is the plasma volume and $R(T)$ the radiation rate. The latter has been estimated ([7] and references therein) to be $\sim 6 \cdot 10^{-31} \text{ W m}^3$, where an enhancement of a factor 2 is applied to account for non-coronal effects due to temperature gradients. There is no neutral W crossing the separatrix, so no W ion source inside. n_w can be related to the W density at the

separatrix, $n_W = \eta n_W^s$; in the absence of pinch, $\eta = 1$. n_W^s can in turn be estimated from the W particle balance in the SOL. Indeed, in the steady state, the W flux across the separatrix is zero, so all the W ions leaving the target and not re-deposited there must be deposited on the first wall. They can only be transported there as ions; in our model, by cross-field diffusion. The diffusive W flux across the SOL can be estimated as $\Gamma_W^W \cong S D_{\perp} n_W^s / \Delta$, where S is the

surface area, D_{\perp} the cross-field diffusivity of the W ions in the SOL and Δ the effective SOL width. Assuming a re-deposition fraction f_p , one comes to the estimate (Γ_W^t is the total flux of W sputtered from the targets):

$$\Gamma_W^t = \frac{S D_{\perp}}{\Delta(1-f_p)} n_W^s = \frac{S D_{\perp}}{\Delta(1-f_p)} \frac{Q_W}{\langle n_e \rangle \eta \langle R(T) \rangle V}$$

In ITER, $V \cong 800 \text{ m}^3$, $S \cong 700 \text{ m}^2$. For $D_{\perp} = 0.3 \text{ m}^2/\text{s}$, $\Delta = 0.1 \text{ m}$ and taking $Q_W \sim 7 \text{ MW}$ (10% of the total heating power) to be acceptable, one gets for $\langle n_e \rangle \sim 3 \cdot 10^{19} \text{ m}^{-3}$ an estimate $\Gamma_W^t \lesssim 10^{18} / (1-f_p) \eta \text{ s}^{-1}$. For prompt re-deposition, $1-f_p = p^2 / (1+p^2)$ [8], where $p = \omega_{ci} \tau_i$ (ion gyrofrequency by ionization time) yields for our parameters $1-f_p \cong 10^{-3}$, leading to an acceptable net W flux $\Gamma_W^t \sim 10^{21} \text{ s}^{-1}$ which would in turn render the range from 3 to 10 Pa (Fig. 4c) or $q_{pk} \sim 2-4 \text{ MW/m}^2$ (Fig. 2a) usable for He operation. Further ionization of W ions and their confinement by the electric field in the magnetic pre-sheath can reduce the estimated value of f_p by an order of magnitude [9]. W release by ELMs will not change this conclusion significantly in the case of He plasma - since T_e at the targets is already so high that the bulk of the He^{++} ions striking the targets are above the sputtering threshold in the inter-ELM phase, the W flux released during ELM phases will be similar.

In conclusion, therefore, non-active operation with a tungsten divertor with H plasmas appears possible, from the standpoint of divertor power load and contamination, except at the lowest neutral pressures. The difficulty of surmounting the H mode threshold in H plasmas is exacerbated by the relatively high separatrix density at the higher neutral pressures. Ne seeding can mitigate this latter problem but has only a minor effect on q_{pk} and only at the higher neutral pressures where it is below the engineering limit already. Operation with a tungsten divertor with He plasmas leads to peak heat loads well below the engineering limits (implying that only those can be tested with the input power available), low separatrix densities (easier H-mode access) and relatively hot plasmas at the target. The higher temperature implies significant W erosion for the He plasmas (unaffected by Ne seeding at the current levels), but rough estimates of the re-deposition probability yield acceptable separatrix W density. An assessment of the W release and transport in the SOL will be refined in future work. However, from the present considerations we can already conclude that a window for non-active ITER operation with tungsten divertor exists.

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

- [1] D.J. Campbell, "Challenges in Burning Plasma Physics: the ITER Research Plan", Proc. 24th Fusion Energy Conference, San Diego, 2012. Paper ITR/P1-18
- [2] R. A. Pitts, S. Carpentier, F. Escourbiac, et al., *J. Nucl. Mater.* **438** (2013) S48
- [3] A.S. Kukushkin, H.D. Pacher, V. Kotov, et al., *Fusion Eng. Des.* **86** (2011) 2865
- [4] H.D. Pacher, A.S. Kukushkin, G.W. Pacher, et al., *J. Nucl. Mater.* **415** (2011) S492
- [5] A.S. Kukushkin, H.D. Pacher, V. Kotov, et al., "ITER Divertor Performance in the Low Activation Phase", Proc. 23rd Fusion Energy Conference, Daejeon, 2010. Paper ITR/P1-33
- [6] H. D. Pacher, A. S. Kukushkin, G. W. Pacher, et al., *J. Nucl. Mater.*, **390–391** (2009) 259
- [7] R.V. Jensen, D.E. Post, et al., *Nucl. Fusion* **17**, 6 (1977)
- [8] R. Dux, A. Janzer, T. Pütterich, *Nucl. Fusion* **51** (2011) 053002
- [9] A.V. Chankin, D.P. Coster, and R. Dux, "On tungsten redeposition at the divertor target", submitted to *Plasma Phys. Control. Fusion*