Numerical simulations of recycling impurity screening on JET

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Introduction

In JET experiments using extrinsic impurity seeding, it was observed that the plasma core contamination and subsequent radiative collapse could be avoided if the deuterium gas inlet level was above a certain level for high triangularity type I ELMy H-mode plasmas. Originally these experiments were modelled using the 1.5D core transport code JETTO/SANCO [1] and the 2D SOL transport code EDGE2D/NIMBUS [2]. In this paper we will use the COCONUT code [3] that couples both transport codes by exchanging the boundary conditions between these two codes in every time step.

Modelling

COCONUT passes from EDGE2D/NIMBUS [4] the temperature and density flux surface averages and the neutral fluxes and impurity fluxes integrated over the last closed flux surface to JETT/SANCO [5]. From JETTO/SANCO, COCONUT distributes evenly at the last closed flux surface the fluxes, a constant value on the last closed flux surface of the impurity density for all ionization stages and all the transport coefficients.

The transport assumed within the SOL is described in [2] and inside the last closed flux surface is described in detail in [1] and the ELM model used is described in [1, 6].

To model the effect of the impurity contamination we use the JET pulse 53549 as a template of a deuterium fuelled discharge for typical JET H-mode plasma with the MARKIIGB divertor. The simulations started with steady state pure plasma with different levels of deuterium gas puff: 1×10^{21} p/s; 5×10^{21} p/s and 9×10^{21} p/s. The deuterium was puffed at the outer mid plane. The impurity (Neon in this case) was puffed at the rate of 6×10^{19} p/s also at the outer mid plane just beneath the deuterium puff position. The simulations were run for 200 ms with constant Neon and Deuterium puff rates. The duration of the runs is comparable with the particle confinement time.

Results

The ion temperature and density profiles in the plasma core at the end of the COCONUT simulation for all deuterium puff rates are shown in figure 1. This figure also shows the profiles of the average over all ionization stages convective impurity velocity and the sum of all ionization stages densities. These results confirm the conclusions made previously with stand alone JETTO/SANCO, but with the advantage to be in a more consistent maner. The increase of the deuterium gas puff level leads to an increase of deuterium density everywhere with the highest increase within the ETB. While the ion temperature decreases with the deuterium gas puff rate.

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[b] See the Appendix of M.L.Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA, (2006)

Considering the impurity transport in the ETB to be neoclassical the impurity flux (excluding the Ware pinch) can be written in the following form:

$$\Gamma_i^{neo} = -Z\Gamma_z^{neo} = -\frac{n_i D}{2}\left[K\left(\frac{1}{n_i}\frac{dn_i}{dr} - \frac{1}{Zn_Z}\frac{dn_Z}{dr}\right) + \frac{H}{T_i}\frac{dT_i}{dr}\right] \quad (1)$$

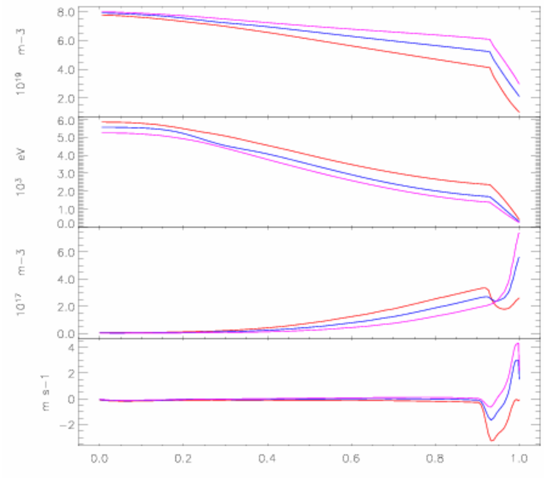

Figure 1: Plasma core profiles for three deuterium puffs levels, 1×10^{21} p/s (red); 5×10^{21} p/s (blue) and 9×10^{21} p/s (pink) of: a) ion density; b) ion temperature; c) total impurity and d) average over all ionisation stages impurity velocity.

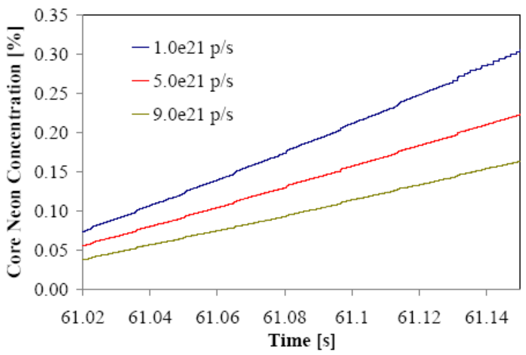

Figure 2: Neon concentration in the plasma core for three deuterium puffs levels, 1×10^{21} p/s; 5×10^{21} p/s and 9×10^{21} p/s and H-mode plasmas.

where n_z and n_i are the densities of impurity and the main ions respectively, Z is the charge of the impurity, $D \propto n_Z$ is the neoclassical diffusion coefficient and K and H are functions of dimensionless plasma parameters, including ion collisionality. From the model the changes of the normalised gradients of the ion temperature and density within the ETB with the gas puff leads to a change of the convective impurity velocity, which is mainly negative (or inward directed) for the lowest deuterium puff level and positive for the highest puff level, see figure 1. This is the reason why figure 1 shows a lower total Neon density inside the separatrix for the highest puff case at the end of the simulations. Figure 2 shows the time traces for the all the duration of the COCONUT runs. This figure shows that the Neon concentration increases during the 200 ms of the run regardless of the convective velocity sign. This is due to the fact that impurity flux (see equation (1)) also depends on the impurity density gradient that is positive in the SOL for the simulations due to the external source. The impurity gradient term during the COCONUT simulations was much higher than main ion terms of the equation (1). This means that there is always impurity contamination in the plasma core. We can conclude that the plasma core dilution not only depends on the convective impurity velocity within the ETB but also on the impurity density at the main SOL. In this region the impurity concentration is dependent on the balance between the inlet neutral flux and the impurity neutral flux that is pumped out from the system. Thus the balance between the parallel friction force in the SOL directed towards the divertor target plates and the parallel thermal force directed away form the divertor target plates is also important to avoid significant dilution in the plasma core that can cause a thermal collapse of the plasma. On other words, the impurity convective velocity and the parallel force balance in the SOL work in the same direction. For instance in the case of low level of deuterium puff the plasma core is contaminated because the neoclassical convective impurity velocity is inward directed and thermal force is higher than the friction force. While for the highest deuterium puff rate case there is much less dilution not only the convective impurity velocity is outward directed but also the friction force is comparable with the thermal force. The impurity particles are pushed towards the divertor plates, which are neutralised and pumped out from the plasma.

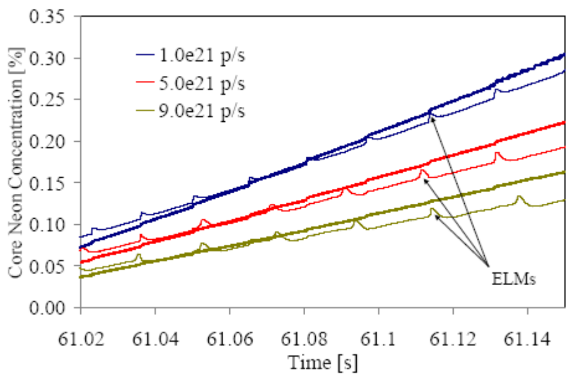

Figure 3: Neon concentration in the plasma core for three deuterium puffs levels, 1×10^{21} p/s; 5×10^{21} p/s and 9×10^{21} p/s and H-mode plasmas with (continuous line) and without ELMs (shaded line)

ELMs

All the simulations described above the plasma were assumed to be in an ELM free H-mode phase. To study the effects of ELMs, the ELMs were turned on in COCONUT. Figure 3 shows the time traces of the Neon concentration inside the separatrix for an ELMy H-mode plasma for the different deuterium gas puff levels which are compared with the correspondent runs without the ELMs. What is clear in this figure is that the Neon concentration inside separatrix is lower for the simulations with the ELMs regardless of the deuterium gas puff level. This seems to be in contradiction with the simulations made previously with the stand alone JETTO/SANCO code for the highest deuterium puff level case, that the Neon concentration in the plasma core was higher for the ELMy H-mode plasma than for ELM free H-mode plasma. It is important to note that JETTO/SANCO does not have the effect of the pump. All the impurity particles that were puffed into the plasma could not be removed. For the highest puff case the impurity particles, between the ELMs, were mainly concentrated outside separatrix. The ELM model used is of diffusive nature, during the ELM the impurity density is evenly distributed within the ETB. This permitted impurities reaching the plasma core during the ELM even if between ELMs impurities were mainly in the SOL-based. The ELM not only removes particles and energy from the ETB to the SOL but also from the main SOL to the divertor region.

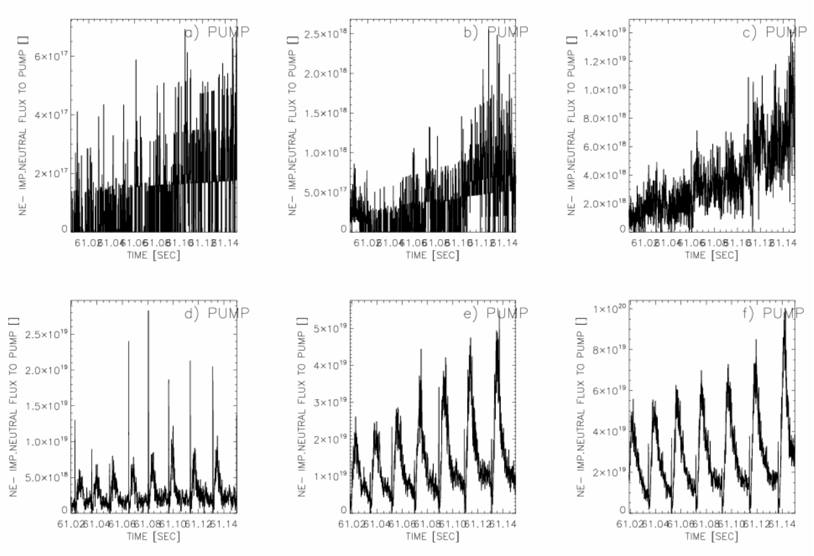

Figure 4: Neutral Neon density at the outer divertor for three deuterium puffs levels, 1×10^{21} p/s (left); 5×10^{21} p/s (centre) and 9×10^{21} p/s (right).H-mode plasmas without ELMs (top) and with ELMs (bottom)

The reason for fewer impurities in the plasma core for the ELMy H-mode is that during the ELM there is a big flux of particles and energy from the ETB and the main SOL to the divertor region. Figure 4 shows the time trace of the impurity neutrals to the pump for the simulations with different deuterium puff and plasmas with ELM free and with ELMs. What it is interesting to note is that the neutral increase after the ELM and reaches its maximum 5 ms after for the highest puff case and lower for the other deuterium puff levels. The reason of this increase is that the time scale for the Neon particles going upstream is larger than the time scale of the atomic processes. This Neon neutralised particles are removed easier from the system, this means that the Neon density would decrease significantly if there was no external source. The Neon neutral impurity density in the divertor is higher for the highest deuterium puff level because of the greater number of Neon particles in the main SOL that reach the divertor region during the ELM dragged by main ions. And fact that impurity particles take longer to reach the main SOL due to higher parallel friction force for this case than the cases with lower puff rates.

Conclusions

The conclusion is that the deuterium gas puffing helps to avoid radiative collapse as it was confirmed the previous conclusions from the simulations with JETTO/SANCO and EDGE2D/NIMBUS stand alone transport codes using a coupled core and edge transport code COCONUT. The impurity convective velocity and the parallel force balance in the SOL work in the same direction. At low deuterium inlet rate the convective impurity velocity is inward directed allowing impurities reaching the plasma core and the parallel thermal force is higher than the parallel friction force avoiding impurities reaching the divertor region. This helps increasing even further the impurity flux towards the plasma core. While for the highest puff rate case although there is still accumulation due to a inward impurity flux this is much less due to a outward directed convective velocity and a higher parallel friction force that pushes the Neon particles to the divertor, where are removed from the system.

We also conclude from this study that ELMs are an important factor for an effective removal of impurities from the ETB and main SOL to the divertor region. That is subsequently neutralised and removed from the system through the cryogenic pump.

Acknowledgments

This work, which has been supported by the European Communities and the Instituto Superior Técnico (IST) under the Contract of Association between the European Atomic Energy Community and IST, was performed under the European Fusion Development Agreement. This work was also partly funded by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission and IST.

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