Towards a better understanding of power loading and carbon radiation in the divertor.

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1 Introduction

Experimentally on ASDEX Upgrade we have observed a regime where the power radiated in the divertor and the peak power flux to the target increase linearly with input power at the same separatrix density (figure 1)[1, 2]. In an attempt to understand this regime an extensive set of B2-Eirene [3, 4, 5] runs have been performed.

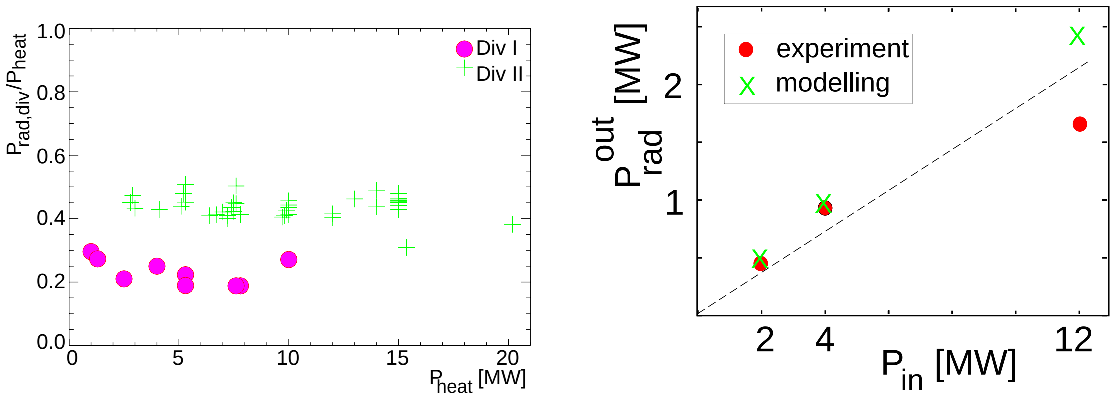

Figure 1: Divertor radiation normalized to heating power as a function of input power (left) and outboard divertor radiation from the experiment and B2-Eirene simulations.

In order to understand how the the power loading on the target plate varies with plasma conditions, we need to understand the physical processes that determine this. In this paper we will start our considerations with the power flux across the separatrix. There is then a competition between radial transport and parallel transport of this power which determines the radial power decay length. If we consider a flux tube linking the main chamber to the divertor, energy can be lost from the flux tube by radial transport (moving the energy to a neighbouring flux tube), by radiation (either from impurities or from hydrogen) and by charge exchange; each of these processes might also deposit energy into the flux tube (though the coupling between flux tubes by radiation is usually unimportant). The remaining energy will reach the target plate. Both the radial and parallel transport of energy can be by convection or by conduction. Under low density conditions most of the energy crossing the separatrix reaches one of the divertor plates (radiation is then usually unimportant though exchange can account for some losses), and the peak power flux is largely determined by the radial power decay length at the midplane and geometry. As the density is increased, losses along the flux tube increase. Extrinsic (e.g. neon or argon) and intrinsic (e.g. carbon or boron) impurities will radiate as will the working gas (hydrogen or deuterium). At high enough densities the temperature in front of the plate will fall to the 1 eV range and volume recombination can occur — further increasing the losses by radiation. Under these high density conditions it is the difference between the input power to the flux tube and the losses from the flux tube, both of which are large, that determines the power reaching the target plate (often small). Thus our understanding of the power flux to the target is predicated on our understanding these two large numbers: the power into the flux tube, and the subsequent losses from the flux tube before the target.

The power flux into the flux tube is determined by the upstream power decay length, or relatedly, the upstream temperature and density decay lengths. For H-mode type conditions with type I ELMs, there seems to be a pressure (P) gradient limit (probably determined by some sort of ballooning criterium) in the pedestal region. If, as seems likely, there is a radial correlation of the transport of a centimeter or so, this will also influence the transport just outside the separatrix. Under the assumption that ∇P is a constant (determined by plasma current and geometry), we have

$$\nabla P = n\nabla T + T\nabla n = n\nabla T(1 + \frac{1}{\eta}) = \text{constant}$$

where η is the ratio of density (n) to temperature (T) scale lengths. In ASDEX Upgrade η seems to a weakly varying number of order two. Thus when the input power is increased, the transport coefficient describing the radial energy flux also increases in this regime. This only weakly affects the amount of impurity radiation but strongly affects the peak power flux to the target (figure 2).

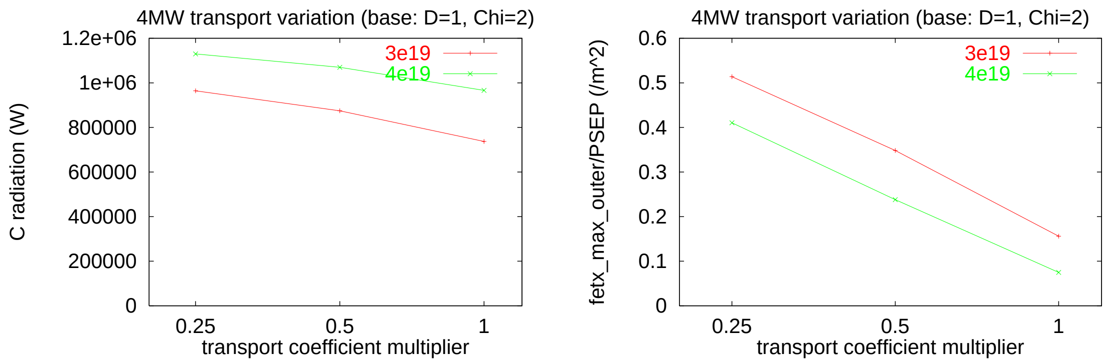

Figure 2: Dependence of impurity and peak target power flux on transport coefficients.

The amount of impurity radiation is proportional to the density of the impurity, and for C this density is partially determined by the chemical sputtering yield. How strongly this affects the peak power flux density depends on the radiated power fraction (figure 3). For the nearly detached regime a relationship exists between the amount of radiation and the input power.

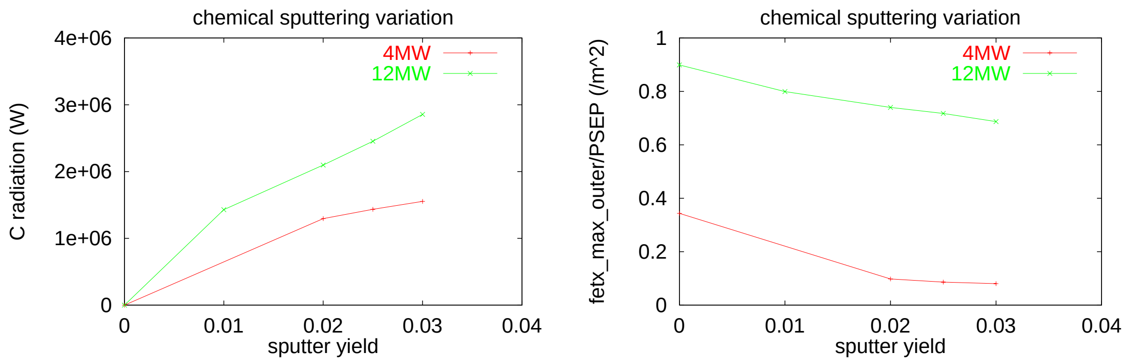

Figure 3: Dependence of impurity and peak target power flux on chemical sputter yield.

2 A simple model of the detached or nearly detached regime

The energy to the target plate, $\Gamma_{e,t}$, is given by $\Gamma_{e,t} = \Gamma_{e,0} - \Gamma_{e,rad}$ where $\Gamma_{e,0}$ is the input energy (energy crossing the separatrix) and $\Gamma_{e,rad}$ is the energy radiated outside the main plasma. Now $\Gamma_{e,t} = \Gamma_t(13.6+\alpha T)$ where Γ_t is the target particle flux, and αT the thermal energy per particle at the target plate. Arising from the plasma particle flux to the target we have a flux of neutrals away from the plate for hydrogen and carbon, respectively, $\Gamma_H = \Gamma_t$ and $\Gamma_C = \gamma\Gamma_t$ where γ is the chemical sputtering coefficient (physical sputtering is ignored because of the low temperatures in the nearly detached regime). Now

$$\Gamma_{e,rad} = 1000\Gamma_C + 20\Gamma_H = \Gamma_{e,t}\frac{1000\gamma + 20}{13.6 + \alpha T}$$

where we have assumed a radiation potential of 1000 eV for C and 20 eV for H. Therefore

$$\Gamma_{e,t} = \Gamma_{e,0} - \Gamma_{e,t}\frac{1000\gamma + 20}{13.6 + \alpha T} = \Gamma_{e,0}\frac{1}{1 + \frac{1000\gamma+20}{13.6+\alpha T}} \approx \Gamma_{e,0}\frac{1}{5}$$

where, for the approximation, we have assumed a chemical sputtering yield of 3% and that $T << 13.6/\alpha$. The carbon radiation as a fraction of the total radiation is

$$f_C = \frac{1000\gamma}{1000\gamma + 20} \approx \frac{30}{30 + 20} \approx 0.6$$

with hydrogen accounting for the remaining 40%.

In this analysis we have made some simplifying assumptions. The fraction of power reaching the target is a function of the target plasma temperature as well as the chemical sputter yield (figure 4).

The actual chemical sputter yield is not a constant, but varies with plasma temperature and flux[6]. This dependence would stabilize the operation in the experiment in this lower temperature regime as the effective yield increases with temperature thus increasing the losses.

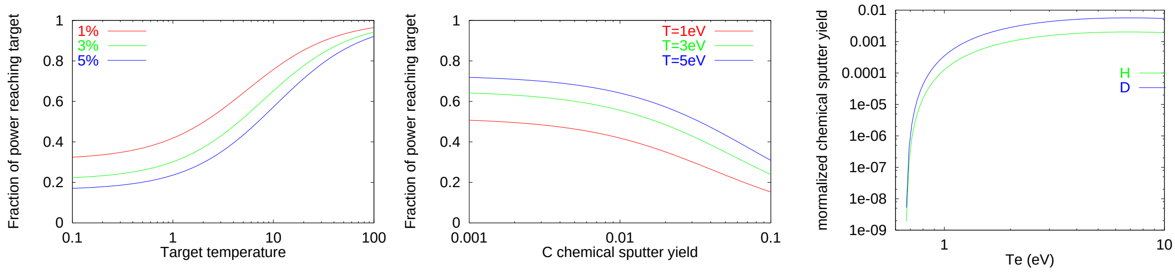

Figure 4: Fraction of power reaching target as a function of target plasma temperature and sputter yield assumptions and the chemical sputter yield normalized to the change in target flux caused by changes in plasma temperature.

The additional assumption of constant radiation potentials is not quite correct in that the B2-Eirene runs show a slight increase in radiation potential with density.

3 Conclusions

The power reaching the target is critically dependent on losses between the upstream region and the target. The peak power flux density is also dependent on these losses, but, in addition, depends on the upstream power decay lengths. The loss due to divertor radiation depends strongly on the amount of impurities and only weakly on the cross field transport. The peak power flux depends strongly on the cross field transport but the strength of its dependence on the impurity concentration depends on the divertor conditions: close to detachment the dependence is strong; in the strongly attached regime the dependence is weak. In the detached or nearly detached regime there exists an approximately linear dependence of radiation from chemically sputtered carbon and hydrogen to the input power.

References

[1] M. Kaufmann, H.-S. Bosch, A. Herrmann, A. Kallenbach, K. Borrass, et al., in *Plasma Physics and Controlled Nuclear Fusion Research 1998*, Vienna, 1998, IAEA.

[2] A. Kallenbach, M. Kaufmann, D. Coster, J. C. Fuchs, A. Hermann, et al., 'Scrape-off layer radiation and heat load to the ASDEX Upgrade LYRA-Divertor', Nuclear Fusion in press (1999).

[3] R. Schneider, D. Reiter, H. P. Zehrfeld, B. Braams, M. Baelmans, et al., J. Nucl. Mater. 196–198 (1992) 810.

[4] D. Reiter, J. Nucl. Mater. 196-198 (1992) 80.

[5] D. P. Coster, K. Borrass, R. Schneider, and ASDEX Upgrade Team, J. Nucl. Mater. 266–269 (1999) 804.

[6] J. Roth, J. Nucl. Mater. 266–269 (1999) 51.