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Simulating divertor detachment of ohmic discharges in ASDEX Upgrade using SOLPS: the role of carbon

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Introduction

With divertor detachment being a prerequisite for burning plasma operation in ITER, numerical codes such as SOLPS [1] have been developed for predicting and interpreting the divertor performance at all operational regimes in current tokamaks and ITER. In ITER complete detachment from the outer divertor target is not permitted as this might result in an X-point MARFE, imposing an upper limit for the upstream separatrix density, n_e^{sep} . Despite the knowledge of the basic mechanisms required for achieving detachment, such as radiative power exhaust, volumetric momentum and charge removal [1], a quantitative evaluation of experimentally observed detached regimes proves to be particularly difficult for several tokamaks. In particular the strong asymmetry of the ion flux density between the inner, Γ_{it} , and the outer target Γ_{ot} with increasing line averaged density, \bar{n}_e , and in particular 'vanishing' of the ion flux, defined as full/complete detachment, at the inner target cannot be reproduced. It is unclear how this is related to divertor target plates or other plasma facing components containing carbon. As part of a combined effort at various experimental devices this paper contributes to the validation of the SOLPS code against experimental data from ASDEX Upgrade, AUG, at the onset of divertor detachment. In the framework established under the International Tokamak Physics Activity (ITPA) Divertor and SOL working group a series of ohmic discharges have been performed in AUG, which had as similar as possible plasma parameters as companion discharges undertaken in DIII-D [2]. The effect of activating drift terms, the influence of the chemical sputtering yield at the inner target and in addition to [3] the role of impurity influx from the inner heat shield are analyzed.

Experiment

The presence of ELMs is avoided by concentrating on ohmic discharges in lower single null configuration in AUG with the divertor IIb and vertical targets. In 2006, the plasma facing components, PFCs, in the divertor volume were made of graphite, whilst the majority of the other PFCs were covered by tungsten [4]. The cryogenic pumps were active in all discharges, with $I_p = 1.0\text{MA}$, $B_T = -2.0\text{T}$ and $q_{95} = 3.4$ and the ion ∇B direction pointed downwards, the forward field direction. The discharges covered \bar{n}_e from $2.7 \times 10^{19}\text{m}^{-3}$ to $6.5 \times 10^{19}\text{m}^{-3}$ with the heating power varying accordingly between 500kW and 800kW . In order to resolve the plasma profiles along the target, the strike point was swept. In this paper, partial detachment is defined as a reduction of Γ_t locally with increasing \bar{n}_e , combined with a loss of plasma pressure

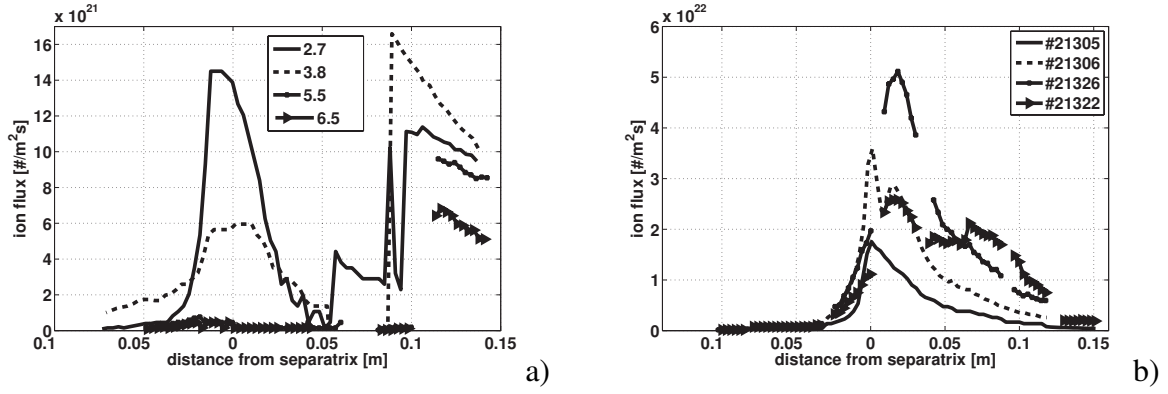


Figure 1: Ion flux densities to the inner (a) and outer targets (b) derived from the ion saturation currents of the fixed Langmuir probes for the discharges #21305 at $\bar{n}_e = 2.7 \times 10^{19} \text{m}^{-3}$, #21306 at $\bar{n}_e = 3.8 \times 10^{19} \text{m}^{-3}$, #21326 at $\bar{n}_e = 5.5 \times 10^{19} \text{m}^{-3}$ and #21322 at $\bar{n}_e = 6.5 \times 10^{19} \text{m}^{-3}$, [3]

between upstream and target locations by more than a factor 2 (assuming $\text{Mach} \geq 1$ at the target). Complete detachment occurs if Γ_t falls to very low levels along the entire target. In Fig. 1 the measured profiles of Γ_t along the inner (a) and outer targets (b) are presented. The inner target peak ion flux, Γ_{pk}^{it} decreases with increasing \bar{n}_e , whilst at the outer target, Γ_{ot}^{pk} at first increases and then decreases as a function of \bar{n}_e (known as 'roll over'). At the same time the inner target is initially partially detached and reaches complete detachment at the highest \bar{n}_e . At the lowest density both targets have a similar Γ^{pk} , however, with increasing \bar{n}_e they rapidly differ by an order of magnitude.

Modelling

The SOLPS5.0 code package [1] is applied, using the fluid code B2.5 coupled to the neutrals Monte Carlo Code EIRENE (version '99) with all drift terms being activated. Despite the earlier version of the code (SOLPS4.0/4.2, no drift terms included) has been and is being used for predicting the operational regime of ITER and successfully demonstrated qualitatively partially detached solutions, there are difficulties in matching experimental results *quantitatively* in the high recycling and detached regimes. The modelling here focuses on the lowest experimental \bar{n}_e in which $n_e^{sep} \sim 0.8 - 1.0 \times 10^{19} \text{m}^{-3}$, equivalent to $\sim 1/3\bar{n}_e$, with the aim of investigating the experimentally observed highly asymmetric divertor with respect to Γ_t as a function of \bar{n}_e . For simulating a large set of parameters, a grid with a relatively low resolution as shown in Fig. 2 with 48 poloidal and 18 radial cells has been used. The power entering the computational domain was varied between 520kW and 700kW. A gas puff of $\sim 6.5 \times 10^{20} \text{s}^{-1}$ and a pumping albedo of 0.91 at the entry to the pump duct are used. The neutral and ion fluxes at the core boundary are balanced and at the targets the Bohm-Chodura criterion is applied. It is important to note, that whilst the neutrals may interact with every surfaces, ions may only interact with surfaces where the grid intersects the vessel at the target plates. It is however, in principle, possible to apply chemical sputtering yields along the outer grid boundary. Physical sputtering is implemented according to the Roth-Bohdansky for-

mula and chemically sputtered carbon (where activated) is, in a simplistic assumption, released as atoms and not as hydrocarbons. Transport coefficients for D_{\perp} and $\chi_{\perp}^{e,i}$ vary radially in the range of $0.2m^2/s$ to $1.0m^2/s$. It has been shown in [3], testing several volumetric and surface processes inside the computational domain of the grid, that the code package in principle simulates detached divertor conditions and numerically accesses at least partially detached regimes at the inner target, while matching upstream profiles in the SOL reasonably well. With the drift terms activated it is possible to drop T_e at the inner target without affecting T_e at the outer target, but this does not reduce Γ_{it} . A very high and experimentally not observed chemical sputtering yield, Y_{chem} , of 10% is required at the inner target to drop the particle flux considerably. However, even then does the code simulate a Γ_{it} that is nearly a factor of 10 higher than measured experimentally and complete detachment at the inner target with rising \bar{n}_e along with the strong asymmetry of Γ_t are not reproduced. It is concluded in [3] that in the modelling, the radiative power and momentum exhaust is not sufficient. Charge exchange processes with increased cross sections due to highly excited atoms ($\propto m^4$, with m being the excitation level) or supra-thermal electrons affecting the radiation efficiency of the recycling fuelling species and of intrinsic impurities in regions of steep parallel gradients may need to be introduced to dissolve the discrepancy.

However, another possible candidate for exhausting sufficient power in the inner divertor to enhance momentum and charge removal may be in AUG the influx of intrinsic impurities from the heat shield at the high field side, HFS, [5]. The radial ion out flux to the grid boundary and the impinging flux of neutrals onto the walls that produce intrinsic impurities could themselves depend on the divertor conditions due to neutrals escaping the divertor volume or neutrals plugged below the magnetic axis on the HFS due to the small gap. Therefore in an attempt to in principle validate what the impact of the impurity influx from the HFS may be, instead of self-consistently calculating the carbon influx from the HFS PFCs on the basis of the modelled radial particle out flux, a carbon gas puff source is considered. The location of the puff is on the HFS above the inner divertor baffle outside of the computational grid and the injection is directed towards the grid with an opening angle of 45° . Carbon does not recycle on PFCs. The influx was varied from $5 \times 10^{18}s^{-1}$ to $1.3 \times 10^{21}s^{-1}$. In the modelling the background plasma directs the injected carbon towards the inner target. Only for carbon influxes larger than $1.6 \times 10^{20}s^{-1}$ is a reduction of Γ_{it} of more than 20% obtained. Influxes larger than $6.5 \times 10^{20}s^{-1}$ increasingly affect the outer target unfavorably. According to Fig. 3 a radiative distribution that is closer to the experimentally observed can be obtained without invoking unrealistic Y_{chem} at the inner target plate applying a carbon influx that is within the experimental margins. The HFS impurity influx

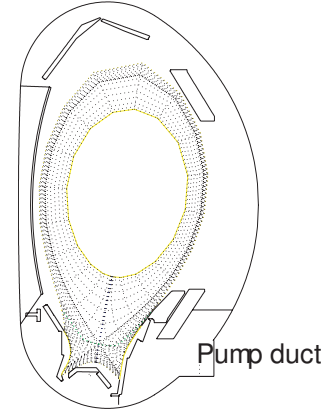


Figure 2: *Poloidal cross section of the magnetic configuration for #21303@3.6s represented by the corresponding grid that has been used for the simulations*

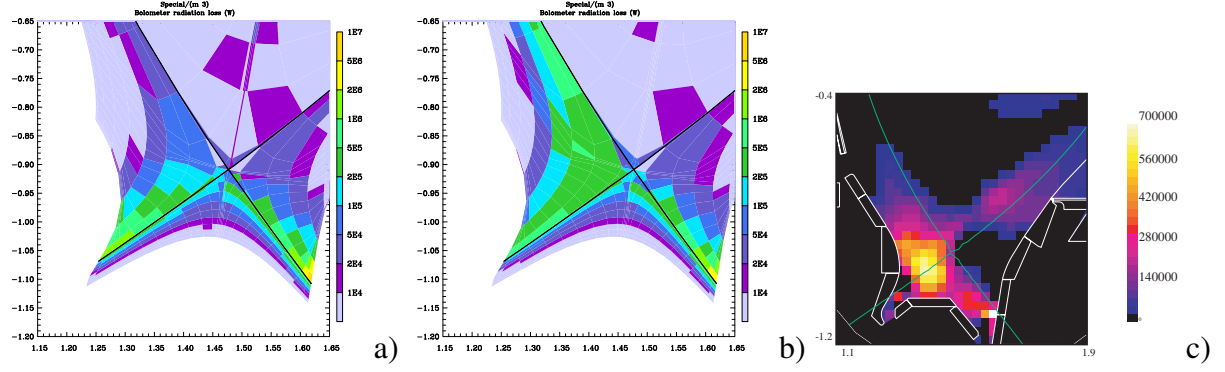


Figure 3: Simulated radiation distribution without carbon (a) and with carbon (b) influx ($3.2 \times 10^{20} s^{-1}$) from the HFS together with experimental bolometric reconstruction (c)

reduces T_e not only close to the strike point, common when assuming a high Y_{chem} at the target, but also in the far SOL. Due to the colder divertor volume at the highest simulated impurity influxes, neutrals leaking across the separatrix on the HFS can increase n_e^{sep} . However only with the highest impurity influxes can Γ_{it}^{pk} be dropped by a factor ~ 2 , not sufficient to agree with experimental data.

Conclusions

Carbon sources and carbon transport play a key role for quantitatively understanding divertor detachment and the ion flux asymmetry observed between the inner and outer targets. Decisive new insight may be expected from the ongoing experimental campaign in a full tungsten machine. Detachment can be influenced by impurity sources that lie outside of the computational grid and self consistent modelling becomes challenging. However, only applying carbon influxes that are larger than those experimentally observed could Γ_{it} be dropped by a factor ~ 2 . The total carbon influx into the divertor needs to be determined and from a modelling perspective the role of supra-thermal electrons on the radiation efficiency of the impurity content remains unknown. Furthermore the perpendicular transport of impurities in the divertor is unknown and may depend on the charge state, Monte Carlo impurity transport codes such as DORIS or IMPMC may be required to determine the 2D distribution. The role of hydrocarbons with respect to momentum removal due to their dissociation chain will be investigated in the future starting from CD_4 .

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