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Identification of the primary processes that lead to the drop in divertor target ion current at detachment in TCV

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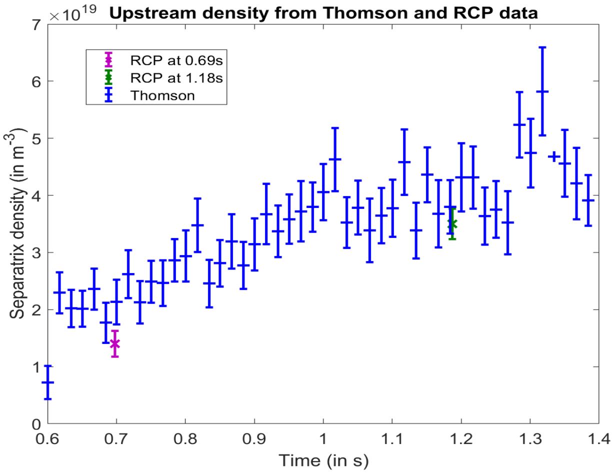
Using SOLPS-ITER we model a TCV conventional divertor discharge [1] [2] density ramp to understand the role of various processes in the loss of target ion current. We find that recombination is not a strong contributor to the rollover of the target ion current at detachment. In contrast, the divertor ion source appears to play a central role in magnitude (the source of most of the ion target current) and time, apparently dropping during the density ramps due to a drop in power available for ionization.

1 Introduction

Operation in a detached regime is needed for ITER and beyond in order to reduce heat fluxes on the divertor plates [3]. In DEMO, surface recombination heat fluxes will also have to be reduced [4]. In tokamaks, detachment is obtained via a chain of atomic processes (ionization, recombination,...), each of them being dominant at different values of density and temperature. Reaching a detached regime is characterized by a reduction of the temperature at the divertor target plates and a decrease of the total target ion fluxes. Experimental and theoretical studies showed that the volume recombination and the ionization source in the divertor are the two main mechanisms responsible for the drop of the ion flux to the targets [5] [6]. Each of these can be the primary mechanism for the observed ion current reduction [7] and recent measurements on TCV [8] showed that the drop of the ionization source was the main mechanism in TCV detached plasmas.

The aim of our research is to use SOLPS-ITER to complete the analysis of the divertor characteristics on TCV and to compare conventional and Super-X configurations. As a first step, it is important to understand the underlying detachment mechanism in a conventional TCV plasma. Consequently, in this paper, we will focus on a particular



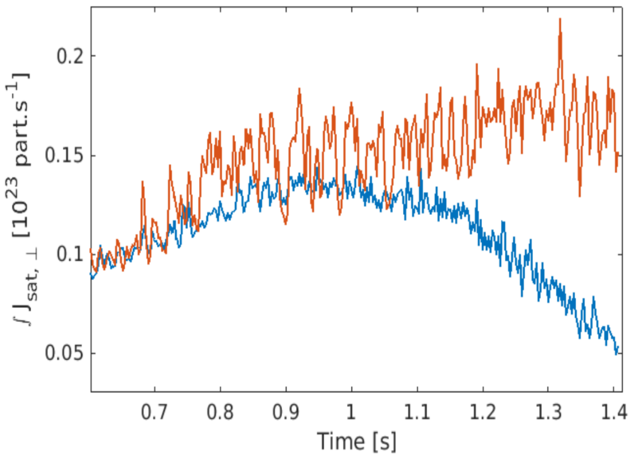


Figure 1: Experimental measurements for TCV shot 52065. Left : Separatrix density (from Thomson Scattering and fast probe [9]). Right: Total ion current for inner (in red) and outer targets (in blue) measured by Langmuir probes.

TCV shot, 52065, which has already been studied experimentally [1]. We start by presenting this experimental shot and its characteristics before moving to its modeling with SOLPS-ITER. Then we compare the simulations with experimental data and conclude.

2 TCV density ramp experiments

TCV density ramp experiments [1] [2] were carried out in a lower single null configuration and the particular shot we are studying in this paper was an ohmic heated L-mode with $I_p = 340kA$, $q_{95} = 2.5$ and $B_\phi = 1.43T$ (reverse field, with grad B away from the X-point). In this shot, the poloidal length of the inner leg was 10 cm and was 40 cm for the outer leg. The poloidal flux expansion between the outer midplane and the outer strike point was ~ 6 and the outer strike point was at $R_{target} = 0.75m$. Figure 1 shows the evolution of the plasma density at the separatrix (that will be called "upstream density") and the evolution of the total ion flux to the inner and outer targets. The ion flux is first increasing linearly (and not as density squared as expected from the 2PM [10]) before rolling over, which corresponds to an upstream density of $n_{e_{up}} \sim 3.5 \cdot 10^{19} m^{-3}$. Note that the equilibrium is obtained from the LIUQE code and that there are some experimental uncertainties on the position of the separatrix and thus on the upstream density measurement. It is also interesting to note that the total ion flux at the inner target does not rollover and keeps increasing during the density scan. Recent measurements using the divertor spectroscopy system (DSS) [8] showed that in similar experimental shots the total ionization source increases at the beginning of the density ramp before decreasing as the ionization region moves up along the outer leg. Those measurements also showed that the recombination plays a minor role and that the recombination region stays very close to the targets throughout the density ramp.

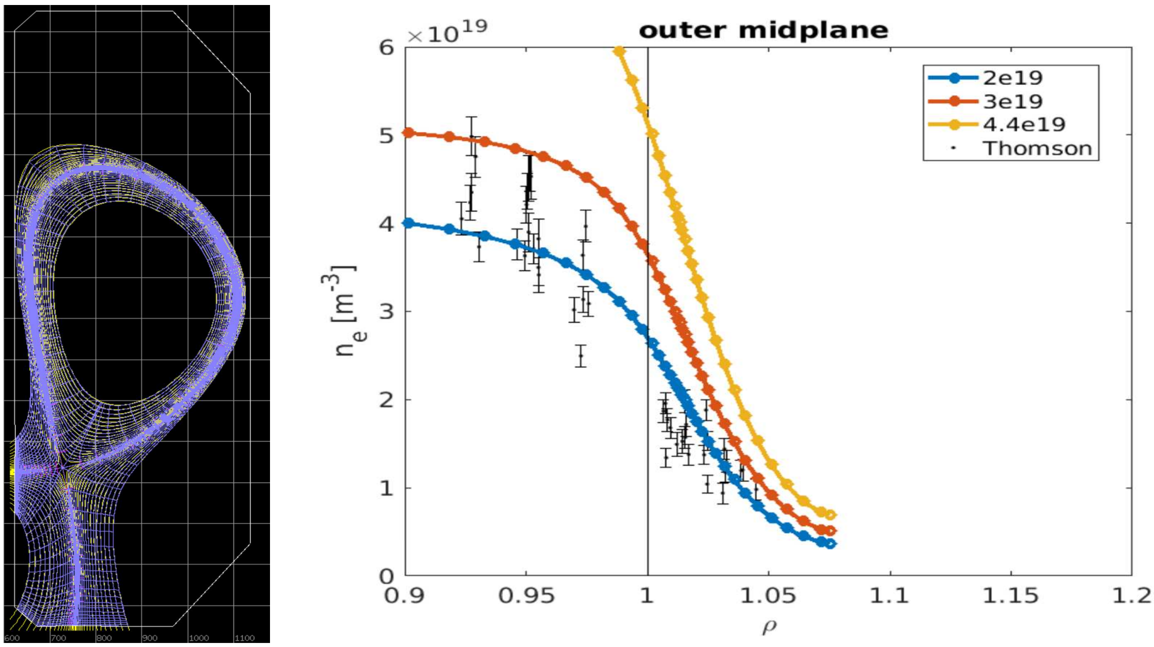


Figure 2: Left: SOLPS-ITER mesh for simulating the TCV shot 52065.
Right: Comparison between experimental density profile (in black, from Thomson scattering) and SOLPS simulation (in blue, red and yellow for increasing upstream densities) along the same line of sight. The Thomson data corresponds to an upstream density of $2 \cdot 10^{19} m^{-3}$, i.e. $t_{exp} \sim 0.6s$ and thus before the rollover

3 SOLPS-ITER modeling of detachment in TCV

We have performed 9 SOLPS-ITER converged simulations at different upstream densities (electron density at the outer midplane separatrix). In the modeling, it is varied from $5 \cdot 10^{18} m^{-3}$ to $7 \cdot 10^{19} m^{-3}$, when this experimental shot explores the $2 - 5 \cdot 10^{19} m^{-3}$ range. All simulations are using the same grid, aligned on the flux surfaces of the same experimental equilibrium (see figure 2). As boundary conditions, we use a constant power crossing the core boundary of the computational domain and a constant density at this boundary (that we increase to perform the density scan). In all the simulations, we use an constant input power of 400kW, which corresponds to experimental measurements using bolometry. Kinetic neutrals (grid for neutrals not shown in Figure 2) and physical sputtering of the carbon wall is included in the simulations. SOLPS-ITER simulations are steady-state simulations and each of those simulations are run for ~ 5000 time steps of $10^{-6} - 10^{-5}$ seconds, until a steady state is reached.

As SOLPS-ITER does not include turbulence, radial transport is chosen as to match experimental upstream profiles from Thomson scattering (see figure 2). Values of $D_\perp = 0.2 m^2 \cdot s^{-1}$ and $\kappa_\perp = 1 m^2 \cdot s^{-1}$ are used in our simulations. Starting at low upstream densities, we first obtain an attached plasma with a low target density and a high temperature at the target ($4.5 \cdot 10^{18} m^{-3}$ and 35 eV). As we increase the upstream density, simulated plasmas progressively reach a detached regime. The ionization region progressively moves away from the outer target as we increase the upstream density (see Figure 3). In simulations with higher upstream densities than the experiment, the ionization region reaches the X-point and also starts to move away from the inner target.

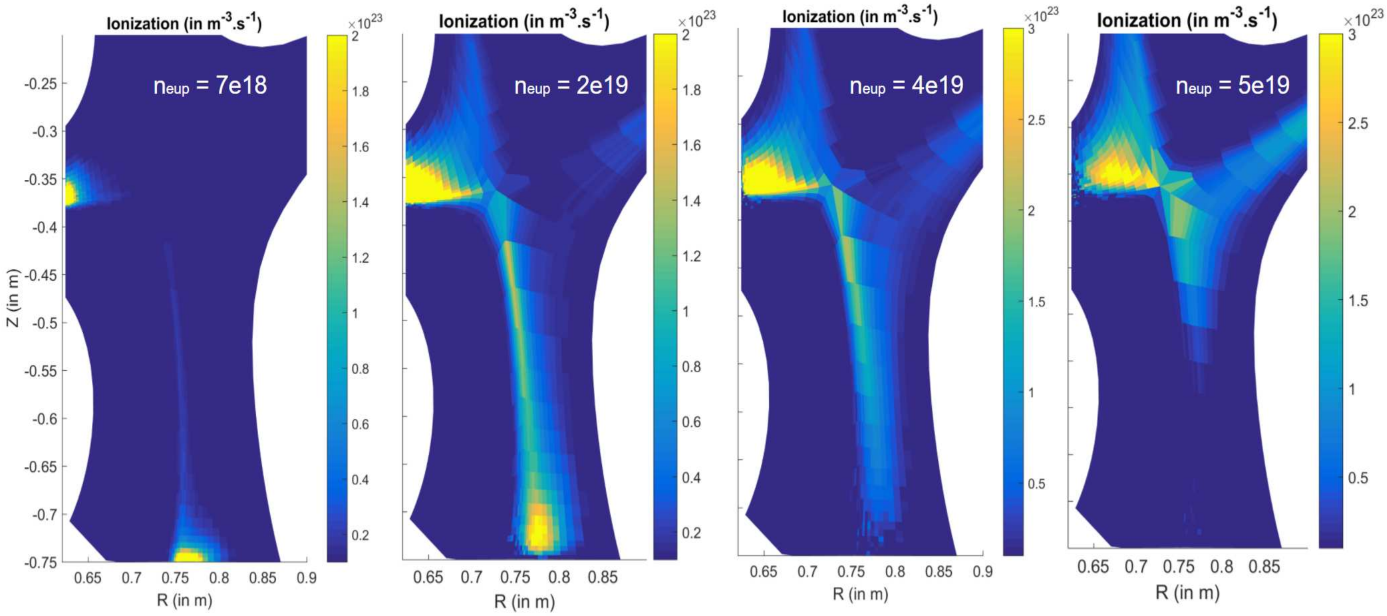


Figure 3: Ionization source contours for simulations at three different upstream densities (in m^{-3}).

Figure 4 displays the ionization source along the outer divertor leg for those simulations. In attached conditions, the ionization is peaked at the target. When increasing the upstream density, the ionization source is extended all along the leg and then peaks close to the X-point when we reach detached conditions. The recombination also plays a role, as can be seen on Figure 5. The level of recombination is however quite low compare to ionization and stays localized close to the target even at high upstream densities. Looking at the ionization and recombination rates in the outer SOL of Figure 5 (from midplane to the target), we can observe that the ion flux rollover seems to coincide primarily with power starvation in the divertor region and a decrease of the total ionization.

Those observations are qualitatively comparable to experimental measurements using divertor spectroscopy in TCV [8]. More quantitative comparison with TCV measurements will be done in a later study, in particular for the carbon impurity levels (which are included in those simulations), the neutral pressure and the ion flux profiles at the targets.

As upstream density is increased, both targets (inner and outer) are indeed detaching and the total ion flux at both targets is rolling over. Those detached plasmas are characterized by a target electron temperature which is below 1 eV and a high target electron density ($6-7e19m^{-3}$). Even after detachment, the peak density region stays very close to the target (a few cm away). If we compare to the experimental total ion flux measured by the Langmuir probes (see Figure 5), we observe that the simulated total ion flux at the outer target rolls over at a higher upstream density. Moreover, it decreases by less than 10% when it experimentally decreases by $\sim 40\%$. An important discrepancy with experiment is that the inner target also get detached when it is not the case experimentally. We are currently running simulations including drifts as we think it will improve the comparison to experiment.

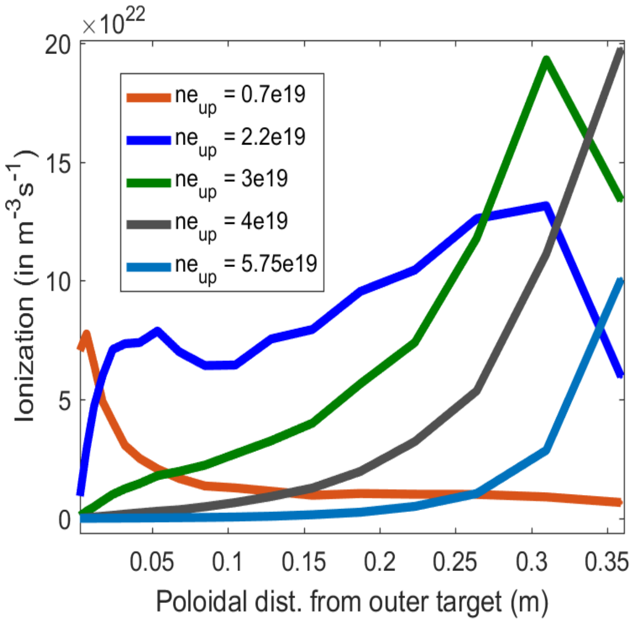


Figure 4: Ionization profiles along the outer divertor leg for 5 different upstream densities (in m^{-3}). The ionization starts peaking at the target (red curve) before moving to the X-point as the degree of detachment increases.

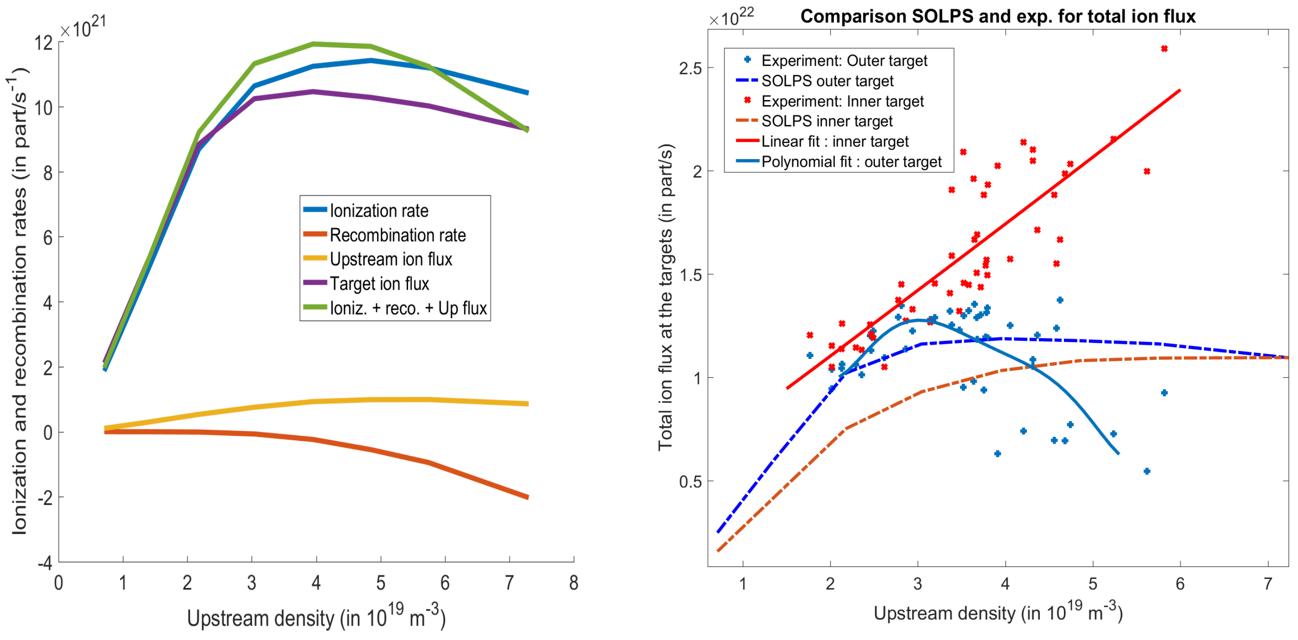


Figure 5: Left: Total ionization and recombination in the outer SOL (from midplane to target). Total ion flux rolls-over when the ionization rolls-over and the recombination increases.
Right: Comparison of the total ion flux at the outer target (in 10^{23} particles per second) between experiment (in blue, from Langmuir probes) and SOLPS-ITER simulations (in red)

4 Conclusion and perspectives

SOLPS-ITER steady-state simulations have been done for TCV L-mode plasmas with different upstream densities.

Detached plasmas are obtained in the simulations, with total ion flux rolling over at both targets. Ionization and recombination regions and their position as the upstream density is increased are in qualitative agreement with divertor spectroscopy measurements in TCV. Simulations show that the ionization peaks at the X-point for upstream densities higher than those reached in the experiment.

Current work aims at improving the quantitative comparison with experiments, in particular to explain the discrepancy between experiment and simulations for the total ion fluxes at both targets. Important progress has already been made concerning the carbon impurity levels. To match experimental measurements, 3% of Carbon chemical sputtering for the whole wall had to be included in the model. Progress is also done in re-doing those simulations with realistic gas puffing and wall pumping instead of using a fixed core density boundary. Finally, shots with higher R_t have just been simulated and are currently being compared to the results presented in this paper, to study the effect of total flux expansion on the detachment threshold.

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References

[1] J. R. Harrison, et al., *Nuclear Materials and Energy* **2016**, *000*.

[2] C. Theiler, et al., *Nuclear Fusion* **2017**, *57*, 072008.

[3] A. Loarte, et al., *Nuclear Fusion* **2007**, *47*, S203.

[4] M. Wischmeier, et al., *J. Nucl. Mater.* **2015**, *463*, 22-9.

[5] A.A. Pshenov, et al., *Nuclear Materials and Energy* **2017**, *12*, 948-952.

[6] S. I. Krasheninnikov, et al., *Phys. Plasmas* **2016**, *23*, 055602.

[7] B. Lipschultz, et al., *Phys. Plasmas* **1999**, *6*, 5.

[8] K. Verhaegh, et al., *Nuclear Materials and Energy* **2017**, *000*.

[9] C. K. Tsui, et al., *Phys. Plasmas* **2017**, *24*, 062508.

[10] P. C. Stangeby, *The Plasma Boundary of Magnetic Fusion Devices (Bristol: Institute of Physics Publishing)* **2000**.