The influence of N_2 and H_2 seeding on detachment in a divertor-relevant plasma by means of modelling and experiments in Magnum-PSI.

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- Introduction.

Understanding and controlling plasma-surface interaction mechanisms in the divertor region is one of the most important challenges towards realizing fusion electricity. Experiments have shown [1,2] that impurity injections lead to a net reduction of power loads onto the targets. Nitrogen is currently the leading candidate for impurity seeding in ITER.[3] Little is known on the detailed physical-chemical processes occurring in such high density, low temperature plasmas in the presence of nitrogen. To study such a complex scenario, an extensive (20+ species, 70+ reactions) global plasma model of H_2+N_2 chemistry has been set up on the basis of *Plasimo* code.[4] Dedicated experiments on Magnum-PSI with hydrogen seeding have been carried out, while N_2 injection measurements are currently under preparation. Magnum-PSI is a unique linear plasma generator designed to simulate the (semi-) detached plasma close to the ITER strike points, i.e. $n_e > 10^{20}$ m^{-3} and T_e between 0.2 and 5 eV in steady state conditions. [5]

- Elementary processes in the divertor and Magnum-PSI reactor

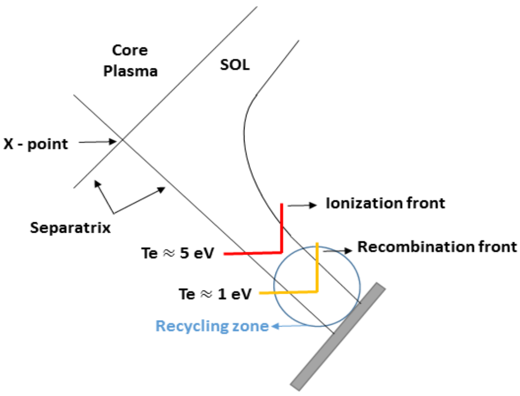

***Figure 1**. Schematic view of regions close to the target in a detached divertor plasma.*

The divertor detached operational regime is characterized by plasma pressure drop along magnetic field lines towards the target in the SOL (Scrape Off Layer)[6] and strong reduction of plasma ions flux onto the target reflecting in low power loads. This pressure drop is due to ions-neutrals interactions which give rise to either plasma momentum transfer to the walls through the neutral channel, and ions removal by means of recombination mechanisms.[7] After passing the ionization front (see *figure 1*), ions flowing towards the target face incoming neutrals while entering the plasma recombination front ($T_e \approx$ 1 eV), where undergo through volume reactions. Ions then partially recombine before reaching the surface or neutralize on it before being re-emitted, hence getting back to the bulk of the plasma in vibrational excited states. Molecular-Activated Recombination (referred to as MAR) and electron-ion recombination (EIR) are very efficient processes in Low T ($\leq$ 1.5 eV)[8] and involve molecular hydrogen in vibrational excited states. Hereby the two fundamental hydrogen MAR processes are reported:

1) $H_2(v) + H^+ \rightarrow H_2^+ + H$

$H_2^+ + e \rightarrow H + H^*(n = 2\text{-}4)$

2) $H_2(v) + e \rightarrow H^- + H$

$H^- + H^+ \rightarrow H + H^*(n = 3)$

The aim of this work is to study qualitatively fundamental plasma chemistry mechanisms that occur adding nitrogen in a detached-like hydrogen plasma together with experimental observation of detachment by means of hydrogen seeding in Magnum-PSI.

- **Global plasma modelling: insights into MAR in the presence of N_2**

In Global Models spatial averages of the physical parameters are calculated from the plasma ignition to the fulfilment of the steady state.[9] The outcomes of the zero-dimensional simulation is collected by solving a system of coupled differential equations i.e. the energy balance, the quasi - neutrality and the particle balance, whose solution describes the evolution of ionic and neutral species as a function of time. The electron energy balance is solved simultaneously. This type of models are simpler and computationally less expensive than spatially resolved hybrid models, hence we are able to provide a detailed and extensive chemistry occurring in near-wall H_2 plasma with N_2 addition, without causing an increasing of the computational effort. The plasma-chemical effects of Nitrogen addition on MAR is reported in this section according to the model outputs. Dyazenilium ion is addressed to play a role of “ionic mediator” in such a plasma. It’s worth underlining that N_2H^+ dissociative recombination reaction is the main source for N_2, which then undergoes through proton transfer with secondary plasma ions i.e. H_2^+ and NH^+. Moreover, N_2H^+ dissociation by electron-impact is also the primary source for NH, main nitrogen-included electron donor in the ion conversion with H^+. The effect of nitrogen addition on MAR mechanisms, according to our model, can be described as follows:

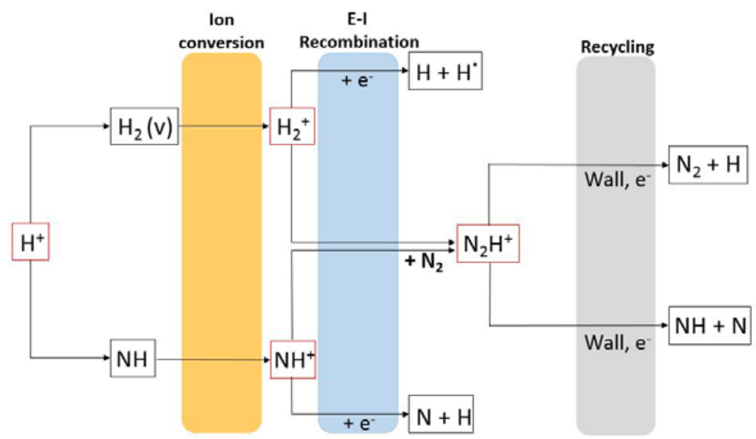

***Figure 2**. Proposed new Molecular Activated Recombination scheme in the presence of nitrogen.*

The processes in *figure 2* control the population dynamics of the chemical species occurring in the plasma close to the target, in the recombination zone. Experimental evidences seem to confirm such behaviours.[1,10] More specific experimental analysis will be pursued.

- **Plasma detachment in linear reactor Magnum-PSI**

A first plasma detachment study in the newly renovated Magnum-PSI has been successfully carried out. Measurements of n_e and T_e have been performed with Thomson Scattering.[11] The movable target holder allowed us to place the target in two different locations, namely 3 cm and 10 cm from the Thomson laser. The heat loads on the target have been measured with calorimetry. The applied magnetic field was set at 1.2 T and the hydrogen gas flow at the source at 4 slm.

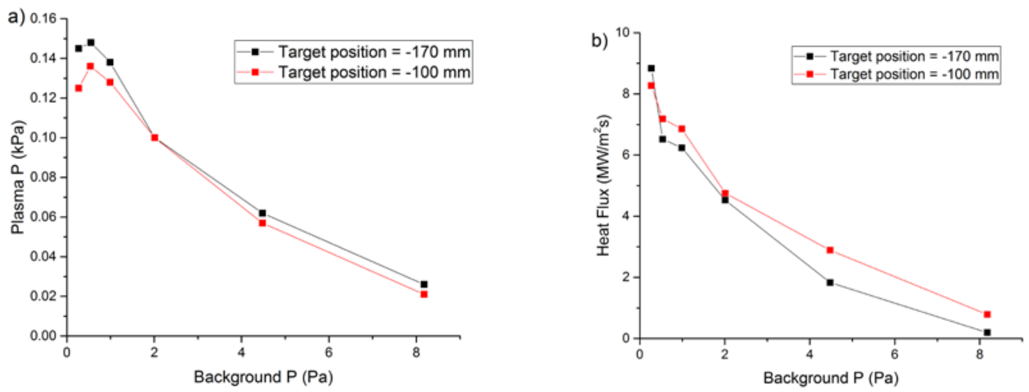

***Figure 3**. Plasma pressure (a) and heat flux (b) as a function of neutral background pressure.*

Plasma detachment has been achieved by increasing the neutral background pressure in the target chamber, as can be observed in *figure 3*. In this study, plasma pressure drops by a factor 7 from the low to the high-background pressure case. This is considered as a key feature characterizing detachment, and is mainly caused by ion-neutral momentum loss.[12] Heat loads on the target surface (a tungsten monoblock) are driven by incident ions recombining at the surface and releasing their potential energy. Starting from background P ~ 1 Pa, a strong decay in the heat flux can be noticed, falling close to 0 at 8.18 Pa. Such behaviour can be explained as follows: in the high-recycling regime the neutrals released from the surface are promptly ionized and return to the target. With increasing neutral pressure, electrons lose energy mainly by means of elastic collisions with neutrals and via the electron-induced vibrational excitation channel of H_2, resulting in lower T_e while n_e is maintained. The plasma scenario becomes then MAR-dominated up to ~4 Pa, causing the observed plasma pressure decay. When T_e goes below 1 eV (pressure above 4 Pa), the system is dominated by EIR, which extinguish the plasma before it reaches the target, resulting in a further strong reduction of the heat flux.

- Conclusions

An extensive volume-averaged global model for low-temperature and high-density H_2/N_2 plasma has been implemented. A new N_2-included Molecular Activated Recombination has been proposed, coherently with the outputs of the model. Moreover, experimental plasma detachment study has been done in Magnum-PSI, showing the parallel heat flux reduction together with plasma pressure drop by increasing neutral pressure in the target chamber.

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