Molecular Effects in Plasma Recombination

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Abstract. The effects of Molecular Activated Recombination in fusion related experiments are discussed and analyzed by applying dimensionless scaling approach for two plasma geometries.

I. Introduction. In experiments with detached plasmas [1-3] plasma recombines before it reaches the targets and the recombination is *the only* process allowing to reduce plasma flux to the wall in fusion experiments without strong impurity radiation loss [1].

In fusion related experiments there are two main paths for plasma recombination [1, 4-7]: i) $e+A^+ \to A$ which includes both two- and three- body recombination of electrons and positive ions and where ions are not involved in any chemical transformations (electron-ion recombination (EIR)), and ii) path involving negative ions (B^-) and molecular ions (AB^+) and going through the channels $H_2(v)+e \to H^-+H$ followed by $A^++H^- \to A+H$ and $A^++H_2(v) \to AH^++H$ followed by $AH^++e \to A+H$ (where $H_2(v)$ is the vibrationally excited hydrogen molecule). In fusion studies second path which cannot be initiated without impact of molecular hydrogen is called Molecular Activated Recombination (MAR). Notice that both paths involve rather complex dynamics of the population of electron excited states while the second one can depend also on vibrational dynamics of the molecules involved. However, the crucial distinction between the EIR and MAR is that the EIR processes does nor require any extra energy to start while MAR needs about $E_{MAR} \sim 2$ eV to be pumped into vibrational levels of the molecule before it goes on.

While the importance of the EIR processes in plasma detachment is well accepted by fusion community, the role of the MAR in fusion experiments is still under discussions and different conclusions are made based on the analysis of different experiments (see Ref. 2, 3, and 8). Here we analyze the role of EIR and MAR channels of plasma recombination in fusion related experiments by using scaling law approach [9-11].

II. Dimensionless parameters and recombining fusion related plasmas. We consider two different model just for the hydrogen recycling region down in the divertor where, however, plasma recombination can take place.

i) Semi-infinite slab model of recycling region. We consider the model where both plasma and neutral gas parameters depend only on the coordinate, Z, perpendicular to the target, Fig. 1. We neglect cross field plasma transport assuming that plasma particle and energy transport goes along the magnetic field $\vec{B}$. This model describes the case of a very baffled divertor design where neutrals coming from the target after plasma neutralization immediately face the plasma. Notice that one of the important difference of this model from that of Ref. 10 is the absence of any prescribed length (e. g. connection length, tokamak major radius, etc.). Then the quantities which are governing continuity, momentum, and energy balances and determining both plasma and neutral gas parameters are: the heat flux, q_∞, which comes to the recycling region from upstream and the plasma pressure, P_∞, at $Z \to \infty$, as well as electron electric charge, e, speed of light, c, ion (or electron) mass, M (m), and effective "ionization energy cost", E_{ion}, which is related to atomic physics effects and can be replaced with any other atomic physics parameter containing Planck constant $\hbar$, e. g. atomic hydrogen ionization potential. By using these quantities it is possible to construct three dimensionless parameters which can be written in the form

$$\hat{q} = q_\infty \Big/ \left(P_\infty \sqrt{E_{ion}/M}\right), \qquad \Lambda = E_{ion}^2 \Big/ \left(e^3 \sqrt{P_\infty}\right), \quad \text{and} \quad \alpha = e^2/\hbar c = 1/137. \qquad (1)$$

Notice that we are not counting here such dimensionless constants as the electron to ion mass ratio, inclination angle of the magnetic field to the target plane and such "wall" parameters as energy reflection and the wall's atom to molecule conversion, $\gamma_{a\rightarrow m}$, coefficients.

While parameter $\hat{q}$ determines energy and, therefore, particle balances, parameter Λ, related to the number of particles in Debye sphere, is responsible also for three-body collisions and, together with the fine-structure constant α, describes competition between electron excitation/de-excitation processes and the processes involving radiation effects in both bound-bound and free-bound transitions.

In Ref. 12 it was shown that the steady state solutions of this model of plasma recycling exist only for

$$\hat{q} \geq \hat{q}_{crit} = \hat{q}_{crit}(\Lambda), \qquad (2)$$

(in dimension variables it can be written as $q_\infty \geq q_{crit}(P_\infty)$, or $P_\infty \leq P_{crit}(q_\infty)$). The reason for this is that plasma temperature near the target decreases with decreasing $\hat{q}$. Therefore, at some point, $\hat{q} \lesssim \hat{q}_{crit}$, plasma EIR becomes important and then it is not possible anymore to sustain energy balance in the neutral ionization region, which can be written as

$$q_\infty > j_N E_{ion}, \qquad (3)$$

since the influx of neutrals into ionization region, j_N, becomes strongly enhanced by the plasma EIR processes resulting in the recombination of plasma before it reaches the target. Here we consider the effects of MAR which was omitted in [12].

Let assume that the impact of the EIR and all other processes (including three-body) associated with Λ are unimportant and the MAR is the only recombination mechanism. Then, in the case of a strong impact of the MAR on plasma flux the main physical picture of plasma, atom, and molecule recycling can be described as follows (see Fig. 2). The molecules originated due to atom-to-molecule conversion at the target move into plasma and participate in the MAR processes. (Notice that volumetric atom-to-molecule conversion due to three-body collisions is negligibly small for the fusion related experiments). Two out of three atoms, formed in the MAR event, move back to the target and convert into molecule while last one moves deeper into plasma and finally is ionized there creating an ion which moves toward the target and then recombines due to MAR.

However, in the MAR one bi-atomic molecule can "recombine" only one atomic ion. Meanwhile, in addition to the MAR, molecules can also be disintegrated due to electron impact dissociation or ionization and the rate constant of these processes go up very quickly with the increase of electron temperature. As a result, for efficient usage of the molecules in the MAR, electron temperature in MAR region should be $\lesssim 1.5$ eV which means that $\hat{q}$ should be relatively small. At higher temperatures in the MAR region the balance of the plasma, atom, and molecule fluxes cannot be maintained for large plasma sink due to the MAR.

When $\hat{q}$ is small then for 1D plasma recycling model we are considering in this section total plasma and neutral gas pressure stays pretty much constant along Z and both particle (neutral and plasma) and energy fluxes can be described in diffusive approximation [12]. Therefore, as an estimate for the molecular, P_M, atomic, P_A, and plasma, P_p, pressures in recycling region, we have $P_M \sim P_A \sim P_p \sim P_\infty$. Then, we find the estimates for both plasma particle, j_p, and energy, q_{MAR}, fluxes into the MAR region (note that neutral flux into ionization region j_N balances plasma flux):

$$j_p \sim j_N \sim \frac{D_{Ni}}{T}\frac{P_A}{Z_A} \sim \frac{T}{MK_{iN}P_p}\frac{P_A}{Z_A} \sim \frac{T}{MK_{iN}}\frac{1}{Z_A}, \qquad (4)$$

$$q_{MAR} \sim \frac{D_{Ni}P_\infty}{T}\frac{T_{ion}^{(-)}}{Z_A} \sim \frac{TP_\infty}{MK_{iN}P_p}\frac{T_{ion}^{(-)}}{Z_A} \sim \frac{T}{MK_{iN}}\frac{T_{ion}^{(-)}}{Z_A}, \qquad (5)$$

where M is the mass of heavy particles, K_{iN} is the rate constant of ion-neutral collisions, $T_{ion}^{(-)}$ (see Fig. 3) is the plasma temperature just at the entrance into ionization region.

Now recall the MAR requires energy E_{MAR}~2 eV per recombination event. Therefore, to recombine plasma flux j_p, the energy flux q_{MAR} must satisfy inequality $q_{MAR} \gtrsim E_{MAR} j_p$, which , taking into account expressions (4), (5), can be written as follows

$$T_{ion}^{(-)} \gtrsim E_{MAR}. \quad (6)$$

But, with decrease of dimensionless parameter $\hat{q}$ (the only dimensionless parameter determining the physics of plasma recycling in our model) the temperature $T_{ion}^{(-)}$ decreases as well.

Indeed, assume that the heat flux q_∞ is fixed and start to decrease $\hat{q}$ by increasing the pressure P_∞. Then, if $T_{ion}^{(-)}$ does not decreases with increasing P_∞, from energy balance $q_\infty \approx j_N E_{ion}$ we find $Z_A \sim 1/q_\infty \sim$ const. Therefore, "optical width" of the plasma layer, $n_e Z_A \propto P_\infty$, will increase with increasing P_∞ and, as a result, neutrals will be ionized well before it reaches temperature $T_{ion}^{(-)}$ which is in contradiction to the definition of $T_{ion}^{(-)}$. Thus, we prove that $T_{ion}^{(-)}$ decreases with decreasing $\hat{q}$.

As a result, at low $\hat{q}$, when $T_{ion}^{(-)}$ drops below E_{MAR} it is not possible to sustain energy balance in the MAR region and it merges with ionization region and MAR becomes unimportant. Recalling that the MAR needs also rather low temperature (which means relatively low $\hat{q}$) we conclude that for the plasma recycling model we consider strong MAR effects may be only possible within rather limited range of dimensionless parameter $\hat{q}\sim 1$. Notice that the effects of EIR and other processes associated with dimensionless parameter Λ do not change the main physical picture considered here, but may additionally limit the MAR effects at low $\hat{q}$ due to a strong three body recombination occurring at low temperatures.

ii) Gas-box model of recycling region. Next we consider a gas-box mode (see Ref. 13) of plasma recycling where we assume that the plasma slab of the width, Δ_p, enters the box (L_b deep and Δ_b wide) with self-sustained neutral gas Fig. 4. This is reasonably good model for the plasma-neutral interactions in divertor simulators and slot divertors. As far as dimensionless parameters is concerned, here in addition to $\hat{q}$ and Λ we have parameter

$$\hat{\Delta} = \Delta_b P_\infty \left(e^4 / E_{ion}^3 \right), \quad (7)$$

which determines effective "optical width" of the box (in addition we now have geometrical parameters as Δ_p/Δ_b and L_b/Δ_b). It is clear that the case $\hat{\Delta}$>>1 can be reduced to the 1D slab model which was analyzed before. Therefore, here we consider an opposite case of "optically " transparent plasma and gas $\hat{\Delta}$<1 (notice, however, that the product $\hat{\Delta} L_b/\Delta_b$ determining "optical depth" of the box can be large due to large ratio L_b/Δ_b). Then, neutrals can almost freely move between sidewalls and the majority of hydrogen particles in the box will be molecules (we assume that $\gamma_{a\to m}$~1). Therefore, even though at plasma temperatures ~2-3 eV dissociation rate is larger than the MAR one, it does not affect neither molecule density nor the MAR rate due to very fast molecular recycling at the sidewalls. As a result, for "optically transparent" gas box like geometry the MAR will be important ingredient in the plasma particle balance already for the temperatures $\lesssim$3 eV when MAR exceed ionization rate. Thus, we can expect that for a box like geometry the MAR effects start and remain to be important at $\hat{q} \lesssim 1$.

III. Discussions. We use dimensionless parameters to analyze the MAR effects in fusion related experiments for two plasma geometries. We find that for 1D slab model, which is relevant for a well baffled tokamak divertor geometry, the MAR effects can be important only within rather limited zone of dimensionless parameter $\hat{q} = q_\infty / \left(P_\infty \sqrt{E_{ion}/M} \right)$ in the range $\hat{q}$ <1. For "optically transparent" gas box model, relevant for divertor simulators and slot divertors, we find that the MAR effects are important at $\hat{q} \lesssim 1$. Our findings may explain the differences in the conclusions of Ref. 2, 3 and Ref. 8 where the effects of MAR were analyzed for experiments in weakly baffled c-Mod inner leg, divertor simulator NAGDIS-II, and well baffled ASDEX-U divertor.

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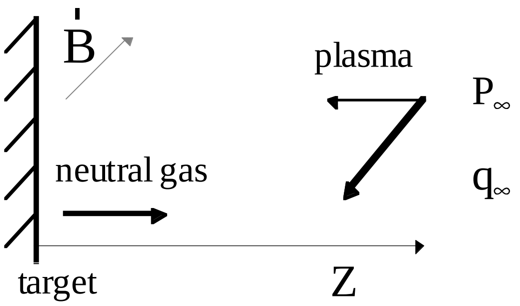

Fig. 1

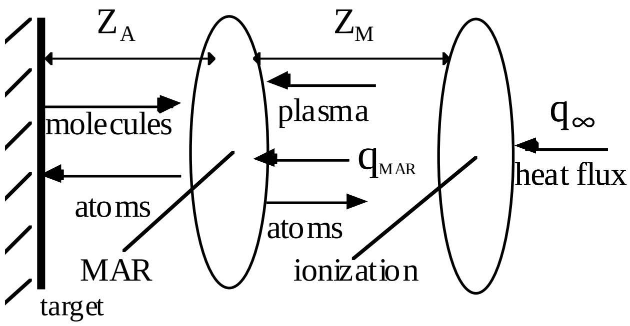

Fig. 2

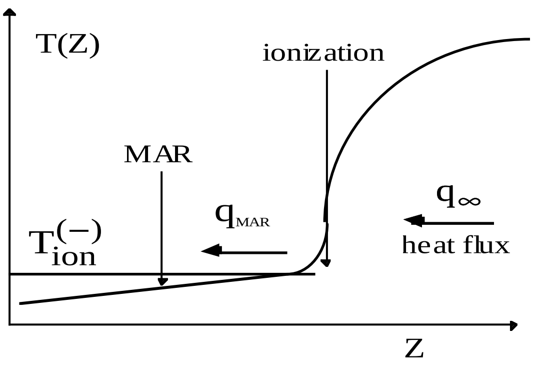

Fig. 3

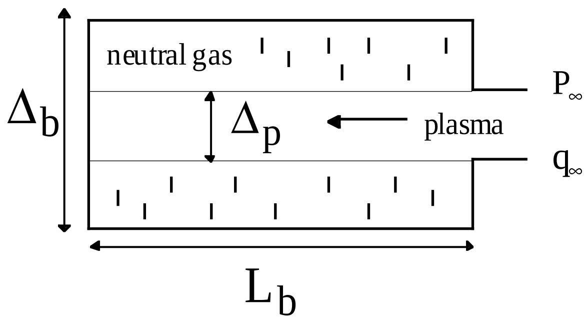

Fig. 4