PLASMA RECOMBINATION AND STABILITY OF DETACHED DIVERTOR OPERATION

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Abstract. We show that volumetric recombination of the plasma can make detached operation of a tokamak divertor unstable which result in the propagation of the ionization-recombination front towards X-point. Recombination inhibits formation of a cold plasma buffer which would otherwise impede the influx of neutrals into the hot ionization region upstream. Recombination effects become important when the upstream plasma pressure in the scrape-off layer (SOL) exceeds some critical value.

1. Introduction

Experimental observations show that when the divertor plasma detaches the detachment region (detachment front) "jumps" towards the X-point. This indicates that the localization of the detachment front in the divertor is unstable. Similar evolution of edge plasma profiles showing movement of the detachment front towards the X-point was also observed in 2D modeling of ITER and Alcator C-Mod divertors [1]. Here we consider a physical picture of an instability of detached divertor plasma, related to a bifurcation driven by the energy loss due to hydrogen radiation.

2. Qualitative analysis

First we note that the SOL plasma is almost entirely sustained by recycling processes in the divertor region including ionization of the neutrals and recombination of the plasma in the volume and on the target surface. A certain amount of power into recycling region , Q_H, is necessary in order to sustain the SOL plasma by recycling processes in the divertor (the ionization of each hydrogen atom "costs" $E_{ion} \tilde{>} 30$ eV). We will show that due to the effects of plasma recombination, sustaining the plasma with given upstream pressure, P_{up}, requires the power Q_H to exceed some critical value, $(Q_H)_{crit}>0$. The main physical arguments for this can be given as follows. If the specific flux of neutrals into the relatively hot, ionization region is $j_{ion}^{(N)}$, then in a steady state, the energy flux $q_H \equiv Q_H / A$, where A is the area of the poloidal cross-section of the SOL, must satisfy the inequality

$$q_H > E_{ion} j_{ion}^{(N)}. \qquad (1)$$

Therefore, when q_H reduces below a certain value, $j_{ion}^{(N)}$ must also reduce in order to sustain the steady state. However, $j_{ion}^{(N)}$ is determined by the source of the neutrals and the neutral transport through a cold plasma region between the neutral source and ionization front (the "plasma buffer"). Neutral transport in this region is dominated by neutral-ion collisions and has a diffusive nature. Therefore the flux of neutrals, j_N, is governed by the expression

$$j_N = -\hat{D}_N\, \partial P_N / \partial y, \tag{2}$$

where $\hat{D}_N = 2T \big/ \left\{ M K_{iN} \left(2P_N + P_p \right) \right\}$; P_p and P_N are the pressures of the plasma and neutral gas; $K_{iN} \propto \sqrt{T}$ is the ion-neutral collision rate constant. With decreasing energy flux q_H, the temperature and plasma pressure near the neutral source also decrease while P_N increases in order to sustain the momentum balance of the plasma plus neutrals along the magnetic filed, $P_N \le P_{up}$. Therefore, one sees from Eq. (2) that in order to reduce j_N in the "buffer", where $j_N = j_{ion}^{(N)}$=const., it is necessary to reduce the ratio $\sqrt{T_b}/\Delta_b \propto j_{ion}^{(N)} \propto q_H$, where Δ_b is the length of the "buffer" and T_b is the plasma temperature. This ratio could easily be reduced (by either a decrease of T_b or an increase of Δ_b) in a case where there is no recombination and the plasma only neutralizes at the target (see Fig. 1). However, in practice recombination is always present, and the three-body recombination rate increases strongly with decreasing temperature. Therefore, a reduction of $j_{ion}^{(N)}$ in order to satisfy Eq. (1) at $q_H \to 0$ by either lowering T_b in the "buffer" or increasing Δ_b leads to an increase of the recombination source of the neutrals in the "buffer" itself. As a result, the neutral source due to the plasma neutralization at the target transforms into the source associated with the plasma recombination in the volume (see Fig. 2). If the plasma recombines before it reaches the target, then further increase of Δ_b or decrease of the temperature in the plasma buffer would cause stronger recombination rate in plasma buffer rather than a reduction of $j_{ion}^{(N)}$. It would shift recombination source upstream which would in turn lead to cooling the upstream plasma and pushing the ionization-recombination front further upstream. As a result, plasma recycling can not be sustained in a steady state for $q_H \to 0$ due to the neutral source provided by the recombination.

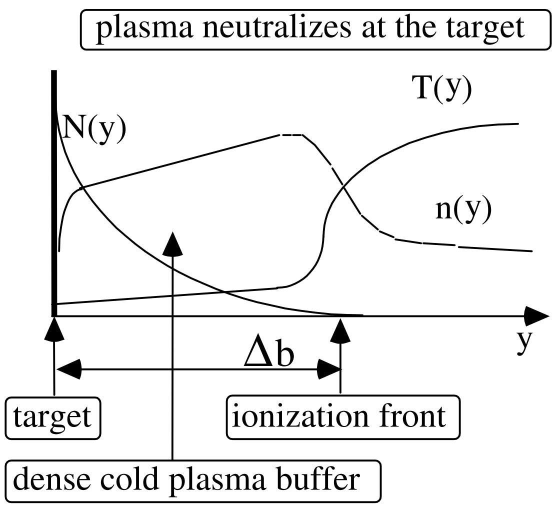

Fig. 1

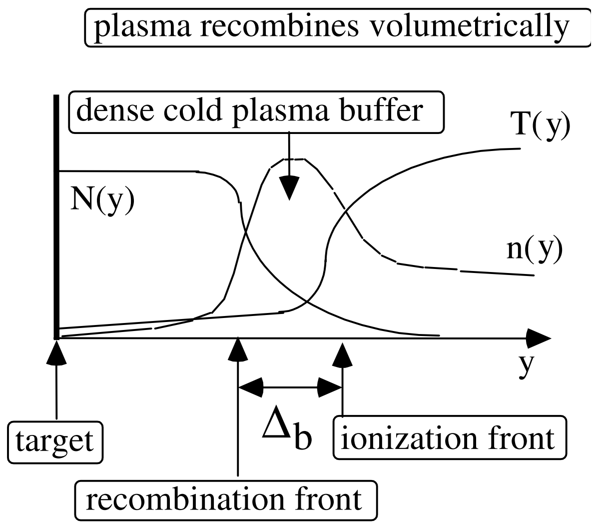

Fig. 2

3. Analysis of coupled plasma neutral equations at low power

We start with examining the plasma recycling in 1D, half-space approximation assuming that (i) the plasma flows only along the magnetic field making angle ψ with the target surface; (ii) the neutrals can flow in both "poloidal" (y) and "toroidal" (z) directions; and (iii) the local temperature of ions, electrons, and neutrals is the same. For the flows, we use a fluid approximation neglecting, however, the thermal force originated from the ion-neutral collisions. We use $P_p = P_{up}$, $P_N = 0$, and $q = q_H > 0$, where q is the net energy flux in both plasma and neutral components towards the target, as the boundary conditions at $y \to \infty$. We assume complete plasma neutralization and no absorption of the particles (100% recycling) at the target which results in zero net mass flow in the y direction. The equations governing the neutral particle balance and the energy balance under this assumption can be written as

$$\partial_y j_N = -S_{ion} + S_{rec}, \tag{3}$$

$$\partial_y q \equiv \partial_y \left(2.5 T j_N + \kappa_\Sigma \partial_y T\right) = E_{ion} S_{ion}. \tag{4}$$

Here $S_{ion} \equiv nNK_{ion}$ and $S_{rec} \equiv n^2 K_{rec}$ are the neutral sink ionization and source due to recombination; n and N are the plasma and neutral densities; K_{ion} and K_{rec} are the ionization and recombination rate constants which depend on the plasma density and temperature; $\kappa_\Sigma = \kappa_N + \kappa_e \sin^2\psi$ is the effective heat conductivity, $\kappa_N \propto (TN)/(nK_{iN} + NK_{NN})$ and $\kappa_e \propto T^{5/2}$ are the neutral and parallel electron heat conductivity; and K_{NN} is the neutral-neutral collision rate constant. In order to find the expression for j_N, we consider an equation of neutral momentum balance along the y-coordinate

$$\partial_y \left\{\left(MV^2 + T\right)N - \eta \partial_y V\right\} = -MK_{iN} nN\left(V - V_p\right). \tag{5}$$

Here $\eta \propto (TN)/(nK_{iN} + NK_{NN})$ is the neutral viscosity, and V and V_p are the neutral and plasma velocity components along the y coordinate. Taking into account the zero net mass flow in y direction, $NV + nV_p = 0$, and assuming that the scale length of the plasma and neutral parameters variation in y direction, L, is larger than the neutral mean-free-path, λ_N, one can significantly simplify Eq. (5) obtaining the Eq.(2) for j_N. Since we are concentrating on the stability of the ionization-recombination front at $q_H \to 0$, we can assume that if the front is stable, then the ratio λ_N / L should decrease following the reduction of q_H in order to ensure that the neutral flux to the ionization front is low. But with $\lambda_N / L \to 0$, the effect of neutral viscosity on the momentum balance becomes small and so the total pressure (plasma + neutrals) must be constant to maintain momentum balance in the system $P_p + P_N = P_{up}$. First, from Eq. (4) and the boundary conditions, we find that $q \geq 0$ and increases along with y. Second, we take into account that the ionization cost has some minimum value, E_{ion}^{min}, so that $E_{ion}(T) \geq E_{ion}^{min} > I_H > 0$ (I_H is the ionization potential). Then, from Eq. (3) and (4) we find

$$q_H^2 = \left\{\left(q + E_{ion}^{min} j_N\right)_t^2 - \left(E_{ion}^{min} j_N\right)_t^2\right\}$$
$$+ 2\int_0^\infty q_{eff}\left(E_{ion} - E_{ion}^{min}\right) S_{ion} dy + 2E_{ion}^{min} \int_0^\infty \left(q S_{rec} + E_{ion}^{min} j_N S_{ion}\right) dy, \tag{6}$$

where $(\ldots)_t$ is a value of (...) at the target. Next, we show that the last integral expression in the right-hand side of the Eq. (6) has a positive minimum value. To do that, we write this integral expression as an integral over the temperature

$$G \equiv \int_0^\infty \left(qS_{rec} + E_{ion}^{min} j_N S_{ion}\right) dy \equiv \int_0^\infty \left(\frac{P_{up}}{2T}\right)^2 \left\{ \frac{P_{up}\kappa_\Sigma(p,T)\hat{K}_{rec}(T)}{2T} p^3 \right.$$

$$\left. + \left(\frac{5P_{up}}{4}\hat{K}_{rec}(T)p^3 + 2E_{ion}^{min} K_{ion}(T)p(1-p)\right)\tilde{D}_N(p,T)\frac{dp}{dT}\right\} dT. \quad (7)$$

Neglecting recombination, one would find from Eq. (7) that in order to make the value of G low, the value of $p(T)$ must stay close to unity for $T >$ T_{ion} which characterizes the ionization front ($K_{ion}(T)$ decreases with decreasing T). Moreover, T_{ion} must approach zero to satisfy Eq. (6) for $q_H \to 0$. However, in practice $\hat{K}_{rec} \neq 0$ and therefore the recombination terms in Eq. (7) increase with $T_{ion} \to 0$. As a result, G has a minimum value, $G_{min} > 0$, determined by ionization and recombination processes and depending on P_{up}. Therefore, in order to sustain a plasma with the upstream pressure P_{up} in the SOL by recycling processes, the energy flux q_H must exceed some critical value, $(q_H)_{crit}$. Crude estimate of $(q_H)_{crit}$ can be obtained assuming a local Saha equilibrium

$$q_H^2 \geq (q_H)_{crit}^2 = 2\int_0^\infty E_{ion}(T)\kappa_S(T)S_{ion}^{(S)}(T)dT, \quad (8)$$

$\kappa_S = \kappa_\Sigma(T) + 2.5T\hat{D}_N(T)\partial_T P_N^{(S)}(T)$, $S_{ion}^{(S)} = P_N^{(S)}(T)P_p^{(S)}(T)K_{ion}(T)/2T^2$, and $P_N^{(S)}(T, P_{up})$ is the neutral pressure determined from the Saha equilibrium.

4. Conclusions

Thus, we have shown that a reduction of the energy flux into the hydrogen recycling region below some critical level (with either reduction of the heating power or increase of the impurity radiation loss) in a 1-D, half-space approximation results in a lack of a steady-state solution due to the effects of plasma volumetric recombination. Recombination does not allow to create cold plasma buffer which would screen hot temperature region from neutrals coming from downstream and reduce neutral influx into hot ionization region which would allow to satisfy energy balance. It results in the propagation of the ionization-recombination front towards energy source. However, in practice, the SOL plasma occupies a finite volume and contains a finite number of particles $\overline{N}_{SOL}$. It stabilizes run-away of the front but implies limitation on upstream plasma density, n_{up}, in the SOL. n_{up} saturates with increasing $\overline{N}_{SOL}$ while the ionization-recombination front moves towards the X-point [2].

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References

[1] T.D. Rognlien, et al.: *24th EPS Conference*, Berchtesgaden, June 1997 (P3.071); A.S. Kukushkin, et al.: *6th PET Workshop*, Oxford, UK, September 1997.

[2] S.I. Krasheninnikov, et al.: *13th PSI Conference*, San Diego, USA, May 1998.