§5. Influence of Wall Recycling on the Thermal Stability and Density Limit

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In the toroidal magnetic fusion devices, operating at higher density is generally desirable since higher $nT\tau_E$ is achieved. However, there is a density limit beyond which the plasma collapses / or the confinement deteriorates. The limiting density is believed to be determined by the power balance or the edge thermal stability, in which the impurity radiative power play a key role. In the LHD discharges, the plasma collapses when the fraction (ε_{rad}) of the radiative power to the total plasma heating power is typically 0.4, quite small. In this report, we propose a mechanism in which plasma collapses at fairly low fraction and the particle recycling plays the key role in determining the thermal stability and the density limit.

We use a simple one dimensional transport model with. the thermal conductivity, given as $n\chi = \frac{n^2}{n_o^\beta}\chi_o\left(\frac{T}{T_o}\right)^{-1/2}$ The feature of this type of transport, $n\chi$ is large in the edge and may be caused by the resistive interchange modes. The arguments below are not sensitive to the parametric dependence of $n\chi$. The impurity radiation cooling rate (f) is assumed to be high and constant for $T < T_o$ (typically T_o~50 eV). The heat flux and the thermal diffusivity at the radial location with $T= T_o$.are denoted by q_o and χ_o, respectively. The transport equation is solved easily.

$$\varepsilon_{rad}[1-\varepsilon_{rad}/2] = \frac{1}{2}\left(\frac{n}{n_o}\right)^4$$

where $n_o = \left(\frac{q_o^2 n_o}{4f\delta_{im}\chi_o T_o}\right)^{1/4} \propto (q_o B)^{1/2}\delta_{im}^{-1/4}$ Here δ_{imp} is the impurity concentration relative to the electron density. At $n= n_o$, 100% of input power is converted into the radiative power. For LHD parameters (P=8.5MW) and assumptions (T_o=50eV, δ_{imp}(Oxygen)=1%, $\chi=1m^2s^{-1}$), n_o is $8.5\times10^{19}m^{-3}$

Now we discuss the stability of the edge thermal equilibrium. We assume that it is stable when density is fixed. For given n, edge thermal equilibrium determined by the time constant ad/χ (~30msec) where d is the radial width of the radiative zone. If we allow the density evolve more slowly following the particle balance equation with time constant ($\tau_p/C >> ad/\chi_o$ for C = 0.01).

In order to find the stability, n is replaced by $n_o+\tilde{n}$. Here n_o and $\tilde{n}$ are the equilibrium density and the perturbed density. The penetration length of the recycled neutrals is inversely proportional to n and hence we also assume that $\tau_p \propto 1/n$.

$\frac{dn}{dt} = -\frac{n^2 C(\varepsilon_{rad})}{\tau_p n_o} + G$ Here C=1-R where R is recycling rate of the divertor plates and wall and G is gas puffing rate.

$$\frac{d\tilde{n}}{dt} = \frac{Cn}{\tau_p}\left(-2-\frac{4(1-\varepsilon_{rad}/2)}{(1-\varepsilon_{rad})}\frac{\varepsilon_{rad}}{C}\frac{\partial C}{\partial\varepsilon_{rad}}\right)\left(\frac{\tilde{n}}{n_o}\right)$$

The quantity $\frac{\varepsilon_{rad}}{C}\frac{\partial C}{\partial\varepsilon_{rad}}$ is replaced by the quantity determined more easily from the experiment by using the relations

$$n = \sqrt{\frac{G\tau_p n_o}{C(\varepsilon)}}, \quad P_{div} = P_o(1-\varepsilon).$$

$$\frac{P_{div}}{n}\frac{dn}{dP_{div}} = \frac{1}{2}\frac{(1-\varepsilon)}{\varepsilon}\frac{\varepsilon}{C}\frac{dC}{d\varepsilon}$$

where P_0 and P_{div} are the total heating power and the power to the divertor plates.

$$\frac{d\tilde{n}}{dt} = \frac{2Cn}{\tau_p}\left(-1-H\frac{P_{div}}{n}\frac{\partial n}{\partial P_{div}}\right)\left(\frac{\tilde{n}}{n_o}\right)$$

where $H = 4\varepsilon_{rad}(1-\varepsilon_{rad}/2)/(1-\varepsilon_{rad})^2$. When $(P_{div}/n)(dn/dP_{div}) > 0$, the equilibrium is stable. When $(P_{div}/n)(dn/dP_{div}) < 0$, it is stable when ε_{rad} is smaller than a critical value of ε_{rad}*. The quantity H is a monotonic function of ε_{rad}. For a typical case of the LHD, $(P_{div}/n)(dn/dP_{div})$ is - 0.3, the stability requires that H is smaller than 3.3 and correspondingly ε_{rad} is less than 0.4. If we want to maintain the equilibrium with 80% of radiative power ($\varepsilon_{rad} > 0.8$), $(P_{div}/n)(dn/dP_{div})$ must be above -0.02. The helium discharges exhibit higher density limit. This is consistent with the proposed model since $(P_{div}/n)(dn/dP_{div})$ is closer to zero for the helium discharges.

Our models predicts that making $(P_{div}/n)(dn/dP_{div})$ positive leads to the higher radiation fraction at the density limit, It may be done by filling the wall and divertor plates with hydrogen particles, opposite to the usual wall conditioning. Higher power may lead to more release of the desorbed hydrogen, namely $(P_{div}/n)(dn/dP_{div})>0$.