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Thermal instability of plasma-wall interaction

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I. Introduction. During relatively long operation of a tokamak, its first wall becomes the main source of neutral gas feeding the plasma. Moreover, in this case the amount of hydrogen fuel stored in the tokamak wall is much larger [1, 2]) than the amount of hydrogen in the plasma. Therefore, desorption of even a small fraction of hydrogen stored in the wall can significantly increase the plasma density and have vital consequences for the tokamak discharge. In this paper, we show that the synergy of plasma particle and energy transport, plasma-wall interactions, and gas desorption processes can play important role (or can even be a cause) in the divertor detachment, formation of MARFE, and plasma disruption.

As a matter of fact, an increase in the amount of hydrogen in tokamak plasma due to uncontrollable release of hydrogen from the walls has been observed experimentally during MARFE, detachment, and disruption (see, for example, Refs. [3-7]). However, neither experimentally nor theoretically this effect was extensively studied. In the most cases studied so far, the particle recycling in plasma and the hydrogen transport inside the wall implantation layer were considered but plasma transport was treated assuming the recycling coefficient at the material surfaces to be independent on the incident flux and discharge history while the wall processes were analyzed assuming fixed plasma parameters (e.g. Ref. 8-11). Although in Ref. 11 the 1D model of plasma particle flux to the wall was coupled to the model describing the evolution of hydrogen concentration in the implantation layer, the power balance between plasma and the wall was not considered self-consistently. Meanwhile, plasma parameters and wall conditions (in particular, the temperature T_W of the wall surface) can strongly affect each other. The simplified 0-D model, describing the non-linear response of hydrogen flux desorbed from the wall to the variations of incident plasma particle and energy fluxes, has been considered in Ref. [12]. It was shown that the interactions of plasma with tokamak plasma-facing components saturated with hydrogen can cause the instability of edge plasma against perturbations of T_W. The physics of this instability is related to the positive loop, in which an increase in T_W results in strong desorption of hydrogen from the wall whereas the heat flux to the wall also increases due to the enhancement of charge-exchange and radiation plasma energy losses, that prompt further increase of the wall temperature. We notice that conventional theories of MARFE and detachment (e.g. see Refs. 13-17 and the references therein) do not account for desorption of hydrogen from the wall even though it was observed, as we mentioned above, in experiments.

Unfortunately, the physics of coupled plasma-wall system is complex and understanding of each part of the problem (plasma energy and particle transport and transport of hydrogen in wall material) is rather poor (see for example Refs. 9, 10 and the references therein). Therefore, at present, it is impossible to make definitive quantitative theoretical predictions of both stability and nonlinear evolution for the coupled plasma-wall system. However, some qualitative assessments, which may help with the interpretation of existing data and may give some hints for future experimental and theoretical studies, can be made.

In the paper, we present stability analysis as well as the results of nonlinear numerical modeling of plasma-wall coupling based on simple 0-D model (see also Ref. 18). Following

Ref. 12, we use the model describing plasma particle and energy balances and the wall heat balance and present the results of our numerical simulations.

II. Stability analysis and nonlinear evolution of plasma-wall coupling. We consider the system of equations for temporal evolution of the effective wall temperature T_w, total number of hydrogen ions in tokamak plasma volume n, and normalized plasma energy W:

$$\frac{dT_w}{dt} = \frac{W}{\tau_E} + n^2 K_{rad} - \frac{T_w}{\tau_w}, \quad \frac{dn}{dt} = -\frac{n}{\tau_n} + \frac{N-n}{\tau_D}\exp\left(-\frac{\Delta E}{T_w}\right), \quad \frac{dW}{dt} = P - \frac{W}{\tau_E} - n^2 K_{rad}, \tag{1}$$

where $\tau_{(...)}$ are the effective equilibration time scales; P is the effective heating power; N is the effective total number of hydrogen atoms in tokamak (including wall); K_{rad} describes both radiation and charge-exchange energy loss, DE is the hydrogen desorption activation energy. In our model we assume that: i) the rate of hydrogen puffing and pumping is much lower than the adsorption/desorption rate by the wall, and ii) re-distribution of hydrogen inside the wall and establishing of the hydrogen desorption rate are relatively fast. We note that, just to demonstrate the physics of the plasma-wall coupling, we use very simple term describing the hydrogen desorption in (1). The discussion of other available models for hydrogen disorption can be found in Ref. 10.

We consider the stability of equilibrium solution of Eq. (1) $\overline{T}_w$, $\overline{n}$, and $\overline{W}$, assuming that all perturbed quantities are proportional to $\exp(-i\omega t)$ and that all $\tau_{(...)}$ as well as K_{rad} are constants. After some algebra we find the following dispersion equation

$$\left(-i\omega + 1/\tau_E\right)\left(-i\omega + 1/\tau_w\right)\left(-i\omega + 1/(\xi_{wall}\tau_n)\right) = -i\omega R(2\varepsilon/\tau_w\tau_n) \equiv -i\omega R\gamma_0^2 \equiv -i\omega\gamma_R^2, \tag{2}$$

where $\varepsilon = \Delta E/\overline{T}_w$, $\xi_{wall} \equiv 1 - \overline{n}/N$ is the wall fraction of total amount of hydrogen, and $R \equiv \overline{n}^2 K_{rad}/P < 1$ is the fraction of radiation and charge exchange in the overall plasma energy loss for equilibrium conditions. From Eq. (2) we find the threshold of the instability, which can be written as follows

$$\gamma_R^2 > \gamma_2^2 - \gamma_3^3/\gamma_1, \qquad \text{or} \qquad R > \left(\gamma_2^2 - \gamma_3^3/\gamma_1\right)/\gamma_0^2 \tag{3}$$

where

$$\gamma_1 = \frac{1}{\tau_w} + \frac{1}{\tau_E} + \frac{1}{\xi_{wall}\tau_n}, \; \gamma_2^2 = \frac{1}{\tau_w\tau_E} + \frac{1}{\tau_E\xi_{wall}\tau_n} + \frac{1}{\tau_w\xi_{wall}\tau_n}, \; \gamma_3^3 = \frac{1}{\tau_w\tau_E\xi_{wall}\tau_n}. \tag{4}$$

Since $R < 1$, from Eq. (3) we conclude that the instability is only possible for $\gamma_0^2 + \gamma_3^3/\gamma_1 > \gamma_2^2$. Since in practice $\varepsilon = \Delta E/\overline{T}_w > 1$, we find that for a saturated wall ($\xi_{wall} \approx 1$) and comparable time constants τ_w, τ_E, τ_n, this inequality can be satisfied relatively easy. As a result, the threshold (3) can be exceeded even at rather modest radiation loss. In the vicinity of the threshold (3), $\gamma_R^2 \approx \gamma_2^2 - \gamma_3^3/\gamma_1$, we find $\omega = \omega_0 + i\gamma$ ($\gamma^2 << \omega_0^2$), where $\omega_0^2 \approx \gamma_3^3/\gamma_1$ and $\gamma = 0.5\gamma_1(\gamma_3^3/\gamma_1(\gamma_2^2 - \gamma_R^2) - 1)$. For large value of γ_R ($\gamma_R > \gamma_1$) from Eq. (2) we have $\omega \approx i\gamma_R$. It is interesting to note that the parameters N and τ_d, the magnitudes of which are not well known, do not enter into dispersion equation (2).

In order to explore nonlinear evolution of unstable regimes we solve Eqs. (1) numerically. In our numerical studies we normalize: time and the time constants $\tau_{(...)}$ over τ_E, wall temperature over $\overline{T}_w$, the plasma energy over $P\tau_E$, and the plasma density over $\overline{n}$. To specify the necessary combinations of the constants N, K_{rad} and DE we set the parameters $\varepsilon = \Delta E/\overline{T}_w$ and R (recall that R is the fraction of radiation loss in the equilibrium plasma energy balance). The initial conditions we used were: i) the normalized plasma density equals to one, ii) the normalized plasma energy equals to 1-R, and iii) the normalized wall temperature equals to 1.01.

In Fig. 1, 2 we show the results of our modeling for $\tau_n/\tau_E = \tau_W/\tau_E = \tau_D/\tau_E = 1$, $\varepsilon = 5$, and different values of R (for $R = 0.3$ in Fig. 1 for and $R = 0.5$ in Fig. 2). The case $R = 0.3$ ($R = 0.5$) is very close to (is quite far from) the stability limit (the critical value of R corresponding to the threshold of the instability is 4/15). Therefore, in accordance with our expectations we observe two different scenarios of time evolution of the solutions of Eq. (1): rather slowly growing oscillating mode with further accelerating transition into the regime with a strong increase plasma density for $R = 0.3$ and fast aperiodic growth of the perturbations which ends up with similar increase plasma density for $R = 0.5$. We find that such type of behavior is quite typical. As other examples, in Fig. 3, 4 we show the results of numerical solution of Eqs. (1) for $\tau_W/\tau_E = 1/3$, $\tau_n/\tau_E = 1$, $\varepsilon = 5$, and different values of R (for $R = 0.25$ in Fig. 3 for and $R = 0.4$ in Fig. 4, critical value of R in this case is 0.213) and τ_D/τ_E ($\tau_D/\tau_E = 1$ (solid) and $\tau_D/\tau_E = 1/3$ (dashed)). From Fig, 3, 4 one sees, that likewise in linear case the magnitude of τ_D does not make any significant difference for the nonlinear evolution as well for the parameters close to and far from the instability threshold.

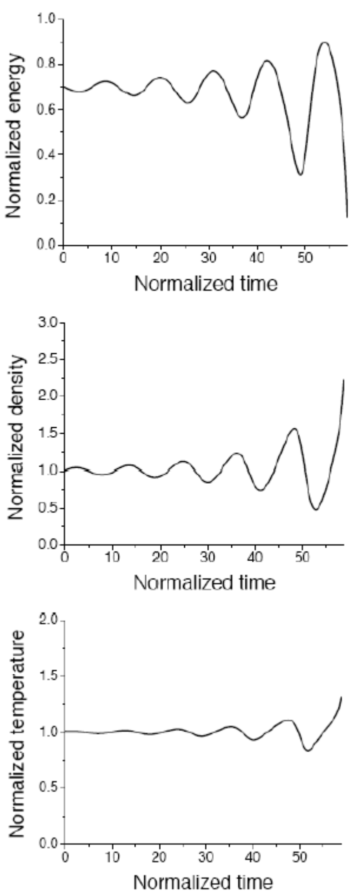

Fig. 1

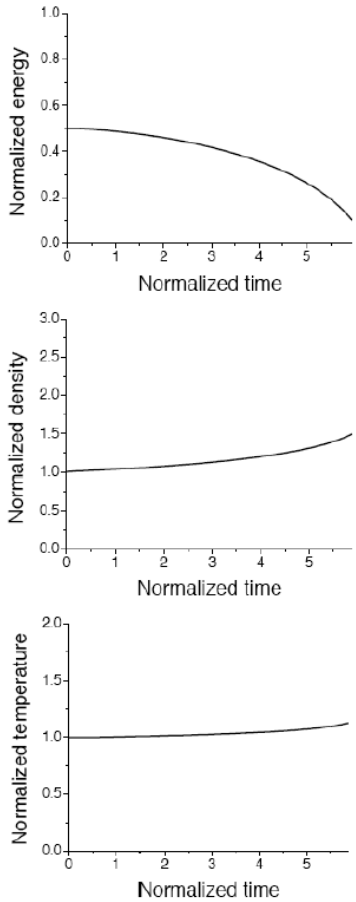

Fig. 2

We emphasize that the results of numerical simulation demonstrate that nonlinear stage of thermal instability caused by plasma-wall coupling leads to large impact on both plasma and wall parameters. We also note that the processes we are considering in our study mainly involve only rather thin layer where plasma recycling and radiation occur. Therefore, this circumstance should be taken into account in the estimates of characteristic time scale τ_E and τ_n, when the results following from our simple 0-D model are applied for the interpretation of experimental data. For a rough estimate of the growth rate γ for reactor-scale tokamak we take $\varepsilon \sim 5$, $\tau_w \sim \tau_E \sim \tau_n \sim 1\,s$, $\xi_{wall} \sim R \sim 1$. Then the inequality $\gamma_R > \gamma_1$ is satisfied and we find $\gamma \sim 3\,s^{-1}$. Taking into account that pumping time-scale τ_{pump} is much larger then plasma particle recycling time-scale τ_n [17], we see that $\tau_{inst} \equiv \gamma^{-1} < \tau_n < \tau_{pump}$. As a result, pumping cannot control such instability.

III. Conclusions. We show that the interactions of plasma with first wall saturated with hydrogen can cause thermal instability resulting in massive desorption of gas from the wall and can trigger the formation of MARFE, detachment, or even disruption. Unfortunately our

0-D model does not distinguishing between local and global modes of the instability which may have different effective time constants $\tau_{(...)}$ and correspondingly evolve into MARFE or detachment and disruption. Nevertheless, we believe that such instability, caused by strong plasma-wall coupling, can play an important role in a long pulse operation with a high fraction of radiation energy loss in both current tokamaks and ITER. In future we plan to implement more accurate and sophisticated 1D models for wall temperature evolution, plasma transport, and neutral absorption/desorption kinetics. We will use these models to study stabiliity of plasma-wall coupling and transient events in the tokamak plasma (e.g., ELMs and blobs). We also plan to implement our wall and plasma recycling models into the edge plasma transport code UEDGE to benchmark our models against experimental data on current tokamaks, and to make solid quantitative predictions for ITER.

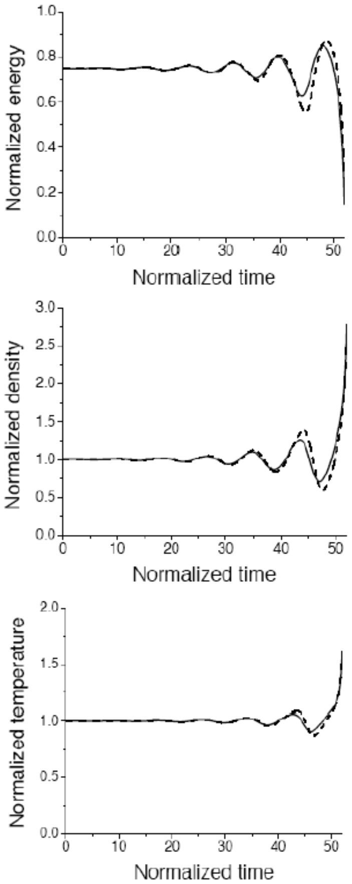

Fig. 3

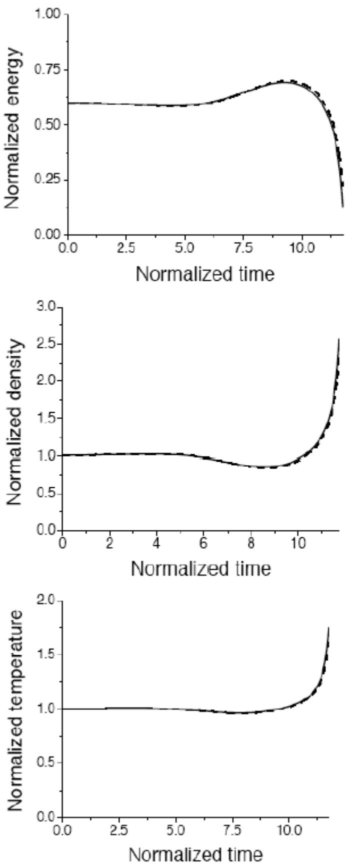

Fig. 4

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