On the thermal instability caused by plasma-wall coupling

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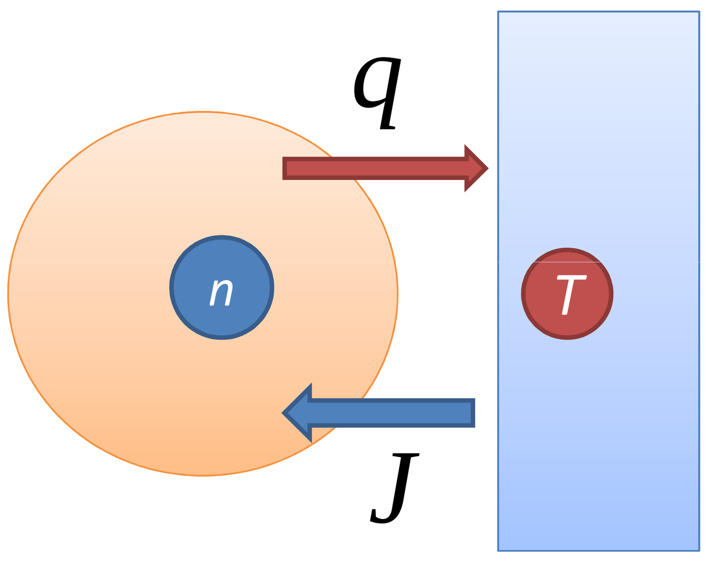
1. Introduction

Hydrogen isotopes recycling and retention in the first wall materials are among major issues in fusion devices and in tokamaks, particularly. Interaction between the edge plasma and surrounding surfaces can strongly influence properties of the core plasma and, consequently, the tokamak discharge. High energy/heat loads can lead to damage of the first wall and to release of trapped hydrogen, which is vitally important for the discharge.

2. The thermal instability



An initial increase of the wall temperature results in a strong increase of the hydrogen desorption rate, and this leads to enhancement of the charge exchange and radiation losses, which increase the heat flux to the wall and prompt further increase of the wall temperature.

3. Basic equations

The particle and energy balance equations in plasma are:

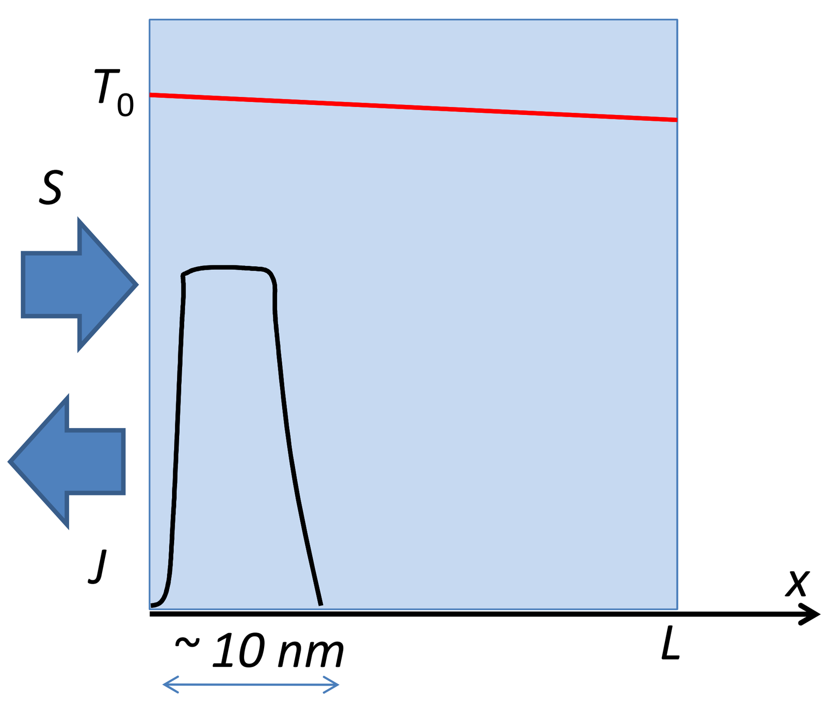
$$\frac{dn}{dt} = -\frac{n}{\tau_p} + J\frac{A}{V} \qquad \frac{dP}{dt} = H - \frac{P}{\tau_E} - n^2 R$$

where n – the plasma particle density, P – energy density, H – effective heating power, $\tau_{(\ldots)}$ – the effective equilibration time scales, J – the desorption flux of hydrogen molecules from the wall into the plasma, A and V – the effective surface and the volume of the chamber, H – the effective heating power. The term n^2R describes both radiation and charge-exchange energy losses.
The temperature distribution is described be the heat-conductivity equation:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

with boundary conditions:

$$-\kappa \left.\frac{\partial T}{\partial x}\right|_{x=0} = q(t), \quad T|_{x=L} = T_r$$



where T_r is the temperature at the outlet side of the wall, maintained constant, κ is the thermal conductivity and

$$q = \frac{V}{A}\left(\frac{P}{\tau_E} + n^2 R\right)$$

is the heat flux from plasma to the wall.

The total amount of hydrogen in the wall C (at./cm^2) varies in accordance with

$$\frac{dC}{dt} = -C\frac{1}{\tau_t}\exp\left(-\frac{E_t}{T_0}\right) + S\left(1 - \frac{C}{C_m}\right)$$

where $S = nV/\tau_p A$ is the hydrogen flux from the plasma to the wall, C_m is the maximum amount of hydrogen which can be achieved in the material, T is the wall temperature, E_t – the detrapping energy, τ_t is the detrapping time-scale.

4. Dispersion equation

A pertubation growthrate is defined by the dispersion equation:

$$\left(\gamma + \frac{1-\bar{h}}{\tau_p} + \frac{1}{\tau_t}\exp\left(-\frac{E_t}{\bar{T}_0}\right) + \frac{\bar{S}}{C_m}\right)\left(\gamma + \frac{1}{\tau_E}\right) = \frac{\gamma\varepsilon\left(1-\bar{h}\right)}{\tau_p}\frac{\tanh z}{z}$$

Here: $z = \sqrt{\gamma L^2/\alpha}$ $\qquad \varepsilon = 2\frac{E_t}{\bar{T}_0}\frac{\Delta\bar{T}}{\bar{T}_0}\xi_r$ $\qquad \xi_r = \bar{n}^2 R/H$

A necessary criterion of instability development is

$$\varepsilon > \left(1 + \sqrt{\frac{\tau_p}{\tau_E\left(1-\bar{h}\right)}}\right)^2 + 2\frac{\beta_t\sqrt{\beta_E}}{\beta_p\left(1-\bar{h}\right)^2}$$

One can see from steady-state equations that $\bar{h} = \left(1 + \frac{C_m}{S\tau_t}\exp\left(-\frac{E_t}{\bar{T}_0}\right)\right)^{-1}$

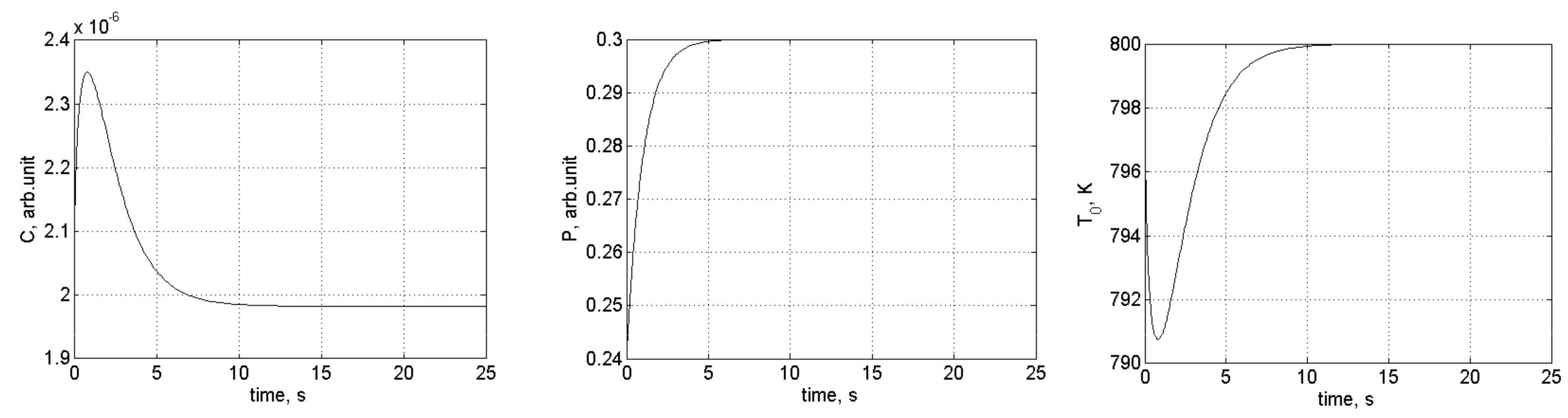
describes relative contribution of induced desorption to the total flux of hydrogen from the wall. Parameters β characterize the ratio between the thermal conductivity time scale and the equilibration times for energy, particles, and desorption:

$$\beta_{p,E} = \frac{L^2}{\alpha\tau_{E,p}} \qquad \beta_t = \frac{L^2}{\alpha\tau_t}\exp\left(-\frac{E_t}{\bar{T}_0}\right)$$

5. Numerical solution

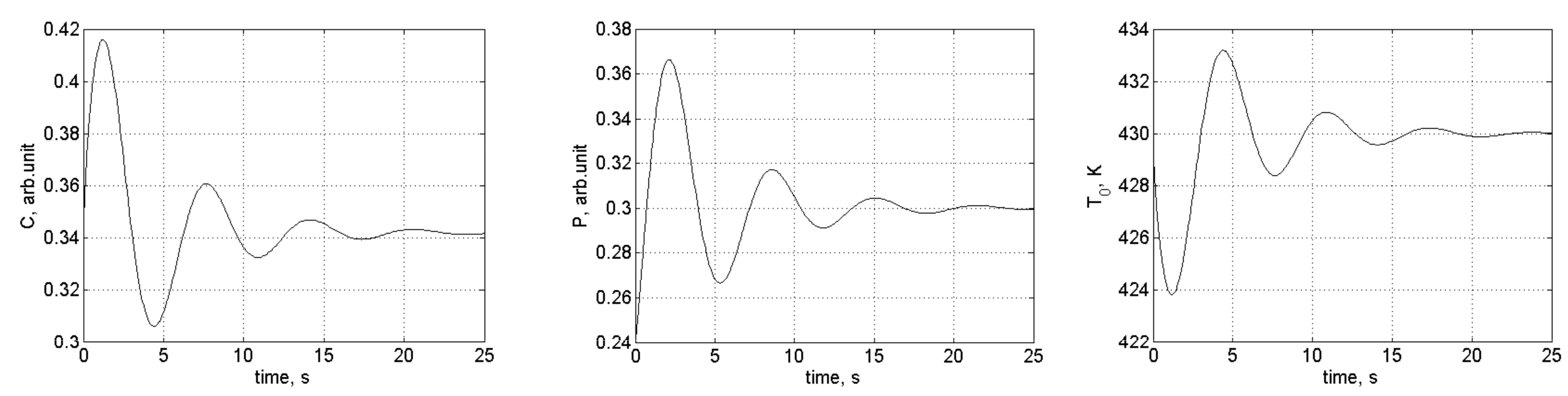
For numerical solution all quantities were normalized: time by τ_E, concentration n by its steady-state value, P by $H\tau_E$. In figures below $C(0)$ and $T_0(0)$ equal their steady-state values, $P(0) = 0.8P_{equ} = 0.8(1-\xi_r)$

Stable behavior:



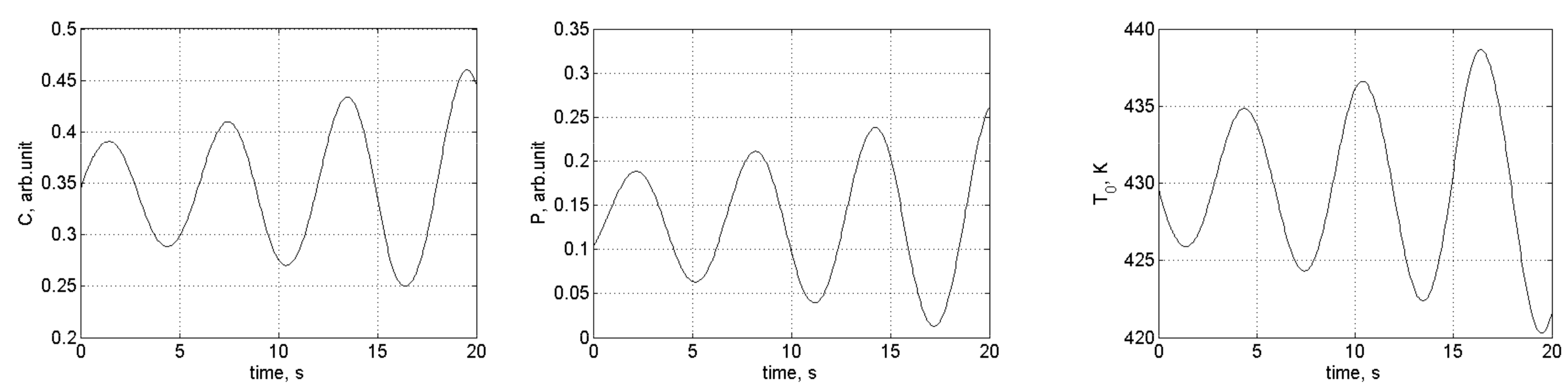
$\tau_E = 1\,\mathrm{s},\ \tau_p = 0.1\,\mathrm{s},\ \tau_t = 10^{-13}\,\mathrm{s},\ \xi_r = 0.7,\ E_t = 1.0\,\mathrm{eV},\ T_0 = 800\,\mathrm{K},\ T_r = 300\,\mathrm{K},\ S = 10^{18}\,\mathrm{cm^{-2}s^{-1}},\ C_m = 10^{17}\,\mathrm{cm^{-2}}$

Stable behavior with oscillations:



$\tau_E = 1\,\mathrm{s},\ \tau_p = 0.1\,\mathrm{s},\ \tau_t = 10^{-13}\,\mathrm{s},\ \xi_r = 0.7,\ E_t = 1.0\,\mathrm{eV},\ T_0 = 430\,\mathrm{K},\ T_r = 300\,\mathrm{K},\ S = 10^{18}\,\mathrm{cm^{-2}s^{-1}},\ C_m = 10^{17}\,\mathrm{cm^{-2}}$

Instability development:



$\tau_E = 1\,\mathrm{s},\ \tau_p = 0.1\,\mathrm{s},\ \tau_t = 10^{-13}\,\mathrm{s},\ \xi_r = 0.87,\ E_t = 1.0\,\mathrm{eV},\ T_0 = 430\,\mathrm{K},\ T_r = 300\,\mathrm{K},\ S = 10^{18}\,\mathrm{cm^{-2}s^{-1}},\ C_m = 10^{17}\,\mathrm{cm^{-2}}$

6. Conclusion

One sees from the dispersion equation that there are three parameters playing an important role in the instability development: τ_E/τ_p, ε, and ξ_r. The more these parameters are, the more probable is the instability growth. This qualitative result is confirmed by numerical calculations. A small perturbation of the plasma energy leads to oscillations of the wall temperature, plasma energy, and hydrogen concentration in the wall with decreasing magnitude, if the temperature gradient in the wall is small enough. If the energy loses are large at the same time, then oscillations magnitude increases with the time, i.e. the instability occurs.

The work was supported by the following organizations and grants: *Impuls- und Vernetzungsfonds der Helmholtz-Gemeinschaft e.V., RFBR Grant #07-08-92280*, the contract with *Russian Ministry of Education and Science within the Federal Target Program «Scientific and pedagogic manpower of Russia, 2009 – 2013».*

13th PFMC WORKSHOP and 1st FEMaS CONFERENCE ROSENHEIM 9-13 MAY 2011