LETTERS

The purpose of this Letters section is to provide rapid dissemination of important new results in the fields regularly covered by Physics of Plasmas. Results of extended research should not be presented as a series of letters in place of comprehensive articles. Letters cannot exceed four printed pages in length, including space allowed for title, figures, tables, references and an abstract limited to about 100 words. ***There is a three-month time limit, from date of receipt to acceptance, for processing Letter manuscripts. Authors must also submit a brief statement justifying rapid publication in the Letters section.***

A possible nature of ''breathing'' plasmas

M. Z. Tokar
Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, Association Euratom-FZJ, 52425, Jülich, Germany

B. J. Peterson, Y. Nakamura, Y. Takeiri, and N. Noda
National Institute for Fusion Science, Toki-shi, Gifu-ken 509-5292, Japan

(Received 28 April 2000; accepted 31 July 2000)

A model for ''breathing'' plasmas observed in the large helical device [Y. Takeiri *et al.*, Plasma Phys. Controlled Fusion **42**, 147 (2000)] is proposed. It takes into account the synergism of radiation losses from both low-Z (carbon, oxygen) and high-Z (iron) impurities in the plasma power balance.
© *2000 American Institute of Physics.* [S1070-664X(00)01411-7]

Recently, a phenomenon of ''plasma breathing'' has been observed in the large helical device (LHD):[1,2] an increase of the electron density above a critical level led to self-sustained oscillations of diverse plasma parameters, e.g., integrated radiation or intensity of impurity spectral lines. Periodic variation of the ion saturation current discloses this phenomenon as repetitive acts of the plasma detachment from and reattachment to the divertor plates. In a detached phase the plasma becomes very cold not only in the divertor but in a significant part of the confined volume. This periodic expansion and contraction of the temperature profile led to the name ''breathing.''

It is well-known that a plasma detachment in tokamaks and stellarators can be caused by radiation from light impurities like carbon and oxygen when a critical density is achieved.[3,4] However, to explain breathing one has to identify processes which account for the periodic reattachment of the plasma. Relevant models elaborated previously (see, e.g., Refs. 5 and 6) do not provide a firm explanation because they neglect a reaction of the plasma core on processes at the edge. In the present letter we discuss a breathing mechanism which takes into account the core response by considering the radiation losses from high-Z ions. This approach was brought to mind by observations[2] that breathing develops only when iron particles produced by erosion of divertor elements of stainless steel pollute the plasma additionally to ''normal'' light impurities. The mechanism proposed can be described as follows. In an attached state with a high enough temperature at the plasma edge there is an intensive erosion of the divertor plates and the density and radiation of iron from the plasma core increase in time. Consequently, the heat outflow to the plasma edge decreases and when it drops to a critical level a detachment owing to radiation of low-Z impurities takes place. With reducing edge temperature the source of heavy impurity diminishes and its concentration in the core decreases due to outward transport of high-Z ions. As a result the radiation losses from the plasma interim reduce and a reattachment occurs.

For a semiquantitative analysis we make some simplifying assumptions whose accuracy can be entirely proven only by a numerical modelling. The edge region where plasma heat conduction and line radiation of low-Z impurities dominate the energy transport is assumed to be thin in comparison with the plasma minor radius. The plasma temperature T is described here by the heat transport equation in a slab geometry:[7,8]

$$-\kappa_{\perp}\frac{d^2T}{dx^2}=-n^2c_{lz}L_{lz} \tag{1}$$

with the heat conductivity $\kappa_{\perp}$, electron density n and fraction of low-Z impurity, c_{lz}, assumed unchanging with the distance x from the last closed magnetic surface (LCMS) toward the plasma core. The cooling rate of low-Z impurities is computed in the ''box'' approximation:[7,8]

$$L_{lz}(T<T_{lz})=L_{lz}^0;\quad L_{lz}(T>T_{lz})=0.$$

The values L_{lz}^0 and T_{lz} are determined by the impurity charge distribution. At the plasma edge this is governed by ionization and transport across magnetic surfaces,[9] and $L_{lz}^0\approx 5\times 10^{-7}\,\mathrm{eV\,cm^3\,s^{-1}}$, $T_{lz}\approx 50\,\mathrm{eV}$, for the impurities in question.

At the LCMS, $x=0$, we assume the boundary condition:[10]

 © 2000 American Institute of Physics

Downloaded 21 Dec 2006 to 134.94.122.39. Redistribution subject to AIP license or copyright, see http://pop.aip.org/pop/copyright.jsp

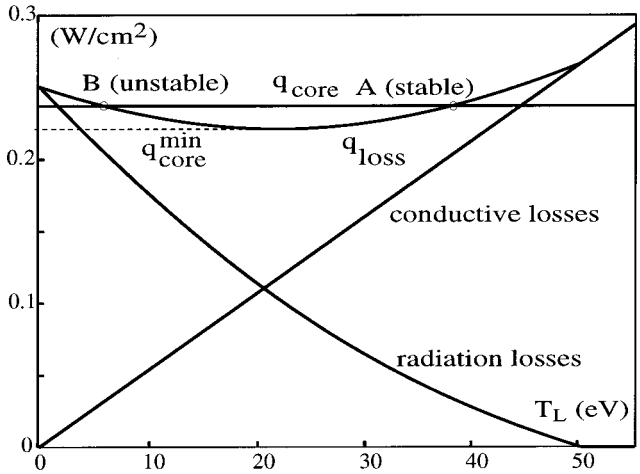

FIG. 1. Energy losses from the plasma and its stationary states.

$$\frac{dT}{dx}=\frac{T}{\delta_T}$$

with the *e*-folding length δ_T determined by the transport in the region with open field lines, i.e., in the stochastic zone and scrape-off layer. At the border of the plasma core, $x=x_{\rm rad}$, defined by the condition $T=T_{lz}$, the heat flux density, $q_{\rm core}$, is prescribed.

Equation (1) is integrated analytically and the temperature at the LCMS, T_L, is governed by the balance between $q_{\rm core}$ and the total energy loss from the edge with conduction and radiation, $q_{\rm loss}=\kappa_\perp T_L/\delta_T+n^2c_{lz}L_{lz}x_{\rm rad}$. A simple computation for $x_{\rm rad}$ gives

$$q_{\rm loss}=\sqrt{\left(\kappa_\perp\frac{T_L}{\delta_T}\right)^2+2\kappa_\perp n^2c_{lz}\Lambda_{lz}}, \tag{2}$$

where $\Lambda_{lz}=L_{lz}^0\times\max(0,T_{lz}-T_L)$.

Figure 1 shows $q_{\rm loss}$ and its conductive and radiative constituents versus T_L for a typical plasma density of 7×10^{12} cm^{-3} in LHD discharges with breathing,[1,2] $\kappa_\perp\approx10^{17}$ cm^{-1} s^{-1} estimated from the measured temperature profile, $\delta_T=3$ cm and $c_{lz}=1\%$. With decreasing T_L the conductive losses reduce while the radiation increases because the edge radiative layer becomes broader. This provides the minimum in $q_{\rm loss}$. For $q_{\rm core}>0.25$ W/cm^2 there is a single stationary state where the input power is transported to the LCMS predominantly by conduction. When $q_{\rm core}^{\rm min}\approx0.22$ W/cm$^2<q_{\rm core}<0.25$ W/cm^2 there are two stationary states but only that with a higher temperature, *A*, is stable.[10] The state *B* is unstable: by a spontaneous decrease of T_L the radiation losses grow stronger than the decrease of conductive losses and T_L drops further. If the heat flux from the plasma core reduces to $q_{\rm core}^{\rm min}$ there are no stationary states at all, the plasma edge cools down and a detachment occurs.[10]

In order to determine $q_{\rm core}$ we consider the heat balance for the central plasma. After averaging over magnetic surfaces this is governed by the equation:

$$\frac{1}{r}\frac{d}{dr}\left(-r\kappa_\perp\frac{dT}{dr}\right)=P-n^2c_{hz}L_{hz}(T), \tag{3}$$

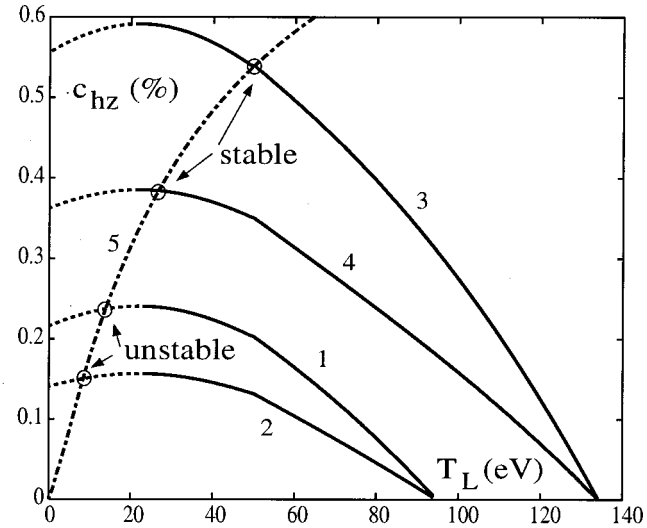

FIG. 2. Concentration of high-*Z* impurity determined from the heat balance for the plasma parameters under breathing conditions with corona (curve 1) and noncorona (curve 2) models for high-*Z* impurity and for a parameter $\Lambda_{\rm heat}$ by a factor of 2 larger (curves 3 and 4, respectively) and from impurity particle balance (curve 5).

where *r* is the effective minor radius of the surface computed by taking into account the three-dimensional (3D) magnetic geometry of the LHD, *P* is the density of heating power, c_{hz} and L_{hz} the fraction and cooling rate of high-*Z* impurity ions. Equation (3), multiplied by $r\,dr$ and integrated between the axis and the radius r_b where the temperature reduces to $T_b=\max(T_{lz},T_L)$, results in

$$q_{\rm core}=\frac{W_{\rm tot}}{4\pi^2Rr_b}-\frac{n^2c_{hz}}{r_b}\int_0^{r_b}Ł_{hz}r\,dr.$$

Here $W_{\rm tot}$ is the absorbed power, *R* the major plasma radius, *n* and c_{hz} the volume averaged values. The integral above can be rewritten as $\int_{T_b}^{T_c}r(-dT/dr)^{-1}L_{hz}\,dT$, where T_c is the temperature at the plasma axis. The measured temperature profile[1] can be roughly approximated by a parabolic one and $r(-dT/dr)^{-1}\approx r_b^2/2T_c$. Finally,

$$q_{\rm core}\approx n^2\frac{r_b}{2T_c}(\Lambda_{\rm heat}-c_{hz}\Lambda_{hz}) \tag{4}$$

with $\Lambda_{\rm heat}=W_{\rm tot}T_c/2\pi^2Rr_b^2n^2$ and $\Lambda_{hz}=\int_{T_b}^{T_c}Ł_{hz}\,dT$. For our qualitative analysis we assume according to Ref. 11 $L_{hz}(T)=L_{\rm cor}(\alpha T)$, where $L_{\rm cor}$ is the cooling rate in corona approximation.[12] For iron impurity with a typical $0.3<\alpha<1$, L_{hz} is much less at $T_c\approx1$ keV than its maximum level achieved at $T\approx70\,{\rm eV}/\alpha$ and the T_c dependence of Λ_{hz} is weak.

Equating $q_{\rm loss}$ and $q_{\rm core}$ from Eqs. (2) and (4) we find a relation between stationary values of T_L and c_{hz}. With the plasma heat conductivity estimated from the core thermal balance as $W_{\rm tot}/8\pi^2RT_c$, this relation can be written as follows:

$$c_{hz}=\frac{\Lambda_{\rm heat}}{\Lambda_{hz}}\cdot\left[1-\sqrt{\left(\frac{r_bT_L}{2\delta_TT_c}\right)^2+2c_{lz}\frac{\Lambda_{lz}}{\Lambda_{\rm heat}}}\right]. \tag{5}$$

In Fig. 2 this dependence is shown for the LHD parameters:

Downloaded 21 Dec 2006 to 134.94.122.39. Redistribution subject to AIP license or copyright, see http://pop.aip.org/pop/copyright.jsp

$r_b \approx 60$ cm, $R \approx 375$ cm, $W_{tot} \approx 450$ kW, with L_{hz} in corona approximation and for $\alpha = 0.5$. The dependences obtained with Λ_{heat} by a factor of 2 larger are also presented; they correspond to discharge conditions of a smaller density or a higher power under which no breathing were observed. Thus if the concentration of high-Z ions lies in the definite range the plasma heat balance allows two stationary states with different values of T_L. One of these states belongs to the dot part of the curves in Fig. 2 where $dq_{loss}/dT_L < 0$ (see Fig. 1) and is unstable.

Additionally to the heat balance there is another interrelation between c_{hz} and T_L given by the particle balance for high-Z impurity. The latter relates c_{hz} with the impurity source due to erosion of divertor plates which is strongly dependent on T_L. The influx of sputtered iron neutrals through the LCMS is given by $J_{hz} \approx \Sigma_j Y_j(E_j) \cdot \Gamma_j$, where Y_j and Γ_j are the sputtering rate and outflow, respectively, of the background ions with different index j corresponding to prefuelled helium, hydrogen from the neutral beam, carbon and oxygen impurities; the ion energy $E_j \approx \gamma_j T_L$ with the heat transmission factor γ_j accounting for ion acceleration in the sheath potential near the plates. According to Ref. 13 $\Gamma_j \approx D_\perp \cdot (n_j / l_j)$ where $D_\perp$ is the diffusivity of charged particles, n_j the core density of j particles, l_j the penetration depth of neutrals determined by the ionization cross-sections $\sigma_j : l_j \approx 1/n\sigma_j$. The balance between J_{hz} and outflow of high-Z ions provides an additional relation between the concentration of the heavy impurity and T_L:

$$c_{hz} = \sum_j \frac{n_j \sigma_j}{n \sigma_{hz}} Y_j(\gamma_j T_L) \tag{6}$$

with σ_{hz} being the ionization cross section of iron atoms. This dependence is shown in Fig. 2 by the dot-and-dash line. The form of this curve is determined mainly by the temperature dependence of the sputtering rates[14] which is very sharp in the vicinity of the threshold energy.

Equations (5) and (6) together determine an unique stationary state in which both the heat and impurity particle balances are satisfied. As one can see in Fig. 2 if the parameter Λ_{heat} is larger enough this state is a one with a stable radiative layer at the plasma edge. This is in accordance with the observations that no breathing has been observed at a small density or a high power. For the conditions of plasma breathing the solutions of Eqs. (5) and (6) correspond to states which are unstable to the detachment at the plasma edge. If we put our system in such a stationary state the instability of the edge radiative layer brings the plasma either to the state O_1 or to O_2 (see Fig. 3). This occurs if the concentration of high-Z impurity does not have enough time to change significantly during the development of this instability. This is really the case because the transport of high-Z ions through the whole plasma requires much more time than cooling of the thin edge. If the system came, e.g., to the detached state O_1, the impurity source disappears and high-Z impurity leave the plasma. When c_{hz} drops down to the level c_{hz}^{min} the heat flux to the edge becomes large enough for the reattachment of the radiative layer, i.e., the plasma "jumps" from the state A to the state B. Here the heavy impurity source increases and c_{hz} grows slowly to the level c_{hz}^{max} when detachment occurs again. Thus instead of a stationary state there is a limit cycle which corresponds to the plasma breathing. This behavior is analogous to oscillations in an electric circuit with a neon tube.

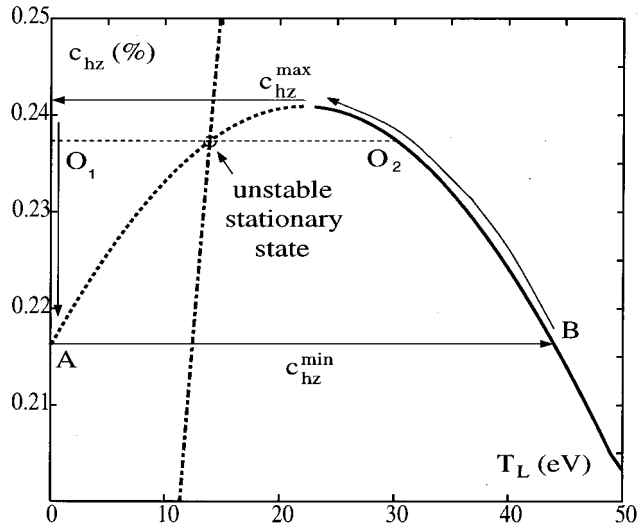

FIG. 3. Limit cycle corresponding to plasma breathing.

Transport of high-Z impurity ions which determines the characteristic period of breathing is still poor understood theoretically for 3D magnetic configurations as in LHD. For a rough estimate we take into account only the diffusive component of impurity flow which clearly restricts the validity of the model. According to the transport analysis done for Wendelstein 7-AS[15] a typical impurity diffusivity in stellarators is of $0.1(m^2/s)$. This gives a characteristic diffusion time of $1s$ in qualitative agreement with observations. A future numerical modelling should include also effects of such factors as the temperature gradient, radial electric field. There are many experimental evidences that these factors influence the particle transport significantly, e.g., through generation of a convective flux component.

[1] Y. Takeiri, Y. Nakamura, N. Noda *et al.*, Plasma Phys. Controlled Fusion **42**, 147 (2000).
[2] B. J. Peterson, Y. Nakamura, Y. Takeiri *et al.*, Plasma Phys. Controlled Fusion (submitted).
[3] G. M. McCracken, J. Allen, K. Axon *et al.*, J. Nucl. Mater. **145–147**, 181 (1987).
[4] U. Samm, P. Bogen, H. A. Claassen *et al.*, J. Nucl. Mater. **176–177**, 273 (1990).
[5] S. I. Krasheninnikov *et al.*, Nucl. Fusion **27**, 1805 (1987).
[6] V. A. Abramov, S. G. Bespoludennov, Yu. L. Igitkhanov, and V. I. Pistunovich, J. Nucl. Mater. **176–177**, 922 (1990).
[7] J. F. Drake, Phys. Fluids **30**, 2429 (1987).
[8] K. Itoh and S.-I. Itoh, J. Phys. Soc. Jpn. **57**, 1269 (1988).
[9] M. Z. Tokar, Nucl. Fusion **34**, 853 (1994).
[10] M. Z. Tokar, Phys. Plasmas **7**, 2432 (2000).
[11] Yu. N. Dnestrovskij and G. V. Pereversev, Nucl. Fusion **23**, 633 (1983).
[12] D. E. Post, R. V. Jensen, C. B. Tarter *et al.*, At. Data Nucl. Data Tables **20**, 397 (1977).
[13] W. Engelhardt and W. Feneberg, J. Nucl. Mater. **76&77**, 518 (1978).
[14] W. Eckstein, J. Bohdansky, and J. Roth, *Atomic and Plasma-Material Interaction Data for Fusion* (Suppl. Nucl. Fusion, International Atomic Energy Agency, Vienna, 1991), Vol. 1, p. 51.
[15] R. Burhenn, A. Anton, J. Baldzuhn *et al.*, *Proceedings of the 8th International Toki Conference* (NIFS, Nagoya, 1997), pp. 2–13.

Downloaded 21 Dec 2006 to 134.94.122.39. Redistribution subject to AIP license or copyright, see http://pop.aip.org/pop/copyright.jsp