Impurity Transport Induced Oscillations in LHD

B.J.Peterson, Y.Nakamura, K.Yamazaki, N.Noda, J.Rice[1], Y.Takeiri, M.Goto, K.Narihara, K.Tanaka, K.Sato, S.Masuzaki, S.Sakakibara, K.Ida, H.Funaba, M.Shoji, M.Osakabe, M.Sato, Y.Xu, T.Kobuchi[2], N.Ashikawa[2], P.deVries, M.Emoto, H.Idei, K.Ikeda, S.Inagaki, N.Inoue, M.Isobe, S.Kado, K.Khlopenkov, S.Kubo, R.Kumazawa, T.Minami, J.Miyazawa, T.Morisaki, S.Murakami, S.Muto, T.Mutoh, Y.Nagayama, H.Nakanishi, K.Nishimura, T.Notake[3], Y.Liang[2], S.Ohdachi, Y.Oka, T.Ozaki, R.O.Pavlichenko, A.Sagara, K.Saito[3], R.Sakamoto, H.Sasao[2], M.Sasao, T.Seki, T.Shimozuma, H.Suzuki, M.Takechi, N.Tamura[2], K.Toi, T.Tokuzawa, Y.Torii[3], K.Tsumori, I.Yamada, S.Yamaguchi, S.Yamamoto[3], M.Yokoyama, Y.Yoshimura, K.Y.Watanabe, T.Watari, K.Kawahata, O.Kaneko, N.Ohyabu, H.Yamada, A.Komori, S.Sudo, O.Motojima

National Institute for Fusion Science, Toki-shi 509-5292, JAPAN
[1] Plasma Science & Fusion Center, Mass. Inst. of Tech., Cambridge, MA 02139 , USA
[2] Dept. of Fusion Science, School of Math. and Phys. Science, Grad. Univ. for Adv. Studies, Hayama 240-0193, Japan
[3] Dept.of Energy Engineering and Science, Nagoya Univ., Nagoya 464-8603, Japan

e-mail contact of main author: peterson@lhd.nifs.ac.jp

Abstract. In LHD during experiments using stainless steel divertor plates a slow (~ 1 second) cyclic oscillation in the plasma parameters known as 'breathing' plasma was observed during NBI-heated long pulse discharges. The core iron density, calculated from measured parameters using the cooling rate from a corona-equilibrium average-ion model, oscillates out of phase with the electron density. The correlation of the iron impurity concentration with the change in electron temperature and with the local power balance between radiation and beam deposition indicates that when radiation from the iron impurity dominates the local power balance the core plasma is cooled. The increase in the calculated iron density during the phase of the oscillation when the divertor electron temperature exceeds the sputtering threshold suggests that sputtering of the stainless steel divertor plate may be the source of the iron impurity. However the shortness of the delay time raises questions about the causality between these two signals and points to the need for a closer examination of the role of impurity transport in this oscillation.

1. Introduction

Impurities from the walls or other plasma facing components can enter the discharge in magnetic confinement devices and degrade plasma performance through radiative cooling and dilution of the fueling gas. While the effects of lighter impurities are limited to the plasma edge, heavy impurities, which radiate at higher temperatures, have the ability to cool the core plasma [1]. Due to the improved confinement of H-mode plasmas in tokamaks, the resulting impurity accumulation may have serious consequences for steady-state reactor operation [2]. In this paper we discuss a slow oscillation that has been observed in LHD [3] and the role that heavy impurity radiation is playing in this phenomenon.

During the second experimental cycle of LHD a slow oscillation in the major plasma bulk parameters was observed during long-pulse neutral-beam operation which is known as the 'breathing' plasma [4]. An example of the global plasma parameters during a 'breathing' plasma oscillation having a period of about 1.5 seconds is shown in Fig. 1. One striking feature of this oscillation is the relationship between the density, the total radiated power and the spectroscopic signals of the light impurities during the rising phase of the density. In a typical LHD discharge the radiated power rises with the line averaged density until a density limit is reached and the plasma collapses radiatively [5]. However, in the 'breathing' plasma, during the rising phase of the density the total radiated power is seen to rise initially then reach a peak equal to the beam deposited power and decrease while the density continues to rise. Meanwhile as the total radiated power decreases the line radiation from the light impurities, carbon and oxygen, increases sharply. This suggests two things. First of all the decrease in the total radiated power as the radiation from light impurities increases indicates that iron, the other intrinsic impurity, is strongly contributing to the total radiated power. Secondly, the decrease in the radiated power as the density increases indicates that the radiation from iron is decreasing rapidly due to either a change in the electron temperature decreasing the cooling rate or a decrease in the impurity density. In this paper, using measured profile data we investigate the role that radiation from heavy impurities may be playing in this oscillation.

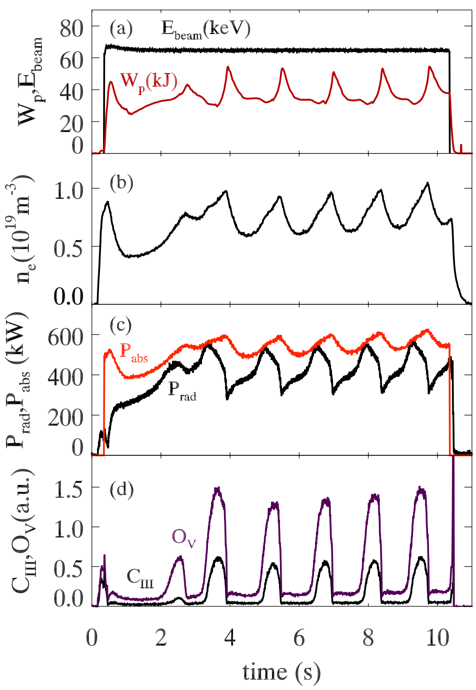

Fig. 1 Evolution of (a) stored energy, (b) line density, (c) total radiated and beam absorbed powers and (d) C_{III} and O_V light impurity brightness during LHD shot #6690.

2. Contribution of impurities to the radiation profile

In Figure 2 the emissivity, S_{rad}, profile evolution from bolometric measurements during the 'breathing' plasma oscillation is shown with the impurity radiation from light impurities and the total radiated power. The peaks at $\rho = 0.8$ and $\rho = 1.05$ at t = 5.2 seconds are well correlated temporally with the line radiation from oxygen and carbon and the minimum in the electron temperature profile at the edge. This indicates that light impurities are contributing to the radiation at the edge of the plasma when temperatures are low. In addition, transport modeling of carbon and oxygen and observations of radiation from fully stripped carbon has indicated that the total densities of these impurities remain nearly constant during this oscillation [6]. The correlation of the peak in the total radiated power with the peak in the radiation profile at ρ = 0.4 and at t = 5 s indicates that heavy impurities are contributing to the radiated power in this region. From spectroscopic measurements we know that during this second experimental campaign, in addition to carbon and oxygen, significant amounts of iron also existed in the LHD plasma[7].

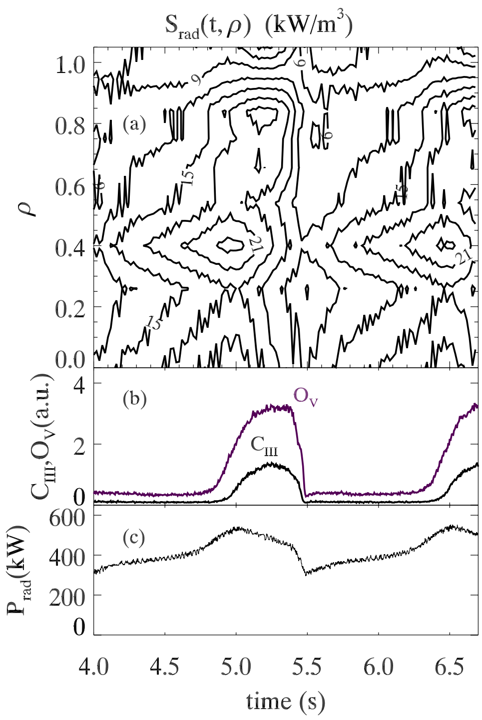

Fig. 2 Evolution of (a) total radiation emissivity profile, (b) radiation for light impurities C_{III} and O_V, and (c) total radiated power during shot # 6690.

3. Local parameter evolution and power balance at ρ = 0.4

By considering the cooling rates from the average-ion, corona-equilibrium model [8] for the intrinsic impurities we have determined that iron is the major radiating impurity in the core plasma. In order to investigate the role that iron may be playing in this oscillation we calculate [6] the iron concentration, n_{Fe}, at $\rho = 0.4$ from the measured local parameters: radiation emissivity measured using bolometer arrays [5], electron density, n_e, and electron temperature, T_e, using the cooling rate for iron [8]. In Fig. 3 we plot the time variation of the parameters n_e, T_e, n_{Fe}, and S_{rad} at $\rho = 0.4$. One notes, as was seen in the global plasma parameters in Fig. 1, that the radiation oscillation is nearly out of phase with the electron density oscillation. This indicates that the oscillation in the electron density does not contribute to the radiation oscillation but detracts from it. The electron temperature at this radius is seen to vary from 600 to 900 eV. From the cooling rate for iron [8] we know that its temperature dependence in this range of temperatures is very weak. Therefore we can attribute the oscillation in the radiation at this location entirely to the change of the iron impurity density which is also shown in Fig. 3. This is in qualitative agreement with spectral measurements from similar discharges such as those from the line emission from Fe^{15+} [9] and the line emission of beryllium-like Fe^{22+} [6].

The beam absorbed power density derived from the electron density and the beam input power using the TOTAL code [10] is also shown in Fig. 3b. Comparing these curves shows that T_e drops when the iron density is above 0.5 % of the electron density. This is also well correlated with the period when the radiated power is high and the absorbed beam power is low. This indicates that when impurity radiation from iron dominates the power balance, a net cooling of the core plasma results.

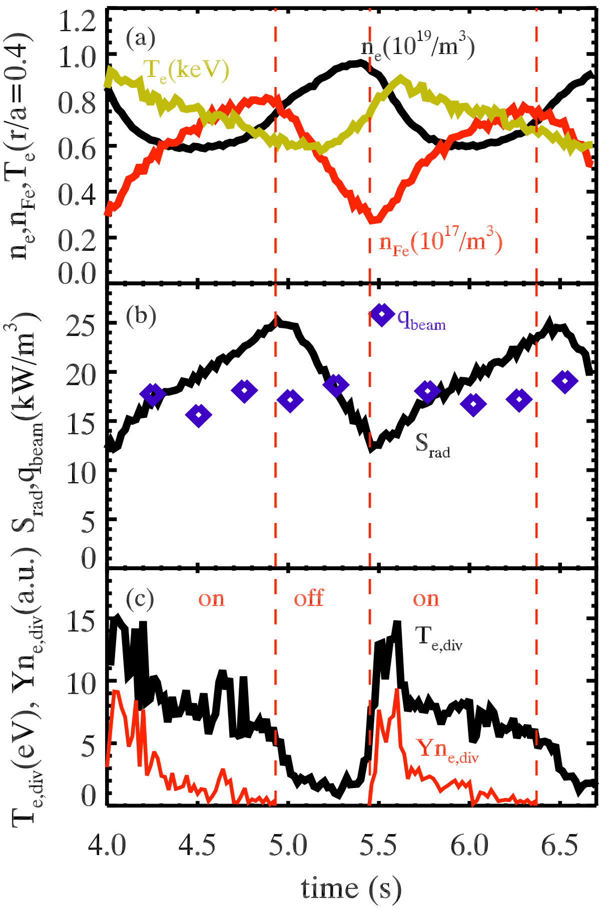

Fig. 3 Evolution of (a) measured electron density and temperature, calculated iron density, and (b) measured radiation emissivity, beam deposition power density at ρ = 0.4 and (c) the measured electron temperature at the divertor and the calculated sputtering yield, during shot #6690.

4. Sputtering of the divertor plates as a possible source of the iron impurity

In Figure 3c we show the electron temperature from a swept Langmuir probe in an inboard divertor plate [11]. If we assume that the ion temperature equals the electron temperature (which has been observed to be the case in the edge plasmas of LHD), and take the sheath potential to be $4T_e$ for helium (assuming singly-charged atoms), we can estimate the ion energy, E_0, from the electron temperature ($E_0 = 5T_e$) and calculate the sputtering yield, Y, using the revised Bohdansky formula with $\varepsilon = E_0/E_{TF}$ and E_{TF} = 5517 eV, E_{th} = 19.54 eV and Q =

0.33 atoms/ion given for iron by Helium[12]. The sputtering yield calculated in this way is multiplied by the electron density measured by the Langmuir probe to give a qualitative estimate of the number of sputtered iron atoms. This is also shown in Fig. 3c. This calculation of the sputtering yield indicates that there is a modulation of the sputtering of iron during the oscillation. The strong correlation between the rise and fall of the iron density and the modulation of the sputtering yield suggests that this process may be the source of the iron impurity that is cooling the core plasma.

This hypothesis is further supported by evidence of the reduction of iron impurity radiation and core and total radiation after the stainless steel divertor strike plates were replaced with graphite tiles [7]. In addition, after the replacement of the stainless steel plates with graphite tiles the same conditions for 'breathing' plasma were reproduced although with a 60% increase in beam port-through power. In this case the density was raised on a shot-by-shot basis by changing the initial gas puffing until the discharge was terminated by radiative collapse. In this situation the highest non-collapsing line density was 6 times higher than that of the 'breathing' plasma shots and the oscillation was not observed [13]. The fact that the 'breathing' oscillation could not be reproduced under similar circumstances after the substitution of carbon tiles gives further credence to the hypothesis that the 'breathing' plasma may be caused by the repetitive influx of iron from the stainless steel divertor plates.

Taking a closer look at the sputtering yield and the calculated core iron density in Fig. 3, one notes that the sudden turn-on of the sputtering and the rise in the iron density occur nearly simultaneously. One would expect for finite impurity transport that initiation of iron sputtering should precede the rise in the core impurity density by a delay time related to the impurity transport time from the plasma edge to the core. The shortness of this time delay raises doubts about the causality between the rise in the divertor electron temperature and the implied sputtering of iron from the stainless steel divertor plates and the rise in the core iron density.

Several other sources of iron impurity other than the divertor plates should be considered. Sputtering of iron by beam shine-through particles is unlikely as the beam dump is made of graphite. Sputtering of the stainless steel walls by charge exchange neutrals has also been suggested. While this possibility has not been thoroughly considered we think this is unlikely due to the inability to reproduce the oscillation after the replacement of the stainless steel divertor plates by graphite tiles.

5. Conclusions and Discussion

We can draw several conclusions from this study of the 'breathing' plasma in LHD. First of all, since the electron density is oscillating out of phase with the radiation and the temperature dependence of the iron radiation at these temperatures is weak we attribute the radiation oscillation to a change in iron impurity density. Secondly, when radiation dominates the power balance the core plasma is cooled. Additionally, evidence that the divertor ion energy is oscillating around the sputtering threshold suggests that the steel divertor tiles may be an intermittent source of the iron impurity. However, the shortness of the time delay between the initiation of the sputtering and the increase in the core iron density and the core radiation brings this role into question.

There are several aspects of this oscillation that are not well understood. While it is clear that the change in electron density is not contributing directly to the radiation oscillation, we don't have a good understanding of why the electron density is oscillating and what role this is playing in the oscillation. Another issue not yet completely clarified is the role of the lighter impurities. While previous work [6] has indicated that the carbon and oxygen densities are not changing significantly during the oscillation, they still play a role in the edge cooling, especially when the edge temperature is low. Recently, this issue has been addressed theoretically [14].

In addition to the change in the source of iron impurity that we are suggesting as a possible explanation for this oscillation, we have observed evidence of a change in the transport from a modification of the electron density profile during the oscillation. This evidence, in addition to the absence of a diffusive time delay mentioned at the end of Section 4 and discussed above, leads us to the conclusion that the role of changing transport in this oscillation should be considered more carefully[15]. We plan to do so through transport modeling of the iron impurity, which uses the sputtering yield resulting from the divertor electron temperature as a model for the changing source.

Acknowledgements

One of the authors (B.J.P.) would like to thank Prof. K. Itoh of NIFS, Japan and Dr. M. Tokar of IPP Juelich, Germany for discussions regarding the possible mechanism for 'breathing' plasma. He would also like to thank Prof. T. Kato and members of the Data and Planning Center at NIFS for discussions regarding the calculation of the sputtering yield. The authors would like to thank Director General M. Fujiwara and Vice Director Y. Hamada for their continued support and encouragement of this work.

References

[1] R.J. Hawryluk, et al., Nuclear Fusion **19**, (1979) 1307.
[2] G. Fussman, et al., J. Nucl. Mater. **162** (1989) 14.
[3] O. Motojima, et al., Phys. of Plasmas **6** (1999) 1843.
[4] Y. Takeiri, et al., Plasma Phys. and Control. Fusion **42** (2000) 147-159.
[5] B.J. Peterson, et al., 1999 Proc. 26th EPS Conf. on Controlled Fusion and Plasma Physics (Maastricht, 1999) Europhysics Conference Abstracts vol. 23J, p. 1337.
[6] B.J. Peterson, et al., to be published, J. Plasma Fusion Res. SERIES **3** (2000).
[7] B.J. Peterson, et al., proc. 14th PSI to be published in J. of Nuc. Mater.
[8] D.E. Post, et al.,Atom. Data Nucl. Data **20** (1977) 397.
[9] S. Morita and M. Goto, Ann. Report of National Inst. for Fusion Science (1999) p. 151.
[10] K. Yamazaki, et al., 1999 Proc. 26th EPS Conf. on Controlled Fusion and Plasma Physics (Maastricht, 1999) Europhysics Conference Abstracts vol. 23J, p. 1349.
[11] S. Masuzaki, et al., et al 1999 Proc. 26th EPS Conf. on Controlled Fusion and Plasma Physics (Maastricht, 1999) Europhysics Conference Abstracts vol. 23J, p. 1345.
[12] W. Eckstein, et al., 'Sputtering Data', Max-Planck-Institut fuer Plasmaphysik, IPP 9/82 (1993).
[13] Y. Nakamura, et al., proc. 14th PSI to be published in J. of Nucl. Mater.
[14] M. Tokar, et al., to be published in Physics of Plasmas.
[15] K. Itoh, et al., 'Modelling of density limit phenomena in toroidal helical plasma', National Institute for Fusion Science (NIFS-627, 2000).