Role of Changing Transport in 'Breathing' Oscillations in LHD

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1. Introduction

In the Large Helical Device a slow oscillation of plasma parameters known as 'breathing' plasma has been observed [1] which limited the density [2] and has been linked to the transport in and out of the plasma of iron impurities [3]. Modelling of the sputtering of the stainless steel from the divertor plates during this oscillation using the electron temperature at the divertor shows the core iron density starts to increase 20 - 60 ms after the initiation of sputtering. This indicates that the stainless steel from the divertor may be a periodic source of the iron impurity [3]. Several theoretical models have been suggested to explain this phenomenon [4-6], however none of them fully address the changes in transport observed during this oscillation. In this paper the evidence for the changes in transport is described and the source of this change in transport and the role that this might be playing in the oscillation are discussed.

2. Observations of changing transport

Changes in transport manifest themselves in two different ways during the 'breathing' oscillation. The first of these is a variation of its frequency during the oscillation. The second is a modification of the electron and iron density profiles during the oscillation. The variation of the frequency can be seen most clearly in Fig. 1(a) in the comparison of the iron density calculated in Ref. [3] with local measurements of electron density, temperature, and radiation emissivity using an average-ion, corona-equilibrium model (ADPAK) for the iron cooling rate and that modeled using the MIST impurity transport code [7]. In this modeling the

MIST code is operated in time dependent mode and the sputtered iron is treated as a series of iron impurity injections with the amount of injected material being modulated by the calculated sputtering yield shown in Fig. 1(c). The MIST model uses a flat diffusion coefficient profile with a value of $D = 0.15 \text{ m}^2/\text{s}$ going to zero at the edge and a flat convection velocity profile v = 0 m/s. The comparison is qualitative in that the amplitude and offset are arbitrarily adjusted to match the ADPAK result to take into account the residual iron content and the effective area of the sputtered divertor plate, both of which are not know. Comparing the shapes of these curves one notes that the rise and decay of the ADPAK iron density is much faster than that from the MIST model while the period where the iron density peaks is rather well at the divertor(black) and resulting model of This indicates that the diffusion matched.



Figure 1 (a) measured electron density(blue), iron density calculated using the ADPAK model(black) and using MIST modeling (red, broken) at r/a = 0.4. (b) Measured radiation emissivity at r/a = 0.4. (c) Electron temperature sputtering yield (red).

coefficient is approximately correct, but that it varies during the oscillation being much higher in the beginning and end of the cycle. Closer examination reveals that the results of the ADPAK modeling diverge quickly from the MIST model at t = 5.5 and 6.5 sec indicating a sharp transitions in the impurity diffusion. This is also clearly seen in Fig. 1(b) in the fast transition from the rising phase to the falling phase and the difference in the rising and falling times in the radiation emissivity at r/a=0.4. This indicates that the change in source resulting from the on/off behavior of the sputtering cannot alone account for the changes in the core iron density, but that a change in transport is also playing a role in this oscillation.

Other evidence of this change in the frequency is the dependence of the oscillation frequency on density, which is shown in Fig. 2. This data is taken from the original 'breathing' discharges observed in the divertor configuration during LHD's 2nd campaign (1998) as well as from discharges in the wall limiter configuration from the 3^{rd} (1999-2000) and 4^{th} (2000-2001) campaigns and discharges in the divertor configuration from the 4^{th}

campaign. These wall limiter discharges were formed by adjusting the helical coil current distribution to fatten the plasma cross-section in plane of the helical (g_{11}) coil to scrape off the plasma on the inboard stainless steel wall. These wall limiter discharges show properties similar to the original 'breathing' oscillations with the exception of a lack of electron density oscillation in some cases. Therefore it is thought that this is the same phenomenon, with the source of iron being the stainless steel wall limiter instead of the divertor. The frequency dependence on $\frac{Fig_1}{bre}$ density seen in Fig. 2 is consistent with the change in



Figure 2 Frequency dependence of 'breathing' oscillation on line averaged density.

frequency of the iron density relative to the electron density level observed in Fig. 1 (a). However it does not explain the rapid changes observed.

The second way in which a variation in transport is observed during the oscillation is in the change of the electron and iron density radial profiles during the oscillation as was pointed out in Figs. 2 (c) and (g) of Ref. [3]. This can be seen clearly in the plot of the positive density gradients shown in Fig. 3. It is interesting to note the temporal and spatial coincidence in the peaks of the gradients with that of the iron impurities slightly preceding that of the electrons. The dramatic changes in these profiles also indicate that transport is changing during this oscillation.

3. Discussion

In seeking a recipe for the 'breathing' oscillation, analysis has made clear that the transport in and out of the core plasma of iron impurities from plasma facing components is the key ingredient. What is not yet clear is the relative importance of the competing ideas of changing source and changing transport. Modeling and experimental observation indicate the source of iron Fi_{i} is most likely the plasma facing components ela(divertor tiles in the divertor case, wall plates in the



Figure 3 Evolution of positive iron (red) and electron (blue) density gradients during the 'breathing' oscillation.

wall limiter case), and that this source is changing during the oscillation. However, further modeling has shown that a change in transport is necessary to explain the time evolution of the core iron density. In addition changes in the iron and electron density profiles indicate a change in bulk particle and impurity transport during this oscillation.

The results shown raise several interesting questions. First of all, why is the oscillation frequency a function of the electron density? One simple explanation is that at higher density the impurities radiate proportionately higher and the cooling necessary to detach from the divertor/wall occurs more quickly. Also there seems to be a density threshold below which the oscillation does not occur. In this case perhaps the radiated power loss relative to the power absorbed from the beam is not adequate to cool the plasma to the point of thermal collapse. This is related to the radiative density limit in LHD which is currently being studied. Probably the most important question to be answered is what is the root cause of the changing transport that is observed in the time evolution of the core iron density and the iron and electron density profiles in general. A related question is why the iron impurities and electrons are accumulating at r/a = 0.4. A possible answer to these two questions lies in the radial electric field profile. Preliminary measurements of the radial electric field show it changing sign at r/a = 0.4 from positive to negative with increasing minor radius. This is coincident with the accumulation of iron impurity ions at r/a = 0.4. Also, at the edge of the plasma, the density regime at which the oscillation takes place is characterized by multiple roots (positive and negative) of the neoclassical E_r [8]. Therefore we propose to investigate in the future the possibilities that a fast sign transition of the radial electric field may be responsible for the observed change in transport and the periodic accumulation of iron impurities at r/a = 0.4.

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