PLASMA AND IMPURITY TRANSPORT MODELING OF NBI-HEATED LHD AND HELICAL REACTOR SYSTEMS

K. Yamazaki, M. Tokar[1], H. Funaba, B.J. Peterson, N. Noda,
A. Cooper[2], Y. Narushima, S. Sakakibara, K.Y. Watanabe, H. Yamada,
K. Tanaka, K. Ida, K. Narihara and the LHD Experimental Group

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, 509-5292, Japan
[1]Institut fuer Plsamaphysik, Forschungszentrum Jelich, D-52425 Juelich, Germany
[2]*Centre de Researches en Physique des Plasma, Ecole Polytechnique Federale de Lausanne, CH-1015 Lausanne, Switzerland*

Abstract

For the precise analysis of toroidal confinement systems, the Toroidal Transport Analysis Code "TOTAL" has been developed and applied to the Large Helical Device (LHD) plasmas and related reactor systems. The new LHD confinement scaling law is derived, which can extrapolate the present data to the reactor regime without confinement improvement.

Slow Relaxation oscillations called "breathing" have been analyzed using the TOTAL code and the physics simulation modeling with impurity sputtering process. The slight change in transport coefficient during oscillation is experimentally found, and roles of high-Z and low-Z impurities are clarified. The breathing waveform and the oscillation period are reproduced depending on plasma density by this modeling.

1. Introduction

Plasma confinement and related impurity behaviors are keys to getting high temperature plasmas and starting reactor plasma operations. In the Large Helical Device (LHD) the confinement times higher than the conventional scaling laws are achieved, which makes it possible to extrapolate the present database to the reactor regime [1]. So-called "breathing" phenomena [2,3] are found in LHD as a result of impurity dynamics. For the explanation and prediction of LHD and reactor plasma confinement, precise transport analysis is required. In this paper, "breathing" plasma analysis and reactor plasma projections are carried out.

2. LHD Transport Analysis Using TOTAL Code

2-1 TOTAL Code Development

For predictive simulation and experimental analysis of toroidal plasmas, a simulation code TOTAL (Toroidal Transport Analysis Linkage) has been developed as an extension of HSTR code [5]. This consists of a 3-dimensional equilibrium with ohmic and bootstrap currents and a 1-dimensional transport with neoclassical loss determined by ambipolar radial electric field as well as anomalous transport (empirical or drift turbulence theory).

2-2 Global Confinement Scaling and Reactor Plasma Projection

NBI-heated plasmas on LHD are analyzed using the TOTAL code. Different from the previous scaling laws, a new global confinement scaling law (New LHD scaling) by regression analysis has been obtained [1] based on heliotron-type experiments:

$$\tau_{NLHD\#1} = 0.263\, P^{-0.58}\, \overline{n}_e^{\,0.51} B^{1.01} R^{0.64} a^{2.59}.$$

Units used here are $\tau_E(s)$, $P(MW)$, $\overline{n}_e(10^{20}m^{-3})$, $B(T)$, $R(m)$, $a(m)$, respectively. This scaling law suggested the strong gyro-Bohm like feature, which is different from previous scaling laws. This feature is also verified by local transport analysis near the edge region. Using this scaling low, Modular Heliotron Reactor plasma [1] can be predicted without confinement improvement.

2-3 Impurity Transport Analysis Using TOTAL Code

Consideration of the transport of impurities and their influence on plasma performance is one of important elements in a consistent predictive modeling. In particular, the development of "breathing" oscillations in LHD [2,3] gives an interesting example of impurity effects in helical devices.

The impurity dynamics is calculated using measured electron temperature and electron density. Figure 1 shows the breathing oscillation of measure input profiles and calculated radial electric field, radiation power and effective Z values. The initial total impurity density was assumed by the percentage of main plasma density. Here the recycling rates of all impurity ions are assumed to be unity. In this analysis, carbon, oxygen, and iron densities are assumed as 1%, 1% and 0.2 %, respectively. Their initial profiles are determined using coronal equilibrium model, and the time-variation of each charge-state impurity ions

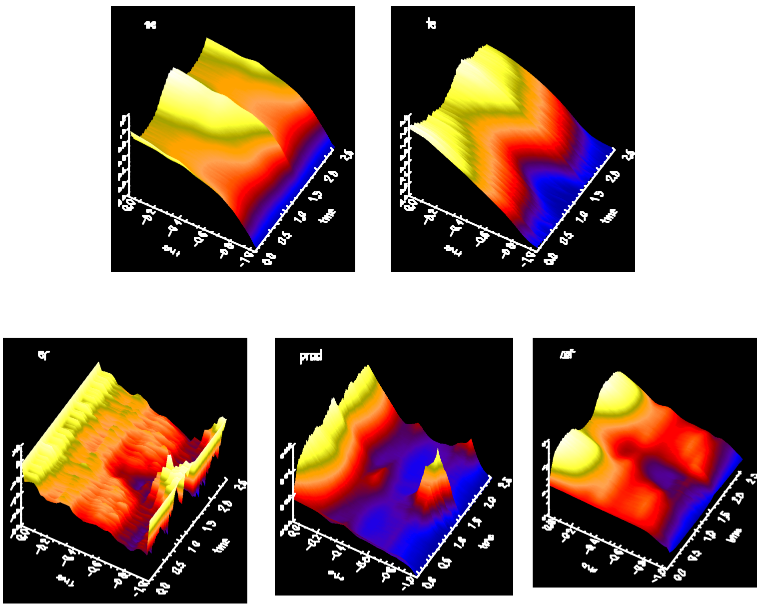

Fig. 1 Transport analysis on LHD plasma.
Upper raw: experimental data (n_e and T_e),
Lower raw: analyzed output (E_r, P_{rad} and Z_{eff})

is dynamically solved by the rate equation of each charge-state and the diffusion equation with the transport coefficient D of 1 m^2/s and without the inward flow (v = 0 m/s). The ambipolar electric field calculated from bulk plasma is negative (ion root), which contradicts with experimental observations. For precise determination of electric field, we might include impurity effects on the ambipolar flux calculation. The radiation profile has two peaks (central and near edge) corresponding to iron and low-Z (carbon and oxygen) impurities, which qualitatively agrees with experimental data.

Typical radial profiles of effective thermal diffusivity are shown in Fig. 2.

$$\chi_{eff} = -(Q_{NBI} + Q_{RF} - \frac{dW_p}{dt}) / (n_e \frac{d(T_e + T_i)}{dr})$$

In higher density, detached small plasma and low-Z impurity radiation dominant phase, the thermal diffusivity is rather low. On the other hand, in the temperature increase, low radiation and larger attached plasma phase, the diffusivity is slightly high. This transport change might also contribute to the appearance of periodic relaxation oscillations.

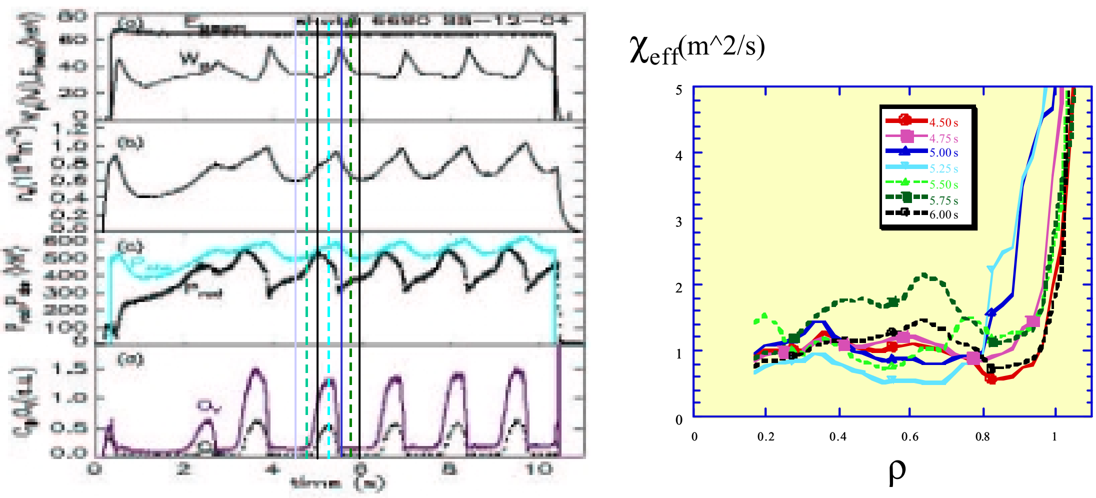

Fig.2 Breathing plasma waveforms and effective thermal diffusivity

3. Physics Modeling on Impurity-Induced Relaxation Oscillation in LHD

In discharges where the plasma touched wall elements of iron, an increase of the electron density in excess of a critical level led to slow with a period of a second oscillations in diverse plasma parameters, e.g., central and edge plasma temperature, integrated radiation losses and intensities of selected spectral lines, line averaged density, etc. A physical picture of this phenomenon proposed recently [5] implies the importance of radiation from both Fe ions in the plasma core and light impurities of C and O at the edge. In phases with a hot edge the sputtered iron particles penetrate into the plasma core and increase the central radiation losses. This leads to reduction of the heat outflow to the edge and detachment due to radiation of C and O. As a result the iron-sputtering source disappears and Fe ions diffuse out of the plasma. The growing heat flow to the edge causes its reattachment.

With an ultimate goal to perform a self-consistent 1-D time-dependent modeling of "breathing" oscillations by the code TOTAL this has been first run in its interpretive option to reconstruct the behavior of transport coefficients. The results for the effective heat conductivity are shown in Fig.2. A modeling of Fe ion transport gives a diffusivity of 0.15-0.25 m^2/s in agreement with that obtained by the code MIST [4]. These coefficients have been used in a simple numerical model elaborated to check the mechanism of "breathing" proposed in Ref.[5]. The model includes a heat balance for the plasma edge and core, the balance of the main particles and a 1-D time dependent description of the total density of Fe ions with a self-consistently computed source of iron neutrals due to physical sputtering of the divertor. As a result the time evolution of the plasma temperature at the last closed magnetic surface and at the device axis, of the line averaged density, total radiation losses and luminosity of light impurities can be simulated. Figure 3 shows an example of such calculations for an NBI power of 1MW. These results are in agreement with measurements including peculiarities of their time phasing. The observed increase of the oscillation frequency with plasma density n can be reproduced firmly in computations if one assumes that the impurity diffusivity varies proportionally to n as it is predicted by neoclassical theory.

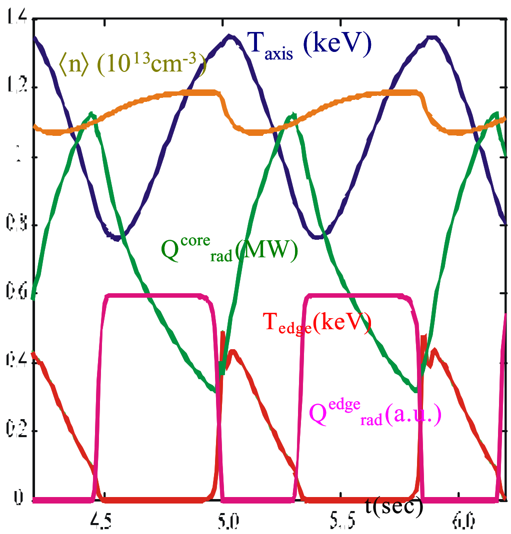

Fig.3 Results of Numerical Modeling

References

[1] K. Yamazaki et al., 18th IAEA Fusion Energy Conference (Sorrento, Italy, 2000) FTP2/12

[2] Y. Takeiri et al., Plasma Phys. Control. Fusion 42 (2000) 147.

[3] B.J. Peterson et al., Nucl. Fusion 41 (2001) 519.

[4] K. Yamazaki and T. Amano, Nucl. Fusion 32, 633 (1992).

[5] M.Z. Tokar et al., Physics of Plasmas 7 (2000) 4357.