Low Concentration of Iron as First Wall Material in LHD Plasmas with Edge Ergodic Layer

S.Morita\textsuperscript{1,2}, C.F.Dong\textsuperscript{1}, M.Kobayashi\textsuperscript{1,2}, M.Goto\textsuperscript{1,2}, I.Murakami\textsuperscript{1}, E.H.Wang\textsuperscript{2}, N.Ashikawa\textsuperscript{1}, Z.Y.Cui\textsuperscript{3}, K.Fujii\textsuperscript{4}, M.Hasuo\textsuperscript{4}, L.Q.Hu\textsuperscript{6}, H.Kasahara\textsuperscript{1}, D.Kato\textsuperscript{1}, F.Koike\textsuperscript{5}, S.Masuzaki\textsuperscript{1,2}, T.Mutoh\textsuperscript{1,2}, K.Saito\textsuperscript{1}, H.A.Sakaue\textsuperscript{1}, T.Seki\textsuperscript{1}, T.Shikama\textsuperscript{4}, C.Suzuki\textsuperscript{1}, Z.W.Wu\textsuperscript{6}, N.Yamaguchi\textsuperscript{7}, N.Yamamoto\textsuperscript{8}, L.Zhang\textsuperscript{6}, H.Y.Zhou\textsuperscript{3} and LHD experiment group

\textsuperscript{1}National Institute for Fusion Science, Toki 509-5292, Gifu, Japan
\textsuperscript{2}Dept. of Fusion Sci., Graduate Univ. for Advanced Studies, Toki 509-5292, Gifu, Japan
\textsuperscript{3}Southwestern Institute of Physics, Chengdu 610041, China
\textsuperscript{4}Dept. of Mechanical Engineering and Science, Kyoto Univ., Kyoto 606-8501, Japan
\textsuperscript{5}Physics Lab., School of Medicine, Kitasato Univ., Sagamihara 252-0374, Kanagawa,Japan
\textsuperscript{6}Institute of Plasma Physics, P.O.Box 1126, Hefei, Anhui 230031, P.R.China
\textsuperscript{7}Physics Lab., Graduate School of Medicine and Pharmaceutical Sciences, Univ. of Toyama, Toyama 930-0194, Japan
\textsuperscript{8}Center of ASSER, Chubu University, Kasugai 487-8501, Aichi, Japan

E-mail contact of main author: morita@nifs.ac.jp

Abstract. Impurity behavior of iron, which is a main element of the first wall made of stainless steel, is studied in Large Helical Device (LHD). The total density of iron in core plasmas is found to be fairly low, at least four or five orders of magnitude smaller than the electron density, even if the impurity accumulation occurs. The density of edge Fe\textsuperscript{15+} ions analyzed from two-dimensional measurement of impurity line emissions in EUV range increases with density. It indicates that the screening effect developed in edge ergodic layer intrinsically existing in LHD works well for the iron. The simulation with EMC3-EIRENE also predicts the impurity screening is more effective for heavier impurities than light impurities. The present result strongly suggests a tolerant use of high-Z materials to the first wall of helical devices.

1. Introduction

Metallic impurity such as iron and tungsten gives a crucial effect in maintaining a good performance of high-temperature plasmas because the radiative cooling rate quickly increases with atomic number of impurities, while light impurity such as carbon determines the upper limit of Lawson criteria due to enhancement of the bremsstrahlung continuum. In order to avoid the current disruption by suppressing the metallic impurity released from the vacuum vessel wall, several methods have been attempted in tokamaks. As the most general method, carbon tiles are used to cover the vacuum vessel and to completely delete stainless steel surfaces facing the plasma. In this case high-temperature wall baking, e.g. 300°C, is necessary to remove hydrogen and oxygen from the carbon tiles. A special wall coating technique using lithium, boron and silicon has been also carried out to replace the carbon wall by the coating material.
In Large Helical Device (LHD), on the other hand, the first wall on the vacuum vessel is composed of rectangular protection plates made of stainless steel, whereas carbon tiles are only placed on the vacuum vessel at divertor region where the magnetic field lines from ergodic layer intersect with the vacuum vessel. The baking temperature of the vacuum vessel and the carbon plates are less than 100°C and the boronization is carried out for a quick start up of well-conditioned discharges once at the initial phase of experimental campaign over four months. However, the impurity behavior is not basically affected so much by the boronization because the oxygen influx can be sufficiently reduced if several hundreds discharges are accumulated. Thus, high-performance discharges have been sustained during past fourteen years without any serious problem based on the metallic impurity [1].

The metallic plasma facing components of beryllium and tungsten are adopted in ITER tokamak instead of the carbon material due to low tritium retention rate and high-melting point. It is known that the stochastic magnetic field layer, so called ergodic layer, at plasma edge surrounding the core plasma of LHD possesses a function of the impurity screening. The impurity screening based on the ergodic layer in LHD has been already confirmed for carbon impurity. In the present report, behavior of the iron impurity in LHD is quantitatively studied with simulation on the edge impurity transport.

2. Edge ergodic layer consisting of stochastic magnetic field

In LHD the ergodic layer is formed by the presence of higher-order Fourier components in magnetic fields created by a pair of helical coils. Figures 1(a) and (b) show a poloidal structure of ergodic layer at horizontally elongated plasma cross section ($\varphi=0^\circ$) in magnetic axis positions of $R_{ax}=3.6m$ and 3.9m, respectively. The position of LCFS in LHD is defined by the outermost flux surface on which the deviation of the magnetic field line is less than 4mm while it travels 100 turns along the torus. The ergodic layer mainly consists of stochastic magnetic field lines with lengths from 10 to 2000 m, which correspond to 0.5-100 toroidal turns of the LHD torus. The thickness of the ergodic layer, $\lambda_{erg}$, varies with the poloidal and toroidal angles exhibiting a complicated three-dimensional structure. The minimum thickness of ergodic layer appears at two poloidal locations near the helical coils, which are here defined as "O-point". The $\lambda_{erg}$ increases not only with $R_{ax}$ but also with $\beta$ value. The magnetic field lines in the ergodic region are sufficiently long to confine the edge plasma, although the field lines frequently repeat radial movement during the toroidal

![Fig.1 Structures of magnetic surfaces, ergodic layer and divertor legs at (a) $R_{ax}=3.6m$ and (b) $R_{ax}=3.90m$ in LHD. Magnetic field connection length, $L_c$, is expressed in different color.](image_url)
Therefore, the electron temperature and density in the ergodic layer are considerably high and range in 10-500eV and 1-10x10^{13}cm^{-3}, respectively. Four divertor legs intrinsically exist outside the ergodic layer, connecting the X-point region to the divertor plates. In R_{ax}=3.6m of Fig.1(a) the total number of field lines directly connecting to the divertor plates, which does not mean the magnetic field strength, at the inboard X-point is much larger than that at the outboard X-point, while such a situation is reversed with shifting the R_{ax} outwardly, as shown in Fig.1(b).

3. Impurity concentration during impurity accumulation

Iron ions intrinsically existing in the LHD discharge has been always monitored as a typical metallic impurity released from the first wall made of stainless steel. However, line emissions of FeXXIII and FeXXIV located in the central part of LHD plasmas are very weak in most of discharges, and it is difficult to exactly analyze the iron density from such weak signals. In contrast to this, those spectra can be clearly identified when the impurity accumulation occurs, which is frequently observed after hydrogen multi-ice pellet injection in NBI discharges. The iron density in the central column of plasmas can be then determined during the impurity accumulation phase. Therefore, it should be noticed that the iron density analyzed here gives the highest density in LHD discharges.

A typical NBI discharge with multi-pellet injection is plotted in Fig.2. The line-averaged electron density in Fig. 2(a) shows line-integrated density, i.e., <n_e>/L. Eight ice pellets are repetitively injected during t=3.7-4.1s and the density is sufficiently increased up to 2.2x10^{14}cm^{-3}. During the pellet injection the iron spectra are dominated by only FeXV and FeXVI due to the temperature drop. After the pellet injection, however, the intensities of FeXXIII and FeXXIV showing the iron behavior at plasma center are quickly increased with recovering the electron temperature, while the intensities of FeXV and FeXVI showing the
iron influx at plasma edge are weakened and does not change after the pellet injection. These time behavior of iron emissions can briefly suggest a sign of impurity accumulation.

Vertical iron emission profiles of FeXV (284.1Å) and FeXXIV (192.0Å) are observed at t=4.5s and 4.9s, as shown in Figs. 3(a) and (b), respectively. The absolute sensitivity of a space-resolved EUV spectrometer used for the measurement is accurately calibrated using bremsstrahlung continuum [2]. The FeXXIV can not be observed until t=4.3s due to the low Te during the pellet injection and begins to appear from t=4.4s again. Effective emission coefficients necessary for the analysis are calculated with a collisional-radiative model [3], in which the fine structures in principal quantum numbers up to n=5 are fully taken into account for FeVII-XXVI in quasi-steady state condition. The density profile of Fe$^{23+}$ is analyzed by reconstructing the chord-integrated FeXXIV intensity profile into local emissivity profile as a function of magnetic surface. The result is plotted in Fig.3(c) at the same time slices as Fig.3(b). It is clear that the density profile of Fe$^{23+}$ is centrally peaked at t=4.9s, suggesting the impurity accumulation occurs. In case of the FeXV profile, on the other hand, the profile is a little complicated because it is composed of emissions from two different edge regions, i.e., O- and X-points (see Fig.1). If we consider only the emission from O-point in range of Z=0.4-0.5m, the density of Fe$^{14+}$ can be estimated to be 4x10$^7$cm$^-3$.

The density profile of Fe$^{23+}$ is simulated using the impurity transport code with parameters of diffusion coefficient D and convective velocity V. The results are shown in Fig. 4. The values of D and V in LHD are already known in previous work [4] as D=0.2m$^2$/s and V=-1m/s in a steady state condition. Since the density decay time around t=4.5s is much longer than the impurity confinement time, e.g. $\tau=\tau_0/(5.8\times D)$~0.35s, the previous value of D is

![Fig.3](image-url) Vertical profiles of (a) FeXV and (b) FeXXIV and (c) Fe$^{23+}$ density against normalized radius at t=4.5s (dashed line) and 4.9s (solid line).

![Fig.4](image-url) Impurity transport analysis of Fe$^{23+}$ density profile as a parameter of (a) D with fixed value of V=-1m/s and (b) V with fixed value of D=0.2m$^2$/s.
applicable in the present discharge. It is clear that the peaked Fe$^{+2}$ profile can not be reproduced at all by changing D (see Fig.4(a)). A considerably large inward velocity is required to obtain a good fitting. The best fitting is made at $V=-6m/s$, as shown in Fig.4(b). Here, the D is fixed to 0.2m$^2$/s as the default value. Since the value is considerably large compared to the commonly observed V value of -1m/s, the impurity accumulation can be reconfirmed. A large density gradient after the pellet injection is certainly a main reason for the appearance of the impurity accumulation [5]. The total density of iron ions calculated by integrating all the charge states is considerably low, i.e., 3x10$^{-5}$ to the electron density, even if the impurity accumulation occurs. In the same discharge the carbon transport is also analyzed based on Z$_{eff}$ profile measurement, since the Z$_{eff}$ value is simply determined by the carbon density. In contrast to the iron, the carbon transport is explained with the default values of D and V, indicating that the impurity accumulation does not occur to such light impurities. The radiation loss of iron, $P_{rad}$(Fe), is smaller than 1MW in normal discharges of LHD, which is negligible to the total input power ($P_{NBI}$~20-30MW). The $P_{rad}$(Fe) is often comparable to the radiation loss of carbon, $P_{rad}$(C), released from divertor plates. The low level of iron impurity concentration is caused by the impurity screening enhanced in the ergodic layer of LHD [6].

![Fig.5 2-D distributions of (a) FeXV (284Å), FeXVI (335Å) and (c) FeXX (132.9Å) and (d) observation range denoted with trapezoidal frame and 3-D shape of ergodic layer. Toroidal trace of inboard and outboard X-points is indicated with dashed and dotted lines.](image-url)
4. **Edge impurity screening of iron**

Since the ergodic layer has three-dimensional structure, contrastively from the scrape-off layer of tokamak, two-dimensional (2-D) measurement is at least necessary for the impurity transport study in the ergodic layer. A space-resolved EUV spectrometer working in wavelength range of 30-650Å has been developed to measure the 2-D structure of impurity emissions from the ergodic layer in vertical and horizontal ranges of 100cm×100cm, respectively [7]. Since the 2-D distribution of impurity emissions is measured by scanning the observation chord horizontally, a steady discharge longer than 5s is required to complete the 2-D measurement. A typical example of the 2-D distribution from iron ions observed at $R_{ox}=3.6m$ plasma axis position is shown in Figs. 5(a), (b) and (c) for FeXV (284.1Å, $E_i=457eV$), FeXVI (335.4Å, $E_i=489.3eV$) and FeXX (132.9Å, $E_i=1582eV$), respectively. The FeXV and FeXVI are located near LCFS in the plasma edge as a typical index of iron influx to the plasma core because the ionization energy, $E_i$, is relatively low. It is clear that such impurity ions existing in the plasma edge have 3-D structure reflecting magnetic field structure of the ergodic layer. On the other hand, the FeXX shows toroidally uniform profile indicating that the intensity is a function of magnetic surface.

The 2-D region measured with the space-resolved EUV spectrometer is indicated in Fig.5(b)

![3-D plot of FeXVI (335Å) distribution.](image)

**Fig.6** 3-D plot of FeXVI (335Å) distribution.

![Comparison of FeXV vertical profiles at $n_e=6x10^{13}cm^{-3}$ between measurement (solid line) and simulation (dashed line). The simulation is normalized at the peak position around $Z=0.46m$.](image)

**Fig.7** Comparison of FeXV vertical profiles at $n_e=6x10^{13}cm^{-3}$ between measurement (solid line) and simulation (dashed line). The simulation is normalized at the peak position around $Z=0.46m$.  


by a red trapezoidal frame with 3-D shape of LHD ergodic layer. The observation range for 2-D image is mainly limited by the trapezoidal LHD port, while the spectrometer port is rectangular (see Fig.5(b)). Seeing Fig.5(b), we notice that the FeXVI intensity is enhanced along a diagonal line from left-bottom (Y=-20cm and Z=-40cm) to right-top (Y=20cm and Z=50cm). The figure is redrawn in Fig.6 as 3-D plot to indicate the diagonal trace more clearly. This enhanced trace is consistent with the position of inboard X-point. It indicates that Fe$^{15+}$ ion and/or electron densities in the inboard X-point region is higher than those in the outboard X-point region. As mentioned above, the number of magnetic field lines in the inboard X-point of $R_{ax}=3.60m$ configuration is much larger than that in the outboard X-point (see Fig.1(a)). The present result strongly suggests the recycling through the magnetic field directly connecting to the divertor plates can be enhanced in the inboard X-point region. When the plasma axis position is shifted outwardly, e.g., $R_{ax}=3.75m$, it has been also confirmed that the impurity emission is enhanced in the outboard X-point region instead of the inboard X-point region, reflecting a structural change of edge magnetic filed lines connecting to divertor plates, as shown in Fig.1(b). Seeing Fig.6, we also notice that the FeXVI emission at the bottom edge near $Z=-50cm$ is considerably stronger than that at the top edge near $Z=+50cm$. At present, the reason is unclear. These toroidal and poloidal nonuniformity of the impurity emission in the edge plasma is of course disappeared from the image of Fe XX located in the plasma core.

The impurity transport in the ergodic layer of LHD is investigated by a three-dimensional edge transport simulation code, EMC3-EIRENE [8]. The numerical transport study predicts that the edge surface layer in the ergodic layer of LHD has a sufficient capability of screening the impurity released from plasma facing components in collisional regime of $10\leq L_{//} \leq 100$, where $L_{//}$ is the Kolmogolov length and $\lambda_{ee}$ the electron mean free path. This prediction is based on an idea that the pressure gradient force along magnetic filed in the ergodic layer of LHD is dominant compared to the ion thermal force, contrastively to the scrape-off layer in tokamaks. The vertical profile of impurity emissions measured here is simulated with the simulation code. A typical result is shown in Fig.7 for FeXV case. The FeXV profile can be roughly divided by two different poloidal positions of O- and X-points, from which the emissions correspond to the ranges of $0\leq Z\leq 0.4m$ and $0.4 \leq Z\leq 0.5m$ in Fig.7 (see Fig.1). The simulated FeXV profile shows a good agreement with the measurement, although its absolute value is fitted to the measurement, indicating the validity of the simulation code.

The density of Fe$^{15+}$ ion, $n_{Fe}^{15+}$, is analyzed from the measured 2-D FeXVI distribution, as

**Fig.8** (a) 2D-averaged Fe$^{15+}$ density as a function of electron density and (b) radial profile of iron density normalized at plasma edge ($r_{eff}=72cm$) of $R_{ax}=3.60m$ simulated with two different densities at LCFS. Value of $r_{eff}$ means poloidally averaged plasma radius and LCFS is positioned at $r_{eff}=60.4cm$. 

[Graph showing Fe$^{15+}$ density vs electron density and radial profile of iron density normalized at plasma edge.]
shown in Fig.8(a). The Fe$^{15+}$ ions located near LCFS in the ergodic layer, i.e. $L_c>200\text{m}$ ($L_c$: connection length), decrease with density, suggesting the reduction in the iron influx to the plasma core. Result of the simulation is also plotted in Fig.8(a), which is normalized to the experiment at $n_e=1.5\times10^{13}\text{cm}^{-3}$. The both results clearly indicate that the impurity screening by the ergodic layer works well to the iron. It is also confirmed that the impurity screening is independent of the source location such as first wall and divertor plates. In order to examine the effect of $L_{\parallel}$ and $L_{\parallel}/\lambda_{\text{ee}}$, the total iron density in the ergodic layer ($60.4(=LCFS)\leq r_{\text{eff}}\leq 71.7\text{cm}$) is simulated with two different density ranges (see Fig.2(c)). The impurity screening is clearly observed in the edge boundary region ($69 < r_{\text{eff}} < 72\text{cm}$), where the $L_{\parallel}$ is nearly 10m. The simulation indicates more efficient impurity screening compared to the carbon case. Since the first ionization energy of iron ($E_{i}(\text{Fe})=7.9\text{eV}$) is lower than carbon ($E_{i}(\text{C})=11.3\text{eV}$) and the velocity is slower, the iron is ionized at outer region of ergodic layer where the parallel thermal gradient, i.e. thermal force, is smaller. Therefore, heavier impurity ions have larger values of $L_{\parallel}/\lambda_{\text{ee}}$ ($\propto L_{\parallel}/\lambda_{\text{ee}}$), and can enhance the friction force along the magnetic field, leading to an efficient impurity screening.

5. Summary

Impurity density of iron analyzed form the radial profile shows a fairly low concentration, i.e. $3\times10^{-5}$ to the electron density, even in discharges with impurity accumulation. Comparison between experiment and simulation indicates that the impurity screening due to the ergodic layer of LHD can efficiently work to heavier impurities. The present result strongly suggests that the stochastic magnetic field layer in helical devices can well work also for tungsten.

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