Magnetic Field Structure and Confinement of Energetic Particles in LHD

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Abstract. It is theoretically and experimentally shown that drift surfaces exist for highly energetic particles being extended over the last closed flux surface (LCFS) in LHD. Those particles are considered as lost particles due to the loss-cone in the previous theories, where the analyses are limited inside the LCFS. The present theory predicts that LHD has no loss-cone and that highly energetic particles confined over the LCFS exist. These are consistent with the LHD experimental results in both the ion cyclotron range of frequency(ICRF) heating experiments and the low magnetic field neutral beam injection (NBI) heating experiments. From particle orbit analyses and studies on the connection length of diverter field lines, it is also shown that plasma can exist in the chaotic field line region located outside the LCFS in LHD. The plasma in the chaotic field line region is clearly detected by CCD-cameras in the LHD experiment. This ambient plasma might be expected to have the role of a kind of impregnable barrier for the core plasma, which suppresses both the MHD instabilities and the cooling of the core plasma due to charge exchange processes.

1. Introduction

The drastically improved plasma has been obtained through the LHD experiments started in 1998. In the recent experiments, the maximum averaged beta value $<\beta_{dia}>$ of 4% was obtained [1] by high power NBI heating up to $12\mathrm{MW}$ in the configuration with $R_{ax} = 3.6\mathrm{m}$ and $B_{ax} = 0.45\mathrm{T}$, where R_{ax} and B_{ax} are magnetic axis position and toroidal magnetic field at R_{ax} respectively. Up to now, the beta collapse phenomenon has not been reported in the LHD experiment.

In the past, many ICRF experiments suffered from a rise in impurities. Furthermore, the ICRF heating in helical systems has been considered to be questionable because of the poor confinement property of the perpendicularly accelerated high-energy particles. The helically trapped particles have large orbit size in the radial direction and tend to diffuse and would escape out by orbit loss. However, high performance for the plasma heating in the ICRF experiments of the LHD has been shown as follows [2, 3, 4]: 1) High heating efficiency is found, which increases with the increase of the plasma temperature. 2) High-energy particles with energies up to 500 keV are produced by ICRF heating. 3) Plasma with a high stored energy can be sustained for more than two minutes by ICRF heating only.

After the 3rd campaign of LHD experiment (2000, Mar), melt-down of leading edge of stainless tube for the pellet injection was found. After the 5th campaign of LHD experiment (2002, Mar), the erosion of the edge of the armor tile was found. Those equipments were installed enough outside the LCFS. These phenomena suggest the existence of the high-energetic particle drift surface extending outside the LCFS, in low B_{ax} case.

The magnetic field structure and the particle orbit must be elucidated to obtain higher performance of the plasma confinement and to evade troubles with high energy NBI particle in low B_{ax} case. In the present study, we analyze the magnetic field structure in the peripheral region

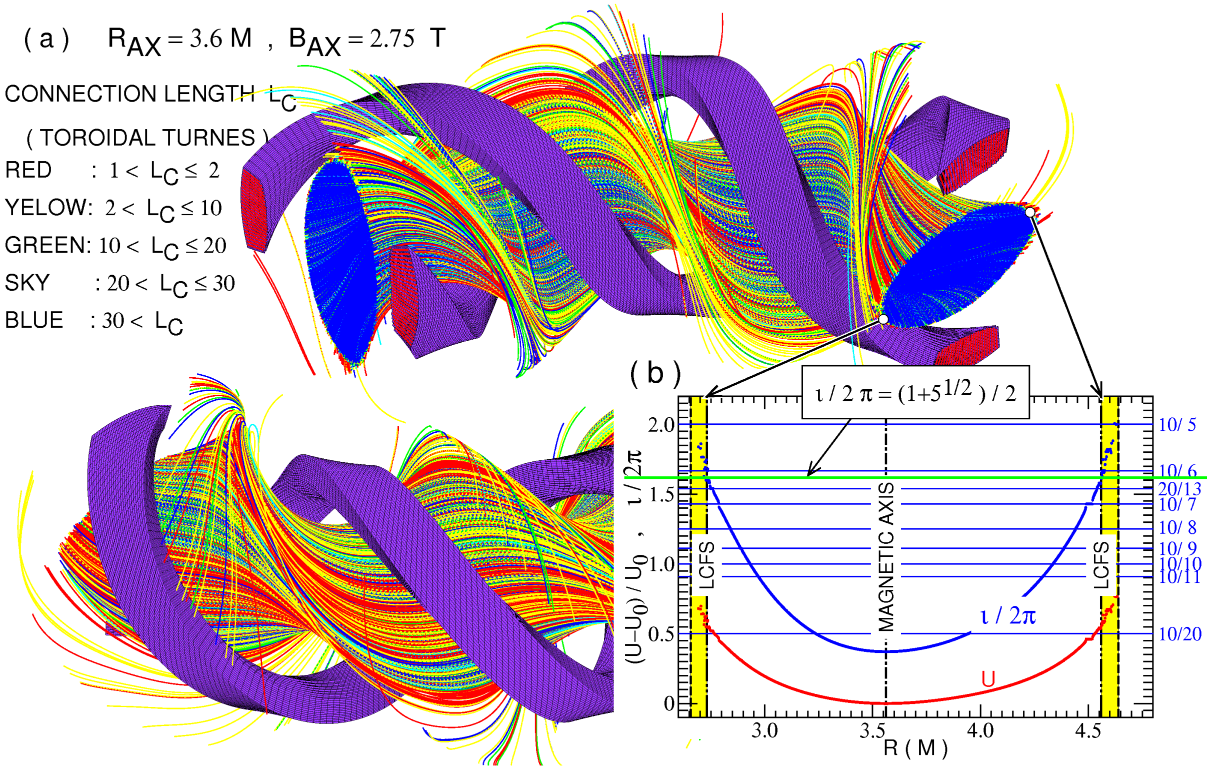

FIG.1. (a) Magnetic field lines in chaotic field line layer surrounding the outside of the LCFS. Helical coils are also plotted. All field lines terminate at footprints in the diverter plates. The lines of force are classified depending on the connection length with different color. It is shown that the connection length of lines of force closely surrounding the LCFS exceed 30 toroidal turns ($\simeq$ 800m : shown by the blue lines). The lines of force that are slipped out from the chaotic field line region reach the diverter plates soon. (b) The rotational transform $\iota/2\pi$ and the specific volume U of magnetic surface (U_0 : the value of U at magnetic axis). Abscissa is the r in oblong cross section ($z = 0$). Values of ι and U in the chaotic field line region, which is painted by yellow, are calculated through the use of islands imbedded in the region. The green line shows the level that the rotational transform becomes the value of golden mean.

of LHD. Moreover, the confinement of energetic particles produced by NBI and ICRF heating are investigated.

2. Magnetic field configuration of LHD

LHD uses superconducting magnets with $\ell/m = 2/10$ and $R_{ax}/a \simeq 3.9\,\mathrm{m}/0.6\,\mathrm{m}$ heliotron-type magnetic field configuration with continuous winding helical coils and without toroidal coils, where ℓ and m are the poloidal and toroidal mode numbers of helical coils respectively, and a is the average minor radius of plasma. The characteristics of the LHD magnetic field are the high magnetic shear configuration in the peripheral region and the existence of the chaotic field line layer which surrounds the LCFS. Magnetic field lines outsides the LCFS show a fractal structure and create a chaotic field line region[5].

We have determined the position of LCFS by numerical calculation of the magnetic field lines. The value of rotational transform of LCFS should be an irrational numbers. The fact that should do special mention, is that the numerically obtained rotational transform of LCFS in LHD (in the case of $R_{ax} = 3.6\,\mathrm{m}$) is almost equal to the golden mean ($= (1+\sqrt{5})/2$) as shown in *FIG.1(b)*. This means that the LCFS of LHD ($R_{ax} = 3.6\,\mathrm{m}$) is robust against perturbations, because the golden mean is the irrational number least easily approximated by rationals [6].

The high magnetic shear makes the connection length, L_c, of the chaotic field line region very long. The connection length of the field lines that pass through the neighborhood of LCFS becomes the order of $10\,\mathrm{km}$ [7]. In contrast, lines of force that are slipped out from the chaotic field line region reach the vacuum vessel wall soon, in the order of $1.5 \sim 2.0\,\mathrm{m}$ as shown in *FIG.1(a)*.

The chaotic field line layer can sustain low temperature ambient plasma due to the long connection length of lines of force and mirror confinement effect of helical ripple nature of magnetic field [7]. This low temperature ambient plasma is clearly observed always by the CCD camera in the LHD experiment. The CCD camera view of the LHD plasma and the structure of chaotic field lines are compared in detail. The CCD image and the numerical 3D view of chaotic field lines are completely corresponding each other as shown in *FIG.2*.

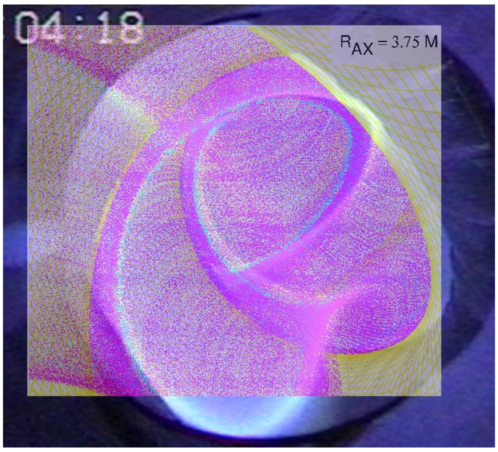

FIG.2. Numerical 3D view of chaotic field lines is superimposed on the CCD camera view of the LHD plasma.

The characteristics of lines of force outside the LCFS has been bringing the following advantage for the high performance of plasma confinement in LHD. (1) The very long connection length of the diverter field line can reduce the heat load to the diverter plate without losing high-performance of core plasma confinement. (2) The plasma contained in the chaotic field line region can protect the core plasma from the cooling down effect by neutrals outside the plasma (role of the plasma blanket). The penetration of neutral atoms to the core plasma are prevented by the chaotic-field-line-region plasma [8]. (3) The chaotic-field-line-region plasma stabilizes the interchange mode due to the neutralization of the charge separation that causes the instability. (4) The lines of force that are slipped out from the chaotic field line region reach the vacuum vessel wall soon. Then, it is expected in chaotic field line region that the plasma pressure can be sustained stably by the line-tying effect of the field lines [9].

3. Energetic particle orbit in LHD

Particle confinement in a non-axisymmetric system is based on the adiabaticity of particle motion. Adiabatic invariants can be obtained by averaging over the rapid oscillation of action variables in a Hamiltonian system. In a helical system, the slow variation is caused by the rotational transform of field lines, and the rapid oscillation is caused by passing of 1 helical period (for passing particles) or by helical trapped bounce motion (for trapped particles). In the LHD configuration, the $\boldsymbol{B} \times \boldsymbol{\nabla} B$ drift motion decreases and increases the rotational transform of particle (positive ion) motion according to the $v_\parallel > 0$ and $v_\parallel < 0$, where $v_\parallel$ is the velocity component along magnetic field $\boldsymbol{B}$. Then, it is easy to confine the $v_\parallel > 0$ passing particle than the $v_\parallel < 0$ passing particle. In a usual LHD operation region ($B_{ax} \gtrsim 1\,\mathrm{T}$, $E \lesssim 180\,\mathrm{keV}$), this difference is small, however, in low magnetic field operation case, the drift surface of co-NBI can extend fairly outside the LCFS and the drift surface of counter-NBI is reduced fairly compared with the LCFS. (*FIG.3*).

The existence of drift surface extending outside the magnetic surface was verified by several experimental results in LHD. After the 3rd campaign of LHD experiment (2000, Mar), melt-down of leading edge of stainless tube for the pellet injection was found. After the 5th campaign of LHD experiment (2002, Mar), the erosion of the edge of the armor tile was found. The drift surface of co-NBI in low magnetic field case had intersected with these equipments (*FIG. 4*).

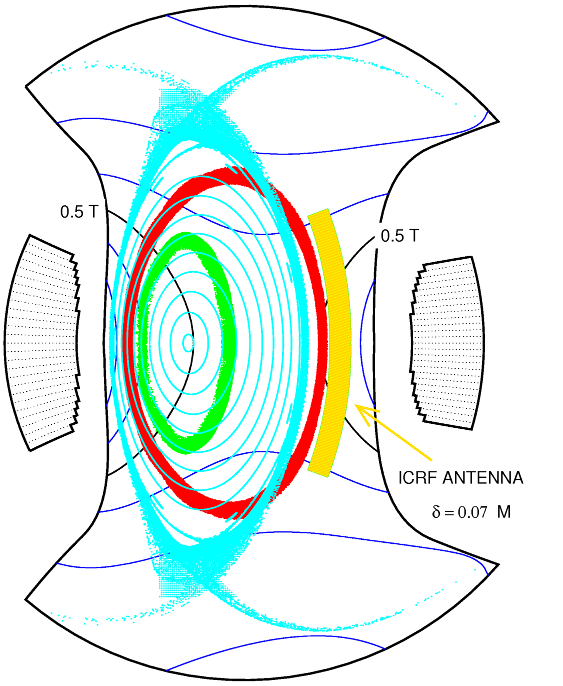

FIG.3. The almost outermost drift surfaces of 180 keV NBI particles. Magnetic field is set as $B_{ax} = 0.5\,\mathrm{T}$. The red (green) dots show the Poincare plot of co(counter)-NBI particles. Magnetic field line structure (blue dots) and magnetic field intensity distribution and the cross section of vacuum vessel wall, ICRF antenna and helical coils are also shown.

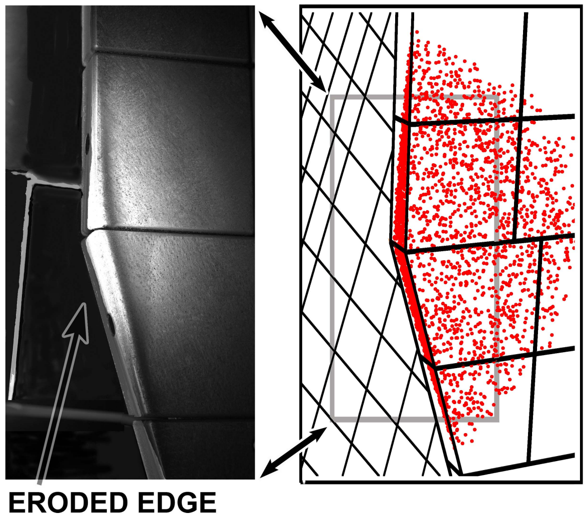

FIG.4. A close-up photograph of the eroded edge of NBI armor tile is shown on the left hand side. The right hand side shows the interference of the corresponding armor tiles and the almost outermost drift surface of 180keV co-NBI particles in the case of $B_{ax} = 0.5$ T (shown by red puncture plots on the armor tiles). The vacuum vessel wall of LHD is also drawn.

The ICRF heating in helical systems has been considered to be questionable because of the poor confinement property of the perpendicularly accelerated high-energy particles. However, the LHD generates the plasma confinement magnetic field with the continuous winding helical coils. Then helical mirror trapped particle can circulate around the magnetic axis. These particles are trapped in minimum B region along field lines, and the basic periodic length of particle motion becomes the bounce period, which is smaller than the helical period. Then the helical trapped particles can manifest stronger adiabaticity and can be confined more effectively compared with the passing particles. This is very convenient for ICRF heating of LHD plasma [10] and mirror confined plasma becomes possible even in chaotic field line region of LHD [7].

If the pitch angle (angle between particle velocity and magnetic field) is located in transition region, a particle iterates transitions between passing motions and trapped-bounce motions and is finally lost to the vacuum vessel. But, the life-time of these transition particles are very long compared with the transit time defined by machine size and thermal velocity of particles. Then LHD magnetic field has no loss-cone.

We have confirmed numerically these characteristic nature of particle motions and the high performance of ICRF heating process in LHD. An illustrative result is shown in *FIG.5*, which shows the Poincare plots in $(v_{\|}, v_{\perp})$ at $\phi = \pi/10$ poloidal section (the starting poloidal section of particles). The starting point of particle orbits is chosen on the ICRF resonance layer in core plasma region ($r = 3.78\,\mathrm{m}, z = -0.31\,\mathrm{m}, \phi = \pi/10$). ICRF resonance heating accelerate particles in $v_{\perp}$ direction mainly, in the initial stage. An accelerated particle crosses the chaotic field region without any degradation effect, and changes to a reflecting particle. Energy increment of reflecting particle becomes large. Particles are lost to the vacuum vessel wall along the diverter

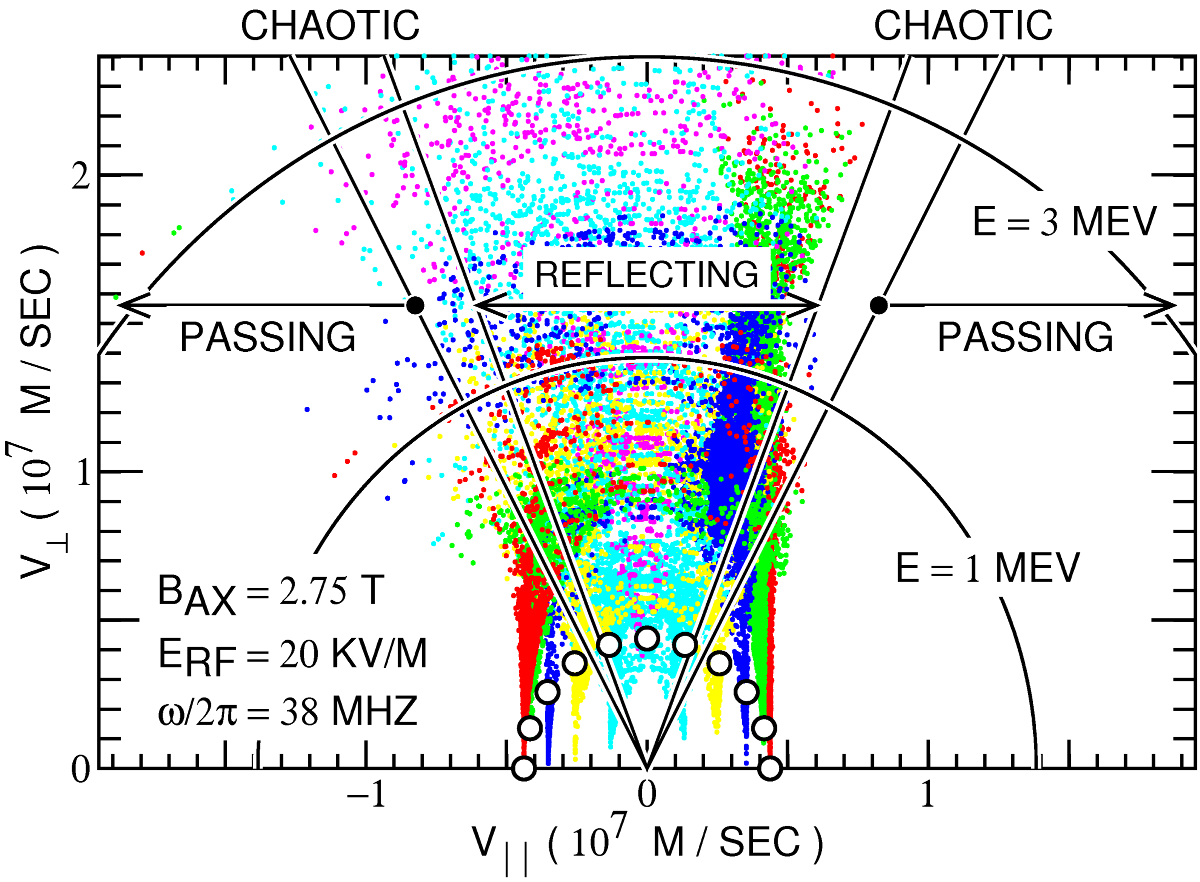

FIG.5. ICRF heating process in LHD. Poincare plots are shown in $(v_\parallel, v_\perp)$ plane at the poloidal section of the vertically elongated poloidal plane, that is the starting poloidal section of particles (total 11 particles shown by open circles). Colors of dots are classified according to the initial pitch angles. The chaotic orbit region has no degradation effect for heating process in LHD. Particles are lost to the vacuum vessel wall along the diverter field lines with $v_\parallel < 0$ when $E \gtrsim 1$ MeV.

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LHD has succeeded in sustaining the plasma (average density $\simeq 0.5 \times 10^{19}\mathrm{m}^{-3}$, central temperature $\simeq 2\,\mathrm{keV}$) during the 150 sec by ICRF ($P_{ICRF} \simeq 0.5\,\mathrm{MW}$) alone in 6th campaign experiment (2003). The plasma was terminated by uncontrollable plasma density rise. At that time, the CCD camera observed red-hot striation on the vertically installed diverter plate (standing diverter plate) as shown in *FIG.6*. These phenomena have suggested the production of high energetic protons in front of the ICRF antenna.

To clarify these experimental results, we have studied numerically the ICRF heating process by ICRF near-field. The ICRF antenna strap of LHD is wide (width

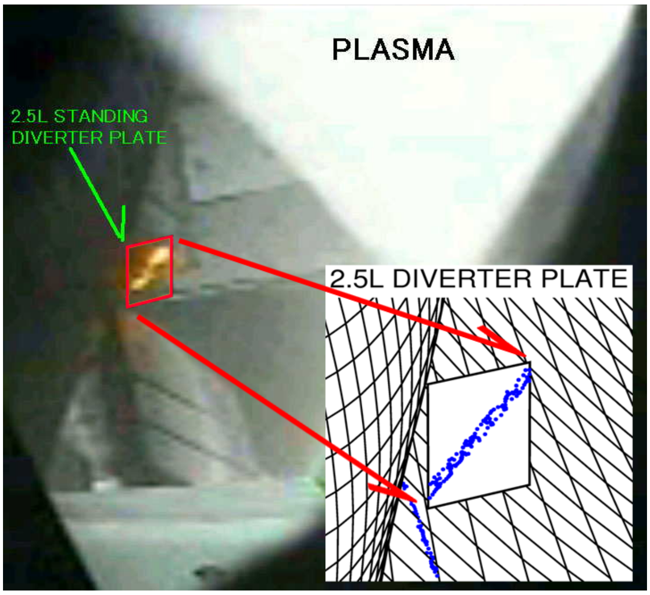

FIG.6. Red-hot striation observed in ICRF heating in 6th campaign of LHD experiment and a numerical result (the lower right corner).

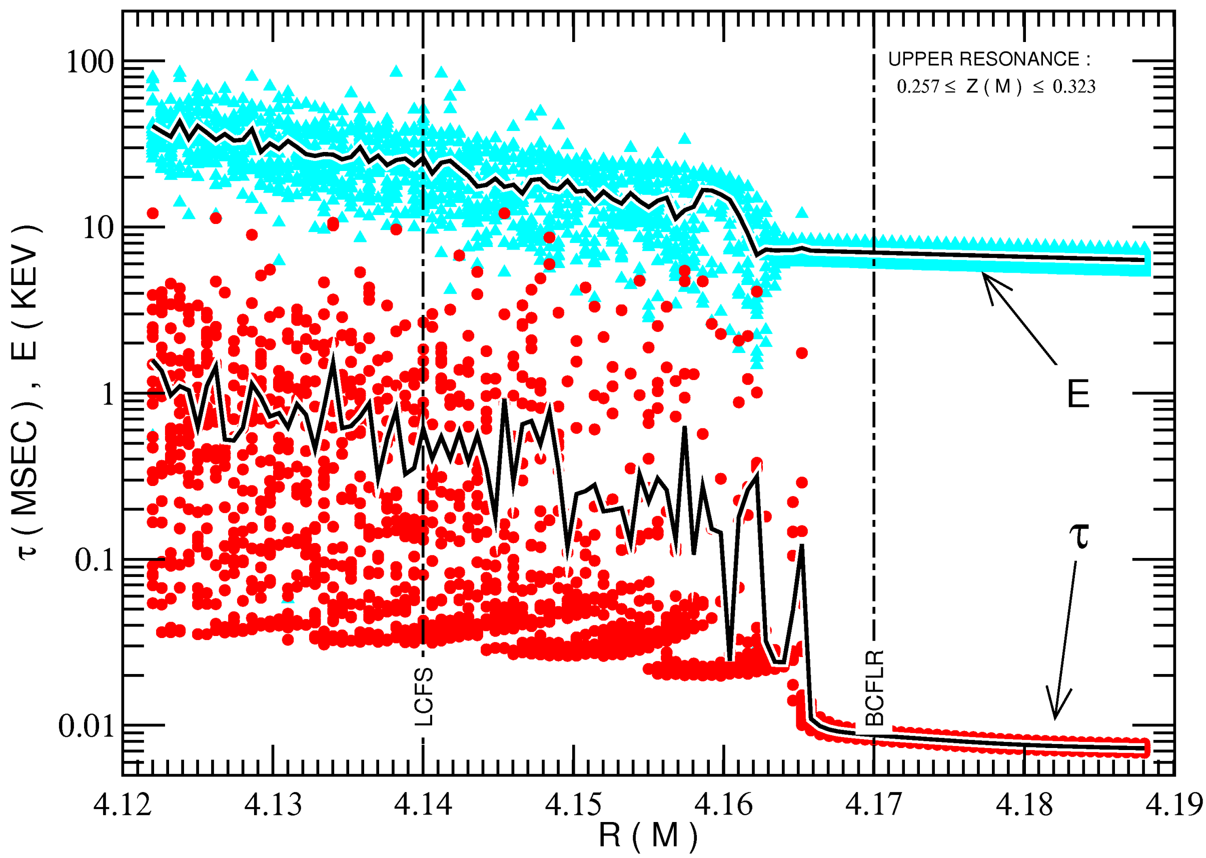

FIG.7. ICRF resonance heating in front of the antenna in the case of $B_{ax} = 2.75\,\mathrm{T}$, $R_{ax} = 3.6\,\mathrm{m}$, $E_{rf} = 20\,\mathrm{kV/m}$, $\omega/2\pi = 38\,\mathrm{MHz}$. *The ordinate represents the energy (shown by blue dots) and the life-time (shown by red dots) of ions. Initial position of ions are located on the upper ICRF resonance layer (* $\phi = \pi/10$, $0.257 \le z(\mathrm{m}) \le 0.323$*,* r : abscissa*). Mean values of energy and the life-time are shown by bold line. The position of the last closed flux surface (LCFS) and the border of chaotic field line region (BCFLR) are also shown by thin chained line.*

$\simeq 0.3\,\mathrm{m}$, height $\simeq 1.2\,\mathrm{m}$). Then, the ICRF near-field can be excited without strong attenuation both the inside and the outside of the LCFS in front of the antenna. RF heating process by ICRF near-field become effective in LHD magnetic field configuration, because ICRF resonance layer can be set up both in core plasma region and in the front of the antenna, simultaneously.

The ICRF near-field accelerate low energy ($= 10\,\mathrm{eV}$) protons starting from the ICRF resonance layer as shown in *FIG.7*. Average values of the maximum energy (E) and the life-time (τ) of each particles show clear jumps near the border of chaotic field line region (BCFLR). This shows that ions, whose starting points are located inside the BCFLR, begin to be confined and begin to be accelerated repeatedly. The position of the LCFS is not significant for the ICRF heated ions. This is consistent with the theoretical prediction for helically trapped particle motion in LHD. ICRF near-field can start up efficiently the LHD plasma.

Ions, whose starting points are located outside the BCFLR, increase energy by one-path ICRF resonance and flow out. These outflow ions made a clear diverter trace on the standing diverter plate. The CCD image of the red-hot striation observed in ICRF heating in 6th campaign of LHD experiment was completely reproduced by this diverter trace as shown in *FIG.6*.

To confirm the efficient sustainment of plasma with a high stored energy by ICRF, we have traced numerically the RF heating process by ICRF near-field. The initial energy of protons is set to $2\,\mathrm{keV}$. The initial positions of all protons are limited just in the front of the antenna and are distributed up to the depth of $10\,\mathrm{cm}$ from the LCFS to the core plasma region. The

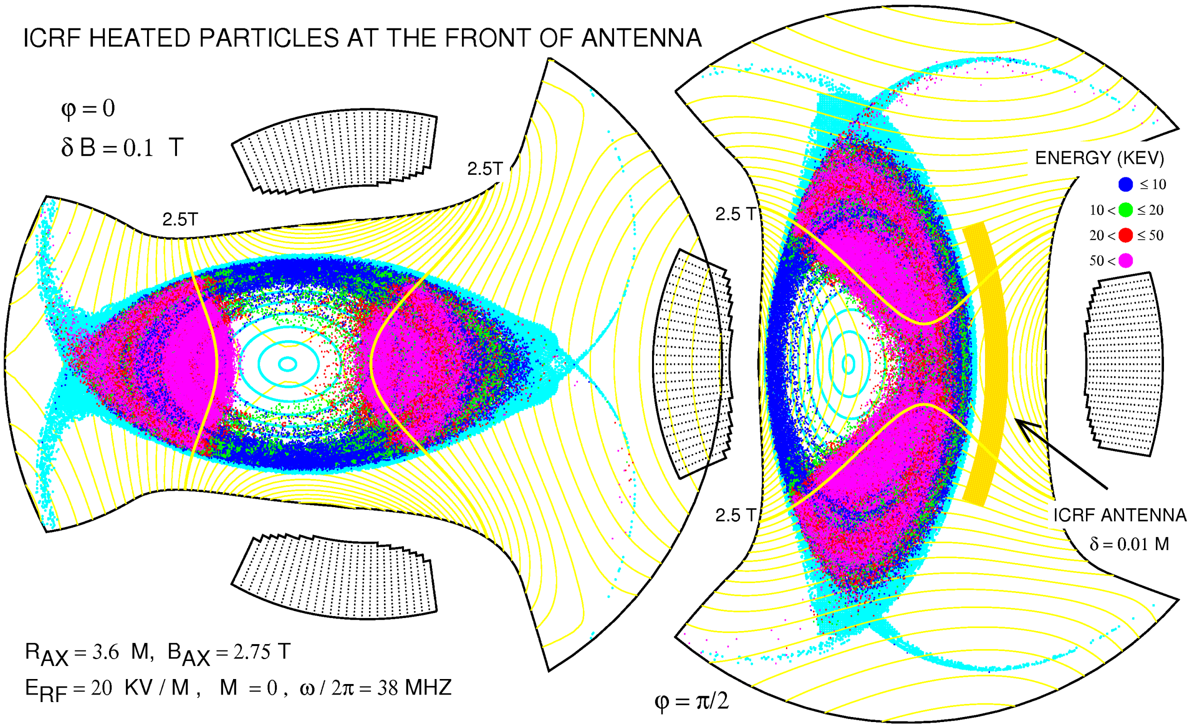

FIG.8. Poincare plots of ICRF heated protons at $\phi = 0 \,\mathrm{and}\, \pi/2$ *. ICRF field is applied in front of the antenna.* $B_{ax} = 2.75\,\mathrm{T}$*,* $R_{ax} = 3.6\,\mathrm{m}$ *,* $E_{rf} = 20\,\mathrm{kV/m}$ *,* $\omega/2\pi = 38\,\mathrm{MHz}$ *. Initial energy is* $2\,\mathrm{keV}$ *and starting position is distributed in front of the antenna and located up to the depth of* $10\,\mathrm{cm}$ *from the LCFS to the core plasma region. Colors of dots are classified by the instantaneous kinetic energy* E *of each protons, (* $E \leq 10\,\mathrm{keV}$ *: blue,* $10 < E \leq 20\,\mathrm{keV}$ *: green,* $20 < E \leq 50\,\mathrm{keV}$ *: red,* $50 < E\mathrm{keV}$ *: magenta). ICRF resonance layer is shown by the bold yellow lines (*$B = 2.5\,\mathrm{T}$ *line). Magnetic field lines are shown by small cyan color dots.*

initial pitch angle is distributed uniformly from $0 \,\mathrm{to}\, \pi$. The initial total particle number is 726. Poincare plots of ICRF heated protons show that relatively deep core region is possible to be heated by ICRF near-field and energy of many chaotic orbits particle exceeds $50\,\mathrm{keV}$ as shown in *FIG.8*.

Furthermore, we can confirm that the all lost particles flow out along diverter field lines with $v_{\|} < 0$. The time trace of average energy and total number of protons are shown in *FIG.9*. This result shows that ICRF heating process in the LHD magnetic field configuration is very much promising. Mev range of protons will be possible by present machine.

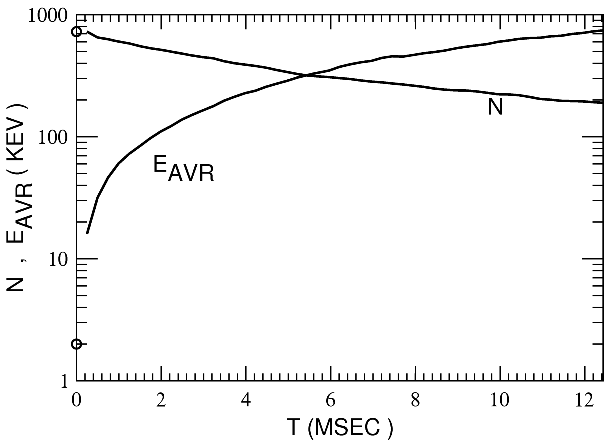

FIG.9. The time trace of average energy E_{avr} *and total number* N *of protons corresponding to the Poincare plot shown by FIG.8. Initial energy and total number are shown by open circles.*

4. Summary

Magnetic field structure in the peripheral region of LHD has studied numerically with high accuracy. We have confirmed that low temperature ambient plasma is always present in the LHD chaotic field line region outside of the LCFS because of the very long connection length of chaotic-field-line and the mirror confinement effect of helical ripple nature of the LHD magnetic field. This is proved by the detailed comparison of the CCD camera view of the LHD plasma and the numerically obtained 3D view of chaotic field lines. Both images are completely corresponding each other. The ambient plasma in the chaotic field line region brings the following advantage for the high performance of plasma confinement in LHD. (1) Reduction of heat load to the diverter plate without losing high-performance of core plasma confinement because of very long connection length of lines of force. (2) The role of the plasma blanket effect. (3) Stabilization effect against MHD instabilities.

The particle orbits were traced numerically both in the presence and in the absence of ICRF field by directly solving the equation of motion in LHD magnetic field configuration. The particle loss boundary was set at the vacuum vessel wall, ICRF antennas and NBI armor tiles.

In the LHD configuration, the $\boldsymbol{B} \times \boldsymbol{\nabla} B$ drift motion decreases the rotational transform of particle (positive ion) motion when $v_{\|} > 0$. Then, it is easy to confine the $v_{\|} > 0$ passing particle than the magnetic surface. The outermost drift surface of passing particles of $v_{\|} > 0$ can extend over the last closed flux surface (LCFS). In a usual LHD operation region ($B_{ax} \gtrsim 1\,\mathrm{T}$, $E \lesssim 180\,\mathrm{keV}$), this difference is small, however, in low magnetic field operation case, the drift surface of co-NBI can extend fairly outside the LCFS. The numerical prediction of the drift surface being extended over the LCFS is verified by the LHD experiments.

The LHD generates the plasma confinement magnetic field with the continuous winding helical coils. Then helical mirror trapped particle can circulate around the magnetic axis, and can manifest stronger adiabaticity and can be confined more effectively compared with the passing particles. This property is verified numerically and is very convenient for ICRF heating of LHD plasma.

Stabilization effect of the chaotic-field-line-region plasma against MHD instabilities is an interesting item in the future experiment of LHD.

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