# Response of plasma toroidal flow to the transition between nested and stochastic magnetic field in LHD

K. Ida,[1,2] M. Yoshinuma,[1] H. Tsuchiya,[1] T. Kobayashi,[1] C. Suzuki,[1] M. Yokoyama,[1,2] A. Shimizu,[1] K. Nagaoka,[1,2] S. Inagaki,[3] K. Itoh,[1] and the LHD Experiment Group[1]

[1] *National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*
[2] *The Graduate University for Advanced Studies, 322-6 Oroshi, Toki, Gifu 509-5292, Japan*
[3] *Research Institute for Applied Mechanics, Kyushu Univ., Kasuga, 816-8580, Japan*

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Response of the plasma toroidal flow to the forward and backward transition between the nested and the stochastic magnetic field is studied using the charge exchange spectroscopy in Large Helical Device (LHD). Abrupt damping of toroidal flow associated with a transition from nested magnetic flux surface to a stochastic magnetic field is observed when the magnetic shear at the rational surface decreases to 0.5 after the exchange of the NBI direction from co- to counter-direction in the Large Helical Device. The stochastization of magnetic field occurs only in a narrow range of magnetic shear near 0.5 and spontaneous back-transition from stochastic to nested magnetic field (healing) is observed in the steady-state phase of magnetic shear. When the NBI direction is changed from counter- to co-direction, the healing of magnetic field occurs associated with the increase of magnetic shear.

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## I. INTRODUCTION

The role of stochasticity on electron and ion heat transport has been studied in the reverse field pinch (RFP) plasmas (in reversed field experiment (RFX)[1–3] and in the Madison Symmetric Torus (MST)[4–6]. In tokamak, the role of stochasticity on heat and particle transport has been recognized to be important in determining the pedestal height and the pressure gradient in the pedestal of H-mode plasma, when a resonant magnetic perturbation (RMP) is applied to reduce the edge pressure gradient and suppress the edge localized modes (ELMs)[7, 8]. However, the role of stochastic magnetic field on the plasma flow has not been discussed before in these devices, in spite of the importance of flow shear on the turbulence in the plasma which determined the transport in the toroidal magnetized plasmas such as in tokamak and reverse field pinch plasmas. In helical plasma, the abrupt flow damping due to the stochastic magnetic field was observed when the magnetic shear is decreased by switching the direction of the neutral beam from co to counter with respect to the equivalent plasma current in LHD[9]. This flow damping is transient and the toroidal flow often spontaneously recovers associated with the healing of magnetic field (disappearance of stochastic magnetic field and the magnetic field becomes nested). In most discharges, the stochastization of the magnetic field is transient and the spontaneous healing of stochastization (back transition from stochastic to nested magnetic field) occurs. The response of plasma flow at the back transition from stochastic to nested magnetic field was not discussed in the previous work, in spite of its importance.

In this paper, the recovery of the toroidal flow at the back transition from stochastic to nested magnetic field (healing) in helical plasmas in the Large Helical Device (LHD) is described. The difference in the time scale of the spontaneous back transition at constant magnetic shear and the controlled back transition by the increase of magnetic shear and the role of plasma flow on healing the stochastizationis are discussed. The dynamic transport analysis of toroidal momentum has been applied to evaluate the change in the effective viscosity in the core due to the stochastization of magnetic field. In Sec. II, how to identify the magnetic topology (nested or stochastic magnetic field and with or without magnetic island) is described. The response of toroidal flow to magnetic topology, i.e., flow damping due to stochastic magnetic field and flow recovery due to nested magnetic field is described in Sec. III. The result of dynamic transport analysis, where the relation between momentum flux and flow shear is analyzed in time, is presented in Sec. IV. The role of flow on the healing is discussed in Sec. V.

## II. IDENTIFICATION OF MAGNETIC FIELD TOPOLOGY BY HEAT PULSE PROPAGATION METHOD IN LHD

The LHD is a heliotron-type device for magnetic confinement of high temperature plasmas. The LHD has three tangential neutral beams, and two beams are used to change the direction of the plasma current from parallel (co-injection) to anti-parallel (counter-injection) with respect to the equivalent plasma current. The toroidal flow and ion temperature are measured with charge exchange spectroscopy[10], while the rotational transform, $\iota/2\pi$, and magnetic shear, $s[= (\rho/\iota)\partial\iota/\partial\rho]$, at the rational surface ($\iota/2\pi$=0.5) are measured with Motional Stark Effect spectroscopy (MSE)[11].

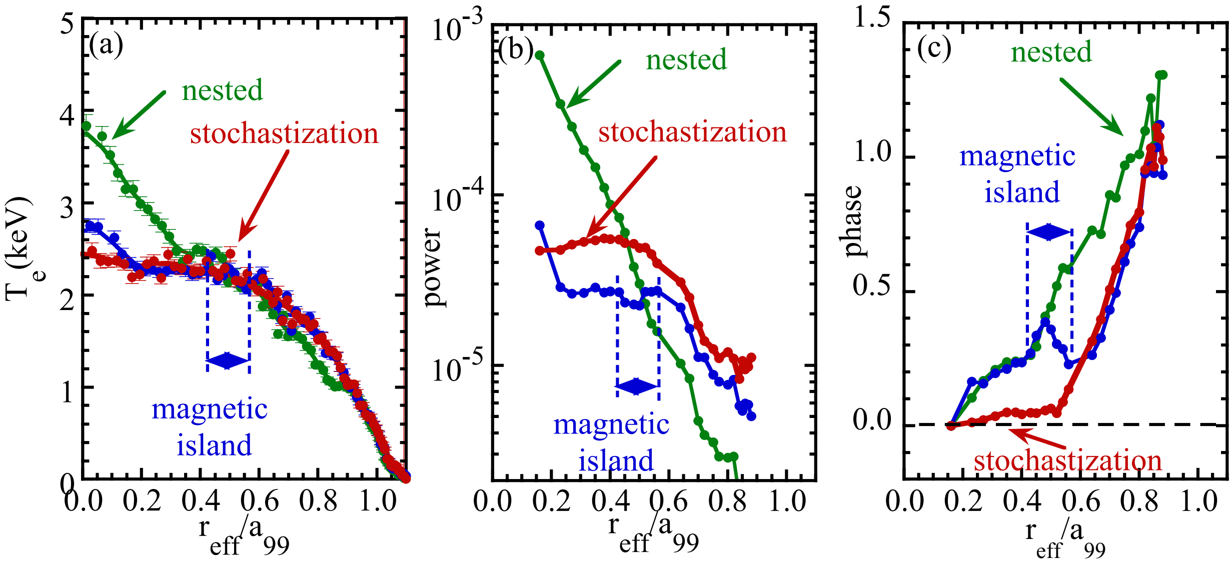


FIG. 1: Radial profiles of (a) electron temperature, (b) power of heat pulse amplitude, and (c) phase delay of heat pulse in the plasma with nested magnetic flux surface (♯107033 t=5.7 sec), stochastization (♯107033 t=6.5 sec), and magnetic island (♯107027 t=6.2 sec).

The total plasma current driven by the neutral beam is in the range of ∼100 kA (counter-direction) to 50 kA (co-direction), which is only 3% - 6% of equivalent plasma current (1.8 MA) produced by the external helical coils. However, the time scale in the change of total current is longer than the beam pulses and the inductive current in the direction opposite to the toroidal current due to neutral beam current drive (NBCD) in the core region plays an important role in this experiment. Therefore, by switching the direction of the neutral beam current drive during the discharge, the magnetic shear near the plasma core can be controlled[12].

Although the identification of magnetic topology is an important issue, a direct measurement of the stochastization of the magnetic field surfaces requires very precise measurements of all components of B in a 3D geometry, which is not possible with current B-field measurement techniques. The transition of magnetic topology, for example, the transition from nested magnetic flux surface to a magnetic island can be identified by heat pulse propagation by taking advantage of the difference in the time scale of cold/heat pulse propagation perpendicular and parallel to the magnetic field line. The cold/heat pulse propagation method has been recognized to be a useful tool to identify the magnetic topology such as magnetic island[13–15] and stochastization[16, 17]. In this experiment, a modulated electron cyclotron heating (MECH) with a frequency of 25Hz focusing at the plasma center ($r_{\rm eff}/a_{99} < 0.2$) is used for the heat pulse propagation study.

Figure 1 shows radial profiles of electron temperature, power of heat pulse amplitude and phase delay of heat pulse in the plasma with nested magnetic flux surface, stochastic magnetic field, and magnetic island. The flattening of electron temperature is observed when the magnetic island or the stochastic magnetic field appears in the plasma, while the temperature profile is peaked when the magnetic flux surface is nested. There is only a small difference in radial profiles of electron temperature between the plasma with the magnetic island and the stochastic magnetic field. In contrast, the radial profile of heat pulse propagation shows a clear difference between the plasma with the magnetic island and the stochastic magnetic field. The radial profile of modulation power (square of amplitude) indicates the clear difference in the plasma with nested, magnetic island, and stochastic magnetic field.

The modulation power profile (square of amplitude) is peaked in the plasma with nested magnetic flux surface, while it shows a slight follow profile inside the magnetic island and flat profile in the stochastic magnetic field region. The phase delay of the heat pulse increases monotonically towards the plasma edge when the magnetic flux surface is nested. However, when there is a magnetic island in the plasma, the radial profile of the phase delay shows a small peak at $r_{\rm eff}/a_{99} \sim 0.5$, which indicates the location and the width of the magnetic island, because the heat pulse propagates from the boundary to the O-point location of the magnetic island. In the plasma with stochastic magnetic field, the phase delay of the heat pulse shows flattening in the plasma core ($r_{\rm eff}/a_{99} < 0.52$), which indicates the region where the magnetic field becomes stochastic, because the heat pulse propagates along the magnetic field line which is deviated radially due to the stochastization.

The possible physics mechanism for the stochastization of magnetic field is overlapping of magnetic island with lowest mode number of $m/n = 2/1$ and the magnetic island with higher mode number of $m/n = 4/2$, 6/3, and 8/4. The stochastization of magnetic field can be reproduced by adding the $m/n = 2/1$ 4/2, 6/3, and 8/4 perturbation of toroidal current to the equilibrium magnetic field estimated from the pressure profile and rotational transform profile measured[17]. When the magnetic shear decreases below 0.5, only the magnetic island with the lowest mode number grows and the stochastic magnetic field disappears.

## III. DAMPING AND RECOVERY OF TOROIDAL FLOW DUE TO THE STOCHASTIZATION AND HEALING OF MAGNETIC FIELD

Figure 2 shows the time evolution of NBI power, line averaged density, toroidal plasma current, rotational transform and magnetic shear at rational surface of $\iota/(2\pi) = 0.5$ ($q = 2$) measured with MSE and toroidal flow measured with CXS in the discharge where the direction of neutral beam injection (NBI) is switched from co-injection to counter-injection (parallel to anti-parallel to the equivalent plasma current that gives the poloidal field produced by the external coil current) at t = 5.3 sec. The line averaged density increases from $1 \times 10^{19}\mathrm{m}^{-3}$ to $2 \times 10^{19}\mathrm{m}^{-3}$ and the toroidal plasma current changes its sign from positive (co-direction) to negative (counter-direction) after the direction of NBI is switched as seen in Fig.2(b)(c). In the low density regime in LHD plasmas, the beam driven current and resulting inductive current can be large enough to change the radial profile of rotational transform. The edge rotational transform decreases due to the beam driven current, and the central rotational transform increases due to the inductive current. Then the magnetic shear at the $\iota/(2\pi) = 0.5$ rational surface starts to decrease and reaches the steady state value of 0.5 at $t = 5.65$ sec a few hundred milliseconds after the switch of the NBI. This decrease of the magnetic shear increases the magnetic island width and finally causes stochastization due to the overlapping of magnetic islands with higher modes. The parameter regime of magnetic shear causing the stochastization is $\sim 0.5$ and relatively narrow. This is because the stochastic magnetic field is healed to the nested magnetic flux surface in the high magnetic shear. When the magnetic shear becomes too weak, the fundamental mode of the magnetic island becomes dominant and it causes the transition from stochastic magnetic field region to magnetic island[17].

The toroidal flow velocity changes its sign from positive (co-rotation) to negative (counter-rotation) and becomes steady state with the central toroidal flow velocity of $\sim 20$ km/s. Associated with the transition from nested magnetic flux surface without magnetic island to stochastic magnetic field, the abrupt drop and a clear flattening of the toroidal flow velocity are observed at $t = 6.0$ sec, although the NBI continues to be injected until $t$= 7.3 sec. The damping of toroidal flow due to the stochastization is transient and it recovers even with constant magnetic

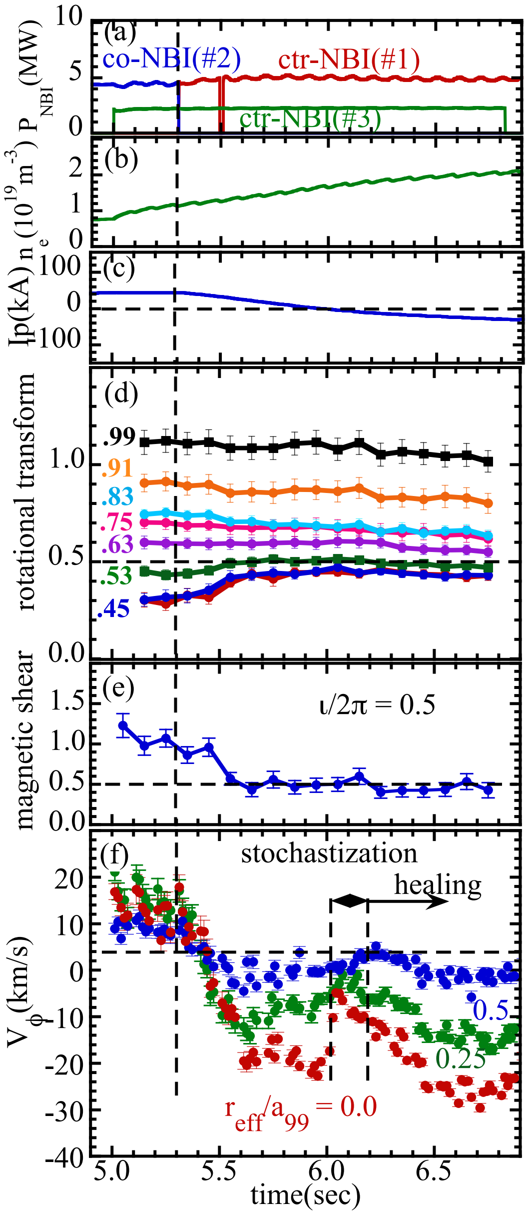


FIG. 2: Time evolution of (a) NBI power, (b) line averaged density, (c) toroidal plasma current, (d) rotational transform at $r_{\mathrm{eff}}/a_{99} = 0.99$, 0.91, 0.83, 0.75, 0.63, 0.53, 0.45, 0.38 and (e) magnetic shear at rational surface of $\iota/(2\pi) = 0.5$ ($q = 2$) measured with MSE and (f) toroidal flow velocity measured with CXS (♯114605). The partial stochastization of magnetic field occurs at $t = 6.0$ sec. Here the direction of the NBI is exchanged from co- to counter-direction respect to the equivalent toroidal current.

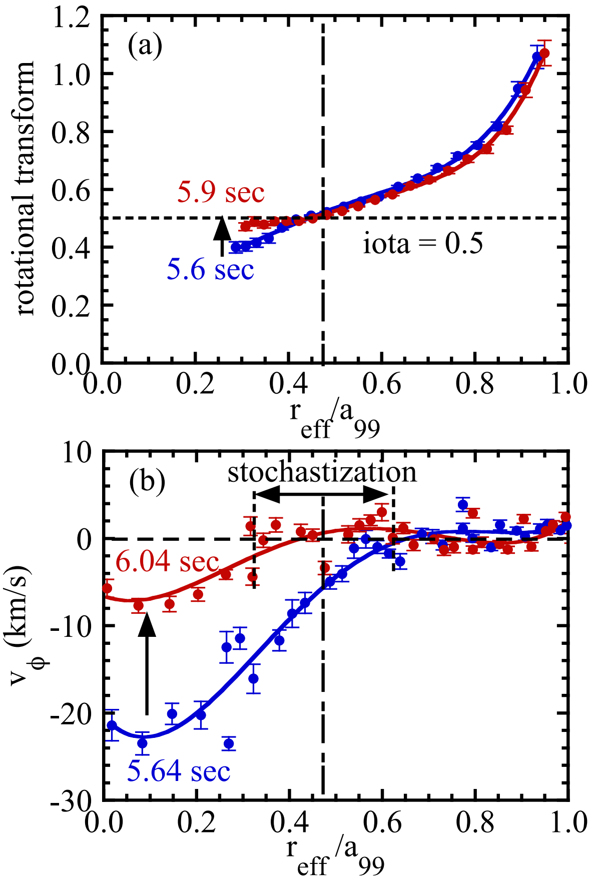


FIG. 3: Radial profile of (a) rotational transform measured with MSE and (b) toroidal flow velocity measured with CXS (♯114607). The normalized effective minor radius of rational surface of $\iota/2\pi$= 0.5 is 0.47 and partial stochastization of magnetic field is from 0.32 to 0.62.

shear. This spontaneous recovery of toroidal flow is due to the back-transition from stochastic magnetic field to nested magnetic field with magnetic island at $t$ = 6.2 sec. The stochastization of magnetic field is transient and the time period is only 0.2 sec, while the time scale of the flow recovery is relatively long and 0.5 sec ($t$ = 6.2 - 6.7 sec). After the healing of magnetic field, the magnetic field becomes nested with magnetic island, which is in contrast to the nested magnetic field without magnetic island before the stochastization in this discharge. There are two type of forward transition to stochastic magnetic field, one is a transition from nested magnetic flux surface without magnetic island to the stochastic magnetic field[9] and the other is a transition from nested magnetic flux surface with magnetic island to the stochastic magnetic field[18]. In contrast, the back transition is usually from the stochastic magnetic field to the nested magnetic field with magnetic island.

The rotational transform outer half of the plasma ($r_{\rm eff}/a_{99} > 0.5$) decreases due to the beam driven current of counter-NBI. However, the rotational transform inner half of the plasma ( $r_{\rm eff}/a_{99} < 0.5$) increases as seen in Fig.3(a). Because the pivot point of the change in rotational transform locates at $r_{\rm eff}/a_{99} > 0.47$ near the rational surface of $\iota/(2\pi) = 0.5$, the exchange of the NBI direction from co- to counter-direction gives a significant drop of magnetic shear at the rational surface as seen in Fig.2(b). The toroidal flow velocity profile is peaked in the core region $r_{\rm eff}/a_{99} < 0.6$ before the stochastization of the magnetic field at $t$ = 5.64sec, while the central toroidal flow velocity drops due to the flattening of flow velocity near the rational surface at $t$ = 6.04 sec as seen in Fig.3(b). In this discharge, only partial stochastization[19] (the region with stochastic field is localized) occurs and the flattening of toroidal flow due to the stochastization is observed in the one-fourth of the plasma minor radius at $r_{\rm eff}/a_{99}$ = 0.36 - 0.62 near the rotational surface of $\iota/(2\pi) = 0.5$ as indicated by arrows in Fig.3(b). Note that there is finite toroidal flow shear at $r_{\rm eff}/a_{99} < 0.3$, which indicates the existence of nested magnetic flux surface near the magnetic axis. This is in contrast to the discharge with full stochastization (the region with stochastic magnetic field extends to the magnetic axis), where the complete flattening of toroidal flow is observed (discussed in Sec. IV). The partial stochastization of magnetic field is always initiated at the rational surface, which suggest that the overlapping of the magnetic island between fundamental mode and higher harmonic modes is a strong candidate of the possible mechanism for the stochastization as discussed in Sec. II.

Figure 4 shows radial profiles of ion temperature, electron temperature, and electron density before ($t$ = 5.64 sec) and after ($t$ = 6.04 sec) the stochastization of the magnetic field. Both central ion and central electron temperatures decrease and their profiles show the flattening after the stochastization of the magnetic field. It should be noted that the magnitude of the flattening of the temperature is different between the ion and the electron temperature profiles because of the difference in the thermal velocity of the ion and the electron. More temperature flattening is observed in the electron temperature profiles than in the ion temperature profiles.

The radial profile of electron density is almost identical, although the averaged level increases after the stochastization. The increase of the electron density is not due to the stochastization but due to the increase of recycling and beam fueling in the counter-NBI phase. It is not clear how the stochastization of the magnetic field affects the particle transport, because the density profile is flat in the core region even in the plasma with nested magnetic flux surface.

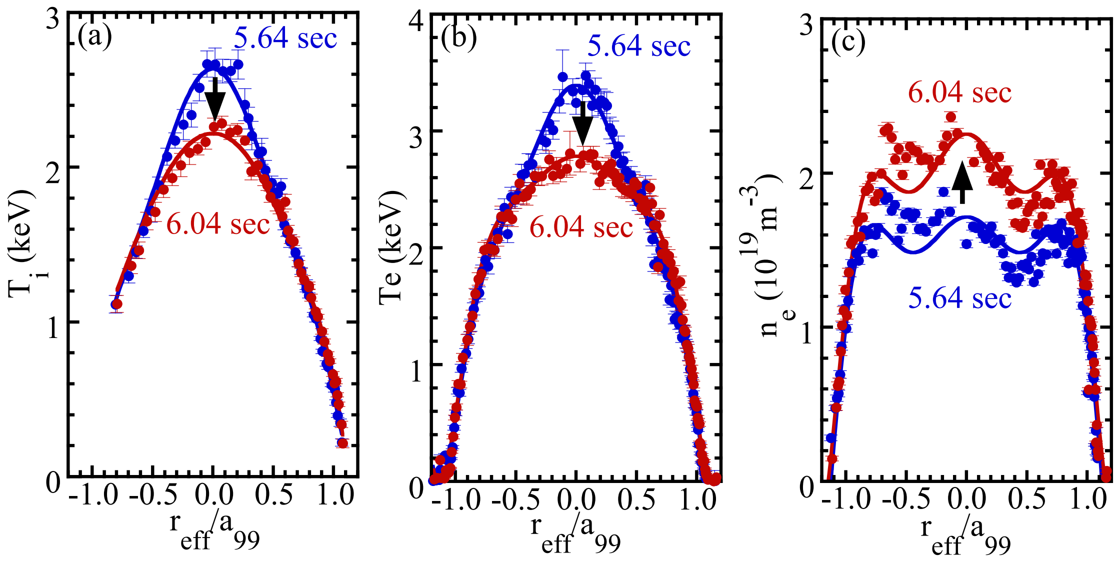


FIG. 4: Radial profiles of (a) ion temperature, (b) election temperature, (c) electron density before ($t$ = 5.64 sec) and after ($t$ = 6.04 sec) the stochastization of magnetic field (♯114607).

## IV. DYNAMIC MOMENTUM TRANSPORT ANALYSIS

The electron/ion thermal diffusivity, $\chi_e$, $\chi_i$ are evaluated from the electron/ion heat flux and electron/ion temperature gradients. The viscosity of toroidal flow, $\mu_\phi$, is evaluated from the toroidal momentum flux and toroidal flow velocity gradient. Here the heat and the momentum fluxes are calculated with FIT-3D code[20], while the temperature and velocity gradients are measured with YAG Thomson scattering and charge exchange spectroscopy.

The electron thermal diffusivity ($\chi_e$) at $r_{\rm eff}/a_{99} < 0.2$ increases by more than one order of magnitude ($\chi_e$ = 4 m$^2$/s $\rightarrow$ > $10^2$ m$^2$/s), while the ion thermal diffusivity ($\chi_i$) increases only by a factor of 1.6 ($\chi_i$ = 4 m$^2$/s $\rightarrow$ 6 - 7 m$^2$/s)[19]. Theoretically, the electron and ion thermal diffusivity in the stochastic region can be evaluated as $\chi^{st}_{i,e} = D_M v_{e,i}$, where $v_e$ and $v_i$ are the thermal velocities of electrons and ions, respectively, and $D_M$ is the diffusion of the field line defined by $2\pi(r_s^2/R)B_n^2$, $r_s$ is the radius of the resonant surface. And here $B_n$ [$=(RB_r)/(r_sB_\phi)$] is the normalized perturbation field[21]. Then $\chi_e$ in the stochastic region is expected to be much larger than that of the ions by $(m_i/m_e)^{1/2}$ because of larger thermal velocity of electrons[22, 23]. The thermal diffusivity in the stochastic region $\chi^{st}$ evaluated from similar discharges [17] is 2 - 3 × $10^2$ m$^2$/s for electrons and 5 - 7 m$^2$/s for ions, which is consistent with this experimental observation.

Figure 5 shows the time evolution of toroidal flow in the discharge where the direction of the NBI is changed from co- to counter-direction in respect to the equivalent toroidal current the and the flux gradient relation of toroidal momentum in the plasma with full stochastization of the magnetic field. In the steady-state of co-injection phase (normalized momentum flux, $P_\phi/(n_im_i)$, is 600×$10^3$m$^2$s$^{-2}$), the viscosity coefficient of the toroidal flow ($\mu_\phi$), defined by the ratio of normalized momentum flux to velocity shear, is 4.1 m$^2$/s, which is identical to the value of $\chi_i$) (4 m$^2$/s) before the stochastization of the magnetic field. After the exchange of NBI direction from co-injection to counter-injection, both the momentum flux and velocity shear change their sign from positive to negative. In the steady-state phase of counter-injection ($P_\phi/(n_im_i)$ ∼ -1100 ×$10^3$m$^2$s$^{-2}$), a sudden decrease of the absolute value of velocity gradient to 50 ×$10^3$s$^{-1}$ is observed. The $\mu_\phi$ increases to 19 m$^2$/s after the stochastization of the magnetic field. The increase in $\mu_\phi$ is by a factor of 5, which is much larger than that in $\chi_i$ of a factor of 1.6.

This fact suggests that the damping of the toroidal flow is not only due to the increase of the viscosity coefficient. Because the toroidal flow velocity is much more peaked in the core region ($r_{\rm eff}/a_{99}$ < 0.5), where the stochastization occurs, than the ion and the electron temperature, the change in toroidal flow is most significant at the topology bifurcation from nested flux surface to the stochastic magnetic field. The good agreement between the electron thermal diffusivity estimated from the power balance and the analytic predictions of the Rechester-Rosenbluth model[22] has been reported[9]. After the

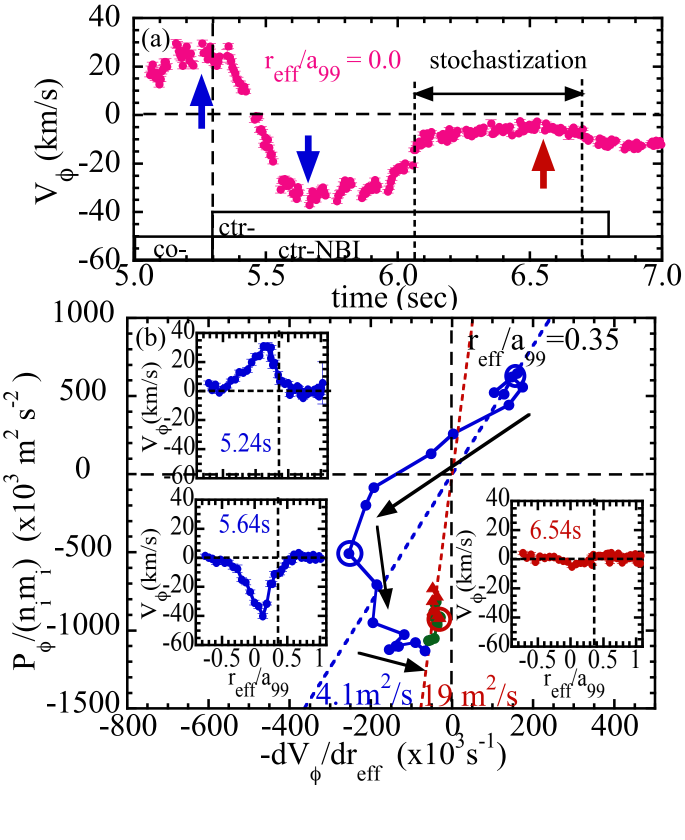


FIG. 5: (a)Time evolution of toroidal flow in the discharge where the direction of the NBI is changed from co- to counter-direction in respect to the equivalent toroidal current and (b) the flux gradient relation of toroidal momentum at $r_{\rm eff}/a_{99} = 0.35$ (♯114496).

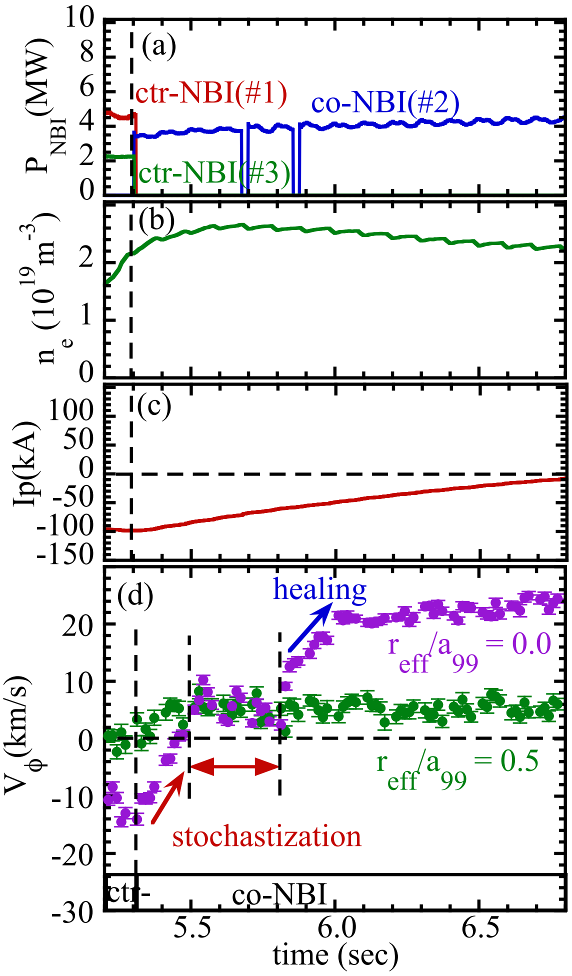


FIG. 6: Time evolution of (a) NBI power, (b) line averaged density, (c) toroidal plasma current, (d) toroidal flow velocity in the discharge where the direction of the NBI is exchanged from counter- to co-direction respect to the equivalent toroidal current. (♯114628).

stochastization of the magnetic field, the increase of $\chi_e$ is much larger than that of the ions ($\chi_e/\chi_i > 15$) because of the difference in thermal velocity, which is consistent with the Rechester-Rosenbluth model ($\sim$ 40). In contrast, the large effective Prandtl number observed during stochastization ($\mu_\phi/\chi_i = 3$) is inconsistent with the prediction of the Rechester-Rosenbluth model ($\sim$ 1).

Figure 6 shows the time evolution of NBI power, line averaged density, toroidal plasma current, and toroidal flow velocity in the discharge where the stochastization occurs when the toroidal flow becomes small during the switch of the NBI direction from counter- to co-injection. The line averaged density is $2.5 \times 10^{19}\mathrm{m}^{-3}$ and the negative toroidal plasma (in the counter-direction) decays after the direction of NBI is switched as seen in Fig.6(b)(c).After the direction of NBI is switched from counter- to co-direction, the magnetic shear in the plasma becomes strong due to the increase of edge rotational transform and the decrease of rotational transform in the core region by the inductive current[12]. The stochastization appears transiently ($t$ = 5.5 - 5.8 sec) and the gradient of toroidal flow velocity in the plasma core ($r_{\rm eff}/a_{99} <$ 0.5) becomes zero after the switch of the NBI direction. In this discharge, the time scale for the recovery of toroidal flow is 0.2 sec ($t$ = 5.8 - 6.0 sec) , which is much faster than that ($\sim$ 0.5 sec) observed in the spontaneous healing plotted in Fig. 2(f) ($t$ = 6.2 - 6.7 sec). The fast recovery of toroidal flow implies that there is some acceleration mechanism for the healing (disappearance of stochastic magnetic field) and the toroidal flow itself contributes to the acceleration of the magnetic field healing. The healing of the stochastic magnetic field after $t$ = 5.8 sec is due to the increase of magnetic shear by co-NBI and the fast toroidal flow recovery and magnetic field healing shows the existence of the acceleration due to the positive feedback between the magnetic field healing and flow recovery.

The flux gradient relation of toroidal momentum in the plasma with the spontaneous healing of the mag-

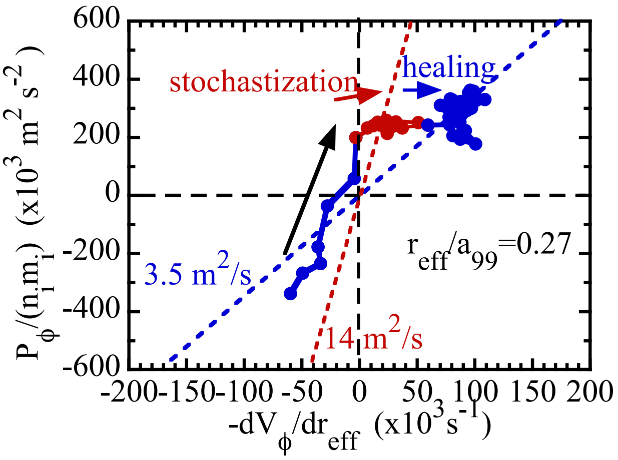


FIG. 7: The flux gradient relation of toroidal momentum at t $r_{\rm eff}/a_{99} = 0.27$ (♯114628).

netic field is plotted in Fig.7. The viscosity coefficient of the toroidal flow ($\mu_\phi$) is 14 m$^2$/s during the stochastization and decreases to 3.5 m$^2$/s after the healing of the magnetic field. The reduction of the viscosity coefficient of the toroidal flow associated with the healing of the magnetic field (by a factor of 4) is consistent with the enhancement due to the stochastization of the magnetic field plotted in Fig.5(b).

## V. DISCUSSION AND SUMMARY

It is well known that the toroidal flow contributes to heal the magnetic islands by screening of the perturbed magnetic field. Therefore, once the stochastization of the magnetic field starts near the rational surface, the region of the stochastization of the magnetic field expands due to the flow damping. In contrast, once the healing of stochastization occurs at the plasma center, the region of the stochastization of the magnetic field contracts due to the toroidal flow. This feedback process would accelerate the time scale of damping and the healing of stochastization, which is much faster than the time scale of change in magnetic shear. The feedback process is also consistent with the linear decay of toroidal flow and flow velocity, which is in contrast to the exponential decay of ion temperature gradient, observed in the previous experiment[9].

In summary, this paper reports important findings on the response of plasma toroidal flow to the transition of magnetic topology (nested and stochastic magnetic field) i.e., 1) strong toroidal flow damping occurs associated with the forward transition from nested magnetic field to stochastic magnetic field when the magnetic shear at the rational surface is approaching to 0.5, 2) spontaneous healing of magnetic field (backward transition from stochastic to nested magnetic field) and recovery of toroidal flow is observed in the steady-state of magnetic shear, 3) the flattening of toroidal flow (and stochastization of magnetic field) appears near the rational surface and extends to the magnetic axis in the case of full stochastization, and 4) the change in effective viscosity of toroidal flow at the forward and backward transition is by a factor of 4 - 5, which is much larger than that in ion thermal diffusivity.

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