TF Ripple Induced Stochastic Diffusion of Energetic Particles in Advanced Tokamak Configurations on HL-2A[1]

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Abstract. A NBI heated discharge is modeled with TRANSP under the HL-2A condition. LH wave is injected into the target plasma heated by NBI with a nearly symmetric power spectrum to control the current profile. Due to the off-axis driven current and electron heating, an optimized q-profile, of which the magnetic shear is weak in the central region and negative in the mid-plasma region (x~0.5-0.65), is formed. The NBI heating discharge with the optimized q-profile enters into operation scenario of enhanced ion confinement. The ripple loss of the energetic particles is studied by using the Golaston-Whiet-Boozer threshold for stochastic ripple diffusion. Compared to the discharge of conventional tokamak configuration, the ripple loss fraction of the captured NBI power is much higher (more than 25%) in the discharge with the optimized q-profile. The factor of the ripple loss fraction of particles against that of energy, K_{sp}, is much higher than unity showing that the most of particles are lost during the slowing down of the injected ions. K_{sp} is dependent on the energy of injected particles, the injecting angle of neutral beam line, and electron temperature of the bulk plasma. With NBI of lower energy, the ripple loss fraction of the captured NBI power is larger than that for the case of higher NBI energy because the lost particles are richer in ones of relatively higher energy in the case of lower NBI energy.

1 Intrduction

Control and optimization of the plasma current profile is a key point in enhancing the plasma performance. Although several tools have been identified to modify transport directly, the effect of the current profile on transport is large and remains an important transport control feature. Many improved confinement scenarios have been established by tailoring current profile with various auxiliary heating schemes. Reversed shear (RS) operation, in which the magnetic shear is negative in the core and positive in the outer plasma, is desirable for confinement, stability and bootstrap alignment. In many tokamaks, RS plasmas develop an internal transport barrier (ITB) that produces improved central confinement [1, 2]. It is also demonstrated that the configuration with flat q-profile in the central plasma region is beneficial to improving plasma confinement. Discharges with ITB have been established with optimized magnetic shear (OS) in JET and ASDEX Upgrade, where the q-profiles showed an extended low shear region in the plasma center and the developed ITB improved central plasma confinement. Recently, so called hybrid scenarios characterized by a current density profile, enclosing a large volume of low magnetic shear with q_0 near 1, have achieved improved confinement and higher beta limits [3,4].

HL-2A is a divertor tokamak at SWIP (Southwestern institute of Physics), Chengdu, China, with main parameters of major radius R = 1.64m, minor radius a = 0.4m, toroidal magnetic field B_T = 2.8T, and plasma current I_p = 0.48MA. In HL-2A, the various schemes of auxiliary heating and current drive including NBI (2MW), LHCD (1MW) and ECRH (2MW) combined with diversities of plasma fuelling method including pellet injection, SMBI

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(supersonic molecular beam injection), and gas-puffing offer opportunities to optimize the plasma profiles. In order to elevate the plasma parameters and achieve more interesting operation scenarios, optimization of the plasma profiles will be carried out using the available controlling schemes. In advanced tokamak scenarios based on reversed shear, the effect of the safety factor q on the ripple-induced loss of energetic particles is an important issue to be concerned. High q values lead to an expansion of the ripple trapping region and the boundary for stochastic ripple diffusion. The system of toroidal magnetic field in HL-2A consists of 16 D-shaped coils. Although the smaller number of coils is beneficial to accessibility for auxiliary heating instruments and diagnostics, it generates higher TF ripple.

2 Hot ion regime in advanced confinement configuration.

In hot ion plasmas the ion temperature exceeds the electron temperature largely, which has the advantage of reducing the plasma transport [5]. In order to study hot ion plasma, the low-density discharges, in which the ion and electron channel are decoupled, are modeled under the HL-2A condition. We control the plasma current profile with LH wave injected into an Ohmic plasma, in which $T_i<T_e$, and an NBI heated plasma, in which $T_i>T_e$, respectively. Firstly, with a nearly symmetric power spectrum ($\Delta\varphi$ = 170°), 1.5MW LH wave power is injected into an Ohmic plasma during t = 1.0 – 1.8s. The parameters of the target plasma are: I_p = 200kA, B_T = 2.0T, and line average density $\bar{n}_e = 1.0\times10^{19}\,m^{-3}$. The geometry of a single null divertor plasma, which has been obtained in the previous experiment [6], is used in the simulation. Simulation shows that the electron temperature increases significantly due to higher power electron Landau heating. The central electron temperature is about 0.6keV before injection of the LH wave, and increases to more than 1.4keV during the LH heating phase [Fig. 1(a)]. In contrast to the large increment of the electron temperature, the ion temperature only has a small change (namely, the central T_i only has an increment of $\Delta T_{i0}\approx 0.13keV$ from the Ohmic value T_{i0} = 0.5 keV) because of the low plasma density. Since parallel refractive index of the used LH power spectrum ($\Delta\varphi$ = 170°) is rather high (the central refractive index $n_{//0}\approx 5.0$), the injected LH wave of lower phase velocity can be absorbed in the outer region resulting in off-axis electron heating [7]. In addition to the plasma heating, a non-inductive current ($I_{LH}\approx$ 80kA) is driven by the LH wave because of the slight asymmetry of the LH wave spectrum and the asymmetry of electron velocity distribution function caused by the electric field, E_{DC}. Due to the off-axis driven current and electron heating, an optimized q-profile, of which the magnetic shear is weak in the central region and negative in the mid-plasma region ($x\approx$ 0.5-0.65), is formed.

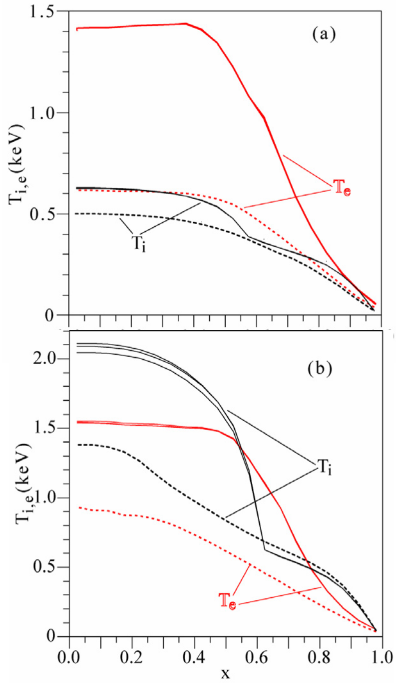

Fig. 1 Temperature profiles in (a) Ohmic target discharge, and (b) NBI heating discharge. Dotted lines indicate profiles before LH injection at t=0.95s, and full lines indicate profiles in the LH heating phase at t=1.5, 1.6, 1.8s.

To produce hot ion plasma, the same target plasma is heated by neutral beam injection (NBI) of injected power P_{inj} = 0.65MW and beam energy E_b = 20keV during 0.3-1.8s.

Then the same LH heating power is injected during 1.0-1.8s to heat the plasma further and control the current profile, and the similar q-profile as in the Ohmic case is produced (Fig. 2). Accordingly internal transport barrier (ITB) is developed because of the shear reversal [8]. During the LH wave injection phase, not only the electron temperature has a large increment, but the ion temperature increases significantly (from $T_{i0} < 1.4keV$ to $T_{i0} \sim 2.1keV$) as well [Fig. 1(b)]. As we see above, the ion temperature only has a small increment when the Ohmic target plasma is heated by the LH wave. Nevertheless, with the same LH wave injected into the NBI heated target plasma of T_i much higher than T_e, the ion temperature increases largely. It is implied that the plasma enters into the hot ion mode of reduced transport.

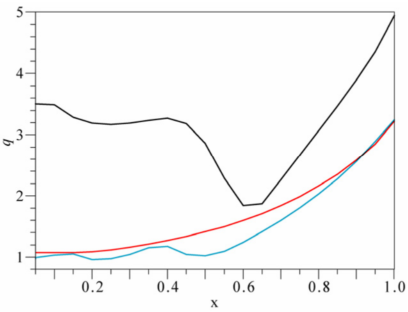

Fig. 2 q-profiles for discharge of optimized current profile (black), conventional discharge (red) and discharge of hybrid configuration (blue).

The energy variation of the beam particles can be described by the following energy loss equation [9] when $v_e >> v_b >> v_i$ (where v_b is the injected ion velocity, v_e and v_i are the electron and ion thermal velocity, respectively),

$$\left\langle \frac{dE_b}{dt} \right\rangle = -2\pi Z_b^2 e^4 \ln\Lambda \left[\frac{A_b}{W} \sum_j \frac{n_j Z_j^2}{A_j} + \frac{4}{3\sqrt{\pi}} \frac{E_b^{1/2}}{T_e^{3/2}} \left(\frac{A_e}{A_b} \right)^{1/2} n_e \right] + Z_b e E_{//} - F_{ed} \qquad (1)$$

where E_b is energy of the injected particles, A_b, A_j, and A_e are the atomic weights of the injected ions, plasma ions, and electrons, respectively, n_j and n_e are densities of the plasma ions and electrons, respectively, and Z_b and Z_j are the charge numbers of the injected ions and plasma ions, respectively. $E_{//}$ is the magnitude of the average Ohmic field parallel to the injected ion trajectories, and F_{ed} is the average drag force on the injected ions exerted by the drift component or current-carrying component of the electron distribution. In a homogeneous plasma with a single ion species, the attainment of steady-state resistive current flow implies that the force, F_{ed}, on an injected ion of the same species is balanced by the Ohmic heating field, $E_{//}$. We restrict our considerations to the case in which the cancellation of $ZeE_{//}$ and F_{ed} is valid. For this case, equation (1) can be written

$$\langle dE_b / dt \rangle = -g_i / E_b - g_e E_b^{1/2} \qquad (2)$$

where $g_i = \sigma_i A Z^2 \ln\Lambda \sum n_j Z_j^2 / A_j$, $g_e = \sigma_e Z^2 n_e \ln\Lambda / (A^{1/2} T_e^{3/2})$, and $\sigma_i = 1.30\times10^{-13}$, $\sigma_e = 2.28\times10^{-15}$ when E_b and T_e are in eV. In the right-hand of equation (2), the first part is the beam particle energy lost to the bulk ions, and the second part is that lost to the electrons. If we consider the beam particles of energy E_b which undergo complete thermalization, then the average fraction of the total energy given up by the beam particles, which goes into the bulk ions of the plasma, is

$$F_i = \frac{2}{H(T_e)} \left[\frac{1}{\sqrt{3}} \left(\tan^{-1} \frac{1}{\sqrt{3}} + \tan^{-1} \frac{2\sqrt{H(T_e)} - 1}{\sqrt{3}} \right) - \frac{1}{6} \ln \frac{[1+\sqrt{H(T_e)}]^2}{1-\sqrt{H(T_e)} + H(T_e)} \right] \qquad (3)$$

with $H(T_e) = \left(\frac{A^{3/2}}{n_e} \sum_j \frac{n_j Z_j^2}{A_j} \right)^{-2/3} \frac{E_b}{14.8 T_e}$. The average time, t_d, required for slowing the injected ions of energy E_b down to thermal energy, is approximately

$$t_d = \frac{\tau}{3}\ln[1+(E_b / E_b^{(c)})^{3/2}], \quad (4)$$

where $\tau(s) = 6.27\times10^8 A T_e^{3/2}/(\ln\Lambda Z^2 n_e)$, and $E_b^{(c)}$ is a critical value of the beam particle energy at which the loss rate of energy to the electrons and to the ions is equal.

$$E_b^{(c)} = 14.8 T_e \left[\frac{A^{3/2}}{n_e}\sum \frac{n_j Z_j^2}{A_j}\right]^{2/3}. \quad (5)$$

Thermalization of the beam ions due to collisions shows that the average fraction of the total beam particle energy that goes into the bulk ions increases with T_e increasing. It seems that the large increment of T_i during LH heating is relevant to the increase of T_e caused by the LH heating. Nevertheless, as shown in Fig. 3, the NBI power losses during the energetic particles slowing-down, including the power losses caused by the TF ripple, charge-exchange, and the beam power shone through, increase in the LH heating phase, while the power losses due to thermalization of the beam ions and the orbit loss are nearly unchanged. Accordingly, not only fraction of the NBI power going into the bulk electrons is reduced largely during LH heating, as expected, that going into the bulk ions decreases as well [Fig. 3(b)]. The NBI power that goes directly into the bulk ions and the power introduced by thermalization of the beam ions compose the ion heating power, and it is reduced obviously in the LH phase. For the low density plasma, the effect of electron-ion equipartition is negligible. Therefore, compared to the discharge with the LH heating only, in the NBI heating discharge the large increment of T_i during the LH heating should be caused by improvement of the ion channel confinement. This is consistent with the advantage of decreasing the plasma transport in the hot ion regime.

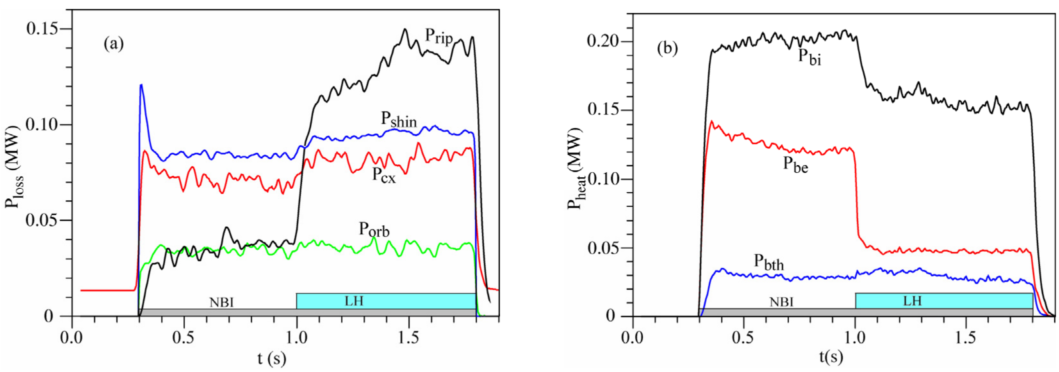

Fig. 3 (a) NBI power losses versus time, and (b) NBI heating power. P_{bi} is the NBI power that goes into ions, P_{be} the NBI power that goes into electrons, P_{bth} the power from thermalization of the beam ions, P_{cx} the NBI power lost by charge-exchange, P_{rip} the NBI power loss due to ripple, P_{shin} the NBI power shone through, and P_{orb} the orbit loss power of the beam ions.

3 Stochastic rippling loss of energetic particles

The loss of perfect axisymmetry caused by the TF ripple modifies the banana orbit. As particle moves about along the banana orbit it conserves energy, and magnetic moment, which causes variation of the particle velocity. This velocity variation diverges at the banana tip where the parallel velocity is zero, and it modifies the time spent near the tip when particle moves along the banana orbit. Consequently, the variations of the poloidal velocity coupled with the usual ∇B drift cause net excursions across the magnetic surfaces. The radial excursion is taken to be [10]

$$\Delta r = \sqrt{\frac{q|\sin\theta_t|}{\varepsilon N}} D(\eta, \zeta_{ts}) \qquad (6)$$

where N is the number of toroidal field coil, ε the inverse aspect ratio, q the safety factor, θ and ϕ the poloidal and toroidal angle in a tokamak configuration, $\zeta = N\phi$ with ζ_{ts} used to parameterize the ripple phase of a banana orbit, and $\eta = \varepsilon \sin\theta_t / Nq$ which is a very small quantity. $D(\eta, \zeta_{ts})$ is a dimensionless displacement. For small η,

$$D(\eta, \zeta_{ts}) = \int_{\zeta_{ts}}^{\infty} \frac{1}{\sqrt{(\zeta - \zeta_{ts})}} d\zeta - \int_{\zeta_{ta}}^{\infty} \frac{1}{\sqrt{(\eta\zeta - \eta\zeta_{ta} + \delta \sin\zeta)/\eta}} d\zeta \qquad (7)$$

where δ is the toroidal field ripple (TF ripple). $D(\eta, \zeta_{ts})$ is sinusoidal with respect to ζ_{ts}, and can be approximated to be

$$D(\eta, \zeta_{ts}) = (\pi^{1/2}/\eta)\delta\cos(\zeta_{ts} + \pi/4) \qquad (8)$$

Thus the radial excursion of a banana turning point after a single bounce is $\Delta r = \Lambda \cos(\zeta_{ts} + \pi/4)$ with the step-size

$$\Lambda = (q/\varepsilon)^{3/2} (\pi N / \sin\theta_t)^{1/2} \delta \qquad (9)$$

The difference in the step-size values between consecutive turning points causes non-closure of banana orbits, which, for small values of Λ, results in a complicated vertical motion of the banana tip on consecutive bounce. This vertical motion is determined by two periodicities, e.i. the toroidal periodicity of ripple field and the periodicity of the banana procession motion, and it is essentially periodic, and does not lead to losses. If the step-size, Λ becomes large, however, it will lead to decorrelation of the banana orbit causing stochastic ripple diffusion. By a composite of the Chirikov stochasticity criteria the threshold for stochastic ripple diffusion is obtained by Goldston, White and Boozer [11]

$$\delta_s = (\varepsilon / N\pi q)^{3/2} (\rho_i |q'|)^{-1} \qquad (10)$$

where ρ_i is gyro-radius of the NBI ions at the banana tip. If the TF ripple exceeds the threshold δ_s, energetic particles are subjected to banana orbit diffusion.

Monte Carlo technique is used to calculate neutral beam injection with artificial acceleration of pitch angle collisions relative to the banana bounce time. In the TRANSP simulation, Monte Carlo ions are followed so that at each bounce point the TF ripple is compared to the threshold δ_s. The TF ripple $\delta(R,Z)$ generated by 16 D-shaped coils in HL-2A is calculated. Contours of the TF ripple are of elongated D-shape as shown in Fig. 4 where the red circle indicates the plasma boundary. Once beam neutrals are ionized in the plasma, the guiding center orbit equations are integrated during the slowing down process to find where the energy and thermalized ions are deposited in the plasma. If $0.5\delta_s / \delta > 1$ (where a factor 0.5 is added by comparison with the guiding center code simulations) at an ion's bounce point, it is declared ripple lost and immediately deleted from the calculation, unless this is a first orbit loss. The occurrence of an ion bounce point is

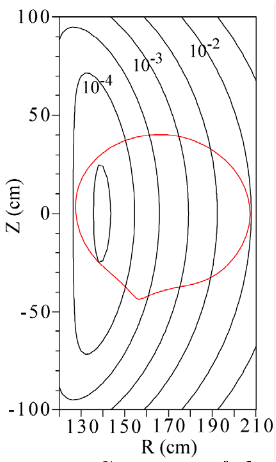

Fig. 4 Contour of the TF ripple in HL-2A. Red line is the plasma boundary

identified when $v_{//}/v$ changes sign in the laboratory frame. Total ripple loss particle number and energy are calculated. The TF ripple array $\delta(R, Z)$ for HL-2A is used in evaluating the $0.5\delta_s/\delta>1$ criterion by making bilinear interpolations of the logarithm of the ripple field.

The stochastic ripple diffusion of the energetic particles in the NBI heating discharge with optimized q-profile as achieved above is calculated. The ripple loss fraction of the captured NBI power is rather large. It can be up to more than 25% (black line in Fig. 5) in the RS phase (t=1.0-1.8s). To show the effect of q-profile on the ripple loss, a conventional tokamak discharge is established with the same NBI injected into a target plasma of I_p=400kA, B_T =2.43T, and $\bar{n}_e = 1.0\times10^{19}\,m^{-3}$. To keep the slowing down of the NBI particles similar as that in the discharge with optimized q-profile, ECRH is used at t=1.0-1.8s to keep the average T_e being the similar value as in the optimized q-profile discharge. In the conventional discharge a monotonic q-profile with q_a=3.2 an $q_0\geq1.0$, is formed (red line in Fig. 2). For the conventional discharge the ripple loss fraction of the captured NBI power is nearly an order of magnitude less than that in the optimized q-profile discharge (red line in Fig. 5). We evaluate the stochastic diffusion threshold for the energetic ions of initial velocity in the plasma cross-section to depict the stochastic ripple loss region (fig. 6). For the configuration of optimized q-profile, the stochastic domain where $0.5\delta_s/\delta>1$ occupies more than half of the plasma cross-section excluding some small islands. For the conventional tokamak configuration, however, the stochastic domain is a narrow region on the low field side. The much higher ripple loss in the optimized q-profile discharge can be attributed to two reasons. One is the wider stochastic domain that is formed due to higher q value and low magnetic shear in the central plasma region. Another is that the stochastic domain located in the center encircles the magnetic axis, and the loss region on the strong field side makes it is possible that the barely trapped particles, which are easily formed in the case of tangentially neutral beam injection, are lost due to stochastic ripple diffusion.

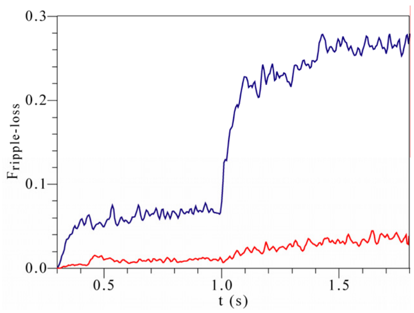

Fig. 5 Ripple loss fraction of the captured NBI power in discharge with optimized q-profile (blue), and conventional configuration (red).

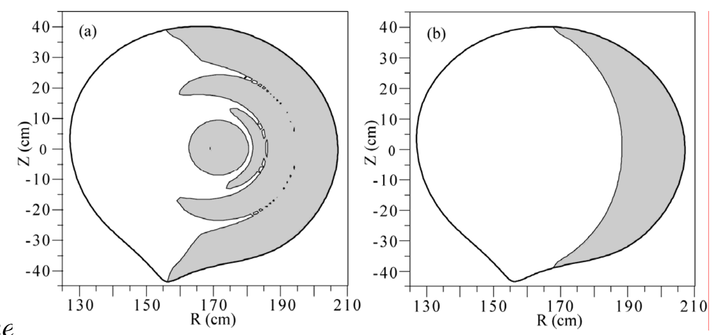

Fig. 6 Stochastic ripple loss domain (shaded area) in plasma with (a) optimized q-profile, and (b) conventional tokamak q-profile.

As the stochastic ripple loss is caused by banana orbit diffusion, it is related to the slowing down process of the energetic particles. To investigate the characteristics of the stochastic ripple loss during the energetic particle slowing down, we use NBI of higher injecting particle energy (E_b=50keV) to heat higher density plasma of I_p=300kA, B_T=2.8T, and $\bar{n}_e = 2.32\times10^{19}\,m^{-3}$. In this discharge 1.6MW NBI is injected during t=0.3 – 1.8s, then LH wave is injected at t =1.0 – 1.8s to heat electrons. Similar optimized q-profile as produced above is obtained. As shown in Fig. 7, the factor of the ripple loss fraction of the injected NBI particles against that of the injected NBI power, K_{sp}, is much higher than unity showing that the most of fast particles are lost during their slowing down. We study different neutral beam injection scenarios while keeping the average T_e nearly the same in all the scenarios (Fig. 7). As the energy of injected particles E_b =50keV changes to E_b =20keV or T_e increases in the LH heating phase, K_{sp} decreases. Decreasing E_b and/or increasing T_e will cause stronger interaction between the beam ions and the bulk ions (Equation 3), and only collisions with the bulk ions can change the beam ion momentum effectively. Therefore, more beam ions become trapped at their initial injecting phase subjecting to probability of stochastic ripple diffusion when E_b decreases and/or T_e increases. The injecting angle of beam line affects the stochastic ripple loss as well. We use tangency radius of the beam line, R_t (defined as major radius of the tangential point of the beam line with respect to the toroidal field line) to indicate the injecting angle of beam line. Compared with the case of R_t =1.24m, K_{sp} increases in the case of R_t =1.64m (Fig. 7) because less injected particles become trapped in the case of more tangential injection.

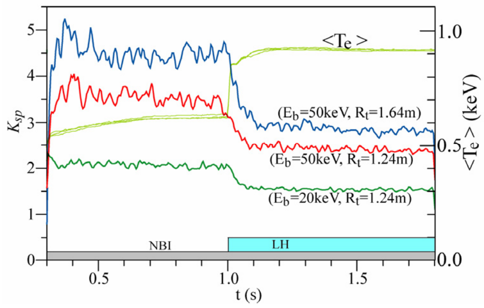

Fig.7 K_{sp} versus time for different NBI scenarios. <T_e>, the volume average T_e for the different scenarios.

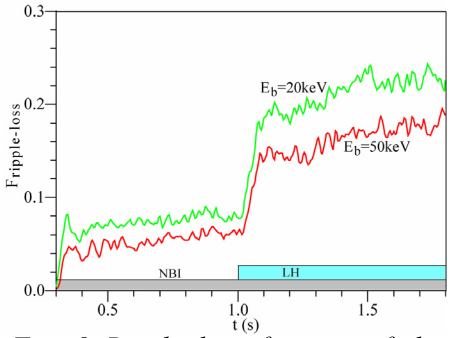

Fig. 8 Ripple loss fraction of the captured NBI power for the case of E_b=50keV (red), and E_b=20keV.

Since the lost particles are richer in ones of relatively higher energy in the case of lower E_b, even though ρ_i is smaller in this case, the ripple loss fraction of the captured NBI power is larger than that for the case of higher injected particle energy (Fig. 8). The analysis on the energy variation of the injected beam ions shows that the electron temperature T_e governs the slowing down process. To study the effects of T_e on the stochastic ripple loss, we heat the plasma by using ECRH to increase T_e while keeping the similar q-profile. As shown by the inserts in Fig. 9, the stochastic domain after ECRH at t =1.2s does not become larger (even the domain in center becomes a little bit smaller) than that before ECRH at t=0.95s. However, the increase of T_e due to the EC heating boosts up the interaction of the injected NBI ions with the bulk ions. Therefore the ripple loss fraction of the captured NBI power increases significantly in the ECRH phase (Fig. 9).

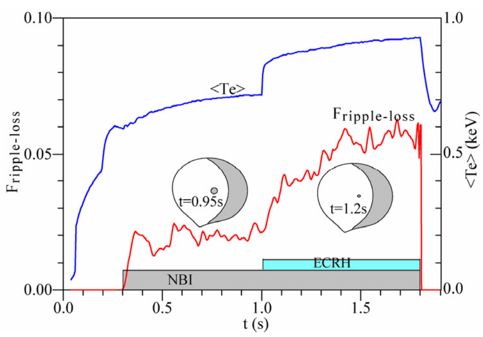

Fig. 9 Average T_e (blue), and ripple loss fraction of the captured NBI power (red). Inserts show the stochastic domains before ECRH (t=0.95s) and after ECRH (t=1.2s).

Hybrid scenarios have been produced under dominant electron heating in HL-2A [12]. Here, a hybrid configuration is established in NBI heated plasma with the plasma current profile controlled by LHCD. For this configuration the q-profile (blue line in Fig. 2) shows that it is of weak shear in the plasma center and q is lower than that in the conventional configuration. Thus the stochastic domain will not exceed the stochastic domain in the conventional tokamak configuration.

4 Conclusions

The NBI heated discharge is modeled with TRANSP under the HL-2A condition. LH wave with a nearly symmetric power spectrum is injected into the NBI heated plasma to control the current profile and elevate the electron temperature. Due to the off-axis driven current and electron heating, an optimized q-profile, of which the magnetic shear is weak in the central region and negative in the mid-plasma region (x~0.5-0.65), is formed. Accordingly an ITB is developed because of the shear reversal, and plasma enters into a hot ion mode of enhanced confinement.

The ripple loss of energetic particles is studied by using the Golaston-White-Boozer threshold for stochastic ripple diffusion. In the configuration with the optimized q-profile ripple loss fraction of the captured NBI power is rather large (>25%) with more than half of the plasma cross-section occupied by the stochastic ripple loss domain excluding some small islands. In the conventional tokamak configuration of monotonic q-profile, however, the stochastic domain is only a narrow region on the low field side, and the ripple loss is roughly an order of magnitude less than that in the configuration with the optimized q-profile.

The factor of the ripple loss fraction of particles against that of energy, K_{sp}, is much higher than unity showing that the most of particles are lost during the slowing down of the injected ions. K_{sp} is dependent on E_b, T_e, and the injecting angle of neutral beam line. With NBI of lower energy, the ripple loss fraction of the captured NBI power is larger than that for the case of higher NBI energy because the lost particles are richer in ones of relatively higher energy in the case of lower NBI energy. Since increasing T_e boosts up the interaction of the injected NBI ions with the bulk ions, the ripple loss fraction of the captured NBI power increases as T_e increased.

In the NBI heated discharge hybrid scenario is produced by profile control with LHCD. Enclosing a large volume of low magnetic shear with q_0 near 1.0 in this configuration, the stochastic domain can not exceeds that in conventional tokamak configuration

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