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Comparison of neutral particle flux decay times on the NBI plasmas in Large Helical Device

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We compare the decay times of charge exchange neutral particle fluxes in various NBI plasmas after switching-off NBI by using the Compact Neutral Particle Analyzer in Large Helical Device. Here the decay times at co-, counter and perpendicular injections are observed at the magnetic axis of R_{ax}=3.65. The decay times are determined mainly by the electron drag in tangential NBI. The decay time decreases by the weak magnetic field same as the simulation. The decay time at the perpendicular beam NBI is several – ten ms, which is less than one tens of that at the tangential injections. The decay time determined by the ion-ion collision, which is the main process of the energy loss and the pitch angle scattering at the injection energy of 40 keV, is about 10-20 ms. The observed decay times are still several times smaller than those values. The results are compared with the results from Angular Resolved Multi-Sight line neutral particle.

Keywords: Loss cone, Chaotic region, Decay time, Compact Neutral Particle Analyzer, Angular Resolved Multi-Sight line neutral particle analyzer, LHD, NBI

1. Introduction

Helical Devices have plasma stabilities even if the plasma density is high, because the magnetic field to confine the plasma is created by the external coil current. Recently the high-density scenario [1] toward the achievement of Lawson criterion for the nuclear fusion has been proposed in Large Helical Device (LHD) [2]. In this scenario, the heat load at the first wall can be reduced because the plasma temperature can keep low although the plasma density is extremely high. However the loss particle in loss region, which reduces the plasma quality and damages the first wall, still remains in helical devices. In LHD, the loss cone is minimized by the magnetic configuration so as there is no loss cone within one third of the minor radius [3] at the high magnetic field and at the inner magnetic axis shift. In this design, all particles outer from the last magnetic surface are assumed to be lost. In real, some particles re-enter to the plasma although partially particles are lost by the enhanced charge exchange at the outer region of the plasma. There is also the chaotic region near the last magnetic surface, which consists of the un-closed magnetic field line [4]. The chaotic region actually can be relax the particle loss because the particle in this region can be alive with longer life-time than in the loss cone.

From previous experiments in LHD, the loss cone is not serious for the high-energy particle confinement at the strong magnetic field and at inner magnetic shift indirectly by observation and simulation. Actually the energetic particle over 1 MeV, can be observed on the ion cyclotron heating plasma. This fact means there is not a big loss cone in LHD. Perpendicular neutral beam heating (NBI) [5] is applied to the perpendicular direction against the magnetic axis, where is near the loss cone (of the traditional prediction). However the NBI heating is successfully performed if the base plasma exists.

The decay times of the neutral flux can provide to understand the loss mechanism indirectly. Here we discuss them at the switching-off the heating on different NBI directions. Each beam is individually used instead of the beam modulation overlapped base plasma [6] in order to obtain clear signals. The decay time consists of the classical atomic process and another loss mechanism. Therefore quick decay time may be due to additional loss mechanism. We also measure the loss cone directly by the Angular Resolved Multi-Sight line neutral particle analyzer (ARMS). The results are compared each other.

2. Experimental Apparatus

LHD has a toroidal mode number of m=10, and a helical mode number of l=2. The major and minor radius are 3.9 m, 0.6 m, respectively. The helical ripple is 0.25 and the magnetic field is a maximum of 3 T. Although the standard magnetic axis is 3.75 m, it can be changed from 3.4 m to 4.1 m by applying a vertical magnetic field. The maximum electron temperature of over 10 keV can be observed by using Thomson scattering and electron cyclotron emission. The electron density can be changed

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from 0.01 to 1×10^{21} m^{-3}. The density profile is measured with a multi-channel interferometer [7]. The stored energy is monitored by a magnetic probe.

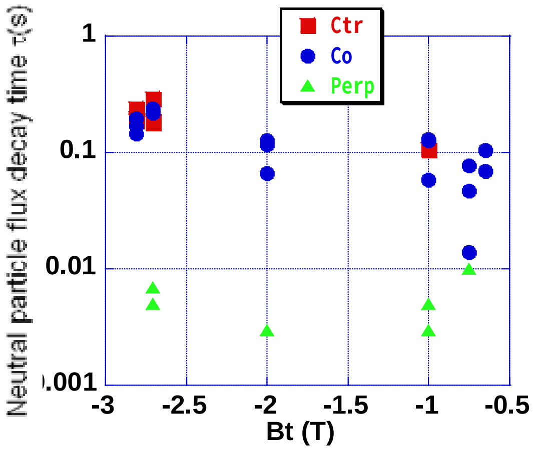

Fig. 1. The magnetic field dependence of the neutral flux decay time at R_{ax}=3.65 m. Ctr, Co and Perp mean the NBI injection direction against the magnetic field, counter, co and perpendicular, respectively.

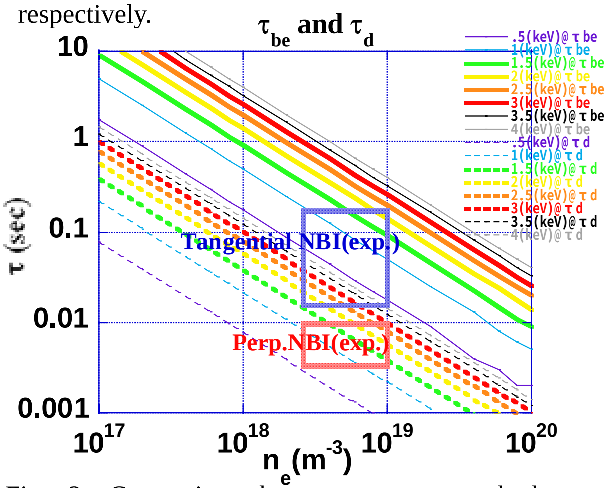

Fig. 2. Comparison between τ_{be}, τ_d and the experimental results. τ_{be} and τ_d can be obtained from eqs. (1)-(4).

Time and energy resolved charge exchange neutral particle is measured by the Compact Neutral Particle Analyzer (CNPA) [8], which is installed in the perpendicular direction against LHD plasma near the mid-plane. CNPA is a traditional E//B particle analyzer with a diamond-like carbon film as a stripping foil, a permanent magnet for the energy analysis of particles and condenser plates for particle mass separation. Mainly hydrogen ions with the energy range from 0.8 to 168 keV can be observed using 40 rectangular channeltrons.

It is determined that the spatial resolution is 5 cm using several apertures in the neutral particle flight. Time resolution is set to be 0.1 ms.

ARMS is the silicon detector with different sight lines of 20 channels. It has the energy range from 20 keV to 1000 keV with the energy resolution of few keV. The time resolution is 5 ms. A detail specification of ARMS is mentioned in the reference [9].

3. Experimental Results (CNPA)

In experiments, the NBI plasmas are created at the same magnetic axis and various magnetic fields. The neutral particle flux is observed by CNPA when the NBIs#1-4 are applied. NBI#1 and #3 have the same tangential direction. NBI#2 is also a tangential injection although it is different direction from NBI#1 and 3. NBI#4 is a perpendicular direction. Here we compare the neutral particle flux decay times when the co-, counter and perpendicular NBIs are applied at the magnetic axis of R_{ax}=3.65 m. In simulation, the chaotic region is minimized and the energetic particle is well confined at R_{ax} =3.65 m [4]. The decay time of the neutral particle flux with a certain energy, which is originated from NBI, is determined by the electron drag (at the high energy region), the charge exchange loss (at the middle and low energy regions), the pitch angle dispersion (which is occurred in low energy region), and the orbit loss in the loss cone or chaotic region. Former three effects may be independent on the injection direction of NBI. Therefore if there is large discrepancy of the decay times between the tangential and perpendicular injections, the orbit loss is the most probable candidate of the loss mechanism.

Figure 1 shows the decay times in different magnetic fields. The difference between the beam directions can be found clearly. The energy loss time due to the electron drag τ_{be} is given by [10]

$$\tau_{be} = \frac{3\pi\sqrt{2\pi}\,\varepsilon_0^2 m_b T_e^{3/2}}{n_e Z_b^2 e^4 \sqrt{m_e}\,\ln\Lambda}, \qquad (1)$$

where, ε_0, m_b, m_e, T_e, n_e, Z_b, e and lnΛ are the permittivity in vacuum, the beam ion mass, the electron mass, the electron temperature, the electron density, the beam charge state, the electron charge and the Coulomb logarithm, respectively. If the experimental parameters are chosen, the decay time is almost agreed with the energy loss time by the electron. This means the decay of the neutral particle is determined by the electron drag. When the magnetic field increases, the decay times in the tangential NBIs also increase. Two possibilities are proposed. One candidate is that the electron temperature is high because the good particle confinement can be achieved in the high magnetic field. Another possibility is that the chaotic region is narrow in the high magnetic field.

In the perpendicular NBI case, the decay time is from several ms to 10 ms. Here maximum injection energy is 40 keV. Therefore the ion-ion collision is essential for the energy relaxation and the pitch angle scattering. The neutral particle from the tangential NBI has uniform angular distribution when the particle injects to the CNPA. However we must be aware of the escape from the sight line because the sight line of CNPA is also perpendicular. The energy loss time τ_{bi} by the ion-ion collision is given by [10]

$$\tau_{bi} = \frac{2\pi\varepsilon_0^2 A_b A_i m_p^2 V_b^3}{n_i Z_i^2 Z_b^2 e^4 \ln\Lambda}, \quad (2)$$

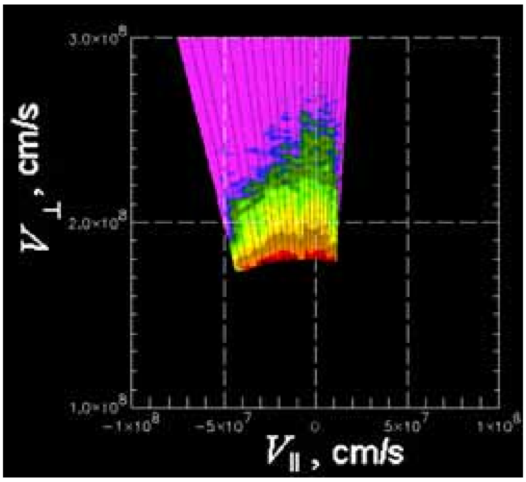

Fig. 3. The ARMS signal in NBI#4 plasma. The intensity of the flux is colored. The analyzer is covered from 70 to 100 degrees of the pitch angle.

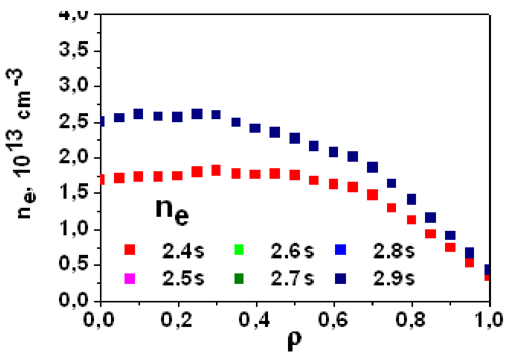

Fig. 4(a). Plasma density profiles at the tangential NBI experiments. The penetration depth of the background neutral depends on the plasma density.

where A_b, A_i, m_p, V_b, n_i and Z_i are the beam mass number, the plasma ion mass number, the proton mass, the beam velocity, the plasma ion density and the plasma ion charge state, respectively. For typical plasma parameters, the energy loss time by the plasma ion τ_{bi} is 100 ms. The value is too large than the experimental value. The ion-ion collision time τ_{ii} for occurring the pitch angle is given by [11]

$$\tau_{ii} = \frac{25.8\sqrt{\pi}\varepsilon_0^2\sqrt{m_i}T_i^{3/2}}{n_i Z_i^4 e^4 \ln\Lambda}, \quad (3)$$

For typical plasma parameters, ion-ion collision time τ_{ii} is about 10 ms, which is smaller than τ_{bi}. This means the decay of the perpendicular NBI is determined mainly by the escaping from the sightline due to the ion-ion collision. Therefore the decay time τ_d is defined by the convolution of those times as,

$$\tau_d = \frac{1}{\tau_{bi}^{-1} + \tau_{ii}^{-1}}, \quad (4)$$

The perpendicular injected particle is lost from the sight line with the ion-ion collision time, and decays with the beam-ion decay time. The observed decay time is still slightly small than the calculation value.

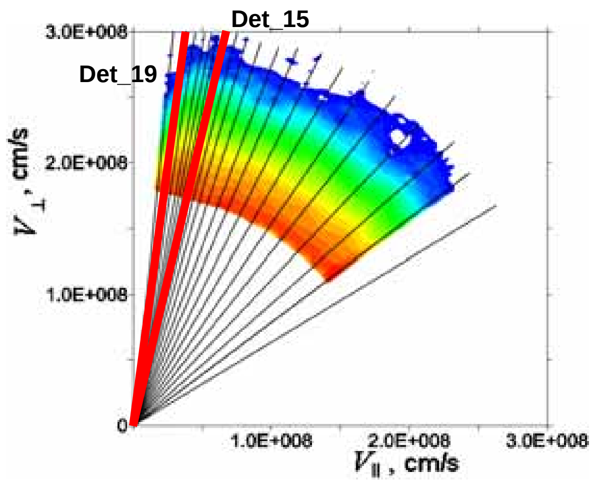

Fig. 4(b). The ARMS signal in tangential NBI plasma. To study the loss region, we compare two signals of the different chords, No. 15 (non-loss), No. 19 (loss).

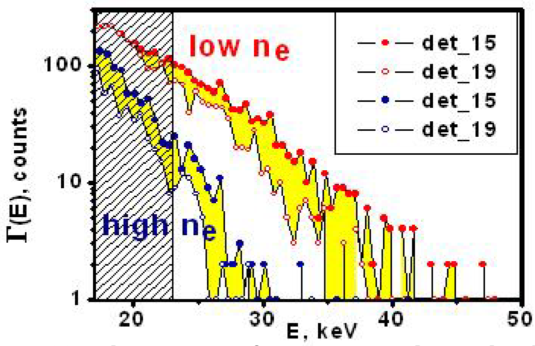

Fig. 4(c). The spectra of ARMS signals in chords, No.15 and No.19. The spectra of two different chords are compared at the high- and low-density case. At less than 30 keV, the particle loss is large in the high-density plasma.

Figure 2 shows the comparison between the calculation of τ_{be} (strait lines) and τ_d (broken lines) obtained from eqs. (1)-(4) and the experimental results. The experimental data areas are shown by the rectangular in Fig. 2. In τ_{be} and τ_d, the experimental decay times both in the tangential and perpendicular NBIs are smaller than the calculated values. However it is not true that the most of particles are lost in the classical loss cone because the loss time should be several μs if there is a large loss cone. . The particle loss from the classical loss cone or chaotic region is not so large especially in the high magnetic field.

4. Experimental Results (ARMS)

Figure 3 shows the neutral particle angular distribution around the pitch angle of 90 degrees obtained by ARMS when the perpendicular NBI is applied. The horizontal and vertical velocities of the neutral particles are on the horizontal and vertical axes. Therefore the radial axis means the particle speed. The logarithmic flux of the particle is colored.

In Fig. 3, the flux near 90 degrees is observed slightly intensive but broad because the NBI is applied to the perpendicular direction. This means the trapped particle near 90 degrees is well confined. The particle, which is injected to the perpendicular, is decreasing its energy and pitch angle by the ion-ion collision. In decreasing of the total particle flux over 15 keV at the pitch angle of 85 degrees or less, the effect from the loss cone or loss from the chaotic region may be involved. The uniform angular distribution can be obtained from short ion-ion collision time of 10 ms.

Figure 4 shows the pitch angle distribution when the tangential NBI is applied. When the tangential NBI is applied, the beam energy decreases by the electron drag, it has the large pitch angle at the low energy by the beam ion collision. Therefore the angular distribution of the beam is uniform at the low energy. However we find that the beam with the pitch angle over the 85 degrees strongly decreases (dent) from the measurement by ARMS. This suggests there is the loss region around there.

It is very important to know where is the loss region and it is serious or not. For this purpose, we check the change of the dent near the pitch angle of 85 degrees by the plasma density. Figure 4(a) shows the density profiles of two different discharges with same NBI heating. Here we assume that the dent is due to the particle loss from the loss region. Usually the dent should change by the electric field in the plasma. The negative electric field enhances the loss, this means, makes deep dent. If the plasma density is high, the electric field becomes negative [12]. Therefore the dent should be deep. But the dependence between the density and electric field is not so strong at the density over 10^{-19} m^{-3}. Actually at Fig. 4(a), the electric fields may be almost the same. On the other hand, the flux will decrease because the background neutral, which is source of the charge exchange, cannot invade to the plasma at high-density case. The fluxes at the high and low-density plasmas come from the plasma outer and the whole region, respectively. Therefore by the comparison of the flux from between the high- and low-density plasma, we can estimate where the charge exchange occurs. Figure 4(b) shows the spectra of two different sight lines at the high and low-density plasmas. At one sight line (No.15), the energetic particle is well confined. Another sight line (No. 19) reflects the loss region. We compare the discrepancy between the No.15 and No.19 at the high- and low- density plasmas. The discrepancy at the high-density plasma is larger than that at the low-density plasma. This means that the loss region is localized at the outer plasma. According to Aurora code calculation [13], the penetration depth of the background neutral is changed at ρ=1/3. Therefore there may be the loss region out of ρ=1/3 same as the original design of LHD.

5. Summary

We compare the flux decay times from CNPA at the end of NBIs. In co- and counter- tangential NBIs, the decay times are determined by the electron drag. The decay time is smaller than the escaping time from the sight line, which is determined by the ion-ion collision. But it is long enough than the specific time by the loss cone. This means part of the particles are lost. For checking this, we observe the angular distribution of the neutral flux by using ARMS. The loss region can be seen near 85 degrees. To specify the position of the loss region, we compare the angular distributions at different density plasmas. The loss region may be localized near the plasma edge. This means the loss region is not serious especially at the high magnetic field.

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