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Temperature, Density, Magnetic Field and Pitch Angle Dependence of Neutral Particle Spectrum in Large Helical Device

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Abstract

In a helical device, the particle loss by the resonance between the ∇B drift and the $\boldsymbol{E} \times \boldsymbol{B}$ drift is well known as a resonant loss. The behavior is observed as a dip in the charge exchange neutral particle spectrum. It is not easy directly nor experimentally to observe the loss cone itself, which is the characteristic effect in the helical device, because it appears in the velocity space. However the experimental observation of resonant loss suggests the evidence of the loss cone. The depth of the dip is strongly dependent on the electric field. It is difficult to observe in an NBI plasma in LHD since the NBI is tangentially injected in order to avoid inserting of the particles in a loss cone region. Since an electron is strongly heated by ECH at low plasma density, the positive electric field can be easily obtained. Therefore it is easy to observe a change of the spectrum by the strength of ECH power. In this paper, the dependence of the resonant loss on the density, the temperature, the magnetic field, the magnetic axis and the pitch angle is clarified. According to the present analysis, the dip in the spectrum becomes deeper with the outer shift of the magnetic axis. The dependence of the dip depth on the density or temperature, *i.e.*, the electric field is in accord with theoretical prediction.

Keywords:

resonant loss, loss cone, electric field, helical ripple, time-of-flight neutral particle analyzer

1. Introduction

On helical devices, particle orbits in plasma are very complicated due to the magnetic field ripple. The particle is trapped by the helical or/and the toroidal ripples. When these orbits are drawn in velocity space, some particles with large pitch angles are lost. This phenomenon is known as a loss cone and it express well the features of particle confinement in helical device. One of the main subjects in helical devices and the future fusion reactor with the helical system is, how this loss cone can be reduced. This phenomenon can be reduced by the control of the magnetic configuration, the heating method and the electric field *etc*. In the Large Helical Device (LHD), the device design is devised so that the loss cone at ρ (radial position on the magnetic surface) < 1/2 may not exist. Moreover, most of the particles heated by tangential NBI (Neutral Beam Injection) do not have a pitch angle perpendicular to a magnetic field. However, if the slowing down of the incident particle by electron collision occurs, not only in ICH (Ion Cyclotron resonance frequency Heating) heating but also in NBI heating, the particle with a large pitch angle actually will be generated due to the scattering between the particle and a plasma ion at several times the plasma temperature. These particles cause the drift motion and rotate poloidally. They can almost be confined in the plasma because the energy of these particles is not so large. However part of them are not confined by balance with the electric field $\boldsymbol{E}$. It is known for helical devices that the particle with a specific energy is lost by cancellation of the ∇B drift and the $\boldsymbol{E} \times \boldsymbol{B}$

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drift resulting from the electric field $\boldsymbol{E}$ [1]. This phenomenon occurs at the negative radial electric field. The reason why we are interested in the resonant loss is that we can find it from the dip in the high-energy particle spectra measured by the neutral particle analyzer. (We can find only the decreasing flux in the loss cone, therefore it is very difficult to distinguish the effect of the loss cone from other effects).

2. Theoretical prediction

The conditions under which degradation of confinement occur have been made clear by the theory [2]. The resonance occurs when the following condition is satisfied,

$$\mu B / e\phi = -1 / \varepsilon_h \,, \qquad (1)$$

where, μ, B, e, ϕ and ε_h are the magnetic moment, the magnetic field, the electron charge and the helical ripple, respectively. According to eq. (1), the degradation is strongly related to the helical ripple and the plasma potential (the electric field). Since ε_h is 0.25 in LHD, the equivalent energy is roughly 4 times the potential. Here, we describe how the resonant loss depends on various kinds of plasma parameters, and compared it with theory. The helical ripple increases if the magnetic axis is shifted outward and it will become smaller with an inward shift. If the helical ripple is small, it is inevitably expected that the dip on the spectrum becomes also small since the degree of resonance is small. At positive radial electric field, since resonance for ion cannot take place easily, the dip becomes small too.

To obtain the positive electric field, if all other conditions are same, lower density and higher electron temperature etc. are required [3]. Another way is using the central heating of ECH (Electron Cyclotron resonance frequency Heating). Moreover, pitch angle dependence is also an interesting subject. Theoretically the resonant loss cannot take place for the particle with lower pitch angle. However, the number of particles with lower pitch angle also may be reduced because certain energetic particles with higher pitch angle are lost due to the resonant loss. Here, the high-energy particle spectrum is measured using a neutral particle analyzer, and the resonance loss is shown from the dip on the spectrum. The various plasma parameter dependences of the resonant loss are clarified, and compared with theoretical prediction.

3. Experimental arrangement

The time-of-flight (TOF) type neutral particle analyzer has a large S/N ratio for various kinds of radiation noise from soft X-rays. Its detail and experimental configuration are described in ref. [4]. The analyzer with its driving stage is installed on the plasma mid-plane (port 10-O). As for the position of 10-O, NBI#1 and NBI#2 are installed at the right and left sides of the analyzer sight line, and especially the beam path of NBI#1, which crosses the sight line near the plasma center, can be expected to generate neutral particles because of charge exchange in the central part of the plasma.

The possible scanning angle is equivalent to the pitch angles from 40 degrees to 100 degrees. The pitch angle in this paper is defined as the angle between the magnetic axis and the sight line, not the actual pitch angle for each particle because it is difficult to find the generation point of each particle. About the vertical scan, it is possible from –12 to +15 degrees. A very high-speed scan of one degree per second in the vertical system is possible since a counter weight is used to compensate the weight of the analyzer (700 kg).

LHD has the toroidal mode number of m = 10 and helical mode number of l = 2. The major radius and minor radius are 3.9 m, 0.6 m, respectively. The helical ripple is 0.25 and a 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. There are three kinds of heating system of ECH (10 MW), NBI (15 MW) and ICH (3 MW). As for electron temperature, a maximum of 10 keV is observed by using Thomson scattering and ECE (Electron Cyclotron Emission). Electron density can be changed from 0.1 to 4×10^{19} m^{-3}. The density profile is measured with the multi-channel interferometer.

4. Experiment results

We start by confirming that the dip on the spectrum is the resonant loss. The number of energy channels in the TOF analyzer is restricted since its merit is compactness. Moreover, the detection efficiency error of each channeltron may produce another dip on the spectrum. Therefore we must consider carefully that the dip on the spectrum means a resonant loss or a problem of the measurement. To make sure of this, we use a spectrum comparison with/without the powerful central ECH in the low-density plasma, just as in Compact Helical System experiments [5,6]. It produces a positive radial electric field. In this way, the drift motion due to the ∇B can be canceled out by the $\boldsymbol{E} \times \boldsymbol{B}$ drift originating from this electric field. As a result, the dip in the spectrum around 5 keV is found as shown in Fig. 1. From the analogy of the CHS experiments, it seems to be the resonant loss. The dip at the energy of 5 keV is consistent with the expected potential value and the energy as which the pitch angle scattering of the NBI particles is dominant. If the slowing down of the incidence particles by electron collision occurs even in the tangential injected NBI, particles with large pitch angle can be actually generated due to the scattering between the particle and plasma ions at several times the plasma temperature (typically 5 keV for the plasma temperature of 1–2 keV).

As mentioned above, since it is assumed that the dip observed near 5 keV is the resonant loss, the comparison of the spectrum for various plasma parameters is performed at this energy. Figure 2 shows the density dependence in the plasma whose conditions are similar. From the results of charge exchange spectroscopy, the electric field in LHD is positive at densities less than about 1×10^{19} m^{-3} and negative at larger [3]. The critical density depends on the magnetic axis position and the plasma temperature. The parameter d on the vertical axis in Fig. 2 is given by eq. (2) as the degree of the dip near 5 keV.

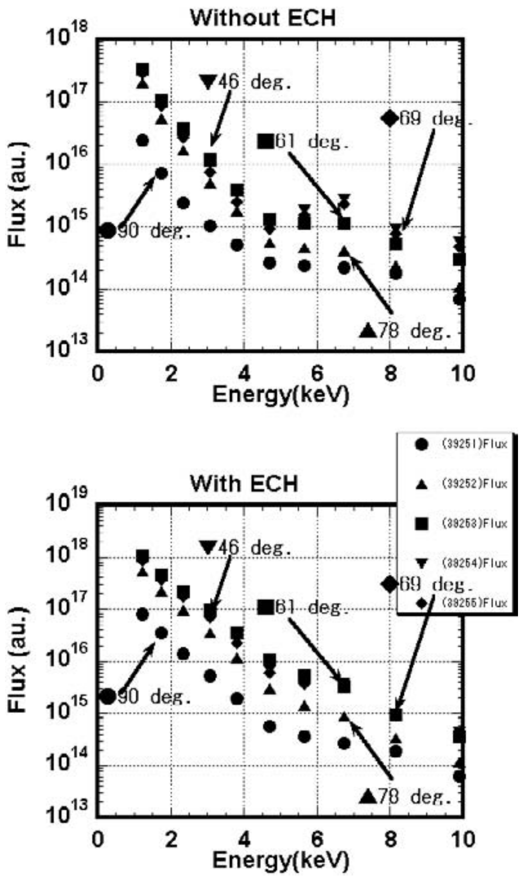

Fig. 1 The spectra without (a)/with (b) ECH.
During ECH, the dip around 5 keV disappeared.

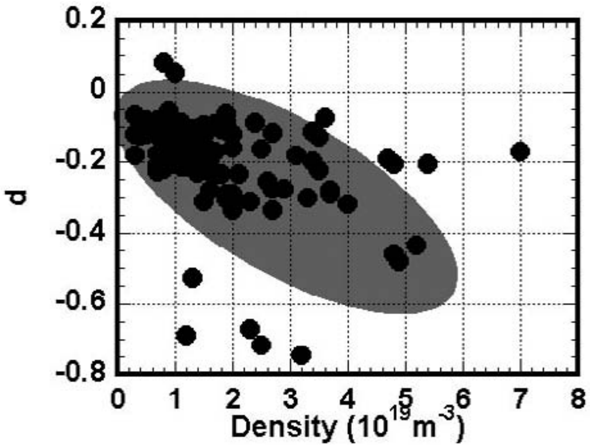

Fig. 2 The density dependence of the dip depth.
The shadow emphasizes the dependence between d and density. Deep dip at high density is due to the negative electric field.

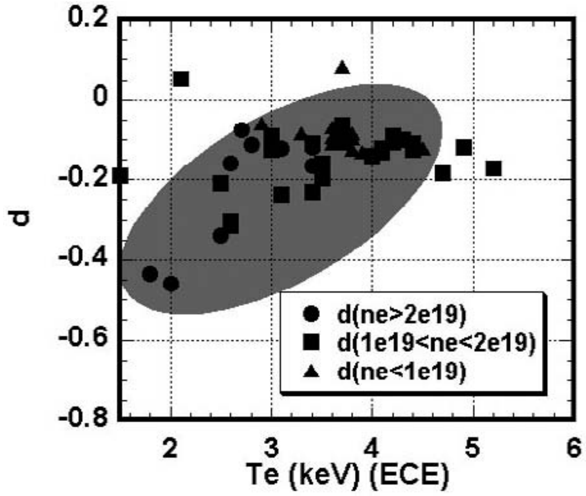

Fig. 3 The temperature dependence of the dip depth.
The shadow emphasizes the dependence between d and temperature. The shallow dip at high temperature is due to the positive electric field.

$$d = \log(Real\ Flux) - \log(Expected\ Flux)\ , \qquad (2)$$

where '*Expected Flux*' is the flux at the dip point, obtained from the polynomial fitted spectrum excluding the flux at the dip. The magnitude of the negative electric field around ρ = 0.9 slightly increases when the density becomes high [7]. This means two things. One is that the resonant energy, at which the ∇B drift compensates the $\boldsymbol{E} \times \boldsymbol{B}$ drift, increases. Another is that if we consider the same energy, the region with the equivalent potential is shifted inward where the background neutral is poor (back ground neutral density decays in the plasma center), that is, the neutral flux at that energy decreases. The extension of the dip at high density can be explained by this effect. Figure 3 shows the dependence of d on the electron temperature in three different density region cases because the electric fields are strongly dependent on the density. When the electron temperature increases, the radial electric field becomes positive. Therefore the dip depth (absolute value of d) decreases as the temperature increase. In the low-density region, the correlation between the temperature and the d looks weak since the electric field is sensitive against the density. Figure 4(a) shows the dependence of d on the magnetic axis position. Plasma parameters also change as a function of the magnetic axis position or the magnetic field strength in many cases. We choose similar plasma parameter shots. When the magnetic axis is shifted outward, the particle loss increases because the helical ripple increases. The increase of the dip depth indicates the effect. If the magnetic axis is shifted outside, although it will become stable in the magnetic hydrodynamics (MHD), from the viewpoint of particle confinement, it is not desirable theoretically. Figure 4(b) shows the dependence of the d against the magnetic field strength. The increase of the dip depth at the lower magnetic field indicates bad particle confinement. Finally, the dependence of the d on the pitch angle is studied as shown in Fig. 5. According to the experimental results, the dependence of the pitch angle is not so remarkable. The typical time scale of the pitch angle scattering T_D^{ii} is

$$T_D^{ii} = 4.53 \times 10^{-3}\ \frac{A_i^{1/2}\ T_i^{3/2}}{Z_i^4\,(n_i/10^{20})\ln\Lambda}\ [\mathrm{sec}]\ , \qquad (3)$$

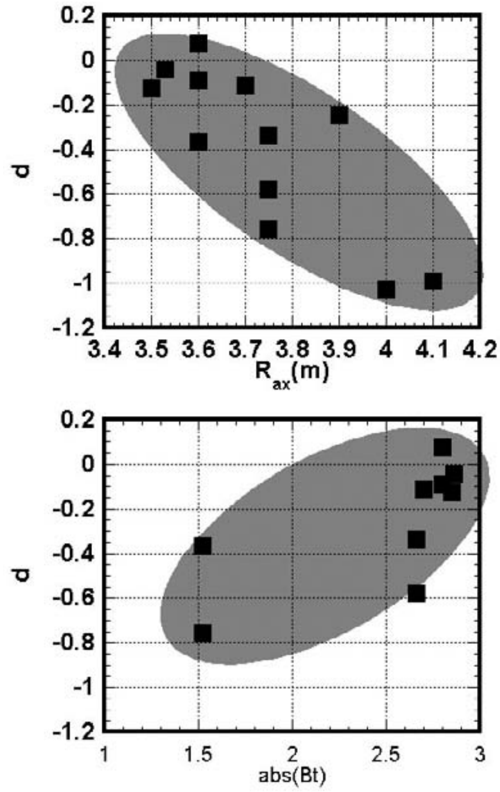

Fig. 4 Magnetic axis dependence (upper) and magnetic field strength dependence (lower).
The shadow emphasizes the dependence between *d* and magnetic axis/ magnetic field. When the magnetic axis is shifted outward, the dip depth becomes extended due to the large ripple.

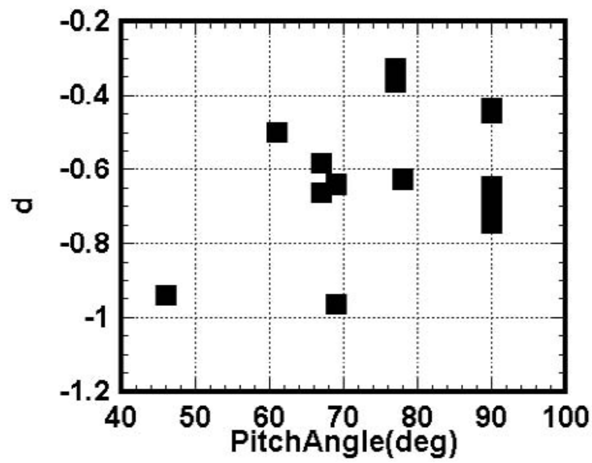

Fig. 5 The pitch angle dependence.
The pitch angle dependence is not so remarkable.

Table I The dependence of /*d*/.
/*d*/ is the amplitude of d given by eq.(2).

	prediction	*experiments*
density	*enlarge*	*enlarge*
temperature	*smaller*	*smaller*
magnetic axis shift	*enlarge*	*enlarge*
magnetic field strength	*smaller*	*smaller*
pitch angle	*enlarge*	*not clear*

where A_i, T_i, Z_i, n_i and $\ln\Lambda$ are the mass number, the ion temperature, the ion density and the Coulomb logarithm, respectively. T_D^{ii} is a few milliseconds for the actual LHD plasma although the NPA detection duration is several tens of milliseconds. Since pitch angle scattering is dominant and reaches equilibrium at the energy of 5 keV, the number of particles with lower pitch angle also decrease if the particle with higher pitch angle are lost.

5. Summary

The resonant loss, which is a certain phenomenon in the loss cone, is studied under various plasma conditions. The results are summarized in Table I. To verify if the dip on the energy spectrum is due to the resonant loss, the comparison of spectra with and without strong ECH has been performed. The dip depth is introduced to compare the strength of the resonant loss. The various dependencies on density, temperature, magnetic axis position, magnetic field strength and pitch angle, have been obtained. The results can be compared with theoretical prediction. However the actual effect of the loss cone on the plasma performance is not so serious in LHD due to the magnetic configuration design and the tangential NBI heating.

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