Horizontal and Vertical Structure of the High-Energy Particle Distribution in Large Helical Device

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There are two neutral particle analyzers, the time-of-flight (TOF-NPA) and the silicon detector (SD-NPA), which are scannable horizontally and vertically. In horizontal scan, it is interesting to measure the pitch angle distribution and to investigate the loss cone feature obtained by it. It is very important to control the trapped particle by the helical ripple to realize the helical type plasma fusion device. Here the charge exchange neutral particle between the high-energy ion and the background neutral is measured to obtain the pitch angle of the high-energy ion in the plasma. Tangential injected NBI heating in long discharge is suitable for this purpose in LHD. The energy of the high-energy ion supplied from NBI decreases by the plasma electron. The pitch angle scattering is occurred by the collision of the plasma ion with several times energy of the electron temperature. Therefore we can easily compare the experimental pitch angle distribution with the simulation result, which is obtained by considering the initial pitch angle distribution and the atomic process. The pitch angle distribution from 40 to 100 degrees can be obtained by horizontal scanning the TOF-NPA during the long discharge over 100 seconds sustained by the NBI#2 (co-injection) at the magnetic axis (R_{ax}) of 3.6 m. The trapped particle by the helical ripple can be clearly observed around the pitch angle of 90 degrees. The loss cone feature is agreed with the result. It is interesting to investigate the dependence of R_{ax} of the loss cone feature. However it is not suitable to use the scanning of TOF-NPA during NBI plasma discharge although it can provide the precise structure of the loss cone because it is very difficult to sustain the long discharge at different magnetic axis. We use SD-NPA, which has ability of 6 different pitch angle measurement at R_{ax} =3.5, 3.6 and 3.75 m. More trapped particle can be observed at R_{ax} =3.5 m because the large helical ripple can be expected at inner magnetic axis.

In vertical scan, the heating deposition profile of the ion cyclotron resonance heating (ICH) has been discussed. In LHD, the long discharge over 30 minutes with the total energy of 1GJ can be sustained by the ICH. The deposition profile can be obtained by the vertical scan of the SD-NPA. The region where the high-energy particle is generated, is agreed with the resonance region of ICH. Similar result can be obtained by the pellet charge exchange measurement in the short discharge.

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.[1] This phenomenon is known as a loss cone and it expresses 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),[2] the device design is devised so that the loss cone at ρ (radial position on the magnetic surface) <1/2 may not exist.[3] Moreover, most of the particles heated by tangential NBI (Neutral Beam Injection) do not have a pitch angle perpendicular to the 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 *E*. [4] Here we are thinking about the single particle orbit model excluding the electric filed for simplicity.

The simulation of the single particle orbit in LHD magnetic field configuration had been precisely done by Kamimura [5] and Watanabe [6]. In calculation, test particles with uniform initial pitch angle are put on a certain poloidal surface grid. Typical simulation results are shown in Ref. [5]. Protons with the energy of 50 keV, which are settled on the poloidal surface initially, move on LHD magnetic configuration in vacuum. The figure shows alive particles map with major radius in horizontal axis and pitch angle in vertical axis. The symbols indicate the difference of the particle orbits. Particle confinement by the different magnetic fields are shown in Ref. [5]. The trapped particle sby the helical ripple are remarkably observed around 90 degrees of the pitch angle at the inner magnetic shifts. Some of the particles are lost when the pitch angle is slightly lower or higher than 90 degrees. However when the pitch angle becomes much lower (or higher), the particle has the transit orbit. Therefore many particles can be confined in this region. When the magnetic axis moves inward, the trapped particle is well confined because the orbit of the trapped particle closes the plasma magnetic surface.

2. 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. [7]. 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 (700kg).[8]

Silicon surface barrier diode type neutral particle analyzer (SD-NPA) is installed under the TOF-NPA.[9,10] It has 6 liquid nitrogen cooled detectors with different sight lines from 35 to 90 degrees. Minimum observable energy is 25 keV which is determined by the thickness of

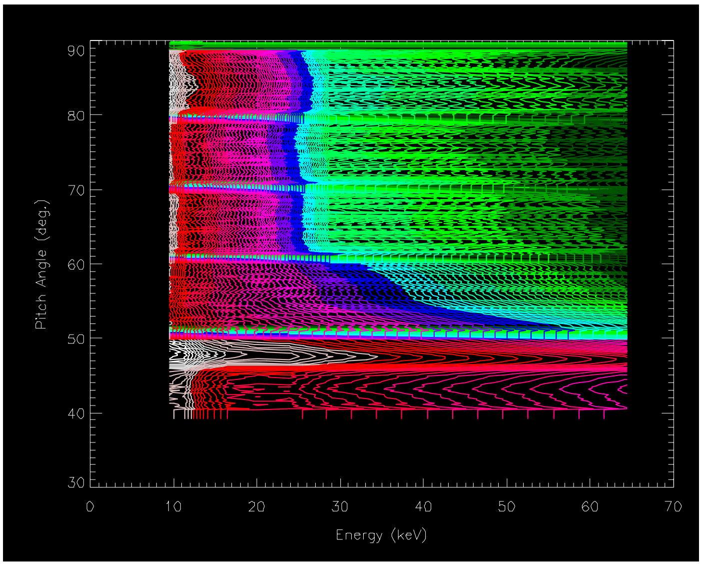

Fig. 1. The contour plot of the pitch angle distribution.
The color (or density) means the flux of the particle. The trapped particle around the pitch angle of 90 degrees is clearly observed. The effect of loss cone is not so large because the particle loss near the 20 keV is not remarkable.

aluminum coating for light protection and the inactive layer of the silicon detector. The simultaneous six energy spectra with energy resolution of several keV can be obtained by traditional pulse height analysis. The time resolution is 5 ms. It has vertical scanning mechanism by moving the aperture.

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 3.4m to 4.1m by applying a vertical magnetic field. There are three kinds of heating system ECH (10MW), NBI (15MW) and ICH (3MW). As for electron temperature, a maximum of 10keV 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.

3. Experimental Results

Figure 1 shows the contour plot of the pitch angle distribution measure by the scanning of TOF-NPA during NBI long plasma discharge. Horizontal and vertical axes indicate the particle energy of hydrogen and the pitch angle, respectively. Here the pitch angle is defined as the angle between the magnetic axis and the sight line. The color (or density) means the flux of the particle. We must take account the line integration of the particle flux in experiment. The observed neutral particle flux is the products of the high-energy particle and the background neutrals amounts. The penetration depth of the background neutral depends on the plasma density. However main region of the neutral particle source is outer than 2/3 of the plasma radius. Loss cone appears outer than 1/2 of plasma radius. Therefore the experiment results are expected to reflect the simulation results. Horizontal axis in Fig. 2 is the particle energy not the major radius which is shown in Fig. 1. However the trapped particle around the pitch angle of 90 degrees is clearly found in Fig. 1. The magnetic axis of R_{ax} =3.6 m in this experiment is equal to the 0.15 m inner shift in the simulation. Both results are qualitatively agreed. Although some particles are disapperaed by escaping to the loss cone, most of particles with large pitch angle are well confined by the inner shift of the magnetic axis. The flux in the pitch angle of less than 90 degrees is smaller. In this experiment, the critical energy is expected to be 20 keV because the electron

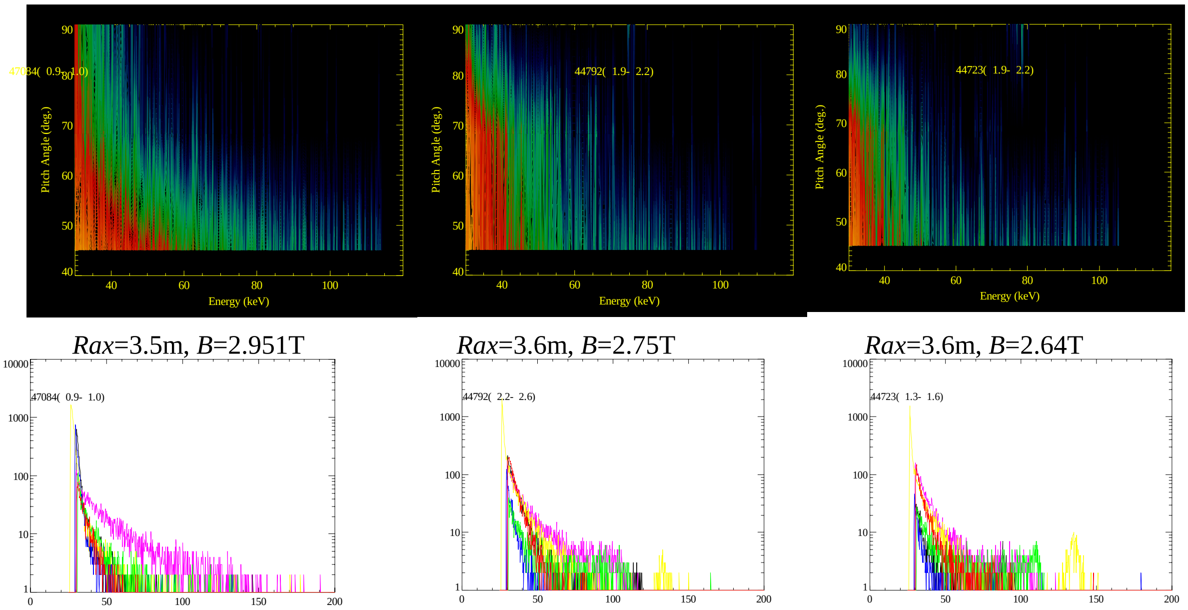

Fig. 2. The contour plots and spectra of the pitch angle distribution at three different magnetic axes.
. By inward shift of the magnetic axis, the trapped particle near the pitch angle of 90 degrees increases.

temperature is 4 keV. Uniform initial pitch angle distribution can be expected on 20 keV. The effect of loss cone is not so large because the particle loss near the 20 keV is not remarkable.

In the long discharge experiment, it is very difficult to choose the different magnetic axis position because the long discharge cannot maintain except R_{ax} =3.6 m. We use SD-NPA which has different 6 sight lines in order to obtain the pitch angle distribution in single short discharge. The pitch angle distribution in different magnetic axes can be obtained by using SD-NPA. Figure 2 shows the contour plots of the pitch angle distribution at three different magnetic axes, R_{ax} =3.53, 3.6 and 3.75 m. Horizontal and vertical axes indicate the particle energy of hydrogen and the pitch angle, respectively. The color (or density) means the flux of the particle. Each spectrum is also shown in Fig. 2. By inward shift of the magnetic axis, the trapped particle near the pitch angle of 90 degrees increases. This means the trapped particle is well confined because the orbit of the trapped particle closes the magnetic surface when the magnetic axis moves inward.

3. Vertical scan

In LHD, the long discharge over 30 minutes with the total energy of 1GJ can be succeeded by the ICH. SD-NPA has an ability of the vertical scan of 0.03 degree/seconds by the sliding of the pinhole in order to obtain the vertical distribution of neutral particle energy spectra. The deposition profile of ICH can be determined by the distribution. Much high-energy flux can be observed near the resonance region of ICH as shown in Fig. 3. Similar result can be obtained by the pellet charge exchange measurement in the short discharge. The details of the results are mentioned elsewhere.[11]

4. Summary

Two neutral particle analyzers, TOF-NPA and SD-NPA, which are scannable horizontally and vertically, are used for observing the pitch angle distribution of high-energy particle and studying loss cone feature. In NBI long discharge, precise pitch angle distribution, which can be compared with the simulation, can be obtained. The dependence of tapped particle against the magnetic field can be obtained using SD-NPA. In LHD, large loss cone is not observed when the magnetic axis is shifted inward. The ICH heating near the resonance region can be observed using vertical scan of SD-NPA.

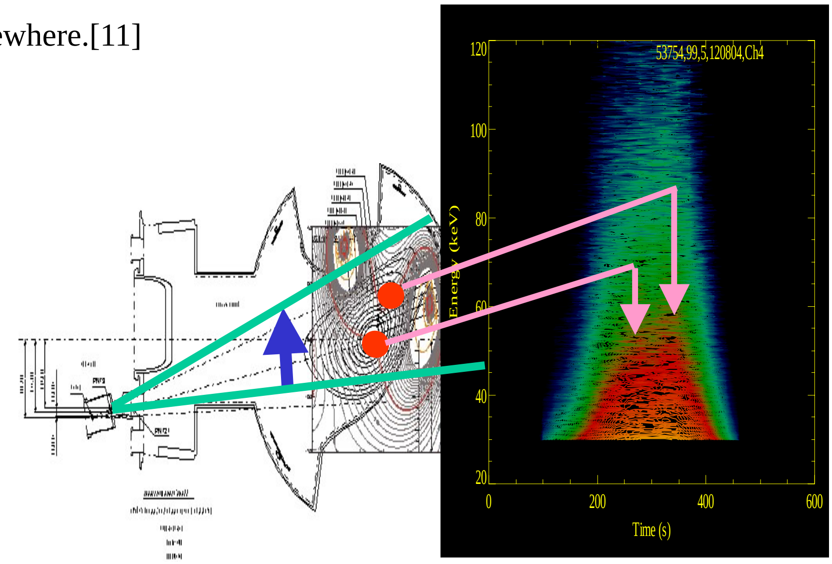

Fig. 3. The vertical scan of SD-NPA.
. SD-NPA is scanned from the bottom to top. During scanning, two peaks appears when the sight line cross the strong resonace positions of ICH.

Acknowledgements

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