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High Energy Particle Measurements during Long Discharge in LHD

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Abstract

The spatial resolved energy spectra can be observed during a long discharge of NBI plasma by continuously scanning the neutral particle analyzer. In these discharges, the plasmas are initiated by the ECH heating, after that NBI#2 (Co-injection) sustains the plasma during 40–60 seconds. The scanned pitch angle is from 44 degrees to 74 degrees. The injected neutral beam (hydrogen) energy of NBI#2 is only 130 keV because the original ion source polarity is negative. The shape of spectra is almost similar from 44 degrees to 53 degrees. However the spectra from 55 degrees are strongly varied. It reflects the injection pitch angle of the beam according to the simulation (53 degrees at R_{ax} = 3.75 m in simulation). The beam keeps the pitch angle at incidence until the beam energy becomes to the energy, which the pitch angle scattering is occurred by the energy loss due to the electron collision. The low flux region can be observed around 10–15 keV, which is 15 times of the electron temperature. The energy region may be equal to the energy at which the pitch angle scattering is occurred. At the energy, the particle is scattered by the collision with the plasma ions and some of particles may run away from the plasma because they have a possibility to enter the loss cone. According to the simulation, the loss cone can be expected at the 10 keV with the small angular dependence. The depth of the loss cone is deep at the small pitch angle. The hollow in the spectrum may be concluded to be the loss cone as the tendency is almost agreed with the experimental result.

Keywords:

TOF neutral particle analyzer, long discharge, horizontal scan, pitch angle

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1. Introduction.

The time-of-flight type NPA (neutral particle analyzer, maximum/minimum observable energy 0.5/ 370 keV, typical energy resolution 7%) has the capability of a high S/N ratio against the radiation including soft/hard X-rays from plasmas [1]. The analyzer and the movable stage are installed at the mid-plane of LHD on the 10-O port. There are two NBIs (NBI#1 and #2) at neighboring ports to 10-O. (Fig.1) In particular, the beam path of NBI#1 crosses the sight line of the analyzer. Therefore a large amount of particles from the plasma center can be expected, which is suitable for the high-energy distribution measurement. The scanning is performed with the pivot in front of the 10-O port by using a motor, which is remotely controlled from –2 degrees to +31 degrees (0 degrees indicates the direction perpendicular to the 10-O port flange surface). The angles are equal to the pitch angle (the angle between the magnetic axis and the sight line) of 100 degrees and 40 degrees, respectively. A CCD camera monitors the angle.

The scan control and the angle reading system are shown in Fig.2. The position (=angle) can be measured from the length of the stainless wire between the stage and a fixed point. The position data are sent to a Windows computer. At the same time, the timing data can be provided to the computer from a timer, which is triggered by the LHD discharge initiation.

2. Results in NBI Long Discharge

The spatial resolved energy spectra can be observed during a long discharge of NBI plasma by continuously scanning the neutral particle analyzer [2]. Figure 3(a) shows the time evaluated (=angular distributed) 3 dimensional spectrum obtained by overlapping of three NBI plasma discharges. The pitch angle means the angle between the sight line and the central magnetic axis. In these discharges, the plasmas are initiated by the ECH heating, after that NBI#2 (Co-injection) sustains the plasma during 40–60 seconds. The scanned pitch angle

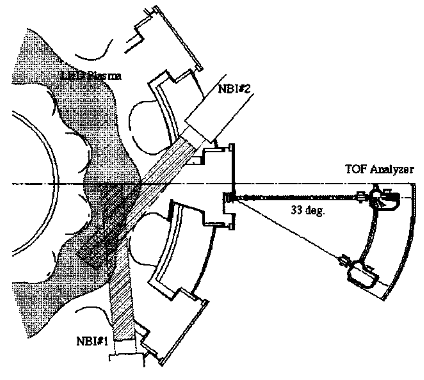

Fig. 1 The spatial-resolved neutral particle energy spectrum in NBI long discharge.

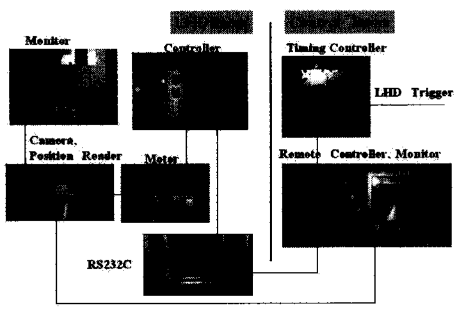

Fig. 2 The apparatus of the neutral particle analyzer and LHD.

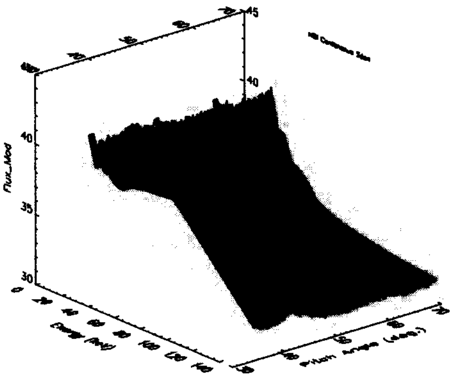

Fig. 3 (a) The spatial-resolved neutral particle energy spectrum in NBI long discharge.

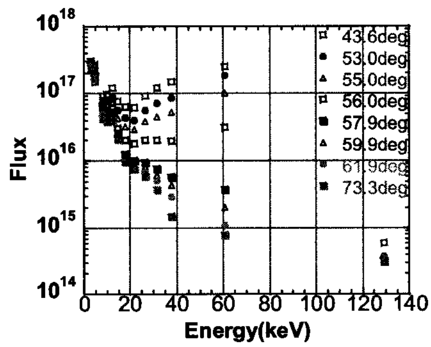

Fig. 3 (b) Energy spectrum of each pitch angle obtained by Fig. 3(a).

is from 44 degrees to 74 degrees. The electron density measured by an interferometer is kept to be almost 2×10^{19} cm^{-3} during the discharge except the plasma initiation phase. At the initiation phase by ECH plasma, the high-energy particle flux is enhanced as the density is too low and the background neutral density is high. The injected hydrogen neutral beam energy of NBI#2 is only 130 keV because the original ion source polarity is negative. The high-energy beam over the injection beam energy cannot be observed, as there is no ICRF heating. Figure 3(b) shows the spectra at some typical pitch angles. The shape of spectra is almost similar from 44 degrees to 53 degrees. However the spectra from 55 degrees are strongly varied. It reflects the injection pitch angle of the beam according to the simulation (53 degrees at R_{ax} = 3.75 m in simulation). The beam keeps the pitch angle at incidence until the beam energy becomes to the energy, which the pitch angle scattering is occurred by the energy loss due to the electron collision. The low flux region can be observed around 10–15 keV which is 15 time so the electron temperature. The energy region may be equal to the energy at which the pitch angle scattering is occurred. At the energy, the particle is scattered by the collision with the plasma ion and some of particles may run away from the plasma because they have a possibility to enter the loss cone (the ripple diffusion). Figure 4 shows the simulation result. According to the simulation, the loss cone can be expected at the 10 keV with the small angular dependence. The depth of the loss cone is deep at the small pitch angle. The hollow in the spectrum may be concluded to be the loss cone as the tendency is almost agreed with the experimental result. Changing the plasma magnetic axis can reduce the loss cone.

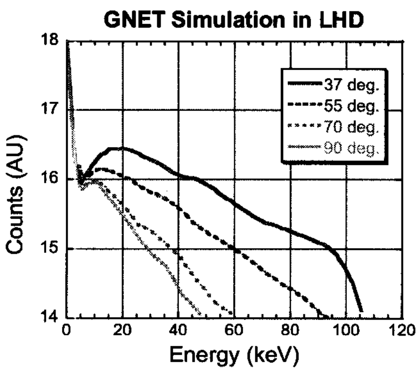

Fig. 4 GNET Simulation in NBI plasma.

3. Results in ICH Plasma

High-energy particles over 250 keV can be observed from ICH in NBI plasma. The pitch angle distribution can be obtained by using the same scanning method as the scanning in NBI plasma. Figure 5(a) shows the spectra during the ICH phase. The complicated energy spectrum can be obtained when the particle is integrated along the sight line because the high-energy particle has the pitch angle dependence. It is easy to compare with the predicted simulation result when the spectra are translated on to the velocity phase space. (Fig. 5(b)). The Vperp and Vpara can be obtained from the pitch angle and the energy in Fig. 5(b) [3]. The equatorial line shows the logarithm of the flux. The "butter-fly" shape structure (peak angle of 63 degree), which is well known in the theory, can be obtained. The difference of the sight line length (flux) is not so effective against the structure because the equatorial line is plotted in logarithmic scale. The pitch angle of particles accelerated by ICH is oblique rather than

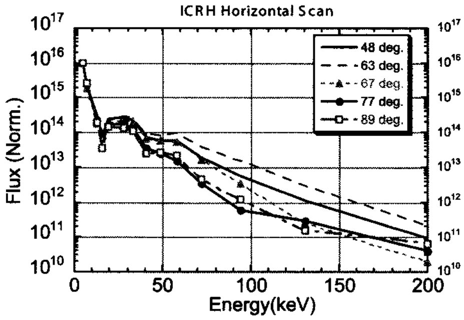

Fig. 5 (a) The energy spectrum of each scanning angle. The vertical error bars are smaler than simbols.

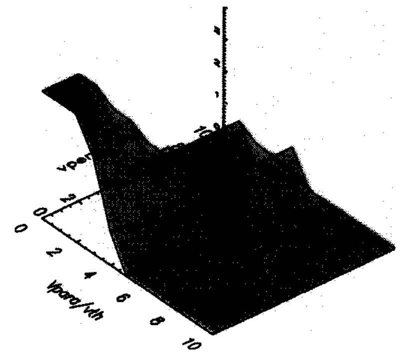

Fig. 5 (b) Flux plotting on the velocity phase space. The maximum flux is observed at the pitch angle of 63–70 degree.

perpendicular against the magnetic axis. The fact shows observed particles are mainly the helically trapped particles. The helically trapped particles draw the banana orbit. The particle is perpendicularly accelerated against the magnetic line by the ion cyclotron heating at the tip of the banana orbit. However the banana tip is at the lower magnetic side than the ion cyclotron resonance. Therefore the velocity of the particle on the cyclotron resonance has the parallel component against the magnetic line. The peak angle of the butter-fly shaped depends on the resonance position. The peak angle is about 70 degree on the 4th cycle experiment when the resonance is off axis.

4. Results in ICH Long Discharge

The energy spectra are measured when the analyzer is continuously scanned in the long discharge. 120 seconds on ICH plasma can be succeeded in the 4^{th} campaign of LHD. The merit in the diagnostics of the long discharge is the capability of the accumulation of data and the spatial scanning under the almost same experimental condition. In the experiment, the analyzer is scanned from 75 to 90 degrees during three-60 seconds discharges (Fig. 6). The experimental condition is as follows; the magnetic axis, the magnetic field, the stored energy and the density are 3.6 m, 2.75 T, 100 kJ and 1×10^{-19} m^{-3}, respectively. ICH of the power of 1.0 MW is applied from two antennas at 3.5U and 3.5L. It makes the resonance region around $a/2$ at the lower magnetic field side. Unfortunately we cannot succeed to see the scanning region, which the structure of the butter-fly can be expected. However another peak of the flux can be observed near 85 degree lower than 6 keV. Now we are considering the reason. We can show the possibility to make clear some generation mechanism of high-energy particle structure by the continuous scanning on LHD long discharge.

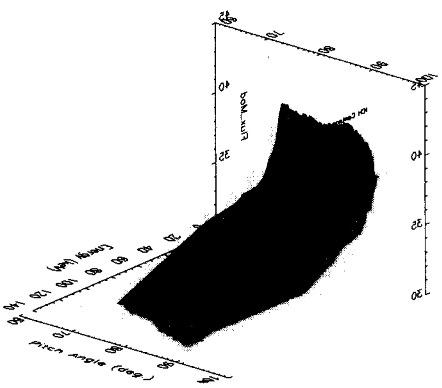

Fig. 6 The spatial-resolved neutral particle energy spectrum in ICH long discharge.

5. Summary

The time-of-flight type neutral particle analyzer system can be provided the pitch angle distribution in NBI and ICRF heating plasmas. The hollow in the energy spectrum of NBI plasma may be the loss cone according to the comparison with the simulation. The spatial distribution of high-energy particles in ICH plasma can be also obtained. The butter-fly structure of the distribution function based on the helically trapped particle can be observed in NBI plasma.

References

[1] T. Ozaki, V. Zanza, G. Bracco, A. Moleti, B. Tilia, A. Sibio, S. Sudo, H. Nakanishi, M. Kojima, M. Shoji and G1/G2 experimental group, Rev. Sci. Instrum. **71**(7), 2698 (2000).

[2] T. Ozaki, S. Sudo *et al.*, J. Plasma and Fusion Res. SERIES **3**, 444 (2000).

[3] K. Saito, R. Kumazawa, T. Mutoh, T. Seki, T. Watari, T. Yamamoto, Y. Torii, N. Takeuchi, Y. Zhoa, A. Fukuyama, F. Shimpo, G. Nomura, M. Yokota, K. Kato, M. Sasao, M. Isobe, T. Ozaki *et al.*, to be published in Plasma Phys. Control. Fusion.