J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 444–448

Preliminary Results of the Neutral Particle Measurements in Large Helical Device

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(Received: 18 January 2000 / Accepted: 19 April 2000)

Abstract

The development of high energy neutral particle measurement system for ion temperature measurements and high energy particle confinement analysis during neutral beam injection and ion cyclotron resonance frequency heating experiments in the Large Helical Device (LHD) is described. The control, data acquisition systems and the horizontal movable stage are prepared to investigate pitch angle distribution and loss cone for a long discharge in LHD. The preliminary results in plasma experiments including long discharges are described.

Keywords:

TOF neutral particle analyzer, ion temperature, high energy tail, horizontal scan, long discharge

1. Introduction

High energy neutral particle measurement is among the important diagnostics for ion temperature and high energy particle confinement analysis during electron cyclotron resonance (ECR) heating (ECH), neutral beam injection (NBI) heating and ion cyclotron range frequency (ICRF) heating (ICRH) in the Large Helical Device (LHD, major radius = 3.9 m, average minor radius = 0.6 m) [1]. Concerning NBI heating, two 180 keV hydrogen beams (8 MW, from 10 sec to 30 min) from the negative ion sources will be used in Phase I of the LHD experiment schedule and three or four 360 keV deuterium beams (15 MW) will be used in Phase II. NBIs will inject tangentially and the birth pitch angle of the ions from NBI is 0–20 degree. In the experiment with the ICRF heating of 12 MW, the hydrogen and He3 will be used as minorities, whose high energy tails of over 100 keV can be expected.

It is important to observe the energy dependence of

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the pitch angle distribution to investigate the confinement of high energy particles. For this purpose the neutral particle analyzer should have a wide observation energy range for accelerated particles by (ICRH) and the ability to separate the particle above the maximum energy of the NBI (or accelerated species of hydrogen, deuterium and helium-3/-4. It is important that it has the ability to exclude the noises from D-D neutron and the strong radiation during heating. We adopt a time-of-flight (TOF) neutral particle analyzer which had been developed in ENEA Frascati [2].

The first initiation of LHD succeeded on March of 1998. Until now a 80-second discharge has been achieved. It is important that the analyzer should be matched to long pulse discharges in the control and data acquisition systems. The spatial scanning of the analyzer during long discharges is also important for investigating the pitch angle and ion temperature distributions. The detailed neutral particle measurement system is described in the reference [3,4].

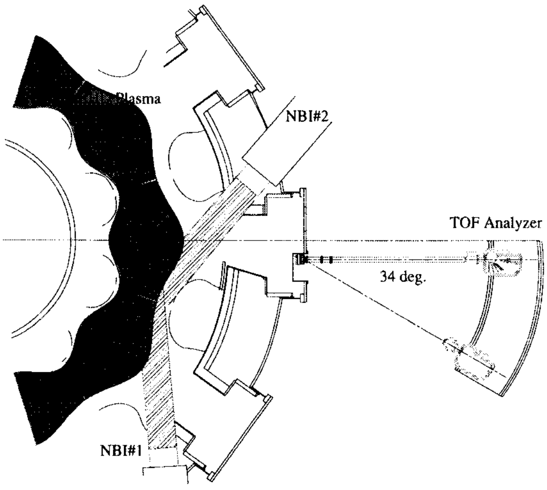

Fig. 1 The arrangement of NBI#1, #2 and analyzer. The analyzer can be scanned horizontally 35 degrees. NBI#1 and #2 are the co- and counter-injectors, respectively.

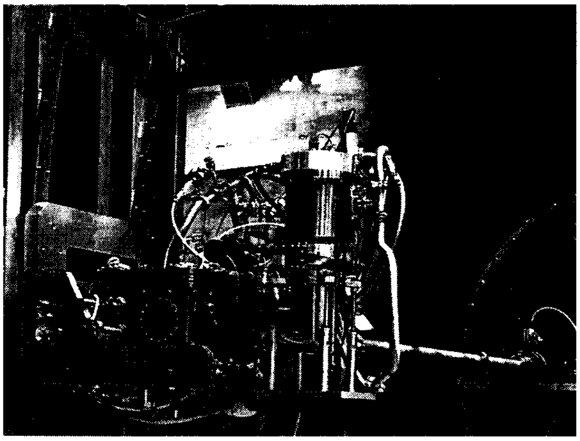

Fig. 2 Photograph of the analyzer stage in LHD. The analyzer is settled on the movable stage. To prevent the strong magnetic field of LHD, the turbo pumps are set vertically.

2. The Experimental Setup

The analyzer and the movable stage are installed at the middle plane of LHD on 10-O port. Many diagnostics for observing the mid-plane plasma are on the central stage (in our case, A1 stage) because the mid-plane is located 6 m above the LHD floor. We put the analyzer/stage at a fan-shape base on A1 stage because the weight of the analyzer/stage is 2 tons and A1 stage above is not strong enough. There are two NBIs (NBI#1 and #2) at neighboring ports to10-O. Especially the beam path of NBI#1 is crossed to the sight line of the analyzer. Therefore a large amount of particle from the plasma center can be expected, which is suitable for the high energy distribution measurement (Fig. 1 and Fig. 2). The analyzer is set at 5 m from the plasma center in order that the confinement magnetic field is not disturbed by the analyzer box (magnetized material). The analyzer can be scanned from –2 degrees to +33 degrees (0 degrees indicates the direction perpendicular to the 10-O port flange surface).

The merit of LHD is the production of a long steady plasma. Therefore the spatial ion energy spectrum/temperature and pitch angle distribution can be obtained by scanning the analyzer during long shots. We have prepared the movable stage with the scanning radius of 4 m, the horizontal angle of 35 degrees and the vertical angle of 27 degrees (vertical scan is now improving). During horizontal scanning, the scanning angle ranges from 23 to 93 degrees against the central magnetic axis of the standard configuration plasma, which can cover the loss cone region according to particle transport calculations. The rail and screw for the horizontal scan are made from stainless steel 304 (SS304) because the installation of magnetized material to LHD is restricted. SS304 is too soft to move the stage smoothly due to bending when the stage with the weight of 2 tons is put on it. Therefore we prepare the fan-shaped stainless base under the rail. A stepping motor with water cooling which has enough torque is used to drive the stage. The maximum scanning speed is 20 seconds per degree in horizontal scan due to lower motor torque, therefore 12 minutes is required for full scanning.

Due to the super-conducting coil of LHD, the LHD vacuum vessel is covered by a bell-jar. Therefore the viewing port is too narrow to obtain the large viewing angle. To obtain the viewing angle of 35 degree, the pivot of the movable stage which is supported by 10-O port is inside the main port surface of 10-O. The analyzer system is electrically insulated by a ceramic break at the pivot and by the glass-epoxy at the fan-shaped base. The bending by scanning at the pivot is absorbed by the bellows. The stress at the pivot due to the fluctuation of the stage in forward-backward direction is absorbed by another one-dimensional bellows at the duct.

The slit for limitation of particle is exposed to strong magnetic fields (0.1 T) because it is set near the LHD port. Therefore it is driven by super-sonic motors with encoders. The controllers/drivers of both the stepping motor and the super-sonic motors are settled on the movable stage. They are remotely controlled by RS232C with optical fibers and the Windows NT machine in the control room.

3. The Preliminary Results

In the third experimental cycle, not only ECH but also NBI and/or ICRH plasma experiments were performed. The analyzer is set at the standard position at the center of the horizontal fan (= 17 degrees). The stress for the bellow and the cutoff of the viewing are the smallest there. The angle between the viewing and the central magnetic axis is 68 degrees at this position. Figure 3 shows the typical energy spectrum of the hydrogen plasma heated by NBI. In this shot, ECH plasma is heated by NBI (NBI#2, 160 keV, 1MW, counter injection). The spectrum has a Maxwellian distribution at the low energy range. The ion temperature can be obtained from the slope of the spectrum. The electron temperature and the electron density profiles are measured by the Thomson scattering and the millimeter wave/the fir infrared interferometer, respectively.

Assuming the background neutral profile and the central ion temperature, we can calculate the neutral flux and compare the spectrum with the experimental one. The straight line in Fig. 3 indicates the calculated spectrum under the experimental condition. Both spectra are agreed well at $T_i = 3$ keV. The results shows that the energy range whose slopes are agreed is from twice to five times the central temperature.

The ion temperature obtained from the neutral particle measurement is compared with one from the charge exchange recombination spectroscopy (CXRS). The central ion temperature by CXRS is assumed that the shape of the ion temperature profile is equal to one of the electron temperature because CXRS did not view the central ion temperature profile in the experiments. The both results agree within the accuracy of 10% as shown in Fig. 4.

The neutral flux and ion temperature increase extremely during ICRH phase. An ion temperature increase of 300 eV is observed although the stored energy increases only 70 kJ in this shot. The temperature of 2.5 keV is observed. The power dependence between the absorbed ICH power and the ion temperature increase is shown in figure 5. The ion temperature and the stored energy are increased by the ICH power. The fact indicates that the ion cyclotron heating performs efficiently to the ion energy deposit.

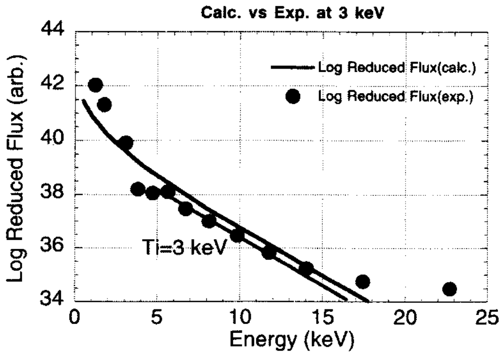

Fig. 3 Typical Energy spectrum at the NBI plasma. The straight line indicates the calculation results.

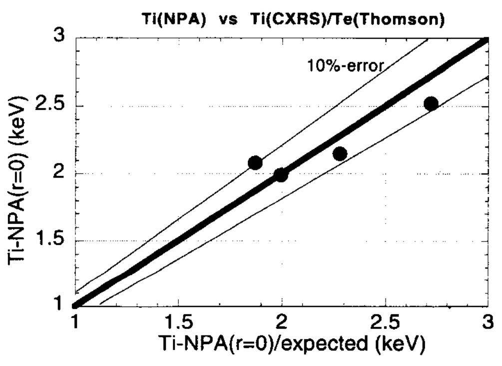

Fig. 4 The comparison of NPA with CXRS. Two straight lines shows the 10% errors.

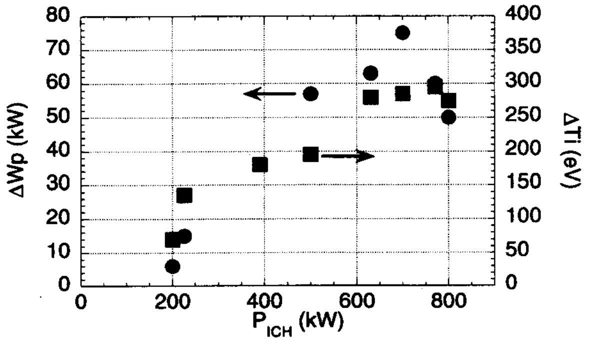

Fig. 5 The preliminary results of ICH heating.
The stored energy and ion temperature increase by the ICH.

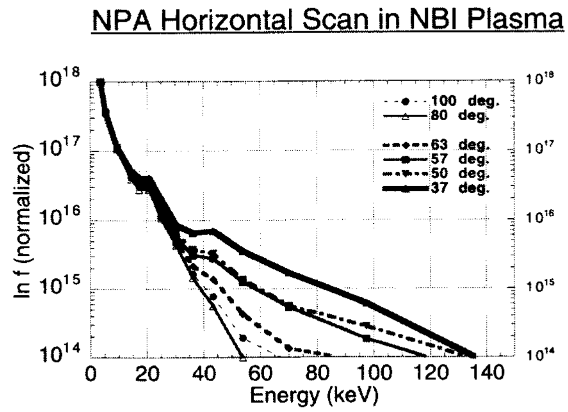

Fig. 7 Horizontal Scan in NBI plasma.
The values are normalized at the lowest energy.

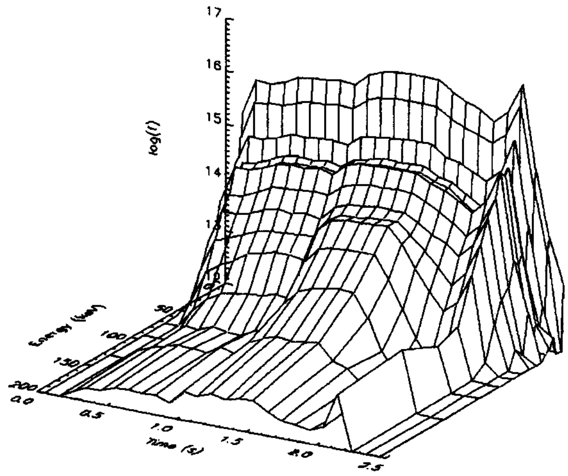

Fig. 6 High Energy Tail in ICH plasma.
The high energy tail can be observed during ICH.

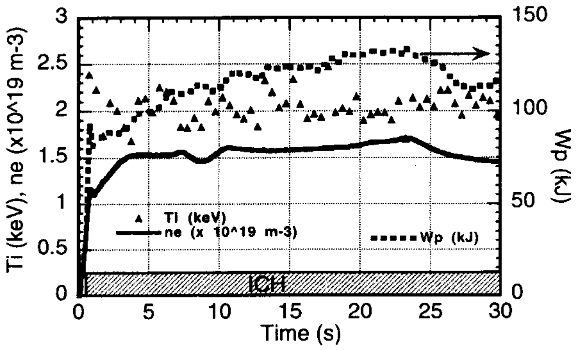

Fig. 8 Long Discharge.
Typical ICH long discharge is shown.

In the ion resonance mode on ICH plasma, the high energy tail above 200 keV is observed (Fig. 6). This behavior is remarkable at the low density plasma, and the high energy tail decreases by the density increase. The same result can be obtained by the diamond detector. The angular distribution of the high energy tail is not so large than we expected according to the horizontal scan.

We try the horizontal scanning of the neutral particle measurement in the NBI plasma in order to investigate the high energy particle confinement and the loss cone analysis as shown in Fig. 7 (beam energy of 135 keV). Now we are studying and comparing the simulation results. The spectrum variations above 40 keV come from the amounts of particles with different pitch angles at the NBI deposition. The significant loss cone can not be found because each spectrum agrees with each other up to the energy of several times the electron temperature.

4. Long Discharge Experiments

In the third cycle, we could succeed a 80-second discharge by NBI or ICH. Figure 8 shows a typical waveform and ion temperature. The helium plasma (hydrogen minority) is produced by the initiation by ECH and additional heating of ICH from 0.5 second to 68.8 second. The radiation slightly increases during discharge. The breathing was not observed in spite of the high density (1×10^{-19} m^{-3}) because the divertor was covered with graphite tiles. The ion temperature was kept 1.4 keV. We had measured the ratio of helium to hydrogen by accumulating many signals. The ratio of fluxes around 10 keV was equal to the ratio of the gas abundance. We have to keep in mind that this ratio is near the plasma edge because the helium neutral particle is mainly generated there. The long discharge enables us to obtain the ratio in one shot. Sometimes by the increase in the ICH power the density decreased.

In NBI plasma, a 80-second discharge could be succeeded. The ion temperature was about 1 keV during the discharge. The plasma was very stable and quiet similar to the ICH plasma.

5. Summary

We have developed the high energy neutral particle measurement system for LHD. It enables us to observe the ion temperature and to investigate the high energy particle confinement during ECH, NBI and ICRH plasmas including long duration plasmas. The horizontal scan of the analyzer to measure the pitch angle distribution, especially in the long pulse discharge on LHD has been succeeded. We can confirm the successful operation of the analyzer system in the plasma experiment.

Acknowledgements

The authors thank Director General Prof. Fujiwara for the encouragement. This research is supported by Gakujutu Kenkyu of Monbusho.

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