

## Two-dimensional scanning high-energy particle diagnostic system in Large Helical Device

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A high-energy neutral particle measurement is one of the important diagnostics for ion temperature and high-energy particle confinement analysis. The neutral particle analyzer in the large helical device is capable of wide range scanning as a feature. We have obtained various data using the horizontal scan of the analyzer. Recently, in addition to the horizontal scan, a high-speed perpendicular scan became possible which enables acquisition of new information in the poloidal direction. Two stainless blocks are set on the opposite sides of the chain in order to balance the weight (700 kg) of the analyzer and reduce the load for the motor. Therefore a very high scan speed of 1°/s can be obtained. The scanning speed is 1°/s. By adding the vertical scan, the ion temperature profile and the radial variation of the signal loss associated with the resonant loss was obtained in preliminary experimental results. © 2004 American Institute of Physics.  
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### I. INTRODUCTION

High-energy particle measurement is important for monitoring ion temperature, studying high-energy particle confinement, and clarification of the electric field formation mechanism and particle transport research. In particular, in a helical system like the large helical device (LHD), there are various particle orbits; not only transit particle orbits but also the trapped particle orbits due to the complicated magnetic configuration. These orbits create new electric fields and the electric fields produce new particle orbits. In addition, there are three different heating systems in LHD: neutral particle injection heating (NBI), ion cyclotron resonance frequency heating (ICH) and electron cyclotron resonance frequency heating (ECH). These heating sources produce high-energy particles with different energy ranges and pitch angles. The neutral particle measurement system with a spatially scannable mechanism is indispensable to the study of high-energy particle confinement. Therefore a two-dimensional scanning system using the time-of-flight neutral particle analyzer (NPA) has been prepared on a horizontal port in LHD.

The vertically scanning system has been available since the middle of the sixth cycle (2002) in addition to the horizontally scanning system. A detailed explanation of the vertically scanning system will be described in Sec. III. Various measurements, for example, the ion temperature profile during a single shot, the neutral particle flux distribution in the poloidal direction, optimization of the ion temperature measurement by combination with the horizontal scan, and the variation of the pitch angle measurement at the same average radius, can be expected by vertical scanning.

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Here we will summarize the typical results obtained by horizontal scanning of the NPA, and describe the preliminary results obtained from the newly installed vertical scannable NPA system, especially the ion temperature profile and the resonant loss.

### II. THE RESULTS FROM HORIZONTAL SCAN

The horizontal scan of NPA was performed by a remote motor drive of the NPA stage. The scanning speed is 0.17°/s. The scanning center pitch angle, which is defined as the angle between the magnetic axis and the sightline, ranges from 40° to 100°.<sup>1</sup>

The high-energy neutral particle spectrum during NBI discharge was measured by scanning the NPA shot by shot. The passing particles are mainly observed at the tangential position of NPA, although the trapped particles are observed at the vertical position. The high-energy particles were confined in LHD plasma without large loss because the experimental result agreed with simulation.<sup>2</sup> Comparison between co- and counter NBI injection has been studied. The experiments were performed on two different long pulse discharges with normal and reverse magnetic fields. The NPA scan has been continuously proceeded during the long discharge to obtain accurate dependence of the spectra. A higher energy particle can be confined in the coinjection case than in counterinjection case.<sup>3</sup>

Horizontal scan measurements were performed in ICH plasmas as well. The result is that the spatial distribution of the neutral particle flux had a butterfly shape predicted theoretically.<sup>3-5</sup> Resonant loss (see Sec. IV) can be observed at about 5 keV, especially in low magnetic fields and with the outer magnetic axis configuration. The pitch angle depen-

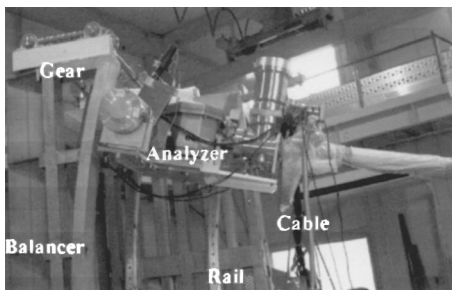


FIG. 1. Photograph of NPA system. A stainless balancer compensates the weight of the analyzer. A high speed scan of  $1^\circ/\text{s}$  can be achieved.

dence of the resonant loss was not clear. In the ECH experiments, the disappearance of the resonant loss can be observed by the radial electric field produced by the strong ECH.<sup>6</sup>

III. VERTICALLY SCANNING SYSTEM

The vertically scanning system is realized by adding a movable mechanism to a current horizontally scanning system (Fig. 1). The analyzer slides along three stainless steel rails, which are arcs with radii of 4 m. One of the rails defines the accurate position of the analyzer. Another rail, which is set at the front of this rail, fixes the vertical position and the other rail, which is set at the side, fixes the side position. Therefore, a smooth and nonvibrating vertical driving can be obtained. Two chains and the gears, which are connected with the motor, support the analyzer. Two stainless blocks are set on the opposite sides of the chain in order to balance the weight (700 kg) of the analyzer and reduce the load in the motor. Therefore a very high scan speed of  $1^\circ/\text{s}$  can be obtained. To avoid tilting of the bellow at the pivot point, there are two different bellows for the horizontal and for the vertical scans. Both scans are performed by the remote. A charge coupled device camera is used to monitor the position, and the time history of the exact position is recorded using a position detector.

IV. VERTICAL SCANNING RESULTS

The time history of an ion temperature profile can be obtained by changing the vertical position shot by shot. The plasma poloidal section is varied by changing the toroidal position. We choose a horizontal position for the center pitch

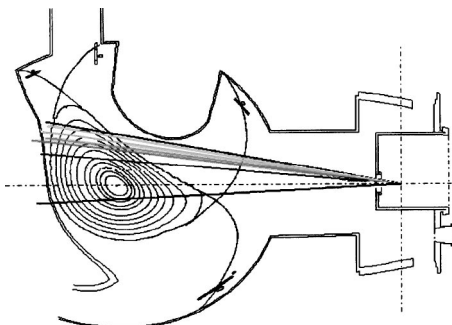


FIG. 2. Plasma cross section at the vertical scan position. To avoid observation of the diverter region, a horizontal position with a center pitch angle of  $60^\circ$  is chosen.

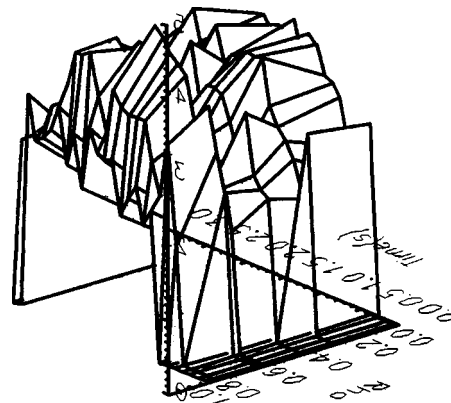


FIG. 3. Time history of the ion temperature profile. The ion temperature profile was obtained by changing the vertical position shot by shot.

angle of  $60^\circ$  to avoid observation in the diverter region where there is a large background neutral population. (Fig. 2) The time history of the ion temperature profile is shown in Fig. 3. The ion temperature profile is comparatively flat and the central temperature is low observed as compared with a crystal spectroscopic measurement. Since the main component of this plasma is the argon, the contribution to the charge exchange between the lower ionization state of argon and the proton should be considered. The lower ionization states of argon exist, near the plasma outer region. Therefore the observed ion temperature may be affected by the contribution to the neutral flux from the outer region rather than the core region. In calculation, these cross sections are too small to significantly contribute to the neutral flux. Neutral particle scattering with high-Z plasma may be one reason for the profile flattening.

It is possible to obtain the poloidal profile of the neutral particle flux or the ion temperature profile by vertical scanning of the analyzer during a single long discharge. Figure 4 shows a typical ion temperature profile obtained by vertical scanning the analyzer from  $+9^\circ$  to  $-9^\circ$  with a scanning speed of  $1^\circ/\text{s}$  during a 40 s discharge. The horizontal measurement position is at a central pitch angle of  $60^\circ$ . The fluctuation of the ion temperature at  $\rho=0-0.5$  may reflect charge exchange neutrals from the high background neutral density in the diverter region.

On helical devices, particle orbits in plasmas are very complicated due to the magnetic field ripple. The gradient of

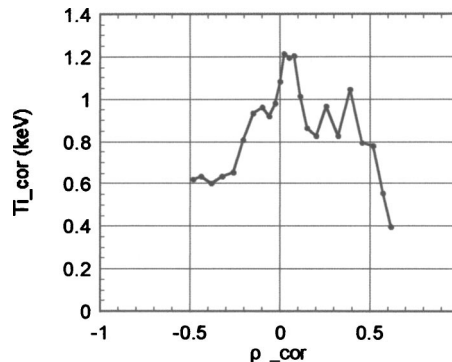


FIG. 4. Ion temperature profile. The ion temperature profile can be obtained by vertical scanning of the analyzer during a single long discharge.

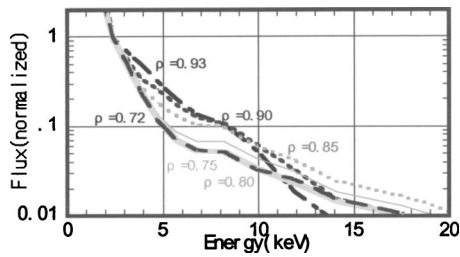


FIG. 5. The radial variation of the dip due to the negative electric field. The depth of the dip is related to the resonant loss. It strongly affected by the electric field.

the magnetic field causes the poloidal drift motion of the particles and rotates poloidally. However some particles are not confined by balance with the electric field  $E$ . It is known for helical devices that some particles with a certain energy are lost by cancellation of the grad  $B$  drift and the  $E \times B$  drift resulting from the electric field  $E$ .<sup>7</sup> This phenomenon occurs for a negative radial electric field. The reason why we are

interested in such resonant loss is that we can observe it from the dip in the high-energy particle spectra measured by the neutral particle analyzer. The plasma parameter dependence of the dip has been investigated elsewhere.<sup>8</sup> However the radial dependence of the dip is not clearly shown. During steady-state operation of NBI plasma, the analyzer has been scanned continuously from  $\rho=0.9$  to 0.7. The spectra are shown in Fig. 5. At the inner region of the plasma, a larger dip can be observed. This may mean there is a large negative electric field at  $\rho=0.7$ .

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