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Neutral Particle Measurement in High Z Plasma in Large Helical Device

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Abstract

In Large Helical Device (LHD), the discharges of high *Z* are often used in order to obtain high ion temperature. The ion density is relatively smaller than the electron density in high *Z* plasma. Therefore the high ion temperature can be obtained since the input energy per ion atom is large. In the charge exchange neutral diagnostic, the ion temperature can be obtained by observing the spectra of neutral particles, which are generated by the charge exchange between the background neutral and the plasma ion, and assuming the Maxwellian distribution of the spectra. In calculation, we also consider the charge exchange between the partially ionized high *Z* ion and proton. The contribution of neutral particle from the charge exchange between argon and proton is small near the center but cannot be neglected near the peripheral region comparing with that of hydrogen charge exchange

Keywords:

argon plasma, charge exchange cross section, background neutral, ion temperature, time-of-flight neutral particle analyzer

1. LHD ion temperature measurement

To achieve the high ion temperature on the neutral beam injection (NBI) [1] experiments in Large Helical Device (LHD) [2], the energy of NBI particle should be completely deposited in plasma and the absorbed energy per unit ion density should be maximized by decreasing the plasma ion density. We can keep the plasma density low without the ”shine through” to choose the high *Z* noble gas plasma which has large charge exchange cross section with NBI hydrogen. In LHD, the neon and argon plasma discharges have been tried. It is important to reduce the hydrogen component in order to obtain pure neon or argon plasma. The neon/argon glow discharges have been done as much hydrogen is absorbed in vacuum wall due to the previous hydrogen discharge. By this procedure, the hydrogen contamination can be reduced remarkably.

The standard ion temperature measurement has been done by the crystal spectroscopy [3] and the charge exchange recombination spectroscopy [4]. The ion temperature can be obtained from the Doppler broadening of the spectral line of highly ionized argon (XVII) plasma between the excited level and the stable level. Therefore the central ion temperature can be obtained if we choose a line from highly ionized argon ion, which is localized near plasma center. The neon puffing is sometimes required on the charge exchange recombination spectroscopy in LHD although the ion profile can be obtained by it.

The ion temperature has also been monitored by using the passive charge exchange neutral particle analyzer. In this measurement, the energy spectrum of the hydrogen atom generated by the charge exchange between the proton in plasma and the background neutral is detected. The time-of-flight neutral particle analyzer has been used in LHD as mentioned in reference [5]. A few charge exchange neutral particle can be ob-

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served from the central region because the background neutral cannot penetrate to the plasma center in large radius plasma as LHD. In principle, the slope of the high-energy tail in the spectrum reflects the ion temperature. However it is very difficult to obtain the central ion temperature because the decelerated NBI particle component is overlapped around the tail.

Here we obtain the central ion temperature by combination the slope of the spectrum at the lower energy range instead of the tail, and the correction factor obtained by the calculation. The ion temperature obtained from charge exchange neutral measurement has smaller accuracy than that from the crystal spectroscopy in LHD. However it is very useful to obtain it at the low impurity density, where the crystal spectroscopy cannot be utilized. We also interest the discrepancy between the impurity temperature and hydrogen temperature. If this measurement can be utilized in high-*Z* plasma, we can use it as the ion temperature monitor the in wide plasma parameter.

Another problem on the charge exchange measurement in argon plasma is the estimation of the background neutral density. In hydrogen plasma, the background neutral density from peripheral region decreases by the ionization and the charge exchange with the plasma proton. However there is much hydrogen background neutral even near the plasma center because new hydrogen atoms are generated by this charge exchange. In pure argon plasma, the background 'neutral' particle cannot be obtained because the target ionization states are not unique. Therefore there are few background neutrals around pure argon plasma center.

2. Charge exchange cross section of the highly ionized plasma

The charge exchange between the partially ionized argon ion and proton should be considered at the charge exchange measurement. The cross section has been considered to be small due to Coulomb repulsion between both ions. However Saida *et al*. [6] mentioned that the charge exchange cannot be neglected at the energy region over 50 keV on neon plasma in LHD. We consider the contribution of the charge exchange in the interest energy region by calculating the cross section using the model mentioned in reference [7], and the argon ion density profile using the impurity transport code [8]

The cross section between the partially ionized argon ion and proton, is experimentally not well known. We estimate it from the similar model. We consider the following reaction,

$$A^{q^+} + B \rightarrow A^{(q-j)^+} + B^{j^+}, \qquad (1)$$

where A^{q^+} is the incident particle with ionization state q, B is the target particle and j is number of transferred electrons, respectively. Although B is the neutral particle in reference [7], we assume that it is the partially ionized argon ion. The charge exchange occurs when the two particles crosses within the Coulomb barrier. Therefore the reaction can be expected even if they are ions. The charge exchange cross section σ^k strongly depends on the ion potential of each charge state.

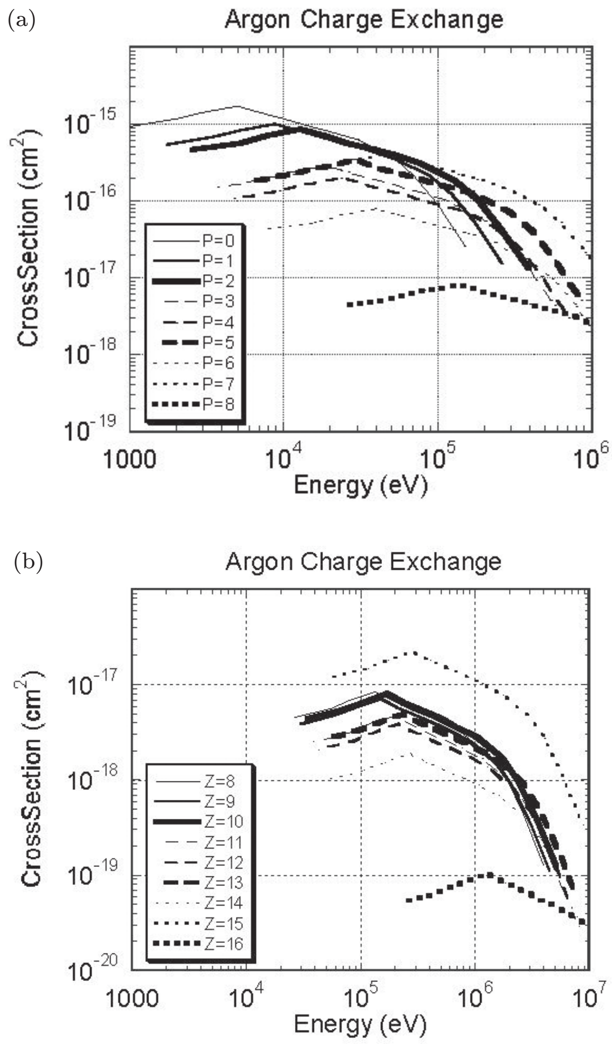

Fig. 1 The charge exchange cross section between argon ion and proton, Each energy dependence of the cross section is derived from the assumption of same energy dependence of the cross section in $Z = 0$ because the cross section is determined by the relative velocities between the orbital electron and incident particle. There are few experimental data in the charge exchange cross section between the proton and partially ion. Therefore physical contradiction is still remained because many ambiguous assumptions are used in calculation. (a) charge states from 1 to 8, (b) charge states from 8 to 16.

$$\sigma^k = \pi_{R_k}^2 + \pi_{R_k+1}^2 = Q_k - Q_{k+1}, \qquad (2)$$

where k is the charge state of the argon ion, R_k is the Coulomb barrier radius and Q_k is the effective cross section, respectively. The effective cross section in Å^2 can be estimated as follows,

$$Q_k = 2.6 \times 10^3 kq/I_k^2, \qquad (3)$$

where I_k is the ionization potential in eV unit at the charge state k. In our case, A^{q+} is the proton and $j = q = 1$. The calculated charge exchange cross section are shown in Figs. 1(a) and 1(b).

3. The argon ion density distribution and contribution for the neutral particle

The next step is the calculation of the argon ion distribution with each charge state in plasma. The distribution can be obtained by using the impurity transport code [8] assuming the given plasma density and temperature profiles and the diffusion coefficient. In this code, the state equation and the transport equation are resolved under the given plasma parameters, and the argon ion density profile with the each charge state can be obtained at the steady state. The electron density and temperature profiles, which are obtained from the Thomson scattering measurement [9] and the far infrared laser interferometer measurement [10] are approximated to be parabolic functions so as to be convenient to calculation. The diffusion coefficient of each ion is used in typical value ($D = 1\,\mathrm{m^2/s}$) in LHD plasma. Figure 2 shows the calculated results of the argon ion distribution profiles. Many neutrals can be expected because those with the energy of several eV are supplied from the wall although the argon becomes higher ionized ion immediately. On the other hand, the ionization rates of $Z = 12, 13$ are larger than that of the neighbor charge states. Therefore the neutral density is sometimes larger than the ion density with a certain charge state.

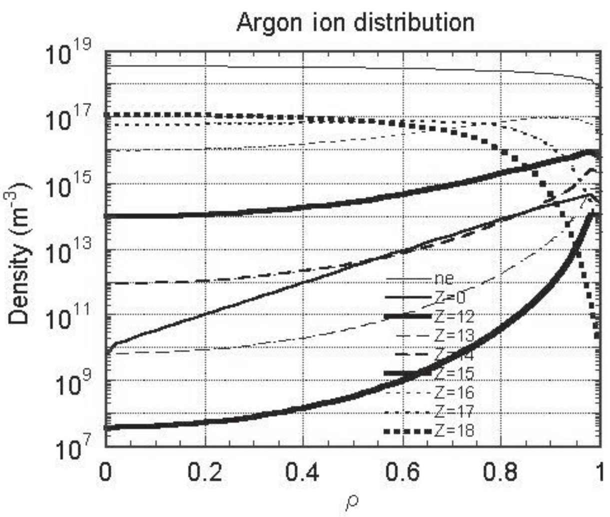

Fig. 2 The argon ion distribution in pure argon plasma. n_e is the electron density. The neutrals are large contribution because it supplied from the wall continuously. The contribution of Z=12,13 is small due to their large ionization.

We can estimate the contribution profile for the charge exchange neutral particles, which are detected by the neutral particle analyzer (Fig. 3). In the calculation, all charge exchange reactions including $Z = 0$ are considered. The contribution from the charge exchange neutral particle between proton and the argon ion with $Z = 15$, is most dominant near the plasma center although this between the proton and argon neutral is dominant near the edge according to the calculation. The hydrogen ion density near the peripheral region is observed to be about 25 – 40 % of the plasma density by the spectroscopic measurement [11]. The reason why such huge amount of hydrogen can be observed, is due to the hydrogen injection from NBI. The total neutral particle amount from central region in the pure argon plasma is only 1/10 times of that in hydrogen plasma, and that from the peripheral region is comparable. Much contribution of the charge exchange neutral particle near the peripheral region, means that the ion

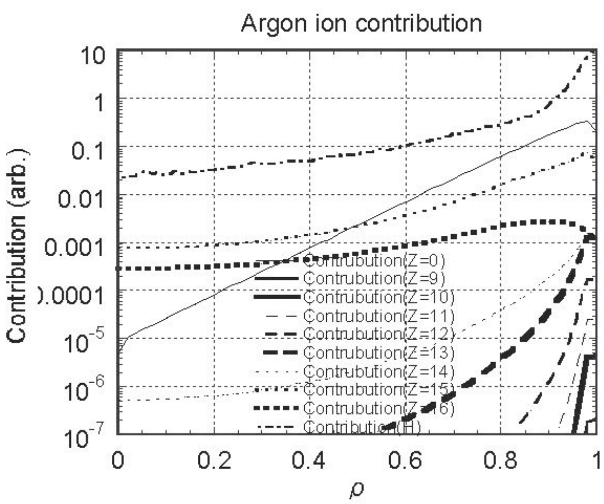

Fig. 3 The contribution distribution of neutral particles from the charge exchange cross section between argon ion and proton. The contribution means the amount of the charge exchange neutral particles, (products of the proton density, target density and cross section). In calculation the proton density is assume to be $\sim 0.3 \times n_e$ because proton remains to be 25 – 40 %. Ion temperature profile is similar to be the electron temperature but the peak value is equal to be 10 keV. The argon ions with low charge states are too few to generate the neutral particles.

temperature may be estimated to be lower, because the temperature at the peripheral region is low. In actually, the poloidal scanned temperature profile in the (line averaged) charge exchange neutral particle measurement seems to be flat in LHD [12]. Therefore we consider argon and hydrogen charge exchange processes on the argon plasma in LHD.

4. Ion temperature result in high *Z* plasma

We calculate the ion temperature on high *Z* plasma in LHD based on the previous argument. The hydrogen background neutral is calculated by the Aurora code using the electron density and temperature profiles which are obtained from the Thomson scattering measurement and the far infrared laser interferometer. Figure 4 shows the typical background neutral profile. The profile shape of the ion temperature is assumed to be the electron temperature profile. The factor means the ratio of the slope between the higher energy (it means the central temperature) and at the observed energy. As mentioned in Sec. **1**, the slope of the high-energy tail in the spectrum reflects the ion temperature in principle. However the decelerated NBI#2 particle component is overlapped around the tail. At first, the temporal temperature is obtained using the slope of the spectrum at a lower energy range. The correction factor can be obtained by using simple model as shown in Fig. 5. The result in Fig. 4 is used at calculating the correction factor. The central temperature is obtained from multipli-

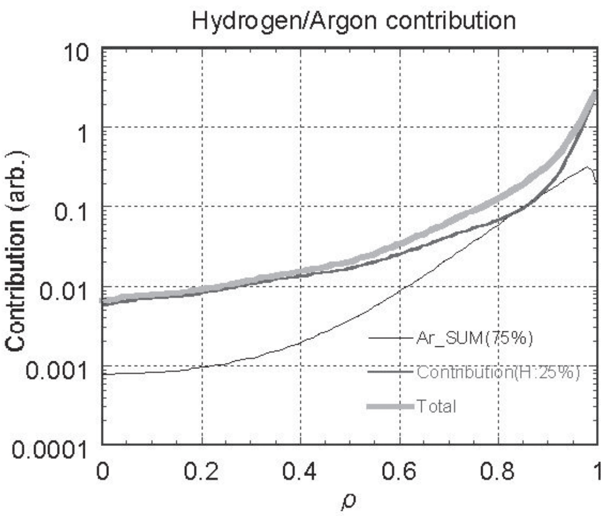

Fig. 4 Calculated background neutral considering the hydrogen component only. In this calculation, the proton density profile shape is assumed to be same as the electron density profile but the value is 30 % of the electron density according to reference 11 (new). Ion temperature profile is similar to be the electron temperature but the peak value is equal to be 10 keV.

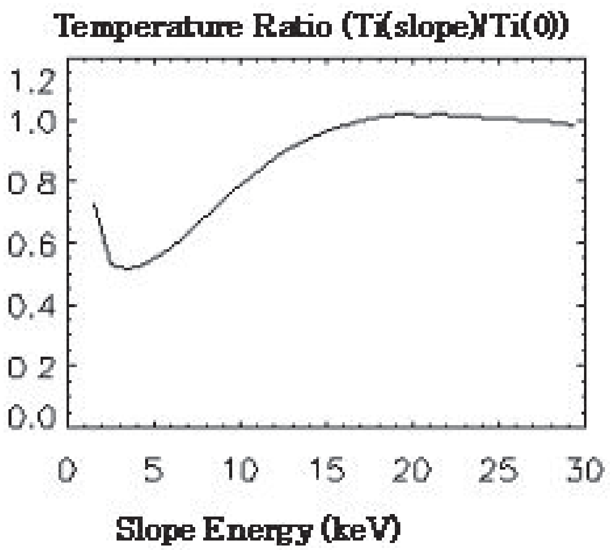

Fig. 5 The correction factor to obtain the ion temperature.

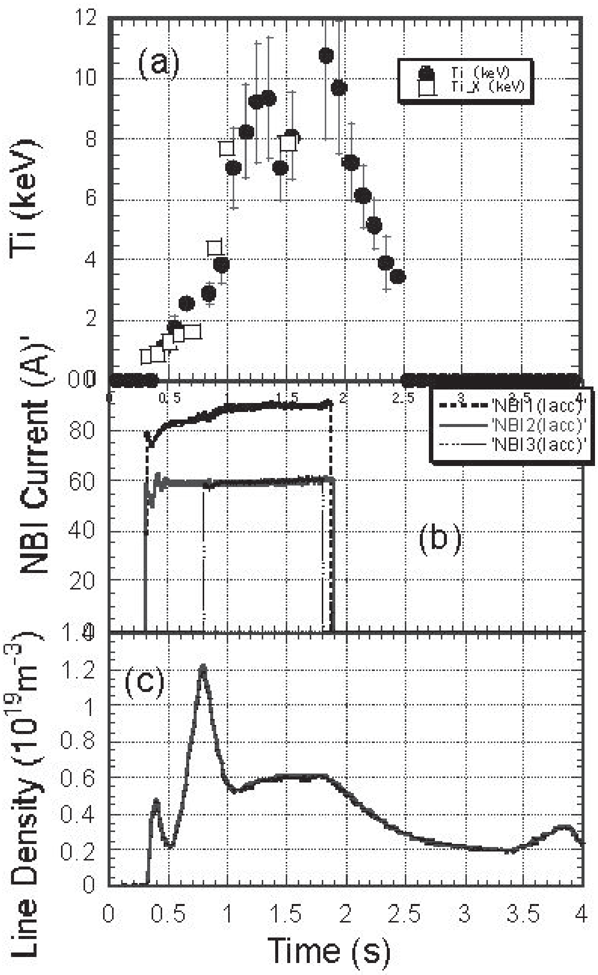

Fig. 6 The time history of the ion temperature.The temperature from charge exchange neutral measurement is compared with that from the crystal spectroscopy. (a) The time history of the ion temperature, (b) NBI, (c) Line density.

cation of the temporal temperature and the correction factor. The factor means that the temporal temperature is obtained not at but near the center, the central temperature can be obtained if the similarity between the electron and ion temperature profiles is assumed. Figure 6 shows the time history of the typical ion temperature and comparison with the temperature from the crystal spectroscopy. From this result, the large deviation between both temperatures cannot be found. The difference of ion temperature is checked when the diffusion coefficient is changed. The large deviation of temperatures cannot be found even if the diffusion coefficient is varied.

5. Summary

In LHD, the discharges of high Z plasma are often performed in order to obtain a high ion temperature. In calculation, we also consider the charge exchange between the partially ionized high Z ion and proton. The contribution of neutral particle from the charge exchange between argon and proton is small near the center but cannot be neglected near the peripheral region comparing with that of hydrogen charge exchange. We calculate the ion temperature on considering the hydrogen plasma in spite of high Z plasma in LHD. From this result, the large deviation between both temperatures cannot be found even if the diffusion coefficient is varied. One of the reasons may be that the energy transfer between the proton and argon ion is steady because the collision cross section between both ions is large.

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