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Plasma Diagnostics Using Two-Component Neutral Beam

By

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Abstract

A method is proposed for simultaneously determining the electron temperature and the density of a plasma by using a two-component neutral beam of argon and hydrogen. The feasibility of this method has been demonstrated on the tokamak NOVA II, using an argon and a hydrogen beam separately. The electron temperature was determined from the attenuation of an argon beam. In the central electron temperature from 100 to 250 eV, the results obtained are in good agreement with the line-averaged values of the electron temperature estimated from the temperature and density profiles which have been measured by the Thomson scattering. The ion density was determined with a hydrogen beam, and was found to be consistent with the electron density measured by microwave inter-ferometry. This method of a two-component neutral beam probing can be applied to the diagnostics of the scrape-off layer plasmas in large devices.

1. Introduction

The plasma probing with a neutral particle beam is one of the most promising methods for the diagnostics of high temperature plasmas. Its space and time resolutions are excellent without significantly perturbing the object plasma, provided that the species and the energy of the beam particles are properly chosen.

In this paper, a new method of plasma probing is proposed for simultaneously determining the electron temperature and the density, using a two-component neutral beam of argon and hydrogen. For the purpose of demonstrating the feasibility of this method, two kinds of experiments were performed on the tokamak NOVA II(1), using an argon and a hydrogen beam separately. The line-averaged electron temperature was determined from the transmission of an atomic argon beam passing through the plasma column, while the ion density was obtained by using a neutral hydrogen beam.

It was pointed out that the transmission measurements with an atomic argon beam could be used for determining the line-averaged electron temperature(2,3). This technique was successfully applied to a turbulence-heated plasma(4). In

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earlier works, however, the results were not comparatively examined with those of other reliable methods. In this paper, the results obtained by using an atomic argon beam probe (" beam-probe temperature ") are comparatively shown with the electron temperature obtained through the Thomson scattering experiment (" Thomson temperature "). The central electron temperature was in the range from 100 to 250 eV, while the line-integrated electron density, $\int n_e dl$, lay around 1.6×10^{14} cm^{-2}. The beam-probe temperature is in good agreement with the line-averaged value of the Thomson temperature. Because of its high resolution in space and time, this method of plasma probing can follow the behaviors of magnetically confined plasmas. Unfortunately, however, the applicability of this method is limited to a plasma temperature lower than about 200 eV.

It has been known that the ion density can be determined from the transmission of a fast hydrogen or alkali-metal beam[2,4,5~15]. This technique has been extensively examined in comparison with microwave inter-ferometry and electro-static probing[4,7,10,14,15]. The effects of impurity ions on the hydrogen beam probing was pointed out in the course of the TM-3 experiments[7]. The impurity effects were also investigated in detail on the TFR[14,15].

The authors' proposal is to combine this established technique with the above mentioned neutral argon beam probing in the form of a two-component beam probe, for simultaneous measurements of the line-averaged electron temperature and the density. In §2, the principle of the neutral beam attenuation method is described, including a proposal of the two-component beam probing. The experimental arrangement is shown in §3. The experimental results of the transmission measurements with an atomic argon beam are described in §4, and the results with an atomic hydrogen beam follow in §5. A summary and discussion are given in §6. It is shown in this section that the proposed method of the two-component neutral beam probing can be applied to the diagnostics of scrape-off layer plasmas in large machines.

2. Principle

We consider a magnetically confined hydrogen plasma. When a neutral beam of intensity I_0 is injected into the object plasma, a fraction of the injected beam is ionized and deviates from the original straight beam path. If we choose the velocity of the probing beam v_b so that $v_0 \ll v_b$ and $v_{\mathrm{thi}} \ll v_b \ll v_{\mathrm{the}}$, where v_0, v_{thi}, and v_{the} are the thermal velocities of the residual neutral gas, plasma proton, and electron, respectively, the beam intensity I becomes

$$I = I_0 \exp\left\{ -\left(\bar{n}_e L_p \frac{\langle \sigma_e v \rangle}{v_b} + \bar{n}_p L_p (\sigma_{cx} + \sigma_i) \right.\right.$$

$$+\sum_{j}\bar{n}_jL_p(\sigma_{cx,j}+\sigma_{i,j})+\bar{n}_0L_0\sigma_{st}\Big)\Big\}, \tag{1}$$

after passing through the plasma of the path length L_p and the peripheral neutral gas region of the path length L_0. The beam transmission is defined by the ratio I/I_0. Here, $\bar{n}_e$, $\bar{n}_p$, $\bar{n}_j$ and $\bar{n}_0$ are the line-averaged densities of the electrons, protons, impurity ions of the j-type species and residual neutrals; σ_{cx} and σ_i are the cross sections of the beam species for the charge transfer with proton and ionization by the proton impact; $\sigma_{cx,j}$ and $\sigma_{i,j}$ are the charge transfer and ionization cross sections for collisions between the beam particles and impurity ions; $\langle\sigma_e v\rangle$ is the rate coefficient of ionization by the electron impact, and σ_{st} is the cross section for the charge stripping by the molecular hydrogen impact, respectively. The summation Σ_j should be taken over impurity ion species and their multiple charged states.

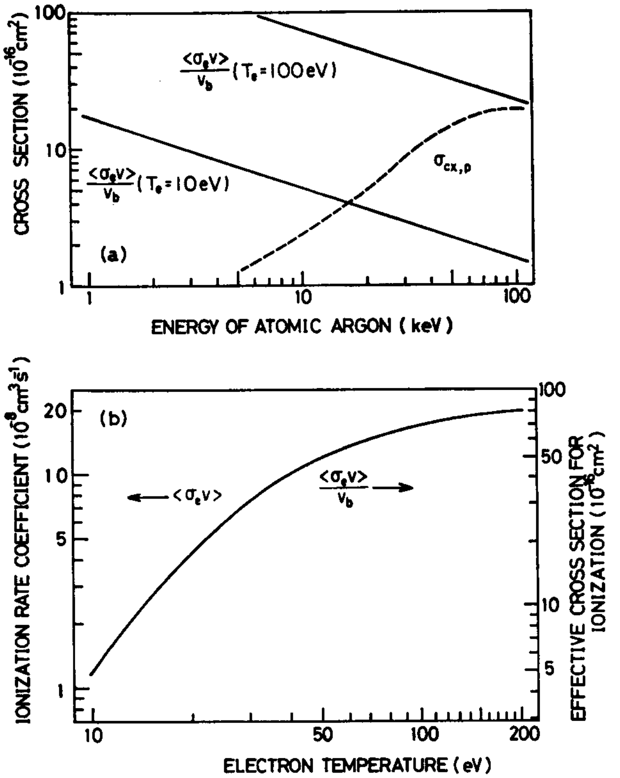

Fig. 1. (a) Cross sections of atomic argon for ionization by electron impact $\langle\sigma_e v\rangle/v_b$ and charge transfer with proton $\sigma_{cx,p}$, where v_b is the velocity of argon. (b) Ionization rate coefficient $\langle\sigma_e v\rangle$ and effective cross section $\langle\sigma_e v\rangle/v_b$ of 10-keV atomic argon by electron impact as functions of electron temperature.

Figure 1(a) shows the cross sections of atomic argon for the ionization by electron impact and for the charge transfer with proton[2,16~19]. In Fig. 1(b), the rate coefficient and the effective cross section for the ionization of 10-keV atomic argon by electron impact are shown as functions of the electron temperature. The charge transfer cross section of atomic argon with multiple charged carbon ions is of the order of magnitude 10^{-15} cm^2 [20]. Moreover, the concentration of impurity ions is as low as a few % of the density in the number of plasma particles. Therefore, the effect of impurity ions on the attenuation of the atomic argon beam is negligibly small. Thus, the first term is dominant on the r.h.s. of Eq. (1). In this situation, the transmission of the argon beam is approximately given by

$$I=I_0 \exp\left(-\bar{n}_e L_p \frac{\langle\sigma_e v\rangle}{v_b}\right). \tag{2}$$

Since the ionization rate coefficient $\langle\sigma_e v\rangle$ in this expression is strongly dependent upon the electron temperature, as shown in Fig. 1(b), the electron temperature can be determined by transmission measurements, provided that the line-averaged electron density is known.

Figure 2 shows the cross sections of atomic hydrogen for a charge transfer with ionization by proton, ionization by electron impact, and charge stripping by mo-

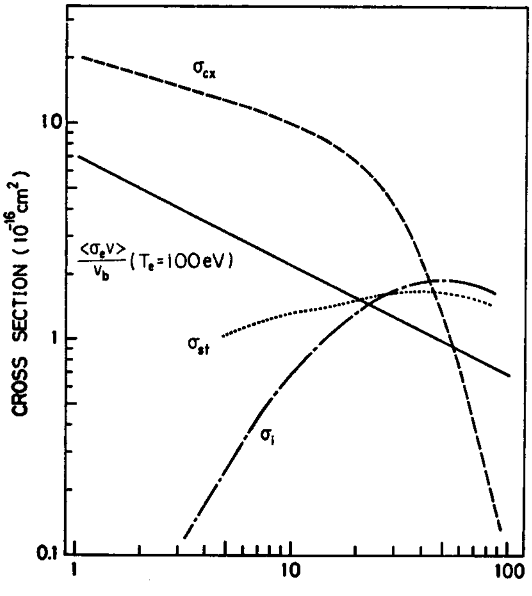

Fig. 2. Cross sections of atomic hydrogen for charge transfer with proton σ_{cx}, ionization by proton impact σ_i, ionization by electron impact $\langle\sigma_e v\rangle/v_b$, and charge stripping by molecular hydrogen σ_{st}.

lecular hydrogen[21,22]. In the case of a fast hydrogen beam, therefore, the attenuation is mainly due to the charge transfer or proton impact. Accordingly, Eq. (1) can be rewritten as

$$I=I_0\exp\left\{-\left[\bar{n}_eL_p\frac{\langle\sigma_ev\rangle}{v_b}+\bar{n}_pL_p(\sigma_{cx}+\sigma_i)+\bar{n}_0L_0\sigma_{st}\right]\right\}. \tag{3}$$

Using this relation, the plasma proton density $\bar{n}_p$ can be determined by transmission and electron density measurements.

The following expression for the plasma capture cross section σ_c can be derived from Eq. (1)

$$\begin{aligned}\sigma_c&=\frac{1}{\bar{n}_eL_p}[\ln(I_0/I)-\bar{n}_0L_0\sigma_{st}]\\&=\frac{\langle\sigma_ev\rangle}{v_b}+\frac{\bar{n}_p}{\bar{n}_e}(\sigma_{cx}+\sigma_i)+\sum_j\frac{\bar{n}_j}{\bar{n}_e}(\sigma_{cx,j}+\sigma_{i,j}).\end{aligned} \tag{4}$$

This expression shows that impurity ions can bring about an appreciable deviation of the capture cross section from that of a pure hydrogen plasma. On this account, the concentration of impurity ions, or the effective ion charge Z_{eff}, can be estimated from the deviation observed in the capture cross section.

It is possible to measure the beam transmission in the range from 0.1 to 0.9 with a sufficient accuracy. In the case of an electron temperature measurement with a 10-keV argon beam, this range of beam transmission corresponds to the line-integrated densities from 2×10^{14} to 5×10^{15} cm^{-2} for an electron temperature around 10 eV, and to densities from 1×10^{13} to 3×10^{14} cm^{-2} for a temperature around 100 eV, respectively. For the ion density measurement with a 10-keV hydrogen beam, the density region is from 1×10^{14} to 2×10^{15} cm^{-2}, irrespective of the electron temperature. The same instrumentation is used for the argon-beam and the hydrogen-beam transmission measurement. Therefore, both measurements can be performed simultaneously with a single system of instrumentation in the density region from 1×10^{14} to 2×10^{15} cm^{-2}, depending upon the electron temperature.

In this paper, the authors propose a new method of transmission measurement using a two-component neutral particle beam of argon and hydrogen. By mass- and energy-analysis of the transmitted neutral particles, the time behaviours of both the electron temperature and the density can be determined simultaneously. The two-component neutral beam can be obtained without difficulty by applying a mixture of argon and hydrogen to the ion source, using a neutralizing gas of either hydrogen or argon. By choosing an adequate beam energy, the applicability of the proposed technique of beam probing can be considerably extended.

3. Experimental Arrangement

A series of experiments were performed on the neutral beam transmission

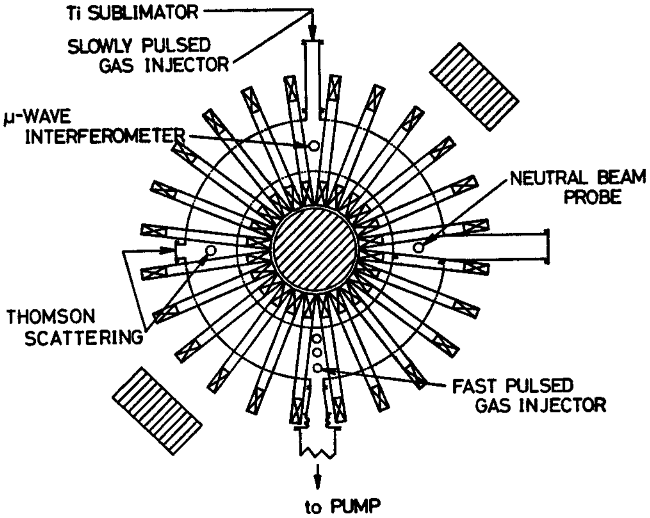

Fig. 3. Top view of the experimental arrangement.

measurements with the NOVA II ($R=30$ cm, $a=6$ cm, where R and a are the major and the minor radii, respectively), using a neutral argon and a hydrogen beam separately. A top view of the experimental arrangement is schematically shown in Fig. 3. For the purpose of reducing impurity ions as well as to control gas recycling, the well-known techniques of titanium gettering and gas puffing have been applied. The line-averaged electron density $\bar{n}_e$ was measured with a 6-mm microwave inter-ferometer, while the radial profiles of the electron temperature $T_e(r)$ and density $n_e(r)$ were determined by the method of Thomson scattering.

The time sequence of the gas puffing is as follows. A slowly pulsed gas injector was actuated about 10 ms before the start of discharge. The plasma density was maintained by this slow gas puffing during a discharge. In addition to this, a fast pulsed gas injector was actuated about 2 ms before the ignition, in order to suppress the production of runaway electrons and to reduce the interaction between the plasma and the limiter in the current rise stage. In the methane-gas injection experiments, which will be described in §5, the base plasma was produced by the slow gas puffing only, and the methane gas was injected via the fast pulsed gas injector after attaining a quasi-steady state of discharge.

The toroidal magnetic field intensity was typically 1.0T. In the experiments of the neutral argon beam transmission measurements, the plasma current was varied from 5 to 11 kA in order to vary the electron temperature, while the average electron density was kept around 1.4×10^{13} cm^{-3}. In the hydrogen beam transmission measurements, the plasma current was typically 10kA, and the average electron density was varied from 1.3×10^{13} to 2.0×10^{13} cm^{-3}.

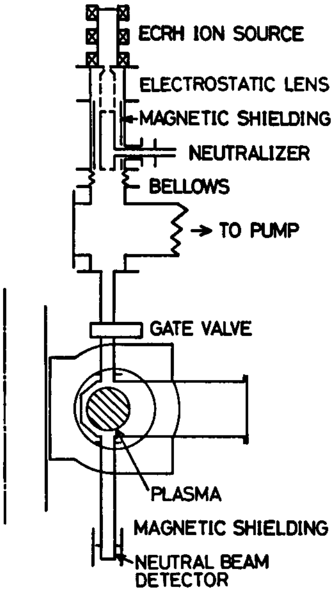

Fig. 4. Schematic view of the apparatus used for neutral beam probing.

As shown in Fig. 4, the apparatus used for neutral beam probing consists of the ion source, the electro-static lens, the gas cell for neutralization, and the neutral beam detector. The source plasma is produced by the electron cyclotron resonance at 2.45GHz. The extracting electrode, the electro-static lens, and the neutralizer gas cell provide the neutral beam for plasma probing of energies from 4 to 20keV. The beam diameter is 4 mm, which is determined by the entrance and exit slits of the neutralizer gas cell and by the aperture slit of the gate valve. The intensity of the transmitted neutral beam is measured with a neutral beam detector. A Faraday cup with a differential amplifier is used in order to suppress the detector noise due to plasma radiations. The equivalent current of neutrals is 0.1 to 10 μA at the detector, 150 cm away from the extracting electrode. The beam injector is evacuated to a pressure of 1×10^{-5} Torr by a differential pump.

4. Transmission Experiment with Atomic Argon Beam

Figure 5 shows the time behaviors of the plasma current I_p, the loop voltage V_l, the line-averaged electron density $\bar{n}_e$, and the intensity of the transmitted 10-keV argon beam I. The plasma capture cross section σ_c can be determined from Eq. (4): Using the measured values of the plasma parameters in this expression, the result in the quasi-steady state of discharge is as shown in Fig. 6. This figure shows that the capture cross section is inversely proportional to the beam velocity v_b or $\sqrt{E_b}$,

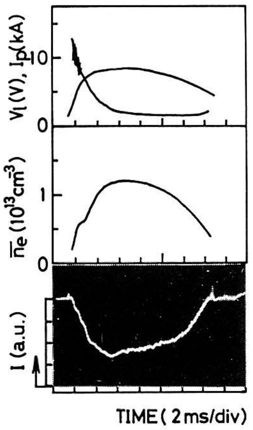

Fig. 5. Intensity of the transmitted 10-keV argon beam I with the time behaviors of the loop voltage V_l, the plasma current I_p, and the line-averaged electron density $\bar{n}_e$.

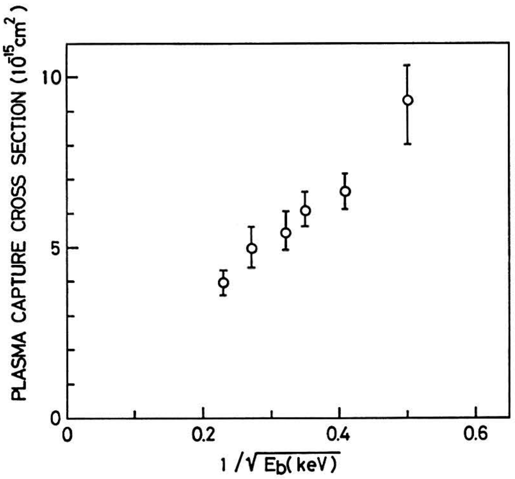

Fig. 6. Plasma capture cross section σ_c determined in the quasi-steady state of discharge as a function of the beam energy E_b. The abscissa is $1/\sqrt{E_b}$, which is inversely proportional to v_b.

where E_b is the beam energy. This indicates that the attenuation of the neutral argon beam passing through the hydrogen plasma was mainly due to ionization by the electron impact (the first term on the r.h.s. of Eq. (4)), and that impurity ions did not appreciably ionize the argon beam.

The beam-probe temperature $T_e{}^B$ was determined from the transmission measurement. The results versus the plateau value of the plasma current I_p are shown by the open circles in Fig. 7. The Thomson temperature at the center

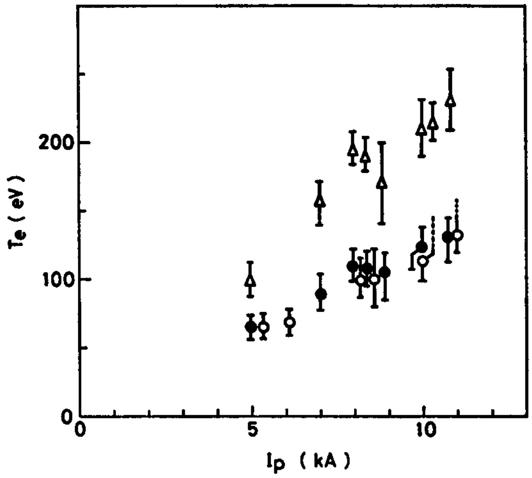

Fig. 7. Three kind of electron temperature in the quasi-steady state of discharge as functions of the plateau value of plasma current I_p. Open circles: the beam-probe temperature $T_e{}^B$ determined from the transmission of 10-keV argon beam; triangles: Thomson temperature at the plasma center $T_{e0}{}^{\mathrm{Th}}$; filled circles: the line-averaged temperature $\overline{T}_e$ estimated from the temperature and density profiles which have been measured by Thomson scattering by using Eq. (5).

$T_{e0}{}^{\mathrm{Th}}$ is also shown in the figure by triangles. The average density was kept around $1.4\times 10^{13}\,\mathrm{cm}^{-3}$. All of the comparisons were made in a quasi-steady state of the discharge.

We define the line-averaged electron temperature $\overline{T}_e$ with respect to the effective cross section of the beam particles for ionization by electron impact by the following relation

$$\frac{\langle\sigma_e v\rangle}{v_b}(\overline{T}_e)=\frac{1}{n_e L_p}\int_0^{L_p} n_e(l)\frac{\langle\sigma_e v\rangle}{v_b}(T_e(l))\mathrm{d}l. \tag{5}$$

The typical radial profile of the electron temperature of NOVA II plasma is as shown in Fig. 8, which can be approximately expressed by

$$T_e(r)=[T_e(0)-T_e(a)][1-(r/a)^2]^2+T_e(a). \tag{6}$$

The electron density profile is also shown in Fig. 8, somewhat broader than the temperature profile, and can be expressed by

$$n_e(r)=[n_e(0)-u_e(a)][1-(r/a)^2]+n_e(a). \tag{7}$$

The line-averaged electron temperature $\overline{T}_e$, estimated by using the experimental data of the Thomson temperature in Eq. (5), is shown in Fig. 7 by the filled circles. The figure shows that the beam-probe temperature is in good agreement with the line-averaged Thomson temperature in the range from 100 to 250 eV of the central temperature. Disagreement is observed in the higher temperature region. This

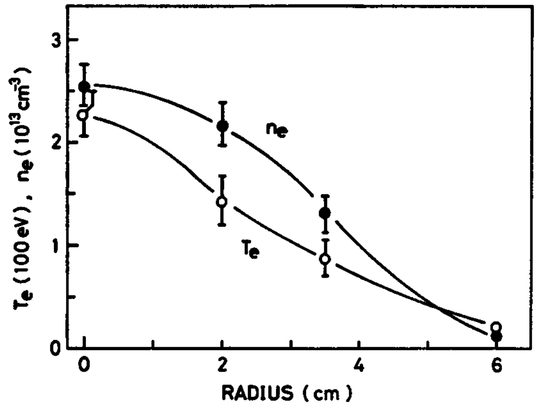

Fig. 8. Typical radial profiles of the electron temperature and density of the NOVA II plasma measured by Thomson scattering in the quasi-steady state.

is probably because the ionization rate coefficient depends weakly upon an electron temperature above 150 eV.

5. Transmission Experiment with Hydrogen Beam

The plasma ion (proton) density was determined from the transmission measurements with a 10-keV atomic hydrogen beam. The line-averaged electron density $\bar{n}_e$ varied from 1.3×10^{13} to 2.0×10^{13} cm^{-3}, while the plasma current was kept around 10kA. Comparisons are made between the proton and the electron density in a quasi-steady state of discharge. Figure 9 shows the proton density determined

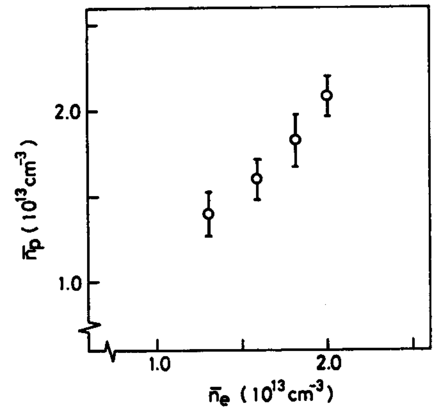

Fig. 9. Plasma proton density $\bar{n}_p$ determined from the transmission of 10-keV hydrogen beam as a function of the average electron density $\bar{n}_e$. Comparisons are made in the quasi-steady state of discharge.

from the transmission measurements by using Eq. (3) as a function of the average electron density. The proton density increases with an increased electron density so that the quasi-neutrality condition is satisfied without taking into account the impurity ions. This means that the proton density is consistent with the electron density measured by microwave inter-ferometry. This is also in agreement with the fact that the effective ion charge Z_{eff} estimated from the plasma resistivity was very close to unity.

Transmission measurements with a 10-keV hydrogen beam were performed through methane-injected hydrogen plasma. The methane gas was injected 4 ms after the ignition of the base hydrogen plasma of a density around 6×10^{12} cm^{-3}. The electron density increased up to 2×10^{13} cm^{-3} in about 1.5 ms, then a decrease with a decay constant of 2 to 3 ms followed. The plasma capture cross section was determined from the beam transmission measurement at the instant of the maximum density. It was observed in this experiment that the plasma capture cross section was reduced about 20% by the injection of methane. This observation is in agreement with the theoretical estimation derived from Eq. (4) by using the Olson-Salop model[23,24) in the calculation of the charge transfer cross section between hydrogen and multiple charged carbon ions. The details on the hydrogen beam transmission measurements performed through methane-injected hydrogen plasma will be described elsewhere.

Throughout the transmission experiment, inevitable fluctuations in the beam intensity and the limited reproducibility of the discharge condition caused considerable scattering in the experimental data.

6. Summary and Discussions

A method is proposed for plasma probing by a two-component neutral beam of argon and hydrogen. The feasibility of the proposed method has been demonstrated on the tokamak NOVA II by using an argon and a hydrogen beam separately. The results of the present experiments are summarized as follows:

(1) The electron temperature was determined from the transmission measurements of an atomic argon beam. In the region of the central electron temperature from 100 to 250 eV, the results obtained are in good agreement with the line-averaged values of the electron temperature estimated from the temperature and density profiles which were measured by the Thomson scattering.

(2) The proton density was determined by using an atomic hydrogen beam. The results are consistent with the electron density measurements by microwave interferometry in the region of the line-integrated electron density from 1.6×10^{14} to 2.4×10^{14} cm^{-2}. In other words, the plasma density $n(=n_e=n_p)$ can be obtained

from Eq. (3) by assuming $n_p=n_e=n$, provided that the concentration of impurity ions is small enough.

We will investigate the feasibility of the two-component neutral beam probe for simultaneous temperature and density measurements of the scrape-off layer plasma in a large device. For this purpose, we assume that the minor radius of the main plasma column is 1 m, and that the scrape-off layer is 20 cm thick. The chords 1 through 5 are five vertical chords each separated by 4 cm, with the innermost chord, chord 1, just passing the inner plasma boundary. The radial profiles of the electron temperature and density in the scrape-off layer are assumed so that $T_e(r)=\text{constant}=T_e(a)$ and $n_e(r)=n_e(a)\exp[-(r-a)/\lambda]$, where λ is the scale length of density gradient[25]. If we further assume that $n_e(a)=1\times10^{13}\ \mathrm{cm}^{-3}$, $T_e(a)=100\mathrm{eV}$ and $\lambda=10$ cm, then the transmission of the 10-keV argon beam becomes, for the chords 1 through 5, 0.005, 0.03, 0.14, 0.47, and 0.73, respectively. The beam energy should be increased as high as 30 keV for the plasma probing along chords 1 and 2 for a sufficiently accurate measurement of transmission. The density can be determined from the transmission of a hydrogen beam with the same instrumentation. The transmission of a 10-keV hydrogen beam becomes 0.41, 0.55, 0.71, 0.80, and 0.95, for the chords 1 through 5, respectively. For chord 5, the beam energy of 2 to 3 keV is adequate for an accurate measurement of transmission.

The above estimates, as well as the cross section data shown in Figs. 1 and 2, indicate that we can determine the electron temperature and the density of the assumed scrape-off layer plasma simultaneously by a two-component neutral beam of 2- to 30-keV energy with a sufficient accuracy. Thus, the proposed method of a two-component neutral beam probing can be applied to the diagnostics of the scrape-off layer plasmas in large machines.

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