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MEASUREMENTS OF BALMER Hα-LINE EMITTED FROM TOKAMAK PLASMAS IN JFT-2a DEVICE

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Measurements of Balmer H_α-Line Emitted from Tokamak Plasmas in JFT-2a Device

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Visible radiation of Balmer H_α-line has been spectroscopically investigated on hydrogen tokamak plasmas in JFT-2a device with toroidal magnetic field 10 kG, plasma current 15 kA and ratio of divertor to plasma currents 1.1. The profiles of H_α-line were measured on the equatorial plane horizontally along both perpendicular and tangential paths to the toroidal magnetic field, and vertically along different three paths in the minor cross-section. The typical measured profiles are interpreted in terms of the doppler broadening at line wings due to high-temperature hydrogen atoms originating through the resonance charge-exchange process and the doppler broadening at the line center due to low-temperature particles corresponding to Franck-Condon neutrals from dissociation of molecular hydrogen neutrals or ions. The peak value of doppler temperature for the hot particles is approximately 50 eV, and temperature of the cold neutrals is a few--several eV. It is noticed that equal temperatures are obtained in measurements along perpendicular and tangential directions to the toroidal magnetic field. Distributions in the minor cross-section of photon numbers of H_α-line are measured, from which the confinement time of charged particles is determined to be 0.5--2.5 msec.

JFT−2a トカマクプラズマから放射されるバルマーH_α線の測定

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JFT−2a 装置の水素トカマクプラズマ（トロイダル磁場強度10 kG，プラズマ電流10 kA およびダイバータ電流対プラズマ電流比1.1）について，バルマーH_α線の可視域放射を分光学的方法で究明した。バルマーH_α線プロファイルの測定は，磁力線（トロイダル磁場）に対して垂直および接線方向光路に沿って赤道面上において水平方向に，またプラズマ断面内で三つの異なる光路に沿って垂直方向に行った。典型的なプロファイルは，その翼部における共鳴電荷交換によって生ずる高温な水素原子によるドップラー拡がり，およびプロファイル中心部における中性水素分子あるいはその分子イオンの解離過程において生ずるFrank − Condon 中性水素原子による拡がりとによって説明される。ドップラー温度の高温成分の最大値は約50 eV，低温成分は数eVである。更に，磁力線に対して垂直および接線方向の温度成分が等しいことを示す測定結果が得られた。またH_α線の光子数のプラズマ断面における分布の測定を行ない，荷電粒子閉じ込め時間0.5〜2.5 msec なる値を得た。

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1. INTRODUCTION

The spectroscopic measurements on high-temperature tokamak plasmas provide important information for the following physical quantities. That is,

(a) doppler temperatures of spectral lines emitted from resulting impurities and operating gases, i.e., hydrogen, deuterium or helium atoms (or ions),

(b) confinement times of charged particles and densities of operating-gas atoms from measurements of absolute intensities of spectral lines emitted from operating gases,

(c) radiation losses emitted from hot plasmas, quantities of impurities and the effective plasma charge from absolute measurements of impurity lines, and

(d) transports of impurity-ions.

The present paper is the first report of spectroscopic investigations on JFT-2a device in JAERI, which is describing measurements on broadenings and doppler temperatures of Balmer H_{α}-line, confinement times of charged particles and neutral-hydrogen atom densities. Results of impurity studies (mainly on light elements such as oxygen, carbon and nitrogen) from measurements in a vacuum-ultra-violet region will be published in ref. 1.

Up to now a few works have been reported on measurements of doppler temperatures for hot tokamak plasmas.[2-4] The first measurement of doppler temperatures on tokamak plasmas was reported by Mirnov and Semenov.[2] They measured the doppler profiles of H_{α}-line emitted from hydrogen-atoms which were added in a short pulse to deuterium plasmas in T-3 device. In their report the measured doppler temperatures were from 50 to 150 eV and from 0.5 to 0.7 of ion temperatures determined from energy spectra of charge-exchanged, neutral particles. Dimock et al.[3] determined in Princeton ST tokamak device the distribution of ion temperatures from measurements of doppler temperatures of CIV(1548 Å) and OVII(1623 Å) lines which were located in specified positions of a minor cross-section and the central temperature from neutral-particle energy spectra. Emission spectra of hydrogen-atoms on ORMAK device in ORNL were measured with a rapid-scanning spectrometer by McNally and Neidigh,[4] which were characteristic of the initial proton motions prior to the charge-exchange process and doppler-broadened in the wings of the spectral lines. The doppler temperatures 70 -- 250 eV from broadenings of hydrogen-atom lines were less than those from CIII, CIV and OV lines in their measurements.

In tokamak plasmas the confinement times of charged particles are usually deduced from measurements of electron densities and ionization rates of neutral-hydrogen or operating atoms by using a straightforward, particle-balance equation of charged particles.[3,5--7] The ionization rates can be estimated[8,9] from absolute photon numbers of a spectral line of operating gases and calculations based on the collisional-radiative model.[10] Some papers described significant effects due to ionizations of impurities on the confinement times of charged particles.[5,11] However, many related works have often adopted the particle confinement times which are determined by neglecting the effects of impurities, in order to evaluate confinement times of particles in individual tokamak devices. We also present the (apparent) particle confinement time on JFT-2a plasmas in the present report.

We will present briefly JFT-2a device and experimental arrangements in the next section. In Section 3, experimental results will be mentioned on doppler broadenings and photon numbers of H_α-line and the confinement times of charged particles. Section 4 is devoted to some discussions on comparisons between doppler temperatures and proton temperatures and on influences of impurity-ionizations on the particle confinement times. Finally, we are going to summarize the present studies on JFT-2a plasmas.

2. JFT-2a DEVICE AND EXPERIMENTAL ARRANGEMENTS

The JFT-2a device is a non-circular tokamak with fundamental parameters of the maximum toroidal magnetic field 10 kG, major radius 60 cm, treadrop-like minor cross-section 10.5 cm × 14 cm in radius (of the shell), plasma current $I_p \lesssim 25$ kA, and divertor current $I_D \simeq (1.1 -- 1.4)\ I_p$. The detailed descriptions of the device have been reported in ref. 12. The typical hydrogen-plasma parameters are follows, i.e., the average electron density is about 10^{13} cm^{-3}, and the central electron and ion temperatures are approximately 200 eV and 100 eV respectively[12c] from measurements on Thomson scattering of a ruby laser light and energy spectra of charge-exchanged, hydrogen atoms.

Figure 1 shows a plan view of JFT-2a device.[12] In the present experiments a 100 cm Czerney-Turner spectrometer (SPEX 1802) is used to determine broadened profiles and total intensities of Balmer H_α-line. The spectrometer is placed on the equatorial plane to observe through D5 port horizontally the H_α-line intensities integrated along both perpendicular and tangential directions to the toroidal magnetic field by using an optical mirror, in order to compare the perpendicular, doppler temperatures with the parallel temperatures. To determine spatial distributions of broadenings and intensities of H_α-line in the minor cross-section, the spectrometer is also able to measure vertically the integrated intensities along different vertical paths through D_1II port by using an additional optical system. Total intensities of H_α-line are measured horizontally on the equatorial plane along perpendicular directions to the toroidal field through side ports D5, D_2II and D4, in order to confirm the inhomogeneity in the toroidal direction. Through D5 port, the total intensities are also observed along two tangential directions to the toroidal field. One of these tangential optical paths aims at the center in the minor cross-section, whose toroidal position is one furnished with a limiter as shown in the figure. Microwave interferometers operating at 70 GH_Z-band are used to measure through D_1I port the electron densities averaged along five vertical paths, R = 45, 51, 57, 63 and 69 cm with the major radius R.

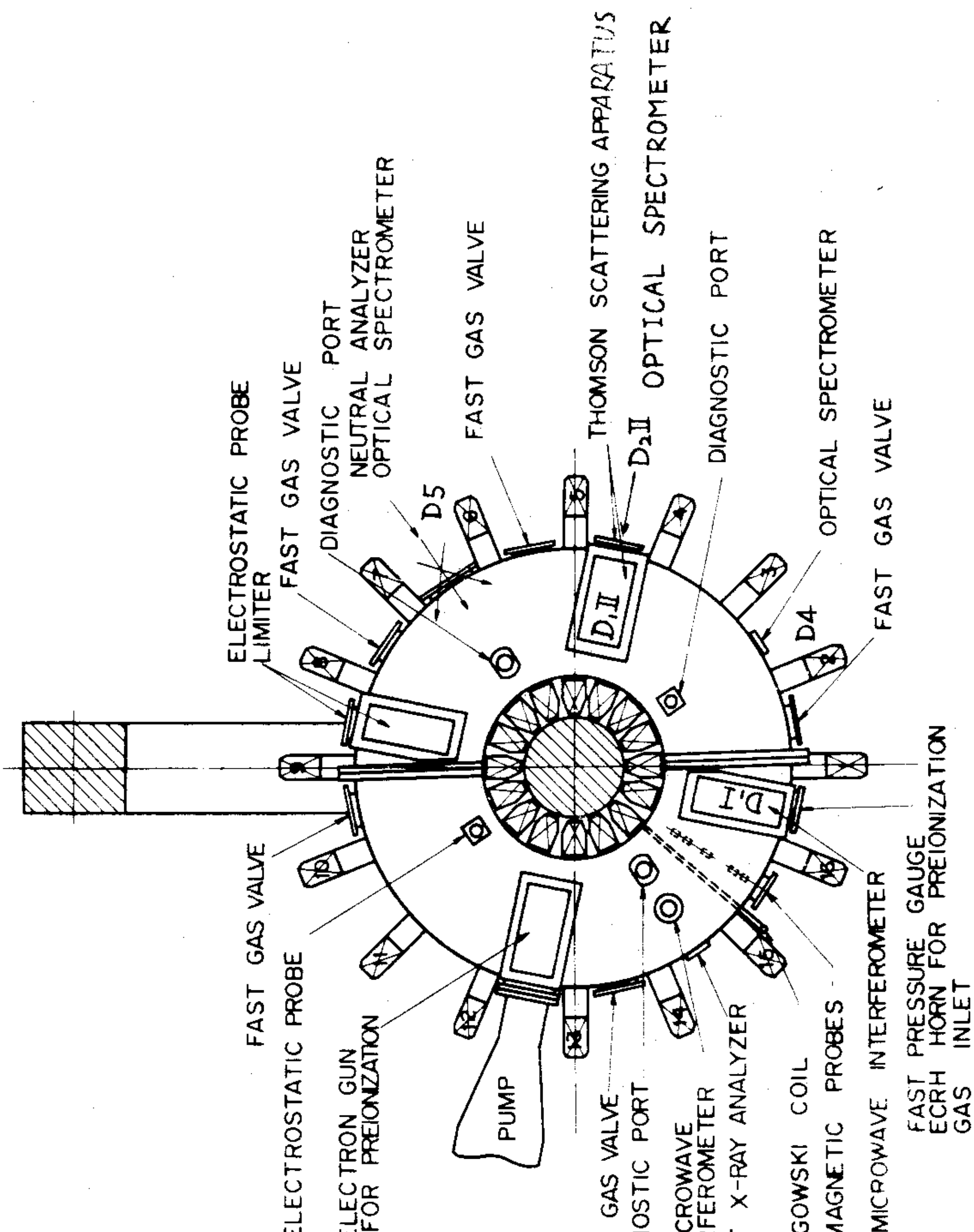

Fig. 1 Plan view of JFT-2a device and diagnostic apparatus.[12)]

3. EXPERIMENTAL RESULTS

3.1 Plasma parameters

Figure 2 provides basic plasma parameters under the typical operating condition[12c] of JFT-2a device, i.e., the toroidal magnetic field $B_t = 10$ kG, peak plasma current I_p = 15 kA, and ratio of divertor current to plasma current I_D/I_p = 1.1. In the figure are shown time evolutions of the electron density averaged along a vertical path R = 63 cm with a 70 GH_Z-wave interferometer, loop voltage, $I_D + I_p$, and I_D for the filling pressures in plenums of fast acting valves[12a] 132 Torr in H_2.

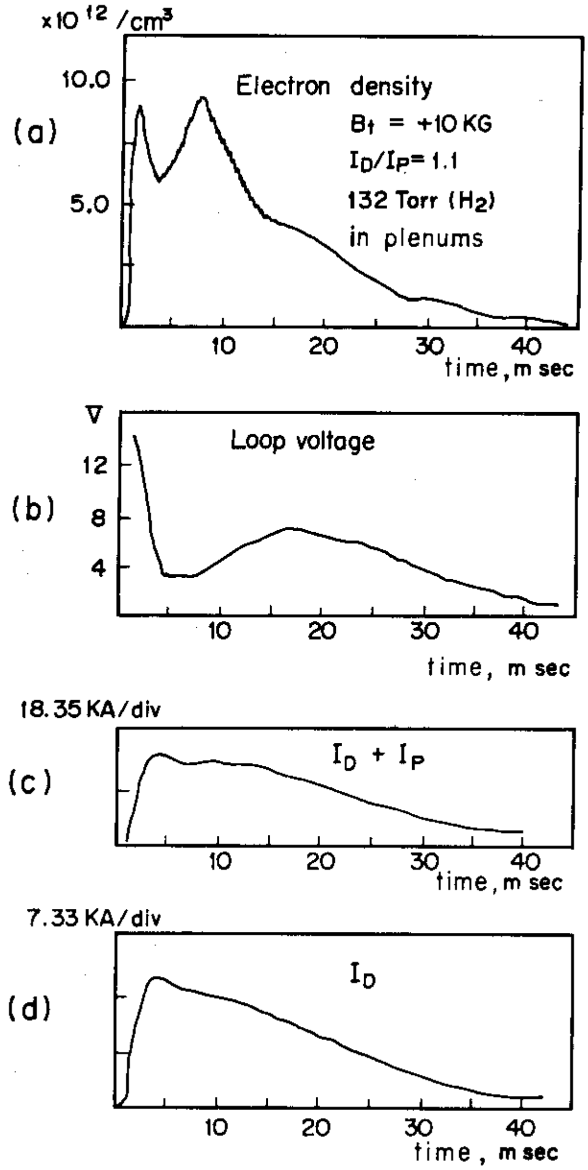

Fig. 2 Time evolutions of the electron density averaged along R = 63 cm (a), loop voltage (b), divertor current plus plasma current $I_D + I_p$ (c), and divertor current I_D (d).

3.2 Doppler profile of H_α-line radiated from charge-exchanged, hydrogen atoms

The doppler profile $I(\Delta\lambda)$ of a spectral line radiated from particles with the Maxwellian velocity-distribution of a temperature T is expressed by the following equation.[13,14)]

$$I(\Delta\lambda) = \frac{I_t}{\sqrt{\pi}\Delta\lambda_D} \cdot \exp\left[-\left(\frac{\Delta\lambda}{\Delta\lambda_D}\right)^2\right] \quad \text{------------------} \quad (1)$$

with

$$\Delta\lambda_D \equiv \frac{\lambda_0}{c} V_T = \frac{\lambda_0}{c}\left(\frac{2RT}{\mu}\right)^{1/2} \quad \text{------------------} \quad (2)$$

where I_t is the total intensity of the spectral line, $\Delta\lambda$ the displacement of wavelength from the line center λ_0, c the light velocity, V_T the thermal velocity of the radiating particles, R the gas constant, and μ the atomic weight of the radiating particles. The full width $\Delta\lambda_D^{(1/2)}$ of the spectral line at a half of the maximum intensity is given by a well-known equation, i.e.,

$$\Delta\lambda_D^{(1/2)} = 7.70 \times 10^{-5} \cdot \lambda_0 \left[\frac{T(eV)}{\mu}\right]^{1/2} \quad \text{------------} \quad (3)$$

From Eqs. (1) and (2), a semi-logarithmic plot of intensity profile $I(\Delta\lambda)$ versus $(\Delta\lambda)^2$ gives a straight line corresponding to the temperature T of the radiating particles.

Figures 3(A) and (B) provide the measured profiles of Balmer H_α-line (λ_0 = 6562.8 Å) in a linear plot at 7 msec and at 8 msec after a breakdown of JFT-2a discharge. These profiles are obtained by scanning a wavelength of the spectrometer and by assuming the shot-to-shot reproducibility of the plasma. The intensity is observed horizontally on the equatorial plane along the central major-radius direction (perpendicularly to the toroidal magnetic field). It is found from these figures that the observed profile consists of a bright, peaked component at the line center and a broad, high-energy component at the line wings superposed on the central narrow intensity.

The semi-logarithmic plots of these profiles are shown in Figs. 4(A) and (B), where the results measured for a few plasma-shots under the same operating condition are also presented to confirm the shot-to-shot reproducibility of the plasma. These figures show clearly that there are the cold component with a few -- several eV and the hot portion of about

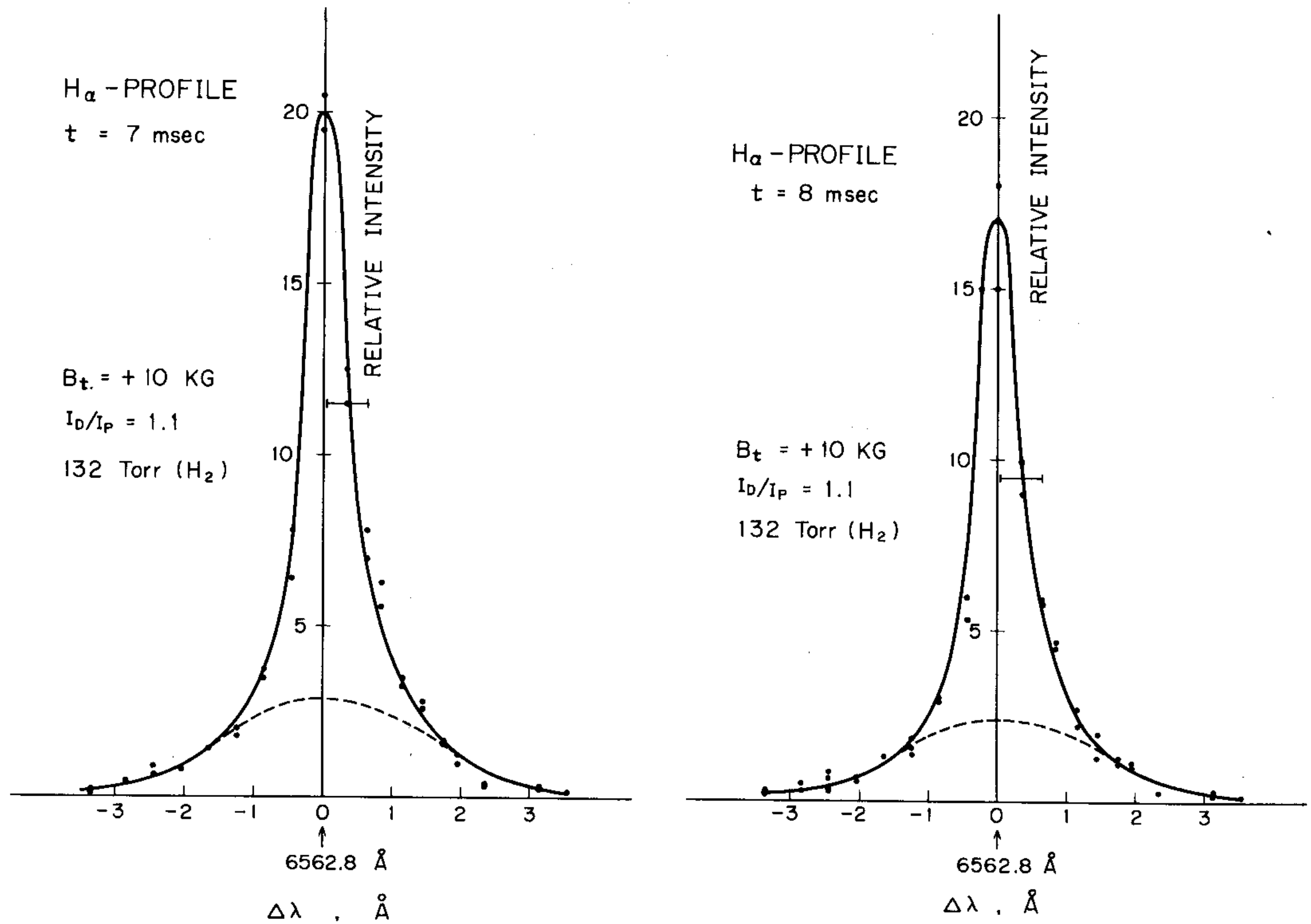

Fig. 3 Measured profiles of Balmer H_α-line in a linear plot at (A) 7 msec and (B) 8 msec after a breakdown of JFT-2a discharge. The operating condition is $B_t = 10$ kG, $I_p = 15$ kA, $I_D/I_p = 1.1$ and plenum pressures of fast acting valves 132 Torr in H_2.

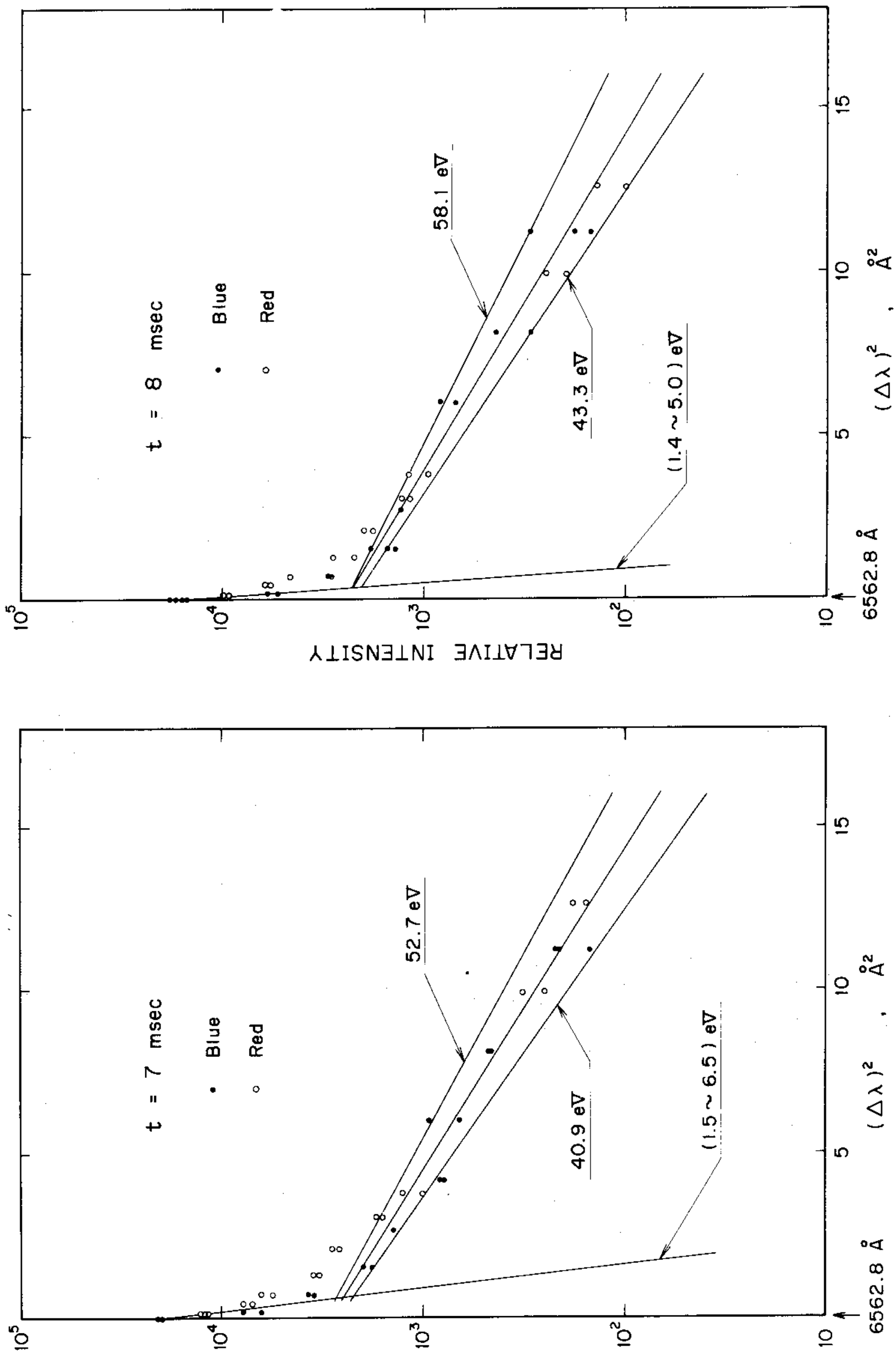

Fig. 4 Measured profiles of H_α-line in a semi-logarithmic plot at (A) 7 msec and (B) 8 msec after a breakdown.

50 eV (full half-width ≃ 3.5 Å). For example, in Fig. 4(A) the temperatures of cold and hot portions are (1.5 -- 6.5) eV and 46.8 ± 5.9 eV respectively. In determining the temperatures a correction due to an instrumental width of the spectrometer is necessary, particularly for the cold component. The instrumental correction is given by the relation,

$$(\Delta_t\lambda)^2 = (\Delta_a\lambda)^2 - (\Delta_i\lambda)^2 \qquad (4)$$

if the true shape of the line and instrumental profile are both Gaussian.[14] In the equation, $\Delta_t\lambda$ is the true half-width, $\Delta_a\lambda$ the apparent, measured half-width, and $\Delta_i\lambda$ the instrumental half-width of the spectrometer. In the present experiments the typical value of $\Delta_i\lambda$ is about 0.66 Å, which corresponds to the temperature of 1.7 eV.

The central portion of observed profiles is interpreted to be due to Franck-Condon neutrals from dissociations of molecular hydrogen neutrals or ions originating near the plasma surface. And broadenings at the line wings may indicate preferably contributions from the hot atoms, which are produced through the resonant charge-exchange process. In other words, the broadened profiles observed at the wings are coming from doppler broadenings of H_α-line emitted from charge-exchanged, hot atoms. Hence one can infer the temperatures of protons in the deeper position of the plasma from observed spectra at the wings. However, such spectra of hydrogen-atom lines (integrated along an observing optical path) do not seem to provide a local value of proton temperature at a specified position because of radial distributions of proton temperature and spectral intensity. A spectral line radiating from impurities which are located within a peculiar position is useful to determine a local temperature at the position, as mentioned in ref. 3.

The effects of normal Stark broadenings due to microfields produced by charged particles are negligibly too small to be observed in these measurements. The full half-width of the normal Stark broadenings $\Delta\lambda_s^{(1/2)}$ is given, for example, by the following equation,

$$\Delta\lambda_s^{(1/2)} \simeq \left(\frac{n_e}{5\times10^{15}}\right)^{2/3} \qquad (5)^{15)}$$

with $\Delta\lambda_s^{(1/2)}$ in Å and the electron density n_e in cm^{-3} for plasmas with temperatures a few eV. For $n_e \lesssim 10^{13}$ cm^{-3} in the present experiments, the value of $\Delta\lambda_s^{(1/2)}$ becomes less than 1.5×10^{-2} Å which is much smaller than full half-widths (≃1 Å) even for the central, peaked profiles. In the estimation of $\Delta\lambda_s^{(1/\ )}$ given by Eq. (5), ions are assumed to be singly ionized. For a case where effects of highly-ionized impurities are important, some corrections should be necessary to the equation. Since a correction of Stark broadening due to ions with their charge Z is of the order $Z^{1/3}$ and by assuming that the effective charge of JFT-2a plasma $Z_{eff}(\simeq 3)^{(*)}$ provides equivalently the value of Z, the values of $\Delta\lambda_s^{(1/2)}$ do not seem to exceed 2.5×10^{-2} Å under the present experiments. Accordingly, contributions from Stark broadenings can be neglected in observed profiles.

3.3 Doppler temperature of H_α-line

Figure 5 shows the time evolution of doppler (perpendicular) temperature $T_\perp$ measured with the spectrometer, which observes horizontally the plasma center along the major-radius direction on the equatorial plane. Poor ratio of signals to noises prevent one from measuring doppler temperatures after 14 msec, when the central, average electron densities decrease down less than 4×10^{12} cm^{-3} (as shown in Fig. 2(a)). Although cold neutrals have nearly constant temperatures (2 -- 5 eV), the doppler temperature of charge-exchanged, hydrogen atoms rises with time and attains to its maximum value 56 eV at 10 -- 12 msec.

Doppler profiles of H_α-line are also measured horizontally along the troidal magnetic field direction. In the measurements the spectrometer is positioned to observe integrated intensities along a tangential optical path which aims at the plasma center on the equatorial plane. Since emission spectra of charge-exchanged atoms are characteristic of the initial proton motions prior to the charge-exchange process, tangential (doppler) profiles represent parallel velocity-distributions of protons in the direction of toroidal magnetic field. Figures 6(A) and (B) indicate measured, tangential profiles in a linear and semi-logarithmic plots respectively. It is found that these tangential profiles have the same characteristics as perpendicular ones presented in Figs. 3 and 4. The time evolution of parallel temperature $T_\parallel$ is shown in Fig. 7, which is found to be very similar to Fig. 5. In particular, the values of doppler

(*) This value of Z_{eff} is deduced from the electron temperature from laser-scattering measurements and the conductivity temperature from the plasma current and loop voltage.

temperatures $T_{\perp}$ and $T_{\parallel}$ on charge-exchanged, hot atoms accord fairly each other within a few percents. It is seen from Figs. 5 and 7 that protons seem to have isotropic velocity-distributions to the magnetic field direction. Measurements along different vertical paths permit one to obtain some information on radial distributions of temperature. Figure 8 shows spatial (horizontal) distributions of measured doppler temperature on charge-exchanged atoms at 6, 8 and 12 msec. These distributions do not seem to indicate directly distributions of proton temperature because of spatial inhomogeneities in physical quantities. The dotted curves shown in the figure represent a relation written by

$$T_D(X) = T_D(0)[1 - (X/a)^4] \qquad (6)$$

with X = (R - 60) cm and the minor radius a which is here assumed to be 11 cm. Horizontal distributions of doppler temperatures seem to accord with Eq. (6). The squares indicated in the graph at 8 msec of the figure are deduced by utilizing numerical calculations on the transport equation of neutral atoms, which is described in Section 4.1.

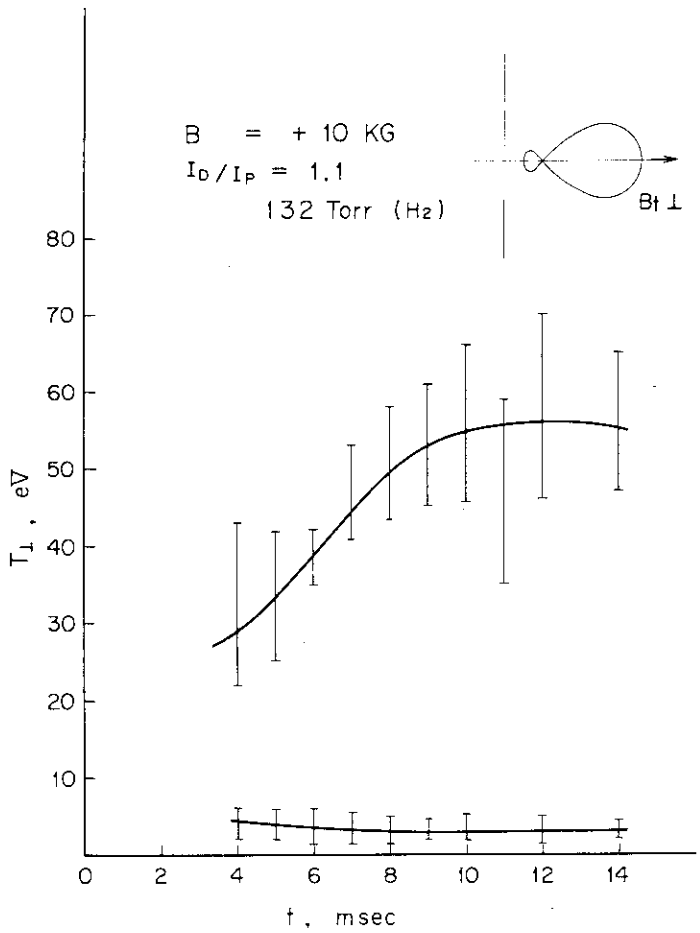

Fig. 5 Time evolution of perpendicular, doppler temperature $T_{\perp}$.

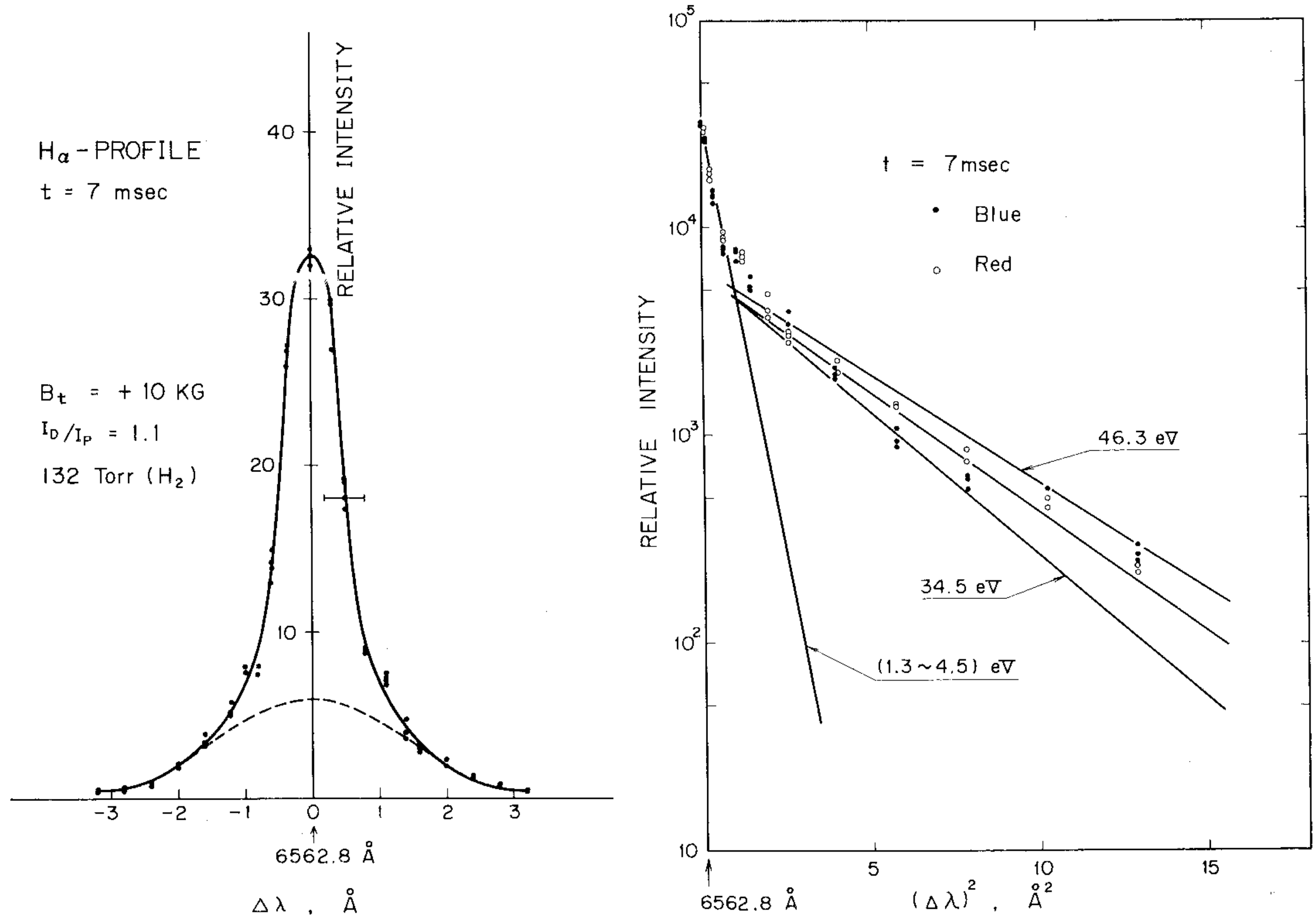

Fig. 6 Measured tangential profiles of H_α-line in a linear plot (A) and in a semi-logarithmic plot (B).

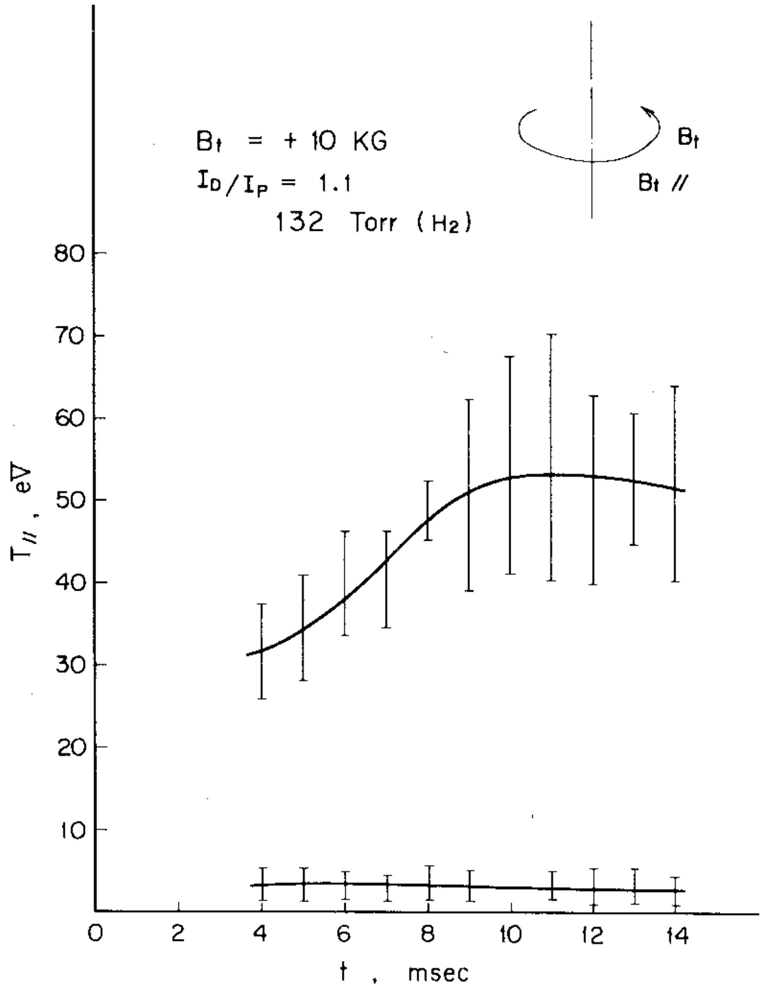

Fig. 7 Time evolution of parallel, doppler temperature $T_{\parallel}$.

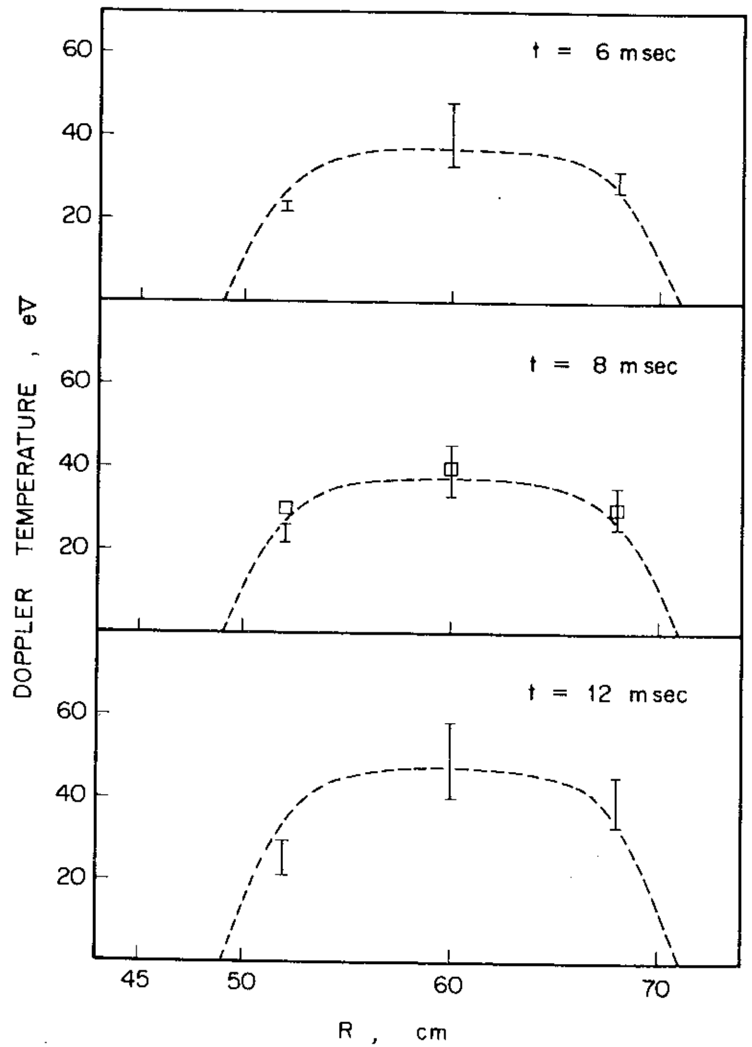

Fig. 8 Horizontal distributions of measured, doppler temperature.

3.4 Photon numbers of H_α-line and confinement times of charged particles

Figure 9 shows spatial distributions in the minor cross-section of integrated, total intensities of H_α-line measured vertically. In the figure the abscissa is the horizontal position on the equatorial plane, and the ordinate provide the integrated, spectral intensity or photon number which is absolutely calibrated with a standard tangsten lamp. Scatters of integrated, total intensities measured perpendicularly at three different positions in the toroidal direction through D5, D_2II and D4 ports are found to be limited within about ten percents. Measurements through D5 port along two tangential paths show that the total intensity integrated along the tangential path observing the center in the minor cross-section whose toroidal position is one furnished with a limiter also accords with that along another tangential path within ten percents.

The following equation has been often used to evaluate the confinement time of charged particles τ_p, by neglecting influences of impurity-ionizations.

$$\tau_p = \frac{\bar{n}_e}{i_H - \frac{d\bar{n}_e}{dt}} \qquad \text{------------------} \qquad (7a)$$

or

$$= \frac{\int \bar{n}_e dS}{\int J\cdot\xi dS - \frac{d\int \bar{n}_e dS}{dt}} \qquad \text{------------------} \qquad (7b)$$

where $\bar{n}_e$ is an average electron density, dS an area element in the minor cross-section and $i_H = J\cdot\xi$ is the ionization numbers of hydrogen atoms per cubic centimeter and per second with the photon number J of hydrogen lines and the ionization rate ξ per photon number. Figure 10 presents the time evolution of the average density which is deduced from dividing electron numbers per unit length of toroidal direction by an area of the minor cross-section. In the present report the value of ξ for H_α-line is adopted to be 10[9] and assumed to be approximately constant over the minor cross-section. Figure 11 provides the ionization numbers per second and per unit length of toroidal direction $I_H \equiv \int J\cdot\xi dS \cong \xi\cdot\int J dS$. The solid lines of Fig. 12 shows the time evolution of τ_p determined from Figs. 10 and 11 by using Eq. (7b). The values of these apparent confinement times τ_p of charged particles are found to be 0.5 -- 2.5 msec. The energy confinement time is estimated to be 0.7 msec at 8 -- 9 msec,[12c] when the particle confinement time is 1.2 -- 1.5 msec. The average density of hydrogen atoms at 8 -- 10 msec are about 10^9 cm^{-3} determined from Fig. 9 by using calculations[9] on the collisional-radiative model.

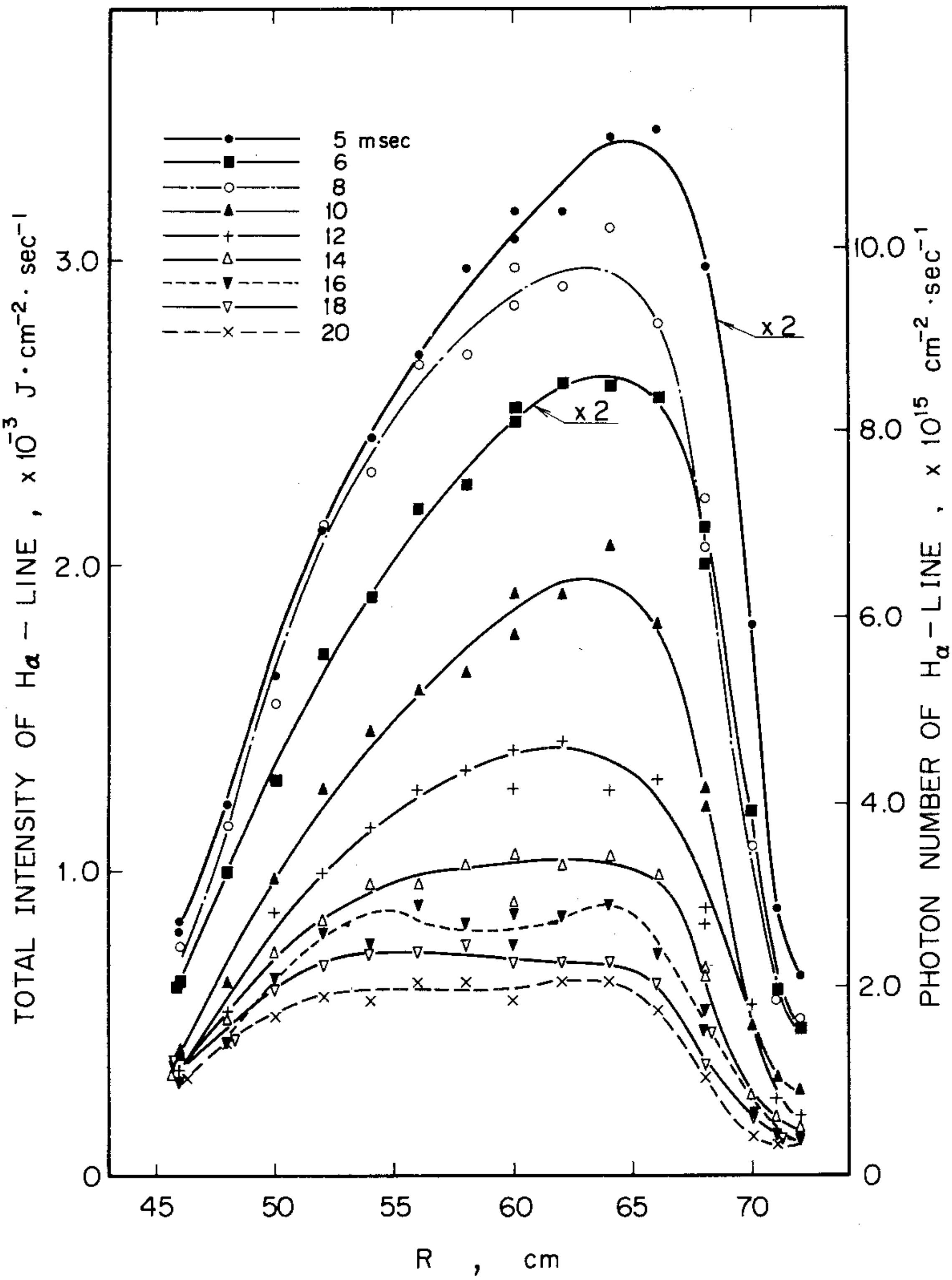

Fig. 9 Integrated, total intensity of H_α-line measured vertically. (These data are not inverse-transformed)

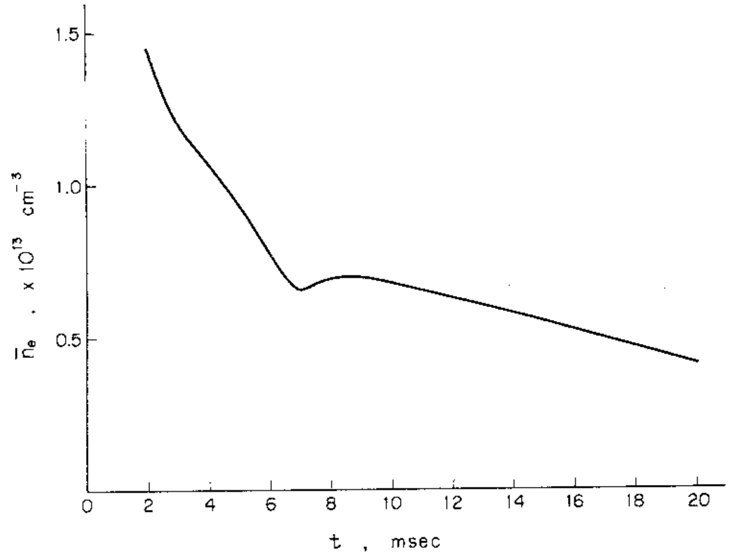

Fig. 10 Time evolution of the average electron density.

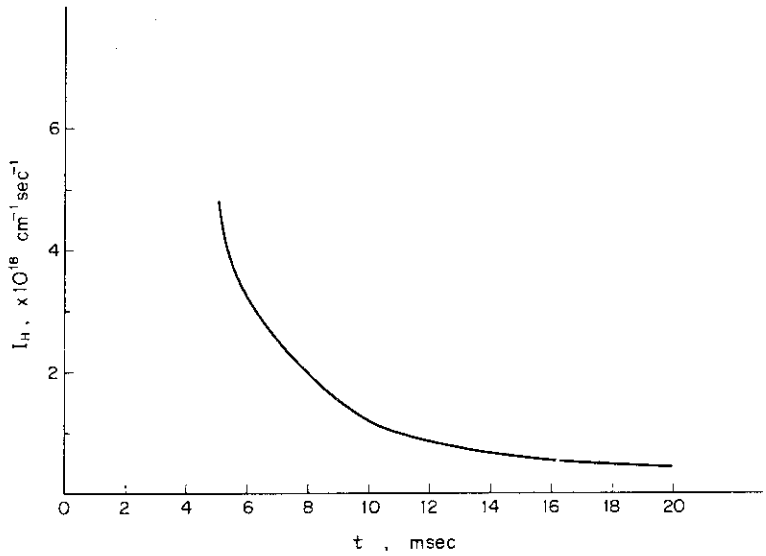

Fig. 11 Ionization numbers of hydrogen atoms per unit length of toroidal direction and per second.

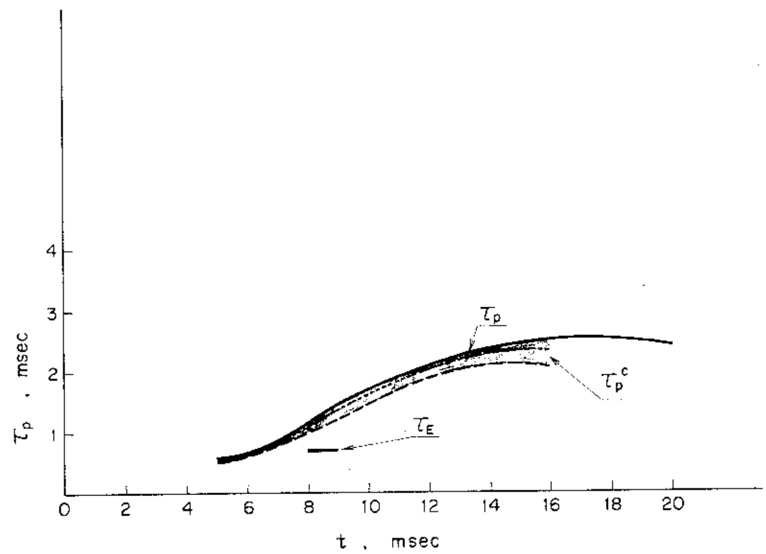

Fig. 12 Time evolution of the particle confinement time τ_p.

4. DISCUSSIONS

4.1 Comparisons between doppler temperatures and proton temperatures from energy spectra of charge-exchanged atoms

In the present experiments simultaneous measurements are performed of proton temperatures from energy spectra of charge-exchanged atoms with a 10-channel neutral particle energy analyser.[16] Figure 13 shows

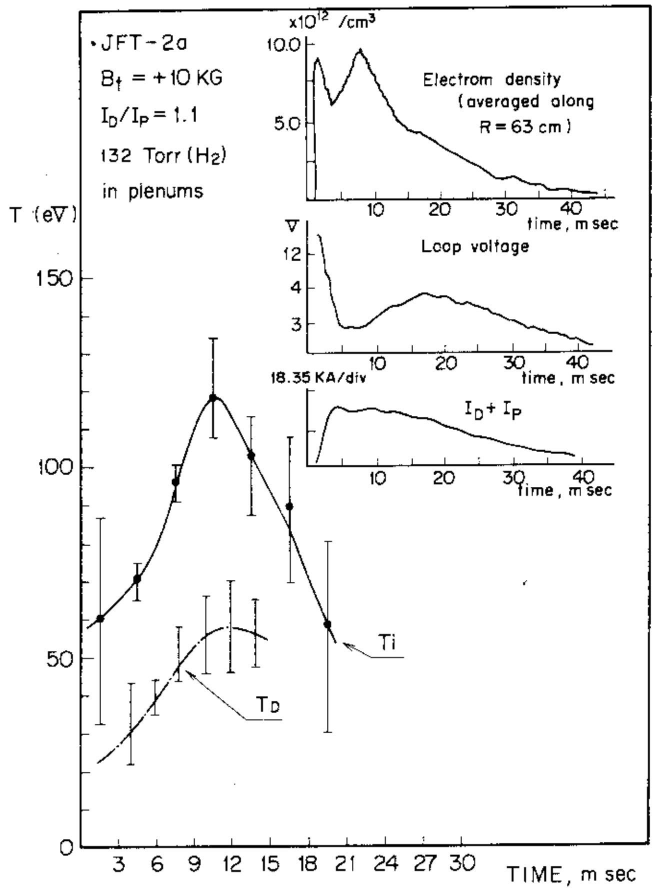

Fig. 13 Comparisons of time evolutions between proton temperatures T_i and doppler temperatures T_D.[17]

comparisons of time evolutions between proton temperatures T_i and doppler temperatures T_D of the hot component in observed profiles. The doppler temperatures are found to be approximately a half of the proton temperatures. The proton temperatures are determined with the 10-ch energy analyser, which observes the plasma center horizontally on the equatorial plane. The spatial resolution in determining the proton temperatures on JFT-2a plasmas is approximately 3.0 cm in the plasma center. The time evolution of T_D in the figure is again drawn from Fig. 5.

The values of proton temperatures 60 -- 110 eV shown in Fig. 13 are determined from energy spectra in a range between 400 eV and 800 eV of neutral atoms, as mentioned in ref. 16. Since energy spectra in the energy range of 400 eV $\leqq$ E $\leqq$ 800 eV are particularly representative of contributions from charge-exchanged, hot particles in the central region of plasma column, these proton temperatures may indicate preferably the central values. In measurements of profiles of H_α-line, on the other hand, doppler temperatures on the hot components are determined from observed broadenings at the displacement from the line center $\Delta\lambda$ of between 1.5 Å and 3.5 Å, for example, as shown in Fig. 4(A). The range of 1.5 Å $\leqq \Delta\lambda \leqq$ 3.5 Å is corresponding to an energy range from 24.5 eV to 130 eV. Therefore it seems most plausible to consider that the observed profiles at the wings result from the contributions of doppler broadenings due to charge-exchanged, hot atoms whose temperatures are distributed over an range from a few ten eV to about one hundred eV because of their spatial distributions.

Recently, Azumi and Takizuka[17)] have presented resonable interpretation of the apparent difference between the values of T_i and T_D from numerical calculations on the transportation of neutral-hydrogen atoms by solving the Boltzman equation of neutral particles through Monte-Carlo method and by considering the charge-exchange and ionization processes. According to their calculation, the observed profiles of H_α-line are explained to reflect hydrogen atoms in off-center warm layers as well as the central hot region at the wings of H_α-line and to be originating from Franck-Condon neutrals with their temperatures of a few -- several eV near at the line center. They have also given a spatial distribution of doppler temperatures, which is successfully consistent with the experimental one, as shown in Fig. 8. For example, the calculated values at 8 msec are 40 eV and 30 eV at R = 60 cm and 68 cm (or 52 cm) respectively. These calculated values are simulated from the central proton temperature 100 eV (determined from energy spectra of hot atoms), electron temperature 200 eV[12)] (from scattered intensities of a ruby light) and averaged electron density 1×10^{13} cm^{-3} and by assuming appropriate distributions of above-mentioned quantities. These results might indicate that combinations these numerical calculations with observed profiles of hydrogen lines seem to provide a helpful method to determine real distributions of proton temperature in tokamak-plasmas.

4.2 Influences of impurity-ionizations on the confinement times of charged particles

Considering ionizations of impurities existing in tokamak plasmas, the confinement times of charged particles should be corrected. Equation (7a) should be replaced by the following, corrected equation, i.e.,

$$\tau_p{}^c = \frac{\bar{n}_e}{i_H + \Sigma i_I - \frac{d\bar{n}_e}{dt}} \qquad \text{-------------------} \qquad (8)$$

where Σi_I is the summation of ionization rates of impurities. Recent spectroscopic measurements on the JFT-2a plasma in a vacuum-ultra-violet, normal-incidence region have shown that a dominant element of light gas-impurities is oxygen whose concentration is at most a few percents of proton density.[1] Here Σi_I is taken to be

$$\Sigma i_I \simeq n_e n(O^{+5}) S(5\rightarrow 6) \qquad \text{-------------------} \qquad (9)$$

In this equation, $n(O^{+5})$ is the density of oxygen ions in the 5-th ionized state, and $S(5\rightarrow 6)$ rate coefficient of oxygen ionizations from the 5-th to 6-th ionized state. The values of i_H, $n_e n(O^{+5}) S(5\rightarrow 6)$ and $d\bar{n}_e/dt$ at 8 msec are 6.4×10^{15} cm^{-3} sec^{-1}, (2.5 -- 7) $\times 10^{14}$ cm^{-3} sec^{-1} and 2.5×10^{14} cm^{-3} sec^{-1} respectively. In Fig. 12 are also shown the values of determined from Eqs. (8) and (9) and measured values of $n(O^{+5})$. Corrections due to impurity-ionizations decreases the values of τ_p by 10 -- 20 percents, in this rough estimation.

Precise measurements on metal impurities, in the present experiments, have not been performed yet. Therefore, influences of ionizations of the metal impurities cannot be here evaluated. We are now preparing measurement in a grazing-incidence region, which is expected to give helpful information on metal-impurities.

5. SUMMARY

In concluding the present report, we are summarizing our results in the following way;

(1) Detailed measurements of Balmer H_α-line emitted from tokamak plasmas in JFT-2a device have been performed under the typical operating condition of JFT-2a device, toroidal magnetic field B_t = 10 kG, plasma current I_p = 15 kA, ratio of divertor current to plasma current I_D/I_p = 1.1, and plenum pressures of fast acting valves 132 Torr in H_2.

(2) The broadenings of H_α-line have been measured with a 100 cm Czerney-Turner spectrometer horizontally on the equatorial plane along perpendicular and tangential optical paths to the toroidal magnetic field, and vertically along different three paths in the minor cross-section.

(3) The observed profile of H_α-line has consisted of a bright, peaked component at the line center and a broad, hot component at the line wings superposed on the central narrow intensity.

(4) The central portion of observed profiles has been interpreted to be due to Franck-Condon neutrals from dissociations of molecular hydrogen neutrals or ions originating near the plasma surface. Broadenings at the line wings have been determined to indicate contributions from charge-exchanged, hot hydrogen atoms.

(5) The central portions of observed profiles have given temperatures of a few -- several eV, which are nearly constant both during the whole period of JFT-2a discharge and in the whole minor cross-section.

(6) The broadened profiles at the line wings have provided the doppler temperatures of 25 -- 56 eV. The doppler temperature has rised with time after an initial formation stage of JFT-2a plasma and attained to the maximum value of 56 eV at 10 -- 12 msec.

(7) The profiles observed tangentially to the toroidal magnetic field direction are very similar to those observed perpendicularly to the toroidal field direction.

(8) Doppler temperatures determined from perpendicular and tangential profiles have fairly accorded each other within a few percents. This result have indicated that protons have isotropic velocity distributions to the direction of magnetic field.

(9) Spatial, horizontal distributions of doppler temperatures T_D have seemed to accord with

$$T_D(X) = T_D(0) \cdot [1 - (X/a)^4]$$

where X = (R - 60) cm and the minor radius a is assumed to be 11 cm.

(10) The values of doppler temperatures have been about a half of proton temperatures measured from energy spectra of charge-exchanged atoms in an energy range from 400 eV to 800 eV. Numerical calculations by Azumi and Takizuka on the transportation of neutral particles have presented reasonable interpretation of the apparent difference between doppler and proton temperatures and successfully explained the observed profiles of H_α-line. In addition the calculations have seemed to provide a helpful method to determine distributions of proton temperatures in tokamak-plasmas.

(11) Horizontal distributions have been measured of total intensities integrated vertically. Photon numbers are about 10^{16} cm^{-2} sec^{-1} and 6×10^{15} cm^{-2} sec^{-1} along R = 60 cm at 8 msec and 10 msec. Horizontally integrated intensities at three points in the toroidal direction have been found to accord each other within about ten percents.

(12) The ionization numbers of hydrogen atoms per second and per unit length of the toroidal direction have been (1 -- 2) $\times 10^{-18} sec^{-1} \cdot cm^{-1}$ at 8 -- 10 msec.

(13) The (apparent) particle confinement times τ_p have been determined to be 0.5 -- 2.5 msec, by neglecting the effects of impurity-ionizations. The value of τ_p has been 1.2 -- 1.5 msec at 8 -- 9 msec, when the energy confinement time τ_E is about 0.7 msec.

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REFERENCES

1) T. Sugie et al.: to be published.
2) S. V. Mirnov and I. B. Semenov: Soviet Atomic Energy 28 (1970) 160.
3) D. Dimock et al.: Proceedings of the Fourth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, June 1971, Madison (IAEA, Vienna, 1971) vol.1 451.
4) J. R. McNally, Jr. and R. V. Neidigh: Nuclear Fusion 13 (1973) 919.
5) D. Dimock et al.: MATT-906 (July 1972), Nuclear Fusion 13 (1973) 271.
6) M. J. Forrest et al.: Culhum Report CLM-R-107 (July 1970).
7) N. Fujisawa et al.: Proceedings of the Fifth International Conference of Plasma Physics and Controlled Nuclear Fusion Research, November 1974, Tokyo (IAEA, Vienna, 1975) vol.1, p.3.
8) L. C. Johnson: Astrophys. J. 174 (1972) 227.
9) N. Fujisawa et al.: JAERI-M 5431 (October 1973, in Japanese).
10) D. R. Bates and R. W. P. McWhirter: Proc. Roy. Soc. (London) A 267 (1962) 297.
11) T.F.R. Group: Proceedings of the Fifth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, November 1974, Tokyo (IAEA, Vienna 1975) vol.1, p.127.
12a) Y. Shimomura et al.: JAERI-M 6102 (April 1975).
12b) M. Yoshikawa et al.: Proceedings of the Fifth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, November 1974, Tokyo (IAEA, Vienna, 1975) vol.1, p.17.
12c) Y. Shimomura et al.: to be published in Phys. of Fluids.
13) for example, W. L. Wiese: Plasma Diagnostic Techniques, edited by R. H. Huddlestone and S. L. Leonard (Academic Press, New York and London, 1965) Chap. 6, p. 265,
G. Traving: Plasma Diagnostics, edited by W. Lochte-Holtgreven (North-Holland Publishing Company, Amsterdam, 1968) Chap. 2, p. 66.
14) A. N. Zaidel et al.: Soviet Phys. - Tech. Phys. 6 (1961) 93.
15) H. R. Griem: Plasma Spectroscopy (McGraw-Hill Book Company, New York San Francisco Toronto London, 1964) Chap. 14, p. 303.
16) H. Takeuchi et al.: JAERI-M 6605 (July 1976).
17) M. Azumi and T. Takizuka: to be published.