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DERIVATION OF THE RADIAL PROFILE OF ION TEMPERATURE FROM THE "MEASURED" ENERGY SPECTRA OF CHARGE-EXCHANGED NEUTRALS

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In the TRIAM-1 tokamak the energy spectra of charge-exchanged neutrals are observed by scanning the neutral energy analyzer vertically. The "measured" ion temperature obtained from only energy spectrum observed in the peripheral region is much higher than that predicted by the neoclassical transport theory because of reflection (backscattering) of neutrals at the wall. The "actual" ion temperature profile is derived from all observed energy spectra by using the numerical code in which a wall-reflection effect of neutrals and an impermeability of plasma are taken into account. In this numerical analysis, the reflection coefficient is adjusted so that the above calculated ion temperature profile should be best fit for the ion temperatures measured by the Doppler broadening of the visible lines HeII 4686 A and H_α at the relevant radial positions.

Key words: High-field tokamak TRIAM-1, neutral energy analyzer, ion temperature profile, impermeability of charge-exchanged neutrals, backscattering by the wall, Doppler broadening, neoclassical transport theory

1. Introduction

In the TRIAM-1 tokamak we investigate the confinement of the high-density plasma[1] and the turbulent heating[2),3)]: the major radius $R=25.4$cm, the minor radius of the molybdenum limiter $a_L=4$ cm and the maximum toroidal field $B_T=40$kG. In these experiments the measurement of ion temperature is important and is made by a neutral energy analyzer[4].

The energy spectra of neutral flux emitted from a tokamak plasma have

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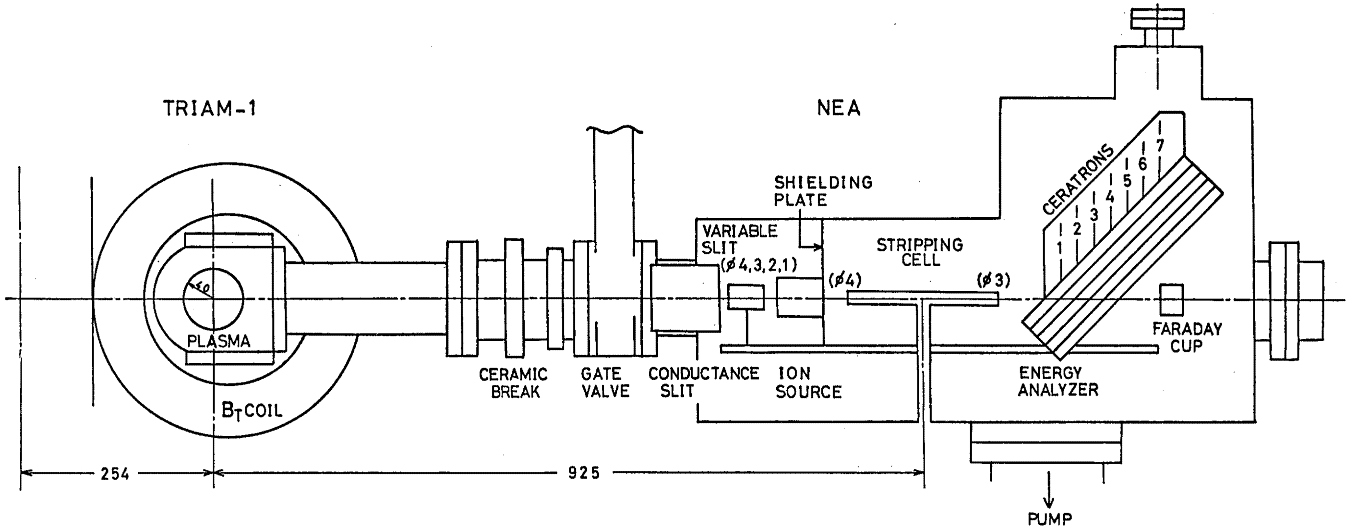


Fig. 1 The schematic view of the neutral energy analyzer (NEA) in the TRIAM-1 tokamak. The variable slit, ion source, stripping cell, energy analyzer and ceratrons are equipped on the same base. The base can be moved vertically from $z=-4.5\,\text{cm}$ to $z=+4.5\,\text{cm}$ to measure the radial profile of ion temperature.

been measured at the several vertical positions by scanning the neutral energy analyzer[4]. The radial profile of ion temperature obtained from each spectrum may not give the "actual" profile, since the energy spectrum of neutral flux emitted from the plasma center is distorted by the attenuation due to charge-exchange and ionization[5-7] and the one from the plasma edge is distorted due to reflection (backscattering) at the wall[8-10]. That is, the "measured" central ion temperature may be lower than the "actual" one and

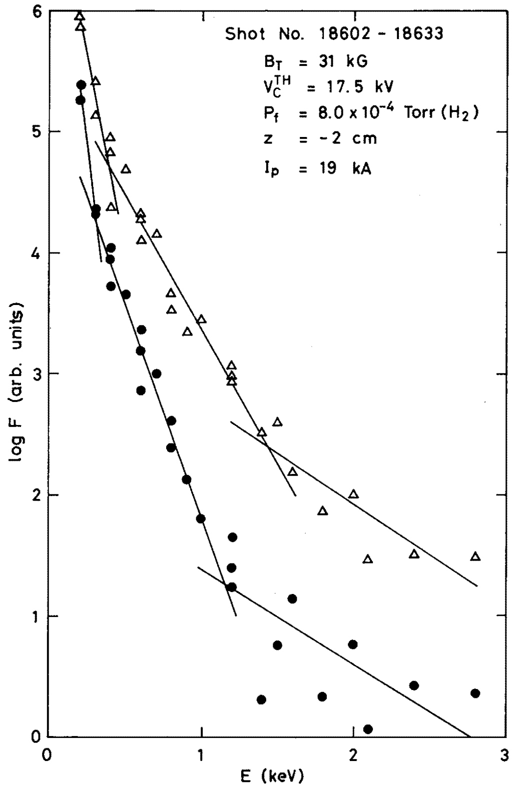


Fig. 2 The energy spectra of the neutral flux measured at the vertical position $z=-2$cm (below the torus midplane) before (●) and after (△) the current pulse for turbulent heating. In the ordinate F is defined as follows:

$$F=\frac{N}{\eta E V \sigma_{10} \zeta},$$

where N is the neutral flux, η the conversion factor of the stripping cell, E the neutral particle energy, V the voltage applied between the parallel plates of the energy analyzer, σ_{10} the charge-exchange cross-section of H^+ with H in the plasma and ζ the relative sensitivity of each ceratron detector.

the "measured" peripheral ion temperature may be higher than the "actual" one.

In this paper we propose the numerical method to derive the "actual" radial profile of ion temperature from the "measured" energy spectra of neutral flux, taking into account the effect of impermeability and reflection (backscattering).

2. The "measured" ion temperature and the "predicted" one

Figure 1 shows the schematic view of the neutral energy analyzer in the TRIAM-1 tokamak. The variable slit, ion source, stripping cell, energy analyzer and ceratrons are equipped on the same base. The base can be

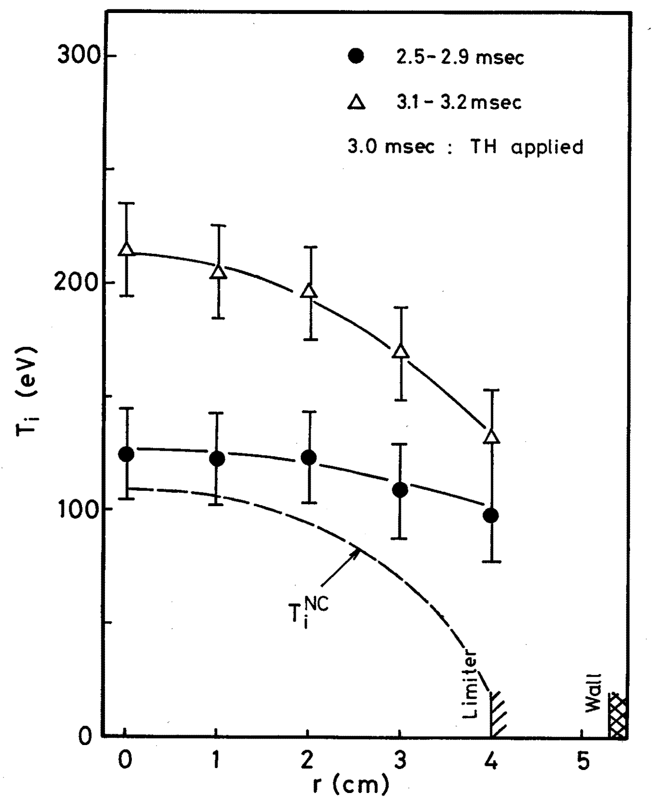


Fig. 3 The profile of ion temperature obtained directly from the intermediate slope of each "measured" energy spectrum of the neutral flux shown in Fig. 2. The broken line (- - -) indicates the ion temperature profile "predicted" by the steady-state ion thermal transport with the neoclassical transport coefficients[15].

moved vertically from $z=-4.5$ cm to $z=+4.5$ cm in order to measure the radial profile of ion temperature. Throughout this experiment, however, the energy spectra of charge-exchanged neutrals are measured at 9 vertical positions[4], i.e. $z=0$, ±1, ±2, ±3 and ±4 cm.

Figure 2 shows the energy spectra of neutral flux measured at the vertical position $z=-2$cm (below the torus midplane) before and after the current pulse for turbulent heating. The fitting curves have been obtained by the nonlinear optimization method[11),12)] so that the following objective function D should be minimized with respect to six parameters (A_1, A_2, A_3, T_1, T_2 and T_3) on two constraining conditions,

$$D=\sum_j[A_1 e^{-E_j/T_1}+A_2 e^{-E_j/T_2}+A_3 e^{-E_j/T_3}-F(E_j)]^2, \tag{1}$$

$$A_1 \geqq A_2 \geqq A_3 \geqq 0, \tag{2}$$

$$0 \leqq T_1 \leqq T_2 \leqq T_3, \tag{3}$$

where the simplex method[13] is used as the minimizing code. The temperature T_3 represents the temperature of superthermal ions. The spectrum excluding the superthermal part ($A_1 e^{-E_j/T_1}+A_2 e^{-E_j/T_2}$) measured at the height z has the information concerning the thermal ions in the region $z \leqq r \leqq a_L$. The temperatures T_1 and T_2 approximately represent the ion temperatures near the region $r \simeq a_L$ and $r \simeq z$, respectively, if the effect of impermeability and reflection (backscattering) can be ignored.

Figure 3 shows the radial profile of the "measured" ion temperature T_2 obtained from each spectrum by the above mentioned numerical method. The broken line in Fig. 3 shows the ion temperature profile "predicted" from the steady-state ion thermal transport equation with the neoclassical transport coefficients[15] by using the experimentally obtained profiles of electron temperature and electron density[14]. In the peripheral region, the "measured" ion temperature is considerably higher than the "predicted" one. The enhancement of the ion temperature in the outer plasma region can be explained that the neutral energy analyzer detects the neutrals emitted from the central hot region via reflection at the wall as well as the ones emitted from the outer plasma region without reflection at the wall.

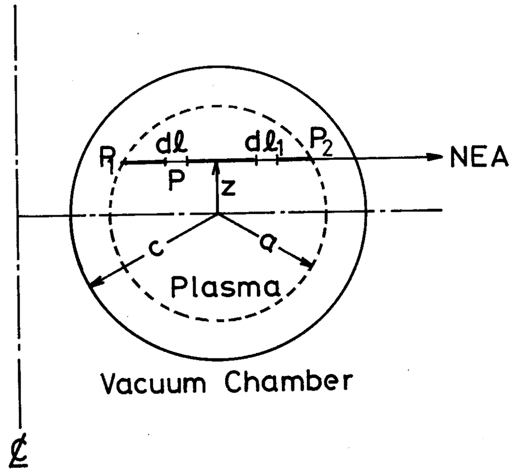
3. "Actual" ion temperature profile

3.1 Numerical procedure by nonlinear optimization

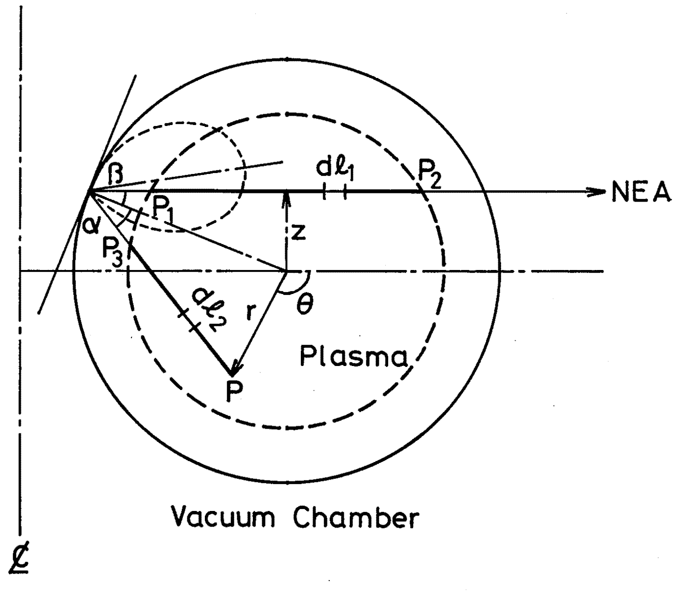
In this section, we calculate the "actual" profile of ion temperature from the "measured" energy spectra of neutral flux, taking into account the effect of impermeability and reflection (backscattering).

The ion temperature profile is assumed to be a peaky or uniform profile ($x \equiv r/a_L$),

$$T_i(r)=T_i(0)\{(1-t_1)(1-x^2)^{t_2}+t_1\}, \tag{4}$$



(a)



(b)

Fig. 4 The schematic view of the integral path calculating the neutral particle flux coming directly from the plasma (a) and after reflection (backscattering) at the wall (b). The inner radius of the vacuum chamber c is 5.5 cm.

where $T_i(0)$, t_1 and t_2 are the unknown parameters which are determined in the iteration process. From this profile and the experimentally obtained profiles of electron temperature $T_e(r)$ and electron density $n_e(r)$, the neutral density profile $n_0(r)$ is calculated by the Düchs code[15]. In this code the mono-energetic cold neutrals with $v_0=3$ eV are assumed to enter the plasma from the wall.

If $n_0(r)$, $n_e(r)$, $n_i(r)$, $T_e(r)$ and $T_i(r)$ are given, the neutral particle flux coming directly from the plasma to NEA arranged as shown in Fig. 4(a) is estimated by the following relation,

$$F_1(z, E) = K\int_{P_1}^{P_2} \frac{n_0(r)\, n_i(r)}{T_i(r)^{3/2}} e^{-E/T_i(r)} \times \exp\{-\frac{1}{v_i}\int_{P}^{P_2} N\Sigma V \mathrm{d}l_1\}\mathrm{d}l, \tag{5}$$

where $$N\Sigma V = n_e(r)\langle\sigma v\rangle_I + n_i(r)\langle\sigma v\rangle_{cx}, \tag{6}$$

and K is the constant peculiar to the neutral energy analyzer. The rates of the ionization $\langle\sigma v\rangle_I$ and the charge-exchange $\langle\sigma v\rangle_{CX}$ have been obtained by the relations (30) and (31) in Ref. 15. The ion density profile $n_i(r)$ is assumed to be equal to $n_e(r)$.

We estimate the neutral particle flux coming after reflection (backscattering) at the wall to NEA as follows (Fig. 4(b)),

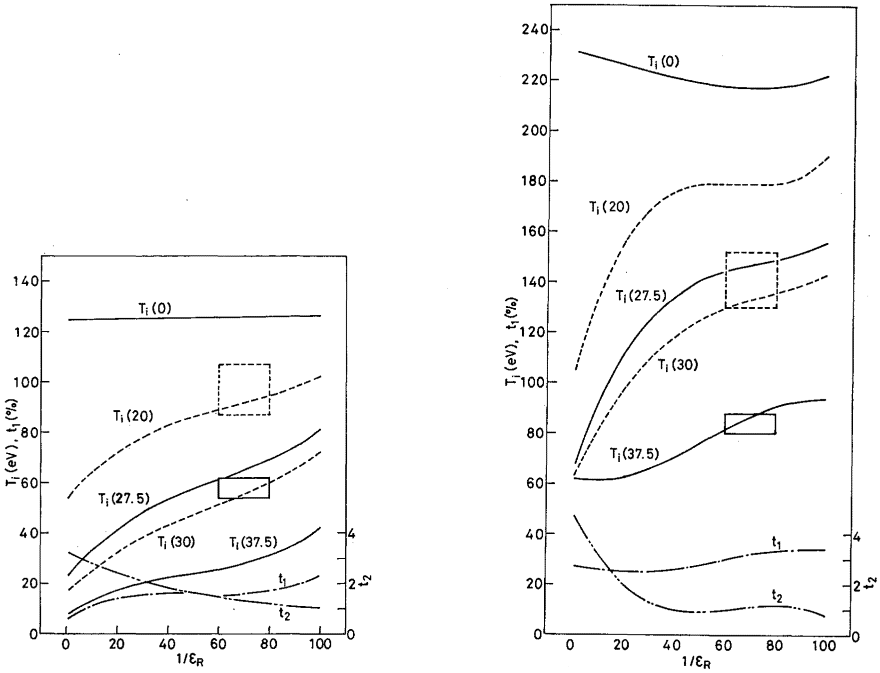
$$F_2\left(z, \frac{ER_E(E)}{R_N(E)}\right) = K\iint \frac{n_0(r)\, n_i(r)}{T_i(r)^{3/2}} e^{-E/T_i(r)} \times \exp\left\{-\frac{1}{v_i}\int_{P_1}^{P_2} N\Sigma V \mathrm{d}l_1\right\} \times \frac{1}{4}\ \frac{\pi/2-|\alpha|}{\pi/2} \cos\frac{\pi/2(\alpha+\beta)}{\pi/2-|\alpha|}\ \frac{R_N(E)}{\cos\alpha} \times \exp\left\{-\frac{1}{v_i}\int_{P}^{P_3} N\Sigma V \mathrm{d}l_2\right\} \frac{r\mathrm{d}r\mathrm{d}\theta}{2b\cos\beta}, \tag{7}$$

where $$\alpha = \tan^{-1}\left(\frac{r\sin\theta}{c+r\cos\theta}\right), \tag{8}$$

$$\beta = \sin^{-1}(z/c), \tag{9}$$

$$2b = \frac{(c+r\cos\theta)^2+(r\sin\theta)^2}{(c+r\cos\theta)^2}, \tag{10}$$

c is the minor radius of the liner (=5.5 cm), $R_N(E)$ and $R_E(E)$ are the particle and energy reflection coefficients, respectively[16),17)]. The particle reflection coefficient is assumed to be proportional to $1/\cos\alpha$ with respect to the incident angle α and the reflected particles are assumed to present the cosine distribution[18)] with respect to the reflection angle β as shown in Fig.



(a) (b)

Fig. 5 Dependence of the unknown parameters representing the ion temperature ($T_i(0)$, t_1 and t_2 in eq. (4)) on the reducing factor ε_R of reflection coefficient $R_N(E)$: (a) before and (b) after the current pulse for turbulent heating. The dotted lines $T_i(20)$ and $T_i(30)$, and solid lines $T_i(27.5)$ and $T_i(37.5)$ indicate the calculated ion temperatures at $r=20$ and 30 mm, and $r=27.5$ and 37.5 mm, respectively. The square of dotted line indicates the ion temperature at $r=20$ $\sim$30 mm obtained by the Doppler broadening of HeII 4686 A. The square of solid line indicates the ion temperature at $r=27.5\sim37.5$ mm obtained by the Doppler broadening of H_α. The ε_R value reasonable in TRIAM-1 is about 1/70 by comparison of the calculated ion temperatures with the measured ones.

4(b). The integral with respect to r and θ is over the (r, θ) plane satisfying

$$2|\alpha|+\beta\leqq\pi/2. \tag{11}$$

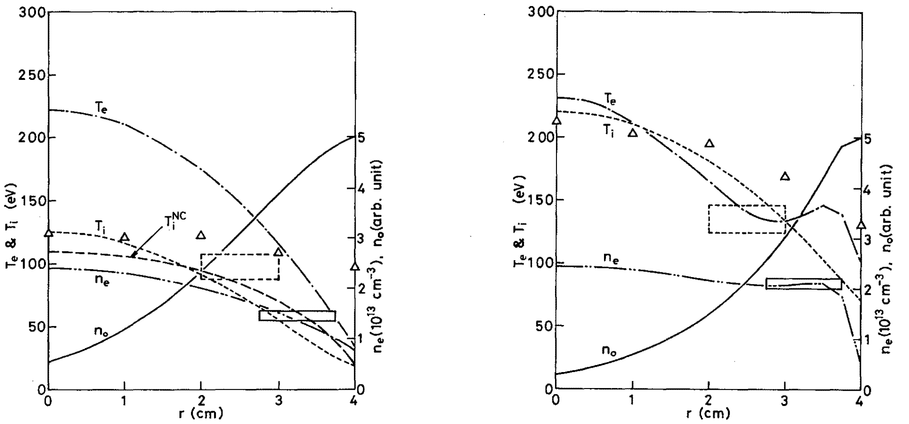
We determine the unknown parameters $T_i(0)$, t_1 and t_2 so that the following objective function Φ is minimized with respect to those parameters,

$$\Phi(T_i(0), t_1, t_2)=\sum_i\sum_j[F_1(z_i, E_j)+F_2(z_i, E_j)-F(z_i, E_j)]^2, \tag{12}$$

where $F(z_i, E_j)$ is the neutral particle flux measured at the vertical position z_i. The simplex method[13] is used also here.

3.2 Calculated results and discussions

The nonlinear optimization calculation mentioned in the previous subsection has been proceeded for various values of reducing factor ε_R of $R_N(E)$. Figures 5(a) and 5(b) show the dependence of the unknown parameters representing the ion temperature ($T_i(0)$, t_1 and t_2 in eq. (4)) on the reducing factor ε_R, where $T_i(0)$, t_1 and t_2 are obtained after convergence of the nonlinear optimization calculation. If the ε_R is determined beforehand, we can obtain the "actual" ion temperature expressed by $T_i(0)$, t_1 and t_2 from Fig. 5. It is difficult, however, to determine ε_R for the vacuum wall of TRIAM-1 experimentally. By introducing the Doppler ion temperatures[19] at $r \simeq$



(a) (b)

Fig. 6 The "actual" radial profile of ion temperature calculated from the spectra shown in Fig. 2 by using the numerical code in which the effect of impermeability in plasma and reflection (backscattering) at the wall ($\varepsilon_R = 1/70$) are taken into account: (a) before and (b) after the current pulse for turbulent heating. The profiles of electron density $n_e(r)$ and electron temperature $T_e(r)$ are the experimentally obtained ones. The neutral particle density profile $n_0(r)$ is the calculated one by the Düchs code[15] from the profiles $n_e(r)$, $T_e(r)$ and $T_i(r)$ self-consistently. The broken line (- - -) shows the ion temperature profile calculated by the steady-state ion thermal transport equation with the neoclassical transport coefficients[15]. The square of solid line and dotted line indicate the same ion temperatures as the ones in Fig. 5. The triangles (△) indicate the "measured" profile of ion temperature shown in Fig. 3.

2.5 cm (HeII 4686 A) and $r \simeq 3.25$ cm (H_α), we determine ε_R so that the calculated ion temperatures should be best fit for the Doppler temperatures at two radial positions. The good agreement between the calculated ion temperatures and the Doppler ones has been obtained at $\varepsilon_R \simeq 1/70$ for both cases before (Fig. 5(a)) and after (Fig. 5(b)) the current pulse for turbulent heating.

Figures 6(a) and 6(b) show the radial profiles of ion temperature derived by the above numerical method for $\varepsilon_R \simeq 1/70$. For both Figs. 6(a) and 6(b), the "actual" ion temperature (dotted line) is slightly higher than the "measured" ion temperature (triangle) at the center in this relatively low density plasma. On the other hand, the "actual" ion temperature at the plasma edge is lower than half of the "measured" one. The above results are due to impermeability by charge-exchange and ionization, and reflection (backscattering) at the wall.

In Fig. 6(a) is also shown the ion temperature profile "predicted" from the steady-state ion thermal transport equation with the neoclassical transport coefficients[15] (Fig. 3) and agrees well with the one derived by the above mentioned numerical method.

The result that the ε_R value for the best fit is very small to be about 1/70 may suggest that the absorption effect by the wall is much larger than the reflection effect.

The value t_1 after the current pulse for turbulent heating is larger than that before it, though the value t_2 does not vary. This means the slight broadening of the ion temperature profile, i.e. the peripheral region is heated more than the central region.

4. Conclusion

In the TRIAM-1 tokamak the energy spectra of charge-exchanged neutrals were "measured" at the several vertical positions by scanning the neutral energy analyzer. The radial profile of ion temperature directly obtained from each spectrum is different from the ion temperature profile "predicted" by the steady-state ion thermal transport equation with the neoclassical transport coefficients. The "actual" radial profile of ion temperature is derived from all observed energy spectra by using the numerical code in which a wall-reflection effect of neutrals and an impermeability of plasma are taken into account. In this numerical analysis, the reflection coefficient is reduced to be 1/70 of the one of Behrisch[16] so that the above calculated ion temperature profile should be best fit for the ion temperatures measured by the Doppler broadening of HeII 4686 A and H_α at the relevant radial positions.

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