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A Method for Neutral Spectra Analysis Taking Ripple-Trapped Particle Losses into Account

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Abstract.

An analysis technique of charge exchange neutral spectra is proposed and tested to obtain ion temperatures of a tokamak plasma. The technique models the deviation of the ion distribution from Maxwellian because of ripple trapped particles and introduces a hot ion effective temperature as a fitting parameter. The analysis code has been used to analyze active charge exchange data from TEXT discharges in which a significant up-down asymmetry in the neutral spectra was noted. An analysis considering ripple trapped particles removed some of the asymmetry and indicated the need for another mechanism for distorting charge exchange spectra. The estimations of halo neutrals effect on charge exchange neutral spectra are performed.

Introduction

For the study of confinement properties and transport processes in high temperature fusion plasmas, a detailed profile of ion temperature is needed. One technique for obtaining ion temperatures is the charge exchange technique where plasma ions become neutrals via a charge exchange reaction and escape from the plasma. The escaping neutrals are detected and analyzed. If a beam of energetic neutral atoms is injected into the plasma, it enhances the charge exchange flux and allows a local measurement of the ion temperature. The usual assumption is then made that the local ion energy distribution is Maxwellian and the ion temperature is obtained from the slope of the energy spectra of the emitted neutral particles. However, for many regions of tokamak operation, the energy spectra of the escaping neutrals does not fit a single Maxwellian ion distribution and a straight forward interpretation of the energy spectra may lead to asymmetric and unphysical ion temperature profiles. In particular, hot ions trapped in toroidal magnetic ripples can cause significant distortions of ion distribution functions from a local Maxwellian

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distribution. The detail investigation of this effect on ion distribution function was performed in Ref. 1 and 2 using kinetic description of transport processes. Calculations of ion temperature in different plasma regimes were presented in Ref.3. In this manuscript we develop a new analysis procedure for obtaining ion temperature profiles from active charge exchange data and analyze TEXT data for a plasma condition with a strong up-down asymmetry. Our procedure is founded on the results of kinetic approach obtained in Ref.1-3.

Description of method

A ripple in the toroidal magnetic field creates local magnetic wells which can change hot ion transport from a diffusive process to a convective transport with particles drifting across magnetic surfaces. This can cause a significant distortion of the ion distribution function from a Maxwellian at locations away from the center since trapped hot ions move quickly from the hot central part of the plasma towards the edge. Following the work¹⁻³ of Gurevich *et al* and Berezovskij *et al*, we model the ion distribution function with

$$f(x, E) = \begin{cases} C_1 e^{-E/T_i(x)}, & E < E_0 \\ C_2 e^{-E/T_h}, & E_0 < E < E_{dr} \\ C_3 e^{-E/T_o}, & E_{dr} < E \end{cases} \quad (1)$$

as is shown in figure 1, where x is the normalized plasma radius. The two characteristic energies in the model distribution function are E_{dr} , the drift energy in the magnetic ripple,

$$E_{dr} = \frac{e^2}{2} \left(\frac{4\pi Z_{eff} \lambda Z_i^3 R a n_e}{c \Delta \sqrt{m_i}} \right)^{\frac{2}{5}} \quad (2)$$

and E_0 is the energy at which hot ions become important and is defined by $E_0 = E_{dr} * T_i(x) / T_o$. Δ is the depth of local magnetic wells along the magnetic field lines, λ is the Coulomb logarithm, R is the major radius, and a is minor radius. $T_i(x)$ is the ion temperature at position x which corresponds to a Maxwellian distribution, T_h is effective ion temperature in the energy ranges indicated where the observed spectra may be distorted by hot ions, and T_o is central ion temperature. In our experiments, E_{dr} is high and not in the energy range of our data.

The ion temperature profile is assumed to be constant on a flux surface and to have the form $T_i(x) = T_o \frac{(1-x^\alpha)^\beta}{1+cx^2}$ where α , β , c and T_o are unknown parameters to be found from the fitting procedure. The set of parameters α , β , c , T_o , and T_h are found from the procedure of functional minimization between experimental spectral data and the theoretical spectra. The function to be minimized is

$$J = J(\alpha, \beta, c, T_o, T_h) = \sum_{i=1}^l \int_{E_{\min}^i}^{E_{\max}^i} dE \rho(E) \left(\frac{F_i^{\text{exp}}(E) - A_i F_i(E)}{F_i(E)} \right)^2 \quad (3)$$

where the summation is over the set of all experimental measurements, $\rho_i(E) > 0$ is a weighting function, and A_i is a normalization coefficient. $F_i^{\text{exp}}(E)$ is the set of all experimental spectra, and $F_i(E) = F_i(\alpha, \beta, c, T_o, T_h) = \int_{V, \Omega} dF$ is the theoretical neutral

spectra from volume dV into solid angle $d\Omega$ with energy between E and $E + dE$ based on the model ion distribution function of equation (1), and

$$dF = \epsilon f(x, E) N_b(R_p) < \sigma_{cx} v > \exp\left(-\int_x^a \frac{dx}{\lambda_{tot}}\right) dE dV d\Omega \quad (4)$$

where $N_b(R_p)$ is the beam neutral density, depending on sighting parameter R_p , ϵ is the analyzer efficiency, $< \sigma_{cx} v >$ is the rate coefficient for the charge exchange process and λ_{tot} is the total mean free path for neutrals.

This analysis procedure input is the charge exchange spectra at a number of positions. The output is a best fit ion temperature profile, which allows for a distorted ion distribution function, rather than an ion temperature for a position x determined completely from the charge exchange spectra at that point. The procedure of determining the fitting parameters, T_o , T_h , α , β , and c , uses the entire set of charge exchange spectra at all positions simultaneously, and thus produces the best possible profile which is of importance for an accurate estimation of transport coefficients.

Experimental results

The experiments were performed on the TEXT tokamak ($R = 1m$, $a = 0.27m$, $BT = 1.5-2.8T$, $I_p = 150-350kA$, line averaged density $\bar{n}_e = 1.0-4.5 \times 10^{13} cm^{-3}$). The tokamak conditions for this analysis are $BT = 2T$, $I_p = 200kA$, and $\bar{n}_e = 1.5 \times 10^{13} cm^{-3}$, chosen because of the large up-down asymmetry in the experimental neutral spectra. The magnetic field and current were in the same direction and the ion drift direction was upwards. The TEXT diagnostic neutral beam (DNB) is directed vertically and is perpendicular to the plasma current and toroidal magnetic field. The DNB operated with working gas of H_2 , D_2 , and He in a voltage range of 25-50 kV with a beam current up to 5 A. The TEXT neutral particle analyzer (NPA) is an E parallel to B analyzer [4] with a helium stripping cell and 26 detector channels separated in energy. The energy range of the analyzer is 1-14 keV but for this study, we concentrated on energies in the range 1.5-5 keV. The NPA viewed an area at the center of the plasma of a 2 cm circle. The NPA was scanned vertically between shots along the neutral beam. The viewing direction of

the analyzer is 5° off radial to minimize trapping effects. Details of the experimental arrangement are given in reference 4.

Figure 2 shows experimental neutral energy spectra for several radial locations and demonstrates the difficulty of fitting the spectra with a temperature defined by a single Maxwellian distribution. There is also a significant up down asymmetry in the energy spectra which results in very different ion temperatures in the top and bottom of plasma when fit with a single Maxwellian distribution.

To test this analysis technique under conditions of a dramatic up-down asymmetry (low density, low magnetic field) we have analyzed the charge exchange spectra for the top and bottom independently. We assume, with support from experimental data, that the population of trapped and non thermal particles in the lower half is small and trapped ions ∇B -drift to the upper half where there is a significant distortion from a single Maxwellian ion distribution. Figure 3 shows temperature profiles in the bottom and top plasmas along with temperatures reduced from assuming a local Maxwellian distribution. There is little difference between the ion temperature profile calculated from the minimization technique and the assumption of a local thermal distribution in the bottom half of torus. Several points are clear from these data reductions: first, the assumption of a local Maxwellian distribution in the upper half is not appropriate, second, the ion temperature profiles are closer to symmetric when analyzed with the model ion distribution function of eq. 1 and third, there is still a significant distortion of distribution function which is not accounted for by the ripple trapped model.

We can speculate about additional effects which could be relevant in producing the up-down asymmetry observed at low density, high current conditions. In the original development of ripple trapped ion theory by Gurevich¹ there was an assumption of no radial electric field. However, there are radial electric fields in tokamak plasmas and the radial fields could be important in the transport of trapped ions⁵. Another possibility is halo neutrals in the analyzer collecting volume⁶. Next section is devoted to the estimations of halo effect.

Effect of halo neutrals on the analyzer signal.

The diagnostic neutral beam in the plasma is surrounded by a neutral halo as a result of charge exchange of the beam with plasma ions. The active neutral flux seen by the analyzer consists of the charge exchange neutrals from the beam and from the halo neutrals :

$$F^{\Sigma} = F^{halo} + F^{DNB}.$$

The halo neutrals can penetrate in any part of plasma core, including high ripple zone of the plasma where ion distribution function is distorted. Ripple structure of TEXT is

presented on figure 4. One can see that parameter δ (δ is the relative depth of local magnetic well $\delta = \frac{B_{\max} - B_{\min}}{B_{\max} + B_{\min}}$ where $B_{\max}$ and $B_{\min}$ are maximal and minimal values of magnetic field taken along the field line in the given local well) shown on figure 4 exceeds the value of 2% in the outside part of the plasma for distances $>10\text{cm}$ from the magnetic axis. Thus the resulting signal into the analyzer may be distorted by charge exchange of the halo neutrals and trapped hot ions in high ripple zone even in the case, when the active charge-exchange signal is assumed to be from ripple free zone.

We estimate of this effect here. We used the assumption that halo neutrals have energy equal to the ion temperature and are distributed homogeneously in velocity space. We also suppose that they travel in the plasma without collisions that means in nondiffusive way because neutral mean free path λ^{tot} is larger than the plasma minor radius, a .

Let define the density of halo neutrals, $N_0(R_p, x)$, at the point x on the analyzer viewing chord with sighting parameter R_p (figure 5). Halo neutral flux dG from the volume $S_b dy$ (S_b is the square of transverse section of beam, y is vertical coordinate) of DNB into unit square at the distance ξ (x is the horizontal coordinate) is the following:

$$dG = n_i N_b(y) < \sigma_{cx} v > \frac{S_b dy}{4\pi \xi^2} \quad (5)$$

where we assume that all neutrals have ion thermal energy.

Density of neutral beam at the point y is:

$$N_b(y) = N_b(-a) \cdot \exp(-\tau(-a, y)) \quad (6)$$

where τ is the attenuation of the beam and is defined as:

$$\tau(y_1, y_2) = - \int_{y_1}^{y_2} \frac{dy}{\lambda^{tot}}$$

and here λ^{tot} is the total mean free path of DNB neutrals. At the same time this flux gives the horizontal component through the unit area:

$$dG = dN_0 v_{N_0} \cos \alpha \quad (7)$$

where

$v_{N_0} = v_{T_i}(y)$ - is the ion thermal velocity at the y position in the beam and dN_0 is the halo neutral density created by the part of DNB with length dy , and α is the angle between direction to this volume and direction to the analyzer at the point x (see figure 5). From (5)-(7) we define:

$$dN_0(x) = dy \frac{S_b < \sigma_{cx} v > n_i(y)}{4\pi \xi^2 v_{T_i}(y) \cos \alpha} N_b(-a) \exp(-\tau(-a, y)) \quad (8)$$

and the total neutral density:

$$N_0(R_p, x) = \int_{-a}^a dN_0(x) \quad (9)$$

The calculated halo neutral density for the distance $5\text{cm} < x < 25\text{cm}$ from DNB for $y = -10\text{cm}$ and $y = 10\text{cm}$ is shown on figure 6. We don't consider zones close to the DNB ($x < 5\text{cm}$) because of singularity in the integral (9). Halo density N_0 can reach the value at least 10^9 cm^{-3} , that is, the same order of magnitude as the density of background neutrals penetrating from the wall to the plasma. The value of halo neutral signal F^{halo} at the analyzer must be comparable with the value of signal from background plasma F^{bgd} . From other side the active signal from the beam F^Σ and passive signal from the background neutrals F^{bgd} have the same order of magnitude. Thus the halo term F^{halo} in active neutral signal F^Σ can be significant.

The dependance of the fraction F^{halo}/F^Σ on the sighting parameter R_p is shown on figure 6. Halo signal to analyzer collected from the right half of chord (curve 1 on figure 7) reaches 40% of total signal. That signal collected from high ripple zone ($x > 10\text{cm}$, curve 2 on figure 7) can be as large as 1/3 of the total halo signal and thus can add significant distortions to the total signal. The maximum of this perturbation is in the upper half of plasma, where distortions of neutral spectra are observed. So we conclude that neutral spectra from upper half of plasma must be analyzed with halo effects included.

Further research is underway to quantify the effects of radial electric fields and halo effects on trapped particle distributions, and thereby their importance in ion temperature measurements.

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Figure Captions

- Figure 1 Ion distribution function vs energy. T_i is the ion temperature on a magnetic surface, T_h is the effective temperature in the intermediate energy zone, and T_0 is the central ion temperature.
- Figure 2 Measured energy spectra at locations $R_p = 9$ cm O, 13 cm ▲, and 15 cm Δ, indicating a non Maxwellian distribution.
- Figure 3 Solid line-Ion temperature profiles reduced independently from the lower and top half of torus. Δ Ion temperature reduced assuming a local Maxwellian distribution.
- Figure 4 Contour lines, $\delta = \text{constant}$, of the depth of local magnetic wells along the field, in percent. Magnetic axis is shown by point O, R is the major radius, m, Z is the vertical coordinate, m. This picture was obtained numerically (courtesy of Azita Valinia) for TEXT-U.
- Figure 5 Geometry of experiment. S_b is the square of transverse section of DNB, x and y are the horizontal and vertical coordinates, R_p is the sighting parameter of analyzer, α is the angle between direction to the beam point and horizontal direction, ξ is the distance to the beam point, a is the minor radius.
- Figure 6 Density of halo neutrals N_0 , 10^8 cm^{-3} , along the horizontal chord x at $R_p = -10$ cm and 10 cm.
- Figure 7 Part of halo signal to the analyzer $F^{\text{halo}}/F\Sigma$ vs. sighting parameter R_p . 1 - signal collected from right half of horizontal chord ($x > 1$ cm), 2 - signal collected from high-ripple zone ($x > 10$ cm).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

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