INFLUENCE OF NON-MAXWELLIAN VELOCITY DISTRIBUTIONS ON ELECTRON TEMPERATURE MEASUREMENTS BY HEAVY ION BEAM PROBING

I.S. Nedzelskij, A. Malaquias, **C.A.F. Varandas** and J.A.C. Cabral

Associação EURATOM/IST, Centro de Fusão Nuclear
Instituto Superior Técnico, 1096 Lisboa Codex, Portugal

Abstract

This paper presents an analysis of the influence of non-Maxwellian velocity distributions on the determination of the electron temperature by heavy ion beam probing. Bi-Maxwellian and distorted distributions have been considered. The associated errors can be significant and seem to depend on the disturbance coefficient and on the expected range of the electron temperature.

1. Introduction

A modern heavy ion beam diagnostic, collecting the secondary ions with multiple cell array detectors, may be used to measure the plasma density (n_e), electron temperature (T_e), poloidal B-field and plasma potential radial profiles, with good spatial and temporal resolutions [1].

Neglecting the beam attenuation and the electron secondary emission, the current detected by each cell is given by

$$I_s^j = I_b Z_s n_e(r_j)\sigma_{eff}(T_e)L_j \tag{1}$$

where I_b is the intensity of the primary single ionized beam, Z_s is the charge state of the secondary ions, $n_e\ (r_j)$ is the plasma density at the ionization point, L_j is the observation length along the primary beam trajectory and σ_{eff} is the effective cross-section of the ionization process averaged over the electron Maxwellian (M) distribution function.

The electron temperature is determined by collecting either two different ion species or ions with different ionization stages, created at the same plasma volume, and comparing the experimental parameter

$$R_{\exp}(T_e) = \frac{I_{s1}}{I_{s2}} \frac{I_{p2}Z_{s2}}{I_{p1}Z_{s1}} \tag{2}$$

with that obtained dividing the effective cross sections of the considered ionization processes

$$R^M(T_e) = \frac{\sigma^M_{eff\,1}(T_e)}{\sigma^M_{eff\,2}(T_e)} \tag{3}$$

The interval in which T_e can be determined by this diagnostic is defined by the condition

$$S > S_{\max}(SNR)^{-2} \tag{4}$$

where

$$S = R^M \frac{dR^M}{dT_e} \qquad (5)$$

and SNR represents the experimental signal-to-noise ratio.

Figure 1 shows that with a 20 kV Cs^+ primary beam and SNR = 10, T_e can be determined in the range 20 to 1000 eV by collecting the secondary and tertiary ions.

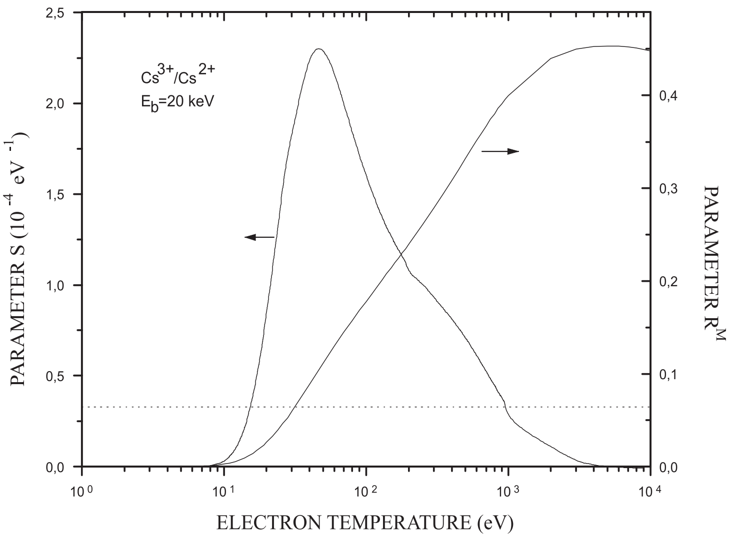

Fig.1 Variation of R^M and S with T_e for the ionization processes $Cs^+ \rightarrow Cs^{2+}$ and $Cs^+ \rightarrow Cs^{3+}$.

This paper presents an analysis of the influence on these measurements of the deviations from the electron Maxwellian distribution. An algorithm has been developed to compute the associated errors when a bi-Maxwellian (BM) or a distorted Maxwellian (DM) distribution are considered.

2. Bi-Maxwellian distribution

The bi-Maxwellian distribution is characterized by "cold" (T_c) and "hot" (T_h) temperatures of two populations of Maxwellian electrons with densities respectively equal to n_{ec} and n_{eh} with $n_e = n_{ec} + n_{eh}$ and $\alpha = n_{eh}/n_e$.

Equation (1) can be written as

$$I_s^j = I_p Z_s n_e(r_j) \sigma^{\Sigma}(T_c, T_h) L_j \qquad (6)$$

where

$$\sigma^{\Sigma}(T_e, T_h) = (1-\alpha)\sigma_{eff}^M(T_c) + \alpha\sigma_{eff}^M(T_h) \qquad (7)$$

is the combined effective cross section and $\sigma_{eff}^M(T_c)$ and $\sigma_{eff}^M(T_h)$ are the usual Maxwellian averaged effective cross-sections [2]. Generally $\sigma_{eff}^M(T_h)$ should be replaced by $\sigma_{eff}^{MA}(T_{h\|}, T_{h\perp})$ obtained by averaging the raw cross sections over anisotropic Maxwellian distribution.

Equation (3) can be written as

$$R^{BM}(T_c, T_{h\|}, T_{h\perp}) = \{(1-\alpha)\sigma_1^M + \alpha\sigma_1^{MA}\} / \{(1-\alpha)\sigma_2^M + \alpha\sigma_2^{MA}\} \qquad (8)$$

Two situations have been considered:

(i) the so-called beam-like distribution (BLD) $(T_{h\|} << T_{h\perp}, \mu_o \neq 0)$, which is characteristic of the beam-plasma systems and of the presence of runaway electrons in tokamak discharges [3]. The anisotropic distribution function of the hot electrons is defined by

$$F_h^{MA} = \left(\frac{m_e}{2\pi k T_{h\|}}\right)^{1/2}\left(\frac{m_e}{2\pi k T_{h2}}\right)\exp\left(-\frac{m_e(v_{e\|}+u_0)^2}{2kT_{h\|}}\right)\exp\left(\frac{m_e v_{e\perp}^2}{2kT_{h\perp}}\right) \qquad (9)$$

(ii) the non-beam like distribution (NBLD) $(T_{h\|} > T_{h\perp}, \mu_o = 0)$, which is characteristic of the hot electron population in a bumpy torus, superthermal electrons in the edge region of a reversed-field pinch plasma [4], and the tokamak discharges with lower-hybrid or electron cyclotron current drive. In the last case the distribution function can be considered as radially uniform [5].

Numerical calculations permitted to conclude that: (i) There are two α-independent T_c values (T_{cross}) for which σ_1^Σ and σ_2^Σ cross respectively σ_1^M and σ_2^M, σ_1^Σ and σ_2^Σ are higher (smaller) than σ_1^M and σ_2^M for $T_c < T_{cross}$ ($T_e > T_{cross}$); (ii) for a NBLD, σ_1^Σ and σ_2^Σ are very low sensitive to the ratio $T_{h\|}/T_{h\perp}$. The parameter R^{BM} (Fig. 2.IIa) is dominated by the hot component for $T_c < T_{turn}$, being T_{turn} the T_e value that verifies the equation

$$\frac{d\sigma_1^M}{dT_c} / \frac{d\sigma_2^M}{dT_c} = R^{BM}(T_c, T_h), \qquad (10)$$

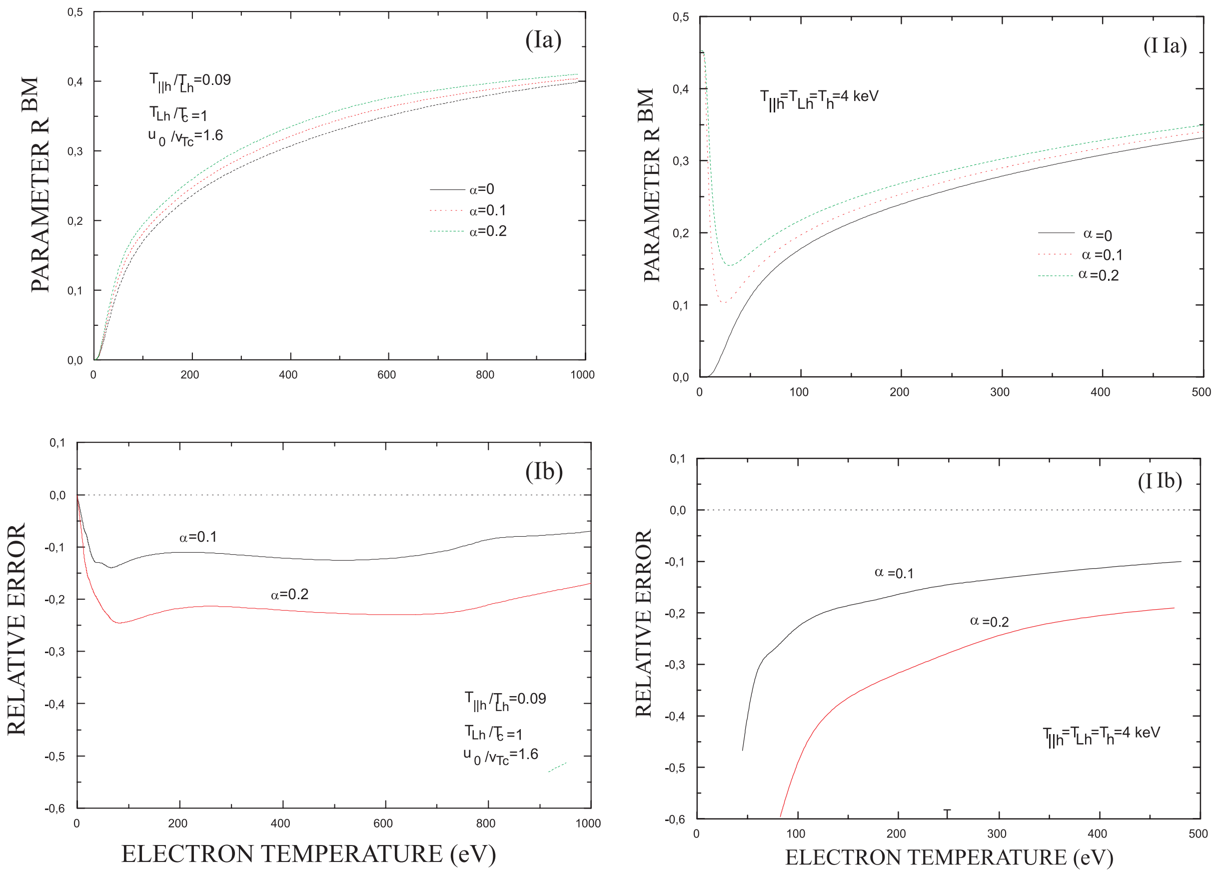

Fig. 2. Variation with T_e of R^{BM} and the relative error in the T_e determination for a beam-like (I) and a non-beam-like (II) velocity distribution

(iii) in both cases, R^{BM} is higher than R^{M} in the entire range of interest ($20 \leq T_e \leq 1000$ eV) and increases with α (Fig. 2a); (iv) the electron temperature determined using Maxwellian cross sections when deviations from the Maxwellian distribution occur is overestimated (Fig. 2b). The errors depend on the fraction of the hot electrons. The largest errors (up to 60% for the NBLD with α=0.2) happen for $T_e < 100$ eV. For $T_e > 100$ eV the errors decrease (are practically constant) for the NBLD (BLD).

3. Distorted Maxwellian distribution

The distorted Maxwellian distribution, modelled by the sum of two slightly modified "hot" and "cold" Maxwellian functions, $F^{DM} = F_h^M + F_c^M$, where

$$F_h^M = \frac{1}{2}\left(\frac{m}{2\pi T}\right)^{3/2} \exp\left\{-\frac{mv_e^2}{2(1+\xi)^2 T}\right\} \qquad F_c^M = \frac{1}{2}\left(\frac{m}{2\pi T}\right)^{3/2} \exp\left\{-\frac{mv_e^2}{2(1+\xi)^2 T}\right\}$$

describe situations that can occur in experiments with additional plasma heating [6] and in slide-away tokamak discharges when the ratio of the electron drift by the thermal velocities is high [7].

Numerical calculations have led to conclusions similar to those presented in the previous section $R^{DM} > R^{M}$ and for $T_e > 100$ eV the errors in the T_e determination diminish with T_e and increase with ξ.

4. Conclusions

Deviations of the electron velocity distribution from a Maxwellian function could lead to significant errors (up to 60%) in the determination of the electron temperature by a heavy ion beam diagnostic if the effective cross sections were not calculated taking into account the real velocity distribution.

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