Underestimation of ion temperature in CXRS diagnostics of D-alpha spectra

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The CXRS active diagnostics measurements of the ion temperature T_i using carbon C^{+5} transition n = 8-7 λ=5291Å ($T_i(C_{87})$) and hydrogen D_α n=3-2 λ=6561Å ($T_i(D_\alpha)$) spectral lines are provided in T-10 device [1]. It was shown that there is a systematic difference between temperature profiles of $T_i(C_{87})$ and $T_i(D_\alpha)$. As it can be seen in Figure 1 $T_i(D_\alpha)$ lowered by 10-15% in the central zone of the plasma and inflated on the periphery compared to $T_i(C_{87})$. This discrepancy is essential and may be caused by the following reasons. First, the line D_α is emitted by neutral atoms, whereas line C_{87} – by ions which are bounded to the magnetic force lines. Second, the concentration of thermal neutral atoms of the working gas increases during the beam phase around the beam, which gives an additional contribution to the active signal D_α, - 'halo effect". In T-10 condition the spectral C_{87} line does not contain the "halo effect", that was confirmed experimentally by scanning the observation chord across the neutral beam [2]. This Report is aimed to identify the causes of discrepancies between $T_i(C_{87})$ and $T_i(D_\alpha)$. This discrepancy is well described by the calculations with the Monte Carlo code FIDA [3], as shown in Figure 1. Code calculates the three-dimensional spatial motion of neutral particles and includes a collision-radiated n-model of the hydrogen atom up to n_{max} = 10, taking into account collisions with electrons, deuterons and carbon ions. We assume $T_i(C_{87})$ as reliable and use it as input data to the code, the output is the D_α emission line contour which is treated then with CXSFIT code [4] to determine $T_i(D_\alpha)$.

Figure 2 shows the D_α line emission of one averaged unmoving particle in time from the charge-exchange with the beam prior to its ionization. Contribution to the emission consists of two components. First, initial excitement after beam charge-exchange is emitted during the decay time $\tau_d \sim 2\cdot10^{-8}$c (region I in Figure 2). Then the electrons impact processes of excitation give its contribution (region II Fig. 2) - the halo effect. The Doppler effect leads to a broadening of the line, allowing to determine the temperature of the particles. The distortion of the temperature takes place due to the fact that particles with different velocities give a different contribution to a different part of D_α line spectral profile. In this paper we examine these effects.

Fast neutrals runaway from the observation zone.

For the demonstration of fast atoms runaway effect the normalized spectral lines obtained from emission of maxwellian atoms with Doppler broadening in the one dimensional case are shown in Fig.3. The Gauss spectrum is obtained when the emission time per each atom is fixed. When the emission time is inverse proportionally to the atom velocity, that corresponds to the strong growth of fast particle losses, the narrowing of the spectral line is taken place. In a plasma with ion temperature of ~ 1 keV for the time τ_d (zone I in Fig. 2) neutral moves with the thermal velocity $V_{Ti} \sim 2\cdot10^7$cm/s over a distance $\Delta = V_{Ti}\tau_d \sim 0.4$ cm. Having higher velocity $V = 2\text{-}3V_{Ti}$ neutrals coming out of the observation zone without emission. The same applies to the neutrals, excited by collisions - a halo neutrals. Note, impurity ions do not have such movement in the direction across the magnetic field line.

Consider losses of the fast neutrals contribution to the line emission with the kinetic equation for the distribution function of velocity and coordinate *f(V, x, t,)* for thermal neutrals:

$$\frac{\partial f}{\partial t} + V\frac{\partial f}{\partial x} = D\frac{\partial^2 f}{\partial x^2} + S(x,V) - \frac{f}{\tau_i} \qquad (1)$$

Here τ_i - ionization time of the neutral, S – maxwellian source of neutrals with a temperature Ti, localized in the region -3 <x <3 cm, the diffuse scattering of neutrals is described by the diffusion coefficient $D = V_{Ti}^2\tau_{cx}$, where τ_{cx} – thermal neutral charge-exchange time, and convective movement of particles (the second term of l.h.s.(1)). Instead, the ionization time one can substitute the time of initial decay τ_d to consider the effect of excitation without halo. The x coordinate specifies the distance from the observation point to spatially localized source of charge-exchange neutrals. The solution of (1) in the point (V, x_0, t_0) with zero initial condition in infinite x-space, assuming constant D and τ_i can be written as:

$$f(V,x_0,t_0) = \int_{-\infty}^{\infty} S(x,V)dx \int_0^{t_0} \frac{dt}{2\sqrt{\pi D(t_0-t)}} \exp\left[-\frac{(x_0-x)^2}{4D(t_0-t)} + \frac{V(x_0-x)}{2D}\right]\cdot \exp\left[(t-t_0)\left(\frac{V^2}{4D}+\frac{1}{\tau_i}\right)\right]$$

We are interested in a stationary solution, which is achieved in neutral ionization time $t_0 \approx \tau_i \approx 5\cdot10^{-7}$s (in T-10 condition, $n \sim 6\cdot10^{13}$ cm^{-3}). The shape of the velocity distribution function determines the shape of the spectral line of particles in the x-direction according to the Doppler effect. Figure 4 shows the calculation of the ion temperature as a function of the x coordinate for different values of the plasma density n, which contains in the equation (1) through the diffusion coefficient $D \sim 1/n$. Increasing the plasma density causes the reduction of D, which leads to the high x-space localization of the neutrals and to the increase of particle loss due to the convective term in (1). This explains the narrowing of the distribution function shape and a greater underestimation of the ion temperature for the high-density plasma. This result is confirmed by calculations of $T_i(D_\alpha)$ with the FIDA code with given uniform ion temperature T_i = 700eV, as shown in Figure 5. At a higher density halo plasma neutrals are more localized near the beam, which gives a strong gradient effect and less temperatures $T_i(D_\alpha)$.

The following conditions must be fulfilled in the experiment for this effect takes place: (1) Path of excited D-atoms before emission (Δ) must be larger than the size of observation zone; (2) Space inhomogeneity of the excited D atoms source must be less than Δ otherwise the effect can be cancelled by the atoms from neighbour area; (3) The observation chord must get the signal from area with homogeneous ion temperature otherwise the chord integration effect can be strong.

The effect of integration signal along the chord.

Calculations with the FIDA code have shown that the effect of the integration along the chord line do not lead to an underestimation of ion temperature in comparison of the distortion of the local spectra effect. Figure 6 shows the higher T_i (D_α) obtained from the chord signal than one from the local line spectra. Fast neutrals moving along the observation chord keep their contribution to the observed emission line spectra.

Conclusions

Calculations by the Monte Carlo code FIDA describe the effect of underestimating the measured ion temperature Ti(D_α). The main reason of it is the spatial inhomogeneity of the source of the excited thermal neutrals: the number of excited neutrals moving into the observation zone is less than value of neutrals moving out of it. The narrowing of the spectral line shape D_α takes place in the emission of neutrals excited both due to charge exchange and due to electrons impact (halo effect). With the growth of density this effect is more pronounced, as neutrals are distributed more locally. For the conditions of the T-10 the effect of underestimating of the ion temperature from the local emission spectra can reach 20% in the central zone. But the integrated signal by the chord smoothes the effect to 10-15%.

The localization of the emission line D_α, for example in the diagnostic beam, unlike the heating beam, or increase the plasma density leads to a stronger of Ti(D_α).

Note that there are no such effects for CXRS measurements for impurity ions emission as ions are bounded to the magnetic field line but in the case when the observation chord is directed transversely to the magnetic force line. It is necessary to check this effect during the observation of impurity line emission spectra in the longitudinal direction. Although in the T-10 plasma halo effect in the emission of carbon line is not present, in the ITER conditions according to our estimates this effect can be strong, so it can also distort the measurement of the ion temperature.

References

[1]. Krupin V.A. et al., Plasma Physics Reports, 2013, to be published.

[2]. Klyuchnikov L.A. et al., Measurements of ion temperature of plasma via CXRS at T-10, 39th EPS Conference & 16th Int. Congress on Plasma Physics (2012), P1.090

[3] Heidbrink W., Commun. Comput. Phys. Vol. 10, (2011) No. 3, pp. 716

[4] Whiteford A D, von Hellerman M G et al., CXSFIT User Manual, 2007

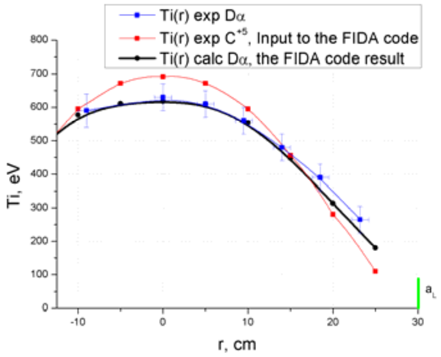

Fig.1 Radial distribution of the ion temperature $T_i(C_{87})$ (red), $T_i(D_\alpha)$ (blue) and calculated with the FIDA code (black) [1].

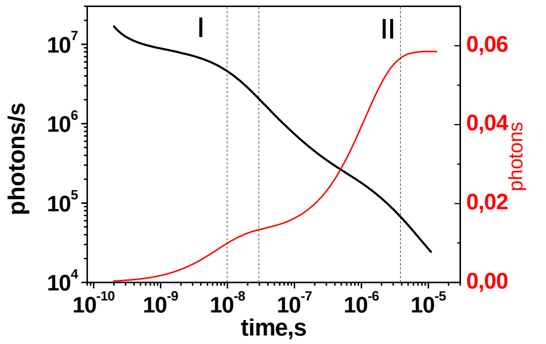

Fig.2 Emission intensity of D_α line of averaged neutral particle (black) and its time integral (red) vs. time.

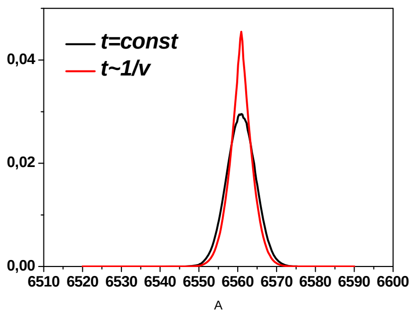

Fig.3. 1D Doppler broadening of emission spectra of maxwellian particles with fixed life time (black) and life time depended on their velocity as 1/v (red).

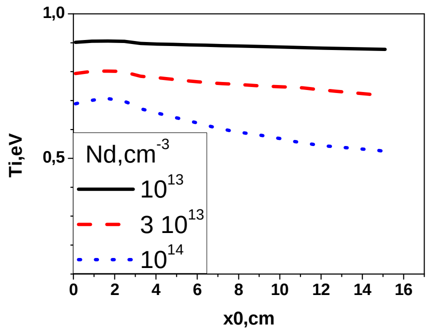

Fig.4. Ion temperature calculated in model (1) vs distance from the source for different plasma densities

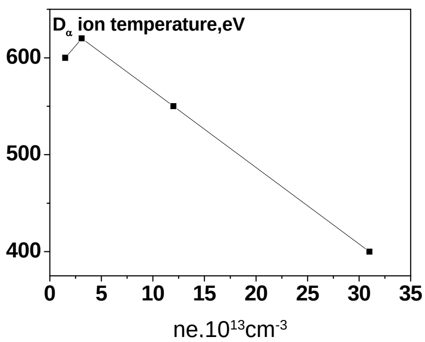

Fig.5 Central $T_i(D_\alpha)$ value calculated with the FIDA code vs the plasma density. Integrated chord spectra

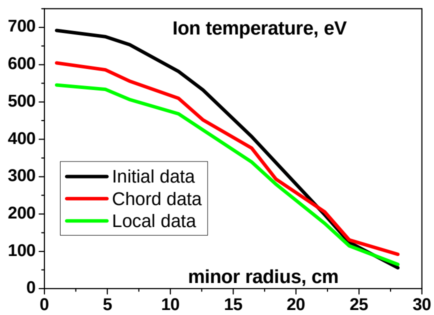

Fig.6 Radial distribution of the ion temperature $T_i(C_{87})$ (black) and calculated with the FIDA code from the chord integrated emission (red) and from the local emission (green)