Improvement of physical basis of PCX diagnostics using NIOS data on LHD

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Introduction. The Pellet Charge Exchange (PCX) diagnostic method was proposed in [1] to measure the energy spectrum of fast α-particles using carbon pellet injection. PCX diagnostic was used for measuring the energy distributions of alphas and minority-heated ions on TFTR with Li pellets [2] and of the NBI injected ions on Large Helical Device (LHD) with polystyrene $(\text{-}C_8H_8\text{-})_n$ pellets [3]. To obtain the spectra of fast ions entering the cloud from the measured fluxes of fast neutralized particles leaving the cloud, it is necessary to evaluate the neutral fraction $F_0(E, S_n)$ as a function of the particle energy E and the cloud "optical thickness" S_n corresponding to a certain composition of ion species in the cloud. Particularly for LHD conditions, $F_0(E, S_n)$ was obtained and used in Ref. [3] for a variety of cloud compositions, taking into account cloud plasma density values evaluated in [4] averaged over the whole cloud.

Recently, 2D distributions of both polystyrene cloud electron density and temperature have been measured during TESPEL ablation in LHD by means of 9 channel filter-lens imaging polychromator (NIOS system) [5]. This paper is devoted to improvement and validation of physical basis of the PCX diagnostics using the newest NIOS data on LHD.

Geometry and models. The geometry of PCX measurements in 14th LHD experimental cycle is illustrated in Fig. 1. One can see that the viewing angle of the compact neutral particle analyzer (CNPA) of about 6 cm in diameter is a part of the luminous (in Balmer-beta H_β line) pellet cloud in the direction of the magnetic field line (z axis) and obviously exceeds the transversal cloud dimension (r axis).

To evaluate the heavy particle composition of the pellet cloud we use two assumptions made for T_{ecl} measurements in Ref. [2], namely, that the pellet cloud is optically thin and that LTE conditions are valid over the whole cloud. This makes possible the use of seven Saha-Boltzmann equations:

$$\frac{n_e n_{H^+}}{n_{H^0}} = \frac{2\cdot Z_{H^+}(T_{ecl})}{Z_{H^0}(T_{ecl})}\left(\frac{m_e k T_{ecl}}{2\pi\hbar^2}\right)^{3/2}\exp\left(-\frac{E^\infty_{H^0}}{kT_{ecl}}\right),\quad \frac{n_e n_{C^{(i+1)+}}}{n_{C^{i+}}} = \frac{2\cdot Z_{C^{(i+1)+}}(T_{ecl})}{Z_{C^{i+}}(T_{ecl})}\left(\frac{m_e k T_{ecl}}{2\pi\hbar^2}\right)^{3/2}\exp\left(-\frac{E^\infty_{C^{i+}}}{kT_{ecl}}\right) \quad (1)$$

where i = {0, 1, .., 5}, $Z(T_{ecl})$, E^{∞} are the partition functions (calculated using Ref. [6]) and ionization energies of the corresponding species ionization states. To check conditions for validation of LTE, ionization lengths of species were estimated as the ion-sonic cloud velocity divided by the corresponding ionization frequency using data of Ref. [7]. Estimations show that for H^0,C^0,C^+,C^{2+} the lengths are less than cloud dimensions while for C^{3+}, C^{4+} they are comparable and may exceed cloud size. It means that a validity of LTE approach (or existence of the partial LTE) for these high carbon charge states is questionable. For sample, ionization from excited levels could decrease values of these ionization lengths [8]. It should be noted that existence of LTE in a case of the pure hydrogen cloud was revealed in Ref. [9].

Additionally, one can use the quasi-neutrality equation (2) and an assumption that chemical composition is constant all over the cloud (3)

$n_{ecl} = n_{H^+} + n_{C^+} + 2n_{C^{2+}} \ldots + 6n_{C^{6+}}$, (2) $n_{H^0} + n_{H^+} = n_{C^0} + n_{C^+} + n_{C^{2+}} \ldots + n_{C^{6+}}$. (3).

Thus, the set of nine equations with the known n_{ecl} and T_{ecl} profiles allow us to derive nine distributions n_H^0, n_H^+, n_C^0, n_C^+,…, n_C^{6+}. These distributions were used as input data for solving the set of equations (4) for calculations of the fast ion charge states along its path within the cloud.

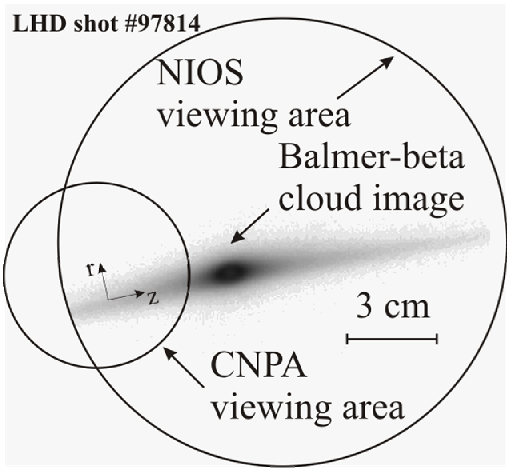

Fig.1. The geometry setup of the PCX measurements in 14th LHD cycle

For simplicity, the assumption of the infinite gyro radii of the incident protons was made that allows us to calculate the neutral fraction without Monte-Carlo calculations, although this assumption is actually valid in real experimental conditions for rather energetic ions (> several 100 keV). Let's consider a flat homogeneous monoenergetic flux of fast protons H^+ of energy E entering the cold dense cloud surrounding an ablating solid pellet; l is the transversal distance across the cloud. Due to the charge changing collisions with cloud particles, i.e. electron and ion impact ionization and charge exchange, the total hydrogen flux within the cloud will consist of F_0 and F_1 fractions of the H^0 and H^+ species. The spatial variation of these fractions is described by the set of equations:

$$\frac{dF_0}{dl} = F_1 \sum_q n_q \sigma_{10}^{(q)} - F_0 \left(\sum_Q n_Q \sigma_{01}^{(Q)} + n_e \sigma_{01}^{(e)} \right), \quad \frac{dF_1}{dl} = F_0 \left(\sum_Q n_Q \sigma_{01}^{(Q)} + n_e \sigma_{01}^{(e)} \right) - F_1 \sum_q n_q \sigma_{10}^{(q)} , \quad (4)$$

where n_q and n_Q are the densities of the pellet cloud atomic and ionic species, q = { H^0, C^0, C^+, C^{2+}, C^{3+}, C^{4+}, C^{5+}}, Q = {H^0, H^+ , C^0, C^+, C^{2+}, C^{3+}, C^{4+}, C^{5+}, C^{6+}}, $\sigma_{01}^{(Q)}$ and $\sigma_{10}^{(q)}$ are, correspondingly, the effective cross-sections of electron loss by H^0 and of electron capture by H^+. The conservation of the total number of hydrogen particles requires that $F_0(l, E) + F_1(l, E) = 1$. The boundary condition for the neutral fraction is $F_0(l=0, E) = 0$. The cross-sections for equations (4) have been recently published elsewhere [10].

Results and discussion. In Fig. 2, the longitudinal (a) and the transversal (b) profiles of the cloud electron density and temperature measured in LHD shot #97814 [5] are shown. Details of these evaluations can be found in Ref. [5]. Co-ordinates in z-axes are given relative to the pellet position that is assumed to be at the maximum of the H_β line emission in Fig. 1.

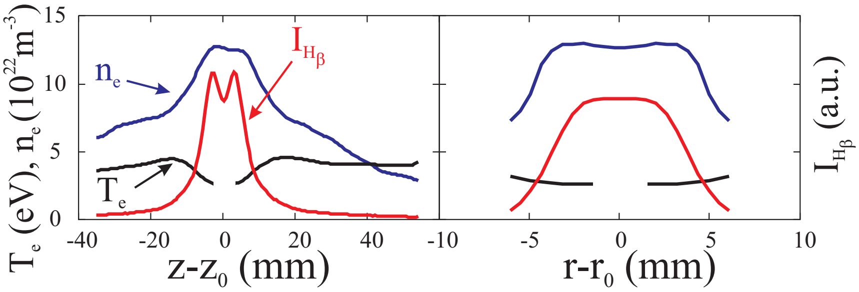

Fig.2. Cloud temperature and density profiles in LHD shot #97814 [5]

Results of calculation of the ion charge state composition within the pellet cloud by means of equation (1)-(3) are shown in Fig. 3,4 for hydrogen and carbon species correspondingly. One can see that protons dominate hydrogen atoms all over the pellet cloud area. In the pellet vicinity ($\Delta z = \pm 10$ mm, $\Delta r = \pm 3$ mm), carbon ions C^{1+} and C^{2+} are present, while C^{3+} and C^{4+} ions dominate far from this region. This result is rather interesting and points out the necessity to measure CIII-CV lines in the ablated polystyrene pellet while the previous attention was usually given to CI, CII lines [5]. It could also help to validate the LTE approach application.

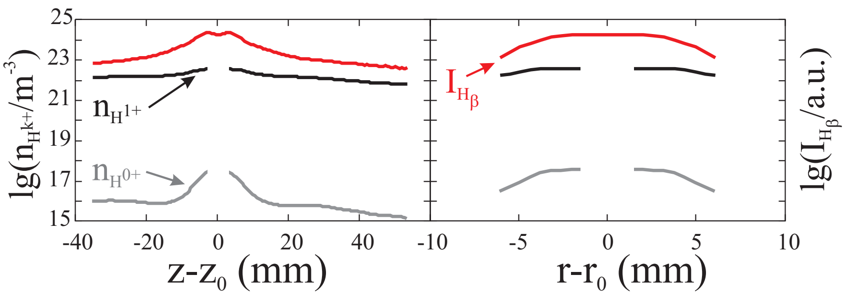

Fig.3. Distributions of H species calculated by eqs.(1)-(3) in shot #97814

Energy losses and scattering angles of fast protons in the polystyrene cloud are estimated for the calculated cloud density values. The assumption [3] that these factors are negligible for the energy range 50-170 keV measured by CNPA is verified.

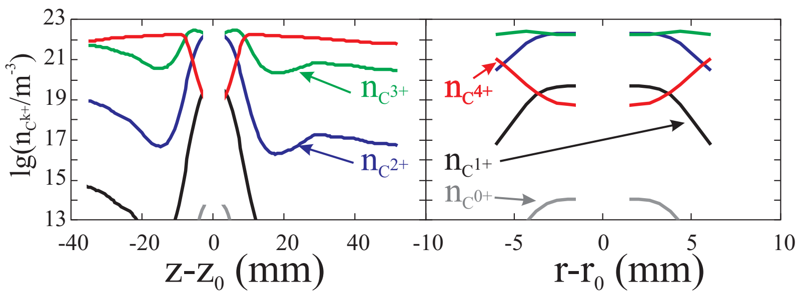

Fig.4. Distributions of C species calculated by eqs (1)-(3) for shot #97814

The neutral fraction $F_0(E, S_n)$ was obtained by integration of the equations (4) along the viewing chord of the CNPA. Actually, integration was done in the direction perpendicular to the plot plane of Fig.1 because of a rather large 3.5 m distance between the CNPA and the pellet cloud positions in experiments. A contour plot of the neutral fraction (in %) for LHD shot #97814 is shown in Fig. 5 together with the CNPA viewing area. One can see that F_0 values vary by more than one order of magnitude in the detection area. This fact should be taken into account when calculating the fast ion energy distribution function from the CNPA signals.

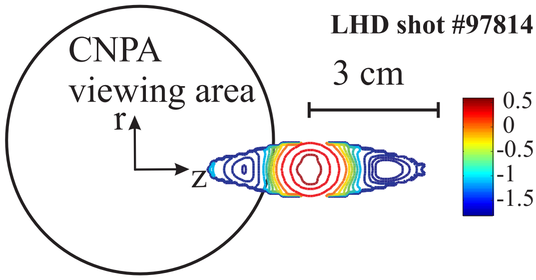

Fig.5. Contour plot of the logarithm of the line-averaged neutral fraction calculated using eq. (4) for LHD shot #97814 and for 100 keV ion energy.

Summary. The models for evaluations of the charge state composition of carbon ions and of the neutral fraction F_0 of fast hydrogen particles in the polystyrene pellet cloud have been developed. Results of evaluations demonstrate that in the solid pellet vicinity carbon ions C^{1+} and C^{2+} are present, while far from this region C^{3+} and C^{4+} ions dominate. The F_0 values vary by more than one order of magnitude in the detection area and this should be taken into account for calculation of fast ion energy distribution function from the CNPA signals.

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