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Analysis of first PCX measurements in LHD

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Introduction. The behavior of fast ions, alphas and ICR-driven minorities is a key problem of the controlled fusion research. Among a few diagnostics capable to measure the energy distribution of the confined fast ions, the Pellet Charge eXchange (PCX) approach using the Neutral Particle Analyzer (NPA) as a detector of helium atoms emitted by pellet clouds has been successfully applied in D-T and ICR-driven minority experiments in TFTR [1]. First results of a new PCX scheme with the Natural Diamond Detector (NDD) have been recently reported in Ref. [2]. In this paper we present and discuss new algorithms developed to derive the energy distribution function from the NDD signal.

Experiment. A tracer-encapsulated solid pellet technique (TESPEL) is widely used nowadays [3,4]. A pellet made of polystyrene polymer (-CH (C_6H_5) CH_2-) with outer shell (typically, 0.7-0.9 mm in diameter) was used to investigate the behavior of fast NBI (E_{NBI} = 150 keV) ions. Being injected in the core direction of plasma heated by 3.4 MW NBI, the pellet makes a dense enough (neutrals and ions of H, C) target responsible for charge exchange between plasma ions and cloud atoms. NDD has been utilized to as an energy analyzer for neutral fluxes emerging the cloud. Details of this experimental set-up were published elsewhere [2].

A calibration of the whole receiving channel of NDD has been done using the ^{241}Am (5.5 MeV) source by placing it into the vacuum vessel. The calibration signal $F_{NDD}(t)$ (Fig. 1a) is lasting a time interval comparable with the total pellet ablation time t_{abl} of about 1 ms. A typical NDD signal for NBI heated LHD shot #37771 together with the pellet ablation light are shown in Fig. 1b and c. Odd negative NDD pulses, especially when pellet ablation is over, will be explained using simulations presented below.

Modeling and discussion. The measured $U_{NDD}(t)$ signal of NDD was simulated as follows

$$U_{NDD}(t) = \sum_{i=1}^{N} A(E_i) F_{NDD}(t - t_i),\ t_i = \sum_{j=1}^{i} \Delta t_i\ , \tag{1}$$

where $A(?_i)$ is a signal amplitude that is proportional to energy E_i of "*i*"-particle that arrives to the detector at t_i time, Δt_i is the delay time between arrivals of "*i*" and "*i+1*"particles, N is the number of measured particles during t_{abl}. In simulations, the energy distribution function

$$f_{NBI} \propto \begin{Bmatrix} E^{1/2} / \left(E^{3/2} + E_c^{3/2}\right), for\ E \le E_{NBI} \\ 0 \qquad\qquad\qquad\qquad ,otherwise \end{Bmatrix} \tag{2}$$

was used with the critical energy $E_c \cong 45$ keV evaluated according to the simple slowing down model [6]. The Δt_i time depends on the NDD aperture. In the simulations it was assumed to be uniformly distributed within 0.5-2.5 μs time interval. Simulated signals $U_{NDD}(t)$ with an experimental noise added and without it are shown in Fig. 1d,e correspondingly. One can see from Fig. 1c that NDD signal has a 0.2 ms delay relative to the start of pellet ablation. Therefore, it was assumed that fast plasma particles start to expose NDD detector with this delay as well. One can see that the simulations reproduce main features of the experimental signal shown in Fig. 1c. Negative values of signals occur due to the shape of the $F_{NDD}(t)$. We should note that the realized detection scheme had a limitation on the detector load. NDD signal saturated when the detector aperture was increased.

To restore the energy distribution function of fast neutrals from the $U_{NDD}(t)$ time evolution the following algorithm based on Fourier analysis has been developed. One can show that the following V transformation

$$V\ (U_{NDD})\big|_{\xi = t} = F^{-1}\left(\frac{F\ (U_{NDD})}{F\ (F_{NDD})}\right) \tag{3}$$

applied to $U_{NDD}(t)$ in form (1) gives the following expression

$$U_{NDD}(t) = \sum_{i=1}^{N} A(E_i) \times \delta[t - t_i] \tag{4}$$

which is more appropriate for subsequent Pulse Height Analysis (PHA) and derivation of the $f_{PCX}(E)$ energy distribution function of particles measured by NDD. Here, F and F^{-1} are the Fourier and reversed Fourier transforms correspondingly.

The developed algorithm has been tested using the modeled signal with experimental noise shown in Fig. 1d. In Fig. 2a the $f_{NBI}(E)$ ion energy distribution function used for simulation and histogram of the restored $f_{PCX}(E)$ distribution function are shown correspondingly. One can see that the algorithm gives appropriate results for the energies above the noise level.

NDD *principally* operates with the room-temperature noise level so that the experimental noise level was comparable with the maximal energy of plasma particles. Therefore, the following procedure of processing the NDD signal was developed. Briefly, U_{NDD} and F_{NDD} signals were smoothed so that to keep the initial rising part of the $F_{NDD}(t)$ signal with duration of about 0.05 μs. Then, a $S_{NDD}(t')$ initial part of the $F_{NDD}(t)$ signal lasting $\Delta t' = 0.25\ \mu s$ was chosen for calculating the following parameter

$$\Delta U_{NDD}(t) = \int_{\Delta t'} \left(U_{NDD}(t) - A(E_i) S_{NDD}(t-t')\right)^2 d$$

Here, $A(?_i)$ was varied so that to determine minimums of the ΔU_{NDD}(t) parameter in time. Then, times of minimums and the corresponding $?_i$ values were assumed to be the arrival time t_i of "*i*"-particle and its energy. The evaluated histogram of the $f_{PCX}(E)$ ion distribution is shown in Fig. 2b together with function (2) calculated for E_{NBI} = 150 keV. The $f_{NPA}(E)$ function measured using the central NPA channel in shot #39970 is shown as well. One can see that the measured function has a lack of fast particles. Maximal energy values of about 40 keV measured by PCX diagnostics is in agreement with data of the LHD passive CX diagnostics.

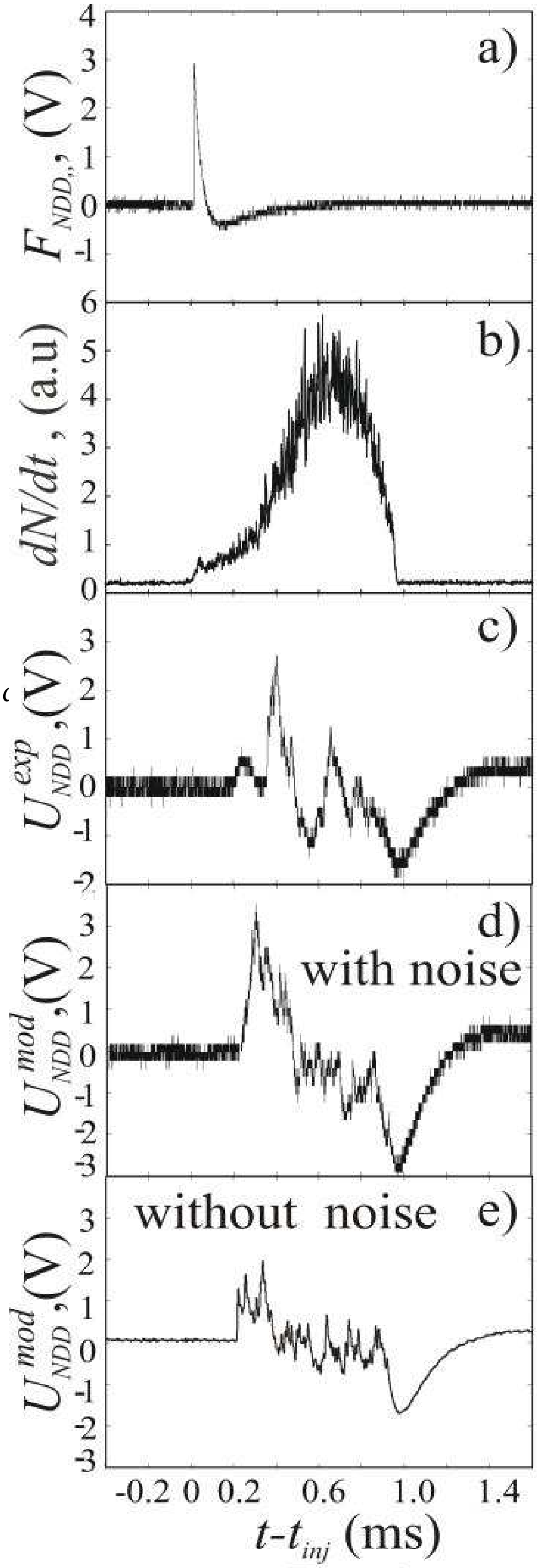

Fig. 1

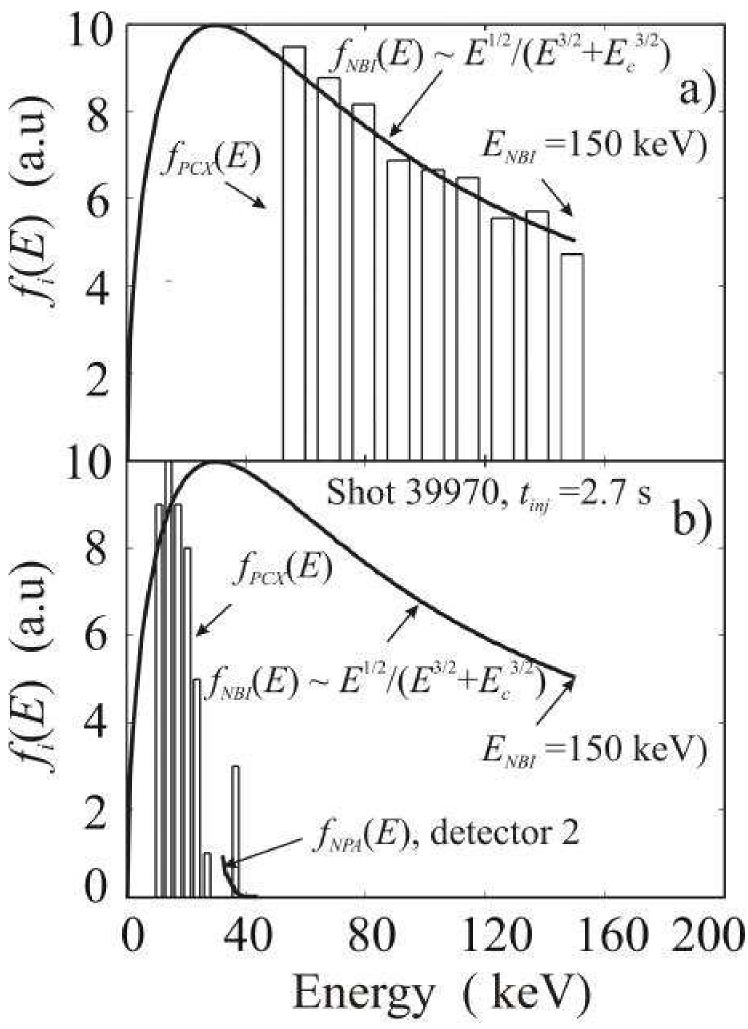

Fig. 2

It is clear from Fig. 2 b that for further studies, the noise level of receiving detector should be reduced to 8-10 keV. For instance, a cooled semiconductor detector and/or cooling the NDD pre-amplifier could be considered. One reason of the lack of detected neutrals was operation with too low detector aperture to exclude a saturation of the NDD signal in the used amplifier scheme. The scheme could be improved by means of the fast switcher that restores a working point of the amplifier within a few microseconds which is much shorter than a pellet ablation time.

Summary. Algorithms for restoring the energy distribution of fast neutrals emerging the pellet cloud in LHD PCX experiments were developed. The maximal neutrals values of about 45 keV measured using PCX diagnostics are in agreement with data of the passive CX diagnostics of LHD. An improvement of the measuring scheme for further studies of fast ions in PHA regimes is offered.

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