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# Study of fast tangentially beam-injected ion behavior in LHD using natural diamond detectors

A.V.Krasilnikov[2], M.Isobe[1], T.Saida[1], S.Murakami[3], M.Nishiura[1], M.Osakabe[1], M.Sasao[4], K.Toi[1], F.Watanabe[5], V.N.Amosov[2]

[1]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*
[2]*Troitsk Institute for Innovating and Fusion Research, Troitsk, Moscow region, Russia*
[3]*Kyoto University, Kyoto, Japan*
[4]*Tohoku University, Sendai, Japan*
[5]*Nagoya University, Nagoya, Japan*

## 1. Introduction

Due to ripple structure, $q$ profile and topology of fast ions trajectories the issue of fast ion confinement is more crucial in stellarator based fusion reactor. Experiments on LHD [1] with neutral beam injection (NBI) are providing the possibility to study the fast ion behaviour in the largest stellarator plasma. Diagnostic complex of LHD is providing not only the data about spatial distributions of the number of LHD plasma characteristics important for this studies, but in particular the possibility to measure the time evolution of the perpendicular and tangential confined fast ion energy distributions. The purpose of our work was to study the efficiency of confinement of fast tangential and perpendicular ions in relatively MHD-quiescent hydrogen plasma of LHD and under influence of some MHD instabilities.

## 2. Experimental arrangement

The behavior of fast protons was studied using charge exchange (CX) atom spectrometers based on natural diamond detectors (NDD) viewing tangentially at R=3.65m in equatorial plane and vertically at $R$=3.67m [2,3]. Fast ions were tangentially co- and counter-injected with energy of 150 keV. To provide both spectrometry and flux dynamic studies of tangential and perpendicular CX atoms, measurements were performed during experimental program with stationary and modulated (200ms–on/200ms–off) co- and counter-injected beam blips [1]. Applied NDDs were developed for fast ($E > 25$keV) CX atom spectrometry [3]. Tangential NDD placed at distance 6.8m from the plasma center has input window with diameter of 2mm and additional aperture with diameter of 1 mm installed at distance 285mm from it. So this NDD has plane angle of its cone of view ~0.30°, and sees the plasma region with diameter of ~6 cm at the axis. NDD integrates from its cone of view the CX atom flux created by fast ions having pitch angles 140-175° with respect to co-clockwise direction of $B_t$. Measurements were performed in plasma configurations with magnetic axis at $R_{ax}$ = 3.75, 3.6 and 3.53 m and magnetic fields $B_t$ = 2.5, 1.5, 0.75 (co-clockwise) and -2.5 T.

## 3. Results fast ion confinement studies

### *3.1. CX atom spectrum and flux measurements in MHD-quiescent plasma of LHD*

To study the difference in confinement of co- and counter-moving tangential and perpendicular ions in a number of LHD plasma configurations the most of CX atom spectra measurements were performed in MHD-quiescent plasmas with similar parameters ($n_e \sim (0.75 \div 1) \times 10^{19}\ \mathrm{m}^{-3}$, $T_e \sim 1.8 \div 2$ keV).

Another way to study the efficiency of fast ion confinement is connected with fast ($E >$ 25 keV) CX atom flux (figs.1,2) decay time measurements after beam-end in experiments with modulated NBI and their comparison with calculated: 30°scattered times for tangential measurements and slowing down time for perpendicular ones. It could be seen in figs.1,2 that perpendicular CX atom flux exists longer then tangential one. This indicates that tangential NDD measured atom flux from more periphery region than perpendicular one. As shown in fig.2, perpendicular CX atom flux is increasing and time delay of its maximum is diminishing with plasma density (in shown discharge with $R_{ax}$=3.53m $n_e$ changed from 0.8 to $1.2 \times 10^{19}\mathrm{m}^{-3}$ during time interval 0.85–2.2s). Such relative behavior of tangential and perpendicular fast CX atom fluxes is in good agreement with pitch angle scattering by Coulomb collisions.

In $B_t$=2.5T experiments the tangential spectra of co-moving CX atoms for $R_{ax}$=3.53 & 3.6m plasmas and counter-moving atoms for $R_{ax}$=3.6m plasma were very similar to each other and a bit lower in energy range 20-85keV than also similar co- and counter-moving atom spectra for $R_{ax}$=3.75m plasmas. This shows the absence of difference in confinement of co- and counter moving ions with energies up to 140keV in these LHD plasma configurations. Measured decay times of co- and counter-moving CX atom flux were higher in $R_{ax}$= 3.75m plasma than in $R_{ax}$=3.6 or 3.53m (fig.3) ones. These results could be treated as illustration of slightly better orbit confinement of measured by NDD both co- and counter- moving fast ions in the case of $R_{ax}$=3.75m (when NBI deposition is more central and NDD sees plasma closer to the axis) than in $R_{ax}$=3.6 and 3.53m. Very low values of measured co-moving CX atom flux decay times in $R_{ax}$=3.53m plasma configuration could be partly explained by CX loss.

Tangential counter-moving CX atom spectra (fig.4) are slightly diminishing with $B_t$ change from 2.5 T to 1.5 T and essentially diminishing for $B_t$ = 0.75 T in plasmas with Rax = 3.6 m. The measured fast CX atom flux decay times (see fig.5) in these experiments were slightly ($B_t$ = 1.5 T) or essentially ($B_t$ = 0.75 T) shorter than calculated 30° scattering time. These spectrometry and decay time data could be treated as illustration of some degradation of the confinement of counter-moving ions in plasma with diminished $B_t$, especially at $B_t$ = 0.75

T. Measured results could be also assigned lower $T_e$ at lower $B_t$ and to wider fast ion trajectory excursions to plasma periphery and so lower slowing down time and higher CX loss there.

Perpendicular CX atom spectra, $T_{eff,\perp}$ and fast CX atom flux decay time (see fig.6 & 7) were lower in $R_{ax}$=3.75 m configuration than in $R_{ax}$=3.6 and 3.53 m. All this illustrates better confinement of helically trapped ions in inward shifted configurations than in $R_{ax}$=3.75m one.

### *3.2. CX atom flux measurements in LHD plasma with MHD activity.*

Sharp increases of co-moving CX atom fluxes were measured in experiments with 200ms co-beam blip injection in $R_{ax}$=3.53m and not so clear but also in $R_{ax}$=3.6 m plasma configuration during the second part of the beam time (see fig.1). Essential MHD activity was developed in these experiments with inward shifted LHD plasma and modulated co-NBI. Development of MHD activity in LHD discharge with $R_{ax}$ =3.53 m, which CX atom fluxes presented in figs. 1 and 2 is shown in fig.8. Measured sharp increases of CX atom fluxes correlate with appearance in plasma 50-60 kHz MHD instabilities. This effect was almost not seen in $R_{ax}$=3.75m plasma configuration. Instant beginning of co-CX atom flux decay after co-NBI termination and delay with decay of counter-CX atom flux after counter-NBI termination were also measured. Increase of co-moving ion transport from plasma center to periphery by 50-60 kHz energetic particle modes in $R_{ax}$=3.53 and 3.6 m plasma configurations could be discussed as the reason for measured increase of fast CX atom flux.

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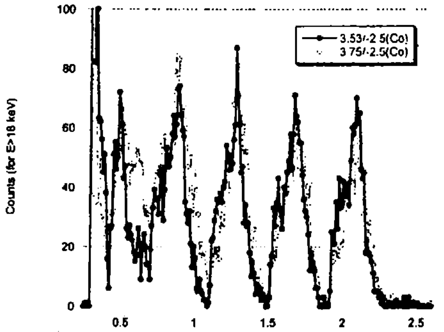

*Fig.1 Tang. co-CX atom flux during 200ms beam blips turned-off at 0.9, 1.3, 1.7, 2.1 s.*

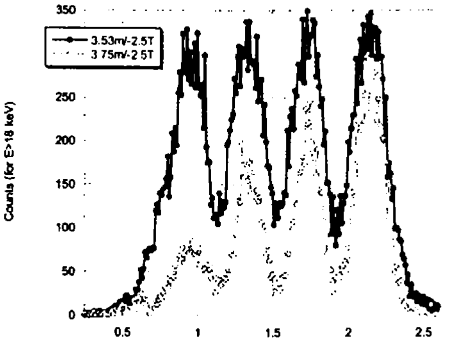

*Fig.2. Perp. CX atom flux during 200ms beam blips turned-off at 0.9, 1.3, 1.7, 2.1 s.*

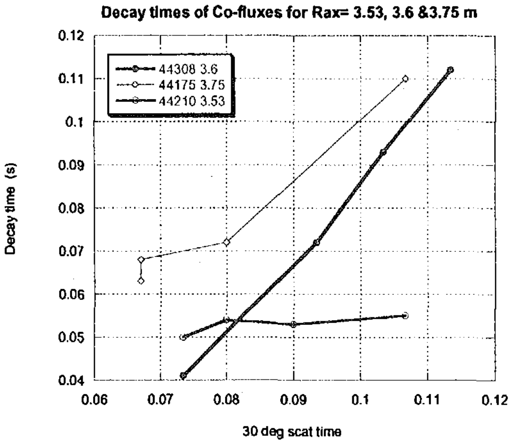

Fig.3. Co-CX atom fluxes decay times upon $R_{ax}$.

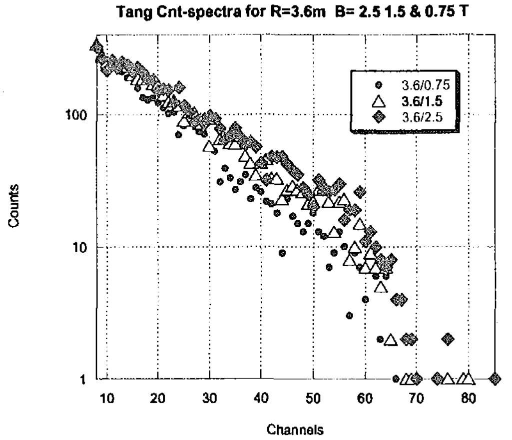

Fig.4. Cnt-CX atom spectra at different $B_t$.

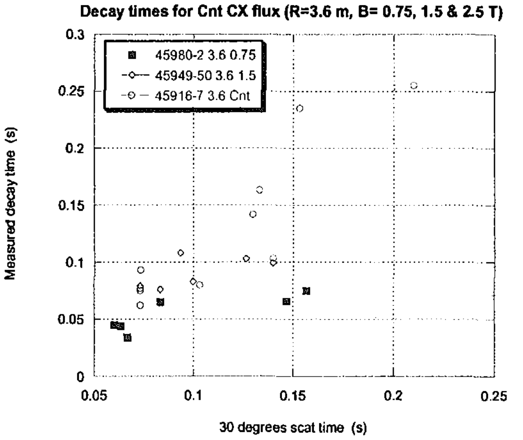

Fig.5. Cnt-CX atom flux decay time upon $B_t$.

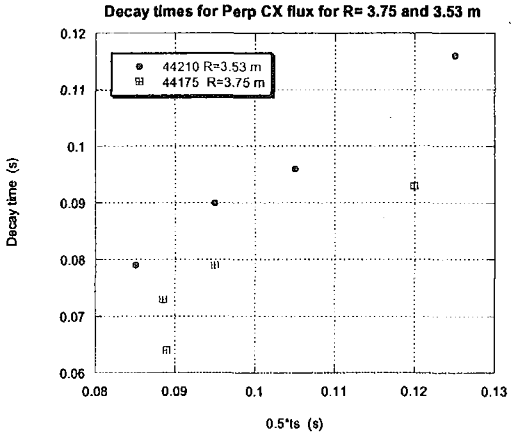

Fig.6. Perp. CX atom flux decay time upon $R_{ax}$.

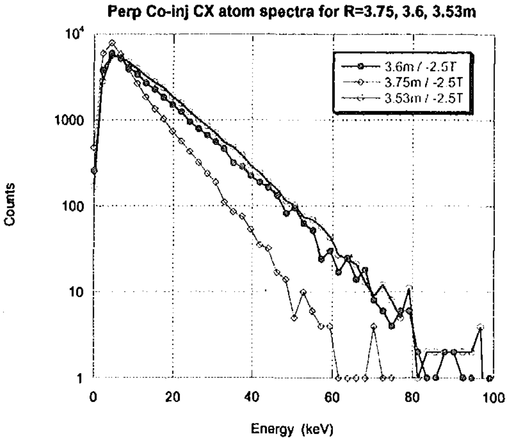

Fig.7. Perp. CX atom spectra at different $R_{ax}$.

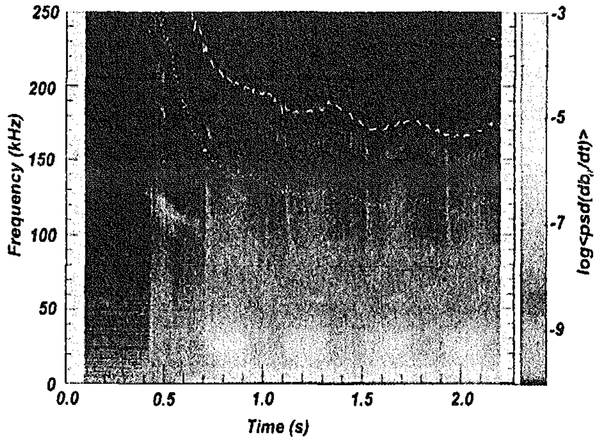

Fig.8. MHD activity during co-beam blips.

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