Study of Tangentially Beam-injected Ion Behavior in LHD Using Natural Diamond Detectors

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Abstract. Both energy spectra and dynamic of flux of fast ions originally tangentially injected into Large Helical Device plasma with energy 150 keV was studied using tangentially and perpendicular viewing charge exchange (CX) atom spectrometers based on natural diamond detectors. Measurements were performed in plasma configurations with magnetic axis at R_{ax} = 3.75 m, 3.6 and 3.53m for axial magnetic field .B_t = +2.5, -2.5, 1.5 and 0.75 T. The degradation of energy distribution and diminishing of decay times of fast CX atom flux were measured at B_t=0.75 T. Sharp increases of fast co-CX atom fluxes were measured in experiments with 200ms co-beam blip injection in R_{ax} = 3.53m and 3.6m configurations during the second part of the beam time when 50-60 kHz MHD instabilities appeared in plasma. Increase of fast co-moving ion transport from plasma center to periphery by 50-60 kHz energetic particle modes in R_{ax} = 3.53 and 3.6m configurations could be discussed as the reason of measured increase of fast CX atom flux.

1. Introduction

Fast ion behaviour in fusion reactor is of great importance for its design. Due to ripple structure, q profile and topology of fast ions trajectories the issue of fast ion confinement is more crucial in fusion reactor based on stellarator configuration. Experiments on Large Helical Device (LHD) [1] with neutral beam injection (NBI) are providing the possibility to study some aspects of fast ion behaviour in largest for today stellarator plasma configuration. Well developed diagnostic complex of LHD [2] 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 evolution in time of the perpendicular and tangential confined fast ion energy distributions. The purpose of our work was to study experimentally 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 tangential and perpendicular protons confined in LHD plasma was studied using viewing tangentially to plasma at R = 3.65 m in equatorial plane and perpendicular vertically at R = 3.67 m [3] charge exchange (CX) atom spectrometers based on natural diamond detectors (NDD) [4]. The tangential and perpendicular NDDs integrate from their cones of view the CX atom fluxes created by fast ions having pitch angles of 140-180 (0-40 for counter-clockwise directed magnetic field) and 87-102 degrees [3] with respect to co-clockwise direction, respectively. Fast ions were originally tangentially co- and counter-injected with energy 150 keV into LHD hydrogen plasma. To provide both spectrometry and flux dynamic studies of tangential and perpendicular CX atoms, measurements were performed during experimental program of high energy ion task force with stationary and modulated (200 ms – on / 200 ms – off) co- and counter- beam injection [1]. Applied NDDs were specially developed for fast (E > 18 keV) CX atom spectrometry [4]. Tangential NDD was placed at distance 6.8 m from the plasma center. It has input window with diameter 2 mm and additional aperture with diameter 1 mm installed at distance 285 mm from the detector. So this NDD has plane angle of its cone of view ~ 0.3 degree, and sees the plasma region with diameter ~ 6 cm at the axis. Measurements were performed in standard plasma configurations with magnetic axis at R_{ax} = 3.75 m and in inward shifted configurations with R_{ax} = 3.6 and 3.53 m and average minor radius a = 0.6 m with values of magnetic field equal to 2.5, 1.5, 0.75 (co-clockwise) and -2.5 T (counter-clockwise). Electron density and temperature of plasma in these experiments were in the ranges $0.5\div 2\times10^{19}$ m^{-3} and 1 ÷ 2 keV.

3. Results of Fast Ion Confinement Studies

3.1. Methodology of the Studies

Behaviors of co- (with respect to magnetic field (B_t)) and counter-moving fast ions were studied in plasma discharges with counter- and co-directed B_t, respectively.

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 ~ $(0.75\div1)\times10^{19}$ m^{-3}, T_e ~ 1.8÷2 keV).

Another way to study experimentally the efficiency of fast ion confinement is connected with measurements of the decay times of fast (E > 18 keV) CX atom fluxes after beam cancellation in experiments with modulated NBI and their comparison with calculated: 30 degree scattered times for tangential CX atom flux measurements and Coulomb slowing down time for perpendicular CX atom flux measurements. It was measured that after beam cancellation the perpendicular fast CX atom flux exist longer then tangential one. This indicates that due to reionization of CX atoms integrated from respective cone of view the tangential NDD has measured CX atom flux from more periphery region of plasma than perpendicular NDD. It was measured that perpendicular CX atom flux is increasing with plasma density and time delay of its maximum with respect of beam cancellation is diminishing with plasma density. Such relative behavior of tangential and perpendicular fast CX atom flux is in good agreement with pitch angle scattering by Coulomb collisions.

3.2. CX Atom Spectrum and Flux Measurements in MHD-quiescent LHD Plasma

Tangential spectra of co- and counter-moving CX atoms were very similar in whole energy range for plasma configurations with R_{ax} = 3.75 and 3.6 m and $|B_t|$ = 2.5 T. This demonstrated the absence of essential difference in confinement of fast co- and counter moving ions with energies up to 140 keV in these LHD plasma configurations.

Tangential spectra of co-moving CX atoms measured for R_{ax} = 3.53 m and 3.6 m plasmas were equal to each other and a bit lower than for R_{ax} = 3.75 m plasma in the energy range 20-85 keV. Similar, as shown in fig.1, tangential spectra of counter-moving CX atoms measured for R_{ax} = 3.6 m plasmas were a bit lower with respect to those measured from the R_{ax} = 3.75 m plasmas in the same energy range. Measured decay times of co- and counter-moving CX atom flux were slightly lower in R_{ax}= 3.6 m configuration with respect to R_{ax}= 3.75 m one and essentially lower in R_{ax}= 3.53 m (see fig.2) plasma. Fast beam ion minor radial distributions in standard and inward shifted plasma configurations were calculated using FIT code [5] for LHD discharges 45896 (R_{ax} = 3.75 m) and 45908 (R_{ax} = 3.6 m) using experimentally measured by Thomson scattering electron density and temperature minor radial distribution. Results of calculations shown, that the beam ion minor radius distribution is becoming broader with the inward shift of plasma axis from standard configuration. In addition to this due to reionization of CX atoms the input of more periphery component in the integrated by NDD along its line of sight fast CX atom flux is increasing with the inward shift of the plasma axis. So, the obtained results of some diminishing of fast ion distribution function in low energy range and fast CX atom decay time after beam cancellation with the inward shift of LHD plasma axis could be treated as illustration of slightly higher losses of both co- and counter- moving fast ions from more periphery plasma regions (measurements in R_{ax} = 3.6 and 3.53 m configurations) than from more central regions (measurements in R_{ax} = 3.75 m configuration). Due to the absence of the loss cone for tangentially moving fast ions with studied energies in almost whole LHD cross section [5] these losses should be assigned to charge exchange processes of fast ions with residual in plasma atoms, that are increasing to plasma periphery due to higher atom density there.

As shown in fig.3, in plasma configuration with R_{ax}=3.6m tangential counter-moving CX atom spectra are slightly diminishing with B_t change from 2.5T to 1.5T and essentially diminishing for B_t=0.75T in whole energy range. The comparison of measured in these experiments fast CX atom flux decay times with calculated 30 degree scattered times are presented in fig.4. These results are showing that for lower axial magnetic field measured decay times are very slightly (B_t=1.5T) or essentially (B_t = 0.75T) shorter then calculated 30 degree scattered time. These decay time data could be treated as an illustration of some degradation of the confinement of counter-moving ions in plasma with B_t diminished down to 0.75T. But measured results, and spectrometry data in particular, could be also assigned to lower T_e in discharges with lower B_t and to wider fast ion trajectory excursions to plasma periphery at lower B_t and so lower slowing down time and higher CX loss there. Further detail mathematical modeling of measured by NDD CX atom fluxes is required for making the final conclusion.

The perpendicular CX atom spectra, $T_{eff,\perp}$ (see fig.5) and fast CX atom flux decay time shown in fig.6 were lower in R_{ax} =3.75m configuration than in cases of R_{ax} =3.6m and 3.53m. All this could be explained by better confinement of helically trapped ions in inward shifted configurations with respect to standard one [6].

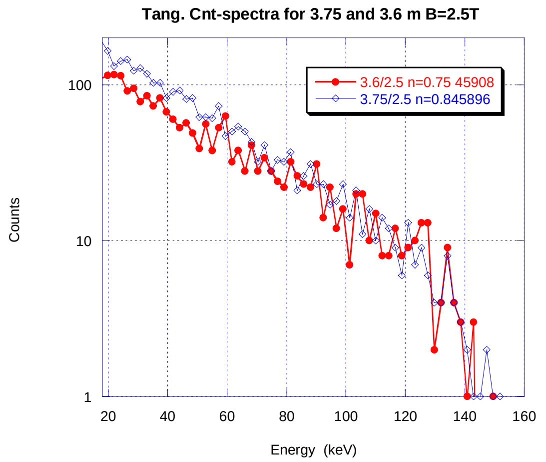

Fig.1. Tangential spectra of counter-moving CX atoms for B_t=2.5T, R_{ax}=3.6m (discharge 45908, n_e=7.5×10^{18}m^{-3}) and 3.75m (45896, n_e=8×10^{18}m^{-3}).

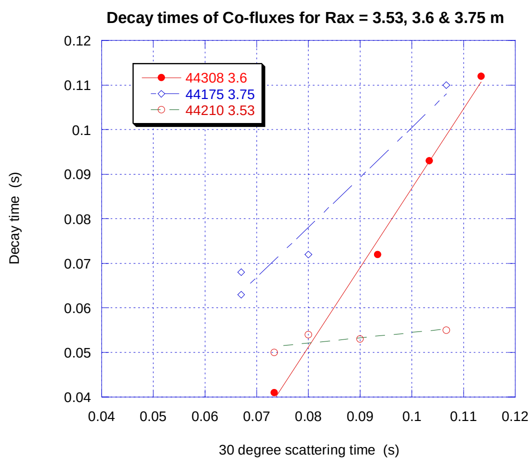

Fig.6. Comparison of measured Co-CX atom flux decay times with calculated 30 degrees scattered time of 50keV protons for R_{ax}=3.75m (discharge 44175, diamonds), 3.6 m (44308, circles), 3.53 m (44210, empty circles).

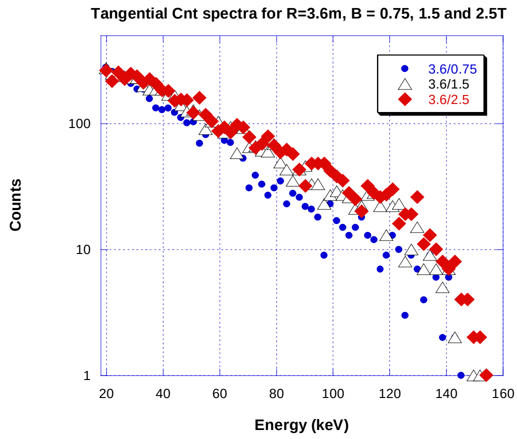

Fig.3. Counter-CX atom spectra (for E>18 keV) measured in plasmas with R_{ax}=3.6m and B_t=2.5T (diamonds), 1.5T (triangulars) and 0.75T (circles).

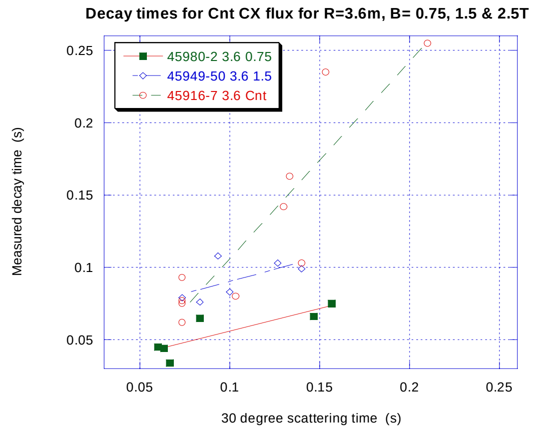

Fig.4.Counter-CX atom flux decay times (R_{ax}=3.6m, B_t=2.5T (open circles), 1.5T (diamonds), 0.75T (squares) upon 50 keV proton 30^0 scattered times.

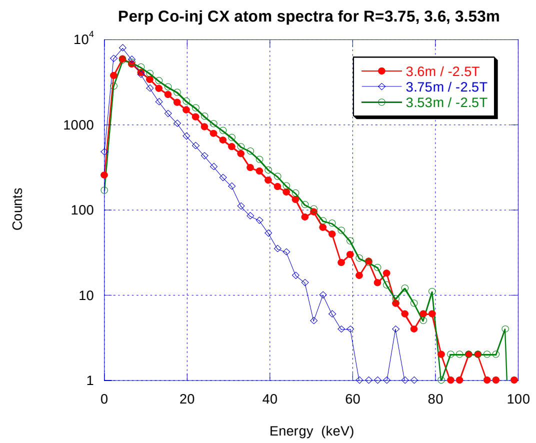

Fig.5.Perpendicular CX atom spectra (E>18 keV) in plasmas with B_t=-2.5T, R_{ax}= 3.75m (diamonds), 3.6m (circles) and 3.53 m (open circles).

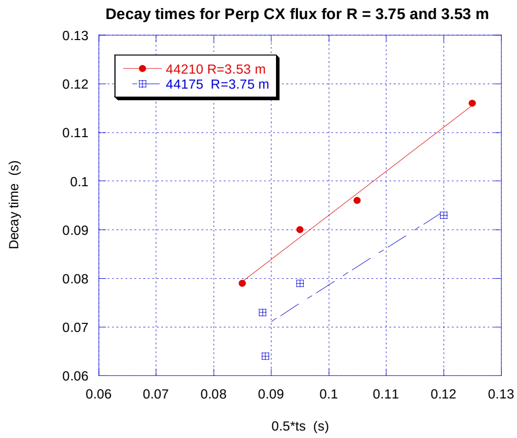

Fig.6. Perpendicular CX atom flux decay times for B_t=-2.5T, R_{ax}=3.75m (squares) and 3.53m (circles) upon calculated slowing down times t_s.

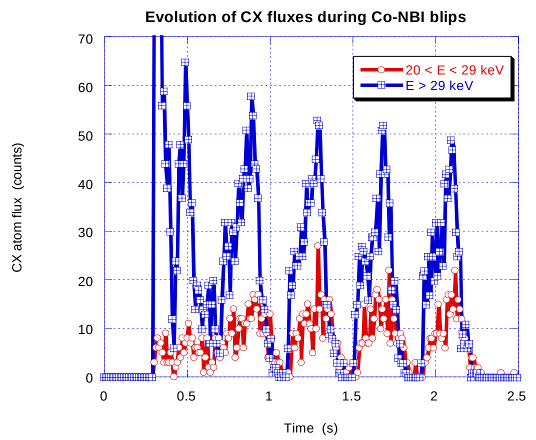

Fig.7. Tangential CX atom fluxes (E = 20-29 keV (circles) and >29 keV (squares), shot 44210, R_{ax}= 3.53m,co-NBI blips turned-off at 0.9, 1.3, 1.7, 2.1s.)

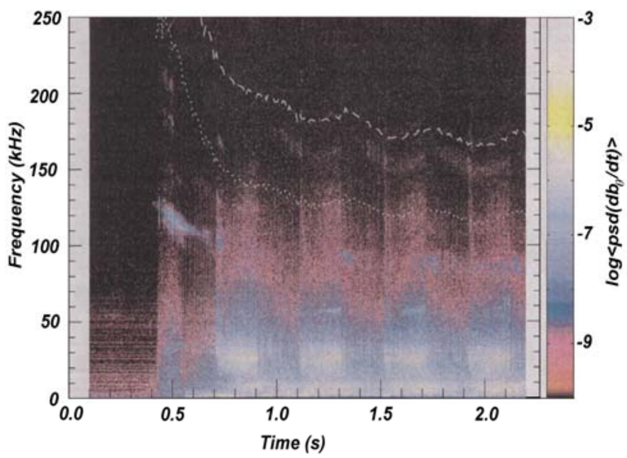

Fig.8. MHD activity during co-beam blips turned-off at 0.9, 1.3, 1.7, 2.1 s (44210, B_t = -2.5 T, R_{ax}= 3.53 m).

3.3. 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}=3.6m plasmas during the second part of the beam time (see Fig.7). 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}=3.53m, which CX atom fluxes presented in fig.7 is shown in Fig.8. The evolution of fast CX atom flux from plasma with Rax=3.53m configuration was studied for different energy ranges. As shown on fig.7 it was measured that fluxes of CX atoms with energy 20–29 keV did not have fast increases during beam time but fluxes of CX atoms having energy higher than 29 keV have sharp peaks during second parts of beam time. Measured sharp increases of fast CX atom fluxes correlate with appearance in plasma 50-60 kHz MHD instabilities showing on fig.8. 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 fast co-moving ion transport from plasma center to periphery by 50-60 kHz energetic particle modes in R_{ax}=3.53 and 3.6m plasma configurations could be discussed as the reason caused measured increase of fast ($E > 29$ keV) CX atom flux.

4. Conclusions

Results of CX spectrum and flux dynamic measurements:

- Demonstrated that there is no essential difference in confinement of fast co- and counter-moving ions with energy up to 140keV in LHD plasma with R_{ax}=3.75 and 3.6m, $|B_t|$=2.5T.
- Could be treated as illustration of slightly higher CX losses of both co- and counter-moving fast ions from more periphery plasma regions (measurements in R_{ax} = 3.6 and 3.53m configurations) than from more central regions (measurements in R_{ax} = 3.75 m configuration).
- Could be treated as illustration of some degradation of counter-moving ion confinement in plasma with magnetic field decrease down to B_t = 0.75 T. But measured results could be also assigned to lower T_e in plasma discharges with lower B_t and to wider fast ion trajectory excursions to plasma periphery and so lower slowing down time and higher CX loss there.
- Demonstrated the better confinement of helically trapped ions in inward shifted (R_{ax}= 3.53 and 3.6 m) configurations with respect to standard one (R_{ax} = 3.75 m).

Increase of fast ($E > 29$ keV) 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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References

[1] M.Osakabe, et. al., presented at IAEA Fusion Energy conference (EX-P4/44) Villamura, Portugal (2004).
[2] S.Sudo, et.al., Plasma Phys.Control.Fusion, 45, A425-A443 (2003).
[3] M.Isobe, et.al., Rev. Sci. Instrum., 72, 611-614 (2001).
[4] A.V.Krasilnikov, et.al., Nuclear Fusion, 42, 759-767 (2002).
[5] S. Murakami, N. Nakajima, S. Okamura, M. Okamoto, Nucl. Fusion 36 789-796 (1996).
[6] S.Murakami, H.Yamada, M.Sasao,et.al. Fusion Science & Technology 46, 241-247 (2003)