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Experimental Study of Fast Ion Confinement in CHS

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Abstract

The confinement property of neutral beam (NB)-injected fast ions has been investigated by means of neutron diagnostics and neutral particle analyzer in Compact Helical System (CHS). In a series of this experiments, an 1% deuterium-doped short pulse NBs with the duration of 6 ms was tangentially injected into target deuterium plasmas. After beam turn-off, the energy loss of beam ions was measured with a neutral particle analyzer and the neutron emission decay was measured with a BF_3 proportional counter. The energy loss of beam ions was consistent with classical slowing down theory. In a low density operation of CHS, the charge exchange loss of beam ions is not negligible. It seems that the dominant loss process of beam ions is different between high field and low field plasmas.

Keywords:
Compact Helical System (CHS), neutron diagnostics, neutral particle analyzer, fast ion, slowing down, charge exchange loss

1. Introduction

The behavior of energetic ions in toroidal plasmas is one of the important research subjects in fusion experiment because good confinement property of energetic ions is an essential requirement for realization of a fusion reactor. In tokamak experiments, many efforts have been so far made on the study of fast ion behavior as reviewed in Ref. 1. It is recognized that fast ion behavior is in general explained with classical theory in tokamaks. On the other hand, in stellarators, fast ion behavior is not very well understood comprehensively from experimental approach although several efforts have been made on it[2-4].

In the present study, the neutron diagnostics was applied to CHS deuterium discharges to study the confinement property of injected fast ions. The time trace of fusion neutrons originating in beam-thermal reactions provides the information of slowing-down and loss of fast ions. In CHS, deuterium beam of 100% have never been injected because of an insufficient neutron shield. Here, 1% deuterium-doped hydrogen beams were injected for our purpose.

In this paper, the energy loss of beam ions and confinement characteristics of beam ions are described. The contribution of charge exchange loss to the beam ion loss is also discussed.

2. Experiment and Analysis

2.1 Energy loss of beam ions

In CHS, two neutral beams (NBI-1 and NBI-2) are installed. The injection angle of NBI-1 is variable from tangential to perpendicular. NBI-1 is ordinarily set to be tangential and the beam energy is typically 35 ~ 40 keV. In a series of this experiment, a short pulse neutral beam with the duration of 6 ms was tangentially injected into a target deuterium plasma sustained by electron cyclotron heating.

To investigate energy loss rate of injected beam ions, a charge exchange neutral particle analyzer (NPA)

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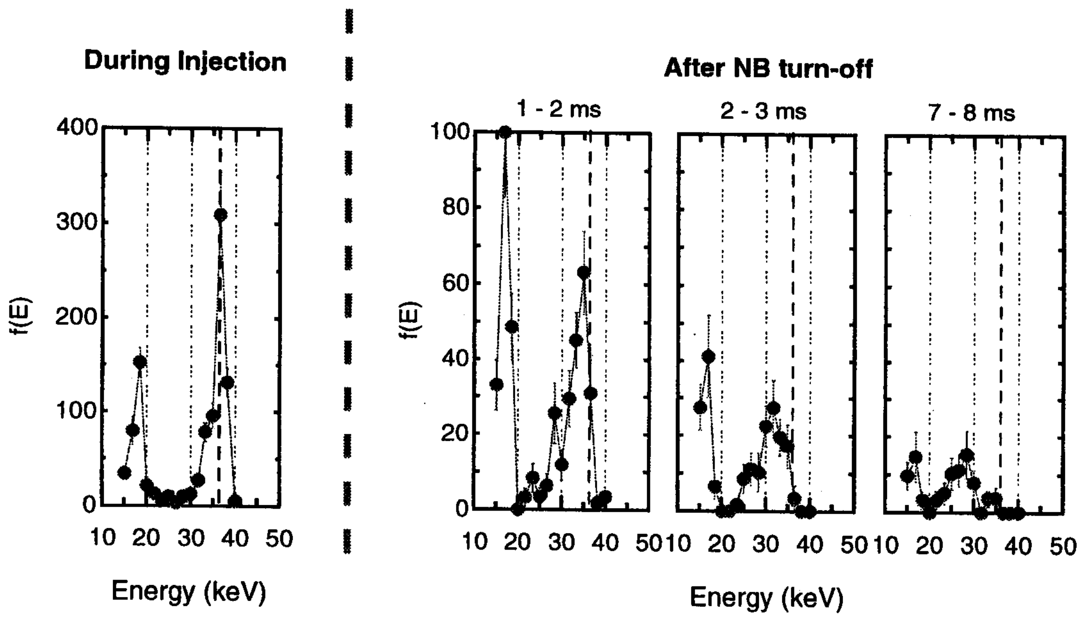

Fig. 1 Time variation of charge exchange neutral particle spectra. Neutral beam was tangentially injected. The neutral particle analyzer was set to be tangential. The beam injection energy E_{inj} was 36 kV.

was employed. The view line of NPA is on the midplane and the view angle can be varied. In this study, the view line was fixed to be tangential and the energy range of NPA was focused from 20 to 40 keV.

In Fig. 1, the charge exchange fast neutral spectra during the beam injection and after the beam turn-off are shown. During the beam injection, a delta function-like energy spectrum was observed and the peak energy of spectrum agreed with the injection energy of NB. It is seen that the peak energy is shifted to low energy side with time because of slowing-down of fast ions. Fig. 2 shows the peak energy of full energy component as a function of time and the energy loss $\{dE/dt\}_{\text{classical}}$ calculated with classical slowing down theory[5] for two cases of electron density. As seen in Fig. 2, the slowing down behavior of fast ions is consistent with classical theory.

2.2 Neutron emission decay after NB turn-off

Our interest was also in the neutron emission decay after the termination of short pulse NB. This method is one of the quantitative methods to study the beam ion confinement. The studies focusing on neutron emission decay have been carried out in several tokamaks[6,7]. The confinement time of fast ions can be roughly deduced by comparing the experimental neutron decay time with the decay predicted from classical slowing down theory.

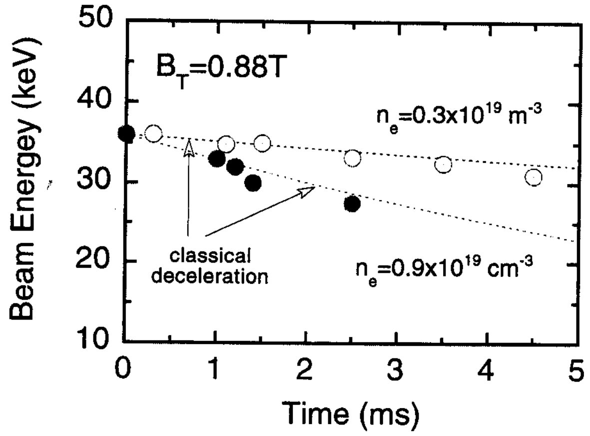

Fig. 2 Averaged energy loss of beam ion loss measured with a neutral particle analyzer and energy loss predicted by classical slowing down theory. The dotted line was calculated with taking account of line-integrating effect of NPA view line.

In CHS, d-d neutrons due to short pulse beam injection were measured with a calibrated BF_3 proportional counter with the sampling time of 1 ms[8]. Figure 3 shows the time evolution of neutron emission rate. The neutron emission starts to decay just after the NB turn-off. The neutron decay time $\tau_{\text{n-classical}}$ predicted by classical theory is defined as follows[9],

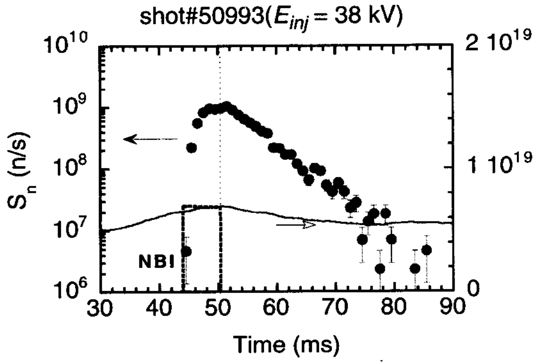

Fig. 3 Typical neutron time evolution due to short pulse beam injection. The beam injection energy E_{inj} is 38 kV. The toroidal magnetic field B_T and the plasma major radius R_p was 1.76 T and 92.1 cm, respectively.

$$\tau_{\text{n-classical}} = -\int_{E_n}^{E_{inj}} \frac{dE}{\{dE/dt\}_{\text{classical}}}$$

$$= \frac{\tau_{se}}{3} \ln \left(\frac{E_{inj}^{3/2} + E_{crit}^{3/2}}{E_n^{3/2} + E_{crit}^{3/2}} \right) \qquad (1)$$

where E_{inj} is the beam injection energy, E_n is the energy at which the d(d,n)^{3}He reaction has fallen by 1/e, E_{crit} is the critical energy of beam ions at which the electrons Coulomb friction equals to the bulk ion Coulomb friction, τ_{se} is the Spitzer's slowing down time on electrons. If we take account of beam ion loss, the experimental decay $\tau_{\text{n-exp}}$ is expressed as[8],

$$1/\tau_{\text{n-exp}} \approx 1/\tau_c + 1/\tau_{\text{n-classical}} \qquad (2)$$

Figures 4(a) and (b) show $\tau_{\text{n-classical}}$ *vs.* $\tau_{\text{n-exp}}$ plot for B_T of 0.88 T and 1.76 T, respectively. In this analysis, the estimate of $\tau_{\text{n-classical}}$ was done with plasma parameters averaged in the core region of $\rho < 0.2$ because the neutron emission profile is expected to be very peaked. The solid line represents the condition of $\tau_{\text{n-exp}} = \tau_{\text{n-classical}}$. In both B_T, it is seen that $\tau_{\text{n-exp}}$ is shorter than $\tau_{\text{n-classical}}$, especially in the plasma with a long $\tau_{\text{n-classical}}$. From Eq.(2), the confinement time τ_c of fast ions is deduced to be about 3 ms in the plasma with B_T of 0.88 T. The confinement time of beam ions in B_T of 1.76 T is roughly 10—20 ms, longer than in B_T of 0.88 T. It suggests that there exists beam ion loss. The possible candidates for beam ion loss are charge exchange loss and orbit loss.

Next, in order to deduce the contribution of charge exchange (CX) loss, the neutral density n_0 was estimated by the toroidal transport code PROCTR[10]. The computed result of n_0 depends on global particle confinement time τ_p*. In this calculation, τ_p* was inputted to be 10—20 ms[11]. The characteristic time of CX loss is expressed by $\tau_{cx} = 1/n_0 \cdot \sigma_{cx} \cdot v$. Then, the neutron decay time $\tau_{\text{n-th}}$ with taking account of CX loss is estimated as $1/\tau_{\text{n-th}} = 1/\tau_{\text{n-classical}} + 1/\tau_{cx}$. The disqcrepancy between $\tau_{\text{n-exp}}$ and $\tau_{\text{n-th}}$ still can not be

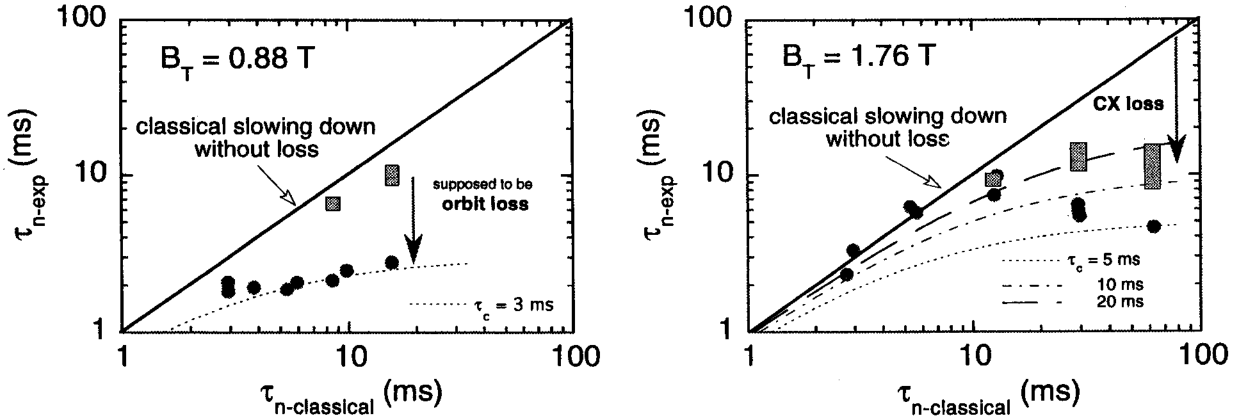

Fig. 4 Experimental neutron decay time $\tau_{\text{n-exp}}$ *vs.* predicted decay time $\tau_{\text{n-classical}}$ with classical slowing down theory. The solid line means the condition of $\tau_{\text{n-exp}} = \tau_{\text{n-classical}}$. The rectangular symbols in the figure corresponds to $1/\tau_{\text{n-th}} = 1/\tau_{\text{n-classical}} + 1/\tau_{cx}$, and its vertical upper value and lower value of rectangular symbols corresponding to $\tau_{\text{n-th}}$ is estimated with τ_p* of 20, 10 ms, respectively.

explained even if CX loss is taken into account, especially in the case of 0.88 T. The remaining loss is supposed to be due to the orbit loss. As seen in Fig. 4, there is no significant difference in charge exchange loss between both plasmas of 0.88 T and 1.76 T. In contrast, the remaining loss in the plasma of 0.88 T is much larger than in the plasma of 1.76 T. Here, if the characteristic time τ_{orbit} due to the orbit loss is introduced, τ_{orbit} is deduced to be about 5 ms for a low field plasma having $\tau_{\mathrm{n\text{-}classical}}$ of ~10 ms. In contrast, τ_{orbit} would be deduced to be about 50 ms for a high field plasma. This is qualitatively explained by the difference of the drift orbit between a low magnetic field plasma and a high field one. The fast ions in the low field plasma is easier to suffer orbit loss because the drift orbit from magnetic flux surface tends to deviate largely and shift outward compared with the drift orbit in B_T of 1.76 T.

3. Summary

The confinement property of fast ions was investigated in CHS by injecting a very short pulse neutral beam. The analysis was focused on the beam deceleration phase after the NB turn-off. The time trace of NPA spectra indicates that the injected beam ions slow down classically. The analysis of neutron emission decay shows there exists beam ion loss. The confinement time of beam ions in the plasma of 0.88 T and 1.76 T is deduced to be about 3 ms and 10–20 ms, respectively. For the plasma of 1.76 T, the contribution of CX loss fraction to total loss becomes roughly half. In contrast, the orbit loss becomes dominant loss channel in the plasma of 0.88 T. It turns out that charge exchange loss of fast ions is not negligible in the low density plasmas ($n_e < 1.0\times10^{13}$ cm^{-3}) of CHS. By strengthening B_T, the improvement of fast ion confinement was clearly observed.

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