JAERI-Research
96-005

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February 1996

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編集兼発行　日本原子力研究所
印　　刷　㈱原子力資料サービス

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(Received January 9, 1996)

The effect of the ion ∇B drift direction on ripple-induced fast ion loss was experimentally investigated by switching the direction of the toroidal magnetic field in JT-60U deuterium discharges with vertically asymmetric ripple well. Neutral beam (NB)-injected fast ion loss was estimated from the neutron decay following short NB pulse D^0 beams (90 keV) . No significant difference was seen in the loss for upward and downward ∇B drift discharges, indicating that ripple-induced loss of fast ions is independent of the ion ∇B drift direction even for plasmas with up-down asymmetric ripple well.

Keywords: JT-60U, ITER, Ripple Well, Up-down Asymmetry, Ion ∇B Drift, Fast Ion, Ripple Loss

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JT-60Uにおける高速イオンリップル損失に与えるイオン∇Bドリフト方向の影響

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（1996年1月9日受理）

JT-60Uの上下非対称なリップル井戸領域を持つ配位において，トロイダル磁場の向きを変えることにより，イオン∇Bドリフト方向の違いが高速イオンのリップル損失に与える影響を調べた。高速イオンの損失は，短パルスの重水素中性粒子ビーム（90 keV）停止後の中性子発生率の減衰時間から評価した。イオン∇Bドリフト方向が上向きの場合と下向きの場合の中性子減衰時間を比較した結果，有為な差は現れなかった。磁場リップル井戸が上下非対称な配位において，リップルによる高速イオンの損失はイオン∇Bドリフト方向に依存しないことが分かった。

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1. Introduction

The finite number of toroidal field coils gives rise to perturbation of the toroidal magnetic field(TF ripple), and thus induces TF ripple trapping[1] and the radial drift of banana particles [2]. The transport of fast ions in TF ripple well is one of the most important issues to realize a nuclear fusion reactor. The ripple-induced loss should be as low as possible not only to reduce the input power loss of neutral beam(NB) but also to avoid the resulting heat load on the first wall. So far theoretical[3,4], simulational[5,6] and experimental efforts[7-10] have been made on suprathermal ion behaviors in rippled magnetic fields.

The objective of the present study is to investigate the effect of up-down asymmetric ripple well on fast ion loss. The backgrounds are as follows. First, in a reactor-relevant tokamak having a single null-divertor on lower side such as ITER(International Thermonuclear Experimental Reactor), the ripple amplitude tends to be larger on the upper side than on the lower side because of the requirement of a long divertor throat. Second, it would be preferable that B_t direction of the ITER tokamak is reversible for unexplored advanced operation scenarios[11]. A possible problem for the B_t-reverse operation is that the up-down asymmetry may enhance ripple-trapped loss when ion ∇B drift directs upward, because, once trapped in a ripple well, fast ions move toward the deeper side of the well and thus have little chance of detrapping. With regard to the fast ion behavior in the up-down asymmetric ripple well, there are following previous works. Fast ion transport in the up-down asymmetric ripple was theoretically studied by Yushmanov *et al.*[12]. Their theory indicated that the up-down asymmetry did not enhance diffusive ion transport coefficients in the core region irrespective of the ion ∇B drift direction. In order to examine the possibility of B_t-reverse operation in ITER, the orbit following simulation concerning the ripple-induced α particles loss has been carried out for the configuration of ITER[13]. The calculated results indicated that the power loss fraction did not depend on the B_t direction in spite of the up-down asymmetry, however, the peak heat load in the upward drift was concentrated compared with that in the downward drift. In ITER, the heat load in the case of the upward drift is concluded to be acceptable.

The present study in JT-60U was conducted to make sure of the effect of the ion ∇B drift direction on the total ripple loss of NB-injected fast ions, i.e. the summation of ripple-trapped loss and banana drift loss, in plasmas with the up-down asymmetric ripple well, and to verify experimentally the possibility for B_t-reverse operation in a fusion reactor tokamak. In the Section 2, the conditions and method of the TF ripple experiment in JT-60U are described. Results and discussion are presented in the Section 3. Summary is given in Section 4.

2. Experiment

2.1 Experimental conditions in JT-60U

JT-60U is a tokamak device with a single null divertor and has the major radius $R = 3.4$ m and the average minor radius $a_p = 1.0$m. Toroidal magnetic field B_t up to 4.5T is produced by circular 18 TF coils. The ripple amplitude δ [$\equiv (B_{max} - B_{min}) / (B_{max} + B_{min})$] at the outer edge of the full-sized plasma of JT-60U goes up to 2.5%, which is comparable with that of ITER in which the ripple amplitude at first wall is recommended to be less than 2.5%. JT-60U has neutral beam injectors(NBI) of 14 units, consisting of 10 nearly perpendicular injectors and 4 tangential (2 co- and 2 counter-) injectors. The beam injection energy E_B is typically 90keV and the total beam power of up to 35MW is delivered. The NB power fractions are $E_B : E_B/2 : E_B/3 = 78\% : 15\% : 7\%$.

A ripple trapping region is formed in the region where the effective ripple well parameter α^* [$\equiv (\partial\bar{B}/\partial l)/(\partial\tilde{B}/\partial l)$] satisfies the condition $|\alpha^*|<1$, where $\partial\bar{B}/\partial l$ and $\partial\tilde{B}/\partial l$ stand for the variations of axisymmetric and non-axisymmetric components of B_t along the magnetic field line, respectively. The trapping region of ITER is illustrated in Fig. 1, and those of JT-60U with TF ripple contours are illustrated in Fig. 2 (a) and (b). The configuration in Fig. 2(a) has an ITER-like ripple well. In Fig. 2(b), the ripple amplitude on the upper plane is larger than on the lower plane although the ripple well region is almost up-down symmetric. In the present experiment, the ion collisionality ν_i was ranged around $3s^{-1}$ which was in the intermediate region between ripple plateau diffusion[14] and stochastic diffusion[15]. The maximum ripple amplitude δ, the width of banana orbit at the plasma surface Δ_B and the parameter Δ_B/a_p for ITER and JT-60U are shown in Table 1. It is seen that the parameter Δ_B/a_p for 3.5MeV α particles in ITER and 90keV deuterons in JT-60U is almost same. In addition, ν_i is ranged in the low collisinality regime. The present experiment, therefore, can predict the ripple loss of α particles in ITER. Plasma parameters are shown in Table 2.

2.2 Experimental method

2.2.1 Estimation of NB-injected ion loss

The total ripple loss for NB-injected fast ions is deduced from the neutron decay following a short deuterium NB pulse of which duration is much shorter than the slowing down time of the injected ions. Such a short NB pulse allows us to treat the velocity distribution of the fast ions as monoenergetic. This is an important simplification in data analysis. The short pulse technique has been widely used to study fast ion behavior. The applications are DIII-D experiment for beam slowing down[16,17], the diffusion study of fast ions in TFTR[18] and the ripple-induced loss study of fast ions in JT-60U[19].

The neutron decay after NB turn-off is approximately exponential. The neutron decay time τ_n (= $\tau_{n\text{-exp}}$) is expressed as follows,

$$1/\tau_{n\text{-exp}} \approx 1/\tau_c + 1/\tau_{n\text{-classical}} \ ,$$

where τ_c is the confinement time of beam particles and $\tau_{n\text{-classical}}$ is the neutron decay time for the classical slowing down without loss, which is approximately equal to $\tau_s/2.3$. Here, τ_s is the Braginskii's energy relaxation time. The factor '2.3' originates in the D-D fusion reactivity $\sigma_{DD}(E_B)E_B{}^{1/2}$ for beam-target reaction which is approximately proportional to $E_B{}^{2.3}$ in the energy range of 50 to 100 keV. The contribution of the half E_B and one third E_B component to total neutron emission is neglected because the neutron emission due to the half E_B and one third E_B component is more than one order smaller than that of E_B(=90keV) component in our case. In the present experiment, the low density target plasma satisfying the condition $\tau_s >> \tau_c$ was required to investigate the ripple-induced loss of fast ions from the neutron emission.

Fig. 3 shows the typical time evolution of the line-integrated electron density $n_e l$, the central electron temperature $T_e(0)$, the NBI power P_{NB} and the total neutron emission S_n. We employed the perpendicular NBI with the pulse duration of ~30ms throughout the experiment. NBI power ranged from 4MW to 12MW. The electron density was changed by using deuterium gas puffing to change the slowing down time. In Fig. 3, it should be noted that the beam injection does not cause significant perturbation on n_e nor T_e.

2.2.2 Diagnostics

A ^{235}U fission chamber[20] was employed to measure the total neutron emission with the time resolution of 2ms. The electron density was obtained with two FIR interferometers and Thomson scattering measurement, and the electron temperature was obtained by Thomson scattering measurement and electron cyclotron emission Michelson interferometer.

3. Result and Discussion

In order to deduce the ripple-induced loss of NB-injected fast ions, we compared the measured neutron decay time and the calculated one assuming classical slowing down without ion loss. Fig. 4 shows the typical neutron decay in a low density plasma with an ITER-like ripple well and the calculated neutron decay. After NB turn-off, neutron emission decays approximately exponentially as mentioned in Section 2.2.1. It is seen that the measured neutron decay time for the perpendicular short NB pulse is faster than the calculated one. The difference between the measured and calculated decays suggests the loss of fast ions during the deceleration. The ion loss, which is estimated from the difference between the measured and calculated decays, was deduced to be about 13%. Considering the results obtained in Ref. 18, the fast ion loss is attributed to TF ripple loss. On the other hand, the decay of neutron emission due to the tangential short NB pulse have indicated no fast ion loss in JT-60U[18].

By switching the direction of B_t, the effect of the ion ∇B drift direction on the fast ion loss was investigated in plasmas with the up-down asymmetric ripple well. The correlation between $\tau_{n\text{-exp}}$ and $\tau_{n\text{-classical}}(=\tau_s/2.3)$ for the ITER-like configuration(Fig. 2(a)) are shown in Fig. 5(a), and that for the configuration with the wider ripple trapping region(Fig. 2(b)) are shown in Fig. 5(b). The closed and open circles indicate data for the upward and downward ion ∇B drift, respectively. The error bars in $\tau_{n\text{-classical}}$ were determined from the width of τ_s in the area with high neutron yield (normalized minor radius ρ=0.2-0.6). In both configurations, there is no significant difference in the total ion loss between the upward and downward ion ∇B drift, indicating that the fast ion loss does not depend on the ion ∇B drift direction.

The OFMC(Orbit Following Monte-Carlo) calculation was carried out for the plasma with an ITER like ripple well shown in Fig. 4. The OFMC results are shown in Table 3. It is seen that the ion ∇B drift direction does not affect the total ion loss but the dominant loss channel is different between the cases of the upward and downward ion drift. The following picture is given for the ripple-induced fast ion loss in the asymmetric ripple well. Most of the fast ions diffused outward by ripple trapping or banana drift are lost from the plasma. In the case of the upward ion ∇B drift, the ripple-trapped loss becomes a dominant loss process because the fast ions trapped in the ripple well have little chance to detrap and go out of the plasma. The heat load profile will be concentrated because of the increased ripple-trapped loss. On the other hand, in the case of the downward ion ∇B drift, the banana drift loss becomes dominant because the trapped fast ions move toward the shallower side of the well and most of them become to follow banana orbit.

4. Summary

In the up-down asymmetric ripple well of JT-60U, the effect of the ion ∇B drift direction on the ripple-induced loss of NB-injected fast ions was experimentally investigated to make sure of the effect of the ion ∇B drift direction on total ripple loss of NB-injected fast ions. Fast ion loss was estimated from the neutron decay following short NB pulse whose duration is shorter than τ_n. No significant difference in the fast ion loss was observed between upward and downward ion ∇B drift in the two configurations : a) the ITER-like ripple well (δ=~0.6%), b) the wider ripple well region (δ=~2.2%). In the present experiment, the ripple-induced loss of NB-injected fast ions in low collision regime were independent of ion ∇B drift direction. The OFMC calculation performed for the ITER-like ripple well of JT-60U plasma indicated the total ion loss does not depend on the ion ∇B drift direction although the loss mechanism is different between the upward and downward ion ∇B drift. From the viewpoint of the power loss caused by the toroidal filed ripple, the experimental result shows the operation with the upward ion ∇B drift is not limited in a fusion tokamak with the up-down asymmetric ripple like ITER.

Acknowledgements

The authors wish to thank Drs. H. Kishimoto, M. Azumi, M. Mori and R. Yoshino for their support throughout this work. One of the authors(M.I.) is grateful to Drs. A. Iiyoshi, J. Fujita and T. Kuroda of NIFS for their continuing encouragement.

4. Summary

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Table 1 Parameters δ, ∇B and $\nabla B/a_p$ for ITER and JT-60U

Parameters	ITER	JT-60U	
		Fig.2(a)	Fig.2(b)
δ (%)	~2.0	~0.6	~2.2
Δ_B (m)	~0.2 $^{1)}$	~0.06 $^{2)}$	~0.08 $^{2)}$
Δ_B/a_p	~0.06 $^{1)}$	~0.07 $^{2)}$	~0.08 $^{2)}$

1) estimated for 3.5MeV α particle, 2) estimated for 90keV D^+

Table 2 Plasma parameters in the ripple loss experiment

Plasma parameters	JT-60U configuration	
	Fig.2(a)	Fig.2(b)
Plasma current I_p (MA)	1.5	1.3
Toroidal magnetic field B_t (T)	3.5	3.0
Major radius R_p (m)	3.15	3.48
V_p (m^3)	56	84
Effective safety factor q_{eff}	~5.0	~5.4
Electron density n_e (m^{-3})	$0.3\text{-}1.2\times10^{19}$	$0.3\text{-}1.0\times10^{19}$
Central electron temperature $T_e(0)$ (keV)	3.0 - 4.8	1.8 - 4.0
Effective ionic charge Z_{eff}	2.0 - 6.0	2.0 - 6.0

Table 3 Analysis for an ITER like ripple well by OFMC calculation

	ion ∇B ⇓	ion ∇B ⇑
banana drift	7.7(±0.6)%	0.6(±0.2)%
ripple-trapped	1.8(±0.2)%	9.7(±0.6)%
total loss	9.5(±0.6)%	10.3(±0.6)%

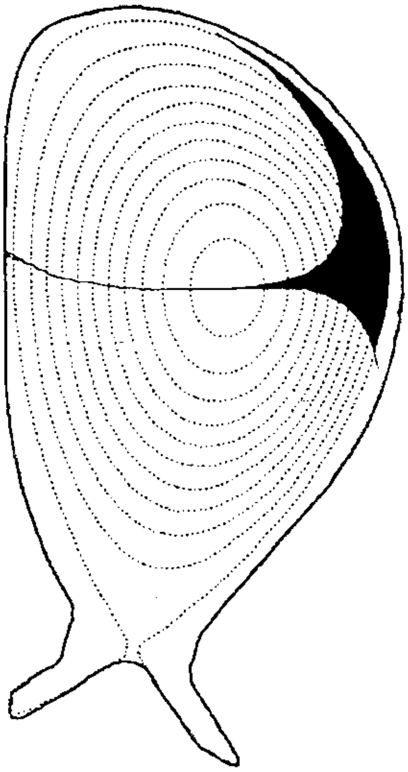

Fig. 1 The poloidal cross section and the ripple trapping region of ITER [12]. The painted area corresponds to the ripple trapping region.

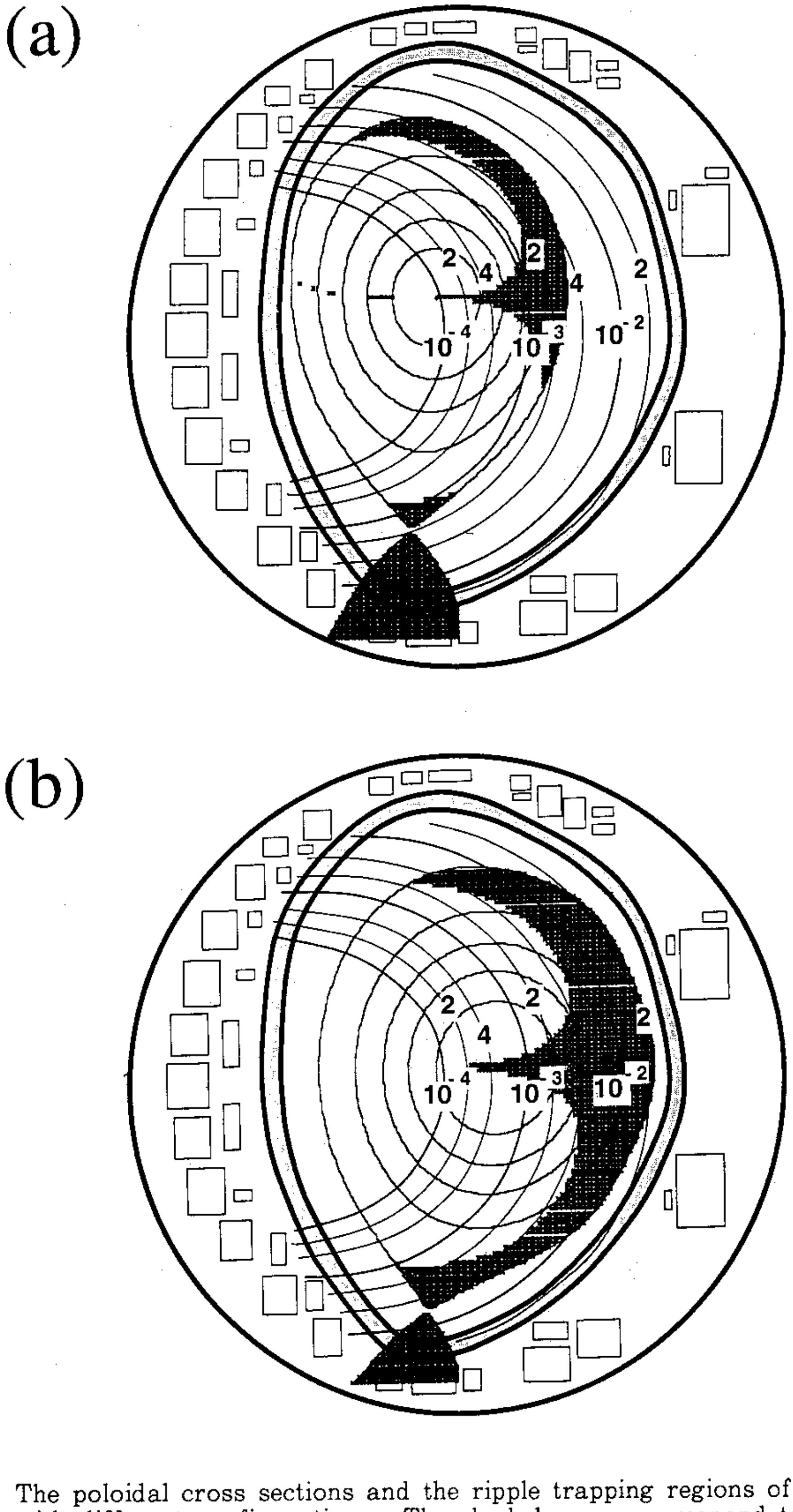

Fig. 2 The poloidal cross sections and the ripple trapping regions of JT-60U with different configurations. The shaded areas correspond to the ripple trapping regions, and the contours represent TF ripple amplitude δ. (a) ITER-like ripple well, (b) wider ripple well domain.

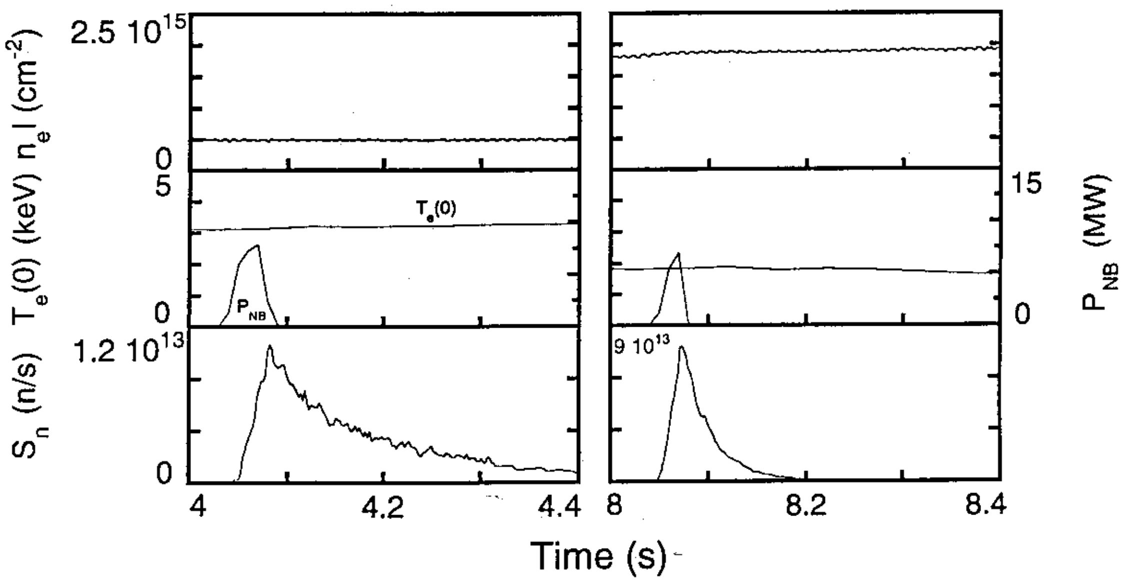

Fig. 3 Typical time evolution of n_e, T_e, P_{NB} and S_n in a low density regime (left hand side) and a relatively high density regime (right hand side). Beam component does not give rise to significant perturbation in n_e nor T_e.

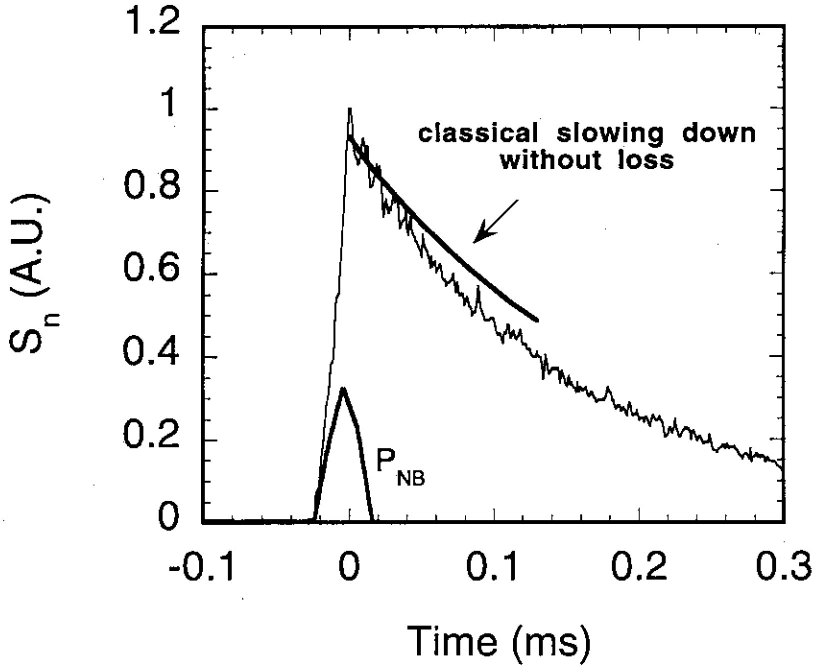

Fig. 4 Experimental and calculated neutron decay following short pulse D^0 injection into the low density plasma with the ITER-like ripple well region (see Fig. 2(a)).

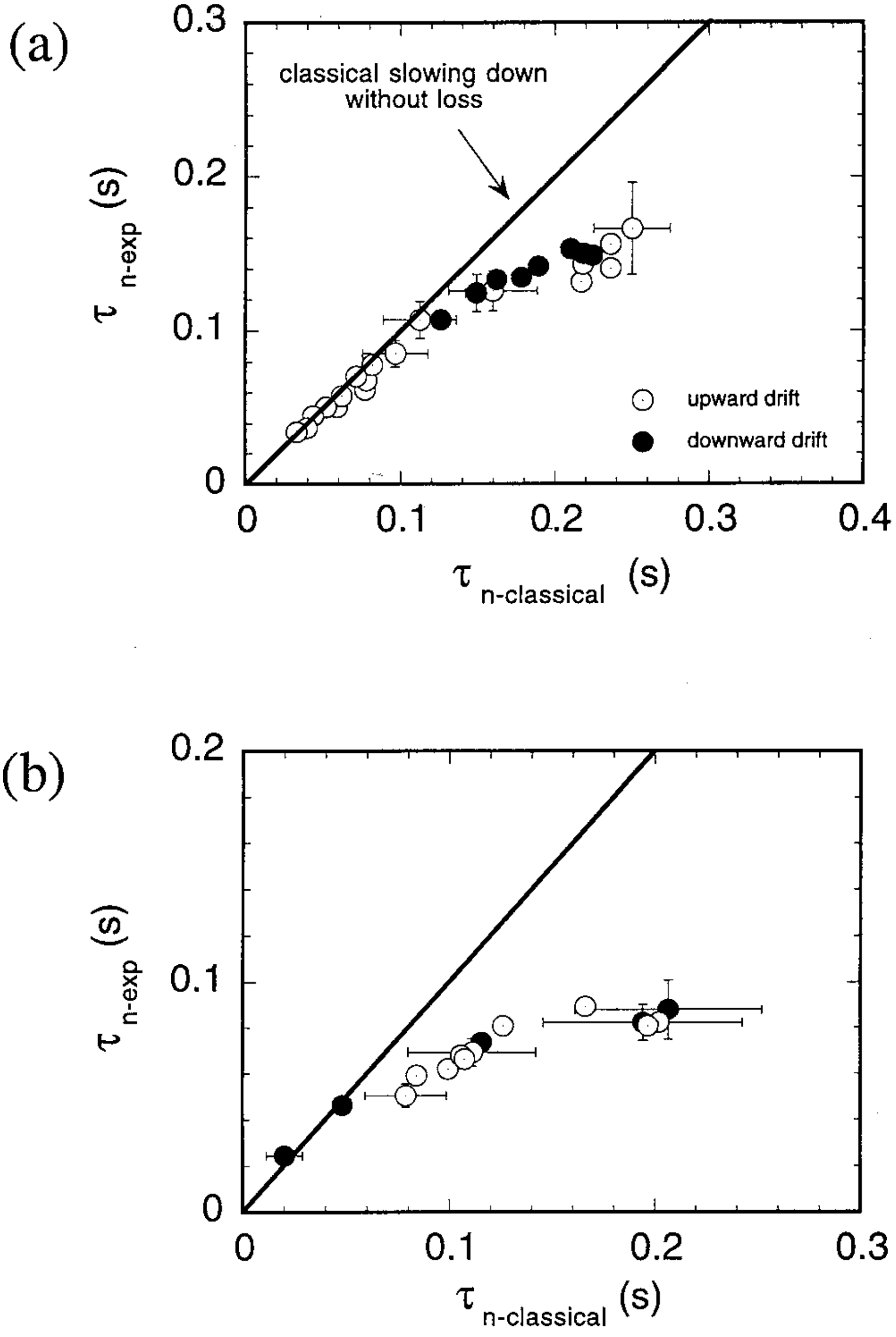

Fig. 5 Measured neutron decay time $\tau_{\text{n-exp}}$ against the predicted decay time $\tau_{\text{n-classical}}$ assuming classical slowing down of NB-injected fast ions. (a) the ITER-like ripple well (Fig. 2(a)), (b) the wider ripple well (Fig. 2(b)). The solid line represents $\tau_{\text{n-exp}} = \tau_{\text{n-classical}}$, namely classical slowing down without fast ion loss.