Classical and non-classical confinement properties of energetic ions on LHD

M.Osakabe, S.Murakami*1, T. Seki, S.Yamamoto*2, K.Toi, S.Sakakibara, O.Kaneko, K.Saito, Y.Takeiri, M.Isobe, T.Ozaki, M.Sasao*3, K.Tanaka, K.Narihara, and LHD-experimental Group

National Institute for Fusion Science, Toki 509-5292, Japan
**1Department of Nuclear Engineering, Kyoto University, Kyoto, Japan*
**2Institute of Advanced Energy, Kyoto University, Gokasho, Uji, 611-0011, Japan*
**3Dept. of Quantum Science and Energy Engineering, Tohoku University, Sendai, Japan*

Corresponding author's email address: osa@nifs.ac.jp

Abstract

The confinement properties of tangentially injected energetic particles are experimentally investigated on the Large Helical Device(LHD). The local confinement times of energetic particles are evaluated by experiments and have good correlation with pitch-angle scattering times in the core region and with charge exchange loss times in the edge regions. Thus, the classical process is considered to be the dominant process of the energetic particle confinement on LHD. In addition to these classical effects, the enhanced energetic particle transports induced by MHD-instabilities are observed on LHD. These effects become significant at low magnetic field(B_t<~0.75) configurations.

I. Introduction

Confinement of energetic particles is one of the most important issues in helical devices since a large helical ripple has a significant influence on the topology of energetic particle orbits. Following three topics are considered to be important in the energetic particle confinement studies in helical devices: (1) The confinement property of energetic particle during its slowing-down process, (2) the wave-particle interactions between energetic particles and waves, e.g., ICRF-wave or MHD-instabilities, and (3) the effect of radial electric field on the confinement property of energetic particles. In realizing a helical fusion reactor, we need to investigate these influences on α-heating. In this paper, we will focus on the first and the second topics of the energetic particles on LHD.

On LHD, a series of experiments with a short pulse(blip) of tangential neutral beam(NB) injection was performed to investigate the confinement property of tangentially injected energetic particles. The NB-blip method is a well-known experimental technique in investigating the confinement property of energetic particles for neutron diagnostics and charge-exchange(CX) neutral diagnostics, and are widely applied to many devices[1-9]. We have developed new experimental method based on Maximum Entropy and Maximum Likelihood Method(MEMLM) to analyze the CX neutral diagnostics during NB-blip experiments. The method was applied to LHD to evaluate the confinement time of passing particles on its birth orbits.

During the high-beta experiments of LHD, fast changes of energetic neutral particle fluxes were observed with the MHD bursts on the signals of a tangential CX neutral diagnostic. The signals of neutral particles at high energy(typically ~130-keV) were simultaneously increased with the MHD-bursts. The signal increase of lower energy particles occurred with a certain delay time for the increase of the high energy particles. It seems that the increased neutral flux has a characteristic time of energy decay. This phenomenon was typically observed when the magnetic field strength is lower than 0.75[T].

In this paper, we will describe and discuss the classical and non-calssical aspects of energetic particle confinements on LHD. In Sec. 2, we will show the experimental apparatus. The confinement property of the energetic particles being evaluated by the NB-blip experiments are described in Sec. 3. The interaction of MHD-instabilities with energetic particles are shown and discussed in Sec.4. Sec.5 is a summary.

2. Experimental Set-up

On LHD, NBs are tangentially injected by using three beam-lines (one for co.-NB and two for counter-NB) which are based on the negative-ion sources[10]. Each beam line has two ion sources and the tangency radii of these ion-sources are 3.63[m] and 3.77[m], respectively. To investigate the confinement property of passing energetic particles, the E//B-type CX neutral particle analyzer(NPA)[11] is installed on the tangential port, which is located at 10 cm below the mid-plane. The NPA is placed to measure the counter-NB particles for the LHD standard magnetic field direction. The NPA is horizontally movable and its scanning angle is from 0-deg. to 9-deg., where these angles are defined by the angle between the normal of the port and the NPA line of sight. The NPA has 39 energy-channels and 3 mass-column (117channels in total). The measurable energy range of the NPA is $0.5 \leq E\ A \leq 200$ [keV amu], where E and A denote the energy and the mass number of the measured particle, respectively. The electron density and temperature distributions are obtained by the FIR interferometer and YAG Thomson scattering measurement, respectively. Figure 1 shows a plot of the pitch-angles to the normalized minor radii ($\rho \equiv r/a$) along the center lines of ion sources of a counter-NB and the

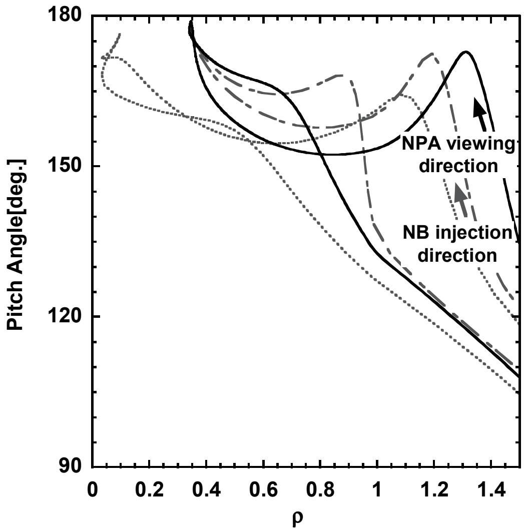

FIG.1. Pitch-angles and normalized minor-radii distributions along the center line of the outer ion-source of a conter-NB. (gray center-dashed curve) and of the inner ion-source(gray dashed curve). Those along the E//B-NPA line of sight are shown by a black solid-curve for the scanning angle of 0-deg.

E//B-NPA sight line at 0-deg.position. Considering the width of the beam, this graph shows that the E//B-NPA observes the injected energetic particles directly.

3. Evaluation of energetic particle confinement by NB-blip experiments

Figure 2 shows typical waveforms of NB-blip experiments. The blipped particles were injected at 150keV with 20ms pulse duration and 250ms cycle. As shown in this figure, the influence of the NB-blip injection on the plasma parameters are negligible. The flux decay of blipped particles during their slowing-down process from 150keV down to 55keV was evaluated by using a tangential Charge eXchange Neutral Particle Analyzer (CXNPA). Analysis is done using the data in the period between t=1.0 and 2.3s, as indicated by the gray area in Fig.2. The NPA data are accumulated according to the blip-cycle to obtain the better statistics.

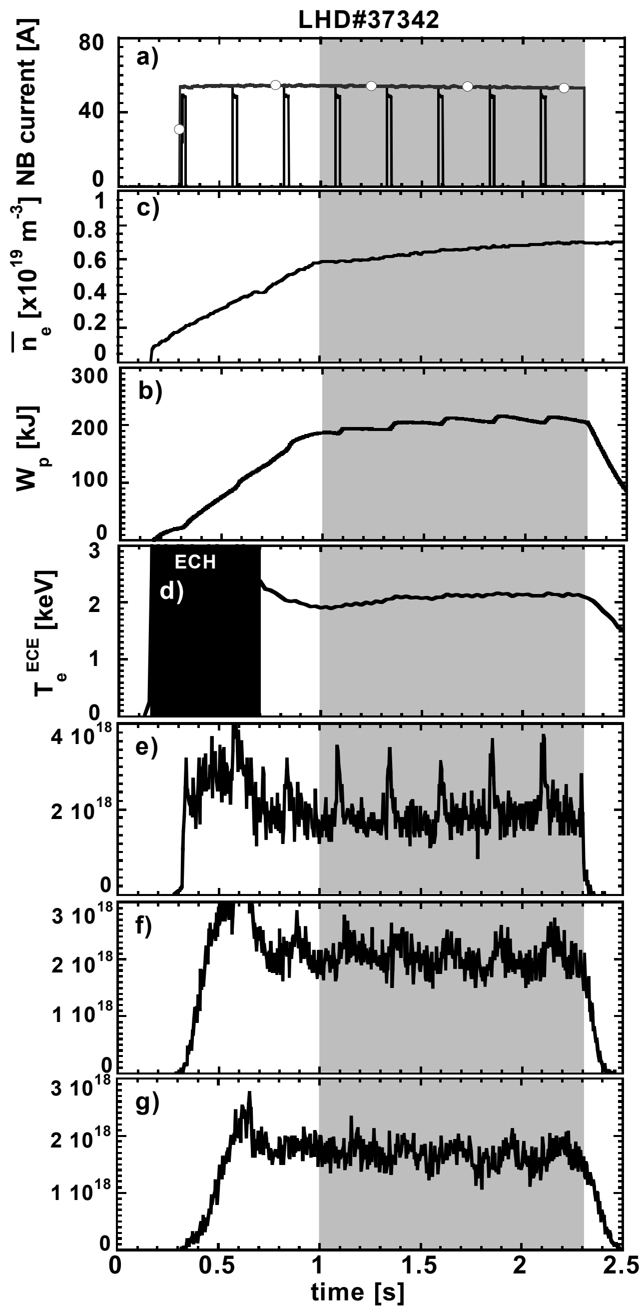

FIG. 2. Typical waveforms at an NB-blip experiment. (a)Beam current of counter-NB for plasma sustention (solid-lines) and for blip injections(solid-lines with open circles), (b) plasma stored energy, (c) line averaged electron density, (d) central electron temperature are shown. The neutral flux of (e)148keV, (f)110keV, and (g)83keV, which are measured by E//B-NPA are also shown.

Using the waveforms of the NPA for blipped-particles at the injection energy($\psi_0(t)$) as a response function ($R_0(t) \equiv \psi_0(t)/\alpha$), the contribution of energetic particles on the location of ρ to the waveform of the NPA for blipped particles at the energy (E_i) can be expressed by $w_i(\rho)R_0(t-\tau_i)$ if we neglect the effect of energy diffusion in the slowing-down process. Here, the α is the normalized parameter so that it makes the integration of $R_0(t)$ over time unity and the τ_i is the slowing-down time from the injection energy to the energy of E_i. Therefore, the waveform of the NPA at E_i for the blipped particles can be written as;

$$\psi_i(t) = \int_{l_{close}}^{l_{distant}} w_i(\rho(l)) R_0(t - \tau_i(\rho(l))) dl$$
$$= \int_{\tau_{\min}}^{\tau_{\max}} \left(w_i^1(\tau_i)(dl_1/d\rho) - w_i^2(\tau_i)(dl_2/d\rho) \right)(d\rho/d\tau_i) R_0(t - \tau_i) d\tau$$
$$= \int_{\tau_{\min}}^{\tau_{\max}} w_i'(\tau_i) R_0(t - \tau_i) d\tau_i \quad (1)$$

where l is a path length along the NPA sight line. The l_{close} and $l_{distant}$ correspond to the lengths of the close plasma edge to the NPA-port and of the distant edge, respectively. The τ_{min} is the minimum of τ_i on the path and is usually the value of τ_i at the edges, while the τ_{max} is the maximum and is usually the value at the closest point to the plasma center on the path. The subscript of l and superscript of w denote the region of the path. The l_1 and w^1 are for the region within the point of $\tau_i = \tau_{max}$, while the l_2 and w^2 are for the region beyond the point.

We have to note all of the information, such as the density profile of the bulk neutrals($n_0(\rho)$), the density profile of the energetic particles($n_{bi}(\rho)$) at E_i, the charge exchange reaction rate($\sigma_{cx}v$), and reionization loss effect of escaping neutrals($\exp(-(\sigma_{cx} + \sigma_{ion})\int_{l_{close}}^{l} n_i dl')$) contribute to $w'_i(\rho)$. In those quantities, only the density of energetic particles($n_{bi}(\rho)$) is unknown variables when the bulk plasma is in quasi-steady state condition. The rest are constant in time or can be evaluated. Therefore, the confinement ratio of energetic particles ($n_{bi}(\rho)/n_{b0}(\rho)$) can be obtained from the ratio $w'_i(\rho)/w'_0(\rho)$ with the correction of CX-reaction rate and reionization loss of escaping neutrals. We do not need to know the bulk neutral density and the birth energetic ion density profiles since they appear both in the denominator and in the numerator of the ratio and are canceled out. Only assumptions we have made are that the energy loss of the particle is given by the classical deceleration rate and that the particles are staying on the same orbit

To evaluate the $w'_i(\rho)$, we need to deconvolute the integral of Eq(1). For the deconvolution, we had developed an technique based on the Maximum Entropy and Maximum Likelihood Method (MEMLM) [12]. Confinement times of energetic particles were evaluated from the decay time of $w'_i(\rho)$. In Fig.3, the confinement times of energetic particles($\tau_{exp.}$), which were evaluated from NB-blip experiments, are compared to the pitch-angle scattering time($\tau_{90\text{-deg.}}$) and charge exchange loss time($\tau_{cx.}$) for LHD-plasmas of Rax=3.6[m] and Bt=2.5[T]. These times are calculated from plasma parameters of the discharges and are averaged along the orbit of the measured energetic particles. In Fig.3, the confinement times of energetic particles have good correlation with the pitch-angle scattering times at the core region, i.e. r/a≤0.83, and with the charge exchange loss time at the edge (r/a=0.95). This result indicates the confinement times of tangential energetic particles are explained by the classical theory with orbit effect at high magnetic field configurations.

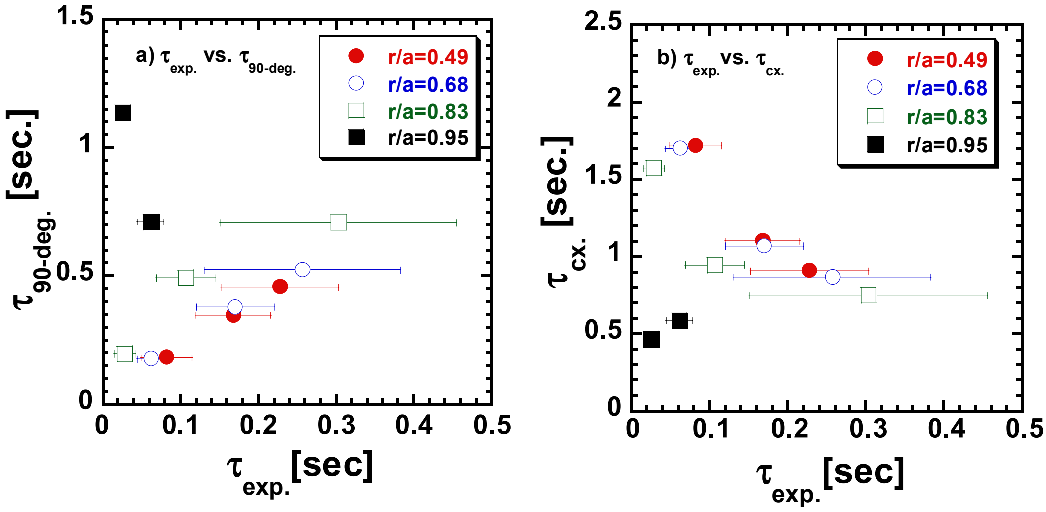

FIG..3. Correlations of particle confinement time(τ_{exp}) to (a) the 90-degree pitch-angle scattering time($\tau_{90\text{-}deg.}$) and to (b) the charge exchange loss time($\tau_{cx.}$) for LHD plasmas of R_{ax}=3.6[m] and B_t=2.5[T] configuration. In evaluating the pitch angle scattering time and charge exchange loss time, the particle energy of 100keV is assumed. The neutral density profile is obtained from AURORA code.

4. Interaction of MHD-instabilities on energetic particle confinement

In addition to these classical effects on the energetic particle transport, we have observed the other effect when the magnetic field strength is low (B_t<~0.75). With this magnetic field strength, the tangential NPA signals are often modulated by MHD-bursts, while the NB is continuously injected[13]. Figure 4 shows the typical waveforms of a Mirnov-coil signal and NPA signals. As shown in this figure, the high energy components (>113keV) of NPA signals were increased during MHD-bursts. The flux increase at lower energy component had some time delay and this delay became larger as the energy became lower. The mode analysis of the MHD-burst at t=0.943s indicates that the burst was TAE of n=2[14].

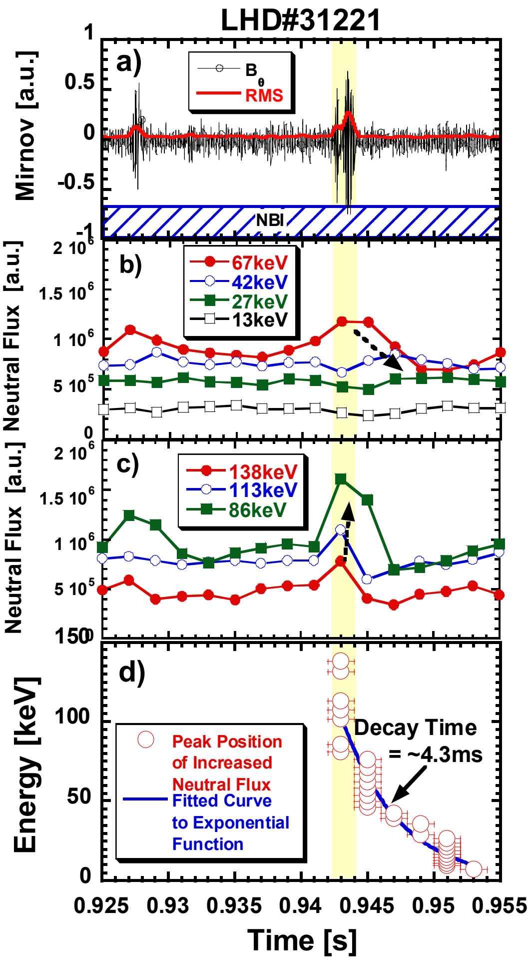

FIG. 4. Typical waveforms of (a)mirnov-coil and (b, c) NPA signals when the NPA signals fluctuate with a MHD-burst. (d)The peak position of NPA signals are shown with circles.

In Fig.4(d), the peak position of signal increase at each NPA energy channel is shown. The decay time of the flux peak was obtained by exponential fitting of the peak positions and was about 4.3ms. In

Fig.5, the energy decay times of the NPA flux peak associated with the MHD- bursts are compared to the inverse of the line averaged electron densities. This figure indicates that the delayed signal increase in the lower energy region can be explained by the result of energy slowing-down of the increased particles at the high energy region with the MHD-burst. But, the signal increase in the high energy region cannot be explained by the classical process.

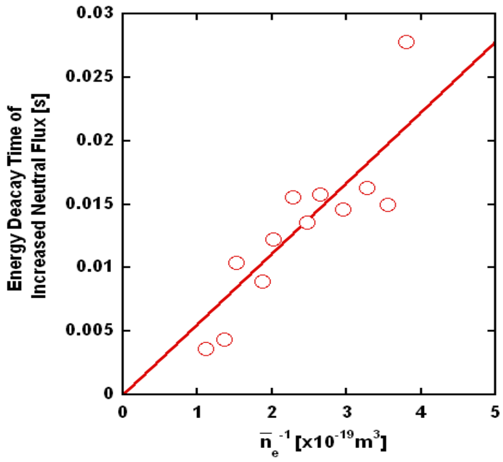

FIG. 5. inverse line averaged electron densities versus measured energy decay time of flux peak associated with MHD-bursts.

Comparing the decay time in Fig.4(d) to the slowing-down times of particles which were circulating on the NPA sight line, it turned out that the increased particles were on the orbit which is circulating around r/a=0.57(Fig.6(a)). This orbit had a maximum probability to stay at r/a=~0.75, where the TAE gap of n(toroidal mode number)=2 and m(poloidal mode number)=3~4 locates (Fig.6(b) and (c))[15]. This suggests that the signal increase with the MHD burst at the high energy region is due to the result of enhanced transport of energetic particles by the TAE-mode.

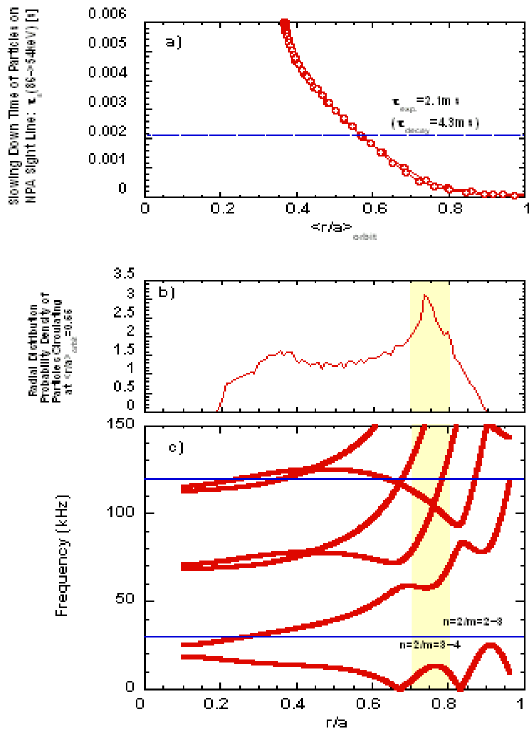

FIG. 6. (a)Orbit averaged energy slowing-down time of a particle circulating on the NPA sight line(red-lines with opn circles). The energy deceleration time from 86keV to 54keV is used as a energy slowing-down time. The blue line indicates the corresponding deceleration time to the energy decay time of 4.3ms. (b) the probability of a particle staying at a certain minor radius for the orbit of $<r/a>_{orbit}=0.57$. (c)The shear-alfven spectrum for the toroidal mode number n=2. The blue line indicates the frequency range of the MHD burst shown in Fig.4(a).

5. Summary

Confinement properties of passing energetic particles are investigated on LHD using NB-blip method. The confinement time of the particle on the passing orbit is consistent with classical theory when the magnetic field strength is high. The energetic particle confinement was influenced by the TAE-mode. The influenced particle has a maximum probability on the gap of the mode.

References

[1] R.J.Goldston, et al.,Nucl.Fusion **15**(1975)651
[2] W.W.Heidbrink, et al.,Nucl.Fusion **28**(1988)1897
[3] W.W.Heidbrink, et al., Phys. Fluids **B2**(1990)4
[4] W.W.Heidbrink, et al., Phys. Fluids **B3**(1991)3167
[5] K.Tobita, et al.,Nucl.Fusion **34**(1994)1097
[6] E.Ruskov, et al.,Nucl.Fusion **35**(1995)1099

[7] M.Isobe, et al.,Nucl.Fusion **37**(1997)437
[8] M.Isobe, et al.,Nucl.Fusion **41**(2001)127
[9]W.W.Heidbrink, et al.,Plasma Phys. **9**(2002)28
[10] O.Kaneko, et al., Nucl.Fusion **43** (2003) 692.
[11] S.S.Medley, et al., Rev. Sci. Instrum.**69** (1998) 2651
[12] M.Osakabe, et al., to be published in RSI.
[13] M.Osakabe, et al., Proc. 30th EPS Conf. (2002) P1-083
[14] K.Toi, et al., PPCF **46**, S1(2004)
[15] S.Yamamoto, et al., this conference paper EX/5-4Rb