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Selfconsistent Analysis of Radial Electric Field and Fast Ion Losses in CHS Torsatron/Heliotron

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SELFCONSISTENT ANALYSIS OF RADIAL ELECTRIC FIELD AND FAST ION LOSSES IN CHS TORSATRON/HELIOTRON

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ABSTRACT

A selfconsistent analysis is developed to determine the radial electric field and loss cone boundary in Torsatron/Heliotron plasmas under the influence of non-classical ion losses such as the loss cone loss and charge exchange loss of fast ions with neutrals. Analysis is applied to the NBI heated plasmas in the Compact Helical System (CHS) device. Comparison is made between theoretical results and experimental observations. The increased ion particle losses caused by the orbit loss and charge exchange loss with neutrals make the radial electric field more negative than the value of purely neoclassical calculation. The partition of the injection energy among the shine through, direct orbit loss, change exchange loss and bulk heating is evaluated by using the selfconsistent electric field profile. On-going experiments in the CHS device are briefly introduced.

Keywords : radial electric field, CHS torsatron/heliotron, neoclassical, fast ion orbit loss, charge exchange loss, anomalous loss, energy partition.

1. INTRODUCTION

An important role of the radial electric field on the improved plasmas confinement has been pointed out in various devices with different configurations, sizes and plasma parameters. The recent observations in tokamaks such as DIII - D, CCT, JIPP - TII - U and JFT - 2M have provided the basis for an increased understanding of the physics associated with radial electric field, showing that the radial profiles of plasma rotation are different for L - and *H* - mode equilibria, respectively. Theoretical models have predicted the structural change of radial electric field to explain the transition between two equilibria, motivating these experimental studies [1,2]. Although the importance in the coupling between the radial electric field and ion loss cone has been discussed in tokamaks, the quantitative analysis and comparison with experiments are far from sufficient. Study on the model of the generation of the radial electric field and its verification are urgent tasks.

In heliotron/torsatron and stellarators, the relationship among the electric field, fluctuations and plasma confinement was studied in the past $\ell = 3$ stellarator experiments such as B - 3 [3] and JIPP - I [4] devices. The poloidal rotation has also been measured by using the intrinsic impurity radiation in the Wendelstein VII - A stellarator (W7 - A) [5] and Heliotron - E (H - E) [6] devices. It has been explained that a large negative electric field was bult up by the fast ion orbit loss in W7 - A experiment. It should be noted that the measurements were limited only near the plasma pheriphery in these experiments. In the CHS experiment, however, the electric field profile in the whole plasma region has been evaluated from both toroidal and poloidal rotation velocities and pressure gradient by using the charge exchange spectroscopy (CXS) [7]. The improvement on the measurement techniques encourages the study on the physical process of the generation and structure of E_r, which is the basis to investigate the role of the electric field on the improved confinement. The influence of the neutral particles on the radial electric field is studied in tokamaks [8,9] as well as torsatron/heliotron [10,11] and stellarator [12]. Recently, the radial profile of neutral density in the CHS has been evaluated accurately by using new techniques, namely, a calibrated TV camera with an H_α optical filter and a laser - induced fluorescence method (LIF) [13].

The purpose of the present study is an understanding of the cooperative mechanism between the radial electric field and loss of energetic particles. We develop a selfconsistent analysis, which determines the electric field and loss of energetic particles simultaneously by taking into account of the orbit loss and charge exchange loss with neutrals. A flow chart of mutual relations involved in the analysis is sketched in Fig.1.

2. PLASMA PARAMETERS

The Compact Helical System (CHS) is a heliotron/torsatron device, which is characterized by its low aspect-ratio. The major parameters are as follows; $B_t = (1 \sim 2)$T, $\ell = 2$, $m = 8$, the major radius of vacuum vessel is 1m and the plasma minor radius is 20cm. The magnetic field configuration of this type of device has flexibility because it is controllable by adjusting the poloidal field coil currents. The machine parameters and typical plasma parameters for the NBI and NBI + ECH operations in the CHS are summarized in Table 1. The sample distributions of density and temperatures, simulating the NBI experimental results are shown in Fig. 2 for low density (A) and high density (B) discharges. For the distributions for fast particles and neutral particles, we choose a model distribution as

$$n_o(\rho) = n_{os}\exp[-\alpha_o(1-\rho)^2], \tag{1}$$

$$n_f(\rho) = n_{fo}\exp[-\alpha_f\rho^2], \tag{2}$$

where the suffix o and f denote the neutral and fast particles, respectively, and α_o and α_f are assumed to be constant and we take $\alpha_o = 10$ and $\alpha_f \simeq 2$, modelling the broad fast ion profile and reproducing the profile of neutral density as shown in ref.[13].

3. RADIAL ELECTRIC FIELD IN NBI HEATED PLASMA

In the CHS, the electron temperature and density profiles are measured with Thomson scattering. The ion temperature and poloidal as well as toroidal rotation velocity profiles, are measured by the CXS. The neutral density profile is also evaluated by a laser-induced fluorescence technique. Radial electric field profile is obtained from these data with use of momentum balance equation

$$E_r = (\partial P_I/\partial r)/eZ_I n_I - (B_\theta U_\phi - B_\phi U_\theta). \tag{3}$$

In order to determine theoretically the radial electric field, we apply the follwing ambipolarity equation

$$\Gamma^e_{nc} = \Gamma^i_{nc} + \Gamma^i_{\ell c} + \Gamma^i_{cx}, \tag{4}$$

where the suffix NC indicates the neoclassical contribution, ℓc for loss cone and cx for the change exchange loss, respectively. The explicit expressions of respective loss fluxes in Eq.(4) are given in [10,11]. In order to determine the loss of energetic particles and electric field simultaneously, analytic formulas [14], which describe the relation between radial electric potential and the minimum energies of the deeply trapped particles and barely trapped particles entering the loss cone, are also required to combine the analysis on loss cone under the influence of radial electric field with transport study based on Eq.(4).

We study the effect of orbit loss and charge exchange loss of fast ions with neutrals on E_r and the partition of beam power. For the theoretical calculation, we assume almost perpendicular neutral beam injection with $P_{NBI} \simeq 1MW$ and $W_b = 18$keV. The fast ion loss caused by the loss cone makes the electric field more negative but the influence of the orbit loss appears only in the plasma edge with $r \geq 0.9a$. Since the experimental observation indicates $E_r \simeq -60V/cm$ for low density and -120 V/cm for high density at $r \simeq (0.6 \sim 0.8)a$, some other ion loss process, which is several times as large as the neoclassical loss, is necessary in the region of $0.6a < r < 0.8a$ to explain the discrepancy between theoretical results and experimental observations. Figure 3 shows the selfconsistent solution of the radial electric field for the low density (A) and the high density (B) in the presence of neutral particle contributions without orbit loss effect. Open and closed data points are the experimental values. The charge exchange loss of fast ions can be effective in enhancing the electric field, and the theoretical results approach to the experimental data as the neutral density increases up to the level of $10^{17}/\mathrm{m}^3$ for the low density and $10^{18}/m^3$ for the high density although these values seem to be higher than the experimental values.

Charge exchange loss affects the loss cone boundary by changing the radial electric field. We therefore determine selfconsistently E_r under the influence of both the orbit loss and charge exchange loss of fast ions. The power partition rates among the shine through (η_{st}), orbit loss (η_{ol}), charge exchange loss (η_{cx}) and bulk heating (η_{bh}) versus the neutral density at the edge n_{os} are shown in Fig.4 for the low (A) and high (B) density cases. (note that $\eta_{st} + \eta_{ol} + \eta_{cx} + \eta_{bh} = 1$ holds, which is the energy conservation relation.) The radial electric fields at $\rho = 0.7$ and 0.9 are also plotted. This clearly shows that the further enhancement of E_r by using the orbit loss in addition to the charge exchange process is not useful to improve the heating efficiency, so long as one consider the neoclassical energy loss.

4. ON-GOING EXPERIMENTS IN CHS

Two experiments, which may reveal the impact of E_r on plasma confinement, are carried out recently in the CHS device.

The one is the power deposition control experiment of the electron cyclotron heating (ECH) at the second harmonic resonance. For the purpose of this experiment, the microwave system to focus and control the focal point of the microwave power from the gyrotron has been developed. One of the current topics of this experiment is to clarify the particle confinement degradation phenomena during ECH. Plasma parameters in this experiment is also summarized in Table 1. The experimental results indicate that the degradation of the particle confinement has close correlation with the confinement of perpendieularly accelerated electrons produced at the second harmonic resonance region [15]. Loss of these energetic electrons may enhance the electron loss flux (RF- induced loss flux) [16, 17]. By taking account of the RF-induced loss flux, Γ_{RF} on the LHS of Eq.(4), we can evaluate the variation of radial electric field and compare the theoretical results with the experimental observations, showing that the transition from the ion root ($E_r < o$) into the electron root ($E_r > o$) may appear at the plasma periphery by changing the ECH power.

The other is the plasma rotation drive experiment by an electrode discharge [18]. Experimental evidence on the observation of bifurcation in poloidal rotation in tokamaks motivates to demonstrate these phenomena in $\ell = 2$ torsatron/heliotron devices. We note that in the past $\ell = 3$ stellarators such as B - 3 [3] and JIPP - I [4], the shock-like structure of density and potential profiles appeared and the fluctuations were enhanced as the rotation velocity approaches the critical one with $M_p \simeq 1$ (M_p is the poloidal Mach number of poloidal ratation). The preliminary results show that the radial current caused by electrode discharge enhances the poloidal rotation but its velocity does not reach the bifurcation point at present and more radial current is required to overcome this barrier. This is due to the fact that the viscous damping force in helical systems is stronger by a factor of $(m - \ell q)^2$ than that of tokamaks. These experimental results will be reported elsewhere.

5. SUMMARY

We have developed a selfconsistent analysis in determing the radial electric field and loss cone loss in torsatron/heliotron configurations under the influence of nonclassical ion losses. Analysis was applied to the NBI heated plasma in the CHS device. Comparison was made between the theoretical results and experimental observations.

The increased ion particle losses caused by the orbit loss and charge exchange loss of fast ions with neutral particles make the radial electric field more negative compared to the prediction of the neoclassical theory. The partition among the shine through, the direct orbit loss, charge exchange loss through changing the radial electric field was also evaluated. Furthermore, the on-going ECH experiment and the rotation drive experiment by electrode discharge are also introduced briefly.

The particle and energy balance in real experiments are strongly influenced by an anomalous transport. Therefore, the role of the radial electric field on the anomalous transpot needs further investigations experimentally and theoretically [19] in order to conclude the over all trade-off on the energy balance.

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FIGURE CAPTION

Fig.1 A flow chart of several topics associated with E_r and /or E_r' involved in the present analysis.

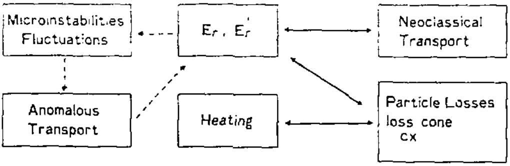
Fig.2 Radial profiles of the density ($n(\rho)$), ion and electron temperatures (T_i, T_e) for the low density (A) and high density (B) NBI discharges in CHS device.

Fig.3 Radial electric fields in the presence of neutral particle contribution. (A) and (B) correspond to the low and high density cases. Experimental observations are also shown by open and closed data points. In (A),$(a)n_{os} = 0, (b)4.0 \times 10^{16}/m^3$, $(c)8.0 \times 10^{16}/m^3$, $(d)2.0 \times 10^{17}/m^3$, and $(e)5.0 \times 10^{17}/m^3$. In (B), $(a)n_{os} = 0$, $(b)1.5 \times 10^{17}/m^3$, $(c)4.0 \times 10^{17}/m^3$, $(d)8.0 \times 10^{17}/m^3$, and $(e)1.5 \times 10^{18}/m^3$. These results are quoted from ref.[9].

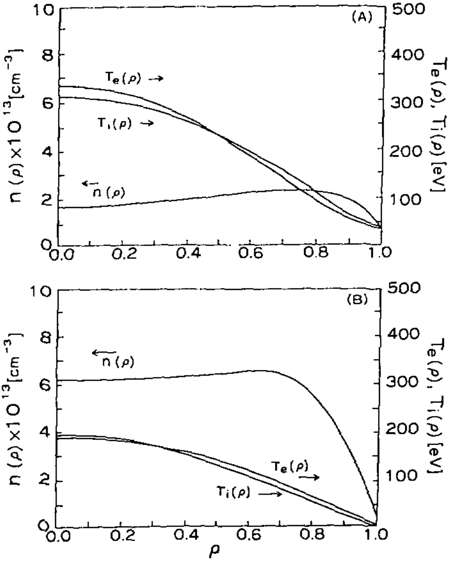
Fig.4 Partition rates among the shine through (η_{st}), orbit loss (η_{ol}), charge exchange loss (η_{cx}) and bulk heating (η_{bh}) versus the neutral density n_{os}. Here, both orbit loss and charge exchange loss are taken into account. (A) and (B) represent the results of low and high density cases. Radial electric field at $\rho = 0.7$ and 0.9 are also shown. These results are quoted from ref.[9].

Table I Machine and plasma parameters for NBI and NBI + ECH experiments

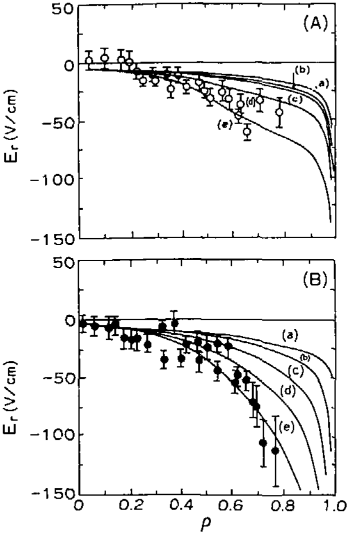
parameter		NBI + ECH	NBI (Low, High)
Magnetic configuration		Heliotron/Torsatron	
Major radius	R	100cm	
averaged minor radius	a	20cm	
toroidal field	$B_t(0)$	1T	
inverse aspect ratio	$\epsilon_t(a)$	0.2	
helical ripple	$\epsilon_h(a)$	0.29	
rotational transform	$\iota(0)$	0.3	
rotational transform	$\iota(a)$	1.2	
NBI/ECH Power	P_{NBI}	1MW	1MW
	P_{ECH}	Max140kW(2nd)	
NBI direction		tangential	tangential
electron density	$n_e(0)$	$6.6 \times 10^{13}/cm^3$	$1.8, 5.6 \times 10^{13}/cm^3$
electron temperature	$T_e(0)$	0.39keV	0.3, 0.2keV
ion temperature	$T_i(0)$	0.18keV	0.2, 0.18keV
electric Field (maximum)	$E_{r,\max}$	$+40V/cm$ (at $r/a \sim 0.8$)	$-50, -120V/cm$ (at $r/a \sim 0.8$)


Microinstabilities
Fluctuations
E_r , E_r'
Neoclassical
Transport
Anomalous
Transport
Heating
Particle Losses
loss cone
cx

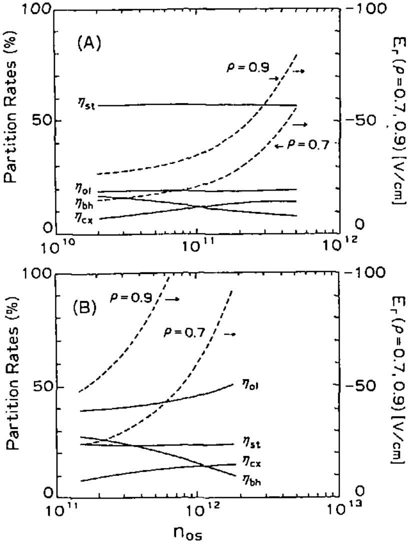
F i g. 1


(A)
$n(\rho)\times10^{13}$[cm^{-3}]
$T_e(\rho)$, $T_i(\rho)$ [eV]
$T_e(\rho)$ →
$T_i(\rho)$ →
← $n(\rho)$
0
2
4
6
8
10
100
200
300
400
500
0.0
0.2
0.4
0.6
0.8
1.0
(B)
$n(\rho)\times10^{13}$[cm^{-3}]
$T_e(\rho)$, $T_i(\rho)$ [eV]
← $n(\rho)$
$T_e(\rho)$ →
$T_i(\rho)$ →
0
2
4
6
8
10
100
200
300
400
500
0.0
0.2
0.4
0.6
0.8
1.0
ρ

F i g. 2


(A)
(B)
E$_r$ (V/cm)
50
0
−50
−100
−150
0
0.2
0.4
0.6
0.8
1.0
ρ
(a)
(b)
(c)
(d)
(e)

F i g . 3


(A)
(B)
Partition Rates (%)
100
50
0
−100
−50
0
E$_r$ (ρ=0.7, 0.9) [V/cm]
10^{10}
10^{11}
10^{12}
10^{13}
n$_{os}$
ρ=0.9
ρ=0.7
η_{st}
η_{ol}
η_{bh}
η_{cx}

F i g . 4

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