ISSN 0915-633X

INTERNATIONAL ATOMIC ENERGY AGENCY

THIRTEENTH INTERNATIONAL CONFERENCE ON
PLASMA PHYSICS AND CONTROLLED NUCLEAR FUSION RESEARCH

Washington, DC, United States of America, 1–6 October 1990

IAEA-CN-53/C-3-3

NATIONAL INSTITUTE FOR FUSION SCIENCE

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(Received – Aug. 29, 1990)

NIFS-41 Sep. 1990

RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

INTERNATIONAL ATOMIC ENERGY AGENCY

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ABSTRACT

Toroidal and poloidal rotation profiles have been measured on the JIPPT-IIU tokamak and CHS heliotron/torsatron devices with charge exchange recombination spectroscopy. Comparison of toroidal/poloidal rotation profiles between CHS and JIPPT-IIU is made for the L-mode plasmas. The parallel viscosity damping and anomalous radial transport of the momentum are studied. Comparison of electric field profiles inferred from plasma rotation and ion pressures also made. The plasma in CHS rotates poloidally near the plasma periphery and rotates toroidally at the center. The toroidal rotation velocity is localized at $r < 0.3a$, which is consistent with the estimate of neoclassical parallel viscosity due to helical ripples. The plasma in JIPPT-IIU rotates toroidally. The poloidal rotation is damped to less than a few km/s, which also supports neoclassical parallel viscous damping. The radial transport of toroidal rotation velocity on both devices is found to be anomalous and about 2-4 m^2/s. This value is comparable to the thermal diffusivity in JIPPT-IIU. The radial electric field in CHS has negative gradient $(\partial E_r/\partial r < 0)$, while the electric field in JIPPT-IIU has positive gradient $(\partial E_r/\partial r > 0)$ near the plasma periphery. The relation of space potential to ion temperature is also discussed.

"keywords" plasma rotation, electric filed, neoclassical flux, tokamak,
heliotron/torsatron

1. INTRODUCTION

Plasma rotations play an important role in plasma confinement. The peaked-density-profile mode often associates the peaked totoridal rotation[1]. Recently a jump of radial electric field and poloidal rotation velocity has been found theoretically and experimentally to be important in the transition from L-mode to H-mode [2-5]. In the H-mode model, neoclassical parallel viscosity is used to get solutions of poloidal rotation velocity. It becomes crucial issue to study parallel viscosity (poloidal viscosity in tokamaks) experimentally. It is difficult, however, to estimate poloidal viscosity in tokamaks, since the source term of poloidal momentum contains bipolar flux due to ion orbit loss, which is still undetectable experimentally. On the other hand, in helical device, we can estimate parallel viscosity (toroidal viscosity in heliotron/torsatron) from the measurements of toroidal rotation velocity profile, in the presence of momentum input associated with tangential neutral beam injection(NBI).

Radial electric field, which affects energy and particle confinement in plasma, can be measured indirectly from plasma rotation velocity. The VxB radial force by poloidal and toroidal rotations balances electric field and pressure gradients in an MHD equilibrium time scale. In this paper we describe radial electric field measured in JIPPT-IIU tokamak and CHS heliotron/torsatron and compare with the estimate of neoclassical values. Parallel viscosity and momentum in transport in radial direction in JIPPT-IIU and CHS are also discussed.

2 EXPERIMENTAL SET UP

2.1 Charge exchange spectroscopy

A multi-channel space resolved visible spectrometer system using CCD detector coupled with image intensifier has been developed to measure profiles of ion temperature, toroidal and poloidal rotation velocity simultaneously with time resolution of 16.7

ms, using the charge exchange spectroscopy. Charge exchange transfer between fully ionized carbon and fast neutral of heating NBI results in an excited ion with one more electron. The emission of hydrogen-like carbon (CVI n=7-6 and n=8-7) is localized at the cross section of neutral beam line and the line of sight of viewing array. Two sets of viewing optical fiber arrays, one viewing a fast neutral beam and the other viewing off the neutral beam line have been installed on CHS and JIPPT-IIU to subtract background radiation [6]. The background radiation (cold component) is mostly due to the charge exchange reaction between fully ionized impurity and background thermal neutral in the plasma periphery.

2.2 Plasma parameter in JIPPT-IIU and CHS

The plasma parameters of JIPPT-IIU [7] tokamak and Compact Helical System CHS [8] heliotron/torsatron (l=2, m=8) investigated in this study are summarized in Table 1. These devices have similar plasma size but quite different structure of magnetic field and characteristic of parallel viscosity associated with transit-time magnetic pumping(TTMP)[9]. A 28 GHz gyrotron with the power of 0.1MW produces ECH plasma of low density below $1\mathrm{x}10^{13}$ cm^{-3}, while tangential NBI (0.9 MW) can sustain the plasma with high density up to $1\mathrm{x}10^{14}$ cm^{-3}. The plasma in JIPPT-IIU is heated by Ohmic input, perpendicular NBI (0.7MW) or tangential NBI (0.4 MW) and ICRF (1-1.5MW). Radial profiles of electron density and electron and ion temperature in these devices are shown in Figs. 1. The profile of the electron density in CHS is hollow, while the electron density in JIPPT-IIU is slightly peaked at the center.

3. TOROIDAL ROTATION VELOCITY AND VISCOSITY

Comparison of toroidal rotation profile in the presence of parallel NBI is made between CHS and JIPPT-IIU for the L-mode plasmas to study the parallel viscosity damping due to the helical ripples in CHS, and the radial momentum transport in JIPPT-IIU. For this study, the neutral beam is injected tangentially (tangency radius of beam line,

R_{nbi}=84cm in JIPPT-IIU and 87 cm in CHS). Figure 2 shows the toroidal rotation profiles measured both in JIPPT-IIU and CHS for the plasma with tangentially injected neutral beam.

The toroidal rotation velocity in CHS has very narrow profile, since the toroidal rotation velocity is strongly damped at $r > 0.3a$, where the neoclassical parallel viscosity[9,10] due to the helical ripples become large ($\varepsilon_h=0.25\rho^2$). The solid line indicates the limit by neoclassical(NC) parallel viscosity. Although the error bar is large, the experimental data at r>0.25a agrees with the prediction of the parallel viscosity. Since there is no helical ripple at the plasma center, the toroidal rotation velocity is not limited by the neoclassical parallel viscosity, but by the anomalous radial momentum transport. The radial momentum transport coefficient estimated from the gradient of toroidal rotation velocity was 2 m^2/s, which is comparable to electron thermal diffusivity (2-10m^2/s) [11].

Broader profile of toroidal rotation in JIPPT-IIU is mainly determined by the radial transport. The absolute value of toroidal rotation velocity in ctr-injection case (NBI is injected in the direction opposite to the plasma current) is larger than that in co-injection case (NBI is injected parallel to the plasma current). There is a rotation in counter direction in ohmic plasma without apparent momentum source. The change of toroidal rotation velocity from ohmic plasma is comparable for co- and ctr- injection cases. The toroidal momentum diffusivity in JIPPT-IIU is found to be anomalous and is 3-4 m^2/s at $r/a < 1/2$, which is comparable to the ion and electron thermal diffusivity, showing a qualitative agreement with theoretical estimation [12].

4. RADIAL ELECTRIC FIELD

Radial electric field profiles are obtained from the profiles of ion pressure gradient and toroidal/poloidal rotation with the use of momentum balance equation;

$$E_r = \frac{\partial p_I}{e Z_I n_I \partial r} - (B_\theta V_\varphi - B_\varphi V_\theta), \tag{1}$$

where I stands for the measured impurity species. Here radial frictional force between different species is small enough to be neglected.

4.1 CHS

The toroidal rotation contribution is very small in CHS . The radial electric field in CHS as in Fig. 3(a) has a strong shear at the plasma periphery associated poloidal rotation velocity shear. This edge electric field increases as the electron density is increased. This negative electric field is -80 V/cm for low density and -120 V/cm for high density plasma. The ion collisionality ν_{*i} at r=a/2 is 2.4 for low density (n_e=2x10^{13}cm^{-3}) and 22 for high density (n_e=6x10^{13}cm^{-3}) discharges. The radial electric field shows different behavior in collisionless regime (ν_{*e} = 0.2) produced by ECH in CHS. E_r at r=0.7a is 16V/cm (positive) in the plasma with low density (n_e=4x10^{12}cm^{-3}).

The radial electric field profiles measured in CHS is compared with neoclassical estimates[13,14] in Fig. 3(a). These calculated electric field are smaller than those measured from poloidal rotations. These theories do not explain the electric field shear near the plasma edge (r/a>0.6). The large electric field measured near the plasma edge may need other explanation such as orbit loss.

4.2 JIPPT-IIU

The pressure gradient and toroidal rotation are the dominant terms in Eq. (1), since the poloidal rotation is small. Poloidal rotation velocities 3-5 cm inside the plasma are measured with intrinsic CVI line radiation without neutral beam. They are found to be below the detection limit (2-3 km/s). This does not contradict to neoclassical estimation[15]. The electric field E_r can be derived from the measured toroidal rotation velocity v_φ and the ion pressure gradient and the neoclassical estimation for v_θ. To eliminate the influence of toroidal momentum input on electric field, perpendicular neutral beam has been injected. The beam line of NBI is still tilted by ±9 degree (R_{nbi}= 20 cm). The direction of the plasma current was reversed to check the effect of the momentum input of NBI. The plasma rotates in the ctr-direction during NBI, even when the NBI is tilted to co-direction ($v_\varphi(0)$ is -30km/s for co- and -60km/s for ctr-injection). The radial electric field profile is peaked at a radius of $r = (2/3)a$ as shown in Fig. 3(b). The peak values are -190 V/cm in co- and -250 V/cm in ctr-injection for NBI plus ICRF heated plasmas. The plasma space potential depends mostly on the ion temperature, and these values were found as $\Phi(a)-\Phi(0)\approx 1.5T_i(0)$, where $\partial\Phi/\partial r=-E_r$, for both NBI and ICRF heated plasmas[16]. Bipolar flux should exist in the plasma, since the negative plasma potential are observed. According to the neoclassical ripple transport theory [17,18], there is a finite residual toroidal rotation velocity due to toroidal field ripples in the banana regime and the electric field can be predicted to balance this toroidal rotation velocity. The measured values as shown in Fig.3(b) are smaller than these in predicted.

5. DISCUSSIONS

Radial profile of toroidal rotation velocity in CHS demonstrates the neoclassical parallel viscosity damping process. Poloidal rotation measurements in JIPPT-IIU supports this damping. The radial momentum transport in both devices was found to be anomalous (2 m^2/s in CHS and 3-4 m^2/s in JIPPT-IIU for the case of this study). The radial electric field in CHS has negative gradient ($\partial E_r/\partial r<0$) , while the electric field in JIPPT-IIU has positive gradient ($\partial E_r/\partial r>0$) near the plasma edge. The role of electric field on helical ripples will be studied in future. The mechanism which causes the difference of density profile between CHS and JIPPT-IIU is still open question, however the difference of toroidal rotation is one of the candidate, since the rotation velocity shear produces particle pinch [19].

We would like to thank Dr.K.C.Shaing (ORNL) for his useful discussions. Calculation with neoclassical estimation on CHS electric field has been done by Dr.K.Yamazaki.

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parameter		JIPPT-IIU			CHS	
magnetic configuration		tokamak			heliotron	
major radius	R(cm)	93			95	
averaged minor radius	a (cm)	24			20	
toroidal field	B_t (T)	3			1	
inverse aspect ratio	$\varepsilon_t(a)$	0.26			0.21	
helical ripple	$\varepsilon_h(a)$	0			0.25	
rotational transform	$\iota(0)$	1			0.3	
rotational transform	$\iota(a)$	0.22	0.16	0.25	1.0	
ohmic heating power	P_{OH}(MW)	0.3	0.2	0.3	0	
NBI Power	P_{nbi}(MW)	0.3	0.3	0.7	0.9	
NBI direction		Co	Ctr	Co/Ctr	Co	
NBI tangency radius	R_{nbi}(cm)	84	84	20	87	
ICRF Power	P_{RF} (MW)	0	0	1.5	0	
electron density	$n_e(0)$ ($10^{13}/cm^3$)	3	6	8	1.6	6
electron temperature	$T_e(0)$(keV)	1.6	1.1	1.7	0.3	0.2
ion temperature	$T_i(0)$ (keV)	0.5	0.7	1.7	0.3	0.2
collisionality	$\nu^*_i(a/2)$	0.6	1.3	0.14	2.4	22
toroidal rotation	$V_\varphi(0)$ (km/s)	+34	-75	-30/-60		14
poloidal rotation	$V_\theta(a)$ (km/s)		< 2-3		6	9
plasma potential	$\Phi(0)$ (keV)	0	-2.6	-2.5	-0.36	-0.32

Table I. Plasma parameter for the comparison

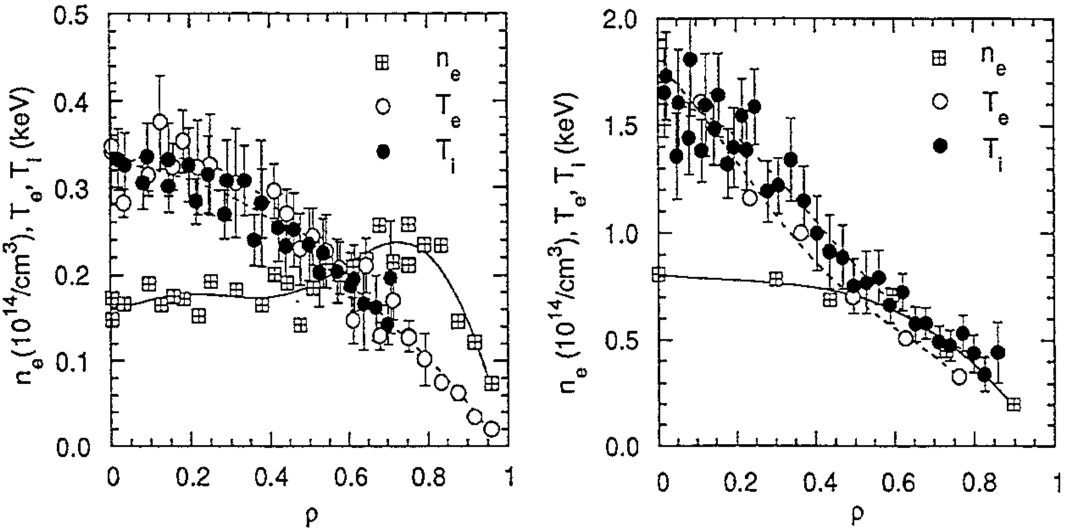

Fig.1 Electron density and electron and ion temperature profiles in (a) the CHS heliotron/torsatron and (b) the JIPPT-IIU tokamak.

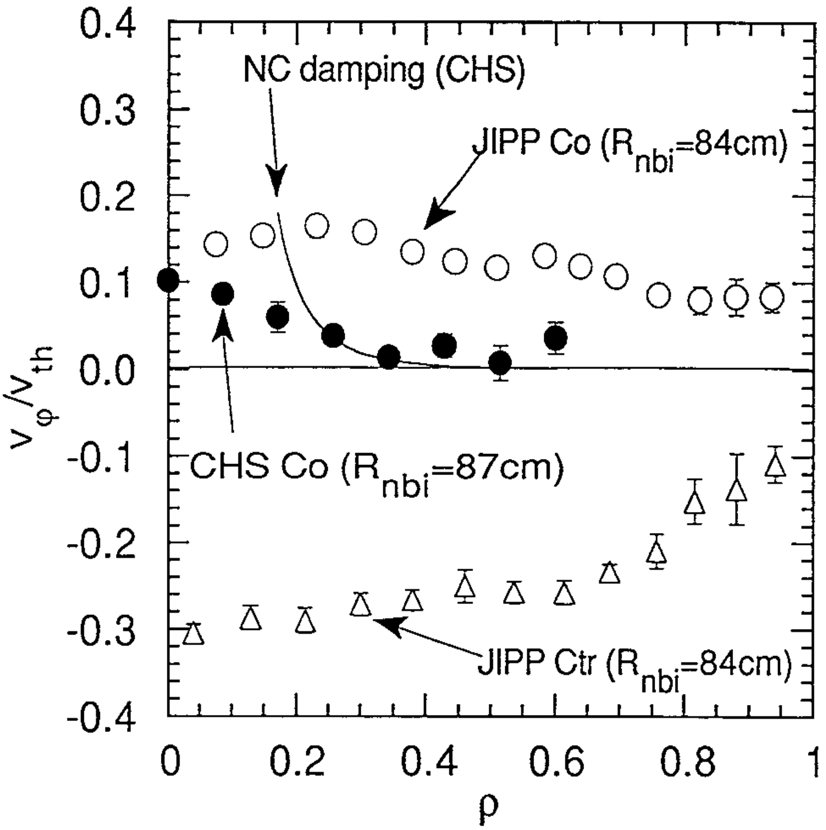

Fig.2 Radial profile of toroidal rotation velocity normalized by ion thermal velocity for tangentail (R_{nbi}=84cm) co-NBI in CHS and tangential (R_{nbi}=84cm) co- and ctr-NBI in JIPPT-IIU. Solid lines are calculated toroidal rotation velocity with neoclassical parallel viscosity damping.

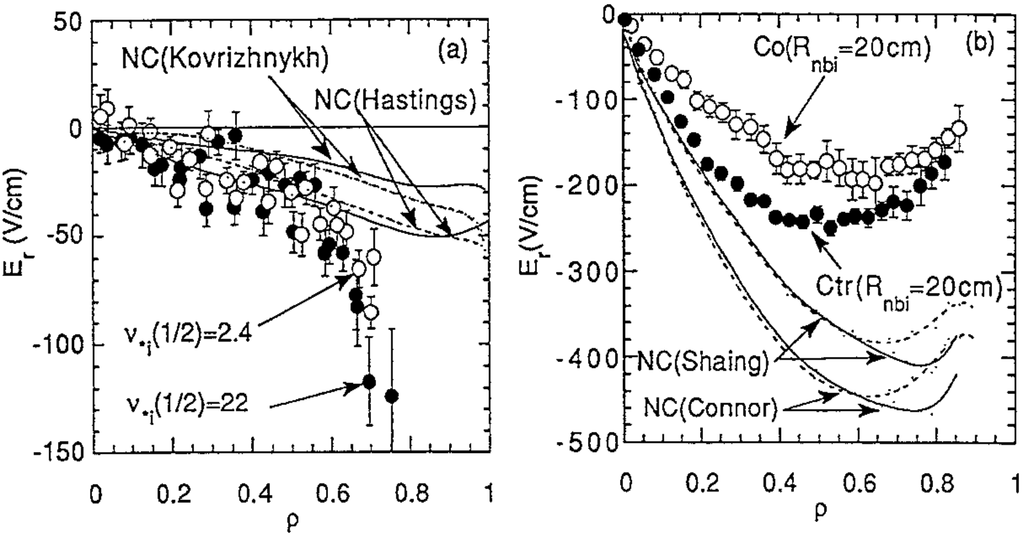

Fig.3 Radial electric field profiles measured in (a) the CHS and (b) the JIPPT-IIU with the neoclassical estimates. (a); Solid lines are calculated radial electric field for high density plasma, while the dashed lines for low density plasma. (b); Solid lines are calculated radial electric field for perpendicular (R_{nbi}=20cm) ctr-NBI, while the dashed lines for co-NBI.