ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

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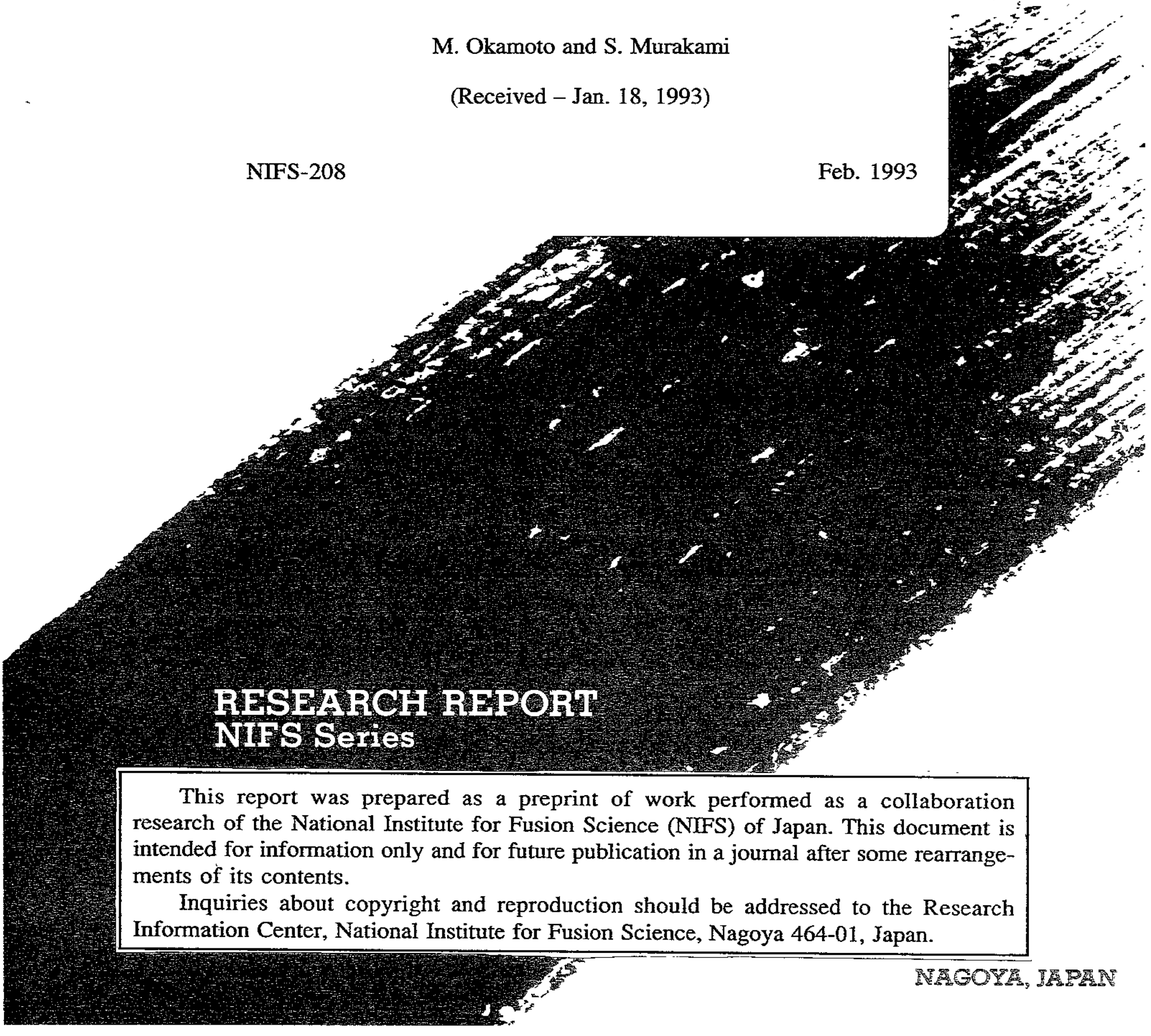
M. Okamoto and S. Murakami

(Received – Jan. 18, 1993)

NIFS-208 Feb. 1993



RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

PLASMA HEATING IN TOROIDAL SYSTEMS*

Masao Okamoto and Sadayoshi Murakami

National Institute for Fusion Science, Nagoya 464-01 Japan

ABSTRACT

The purpose of this paper is to review the present status of plasma heating in toroidal systems (mainly tokamaks and helical systems) for astrophysical plasma scientists. The main method of plasma heating in toroidal systems or tori is to utilize fast ions (NBI heating and alpha heating). The maximum ion temperature of 38 keV has been achieved at the plasma center by neutral beam injections (NBIs) in the JT-60U tokamak. Ripple-trapped losses of fast ions produced by NBIs have been measured also in the JT-60U. The first tokamak discharges in deuterium-tritium fuelled mixtures have been carried out successfully in the JET tokamak. These experimental results are compared with the theoretical predictions based on the Coulomb collisions. Another powerful method is the ICRF heating (Ion Cyclotron Range of Frequency). However, this article will be focussed mainly on the NBI and alpha heatings. Related to plasma heating the current drive will be mentioned briefly placing an emphasis on the bootstrap current.

Keywords : plasma heating, fast ions, alpha heating, NBI heating, wave heating, ICRF heating, current drive, bootstrap current.

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[*] Review talk presented at the 4th International Toki Conference on Plasma Physics and Controlled Fusion — ITC-4 Fusion and Astrophysical Plasmas, 17 - 20 November 1992, Seratopia Toki, Toki.

1. INTRODUCTION

Among various nuclear fusion reactions the deuterium-tritium (D-T) reaction has the maximum reaction rate. The first goal of fusion researches is to attain an ignition and burning of the D-T fuelled mixture. The D-T reaction produces an alpha particle (^4He) with 3.56 MeV and a neutron (^0n) with 14.03 MeV :

$$D + T \rightarrow {}^4He(3.56\text{MeV}) + {}^0n(14.03\text{MeV}). \tag{1}$$

The alpha particles created by this reaction are ionized to be trapped in the plasma. Through the slowing down process of high energetic alpha particles the plasma electrons and ions are heated. The self-ignition condition of the D-T plasma is easily obtained from the energy balance equation at the steady state to yield

$$n\tau_E = \frac{3T}{\frac{1}{4} < \sigma v >_{DT} E_\alpha(1 - f_\alpha) - P_R/n^2} \tag{2}$$

Here we considered the plasma of a fifty-fifty D-T mixture, equal ion and electron temteratures ($T = T_i = T_e$), and equal densities ($n = n_i = n_e$). In Eq.(1), τ_E is the energy confinement time, $< \sigma v >_{DT}$ is the D-T reaction rate, E_α is the birth energy of alpha particles (3.56MeV), f_α is the loss fraction of alpha particles, and P_R is the total radiation losses of bremstrahlung and line radiations of impurities. It is apparant that the ignition criterion given by Eq.(1) increases with impurity content and loss of alpha particles. If $f_\alpha = 0$ (complete confinement of alpha particles) and P_R is determined only by bremstrahlung radiation, the ignition condition requires $n\tau_E \simeq 3.3 \times 10^{20}\text{m}^{-3}\text{s}$ for $T \simeq 10$ keV. If iron impurities are contained in the plasma over by 0.1 %, the ignition condition is hard to be attained for 10 keV [1]. To achieve the ignition it is required to reduce impurity content and loss of alpha particles below a certain level and to heat the plasma up to $T = 10 \sim 30$ keV. (Here T is the average temperature.)

The ohmic heating becomes less effective as the temterature rises. Additional heating methods are used to heat up the plasma.

The main heating method for toroidal plasmas is to inject neutral atoms into the plsma where neutral atoms are ionized to be trapped in the magnetic bottle (heating by neutral beam injection : NBI heating). The fast ions produced in this way slow down colliding with bulk ions and electrons and transfer their energies and momenta to bulk ions and electrons. The mechanism of alpha heating is the same. Other heating utilizing fast ions is the ICRF minority heating. In this case the minority ions (for instance, minority protons in majority deuterons) are accelerated to become high enrgetic particles or fast ions by the electric field due to excitation of RF waves with ion cyclotron frequency.

The best record of central ion temperature ($T_i \approx 38$ keV) has been obtained in JT-60U only by NBI heating [2]. By injecting tritium atoms into the deuterium plasma, the first experiment of D-T plasma has been successively performed in the JET tokamak [3].

The other powerful heating is to launch RF waves from the antenna into the plasma. If the launched RF waves are accessible to the plasma, they propagate according to their dispertion relations and are absorbed into the plasma via Landau damping, cyclotron damping, or other damping mechanism. RF wave heating methods are categorized acorging to their frequency ranges ; Alfven heating, ion cyclotron heating (ICH, or ICRF), lower hybrid wave heating (LHH, or LHRF), and electron cyclotron wave heating (ECH, or ECRF). ICRF minority heating is a method using both wave excitation and the resultant fast ions. The experiments of these RF wave heatings have been all tried in toroidal systems and the fast wave heating in ICRF is now the most powerful means next to the NBI heating [4]. Recently the ICRF heating experiments using slow waves (Ion Bernstein wave heating : IBW) have exhibited interesting results in which the plasma has been successfully heated producing no fast ions [5]. Combinations of NBI and ICRF heatings are often used.

Theoretically the behaviour of fast ions are investigated by solving the Fokker-Planck equation. Simulation codes based on the particle orbit following and Monte-Carlo technique for collisions are frequently used for this purpose. Another important roles of fast ions are interactions with MHD modes, but these problems will be discussed in detail in another review talks.

To investigate the wave propagation the eikonal or ray tracing treatment is useful if the wavelength of the wave is short compared to the plasma scale length (the cases of ECH, LHH, or IBW). However if the wavelength is comparable to the system size (for instance, the case of fast wave heating in ICRF) the wave equations have to be fully solved taking into account the realistic geometry including antenna structures [6]. RF waves may cause stochastic particle motions and hence enhance the plasma transport.

In §2 we review the recent NBI experiments and compare the results with theoretical predictions based on Coulomb collisions. RF wave heatings are not discussed in the following due to the limited space. Related to plasma heatings the current drive will be discussed in §3 placing an emphasis on the neoclassical current (bootstrap current). §4 is devoted to summary and discussion.

2. HEATING UTILIZING FAST IONS

2.1 Slowing Down Process

At the present moment the most powerful heating method for toroidal plasmas is the NBI heating. High energetic neutral beam atoms injected into the plasma are ionized to become fast ions. The beam energy and the injection angle are chosen so as to minimize the neutral atoms passing through the plasma without being ionized. The fast ions collide with bulk ions and electrons while moving in the magnetic field. Bulk ions and electrons exert drag forces on the fast ions through collisions. Thus the fast ions slow down and the bulk ions and electrons gain energies and momenta. This classical slowing down process can be described by the Fokker-Planck equation or collision integrals. Usually the speed of fast ions produced by NBI. v_f. lies between the ion thermal speed, v_i, and electron thermal speed, v_e : $v_i \ll v_f \ll v_e$. This condition holds also for alpha particles produced by the D-T reactions. If the density of fast ions, n_f. is low ($n_f \ll n_e$). the Fokker-Planck equation for fast ions can be reduced to a simple form, which consists of electron and ion drag terms (or friction terms). pitch angle scattering, energy diffusion. charge exchange loss, particle loss, and particle source terms [7]. The energy diffusion term is small and only the drag forces contribute to plasma heating. There is a critical energy, E_c. above which electron drag forces are dominant. Accordingly if the energy of the fast ions, E_f, is much higher than E_c, electrons are dominantly heated. In the case of alpha particles ($E_f \leq 3.56$ MeV). $E_c \simeq 33T_e$ (if there are no impurities), and hence the energy of alpha particles are transfered mainly to electrons. If the charge exchange loss is negligible. around 80 % of alpha particle energy go to electrons. As mentioned in the Introduction, to heat the plasma effectively it is important to reduce loss of fast ions or alpha particles. If there are loss cones in the velocity space. fast ions born in a loss cone escape directly out of the plasma region and also do fast ions fallen into a loss cone by pitch angle scattering during the slowing down process. The important loss mechanism other than such the orbit losses is the charge exchange loss due to the presence of background neutral atoms. In axisymmetric tokamaks, however, almost all the fast ions can be confined if $I_p(\mathrm{MA}) \geq 4/\sqrt{A}$ (I_p is the plasma current and A the aspect ratio) and if the charge exchange loss is enough small. The characteristic time of slowing down process is the Spitzer slowing down time. τ_s. For a plasma of $n_e \simeq 10^{20}\mathrm{m}^{-3}$ and $T_e \simeq T_i \simeq 10$ keV, $\tau_s \simeq 400$ ms, which is much shorter than the particle and energy confinement times required for the ignition. Thus the alpha particle heating or the self-ignition can be easily attained in an axisymmetric tokamak with toroidal current of over a few mega-amperes, if the slowing down process is dominanted by Coulomb collisions.

2.2 Effects of Fielf Ripples

Real geometries of tokamaks are not axisymmetric, because the field ripples are created in the toroidal direction due to the finite number of toroidal field (TF) coils. The particles circulating around the torus feel well the rotational transform and the deviation of the drift surface from the magnetic surface, Δ_c, is small ($\Delta_c \simeq \epsilon_t \rho_p, \epsilon_t = r/R$ and ρ_p is the poloidal Larmor radius). Banana particles feel less the rotational transform and the deviation is large ($\Delta_b \simeq \epsilon_t^{1/2} \rho_p$). The particles trapped in the local ripple well do not feel the rotational transform at all and escape vertically due to ∇B drift (or toroidal drift). In the classical slowing down process the effects of field ripples are most important on the confinement of fast ions, because ripples make small but many complicated loss cones. If the toroidal field is given by

$$B_\phi(r,\theta) = \bar{B}(r,\theta) + \tilde{B}(r,\theta)\cos N\phi \tag{3}$$

where the second term on the right hand side is the ripple field and N the number of TF coils. The effective ripple well parameter is defined as

$$\alpha = (\partial \bar{B}/\partial l)/(\partial \tilde{B}/\partial l) \tag{4}$$

where l is the length along a magnetic field line. If $\mid \alpha \mid < 1$, ripple wells are formed (mainly in the outer region of the plasma). The particles trapped in these wells go straight up or down due to ∇B drift to escape from the confined region. During the ∇B drift the particles may be detrapped by pitch angle scattering or may be detrapped reaching the region with $\mid \alpha \mid > 1$. If a particle is lost in this way, such the process is called the ripple-trapped loss. Another important loss is the banana drift loss, or ripple enhanced banana drift loss [8]. Even in the region with $\mid \alpha \mid > 1$, the banana tip is disturbed by small ripples. The banana particle behaves stochastically drifting out of the plasma without collisions or under the influence of collisions. The ripple-trapped loss and the banana drift loss are the main loss mechanisms of fast ions or alpha particles in the classical slowing down process. These loss mechanisms depend on various parameters such as the aspect ratio, banana width, safety factor, ripple well depth, the shape of plasma cross sections (elepticity and triangularity), and others [9]. In rippled tokamaks and helical systems, particle trajectories are so complicated that sophisticated computer codes handling particle orbit following and Monte-Carlo method for collisional process are useful to investigate the confinement of fast ions.

2.3 NBI Experiments

Recently a high poloidal beta discharge of JT-60U produced the central ion temperature $T_{i0} \simeq 38$ keV, which is the best record at the present moment, under the conditions of $B = 4$T, $I_p = 1.85$MA, $q_{eff} = 5.4$, and $\bar{n}_e = 2.2 \times 10^{19}\mathrm{m}^{-3}$ [2]. The plasma was heated only by NBIs with the absorbed power of 19 MW. The central electron temperature was 12 keV and the confinement time was around 400 ms, which is longer than $\tau_E^{ITER-89}$ by a factor of 2.38. It is noted that the fraction of bootstrap current to total plasma current, I_{bs}/I_p, amounted to 0.58 in such a high poloidal beta discharge.

The experiments on the ripple-trapped loss of nearly-perpendicularly injected fast ions were carried out also in the JT-60U and a comparison was made between the experimental data and the orbit following Monte-Carlo code calculations [2,10]. The experimental conditions were $B = 2 \sim 4$T, $I_p = 1 \sim 4$MA, $\delta = 0.2 \sim 2.0\%$ (the ripple depth at the outer edge). Deuterium atoms with the energy of $80 \sim 90$ keV and the power of $10 \sim 18$ MW were injected perpendicularly into the deuterium plasma. The heat deposition was measured by thermocouples mounted on the first wall and a fast infrared TV camera viewing the wall. Two dimensional profiles of the heat load depositions onto the first wall were exhibited. The heat flux peaks lie just between the adjacent two TF coils. Dependences of ripple loss fraction on δ and q were also examined.

These experimental data were compared with the calculations done by the OFMC code (orbit following/Monte-Carlo code) [11]. The OFMC code calculates the ionization of injected neutral atoms (fast ion birth deposition), particle orbit of guiding center in non-axisymmetric geometry, charge exchange of fast ions and re-ionization, and Coulomb collisions. Fairly good agreements have been obtained between the experiments and the calculations, but there remained a small difference in the position of the peak heat load between the experiments and the calculations. It is conjectured that this difference may be attributed to the effect of the radial electric field on the particle orbits. The calculations revealed that the measured heat fluxes on the first wall were due to escaped ripple-trapped fast ions. These fast ions escaped in the direction of the ion ∇B drift. On the other hand the OFMC code calculations showed the presence of collisional banana drift losses in the opposite direction, which were not experimentally measured.

The comparisons between the NBI experiments and the calculations suggest that the slowing down process of fast ions is not anomalous but classical or neoclassical.

2.4 The First D-T Experiment

The first D-T experiments have been carried out successfully in JET tokamak by injecting neutral tritium and deuterium beams into deuterium plasma [3]. A single null X-point configuration was employed. The experiments were limited by vessel activation and tritium usage. A discharge with 100 % tritium gas feed to 2 ion sources was performed. In this discharge deuterium beams with 75 keV or 135 keV from 14 ion sources and tritium beams with 78 keV from 2 sources were injected to the deuterium plasma. The total beam power was 14.3 MW. The main parameters of the experiment were $B = 2.8$T, $I_p = 3.1$MA, $< n_e > = 2.5 \times 10^{19}\text{m}^{-3}$ ($< >$ means volume average). The content of tritium in the plasma was 11 % and $< T_e > = 6.0$ keV, $T_{e0} = 9.9$ keV, $< T_i > = 8.0$ keV, $T_{i0} = 18.8$ keV, $\bar{Z}_{eff} = 2.4$ (line average), and $\tau_E = 0.9$ s were obtained. The maximum total neutron emission rate was $6.0 \times 10^{17}\text{s}^{-1}$. The actual fusion amplification factor, Q_{DT}. was about 0.15, but if the D-T mixture was optimized, the discharge would have produced a fusion power of 5 MW and a nominal $Q_{DT} \simeq 0.46$. This experiment was checked by the TRANSP code which is a transport code using experimental profiles and Monte-Carlo calculations for fast ions [12]. The experimental data was established with the TRANSP code calculations. It was shown that thermal-thermal and beam-thermal reactions contributed about equally to the neutron emission.

3 CURRENT DRIVE AND BOOTSTRAP CURRENT

3.1 Current Drive

An effective non-inductive current drive is inevitably necessary to realize a steady state tokamak fusion reactor. The beam-driven current utilizing parallel neutral atoms injections is one of candidates for the steady state current drive. There are many possible methods for the current drive by using RF waves. Among them the most successful current drive is to excite lower hybrid waves injected from a launcher (LHCD). Recently the LHCD generated a toroidal current of 2 MA in JT-60U [13]. However, the circulation power required to drive a large current in tokamaks is not small. The existing of the pressure-driven neoclassical current (bootstrap current) was theoretically predicted twenty years before [14]. As the bootstrap current is basically a spontaneous current, the circulating power for current drive would be much reduced if the fraction of the bootstrap current to the total plasma current is large. In tokamaks a large amount of bootstrap current was first observed in TFTR [15]. Subsequently it was measured in JT-60 [16]. Recent experiments from JT-60U showed that $I_{bs}/I_p \simeq 58\%$ [2].

On the other hand in helical systems the bootstrap current should be reduced as small as possible to obtain a currentless plasma. It is well known that the bootstrap current in the $1/\nu$ regime depends strongly on the magnetic field structures in helical systems [17,18]. In the following we describe the recent development of the neoclassical theory for parallel flows, currents. and plasma rotations.

3.2 Neoclassical Current

Neoclassical theories for parallel flow are extended to a multispecies plasma in general toroidal systems. in which each species lies in a regime of different collisionality[19]. This extended neoclassical theory includes axisymmetric and rippled tokamaks. It is shown in Ref. [19,20] that a current directly proportional to the radial electric field, which does not exist in axisymmetric systems, exists in non-axisymmetric systems in addition to the conventional pressure driven bootstrap current. In the following we show this new result in a simple form. For a simple plasma consisting of electrons and protons the bootstrap current is given by

$$\begin{aligned}\left\langle BJ_{\parallel}\right\rangle &= L_{11}\left\langle G_{BS}\right\rangle_e\left(\frac{dP_e}{d\psi}+en_eE_\psi\right)\\ &+ L_{11}\left\langle G_{BS}\right\rangle_i\left(\frac{dP_i}{d\psi}-en_eE_\psi\right)\\ &- L_{12}\left\langle G_{BS}\right\rangle_e n_e\frac{dT_e}{d\psi}+L_{11}L_{34}\left\langle G_{BS}\right\rangle_i n_e\frac{dT_i}{d\psi}\end{aligned} \tag{5}$$

where L_{ij}, $\langle G_{BS}\rangle_{e,i}$ and E_ψ are the transport coefficients, the geometric factor [21] and the radial electric field, respectively. The direction of flow damping due to the parallel viscosities is, in terms of the geometric factor, given by,

$$\nabla\theta_\alpha^* \equiv \nabla\left[(I+\langle G_{BS}\rangle_a)\theta+(J-\iota\,\langle G_{BS}\rangle_a)\zeta\right] \tag{6}$$

where θ and ζ are the poloidal and toroidal angles in Boozer co-ordinates, respectively, and I, J, and ι are the toroidal current inside the flux surface, the poloidal current outside the flux surface, and the rotational transform, respectively. In axisymmetric systems, as is seen from Eq.(6), the flow damps only in the poloidal direction, regardless of the collisionality of each particle species. i.e. $\langle G_{BS}\rangle_e = \langle G_{BS}\rangle_i = J/\iota$. Therefore, the current proportional to E_ψ vanishes in Eq.(5), which is a direct result of symmetry, momentum conservation of friction forces and charge neutrality. On the other hand. in non-axisymmetric systems. lack of symmetry allows the flow in any direction to damp, and the damping direction becomes to depend on the collisionality, which generates a current directly proportional to E_ψ if $\nu_e^* \neq \nu_i^*$ ($\langle G_{BS}\rangle_e \neq \langle G_{BS}\rangle_i$). This newly found current can be comparable with the conventional pressure driven neoclassical current since $e\phi \gtrsim T$ ($E_\psi = -d\phi/d\psi$). In the region where $|\langle G_{BS}\rangle_{e,i}|$ increases as $\nu^*_{e,i}$ decreases, if $\nu^*_e < \nu^*_i$, then $|\langle G_{BS}\rangle_e| > |\langle G_{BS}\rangle_i|$ and $E_\psi > 0$ would be realized according to the neoclassical theory. In such a situation the first term with $\langle G_{BS}\rangle_e$ in Eq.(***) dominates and the current proportional to E_ψ tends to cancel the conventional pressure driven current. In the opposite case of $\nu^*_e > \nu^*_i$ where $|\langle G_{BS}\rangle_e| < |\langle G_{BS}\rangle_i|$ and $E_\psi < 0$, the resultant current would also be reduced. If $|E_\psi|$ is enough large we can expect even an inverted bootstrap current in the Heliotron/Torsatron.

The extended neoclassical theory is applied to the poloidal and toroidal rotations in a plasma consisting of electrons, ions, and impurity ions in the Pfirsch-Schlüter regime [22]. It is found that the differences between bulk ions and impurities come from the different diamagnetic flows and the ion temperature gradient in the $1/\nu$ regime, but depend strongly on the field structure in the Heliotron/Torsatron, in contrast to the tokamak case [23]. For the experimental parameters of CHS helical device, the differences are small and of the order of bulk ion diamagnetic flow.

4 SUMMARY AND DISCUSSION

The present status of plasma heating in toroidal systems has been briefly summarized putting an emphasis on the heating utlizing fast ions. The theory of classical slowing down process for fast ions has been mentioned and the importance of field ripples has been stressed. NBI experiments from JT-60 and the first D-T experiments from JET have been reported. From these experimental results it is likely that the heating process utlizing fast ions (NBI heating and alpha heating) can be explained by classical or neoclassical theories based on the guiding centr motions of particles and the Coulomb collisions.

It should be noted, however, that fast ions produced by NBI or ICRF and alpha particles by D-T reactions may interact strongly with MHD modes such as sawtooth oscillation, fishbone instability, and ballooning mode. Recently it is pointed out that fast ions can destabilize the TAE mode (toroidicity-induced Alfven eigenmode) [24] or HAE mode (helicity-induced Alfven eigenmode in helical systems) [25] , resulting in causing a large loss of alpha particles due to the excited magnetic fluctuations [26)].

It is well known that the energy confinement times scale as roughly $P^{-0.5}$ (P is the heating input power) in tokamaks and helical systems. It should be emphasized that this scaling basically does not depend on the heating methods. Another problem is the electric field build-up due to escaping alpha particles, which alters the loss cone structures, plasma rotations, and alters the plasma transport.

Because of space limitations RF wave heating was not summarized. Recent review of

Japanese results on RF heating and current drive should be referred to Ref.[27]. Concerning the current drive recent development of neoclassical theory for parallel flows have been mentioned for general toroidal systems.

ACKNOWLEDGEMENT

The author is grateful to Dr. M. Azumi, Dr. K. Tani and Prof. T. Watari for fruitful discussions. He also acknowledges Prof. A. Iiyoshi, Prof. T. Sato, and Prof. M. Fujiwara for continuous encouragement.

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