ISSN 0915-633X

INTERNATIONAL ATOMIC ENERGY AGENCY

SIXTEENTH IAEA FUSION ENERGY CONFERENCE

Montréal, Canada, 7-11 October 1996

IAEA-CN-64/A6-5

NATIONAL INSTITUTE FOR FUSION SCIENCE

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(Received - Aug. 28, 1996)

NIFS-442 Sep. 1996

RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

INTERNATIONAL ATOMIC ENERGY AGENCY
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Keywords: Tokamak, Perturbative Plasma Transport,
Nonlocal Electron Heat Transport, Pellet Ablation,
Sawtooth Crash, Heavy Ion Beam Probe

Studies of Perturbative Plasma Transport, Ice Pellet Ablation and Sawtooth Phenomena in the JIPP T-IIU Tokamak

Abstract

In the JIPP T-IIU tokamak edge cooling imposed by positive biasing of an inserted electrode and injection of a small ice pellet induces an almost instantaneous increase in the electron temperature near the center. Rapid current ramp-up increases electron temperature at the edge. Thus produced hot front quickly propagates toward the center, although the toroidal current density increased by the ramp-up is still confined in the edge region of $r/a \geq 0.7$. Rapid current ramp-up also induces a small but sudden drop of the central electron temperature which takes place at much earlier time than the current penetration. The results from cold pulse and current ramp-up experiments suggest nonlocal electron heat transport.

A long helical shape ("tail") of ablation light is observed when an ice pellet is injected on-axis(horizontal) and slightly upward or downward off-axis. The direction of the tail is found to be closely related to plasma rotation. Plasma potential and density profile are widely controlled by changing the injection angle of a pellet and pellet size. Radial profiles of particle diffusion coefficient and inward convection velocity are derived from time evolution of density profiles realized by the pellet injection.

Rapid potential change is observed during sawtooth crash by a heavy ion beam probe(HIBP). This potential change is caused by combination between ambipolar electric field and rapid MHD motion across the magnetic field. However, poloidal magnetic flux near the sawtooth inversion radius measured by HIBP hardly changes at the crash. A multichannel motional stark effect polarimeter has revealed that the safety factor at the plasma center becomes well below unity, i.e., 0.7-0.8 during sawtoothing phase. These results suggest a partial reconnection takes place at the sawtooth crash.

1. Introduction

Experiments in JIPP T-IIU are dedicated to investigate fundamental processes in a toroidal plasma confinement, where the JIPP T-IIU device is a medium sized tokamak with major radius R=91 cm, minor one a=23 cm and the maximum toroidal filed Bt=3T[1]. This paper summarizes the following three topics on (A)perturbative plasma transport, (B)ice pellet ablation and (C)sawtooth phenomena. In these experimental researches several new plasma diagnostics as well as usual diagnostics are effectively used, that is, a 28 channel YAG laser Thomson scattering system[2], a 500 kV heavy ion beam probe(HIBP)[3], a fast response Zeeman polarimeter[4], and a 15 channel motional stark effect(MSE) polarimeter[5]. Moreover, a new pellet injection system has been developed, where the injection angle with respect to the horizontal plane and pellet size can easily and precisely be controlled[6].

Anomalous plasma transport in a tokamak is very complicated and our understanding is still preliminary. Usually plasma transport is studied through a steady state power and particle balances based on experimentally obtained radial profiles of various plasma parameters. On the other hand, transient response of a plasma to various types of perturbations may give us some hints to elucidate anomalous transport. This perturbative transport study was initiated by the analysis of radial propagation of a heat pulse generated by sawteeth[7]. Modulated electron cyclotron heating power and gas oscillation are also used for the perturbative transport study. A cold pulse produced by sudden edge cooling is also used for the perturbative transport study. Recently, a strong nonlocal or non-diffusive electron heat transport has been observed in the cold pulse experiment[8]. In JIPP T-IIU we have carried out perturbative plasma transport using a cold pulse produced by electrode biasing and ice pellet injection and using edge heating by rapid current ramp-up. This topic is described in Sec.2.

Ice pellet injection is considered to be a most promising fueling technique for a reactor grade plasma. Therefore, ablation process should be studied to understand anomalous plasma transport, in particular, particle transport. This paper describes detailed ablation processes at various injection angles and pellet sizes, and rapid potential change and density profile evolution associated with the pellet injection. Two CCD cameras arranged in the toroidal locations and a high speed framing camera are effectively used in the ablation study. This topic is described in Sec.3.

Sawtooth phenomenon is also an important subject to be understood clearly, because it has a close connection with heat transport and energetic particle confinement. In this study the HIBP is effectively applied to detect fast change of plasma potential and poloidal magnetic flux. The MSE polarimeter is also used to investigate whether or not the central safety factor q(0) is decreased well below unity during sawtooth oscillations. This topic is described in Sec.4.

2. Perturbative Transport Studies by Cold Pulse and Rapid Current Ramp-Up

In JIPP T-IIU perturbative transport experiments are carried out by a cold pulse and rapid current ramp-up. The cold pulse is produced with a positively biased electrode inserted just inside the last closed flux surface(LCFS). Fast electrons bombard the carbon electrode and release impurities and hydrogen. Electron temperature near the edge is slightly but suddenly reduced by the enhanced impurity influx and hydrogen recycling. Figures 1(a) and 1(b) show time evolutions of the plasma current, loop voltage, electron density, $H\alpha/D\alpha$ emission and radiation power in an ohmic discharge where the electrode biasing is applied. The time evolution of electron temperature (T_e) in this discharge is shown in Fig. 1(c), where the electrode is inserted at $r/a \sim 0.8$. Electron temperature near the peripheral region ($r/a>0.5$) is decreased and that in the region of $r/a=0.30$-0.35 remains almost unchanged. Significant point is that the electron temperature near the center($r/a<0.2$) rises without any long time delay as the drop of edge electron temperature. The loop voltage is kept almost constant or slightly increased during the edge cooling, as seen from Fig.1(a). This time behaviour of electron temperature suggests strong nonlocal (or non-diffusive) transport nature. The positive biasing of the electrode increases the ion saturation current in the scrape-off layer(SOL). This indicates the enhanced transport due to edge cooling induced by positive biasing. Incoherent magnetic fluctuations detected up to 100 kHz are enhanced during biasing. Amplitude of the coherent mode with $m=3/n=1$ remains unchanged, even if the coherent mode is already excited just before the biasing. The frequency of the coherent mode

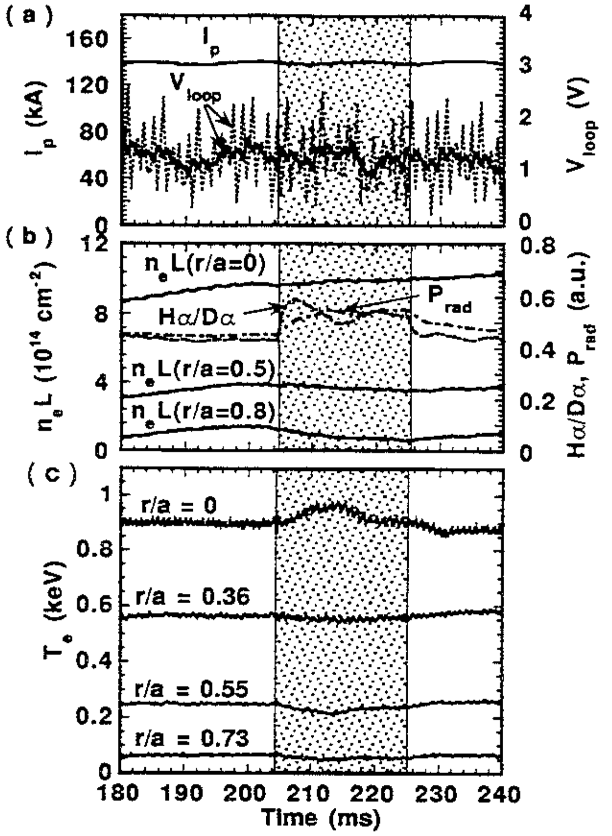

Fig.1 *Time evolution of plasma parameters in an ohmic discharge where a cold pulse is produced by positive biasing of an inserted electrode. A shaded area denotes the biasing phase. (a) plasma current, loop voltage and smoothed loop voltage, (b)line integrated electron density, Hα/Dα emission and total radiation power, and (c)Electron temperatures at various radial positions.*

is also unchanged. It is thought that there is no obvious change of poloidal rotation in the area near q=3 surface predicted to be r/a~0.7. The inversion radius of sawteeth remains unchanged, although the normalized internal inductance *li* is increased by about 0.1 in 10 ms. This suggests that the toroidal current density is appreciably modified near the edge by the edge cooling. Note that the ohmic input near the edge is not enhanced due to edge cooling.

Similar phenomena are observed in an ohmic discharge just after ice pellet ablation where a small pellet is injected at a low speed. Figure 2 shows time evolution of various plasma parameters in an ohmic discharge where a hydrogen pellet is injected horizontally. As seen from interferometer and ECE signals shown in Fig.2, the pellet is almost ablated outside an half way of the plasma. The Hα signal obtained at the injection port rises rapidly and decays less than 1 ms due to completion of ablation(Fig.2(b)). Electron temperature near the edge is suddenly reduced by pellet ablation, and the cold pulse front propagates inward (Fig.2(c)). Electron temperature near the center suddenly increases well before the arrival of the cold front produced by pellet ablation. In this case the loop voltage is appreciably increased as shown in Fig.2(a). However, the loop

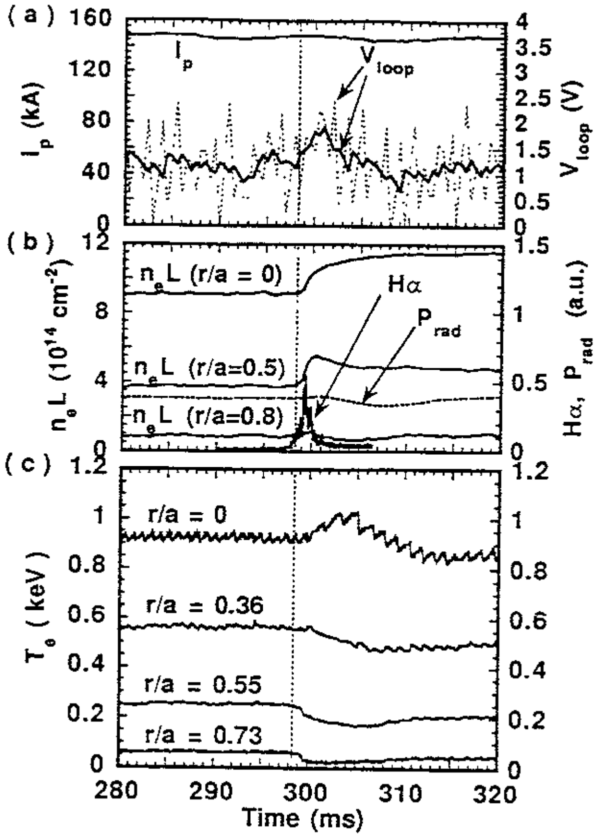

Fig.2 *Time behaviors of an ohmic discharge where a cold pulse is generated by ice pellet injection(horizontal injection). The vertical dotted line denotes the injection of the pellet, where the ablation is almost completed about 1 ms later from the injection. Parameters shown in (a) to (c) are same as those in Fig.1.*

voltage increase can be explained by the increase of the internal inductance as described later. This behaviour of electron temperature suggests a strong nonlocal transport nature. In contrast to the cold pulse experiment by electrode biasing the ion saturation current in SOL is suddenly reduced by the pellet ablation. Magnetic fluctuations are also reduced just after the ablation. In particular, coherent m=3/n=1 mode is clearly suppressed at same time of the sudden drop of edge electron temperature. This suggests an appreciable change of the toroidal current density profile near and outside q=3 surface(i.e., r/a≥ 0.7). The normalized internal inductance is increased by about 0.1 in 6 ms. As described above, the increase of the loop voltage is explained by the increase of an inductive voltage due to the change of l_i. That is, the ohmic input *near the edge* estimated from the change of the loop voltage is almost unchanged. These data suggest the current density profile is decreased near the edge and increased in the more interior, because the total plasma current is kept constant. As seen from Fig.2(c) the inversion radius of the sawteeth seems to expands slightly during the Te-rise near the center. The above mentioned Te-rise near the center is interpreted by either or both of the following causes: one is the reduction of heat diffusivity near the center, and the other the increase in the ohmic heating power density *near the center*. The former cause seems to be more plausible from a consideration of the resistive diffusion of the poloidal magnetic field.

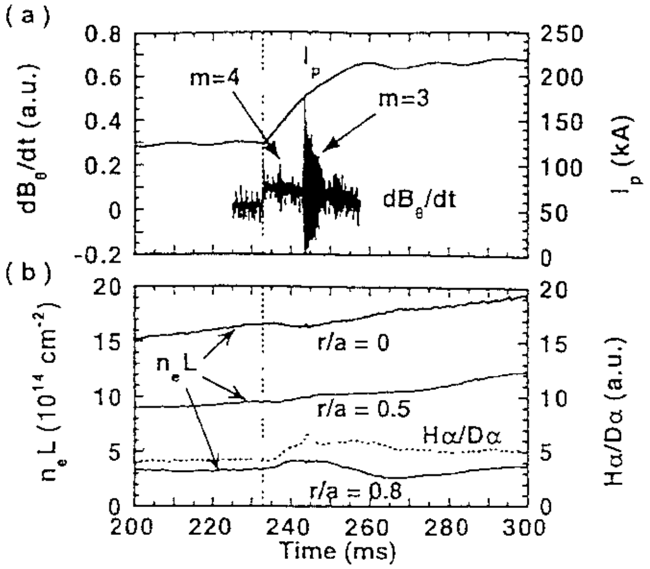

Fig.3 Time behaviors of discharge with rapid current ramp-up. (a) plasma current and Mirnov coil signal, and (b) line integrated electron density and Hα/Dα emission. During the ramp-up coherent modes with m=4/n=1 and m=3/n=1 are destabilized.

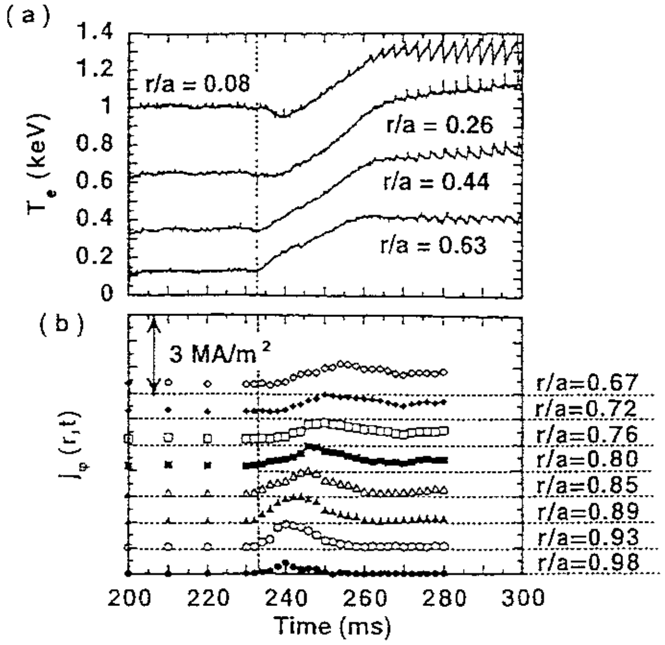

Fig.4 Time behaviors of electron temperature and toroidal current density in the discharge shown in Fig.3(a). (a) Electron temperatures are obtained with ECE signals, and (b) time evolution of the toroidal current density obtained with a fast response Zeeman polarimeter, where each dotted horizontal line shows the zero-level of the respective current density.

It is interesting to study the transient response of electron temperature to edge heating by the rapid current ramp-up, and compare the results with those in above-mentioned cold pulse experiments. Figure 3 shows time behaviours of an ohmic discharge with rapid current ramp-up. During the current ramp-up $H\alpha/D\alpha$ emission is enhanced and electron density near the edge is increased. However, the electron density near the center ceases to increase or slightly decreases only a few milliseconds later from the turn-on of the ramp-up(Fig.3(b)). This enhanced particle loss seems to take place at the same time of the onset of $m=4/n=1$ magnetic fluctuations. The fast response Zeeman polarimeter has revealed that a skin effect of the toroidal current density produced by the ramp-up propagates to the region of $r/a=0.7$ in about 20 ms from the turn-on of the ramp-up(Fig.4). However, electron temperature in the plasma interior of $r/a<0.4$ starts to rise well before the arrival of the increased toroidal current density by the ramp-up. Moreover, the electron temperature at the center is suddenly decreased only about 4 ms later after the turn-on of the ramp-up, of which phenomenon also seems to correlate with the appearance of $m=4/n=1$ mode. The results clearly show that electron heating in the interior takes place much faster than the radial diffusion of ohmic heating power increased at the plasma edge. This cannot be explained by a usual diffusive transport model. The nonlocal electron heat transport may correlate with coherent low mode number ($m=4$ or 3) magnetic fluctuations enhanced during the ramp-up.

Off-diagonal terms in a transport matrix may play a role in nonlocal electron heat transport discussed in this section. Electromagnetic fluctuations having a long radial correlation length should be taken into account of the study, as well as electrostatic fluctuations such as drift waves.

3. Studies of Pellet Ablation Characteristics and Particle Transport

Pellet ablation study is conducted by the specially designed pellet injection system[6]. In this experiment an ablation cloud is measured with two CCD cameras and a fast framing camera, being paid attention to plasma rotation. Rapid potential change is measured with HIBP with high time resolution. Particle transport is intensively studied from analysis of time evolution of electron density profiles obtained with the YAG Thomson scattering system.

In the case of off-axis injection with the injection angle(θ: measured from the mid-plane of a plasma) larger than a certain value ($\theta \geq 4°$), a pellet penetrates straight into a plasma exhibiting a straight trace of the ablation cloud, as predicted by a usual ablation theory. On the other hand, a long helical shape ("tail") of ablation light has been observed in the case of on-axis(horizontal) and upward or downward off-axis injection with a small angle($\theta \leq 4°$). This is confirmed by time dependent measurement of the ablation cloud with the high speed framing camera. The direction of the tail is investigated for various injection angles, by changing the directions of the toroidal magnetic field and the plasma current independently. These results show that the tail of the ablation cloud in ohmic discharges rotates poloidally in the electron diamagnetic direction, and toroidally in the counter direction of the current[6].

The local electron density and temperature in the ablation cloud has been obtained from the Stark broadening of the Balmer Beta (H_β)line(4861.3 Å) , and from the ratio of the line intensity to the continuum intensity, respectively.

Since the time resolution in this measurement is 0.5 ms, the obtained spectrum contains a whole time history during the pellet ablation. The spectrum is best-fitted by the double Lorentzian. The FWHM of each component of the spectra is obtained to be 10.0 Å and 60.0 Å. Each of them corresponds to be the electron density of about 10^{16} and 10^{17} cm^{-3}, respectively. From the ratio of the H_β line intensity integrated over 4861.3 ± 100 Å and the continuum intensity integrated from 4550.0 to 4650.0 Å away from the H_β line, the electron temperature is estimated to be about 1 and 4 eV, for each Lorenzian. The charge exchange equilibrium of protons and hydrogen atoms at extremely high density (10^{15} - 10^{17} cm^{-3}) may be realized in the tail structure, since the charge-exchange and elastic-collision times are much shorter than the ionization time in this parameter range.

A rapid change of plasma potential during pellet ablation is measured for the first time with HIBP which has high time response more than 1 μs. Figure 5 shows relative potential change observed near the plasma center r/a=0.1 well inside the maximum ablation position for two cases. In one case that a pellet is injected upward off-axis, the potential change becomes negative as shown in Fig.5(a). In the other case that a pellet is injected downward off-axis, the potential change becomes positive as shown in Fig.5(b). This change is interpreted as being due to the toroidal drift of charged particles in the high density plasma of the ablation cloud, before the increased density due to ablation becomes uniform on the magnetic surface[9]. The rotation behaviour of the ablation cloud having the above-mentioned tail structure seems to be consistent with the relative potential change as shown in Fig.5.

The above-mentioned pellet injection system can effectively control electron density profile by changing the injection angle, as shown in Fig.6. The on-axis (horizontal) injection produces a usual peaked profile(Fig.6(a)). On the other hand, the (upward) off-axis injection realizes a fairly flat density profile in the core region with a steep gradient at about half radius just after the injection (Fig.6(b)). In this case, the inward pinch effect is clearly observed from time evolution of the density profile. From these time evolutions of electron density profile obtained for various injection angles, particle diffusion coefficient D and inward convection velocity v are derived in the central plasma region of r/a<0.5,

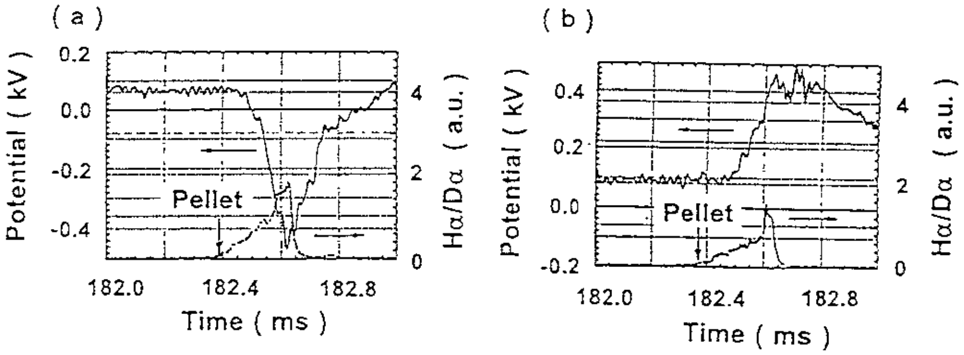

Fig.5 Relative potential change measured by HIBP during pellet ablation in the cases of upward off-axis injection of Z=7 cm (a) and downward one of Z=-7 cm (b), where Z means the chord radius of the injection line.

where D and v are assumed to be kept constant for an analyzed time window after the pellet injection(i.e., for 20ms). The analyzed results for the case of on-axis injection are shown in Figs.7(a) and (b). Figures 7(c) and (d) correspond to those in the upward off-axis injection. In the latter case D and v are estimated with relatively small analyzed errors[10]. This pellet injection system will provide an effective tool for transport study in a toroidal plasma.

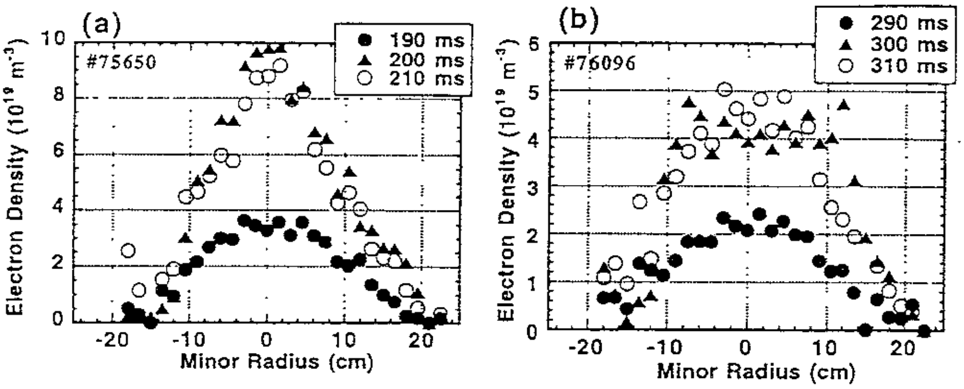

Fig.6 Time evolution of electron density profiles obtained every 10 ms by the 28 channel YAG Thomson scattering system in ohmic discharges where an ice pellet is injected on-axis at t ≈ 195ms(horizontal, Z=0 cm)(a) and upward off-axis at t ≈ 295ms(Z=7 cm).

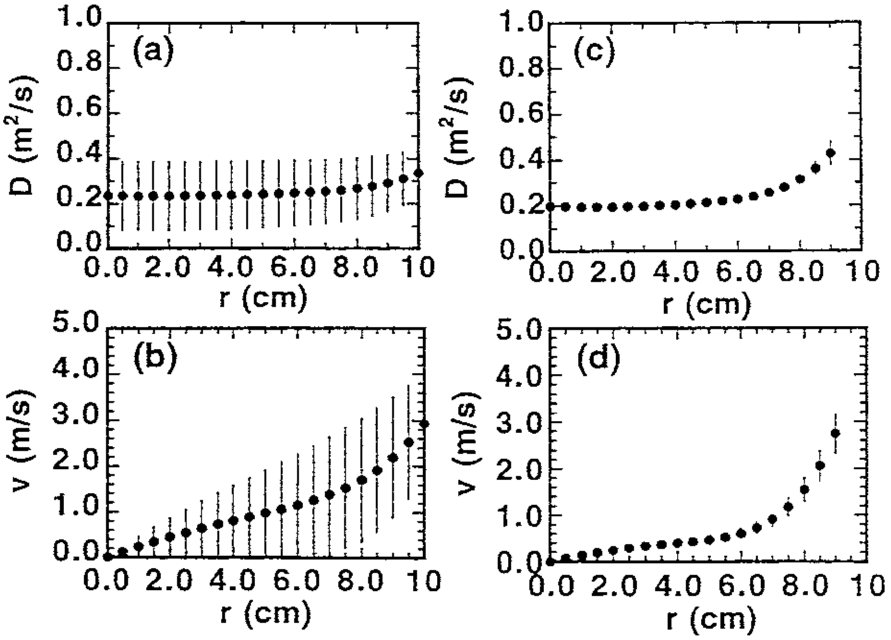

Fig.7 Radial profiles of particle diffusion coefficient and inward convection velocity derived from time evolution of electron density profiles after ice pellet injection, (a) and (b) in the on-axis injection, and (c) and (d) in the upward off-axis one.

4. Studies of Sawtooth Phenomena with HIBP and Polarimeter

The heavy ion beam probe HIBP is very powerful tool to study rapid change of plasma potential and poloidal magnetic field which may be induced by a sawtooth crash. Indeed, rapid change in the plasma potential is detected with HIBP during a sawtooth crash[11]. The potential change with the negative or positive polarity is observed inside the inversion radius(r_{inv}) of the sawtooth. Recently it is clarified that the polarity of the potential change depends on the direction of the fast motion of the hot core(i.e., toward larger or smaller major radius R), at the reconnection. Figure 8 shows an expanded time evolution of the toroidal shift of the secondary beam and plasma potential measured with HIBP near the inversion radius, during the sawtooth crash, where ECE signals obtained inside the inversion radius are also shown. When the hot core is shifted rapidly outward(toward larger R) due to MHD effect, as shown in three ECE signals of Fig.8, a negative potential pulse is observed, and vice versa. According to the MHD theory, a quick plasma motion perpendicular to the magnetic field($v\perp$) means generation of a radial electric field $E=-\mathrm{grad}\ \Phi_{MHD}$.

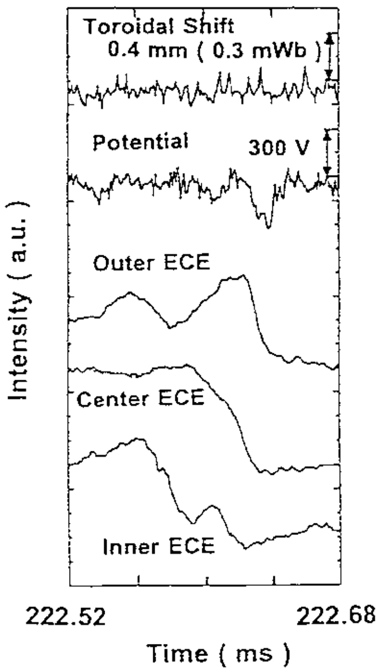

Fig.8 Expanded time evolution of various plasma parameters during a sawtooth crash, where the toroidal shift of the secondary beam and plasma potential near the inversion radius obtained with HIBP, and three ECE signals obtained at outer (larger major radius), center and inner (smaller major radius) inside the the inversion radius.

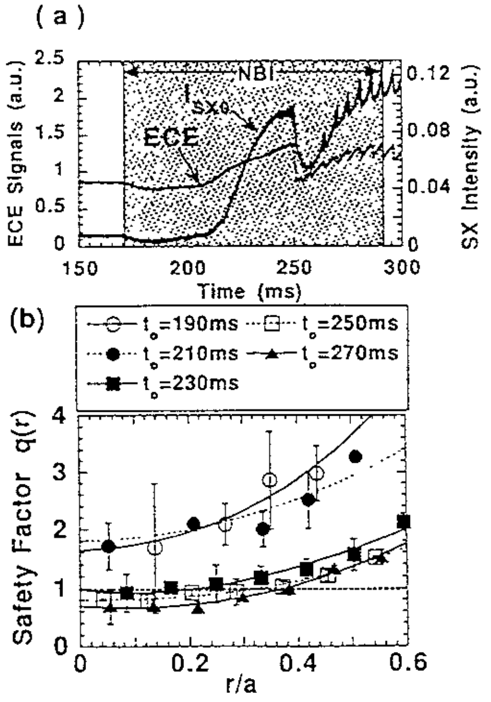

Fig.9 Time evolution of ECE and soft X-ray signals in a current ramp-up discharge with neutral beam injection heating(a), and radial profiles of the safety factor obtained with a MSE polarimeter(b). The profiles are obtained by averaging over each time window from (t_0-10) ms to (t_0+10) ms.

At r< r_{inv} a nearly uniform electric field is predicted to be generated at the sawtooth crash, leading to one directional quick motion toward the inversion radius[12]. The maximum of Φ_{MHD} occurs at r $_{inv}$ is estimated as $\Phi_{MHD}= v_\perp \bullet B_t \bullet r_{inv}$, and to be ~300 V. This magnitude and polarity are consistent with the above experimental results, when HIBP is set away 126 degrees in the toroidal direction with respect to ECE monitor and m=1/n=1 rapid motion is assumed. The toroidal shift of the beam is proportional to the local poloidal flux through the canonical momentum conservation law. The change of the flux at $r<r_{inv}$ is found to be very small. This suggests that the change of q-profile is small at the crash. This seems to be consistent with the fact that the safety factor at the magnetic axis q(0) measured with a 15-channel MSE polarimeter is decreased well below unity, i.e., 0.7-0.8, even in the phase exhibiting obvious sawtooth oscillations, as shown in Fig.9[5].

5. Summary

In JIPP T-IIU perturbative plasma transport experiments are carried our by using a cold pulse induced by electrode biasing and small ice pellet injection and also by using rapid current ramp-up. Strong nonlocal nature in electron heat transport is observed in the perturbative transport study, but the mechanism is open for discussion. Upward or downward off-axis injection as well as on-axis injection of an ice pellet brings about interesting plasma behaviours related to particle transport in a tokamak plasma. Studies of sawtooth with a heavy ion beam probe and MSE polarimeter suggest that only a partial reconnection of magnetic field lines takes place at the sawtooth crash.

Acknowledgments

Authors thank Director General A. Iiyoshi and Professor M. Fujiwara for their continual encouragement.

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