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Review of Japanese Results on Heating and Current Drive

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ABSTRACT

This paper reviews the progress in the application of RF to Heating and Current Drive for Nuclear Fusion made by the Japanese RF community.

KEY WORDS:
plasma heating, current drive, ECH, LHCD, ICRF, IBWH, FWCD, review, Japan

INTRODUCTION

This article covers briefly the major Japanese contributions in the investigation of plasma heating and current drive and, together with other reviews presented at this conference, intend to give a reference for future investigations. The Japanese fusion community has several tokamaks: JAERI (STA) has JT-60 and JFT-2M. TRIAM-1M (Kyushu University), WT-III (Kyoto University), and JIPP T-II U [National Institute for Fusion Science (NIFS)] belong to the Ministry of Education (MOE). A lot of contributions have been made by these devices on heating and current drive in the various range of frequencies: electron cyclotron (EC) frequency range, lower hybrid (LH) frequency range, and ion cyclotron (IC) frequency range.

This paper only deals with tokamak results: Results on LHCD are described in section I; ECH is described in section II; Results on high power ICRF heating are given in section III; IBWH is described in section IV and finally, FWCD is covered in section V.

Because the Matrix of different machine and different frequency range gives an intractable list of results, sampling will be made in describing the progress, i.e., JT-60 for LHCD, WT-III for ECH/CD, JIPP T-II U for IBWH, JT-60 for higher harmonic ICRF heating. Special attention is given to the investigation of fast wave current drive which has some history in Japan. Results from JIPP T-II U, JFT-2M, HT-2, and JT-60 are summarized.

Aside from the tokamak, MOE has an alternative magnetic fusion program centered around CHS and HELIOTORON-E (Kyoto University). LHD (Large Helical Device) is a machine
under construction in the new site of NIFS. Gamma-10 (Tsukuba University) and HIEI (Kyoto University) are tandem mirror type open end systems. Due to the allotted space, works in this field will not be covered in this review. It should also be noted that there are lot of contributions in the field of theory which continued to support experiments very strongly through this decade.

I. Lower Hybrid Current Drive (LHCD)

The principle of LHCD has been proven in JFT-2 (Yamamoto et al., 1980). Since then, a lot of studies have been devoted to LHCD in the world. In Japan, start up of plasma current without any aid of inductive drive was demonstrated in WT-II (Kubo, et al., 1983) and JIPP T-II U (Toi et al., 1984). On the basis of such a proof of principle of LHCD, JT-60 has really demonstrated its usefulness in the moment of getting maximum possible equivalent Q-value (JT-60 Team, 1988). Here, they needed the highest plasma current in order to optimize improvement of energy confinement in the accessible L-mode plasma. This shows that LHCD passed the development level and ready to be used in the next generation machines like ITER.

On the other end, a recent experiment in TRIAM-1M (Itoh, S. et al., 1988) recorded the sustainment of plasma current for longer than 1 hour. In the following, we take JT-60 as an example, and briefly review the achievement of physics understanding in Japan in the area of LHCD. JT-60 is one of the 3 large tokamaks in the world. It is equipped with large LH system with frequency variable from 1.7GHz to 2.3 GHz and an available power of up to 10MW. The RF system was designed a decade ago primarily for ion heating. As JT-60 came into operation, it was known through experiments in smaller sized tokamaks that ion heating is difficult to achieve but, instead, current drive in this frequency range looks promising. LHCD has 3 problems to be solved before successfully usage in a reactor can be envisaged:

1) There is the so called density limit above which LHCD efficiency falls down. The use of high frequency may be beneficial to this problem (Porkolab et al., 1984).

2) LHCD is the most reliable CD scheme ever established. Yet, the efficiency ever achieved is
not enough to be applied in a reactor with a reasonable circulation power level.

3) In a reactor condition, where electron temperature is high, the damping scale length tend to be smaller compared to the minor radius of the tokamak unless the wave k-parallel is chosen low enough to reduce interaction. However, then, the access to the plasma core is limited by the wave accessibility condition.

The results from JT-60 LHCD have contributed especially to the last 2 issues.

a) High Current Drive Efficiency and Te Dependence:

To mention first of all, the LHCD efficiency which is significantly higher than foregoing experiments was obtained in the JT-60 (Ushigusa et al., 1988). It was known before the JT-60 experiment that the CD efficiency is proportional to the electron temperature. The group of data points from JT-60 in Fig.1 locates well above the previous results and gave a firm foundation for the idea which was not explicitly predicted in the Fisch Karney theories (Fisch, 1978). A significant effort was also made to simplify the wave launching method. The use of a multi-junction Grill (Gormezano, 1985) made it possible to launch the LHCD wave in a narrow spectrum leading to higher efficiencies (Bernabei, 1986). The experimental data thus obtained is reproduced in Fig. 1 (Imai, T, et al., 1990). The maximum efficiency ever achieved in JT-60 is \( \eta = n \cdot R \cdot I / P \sim 3.4 \times 10^{19} \text{ m}^{-2} \text{MA} / \text{MW} \). The significance of this value is evident from the fact that it almost satisfies the ITER requirement (\( \eta \sim 5 \times 10^{19} \text{ m}^{-2} \text{MA} / \text{MW} \)). The high efficiency obtained is due to the high electron temperature only attainable in a large tokamak and to the highly shaped wave k-parallel spectrum. The drive efficiency empirically scales

\[
\eta = \frac{n_e R I_0}{P_0} = \alpha \frac{12(T_e)}{5 + Z} \times 10^{19} \text{ [m}^{-2} \text{MA} / \text{MW}] \quad (1)
\]

with \( \alpha = \frac{1}{N_i^2} \frac{1 - (N_2 / N_1)^2}{\ln(N_2 / N_1)} \quad (2) \)
and that predicted in the theory (Fish, 1978) is given by,

$$\eta = \frac{n_e R I_0}{P_0} = \frac{82.8}{5 + Z} \frac{1}{\langle N^2_{//} \rangle} \times 10^{19} \text{[m}^{-2}\text{MA / MW]}$$  \hspace{1cm} (3)

The factor $\alpha$ involved in eq.(1) should be there in order for the improved efficiency obtained with the multi-junction grill to be accounted for. The disagreement between the theory and the experiment will be reconciled by the anzats that wave k-parallel spectrum upshifts itself until the phase velocity matches the thermal velocity of electrons. It is worthwhile to note that this process which is one of the possible explanations of the so called spectrum gap filling puzzle also explains the Te dependence of LHCD.

For the reactor relevant plasma, where Te is even higher, the spectrum gap to be filled may be narrower and saturation of temperature dependence may occur. Indeed, very recent experimental data exhibits such tendency (Imai et al.,1990). A simulation taking this effect into consideration yields

$$\eta = \frac{n_e R I_0}{P_0} \propto \frac{\sqrt{T_e}}{5 + Z} \times 10^{19} \text{[m}^{-2}\text{MA / MW]}$$  \hspace{1cm} (4)

Thus the agreement between theory and experiment is improving thanks to the experiments in JT-60. It is worthwhile to recall the essence of the Fisch-Karney theory: it assumes an asymmetric velocity distribution function and calculate the power to sustain it against coulomb collision. As such, the question whether there are enough particles to absorb that amount of power did not receive always enough attention but has been reported several years ago. It has furthermore been reported that spatial diffusion of hot electrons has to be taken into consideration in a small tokamak (Takase et al.,1987 (a), Maekawa, et al., 1992). As these issues are less critical in large tokamaks as JT-60 better agreement with theories is obtained.
b) Beam Probe Method

It was shown several years ago in the JIPP T-II U experiment that LHW can interact with the high energy ion tail produced by NBI and clamp it (Noda et al., 1982). Recent experiment in JT-60 revisited this aspect and clarified its relation to the so called density limit. In the experiment where LHCD is applied with neutral beam injection, it was found that LHCD fails above a certain density which depends on the beam energy (Ide et al., 1992). It is worthwhile to note that the same effect is related to investigations aiming at explaining the density limit (Wegrowe, 1984; Svedrup et al., 1987). In them, it is assumed that the switch-over from electron heating to ion heating occurs when \( \frac{k_\perp}{k_{\parallel}} \sim \frac{v_e}{v_i} \), where \( v_e \) and \( v_i \) are thermal velocity of ions and electrons, respectively. In JT-60 experiment, beam ions takes the dominant part of the wave-ion interaction and specifies the ion energy. Using beam velocity \( v_b \) in place of \( v_i \) and calculating \( v_e \) using electron temperature, one can estimate \( \frac{k_\perp}{k_{\parallel}} \) at the switch over point. It was shown in this analysis that the interrelation between plasma density and \( \frac{k_\perp}{k_{\parallel}} \) satisfies the following dispersion relation of the lower hybrid wave.

\[
\omega^2 = \omega_{LH}^2 \left( 1 + \left( \frac{k_{\parallel}^2}{k_\perp^2} \frac{m_e}{m_i} \frac{1}{\gamma} \right) \right)
\]  

(5)

This check is important not only because there are few cases where propagation of LHW was directly measured (Watterson et al., 1985), but also it shows that the density limit model (advocated in Wegrowe, 1984; Svedrup et al., 1987) is actually upheld. However, it should be noted that, in usual tokamak situations without beam ions, the current drive density limit is imposed by a violation of the accessibility condition or parametric instabilities. In many cases parametric decay instability is observed near the density limit which is assumed to be the result of the enhanced wave fields at the edge under such conditions.

c) Ion Heating
We here again recall that LH system was designed for plasma heating and that ion heating was observed in some of the smaller tokamaks (Uehara et al., 1982; Ohkubo et al., 1982). However, clear evidence of ion heating has not been reported from experiments in tokamaks of larger size (Porkolab, 1983). An experiment was conducted recently in which, by pellet injection, the plasma density was raised in the plasma core while keeping the edge density low and avoid the parametric decay instability. This scheme was found successful and a heating efficiency as high as that of NBI was obtained (Ushigusa, et al., 1988).

d) Wave Damping Scale Length
A further contribution of JT-60 relates to the theoretical prediction that wave damping length may be smaller than the minor radius in future tokamak plasmas. In the recent experiment in JT-60 (Kondo, et al., 1992), profile of X-ray emission was measured, which represents the channel of the current driven by the LHCD. It was found that centrally peaked profiles are obtained for lower value of N//. Internal inductance was measured for various value of the N// and it was found that higher one was obtained with lower value of N//. These results are consistent to each other and gives another demonstration of good agreement between the theory and experiment.

e) Stabilization Effect
Apart from the current drive which is the absolute mission of lower hybrid, the stabilization effect of Lower Hybrid Current drive should be mentioned. Several years ago, its stabilizing effect on both sawteeth activity (Chiu, et al., 1986) and m=2 MHD modes (Van Houtte, et al., 1984) has been reported. The sawtooth stabilization was also observed in the large tokamak, JT-60 (Imai, T., et al., 1988). From the fact that the sawteeth inversion radius is not zero when sawteething resumes after the turning off of the LH, the mechanism is supposed not due to the loss of q=1 surface but due to the stabilization effect of LHCD. Stabilizing of the m=2 mode has been reported from PETULA experiment (Van Houtte, et al., 1984) followed by JIPP T-II U (Toi et al., 1986) and WT-2 (Maekawa et al., 1989).
Nowadays, this stabilization effect is widely accepted as a useful application to future machine. In JIPP T-II U, LH was applied to impurity pellet injection experiment facilitating it against disruptions which was otherwise inevitable (Morita, et al., 1990). Particularly, in WT-III (Maekawa et al., 1991), a plasma of $\beta_p = 2$ is created with the stability provided by the LHCD reproducing the result of VERSATOR (Luckhardt et al., 1989). Through the above mentioned series of experiments, usefulness of the LHCD in controlling plasma was fully demonstrated. Finally, H-mode was obtained in JT-60 by the use of LHCD with much less threshold power than with NBI (Tsujii et al., 1990). This again shows its unique action to the plasma and its definite usefulness in stabilizing plasma.

f) Technology Development

In the following, a few new results from JT-60 is introduced. In the shot in Fig.2, the plasma position was changed during a shot (Seki, M., et al., 1992). The distance between the plasma position and the wave launcher, $\delta$, varies accordingly. Surprisingly, the reflection coefficient remained low for the $\delta$ changing from 10cm to 3cm. The significance of the result may be clear if an application of LHCD to reactor environment is seriously considered. Because the LHCD is designed so that high energy electrons are artificially created, its thermalization is one of the key processes. If they are not well thermalized before they diffuse out to the separatrix, there is a possibility that diverter plate receive enormously high heat deposition causing a problem. Actually, it was found in the JT-60 experiment that the heat deposition on that diverter plate has a good correspondence to the soft X-ray emission (see Fig.3). It is expected that the heat deposition by the energetic electron may be reduced under the condition where slowing down time is short. Slowing down time was changed in the experiment by changing the plasma density and, since the slowing down time is also dependent on the energy range of wave-particle interaction, by changing the wave $N//$. The experimental result in Fig.4 shows that heat deposition to the diverter plate decreases with decreasing slowing down time (Ushigusa, et al., 1992). A simple extrapolation of it to ITER target plasma gives 0.1 % of the wave energy going to the diverter plate before full slow down; the high
energy electrons produced by LH wave therefore should not cause serious problem of diverter heat load. This point of view is, however, important and more detailed investigations have to be made.

II. EC Heating and Current drive

a) Demonstration of Electron Cyclotron Current Drive

Fisch theory (Fisch, 1978) predicts that EC current drive does not necessarily need momentum input but instead it can be achieved by giving particles an incremental asymmetric perpendicular energy. The first demonstration of EC current drive has been done by Levitron group (Start et al., 1982). ECCD was confirmed in WT-II&WT-III experiments in 1986 in both fundamental (Tanaka,S., et al., 1986) and second harmonics electron cyclotron frequencies (Tanaka,H., et al., 1991). In the latter experiment the EC-driven current reached 70 kA at a power level of 140kW thus providing a proof of principle demonstration of ECH current drive. However, the current drive efficiency obtained in the experiment is \( \eta = n \cdot R \cdot I / P=0.06 \times 10^{19} \text{ m}^{-2} \text{MA} / \text{MW} \), i.e., a factor of 10 smaller compared to LHCD efficiency in the same machine. The current drive efficiency did not vary when the injection angle is switched from counterclockwise to clockwise. This fact may be again attributed to the small single pass absorption. A simulation using a bounce averaged Fokker Planck code predicts current be driven in opposite directions in the two regions separated by the cyclotron resonance. In a small machine like WT-III, experiments have to be carried at such low densities that slide away seed electrons exist which are responsible for directional wave-particle interaction.

b) Sawtooth Stabilization with ECH

A very interesting aspect of ECH is that its power deposition is controllable by changing the resonance layer, i.e., by changing Bt. Such merit of ECH was demonstrated in a WT-III experiment (Hanada, et al., 1991). Here, the sawtooth period increased when the resonance
layer is aligned just on the sawteeth inversion layer. This result strongly supports an application of ECH to stabilization of sawtooth oscillation. The shear at the q=1 surface is calculated in the experimental condition using PEST code (Grimm, R.C., et al., 1982) with the measured electron temperature profile. It was found that the application of ECH at the flux surface in the vicinity of the q=1 surface can lower the magnetic shear and stabilize the plasma against resistive kink mode. The fact that the sawteeth period and amplitude is the longest when the q=1 surface is heated at high field side may be interpreted in terms of the portion of the wave energy absorbed by the passing electrons. Subsequently, the mechanism for stabilization observed in the ECH experiment in WT-III is different from that of JET (JET team, 1986) and TFTR (Philips, et al., 1992) in which ideal or resistive kink-mode is stabilized by the hot ions under the condition $\omega_{dh} > \omega_{di}$ (Porceli, et al., 1990).

c) Importance of Momentum Input on ECCD
In the recent work in WT-III, synergy when LHCD is used in combination with ECH was studied. In this experiment, an X-mode wave was launched from the low field side, and the best result was obtained with the injection angle close to parallel. As it is observed in Fig.5, it was found that current was ramped up by the application of ECCD (Tanaka et al., 1992). Furthermore, the current ramp up efficiency is as high as that of LHCD in the same machine. This finding is interesting because momentum input is needed in current ramp up while theories usually pay little attention to the momentum input in explaining ECH current drive. The experimental data indicates the importance of considering momentum input also in ECH current drive. The wave particle interaction is briefly understood by examining the following three equations:
\[ \omega - k_{||} v_{||} = \frac{n \omega_e}{\gamma} \]  
(6) 

\[ \delta p_{||} / \delta \epsilon = k_{||} / \omega = N_{||} / c \]  
(7) 

\[ (mc \gamma - N_{||} p_{||}) \delta p_{||} = N_{||} p_\perp \delta p_\perp \]  
(8) 

Equation 6 gives the resonance condition including a factor \( \gamma = \sqrt{1 + (p/mc)^2} \) showing relativistic effect. Equation 7 gives the ratio of the parallel momentum input to the energy input where \( \epsilon = (m^2 c^4 + c^2 p^2)^{1/2} - mc^2 \). Equation 8 gives the direction of the kick which a particle receives from the EC wave. The resonance condition in the case of fundamental cyclotron damping is shown by the ellipse in Fig. 6 and the direction of the kick is shown by the arrows. An important study here is that there is considerable parallel momentum input in the relativistic regime. The relativistic effect in the current drive has been analyzed by Fisch (Fisch, 1981). Normalized current drive efficiencies calculated for various values of \( N_{||} \) ranging from 0 to 1 is shown in Fig.7. The top trace is calculated for LHCD where the \( N_{||} \) is changed subject to the inter-relationship \( p_{||} / mc = \gamma / N_{||} \) which is imposed by the resonance condition. Figure 7 contrasts to the non-relativistic case where parallel momentum input yields simply a factor of 4/3 difference. Of the traces shown in Fig.7, the one with \( N_{||}=0 \) is often associated with ECCD case ignoring the moment input. However, the relativistic current drive efficiency of ECH equals to that of LHCD as \( N_{||} \) approaches unity and \( N_{||} \) is actually 0.75 in the present experimental condition.

This gives the explanation of obtaining ECCD efficiency as high as that of LHCD in the WT-III experiment. There is a further reason for the success of this experiment: With parallel injection of X-mode (injection with large \( N_{||} \)), one can take advantage of right handed
paralyzation of the wave which enhances the wave absorption. This idea is particularly important for small devices.

d) Heat Pulse Propagation

Very recently heat pulse propagation was studied in WT-III where two different types of heat pulses were compared: one made by the inherent sawtooth crash and the other by ECH. The delay time, time from the application of the heat pulse to the time observing the peak of the temperature perturbation, is about three times shorter for the former than the latter. The precise analysis in WT-III experiment demonstrated that the difference of the delay time does not always mean the difference of $\chi_e$ but rather should be explained in terms of the difference in their type of perturbations: The one caused by sawtooth crash is essentially dipole type perturbation while the one due to ECH pulse give monopole type perturbation. The result of the WT-III shows that same value of $\chi_e$ is obtained for ECH heat pulse propagation as in the sawtooth crash heat pulse propagation, i.e., no enhancement of $\chi_e$ on the sawtooth crash is observed. This method of analysis was applied to measure the $\chi_e$ in WT-III and improvement of $\chi_e$ was registered when sawtooth was suppressed by the application of LHCD (Tanaka, S., et al., 1992).

e) Other Applications

Besides the contributions presented here, ECH has been used in JFT-2M as a knob to study H-mode mechanism. It was confirmed that the lowest H-mode threshold power in that machine was obtained using ECH with the resonance layer aligned on the periphery of the plasma (Hoshino et al., 1988). Although the experimental data from D-III D (Prator et al., 1988) contradict this result, ECH was thus demonstrated as an adequate tool to control power deposition profile. ECH has also been used as start-up assist in combination with LHCD (Kubo et al., 1983; Toi et al., 1984); these are demonstrations of its potential use in next generation tokamaks like ITER where one need to minimize the loop voltage requirement.
III. ICRH

a) High Power ICRF Heating and H-mode
From 1984 through 1986, JFT-2 M and JIPP T-II U devoted themselves to the establishment of high power ICRF heating. The major concern then was the impurity problem which eventually limited the high power heating through plasma disruption caused by the accumulated impurity. The impurity problems were practically solved by the use of carbon limiters and also taking advantage of high field side launch in which electrons are heated. It is known that electron heating causes less problems as regards impurity production. Their goal of establishing high power ICRF heating was reached when 2MW of ICRF power was successfully injected in the small plasma volume (Odajima et al., 1986; Ogawa et al., 1989). A highlight in this area is the first achievement of the H-mode with ICRF heating only. Before 1986 H-mode was obtained only with NBI and prior to the Japanese experiments, H-mode with ICRF heating was reported from ASDEX (Steinmetz et al., 1986). Here, however, H-mode was ELMy and the ELM's caused a problem in impedance matching of the RF circuit. High quality H-mode was obtained in JFT-2M (Matsumoto et al. (a), 1987). The H-mode obtained in JFT-2M is ELM free. It was found that the ellipticity of the plasma cross section reduced the power threshold drastically (Matsumoto et al. (b), 1987). H-mode was obtained also in JIPP T-II U. It was obtained with limiter configuration and accordingly threshold power was much higher (Watari et al., 1990 (a)). At the power level comparable to H-mode power threshold, transitions to a regime of improved confinement which are referred to as S-mode were observed in JIPP T-II U characterized by the peaked profile.

b) Higher Harmonic Heating and Sawtooth Suppression
Recent Japanese ICRF Heating Experiment was directed to higher harmonic heating regimes which will be important in reactor applications. In JT-60, 130 MHz rf system is used and second harmonic heating of hydrogen has been vigorously investigated (Fujii et al., 1991). It
was found that the heating efficiency of $\pi - 0$ phasing is 50% better than that of 0-0 phasing and that minority second harmonic heating has excellent heating efficiency. The most interesting observation in this experiment is that a very high confinement time is obtained in the low density regime, which may be explained by a good energy confinement time of high energy particles (Kimura et al., 1991 (a)). It was shown in the recent experiment in JT-60 (Imai, Kimura et al., 1991) and JIPP T-II U (Seki et al., 1991) that even third cyclotron harmonic heating can be used as one of the heating scenario. The second and third harmonic heating relies on finite Larmor radius effects and the wave absorption is expected to be small. However it is enhanced when the distorted energy distribution function is taken into consideration. In the case of JIPP T-II U, the experiment was successful only with high energy ion seed with either NBI or fundamental ICRF heating. This is the case in JT-60 too, if the resonant species are majority species.

The 2nd and 3rd harmonic heating in JT-60 concentrated on sawteeth suppression. Monster sawteeth were achieved with minority 2nd harmonic heating in high density regime with relatively small threshold power (P~2MW). Fig.8 shows a map of the operation region for sawtooth stabilization experiment with ICRF heating alone. Compared to those of other devices, sawtooth stabilization occurs in unique zone of high density. It may be attributed to the difference of the heating regime in JT-60 from others. Due to the nature of the finite Larmor effect, more energetic ions are created easily than in other heating regimes. It was found that the appearance of giant sawtooth, i.e., the stabilization of sawtooth, is closely related to the precessional frequency of ions (Yamamoto et al., 1992). Therefore, the sawtooth model of (Porceli et al., 1990) may have relevance in the JT-60 sawtooth stabilization. It was confirmed that the third cyclotron harmonic heating also strongly stabilize sawtooth (Fig.9) (Imai, Kimura, et al., 1990). These results supports the stabilization model and implies that 3rd harmonic heating is established in the future as a method to control plasma properties.

Recently, JT-60 U experiment began and giant sawteeth were reproduced (Fig.10) with the new record of injected power.
c) Progress in the Antenna Design

The ICRF heating experiment in JT-60U has just begun. The new ICRF antenna design was examined in the initial experiment. In Fig. 11, plotted are the loading resistance of new antenna compared to that of the old one. The increase of the loading resistance by an order of magnitude is noteworthy from the technology point of view because it is meant that 10cm of gap can be placed between the antenna and the plasma surface.

IV. ION BERNSTEIN WAVE HEATING

The first demonstration of the Ion Bernstein wave Heating (IBWH) in tokamak has been done in JIPP T-II U (Ono et al., 1985; Ogawa et al., 1989)). There have been further experimental advances in this field made by PLT (Ono et al., 1986), ALCATOR (Porkolab et al., 1986; Takase et al., 1987), TNT (Shinohara et al., 1987), WT-III (Yasaka et al., 1992), and JFT-2M (Tamai et al., 1989), D III-D (Pinsker et al., 1989) tokamak groups. For the general reference of the progress of this area, there is a review paper written by Ono (Ono, 1992). One of the problems in IBW heating seems to be the complicated physics involved in the wave excitation (Chiu, 1991; Brambilla, 1988), another is the impurity generation.

The recent JIPP T-II U experiment uses $f=130\text{MHz}$, i.e. a relatively high frequency compared to those used in preceding experiments, in an effort to solve the impurity problem of IBWH. In the impurity model presented by Itoh et al., impurity production is associated with the particle motion under the influence of the antenna near field (Itoh et al., 1986). The associated quantities are the equivalent velocity, energy, and the excursion length of such ions

\[
  v = \frac{qE}{m\omega}, \quad \varepsilon = \frac{1}{2}m\left(\frac{qE}{m\omega}\right)^2, \quad \xi = \frac{qE}{m\omega^2} \quad (9)
\]

which are reduced with increasing RF frequency. It is, therefore, expected that the adoption of
higher frequencies could be a step in the good direction.

In this high frequency IBW experiment, a power of 400kW has been successfully injected in the experiment (Kumazawa et al., 1991) compared to only 100kW at 40MHz. This factor of 4 improvement indicates that impurity was reduced drastically and that the model we employed is adequate.

The IBW heated plasmas have peaked ion temperature, peaked electron temperature, and peaked plasma density profiles (Seki et al., 1991). Fig.12 shows the ion temperature profile with and without IBW. The increase in the ion temperature is attributed to IBWH. The peaking of the profile is attributed to the plasma transport in the core region during IBWH.

An interesting observation here is that the ion energy distribution function with IBWH sharply drops above a certain energy level (see Fig.13). This unique feature can be explained in terms of quasi-linear Fokker Planck diffusion term which incorporates third cyclotron harmonic damping (Ono, 1992).

V. FAST WAVE CURRENT DRIVE

LHCD is, to date, the most established CD scheme. However, in a reactor situation, the wave damping in the LH frequency range is so strong that access of the wave to the plasma interior is not easy. For this reason, LHCD is more suitably applied to the current profile control in the outer region and development of new current drive scheme to drive the current at the plasma core is required.

The Fast Wave Current Drive experiment is traced back to SYNCROMAK experiment in 1976 (Fukuda et al., 1976). The importance of exciting uni-directionally propagating wave was already known at that time; as shown in the Fig.14 (a), the rf system in this experiment employed the idea of delay-line providing a perfect spectrum control.

However, since this experiment was carried before Fish theory was presented, only the high CD efficiency at the low phase velocity was emphasized.

The JIPP T-II U experiment at 800 MHz (Ohkubo et al., 1986) was the first visit to the FWCD
with the Fish's sense where high phase velocity wave is preferred. This experiment was able to
demonstrate that FW can drive the current by lowering the loop voltage to zero dismissing the
claim that only conductivity was changed. The four element antenna array used in this
experiment (Fig. 14(b)) laid a standard of four element antennas in the experiments which
followed. The puzzle was that the drive efficiency was the largest when the 0-phasing angle
was chosen. This results recalls that LHCD did not show the directionality as in their early
stage. This still is the case even in the contemporary LHCD experiments in small tokamaks.
In the later works, it was recognized that a lower frequency fast wave gives better accessibility
to the plasma core. The 40 MHz experiment (Ando et al., 1986) in JIPP T-II U is the first visit
to this regime. This experiment used 5 element antenna array and succeeded in demonstrating
current drive by obtaining negative loop voltage. The best CD efficiency is obtained when the
wave was launched in opposite direction to the plasma current; this is an aspect predicted by
theories. However, wave phase velocity is so high in this experiment that there is not enough
population of electrons to ensure large single pass absorption of the wave.
Later Japanese experiments on FWCD dealt with these points. Optimization of the antenna has
been studied in JFT-2M choosing f~ 200MHz and comparing two kinds of antennas. The "low
N// antenna" has a N// spectrum peaked around 4 for $\pi / 2$-phasing and around 8 for $\pi$
-phasing. The "high N// antenna" has a N// spectrum peaked about 6 for $\pi / 2$-phasing and 12
for $\pi$ -phasing. The most of the results in the following is obtained with the "low N// antenna".
The experiments in JFT 2M (Yamamoto et al., 1989) may be the first to claim the presence of a
sort of synergy in the combined use of ECH (Fig.15). When FW only is applied to Ohmic
target plasma, the coupling of the fast wave with electrons was recognized only in $\pi$-phasing
and it was weak. The coupling was enhanced substantially with ECH making sizable electron
heating even at 135 degree phasing. Similar synergistic effect was confirmed in JFT-2M also
in the shots with ICRF (Uesugi, et al., 1990). Here, two-ion-hybrid ICRF heating is applied to
enhance the electron temperature of the target plasma. This class of synergy is explained in
terms of filling spectrum gap.
The following dependences of the electron heating efficiency on various plasma parameters
were found: In Fig.16(a), the efficiency is increasing function of electron temperature as explained by the increasing number of electrons which match the wave phase velocity. In Fig.16(b), the efficiency increases with phasing angle because the phase velocity of the wave is slower and there are more number of electrons to match the velocity. In Fig.16(c), the efficiency is an increasing function of electron density. This is attributed to that the waves of slower phase velocity is excited with more proportion.

A pulse modulation method was also applied to obtain the radial profile of the absorbed power. From transport analysis it was shown that electron heating is particularly intense at the plasma axis (Uesugi, et al., 1990). This means that wave phase velocity is a little too high and the wave can couple to the plasma only at the center where electron temperature is high (see Fig.17).

There is a tendency in all FWCD experiments carried out in small tokamaks that wave N//= has to be large. The "high N//= antenna" in JFT-2M was designed to have N//=~6 with $\pi / 2$ phasing. This required an antenna array with close spacing, and it created a situation that coupling of the antenna to the plasma is poor. This problem may be serious particularly when the frequency is high and may present some general problems to be solved in the future. In particular, antennas are required to be placed well away from the plasma in reactor situations.

Though the power level is smaller with "high N//= antenna" than would be obtained with the earlier antenna, it was confirmed in the experiment that electron was heated even at $\pi / 2$ phasing (Kawashima et al., 1992). Therefore, the experimental results are showing agreement with their theoretical predictions.

In parallel to the experiments in JFT-2M, experiments were carried out on HT-2 and JIPP T-II U: Recent experiment (Fig.18) in HT-2 tokamak at 100 MHz demonstrated fast wave current drive again by obtaining loop voltage below zero for the density range one order of magnitude higher than that of LHCD density limit (Watari, Yoshioka et al., 1990). Current drive efficiency is plotted versus plasma density in Fig 19. The current drive efficiency is inversely proportional to the plasma density as predicted by Fisch theory.

The JIPP T-IIU experiment with 130MHz again confirmed electron heating in a higher density
range with $\pi$-phasing ($N//=-4$) (Takase et al., 1990; Seki et al., 1991). Here, Ip of the target plasma was the highest available in that machine in order to get high electron temperature of the target plasma.

It is well known that fast wave current drive is more suitably applied to larger machines. In JT-60, 130MHz RF system which originally designed for 2nd harmonic heating has been used to investigate the possibility of electron heating and current drive. The antenna consists of a pair of current straps. Again synergy is observed when it is superposed on LHCD (Kimura et al., 1991). There are clear difference between the operations with two phasing angles, 0 and $\pi$.

While enhancement of hard X-ray and no change in the bulk electron temperature is observed in the 0-phasing shots, $\pi$-phasing shots are characterized by the reduction of the hard X-ray and bulk electron temperature rise. The electron heating observed in the $\pi$-phasing in JT-60 seems to have similarity to those in D III-D (Prator et al., 1991) and JET (Start et al., 1990) FWCD/FWEH experiments. However, electron Landau damping is the dominant wave absorption mechanism in the JT-60 experiment while transit time damping take over in the latter two experiments.

All these Japanese experiences yields an interim conclusion for the future investigation. 1) The $N//$ spectrum should be chosen to minimize the spectrum gap 2) Too high $N//$ would result in bulk electron heating and current drive efficiency would not be large. 3) These contradicting requirement will be reconciled by the electron temperature anticipated in the future machine or an application of some auxiliary electron heating method.

Deciding proper frequency range for FWCD is becoming the most important concern. The TASK/W1 (Fukuyama et al., 1983) code predicts that fast wave in the frequency range higher than cyclotron frequency has competing two wave absorption mechanisms: absorption by electron and ions. Absorption by electrons is needed in order to obtain efficient current drive.

Once the frequency is chosen as $\omega / \omega_c > 1$, the harmonic number has to be high enough (several times ion cyclotron frequency) to avoid ion heating. Moreover, $N//$ may have to be 2–3 at the cost of drive efficiency in order to ensure the electron heating. The competition of these
mechanisms, is actually seen in the JIPP T-II U and JT-60 experiments. In JIPP T-II U, ion heating took place when neutral beam was injected. In the JT-60 (Kimura et al., 1991) experiments, the $\omega / \omega_c \sim 2.5$ was chosen in the electron heating experiment to be obtained to avoiding 2nd and 3rd cyclotron harmonic layer at the plasma center. The choice of lower frequency range, i.e., $\omega / \omega_c < 1$ may free one from such concern, though there is no experimental activity yet.

With respect to rf technology development plasma heating and CD in the ICRF frequency range, the ICRF antenna developed in JT-60 may be recalled (Nagashima et al., 1986, Fujii et al., 1992). The design adopted transparent type Faraday shield and succeeded in plasma heating. The effort for simpler Faraday shield was extended in the later work in TEXTOR (Van Niewenhove, et al., 1991). In general, there are two antenna concepts; small antenna which has extremely high efficiency and an antenna which covers large area of the wall but looks very similar to first wall. The JT-60 type antenna may represent the former and in favor of the high frequency. The SYNCROMAC (Fukuda et al., 1976) type antenna belong to the latter concept and may be smoothly trans-planted to the low frequency ($\omega / \omega_c < 1$) option of FWCD. The concept of "Panel Heater Antenna" (Kako et al., 1988) also belongs to this class and its application to future devises without Faraday shield is envisaged.

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Figure Caption

Fig.1. The electron temperature dependence of the current drive efficiency.

Fig.2. The change of the reflection coefficient as the plasma position is changed with respect to the wave launcher.

Fig.3. The chords of the Soft X-ray array: The 62-nd chord views one of the divertor plate, where the enhancement of the x-ray emission is well correlated to the heat deposition there.

Fig.4. The heat deposition to the divertor plate versus the slowing down time.
Fig. 5  The current ramp up with ECCD combined with LHCD showing unignorable momentum input.

Fig. 6  The Resonance condition and direction of the kick in the relativistic regime of ECCD. X-mode was injected in parallel direction (N//=0.7), and a down shifted frequency (\( \omega / \omega _c \approx 0.8 \)) was applied.

Fig. 7  The dependence of current drive efficiency in the relativistic region calculated for various N// values.

Fig. 8  Operation region for sawtooth stabilization experiments in q-ne space.

Fig. 9  The sawtooth suppression in the third cyclotron harmonic heating in JT-60 (Ip=1MA, \( \tilde{n}_e \approx 2.8 \times 10^{19} \text{m}^{-3} \)).

Fig. 10  Typical wave form of the minority 2nd cyclotron harmonic heating in JT-60 U(Bt=4T, Ip=2MA, \( \tilde{n}_e \approx 2.2 \times 10^{19} \text{m}^{-3} \), PIC=3.6MW, He discharge).

Fig. 11  The loading resistance of the new JT-60 U ICRF antenna compared to the old one. The difference is by an order of magnitude.

Fig. 12  The radial profile of the Ion Bernstein Wave Heated plasma.

Fig. 13  Ion energy distribution function on IBWH.

Fig. 14  (a) SYNCROMAC current drive antenna
(b) JIPP T-II U 800MHz current drive antenna

Fig. 15  Synergy observed in JFT-2M experiment. Electron heating is enhanced when FWCD is combined with ECH.

Fig. 16  (a) dependence of heating efficiency on electron temperature, (b) dependence of heating efficiency on electron density, (c) dependence of heating efficiency on antenna phasing.

Fig. 17  The power deposition profile on the FW electron heating. Pulse modulation method was applied to FWCD.

Fig. 18  The typical discharge showing FWCD experiment in HT-2 tokamak. The ordinates are from the top: plasma current[kA], loop voltage[V], hard X-ray emission.
intensity, transformer current[A], FW power [kW], and plasma density[10^{18} \text{m}^{-3}]

Fig. 19. The current drive efficiency versus plasma density obtained for HT-2 FWCD experiment.

Fig. 20. The density range of the existing FWCD/FWEH experiments plotted against predicted LHCD density limit. The underlined labels denotes that loop voltage was driven down to zero.
Fig. 1
Fig. 2
$N_{//}^{\text{peak}} = 1.9$

$P_{\text{div}}^{\text{HE}} / P_{\text{LH}}$

$\tau_{\text{SD}}(N_{//}^{\text{peak}})(S)$

Fig. 4
Fig. 5
$P_\perp = \frac{m \gamma v_\perp}{mc}$

$P_\parallel = \frac{m \gamma v_\parallel}{mc}$

$N_\parallel = 0.7$

$\Omega_e/\omega = 0.8$

$n = 2$

LHW

$n = 1$

Bulk E.l.

Fig. 6
Fig. 7

\[ J / P_d \left( 10^{20} \text{AW}^{-1} \text{m}^{-2} \right) \]

\[ P_1 = 0 \]

\[ P_1 = \frac{m \gamma v_\parallel}{mc} \]

\[ N_\parallel = 0.75, 0.5, 0.25, 0, -0.25, -0.5 \]

LHCD

ECCD
Operation Region for Sawtooth Stabilization Study with ICRF Heating Alone

Fig. 8
Fig. 9
Fig. 10

- $W_{\text{dia}}$ (MJ)
- $\bar{n}_e$ (10$^{19}$ m$^{-3}$)
- $T_e$ (keV)
- $P_{\text{ic}}$ (MW)

Graph showing $W_{\text{dia}}$, $\bar{n}_e$, $T_e$, and $P_{\text{ic}}$ over time ($T$ in sec).
Fig. 12

- $T_i$ [keV]
- Major Radius [m]
Fig. 15
Fig. 16
Fig. 17

- $f_{mod} = 50\text{Hz}$
- $D = 3\text{m}^2/\text{s}$, $V = -40\text{m/s}$
- $D = 2\text{m}^2/\text{s}$, $V = -20\text{m/s}$
- $D = 0$, $V = 0$

Graph shows $P_{abs}$ (kW/m$^3$) vs. Minor Radius (m).
Fig. 18

Plasma current [kA]
Loop voltage [V]
Transformer coil current [A]
Hard X-ray [arb. unit]
rf Power [kW]
Electron density [$10^{18}$ m$^{-3}$]
Fig. 19

Electron density $[10^{18} \text{m}^{-3}]$

$I_{rf}/P_{rf} [\text{A/W}]$

- $P_{rf} \leq 30 \text{kW}$
- $P_{rf} \leq 60 \text{kW}$
- $P_{rf} \leq 100 \text{kW}$

$n_{crit}$

$I_{rf}/P_{rf} \propto 1/n_e$
**Fig. 20**

**Predicted Slow Wave Density Limit (m⁻³)**

**Experimential Density (m⁻³)**

**Slow Waves:**
1. Octopole
2. CSTN-I
3. ACT-I
4. JIPP T-II

**Fast Waves:**
A. JIPP T-II U (800 MHz)
B. JIPP T-II U (40 MHz)
C. JIPP T-II U (130 MHz)
D. ACT I
E. PLT
F. Synchrophasor (3 MHz)
G. Irvine Torus
H. JFT-2M (200 MHz, H⁺)
I. JFT-2M (750 MHz)
J. CCT (80 MHz)
K. CCT (22 MHz)
L. JFT-2M (200 MHz, D⁺)
M. JET (34 MHz)
N. HT-2 (100 MHz)
O. DIII-D (60 MHz)
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