ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

Review of Japanese Results on Heating and Current Drive

T. Watari

(Received – Sep. 24, 1992)

NIFS-193 Oct. 1992

RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

Review of Japanese Results on Heating and Current Drive

T. Watari

National Institute for Fusion Science
464-01, Chikusa-ku, Nagoya, Japan

Invited paper at the Europhysics Topical Conference on Radiofrequency Heating and Current Drive of Fusion Devices, Brussels 1992; to be published in Plasma Physics and Controlled Fusion.

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 alloted 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 $\eta = n \cdot R \cdot I / P \sim 3.4*[10^{19} m^{-2} MA / MW]$. The significance of this value is evident from the fact that it almost satisfies the ITER requirement ($\eta \sim 5*[10^{19} m^{-2} MA / MW]$). 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

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

with

$$\alpha = \frac{1}{N_1^2} \frac{1-(N_2/N_1)^2}{\ln(N_2/N_1)} \qquad (2)$$

and that predicted in the theory (Fish, 1978) is given by,

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

The factor α 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

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

Thus the agreement between theory and experiment is improving thanks to the experiments in JT-60. It is worth while 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 $k_\perp / k_{//} \sim ve / vi$, where ve and vi 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 vb in place of vi and calculating ve using electron temperature, one can estimate $k_\perp / k_{//}$ at the switch over point. It was shown in this analysis that the interrelation between plasma density and $k_\perp / k_{//}$ satisfies the following dispersion relation of the lower hybrid wave.

$$\omega^2 = \omega_{LH}^2 \left(1 + (\frac{k_{//}^2}{k_\perp^2} \frac{m_e}{m_i} \frac{1}{\gamma})\right) \qquad (5)$$

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 $\beta p \approx 2$ 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(Tsuji 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, δ ,varies accordingly. Surprisingly, the reflection coefficient remained low for the δ 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 $\eta = n \cdot R \cdot I / P = 0.06*[10^{19}\,m^{-2}MA/MW]$, 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 co- to counter. 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:

$$\omega - k_{//}v_{//} = n\omega_e / \gamma \qquad (6)$$

$$\delta p_{//} / \delta\varepsilon = k_{//} / \omega = N_{//} / c \qquad (7)$$

$$(mc\gamma - N_{//}p_{//})\delta p_{//} = N_{//}p_{\perp}\delta p_{\perp} \qquad (8)$$

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 $\varepsilon = (m^2c^4 + c^2p^2)^{1/2} - mc^2$. 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 means the difference of χ_e but rather should be explained in terms of the difference in their type of perturbations: The one caused by sawtooth crash is essentially is 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 χ_e is obtained for ECH heat pulse propagation as in the sawtooth crash heat pulse propagation , i.e., no enhancement of χ_e on the sawtooth crash is observed. This method of analysis was applied to measure the χ_e in WT-III and improvement of χ_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 etal., 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=130MHz, 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

$$v \approx \frac{qE}{m\omega}, \quad \varepsilon \approx \frac{1}{2} m \left(\frac{qE}{m\omega} \right)^2, \quad \xi \approx \frac{qE}{m\omega^2} \qquad (9)$$

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 π-phasing. The "high N// antenna" has a N// spectrum peaked about 6 for $\pi / 2$-phasing and 12 for π-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 π-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 π -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 π. While enhancement of hard X-ray and no change in the bulk electron temperature is observed in the 0-phasing shots, π-phasing shots are characterized by the reduction of the hard X-ray and bulk electron temperature rise. The electron heating observed in the π-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 ω / ω_c ~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, ie, $\omega / \omega_c < 1$ 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.

ACKNOWLEDGEMENT

The author acknowledges the stimulating discussions with colleagues in JAERI (Drs. H. Kimura, Fujii, T. Imai, T. Yamamoto), Dr. Y. Uesugi in Nagoya University, and colleagues in Kyoto University (Drs. , Terumichi, T. Maekawa, K. Hanada, Y. Yasaka), and their help in the selection of the data to present in this special meeting.

REFERENCES

Ando,R., et al., ICRF Current Drive Experiment on JIPP T-II U, Nucl. Fusion 26(1986)1619

Bernabei,S., et al, Electron Heating and MHD Modes during Lower Hybrid Current Drive on PLT, *Plasma Physics and Controlled Fusion Research* (proc.of the 11th IAEA Conf. on Plasma Physics and Controlled Fusion Research, 1986, Kyoto) IAEA, 1987, vol.1 p-503

Brambilla,M., Theory of Bernstein Wave Coupling with Loop Antennas, Nuclear Fusion,28(1988)549,

Chiu,S.C., et al., Theory of Ion Bernstein Wave Coupling at Low Edge Densities, Rep. GA-A20608, General Atomics, San Diego, CA (1991).

Chiu,T.K., et al., Suppression of Internal disruptions in Inductively Driven Tokamak Discharges by Lower Hybrid Wave Current Drive, Nuclear Fusion, 26(1986)666(PLT sawteeth stabilization)

Fisch, N.J., Confining a Tokamak Plasma with rf-Driven Currents, Phys. Rev. Letters, 41(1978)873

Fisch, N.J., Current generation in a relativistic plasma, Phys. Rev. Letters, 24(1981)3245

Fujii, T., et al., Heating and Confinement Characteristics of Second Harmonic Heating in the Ion Cyclotron Range of Frequencies on the JT-60 Tokamak, Nuclear Fusion, 31(1991)137

Fujii, T., et al., Performance of the JT-60 ICRF Antenna with an Open Type Faraday Shield, Fusion Engineering and Design, to be published

Fukuda,M., et al., Steady Current Generation by RF Travelling Field in a Magnetized Toroidal Plasmas, J. Phys. Soc. Jpn, 41(1976)1376

Fukuyama, A., et al., Kinetic Description of Propagation and Absorption Structure of ICRF Waves, Nuclear Fusion, 23(1983)1005

Gormezano,C., et al., Lower Hybrid Plasma Heating via a New Launcher the Multi-junction Grill, Nuclear Fusion, 25(1985)419

Grimm, R.C., et al., Resistive Instabilities in Tokamak Geometry, in Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, 1982, (IAEA, Vienna, 1983), vol.3, p-35

Hanada,K., et al., Sawtooth Stabilization by Localized Electron Cyclotron Heating in Tokamak Plasma, Phys. Rev. Lett., 66(1991)1974

Hosea, C., in Proc. Joint Varenna Lausanne International Workshop on Theory of Fusion Plasma, Varenna, 27-31 August 1990

Hoshino,H., et al., Transition from the L-Mode to the H-Mode by Electron Cyclotron Heating of a Tokamak Edge Plasma, Nuclear Fusion, 28(1988)301

Ide,S., et al., Investigation of the Wave Spectrum Gap in the JT-60 LHCD Plasma, Nuclear Fusion, 32(1992)282

Imai, et al., Lower Hybrid Current Drive and Higher Harmonic ICRF Heating Experiments on JF-60, *Plasma Physics and Controlled Fusion Research* (proc.of the 13th IAEA Conf. on Plasma Physics and Controlled Fusion Research, 1990, Washinton) IAEA, 1991, vol.1 p-645

Imai,T., et al., Current Drive and Confinement Studies during LHCD Experiments on JT-60, Nuclear Fusion, 28(1988)1341

Itoh,K., et al., A Possible Origin of Metal Impurities in ICRF Heating Experiments, Comments on Plasma Phys. and Cont. Fusion, 10(1986)91

Itoh,S., et al., Steady State Current Drive by Lower Hybrid Wave in TRIAM-1M Tokamak *Plasma Physics and Controlled Fusion Research* (proc.of the 12th IAEA Conf. on Plasma Physics and Controlled Fusion Research, 1988, Nice) IAEA, 1989, vol.1 p-629

JET Team, Radio Frequency Heating in JET, in Plasma physics and Controlled Nuclear Fusion research,1986,IAEA, Vienna, vol.1,p-449, 1987

JT-60 team, Recent Progress in JT-60 Experiments, Plasma Physics and Controlled Fusion Research (proc.of the 12th IAEA Conf. on Plasma Physics and Controlled Fusion Research, 1988, Nice) vol.1, p-67, (IAEA, Vienna, 1989)

Kako,E., et al., Ion Cyclotron Range of Frequency Antenna Design for R-Tokamak, Fusion Technology, 12(1988)293,

Kawashima,H., et al., Optimization of Phased Four-Loop Antenna for Fast Wave Current Drive in JFT-2M, in proc. of IAEA Technical Committee Meeting on Fast Wave Current drive in Reactor Scale Tokamaks, Arles, 1991, p-286

Kimura, H., et al.,(a) Experimental Study on Beam Acceleration with Combined NBI Heating and Second -Harmonic ICRF Heating in JT-60, Nuclear Fusion, 31(1991)83

Kimura,H., et al., (b) Studies on Fast Wave Heating and Current Drive Experiments on the JAERI Tokamaks, in proc. of IAEA Technical Committee Meeting on Fast Wave Current drive in Reactor Scale Tokamaks, Arles, 1991, p-260

Kondo, T., et al., Investigation of High Energy Electrons Produced by Lower Hybrid Waves with Measurement of the hard X-ray in JT-60 U, Int.Conf. on Plasma Physics (proc. 19th EPS Conf. Fusion and plasma physics, Innsbruck,1992), vol.16c, part-2, p-969, (1992)

Kumazawa,R., et al., High Frequency Ion Bernstein Wave Heating Experiments with Minority and Neutral Beam Heating in JIP T-II U, in proc. 18th European Conference on Controlled Fusion and Plasma Physics, Berlin, 1991, vol,15C, part-3, P-325,

Kubo,S., et al., Toroidal Plasma Current Start-up and Sustainment by RF in the WT-2 Tokamak, Phys. Rev. Lett., 50(1983)1994

Luckhardt,S.C., et al., Production and Maintenance of High Poloidal Beta Tokamak Plasmas by Means of rf Current Drive, phys. Rev. Letters, 62(1989)1508

Maekawa,T.,& WT-III group, Lower Hybrid Current Drive and Suppression of MHD Instabilities on WT-3, proc. US-Japan workshop on Advanced Current Drive Concepts,IPPJ-REV-4,1989,p-23

Maekawa,T., et al., Production of High Poloidal Beta Plasma by Bi-directional Lower Hybrid Current Drive in the WT-3 Tokamak, Nuclear Fusion, 31(1991)1394

Maekawa,T., et al., Observation of Heat flux of fast electrons to Limiter in Lower Hybrid Current Drive Plasma on WT-3 Tokamak, Nuclear Fusion, to be published, 1992

Matsumoto,H., et al., (a) H-Mode Phenomena During ICRF Heating on JFT-2M, Nuclear Fusion, 27(1987)1181

Matsumoto, H., et al., (b) Studies of H-mode in the Limiter Discharges on JFT-2M Tokamak, in Controlled Fusion and Plasma Physics(proc. 14th Europ. Conf.Madrid, 1987), Vol.11D, Part I, European Physical Society(1987)5

Morita,S., et al., Impurity Pellet Injection into Current Drive Plasmas of the JIPP T-2U Tokamak, Nuclear Fusion, 30(1990)938,

Nagashima,T., et al., The JT-60 Radio-Frequency Heating System: Description and R&D Results, Fusion Engineering and Design, 5(1986)101

Noda,N., et al., Experiment on Heating with Simultaneous Injection of Neutral Beam and Lower Hybrid Waves in the JIPP T-2, Nuclear Fusion, 22(1982)1103

Odajima,K., et al., Scaling of Incremental Energy Confinement Time in the JFT-2M Tokamak, Phys. Rev. Letters, 57(1986)2814

Ogawa,Y., et al., Characteristics of Ion Bernstein Waves Heating on the JIPP T-II U Tokamak, Nucl. Fusion, 27 (1987) 1379

Ogawa,Y., et al., High Power ICRF Heating Experiments on the JIPP T-2U Tokamak, Nuclear Fusion, 29(1989)1873

Ohkubo,K., et al., Lower Hybrid Heating and Current Drive in the JIPP- Torus, Heating in Toroidal Plasmas,(proc. 3rd Int. Conf.)Grenoble, vol.2, p-439 (1982)

Ohkubo,K., et al., Current Drive by Fast Magnetosonic Waves near the Lower Hybrid Frequency in the JIPP T-IIU Tokamak, Phys. Rev. Lett. 56(1986)2040

Ono,M., et al., Ion-Bernstein-Wave Heating in the JIPP T-II U Tokamak Plasma, Phys. Rev. Lett., 54 (1985) 2239

Ono,M., et al., Ion Bernstein Wave Heating Experiments on PLT, in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 11th Int. Conf. Kyoto, 1986), Vol. 1, IAEA, Vienna (1987) 477.

Ono, M., Review of Ion-Bernstein Wave Heating Research, review paper ; to be published in Physics of Fluids

Phillips,C.K., et al., ICRF Stabilization of sawteeth on TFTR, PPPL-2820,1992

Pinsker,R.I., et al., High Power Ion Bernstein Wave Experiments on DIII-D, in Radio-Frequency Power in Plasmas (Proc. 8th Top. Conf. Irvine, CA, 1989), American Physical Society, New York (1989) 314.

Porceli,F., Champbell,D.J., Diacjhenko, W.D., et al., Sawtooth Stabilization by Fast Ions: Comparison Between Theory and Experiments, in proc.17th EPS Conf. Controlled Fusion and Plasma Physics, Amsterdam, vol.14B, part I,327(1990)

Porkolab,M., et al., Radio-Frequency Heating and Current Drive Experiments on Alcator C and Versator- II, in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 11th Int. Conf. Kyoto, 1986), Vol. 1, IAEA, Vienna (1987) 509.

Porkolab,M., et al., (a) Observation of Lower-Hybrid Current Drive at High Densities in the Alcator C Tokamak, Phys.Rev.Letter, 53(1984)450

Porkolab,M., et al., Lower Hybrid Heating and Current Drive Experiments on the Alcator C and Versator II Tokamaks, Plasma physics and Controlled Fusion Research (Proc. 9th Int. Conf. Baltimore),vol,1, IAEA, Vienna, 227(1983)

Post,D.E., ITER Documentation Series No.21, IAEA, Vienna, 208

Prator,R., et al., Electron Cyclotron Heating Experiments in the DIII-D Tokamak, in proc. 12th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Nice, 1988, vol.1, P-527

Prator, R., et al., Initial Fast Wave Heating and Current Drive Experiments on the DIII-D Tokamak, in proc. of IAEA Technical Committee Meeting on Fast Wave Current drive in Reactor Scale Tokamaks, Arles, 1991, p-308

Seki, T., et al., Application of the Intermediate Frequency Range Fast Wave to the JIPP T-II Plasma, Nuclear Fusion, 31(1991)1369

Seki,T., et al., High Frequency Ion Bernstein Wave Heating in JIPP T-IIU Tokamak,(proc.9-th Int. Conf. on Radio Frequency Power in Plasmas, Charleston, 1991) p-138

Seki,M., et al., The distant Coupling of LHCD Launcher in the JT-60-U, proc. Int.Conf. on Plasma Physics (or 19th EPS Conf. Fusion and plasma physics, Innsbruck,1992), vol.2, p-985

Shinohara,S., et al., Excitation, Propagation, and Heating for the Ion Bernstein Wave in the TNT-A Tokamak, in Proc. 7th Top. Conf.on applications of Radio-Frequency Power to Plasmas, Kissimmee, 1987, vol.159, p-330, (AIP Conf. Ser.,1987)

Start,D.H., et al., Observation of a Plasma Current Driven by RF Waves at the Election Cyclotron Resonance in the Culham Levitron, Phys. Rev. Letters, 48(1982)624

Steinmetz,K., et al., Ion Cyclotron Heating and Lower Hybrid Experiments on ASDEX, Plasma Physics and Controlled Nuclear Fusion Research, Vol. 1, p.461, IAEA, 1987

Svedrup,L.H., et al., Cause of the Lower Hybrid Current Drive Density Limit, Phys. Rev. Letters, 59(1987)1197

Takase,T., et al., (a) Energy Confinement Studies of Lower Hybrid Current Drive Plasmas in The Alcator C Tokamak, Nuclear Fusion 27 (1987)53,

Takase,Y., et al., (b) Study of Directly Launched Ion Bernstein Waves in a Tokamak, Phys. Rev. Lett., 59(1987)1201

Takase,Y., et al., Fast Wave Heating at Intermediate Ion Cyclotron Harmonics on the JIPP T-II U tokamak, Nucl. Fusion, 30(1990)158

Tamai,H., et al.,IBW Experiment on JET-2M Tokamak, in Radio-Frequency Power in Plasmas(Proc.8th Top. Conf. Irvine, CA., 1989), American Physical Society, New York (1989) p-350.

Tanaka,H., et al.,Non-Inductive Current Drive Using Second Harmonic Election Cyclotron Waves on the WT-3 Tokamak, Nuclear Fusion, 31(1991)1673

Tanaka,S., et al.,Electron Cyclotron and Lower Hybrid Current Drive Experiments in the WT-2 and WT-3 Tokamaks in plasma physics and Controlled Nuclear Fusion Research 1986(proc., 11th Int. Conf. Kyoto,1986), vol. 1, IAEA, Vienna(1987)553

Tanaka,S., et al., Combined Current Drive of Electron Cyclotron and Lower Hybrid Waves in WT-3 Tokamak, in Proc. Tropical Conf. on Radio Frequency Heating and Current Drive of Fusion Devices, Brussels, 1992, P-265

Tanaka,S., et al., Experiments on Heat Pulse Propagation Generated by Localized Electron

Heating on the WT-3 Tokamak, Int.Conf. on Plasma Physics (proc. 19th EPS Conf. Fusion and plasma physics, Innsbruck,1992), vol.1, p-79

Toi,K., et al., Start-up and Quasi-stationary Drive of Plasma Current by Lower Hybrid Waves in a Tokamak, Phys. Rev. Letters, 52(1984)2144

Toi,K., et al., Suppression of Magnetic Islands by Injection of Fast Waves in the JIPP T-IIU Tokamak,(in proc. of 13th European Conf. on Controlled Fusion and Plasma physics, Schliersee, 1986, vol. 10-c part II, p-457

Tsuji,S., et al., The Limiter H-mode with Lower Hybrid Current Drive, *Plasma Physics and Controlled Fusion Research* (proc.of the IAEA Conf. on Plasma Physics and Controlled Fusion Research, 1990, Washinton) IAEA, 1990, vol.1 p-659

Uehara,K.,et al., Lower Hybrid Heating Experiment in JFT-2 Tokamak, Heating in Toroidal Plasmas (proc.3rd joint Varenna-Grenoble Int. Symp.), Grenoble, vol.2, p-439 (1982)

Uesugi,Y., et al., Absorption of Fast Waves Excited by a Phased Four-Loop Antenna Array in the JFT-2M Tokamak, Nuclear Fusion, 30(1990)297

Usigusa,K., et al, Direct Loss of Energetic Electrons During Lower Hybrid Current Drive on JT-60, submitted to Nuclear Fusion

Ushigusa,K., et al., Lower Hybrid Experiment in JT-60, *Plasma Physics and Controlled Fusion Research* (proc.of the 12th IAEA Conf. on Plasma Physics and Controlled Fusion Research, 1988, Nice) IAEA, 1989, vol.1 p-621

Van Houtte,D., et al., Stabilization of Tearing Modes in Lower Hybrid Current Drive Discharges on Petula-B, Nuclear Fusion, 24(1984)1485

Van Niewenhove, et al., Ion Cyclotron Heating of a Tokamak Plasma Using an Antenna Without a Faraday Shield, Nuclear Fusion, 31(1991)1770

Watari,T., et al.,Experiments on ICRF Heating and Fast Wave Current Drive in JIPP T-2U, in Plasma Physics and Controlled Nuclear Fusion Research 1986 (Proc. 11th Int. Conf. Kyoto ,1986), Vol.1, IAEA, Vienna (1987)495

Watari,T., Yoshioka, K., et al., Application of Intermediate Frequency Range Fast Wave to JIPP T-II U and HT-2 Plasmas, Plasma Physics and Controlled Nuclear Fusion

Research, (in Proc. 13th IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research, 1990, Washinton), 1992 , IAEA, Vol. 1, p.762,

Watari, T., et al.,Limiter H-mode and other improved confinement regimes with ICRF and NBI Heating in JIPP T-IIU, Nucl. Fusion 30(1990)1197

Watterson,R.T., et al, Spectrum and propagation of Lower Hybrid Waves in a Tokamak Plasma, Physics Fluids, 28(1985)2622,

Wegrowe,J.G., et al.,, The density Limit in Lower-Hybrid Current Drive, Comments on Plasma Physics and Controlled Fusion, 8(1984)221

Yamamoto,T., et al., (a) Experimental Observation of the RF-Driven Current by the Lower Hybrid Wave in a Tokamak, Phys. Rev. Letters,(1980)716

Yamamoto,T., et al., (b) Observation of Direct Electron Heating by the Fast Waves in the Lower-Hybrid Range of Frequencies in the JFT-2M Tokamak, Phys. Rev. Letters, 63(1989)1148

Yamamoto et al., LH Current Drive and ICRF Heating Experiment and Developments of RF Systems for JT-60/U, Proc. 9th Top. Conf. on Radio-Frequency Power in Plasma (Charleston, 1991) AIP, 243

Yasaka,Y., et al, Nonlinear Ion Bernstein Wave Heating Experiment in WT-3 Tokamak, private communication

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 diverter plate, where the enhancement of the x-ray emission is well correlated to the heat deposition there.

Fig.4 . The heat deposition to the diverter 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 ($\omega / \omega_C \sim 0.8$) 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, $\bar{n}_e \approx 2.8 \times 10^{19} m^{-3}$).

Fig.10 Typical wave form of the minority 2rd cyclotron harmonic heating in JT-60 U(Bt=4T, Ip=2MA, $\bar{n}_e \approx 2.2 \times 10^{19} m^{-3}$, 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.

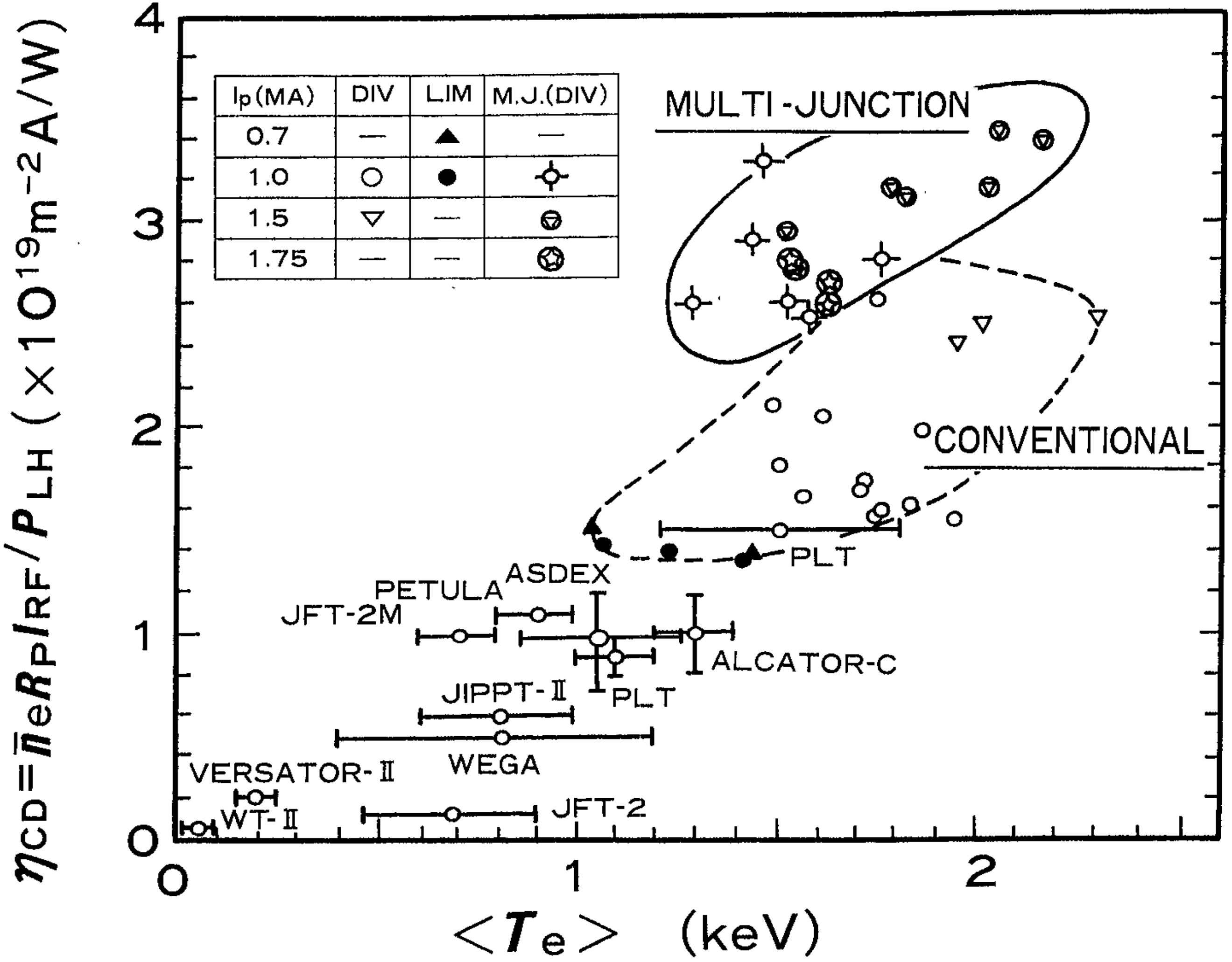
Fig.17 The power deposition profile on the FW electron heating. Pulse modulation method was applied to FWCD.

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[$10^{18}m^{-3}$]

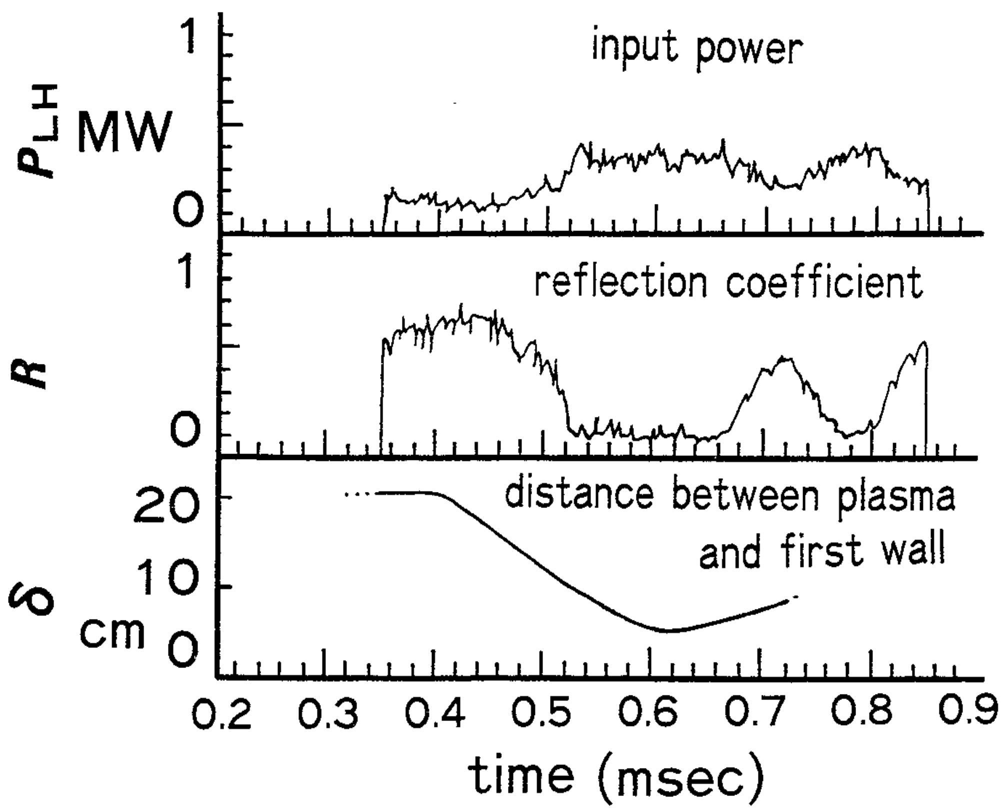
Fig.19. The current drive efficiency versus plasma density obtained for HT-2 FWCD experiment.

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.



ηCD=n̄eRPIRF/PLH (×10^19 m^-2 A/W)
⟨Te⟩ (keV)
Ip(MA) DIV LIM M.J.(DIV)
0.7
1.0
1.5
1.75
MULTI-JUNCTION
CONVENTIONAL
PLT
ASDEX
PETULA
JFT-2M
ALCATOR-C
PLT
JIPPT-II
WEGA
VERSATOR-II
WT-II
JFT-2

Fig.1



1
P_{LH} MW
0
input power
1
R
0
reflection coefficient
20
10
δ cm
0
distance between plasma and first wall
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
time (msec)

Fig.2

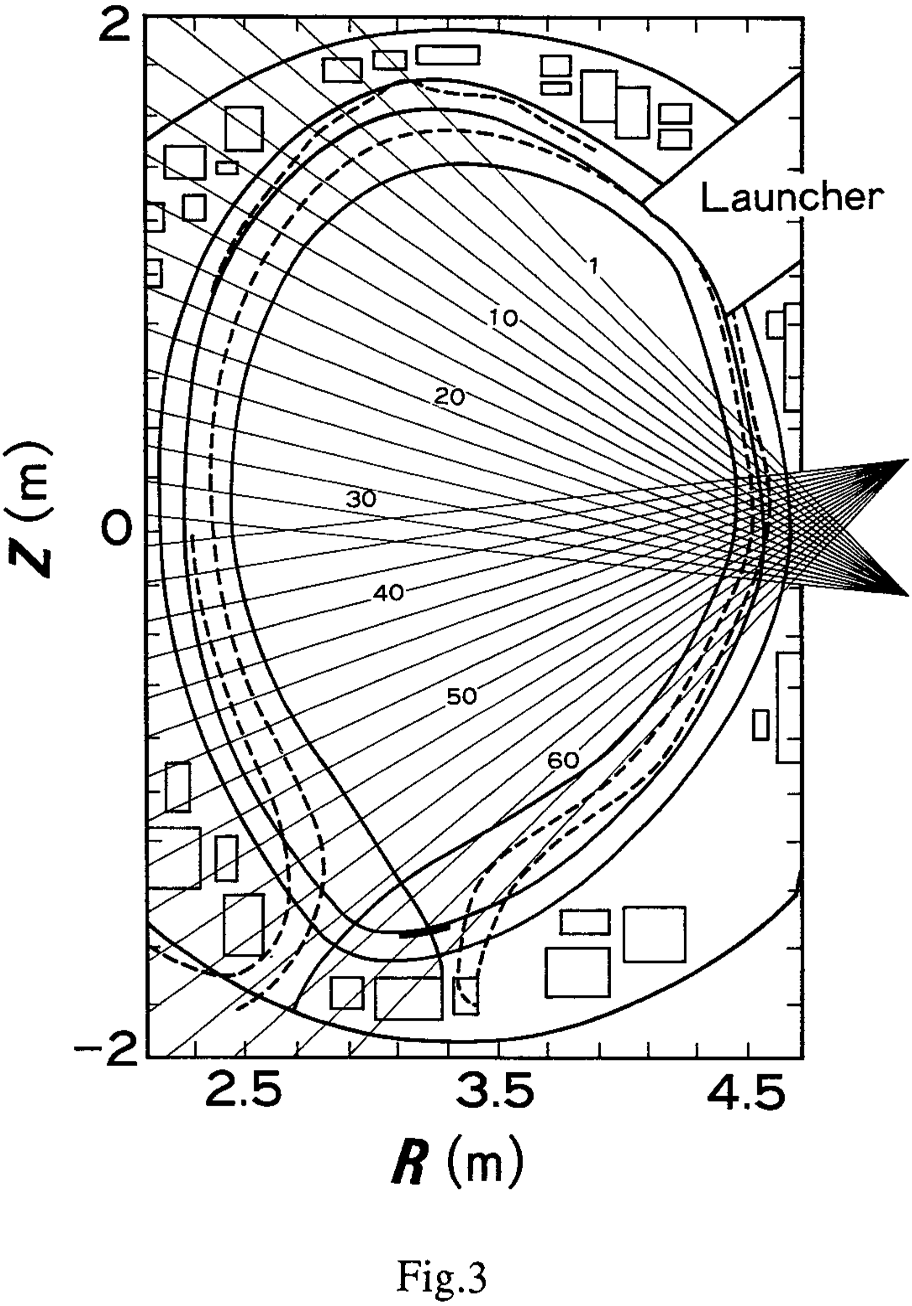


Fig.3

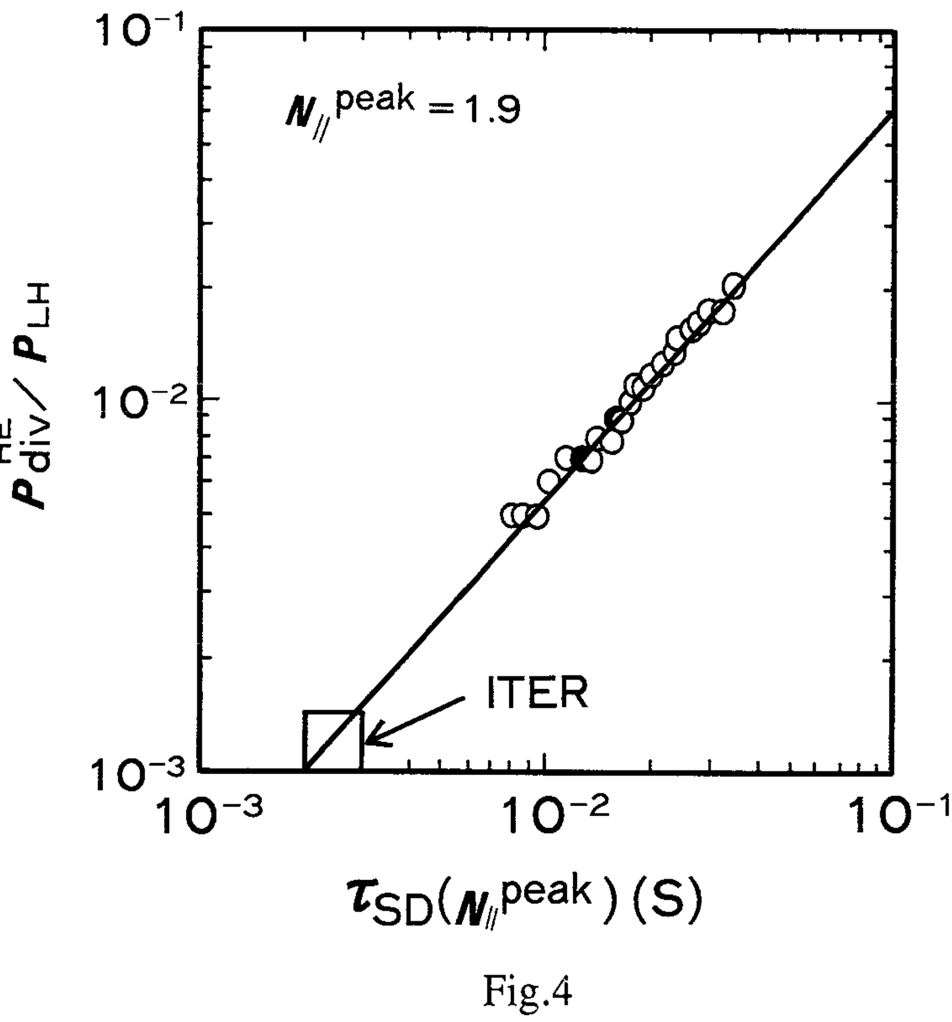
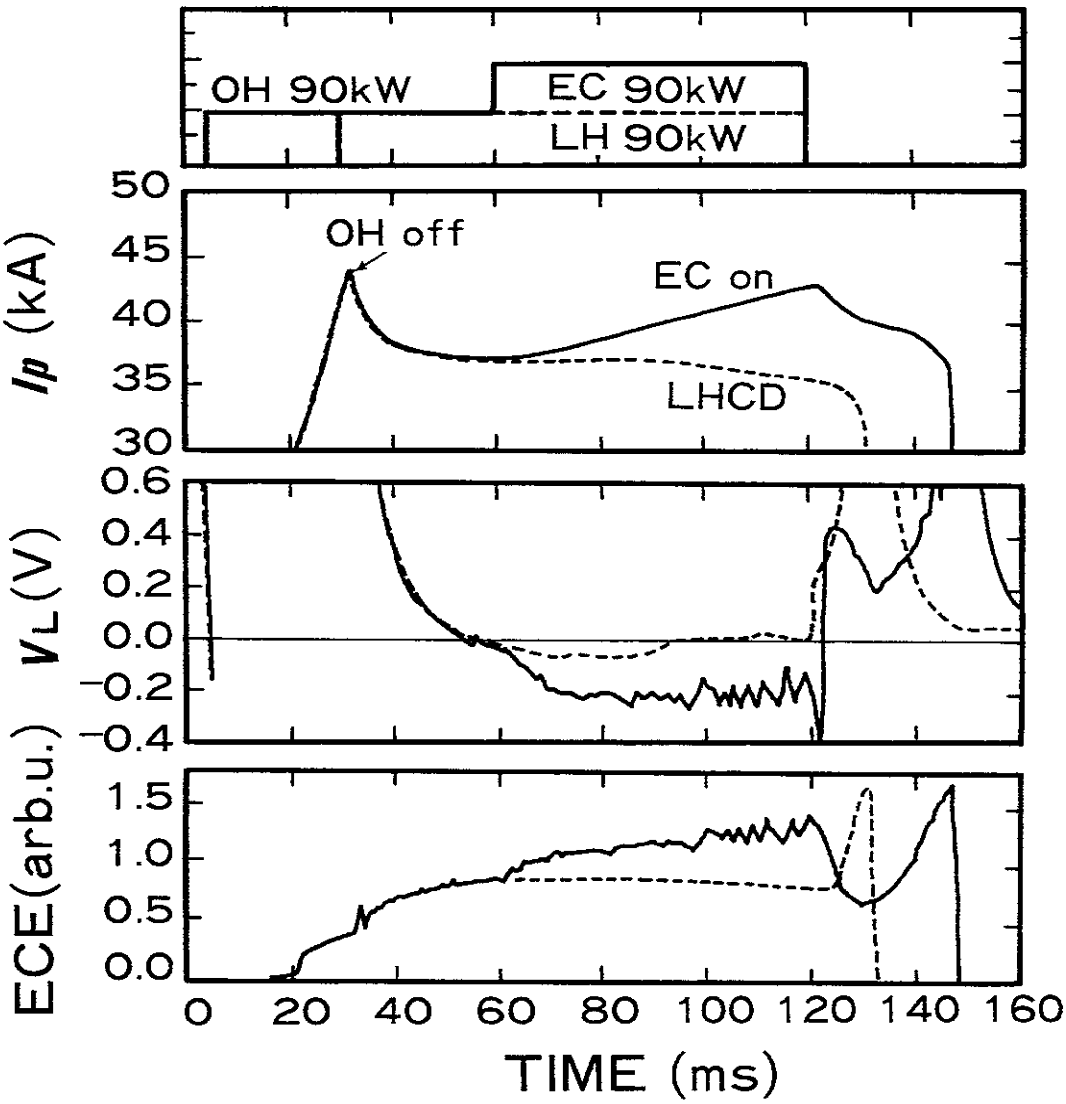


Fig.4



OH 90kW
EC 90kW
LH 90kW
OH off
EC on
LHCD
Ip (kA)
VL (V)
ECE(arb.u.)
TIME (ms)

Fig.5

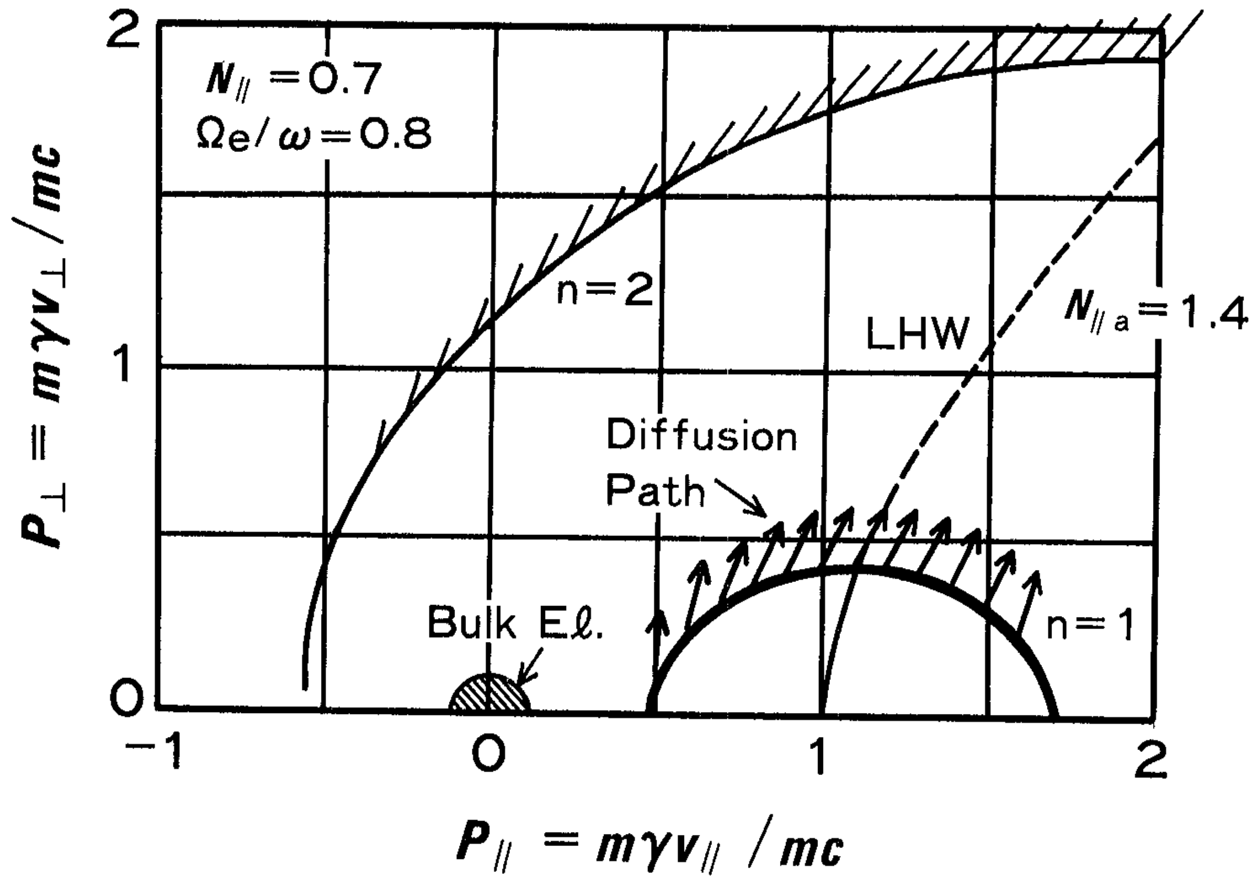
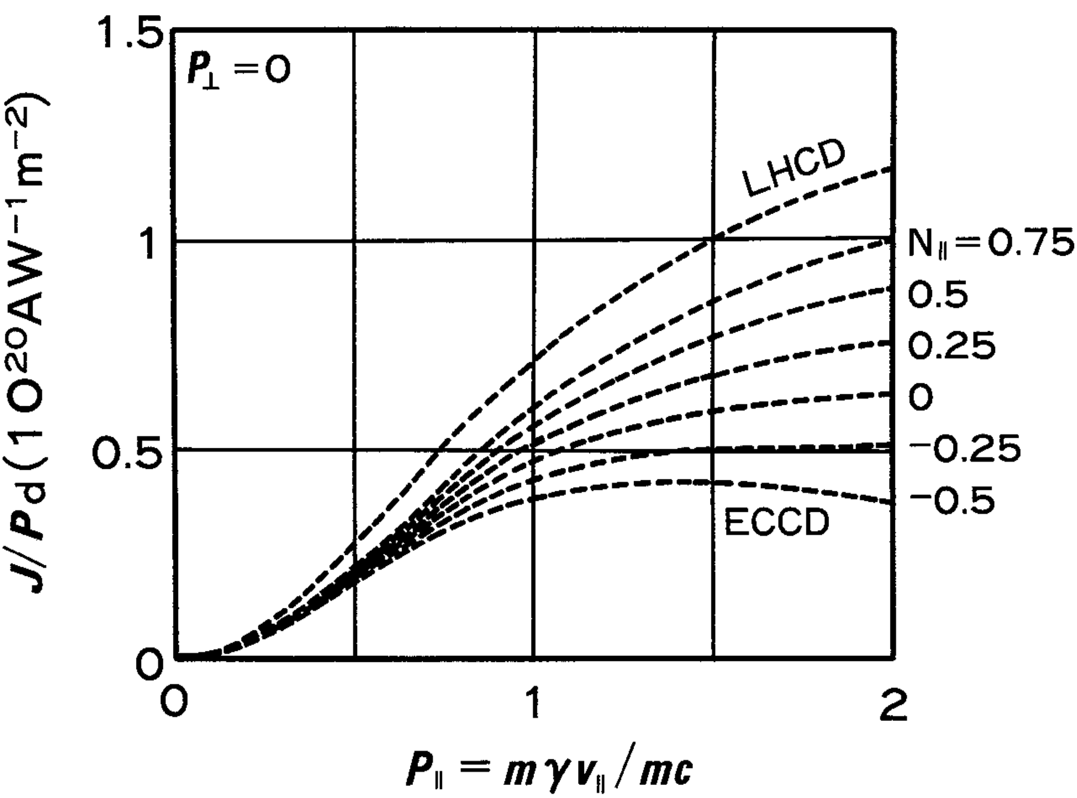

$N_{//}$ =0.7
$\Omega e/\omega$=0.8
n=2
LHW
$N_{//a}$=1.4
Diffusion
Path
Bulk Eℓ.
n=1
2
1
0
−1
0
1
2
$P_{\perp} = m\gamma v_{\perp} / mc$
$P_{//} = m\gamma v_{//} / mc$

Fig.6



1.5
1
0.5
0
$P_\perp = 0$
$J/P_d\,(10^{20}\,\mathrm{AW^{-1}m^{-2}})$
LHCD
$N_\parallel = 0.75$
0.5
0.25
0
−0.25
−0.5
ECCD
0
1
2
$P_\parallel = m\gamma v_\parallel / mc$

Fig.7

Operation Region for Sawtooth Stabilization Study with ICRF Heating Alone

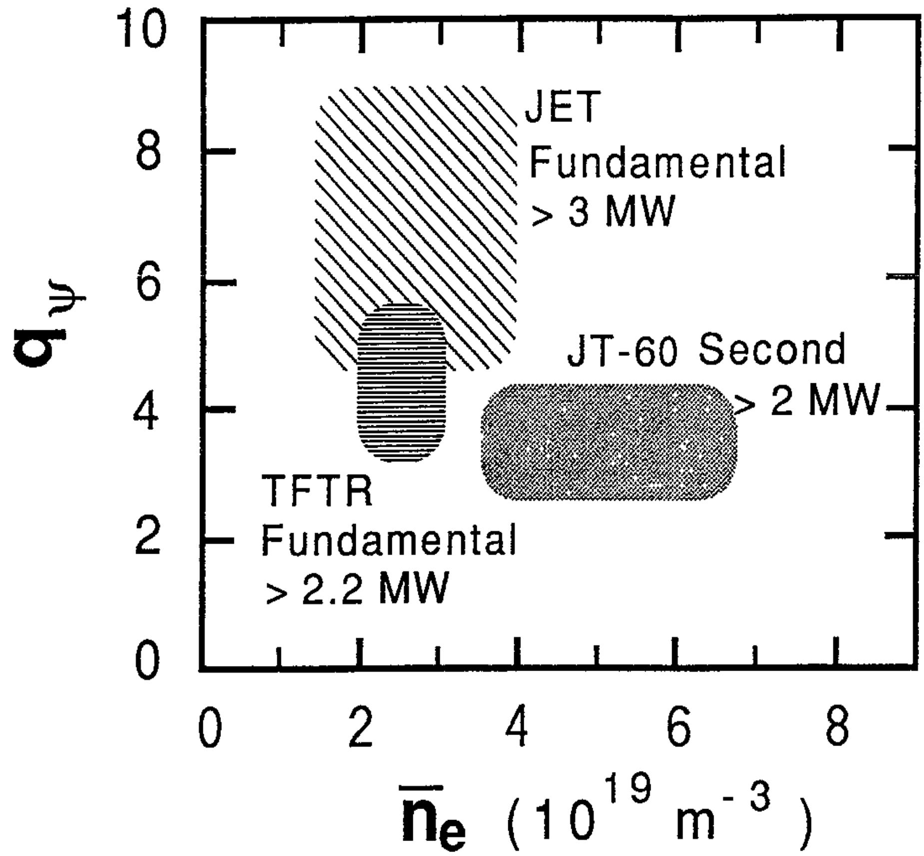
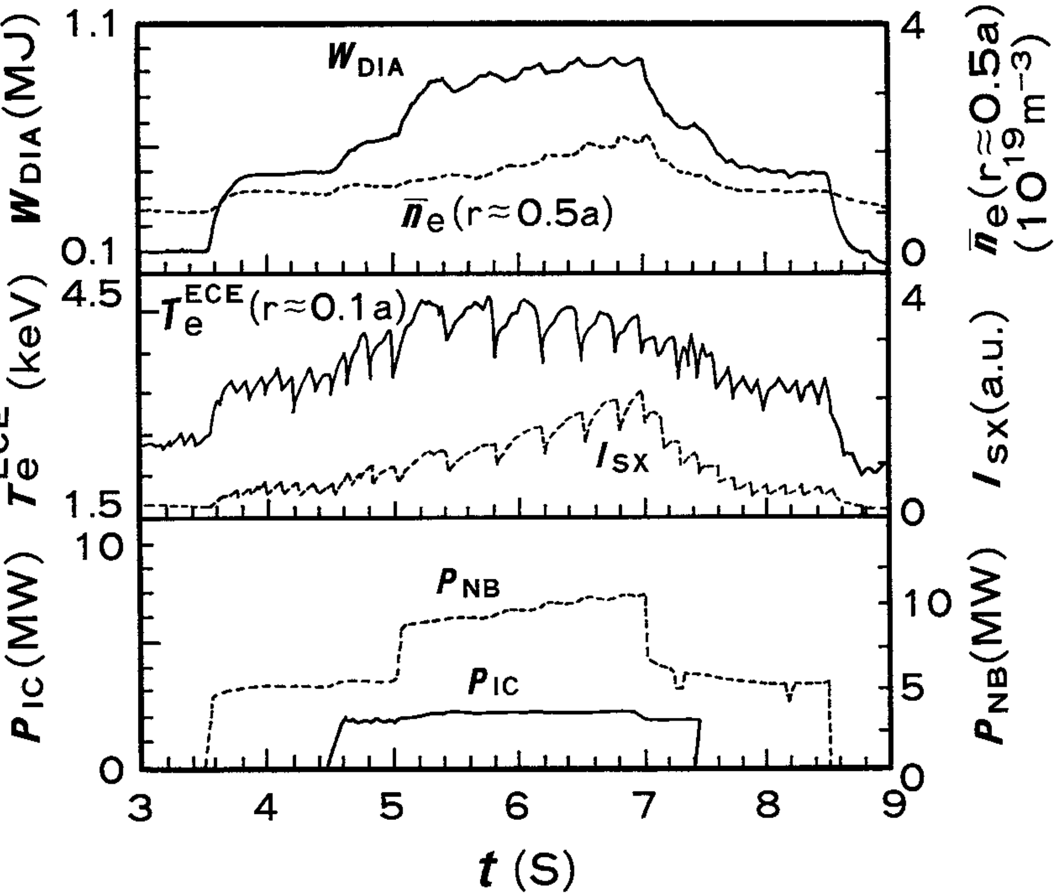
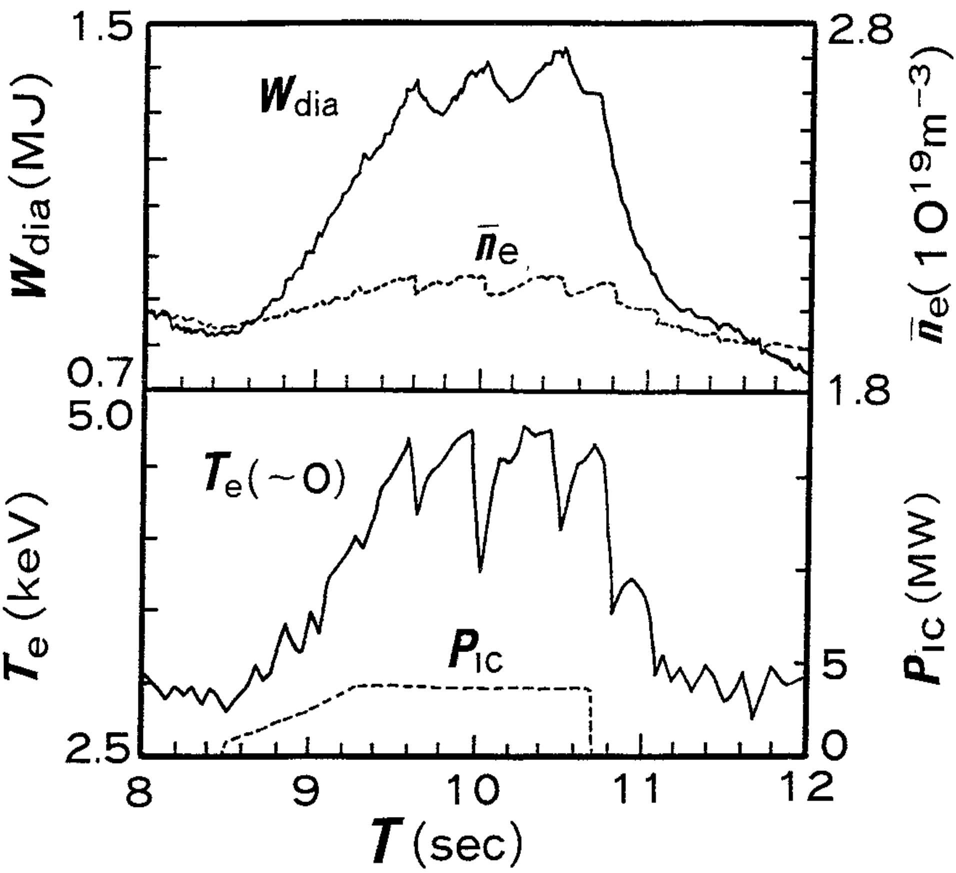


Fig.8



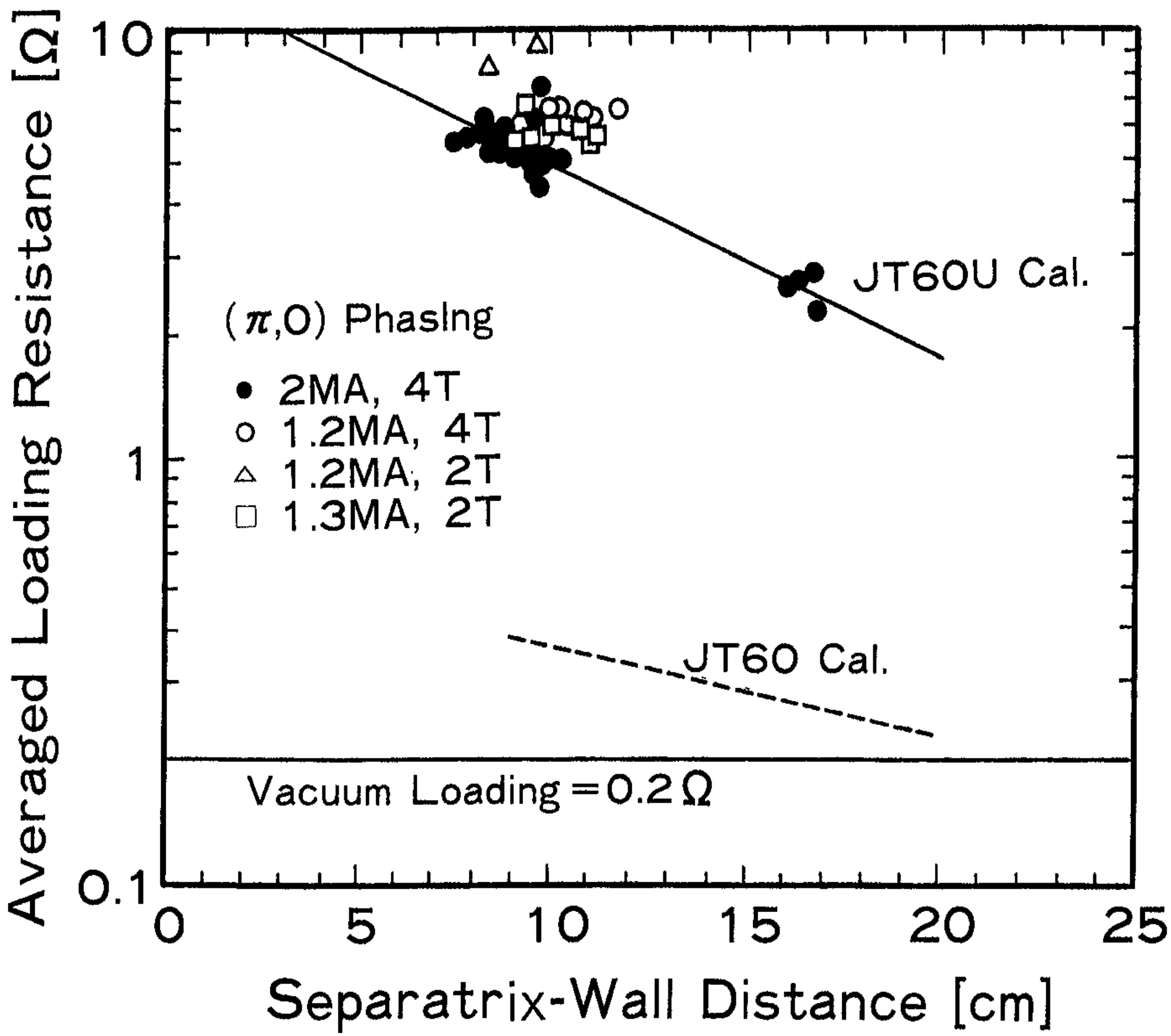
1.1
W_{DIA}
W_{DIA}(MJ)
0.1
$\bar{n}_e(r\approx0.5a)$
4
0
$\bar{n}_e(r\approx0.5a)$ $(10^{19}m^{-3})$
4.5
$T_e^{ECE}(r\approx0.1a)$
T_e^{ECE} (keV)
1.5
I_{SX}
4
0
I_{SX}(a.u.)
10
P_{NB}
P_{IC}
P_{IC}(MW)
0
10
5
0
P_{NB}(MW)
3
4
5
6
7
8
9
t (S)

Fig.9



1.5
0.7
2.8
1.8
W_{dia}
$\bar{n}_e$
W_{dia} (MJ)
$\bar{n}_e$ ($10^{19}m^{-3}$)
5.0
2.5
T_e (~0)
P_{IC}
T_e (keV)
P_{IC} (MW)
5
0
8
9
10
11
12
T (sec)

Fig.10



Averaged Loading Resistance [Ω]
10
1
0.1
0
5
10
15
20
25
Separatrix-Wall Distance [cm]
JT60U Cal.
(π,0) Phasing
2MA, 4T
1.2MA, 4T
1.2MA, 2T
1.3MA, 2T
JT60 Cal.
Vacuum Loading = 0.2 Ω

Fig.11

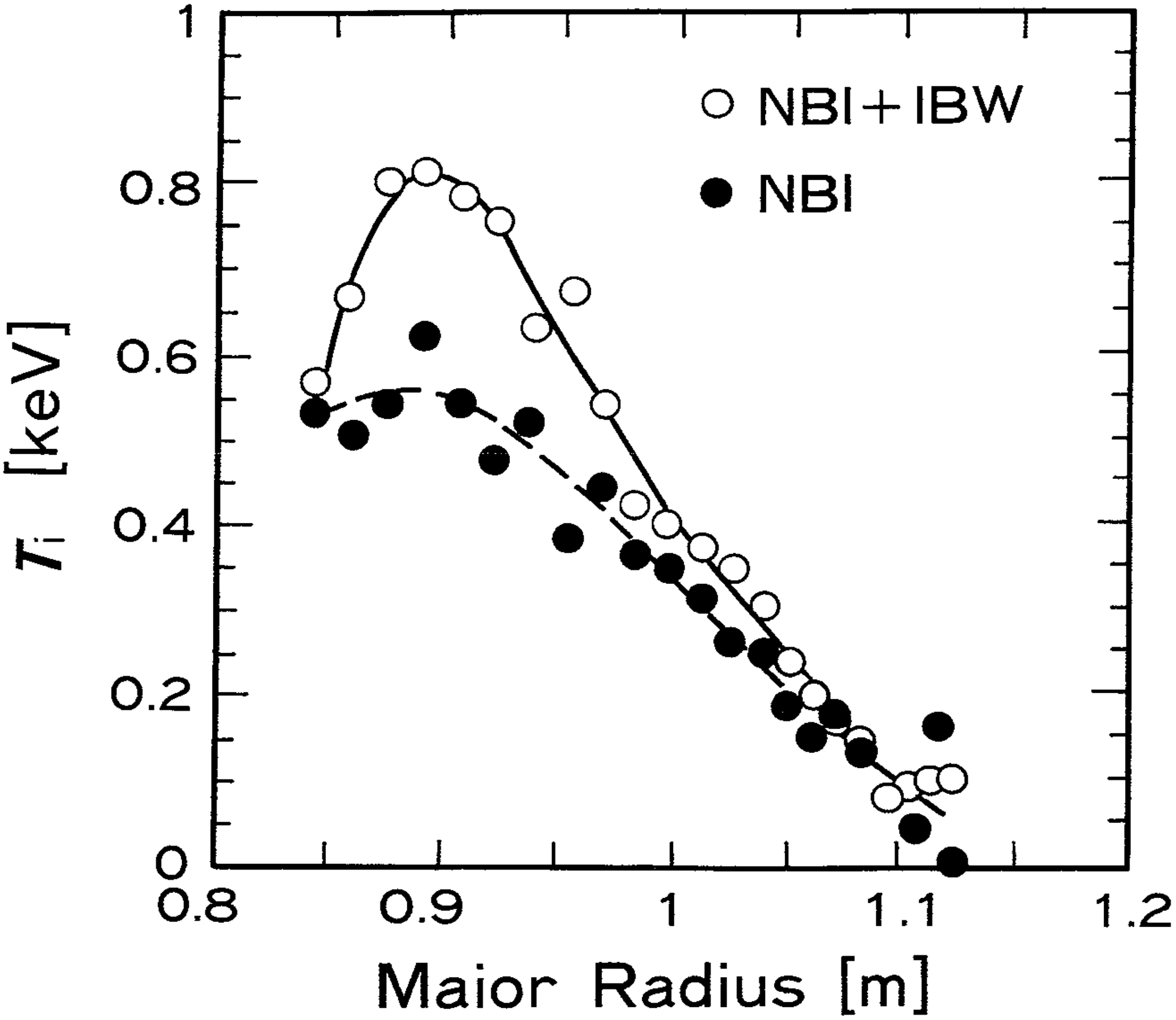


Fig.12

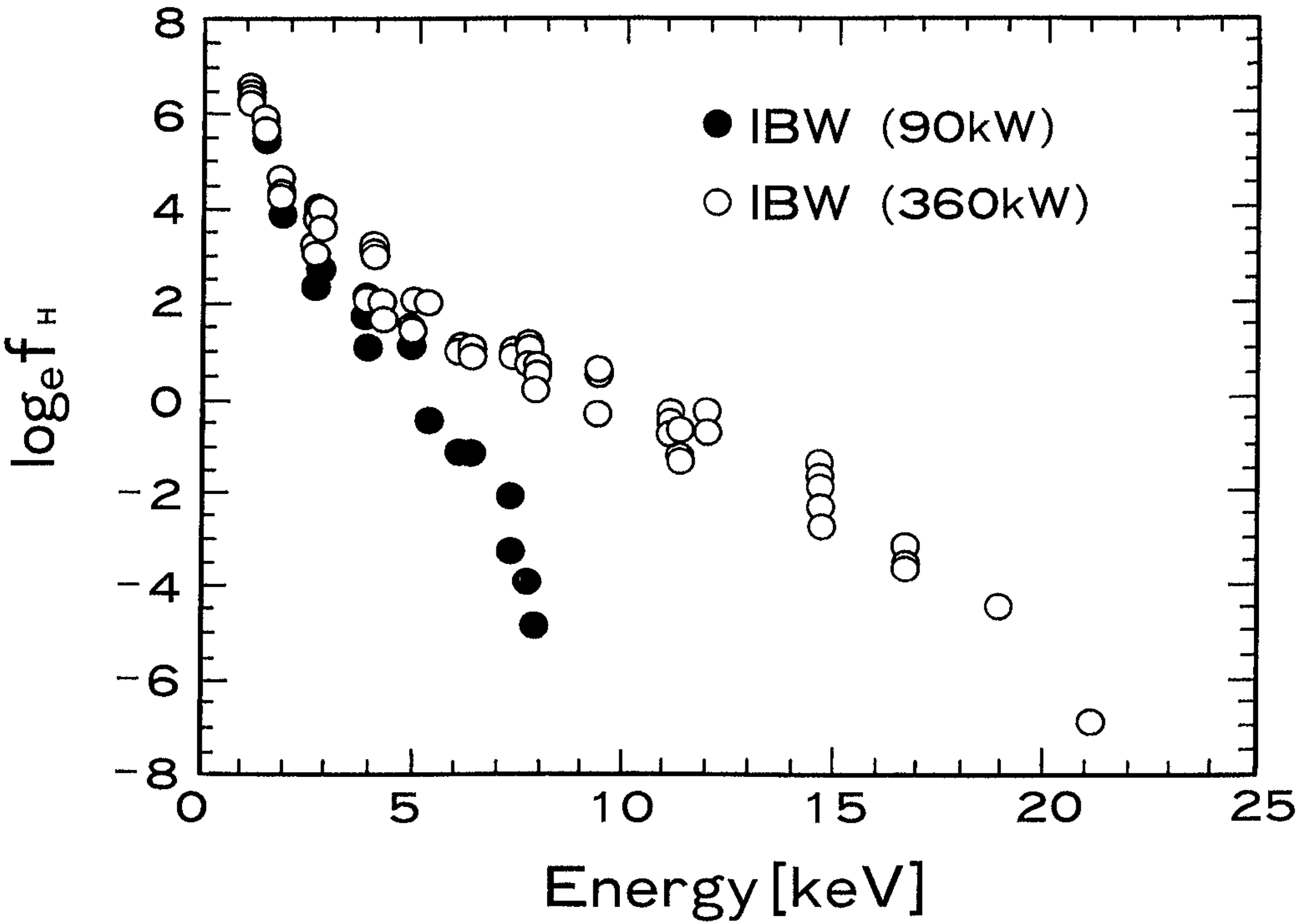


Fig.13

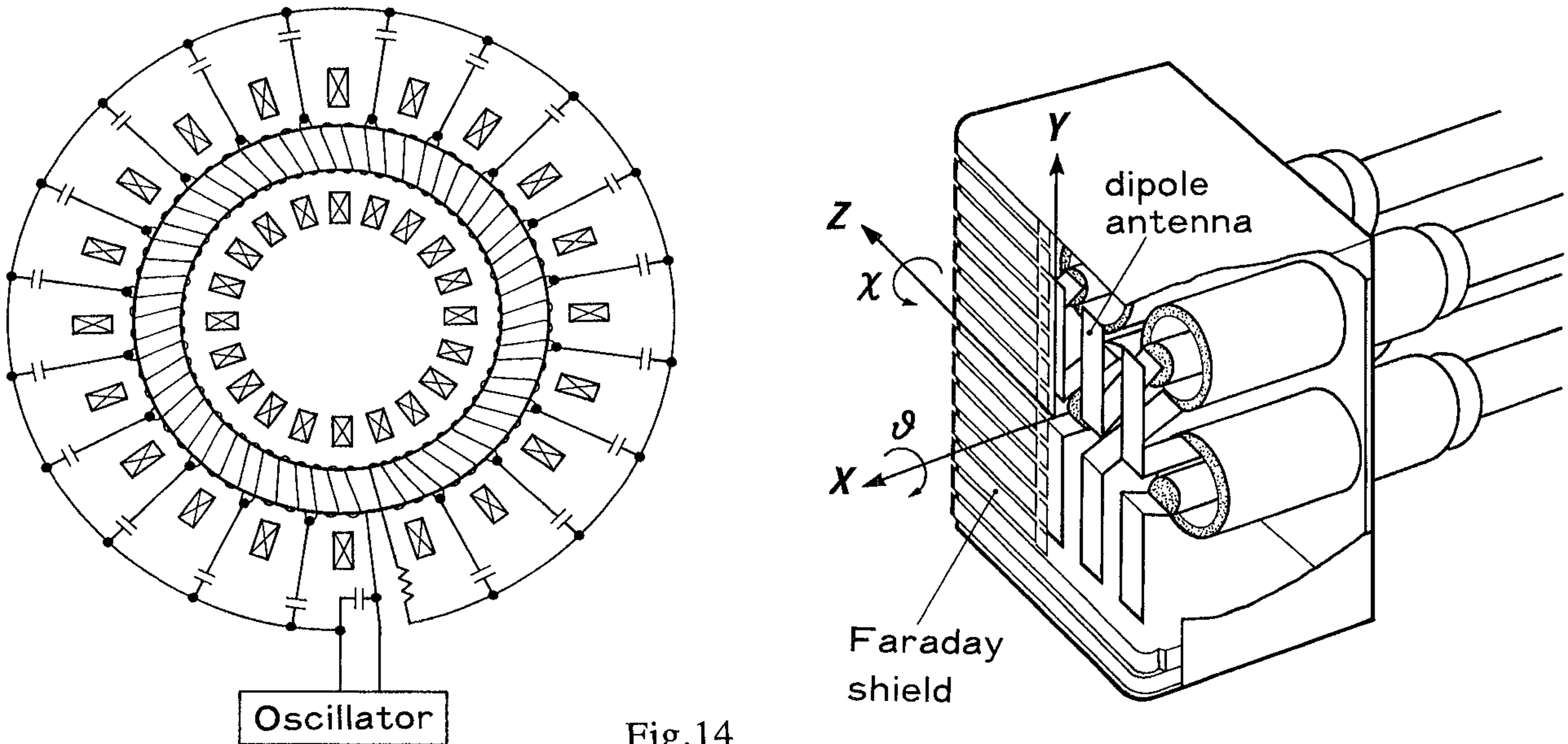
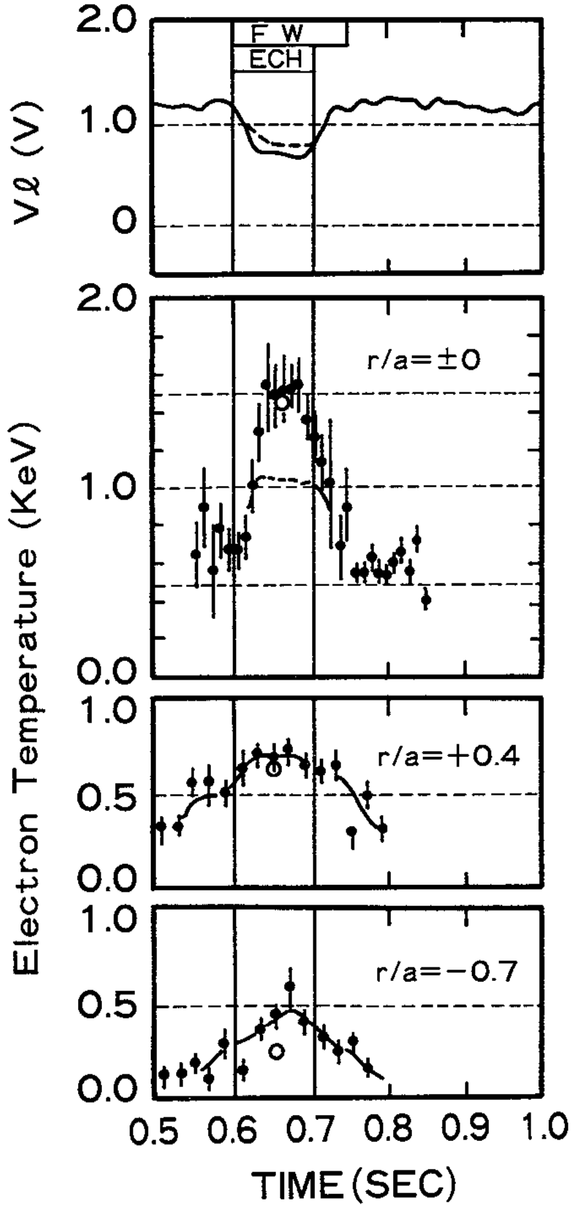
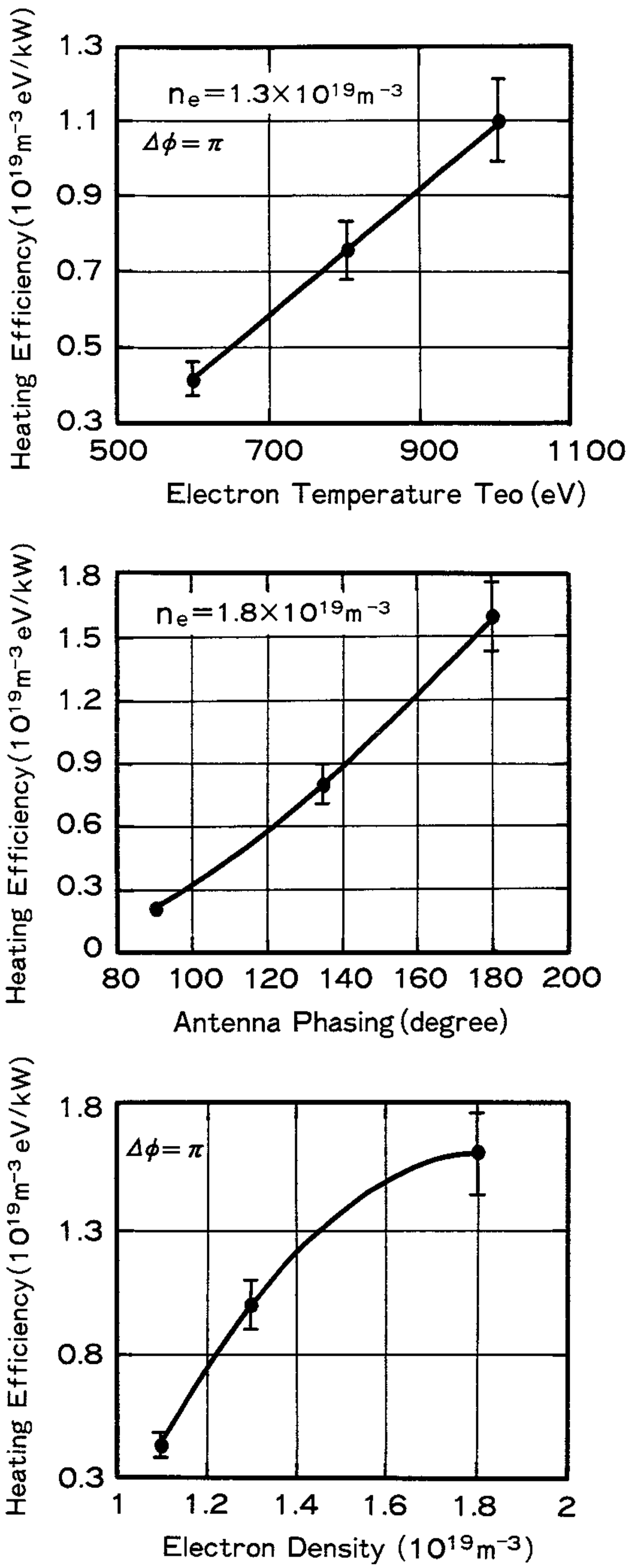


Fig.14



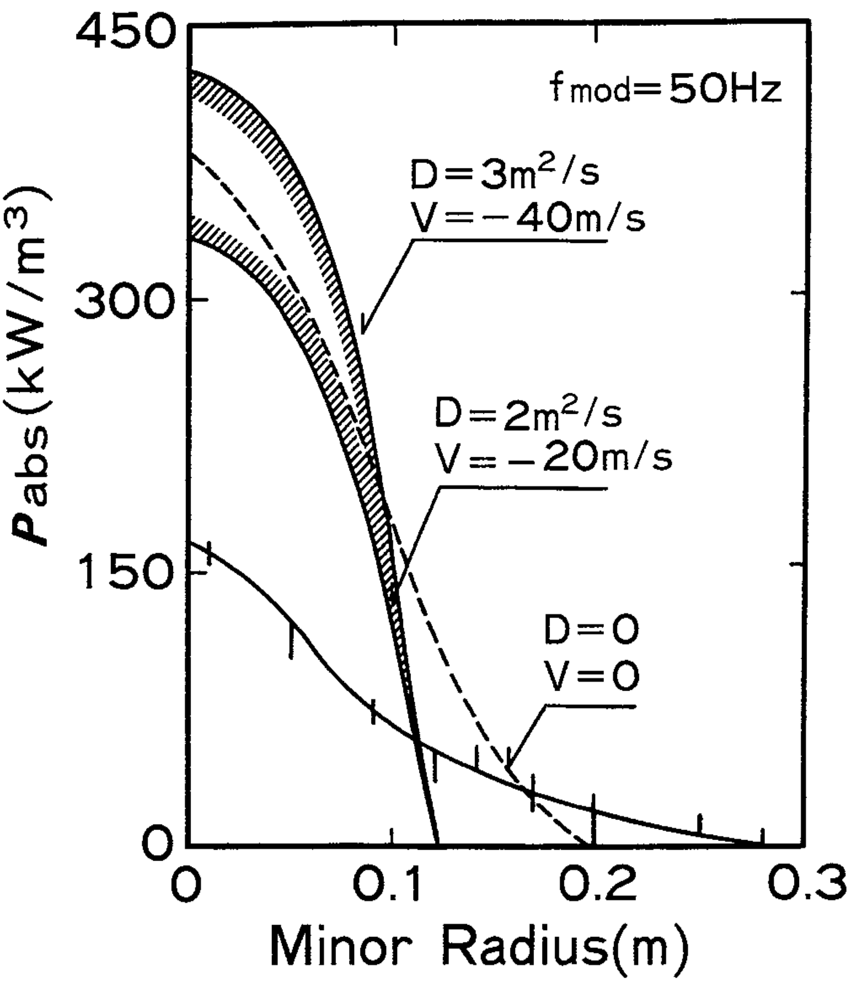
2.0
1.0
0
Vℓ (V)
F W
ECH
2.0
1.0
0.0
r/a=±0
1.0
0.5
0.0
r/a=+0.4
1.0
0.5
0.0
r/a=−0.7
Electron Temperature (KeV)
0.5
0.6
0.7
0.8
0.9
1.0
TIME (SEC)

Fig.15



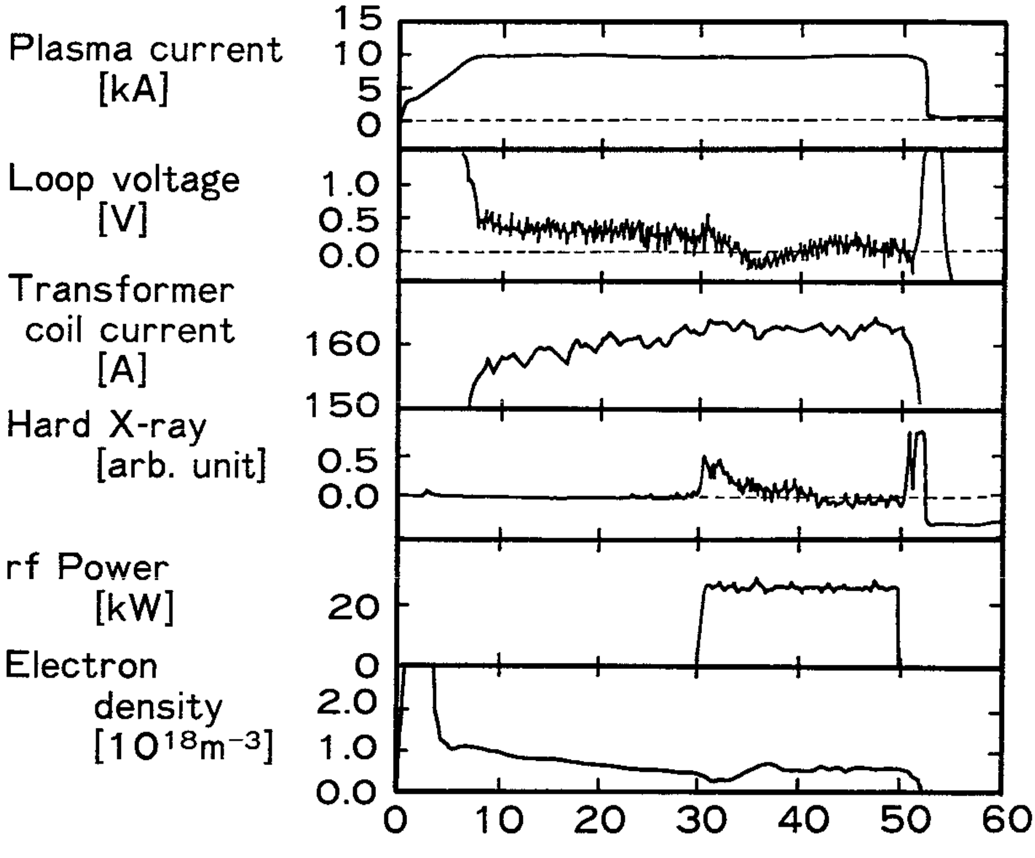
Heating Efficiency (10^19 m^-3 eV/kW)
1.3
1.1
0.9
0.7
0.5
0.3
500
700
900
1100
Electron Temperature Teo (eV)
ne=1.3×10^19 m^-3
Δφ=π
Heating Efficiency (10^19 m^-3 eV/kW)
1.8
1.5
1.2
0.9
0.6
0.3
0
80
100
120
140
160
180
200
Antenna Phasing (degree)
ne=1.8×10^19 m^-3
Heating Efficiency (10^19 m^-3 eV/kW)
1.8
1.3
0.8
0.3
1
1.2
1.4
1.6
1.8
2
Electron Density (10^19 m^-3)
Δφ=π

Fig.16



450
300
150
0
0
0.1
0.2
0.3
Minor Radius(m)
Pabs(kW/m3)
fmod=50Hz
D=3m2/s
V=-40m/s
D=2m2/s
V=-20m/s
D=0
V=0

Fig.17



Plasma current
[kA]
15
10
5
0
Loop voltage
[V]
1.0
0.5
0.0
Transformer
coil current
[A]
160
150
Hard X-ray
[arb. unit]
0.5
0.0
rf Power
[kW]
20
0
Electron
density
[10¹⁸m⁻³]
2.0
1.0
0.0
0
10
20
30
40
50
60

Fig.18

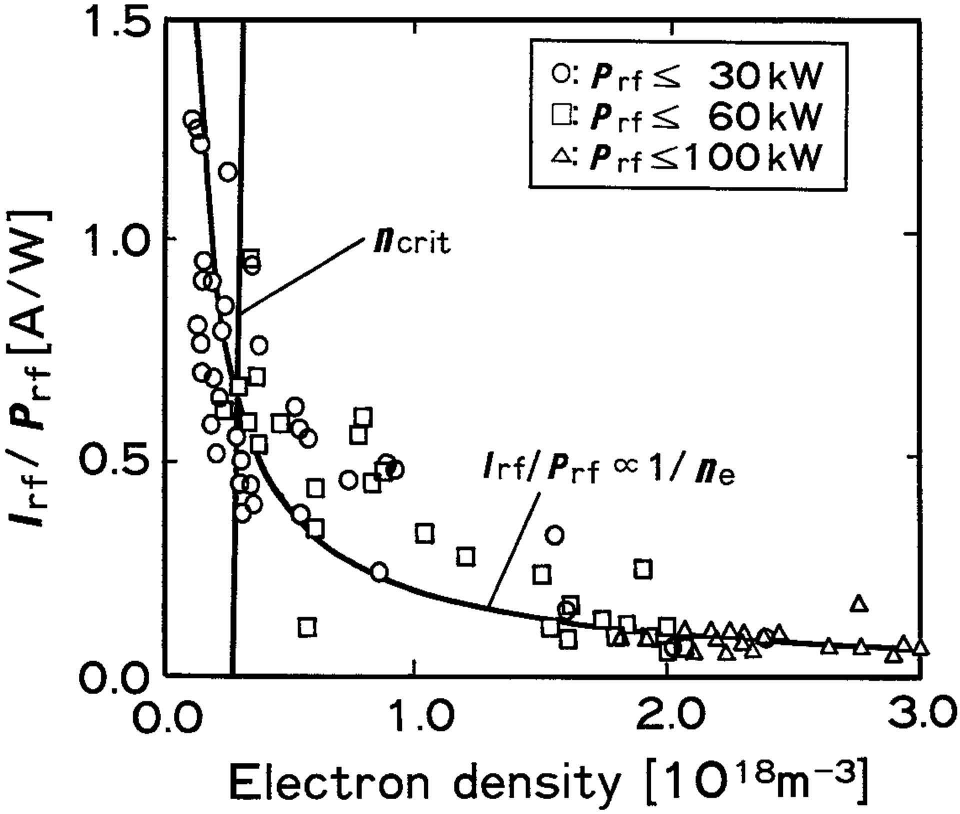

1.5
1.0
0.5
0.0
0.0
1.0
2.0
3.0
○: Prf ≤ 30 kW
□: Prf ≤ 60 kW
△: Prf ≤ 100 kW
ncrit
Irf / Prf ∝ 1/ ne
Irf / Prf [A/W]
Electron density [10^18 m^-3]

Fig.19

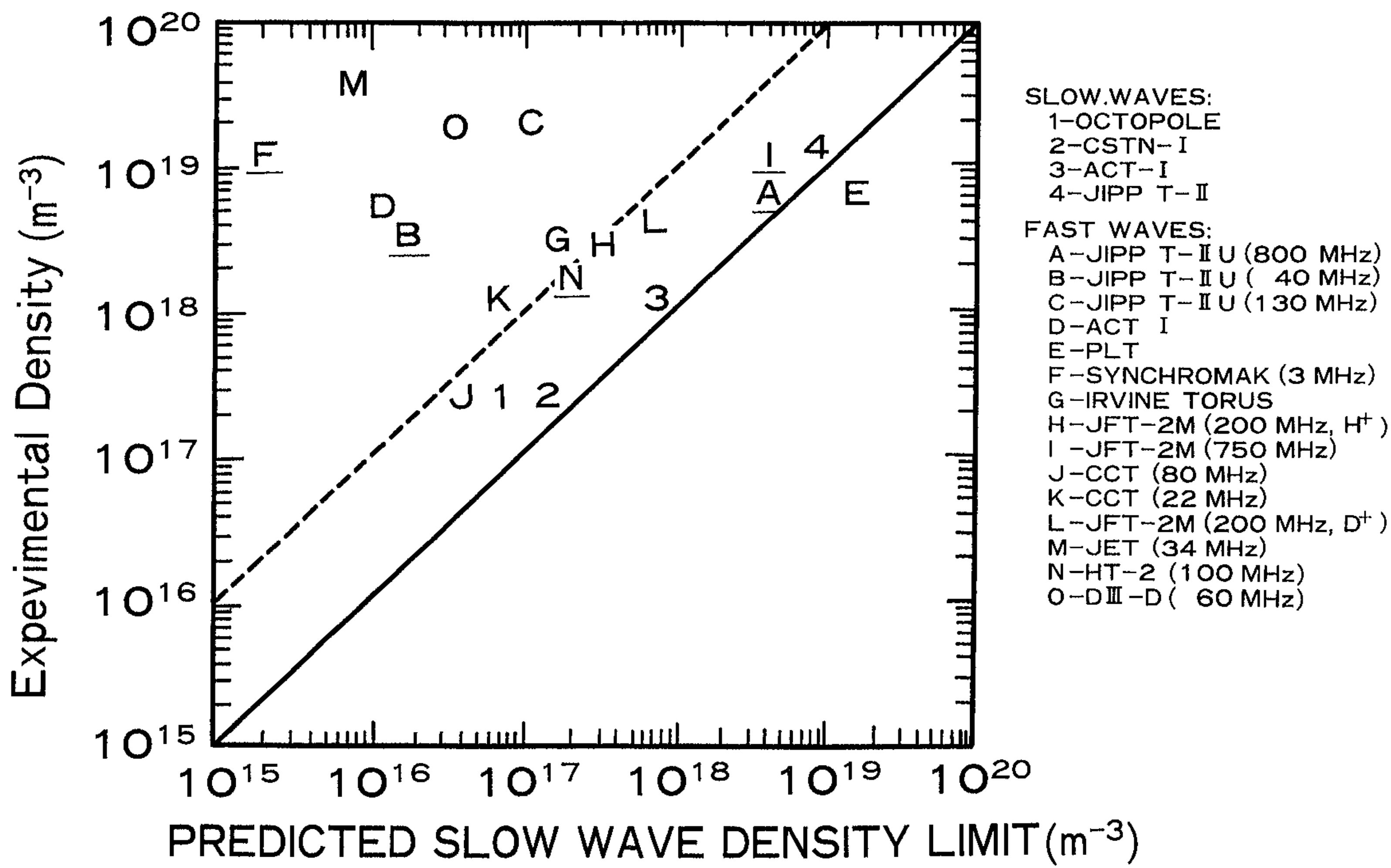

10^20
10^19
10^18
10^17
10^16
10^15
Expevimental Density (m^-3)
PREDICTED SLOW WAVE DENSITY LIMIT (m^-3)
M
O
C
F
D
B
G
H
L
K
N
3
J
1
2
I
4
A
E
SLOW.WAVES:
1-OCTOPOLE
2-CSTN-I
3-ACT-I
4-JIPP T-II
FAST WAVES:
A-JIPP T-IIU (800 MHz)
B-JIPP T-IIU (40 MHz)
C-JIPP T-IIU (130 MHz)
D-ACT I
E-PLT
F-SYNCHROMAK (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)

Fig.20

Recent Issues of NIFS Series

NIFS-152 T. Tanabe, N. Noda and H. Nakamura, *Review of High Z Materials for PSI Applications* ; Jun. 1992

NIFS-153 Sergey V. Bazdenkov and T. Sato, *On a Ballistic Method for Double Layer Regeneration in a Vlasov-Poisson Plasma*; Jun. 1992

NIFS-154 J. Todoroki, *On the Lagrangian of the Linearized MHD Equations*; Jun. 1992

NIFS-155 K. Sato, H. Katayama and F. Miyawaki, *Electrostatic Potential in a Collisionless Plasma Flow Along Open Magnetic Field Lines;* Jun. 1992

NIFS-156 O.J.W.F.Kardaun, J.W.P.F.Kardaun, S.-I. Itoh and K. Itoh, *Discriminant Analysis of Plasma Fusion Data*; Jun. 1992

NIFS-157 K. Itoh, S.-I. Itoh, A. Fukuyama and S. Tsuji, *Critical Issues and Experimental Examination on Sawtooth and Disruption Physics*; Jun. 1992

NIFS-158 K. Itoh and S.-I. Itoh, *Transition to H-Mode by Energetic Electrons*; July 1992

NIFS-159 K. Itoh, S.-I. Itoh and A. Fukuyama, *Steady State Tokamak Sustained by Bootstrap Current Without Seed Current*; July 1992

NIFS-160 H. Sanuki, K. Itoh and S.-I. Itoh, *Effects of Nonclassical Ion Losses on Radial Electric Field in CHS Torsatron/Heliotron*; July 1992

NIFS-161 O. Motojima, K. Akaishi, K. Fujii, S. Fujiwaka, S. Imagawa, H. Ji, H. Kaneko, S. Kitagawa, Y. Kubota, K. Matsuoka, T. Mito, S. Morimoto, A. Nishimura, K. Nishimura, N. Noda, I. Ohtake, N. Ohyabu, S. Okamura, A. Sagara, M. Sakamoto, S. Satoh, T. Satow, K. Takahata, H. Tamura, S. Tanahashi, T. Tsuzuki, S. Yamada, H. Yamada, K. Yamazaki, N. Yanagi, H. Yonezu, J. Yamamoto, M. Fujiwara and A. Iiyoshi, *Physics and Engineering Design Studies on Large Helical Device*; Aug. 1992

NIFS-162 V. D. Pustovitov, *Refined Theory of Diamagnetic Effect in Stellarators;* Aug. 1992

NIFS-163 K. Itoh, *A Review on Application of MHD Theory to Plasma Boundary Problems in Tokamaks*; Aug. 1992

NIFS-164 Y.Kondoh and T.Sato, *Thought Analysis on Self-Organization Theories of MHD Plasma*; Aug. 1992

NIFS-165 T. Seki, R. Kumazawa, T. Watari, M. Ono, Y. Yasaka, F. Shimpo, A. Ando, O. Kaneko, Y. Oka, K. Adati, R. Akiyama, Y. Hamada, S. Hidekuma, S. Hirokura, K. Ida, A. Karita, K. Kawahata, Y. Kawasumi, Y. Kitoh, T. Kohmoto, M. Kojima, K. Masai, S. Morita, K. Narihara, Y. Ogawa, K. Ohkubo, S. Okajima, T. Ozaki, M. Sakamoto, M. Sasao, K. Sato, K. N. Sato, H. Takahashi, Y. Taniguchi, K. Toi and T. Tsuzuki, *High Frequency Ion Bernstein Wave Heating Experiment on JIPP T-IIU Tokamak*; Aug. 1992

NIFS-166 Vo Hong Anh and Nguyen Tien Dung, *A Synergetic Treatment of the Vortices Behaviour of a Plasma with Viscosity*; Sep. 1992

NIFS-167 K. Watanabe and T. Sato, *A Triggering Mechanism of Fast Crash in Sawtooth Oscillation*; Sep. 1992

NIFS-168 T. Hayashi, T. Sato, W. Lotz, P. Merkel, J. Nührenberg, U. Schwenn and E. Strumberger, *3D MHD Study of Helias and Heliotron;* Sep. 1992

NIFS-169 N. Nakajima, K. Ichiguchi, K. Watanabe, H. Sugama, M. Okamoto, M. Wakatani, Y. Nakamura and C. Z. Cheng, *Neoclassical Current and Related MHD Stability, Gap Modes, and Radial Electric Field Effects in Heliotron and Torsatron Plasmas;* Sep. 1992

NIFS-170 H. Sugama, M. Okamoto and M. Wakatani, *K-ε Model of Anomalous Transport in Resistive Interchange Turbulence* ; Sep, 1992

NIFS-171 H. Sugama, M. Okamoto and M. Wakatani, *Vlasov Equation in the Stochastic Magnetic Field* ; Sep. 1992

NIFS-172 N. Nakajima, M. Okamoto and M. Fujiwara, *Physical Mechanism of E_ϕ-Driven Current in Asymmetric Toroidal Systems* ; Sep.1992

NIFS-173 N. Nakajima, J. Todoroki and M. Okamoto, *On Relation between Hamada and Boozer Magnetic Coordinate System* ; Sep. 1992

NIFS-174 K. Ichiguchi, N. Nakajima, M. Okamoto, Y. Nakamura and M. Wakatani, *Effects of Net Toroidal Current on Mercier Criterion in the Large Helical Device* ; Sep. 1992

NIFS-175 S. -I. Itoh, K. Itoh and A. Fukuyama, *Modelling of ELMs and Dynamic Responses of the H-Mode* ; Sep. 1992

NIFS-176 K. Itoh, S.-I. Itoh, A. Fukuyama, H. Sanuki, K. Ichiguchi and J. Todoroki, *Improved Models of β-Limit, Anomalous Transport and Radial Electric Field with Loss Cone Loss in Heliotron / Torsatron* ; Sep. 1992

NIFS-177 N. Ohyabu, K. Yamazaki, I. Katanuma, H. Ji, T. Watanabe, K. Watanabe, H. Akao, K. Akaishi, T. Ono, H. Kaneko, T. Kawamura, Y. Kubota, N. Noda, A. Sagara, O. Motojima, M. Fujiwara and A. Iiyoshi, *Design Study of LHD Helical Divertor and High Temperature Divertor Plasma Operation* ; Sep. 1992

NIFS-178 H. Sanuki, K. Itoh and S.-I. Itoh, *Selfconsistent Analysis of Radial Electric Field and Fast Ion Losses in CHS Torsatron / Heliotron* ; Sep. 1992

NIFS-179 K. Toi, S. Morita, K. Kawahata, K. Ida, T. Watari, R. Kumazawa, A. Ando, Y. Oka, K. Ohkubo, Y. Hamada, K. Adati, R. Akiyama, S. Hidekuma, S. Hirokura, O. Kaneko, T. Kawamoto, Y. Kawasumi, M. Kojima, T. Kuroda, K. Masai, K. Narihara, Y. Ogawa, S. Okajima, M. Sakamoto, M. Sasao, K. Sato, K. N. Sato, T. Seki, F. Shimpo, S. Tanahashi, Y. Taniguchi, T. Tsuzuki, *New Features of L-H Transition in Limiter H-Modes of JIPP T-IIU* ; Sep. 1992

NIFS-180 H. Momota, Y. Tomita, A. Ishida, Y. Kohzaki, M. Ohnishi, S. Ohi, Y. Nakao and M. Nishikawa, *D-^{3}He Fueled FRC Reactor "Artemis-L"* ; Sep. 1992

NIFS-181 T. Watari, R. Kumazawa, T. Seki, Y. Yasaka, A. Ando, Y. Oka, O. Kaneko, K. Adati, R. Akiyama, Y. Hamada, S. Hidekuma, S. Hirokura, K. Ida, K. Kawahata, T. Kawamoto, Y. Kawasumi, S. Kitagawa, M. Kojima, T. Kuroda, K. Masai, S. Morita, K. Narihara, Y. Ogawa, K. Ohkubo, S. Okajima, T. Ozaki, M. Sakamoto, M. Sasao, K. Sato, K. N. Sato, F. Shimpo, H. Takahashi, S. Tanahasi, Y. Taniguchi, K. Toi, T. Tsuzuki and M. Ono, *The New Features of Ion Bernstein Wave Heating in JIPP T-IIU Tokamak*; Sep, 1992

NIFS-182 K. Itoh, H. Sanuki and S.-I. Itoh, *Effect of Alpha Particles on Radial Electric Field Structure in Torsatron / Heliotron Reactor*; Sep. 1992

NIFS-183 S. Morimoto, M. Sato, H. Yamada, H. Ji, S. Okamura, S. Kubo, O. Motojima, M. Murakami, T. C. Jernigan, T. S. Bigelow, A. C. England, R. S. Isler, J. F. Lyon, C. H. Ma, D. A. Rasmussen, C. R. Schaich, J. B. Wilgen and J. L. Yarber, *Long Pulse Discharges Sustained by Second Harmonic Electron Cyclotron Heating Using a 35GH$_Z$ Gyrotron in the Advanced Toroidal Facility*; Sep. 1992

NIFS-184 S. Okamura, K. Hanatani, K. Nishimura, R. Akiyama, T. Amano, H. Arimoto, M. Fujiwara, M. Hosokawa, K. Ida, H. Idei, H. Iguchi, O. Kaneko, T. Kawamoto, S. Kubo, R. Kumazawa, K. Matsuoka, S. Morita, O. Motojima, T. Mutoh, N. Nakajima, N. Noda, M. Okamoto, T. Ozaki, A. Sagara, S. Sakakibara, H. Sanuki, T. Saki, T. Shoji, F. Shimbo, C. Takahashi, Y. Takeiri, Y. Takita, K. Toi, K. Tsumori, M. Ueda, T. Watari, H. Yamada and I. Yamada, *Heating Experiments*

Using Neutral Beams with Variable Injection Angle and ICRF Waves in CHS ; Sep. 1992

NIFS-185 H. Yamada, S. Morita, K. Ida, S. Okamura, H. Iguchi, S. Sakakibara, K. Nishimura, R. Akiyama, H. Arimoto, M. Fujiwara, K. Hanatani, S. P. Hirshman, K. Ichiguchi, H. Idei, O. Kaneko, T. Kawamoto, S. Kubo, D. K. Lee, K. Matsuoka, O, Motojima, T. Ozaki, V. D. Pustovitov, A. Sagara, H. Sanuki, T. Shoji, C. Takahashi, Y. Takeiri, Y. Takita, S. Tanahashi, J. Todoroki, K. Toi, K. Tsumori, M. Ueda and I. Yamada, *MHD and Confinement Characteristics in the High-β Regime on the CHS Low-Aspect-Ratio Heliotron / Torsatron* ; Sep. 1992

NIFS-186 S. Morita, H. Yamada, H. Iguchi, K. Adati, R. Akiyama, H. Arimoto, M. Fujiwara, Y. Hamada, K. Ida, H. Idei, O. Kaneko, K. Kawahata, T. Kawamoto, S. Kubo, R. Kumazawa, K. Matsuoka, T. Morisaki, K. Nishimura, S. Okamura, T. Ozaki, T. Seki, M. Sakurai, S, Sakakibara, A. Sagara, C. Takahashi, Y. Takeiri, H. Takenaga, Y. Takita, K. Toi, K. Tsumori, K. Uchino, M. Ueda, T. Watari, I. Yamada, *A Role of Neutral Hydrogen in CHS Plasmas with Reheat and Collapse and Comparison with JIPP T-IIU Tokamak Plasmas* ; Sep. 1992

NIFS-187 K. Ioth, S.-I. Itoh, A. Fukuyama, M. Yagi and M. Azumi, *Model of the L-Mode Confinement in Tokamaks* ; Sep. 1992

NIFS-188 K. Itoh, A. Fukuyama and S.-I. Itoh, *Beta-Limiting Phenomena in High-Aspect-Ratio Toroidal Helical Plasmas*; Oct. 1992

NIFS-189 K. Itoh, S. -I. Itoh and A. Fukuyama, *Cross Field Ion Motion at Sawtooth Crash* ; Oct. 1992

NIFS-190 N. Noda, Y. Kubota, A. Sagara, N. Ohyabu, K. Akaishi, H. Ji, O. Motojima, M. Hashiba, I. Fujita, T. Hino, T. Yamashina, T. Matsuda, T. Sogabe, T. Matsumoto, K. Kuroda, S. Yamazaki, H. Ise, J. Adachi and T. Suzuki, *Design Study on Divertor Plates of Large Helical Device (LHD)* ; Oct. 1992

NIFS-191 Y. Kondoh, Y. Hosaka and K. Ishii, *Kernel Optimum Nearly-Analytical Discretization (KOND) Algorithm Applied to Parabolic and Hyperbolic Equations* : Oct. 1992

NIFS-192 K. Itoh, M. Yagi, S.-I. Itoh, A. Fukuyama and M. Azumi, *L-Mode Confinement Model Based on Transport-MHD Theory in Tokamaks* ; Oct. 1992