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Second Harmonic ICRF Heating in the JFT-2M

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Pure second harmonic ion cyclotron heating experiments in hydrogen plasma were carried out in the JFT-2M tokamak. In order to improve an absorption characteristics in the second harmonic regime, neutral beam injection heating is used, and effective heating via ICRF is observed. With 550kW of NBI, the plasma is heated up to T_i=0.9keV, and T_e=1.1keV. 30ms after the start of NBI, 520kW of ICRF is applied and plasma is finally heated up to T_i=1.1keV, T_e=1.6keV. Magnetic measurement of $\Lambda+1/2 = \beta_p + (\ell_i - 1)/2$ increases by $\Delta\Lambda$=0.3 with ICRF heating.

Preliminary coupling study of a wave guide coupler is also investigated. A parallel plate TEM electric field coupler, whose electric field configuration is almost the same as a ridged wave guide, are used

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as a simulater of a ridged wave guide coupler. The transmission coefficient with plasma is almost the same as the one obtained by loop antenna at low power level.

Keywords; ICRF Heating, JFT-2M Tokamak, Plasma Heating, Hydrogen Plasma Wave Guide Coupler, Neutral Beam Injection, Temperature, Second Harmonic Regime

JFT－2Mにおける2倍高調波ICRF加熱

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（1983年10月20日受理）

水素プラズマ中における純2倍高調波イオンサイクロトロン周波数における加熱実験がJFT－2Mで行われた。2倍高調波領域における吸収を改善するために中性粒子入射加熱を用い，有効な加熱結果を観測した。550 kWのNBIによりプラズマは$T_i = 0.9$ keV，$T_e = 1.1$ keVまで加熱され，ICRF 520 kWにより，$T_i = 1.1$ keV，$T_e = 1.6$ keVまで温度が上昇した。$A + \frac{1}{2}$の磁気測定でICRFによる上昇分$\Delta A = 0.3$を得た。

導波管結合の予備実験を開始した。リッジ導波管結合器のシミュレータとして，電界配位がほぼ等しい，平行2板電界結合器を製作し，1Wレベルでの結合度を測定した。その結果ループアンテナとほぼ同じ値が得られた。

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1. Introduction

Recently main objectives of tokamak experiments have moved to additional heatings and the plasma properties associated with them. Ion cyclotron range of frequency (ICRF) heating is one of the most promissing schemes among various additional heating methods. In the last few years, much progress has been made[1~3] both in physics and technical aspect of ICRF heating.

In a tokamak plasma, it is known that the minority hydrogen in a deuterium plasma produces two-ion hybrid resonance layer at the higher magnetic field side of the fundamental cyclotron resonance layer of minority protons. The impressed ICRF field generates a fast magnetosonic wave beyond the evanecent region in the peripheral plasma. This wave propagates to the hybrid resonance layer and is converted to an ion Bernstein wave near the layer. The energy of the wave which is converted to the ion Bernstein wave is efficiently transferred to the three species of particles, deuterons, protons, and electrons.[4]

In second harmonic heating case, in which minority component plasma is absent, a mode coupling layer also exists close to the second harmonic cyclotron resonance layer in the high field side as in the two-ion hybrid scheme. The thickness of this layer is proportional to $\beta_i R_0$, where β_i is the local ion toroidal beta value and R_0 is the major radius. In this layer, mode coupling to ion Bernstein waves and enhanced harmonic cyclotron damping can occur. We can thus expect the plasma heating in the second harmonic regime.[5]

The second harmonic scheme has favorable characteristics to heat a reactor plasma; it does not need a minority component, and a high energy ion tail produced by the heating can enhance a nuclear fusion reactivity. In present tokamaks, this scheme allows us to use hydrogen plasma which is free from neutron radiation. This is quite convenient in a high β regime experiments, since we do not have to shield the machine against the neutron damages.

With the given magnitude of magnetic field, the frequency is two times as high as that of the two ion scheme. This high frequency enables us to use wave guide launcher instead of loop antenna as a coupling structure.

In order to apply the ICRF heating to a reactor, the simple structure of the wave guide is more favorable than the loop antenna. Then we must test the wave guide coupling to prove its effectiveness by comparing with the loop antenna coupling.

The heating experiment in the second harmonic regime is tried in the PLT.[2] In this experiment, the high energy tail is observed in a perpendicular charge exchange ion spectrum. The increment of average ion energy is almost the same as that of minority hydrogen scheme. But the increase of electron temperature or poloidal beta value is still not clear.

In this paper, the heating results in the second harmonic regime are investigated in the NBI heated plasma. It is shown that both electron and ion temperatures increase and this increment is consistent with the magnetic measurement of poloidal beta value.

In section 2, experimental configurations are mentioned. Results of heating experiment are shown in section 3. In section 4, we show a coupling results from a TEM electric field couler, which simulate the ridged wave guide. In the last section, conclusions and discussion are presented.

2.Apparatus

JFT-2M is a tokamak with D shaped vacuum vessel with 1.31m major radius and 0.415 x 0.595m minor radius. In the present experiment, the machine is operated with circular cross section and the plasma radius is limited by inner and outer limiter at a=35 cm. The limiter material is carbon graphite.

The rf generator is operated at 38 MHZ which is the second harmonic cyclotron frequency of protons with the toroidal magnetic field B_T=12.5kG. The output power of generator which has single TH116 power triode is about 0.8MW at the 50Ω dummy load, and the maximum pulse duration is 50ms.

Fig.1 shows a top view of JFT-2M and the arrangement of diagnostic instruments. Electron temperature is measured with soft X-ray pulse height analyzer. Energy spectra of hydrogen and deuterium ions are measured with E//B mass sensitive charge exchange neutral analyzer at the same time.[7] The measurement is carried out in slightly off perpendicular direction (14°) with respect to the toroidal magnetic field. The energy spectrum measured in this direction is not affected by ripple-trapped particles.

The increase of poloidal beta value βp is measured by B_θ probes at inner and outer side of the torus, and by suddle loops (half turn closed flux loops).[8] The value $\Lambda + 1/2 = \beta p + \ell_i/2 - 1/2$, where ℓ_i is internal inductance which is related to the plasma current profile, is obtained from this measurement. There are two possibilities in the increase of $(\Lambda + 1/2)$. Those are the increase of β p, and the increase of ℓ_i due to an edge cooling by impurity radiation. But 1-D tokamak simulation code including internal disruption indicates that the change in ℓ_i value is very small, typically within 0.06 in the case of safty factor at limiter radius q_a=3, because the q value at the center of the plasma is almost fixed around 1 by the internal disruption. Thus, when the change of $(\Lambda + 1/2)$ is sufficiently large, typically larger than 0.1, $\Delta\Lambda$ is attributed to the change of βp.

The antenna is shown in Fig.1. This is a quarter turn loop located at the

outer side (lower magnetic field side) of the torus. The radiative region of the antenna is 50cm in length and 7 cm in width. The coupling resistance is critically dependent on the horizontal plasma position. Figure 2 shows the coupling resistence versus horizontal plasma position. The solid line is a calculated value by three dimensional model. The resistance decreases by a factor of 5 with inward plasma shift of 7cm. In the optimum condition, the coupling efficiency is about 85%. The main loss is attributed to an ohmic dissipation in the region between the vacuum feedthrough and the radiative part of the loop which is bent to the toroidal direction so as to avoid an interference with a horizontal port section. The Faraday shield is optimized so as to minimize an ohmic loss at the screen.[6] The loss is estimated to be $0.084\,\Omega$ by the calculation and is negligible compared to the vacuum loading resistance, $0.32\,\Omega$.

3. Experiment

Typical experimental conditions are as follows; plasma current I_p = 170~180KA, the strength of toroidal magnetic field B_T= 12.5KG, in which second harmonic ion cyclotron layer is at the center of plasma, and line average electron density $\bar{n}_e$=2.5~3 x 10^{13} Om^{-3} during the heating.

When more than 100KW of RF is applied to the joule heated plasma, a disruption occurs mainly because of the large increase of radiation loss. The charge exchange spectra before and after the rf is switched on are shown in Fig.4. The significant high energy tail is observed and bulk ion temperature which is determined by the inclination between 1.5keV and 4.5keV increases about 50eV. An appreciable increase of electron temperature is not observed. The magnetic measurement of (Λ + 1/2) increases slightly as shown in Fig.5(a). The increment is 0.03 and we cannot conclude the increase of plasma pressure. These results seem to be due to weak absorption of the rf power, because of low β_i value at the plasma center.

In the case of second harmonic heating, the following merits are expected in the NBI heated plasma; (i) higher temperature and higher β plasma absorb the rf power more effectively, (ii) high energy ion component produced by NBI enhances the absorption of rf power.[9] (iii) neutral beam stabilizes the disruption by compensation the radiation loss. Thus, 600KW of rf power has been coupled to the plasma with assist of NBI.

Figure 5(b) shows (Λ+ 1/2) during the rf heating in 240KW of NBI heated plasma. The rf net power is almost the same as Fig.5(a), and the increment is about 0.1. This value is sufficiently meaningful value compared to the variation of $\ell_i/2$. It shoud be noted that in the NBI heated plasma, the second harmonic heating is more effective than in the joule plasma.

Time evolution of plasma parameteres before and during the NBI and ICRF heating are shown in Fig.6. RF power is applied 30ms after the initiation of NB co-injection. With 550KW of NBI, the plasma is heated up to T_i= 0.9keV

and T_e= 1.1keV. Then 520kW of ICRF power heats plasma up to T_i=1.1keV and T_e= 1.6keV. The increment of plasma pressure $\Delta\Lambda$ from joule phase to NBI heated phase is about 0.2 and from NBI heated phase to ICRF heated phase is about 0.3. These values obtained with magnetic measurement are consistent with the temperature measurement on the assumption that the electron temperature profile is peaked by the ICRF heating. This assumption is reasobale because the increased radiation loss cools the peripheral region of the plasma. The increment of the radiation loss becomes almost the same as the ICRF input power.

Figure 7(a) shows the increase of plasma pressure $\Delta\Lambda$ as the function of hydrogen concentration ratio of hydrogen-deuterium two ion plasma with the injection of hydrogen neutral beam. $\Delta\Lambda$ increases with the increase of hydrogen component. Considering that deuterium does not contribute to the wave damping because the deuterium has only the fourth harmonic cyclotron resonance, this shows that the heating efficiency is determined by the wave damping at the hot core of the plasma. The radiation loss and carbon impurity increase with the decrease of $\Delta\Lambda$ as shown in Fig.7(b).

The increase of other impurities during the ICRF heating is shown in Fig.8. Figure 8(a) is the case of hydrogen plasma with hydrogen NBI. Fig 8(b) is the case of deuterium plasma with hydrogen NBI. The latter case is rather weak heating as can be seen in Fig.7. It should be noted that in both cases, the increment of metalic impurities such as titanium and iron, and oxigen impurities due to ICRF heating are almost the same. But the increment of carbon impurity is clearly different. The carbon impurity in the hydrogen case hardly increases. On the contrary, that in the deuterium case increases significantly.

The carbon is only used at the limiter, and the titanium is only used at Faraday shield of the antenna in the JFT-2M vacuum vessel. Close to the loop antenna, there is TEM electric field coupler, whose side is made of stainless steel. This has a possibility as an iron source, and other parts of the inner vacuumcessel are made of stainless steel. Thus location of metalic impurity

sources in the vacuum vessel can be distinguished.

From the evolution of impurities shown in Fig.8, we can think about two kinds of impurity production mechanisms. One is the mechanism with no correlation to the absorption of the launched wave in the plasma. Metalic impurities from the antenna are released by this mechanism. The other is the one which has some correlation to the absorption of the wave. Carbons are released by this mechanism.

The former mechanism would be considered as follows. Certain percentage of the rf power radiated from the antenna is directly deposited near the antenna and the materials of the antenna are sputtered out. This mechanism may be simple accelation of the rf electoric field because the source of impurity is restricted around the antenna.

The possible explanation of the latter mechanism would be as follows. When the rf power absorption in the hot core is weak, the rf power can be absorbed in a peripheral region resulting in the release of carbon impurity. This mechanism has strong correlation with the strength of the rf power absorption in the hot core region.

In the present experiment, oxygen impurity is dominant. Rough estimation of impurity concentration indicates that the dominant impurity which contributes to radiation loss is oxygen.[8] Thus the metalic impurities are not so harmful compared to the oxygen impurities in the present JFT-2M experiments. But the thorough discharge clearing and/or titanium gettering decrease the oxygen, and in the future experiment with high power ICRF, the metalic impurities will play a dominant role in power balance at the center and have a harmful effect on the plasma confinement. In order to reduce the metalic impurities during the ICRF heating, it is necessary to reduce the impurities released from the antenna region.

4. Coupling experiment of TEM electric field coupler

In order to simulate a ridge wave coupling, TEM electric field coupler is used.[10] Figure 9 shows the coupler. It consists of two parallel plates in a shield box. The parallel plate is 30cm in width and 2cm in thickness. The shield box has rectangular cross section with 40 x48cm. The gap distance between the two parallel plates can be changed from 0 to 10cm. This enables us to study the optimization of the electric field coupling. The mouth of the coupler is 6cm in length and is opened by 60° in order to improve the coupling with the plasma.[11]

The rf power is fed from upper and lower sides with opposite phase. Thus the two parallel plates act as parallel transmission lines. The electric field in the gap is vertical to the parallel plates. Configuration of electric field lines in this parallel plates is almost the same as that of the ridge wave guide.

When the gap distance is sufficiently small compared to the dimension of the shield box, almost all of the rf energy is concentrated in the gap. There is an electric field parallel to the magnetic field line around the edge of the parallel plates. The gap width of the parallel plates is selected so as to minimize the electric field directed to the magnetic field.

In order to shield the electric field in the direction of magnetic field, a simple Faraday shield is placed in front of the mouth of the coupler. This Faraday shield consists of square rods (5mm x 5mm) placed in the direction of magnetic field lines at intervals of 2cm.

The power transmission coefficient is defined by $(1 - \Gamma^2) = 4\rho / (\rho + 1)^2$, where Γ is reflection coefficient and ρ is voltage standing wave ratio in the 50 Ω coaxial line. The voltage standing wage ratio is determined by, $\rho = (V_f + V_r)/(V_f - V_r) = (V_f + V_r)^2/(V_f^2 - V_r^2)$, where V_f and V_r are forward and reflection voltage measured by directional coupler, and $(V_f^2 - V_r^2)$ is the transmission power from the generator.

Fig.10 shows the transmission coefficient as a function of a gap distance of the parallel plates. The transmission coefficient increases almost linearly with the gap distance. With the injection of hydrogen neutral beam, the

coefficient becomes three times as large as that without NBI.

Theoretical analysis by three dimensional coupling code predicts that the transmission coefficient is several percents and that it is almost proportional to the gap distance. In the experiment, the transmisssion coefficient was proportional to the gap distance, but the absolute values were 2 ~ 5 times as large as the theoretical values. Three dimensional full wave code also predicts that the transmission coefficient increases with the increase of the fast wave absorption in the plasma.[12] This prediction was confirmed in the experiment by changing the absorption in the plasma by neutral beam injection. But transmission coefficients observed in the experiments were almost the same in the hydrogen plasma and in the deuterium plasma.

The coupling measurement of electric field coupler is only preliminary and high power heating experiment is now under way.

5. Discussion and conclusions

Second harmonic ICRF heating was successfully demonstrated in JFT-2M. Since profile measurements were not available in the experiment, 1-D tokamak code simulation was made to estimate the power balance of the heating upon following assumptions. $X_e=1 \times 10^{19}/n_e$, $X_i=1.5X_{NC}$ in the joule phase, $X_e=2 \times 10^{19}/n_e$, $X_i=1.5X_{NC}$ during the heating. During the rf heating, neutral beam is also injected. This enhancement of electron heat conductivity during NBI was observed in JFT-2 experiment. Also preliminary result of NBI experiment in JFT-2M shows the same tendency.

The rf power deposition on ions with flat profile within r=10cm and deposition on electrons within r=15cm were simply assumed. Experimental results are well simulated by the time evolution of total rf power deposition on electrons and ions shown in Fig.11. During the first $10 \sim 20$ms of the heating period, the rf deposition to electrons is not significant. In later period, deposition to electrons should be quite significant.

Although profile data are not availabe and this simulation is only presumable, we can say that more than half of the rf heating power is absorbed by electrons in the second harmonic regime. This result is inconsistent with the theoretical works using 1-D kinetic full wave equation in a bounded plasma.[13] There are two possible mechanism which can explain the electron heating in this experiment; (1) mode converted ion Bernstein wave heats electrons by Landan damping. (2)High energy beam ions are preferentially heated, and energy which flows from the beam ions to electrons is enhanced.

The former mechanism seems reasonable, and the rf power deposition to electrons seems to increase with the increase of electron temperature. This can be due to the enhancement of Landan damping resulting from the increase of electron temperature. But the theoretical analysis still cannot explain the experimental results by this mode conversion. As for the latter mechanism, high energy ions above 30keV can preferentially transfer energy to electrons. We do not observe enhancement of such high energy part by the present charge exchange analyzer.

Our experiment is very prelinimary and further experiments are needed for the complete understanding of second harmonic heating. The experimental results are summerized as follows.

(1) Second harmonic ICRF heating is sccessfully demonstrated in the JFT-2M. Both electron and ion temperature increase by applying ICRF to the NBI heated target plasma. The increase of plasma energy is confirmed in the magnetic measurements of poloidal beta. On the other hand, with the joule heated target plasma, the heating results are poor in spite of the production of high energy tail in the ion charge exchange spectrum.

(2) Two kinds of impurity production mechanisms are distinguished. The one is not related to the absorption of the wave in hot core, and this mechanism produces impurities from the antenna region. The other is strongly correlated to the absorption of the wave. Limiter materials is released into the plasma by this mechanism.

(3) Preliminary coupling study of wave guide coupler is investigated. A parallel plate TEM electric field coupler, whose electric field configuration is almost the same as that of a ridged wave guide, is used. The transmission coefficient of the wave from the parallel plated launching structure into the plasma is almost the same as the one obtained by loop antenna at low power level.

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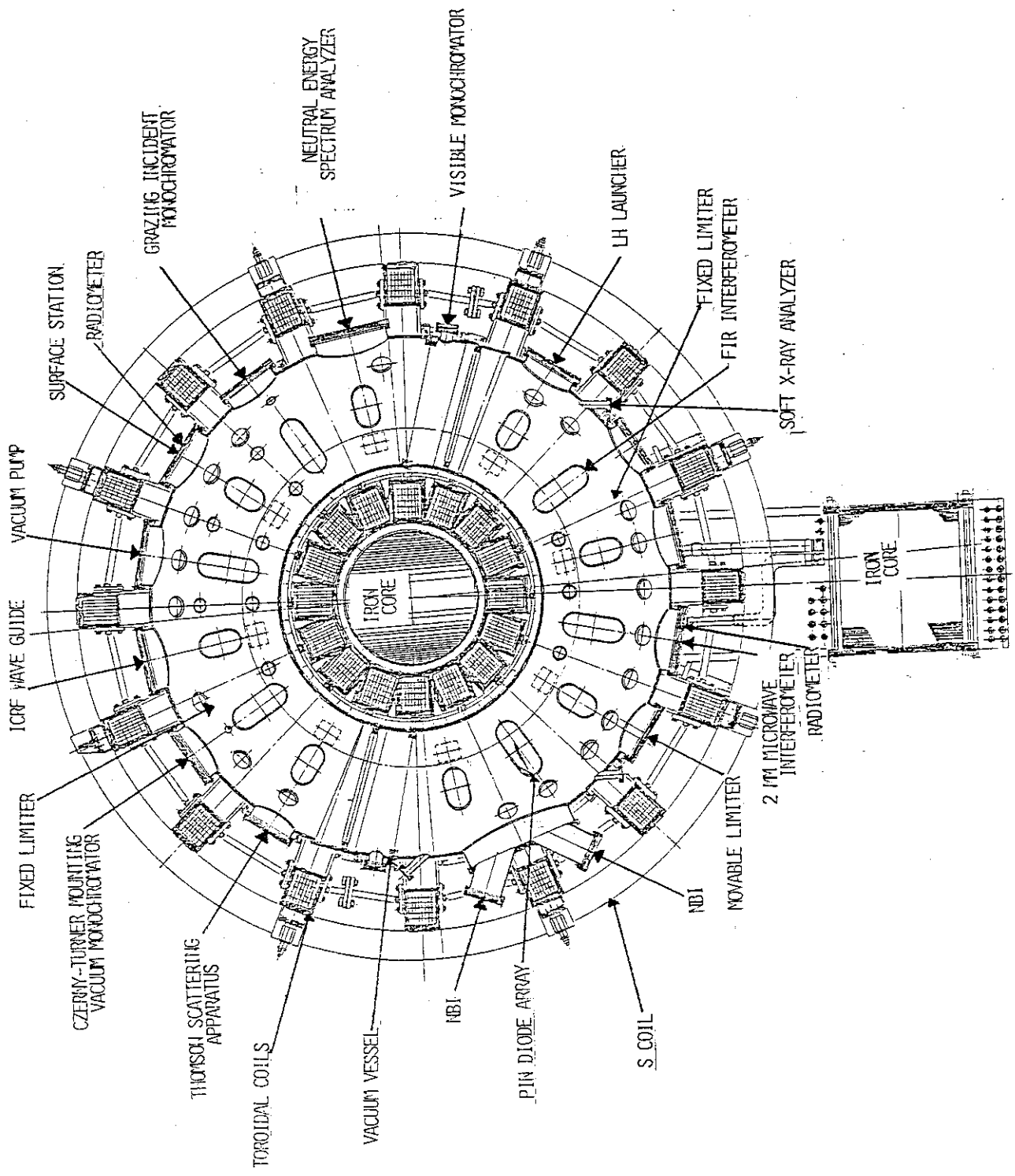

Fig.1 Top view of JFT-2M and the arrangement of diagnostic instruments.

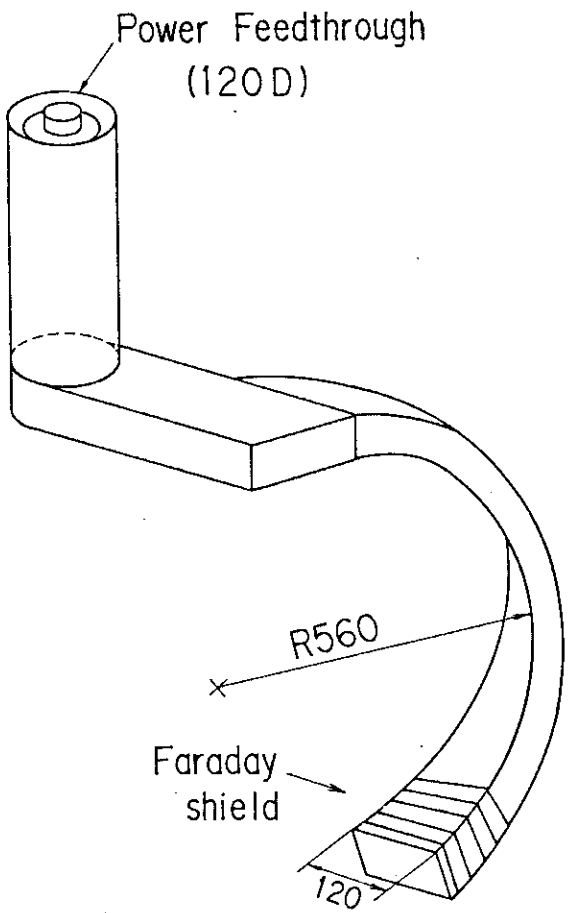

Fig.2 Figure of the JFT-2M loop antenna

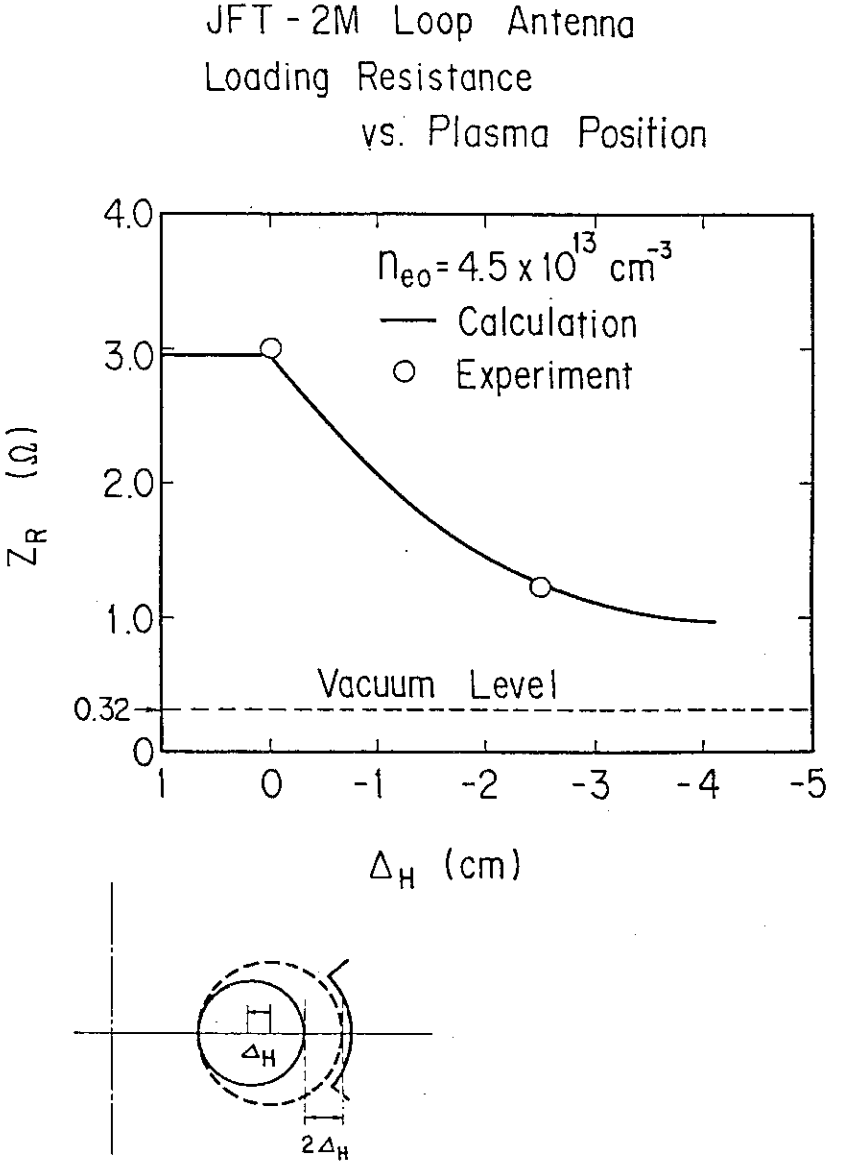

Fig.3 Coupling resistance versus horizontal plasma position

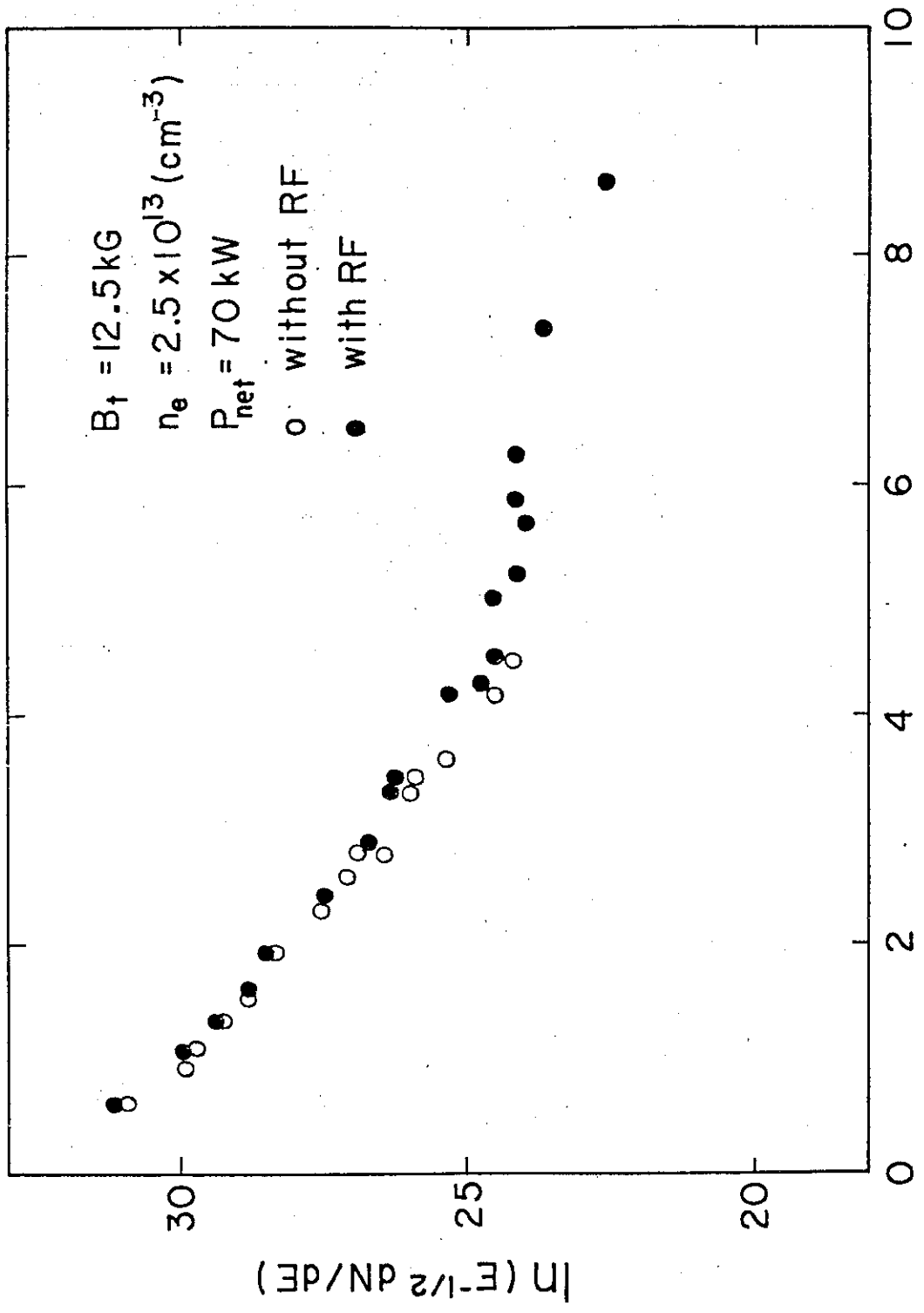

Fig.4 Charge exchange spectrum before and after the onset of the RF heating.

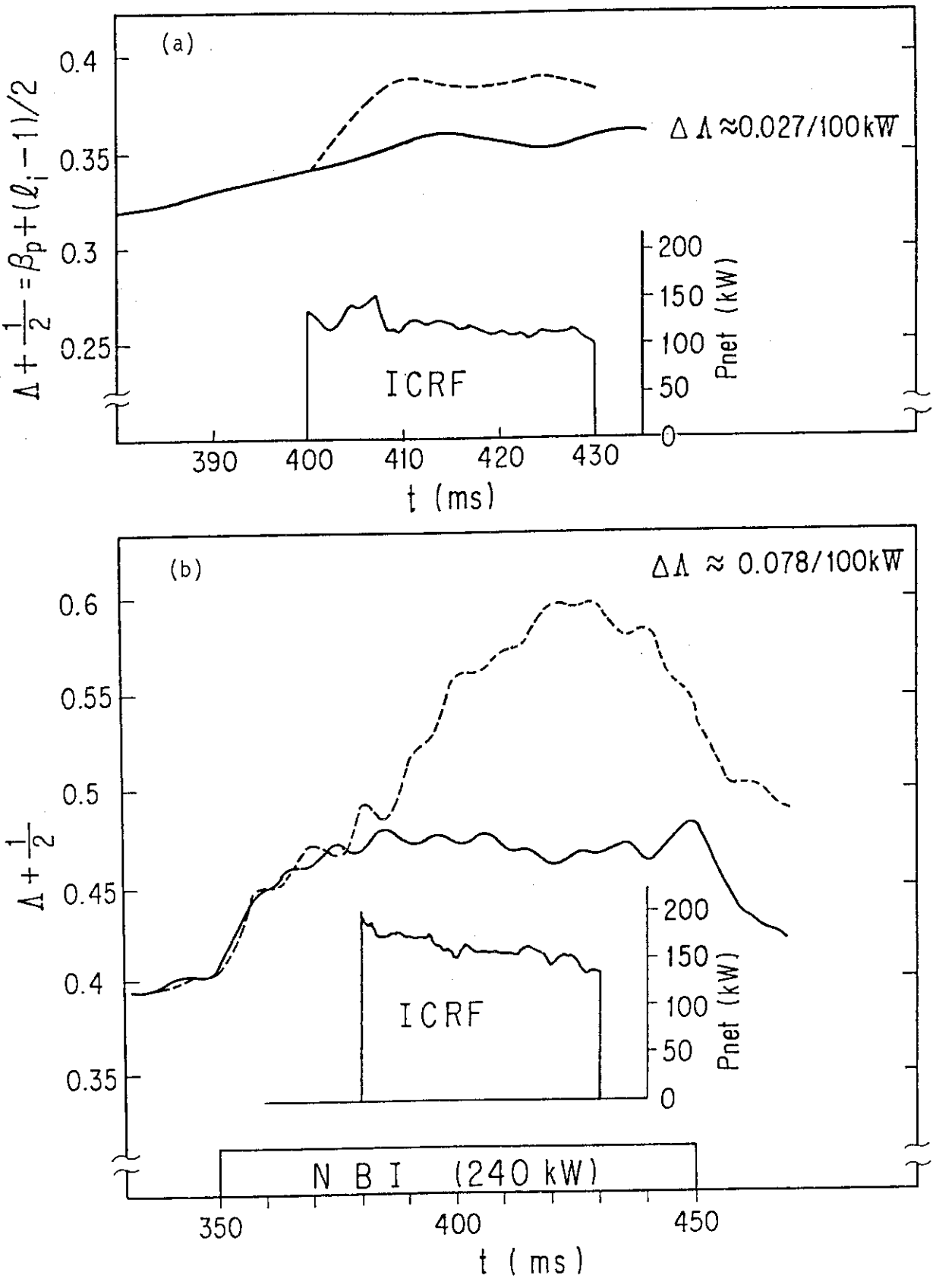

Fig.5 Increase of $\Lambda+1/2$ by the second harmonic ICRF heating (a) without NBI (b) with NBI

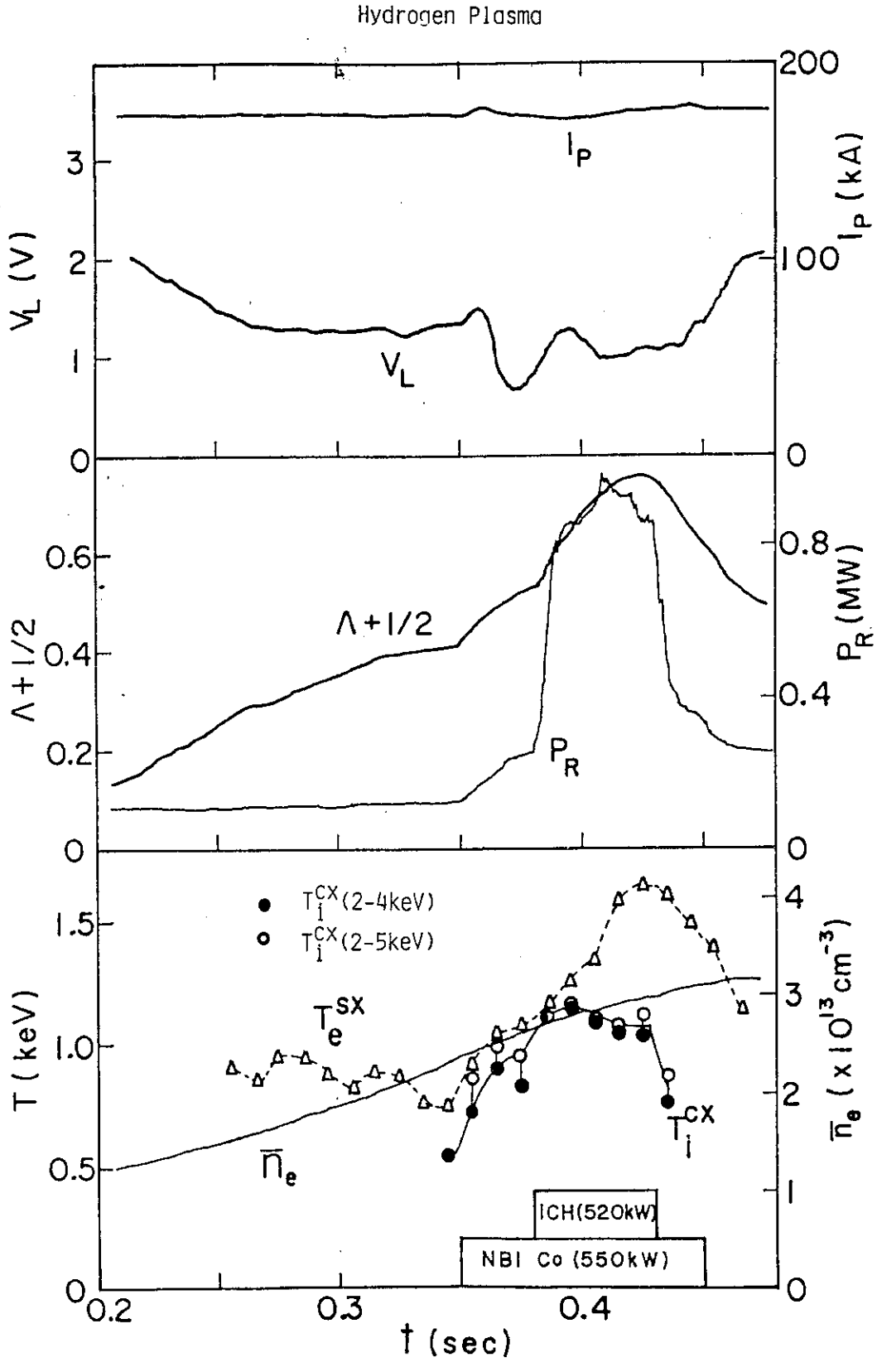

Fig.6 Time evolution of plasma parameters in the second harmonic ICRF heating with NBI.

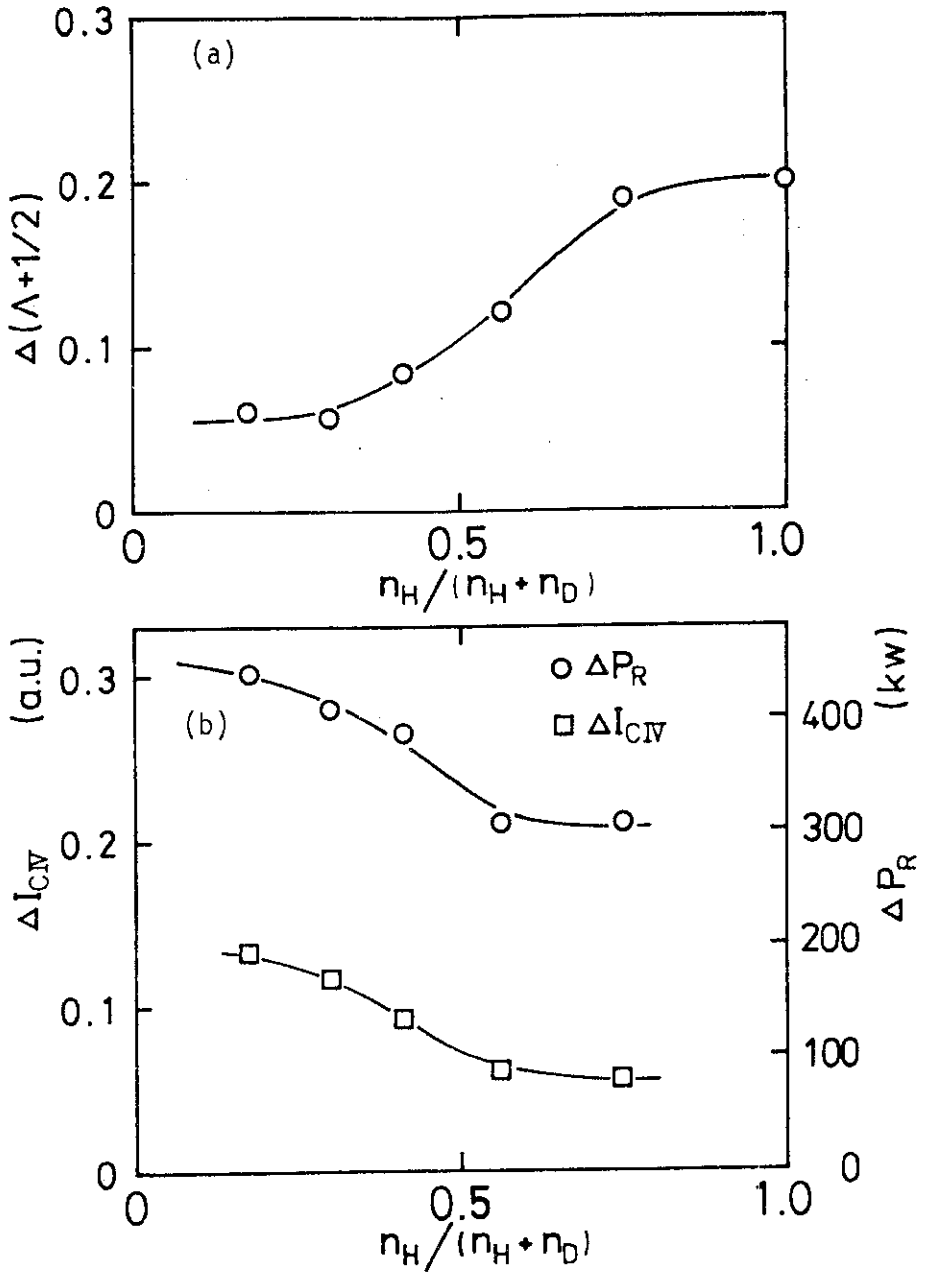

Fig.7 (a) Increase of plasma pressure $\Delta\Lambda$ as a function of hydrogen concentration ratio in hydrogen-deuterium two ion plasma. (b) Increments of radiation loss and carbon impurity by ICRF heating as a function of the hydrogen concentration ratio.

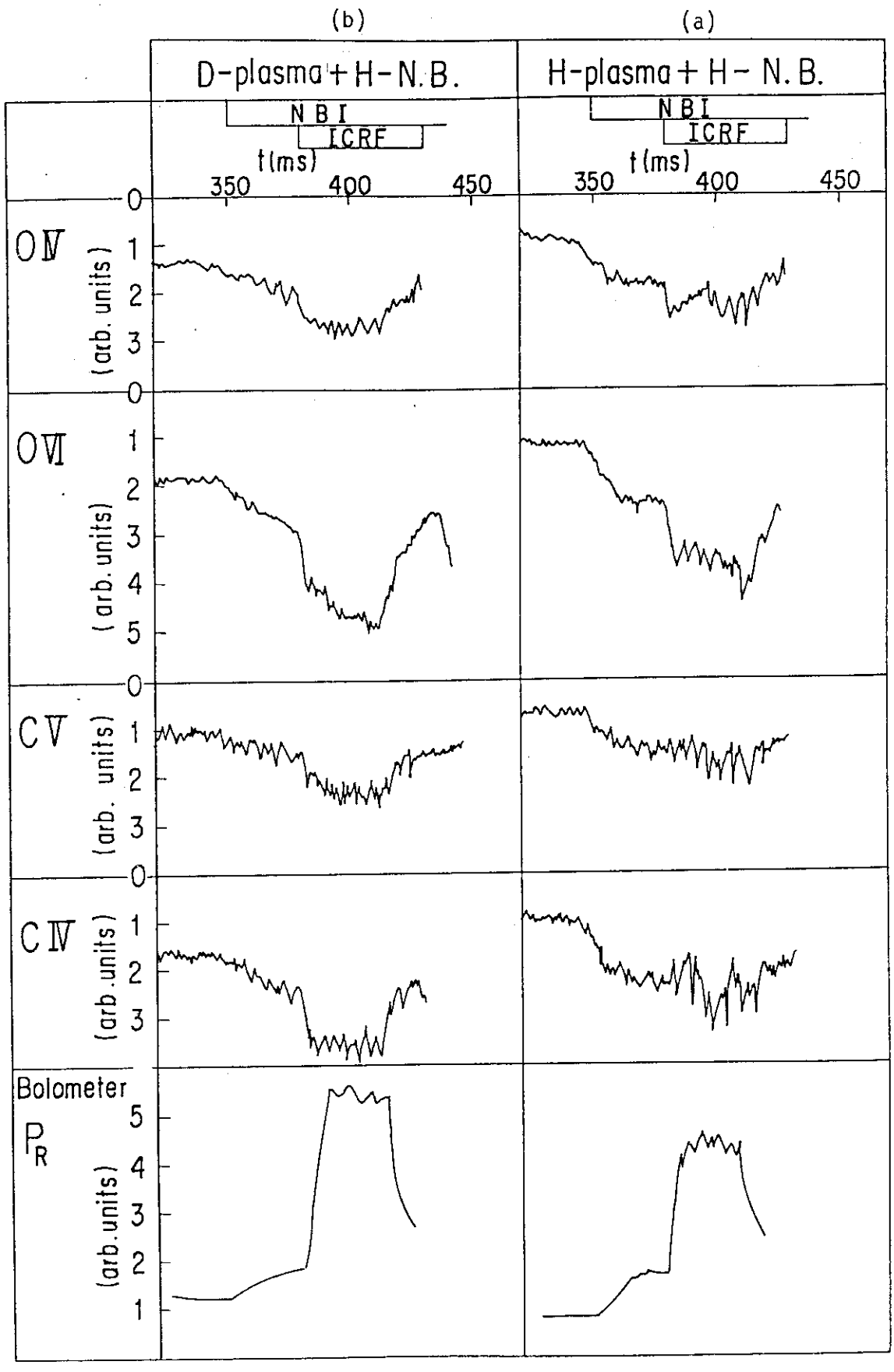

Fig.8 Time evolution of impurity line intensity during the heating (a) with hydrogen plasma (b) with deuterium plasma.

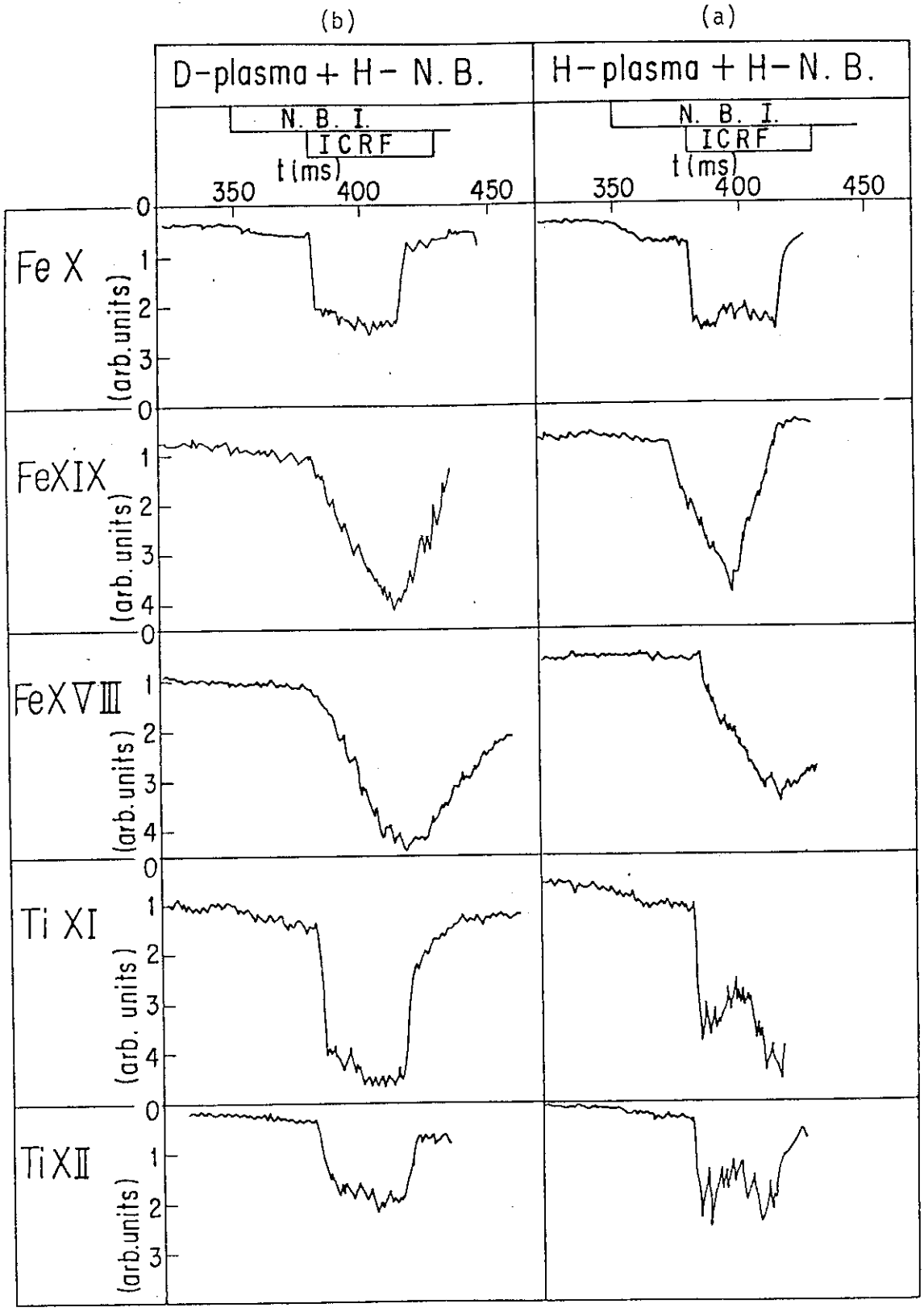

Fig.8 Continued

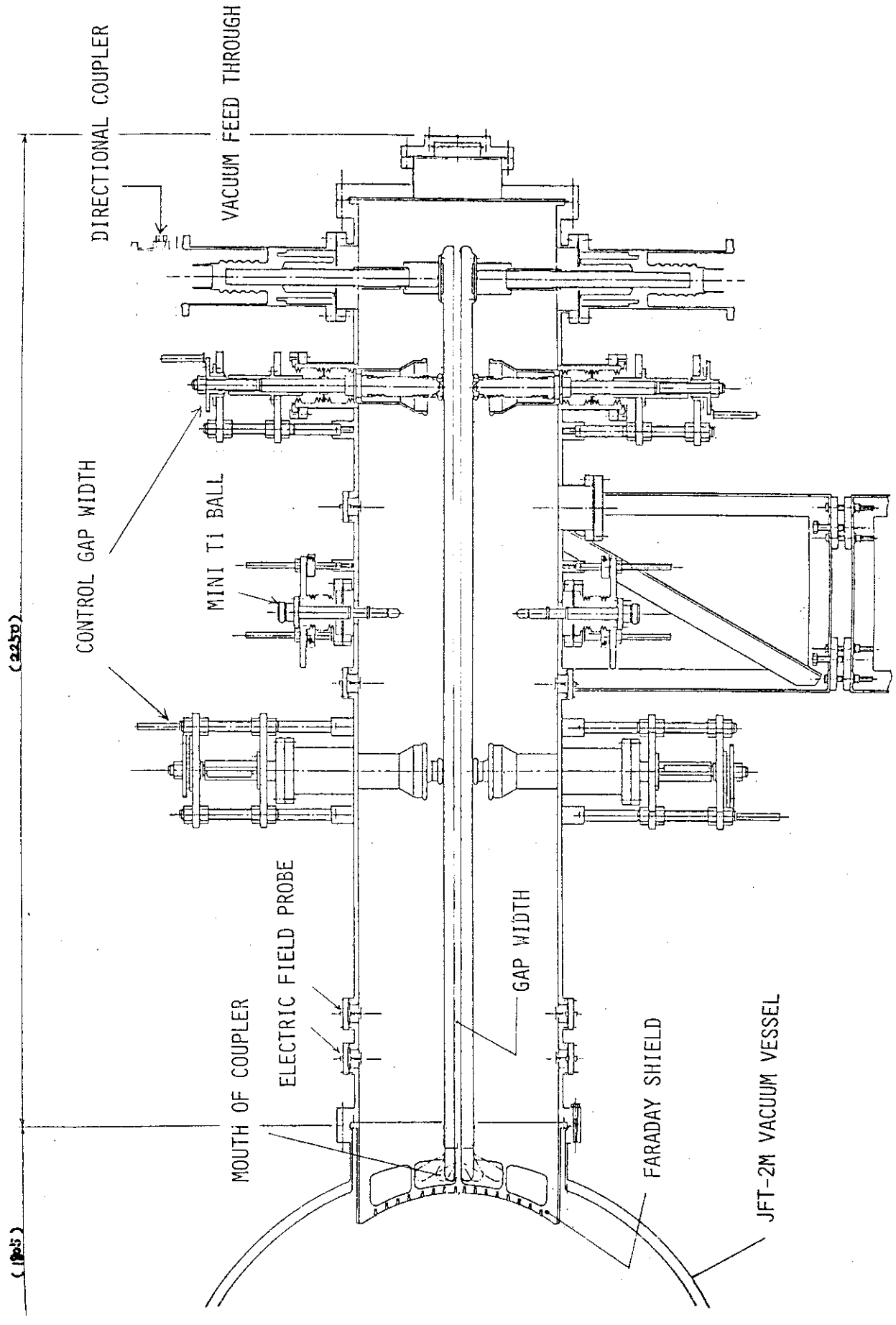

Fig.9 Figure of TEM electric field coupler.

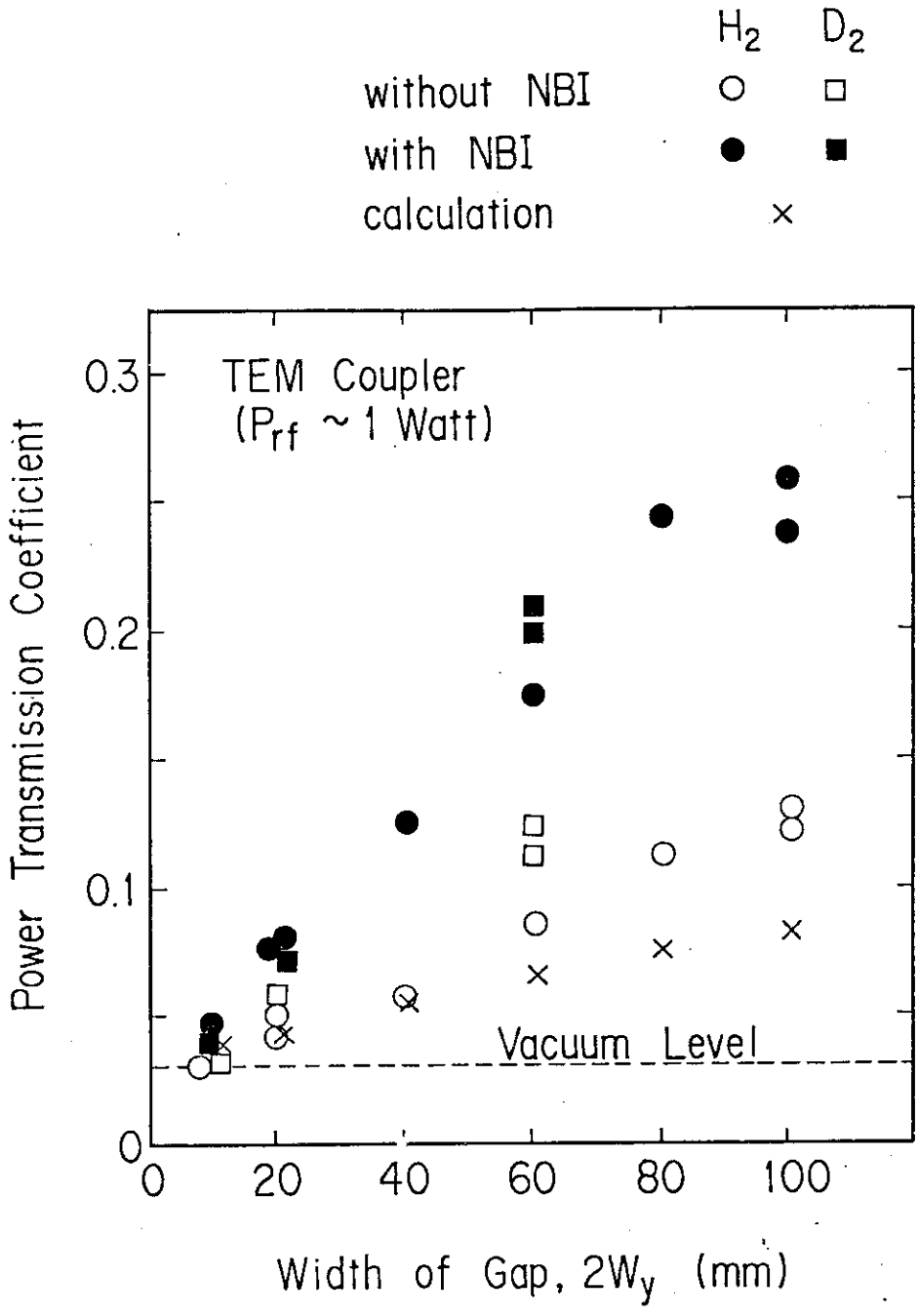

Fig.10 Transmission coefficient as a function of a gap distance between the two parallel plates.

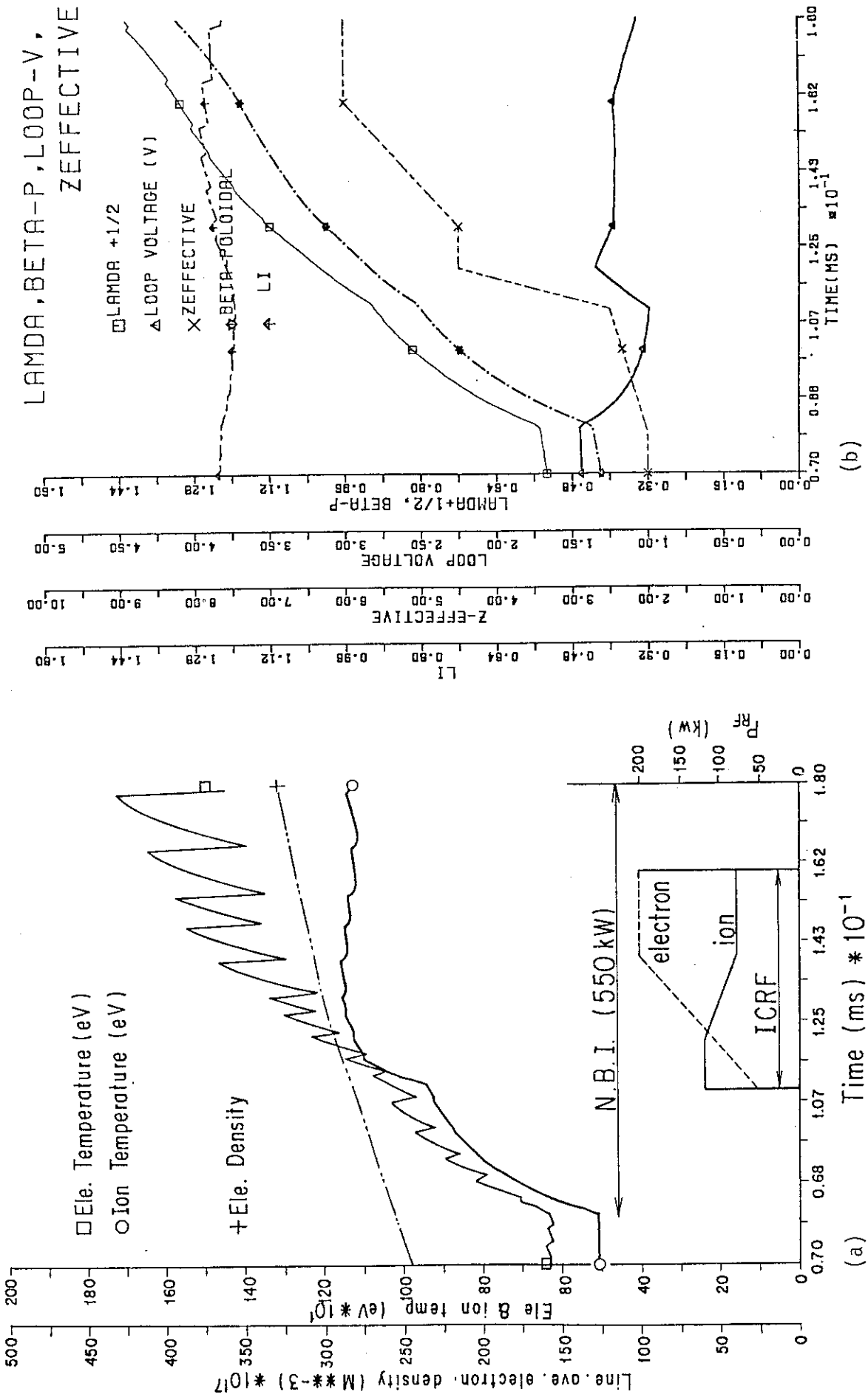

Fig.11 Results of the 1-D tokamak code simulation. (a) Electron and ion Temperatures. Also assumed time evolution of total RF deposition power on electrons and on ions are shown. (b) Assumed evolution of z-effective and the simulation results of Λ+1/2, loop voltage, β_p, and ℓ_i are shown.