ISSN 0915-633X

INTERNATIONAL ATOMIC ENERGY AGENCY

THIRTEENTH INTERNATIONAL CONFERENCE ON
PLASMA PHYSICS AND CONTROLLED NUCLEAR FUSION RESEARCH

Washington, DC, United States of America, 1–6 October 1990

IAEA-CN-53/E-3-3

NATIONAL INSTITUTE FOR FUSION SCIENCE

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(Received – Aug. 29, 1990)

NIFS-42 Sep. 1990

RESEARCH REPORT
NIFS Series

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keywords; fast wave, current drive, higher harmonic heating, JIPP T-IIU, HT-2

IAEA-CN-53/E-3-3

APPLICATION OF INTERMEDIATE FREQUENCY RANGE FAST WAVE TO JIPP T-IIU and HT-2 PLASMA

ABSTRACT

Fast wave well above the fundamental ion cyclotron frequency were applied on JIPP T-IIU and HT-2 tokamak plasma for the study of current drive, electron heating, and third harmonics ion cyclotron heating. In HT-2, up to 10 kA of plasma current was driven by 100 MHz fast wave in the density range of $0.3\sim3*10^{18}m^{-3}$ that corresponds to 1-10 times above the lower hybrid current drive density limit. In JIPP T-IIU, an efficient electron temperature increase was observed on application of 130MHz fast waves in a density range of $2\sim3*10^{19}m^{-3}$ two orders magnitude higher than the lower hybrid density limit. In a further higher density range above $3*10^{19}$ m^{-3} the third harmonics cyclotron heating on the additionally heated target plasma gives a heating efficiency as good as that of fundamental harmonic heating.

1. INTRODUCTION

The intermediate frequency range between third cyclotron harmonic frequency to the lower hybrid frequency has a relevance to the thirmonuclear fusion research in several aspects ; First, the fast wave current drive in this frequency range has a possibility of bulk current drive in hot and dense reactor plasma, which the lower hybrid current drive can not offer[1]. Second, the third cyclotron heating has possibility of Q-enhancement through the selective wave damping on the high energy tritium ions. Third, the coupling of the waves to α-

particles could give a method of α-particle exhaust control.

Fourth, this frequency range offers the use of wave guide launchers.

Several works on this intermediate frequency range have been reported. As for the fast wave current drive in application to standard tokamak plasma[2-4], the electron landau damping of fast wave was confirmed in a plasma with density well above the lower hybrid density limit, although a concrete demonstration waited for further investigation. As for the third harmonics heating, few experimental results are available because of weak damping. But this heating scheme is expected to work better as plasma parameters are improved and may become one of major scheme in reactor grade plasmas. In the present paper, the results of the fast wave current drive and third harmonics ion cyclotron heating experiments in JIPP T-IIU and HT-2 tokamak are reported.

2. FAST WAVE CURRENT DRIVE

HT-2 is an ion core tokamak with the major radius of 0.45 m, the minor radius of 0.12m, and the toroidal field of 2T at maximum. The experiment is conducted in a deuterium slide-away plasma. The three Faraday shielded loop antennas are used to generate the travelling waves with the parallel refractive index $n_{//}$ of 5 by keeping the phase difference between adjacent antennas to be 120 degree. An extensive titanium flashing is applied for the suppression of impurity release from the antenna surface. The time evolution of of plasma parameters in two typical discharges are shown in Fig.1 (a) and (b). The former describes the evolution at relatively lower density of $0.3*10^{18}m^{-3}$ (n_e~n_{crit}) and the latter is at high density of $1.5*10^{18}$ m^{-3} (n_e~$5n_{crit}$), where n_{crit} is the lower hybrid current drive density limit[5]. From case (a), it is seen that, with 25 kW of rf power, the loop voltage drops under zero and transformer current stops increasing according to the application of rf power at 30ms. In case (b), the loop voltage also drops to zero on application of 100kW rf power. However, the density rise due to the impurity release from the antenna surface, seen from the visible light signal of C-III line collimated on the Faraday shield, limit the time duration of the loop voltage drop to only for 2ms. The hard X-ray signal integrated over the energy range above 30 keV using the NaI scintillator placed on the horizontal port strongly increases on application of rf power indicating high energy electron generation.

The dependence of current generated per unit rf power I_{rf}/P_{rf} on the average electron density is shown in Fig.1 (c). The data points well fit the theoretical solid line corresponding to $I_{rf}/P_{rf} \sim 1/n_e$. The current drive efficiency $I_{rf}*n_e*R/P_{rf}$ is found to be 0.01A/Wm^{-2}. According to empirical data base[5], the density limit n_{crit} at 100MHz is $0.3*10^{18}m^{-3}$. The efficiency does not degrade up to the density of $3*10^{18}m^{-3}$ which is 10 times above n_{crit}. Beyond this density the loop voltage drop could not be observed because of the severe impurity release from antenna surface due to increased rf power.

In JIPP T-IIU, the frequency of 130MHz was selected to make a step to asses the absorption mechanism to electrons and ions. The toroidal field is around 3T with which the layer of $\omega=3\omega_{cH}$ locate close to the plasma center. Deuterium is used as working gas with admixture of 10 % hydrogen. A four element toroidal array antenna is placed on the inboard (high field) side.

In plasma density range up to $2\text{-}3*10^{19}m^{-3}$, electron heating by fast wave have been observed. Fig.2 displays typical time evolution of plasma parameters. It is observed that electron temperature rises on application of 200 kW fast waves. Although the density increases due to enhancement in recycling from carbonized materials, the total stored energy increases. The soft X-ray spectra indicates a formation of electron high energy tail above 10 keV.

This density regime is in relevance to fast wave current drive; the wave interacts with electrons at density two orders of magnitude higher than the density limit n_{crit} predicted for lower hybrid current drive[5]. The electron heating in this regime has been identified in previous work with ECRH heated plasma[4]. The present experiment renews the ratio of n_e/n_{crit} by an order of magnitude. It is considered that this was possible due to the relatively high Ohmic electron temperature in JIPP T-IIU because of the relatively high toroidal field which allows for the high plasma current density.

3. THIRD HARMONICS CYCLOTRON HEATING

Electron heating dies out as the plasma density is increased and the other regime appears. In the density range above $2\text{-}3*10^{13}$ cm^{-3}, the third cyclotron harmonics damping dominates. This regime is most clearly established in a superposed use of 130MHz on to the NBI and ICRF(40MHz;two ion hybrid heating regime).
The time history of the typical shot is shown in Fig.3(a), in which the stored energy further increases as 130 MHz is applied, demonstrating that the third cyclotron heating really works in this combined heating. In Fig. 3(b), the ion energy distribution function (with and without 130 MHz) obtained from fast neutral analyzer is shown. It is seen that the high energy of hydrogen tail above 7keV is produced by the application of 130MHz. Without preheating with NBI and 130MHz, 130MHz fast wave could make any appreciable increase in the stored energy. This improved heating efficiency as it is combined with other heating is interpreted as one aspect of the finite Larmor radius effect. In Fig. 3(c), the stored energy dependences on the total power are compared between the combined 130MHz case and only 40MHz heating case. It is found that the heating efficiency of the combined heating is comparable to that of the established 40MHz ICRF heating. We note that, since wave absorption in 130MHz case is significantly large, the heating on the basis of the third cyclotron harmonics may be viable as a new heating regime. In that case, The Q-enhancement through tritium ion tail production and the potential use of wave guide antenna may be counted as

its merit.

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FIGURE CAPTIONS

Fig.1 Time evolution of plasma parameters for typical two shots in HT-2. (a); electron density n_e at $0.3*10^{18}m^{-3}$ and (b); n_e at $1.5*10^{18}m^{-3}$. (c); density dependence of generated current per unity rf power I_{rf}/P_{rf}.

Fig.2 Time history of typical electron heating shot in JIPP T-IIU (a); ECE signal of central chord and 130MHz rf Power, (b); stored energy obtained from diamagnetic signal and flux measurement, (c); Plasma density and internal inductance, (d); Ohmic power; Solid and broken lines are with and without dl_i/dt correction.

Fig.3 The results of the third harmonic ion cyclotron heating in JIPP T-IIU. (a); time evolution of the stored energy; P_{NBI}=300kW, P_{40MHz}=350kW, and P_{130MHz}=400kW (b); the energy distribution of hydrogen ions. (c); power dependence of stored energy.

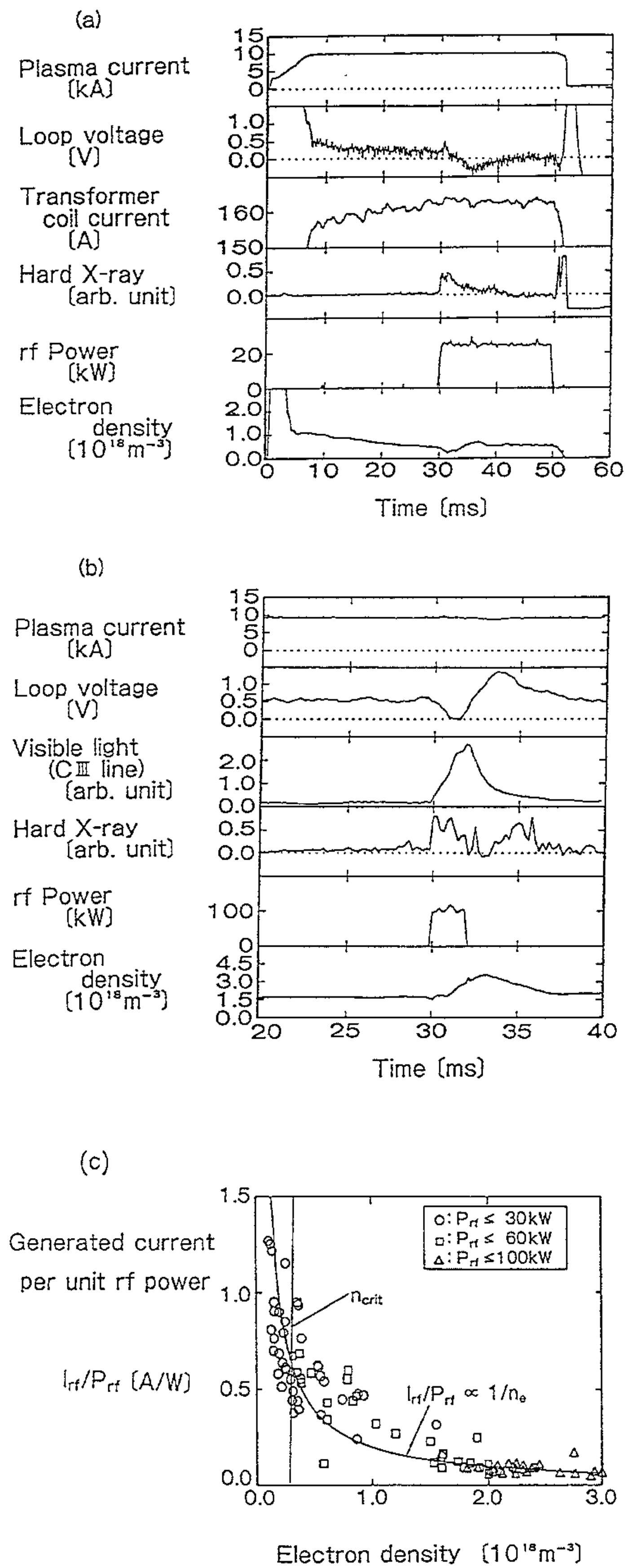
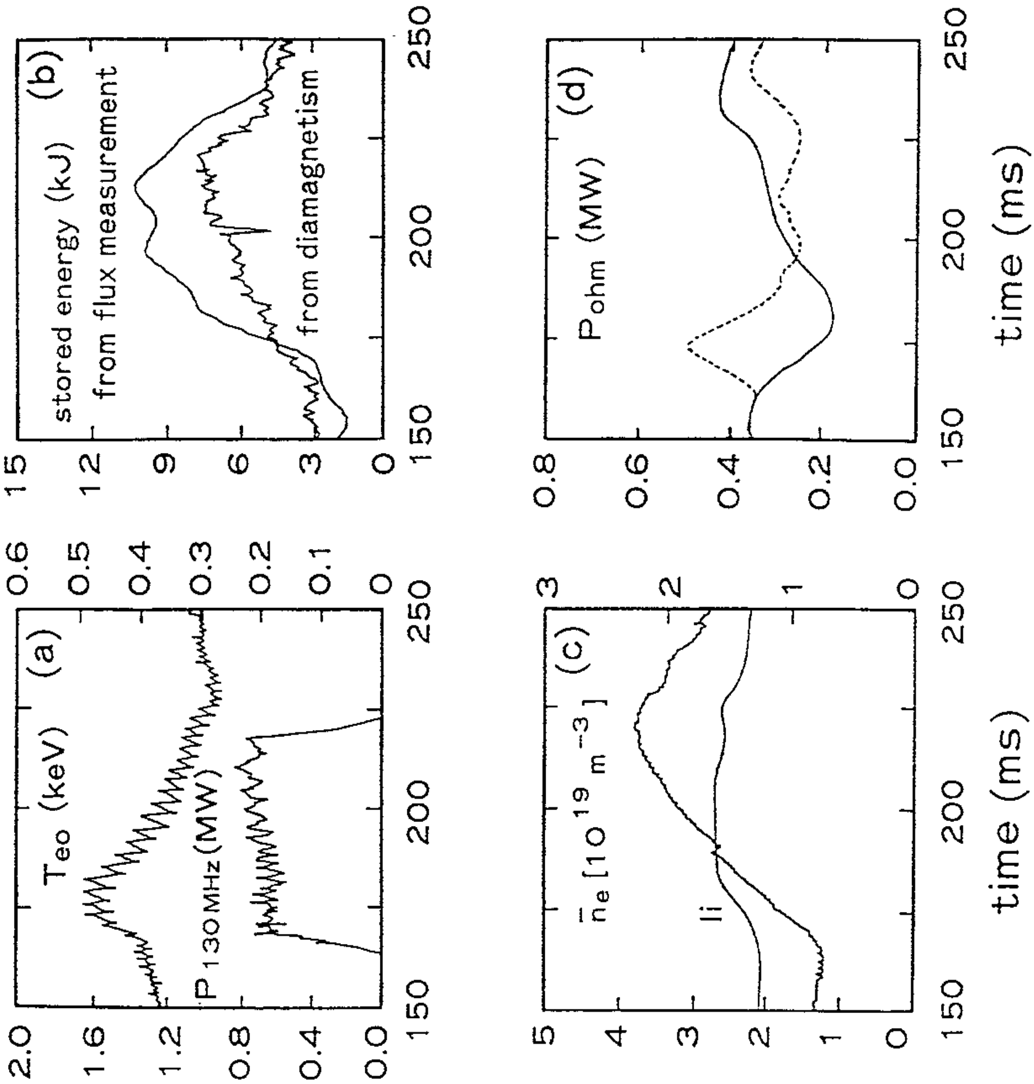

(a)
Plasma current (kA)
Loop voltage (V)
Transformer coil current (A)
Hard X-ray (arb. unit)
rf Power (kW)
Electron density ($10^{18}m^{-3}$)
Time (ms)
(b)
Plasma current (kA)
Loop voltage (V)
Visible light (CIII line) (arb. unit)
Hard X-ray (arb. unit)
rf Power (kW)
Electron density ($10^{18}m^{-3}$)
Time (ms)
(c)
Generated current per unit rf power
I_{rf}/P_{rf} (A/W)
○: $P_{rf} \leq$ 30kW
□: $P_{rf} \leq$ 60kW
△: $P_{rf} \leq$ 100kW
n_{crit}
$I_{rf}/P_{rf} \propto 1/n_e$
Electron density ($10^{18}m^{-3}$)

Fig. 1



(a)
T_{eo} (keV)
P_{130MHz}(MW)
time (ms)
(b)
stored energy (kJ)
from flux measurement
from diamagnetism
(c)
$\bar{n}_e [10^{19} m^{-3}]$
li
time (ms)
(d)
P_{ohm} (MW)

Fig. 2

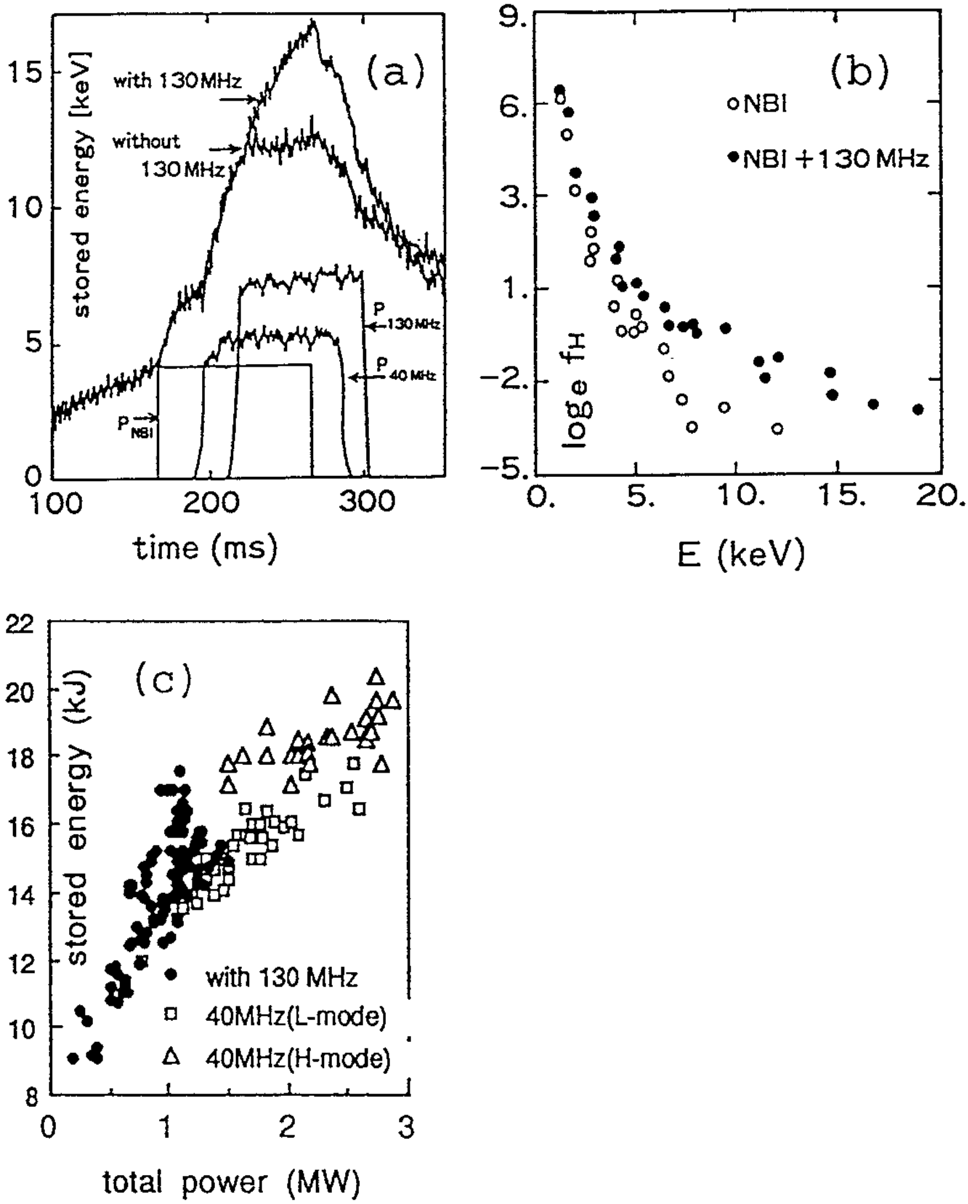

(a)
with 130MHz
without
130MHz
P 130MHz
P 40MHz
P NBI
stored energy [keV]
time (ms)
(b)
NBI
NBI +130MHz
loge fH
E (keV)
(c)
with 130 MHz
40MHz(L-mode)
40MHz(H-mode)
stored energy (kJ)
total power (MW)

Fig. 3