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Key words: Ion Bernstein Wave Heating, high frequency, impurity problem, third cyclotron harmonic heating, profile peaking, bulk heating

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ABSTRACT

Ion Bernstein Wave Heating experiment was conducted in JIPP T-II U tokamak. A relatively high frequency, 130MHz, was used to reduce impurity influx and IBW power up to 400kW was injected without plasma disruption. It was found that the radial profiles of electron density, electron temperature, and ion temperature are all peaked during the IBWH. It was also found that ion distribution function does not have high energy tail above certain critical energy. These are favorable and useful features in optimizing fusion reactivity in reactor applications.

I. INTRODUCTION

Several experiments were conducted for demonstration of IBW heating on tokamaks in the past several years[1-7]. Some of these experiments provide proofs that IBWH works and an unique impact on the plasma confinement has been reported[3-4]. However, other recent experiments did not always reproduce those results[6-7]. Further experimental studies are therefore required in order to improve understanding of physics of IBW Heating. The difficulty in IBWH may partly be attributed to the delicate physics of wave launching[8-10]. We further assume, in this paper, that the impurity problem, which were to some degree problematical in these experiments, may be the other cause of inconsistency between the previous experiments. This thought, combined with the following model of impurity generation[11], made us choose IBWH experiment at a high frequency of 130MHz: A particle in an electric field with frequency ω has velocity v, equivalent energy ε, and excursion length ξ in the following form:

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

These expressions, having inverse power of ω, suggests a prescription for reducing impurity problem in favor of higher frequencies. High frequency also reduces non-linear effects such as ponderomotive potential and ionization.

II. EXPERIMENTAL RESULT

The toroidal magnetic field, B_t, at the plasma center is 3T and hydrogen gas is used as working gas. With this experimental setup, the third cyclotron frequency locates at the plasma axis and fourth harmonic layer behind the antenna. We are thus exploring a new regime of the IBW Heating (3rd hydrogen cyclotron IBW branch) which is another interest we have in the present experiment. The antennas are three T-shaped Nagoya Type-III coils in a toroidal array. The experiment was conducted at density range of $n_e = 2 \sim 6 \times 10^{13} \mathrm{cm}^{-3}$.

The experiment demonstrated that IBW heating also works in the new regime of IBWH. To make this point firm, efforts are made for elaboration of diagnostics. Detailed ion temperature profile was measured by the use of charge-excnage recombination spectroscopy[12]. A significant rise of the central ion temperature occurs during IBWH even with the simultaneous doubling of the central electron density (from $3.7 \times 10^{13} \mathrm{cm}^{-3}$ to $7.5 \times 10^{13} \mathrm{cm}^{-3}$). As shown in Fig.1, the central ion temperature rises from that of NBI heated target plasma by significant amount. As clearly seen in Fig.1, the ion temperature profile of the IBW heated plasma is peaked. The peaking of the profile is not limited to that of ion temperature. Detailed profile measurement revealed similar peaking features of both plasma density and electron temperature profiles. Particularly, density peaking is noted in the comparison of two FIR interferometer signals viewing center and periphery of the plasma(see Fig.2). Improvement of particle confinement on the application of IBW has been reported in the PLT[3] and ALCATOR[4] experiments. The present experiment in JIPP T-II U confirmed that H_α decreases at least around the antenna. The peaking of the electron density profiles described above indicates an improvement of particle confinement at interior of the plasma.

In the past experiments[1-2;40MHz IBWH], the impurity accumulation occurred causing the plasma disruption and prevented them from successful run at higher power level than 100kW. In the present experiment, injection power of 400 kW was readily achieved. Their difference by a factor of four indicates a better performance of high frequency IBWH with regard to impurity problem. The index of the density peakedness, k, defined as some power of the parabolic profile is plotted in Fig.3. The sequential change of k shows that density profile broadens on application of NBI to the Ohmic plasma, peaks when IBW is superposed, and peaks further in the IBW only phase after NBI is terminated.

As another important observation in the experiment, we note that the high energy ion tail is not produced during IBWH. The energy distribution measured with FNA is shown in Fig.4. Though the tail grows with increasing injection power the distribution function drops above a certain energy level. This feature is quite different from those of other ICRF heating regimes and may be explained in terms of the quasi-linear Fokker-Planck RF diffusion model which accommodates third cyclotron harmonic damping, i.e.,

$$\partial f / \partial t = C(f) + Q(f) \quad , \quad \text{with}$$

$$Q(f) = \frac{pZ^2e^2}{2m^2|k_{//}|}|E_X|^2 \sum_n (\partial / v_\perp \partial v_\perp)$$

$$\left(\frac{v_\perp{}^2 n^2}{Z^2} |J_n(Z)|^2 \delta(v_{//}(\text{res}))(\partial f / v_\perp \partial v_\perp) \right) \qquad (2)$$

Here, C(f) is the collision operator and $Z = (k_\perp v_\perp / \omega_i)^2$. For higher harmonic ion Bernstein wave (n=3), $k_\perp \geq \rho_i$ holds and the Bessel function involved in eq.(2) is better approximated by an asymptotic expansion rather than by a power expansion, i.e., the strength of the wave particle interaction reduces with increasing ion energy. Therefore, high energy tail drops off above a certain critical energy.

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FIGURE CAPTIONS

Fig. 1. Ion temperature profiles of NBI heated target plasma and IBW heated plasma.

Fig. 2. Line-integrated density of various lines of sight measured with FIR interferometers; central to peripheral chords from top to bottom.

Fig. 3. The peakedness index, k, of electron density: the labels p-1, p-2, p-3, p-4 refers to Ohmic, NBI, NBI+IBW, and IBW phases, respectively.

Fig. 4. The ion energy distribution function of IBW heated plasma.

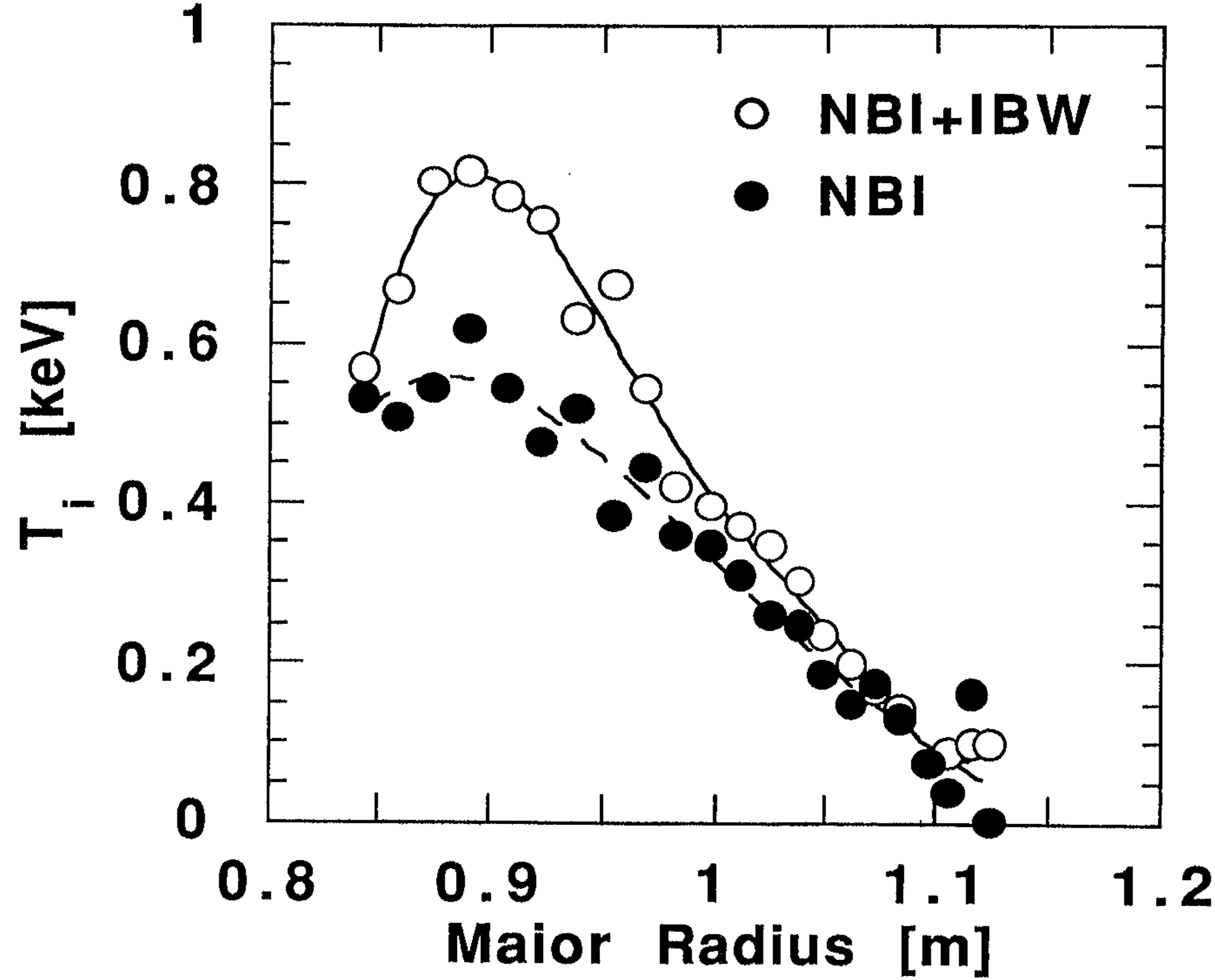
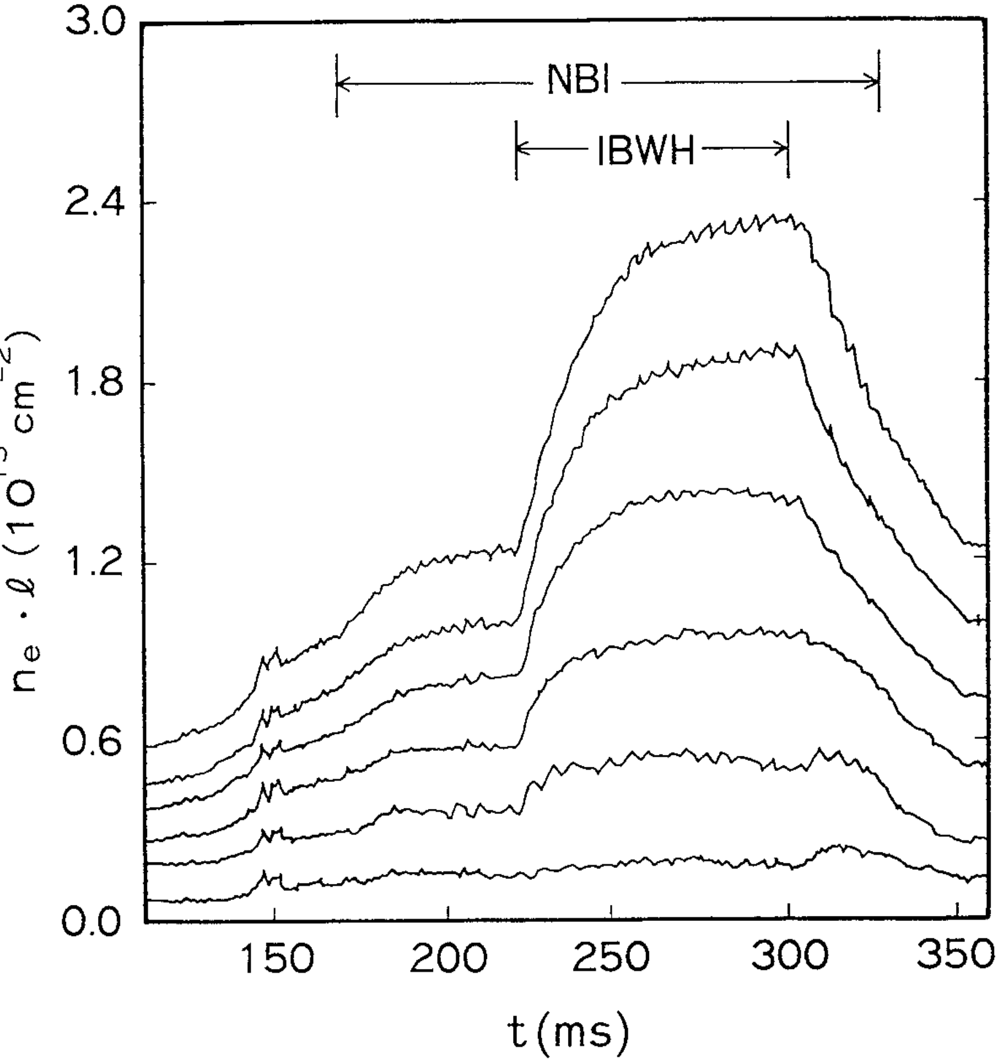


Fig.1



NBI
IBWH
3.0
2.4
1.8
1.2
0.6
0.0
150
200
250
300
350
t (ms)
$n_e \cdot \ell\ (10^{15}\,cm^{-2})$

Fig.2

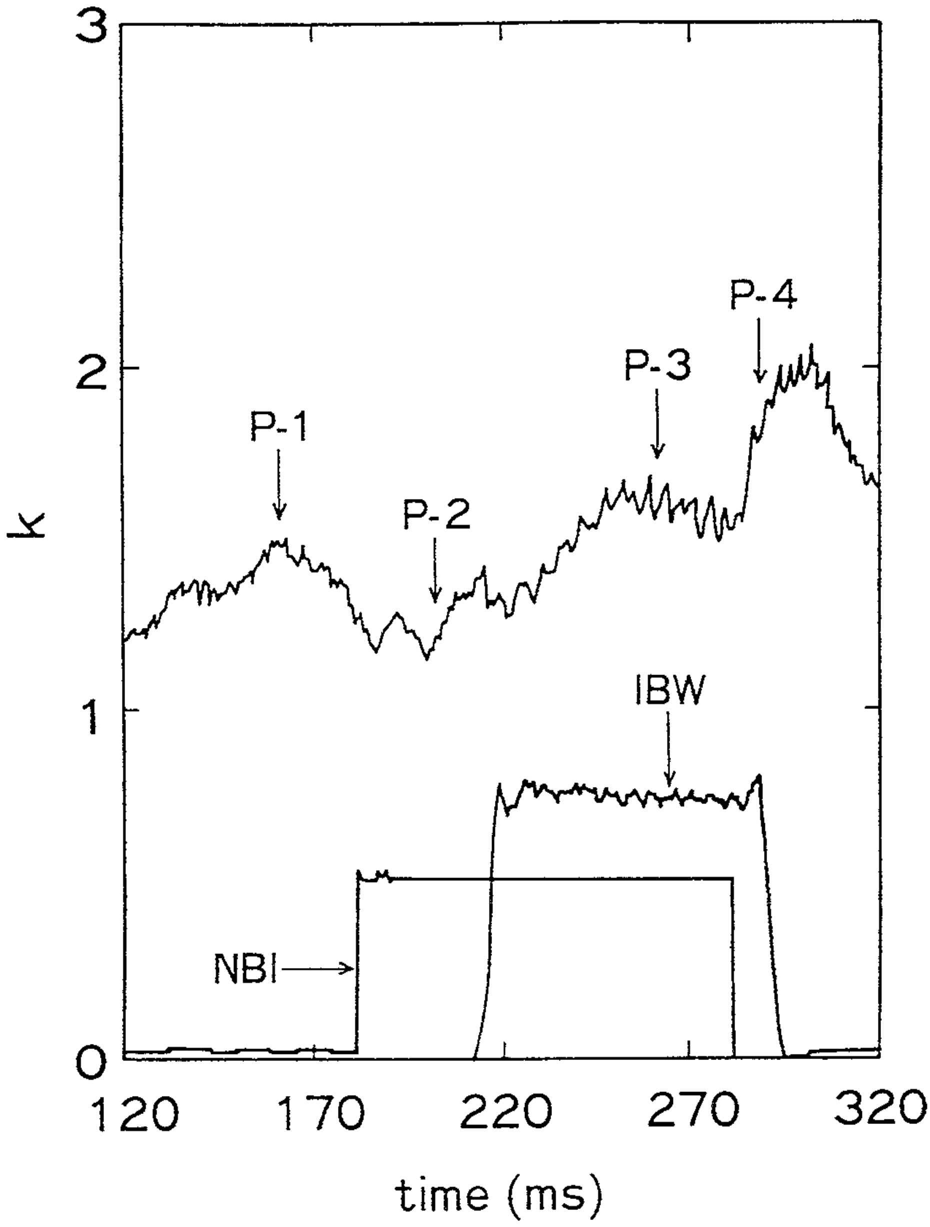


Fig.3

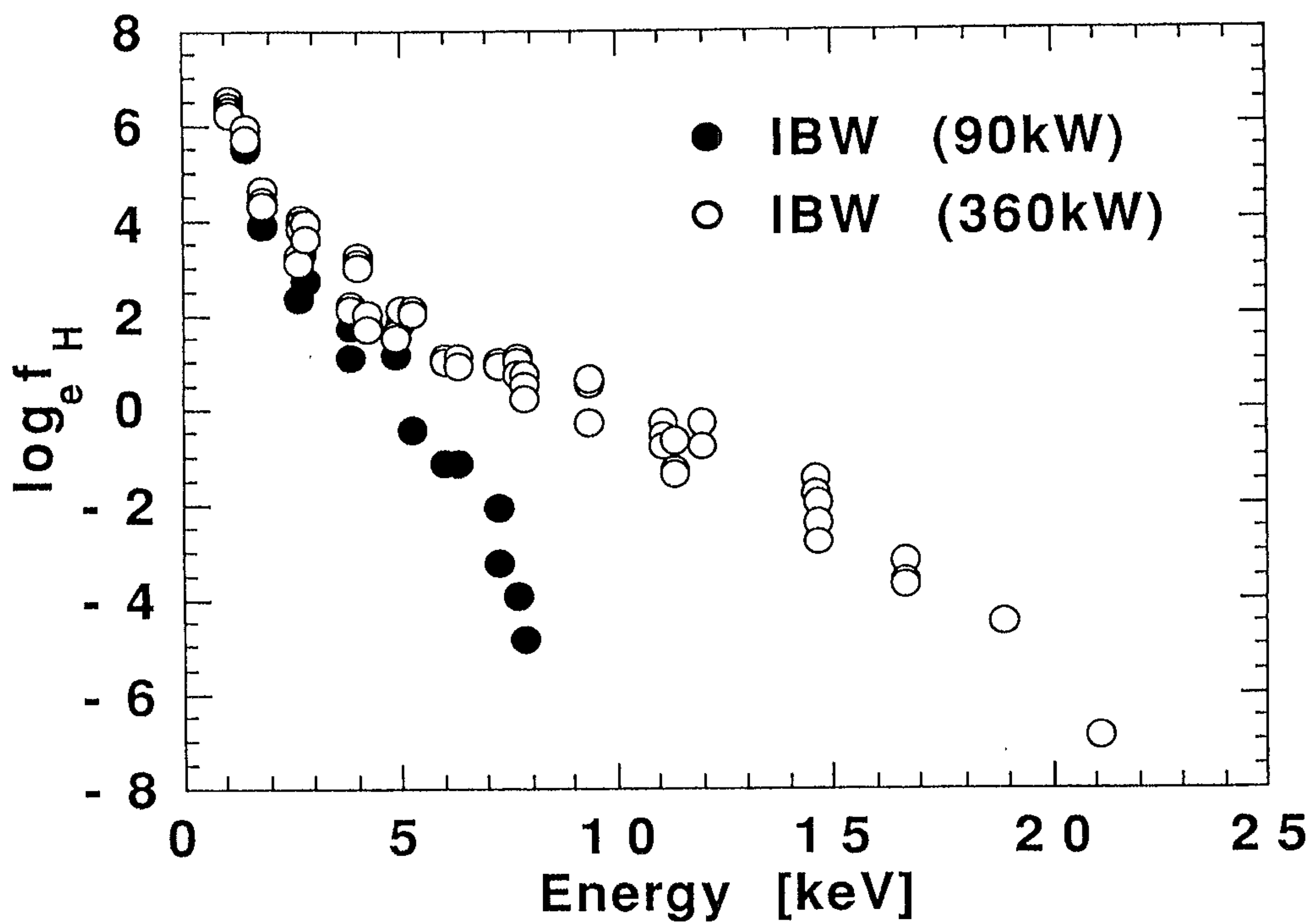


Fig.4

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