JAERI-M
88-259

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December 1988

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編集兼発行　日本原子力研究所
印　　刷　㈱原子力資料サービス

ICRF Enhancement of Power Transfer from Alpha Particles

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(Received November 30, 1988)

Enhancement of the power transfer to a D-T burning plasma from alpha particles heated by ICRF (ion cyclotron range of frequency) waves is investigated by using the rate of linear absorption by alphas based on the energy moments of the quasi-linear RF (radiofrequency) diffusion operator. The effective Q-value, Q_{eff}, which is defined as the ratio of the indirect plasma heating power transferred from alphas to the direct heating power, is evaluated. It is found that the high-Q_{eff} plasma can be realized by use of the fourth harmonic alpha cyclotron wave, which is absorbed mainly by alphas. In the high magnetic field, the third harmonic wave can also enhance Q_{eff} fairly well.

Keywords: Fusion Power Multiplication, Alpha Particle, ICRF Heating, D-T Plasma, Quasi-Linear RF Diffusion

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アルファ粒子からのパワー移行のICRF波による向上

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（1988年11月30日受理）

ICRF（イオンサイクロトロン周波数帯）波により加熱されたアルファ粒子からD－T核燃焼プラズマへのパワー移行の向上について準線型RF（高周波）拡散オペレーターのエネルギーモーメントに基づくアルファ線型吸収率を用いて研究する。アルファ粒子から移行される間接的なプラズマ加熱パワーの直接的な加熱パワーに対する比として定義される実効Q値，Q_{eff}，を評価する。主としてアルファ粒子に吸収される第4高調アルファサイクロトロン波を用いればQ_{eff}の高いプラズマが実現されることが見い出される。高磁場においては第3高調波でもQ_{eff}をかなり増大させることができる。

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1. ICRF ENHANCEMENT OF POWER TRANSFER FROM ALPHA PARTICLES

Achievement of high-Q plasma (Q is the fusion power multiplication factor) is one of the most important issues in the research of thermonuclear controlled fusion. In a high-Q plasma of deuterons(D) and tritons(T), the plasma is sustained mainly by the alpha heating power, which plays an important role in the power balance. The study of the alpha heated plasma, as well as of the alpha particle dynamics, is indispensable for the design of a demonstration reactor. This will be made in an experimental reactor with high Q-value. On the contrary, low-Q plasma experiments which use the intense auxiliary heating are not suitable for the alpha heating studies, since the fraction of the alpha heating of the total heating is small. Recently techniques to study the alpha-like heating without introduction of D-T fuels were proposed [1,2]. Fast ions to simulate fusion-produced alpha particles can be produced by ICRF(ion cyclotron range of frequency) minority heating [1] and by accelerating beam-induced energetic ions with fast waves at frequencies of ion cyclotron harmonics [2]. In the present work, we propose another technique to study high-Q plasma physics by using fusion-produced alphas actively in a low-Q reactor. This is based on the heating of alphas and on the subsequent enhancement of the power transfer to a D-T burning plasma from alphas. The heating of alphas can be performed by using fast waves at frequencies of alpha cyclotron harmonics which are equal to deuteron ones. The wave power absorbed by alphas can be transferred to mainly bulk electrons. Such a mechanism is considered to be used to simulate the enhancement of the alpha heating rate without increasing the input power to heat fuel ions and/or electrons directly, if wave deposition to alphas is significantly large without degradation of the resultant energy confinement time. When the effective fusion power multiplication factor, Q_{eff}, which is defined as the ratio of the indirect plasma heating power transferred from alphas to the direct heating power, is large enough, the alpha heating in a high-Q plasma is substantially simulated: The high-Q_{eff} plasma corresponds to the plasma sustained mainly by the alpha heating. This proposal is more relevant to near future D-T experiments than the above mentioned proposals. In addition, if the energy confinement time is improved by the enhanced alpha heating with centrally peaked deposition, this technique becomes useful for a path to the ignition.

In the present paper, enhancement of the power transfer from alpha particles heated by ICRF waves is investigated to examine the possibility for achievement of the effectively-high-Q plasma. The effective Q-value, Q_{eff}, is evaluated by using the rate of linear wave absorption by alphas based on the energy moments of the quasi-linear RF diffusion operator, which contains the right and left hand circularly polarized amplitudes of the RF electric field [3].

We consider the following situation: Plasma is sustained initially by the direct heating power of P_{in}^0 and the alpha heating power of P_α^0. Then the fusion power multiplication factor, Q_0, is given by

$$Q_0 = 5\frac{P_\alpha^0}{P_{in}^0} , \tag{1}$$

where the factor 5 includes the contribution of the neutron energy to the fusion output power. When the ICRF wave power, P_{RF}, is injected in addition to the direct heating power, P_{in}, P_{RF} is absorbed by alphas with the "alpha absorption fraction", R_α, and the effective Q-value can be defined as

$$Q_{eff} = 5\frac{P_\alpha + R_\alpha P_{RF}}{P_{in} + (1 - R_\alpha)P_{RF}} . \tag{2}$$

Here, the fusion output power due to alpha production, P_α, and the RF power absorbed by alphas, $R_\alpha P_{RF}$, are assumed to be transferred to the background plasma. The quantity Q_{eff} represents the effective fusion power multiplication factor in the plasma sustained by the direct heating power of P_{in} + $(1 - R_\alpha)P_{RF}$ and by the alpha heating power of $P_\alpha + R_\alpha P_{RF}$.

By keeping the total input power constant, $P_{in}^0 = P_{in} + P_{RF}$, and assuming plasma temperatures to be unchanged, $P_\alpha^0 = P_\alpha$, Q_{eff} is written as

$$Q_{eff} = 5\frac{P_\alpha^0 + R_\alpha P_{RF}}{(P_{in}^0 - P_{RF}) + (1 - R_\alpha)P_{RF}} . \tag{3}$$

We note that the actual Q-value is unchanged, $Q = Q_0$. By defining the RF power ratio by $R_{RF} \equiv P_{RF}/P_{in}^0$, Eq.(3) becomes

$$Q_{eff} = \frac{Q_0 + 5R_\alpha R_{RF}}{1 - R_\alpha R_{RF}} . \tag{4}$$

The value of Q_{eff} increases with R_α and R_{RF}. In the calculation of R_α, the velocity distribution of alphas is taken to be a slowing-down one, while Maxwellian distributions are assumed for other species. The wave parameters are determined from the cold plasma dispersion relation. The "alpha absorption fraction", R_α, increases with the harmonic number, $N \equiv \omega/\omega_{c\alpha}$, and ω_{ce}/ω_{pe} [3], where ω, $\omega_{c\alpha}$, and ω_{ce}/ω_{pe} are the wave frequency, alpha cyclotron frequency, and electron cyclotron frequency relative to plasma frequency, respectively. We take the moderate and high toroidal magnetic field of B_t = 5 T and 10 T, and low and moderate electron densities of n_e = 5×10^{19} m^{-3} and 10^{20} m^{-3}. In the figures shown below, the cases of B_t = 5 T and 10 T are depicted by solid and dashed lines, respectively, for (a) n_e = 5×10^{19} m^{-3} and (b) n_e = 10^{20} m^{-3}.

The dependence of R_α on the plasma temperature, T, for N = 2, 3, and 4 is shown in Fig. 1. The electron and ion temperatures are assumed to be the same for simplicity. The value of R_α for N = 2 is not large enough to significantly enhance Q_{eff} by RF injection. The rate of increase of R_α with $T(\geqq 10$ keV) becomes small with T for N = 3. In the range, $T \geqq 10$ keV, R_α is almost unchanged for N = 4. Therefore, the increase of $T(\geqq 10$ keV) can not enhance Q_{eff} markedly. In the following, we examine the enhancement of Q_{eff} by RF injection for N = 3 and 4 in the case of T = 10 keV.

Figures 2 and 3 show Q_{eff} as a function of R_{RF} for N = 3 and 4, respectively. Values of Q_0, which are values of Q_{eff} at R_{RF}=0, are chosen to be 0.1, 0.5, 1, and 5. In the case of N = 3 and B_t = 5 T (solid lines), Q_{eff} of 10 is scarcely achieved for Q_0 = 5 at (a) $R_{RF} \sim 0.6$ and at (b) $R_{RF} \sim 1$. On the other hand, in high B_t of 10 T (dashed lines), Q_{eff} of 10 can be achieved even for Q_0 = 0.1 - 1 at (a) R_{RF} = 0.75 - 0.85 and at (b) R_{RF} = 0.8 - 0.9. For Q_0 = 5, $R_{RF} \sim 0.4$ yields Q_{eff} of 10 and R_{RF} = 1 yields Q_{eff} of (a) ~50 and (b) ~30. The rate of increase of Q_{eff} in the logarithmic scale with R_{RF} increases with decreasing Q_0, which leads to the abrupt increase of Q_{eff} for Q_0 = 0.1 in the range, $R_{RF} \ll 1$. In the case of N = 4 (Fig.3), for Q_0 = 0.1 - 1, R_{RF} of 0.6 - 0.7 gives Q_{eff} of 10 except for the cases of B_t = 5 T and n_e = 10^{20} m^{-3}, shown by solid lines in Fig.3(b), where $R_{RF} \sim 0.8$ is required for Q_{eff} of 10. For Q_0 = 5, R_{RF} of 0.3 - 0.4 gives Q_{eff} of

10. At $R_{RF} \sim 1$, values of Q_{eff} of 20 - 40 are obtained even in the cases of moderate density and moderate magnetic field, which are shown by solid lines in Fig.3(b). Values of Q_{eff} reach up to 10^2 - 10^3 in the high magnetic field or low density. In high B_t of 10 T, Q_{eff} can be improved as compared with the case of B_t = 5 T, especially for (a) $R_{RF} > \sim 0.8$ and for (b) $R_{RF} > \sim 0.5$. Thus, the forth harmonic alpha cyclotron wave, which is absorbed mainly by alphas, is promising for achievement of the high-Q_{eff} plasma. The third harmonic wave can also enhance Q_{eff} fairly well in the high magnetic field: Values of Q_{eff} in the high magnetic field for $N = 3$, which are shown by dashed lines in Fig.2, are comparable to those in the moderate density and moderate magnetic field for $N = 4$, which are shown by solid lines in Fig.3(b).

Finally we discuss the strength of the RF electric field required. The left hand circularly polarized amplitude of the RF electric field, $|E_+|$, can be estimated through the RF power density, $\mathcal{P}_{RF}$ [3]:

$$|E_+|^2 \sim \frac{(1-R_\alpha)\,\mathcal{P}_{RF}}{m_D\, n_D \dfrac{1}{N\,\omega_{c\alpha}} \dfrac{R_0}{r_R} \dfrac{z_D^2\, e^2}{m_D^2} \dfrac{N}{(N-1)!} \left(\dfrac{k_\perp}{2\,\omega_{c\alpha}} \sqrt{\dfrac{2T}{m_D}}\right)^{2(N-1)}} . \tag{5}$$

Here, m_D, n_D, and z_D are the deuteron mass, number density, and charge number, respectively, e the elementary charge, $k_\perp$ the wavenumber perpendicular to the magnetic field, R_0 the major radius of the torus, and the wave deposition region is specified as $r \leqq r_R$. For T = 10 keV, the alpha heating power density, $\mathcal{P}_\alpha^0$, is 0.04 MW/m^3 at $n_e = 5\times10^{19}$ m^{-3} and $\mathcal{P}_\alpha^0$ = 0.15 MW/m^3 at $n_e = 10^{20}$ m^{-3}. We note that the input power density, $\mathcal{P}_{in}^0$, scales with Q_0^{-1} and that the RF power density and hence the RF electric field for achieving the same Q_{eff} decreases with Q_0. Then, $\mathcal{P}_{RF} \sim 5\, R_{RF}\, \mathcal{P}_\alpha^0 / Q_0$ is at most 2 MW/m^3 (7.5 MW/m^3) for $n_e = 5\times10^{19}$ m^{-3} ($n_e = 10^{20}$ m^{-3}), Q_0 = 0.1, and R_{RF} = 1. In Table 1 maximum values of $|E_+|$ are tabulated for these $\mathcal{P}_{RF}$ values in the case of R_0/r_R = 10. They increase with N and B_t. The right hand circularly polarized amplitude, $|E_-|$, is about $\sqrt{3}$ times as large as $|E_+|$ for $N = 3$, and $|E_-| \simeq \sqrt{2}\, |E_+|$ for $N = 4$. Therefore, the strength of the RF electric field required for high-Q_{eff} achievement is at most on the order of 10^5 V/m for Q_0 = 0.1. These values seem rather large but still allowable.

In conclusion, the possibility that the effectively-high-Q plasma is achieved by ICRF wave deposition to alpha particles has been set forth.

The effective Q-value, Q_{eff}, increases with the cyclotron harmonic number and the toroidal magnetic field, although the RF electric field, which gives the same RF power, also increases with them. In the present work, Q_{eff} is evaluated from the linear absorption rate of ICRF waves. The quasi-linear deformation of the deuteron distribution, which is accompanied by the deuteron tail formation, reduces the rate of wave absorption by alphas [3], and hence Q_{eff}, although the RF electric field required to give the same RF power may become lower than that of the linear analysis. The influences of accelerated trapped alpha particles, for example, ripple loss and fishbone instability are also important in ICRF heating. The analyses taking these effects into account are left to future studies.

ACKNOWLEDGEMENTS

The authors would like to thank Drs T. Takeda, S. Matsuda, S. Yamamoto, M. Mori, and S. Nishio for continuous encouragement.

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Table 1 Maximum amplitude of RF electric field, $\lvert E_+\rvert$, for T = 10 keV, Q_0 = 0.1, and R_0/r_R = 10

N		3		4	
n_e (m^{-3})		5×10^{19}	10^{20}	5×10^{19}	10^{20}
$\mathcal{P}_{RF}$ (MW/m^3)		2	7.5	2	7.5
$\lvert E_+\rvert$ (V/m)	B_t = 5 T	2.1×10^4	1.8×10^4	3.7×10^4	3.6×10^4
	B_t = 10 T	7.7×10^4	6.4×10^4	1.5×10^5	1.1×10^5

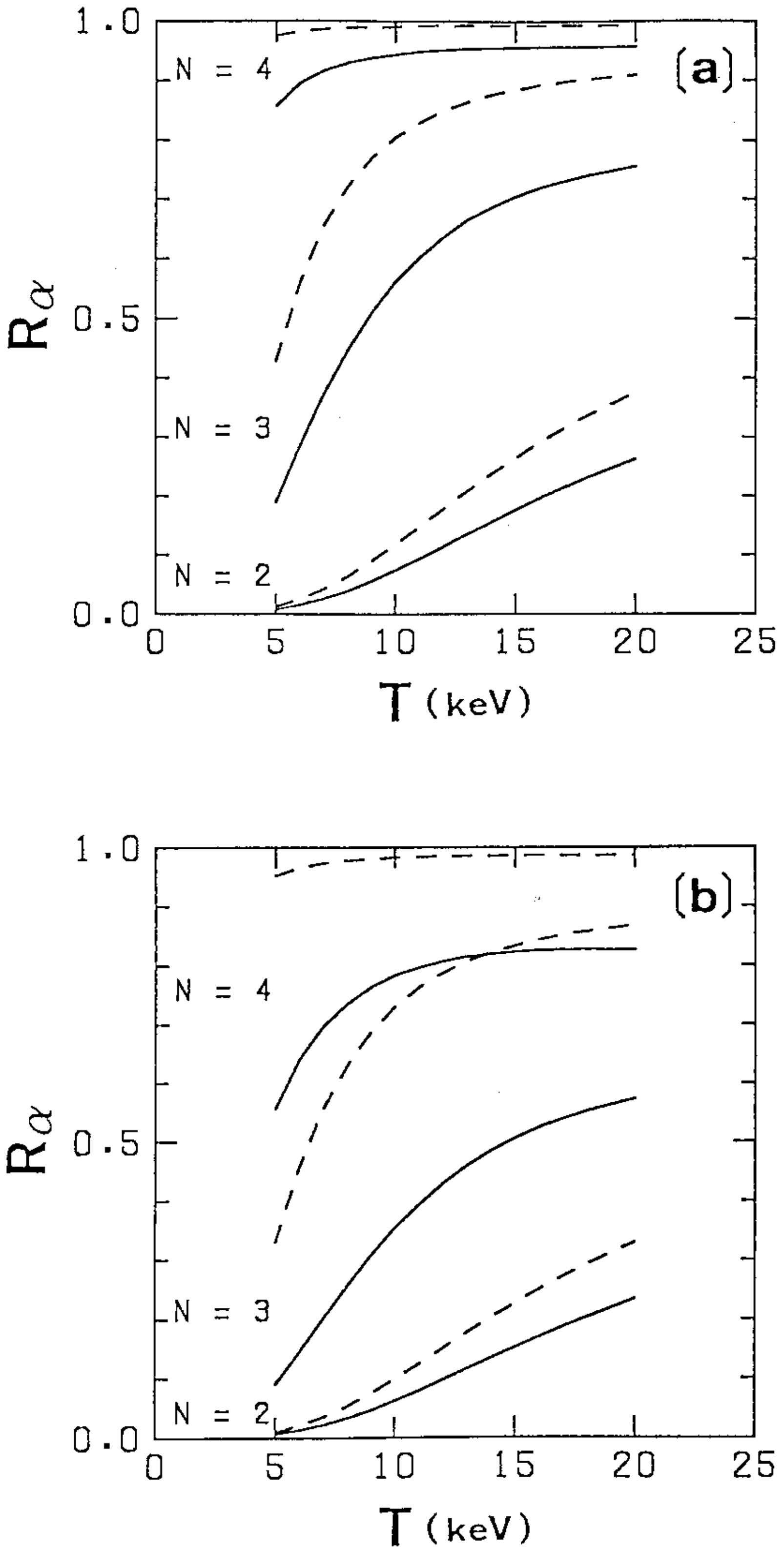

Fig. 1 R_α versus T for N = 2, 3, and 4. Cases of B_t = 5 T and 10 T are shown by solid and dashed lines, respectively, for (a) $n_e = 5\times10^{19}$ m^3 and (b) $n_e = 10^{20}$ m^3.

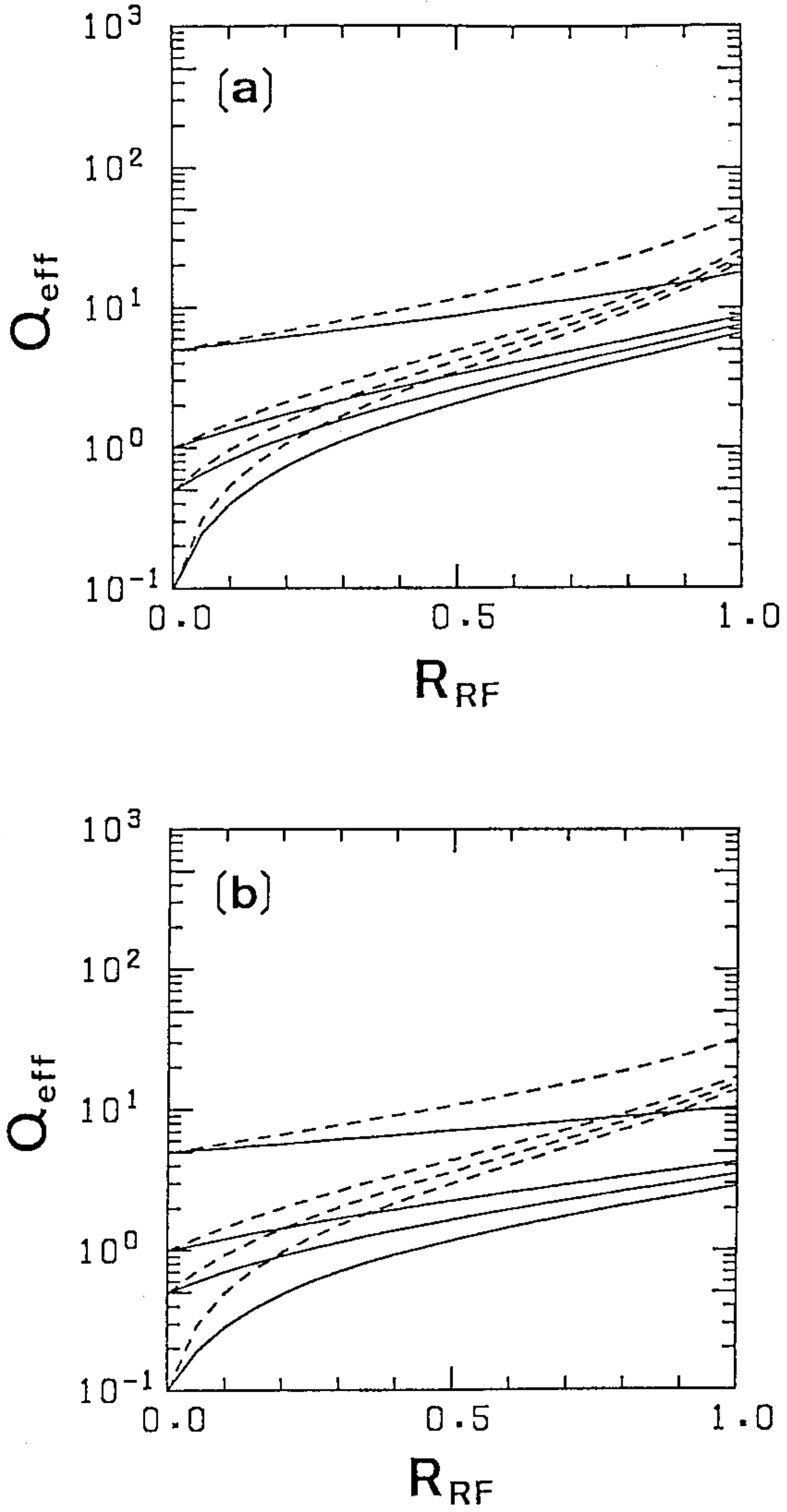

Fig.2 Q_{eff} versus R_{RF} for N = 3. Cases of B_t = 5 T and 10 T are shown by solid and dashed lines, respectively, for (a) n_e = 5×10^{19} m^3 and (b) n_e = 10^{20} m^3. Plasma temperature, T, is 10 keV. Values of Q_0 are chosen to be 0.1, 0.5, 1, and 5.

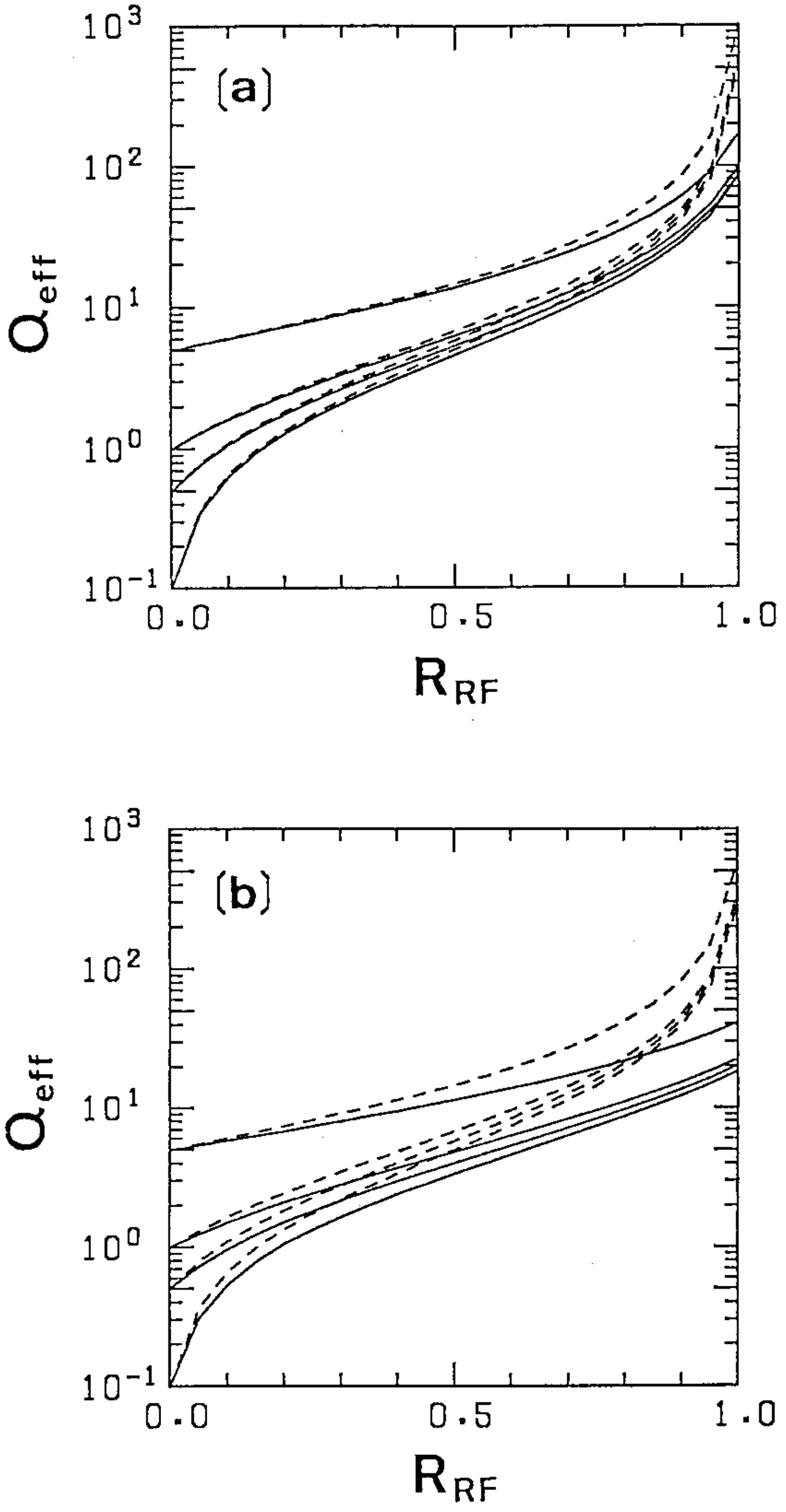

Fig.3 Q_{eff} versus R_{RF} for $N = 4$. Cases of $B_t = 5$ T and 10 T are shown by solid and dashed lines, respectively, for (a) $n_e = 5\times10^{19}$ m^3 and (b) $n_e = 10^{20}$ m^3. Plasma temperature, T, is 10 keV. Values of Q_0 are chosen to be 0.1, 0.5, 1, and 5.