JAERI-M
82-023

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March 1982

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編集兼発行　日本原子力研究所
印　　　刷　(株)原子力資料サービス

Pinch Effect in Current Sustaining Tokamak
by
RF Traveling Wave

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(Received February 15, 1982)

In current sustaining tokamak by use of Landau damping, resonant particles feel an effective DC field in the toroidal direction to drive the plasma current, and the rf field reaches thousand times larger than the Joule field. The density evolution has been simulated using one dimensional tokamak code including the current drive pinch due to inward $E_{rf} \times B_\theta$ drift. This effect could be the basis of the improvement of confinement and impurity control by rf traveling wave.

Keywords; Landau Damping, Current Sustaining, Plasma Currents DC field, One Dimensional Tokamak Code, $E_{rf} \times B_\theta$ Drift Pinch Effect Tokamak

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JAERI－M 82－023

ＲＦ進行波による電流維持トカマクのピンチ効果

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（1982年2月15日受理）

ランダウ減衰を用いる電流維持トカマクでは，共鳴粒子が，トロイダル方向の高周波電場を効果的な直流電場として感じることによりプラズマ電流が発生する。この時の高周波電場E_{rf}は準線形効果により減衰が抑えられて，ジュール電場の千倍以上にも達する。トーラス子午面の内側に向かう$E_{rf} \times B_\theta$ドリフトによるピンチ効果を含んだ一次元トカマクコードを用いて，電流維持トカマクの密度発展がシミュレートされた。この効果はＲＦ進行波による電流維持トカマクにおいて，プラズマ閉じ込めの質的改善をもたらすだけではなく，不純物制御をも可能にするものである。

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目次なし

Magnetic fusion program have been a history of the efforts how can we reduce the anomalous cross field diffusion in magnetic traps. In stars, fusion reaction may be sucessfully occurred by the good confinement due to inward gravitational force even at several keV of the plasma temperature, which is already performed in the laboratory plasma.[1,2] The larger machine we must construct as long as we cannot confine plasmas by the centrifugal force as stars, because the confinement time is proportional to the square of the machine scale in the usual diffusion. In torus configuration, there seems to be two simple cases that plasma can be confined by the centrifugal electromagnetic drift as shown in Fig. 1, that is, poloidal electric field E_θ cross toroidal magnetic field B_t and toroidal electric field E_t cross poloidal magnetic field B_θ. The flux control proposed by Itoh belongs to the former case[3], and Ware pinch being caused by banana motion of neo-classical trapped particles does the latter[4]. Ohkawa suggested that in the counter-injection neutral beam the Ware pinch is enhanced and the resultant suppression of the density clamping which are observed in many NBI experiments is possible[5].

In tokamak configuration, an initial pinch occurs by the Joule field $E_\Omega \times B_\theta$ drift, however, this pinch is negligibly small because of the large B_t, although this seems to be one of the reasons why tokamak is more excellent machine than other tori. A current sustaining tokamak[6] by rf traveling wave may cause not only the continuous toroidal plasma current but also the improvement of confinement by inward $E_{rf} \times B_\theta$ drift, where E_{rf} is the rf electric field. In current sustaining tokamak by use of Landau damping, resonant particles feel an effective DC field in the toroidal direction instead of E_Ω. Although E_Ω is about several mV/cm, the value of E_{rf} in current drive tokamak becomes more than several V/cm by enough suppression due to quasi-linear effect, which is thousand times larger than E_Ω. Therefore, resonant particles may be expected to drift inward in a meridian plane of torus, which may balance the outward flux of electrons in the collision free condition[7].

The density evolution in current drive has been performed numerically using one dimensional tokamak code (CURSUS) in which this current drive pinch effect is included. Basic equation in CURSUS is particle transport equation,

$$\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma) + n\,n_0^* <\sigma v>_i \tag{1}$$

where particle flux Γ is given,

$$\Gamma = -D_\perp \frac{\partial n}{\partial r} - G_I \frac{nCE_\Omega B_\theta}{B^2} - G_W \frac{nCE_\Omega}{B_\theta} L_{13} - G_C\Gamma_C \tag{2}$$

The second term in R.H.S. of eq.(1) is the source term by ionization, where n_0^* is the neutral density and $<\sigma v>_i$ is the rate coefficient for electron ionization. The second term in eq.(2) express the initial pinch which may caused by $E_\Omega \times B_\theta$ drift in a joule tokamak and $B^2 = B_t^2 + B_\theta^2$, the third is Ware pinch and the last is that of current drive pinch. The Alcator scaling is used for the value of $D_\perp$, that is $D_\perp = \alpha/\sqrt{q}\, n$, where q is the safety factor. The value of L_{13} is the coefficient of Ware pinch term[8]. The value of G_I, G_W and G_C denote to be 1 or 0 which of pinch term is considered. The flux of the current drive pinch is calculated using the number of the resonant particles, $\Delta f\Delta v = f(v+\Delta v) - f(v-\Delta v) \simeq \partial f/\partial v(\Delta v)^2$,

$$\Gamma_c = \frac{CB_\theta E_{rf}}{B^2}\Delta f\Delta v\Delta N_z = \int_{n_{zc}-\sqrt{h_z \ln 2}}^{n_{zc}+\sqrt{h_z \ln 2}} \frac{CB_\theta E_{rf}}{B^2} \left.\frac{df}{dv}\right|_{v=\frac{\omega_o}{k_z}} (\Delta v)^2\, dn_z \tag{3}$$

where Δv is the plateau width of resonant particle[9], the value of E_{rf} is calculated assuming the N_z spectrum of the rf power by the Gaussian distribution without using Brambilla coupling theory[10]. The value of n_{zc} and h_z are the central value and the inclination of the Gaussian, respectively, which are defined later. The value of E_{rf} is

$$E_{rf} = \left[\frac{2}{\varepsilon_0} P_{rf}(r,n_z)\left(1+\frac{k_z^2}{k_x^2}\right)^{-1}\left(1+\frac{\omega_{pe}^2}{\omega_{ce}^2}\right)^{-1} L_z^{-1} L_y^{-1} \frac{a}{r} V_{gx}^{-1}\right]^{\frac{1}{2}} \tag{4}$$

where rf power is expressed

$$P_{rf} = \frac{P_{rfo}}{\sqrt{h_z \pi}}\, e^{-2\int_r^a k_{QL} dr}\, e^{-\frac{(n_z - n_{zc})^2}{h_z}} \tag{5}$$

This power is only determined by performing the integral in eq.(3). The value of k_{QL} is

$$k_{QL} = \sqrt{\frac{\pi}{8}} \frac{1}{1+2(\omega_o/k_z v_{the})^2 D_{QL}} \left(\frac{\omega_o}{k_z v_{the}}\right)^3 e^{-(\omega_o/k_z v_{the})^2} \frac{(k_x^2+k_z^2)^2}{k_x k_z^2} , \quad (6)$$

which is the quasi-linear damping rate[11], and D_{QL} is the velocity space diffusion coefficient in quasi-linear theory. When $D_{QL} = 0$, then k_{QL} gives the linear damping rate. Thus, in this calculation, only rf power is sufferred from the quasi-linear effect through the damping rate of eq.(5).

Before calculating the current drive pinch, we must determine the value of α in Alcator scaling to get the background tokamak plasma (G_I=1, G_W=0 and G_C=0). From many trials we get $\alpha = 8.5 \times 10^{16}$ in this code. The transport equation is replaced by the difference equation, and Crank-Nikolson method is used for the precession of the difference equation. The time step for the pursuit is about several microseconds, which is much smaller to the plasma confinement time.

The evolution of the density profile is simulated numerically, which is shown in Fig. 2, where G_I=1, G_W=0 and G_C=1. The rf power is injected from 3 msec to 6 msec. The plasma parameters and the rf frequency are fitted to the JFT-2 current drive case, whose frequency is the lower hybrid frequency[12]. The condition of the simulation is, no turning point in the plasma center and relatively lower density case with rare collision are. The value of E_{rf} becomes about 3.6 V/cm at r = 20 where D_{QL}=1.3, and the generated rf current is limited as large as the Joule current. It indicates that when the current drive begins successfully, the density profile developes to increase inward, that is, the pinch may occur. Time behaviour of the central density is calculated with and without rf as shown in Fig. 3. When the rf power is absent, the central density does not almost change or increase a little. On the other hand, when the rf power is injected, the density distinctly increases in correspond to the rf power. From parameters survey, it is known that the maximum density increase is obtained when the phase velocity of rf wave is near the electron thermal velocity and the N_z spectrum of rf wave is relatively sharp.

In recent current drive experiments of many tokamaks, the effective density increase is observed and it is reported that this is not due to the impurity influx.[12-14] This pinch effect may be an explanation of the density increase in the current drive tokamak, especially the JIPPT-II case[13] seems to be most fitted to this simulation.

It is much concerned problem that the current drive pinch may bring the improvement of plasma confinement. The particle confinement time $\tau_p = \int n dv / \int |\Gamma| ds$ is also simulated in this code. The time behaviour of τ_p is shown in Fig. 3. In this condition the value of τ_p increase about 20 % by rf wave just before the rf power is turned off. It is shown that the inclination of τ_p express the same dependence as the density increase case, that is, the maximum increase of the confinement time is obtained when the phase velocity is near the thermal velocity and the N_z spectrum is relatively sharp. It is noted that the maximum increase of rf current does not correspond to the maximum density increase.

The power dependence of τ_p is calculated as shown in Fig. 5. It indicates that the particle confinement time increases with increase of P_{rf}. The validity of the simulation is also asserted by the simple calculation. The effective particle flux in current drive pinch is expressed;

$$\Gamma' = - D_\perp \frac{\partial n}{\partial r} - \frac{cE_{rf}B_\theta}{B^2} \Delta f \Delta v = - D_\perp' \frac{\partial n}{\partial r} \tag{7}$$

where $D_\perp'$ is the effective diffusion coefficient in the current drive pinch tokamak. The particle confinement time is obtained by using the magnitude of the machine radius a and

$$\tau_p = \frac{a^2}{D_\perp'} = \tau_0 \left(1 + \frac{cE_{rf}B_\theta \Delta f \Delta v}{B^2 \ \nabla n \ D_\perp}\right)^{-1} , \tag{8}$$

where τ_0 is the confinement time without rf current drive. Here we assume in the current drive tokamak; $B_\theta \propto I_{rf} \propto P_{rf}$, $E_{rf} \propto \sqrt{P_{rf}}$, $B \simeq B_t$ and $\Delta v \propto \sqrt{E_{rf}}$ and the second term in eq.(8) is much small unity, we obtain directly

$$\tau_p \simeq \tau_0 \left(1 + \beta \frac{n^2}{B_t^2} P_{rf}^2\right) = \tau_0 \left(1 + \gamma P_{rf}^2\right) \tag{9}$$

In the calculation in Fig. 5, the proportional coefficient γ becomes 4.43×10^{-12}, if we assume that τ_p is proportional to P_{rf}^2. On the other hand, γ in eq.(9) is calculated to be 2.34×10^{-12}, which is good agreement in the order. The problem is that the generated current obtained experimentally is not always proportional to P_{rf} at the high power region,[12-14] although the theoretical prediction is; $I_p \propto P_{rf}$.

The current drive pinch may be expected in all process by use of Landau damping using parallel electric field. In the electron heating case, the density increase is also observed[14]. Since the number of the resonant particle is maximum at the thermal velocity in Maxwellian distribution function, it is reasonable that the maximum pinch is obtained when the pahse velocity of rf wave is near the thermal velocity. The current drive pinch drift may be disturbed by the collision[16], so this pinch may need rather the collision free condition as the case of current drive than the collision dominant region as the case of electron heating.

This current drive pinch may be available for the impurity control. If we can drive rf traveling waves both co- and counter-direction, one is for current drive and the other is for impurity control. The phase velocity of the counter-direction wave must fit to the thermal velocity of impurity ions. The resonant ions diffuse outward by the $- E_{rf} \times B_\theta$ drift in this case. However, this idea is only true that the temperature of electrons and impurity ions is different in the large extent, and the phase velocity in this case is much larger than the current drive case. Motley proposed the idea of rf divertor[17] to control impurity by rf wave. The inverse currend drive pinch discussed here lead to Motley's method except for the point of no accessibility and no mode conversion of the wave.

The enhancement of the bootstrap current is also expected in this current drive pinch, if the density profile really becomes as shown in Fig. 2, because the bootstrap current is proportional to pressure gradient of plasma.[18]

In conclusion, we can say that the current drive pinch is only the enhancement of the initial pinch in Joule tokamak by replacement E_{rf} from E_Ω and its pinch effect may bring the essential improvement in magnetic fusion programme at the standpoint that the confinement time increases with increase of the rf power. In order to confirm the current drive pinch toward the improvement of the confinement, we must accumulate further experiments on current drive, especially the dependence of the generated rf current against the injected rf power must be confirmed.

We want to express graditude to Drs. T. Yamamoto, S. Iizuka and T. Nagashima for their fruitful discussions. We want to thank Dr. T. Takeda for his kind agreement to use ARGUS code in his laboratory on drawing the density profile. The authors also express their thank to Drs. Y. Tanaka, H. Shirakata, M. Tanaka, M. Yoshikawa, Y. Obata, Y. Iso and S. Mori for their continuous encouragement throughout this research.

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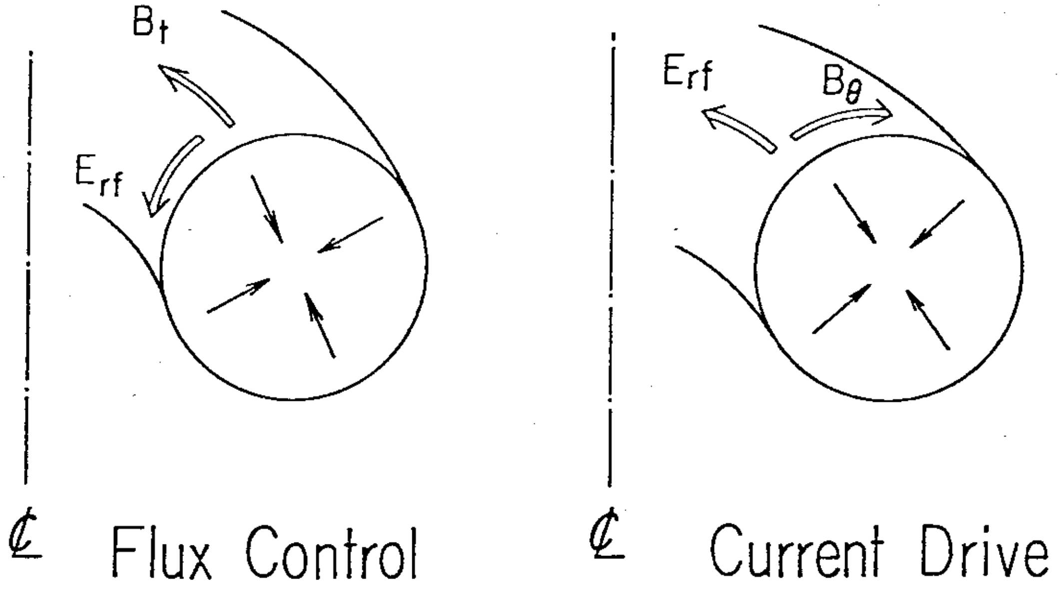

Fig. 1 Two cases of the centrifugal electromagnetic drift; poloidal electric field E_θ cross toroidal magnetic force B_t (left) and toroidal electric field E_t cross poloidal magnetic field B_θ (right).

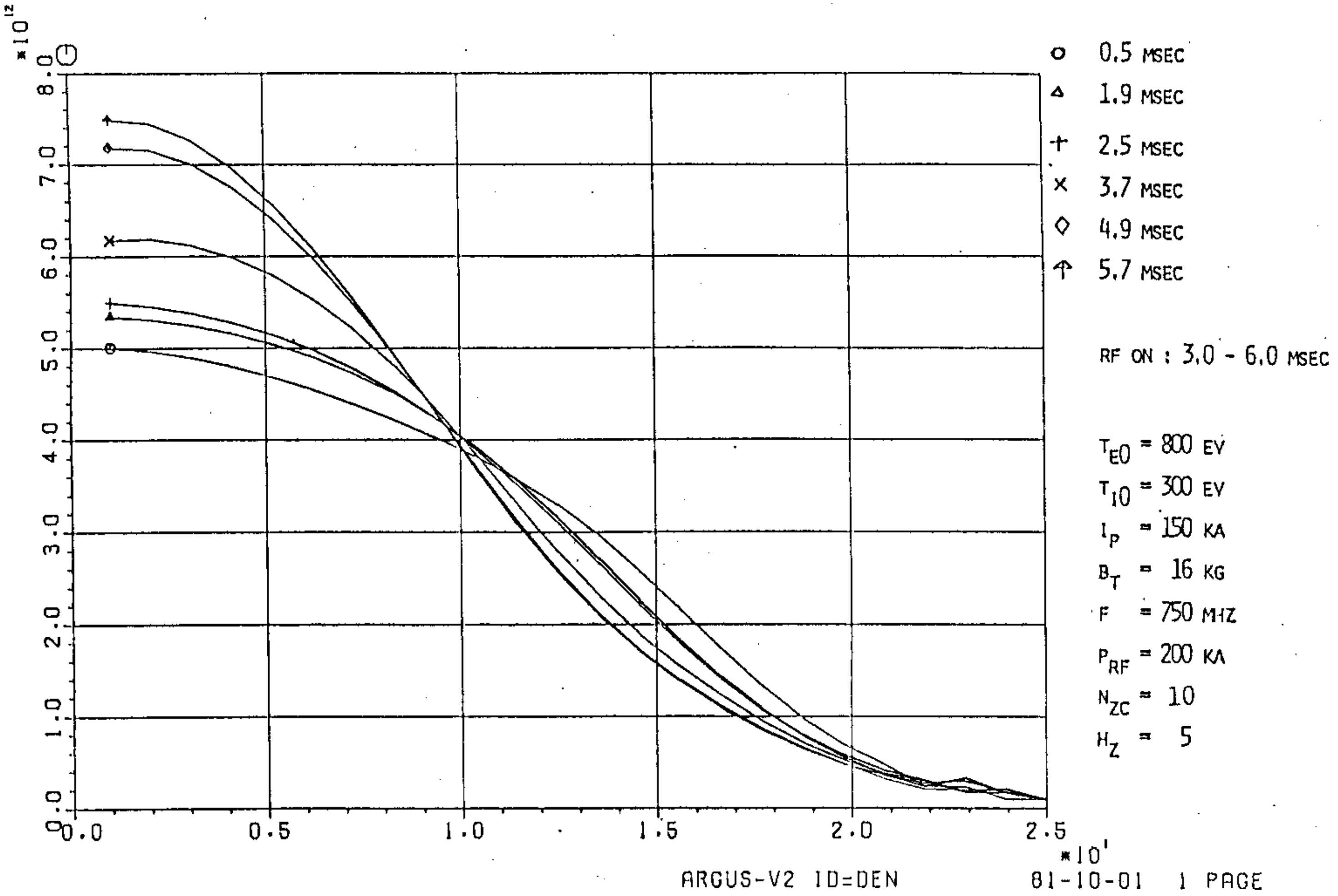

Fig. 2 Density profile evolution is simulated in current drive tokamak, where rf power (frequency f=750 MHZ, rf power $P_{rf} = 200$ kW, $n_{zc} = 10$ and $h_z = 5$) is turn on from 3 msec to 6 msec. Plasma conditions are; central electron temperature $T_{e0} = 800$ eV, central ion temperature $T_{i0} = 300$ eV, plasma current $I_p = 150$ KA and toroidal field $B_t = 16$ KG.

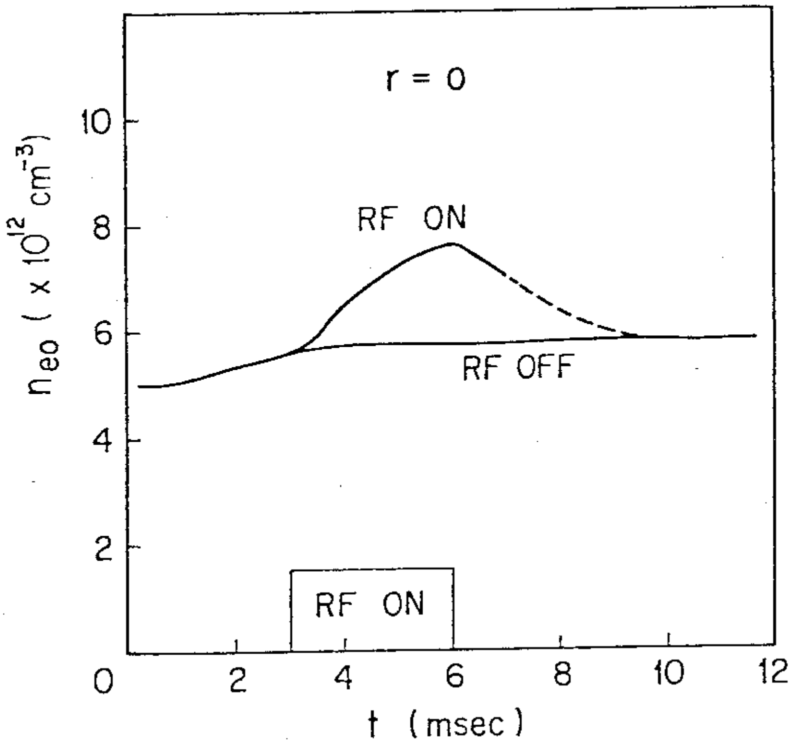

Fig. 3 Time behaviour of central density with and without rf, where $T_{e0} = 800$ eV, $T_{i0} = 300$ eV, $I_p = 150$ KA, $B_t = 16$ KG and f = 750 MHz, $P_{rf} = 200$ kW, $n_{zc} = 10$ and $h_z = 5$. The dotted line mean that CPU time is over in this calculation.

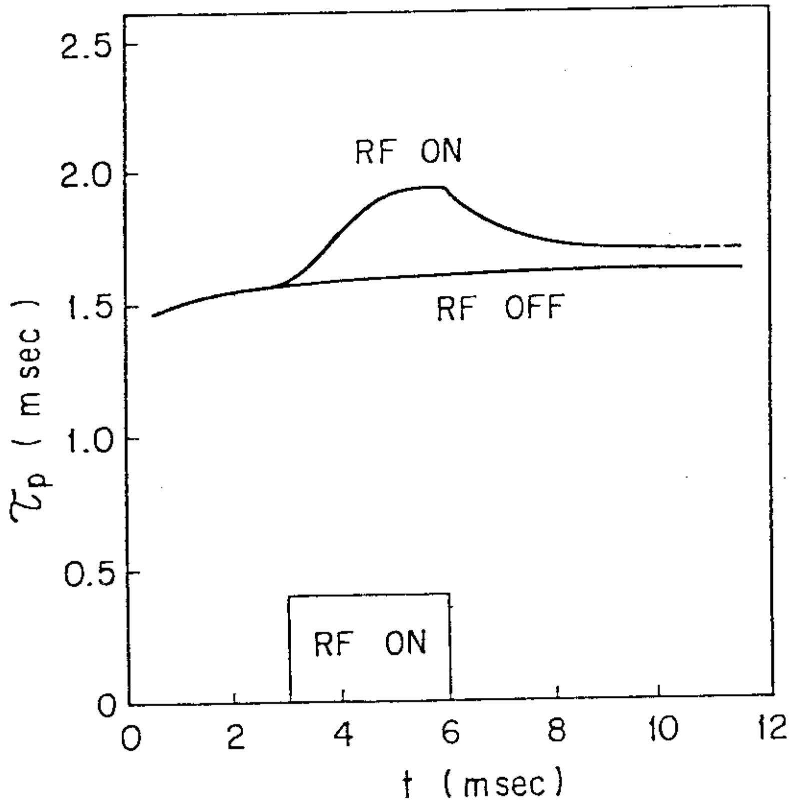

Fig. 4 Time behaviour of particle confinement time with and without rf, where $T_{e0} = 800$ eV, $T_{i0} = 300$ eV, $I_p = 150$ KA, $B_t = 16$ KG and f = 750 MHz, $P_{rf} = 300$ KW, $n_{zc} = 10$ and $h_z = 2.5$.

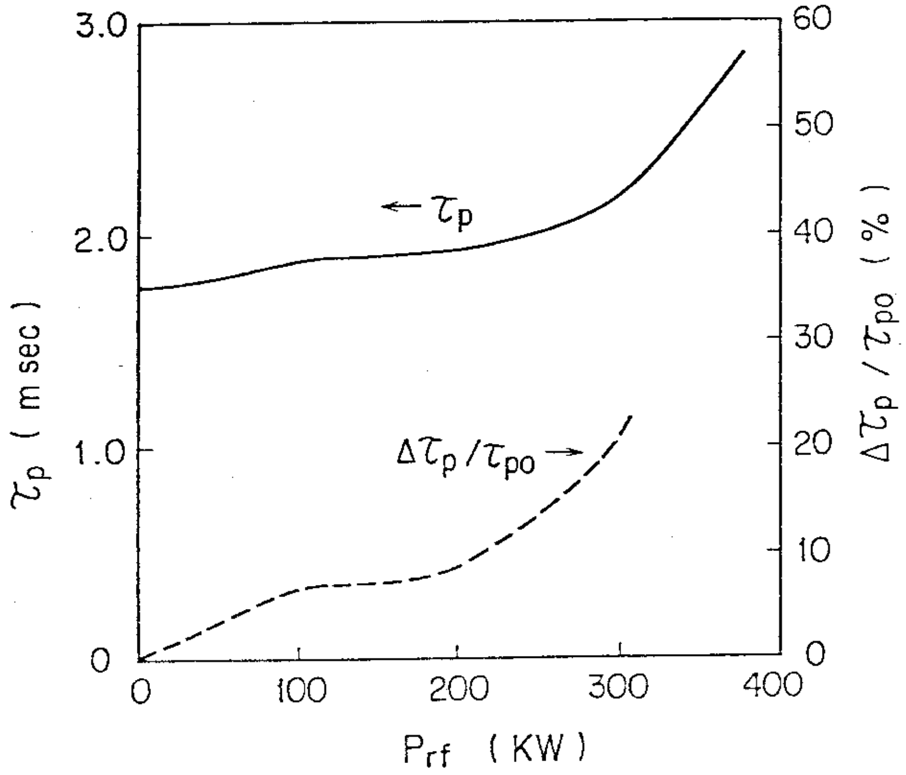

Fig. 5 Power dependence of particle confinement time and the increment rate of it, where $T_{e0} = 800$ eV, $T_{i0} = 300$ eV, $I_P = 150$ KA, $B_t = 16$ KG and $f = 750$ MHz, $n_{zc} = 11$ and $h_z = 2.5$.