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Ryuji YOSHINO and Yutaka KAMADA

日 本 原 子 力 研 究 所
Japan Atomic Energy Research Institute

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Department of Large Tokamak Research
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

(Received September 5, 1989)

The relation between the sawtooth activity and the density profile of hydrogen pellet injected plasmas is experimentally investigated with the limiter configuration of 2.1MA and 2.8MA discharges in JT-60 Tokamak. The time interval of sawtooth crashes becomes longer with the increase in density gradient at the $q = 1$ surface, and the sawtooth-free phase is obtained with $Ln \lesssim 0.4$ m at the $q = 1$ surface, where Ln is the characteristic length of the density gradient defined by $(d \ln n_e/dr)^{-1}$. The maximum density peaking factor is obtained with the lowest Ln at the $q = 1$ surface. The energy confinement is improved with the peaked density profile, and 25 - 30% enhancement in energy confinement relative to the gas fuelled plasmas is obtained in 2.8MA discharge with 10 - 13MW heating (~3MW joule heating, 7 ~ 11MW NB heating and 0 ~ 2MW ICRF heating). Furthermore $n_e(0)\tau_E Ti(0)$ of $1.0 - 1.1 \times 10^{20} m^{-3}$ seckeV has been obtained in $I_p = 2.8$MA discharges with hydrogen pellets, that is ~1.7 times than that is obtained in the 3.15MA discharge with hydrogen gas puffing.

Keywords: JT-60, Pellet Injection, Density Profile, Sawtooth, q = 1

JT－60におけるペレット入射プラズマでの鋸歯状振動と密度分布

日本原子力研究所那珂研究所臨界プラズマ研究部
芳野　隆治・鎌田　　裕

（1989年9月5日受理）

水素ペレット入射プラズマにおける鋸歯状振動と密度分布との関係をJT－60における2.1 MA及び2.8 MAリミタ放電において実験的に調べた。鋸歯状振動の周期は，q＝1面における密度勾配の増大と伴に長くなりq＝1面でのLnが0.4 m以下のときに鋸歯状振動の抑制されることが分かった。ここで，Lnは，$(d\ \ln n_e/dr)^{-1}$で定義される密度勾配の特性長である。又，最も大きくピークした密度分布は，q＝1面でのLnが最低値のときに得られている。エネルギー閉じ込めは，ピークした密度分布とともに改善されており，ガス注入プラズマに対する25－30％の改善が，2.8 MA放電での10－13 MW加熱（～3 MWジュール加熱，7－11 MW　NB加熱，0～2 MW　ICRF加熱)において得られる。さらに，2.8MA放電における水素ペレット入射により，$n_e(o)\,\tau_E\,Ti(o) = 1.0 \sim 1.1 \times 10^{20} m^{-3}$ seckeV が得られておりこれは，3.15 MA放電にてガス注入プラズマにより得られた値の1.7倍である。

那珂研究所：〒311-01　茨城県那珂郡那珂町大字向山801－1

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1. Introduction

The suppression of the sawtooth activity is observed in the pellet injected plasmas in tokamaks[1,2], and is considered to be caused by the increase in q(0) of >1.0 with the accumulation of the impurity to the plasma center[1]. In JT-60, sawtooth-free phase is also observed after the pellet injection. However the numerical investigation of the current profile modified by the pellet injection suggests that q(0) is lower than 1.0 in spite of the long period of the sawtooth-free phase[3].

The energy confinement is improved with the more peaked density profile due to the suppression of η_i-mode by the large density gradient[4]. On the other hand, in JT-60, the plasma stored energy rises largely during the sawtooth-free phase after the pellet injection, and the increase in the stored energy is terminated by large sawtooth crashes[5]. Furthermore the improvement in the global energy confinement is mainly due to the local improvement inside the q=1 surface[5]. Then the relation of the sawtooth activity and the density profile is investigated experimentally by measuring the density profile in 2.1MA and 2.8MA limiter plasmas. And the relation between the density peaking factor and the energy confinement is investigated.

2. Experimental Set-up

The pellet injector is the pneumatic gan type with four hydrogen pellets of $3.0mm^{\phi}x3.0mm^{\ell}$(two small pellets) and $4.0mm^{\phi}x4.0mm^{\ell}$ (two large pellet). Pellets are injected with an angle of 47 degree from the midplane, and the velocity of them is 1900~2300m/sec[6]. In the case of 2.1MA discharges, q(a) is 3.3 and the q=1 surface locates at ~30cm. In the case of 2.8MA discharges, q(a) is 2.3 and the q=1

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The profile of the electron density is measured by Thomson scattering. Line integrated plasma density is measured by the submilimeter interferometer at ~2/3 of minor radius with the path length of 1.4m.

3.Sawtooth Activity and Density Profile

The typical case of the pellet injection in a 2.8MA limiter discharge is shown in Fig.1. NB heating power is 8MW and ICRF heating power is 1.5MW. The stored energy measured by the diamagnetic loop rises for about 300msec after the pellet injection with partially suppressed sawteeth. Then the increase in the stored energy is terminated by a sawtooth crash. The flat-top of the stored energy continues for 400msec, then gradually decreases with the frequent sawteeth.

The complete suppression of the sawtooth activity after the pellet injection is frequently observed in 2.1MA limiter discharges, but the sawtooth-free phase is observed in only one shot in 2.8MA discharges. However, in 2.8MA discharges, the time interval of sawtooth activity becomes longer with the increase in the density gradient at the q=1 surface as shown in Fig.2, where Ln defined by $(d \ln ne /dr)^{-1}$ is the characteristic length of the density gradient.

The time evolution of the peaking factor of the density profile, ne(0)/<ne>, is shown in Fig.3(a), that is measured by Thomson scattering in multi-shots of 2.1MA discharge. In these shots NB heating power is raised from 5MW to 8MW just after the pellet injection as shown in Fig.3(b). A little flat density profile just after the pellet injection becomes more peaked later, and the highest peaking factor of ~3.5 is obtained at 200~300msec after the pellet injection. Then the peaked density profile becomes flat. The stored energy reaches to its maximum value at ~300msec surface locates at ~40cm. The separation length of the pellet injection line from the plasma center is ~0.1m. The minor radius of plasma is 0.9m.

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4. Peaking Factor of the Density Profile and Ln at the q=1 Surface

The typical density profiles at the period of the maximum stored energy after the pellet injection are shown in Fig.4. The difference in the density profile of 2.8MA and 2.1MA discharges can be found in the density at >1/2 of minor radius. The plasma density of the 2.8MA discharge at >1/2 of minor radius is about two times higher than that of the 2.1MA discharge.

Ln at q=1 surface decreases with the increase in the density peaking factor as shown in Fig.5. In the case of 2.8MA, the maximum peaking factor is 2.8 with Ln of 0.5m. In the case of 2.1MA, the maximum peaking factor is 4.7 with Ln of 0.25m. The open points are the case of complete suppression of the sawtooth, that are obtained with $Ln \lesssim 0.4m$.

The density profile after the pellet injection can be modelled by the eq.(1) with decreasing the width of r_c as shown in Fig.6, where two cases are presented;(a)$n_e^0=1.5\times10^{20}m^{-3}$ to simulate the 2.8MA discharge, (b)$n_e^0=0.8\times10^{20}m^{-3}$ to simulate the 2.1MA discharge. In both cases the other parameters are kept constant as $\alpha=1.1$ and $n_e0+n_{add}=3.0\times10^{20}m^{-3}$.

$$n_e(r)=(n_e^0-n_e(a))(1-(r/a)^2)^{\alpha}+n_{add}\exp(-(r/r_c)^2)+n_e(a) \qquad (1)$$

The density peaking factor rises monotonically with the decrease in r_c, however Ln at q=1 surface takes the minimum at a certain value of rc. The peaking factor after the pellet injection as shown in Fig.3(d), so that the maximum stored energy is obtained with the most peaked density profile. The sawtooth activity is well suppressed during the rise of the stored energy. These results suggest that the termination of the increase in the stored energy is caused by the termination of the peaking in the density profile caused by large sawtooth crashes.

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In the pellet experiment, large sawtooth crash terminates the increase in the stored energy and the peaking of density profile as presented before. Solid lines in Fig.5 suggest that the large sawtooth crash is caused by the abrupt increase in Ln at q=1 surface owing to the decrease in r_c, that is the characteristic width of the peaked density profile as shown in eq.(1). The large Ln at q=1 surface stabilizes the sawtooth activity in the resistive tearing mode[7], However the dependence of the growth rate of the resistive m=1 mode on the magnetic shear at the q=1 surface and the the electron temperature must be examined to check the possibility of that.

5.Improved Energy Confinement

The energy confinement time of the pellet injected 2.8MA limiter plasmas measured by the diamagnetic loop versus the absorbed heating power (Pabs) is shown by closed points in Fig.7 comparing with the gas fuelled plasmas presented of density profile and Ln at q=1 surface calculated from eq.(1) reproduces well the experimental results as shown in Fig.5 by dotted lines. The case of Fig.6(a) is shown in Fig.5(a). The minimum Ln(the maximum density gradient) at q=1 surface is obtained with r_c of ~0.2m and the density peaking factor of ~2.7, above that peaking factor Ln quickly rises. Some points are separated from the dotted line at the peaking factor of 1.5-2.0 in Fig.5(a), that are at 800msec after the pellet injection and at the degradation phase of the peaked density profile. The case of Fig.6(b) is shown in Fig.5(b). The minimum Ln of 0.25m is obtained with the density peaking factor of ~4.5, above that the Ln increases abruptly. The maximum density peaking factor obtained in the experiments well agrees with the peaking factor at the minimum Ln calculated from the model of the density profile.

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The relation between the energy confinement and the density peaking factor in 2.8MA limiter discharges at 10.5MW<Pabs<12.5MW (P_{NB} of 7~9MW) is shown in Fig.8. The stored energy is clearly improved with the peaked density profile. This suggests the improvement in the global confinement is mainly due to local improvement in the region of the peaked plasma density.

For the sake of the improvement by the hydrogen pellet injection, the fusion product defined by $n_e(0)\tau_E T_i(0)$ significantly increases upto $10\text{-}11\times10^{19}m^{-3}$seckeV in 2.8MA limiter discharges as shown in Fig.9 by closed points. Open points in Fig.9 are the case of the hydrogen gas fuelled plasmas and the maximum fusion product obtained is $6.6\times10^{19}m^{-3}$seckeV in a 3.15MA limiter discharge.

6.Conclusion

The density profile becomes peaked after the pellet injection with the suppressed sawtooth activity, and the peaking of the density profile is terminated by large sawtooth crashes. The time interval of sawtooth crashes becomes longer with the increase in the density gradient at the q=1 surface, and the sawtooth-free phase is obtained with $Ln \lesssim 0.4m$ at the q=1 surface, where Ln is the characteristic length of the density gradient defined by $(d \ln n_e/dr)^{-1}$. The peaking factor of the density profile has the clear relation with Ln at the q=1 surface. The maximum density peaking factor is obtained with the lowest Ln at the q=1 surface.

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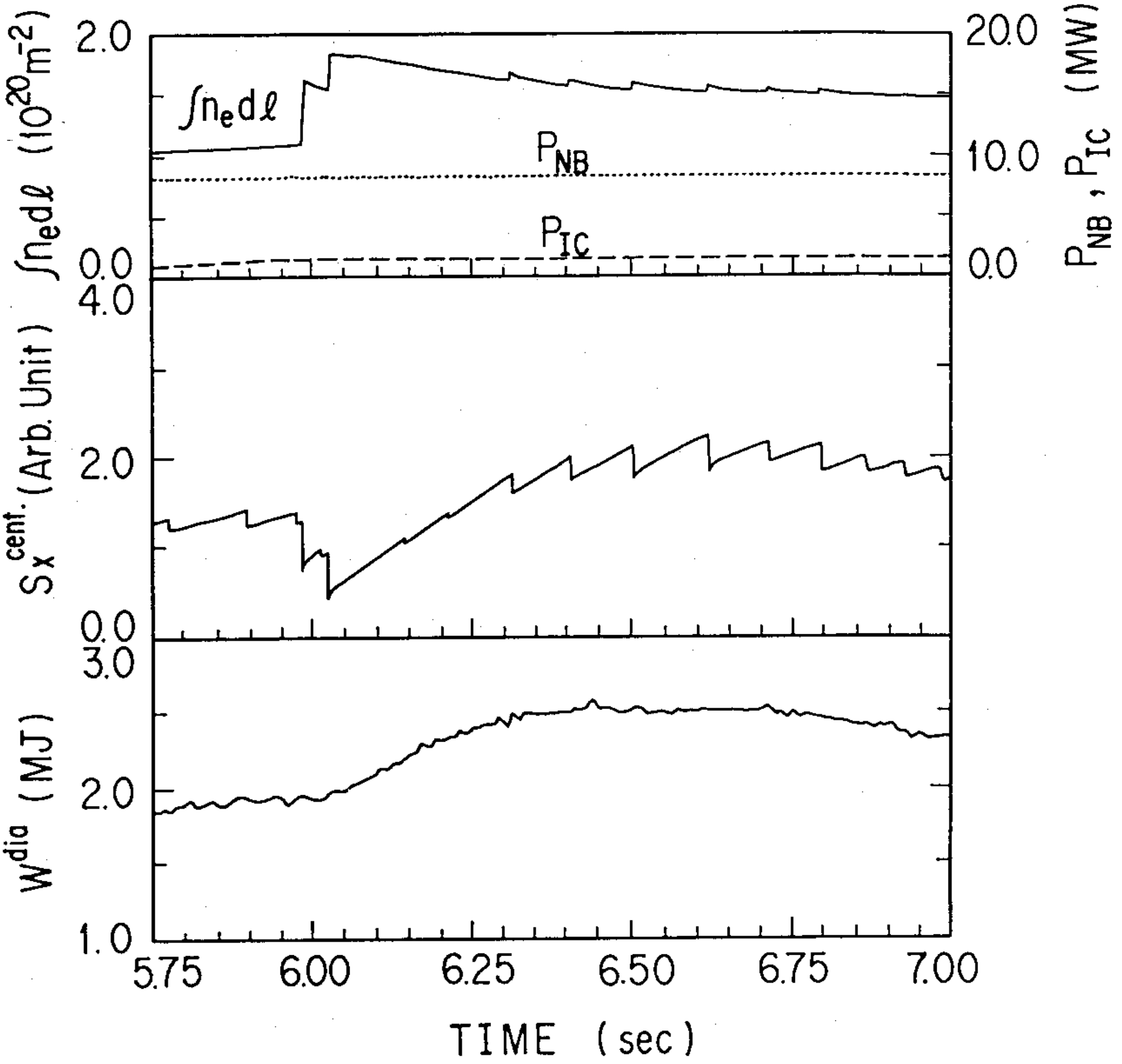

Fig.1 Time evolution of plasma parameters after the pellet injection in a 2.8MA limiter discharge. Line integrated plasma density, NB heating power, plasma stored energy measured by the diamagnetic loop, and the soft X-ray measured by PIN diode that sights the plasma center are presented.

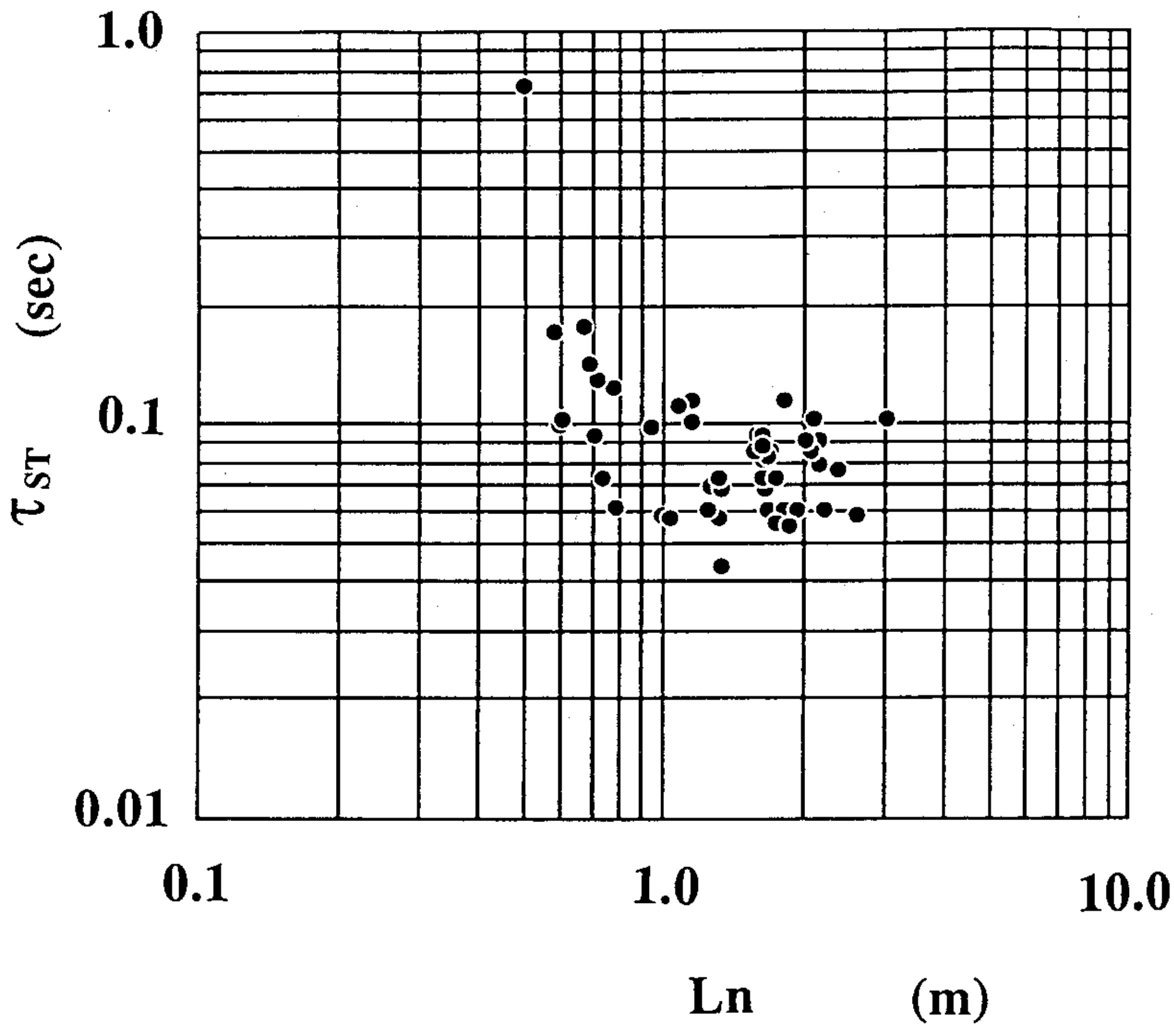

Fig.2 The time interval of the sawtooth crash versus the characteristic length of the density gradient (Ln) at the q=1 surface. Ln is defined by $(d \ln n_e/dr)^{-1}$.

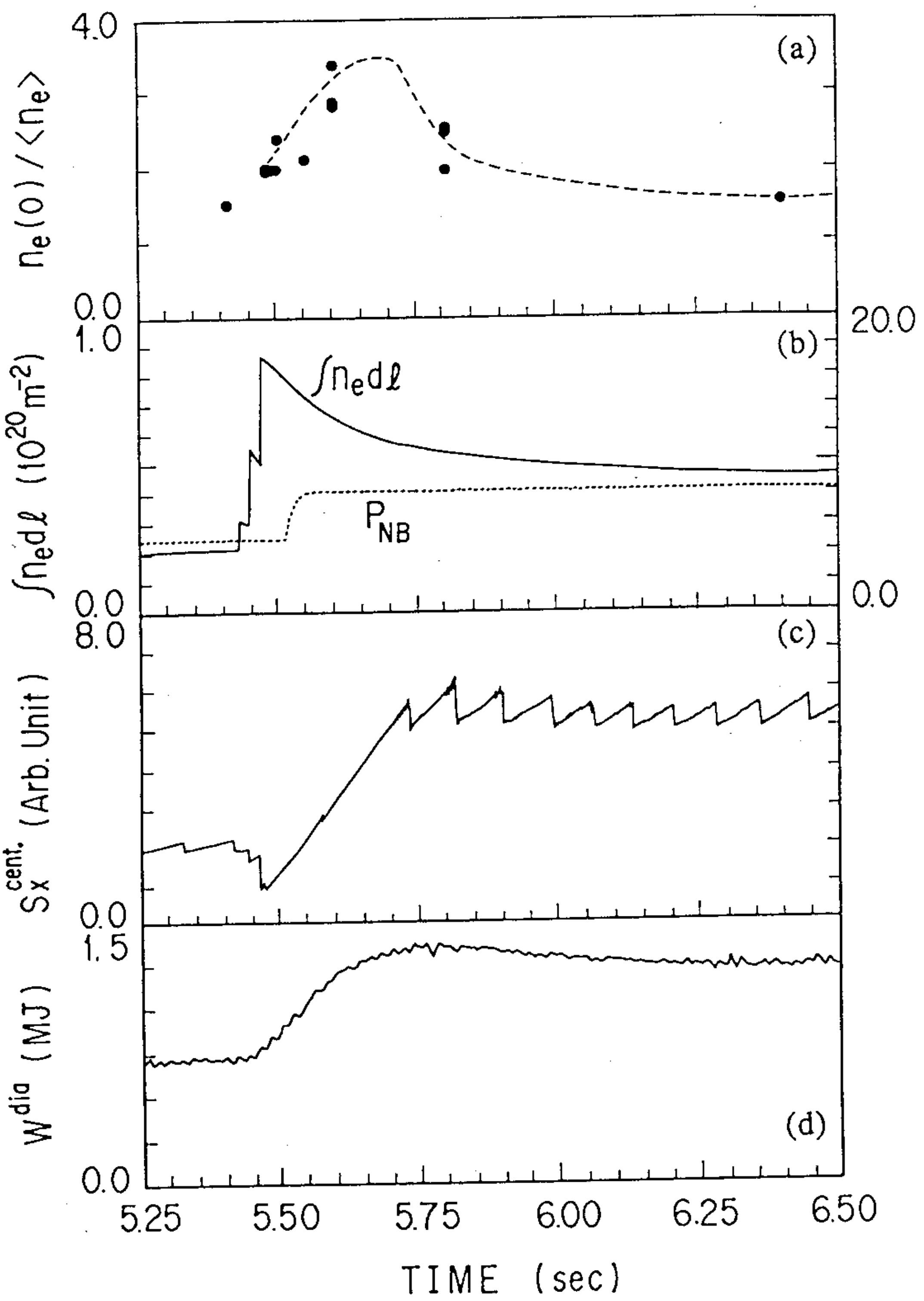

Fig.3 Time evolution of a pellet injected 2.1MA limiter discharge. (a)the peaking factor of the density profile measured by Thomson scattering in multi-shots. (b)the line integrated plasma density at 2/3 of minor radius and NB heating power, (c)the soft X-ray emission measured by PIN diode that sights the plasma center, and (d) the plasma stored energy.

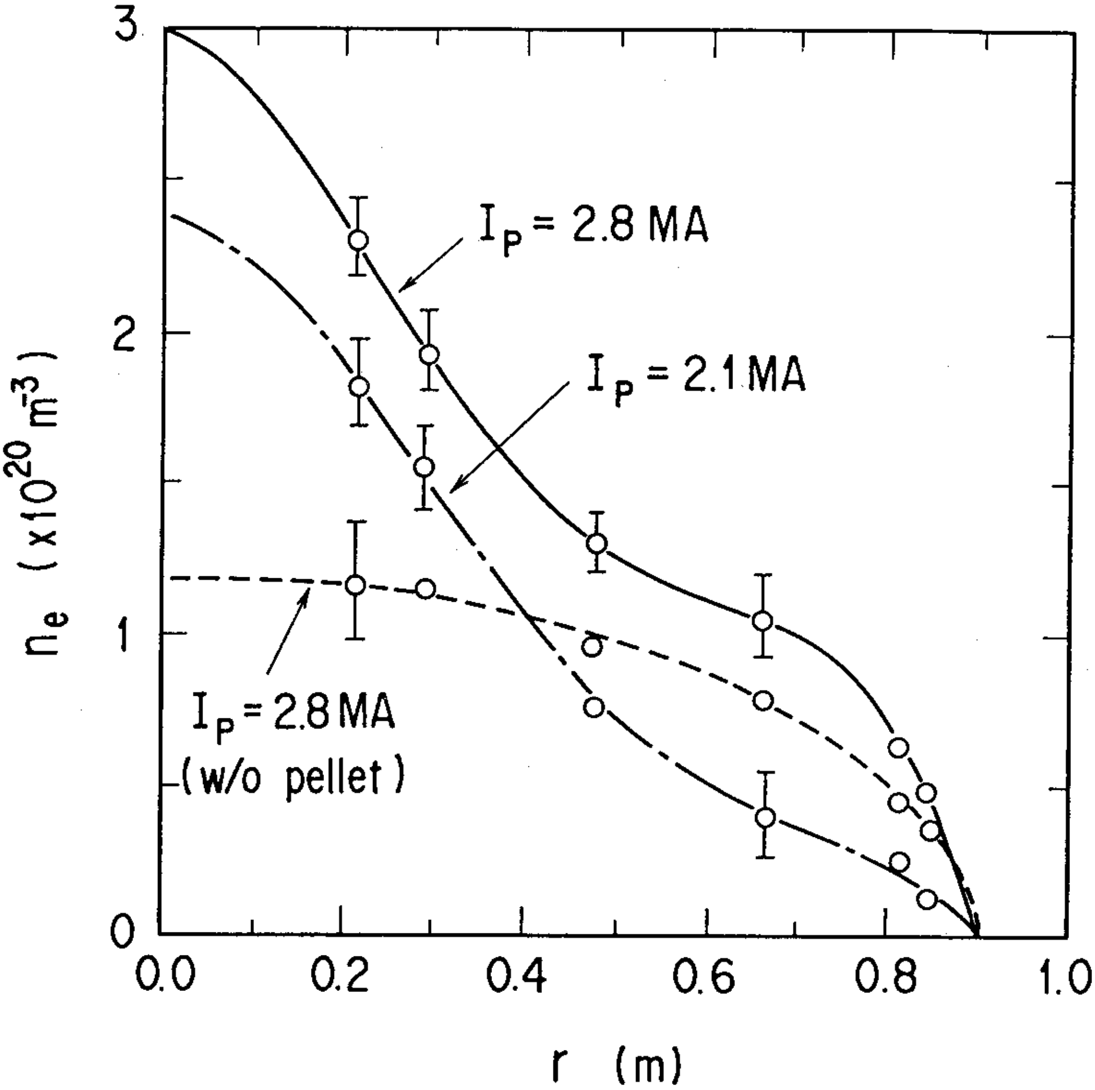

Fig.4 The density profile.

Solid line is the 2.8MA discharge at 400msec after the pellet injection. Broken line is the 2.1MA discharge at 200msec after the pellet injection. Dotted line is the gas fuelled plasmas in the 2.8MA discharge.

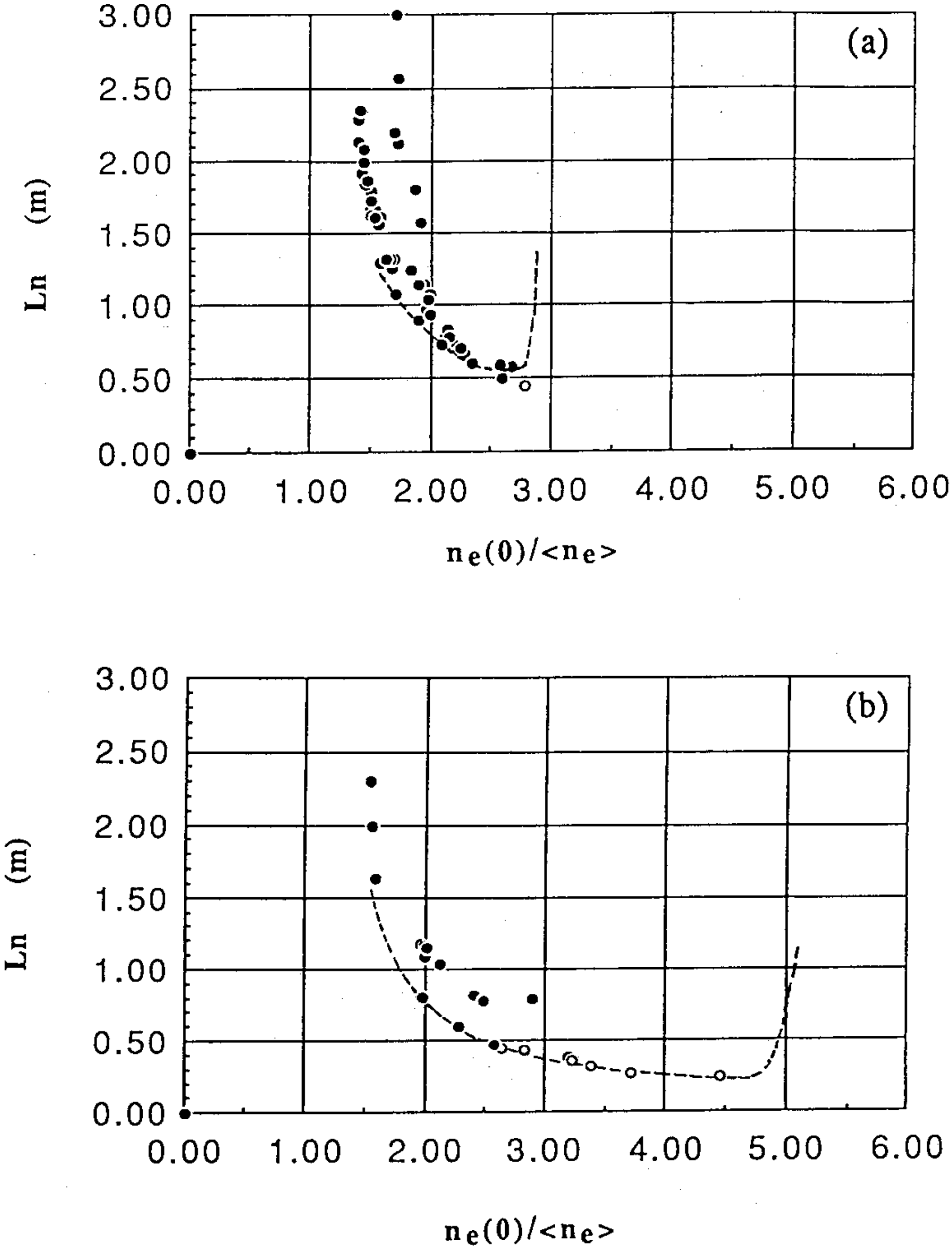

Fig.5 Ln at the q=1 surface versus the peaking factor of density profile.(a)2.8MA, (b)2.1MA. Dotted lines are calculated from the density profiles shown in Fig.6.

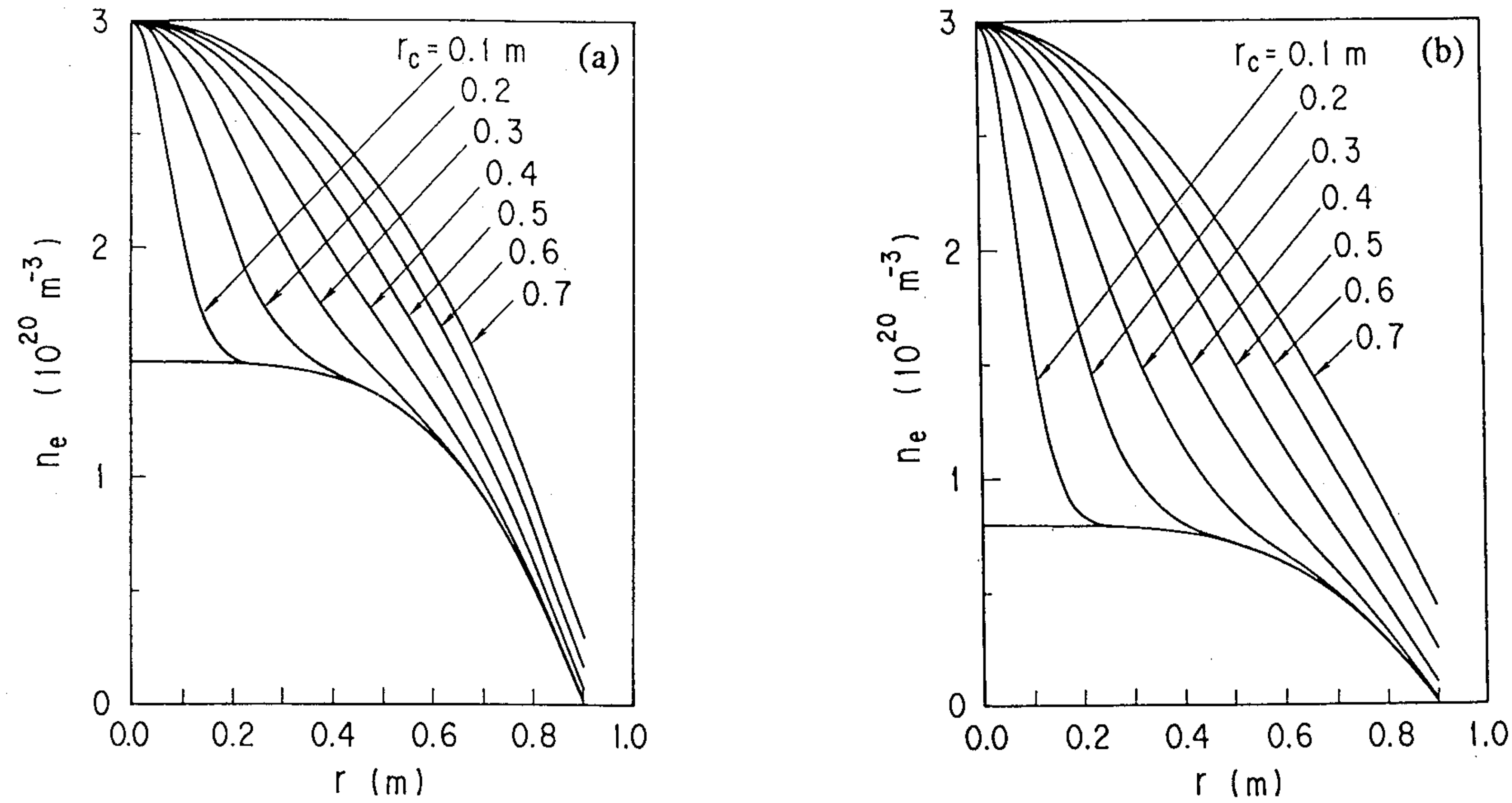

Fig.6 The modelled density profile calculated from eq.(1) scanning r_c from 0.7m to 0.1m. (a)$n_e(0)=1.5\times10^{19}m^{-3}$, (b)$n_e(0)=0.8\times10^{10}m^{-3}$. In both cases $\alpha=1.1$, $n_e(a)=1.0\times10^{18}m\text{-}3$, and $n_e0+n_{add}=3.0\times10^{20}m^{-3}$.

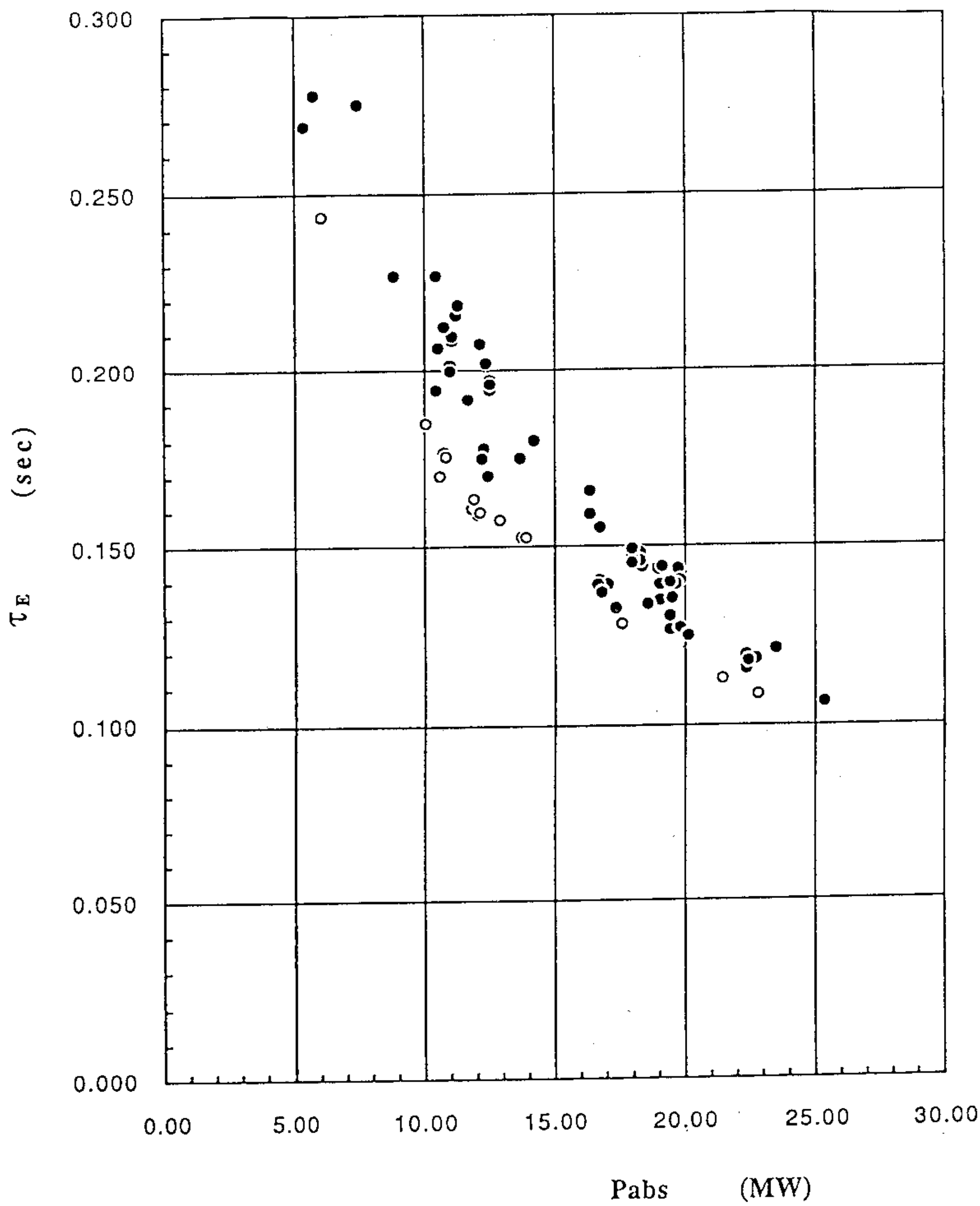

Fig.7 Energy confinement time versus the absorbed power in 2.8MA limiter discharges. Solid points are the hydrogen pellet injected plasmas. Open points are the hydrogen gas fuelled plasmas.

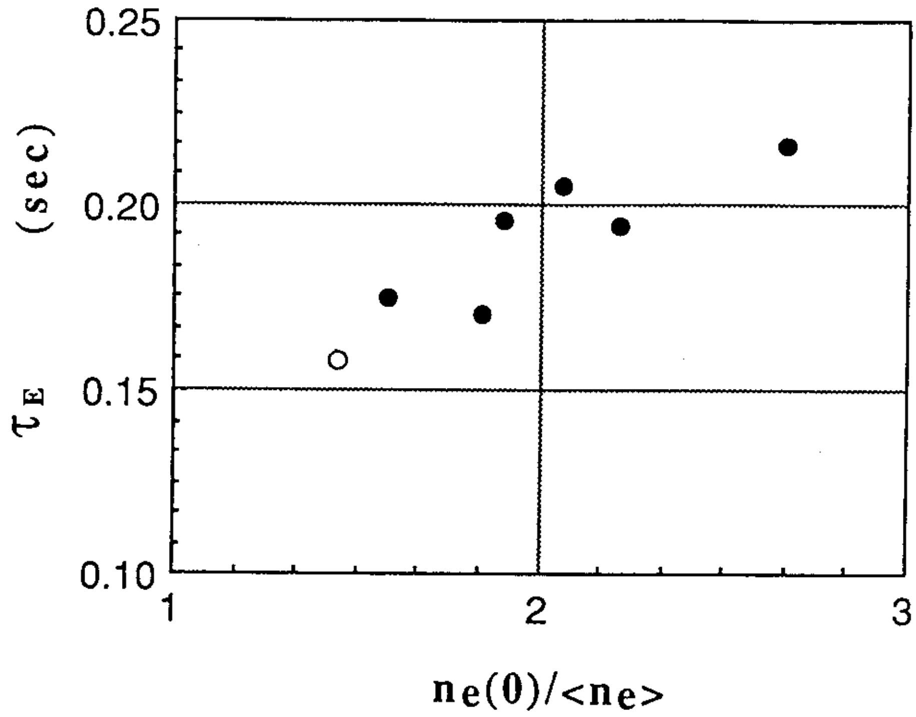

Fig.8 The energy confinement time versus the peaking factor of density profile. Closed points are the pellet injected plasmas. Open points are the gas fuelled plasmas.

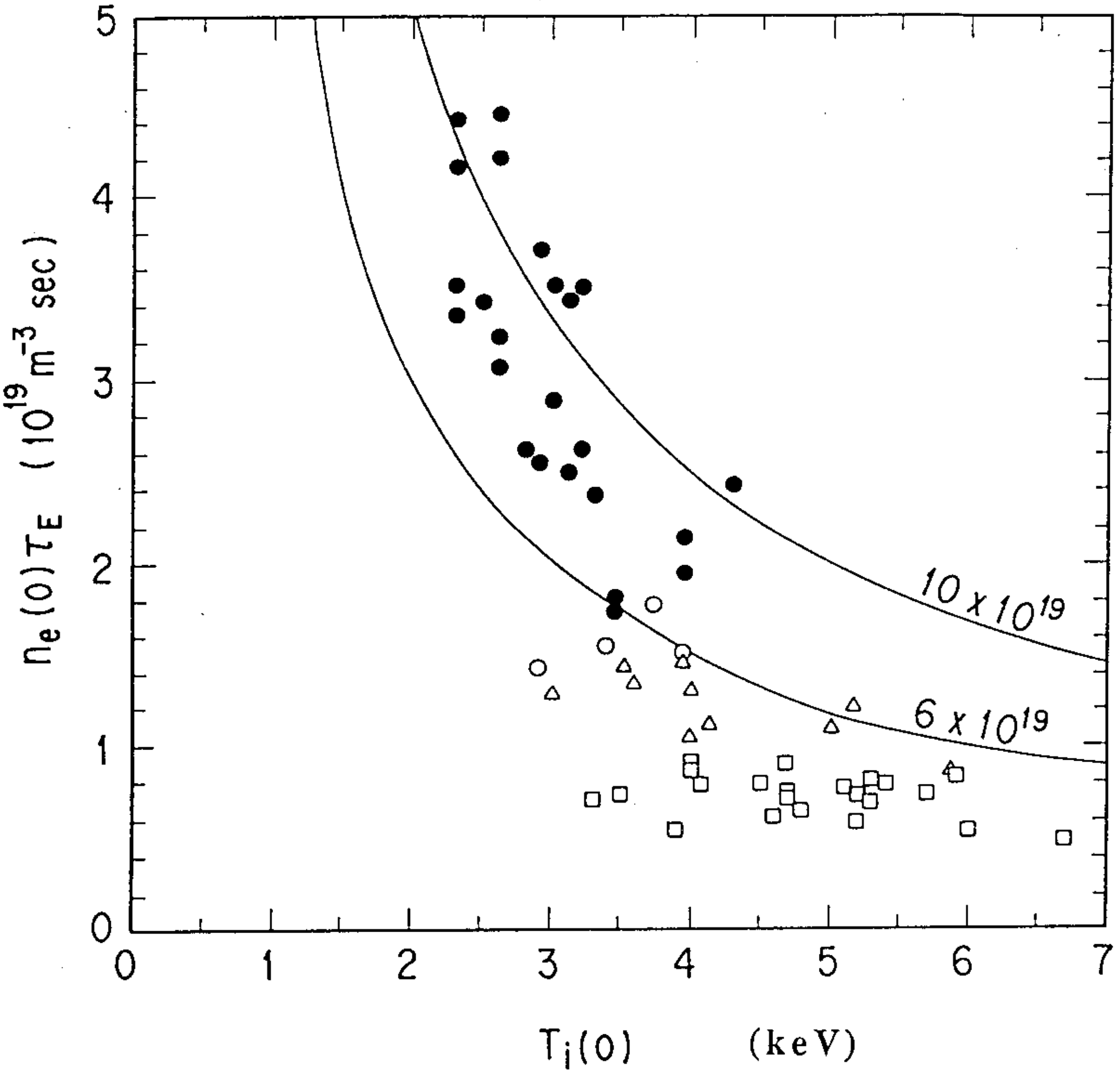

Fig.9 Fusion products.

Closed points are the hydrogen pellet injected plasmas in the 2.8MA limiter discharges. Open points are the hydrogen gas fuelled plasmas in the limiter discharges.(O;3.0-3.2MA, △ ; 2.7-2.9MA, □;2.5-2.6MA)