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Energy Confinement Scaling based on Offset Linear Characteristic

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Scaling of energy confinement time for L-mode are obtained based on the offset linear characteristic, in which a total stored energy during the additional heating can be divided into two parts, those are stored energy of ohmic base plasma and incremental stored energy from additional heating. Dependences of ellipticity and plasma minor radius are discussed and the previous work [1] is revised. This scaling has storng dependence on plasma size and predicts weak plasma current dependence in the very high heating power region. Two types of improvement of energy confinement are discusssed, i.e. improvement of ohmic base plasma and that of incremental stored energy from additional heating. Each of these improvements increases each energies about two times and in the case that both improvements take place simultaneously, gross energy confinement time can be doubled.

Keywords: Tokamak, Energy Confinement Time, L-mode, H-mode
Incremental Energy Confinement Time

[+] Department of Large Tokamak Research

オフセットリニアーの特性に基づくエネルギー閉込めの比例則

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（1988年2月18日受理）

追加熱プラズマでは，加熱入力の増大に対して，直線的に蓄積エネルギーが増えるという関係に基づいてＬモードのエネルギー閉込めの比例則を得た。プラズマの小半径と非円形度に対する依存性が議論されこれまでの比例則が補正された。この比例則ではプラズマのサイズに対して強く依存し，さらに加熱入力の大きい領域においてはプラズマ電流による改善が徐々に弱くなることが予測される。エネルギー閉込めの改善に対して2種類ある。すなわちターゲットとなるオーミックプラズマの蓄積エネルギーと追加熱によって増える増分エネルギーがそれぞれ約2倍程度改善されることが示された。またこれらの改善は2種類同時におこりうることが示され，その場合エネルギー閉込め時間は約2倍になることが示された。

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1. Introduction

Scaling of gross energy confinement time was investigated based on a offset linear characteristics in a total absorbed power P_t vs. total stored energy W_t plane [1]. That is based on the idea that the total stored energy can be given by the sum of stored energy of Ohmic base plasma W_{oh} and that of additionally heated plasma [2,3] , that is

$$W_t = W_{oh} + W_{ad} \qquad (1)$$

where W_{ad} is stored energy from additional heating power given by

$$W_{ad} = \tau_{inc}(P_t - P_{oh}{}^0) \qquad (2)$$

where τ_{inc}, P_t and $P_{oh}{}^0$ are incremental energy confinement time, total absorbed power and initial ohmic input power, respectively. The energy confinement time for L-mode $\tau_E{}^L$ is given by the following equation,

$$\tau_E{}^L = \tau_{inc} + \frac{Poh^0}{Pt}(\tau_{oh}{}^0 - \tau_{inc}) \qquad (3)$$

where $\tau_{oh}{}^0$ is the initial ohmic energy confinement time and saturatated value of the energy confinement of ohmic plasma. Therefore the scaling law for $\tau_E{}^L$ is based on the scaling of the incremental energy confinement time τ_{inc} and that of the stored energy of ohmic base plasma W_{oh}.

This $\tau_E{}^L$ scaling is different from the Kaye-Goldston scaling [4]. τ_{K-G} or Goldston scaling [5] τ_G on the following aspects;

1) Incremental energy confinement time τ_{inc} is proportional to square of plasma radius, $a_p{}^2$[3]. Therefore $\tau_E{}^L$ is improved as increasing a_p in contrast with K-G scaling.

2) Only the term of W_{oh} is improved by increasing plasma current I_p in the scaling of $\tau_E{}^L$. Therefore improvement of $\tau_E{}^L$ by I_p is predicted to reduce in a high heating power regime.

This paper looks at the L-mode scaling again taking into account new results, especially the dependence of ellipticity and plasma radius.

2. Scaing Law for L-mode

2.1 Semi-empirical scaling law for Ohmic base plasma

In a low density discharges, neo Alcator scaling is correct and τ_{oh} is proportional to plasma density $\bar{n}_e$. In high density discharges, however, τ_{oh} saturates for the density and is independent of the plasma density. Many heating experiment have been performed in such a high density regime and this is a reason why the energy confinement is independent of plasma density.

The stored energy of ohmic base plasma in the high density region can be calculated from the empirical scaling law for the saturated value of energy confinement for the Ohmic plasma [1],

$$\tau_{oh}{}^{0} = 0.045\ R\ a_p\ B_t\ \kappa^{0.5} \tag{4}$$

where R and B_t are major radius and strength of toroidal magnetic field, respectively. Plasma current profile is assumed to $j(r) \propto (1-r^2)^{q_a-1}$ and $q(0)=1$. Assuming Spitzer resistivity, the following semi-empirical scaling law for the stored energy of the Ohmic base plasma.

$$W_{oh}=0.062\bar{n}_e{}^{0.6} I_p\ a_p^{0.4}\ R^{1.6}\ B_T{}^{0.2}\ \kappa^{0.2} Z_{eff}{}^{0.4} \left(\frac{15-Z_{eff}}{20}\right)^{0.6} \times \left(\frac{3q_{cy}(q_{cy}+5)}{(q_{cy}+2)(q_{cy}+7)}\right)^{0.6} \sqrt{A_p} \tag{5}$$

Figure 1 shows a correlation between the experimental values of JT-60 and the calculated values obtained from eq.5. The result from JET-2M is also shown in Fig. 2. Stored energy in the deuterium plasma (thin line) is about 2 times of that in the hydrogen plasma (thick line) which is lined with that in JT-60. Thus the mass dependence of W_{oh} can be considered to be $\sqrt{A_p}$, where A_p is ion mass number of the plasma. Noncircularity κ dependence of W_{oh} obtained from JET-2M is shown in Fig. 3(a). This result indicates the dependence is very weak.

2.2 Scaling of incremental energy confinement time

The incremental energy confinement time is independent of plasma current, density and heating power as well as heating method, which means independent of heating power deposition profile and heating species [2,3]. This fact indicates that the incremental energy confinement time plays more essential role than the global energy confinement time $\tau_E{}^L$ in the additionally heated tokamak plasma. In fact in the high heating power region such as $P_t \gg P_{oh}{}^0$, $\tau_E{}^L$ approaches to τ_{inc}.

Size scaling of incremental energy confinement time was discussed in ref.3 and the dependence of ion mass is investigated in ref.1. Recent experiment in the JFT-2M observed that τ_{inc} depends on κ as shown in Fig. 3(b), where τ_{inc} roughly proportional to κ. Adding new data (Table 1) to the data base in ref.3, $\tau_{inc}\sqrt{A_D/A_P}$ is plotted as a function of $a_p\sqrt{\kappa}$ in Fig. 4. This result also supports that τ_{inc} is proportional to κ. Thus we can conclude that

$$\tau_{inc} = 0.12\,\kappa a_p^2\sqrt{A_P/A_D} \qquad (6)$$

where A_p and A_D is mass number of the plasma ion and deuterium, respectively.

2.3 Scaling of Gross energy confinement time

The gross energy confinement time can be calculated from eq.3 using the scaling of W_{oh} and τ_{inc} given by eqs.5 and 6, respectively. When the additional heating power is small or comparable to $\tau_{oh}{}^0$, the first term is small and the following equation is obtained.

$$\tau_E{}^L \sim \frac{P_{oh}{}^0}{P_t}\,\tau_{oh}{}^0 \qquad \text{for } P_t \lesssim P_{oh}{}^0 \qquad (7)$$

This relation describes the steep degradation observed in the early heating experiment and the strong dependence of $\tau_E{}^G$ on the plasma current because of $W_{oh} \propto I_p$. When $P_t \gg P_{oh}{}^0$ the following equation is obtained.

$$\tau_E{}^L \sim \tau_{inc} + \tau_{oh}{}^0\,\frac{P_{oh}{}^0}{P_t} \qquad \text{for } P_t \gg P_{oh}{}^0 \qquad (8)$$

This scaling gives D-III scaling [6], i.e. $\tau_E{}^G \propto \beta+\alpha/P_t$ and the rather weak I_p dependence of $\tau_E{}^G$. This type of scaling are also observed in JT-60. Putting eqs.5 and 6 into eq.8, where $\tau_{oh}{}^0\ P_{oh}{}^0 = W_{oh}$, we can get the gross energy confinement scaling law for L-mode plasma

$$\tau_E{}^L = 0.12\kappa a_p{}^2\sqrt{A_P/A_D} + 0.062\bar{n}_e{}^{0.6} I_p a_p{}^{0.4} R^{1.6}\, B_t{}^{0.2}\kappa^{0.2} Z_{eff}{}^{0.4}\left(\frac{15-Z_{eff}}{20}\right)^{0.6}\cdot\sqrt{A_p} \times\left(\frac{3q_{cy}(q_{cy}+5)}{(q_{cy}+2)(q_{cy}+7)}\right)^{0.6} P_t{}^{-1} \qquad (9)$$

Example of the comparison between the calculated and experimental values are shown in Fig. 5.[7]

3. Improvement of Energy Confinement

The confinement scaling of eq.1 suggests that we can consider two types of improvement on the energy confinement during the heating. The one is the improvement of W_{oh} term and the other is that of incremental energy from the additional heating term [8].

Concerning the former case, even with the almost same operational parameter, a difference of radiation loss conditions changes the $\bar{n}_e$ dependence of W_{oh}. Case A in Fig. 6(a) is obtained with a wall experienced titanium gettering, on the other hand case B without gettering after opening the vessel. In case A, saturation of W_{oh} appears at lower density than in case B. Then the difference of W_{oh} between cases B and A becomes 7.5kJ, and resultant the difference of W_t during the heating reaches about 7kJ at $\bar{n}_e=4\times10^{19}m^{-3}$, and the difference tend to increase as $\bar{n}_e$. τ_{inc}'s for both cases are almost same values, about 16 and 14ms for cases A and B, respectively, but $\tau_E{}^G$ of 31 and 38ms, respectively are significantly changed. The difference tends to increase at the higher density.

This type of improvement may be the same as so called Z-mode[9], which was observed in a dirty plasma without titanium gettering and only in the high density region. Pellet injection also increases W_{oh} beyond the usual saturation level [10,11]. In these cases, W_{oh} was

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$$\times \left(\frac{3q_{cy}(q_{cy}+5)}{(q_{cy}+2)(q_{cy}+7)}\right)^{0.6} P_t{}^{-1} \qquad (9)$$

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This type of improvement may be the same as so called Z-mode[9], which was observed in a dirty plasma without titanium gettering and only in the high density region. Pellet injection also increases W_{oh} beyond the usual saturation level [10,11]. In these cases, W_{oh} was doubled from the usual saturation level. Thus we expect W_{oh} can increase up to about two times of usual value scaled by eq.5, and this increase might reflect to the total stored energy W_t.

The improvement of τ_{inc} concerns to so called H-mode. Figure 7 shows total stored energy W_t as a function of electron density $\bar{n}_e$ in the cases of L- and H-modes. The incremental stored energy is roughly doubled by teh H-transition. Figure 8 shows W_t vs. P_t for fixed $\bar{n}_e$. The inclination of the straight lines show the incremental energy confinement time τ_{inc} is improved two times compared to the L-mode [12]. Thus we expect τ_{inc} can increase up to two times of usual value given by eq.6.

There is a possibility that both types of improvement take place simultaneously. In that case, we can expect the gross energy confinement time may be improved up to two times of the L-mode scaling value given by eq.9. Figure 9 may be an example that both types of improvement take place simultaneously [13]. After reaching the quasi steady state, W_t increases again simultaneously with abrupt decrease of H_α/D_α line emission, i.e. H-transition. Following the transition, $\bar{n}_e$ and radiation loss also increase quickly. After the increase of W_t by the H-transition saturates, the stored energy gradually increases again and again. In contrast to the H-transition, this increase does not follow the decrease of $H\alpha/D\alpha$ emission nor additive increase of radiation loss. This transition can be seen more cleary in W_t vs. $\bar{n}_e$ plane as shown in Fig. 10, where values of each 10ms in one shot are plotted following time history. Total stored energy increases at $\bar{n}_e=2.6\times10^{19}m^{-3}$ by the onset of the heating, at $\bar{n}_e=3.0\times10^{19}m^{-3}$, points pause a little while, which correspond to L-modes, then W_t increases again with increasing $\bar{n}_e$ by the H-transition. At $\bar{n}_e=4.1\times10^{19}m^{-3}$, W_t increases again significantly which may be due to the improvement of W_{oh}. Both types of improvement increase the total stored energy from 20kJ for L-mode to 35kJ for H-mode.

4. Discussions and Conclusions

Energy confinement scaling based on the offset linear characteristics is obtained, and noncircularity κ and minor radius a_p dependence of the energy confinement time scaing $\tau_E{}^L$ are shown. The dependence of a_p is very different from Goldston scaling [5], where τ_G degrades as increasing a_p. Plasma radius a_p scan experiment in JT-60 [14] shows gross energy confinement $\tau_E{}^G$ improves as increasing a_p as shown in Fig. 11(a) and comparison between the experimental and calculated values from $\tau_E{}^L$ and τ_G are shown in Fig. 11(b) and (c), respectively. These figuers shows that experimental data follow the scaling of $\tau_E{}^L$ and not τ_G.

Many additional heating experiments show that the gross energy confinement time $\tau_E{}^G$ does not depend on the density $\bar{n}_e$. The scaling of $\tau_E{}^L$, however, depends on $\bar{n}_e$ because W_{oh} term depends on $\bar{n}_e$. On this point, our scaling is incomplete.

Heating experiment in JT-60 shows an empirical scaling [15] as

$$\tau_E{}^G = 0.19 I_p{}^{1.8}/P_t + 0.062 a_p{}^{1.6} \tag{10}$$

which is independent of $\bar{n}_e$. Operational density in the heating experiments increasing as plasma current I_p and magnetic field B_t. Therefore the I_p dependence of W_{oh} may be larger than the explicit I_p dependence. If we can consider that the term of "$\bar{n}_e{}^{0.6} B_t{}^{0.2} I_p{}^{1}$" in eq.5 has an equivalent dependence of $I_p{}^{1.8}$, the apparent difference between $\tau_E{}^L$ scaling and empirical JT-60 scaling may disappear.

But there is still a discrepancy from the JT-60 experiment. The stored energy of ohmic plasma increases as increasing $\bar{n}_e$ following the scalling of W_{oh}. The total stored energy and gross energy confinement time during the additional heating, however, do not depend on $\bar{n}_e$.

The following explanations can solve the apparent discrepancy;

1) Operational density during the additional heating exceeds a density limit of ohmic plasma, and we do not have experimental value of W_{oh} in such a high density. Therefore we must extrapolate in order to estimate W_{oh}. In ohmic discharges of JT-60, the saturation of W_{oh} has not been observed in spite of the saturation of W_{oh} is observed in the JFT-2M deuterium discharges [12]

(expl. Figs. 6 and 7). If W_{oh} saturates in the sufficient high density region, W_t should be independent of $\bar{n}_e$.

2) Confinement of high energy ion may be different from that of the thermal component of the stored energy W_{th}. JT-60 observed in NBI heating experiment that W_{th} depends on $\bar{n}_e$ as well as W_{oh} depends on $\bar{n}_e$. But the total stored energy including beam component does not depend on $\bar{n}_e$ because ion beam component increases as decreasing $\bar{n}_e$ [16]. Improvement of confinement of high energy ion and resultant increase of the incremental energy confinement time are also observed in the ICRF heating [17] in which second harmonic ICRF heating efficiently enhances the ion beam component produced by NBI.

3) We can not eliminate a possibility that the offset part of the stored energy is irrelavent to W_{oh}, whose value may change due to the change of $\bar{n}_e$.

There are two types of improvement for energy confinement, those are improvement of the stored energy of Ohmic base plasma and that of incremental energy confinement time. Each of them has a possibility to improve by factor two separately or simultaneously. Thus the maximum improvement of energy confinement in the combined mode is about factor two. Therefore, in the case of that the degradation of energy confinement is less than factor two compared to Ohmic value. The gross energy confinement time may recover to the Ohmic value by the improvement (Optimized mode in ref.1). But in the case of very high degradation case, such as high B_t discharge, it is important problem to know whether the energy confinement can recover the Ohmic value or not.

Acknowledgements

The authors wish to thank to Drs. M. Nagami, M. Kikuchi, O. Naito, N. Hosogane, H. Matsumoto, N. Suzuki, JT-60 team and JFT-2M-Group for their fruitful suggestions and discussions. We also wish to express our gratitude to Drs. S. Mori, K. Tomabechi, M. Tanaka, M. Yoshikawa and H. Maeda for their continuous encouragement.

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References

1. Y. Shimomura, N. Suzuki, et al., "Empirical Scaling of Energy Confinement Time of L-mode and Optimized Mode and Some Consideration of Reactor Core Plasma in Tokamak" JAERI-M 87-080.
2. K. Odajima, K. Hoshino et al., Phys. Rev. Lett., 57 (1986) 2814.
3. Y. Shimomura and K. Odajima, Comments on Plasma Phys. and Contr. Fusion 10 (1987) 207.
4. S.M. Kaye and R.J. Goldston, Nucl. Fusion 25 (1985) 65.
5. R.J. Goldston, Plasma Phys. and Contr. Fusion, 10 (1984) 87.
6. M. Nagami et al., in Plasma Phys. and Controlled Fusion Research (IAEA, Vienna, 1985) Vol. 1, p.27.
7. JT-60 team and M. Nagami, "Recent Results from JT-60" Invited paper at Annual Meeting of APS. (1987, San Diego), JAERI-M 87-205.
8. K. Odajima, Kakuyugo Kenkyu, Jr. of Japan Soc. of Plasma Sciecne and Nuclear Fusion 56 (1986) 81, in Japanese.
9. M. Murakami, et al., in Plasma Phys. and Contr. Nucl. Fusion Res. (IAEA, Vienna, 1985) vol. 1, p.87.
10. S. Sengoku, et al., ibid. Vol. 1, p.405
11. M. Greenwald, D. Gwinn, et al., Phys. Rev. Lett., 53 (1984) 352
12. K. Odajima, A. Funahashi, et al., in Plasma Phys. and Contr. Nucl. Fusion Res. (IAEA, Vienna, 1987) vol. 1, p.151.
13. H. Matsumoto, T. Ogawa, et al., Nucl. Fusion, 27 (1987) 1181.
14. JT-60 team, "Review of JT-60 Experimental Results from June to October, 1987" to be published in JAERI-M.
15. O. Naito, N. Hosogane et al., "Energy Confinement of Neutral Beam Heated Plasma in JT-60" Proc. of 15th Euro. Conf. on Contr. Fusion and Plasma Heating 1988, Dubrovnik, Yugoslavia.
16. M. Kikuchi, T. Hirayama,et al., Nucl. Fusion 27 (1987) 1239.
17. T. Fujii, H. Kimura, et al., "Second Harmonic ICRF with Ohmic and Strong NBI heated Plasma in JT-60" in Ref. 14.
18. The JET Team, in Ref. 12, IAEA-CN-47/A-I-2.
19. J.G. Cordey, et al., in Ref. 12, IAEA-CN-47/A-II-3.
20. J. Jacquinot, "ICRF Heating Results in JET", Bull. Am. Phys. Soc. 32 (1987) 9. Invited paper in Ref. 7.
21. K.H. Burrel, R. Prater, et al., in Ref. 6 Vol.1, p.131.

22. A. Kitsunezaki, T. Abe, et al., in Ref. 6 Vol. 1, p.57.

23. T. Watari, K. Ohkubo et al., in Ref. 12, Vol. 2 IAEA-CN-47/F-I-5.

24. T.D. Shepard, C.L. Fiore, et al., "Fast Wave ICRF Minority Heating Experiments on the ALCATOR Tokamak" in Proc. of 7th Topical Conf. on Radiofrequency Plasma Heating, Kissimmee Florida, 1987 (to be published).

Table 1 Incremental energy confinement time τ_{inc} for noncircular plasma. Values of τ_{inc} are given in references or by authors of references or calculated from figures in references.

	R(m)	a_p(m)	κ	B_t(T)	I_p(MA)	τ_{inc}(ms)	Ref.
JT-60	3.22	0.72	0.95	4.5	1.5	35	7
	3.04	0.85	0.95	4.0	1.0	50	
all of JT-60 discharge in hydrogen	3.04	0.85	0.95	4.5	1.5	52	
	3.04	0.90	0.95	4.5	2.0	60	
	3.04	0.90	0.95	4.8	2.5	64	
	3.04	0.90	0.95	4.8	2.8	66	
	3.04	0.93	0.95	4.8	3.1	66	
JET	2.96	1.2	1.4	3.0	2.0	150	18
	2.96	1.2	1.4	3.0	4.0	170	
	2.96	1.2	1.4	3.4	5.0	180	
	2.96	1.2	1.4	2.0	2.0	135	19
	2.96	1.2	1.4	2.0	3.0	150	
	2.96	1.2	1.4	3.4	4.0	205	
	2.96	1.2	1.4	3.4	5.0	170	
	2.96	1.2	1.6	2.1	2.0	250	20
D-III	1.43	0.40	1.4	2.0	0.48	18	21
	1.43	0.44	1.4	2.0	0.80	27	22
JFT-2M	1.29	0.33	1.03	1.24	0.24	13	
	1.29	0.33	1.14	1.24	0.25	15	
	1.29	0.33	1.25	1.24	0.27	18	
	1.29	0.32	1.44	1.24	0.27	24	
JIPPT-IIU	0.91	0.23	1.0	3.0	0.28	8	23
ALCATOR C	0.64	0.12	1.0	12.0	0.15	1.7	24

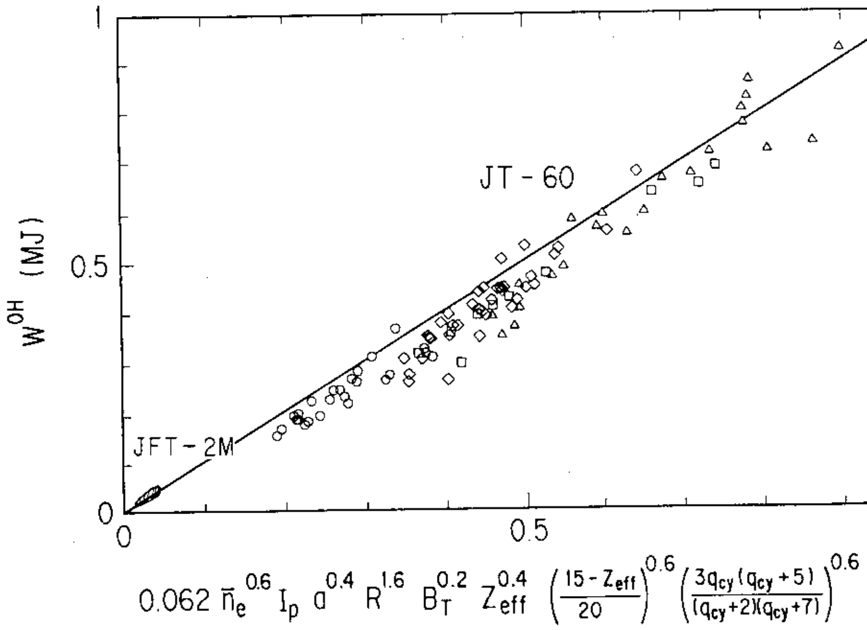

Fig. 1 Comparison between experimental values and calculated value for the stored energy of ohmic plasma given by eq.5. in JT-60.

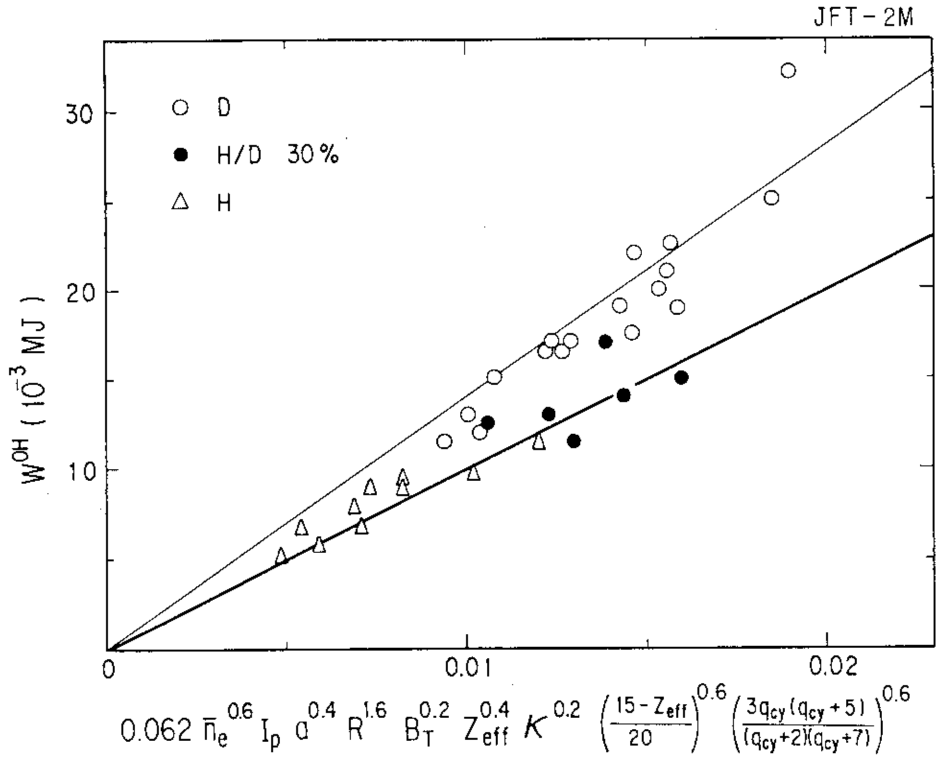

Fig. 2 Comparison between experimental values and calculated value for the stored energy of ohmic plasma given by eq.5. in JFT-2M.

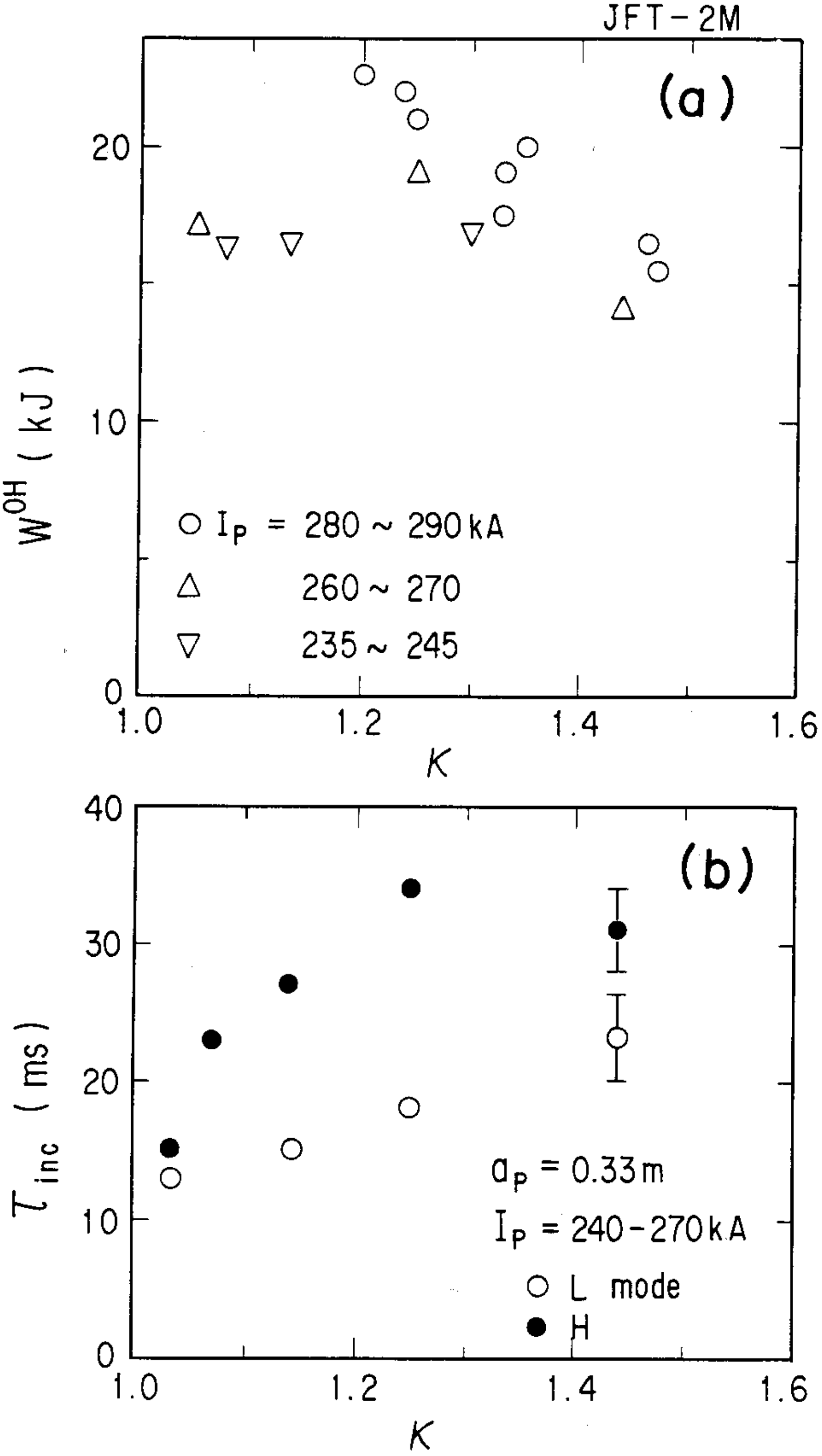

Fig. 3 Noncircularity κ dependence study of W_{oh}(a) and τ_{inc}(b).

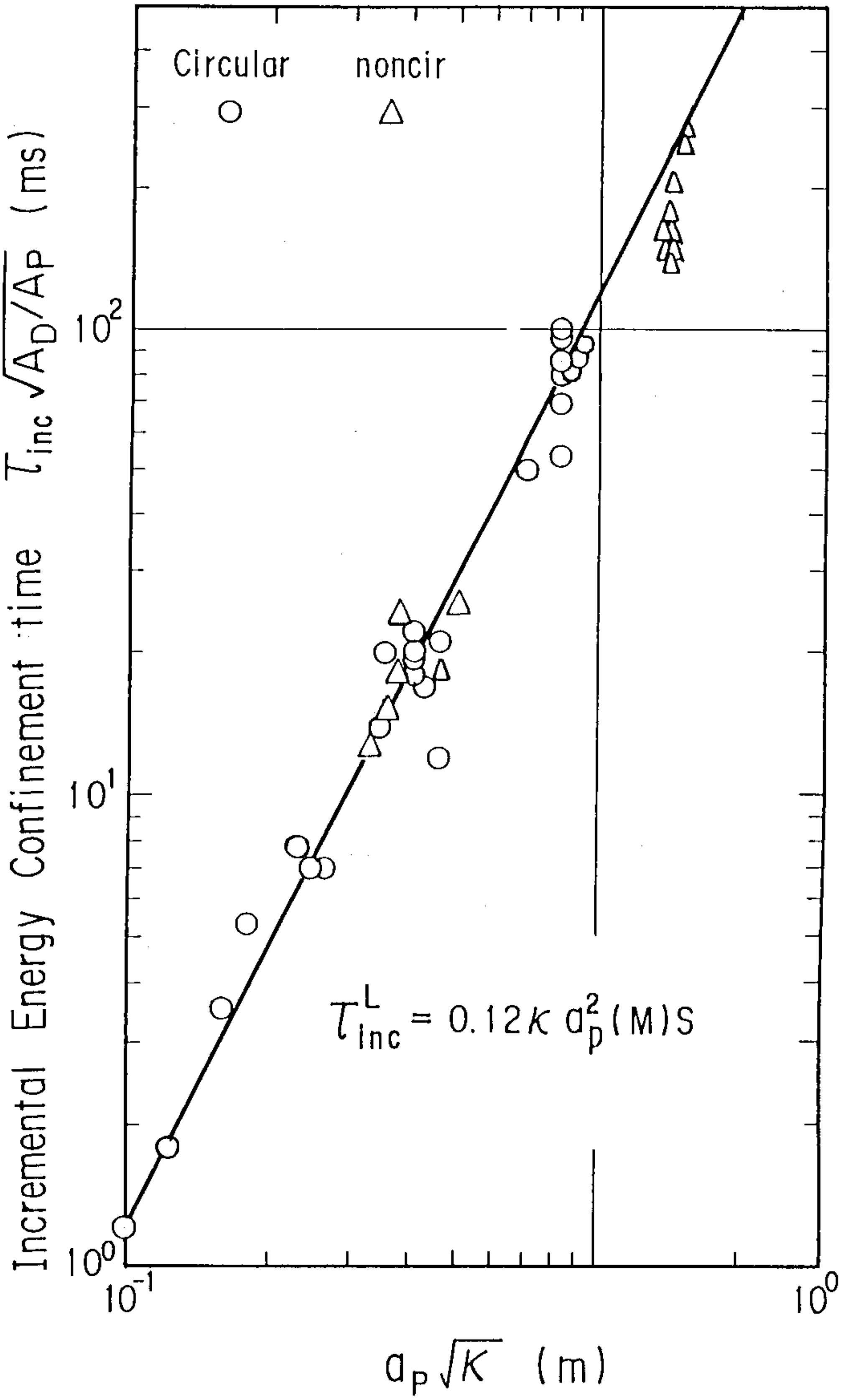

Fig. 4 Empirical Scaling of incremental energy confinement time τ_{inc} in L-mode discharges.

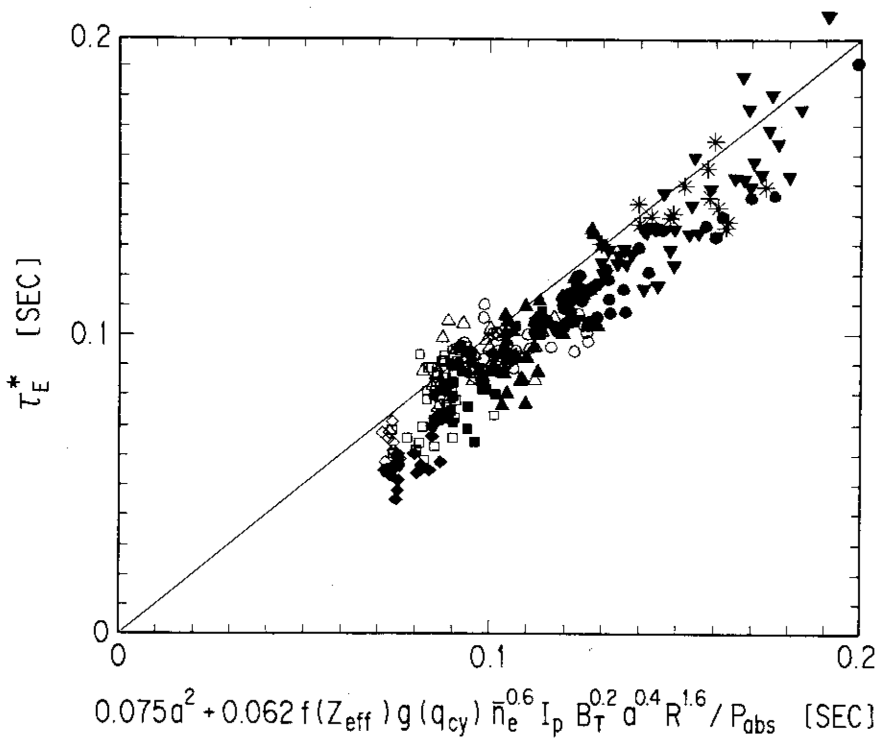

Fig. 5 Comparison between experimental values and calculated value of gross energy confinement scaling given by eq.9. in JT-60.

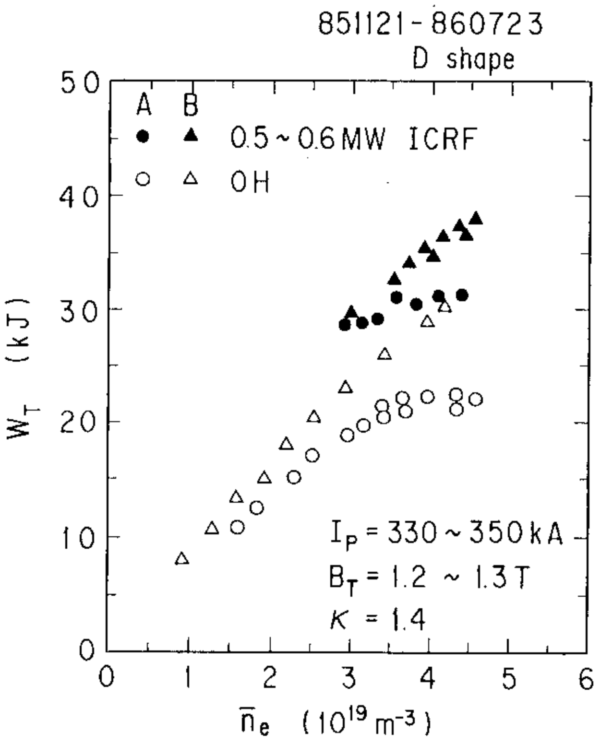

Fig. 6 Total stored energy W_t vs. density $\bar{n}_e$ for ohmic plasma and ICRF heated plasma. The change of saturation characteristics of ohmic plasma directly affects to additionally heated plasma

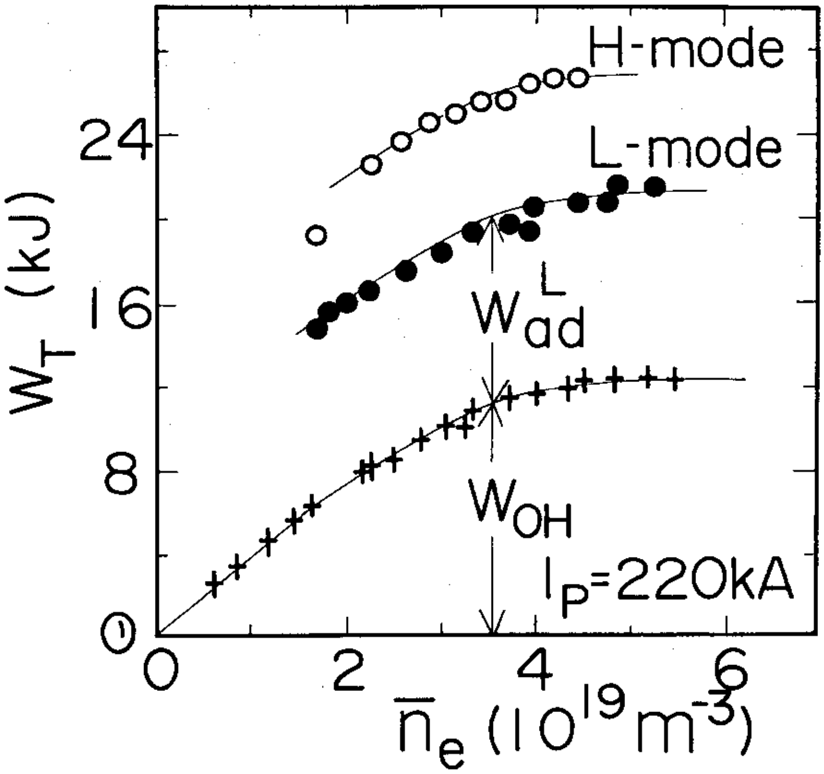

Fig. 7 Total stored energy W_t vs. density $\bar{n}_e$ for ohmic plasma and NBI heated L- and H-mode plasmas. Incremental energy from additional heating is doubled by the H-transition.

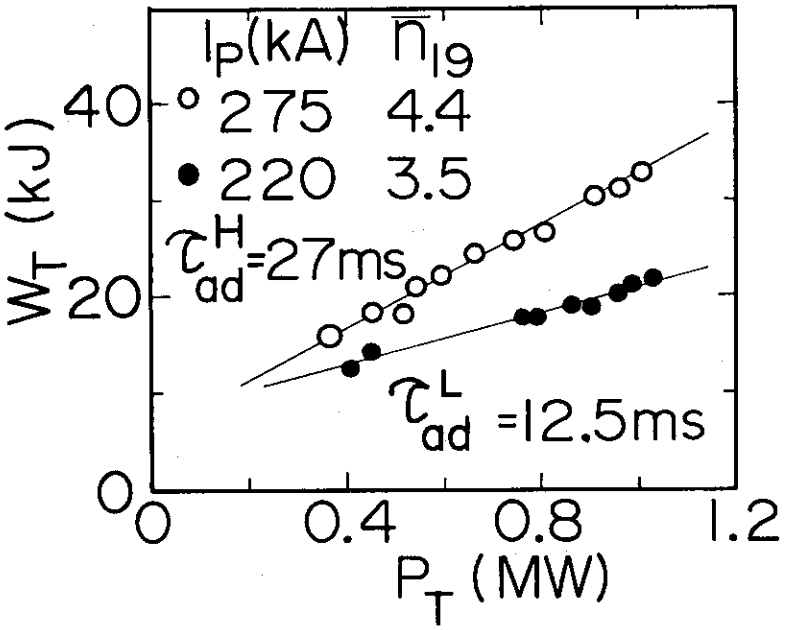

Fig. 8 Total stored energy W_t vs. total input power P_t. The inclination of the offset linear characteristic give the incremental energy confinement time τ_{inc}, and is doubled by the H-transition.

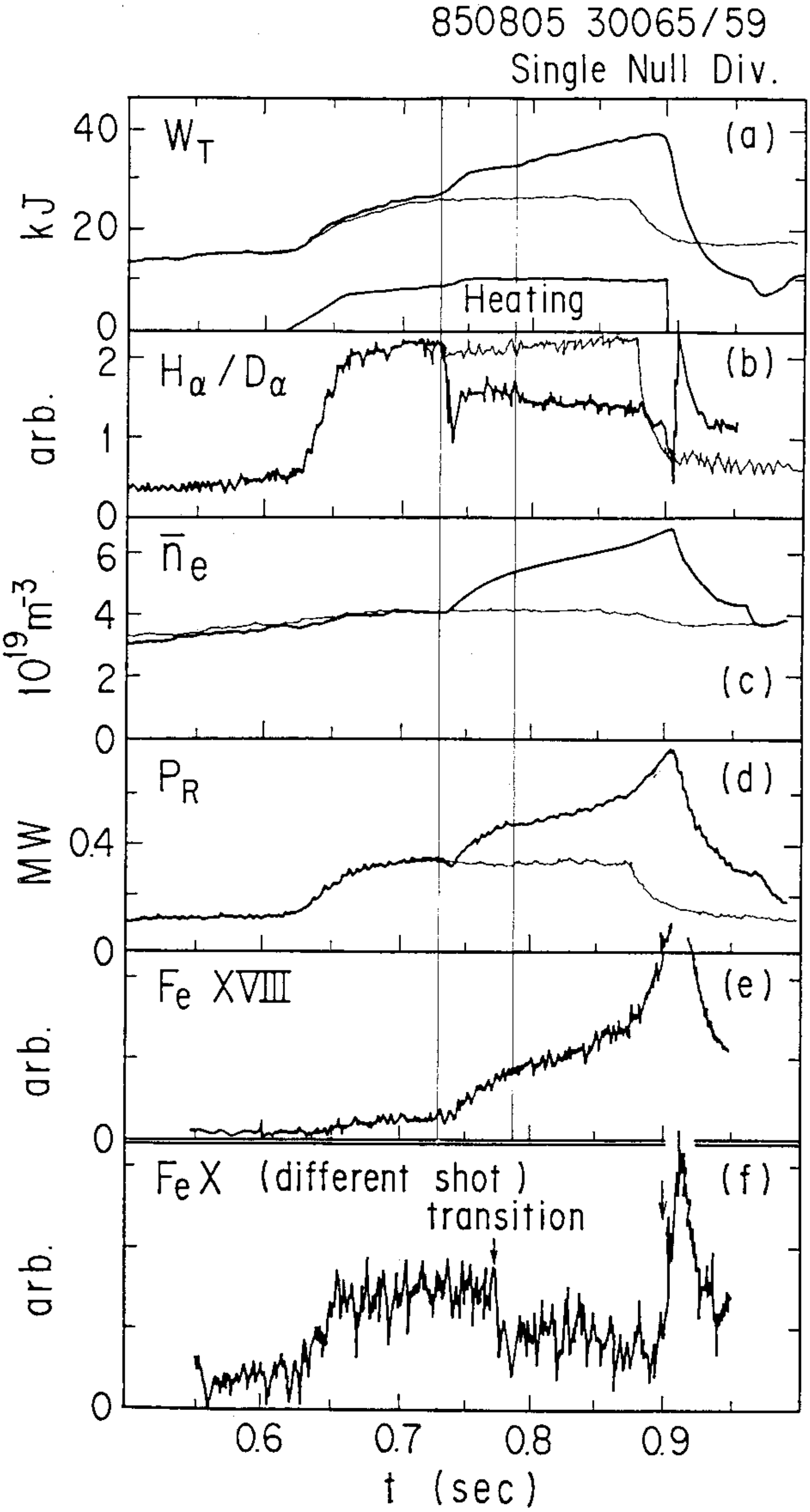

Fig. 9 Example of H-mode discharge with further improvement which may be the improvement of W_{oh}.

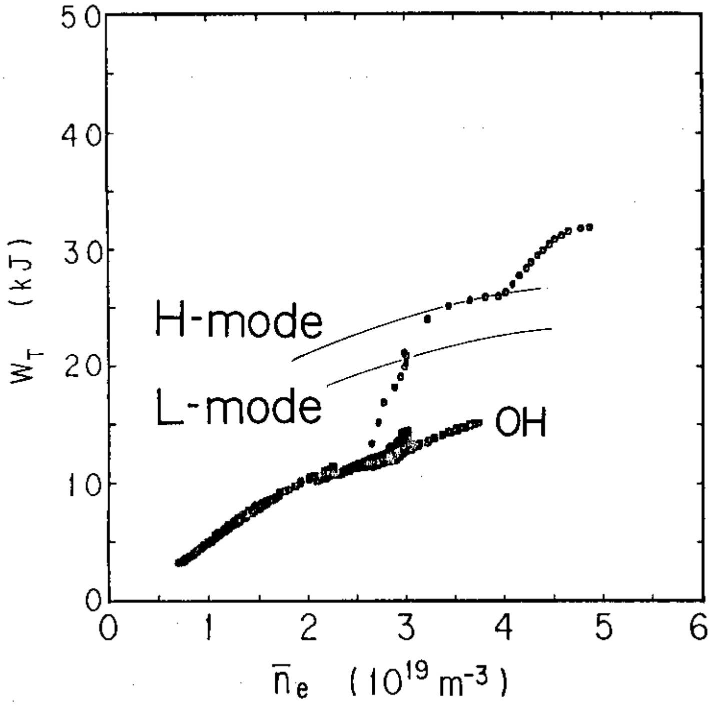

Fig. 10 Total stored energy W_t vs. density $\bar{n}_e$. Values of each 10ms during ICRF heating are plotted.

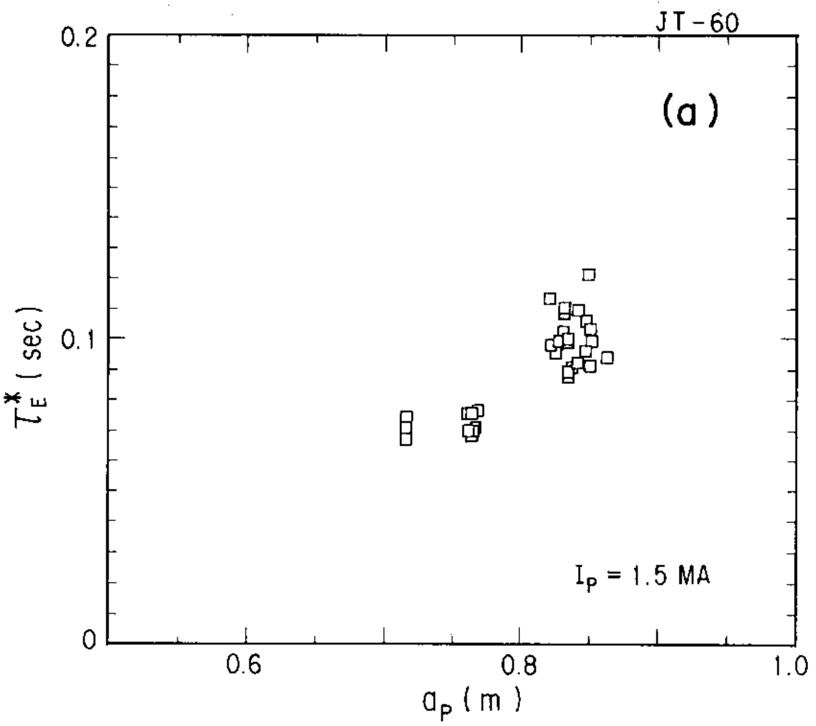

Fig. 11 Plasma radius a_p scan experiment in JT-60. Gross energy confinement time $\tau_E{}^G$ increases as increasing a_p(a), and comparisons between the experimental value and calculated value obtained by $\tau_E{}^L$ scaling (b) and Goldston scaling (c).

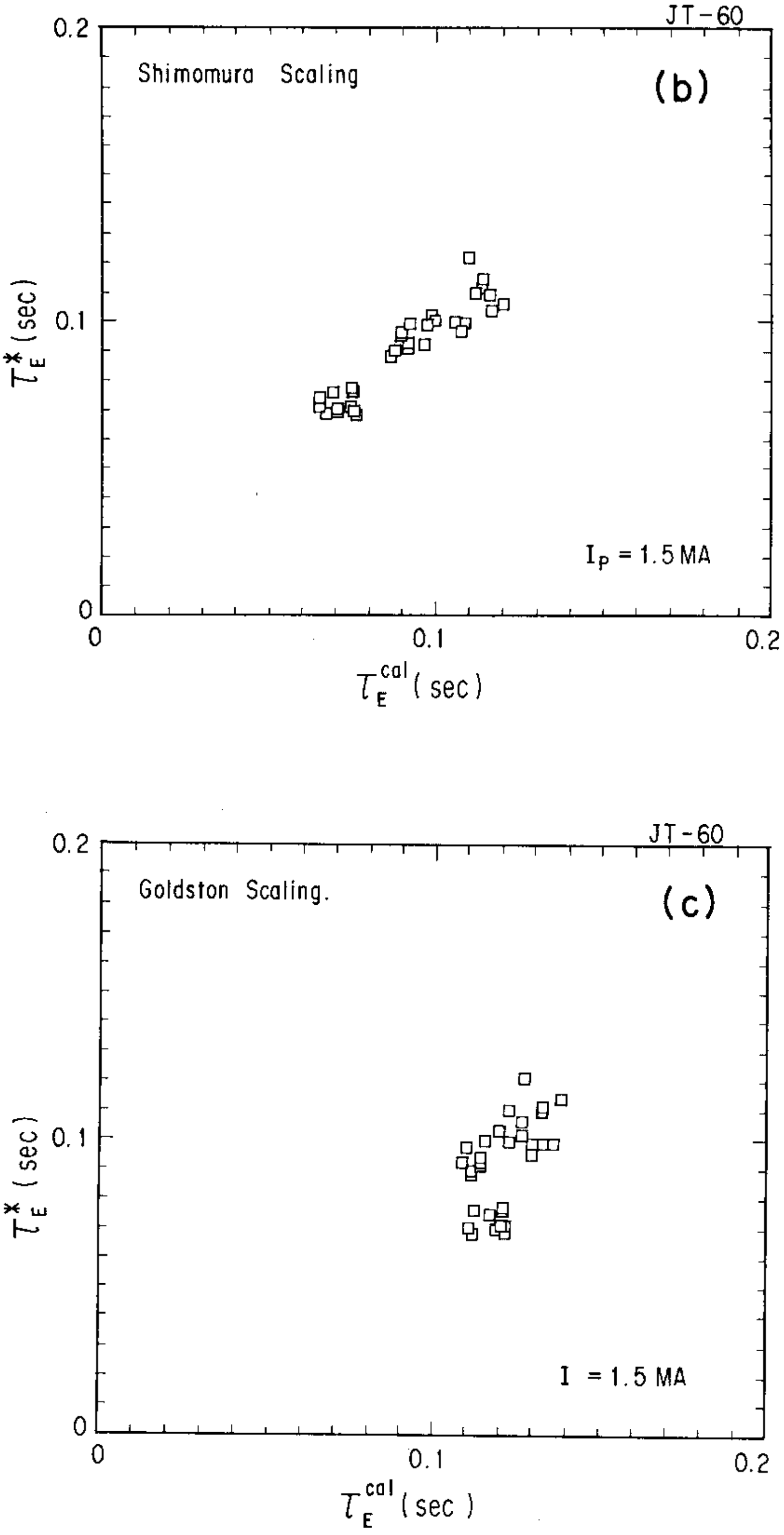

Fig. 11 (Continued)