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EMPIRICAL SCALING OF ENERGY CONFINEMENT TIME OF L-MODE AND OPTIMIZED MODE AND SOME CONSIDERATION OF REACTOR CORE PLASMA IN TOKAMAK

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Empirical Scaling of Energy Confinement Time of L-Mode and Optimized Mode and Some Consideration of Reactor Core Plasma in Tokamak

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Empirical scalings of energy confinement time for both L-mode and optimized mode in tokamak are reduced mainly from JAERI results. The L-mode scaling has strong dependence on plasma size rather than plasma current and the optimized scaling has strong dependence on plasma size and toroidal field or plasma current. Based on the scaling, characteristics of reactor core plasmas in tokamaks are discussed.

Keywords: Tokamak, Energy Confinement Time, L-mode, Optimized Mode, Reactor Core Plasma

+ Department of Thermonuclear Fusion Research

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トカマクにおけるエネルギ閉じ込め時間の経験則及び炉心プラズマについての考察

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（1987年5月11日受理）

トカマクにおけるＬモード及び最適化されたモードにおけるエネルギ閉じ込め時間の経験則を示す。Ｌモードの経験則はプラズマ・サイズに強く依存し，プラズマ電流には強く依存しない。一方，最適化されたモードの経験則はプラズマ・サイズとトロイダル磁場又はプラズマ電流に強く依存する。得られたスケーリング則を用いて，トカマクの炉心プラズマの考察を行う。

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Contens

目　　次

1. Introduction

Scaling of energy confinement time were intensively investigated in many tokamaks. The following scalings were generally believed in past several years.

$$\tau_E^{OH} \propto n_e^{\sim 1} \cdot R^{\sim 2} \cdot a^{\sim 1} \cdot q_{cy}^{\sim 1} \cdot \kappa^{\sim 0.5} \qquad \text{for ohmic plasma} \qquad (1)$$

$$\tau_E^{L} \propto I_p^{\sim 1} \cdot R^{\sim 1.5} / a^{\sim 0.5} \cdot P_t^{\sim 0.5} \qquad \text{for L-mode plasma} \qquad (2)$$

$$\tau_E^{H} \propto \tau_E^{L} \ \text{or} \ \tau_E^{H} \propto I_p^{\sim 1} \qquad \text{for H-mode plasma} \qquad (3)$$

where, τ_E, n_e, R, a, q_{cy}, κ and P_t are gross energy confinement time, electron density, major radius, minor radius, safety factor, non-circularity and total heating power, respectively. These scaling laws are correct only in low level discharges of each device and give strange values for energy confinement time in high level operations as follows:

1) In ohmic discharges, energy confinement time is well described by eq.(1) with low density discharges but saturates as increasing plasma density. The saturated value of τ_E^{OH} has no dependence on n_e nor q_{cy}.(1)
2) In L-mode plasma, the above empirical scaling is correct with relatively low I_p and low P_H. More detailed study gives a different scaling law having week dependence of I_p with high current discharges.(2)
3) In low level H-mode discharges, the energy confinement time reduces as increasing heating power and $\tau_E^H \sim 2\tau_E^L$. In good H-mode plasmas, however, degradiation of energy confinement is small as long as that of ohmic plasmas as observed in D-III (JAERI)(3) and JFT-2M(4).

This situation seems very reasonable because the above scaling laws were obtained with regression analysis of many data mainly from low level operations, e.g. operation with low n_e, low I_p and low P_H. In order to understand the maximum capability of a tokamak or design a new machine, it is essential to reduce scaling laws for high level operations. From this point of view, scaling laws of the high level operations for L-mode and optimized mode are reduced mainly from JAERI results.

Reactor core plasmas in the next generation tokamaks are widely discussed based on the previous scaling laws, i.e. misleading laws. From this point of view, reactor core plasmas are discussed based on the reduced scaling laws in this paper. Ignition margine of various ignition devices under discussion is shown.

2. Empirical Scaling Laws of Energy Confinement time

2.1 L-mode

In L-mode discharge, the incremental energy confinement time τ_E^{inc} is essential as discussed in refs |5 ~ 7|. Experimental data with relatively low current discharges show strong dependence of plasma current on the incremental energy confinement time τ_E^{inc}, e.g. $\tau_E^{inc} \propto I_p$ with $I_p \leq 490$ kA in D-III.[8] In high current discharges with $I_p \geq 490$ kA, however, τ_E^{inc} is constant.[3] This behavior was also observed in JFT-2M, i.e., τ_E^{inc} is constant with $I_p = 0.21 - 0.41$ MA and becomes short with $I_p < 200$ kA. These results show that τ_E^{inc} is independent of I_p with sufficient high current discharges, e.g., $I_p \gtrsim 200$ kA in JFT-2M, $I_p \gtrsim 500$ kA in D-III and $I_p \gtrsim 2$ MA in JET.[9]

In high level operation, the incremental energy confinement time is independent of heating method, heating power deposition profile, plasma current, plasma density and so on as shown in ref.(7). and the empirical scaling was given in ref. (7) as follows:

$$\tau_E^{inc} = 0.12\ a_p^2\ (m) \quad s\ . \tag{4}$$

The more detailed studies were performed in JFT-2M and JT-60 (Appendix I) and the following more general scaling was obtained.

$$\tau_E^{inc} = 0.12\ a_p^2\ (m) \sqrt{\frac{A_{H,D}}{2}} \quad s \tag{5}$$

where $A_{H,D}$ is mass number of hydrogen isotope. This scaling with JAERI data including DIVA[10], JFT-2[11], JFT-2M[6], DIII[3], JT-60[12,13], is shown in Fig. 1. Other data are also well described by this scaling (see ref.(7)).

The gross energy confinement time of L-mode τ_E^L is given by the following equations.

$$\tau_E^L = \tau_E^{inc} + \frac{P_{oh}^0}{P_t} (\tau_E^{oh} - \tau_E^{inc}) \tag{6}$$

where P_t, P_{oh}^0 and τ_E^{oh} are the total heating power, the initial ohmic input power and the initial ohmic confinement time. When the additional heating power is small or comparable to P_{oh}^0, the first term is small and following equation is obtained.

$$\tau_E^L \sim \frac{P_{oh}^0}{P_t}\,\tau_E^{oh} \quad \text{for} \quad P_t \gtrsim P_{oh}^0 \tag{7}$$

This relation describes the steep degradation observed in the early heating experiment and the strong dependence of τ_E^L on the plasma current[14,15] because of $P_{oh}^0\,\tau_E^{oh} \propto \tilde{I}_p^1$. When $P_t \gg P_{oh}^0$ the following equation is obtained.

$$\tau_E^L \sim \tau_E^{inc} + \tau_E^{oh}\,\frac{P_{oh}^0}{P_t} \quad \text{for} \quad P_t \gg P_{oh}^o \tag{8}$$

This equation gives D-III scaling, i.e. $\tau_E^L \sim b + a/P_t$ and the rather weak I_p dependence of τ_E^L.[16,17] The initial stored energy $W_{oh}^0 = \tau_E^{oh}\,P_{oh}^0$ of ohmic discharges with high density is given by the following semi-empirical scaling (Appendix II).

$$W_{OH}^0 = 0.095\ A^{0.2} Z_{eff}^{0.2} \bar{n}_e^{0.6} I_p^{0.8} B_t^{0.2} a_p^{0.8} R^{1.4} \kappa^{0.4} \quad \text{MJ} \tag{9}$$

where A, Z_{eff}, $\bar{n}_e$, I_p, B_t, a_p, R and κ are mass number, effective charge, average density in $10^{20}\ m^{-3}$, plasma current in MA, toroidal field in T, plasma minor radius in m, plasma major radius in m and elongation, respectively.

Therefore the gross energy confinement time of L-mode τ_E^L is given by the following equation with high density plasma and high additional heating power.

$$\tau_E^L = 0.085\ A^{0.5} a_p^2 + 0.095 A^{0.2} Z_{eff}^{0.2} \bar{n}_e^{0.6} I_p^{0.8} B_t^{0.2} a_p^{0.8} R^{1.4} \kappa^{0.4} P_t^{-1} \quad \text{s} \tag{10}$$

where P_t is the total heating power in MW.

2.2 Optimized Energy Confinement Time

In optimized H-mode discharge, the gross energy confinement time τ_E^H is as long as that of ohmic plasma as shown in D-III(JAERI)[3], JFT-2M[4] and D-III Dig-D[18]. Therefore it is very important to understand the scaling low of ohmic plasma with optimized discharge conditions.

The generally believed scaling law given by eq.(1) is correct only in relatively law density plasmas. As increasing plasma density, the energy confinement time τ_E^{OH} saturates as shown in Fig. 2. This behavior is very common except with pellet injection. With pellet injection, however, a steady state plasma will not be obtained with pellet-dominated fueling and will be sustained mainly with recycling particles. Therefore in a large and steady state machine, it is sufficient to obtain the scaling law without pellet injection.

The optimized energy confinement time τ_E^{OP} is the saturated value of τ_E^{OH} in a high density plasmas as shown in Fig. 2 including DIVA,[19] JFT-2,[20] JFT-2M and JT-60[1]. The critical density $\bar{n}_e^c$ (m^{-3}) shown in Fig. 2 is given by the following equation (see ref.(4) and Appendix II)

$$\bar{n}_e^c = 6.7 \times 10^{19}\ q_{cy}^{-1} B_t R^{-1} A^{0.5} \qquad m^{-3} \tag{11}$$

where B_t is the toloidal magnetic field in T. The critical density is given by eq.(11) except with extreme conditions, i.e. pellet fuel and very-low-q. Therefore the optimized energy confinement τ_E^{OP} is obtained from eqs.(1) and (11) as follows:

$$\tau_E^{OP} = 0.045\ R\, a\, B_t \kappa^{0.5} A_{D,H}^{0.5} \qquad s \tag{12}$$

In good H-mode discharges, the energy confinement time is almost constant as increasing heating power as shown in ASDEX[21], D-III(JAERI)[3], JFT-2M[4] and DIII-D[18]. The energy confinement time is proportional to the plasma current. In JFT-2M, the energy confinement time of H-mode approaches to the optimized ohmic confinement time and $\tau_E^H \sim \tau_E^{OP}$ with $q_{cy} \sim 2$ in deutrium plasmas as discussed in Appendix III. Therefore the following simple scaling is obtained for optimized H-mode discharges.

$$\tau_E^H = \tau_E^{OP} \tag{13}$$

with $q_{cy} \sim 2.2$ and $\bar{n}_e > n_e^c$. The optimized confinement time for both ohmic and H-mode plasmas are summarized in Fig. 3.

3. Consideration of Reactor Core Plasma

A variety of next generation devices, such as FER (Japan), NET (EC), TIBER (US), CIT (US), have been proposed to achieve self-ignition or high Q burning experiments. In designing the device to achieve their target, the energy confinement scaling is one of the essential design constraints to be chosen. Thus, in this section, we will examine the capability of each device to achieve their target based on the energy confinement scaling developed in the previous section. As a measure for the capability of the device, we will use the ignition margin C_{ig}, which is defined as the ratio of fusion α-power P_{α} to the total loss power P_{loss}. Here, P_{loss} consists of the transport loss $3(n_e+n_i)T/\tau_E$, and the radiation loss (bremsstrahlung puls synchrotron radiation). There are several other important design constraints to be chosen, e.g. beta limit scaling, profile effect on fusion power density, impurity and fast alpha contribution to the total beta. We chose these constraints according to the FER design constraints[23]. Thus, the plasma parameters and fusion power can differ from their respective nominal values.

We will evaluate C_{ig} for six different confinement scaling laws, Mirnov, ASDEX-H, Kaye-Goldston H mode, Kaye-Goldston L-mode, L mode and optimized confinement τ_E^{OP}. First, we obtain the optimum temperature, which maximizes C_{ig}, for each scaling law. Figure 4 shows C_{ig} as a function of the temperature for each scaling law evaluated for FER. Except for Kaye-Goldston L and H mode scaling (10 keV), temperature of 12 keV gives maximum value of C_{ig}. Then C_{ig} is evaluated at their respective optimum temperature for each device. Table 1 shows the results of the evaluation together with the device and plasma parameters of each device.

From this table, several conclusions can be drawn. First, ignition will be obtained in H-mode discharges but will not be achieved when L-mode scaling of this paper is governing the confinement in the next generation devices including CIT. Kaye-Goldston L-mode scaling, however, gives the ignition condision for CIT. Secondly, although there are large differences in C_{ig} between each devices with Mirnov and ASDEX-H scaling laws, the difference becomes fairly small with optimized scaling law. This tendency is particularly remarkable for the difference of C_{ig} between a highly elongated plasma (TIBER) and a mildly elongated plasma (FER) since the optimized scaling law does contain B_T dependence rather than I_p dependence.

4. Discussion

With the K-G L-mode, an ignition condition is obtained in a compact tokamak with a high field such as CIT. The L-mode scaling given by eq.(10), however, does not give an ignition condition in any devices under design except in a very large device such as a power reactor. From this conclusion, the optimized H-mode operation is required in the next generation machines.

Mornov and ASDEX-H scalings are similar to the optimized H-mode scaling as follows because $q_{cy} \simeq 2.2$ for $\tau_E^H = \tau_E^{OP}$.

$$\tau_E^{OP} = 0.04 \left\{ \frac{R\,\kappa^{0.5} A^{0.5}}{a(1+\kappa^2)} \right\} I_p\, R = 0.04 \left\{ \frac{R^2}{a^2} \frac{A^{0.5}}{1+\kappa^2} \right\} I_p\, a\, \kappa^{0.5} \tag{14}$$

$$\tau_E^{ASDEX} = 0.1\, I_p\, R \tag{15}$$

$$\tau_E^{Mirnov} = 0.155\, I_p\, a\, \kappa^{0.5} \tag{16}$$

Discrepancy between these scaling is rather small but ASDEX scaling gives an optimistic value which is 1.5 ~ 2 times than the ohmic confinement time for a reactor grade plasma. Mirnov scaling gives a lower value than the observed value in JFT-2M, e.g. τ_E^{Mirnov} = 15 ms and $\tau_E^{EXP.}$ = 30 ms and gives optimistic values for TIBER-II and CIT because of their high elongation and low aspect ratio. These optimistic values are 1.5 times higher than the ohmic confinement time and do not seem realistic. The ignition margine is larger than unity but 1.14 ~ 1.41 in various devices such as FER, NET, TIBER II and CIT from the optimized H-mode scaling. Therefore more careful studies based on reliable scaling laws should be required for optimizing machine parameters for a next generation tokamak.

The confinement scaling with high-β is not clear and the optimized H-mode is obtained only with Troyon factor ≤2.5 in JFT-2M. Another question is whether the optimized H-mode will be obtained with Murakami factor of 10 ~ 15 or not. Therefore detailed studies with high-β and high density plasmas with high temperature are required.

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Table 1 Device and plasma parameters and their ignition margins of proposed ignition devices

		FER	NET	TIBER-II	CIT
Q		∞	∞	∞	∞
Burn Length	T_b(s)	800	350	930	3
Major Radius	R_p(m)	5.0	5.18	3.0	1.22
Minor Radius	a_p(m)	1.3	1.35	0.83	0.45
Elongation	κ	1.7	2.1	2.4	1.8
Toroidal Field	B_t(t)	5.0	5.0	5.55	10.4
Plasma Current	I_p(MA)	9.2	10.2	10	9 (10)
Safety Factor	q_{cy}	1.8	2.1	2.1	2.0
Troyon Factor		3.5	3.5	3.5	3.5
Toroidal β	β(%)	4.95	5.6	6.0	6.7
Plasma Temperature $\bar{T}$ (keV)		12	12	12	12
Plasma Density $\bar{n}_e$ (10^{20} m^{-3})		1.24	1.33	2.35	7.3
Fusion Power	(MW)	550	870	680	810
Ignition Margin (P_α/P_{loss})	Optimized H	1.15	1.41	1.14	1.34
	Mirnov	1.13	1.46	1.65	2.31
	ASDEX-H	1.87	2.18	2.27	2.77
	K-G H mode	1.07	1.24	1.45	1.61
Plasma Temperature $\bar{T}$ (keV)		10	10	10	10
Ignition Margin	L-mode	0.14	0.16	0.11	(0.27)
	K-G L mode	0.34	0.39	0.58	(1.12)

( ) limiter operation

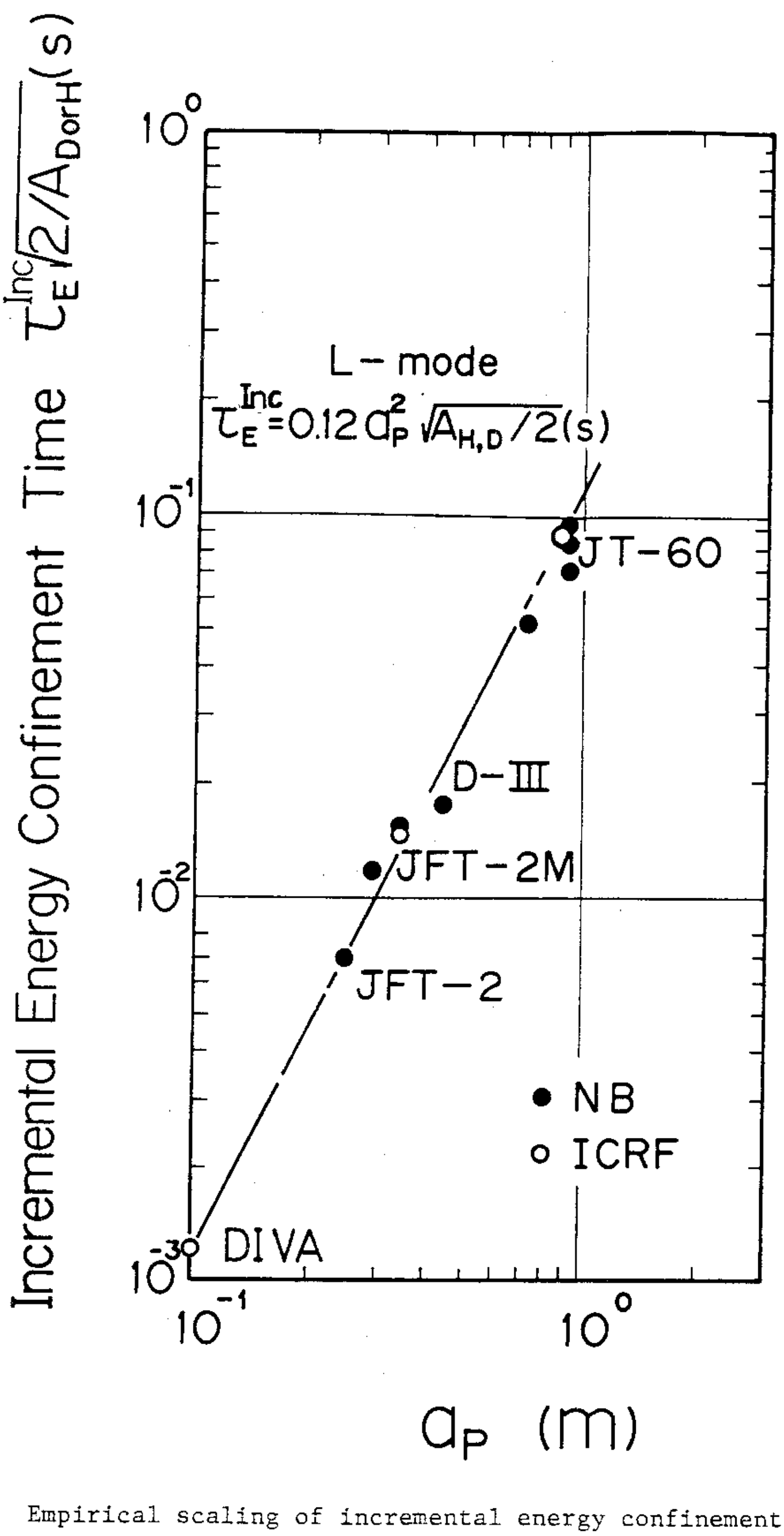

Fig. 1 Empirical scaling of incremental energy confinement time τ_E^{inc} in L-mode discharges.

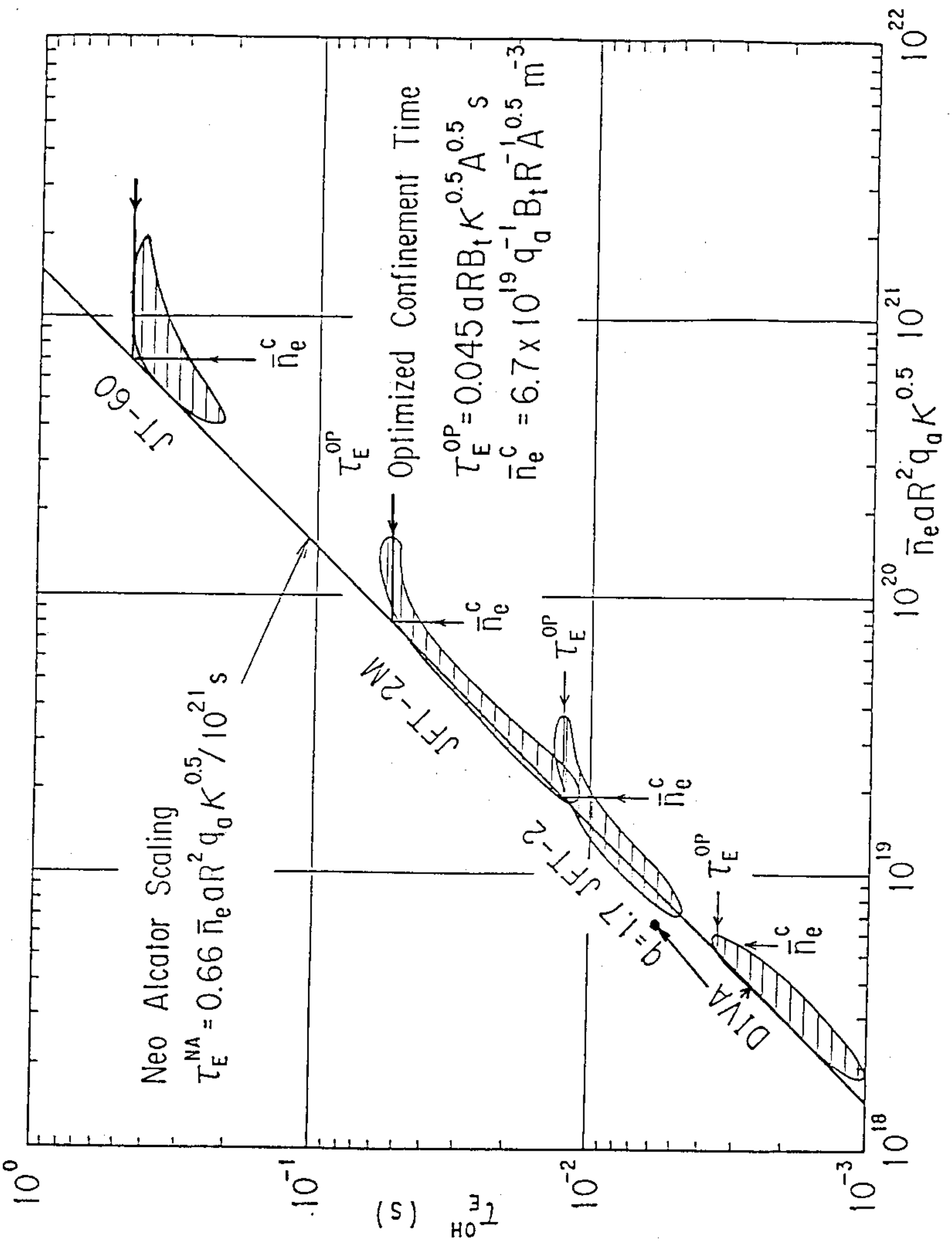

Fig. 2 Energy confinement time of ohmic discharges.

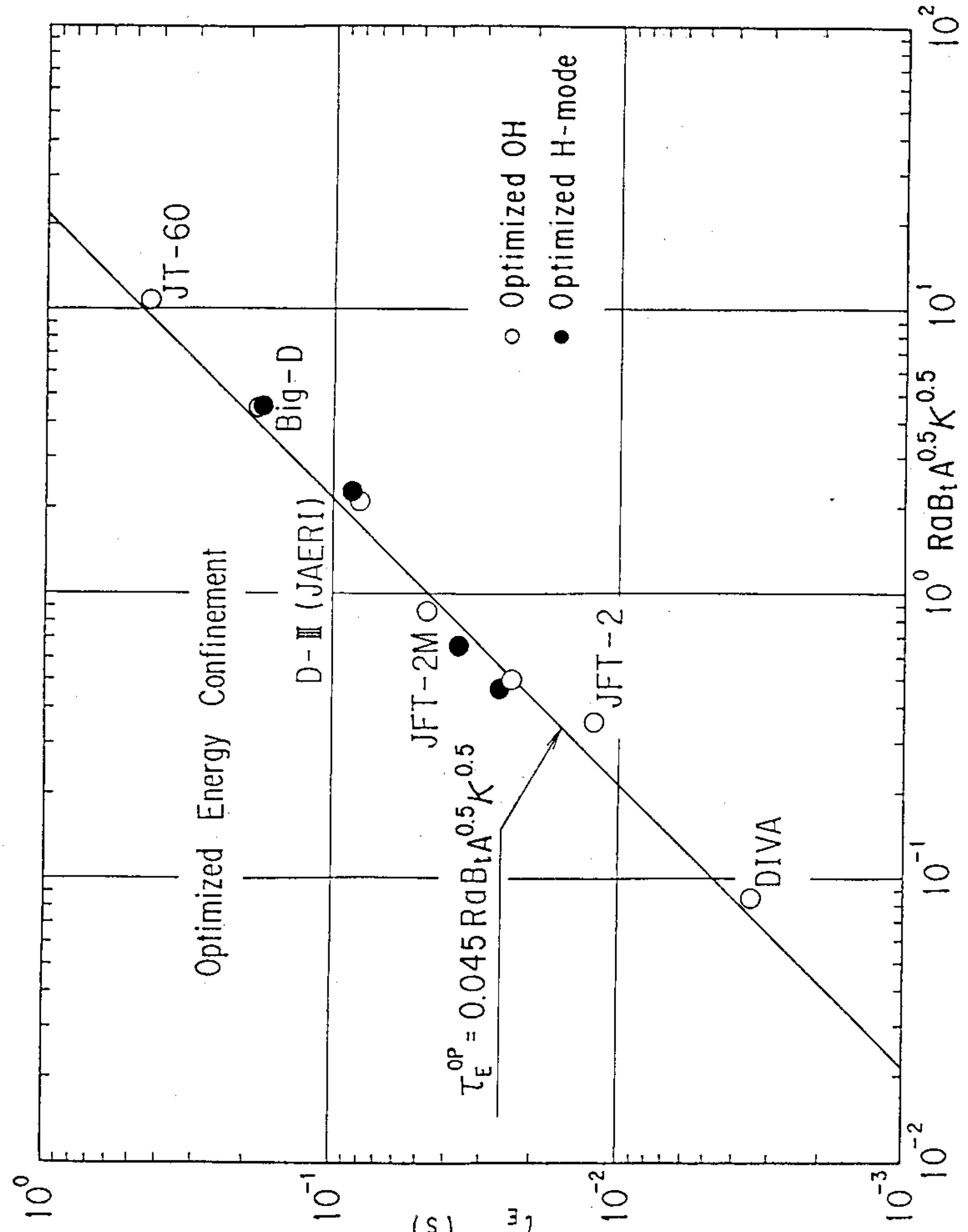

Fig. 3 Empirical scaling of optimized confinement time in ohmic and H-mode discharges.

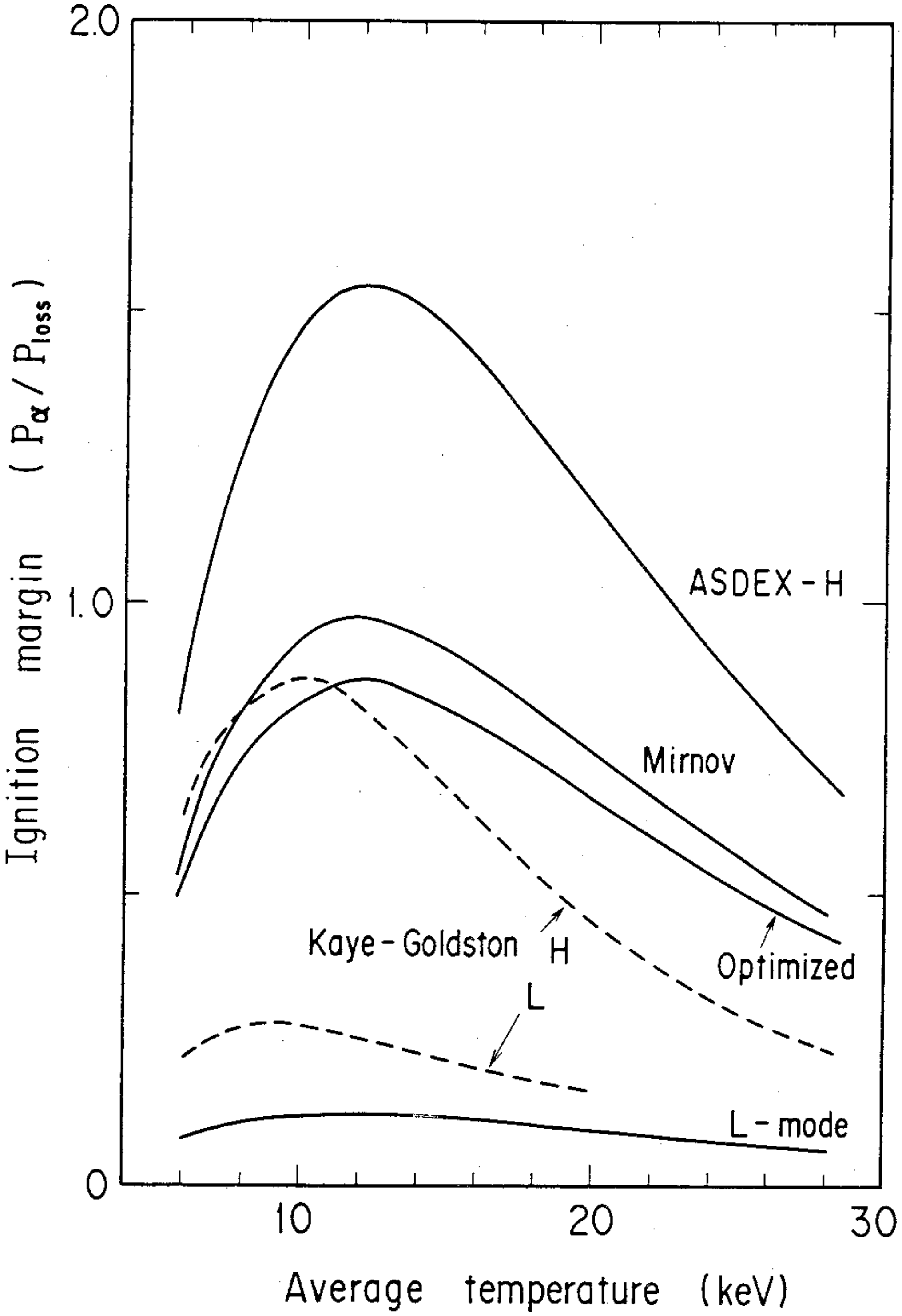

Fig.4 Ignition margin and temperature

Appendix I Comments on L-mode Scaling

In some experiment, the incremental energy confinement time of L-mode plasmas has dependence of plasma density.[24)]

In JT-60 experiments, the similar behavior is observed as shown in Fig. AI-1. In case A, the intial density is low and the density increases during NB heating. The incremental plasma energy ΔW_A is 1.2 MJ and the incremental energy confinement time is 71 ms. In case B, the initial density is high and density cramping is observed. The incremental plasma energy ΔW_B is 0.95 MJ and the incremental energy confinement time is 56 ms and 80% of that of case A. This difference is explained by the change of the stored energy in ohmic plasmas. Keeping the plasma density at a constant value, the incremental energy is 1.05 MJ. Considering this effect, ΔW_A = 1.2 MJ and ΔW_B = 0.95 MJ should be replaced by $\Delta W_A'$ = 1.08 MJ and $\Delta W_B'$ = 1.04 MJ. And the incremental energy confinement time is 62 ms for both cases.

With similar conditions, the density increase during NB heating is large with low density discharges and is small with high density discharges. Therefore the incremental energy confinement time of low density discharges is longer than that of high density discharge without the above correction. The other uncertainty comes from beam component as discussed in ref.(12).

The other important factor of confinement time is mass dependence. In ref.(7), $\tau_E^{inc} = 0.12\ a_p^2$ is reduced from deutrium plasmas. Therefore more general scaling should be $\tau_E^{inc} = 0.12\ a_p^2\ \sqrt{A_{H,D}/2}$ as shown in Fig.AI-2.

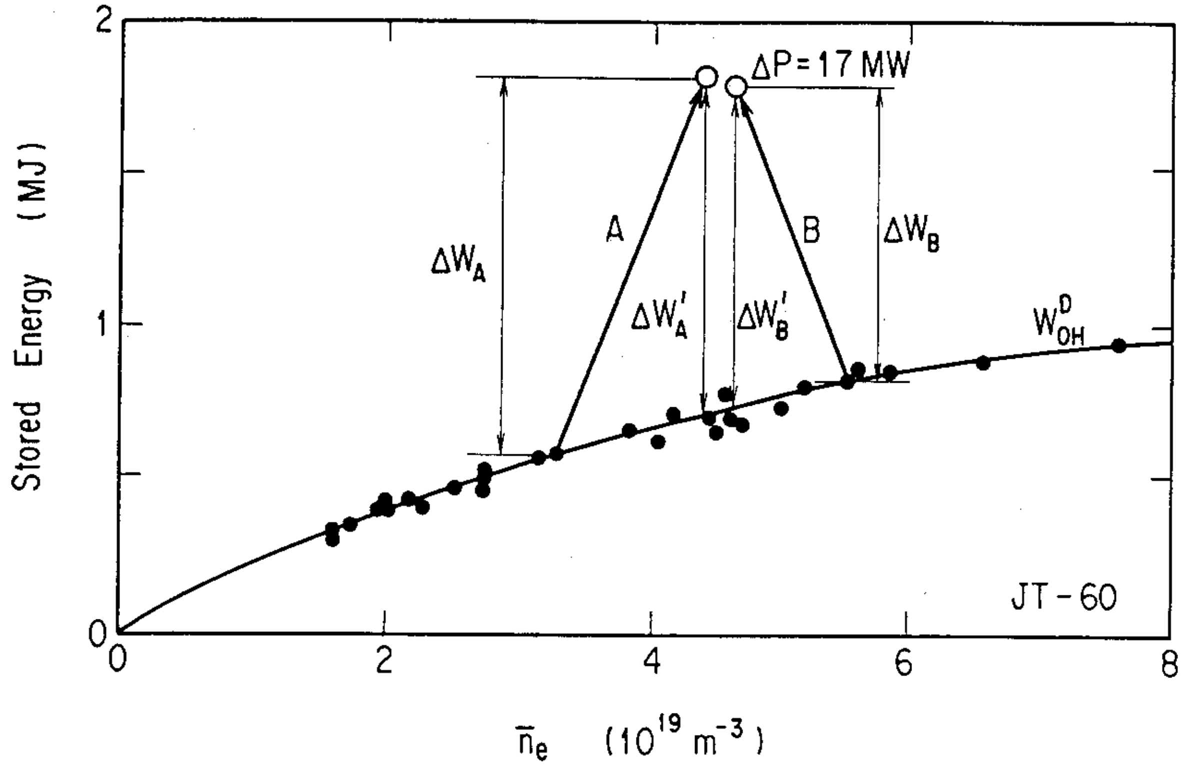

Fig. AI-1 Incremental energy ΔW with NB heating and initial stored energy W^{o}_{OH} v.s. mean plasma density $\bar{n}_e$ in JT-60. P_{NB}=16~18 MW and incremental power is normalized at 17 MW.

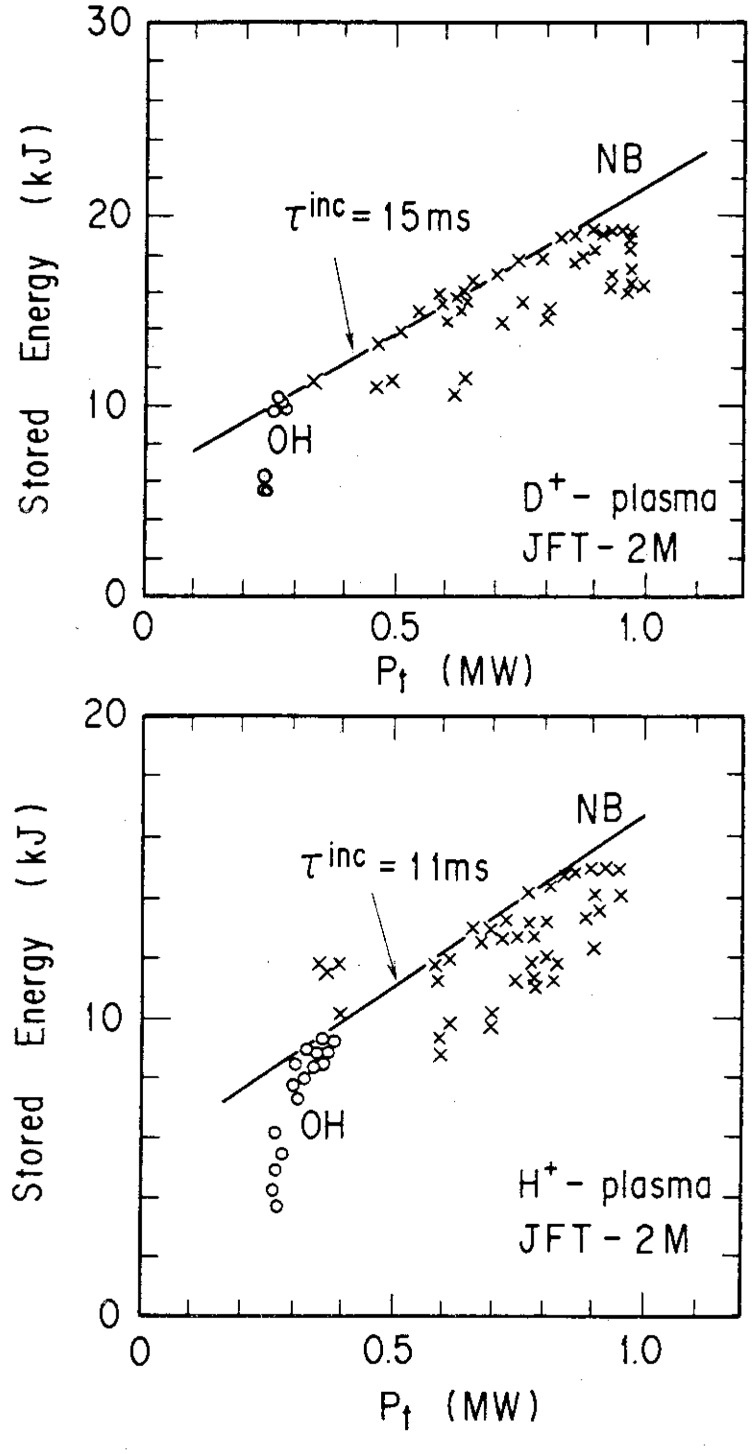

Fig. AI-2 Incremental energy confinement time of deutrium and hydrogen plasmas in L-mode discharges in JFT-2M.

Appendix II Ohmic Confinement Scaling

In low discharges, neo Alcator scaling is correct and $\tau_E^{OH} \propto \bar{n}R^2 a q_{cy}^{-1}\kappa^{0.5}$. In high density discharges, however, τ_E^{OH} has no dependence of the plasma density as shown in Fig. AII-1 ~ 3. The most important confinement time should be the optimized energy confinement time τ_E^{OP} which is the saturated value as increasing plasma density. And $\tau_E^{OP} \propto n_e^{o} I_p^{o} B_T A^{0.5}$ from Fig. AII-1 ~ 2.

Comparing data from JFT-2M (Fig. AII-1 ~ 2) and JT-60[12] (Fig. AII-3) the more general scaling is obtained as follows

$$\tau_E^{OP} \propto R\ a\ B_t\ \kappa^{0.5}\ A^{0.5} \qquad \text{(AII-1)}$$

This scaling law is also reduced from saturated values of neo Alcator scaling as discussed in section 2.2.

The stored energy of ohmic plasma is also very important to understand the gross energy confinement time as discussed in section 2.1 and is given by the following equation as demonstrated in Fig.AII-4. This scaling is also reduced from energy balance equations by using eq.(AII-1).

$$W_{OH} = 0.095 A^{0.2} Z_{eff}^{0.2} \bar{n}_e^{0.6} I_p^{0.8} B_t^{0.2} a_p^{0.8} R^{1.4} \kappa^{0.4}$$

for high density plasma.

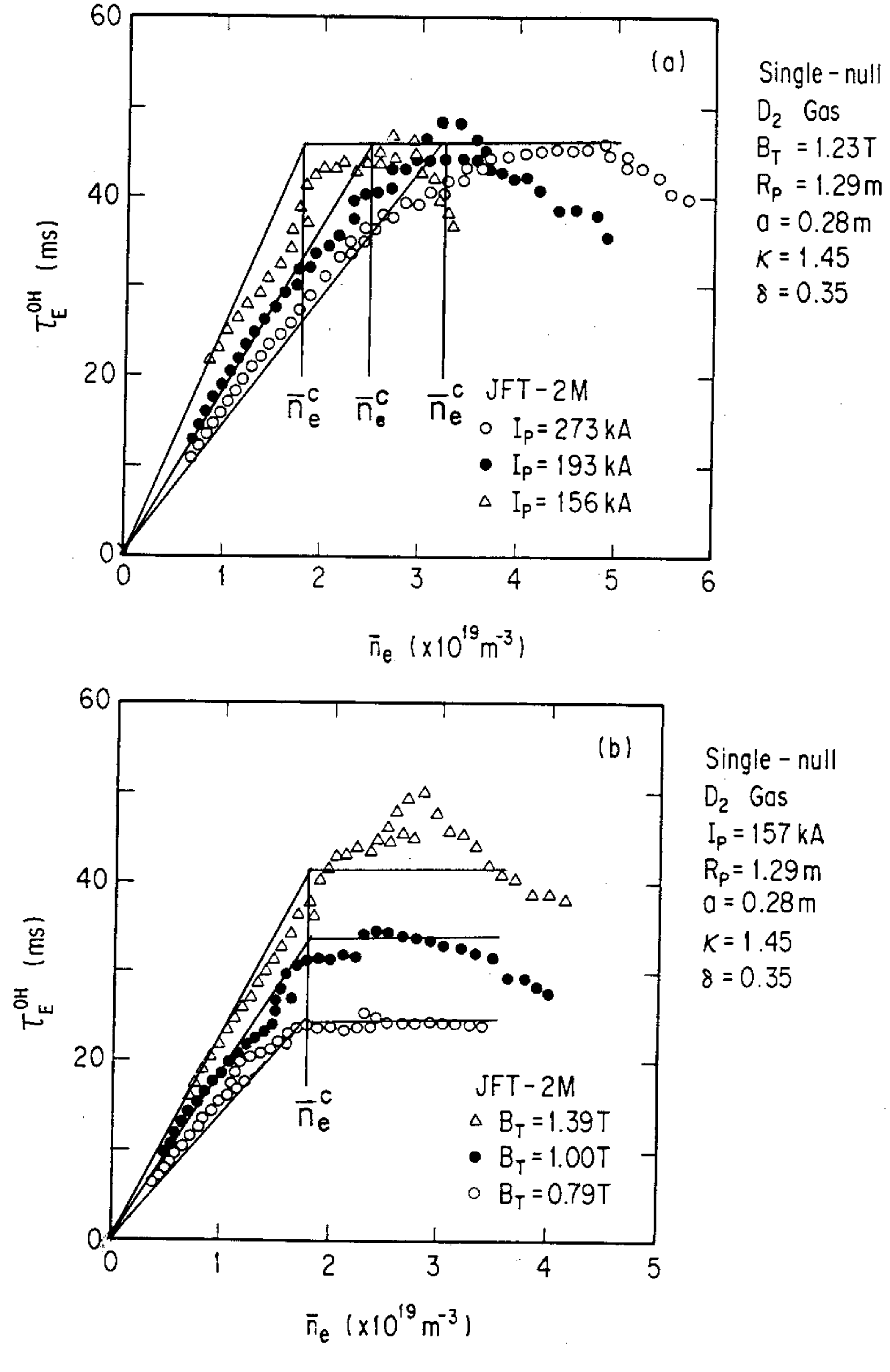

Fig. AII-1 Ohmic confinement time in JFT-2M. $\bar{n}_e^c$ gives the critical density of eq.(11).

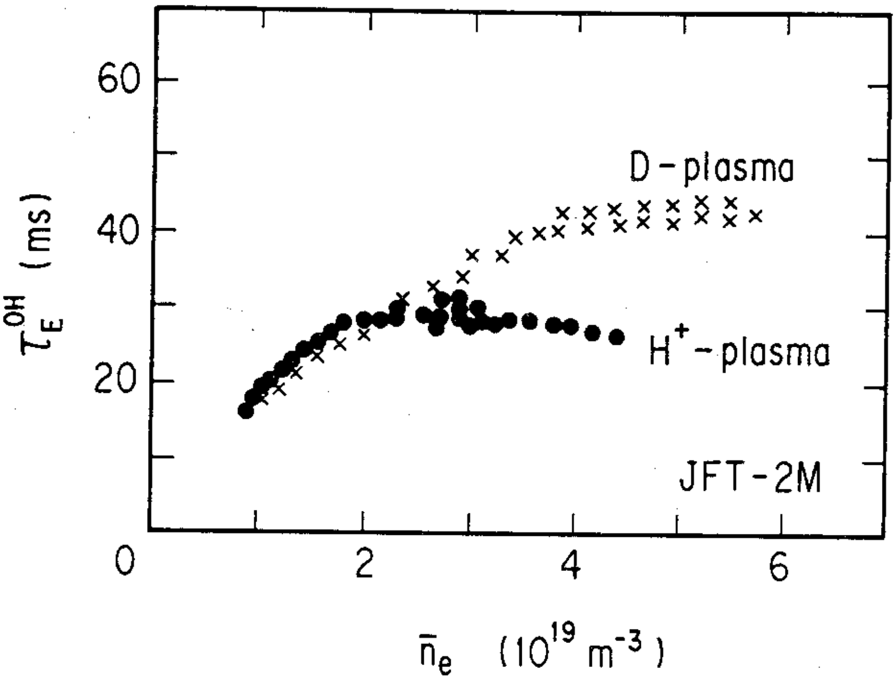

Fig. AII-2 Ohmic confinement time of deutrium and hydrogen plasmas in JFT-2M

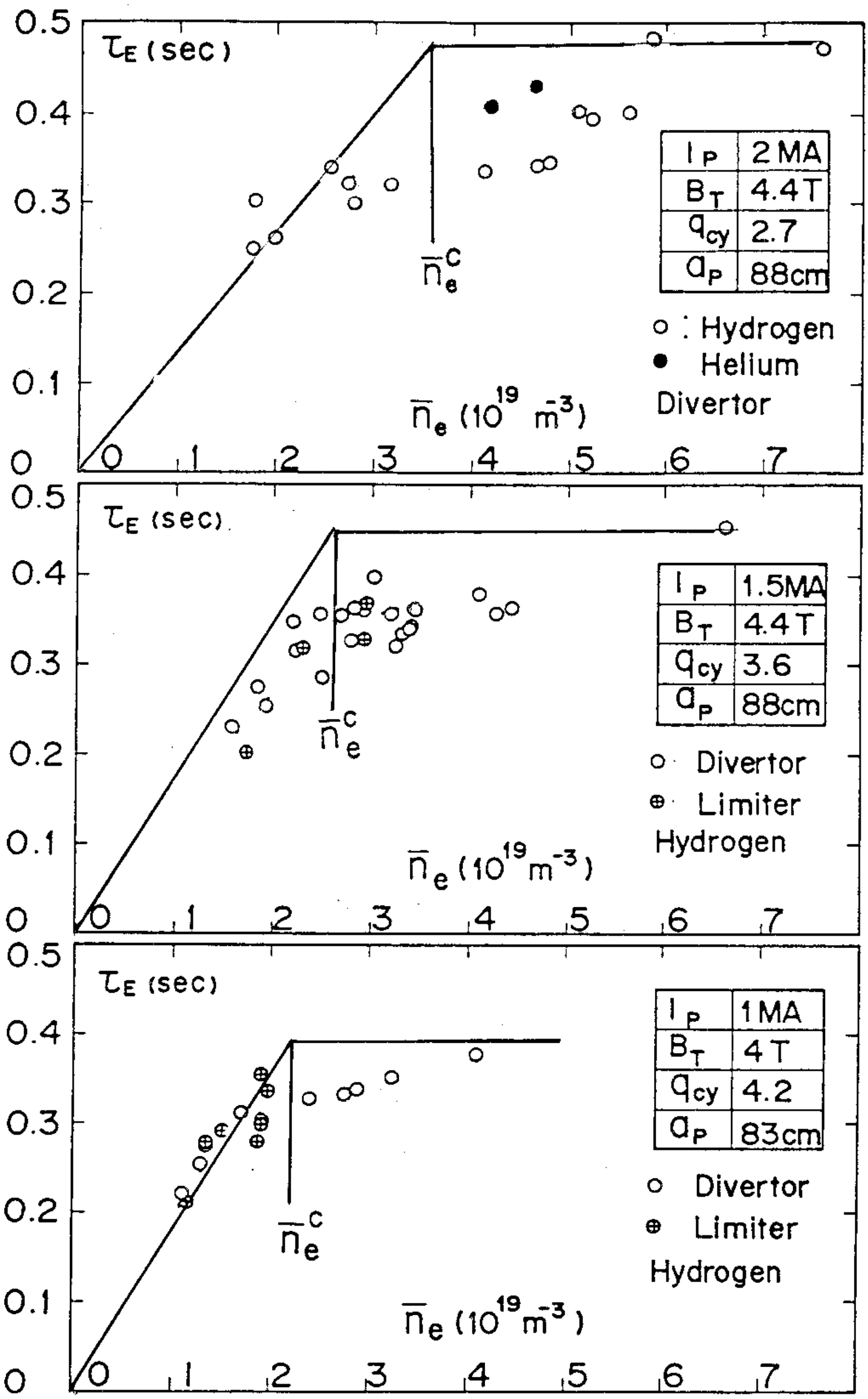

Fig. AII-3 Ohmic confinement time of JT-60. $\bar{n}_e^c$ gives the critical density of eq.(11).

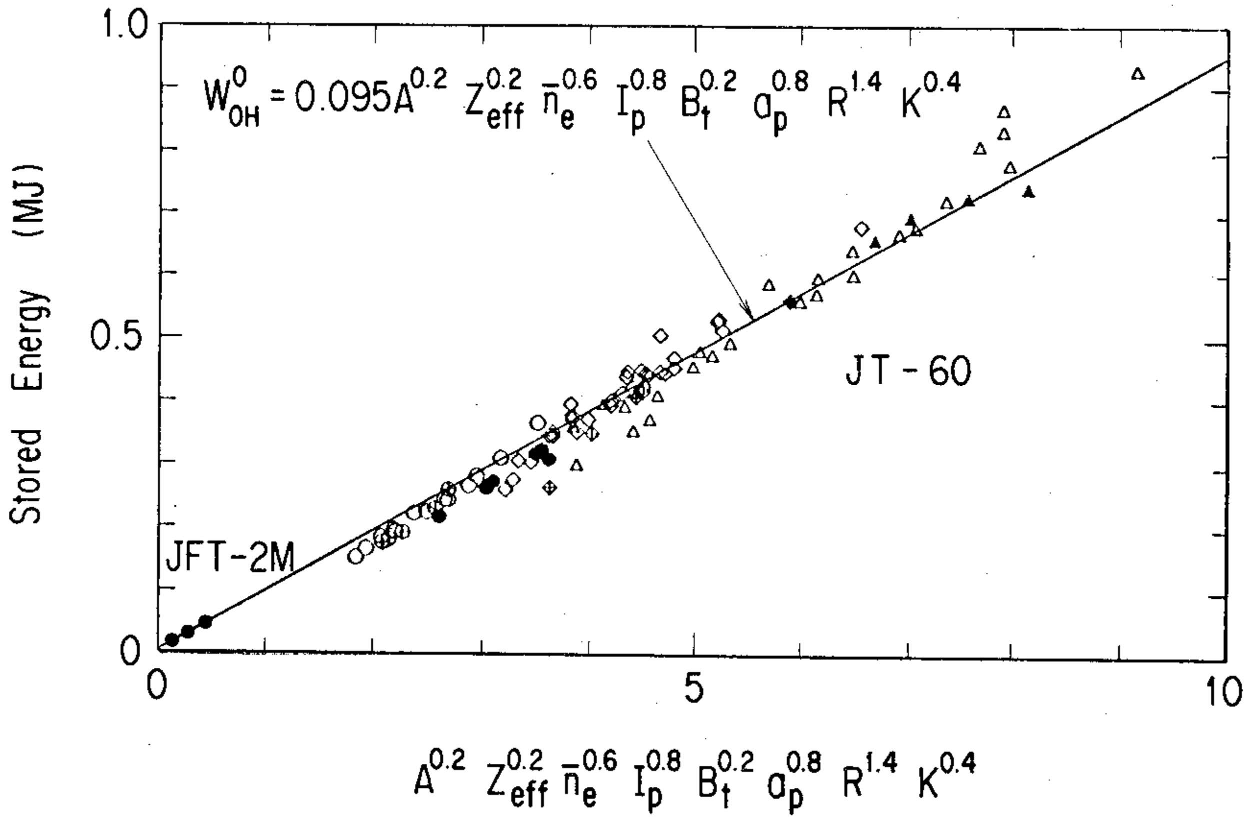

Fig. AII-4 Scaling of stored energy in ohmic discharges.

Appendix A-III Optimized H-mode

The energy confinement time of optimized H-mode τ_E^H is equal to the optimized ohmic confinement time τ_E^{OP} as shown in ASDEX, D-III (JAERI), JFT-2M and D-III-D. Parameter dependence of H-mode confinement is different from that of ohmic plasmas as shown in Fig. AIII-1 2 as follows:

$$\tau_E^{OP} \propto I_p^0 \quad \text{v.s.} \quad \tau_E^H \propto I_p$$

$$\tau_E^{OP} \propto B_T \quad \text{v.s.} \quad \tau_E^H \propto B_T^0$$

The confinement time of H-mode with $q_{cy} \sim 2.2$ is equal to that of ohmic plasma. Therefore $\max(\tau_E^H) \sim \tau_E^{OH}$ or $\tau_E^H \sim \tau_E^{OH}$ with $q_{cy} \sim 2.2$ and high plasma density.

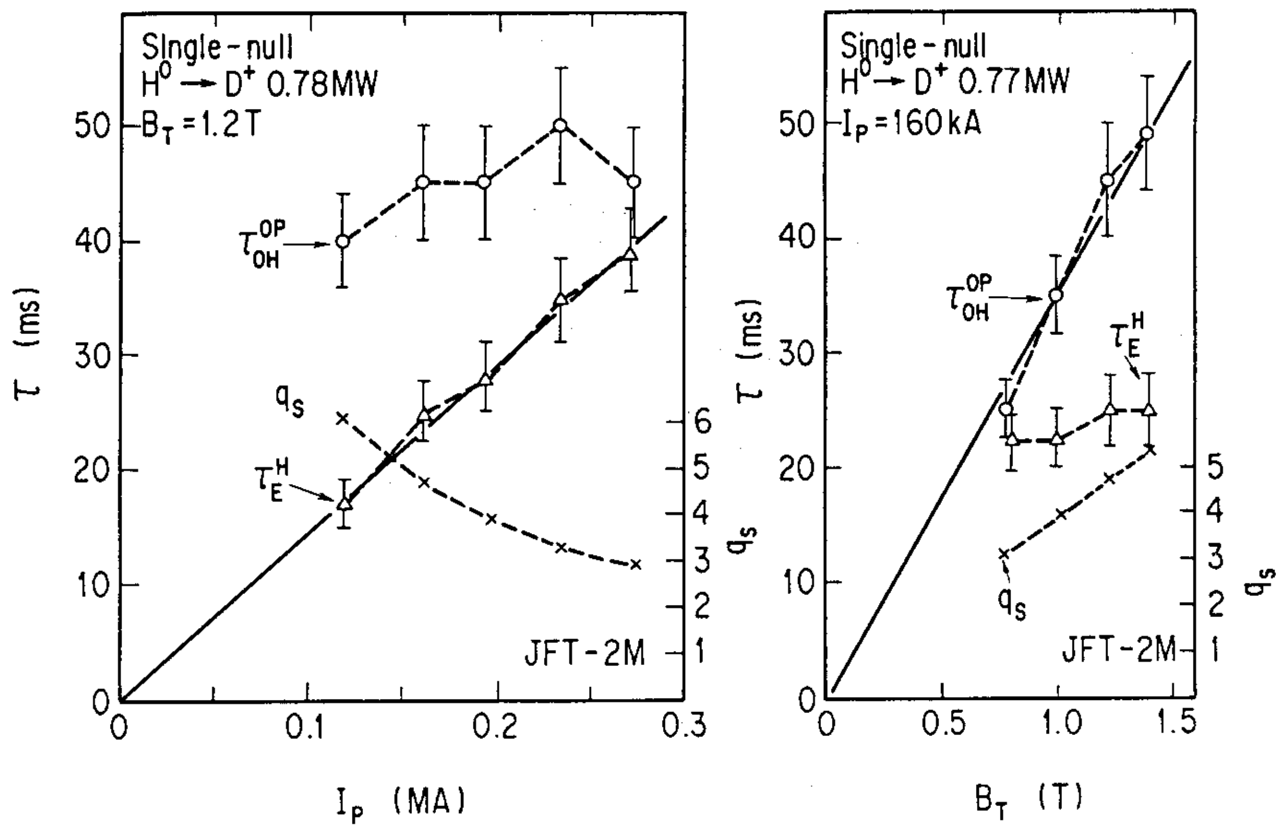

Fig.AIII-1 Optimized ohmic confinement time and H-mode confinement.