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# SCALING OF INCREMENTAL ENERGY CONFINEMENT TIME OF L-MODE PLASMA AND COMMENTS ON IMPROVED CONFINEMENT IN TOKAMAKS

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Japan Atomic Energy Research Institute

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# Scaling of Incremental Energy Confinement Time of L-mode Plasma and Comments on Improved Confinement in Tokamaks

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Incremental energy confinement time defined by $\tau_E^{ad} = \Delta W_p/\Delta P_t$ is reviewed for L-mode plasmas in various tokamaks with various heating methods where $\Delta W_p$ is incremental plasma energy with increase of heating power $\Delta P_t$. It is shown that $\tau_E^{ad} \sim 0.12 a_p^2$ s and $\tau_E^{ad}$ is almost independent of other plasma parameters, heating power and heating methods where $a_p$ is a plasma minor radius in m and $a_p = 0.1 - 1.15$ m. In an optimum H-mode plasma, the incremental energy confinement time is improved by a factor of 4 but the scaling is not clear because of lack of data.

Keywords: L-Mode Plasma, Confinement Time, Tokamak, Plasma Heating

# Lモード・プラズマの増分に関するエネルギー閉じ込め則及び改良された閉じ込めに関するコメント

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下村安夫・小田島和男

（1986年8月4日受理）

$\tau_E^{ap} = \varDelta W_p / \varDelta P_t$で定議される，増分に関する閉じ込め時間を種々の装置に関してレビューした。その結果，Lモードに関しては，$\tau_E^{ad} \sim 0.12\, a_p^2 (\mathrm{m})\ \mathrm{s}$のスケーリング測が得られた。$a_p$ の範囲は，0.1～1.15 mであり，閉じ込め則は，加熱手法や他のプラズマ・パラメータに依存しない。Hモードのプラズマでは，閉じ込めは4倍程度改善されるが，データ点の不足のため，スケーリング則は求まっていない。

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## 1. Introduction

Incremental energy confinement time defined by $\tau_E^{ad} = \Delta W_p/\Delta P_t$ was intensively investigated in JFT-2M with ICRF and NB heating where $\Delta W_p$ is the incremental plasma energy with increase of heating power $\Delta P_t$. And the very simple scaling, i.e. $\tau_E^{ad} \propto I_p^{\circ} n_e^{\circ} P_{ad}^{\circ}$ is obtained.[1] This scaling seems consistent with D-III results which gives $\tau_E^G = b + a/P_{ad}$ where $\tau_E^G$ is the global energy confinement time and b and a are constant value.[2] The recent large tokamak experiments suport the JFT-2M scaling, e.g. $W_p$ linearly increases as increasing $P_{ad}$ and the increasing rate is almost independent of plasma density, plasma current as well as heating methods.[3] Therefore the JFT-2M scaling seems universal in L-mode tokamak plasmas and the incremental energy confinemnt time $\tau_E^{ad}$ plays more essential role than the global energy confinement time $\tau_E^G$ in additionally heated tokamaks. The absolute value is not constant in the above devices, i.e. $\tau_E^{ad}$~15 ms in JFT-2M, ~18 ms in D-III and ~170 ms in JET. In TFTR[4][5], $I_p$ dependence seems strong but other dependence is consistent with JFT-2M results. Therefore it is interesting to get a more universal scaling which gives absolute values of the incremental energy confinement time in different devices. It is more important to clarify the scaling of the incremental energy confinment time for H-mode plasmas.

In this note, the incremental energy confinement in various devices with various heating schemes is reviewed and a universal scaling of the incremental energy confinement time is reduced in L-mode plasmas. Discussions on H-mode and reactors are also given.

## 2. Results

Incremental energy confinement time is reviewed in various devices[1~18] as summarized in Appendix which includes a wide range of plasma parameters, heating power and heating scheme. No clear dependence of $\tau_E^{ad}$ on toroidal field, temperature and elongation as well as plasma current, density, heating power and heating method. A strong dependence of $\tau_E^{ad}$ is observed only on the plasma minor radius $a_p$ as shown in Fig. 1. The following empirical scaling of the incremental energy confinement is obtained.

$$\tau_E^{ad} = 0.12\ a_p^2(\mathrm{m}) \quad \mathrm{s} \tag{1}$$

This scaling is universally correct for the following plasma, device and heating parameters in L-mode plasmas.

| | | |
|---|---|---|
| major radius | $R_p$ = 0.6 - 3.15 | m |
| minor radius | $a_p$ = 0.1 - 1.15 | m |
| aspect radio | $A$ = 3 - 6 | |
| elongation | $b/a$ = 0.8 - 1.6 | |
| toroidal field | $B_t$ = 1.2 - 5.5 | T |
| plasma current | $I_p$ = 0.03 - 4.0 | MA |
| average density | $\bar{n}_e$ = (0.1 - 1.4) × $10^{20}$ | m-3 |
| electron temperature | $T_e$ = 0.3 - 7 | keV |
| heating power | $P_{ad}$ = 0.1 - 10 | MW |
| heating method | NB, ICRF, LH, EC | |

This scaling is independent of not only heating methods but also heating power deposition prfile and should be related with so called "profile consistency" where the gross energy confinement time and electron temperature profile are independent of the heating power deposition profile

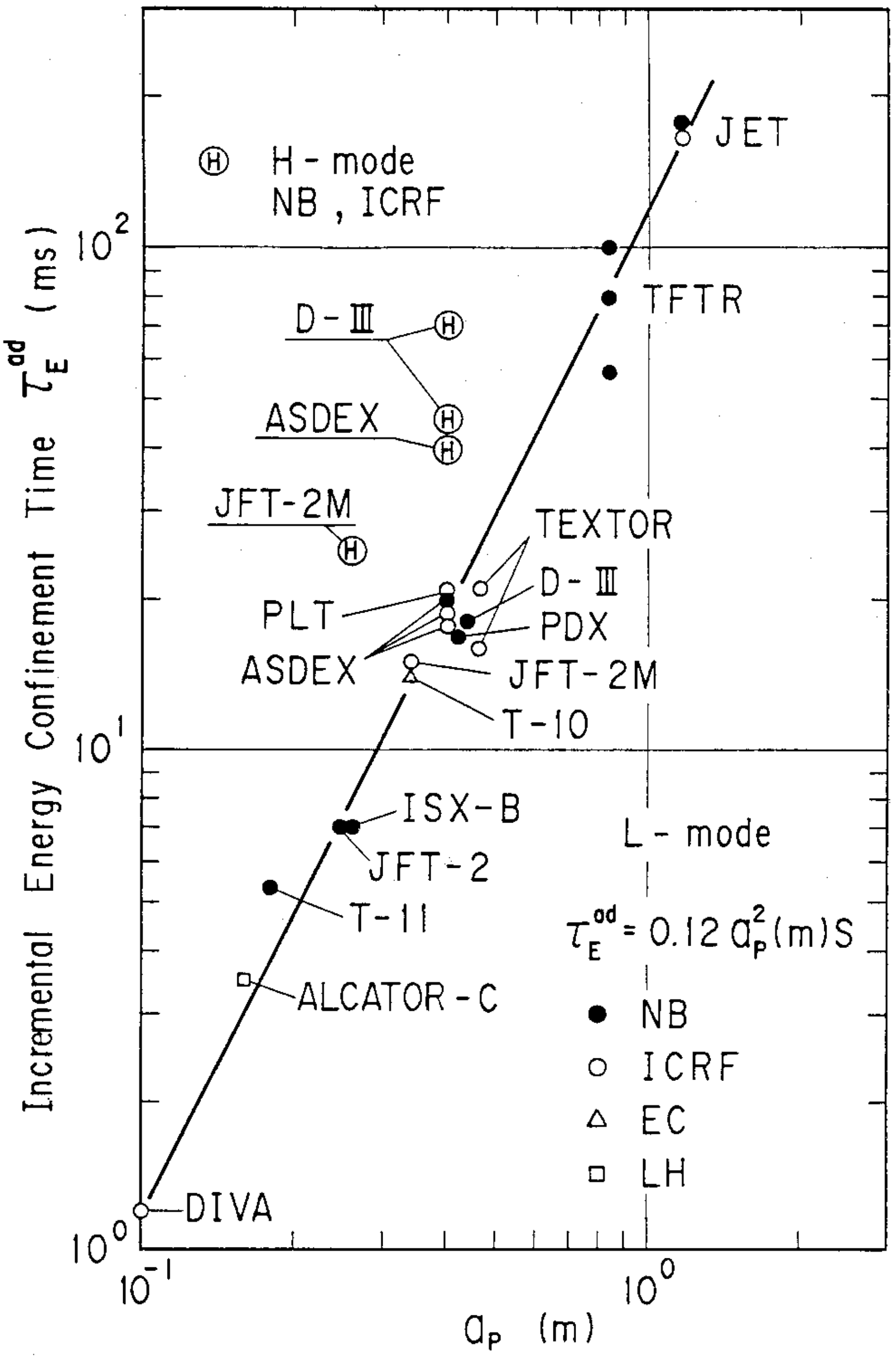

Fig. 1 Scaling of Incremental Energy Confinement Time

in L-mode plasmas.[19] This conclusion suggests that an $\alpha$-heated plasma, i.e. an ignited plasma, will be also described by this universal scaling in a L-mode reactor. The ignition condition should not be realized in a reactor with a reasonable size for the next step.

Improvement of the energy confinement time has been observed in Z-mode of ISX-B,[20] P-mode of D-III[21] as well as H-mode of ASDEX,[11] D-III,[2,7] PDX[22] and JFT-2M.[13] Especially in H-mode, the profile is different from that of L-mode and dramatical improvement on the incremental energy confinement time is obtained in optimized D-III plasmas, i.e. $\tau_E^{ad}$ = 18 ms in L-mode and $\tau_E^{ad}$ = 70 ms in the optimized operation.[7] The scaling of the incremental energy confinement time, however, is not clear because of few data as shown in Fig. 1 but a strong dependence on the plasma minor radius is suggested. Therefore it is essential to develop H-mode plasma in a large tokamak such as JT-60 and to obtain the scaling for H-mode.

## 3. Discussions

Empirical scaling of the incremental energy confinement time in L-mode plasms is obtaied as follows: $\tau_E^{ad} = 0.12\ a_p^2$ s. This scaling is universally correct in a wide range of plasma, machine and heating parameters. The globale energy confinement time $\tau_E^G$ is given by the following equation:

$$\tau_E^G = \frac{W_t}{P_t} \tag{2}$$

Therefore relation between $\tau_E^G$ and $\tau_E^{ad}$ is given by the following equation

$$P_t\ \tau_E^G = (P_t - P^\circ)\tau_E^{ad} + W^\circ \tag{3}$$

where $P^\circ$ and $W^\circ$ are the initial heating power and the initial plasma energy. If we start from ohmic plasma, eq. (3) becomes as follows

$$\tau_E^G = \frac{P_t - P_{oh}^\circ}{P_t}\tau_E^{ad} + \frac{P_{oh}^\circ}{P_t}\tau_E^{oh} \tag{4}$$

where $P_{oh}^\circ$ and $\tau_E^{oh}$ are the initial ohmic input power and the initial ohmic confinement time. When the additional heating power is small or comparable to $P_{oh}^\circ$, the first term is small and following equation is obtained.

$$\tau_E^G \sim \frac{P_{oh}^\circ}{P_t}\tau_E^{oh} \qquad \text{for} \quad P_t \gtrsim P_{oh}^\circ \tag{5}$$

This relation describes the steep degradation observed in the early heating experiment and the strong dependence of $\tau_E^G$ on the plasma current[14,22) because of $P_{oh}^\circ\ \tau_E^{oh} \sim I_p^\gamma$ with $\gamma \gtrsim 1$. When $P_t \gg P_{oh}^\circ$ the following equation is obtained.

$$\tau_E^G \sim \tau_E^{ad} + \tau_E^{oh} \frac{P_{oh}^\circ}{P_t} \qquad \text{for} \quad P_t \ll P_{oh}^\circ \tag{6}$$

This equation gives D-III scaling, i.e. $\tau_E^G \sim b + a/P_t$ and the rather weak $I_p$ dependence of $\tau_E^G$.[23)] In a highly heated plasma, $P_t > 10\ P_{oh}^\circ$, the gross energy confinement time approaches to the incremental energy confinement time.

Not only the incremental energy confinement time but also the global energy confinement time of L-mode plasmas in a fixed machine are given by simple scalings from eq. (1) and eq. (4). For example, the following scaling of JT-60 is expected as follows in L-mode operations.

$$\tau_E^{ad} \sim 0.09\ \text{s} \tag{6}$$

$$\tau_E^G \sim (0.09P_t + 0.22I_p)/P_t \tag{7}$$

The incremental energy confinement time is independent of heating method and heating power deposition profile. This situation seems consistent with so called "profile consistency" where the gross energy confinement time and electron temperature profile are independent of the heating power deposition profile in L-mode plasmas. The plasma tends to maintain the ohmic current profile and temperature profile by changing its transport properties. This conclusion suggests that an $\alpha$-heated plasma, i.e. an ignited plasma, will be also described by the scaling of $\tau_E^{ad}$ in a L-mode operation and an ignited plasma will not be realized in a small machine. An example of the size of an ignition machine with L-mode plasma is as follows:

$$R_p = 7\ \text{m}, \quad a_p = 2.5\ \text{m}, \quad b_p/a_p = 1.6, \quad q_\psi = 2.4\ ,$$

$I_p = 30$ MA, $B_t = 6.4$ T, $\beta_t = 5.7$ %,

$\tau_E = 0.67$ s, $\bar{T}_i = 12$ keV and $\bar{n}_e = 2.4 \times 10^{20}$ m$^{-3}$

This size seems reasonable for a power reactor because the fusion output is 4500 MW and the average wall loading is 5 MW/m$^2$ which is the maximum value for a power reactor because of its high heat flux of 1 MW/m$^2$. We employed the most conservative confinement scaling of the incremental energy confinement time given by eq. (1) and beta limit given by Troyon$^{24)}$ factor of 3 but the ignition margin is larger than unity i.e. 1.3. This core plasma seems suitable for a power reactor but is too large for the next fusion test reactor. Therefore it is necessary to improve energy confinement time.

The dramatical improvement is observed in so called the super H-mode of ASDEX$^{25)}$ or in combination of H-mode and P-mode of JFT-2M.$^{26}$ This improvement, however, is obtained in a short duration and a steady state has not been realized. In a stable H-mode of D-III, the improvement factor is 4 with optimized conditions.$^{7)}$ If we assumed this factor it is possible to realize an ignited plasma in a similar machine of FER, INTOR or NET and we have a high margin in a power reactor. The scaling of the incremental energy confinement time in improved operations, however, is not clear but a strong dependence on the plasma minor radius is suggested. Therefore it is very important to develop H-mode operation in a large tokamaks such as JT-60 and to clarify the scaling for improved plasmas.

## Acknowledgements

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Appendix

Table A1 Incremental energy confinement time. Values of $\tau_E^{ad}$ with under lines are given in references or by authors of references and other values are calculated from figures in references as shown in Figs. A1-A14.

INCREMENTAL ENERGY CONFINEMENT TIME

| | Major radius $R_p$ (m) | Minor radius $a_p$ (m) | Elongation $b_p/a_p$ | Current $I_p$ (MA) | Toroidal field $B_t$ (T) | Max. heating power $P_{to}$ (MW) | Heating method | Incremental contiment $\tau_E^{ad}$ (ms) | ref. |
|---|---|---|---|---|---|---|---|---|---|
| JET | 3.0 | 1.15 | 1.4 | 2 - 4 | 3.4 | 8 | NB, ICRF | 170 | 3 |
| TFTR | 2.6 | 0.82 | 1 | 1.4,1.8, 2.2 | 4.7 | 6.5 | NB | 54,80,100 | 4,5 |
| TEXTOR | 1.75 | 0.46 | 1 | 0.36,0.47 | 2.0 | 1.5 | ICRF | 12,21 | 6 |
| D-III | 1.43 | 0.44 | 1.3 | 0.48-0.8 | 2.0-2.6 | 6.5 | NB | 18 | 2,7 |
| D-III-H | 1.43 | 0.4 | 1.6 | 0.8-0.9<br>0.51 | 2.0-2.6 | 6.5 | NB | 70<br>45 | 7<br>2 |
| PDX | 1.43 | 0.42 | 1 | 0.27 | 1.5 | 5.5 | NB | 17 | 8 |
| PLT | 1.3 | 0.4 | 1 | 0.5-0.6 | 3 | 3 | ICRF | 20 | 9 |
| ASDEX | 1.65 | 0.4 | 1 | 0.28-0.4 | 2.2 | 3 | NB, ICRF, LH | 20 | 10,11 |
| ASDEX-H | 1.65 | 0.4 | 1 | 0.4 | 2.2 | 3 | NB, ICRF | 40 | 10,11 |
| T-10 | 1.5 | 0.34 | 1 | 0.2-0.5 | 2.8-3.4 | 1 | ECH | 14 | 12 |
| JFT-2M | 1.3 | 0.34 | 1.6 | 0.2-0.4 | 1.2 | 2 | ICRF, NB | 15 | 1 |
| JFT-2M-H | 1.3 | 0.26 | 1.4 | 0.21 | 1.2 | 0.6 | NB | 25 | 13 |
| ISX-B | 0.93 | 0.26 | 1.15 | 0.18 | 1.27 | 2 | NB | 7 | 14 |
| JFT-2 | 0.9 | 0.25 | 0.9 | 0.14 | 1.3 | 1 | NB | 7 | 15 |
| T-11 | 0.7 | 0.18 | 1 | 0.1 | 1.3 | 1 | NB | 5.3 | 16 |
| ALCATOR-C | 0.64 | 0.16 | 1 | 0.25 | 5.5 | 1 | LH | 3.5 | 17 |
| DIVA | 0.6 | 0.1 | 0.8 | 0.03 | 1.7 | 0.2 | ICRF | 1 | 18 |

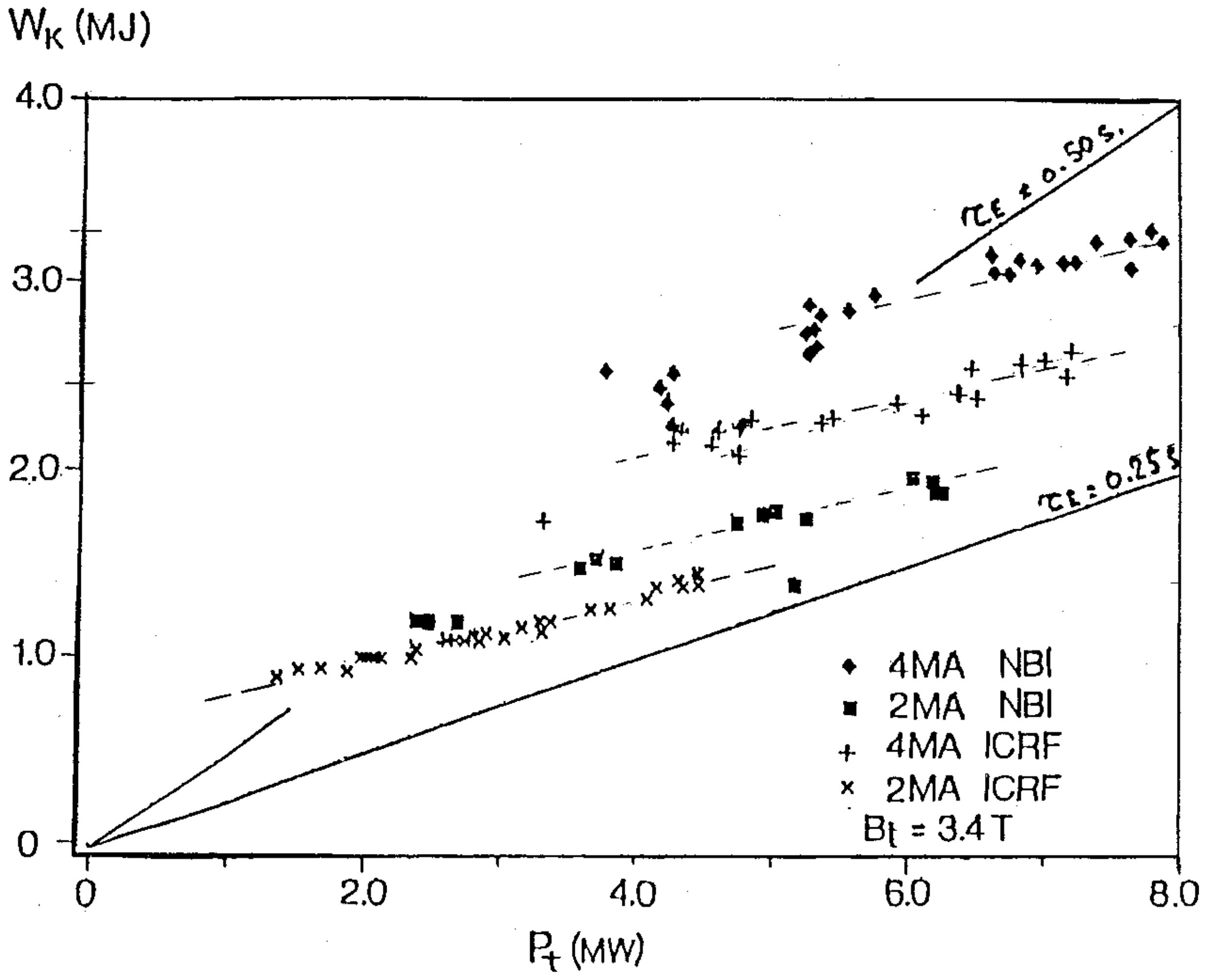


Fig. A1 JET results(3). Dotted lines are added and give $\tau_E^{ad}$ = 170 ms.

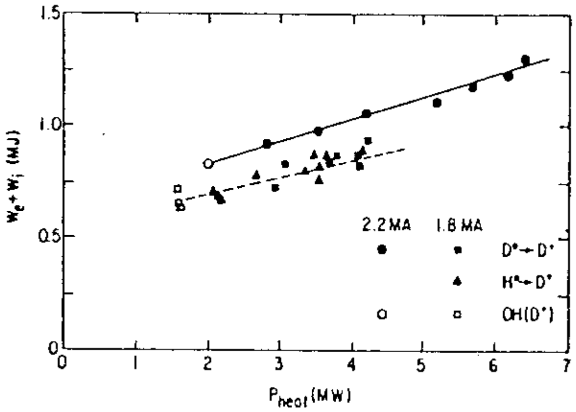


Fig. A2 TFTR results . $\tau_E^{ad}$ = 100 ms at 2.2 MA and 80 ms at 1.8 MA are given in ref. (4).

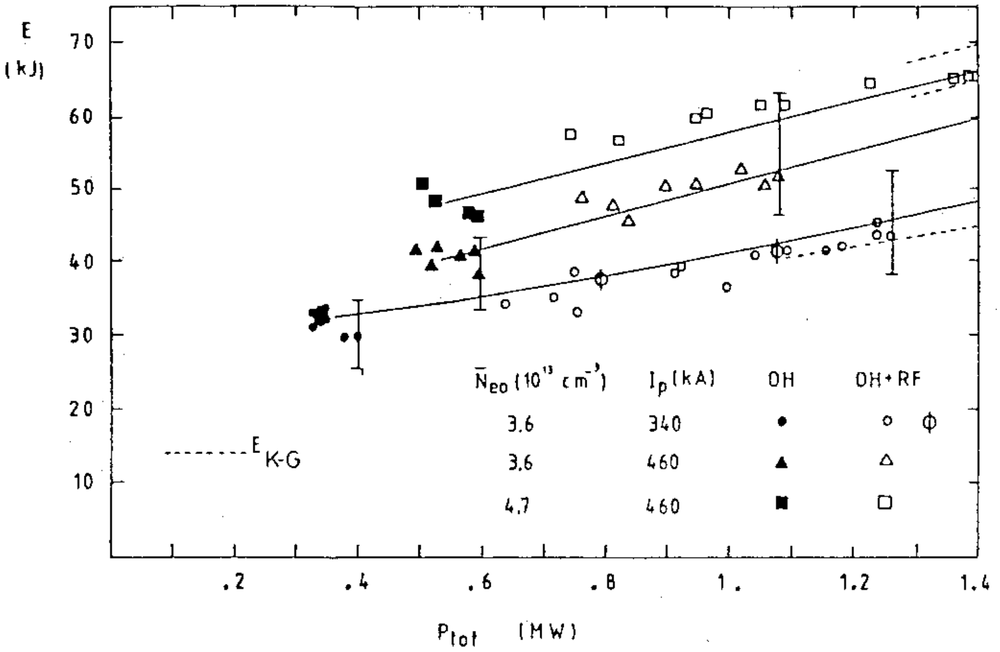


Fig. A3 TEXTOR results(5). $\tau_E^{ad}$ = 21 ms at 460 kA and 12 ms at 340 kA are given in ref. (5).

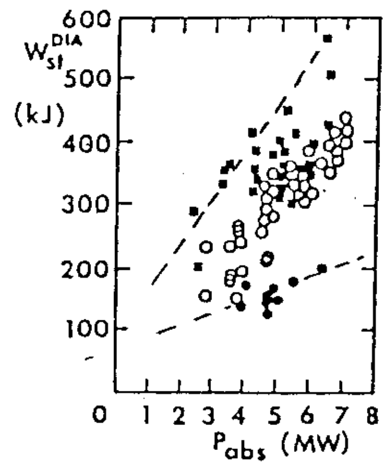


Fig. A4 D-III results(7). Stored energy versus absorbed power. ■H-mode discharge, D-beam injection into D-plasma; ○H-mode divertor discharge, H-beam to D-plasma; ●Limitered discharge, H-beam to D-plasma. $I$ = 800-900 kA (divertor), 740-800 kA (limiter), $B_T$ = 2.0-2.6 T. Dotted lines are added and give $\tau_E^{ad}$ = 18 ms for L-mode and 70 ms for optimized H-mode.

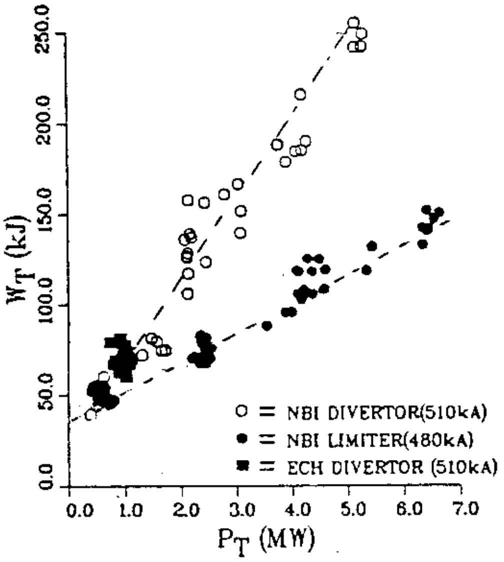
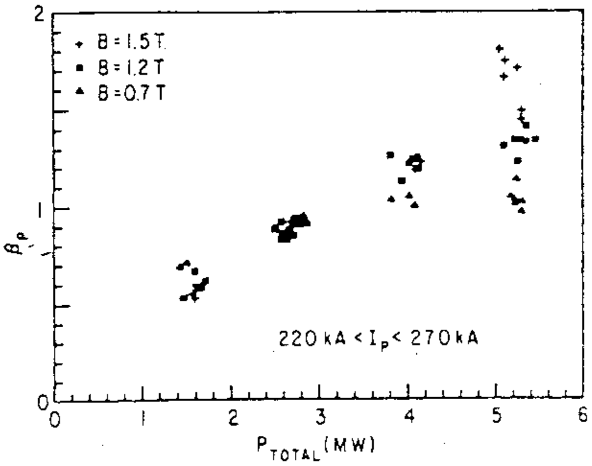


Fig. A5 D-III results(2). Dotted lines are added and give $\tau_E^{ad}$ = 18 ms for L-mode and 50 ms for H-mode



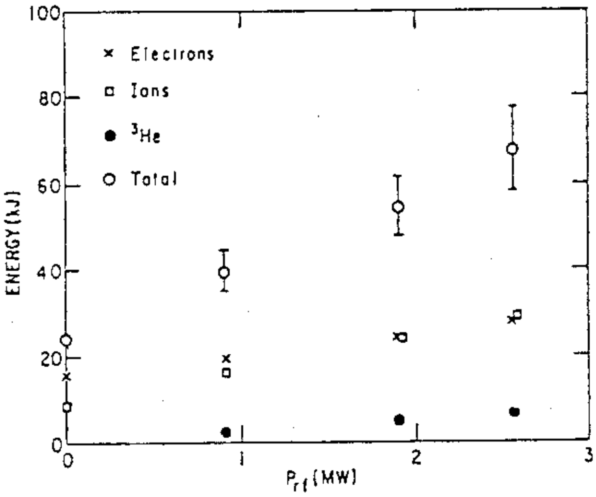


Fig. A6 PDX results(8). $\tau_E^{ad}$ ~ 17 ms at $B_t$ = 1.5 T

Fig. A7 PLT results(9). $\tau_E^{ad}$ ~ 20 ms.

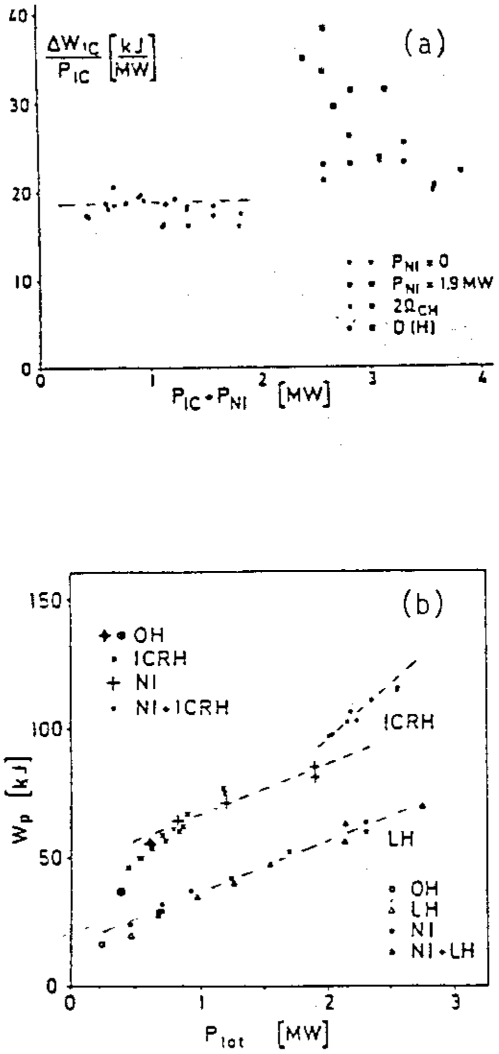


Fig. A8 ASDEX results[10]. Dotted lines are added and give $\tau_E^{ad}$ = 19 ms for L-mode and 40 ms for H-mode.

(a) Change in plasma energy content $\Delta W_{IC}$ normalized to ICRH power launched by the antennae $P_{IC}$ versus total power. The ICRH-power scans without NI preheating were obtained under carbonized wall conditions.

(b) Variation of the plasma energy content with total heating power for NI (400 kA, 2.2 T, $\bar{n}_e = 5 \times 10^{13}$ cm$^{-3}$), ICRH (380 kA, 2.3 T, $3.5 \times 10^{13}$ cm$^{-3}$) and LH (current drive conditions, 280 kA, 2.2 T, $1.2 \times 10^{13}$) and ICRH and LH in combination with NI. In case of ICRH $P_{NI}$ = 1.9 MW is added and $P_{IC}$ is varied; in case of LH $P_{LH}$ = 0.45 MW is added to a beam power scan. $W_p$ of the ohmic (or LH) target plasma is also shown.

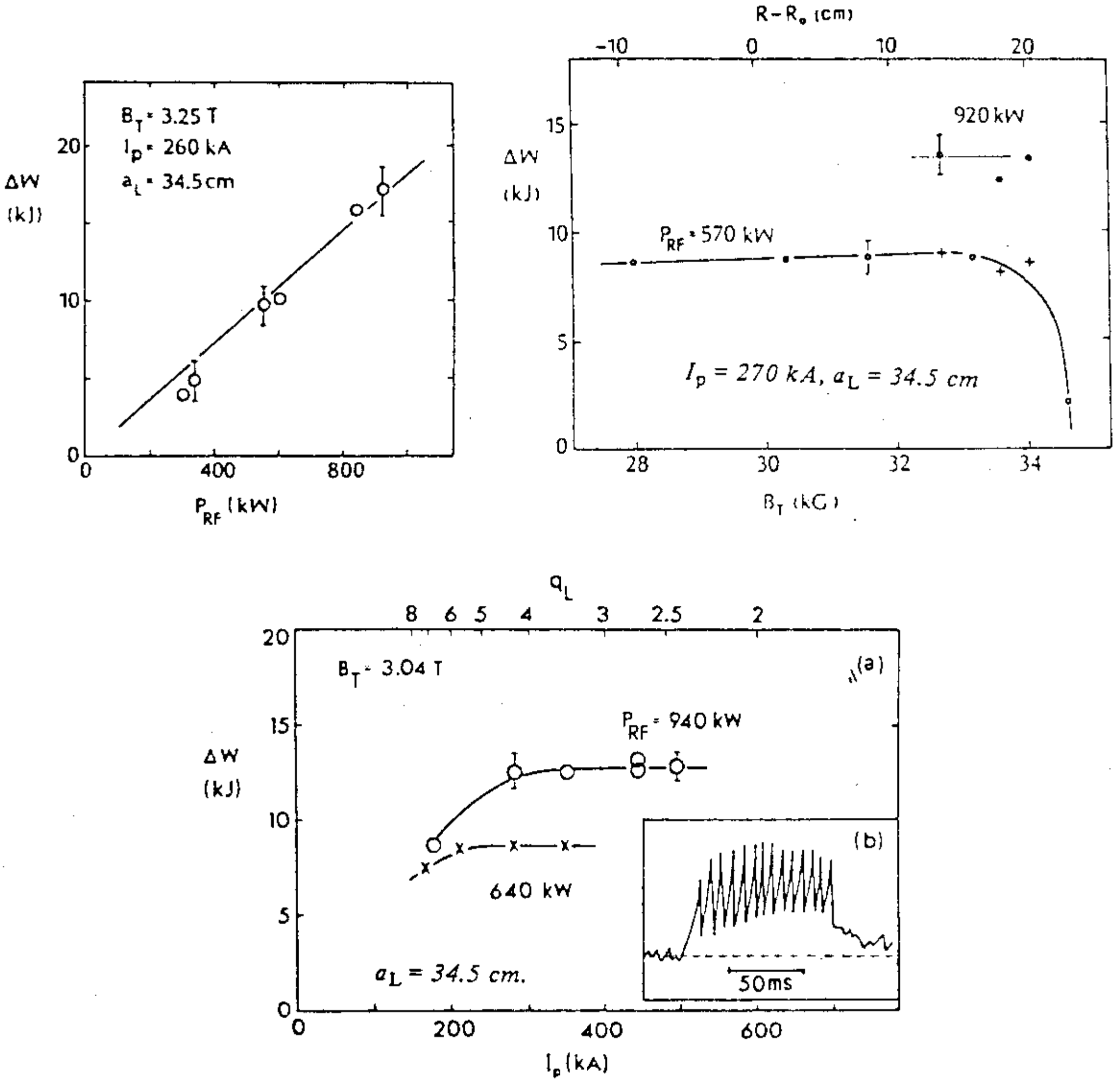


Fig. A9 T-10 results(12).

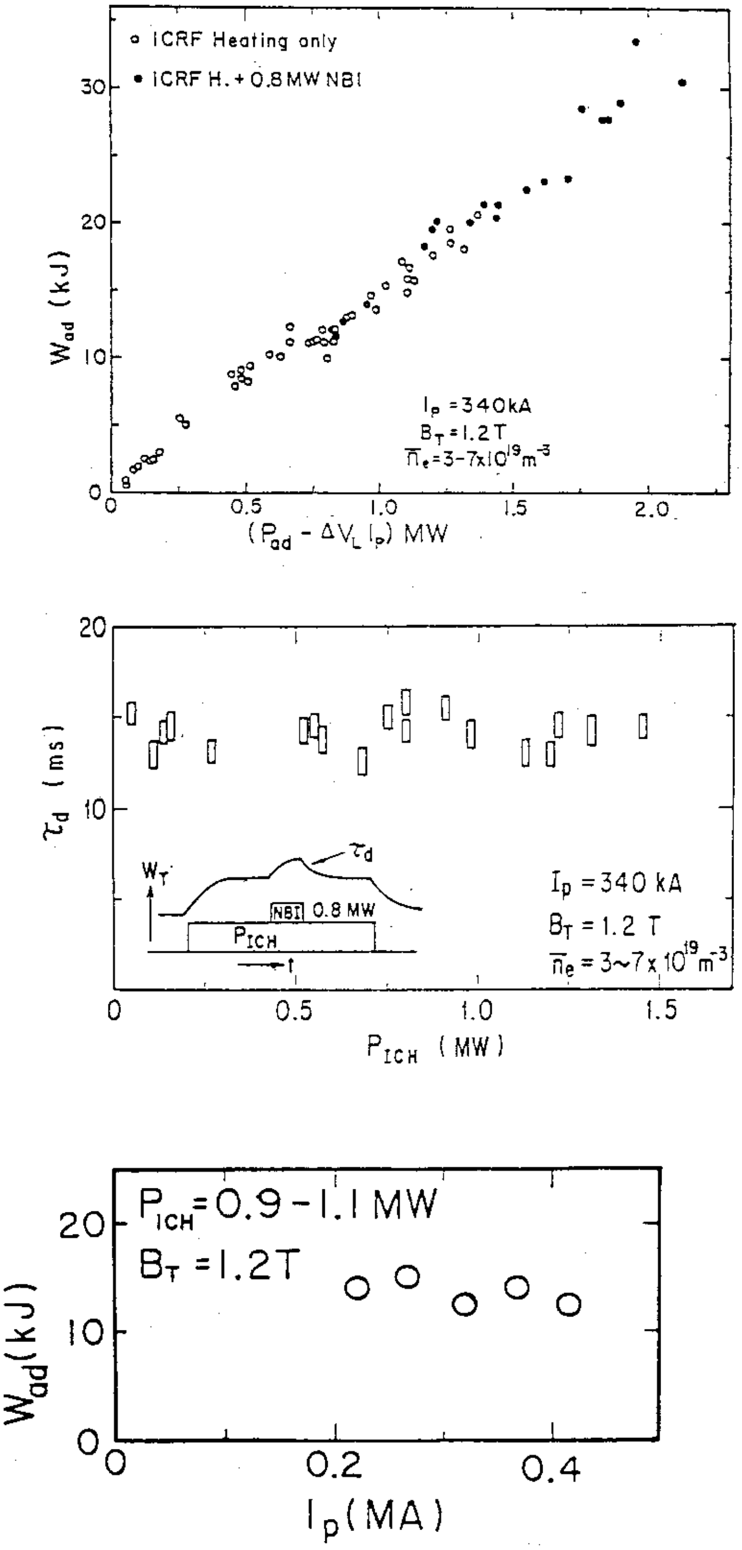


Fig. A10 JFT-2M results(1)

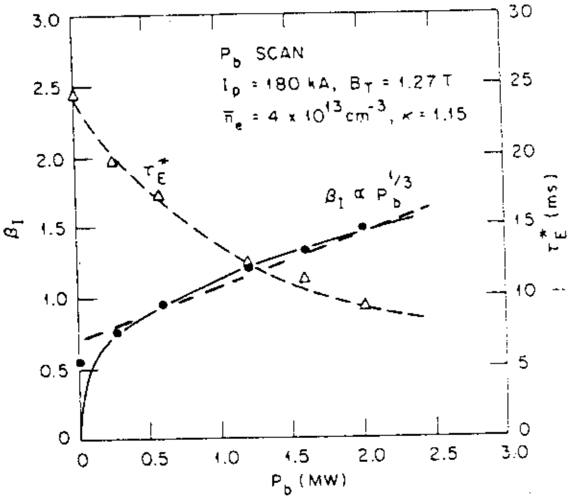


Fig. A11 ISX-B results$^{(14)}$.
A Dotted line is added and gives $\tau_E^{ad}$ = 7 ms

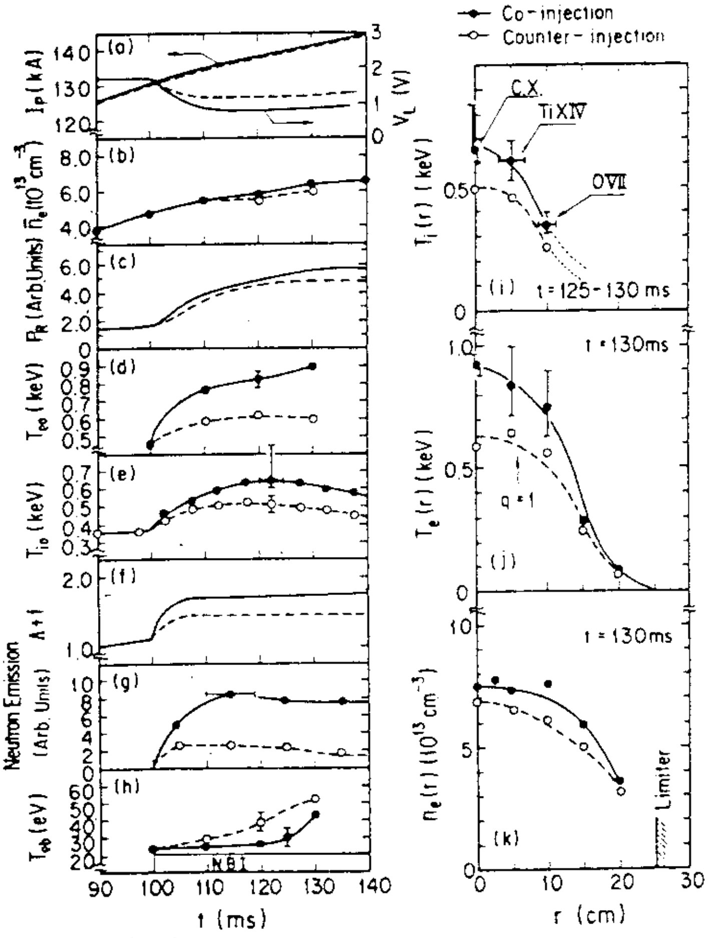


Fig. A12 JFT-2 results$^{(15)}$. Typical time behaviour and radial profile of plasma parameters in 1-MW co-injected (solid lines) and 1-MW counter-injected (dotted lines) discharges, with $B_T$ = 1.3 T; (a) plasma current and loop voltage; (b) line-averaged density; (c) radiation power; (d) central electron temperature; (e) central ion temperature (without density correction); (f) values of magnetic measurement; (g) neutron emission; (h) plasma boundary temperature behind limiter; (i) radial profile of ion temperature; (j) radial profile of electron temperature; (k) electron density profile.

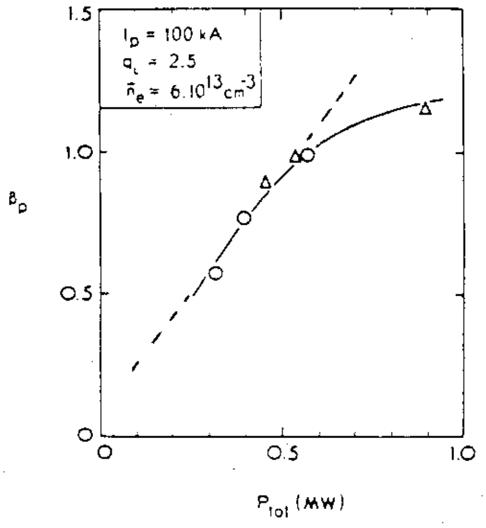


Fig. A13 T-11 results$^{(16)}$. A dotted line is added and gives $\tau_E^{ad}$ = 5.3 ms.

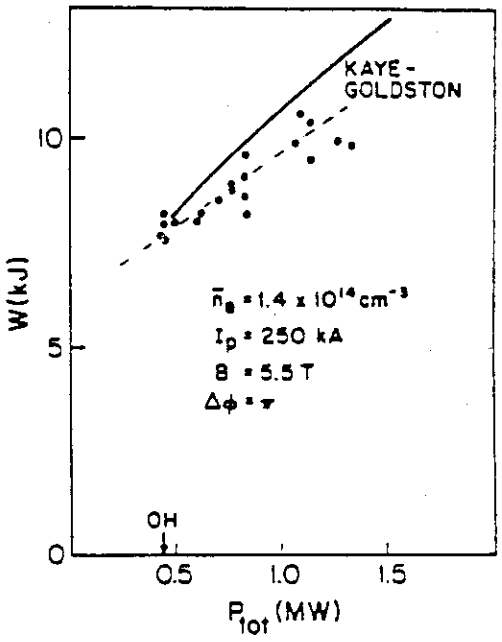


Fig. A14 ALCATOR-C results$^{(17)}$. A dotted line is added and gives $\tau_E^{ad}$ = 3.5 ms.