Scaling of Incremental Energy Confinement Time in the JFT-2M Tokamak

K. Odajima, K. Hoshino, S. Kasai, T. Kawakami, H. Kawashima, T. Matoba, T. Matsuda, H. Matsumoto,
Y. Miura, M. Mori, H. Ogawa, T. Ogawa, H. Ohtsuka, T. Shoji, N. Suzuki, H. Tamai, Y. Uesugi,
T. Yamamoto, T. Yamauchi, M. Hasegawa,[a] S. Takada,[b] and I. Yanagisawa[c]
Department of Thermonuclear Fusion Research, Japan Atomic Energy Research Institute,
Tokai-Mura, Naka-Gun, Ibaraki-Ken, 319-11 Japan
(Received 19 February 1986)

The decay time of stored energy was measured when additional heating power decreased abruptly. The energy decay time is almost constant at 15 ms, irrespective of the gross energy confinement time τ_E^G, which is changed by ion-cyclotron range of frequency heating up to 1.5 MW. The decay time coincides with a confinement time of the additionally heated power defined by $\tau_{ad} = \Delta W_T/\Delta P_{tot}$, which indicates that the incremental energy from the additional heating behaves independently of the gross plasma energy. It is also shown that τ_{ad} is almost independent of density and plasma current as well as heating power.

PACS numbers: 52.25.Fi, 52.50.Gj, 52.55.Fa

Systematic confinement scaling studies in a tokamak plasma showed a deterioration of gross energy confinement time τ_E^G with strong neutral-beam injection (NBI) heating,[1,2] where τ_E^G is defined by $\tau_E^G = W_T/P_{tot}$, where W_T is total stored energy and P_{tot} is total input power. In the case of ion cyclotron range of frequency (ICRF) heating, almost the same deterioration as NBI heating of confinement time has been observed.[3-6]

On the other hand, many heating experiments in tokamaks show that the total stored kinetic energy increases linearly as the additional heating power, although the line does not go through the origin indicating degradation of gross energy confinement time compared to the Ohmic phase. One is tempted, then, to conclude that some sort of "incremental" confinement time τ_{ad} does not deteriorate with increasing input power,[1] but it is not possible to determine whether the increase of W_T is linear or not for the heating power from the available data range.

Recently, some experiments which change our understanding of transport inside a plasma have been presented. That is the so-called "profile consistency," where the gross energy-confinement time and the electron-temperature profile are independent of the heating power deposition. The plasma tends to maintain the Ohmic current-density profile by charge of its transport properties.[1,7,8] This fact suggests to us that the nature maintaining the Ohmic profile deteriorates the confinement of additionally heated plasma.

In this Letter, the incremental confinement time τ_{ad} observed under quasisteady-state conditions is compared with the characteristic time τ_d for change in the stored energy.

The JFT-2M is a tokamak with a D-shaped vacuum vessel with a 1.31-m major radius R_0 and an iron-core transformer. In the present experiment, the machine is operated with a D-shaped cross section and the plasma radius is limited at $a_L = 0.35$ m by inner and outer limiters, with ellipticity $\kappa = 1.2-1.5$. Total stored energy W_T is determined from Λ [$= \beta_P + (l_i - 1)/2$, where β_P is the poloidal beta value and l_i is internal inductance] by use of 24 magnetic probes and 8 saddle loops. The value of W_T thus determined includes contributions from a stacked ion beam by NBI as well as a thermal component. In the present ICRF heating conditions, almost all of the rf power is absorbed by electrons[3] as expected from the mode conversion theory.[9]

The total stored energy increases almost linearly as if the ICRF input power has its own confinement time. Then we define an incremental energy confinement time as

$$\tau_{ad} = \Delta W_T/\Delta P_{tot}\,|_{\bar{n}_e = \text{const}}, \tag{1}$$

where "$\bar{n}_e$ = const" means the elimination of a change of stored energy due to change of electron density $\bar{n}_e$. Total stored energies in the Ohmic and the 1-MW ICRF heating phases are plotted as functions of the density in Fig. 1. The stored energy in the Ohmic phase is almost in proportion to $\bar{n}_e$, and that in the 1-MW heating phase

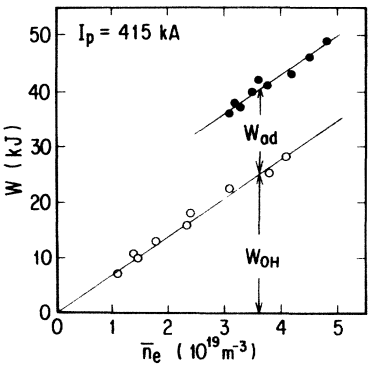

FIG. 1. Total stored energy as a function of electron density in the cases of Ohmic (open circles) and 1 MW of ICRF (filled circles) heating.

linearly increases as $\bar{n}_e$. The difference of the stored energy between the Ohmic and the additionally heated plasma $W_{\rm ad}$ is independent of the density. This result suggests that the total energy W_T stored during the heating can be divided into stored energy of Ohmic base plasma $W_{\rm OH}$, which increases as the density, and incremental stored energy from the additional heating $W_{\rm ad}$, which is independent of the density. Thus the total stored energy can be written as

$$W_T = W_{\rm OH} + W_{\rm ad}. \tag{2}$$

$W_{\rm OH}$ during additional heating is understood as a capacity for stored energy in the Ohmic base plasma. A value of $W_{\rm OH}$ is determined in the Ohmic plasma and is applied in the additionally heated plasma. $W_{\rm OH}$ is roughly proportional to the density in a low-density region. But the increase of $W_{\rm OH}$ is saturated at $\bar{n}_e$ larger than a critical density $\bar{n}_c$. In a case in which the density is changing with time, it is confirmed experimentally in the Ohmic plasma with $0 < d\bar{n}_e/dt < 10^{20}$ m^{-3}/s that $W_{\rm OH}$ follows the change of $\bar{n}_e$ without time delay. With the use of Eq. (2), the definition of Eq. (1) is rewritten as

$$\tau_{\rm ad} = \Delta W_{\rm ad} / \Delta(P_{\rm ad} - \Delta V_L I_P) \tag{3}$$

where $P_{\rm ad}$ is additional heating power and $\Delta V_L I_P$ is a decrease of Joule input power by the additional heating.

Figure 2 shows the incremental stored energy $W_{\rm ad}$ $[=W_T - W_{\rm OH}(\bar{n}_e)]$ as a function of incremental heating power $P_{\rm ad} - \Delta V_L I_P$ for ICRF heating only and for ICRF plus 0.8 MW NBI heating. $W_{\rm ad}$ increases in proportion to $P_{\rm ad} - \Delta V_L I_P$ indicating that the incremental energy-confinement time $\tau_{\rm ad}$ does not depend on the additional heating power, although $\tau_E^G \propto P_{\rm tot}^{-1/2}$.

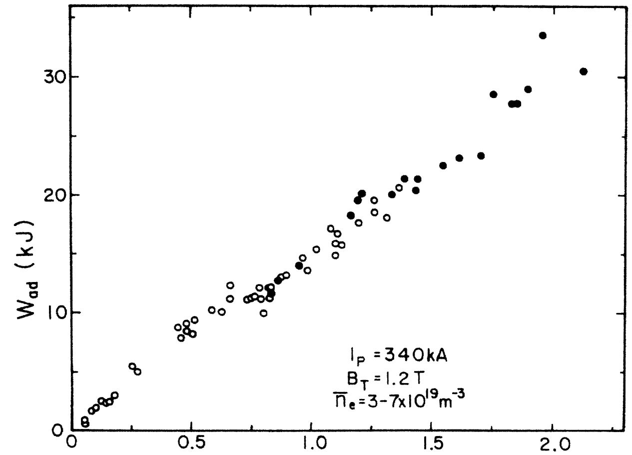

FIG. 2. Incremental stored energy from additional heating $W_{\rm ad}$ as a function of incremental additional heating power $P_{\rm ad} - \Delta V_L I_P$, at ICRF heating only (open circles) and for ICRF plus 0.8 MW NBI heating (filled circles). The slope gives $\tau_{\rm ad} = 15$ ms, which is independent of $P_{\rm ad}$.

The incremental stored energy $W_{\rm ad}$ at about 1 MW ICRF heating is plotted as a function of plasma current in Fig. 3. $W_{\rm ad}$ has no systematic dependence on the plasma current, indicating that $\tau_{\rm ad}$ is independent of the current. Thus, $\tau_{\rm ad}$ scales as

$$\tau_{\rm ad} \propto I_P^0 \bar{n}_e^0 P_{\rm ad}^0. \tag{4}$$

The result that $\tau_{\rm ad}$ does not depend on plasma current seems contrary to the bulk of experimental results on this subject on other tokamaks.[1,2] The discrepancy can be explained by the fact that $W_{\rm OH}$ and $\bar{n}_c$ increase with current, although the energy-confinement time of Ohmic plasma $\tau_{\rm OH}$ does not.

If the incremental energy behaves independently of the gross plasma energy, a transient property of the stored energy is given by

$$dW_{\rm ad}/dt = P_{\rm ad} - \Delta V_L I_P - W_{\rm ad}/\tau_{\rm ad}, \tag{5}$$

and the characteristic time for changes in the incremental energy should agree with $\tau_{\rm ad}$ irrespective of the gross energy-confinement time.

In order to measure the energy-decay time τ_d when the additional heating power changes abruptly, NBI at 34 keV is superimposed on the steady-state ICRF-heated plasma. The gross energy confinement time τ_E^G of ICRF-heated plasma changes from 46 ms at Ohmic heating to 21 ms at 1.45 MW ICRF heating, roughly keeping in line with Kaye-Goldston scaling.[2]

Examples of temporal evolution of stored energy are shown in Fig. 4. For all cases, the stored energy decays roughly exponentially with almost the same time constant. The characteristic decay time is plotted as a function of ICRF heating power in Fig. 5. These measured values are spread from 13 to 16 ms with no systematic dependence on ICRF heating power. It should be noted that the energy-decay time τ_d is independent of gross energy-confinement time τ_E^G and roughly coincides with the incremental energy-confinement time $\tau_{\rm ad}$. Generally, the decay time of the total stored energy includes the effects of time evolution of $W_{\rm OH}$ and V_L but the correc-

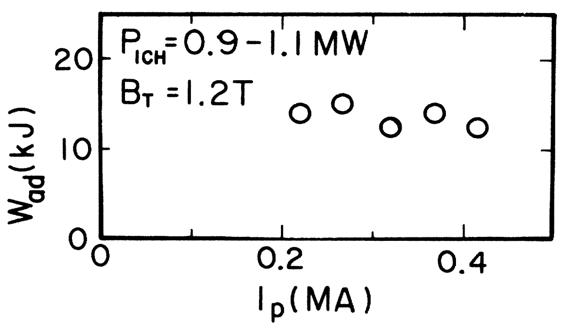

FIG. 3. Increment of stored energy $W_{\rm ad}$ from about 1 MW ICRF heating as a function of plasma current I_P. $W_{\rm ad}$ is roughly constant with changes in the plasma current.

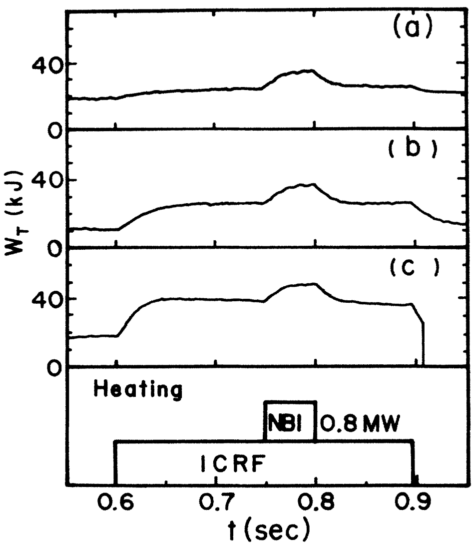

FIG. 4. Temporal evolution of total stored energy, when NBI heating is superimposed on the steady state ICRF-heated plasma: (a) ICRF power $P_{\rm ICH}=120$ kW giving gross energy confinement time $\tau_E^G=46$ ms; (b) $P_{\rm ICH}=570$ kW, $\tau_E^G=28$ ms; (c) $P_{\rm ICH}=1400$ kW, $\tau_E^G=21$ ms.

tions are small in the case of Fig. 5.

The time for thermalization of the stacked ion beam in this experiment is 5–9 ms at the center of the plasma[10] (electron temperature $T_{e0}=0.8$–1.5 keV). In the steady-state NBI phase, the beam component occupies about 30%–50% of $W_{\rm ad}$ at the center of the plasma. The exponential decay of the stored energy continues over 20 ms from NBI turnoff. The beam component decays faster than the stored energy and becomes negligible compared to the thermal component at 20 ms after the NBI turnoff. Therefore, the possibility that τ_d is strongly affected by the confinement of the beam component may be negligible. In the case of ICRF heating, τ_d is almost the same as the NBI case as shown in Fig. 4 at $t>0.9$ s and also shown in Fig. 6 as discussed below.

We can follow the time behavior of the total stored energy by using Eqs. (2) and (5) and the time evolution of $\bar{n}_e$ and V_L, and by putting $\tau_{\rm ad}=15$ ms, as shown in Fig. 6. The thick line in W_T is the experimental value and the thin line is the simulated one. The broken line represents $W_{\rm OH}$ calculated by use of $\bar{n}_e$ without delay time. The simulated value follows the experimental value well in both the increasing and decreasing phases of the heating.

It has been demonstrated experimentally that the incremental stored energy from the additional heating has its own energy confinement time $\tau_{\rm ad}$ which is independent of additional heating power. The characteristic time for changes in the stored energy τ_d does not agree with the gross energy-confinement time τ_E^G but coincides with $\tau_{\rm ad}$. The experimental fact tells us that $\tau_{\rm ad}$ has some physical meaning for the confinement and transport of the additionally heated plasma.

The apparent deterioration in gross energy confinement time τ_E^G is understood as meaning that the confinement of the incremental energy is poorer than that of Ohmic plasma. With regard to the extrapolation to higher heating power, the total stored energy increases linearly as the additional heating power, although the line does not go through the origin. In sufficiently high-power heating such as $W_{\rm ad}\gg W_{\rm OH}$, τ_E^G should agree with

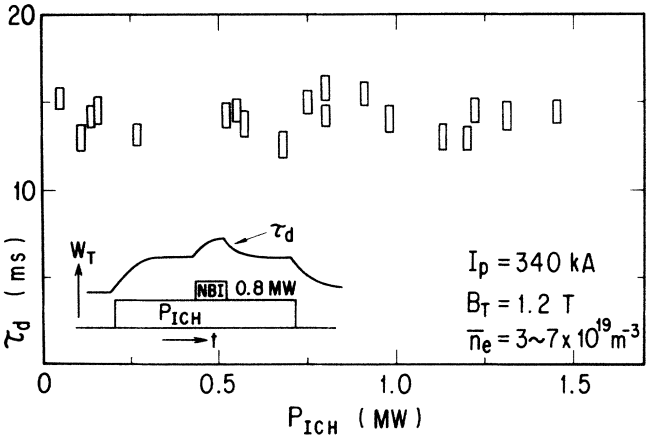

FIG. 5. Decay time of stored energy τ_d when NBI is terminated, as a function of ICRF heating power. τ_d is almost constant irrespective of τ_E^G which changes from 46 to 21 ms.

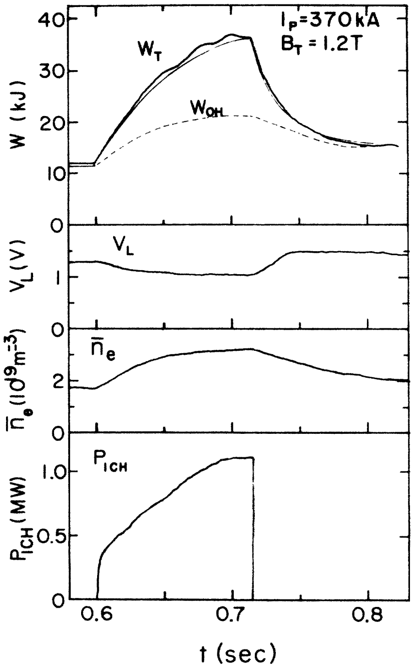

FIG. 6. Temporal evolution of stored energy W_T (thick line) is compared with a simulated value (thin line) with the use of Eqs. (2) and (5), and temporal evolution of $\bar{n}_e$, V_L, and $P_{\rm ICH}$.

τ_{ad}. Thus, it is important to establish a size scaling law of τ_{ad} for the extrapolation to large tokamaks.

The result that τ_{ad} does not depend on plasma current I_P seems contrary to the result that τ_E^G depends on I_P on the other tokamaks. The discrepancy can be explained by the fact that W_{OH} increases with the current, although τ_{OH} generally does not. Even in the case of $P_{ad} \gg P_{OH}$, the contribution of W_{OH} to the total stored energy W_T is still large. For example, in the case of Fig. 1 at 2.1 MW heating, $P_{ad}/P_{OH}=7$; on the other hand, $W_{ad}/W_{OH}=1.7$. Plasma with a large value of P_{ad}/P_{OH} does not necessarily mean that the plasma is free from the confinement scaling of Ohmic plasma.

Experimental results described in this Letter were mainly obtained in an electron-heating regime of ICRF heating, but the present confinement model may be applicable to the NBI-heated plasma, as shown in Fig. 2, and also to the other tokamaks. The JET ICRF heating experiment showed that the energy-decay time of 250 ms almost coincides with the incremental energy-confinement time deduced from $\Delta W_T/\Delta P_{tot}$,[5] which can be explained by the present confinement model.

We cannot yet draw the physical picture of how the incremental energy from the additional heating behaves independently of the Ohmic base plasma energy. But it can be said that each of those energies should not have independent loss channels. Some nature of the plasma changing its spatial transport coefficient may make it seem that the incremental energy behaves independently of the Ohmic plasma. In order to improve the confinement, it is important to understand the nature of the plasma which explains the present experiment.

The authors are grateful to the members of the JFT-2M operation group for their excellent operations and helpful support. Stimulating discussions with Dr. K. Itoh (Plasma Physics Laboratory, Kyoto University), Dr. S. I. Itoh (Institute for Fusion Theory, Hiroshima University) and Dr. T. Takizuka are gratefully acknowledged. We also sincerely thank Dr. A. Funahashi, Dr. M. Tanaka, and Dr. Y. Tanaka for their continuous encouragement.

---

[a] On leave from Mitsubishi Electric Co., Chiyoda-ku, Tokyo 100, Japan.

[b] On leave from Mitsubishi Computer System Tokyo Co., Minato-ku, Tokyo 105, Japan.

[c] On leave from Mitsubishi Atomic Power Industries Inc., Minato-ku, Tokyo 105, Japan.

[1] R. J. Goldston, Plasma Phys. Controlled Fusion **26**, 87 (1984).

[2] S. M. Kaye and R. J. Goldston, Nucl. Fusion **25**, 65 (1985).

[3] M. Mori *et al.*, Plasma Phys. Controlled Nucl. Fusion Res. **1**, 445 (1985).

[4] J. Hosea *et al.*, in *Proceedings of the Twelfth European Conference on Controlled Fusion and Plasma Physics, Budapest, Hungary, 1985,* edited by L. Pócs and A. Montvai (European Physical Society, Petit Lancy, Switzerland, 1985), Vol. 1, p. 120.

[5] J. Jaquinot *et al.*, in Ref. 4.

[6] A. M. Messiaen *et al.*, in Ref. 4.

[7] B. Coppi, Comments Plasma Phys. Controlled Fusion **5**, 201 (1980).

[8] E. Speth *et al.*, in Ref. 4, p. 284.

[9] A. Fukuyama *et al.*, Nucl. Fusion **23**, 1005 (1983).

[10] T. H. Stix, Plasma Phys. **14**, 367 (1972).