A New Time Constant in ASDEX Determining the OH Confinement

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Abstract

The transient response of the stored energy to density variations is studied in ASDEX ohmic discharges. It is found that the phase delay between the stored energy to the density variations, $\tau_r^w$, is much smaller than the energy confinement time, $\tau_E$, in the density regime where $\tau_E$ scales like the Alcator scaling ($n_e < n_c$). The phase delay $\tau_r^w$ increases dramatically in the high density regime where $\tau_E$ saturates with density ($n_e > n_c$). The phase delay $\tau_r^w$ associated with density increase by pellet injection is small for operation at both high and low density. The value observed with pellet injection is as short as that seen in the low density gas puffing regime. Examination of this new time scale, $\tau_r^w$, may help to understand the hidden physics processes in ohmically heated plasmas. The phase delay of the central electron temperature, $\tau_r^T$, to density variations is observed to be small compared to $\tau_E$ at all densities.

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Anomalous transport phenomena in tokamaks remain unresolved. Abundant data for the energy confinement time, $\tau_k$, have been accumulated in tokamaks for various heating methods. The common dependence of the confinement time on plasma parameters has been extracted in a form of empirical scaling laws. The confinement time $\tau_k$ is defined as the ratio of the stored energy, $W_p$, to the absorbed power, $P_{abs}$, in a stationary state. This gives a measure of the rate at which the energy flows out from the plasma. The more precise picture of the transport has been established in a form of the local transport coefficient. Although recent analyses on transport coefficients have made considerable progress\cite{1-8}, the understanding of the scaling law of the global confinement time is far from satisfactory.

Another approach to the study of plasma confinement is to examine the transient response of the stored energy to the external perturbations. If there is only one dominant process in the plasma, which determines the flow rate of the energy, the characteristic time associated with the transient response would be the same as the global confinement time of the stationary state. This method has been applied to study the additional confinement in various tokamaks\cite{5-8}. In experiments on JFT-2M, TEXTOR and TCA, typical time scales associated with the transient response are different from the global energy confinement time, and may be related to the so-called additional confinement time, $\tau_{add}$\cite{6,7} ($\tau_{add}$ is determined by fitting the stored energy $W_p$ and the heating power $P$ in a form \cite{9} as $W_p = W_i + \tau_{add} P$). This method of studying the plasma confinement is particularly important for the investigation of OH plasmas because the heating power cannot be chosen independent of the electron temperature in a stationary state. For instance, if one assumes the Ohkawa model\cite{10}}
for the functional form of $\chi_e$ (electron thermal diffusivity) and writes $\tau_e \sim a^2 / \chi_e$ (a is the plasma minor radius) one sees that there is an invariant relation

$$T^3 / \left( Z_{eff} e^4 B^2 a \right) = 1$$

(1-1)

($\Gamma$ is a dimensionless factor). Because of this invariance, another model of $\chi_e$ which satisfies the relation,

$$\chi_e = \left[ T^3 / \left( Z_{eff} e^4 B^2 a \right) \right] \chi_{e_2}$$

(1-2)

gives a similar Alcator-like scaling law for $\tau_e$. This dependence of $\left[ T^3 / \left( Z_{eff} e^4 B^2 a \right) \right]$ is hidden in the global confinement time. Therefore models of $\chi_e$, such as the Ohkawa model, DETM (Dissipative Trapped Electron Mode) model and Gruber's model and Coppi-Mazzucato model can not be easily determined from the confinement scaling in steady state ohmic discharges. If one solves the transport equation by employing these models of $\chi_e$, in principle one can discriminate $\chi_e$'s through the comparison of the predicted $T_e$ profile. This is, however, difficult because the $T_e$ profile is also constrained by the effects of global MHD modes on the current density profile. This constraint leads to a similar $T_e$ profile for various models of $\chi_e$. The distinction of the $T_e$ profile requires a high accuracy of $T_e$ measurement, for which the present-day level of the error bar is too large. For this reason, the analysis of the transient response in the OH plasma is of particular importance. One of the authors (Y.M.) has observed the response of $W_p$ associated with the density changes in JFT-2M and found that the phase delay is very small. This would be related to the apparent improvement of $\tau_e$ in the case of the density rise if one can define $\tau_e = W_p / (P_d W_p / dt)$ in such a nonstationary case.
In ASDEX discharges, temporal variations in OH plasma are observed in (1) density ramp-up experiments (linear rise of the line-averaged density $\tilde{n}_e$ with a typical rate of $dn_e/dt=2.3\times10^{19}$ m$^{-3}$/sec), (2) the density modulation experiments$^{14}$ ($\Delta \tilde{n}_e/\tilde{n}_e \ll 0.15$, $\omega / 2\pi =5$, 10, 20Hz), (3) pellet injection$^{15}$, (4) $I_p$ and other plasma parameter variations. In this report we study cases (1)-(3). It is found that the phase delay time, $\tau_{rW}$, of $W_p$ to $\tilde{n}_e$ variation is much shorter than the value expected from $\tau_F$ in the regime where $\tau_F$ scales as the Alcator-like scaling law. The phase delay time increases dramatically, so that $\tau_{rW} \sim \tau_F$, in the regime where $\tau_F$ saturates with $\tilde{n}_e$. The value is not explained by the scaling law of the confinement time either. With pellet fueling, the phase delay time is as short as that observed in the low density gas puffing case. In these experiments, however, $\tau_{rW}$ remains much smaller than $\tau_F$ even in the high density regime. These results are examined in detail in section II. This new time scale, $\tau_{rW}$, may help the understanding of hidden basic physics processes in OH plasmas. In order to understand the nature of the different time scales, we examine several models of the transport coefficient, and compare them with experimental results in section III. Summary and discussion are given in section IV.
II Experimental Results

(2-1) Density Ramp-up Experiment

In ASDEX, which is a divertor tokamak with major radius of R=1.65m, minor radius of a=0.4m and toroidal magnetic field strength of $B_T \leq 2.8T$, the line-averaged density is usually feedback controlled to be constant during the flat top of the plasma current. There are a few shots in which the density increased in time. The energy confinement time in the nonstationary phase is defined by $\tau_E = W_P/(P - dW_P/dt)$. We compare the energy confinement time $\tau_E$ of the constant density phase and that determined during increasing phase in Fig.2-1. In evaluating $\tau_E$, $W_P$ is determined by the diamagnetic measurement. In the constant density case, the plasma current $I_P$ is 420kA and the safety factor at the plasma surface $q(a)$ is 2.51. In the increasing density data $I_P$ is 380kA and $q(a)$ is 2.77. These shots are hydrogen discharges. The symbols $\square$ and $\bigcirc$ show $\tau_E$ at the constant density phase and that at the density rising phase, respectively. The vertical length of the bar for the constant density data indicates the error in evaluating $\tau_E^*$. The rising rate of the density, which is also shown in Fig.2-1, is $2.3 \times 10^{19} m^{-3}/s$. The $\tau_E$ is larger during the rising phase of the density. This result, however, is not conclusive because total plasma currents are different for these two cases and we can not distinguish between the effect of $dW_P/dt$ (and/or $d\tilde{n}_e/dt$) and the $q(a)$ dependence on $\tau_E$ in the linear regime. But in the saturation regime, larger $\tau_E$ may

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*The $\tau_E$-values of the scans in Fig.2-1 are higher than those obtained earlier under similar conditions. No effort has been made to carefully compensate the diamagnetic loops. The $\tau_E$-values deduced from carefully compensated diamagnetic loops are shown in Ref.16.
show the effect of $dW_p/dt$ on $\tau_E$. The data of $\tau_E$ at
the density decay phase are necessary to discuss the effect
of $dW_p/dt$ (and/or $d\tilde{n}_e/dt$) on $\tau_E$ without considering the
$q(a)$ dependence. Then we mainly study the density
modulation experiment in this report.

(2-2) Density Modulation Experiment

The main purpose of the density modulation is to
estimate the particle diffusion coefficient $D$, the pinch
velocity $v$ and other parameters$^{14}$. The density is
modulated by applying a sinusoidal voltage to the gas puff
valve. Because the response of the valve is not linear,
the resulting variation of $\tilde{n}_e(t)$ contains higher harmonics
in addition to the fundamental component (frequency $f=5, 10$
and 20Hz). We show two examples of this experiment.
One is a low density case (left column in Fig.2-2: in this
density region $\tau_E$ scales as the Alcator scaling) and the
other is a high density case (right column in Fig.2-2: in
this density region $\tau_E$ saturates with density). The
modulation frequency is 5Hz. These are hydrogen discharges
with $I_p=320kA$ and $q(a)=3.29$. In these two cases, the
temporal behavior of $\tilde{n}_e$, $W_p$ (measured by the diamagnetic
measurement), the central electron temperature $T_{ee}^{ECE}$
(measured by the ECE method) and ohmic input power $P_{oh}$
(loop voltage is measured outside the vacuum vessel) are
compared in Fig.2-2. The diamagnetic loop is located
outside the vacuum vessel, and the skin time of 15.5msec is
compensated numerically. The stored energy determined
from the equilibrium using the magnetic probe inside the
vacuum vessel shows similar time behavior. We therefore
use $W_p$ determined by the diamagnetic measurement to study
the temporal response in this report. The phase delay
time, $\tau_E^{W}$, is defined as the time between the maximum
density and the maximum stored energy as shown in Fig.2-2.
The uncertainty in the magnitude of the phase delay

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measured over the five modulation periods (5Hz), 7~10msec, appears to be due to the noise on the diamagnetic signal. The phase delay time to the minimum of \( T_{e0}^{ECE}, \tau_r^T \), is determined in a manner analogous to that for \( \tau_r^W \). The zero correction chop in ECE measurement, together with the sawtooth variation, produce an uncertainty of about 10msec in \( \tau_r^T \). The observed change of \( T_{e0}^{ECE} \) is the evidence that the temperature changes over the whole plasma column and eliminate the possibility that the modulation is restricted to the plasma periphery (if that were the case, a fast response is expected). Since \( T_{e0}^{ECE} \) is the local value, it has a additional phase lag as will be discussed later. If the volume-averaged density is used for this evaluation of \( \tau_r^T \) and \( \tau_r^W \), we may expect the similar results, because the density profile changes only slightly. The change of density over the whole plasma column is observed by 4-channel FIR (HCN) interferometer.

The Abel-inverted density at the center has a relation of \( \Delta n_e(0)/n_e(0) \sim \Delta \bar{n}_e/\bar{n}_e \).

The density change contains higher harmonics as well as the fundamental component. In the low density case, the phase delay for the stored energy is small and shows the temporal behavior of \( W_p \) is similar to that of \( \bar{n}_e \). This means the stored energy responds linearly even to higher frequency components of the density modulation. In this case, \( \tau_r^W \) is about 5msec and \( \tau_r^T \) is about 20msec. In the high density case, the \( W_p \) signal contains mainly the fundamental component of the density variation and the phase delay is large. The value of \( \tau_r^W \) is about 70msec and \( \tau_r^T \) is about 20msec in this case. Hence \( \tau_r^W \) increases rapidly with increasing density, and reaches a value \( \tau_r^W \sim \tau_E \). The \( \tau_r^T \) is, however, similar for high and low density cases. Figure 2-3 shows the temporal variation of electron temperature on various radial positions in the low density case. The modulation of \( T_{e0}^{ECE} \) indicates that the external perturbation of gas
puffing penetrates to the center part of the plasma. We see the additional time lag of $T_{e0}^{ECE}$ compared with the temperature near the half of the plasma radius $T_{e(a/2)}^{ECE}$. This additional time lag is $15\pm5$ msec in this case.

The modulation amplitude of these two cases is summarized in Table 2-1. The ratio of $\Delta P_{Oh}/P_{Oh0}$ to $\Delta T_{e(a/2)}^{ECE}/T_{e(a/2)0}^{ECE}$ is about -1, and that of $\Delta P_{Oh}/P_{Oh0}$ to $(\Delta W_p/W_{p0} - \Delta \bar{n}_e/\bar{n}_{e0})$ is about -2 in the low density case, where the suffix 0 means the averaged value. This relation shows that the ohmic power changes like $P_{Oh} \propto T_{e0}^{\infty} \left(1 \lesssim 2\right)$. On the other hand, the ratio of $\Delta P_{Oh}/P_{Oh0}$ to $\Delta T_{e(a/2)}^{ECE}/T_{e(a/2)0}^{ECE}$, and that of $\Delta P_{Oh}/P_{Oh0}$ to $(\Delta W_p/W_{p0} - \Delta \bar{n}_e/\bar{n}_{e0})$ in the high density case are -0.2 and -0.4, respectively.

Figure 2-4 shows the time trace contour on the density and the stored energy plane (5/4 period of 5Hz modulation corresponding to the two cases of Fig. 2-2). On this plane, the full ranges of the vertical and horizontal axes ($W_p$ and $\bar{n}_e$) have the relation of $\Delta W_p/W_{p0} \sim \Delta \bar{n}_e/\bar{n}_{e0}$. The thin and wavy line are the experimental raw data. The thick solid line is the fitting curve to average out the high frequency noises. Arrows show the time history on this plane. Since the stored energy follows very fast to the density modulation in the low density case (top in Fig. 2-4), the shape on this plane is close to Y=X line. The shape in the high density case (bottom in Fig. 2-4) is different from that in the low density case, since $\tau_r^{\infty}$ is large and the amplitude of the stored energy $(\Delta W_p/W_{p0})$ is small.

The characteristic times of $\tau_r^{\infty}$ and $\tau_r^T$ at 5Hz and 10Hz are summarized in Fig. 2-5. The dashed line is the global energy confinement time $\tau_E$. The dramatical change of $\tau_r^{\infty}$ from low density to high density can be seen in Fig. 2-5(a). In the low density case, $\tau_r^{\infty} \ll \tau_E$ holds, while we find that $\tau_r^{\infty} \sim \tau_E$ at high density. Solid lines show the theoretically estimated phase delay.
time of 5 and 10Hz (discussed in Sec. III) by using the Alcator-like scaling of $\tau_e (n_e)$. Experimentally observed values of $\tau_r^W$ are different from the theoretically estimated value both in low and in high density case. The $\tau_r^T$ shown in Fig.2-5(b), however, always stays about 20msec. Unfortunately, there is insufficient data to examine the transition from small to large $\tau_r^W$.

(2-3) Pellet Injection Experiment

We have also observed a phase delay between stored energy and density variation created by pellet injection. We are particularly interested in the temporal response of $W_p$ after injecting the first pellet, because this is the first perturbation of the density on a stationary plasma by a pellet. In this case $I_p$ is 380kA and $q(a)$ is 2.76. These are also hydrogen discharges. Figure 2-6 shows the time histories of the line-averaged density and the stored energy which is determined by the diamagnetic measurement. The density increase by the first pellet is about $0.28 \times 10^{19} \text{m}^{-3}$ (line-averaged density). The velocity of the pellet is 600m/s. Because of the slow speed, a major part of the particles are deposited in the outer portion of the plasma column. If the density change is like a step-function, we can measure the $\tau_r^W$ by assuming that the stored energy responds exponentially, i.e. as $[1- \exp(-t/\tau_r^W)]$. Fitting this exponential behavior to the data (thick line in Fig.2-6) shows that this model is acceptable as a first step of analysis. Note that this estimate of $\tau_r^W$ gives an upper limit, since the density does not change as a step-function but rises rapidly initially, followed by a slow rise to equilibrium as shown in this figure. The stored energy signal contains high frequency noise, but the error due to this noise may be less than 10msec. We can not measure the phase delay of the temperature response because the timing of the pellet
injection coincided with the zero correction chop of the ECE measurement. The density dependence of $\tau_{r,w}$ is summarized in Fig. 2-7. The range of density increase by the first pellet is from $0.28 \times 10^{19}$ m$^{-3}$ to $0.53 \times 10^{19}$ m$^{-3}$ in these cases. The response time $\tau_{r,w}$ after the first pellet is small and comparable to the values obtained at low density in the density modulation experiment. It should be noted that in the pellet injection case, $\tau_{r,w}$ is small even in the high density region, where the Alcator-like scaling of $\tau_f$ is recovered by the pellet injection.
Comparison with The Model Calculation

To study the origin of the fast response of $W_p$ to $\bar{n}_e$, we examine a model calculation based on the point model of the energy balance equation, which may be written as

$$\frac{dW_p}{dt} = P - W_p / \tau_E$$ \hspace{1cm} (3-1)

where $P$ is the sum of the Joule heating and losses such as the radiation loss, charge-exchange loss and so on. If we assume that the main loss channel is the electron thermal conduction and that radiation and charge-exchange losses are neglected, then Eq. (3-1) reduces to

$$\frac{dW_p}{dt} = P_{OH} - W_p / \tau_E$$ \hspace{1cm} (3-2)

where $P_{OH}$ is the Joule heating term and $\tau_E$ includes all the parametric dependences of the anomalous loss. For the variation of the density discussed in this report, the characteristic time is much faster than the resistive diffusion time of the current, $\tau_E$. We therefore assume that the current profile and $Z_{eff}$ do not change during the change of the density and that the relation $P_{OH} \propto T_e^{-1.5}$ holds. This relation leads $(\Delta P_{OH}/P_{OH0})/(\Delta T_e/T_{e0}) = -1.5$. As shown in Sec. II, it is not inconsistent with the experimental observation within the error bar. We introduce the notations $\Delta W_p = W_p - W_{p0}$, $\Delta \bar{n}_e = \bar{n}_e - \bar{n}_{e0}$, $t = t / \tau_{E0}$ (the suffix 0 denotes the value in the absence of the density variation) and linearize Eq. (3-2) to obtain the dimensionless equation

$$\frac{d\Delta W}{dt} + \alpha \Delta W = \beta \Delta \bar{n}$$ \hspace{1cm} (3-3)

where
\[
\alpha = 2.5 - \left(1/\tau_{E0}\right) \left(W_{E0}/\tilde{n}_{e0}\right) \left(\partial \tau_{E}/\partial T\right) \tag{3-4}
\]
\[
\beta = 1.5 + \left(\tilde{n}_{e0}/\tau_{E0}\right) \left(\partial \tau_{E}/\partial n\right) - \left(1/\tau_{E0}\right) \left(W_{E0}/\tilde{n}_{e0}\right) \left(\partial \tau_{E}/\partial T\right). \tag{3-5}
\]

For example, if \( \tau_{E} \) follows the Alcator scaling \( (\tau_{ALC} \propto n a R^{2}) \), \( \alpha = \beta = 2.5 \). If, on the other hand, there exists a hidden temperature dependence of \( \tau_{E} \), then the parameters \( \alpha \) and \( \beta \) differ from 2.5. Writing \( \tau_{E} = \tau_{ALC} \left[ T^{3}/(Z_{eff} e^{4} B^{2} a) \right]^{\gamma} \), we have

\[
\alpha = 2.5 + 3 \nu \tag{3-6}
\]
\[
\beta = 2.5 + 3 \nu. \tag{3-7}
\]

We solve Eq. (3-3) for a specified density variation \( n(t) \). The form of \( n(t) \) is chosen by smoothing the noise in the experimental observations. In the case of density modulation we solve Eq. (3-3) with the periodic boundary condition \( [W(t + 2\pi / \omega) = W(t)] \). In simulating the pellet injection, we solve \( W \) with the initial condition of \( W(t=0) = 0 \) \( (t=0 \) coincides with the timing of the first pellet). Figure 3-1 illustrates an example of the simulation of the density modulation experiment \( (\omega / 2\pi = 5\text{Hz}) \). The simulation shows the phase delay and the flattening of the peak of \( W \) which is due to the fact that the amplitude of the m-th higher harmonic is reduced as \( (\beta / [\alpha \sqrt{1 + (m \omega \tau_{E0} / \alpha)^{2}}]) \). The trace of the trajectory in the n-W plane shows that the expected delay time for the case of \( \alpha = \beta = 2.5 \) is longer than that observed experimentally (Fig. 3-2). In Fig. 3-3 the density dependence of the phase delay time is illustrated for various values of \( \alpha \) and \( \beta \). Solid and broken lines correspond to the cases of 5 and 10Hz modulation, respectively. For \( \alpha = \beta = 2.5 \), the predicted phase delay...
in the low density regime is larger than observed experimentally. The sudden increase of the phase delay time in the saturated $\tau_f$ regime is not predicted by the model.

Other models of $\tau_f (n_e, T_e)$ have also been examined. In particular, we examined the behavior for the parameters $\alpha = \beta = 0.5, 3$ (Ohkawa model\(^{10, 11}\)) and 6 (Dissipative Trapped Electron Mode model\(^{4, 5}\)). In order to fit the experimental data, larger values of $\alpha$ and $\beta$ are necessary in low density regime. The simulation result of the case of $\alpha = \beta = 6$ is within the error bar of the experimental data in low density regime, but it is difficult to conclude because the prediction by this model does not agree with the experiment at high density.

In the frame of the linearized point model, the modulation of the average temperature $T$ (from $W=nT$) is given by

$$T = W - n. \quad (3-8)$$

This shows that the average temperature responds to the density change faster than the stored energy. The phase delay time of the central temperature $T_{e0}^{ECF}$, however, is larger than the measured $\tau_r^{W}$, because $T_{e0}^{ECF}$ responds with a time lag as is shown in Fig. 2-3.

In the case of the pellet injection, $W$ is expressed as

$$W = (\beta / \alpha) \left[1 - \exp(-\alpha t)\right] \quad (3-9)$$

if the shape of $n(t)$ is approximated by the step-function. The predicted delay time is simply given as

$$\tau_r \sim \frac{\tau_f}{\alpha}. \quad (3-10)$$

This time is consistent with the experiment if one chooses $3 < \alpha < 10$ (the curve at $\alpha = 2.5$ is illustrated in Fig. 2-7).
IV Summary and Discussion

We have studied the temporal variation of the stored energy $W_p$ associated with changes of the line-averaged density in ASDEX OH discharges. Cases of (1) density ramp-up, (2) density modulation by gas oscillation and (3) density rise due to the injection of the first pellet are studied. We find that the response of $W_p$ to the density change is very fast compared to the global confinement time except in the case of density modulation at high density. The difference of the nature of the global confinement at high and low densities appears more clearly in the difference of $\tau_r^W$.

Defining $\tau_E$ for a time dependent density as $W_p/(P_{oh} - dW_p/dt)$, we find the confinement time for a linearly increasing density to be slightly higher than that observed at steady state. More detailed study is done in the density modulation case, where we examined the dependence of $\tau_r^W$ on density. We find that $\tau_r^W$ changes dramatically in transition from the Alcator regime of $\tau_E$ (regime I) to the saturated-density regime of $\tau_E$ (regime II); i.e.,

$$\tau_r^W \approx 5 - 10 \text{msec} \ll \tau_E \approx 50 \text{msec} \text{ in regime I}$$

and

$$\tau_r^W \sim \tau_E \sim 80 \text{msec} \text{ in regime II}.$$  

The response of $T_{e0}^{ECE}$ to the density is also faster than $\tau_E$; i.e.,

$$\tau_r^{T} \leq 20 \text{msec} \ll \tau_E \text{ in regime I and II}.$$  

And the central temperature $T_{e0}^{ECE}$ has a additional time lag of about 15msec compared with $T_{e(a/2)}^{ECE}$. The nature of the fast response is also observed in pellet injection experiments. It is noted that the value of $\tau_r^W$
is close to that observed in density modulation case in regime I. In contrast to density modulation experiments, \( \tau_r^w \) remains small even in regime II in pellet injection experiments.

These results imply a correlation with the extension of the Alcator scaling of \( \tau_E \) to the high density regime by the pellet injection\(^{17, 18} \). We may have an Ansatz shown in Fig.4-1. The fast response is characterized by the Alcator-like scaling of \( \tau_E \). The saturation of the density dependence of \( \tau_E \) may be related to a physical mechanism which gives a very long delay time. The study of \( \tau_r^w \), therefore, may give new information in the study of transport coefficients. Unfortunately, the transition from small \( \tau_r^w \) to large was not studied in detail. This is left for future study.

A comparison is made with theoretical models based on the O-D model equation for the energy balance. The hidden temperature dependence of the global confinement is examined by fitting the simulation to the experimental data. The fast response can be explained, at least qualitatively, by a strong temperature dependence of \( \tau_E \). Large value of \( (\partial \tau_E / \partial T ) (T/\tau_E) \), say -3.5, gives agreement with the observed \( \tau_r^w \) within the error bar in the low density case. No model, however, is consistent with the experiment at all densities. The reduction of the experimental error will give more deterministic information of relevance to the various models of transport coefficients. Measurement of the parametric dependence of \( \tau_r^w \), if possible, may provide a better understanding of the physics basis of plasma confinement.

It is also noted that the value of \( \tau_r^T \) is close to the so called additional confinement time \( \tau_{add} \).

Further additional heating experiments should be done to determine if there is a relation between \( \tau_r^T \) and \( \tau_{add} \).

We finally mention the profile consistency Ansatz. This Ansatz requires that the temperature profile is

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constrained to a particular class of shapes which is favorable from the view point of the global MHD stability\(^2\). If there is a "force" to recover the temperature profile to the "most probable" profile to keep MHD stability, the "restoring force" would be generated by the deviation of the current profile from what is favorable for stability (at least in the low \(\beta\) regime where \(\nabla p\) term has small contribution to the destabilization of the MHD modes). The observation shows that there is an intrinsic time scale \(\tau_r^T\) against external perturbations. Because this time scale is much much shorter than \(\tau_R\), the current profile does not change during the modulation. The physical basis of this temperature change is not the principle to reserve a favorable current profile.

The establishment of a more dependable data base of \(\tau_r\) (including the parameter dependence) and a more careful analysis of the profiles is necessary to understand the origin of this fast response and the relation to the global confinement. Analysis of the development of the profile is also necessary, in particular, to understand the case of the high density gas puff modulation. The change of the particle diffusion and inward flow was found\(^1\). For the profile analysis, the losses which are neglected here e.g., radiation loss, and the energy flow from electron to ion should be analyzed carefully in the high density regime. We finally note that the sawtooth behavior, which abruptly changes its period during the rising phase of the density shown clearly in Fig.2-2(c) at low density, should be studied. The power dependence of the OH confinement may be studied by this experiment. An example is shown in Fig.4-2 comparing the calculation results (\(\alpha = \beta = 6\)). This may show the limit to apply the point model. The profile analysis also needs in this case. This is left for future work.

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Acknowledgements

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References

11) In the ohmic heating case where the electron loss is dominant the energy balance equation is given as 

\[ \eta J^2 = nT_e / \tau_e \]

where \( \eta \) is the electric resistivity and \( J \) is the current density. Employing the relation 

\[ \eta \propto Z_{\text{eff}} T_e^{-1.5} e^4 \]

and 

\[ J \sim 2B_T / (\mu_0 qR) \]

we have the identity 

\[ \tau_e = C n T_e^{2.5} Z_{\text{eff}}^{-1} (qR/B_T)^2 \]

\( (C \) is a numerical coefficient). If one employs the relation

\[ \chi_e \propto T_e^{1/2} / (qRn) \]

the identity is rewritten as

\[ \eta J^2 = nT_e / \tau_e \]
\[ \frac{T_e^3}{[Z_{\text{eff}} e^4 B_t^2 a]} [C_q R/a] = 1. \]


Figure Captions

Fig. 2-1  The energy confinement time of the OH discharges related to the line-averaged density. The symbols | and ○ show $\tau_e$ at the stationary density phase and that at the density rising phase, respectively. Upper figure shows the time history of the density in the case of density ramp-up. Arrows indicate the data points presented by the symbol ○.

Fig. 2-2  Time dependence of the line-averaged density (a), the stored energy determined by the diamagnetic method (b), the central electron temperature measured by the ECE method (c) and the OH input power (d). The left column shows the low density case and the right column shows the high density case.

Fig. 2-3  Time dependence of the electron temperature on various plasma radius. This figure corresponds to the left column in Fig. 2-2.

Table 2-1  The modulation amplitude of various plasma parameters in low and high density case.

Fig. 2-4  Time trace contour on the density and the stored energy plane.
(a) Low density case. (b) High density case. (a) and (b) correspond to the left and the right column in Fig. 2-2, respectively.

Fig. 2-5  (a) The phase delay time of $W_p$ to $\tilde{n}_e : \tau_{eW}$
(b) The phase delay time of $T_{e0\text{ECE}}$ to $\tilde{n}_e : \tau_{eT}$
The symbols ○ and □ are corresponding to the density modulation by 5Hz and that by 10Hz.
respectively. Solid line shows the estimated $\tau_r^W$ at $\alpha = \beta = 2.5$ (see III).

Fig.2-6 Time history of the line-averaged density and the stored energy by the pellet injection.

Fig.2-7 The response time of $W_r$ to respond to the density increase by the 1st pellet. Solid line shows the estimated value at $\alpha = 2.5$ (see III).

Fig.3-1 Example of the calculation results. Input parameters of $\tau_E$, $\alpha$ and $\beta$ are 50msec, 2.5 and 2.5, respectively, simulating the low density case ($\bar{n}_e \sim 1.5 \times 10^{19} \text{m}^{-3}$).

Fig.3-2 The trace of the trajectory on the density and the stored energy plane compared with the experimental results. Input parameters of $\tau_E$, $\alpha$ and $\beta$ are 50msec, 2.5 and 2.5, respectively. The experimental result shown in this figure is the same as that shown in Fig.2-4(a).

Fig.3-3 The density dependence of the calculated delay time. Solid lines and crosses show the delay time of 5Hz modulation case and dashed line shows that of 10Hz modulation case. Input parameters of $\alpha$ and $\beta$ are shown separately.

Fig.4-1 Schematic drawing of $\tau_E$ and $\tau_r^W$ in the cases of gas puffing and pellet fuelling.

Fig.4-2 Example of the time trace contour on the OH input power and the stored energy (form the equilibrium method) plane. Fat solid line shows the estimated trace [$P = -1.5(W-n)$] at $\alpha = \beta = 6$. 

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\[
\frac{W_p}{P_{OH} - \dot{W}_p}
\]

\(\tau_E\) (msec)

\(\bar{n}_e\) \(10^{19}\) m\(^{-3}\)

- **stationary density**
  
  \# 20741 - 20751
  
  \(I_p = 420\text{kA}\)

- **ramp-up density**
  
  \# 20777
  
  \(I_p = 380\text{kA}\)
<table>
<thead>
<tr>
<th></th>
<th>low density case</th>
<th>high density case</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_e(0)^{\text{ECE}} / T_e(0)^{\text{ECE}}$</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>$\Delta T_e(a/2)^{\text{ECE}} / T_e(a/2)^{\text{ECE}}$</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>$\Delta \bar{n}<em>e / \bar{n}</em>{e0}$</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>$\Delta W_P / W_{P0}$</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>$\Delta P_{\text{OH}} / P_{\text{OH0}}$</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>$\Delta W_P / W_{P0} - \Delta \bar{n}<em>e / \bar{n}</em>{e0}$</td>
<td>-0.05</td>
<td>-0.05</td>
</tr>
</tbody>
</table>
\[ \tau_r^T (5\text{Hz}) \]

\[ \tau_r^T (10\text{Hz}) \]
\[ \tau_E = 50 \text{ msec} \]

\[ \alpha = \beta = 2.5 \]
$\tau_E = 50 \text{ msec}$

$\alpha = \beta = 2.5$

cal.

exp.
The graph shows the relationship between $\tau_r$ (msec) and $n_e (10^{19} \text{ m}^{-3})$ for different frequencies and values of $\alpha = \beta$. The graph includes lines for 5 Hz and 10 Hz, as well as markers for specific values of $\alpha = \beta$ (0.5, 2.5, 3, and 6). The x-axis represents $n_e (10^{19} \text{ m}^{-3})$, ranging from 0 to 3, and the y-axis represents $\tau_r$ (msec), ranging from 0 to 100.