PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073

PPPL-2606

UC-426

PPPL-2606

COMMENTS ON EXPERIMENTAL RESULTS OF ENERGY CONFINEMENT OF TOKAMAK PLASMAS

BY

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APRIL 1989

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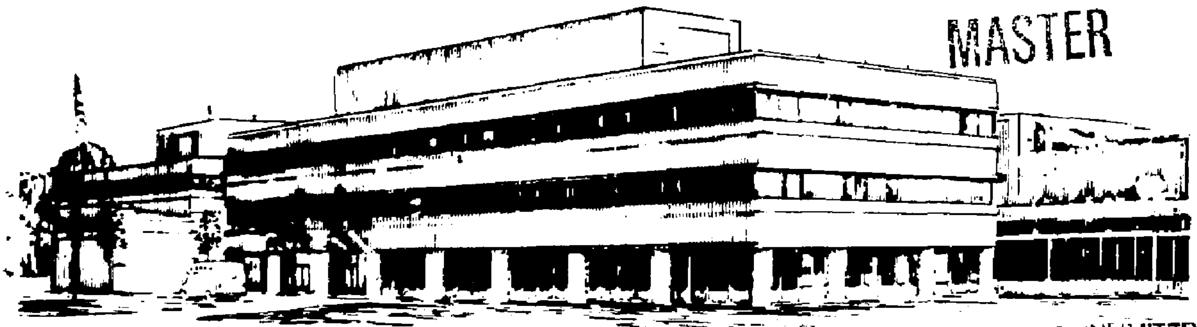

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PPPL--2606

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ABSTRACT

The results of energy-confinement experiments on steady-state tokamak plasmas are examined. For plasmas with auxiliary heating, an analysis based on the heat diffusion equation is used to define heat confinement time (the incremental energy confinement time). For ohmically sustained plasmas, experiments show that the onset of the saturation regime of energy confinement, marfeing, detachment, and disruption are marked by distinct values of the parameter $\bar{n}_e/J$. The confinement results of the two types of experiments can be described by a single surface in 3-dimensional space spanned by the plasma energy, the heating power, and the plasma density: the incremental energy confinement time $\tau_{inc} = \Delta W/\Delta P$ is the correct concept for describing results of heat confinement in a heating experiment; the commonly used energy confinement time defined by $\tau_E = W/P$ is not. A further examination shows that the change of edge parameters, as characterized by the change of the effective collision frequency ν_e^*, governs the change of confinement properties. The totality of the results of tokamak experiments on energy confinement appears to support a hypothesis that energy transport is determined by the preservation of the pressure gradient scale length.

I. INTRODUCTION

For a steady-state tokamak discharge, the energy confinement time is defined as the quotient of the sum of the stored thermal energy W and suprathermal energy divided by the heating power P. For a thermalized plasma

$$\tau_E = W/P. \tag{1}$$

Experiments show that the parametric dependences of τ_E in ohmically sustained discharges [1] are different from those in heating (auxiliary heating) experiments [2]. Furthermore, without exception, τ_E decreases monotonically with heating power [2]. In heating experiments, an incremental energy confinement time has also been defined [3] to represent the observed l· nar relationship between the incremental plasma energy ΔW and heating power ΔP above the ohmic heating values:

$$\tau_{inc} = \Delta W/\Delta P. \tag{2}$$

Results of heating experiments show that τ_{inc} varies as the square of the minor radius a [4], and τ_{inc} is lower than the τ_E of the low-confinement L-mode plasmas. Experiments also show that, except in the core region of $q \leq 1$ and, perhaps in the edge, the profile of electron temperature, normalized to the temperature at a point sufficiently far away from the $q = 1$ surface, remains nearly unchanged [5,6]. Recent analysis of measured profiles shows that, in addition, over a wide range of density, heating power, and plasma current, the thermal diffusivity of electrons χ_e and of ions χ_i changes very little [7]. We attempt in this paper to examine these seemingly unassociated results with the objective of achieving a crude but integrated understanding. Our effort, however, is not aimed at comparing the experimental results with predictions based on any of the many transport theories of tokamak plasmas. In taking up this approach, we suffer from the handicap that our description at times can only be qualitative because there are no measurements or the data are insufficient. But we are also free from defending the limitations that may exist in a particular theoretical model.

We begin in Sec. II with a brief summary of the qualitative behavior of a steady-state tokamak discharge. In Sec. III, we present an elementary analysis of a thought experiment on plasma heating, based on the heat diffusion equation. Using experimentally measured transport coefficients and scale lengths of temperature and density, we obtain a heat confinement time and thus establish a conceptual basis for the incremental energy confinement time in heating experiments. In Sec. IV, we examine results of ohmically heated plasmas. Experiments show that in a gas-puffing fueled discharge with constant plasma current and increasing density the sequential events of the saturation of energy confinement, marfeing, detachment, and disruption are characterized by the parameter $\bar{n}_e/\bar{J}$, the ratio of average electron density to current density. The confinement results in an ohmic experiment and a heating experiment are then represented by a surface of the plasma energy in three-dimensional space spanned by the density, the heating power, and the plasma energy content. The energy confinement time defined in Eq. (1) is not a useful concept for characterizing the results of heating experiments. In Sec. V, we analyze the change of edge parameters in terms of the effective electron collision frequency ν_e^*. Experiments show that different confinement regimes (including L- and H-mode regimes) of tokamak plasmas are marked by distinct changes of electrical resistivity in the edge region, as characterized by the changes of ν_e^*. Thus, the parametric dependence of the plasma energy W in a heating experiment is characterized by its $\bar{n}_e/J$ value in the corresponding ohmic experiment having the same density and current, provided the plasma parameters in the edge region, as characterized by ν_e^*, remain in the same domain for the two experiments. (The precise boundary of these domains can be established by more detailed measurements of edge parameters, and it is in the edge region that systematic documentation is most acutely needed.) In Sec. VI we discuss several topics related to confinement, in particular those related to changes in the density gradient. We advance a hypothesis that tokamak transport is governed by a requirement to preserve the scale length of the (electron) pressure gradient. A few experiments are also suggested, for they may lead to improved understanding of tokamak transport. A summary is given in Sec. VII.

II. A SURVEY

Experiments show that in the ohmic heating regime with gas puffing at the plasma periphery as a means to increase the plasma density, the energy confinement time τ_E of a steady-state tokamak plasma first increases linearly with density (the linear regime), but begins to deviate from the linear increase [8] beyond a certain electron density $\bar{n}_{es}$. At higher densities τ_E becomes independent of, or even to decrease with, density (the saturated regime). The profile of electron density also changes as density is increased, becoming broader, and having a steep gradient only in the edge region [9,10]. A further increase in density results in sharply increased radiation loss in the edge region (marfeing) [11-13]. Finally, at the density limit the discharge disrupts [14,15]. With improved fueling techniques to diminish particle recycling at the limiter and the wall, such as pellet injection [10] or reducing the rate of gas puffing before the steady-state density is reached [16], the peaked density profiles are recovered and the linear regime can be extended to beyond $\bar{n}_{es}$.

When additional heating power is applied to an ohmically produced target plasma, τ_E becomes lower than that in the ohmic heating regime [2]. The magnitude of the decrease is the largest in the low-confinement L-mode regime in which the plasma is conventionally fueled by gas puffing and no special wall or limiter conditioning technique is used to reduce recycling. In tokamaks with divertors (without limiters), this decrease of τ_E is markedly reduced in the high-confinement H-mode regime [17], which is generally characterized by a raised density and temperature pedestal just inside the edge. In the TFTR tokamak, improved τ_E (above L-mode values) is also observed when energetic neutral beams are injected into a low-density target plasma, a condition which is achieved after extensive wall and limiter conditioning [18]; a peaked electron density profile is maintained.

III. A THOUGHT EXPERIMENT ON PLASMA HEATING

We begin with a thought experiment on plasma heating for a thermal plasma: At time t = 0, we turn off all the heating power while keeping the plasma current and its distribution fixed. We monitor the electron energy in the afterglow. Radiative and convective energy losses are neglected. The small energy transfer between electrons and ions is omitted (the heat transported between electrons and ions is retained in the plasma when ion energy conservation is considered). In the cylindrical approximation, T_e is governed by the energy diffusion equation

$$\frac{3}{2} \frac{\partial}{\partial t} (n_e T_e) = \frac{1}{r} \frac{\partial}{\partial r} \left(r \chi_e n_e \frac{\partial T_e}{\partial r}\right) . \tag{3}$$

Since our primary interest is energy and its rate of decrease, we rewri.. Eq. (3) as

$$\frac{3}{2}\frac{\partial}{\partial t}\left(n_eT_e\right) = \frac{1}{r}\frac{\partial}{\partial r}\left\{r\chi_e\left[\frac{\partial}{\partial r}\left(n_eT_e\right) - T_e\frac{\partial n_e}{\partial r}\right]\right\} . \tag{4}$$

Equation (4) states that the rate of decrease of the thermal energy in our thought experiment equals the sum of the radial divergence of an outward diffusive energy flux associated with the energy gradient (pressure gradient) and an inward diffusive energy flux associated with the density gradient.

The density gradient in Eq. (4) can be expressed in terms of the inward particle flow velocity, the particle diffusion coefficient, the particle source, and the boundary conditions governing particle diffusion in the scrape-off layer [19]. For the purpose of arriving at a simple, though quantitatively less accurate, description of heat confinement, we neglect this inward energy flux (we will return to this inward flux later). The justification is given below.

We rewrite Eq. (4),

$$\frac{3}{2}\frac{\partial}{\partial t}\left(n_eT_e\right) = \frac{1}{r}\frac{\partial}{\partial r}\left[r\chi_e n_e T_e\left(-L_{pe}^{-1} + L_{ne}^{-1}\right)\right] , \tag{5}$$

where $p_e = n_eT_e$, $L_{pe}^{-1} = -(1/p_e)\ \partial p_e/\partial r$, and $L_{ne}^{-1} = -(1/n_e)\ \partial n_e/\partial r$. Experiments show that in the bulk of the plasma the scale length of the density gradients, L_{ne}, is 3 to 6 times higher than the scale length of the pressure gradient, L_{pe} [20,21]. We thus omit the inward heat flux associated with the density gradient, keeping in mind that this omission may lead to an overestimation of the heat loss time (an underestimation of heat confinement time) by up to ~30%. In broad density profiles, the overestimation is less.

To solve the remaining heat diffusion equation, we make two simplifying assumptions: (1) the electron cross-field thermal diffusivity $\chi_e(r)$ = constant and (2) $n_e(a)\ T_e(a) = 0$. We then obtain a J_0 Bessel function of n_eT_e on r. Experiments [7,22-24] show that $\chi_e(r)$ increases somewhat with radius, but with an order-of-magnitude increase occurring only in the edge region, especially for high-density discharges. The use of a constant χ_e will result in an inaccurate pressure profile which, however, is not our primary concern here. But clearly, we must truncate our analysis at a position sufficiently inside from the edge to avoid errors introduced by the huge increase of χ_e at the edge in most (but not all) experiments. The analysis, however, may be more accurate in larger minor radius plasmas, since the thickness of the edge layer, strongly influenced by atomic physics processes (including recycling) in the edge and the scrape-off region, should remain relatively unchanged as the minor radius increases. The second assumption is also reasonable since experiments show that the edge density is ~15% of the central density and the edge temperature is only a few percent of the central temperature. The use of the first zero of the Bessel function in evaluating the cooling time, therefore, introduces only a small error. The electron heat confinement time τ_{he} (to distinguish from the conventional energy confinement time τ_E) is, therefore,

$$\tau_{he} = \frac{a^2}{4\chi_e} \quad . \tag{6}$$

The ion heat conduction loss has been a much less studied subject in the laboratory; there are no extensive ion density and temperature profile measurements. But recent measurements of T_i profiles [7,22-24] have shown that (1) $\chi_i \gtrsim \chi_e$, (2) χ_i and χ_e have similar profiles [22,23], and (3) over a wide range of density profile shapes (characterized by the ratio of peak density to the average density) χ_i is about one to two times χ_e at the half-radius point. These experimental results support an assumption that ion heat loss can be described by an equation similar to Eq. (3).

The aspect ratio clusters around $R_0/a \sim 3$ in tokamaks with auxiliary heating; the safety factor at the edge, q_a, is generally between 3 and 4, and $T_e(0)$ is a few keV. In this range of parameters, the measured χ_e just inside the edge region is $\sim 2\ m^2/sec$. Using this χ_e value and $\chi_i = 1.5\ \chi_e$, we can obtain the heat confinement time for the electrons and ions, separately. To facilitate a simple description of heat confinement, we can write a heat confinement time τ_h for the combined electron and ion energy. Because of charge neutrality, the effect of the slightly higher χ_i (than χ_e) decreases rapidly with Z_{eff}. The heat confinement is essentially determined by χ_e and

$$\tau_h = \frac{a^2}{8}\ \text{sec} \tag{7}$$

(which can be obtained by combining the electron and ion heat diffusion equation for a high-density plasma in which $T_e = T_i$). Our analysis establishes a conceptual basis of heat confinement time (the incremental energy confinement time) associated with conduction loss in heating experiments. It must be emphasized that we have not offered a model of the physical mechanism of the thermal diffusivities. The a^2 dependence and the numerical factors in Eqs. (6) and (7) are results of the cylindrical approximation and the use of thermal diffusivities measured in a limited range of parameters. Later, we will return for a more detailed examination of experimental results of the incremental energy confinement time and its parametric dependences.

IV. OHMIC EXPERIMENTS

In a heating experiment, we vary the plasma energy by varying the heating power, the density can be kept constant, though need not be. In an ohmic experiment having the same plasma current, we can change plasma energy only by changing the total number of particles; the ohmic power that sustains the discharge is nearly constant since the electric resistivity is independent of density. Therefore, in an ohmic plasma, we examine the change of confinement and other discharge characteristics in terms of the density and the plasma current.

The apparent parameter that governs the discharge characteristics in a gas-puffing fueled, steady-state tokamak plasma is $\bar{n}_e/\bar{J}$, the ratio of the average (central chord-averaged) electron number density to the average current density. As the density is increased in a discharge, as noted in Sec. II, the first density landmark delineating a change in confinement time is $\bar{n}_{es}$, the density at which the energy confinement no longer increases linearly with density. In Fig. 1 we plot $\bar{n}_{es}/\bar{J}$ versus the toroidal field B_t, the plasma current I_p, the major radius R_0, the minor radius a, and the cylindrical safety factor q(a), based on results as reported for a number of tokamaks [1,8-10,25-34] in the ohmic heating regime. $\bar{n}_{es}/\bar{J} \approx 0.35$ (10^{20}/MA-m) and is nearly independent of all of the parameters. The second landmark $\bar{n}_{em}$ delineates the density at which significant radiation loss at the edge (marfeing) occurs, and it has been found that $\bar{n}_{em}/\bar{J} \approx 0.5$ [35]. Marfeing also has been shown to be due to edge cooling [36]. The third and the last landmark is $\bar{n}_{ed}$ at which disruption occurs, and $\bar{n}_{ed}/\bar{J} \approx 0.6$ [14,15,37]. (In earlier publications, the disruption criterion was expressed as 1/q(a) versus $\bar{n}_e B_T/R_0$ [14,15], which is the same as $\bar{n}_e$ versus $\bar{J}$ [37].) A detached plasma, in which the radiation loss in the edge annulus accounts for the total input power, can also be produced at densities slightly less than the disruption density limit [38]. We note three more points. (1) $\bar{n}_{es}/J$ also coincides with the beginning of a decrease in global particle confinement with density [39,40]. (2) In the linear regime, the energy confinement time decreases with plasma current, as shown in Fig. 2 [31,34]. This inverse dependence of τ_E on J has also been observed in ohmically heated stellarators [41,42] and has been characterized as a dependence on the drift parameter (the ratio of electron drift speed to its thermal speed). (3) The energy confinement time τ_E as defined in Eq. (1) increases with plasma current in the saturated regime (and, therefore, in L-mode discharges). This is because the input ohmic power remains unchanged at $\bar{n}_{es}$ when the plasma current is increased (Fig. 5, Part A, Ref. 43), while the total plasma energy content W increases with $\bar{n}_{es}$ (Fig. 14, Part A, Ref. 43) which is proportional to plasma current.

We can adopt the criterion used in evaluating heat confinement in heating experiments to evaluate the conduction heat loss in ohmic experiments. This heat loss is

$$P_{loss} = (4\pi^2 R_0)\ (rn_e\chi_e\partial T_e/\partial r)_{\sim\ edge} \quad . \tag{8}$$

Using the profile measurements of n_e and T_e in the edge region from the ASDEX tokamak [43], and the DIII-D tokamak [44], we evaluate this loss and give the results in Table 1; the edge quantities are evaluated at r/a = 0.9 (a somewhat arbitrary choice) and a $\chi_e = 2m^2/sec$ (the same value which we used in obtaining the heat confinement time in heating experiments). The electron heat conduction loss accounts for ~80% of input power in both cases. We note that the DIII-D discharge has a low target density, which may account for its high radiative loss from the plasma. (In this discharge there is very little radiation loss from the divertor region.)

TABLE I. Heat Conduction Loss in Ohmic Discharges

Device	I_p (MA)	V_L (V)	P_{OH} (kW)	R_0 (m)	a (m)	k⁺	$\bar{n}_e$ (10^{20} m^{-3})	P_{rad} (kW)	$P_{OH}-P_{rad}$ (kW)
ASDEX	0.32		315	1.65	0.4	1	0.4		
DIII-D	0.48	0.63	300	1.68	0.62	1.8	0.11	~200	~100

⁺k - elongation

Device	Edge values at r/a = 0.9: r (m)	χ_e (m^2/sec)	n_e (10^{20} m^{-3})	$\partial T_e/\partial r$ keV/m	P_{loss} (kW)
ASDEX	0.36	2	0.16	2.2	265
DIII-D	0.75	2	0.06	0.85	80

The energy confinement properties in an ohmic experiment and those in a heating experiment can thus be described by a single surface of plasma energy content in the 3-dimensional space spanned by W, $\bar{n}_e$, and P (the heating power), as sketched in Fig. 3 for a gas-puffing fueled experiment. The change of plasma energy in a heating experiment describes a path on the surface. The two straight lines drawn on the surface represent two different types of heating experiments: a constant-density experiment and an increasing-density experiment. If the incremental confinement time is independent of density, then the slope of the two paths, $\Delta W/\Delta P$, is identical. By normalizing $\bar{n}_e$ by $\bar{n}_{es}$ and W by W_s, where W_s is the total energy content at $\bar{n}_{es}$, the normalized energy surface describes the energy content in experiments with different plasma current. The plasma energy in an ohmic experiment is the lower edge of this surface. We note that among all the points marking the boundaries of the surface, only the $\bar{n}_{es}$ value (associated with experiments fueled by gas-puffing) of an ohmically sustained plasma has been extensively documented (as shown in Fig. 1). If direct fueling or other techniques to reduce recycling at the wall or the limiter is used, the linear confinement regime is extended indefinitely; a sharp boundary marked by $\bar{n}_{es}$ no longer exists. We note in addition that the slope of the surface $\Delta W/\Delta P$ in the regime of $\bar{n}_{es} > \bar{n}_{es}$ is actually not constant, as will be shown later in Fig. 6. The slope of the surface in the regime of $\bar{n}_e < \bar{n}_{es}$ is not known experimentally. But heating experiments in the linear regime (or the extended linear regime) should give a higher slope because of a steepened density gradient in the core region and a reduced χ_e in the edge region, as will be discussed in Sec. VI.

It is clear that the concept of energy confinement time as defined in Eq. (1), which has established its roots in more than two decades of ohmic heating studies (a fueling experiment), is not a useful one in describing the confinement properties of a tokamak when both fueling and heating power are allowed to change. The correct concept for describing the results of these experiments is the incremental energy confinement time.

V. THE EDGE PARAMETERS

We now attempt to find the parameter that may be directly responsible for these changes that occur in gas-puffing fueled experiments. We note first that at densities higher than $\bar{n}_{es}$, not only does the global particle confinement time begin to decrease, but its magnitude also can become much lower than the global energy confinement time [39,40]. If the plasma is thermally homogeneous in the radial direction, such an occurrence is not possible. The rapid loss of particles, therefore, must be primarily restricted to the relatively cold particles in the edge, and the particle confinement time depends strongly on edge diffusion and weakly on profile shape [45]. The relevant density and current density are the edge quantities $n_e(a)$ and $j(a)$. The extension of linear confinement regime in experiments with reduced recycling at the wall or the limiter results in reduced values of n_e in the edge region.

We can find several parameters that can be used to characterize an increase of $n_e(a)$ and a decrease of $j(a)$ when the threshold $\bar{n}_{es}/J$ is exceeded. One parameter, for example, is the drift parameter noted in Sec. IV. Another is the effective electron collision frequency $\nu_e^*[\nu_e^* = \nu_{ei} q R_0/(R_0/a)^{3/2} v_e$, where ν_{ei} is the electron ion collision frequency and v_e is the electron thermal velocity]. Figure 4 shows the ν_e^* profile (with an assumed $Z_{eff} = 2$) in the edge region based on the published edge temperature and density measurements that were obtained by the laser Thomson scattering [44,46,47]. $\nu_e^*(a)$ has values 2 to 10 in the ohmically heated and L-mode discharges (and is higher in ohmic experiments). Using Ohm's law, we can also compare the measured normalized electron temperature profile [6] with the measured normalized current density profile [48]. They are generally consistent with each other (except in the core region where $q \leq 1$ and perhaps in the edge region) when effects of trapped electrons are included in evaluating the electric resistivity. This consistency indicates that neoclassical theory adequately describes the parallel electric resistivity in a tokamak discharge [49]. The rapid transport of particles in the edge at densities higher than $\bar{n}_{es}$ is, therefore, related to an increase in electrical resistivity beginning from the edge and propagating further inward at higher densities.

Many fueling and heating methods [10,16-18,44,50] have been shown to give higher energy confinement time, resulting mainly from a highly peaked density profile or a density plateau just inside the edge. The common feature of the plasma produced by these methods, where measurements are available, is a markedly reduced edge density (together with an increased or decreased edge temperature) even when the density just inside the edge is raised, as in the H-mode cases. (In the H-mode case, measurements show that ν_e^* is reduced in the edge region to below ~ 1, Fig. 4. A precise ν_e^* value requires a knowledge of Z_{eff} in the edge region.) We note that theoretical studies of the resistivity-driven rippling mode [51] are well advanced. But a question can also be raised on the effect of increasing ν_e^* on the very mechanism that causes energy transport (and that has eluded our attention so far). A recent H-mode experiment using electron cyclotron heating [44] shows that near the end of the H-mode, just prior to the reversion back to the L-mode, ν_e^* again increases to a value higher than the H-mode case (perhaps due to a temperature decrease caused by radiation cooling from an impurity accumulation) as shown in Fig. 4c. From this standpoint, other than the change of the magnitude of energy loss and the size of this loss layer in the edge region occurring under different fueling and heating conditions, the energy confinement properties of a thermalized plasma in the L-mode discharge and in the saturated regime of an ohmic experiment are the same. The precise edge values of plasma parameters (including the relevant scale lengths) marking the boundaries of the linear confinement regime, saturated confinement regime, transition to H-mode regime, and perhaps also the low-density ohmic discharge in which the current is carried by runaway electrons [52,53] require additional measurements. Again, we note that we only indicated the correlational relationship between ν_e^* and $\bar{n}_e/J$ and have not provided a basic mechanism that governs the threshold condition at $\bar{n}_{es}/J$ (in Sec. VI, we will pose a hypothesis that addresses the principle that governs the transport). Finally, we note that the density limit for marfeing and disruption can also be raised to higher values when the edge temperature is raised during heating [11,27].

VI. DISCUSSION

In this section, we discuss a few implications and questions that arise from our findings.

1. Plasma Heating

The energy content W in the energy confinement time τ_E defined in Eq. (1) does not distinguish the fractional contributions of density and temperature. Even for a high-density plasma, if its temperature is insufficient for fusion purposes, then the plasma must be heated regardless of how high its τ_E value is. In a constant-density heating experiment, $\Delta W = N\Delta T$, where N is the total number of particles. The required power for an increase of temperatures of ΔT is

$$\Delta P = N\ \Delta T/\tau_h\ . \tag{9}$$

2. Effect of Particle Source on Density Profile Shape

Direct fueling by pellet or by energetic neutral beams tends to recover peaked density profile. We can examine the effect of particle source on the density gradient in the core by analyzing the particle balance. For a steady-state discharge, the particle conservation equation in the cylindrical approximation is

$$\vec{\nabla}\cdot\left(-D\vec{\nabla}n + \vec{v}n\right) = s, \tag{10}$$

where D is the diffusion coefficient, $\vec{v}$ is the inward flow velocity, and s is the particle source. Equation (10) can be integrated in r, and the integration constant can be obtained by matching the density gradient at the edge to that in the scrape-off layer [19]. The solution then gives

$$dn/dr = p(v/D)\left(C_a - \int_0^r f\, dr'\right) - S/rD \quad , \tag{11}$$

where $p = \exp(\int_0^r (v/D)dr'$, $f = p^{-1} S/rD$, $S = \int_0^r sr'dr'$, and C_a is an integration constant determined by the boundary condition at $r = a$.

The density gradient in the interior has a complex dependence on particle diffusion, inward flow velocity, particle source, and boundary conditions. We only wish to point out that the source term contained in the last term in Eq. (11) contributes directly to steepen the density gradient in the core region, while the source term contained in $(-pv/D)\int_0^r fdr'$ is relatively unimportant in this region (it tends to flatten the gradient). An absence of particle source in the interior thus tends to result in a relatively flatter density gradient in the core. A decrease in the edge diffusion coefficient would also allow impurities originating from the edge to penetrate farther into the interior. Experiments show that Z_{eff} decreases with $\bar{n}_e/J$ [54].

3. Energy Content in the Core

When direct core fueling or improved fueling techniques are used to reduce the recycling rate at the wall and the limiter, the density at the edge is lower and the density gradient in the core is higher than corresponding values in gas-puffing fueled experiments, giving a sharply increased density peaking factor $n_e(0)/\langle n_e \rangle$, where $\langle n_e \rangle$ is the volume-averaged electron density [55,56]. Concomitant with the occurrence of a peaked density profile is a higher core energy content (higher core temperature). This is a consequence of the increased inward energy flux associated with the steepening of the density gradient described in Eq. (5). Using that equation and the measured scale lengths [21], we estimate that the percentage of increase of τ_{inc} is approximately one-half of the percentage of decrease of the scale length of the density gradient.

4. Effect of Density Gradient on Sawtooth

The magnitude of the inward heat flux [Eq. (5)] is inversely proportional to the scale length of the local density gradient. For the same χ_e a flatter density profile reduces the heat input during the reheating phase of a sawtooth oscillation and thus affects the sawtooth behavior. Figure 5 shows the sawtooth period τ_{st} versus $\bar{n}_e/\bar{J}$ measured in the PLT tokamak in the ohmic heating regime. The sawtooth period increases with $\bar{n}_e/\bar{J}$ at first, but deviation from the linear increase occurs at $\bar{n}_e/\bar{J} \approx 0.35$, i.e., at the onset of the saturation regime. A similar saturation of the sawtooth period was also observed in the TEXT tokamak [57]. A recent ohmic heating experiment with a reduced gas puffing rate shows that, concomitant with the density peaking, the sawtooth period is doubled when the linear regime is extended to twice the $\bar{n}_{es}$ value [16]; in this experiment no additional heating power is applied. (We cannot offer an explanation for the increase in the sawtooth period with an increase in heating power, a generally observed tokamak phenomenon.)

5. Rapid Restoration of Equilibrium

Experiments show that the incremental energy confinement time depends strongly only on the square of the minor radius. If we ignore the change of density and temperature profiles in the core region, which is dominated by the change of sawtooth behavior, the confinement results verify the unvarying character of profile shapes (and the transport coefficient) for the bulk of the plasma [5,6,48]. The majority of the heating experiments, as compiled in Ref. 4, is carried out with a q_a = 3 to 4 and an aspect ratio R_0/a = 3 to 4. The dependence of thermal transport on geometric configurations and current distribution, therefore, has not been tested extensively. These experiments, however, have used a variety of heating methods which have different power deposition profiles. A question can thus be raised: An unvarying temperature profile under different heating power deposition profiles appears to demand that the transport mechanism be dependent on the method of heating and fueling and their localization. This apparent contradiction can be resolved by allowing the time scale to restore the equilibrium, when a localized perturbation exists, be shorter than the thermal diffusion time during the equilibrium (the steady state). (To be specific, the magnitude of a perturbation is measured by the scale length of the gradient of the perturbation and the transport coefficient depends not only on the local plasma parameters but also on the scale length of the gradient of the parameters.) This feature of rapid restoration of equilibrium is an outstanding characteristic of tokamak transport and has shown up in various experimental phenomena: the higher thermal diffusivity [58] and diffusion coefficient [45,59,60] associated with a sawtooth crash than their corresponding values in the steady state, and the rapid restoration of the equilibrium density and temperature profiles after the injection of a fueling pellet [10,61].

6. Edge Transport and the Existence of an Equilibrium State

Experiments show that, other than in the core region of $q \le 1$, in the bulk of the plasma the scale length of the pressure gradient L_{pe} remains nearly unchanged as plasma parameters are varied [21]. There has been no systematic measurement to test the validity of this observation in the edge region. We propose here a hypothesis on tokamak transport and then apply it to explain the coincidence of the steepened density gradient and the heightened energy loss in the edge region when $\bar{n}_{es}/\bar{J}$ is exceeded.

Our hypothesis is: tokamak transport is governed by the requirement of the preservation of the scale length of the pressure gradient.

Let us apply this hypothesis to an ohmic discharge fueled by gas puffing. Once more we express the heat flux as a sum of the fluxes associated with the pressure gradient and the density gradient. In the edge region χ_e is given by

$$\chi_e = \frac{EI_p}{(2\pi r)\, p_e\, (1/L_{pe} - 1/L_{ne})} , \qquad (12)$$

where $2\pi R_0 E = V_L$ is the loop voltage. As the density n_e is increased, T_e decreases so that $p_e \approx$ constant. In the linear confinement regime, both L_{pe} and L_{ne} are preserved (which is equivalent to the preservation of L_{Te}, its magnitude and distribution being determined by gross stability against MHD modes [62]). Thus, we can achieve a linear increase in τ_E without invoking the generally assumed notion that $\chi_e \propto 1/\bar{n}_e$ in this regime (there has been no measurement to support this notion). In the saturated regime, the preservation of L_{pe} prevails while the continued increase of n_e and decrease of T_e can no longer maintain the integrity of L_{Te} and guard against (MHD or electrostatic) instabilities as L_{ne} decreases. The enhanced χ_e (it is often assumed that χ_e is independent of $\bar{n}_e$ in the saturated regime) is thus related directly to a steepened density gradient in this region (this hypothesis also removes the problem of overdetermination of the electron temperature profile [62]). Farther away from the edge and, therefore, from the controlling boundary condition, there is an increasing latitude for the density profile to accommodate the two demands of MHD stability and equilibrium transport. It is implied in the hypothesis that the flexibility in tokamak profiles to meet the dual demands lies primarily in density profiles. Another consequence of the hypothesis is that τ_{inc} in the linear confinement regime (or the extended linear confinement regime) is higher than that in the saturated confinement regime.

This hypothesis, of course, has not been validated by experimental results (there are theories, based on a variational principle of energy, lending support to this hypothesis [63, 64]). The hypothesis, however, does touch upon another fundamental question in tokamak transport: does there exist an ultimate relaxed state for a tokamak plasma? If such a state does not exist, our hypothesis is meaningless.

If the equilibrium is determined by the relaxation of the current distribution [48], a true steady-state configuration cannot exist, since the current channel would continue to shrink and q(0) would fall below unity for arbitrarily large q(a). Under these circumstances there exists only a quasi-equilibrium with its periodic varying configuration clamped by the internal disruption. The corresponding quasi-steady-state electron temperature profile is a consequence of the relaxation of the current distribution. However, if the equilibrium is determined by energy and particle transport, then the current distribution is a consequence of the relaxation of the temperature profile. In an ohmically sustained plasma, it is then possible to produce a discharge with $q(0) \geq 1$ (without internal disruption) at a finite $q(a)$. Results from the measurements [28] of the q=1 rational surface position, r_1, in steady-state plasmas in the TFTR tokamak have been interpreted as

$$r_1/a = 1/q(a) \quad . \tag{13}$$

If Eq. (13) is correct, then indeed $q(0)$ would fall below 1 for arbitrarily large $q(a)$. A careful examination of the experimental results (Fig. 11 of Ref. 28) shows that the data, when extrapolated, suggest a finite $q(a)$ value (about 15) when $r_1 \to 0$. The same extrapolation of measurements in the TEXT tokamak (Fig. 23 of Ref. 57) also gives a finite $q(a)$ as $r_1 \to 0$ (also about 15). If such a $q(a)$ exists, then the existence of an ultimate relaxed state of a tokamak plasma, due to transport, must be accepted as a possibility.

7. The Direction of Radial Electric Field in the Edge Region

The demarcation point in energy confinement of an ohmically sustained plasma with gas-puffing fueling (and perhaps also in an auxiliary heated plasma as will be discussed in the next paragraph) is $\bar{n}_{es}/J$, and experiments show that this is caused by an increased particle loss, beginning from the edge region. Measurements of plasma potential in the edge region [65] show that in the linear confinement regime ($\bar{n}_e/J = 0.18$ in the experiment of Ref. 65) the radial electric field points inward inside the edge (the density fluctuations therefore propagate in the electron diamagnetic direction) and outward outside the edge; the peak of the plasma potential coincides with the edge. This is to be expected for a plasma with the edge being a well-defined insulation barrier for the electrons [66]. Experiments [67] also show that the propagation velocity of density fluctuations changes from the electron diamagnetic direction to the ion diamagnetic direction when $\bar{n}_{es}/\bar{J}$ is exceeded (the location of the peak level of the density fluctuation also changes from the plasma interior to the edge). This reversal in the propagation direction indicates that when $\bar{n}_{es}/\bar{J}$ is exceeded the location of the peak plasma potential has moved further inward, i.e., the edge has lost its property of insulation for the electrons; the electron transport across the edge in the edge region has increased markedly.

8. A Few Probing Experiments

The present work suggests that the following experiments, in addition to systematic measurements of edge parameters, may lead to improved confinement and understanding of plasma transport in tokamaks. Heating experiments in the linear regime of confinement are needed to verify if τ_{inc} is a constant and higher than τ_{inc} in the saturated regime (τ_{inc} decreases with increasing $\bar{n}_e/\bar{J}$ when $\bar{n}_{es}/\bar{J}$ is exceeded as shown in Fig. 6 [29,68]). Driving a localized current in the edge (and thus lowering the n_e/j value), where the thermal diffusivity is usually the highest, leads to a different distribution of current density and, therefore, possibly to a different thermal transport. The present analysis examines only thermalized plasmas. It has been shown in experiments [69] that energetic ions in passing orbits are far better confined; plasmas with runaway electrons carrying the current [52,53] also show improved confinement. It would be useful to find out whether the good confinement shown in these experiments is because the energy of the particles along the direction of the magnetic field is suprathermal, or simply because the particles are more energetic. In the latter case, we may expect improved thermal confinement in hotter plasmas. In the case of energetic ions, it would be particularly interesting to find out if their confinement is affected by different values of $\bar{n}_e/\bar{J}$. To retain peaked profiles and eliminate impurity accumulation in the core region, both direct core fueling and purity in the scrape-off region are needed. Finally, since the power required in plasma heating is proportional to the temperature increment, it is beneficial to obtain as high a temperature as possible in the ohmically heated target plasma. From this viewpoint, a low aspect ratio tokamak, which generally has a lower loop voltage [70] and, therefore, a higher $T_e(0)$, and a tokamak shaped to carry a higher plasma current and, therefore, a higher volume-averaged electron temperature, offers an advantage.

VII. SUMMARY

We attempted to gain a crude but integrated understanding of the experimental results of energy confinement in steady-state, thermalized tokamak plasmas. Our approach is to examine and analyze the relationship between different aspects of the results, without making comparisons to theoretical predictions based on specific transport models.

We first defined the concept of heat confinement (the incremental energy confinement time) by considering a thought experiment of plasma heating: We monitor the rate of decrease of energy in the afterglow. Based on the measured scale lengths of density, temperature, and pressure as well as thermal diffusivities, we arrived at a heat confinement time. We thus provide a conceptual basis for the incremental energy confinement time and bring out the distinction between heat confinement time in heating experiments and the commonly used energy confinement time in ohmic experiments, in which only the particle density can be varied.

We then examined the parametric variations of energy confinement in ohmic experiments. In particular, in an experiment with increasing density, the sequential phenomena of saturated energy confinement, marfeing, detached plasma, and the density-limit-induced disruption are characterized by the parameter $\bar{n}_e/\bar{J}$. (We have omitted a discussion of very low density discharges in which the current is carried by runaway electrons [52,53]. These discharges may not follow the linear confinement scaling.) The confinement properties of a tokamak plasma are, therefore, represented by a surface in 3-dimensional space spanned by the plasma energy, the particle density, and the heating power. The conventional energy confinement time, $\tau_E = W/P$, is inadequate to describe the property of this surface. We then examined the edge parameters, showing that an increase of $\bar{n}_e/\bar{J}$ marks an increase of electric resistivity, beginning from the edge region.

Finally, we discussed a few topics related to confinement, in particular the role of density gradient. We also posed a hypothesis on the preservation of the scale length of the pressure gradient and discussed the experimental evidence of an ultimate, relaxed state in a tokamak plasma due to transport, rather than due to the relaxation of current distribution. We concluded by proposing several experiments which may lead to improvement and understanding of tokamak transport. It is clear that a systematic documentation of plasma parameters in the edge region, including particle and impurity diffusion, both in the linear regime and the saturated regime of confinement, is vital to the understanding and improvement of tokamak transport at this juncture.

ACKNOWLEDGMENTS

I have benefited from discussions with E. Mazzucato, R. Wilson, and B. Lipshultz (MIT). J. Johnson, S. Zweben, G. Bateman, and R. Goldston gave valuable comments. S. Wolfe (MIT), R. Prater, and J. Lohr (GA) took time to provide tabulations of the experimental data used in their publications and the details of their experiments.

This work is supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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FIGURE CAPTIONS

FIG. 1 $\bar{n}_{es}/\bar{J}$ vs B_T, I_p, R_o, a, and q(a) for ohmically heated deuterium (except as noted) tokamak plasmas. ◇, ISX-A, ◆, ISX-A hydrogen [8]; ▽, DIII [33,34]; □, JFT-2 [26]; ○, Alcator C, ●, Alcator C hydrogen [1,9,10]; ×, TFTR, +, TFTR helium [28-37]; ▲, ASDEX, ▼, ASDEX hydrogen [27]; △, T-10 [32].

FIG. 2 The inverse dependence of energy confinement time on plasma current in the linear confinement regime. (a) $\tau_E/\bar{n}_e$ vs. $1/\bar{J}$ measured in the TFTR tokamak [31], and (b) $\tau_{Ee}/\bar{n}_e$ vs. $1/\bar{J}$ for the D-III tokamak [34], where τ_{Ee} is the electron energy confinement time.

FIG. 3 A sketch of the energy-content surface in 3-dimensional space spanned by the energy content W, the electron density $\bar{n}_e$, and the heating power P for gas-puffing fueled experiments. The slope of the surface $\Delta W/\Delta P$ in the regime of $\bar{n}_e > \bar{n}_{es}$ actually is not constant, as shown in Fig. 6. The plasma energy in ohmic experiments is the lower edge of the surface. In ohmic plasmas with pellet fueling or other recycling reduction techniques, the linear regime is indefinitely extended. The slope $\Delta W/\Delta P$ in the linear confinement regime ($\bar{n}_e < \bar{n}_{es}$) or the extended linear regime, though not known experimentally, can be expected to be higher than that in the saturated regime because of a steepening of the density gradient in the core region and a reduced χ_e in the edge region.

FIG. 4 Profile of the effective electron collision frequency ν_e^* in the edge region as calculated from measured profiles in (a) ASDEX [46], (b)

PDX [47], and (c) DIII-D [44]. Z_{eff} is assumed to be 2 in the calculation. In (a), the separatrix is at $\Delta r = 0$; in (b) the separatrix is in the shaded region (between 180.5 cm and 182.5 cm, $R_0 = 140$ cm, and $a = 40$ cm); in (c) it is at $r/a = 1$. OH for ohmic heating discharge, L for L-mode discharge, H for H-mode discharge. The DIII-D experiment has a lower target plasma density ($\bar{n}_e = 0.11 \times 10^{20}$ m^{-3}), hence a low ν_e^* (with the assumed $Z_{eff} = 2$). All three profiles are calculated from the smoothed curves in the references listed.

FIG. 5 Sawtooth period τ_{st} measured in the PLT tokamak showing the deviation from the linear increase of the sawtooth period at the onset of the saturation regime of energy confinement. These results have not been published before.

FIG. 6 τ_{inc} vs $\bar{n}_e/J$ measured in the TFTR tokamak [29,68].

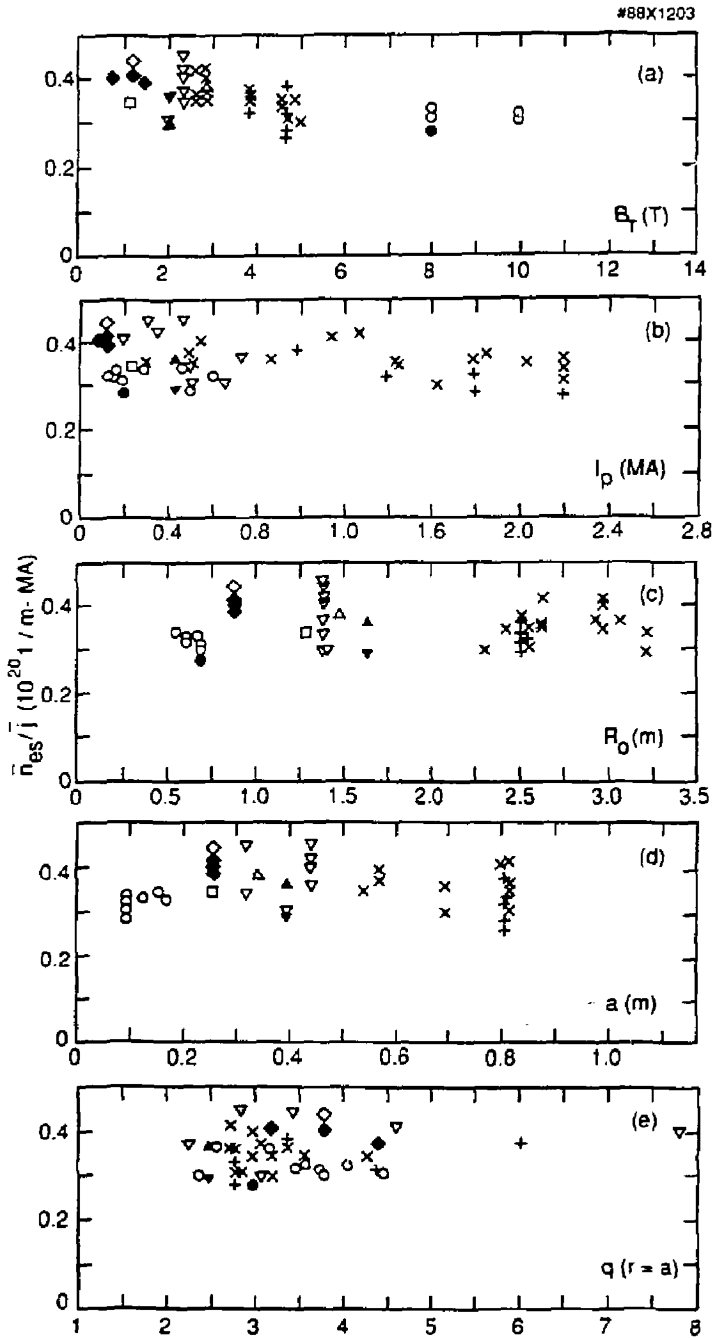
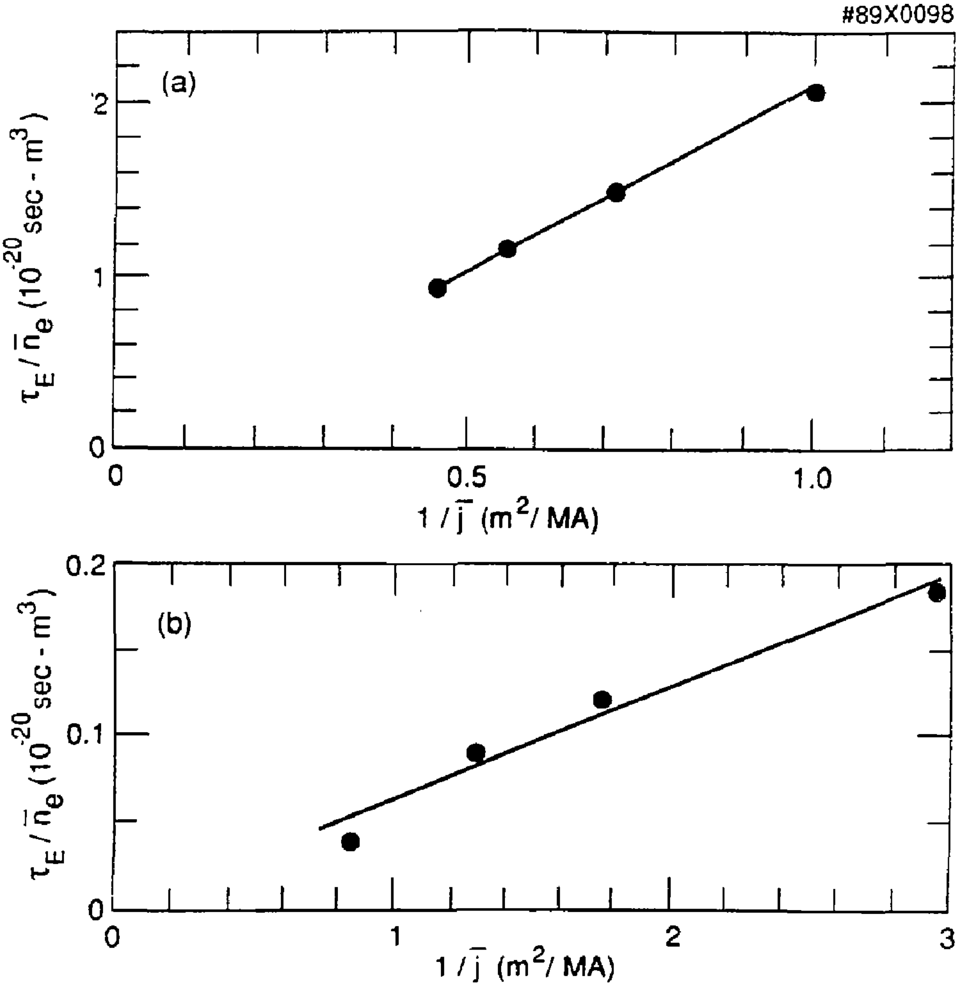


Fig. 1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τE / n̄e (10^-20 sec - m^3)
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1
2
0
0.5
1.0
1 / j̄ (m^2/ MA)
(b)
τE / n̄e (10^-20 sec - m^3)
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0.1
0.2
0
1
2
3
1 / j̄ (m^2/ MA)

Fig. 2

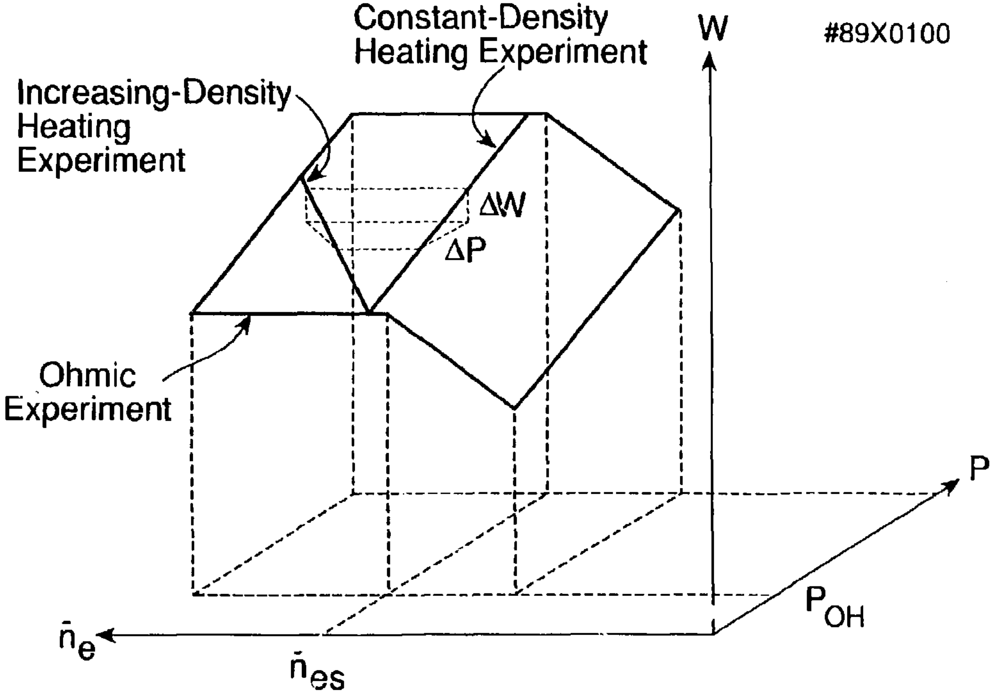
Constant-Density
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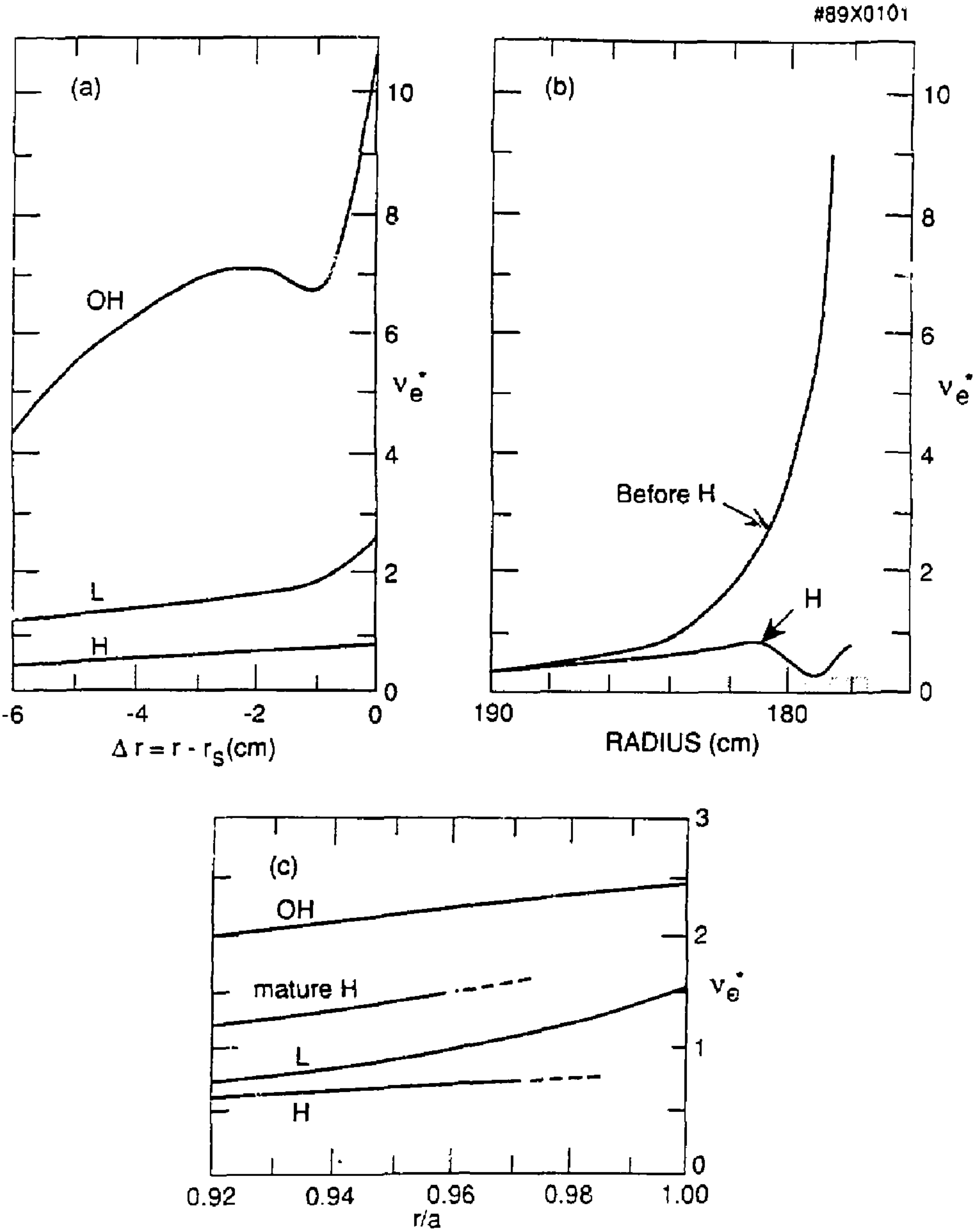
Fig. 3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(a)
OH
L
H
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-4
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0
2
4
6
8
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ν_e^*
$\Delta r = r - r_S$(cm)
(b)
Before H
H
190
180
RADIUS (cm)
0
2
4
6
8
10
ν_e^*
(c)
OH
mature H
L
H
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0.94
0.96
0.98
1.00
r/a
0
1
2
3
ν_e^*

Fig. 4

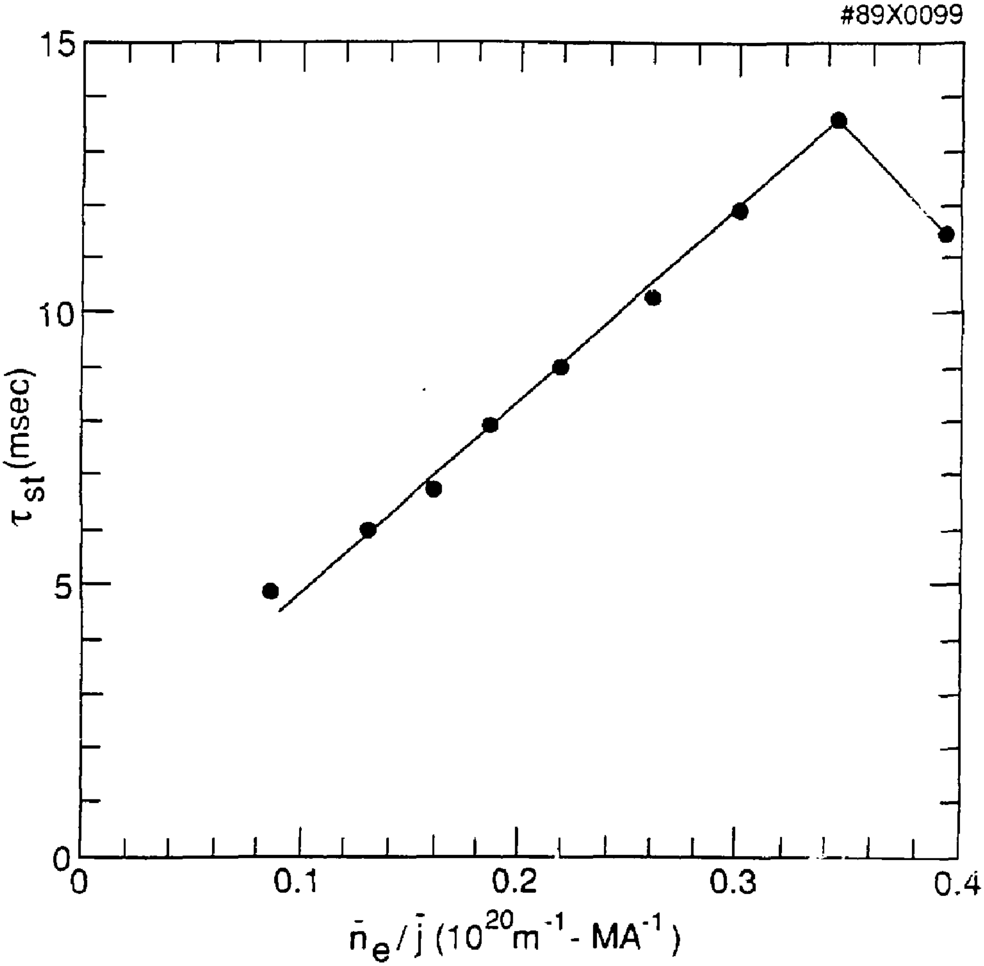
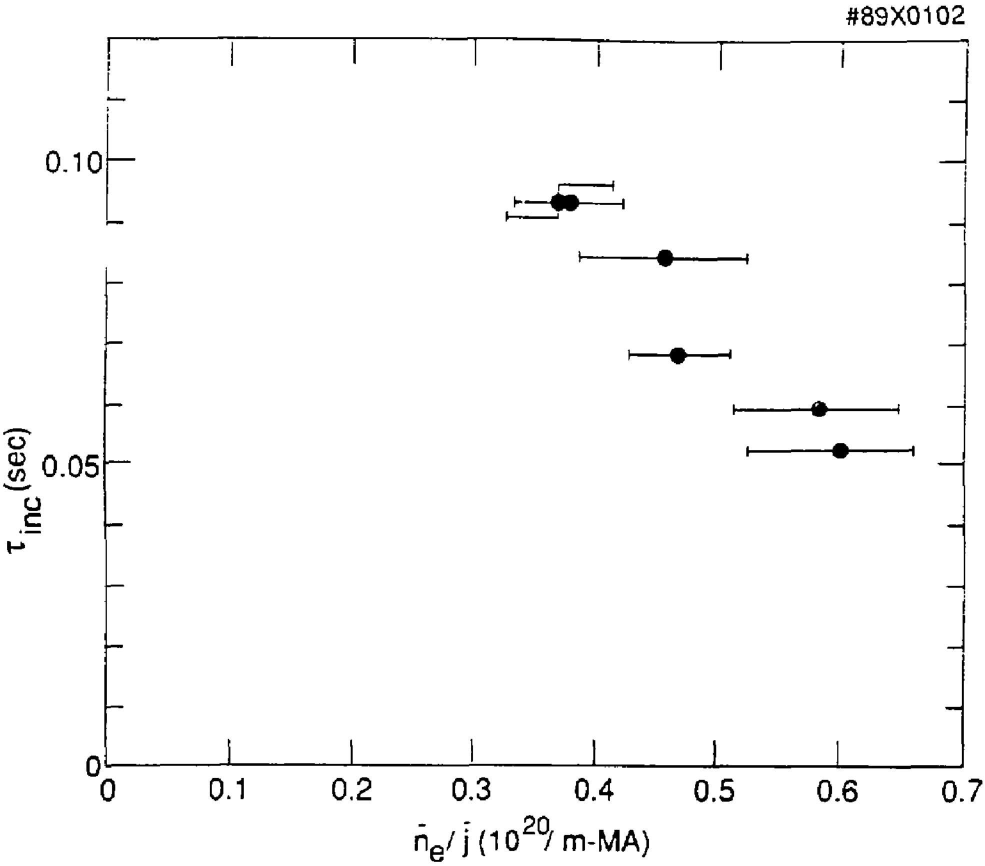


Fig. 5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0.10
0.05
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
τ_inc (sec)
n̄_e/ j̄ (10^20/ m-MA)

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