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By

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Enhancement of Confinement in Tokamaks

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Abstract

A plausible interpretation of the experimental evidence is that energy confinement in tokamaks is governed by two separate considerations: (1) the need for resistive MHD kink-stability, which limits the permissible range of current profiles -- and therefore normally also the range of temperature profiles; and (2) the presence of strongly anomalous microscopic energy transport near the plasma edge, which calibrates the amplitude of the global temperature profile, thus determining the energy confinement time τ_E. Correspondingly, there are two main paths towards the enhancement of tokamak confinement: (1) Configurational optimization, to increase the MHD-stable energy content of the plasma core, can evidently be pursued by varying the cross-sectional shape of the plasma and/or finding stable radial profiles with central q-values substantially below unity -- but crossing from "first" to "second" stability within the peak-pressure region would have the greatest ultimate potential. (2) Suppression of edge turbulence, so as to improve the heat insulation in the outer plasma shell, can be pursued by various local stabilizing techniques, such as use of a poloidal divertor. The present confinement model and initial TFTR pellet-injection results suggest that the introduction of a super-high-density region within the plasma core should be particularly valuable for enhancing $n\tau_E$. In D-T operation, a centrally peaked plasma pressure profile could possibly lend itself to alpha-particle-driven entry into the second-stability regime.

Introduction

The present analysis begins by identifying a hypothetical model of tokamak confinement that is designed to take into account the conflict between $T_e(r)$-profile shapes arising from microscopic transport and $J(r)$-profile shapes required for gross stability (Section 1). On the basis of this model, a number of hypothetical lines of advance are developed (Section 2). Some TFTR experiments that may point the way to a particularly attractive type of tokamak reactor regime are discussed in Section 3.

1. Confinement Model

The high quality of confinement that is already being achieved in tokamaks depends, first of all, on experimental operation in reasonably MHD-quiescent regimes. The usual practice is to let the central safety factor q(o) fall slightly below unity. Mild $m/n = 1$ sawtooth activity then limits the tendency of J(r) to peak at small r/a (driven by the neoclassical resistivity profile), while the rest of the J(r)-profile is allowed some latitude for stability against the higher m/n kink modes.

For a given J(r)-profile, Ohm's law specifies the steady-state profile of the normalized temperature $T_e(r)/T_e(o)$. [Neglecting $Z_{eff}(r)$ and neoclassical effects, this profile is simply $\{J(r)/J(o)\}^{2/3}$.] A second way to determine both the profile shape and the magnitude of $T_e(r)$ is on the basis of the heat-flow equation

$$-n\,\chi_e\, dT_e/dr = (1/r)\int_0^r dr_1\, r_1\, P_e(r_1) = \phi(r), \qquad (1)$$

where $P_e = P_{heat} - P_{rad}$ represents the net power input into the electrons and χ_e is the electron heat conductivity -- generally found to be anomalous and subject to a variety of physical interpretations. The $T_e(r)$-profile is now overdetermined, since the prescription of Eq. (1) will not, in general, coincide with the requirements for a kink-stable J(r)-profile. A logical resolution of this conflict is to assume that χ_e consists of two elements: a "microscopic," locally determined contribution χ_m, and a "macroscopic," globally determined contribution χ_s that shapes $T_e(r)$ so as to minimize MHD instability. A particularly conspicuous phenomenon of the latter type is the enhancement of χ_e by sawtooth activity in the central tokamak region.

The experimentally observed tendency of tokamak $T_e(r)$-profiles to fall within a fairly narrow range was pointed out in Ref. 1 as an important clue to the physical understanding of tokamak confinement. The explicit form of profile-consistency theory that is illustrated in Fig. 1 was developed independently by the authors of Refs. 2 and 3: The constraint on the J(r) and $T_e(r)$-profile shapes is related to the Δ'-limit for resistive kink stability,[4] and the role of Eq. (1) is reduced to calibrating the magnitude of $T_e(r)$ at some critical radius r_c, beyond which χ_m becomes dominant over χ_s. (In the presence of an outer separatrix, the situation is somewhat different; cf., Section 2.)

The immediate stimulus for the model of tokamak confinement illustrated in Fig. 1 was the experimental observation[5,6] of a systematic variation of $\chi_e(r)$ as a function of the power deposition profile $P_e(r)$. Particularly persuasive evidence in favor of the present model was provided by the discovery that the global τ_E is insensitive to the precise radius of auxiliary power deposition out to some critical point r_c that is apparently located just outside the $q = 2$ surface.

The main weakness of the model as a "physical explanation" of tokamak confinement is the lack of direct experimental evidence concerning the mechanism that is supposed to control the shape of $T_e(r)$ by way of $\chi_s(r)$. To be sure, in the case of large, sporadic MHD-phenomena such as the sawtooth and the magnetic reconnections occurring at higher m/n-values, there is a close correspondence between violation of the Δ'-criterion and spontaneous self-adjustment of the J(r)-profile.[7] Another hopeful feature is that the physically expected effect of MHD disturbances at $q(r_{mn}) = m/n$ is to reduce the gradients of T_e and J at r_{mn}, thus providing just the sort of theoretical mechanism that is needed to explain the profile-shaping transport χ_s. The experimental puzzle is that, even during apparently MHD-quiescent periods, Δ'-stable J(r)-profiles tend to maintain themselves against potentially destabilizing variations of $P_e(r)$. One fairly plausible explanation (cf. Section 1.2) is that the "local" transport χ_{in} tends to be larger near the low-order rational surfaces of the tokamak, thus making an inconspicuous MHD-stabilizing contribution to χ_s.

While a better understanding of the physical nature of χ_s would clearly be of great interest, the purposes of the present discussion can be served sufficiently well by the assumption that some mechanism acts to enforce Δ'-stable J(r)-profiles -- in accordance with experimental observation. The following two subsections spell out some further details of the overall confinement model.

1.1 Requirements for Gross Stability

The specification that Δ'-stability must be maintained is meaningful only if it helps to impose a fairly close constraint on the J(r)-profile. Reviewing this topic, one notes, first of all, that Ref. 4 was unable to find any resistive-kink-stable J(r)-profile within the q(o)-range of interest.

This deficiency was remedied in Ref. 8, by tailoring optimal J(r)-profiles to fit specific choices of q(o). In other words, the toroidal periodicity condition of the tokamak was found to be an essential stabilizing factor, not only for the m = 1, n = 1 mode (i.e., at the Kruskal-Shafranov limit), but also for higher order kinks -- notably for the m = 2, n = 1 mode. Reference 8 succeeded in finding a stable J(r)-profile with $q(o) \gtrsim 1$ and q(a) = 2.6. The peculiarity of the required profile shape was considered a drawback, since one expected that tokamak experimentalists would have to apply unusual techniques to realize the stable J(r)-profile in practice.

The present assumption of a self-serving χ_s-mechanism that seeks Δ'-stability, on the other hand, encourages highly specialized profile optimization. C.Z. Cheng[9] has developed a semiautomatic profile-search process where Δ' is computed for all modes up to m,n = 20, and certain local adjustments in dJ/dr are then made, designed to eliminate the residual unstable modes. As illustrated in Fig. 2, a typical search begins with a simple "cylindrical-type" profile (A) like those considered in Ref. 4, then specializes to take advantage of the toroidal periodicity (B and C), and finally arrives at a stable profile (D).

This technique has been used by Cheng to prove the existence of a one-parameter family of stable J(r)-profiles arbitrarily close to q(a) = 2, for q(o) = 1. [The nonexistence of stable solutions below q(a) = 2, for q(o) = 1, can be proved analytically.] This extreme example helps one appreciate the peculiar nature of the Δ'-constraint: On the one hand, the choice of J(r)-profile does not literally become unique, even at very low values of q(a); on the other hand, the stable J(r)-profiles become so specialized that barely visible deviations can induce major violations of the Δ'-limit.

A detail worth noting in Fig. 2 is the compound slope of J(r) in the edge region. To avoid high-m instability at q = m/n points located in the vacuum just outside r = a, the slope of J(r) near the very edge of the plasma must be kept within an appropriate constraint. This result may have some bearing on the ELM relaxation phenomenon observed in sharp-edged H-mode plasmas[10] -- which are further discussed in Section 2.

As the q(a)-value is raised well above 2, the degree of latitude for variation in J(r) obviously increases: The stable solution with the highest self-inductance is always provided by a J(r)-profile shape that would be stable even for $q(a) = 2$ -- scaled down in its radial extent in proportion to $[2/q(a)]^{1/2}$ and surrounded by a vacuum region that extends out to the new $r = a$ point. In addition, there is a range of lower inductance cases that have $J(r)$-profiles extending all the way out to $r = a$, with correspondingly relaxed shapes.

[The preceding discussion of Δ'-stability is specialized to nonreliance on stabilization by an external conducting shell. Present experiments are rarely equipped with sufficiently close-fitting shells to have much impact on Δ', but the potential of the wall-stabilization technique deserves to be kept in mind for the future. Its effectiveness will, of course, depend on the degree to which plasma rotation or active feedback control can compensate for the finite skin-relaxation time of a nonideal conducting shell.]

Figure 3 illustrates how the confinement model of Fig. 1 lends itself to the selection of a particular Δ'-stable $J(r)$-profile from a broader family of stable profiles (curves H, K, L). For simplicity, the $T_e(r)$-profiles in Fig. 3b are made proportional to $[J(r)]^{2/3}$. The heat-conduction equation (1) is assumed to limit dT_e/dr in the outer plasma shell, thus determining the magnitude of $T_e(r)$. The $T_e(r)$-profiles have therefore been calibrated according to a common dT_e/dr-limitation in the region between the arrows in Fig. 3a. The amplitude $T_e(o)$ is found to have its maximum Δ'-stable value for case (L). Since $T_e(r)$ in the plasma core is assumed to be limited by profile-shaping requirements, rather than by χ_m, one would expect that, for sufficiently strong central heating, $T_e(r)$ will rise to some marginally stable solution of type (L), independent of the detailed form of the power-deposition profile.

The marginal Δ'-stability of the tokamak $J(r)$-profile offers a possible explanation of the anomalously fast diffusion of heat pulses superimposed on the equilibrium $T_e(r)$. The speculation that the χ_s increment associated with heat pulses is due to the response of $J(r)$ to rapid changes in $T_e(r)$, however, is not quite so natural as the hypothesis of direct $T_e(r)$-profile consistency, where χ_s responds to the temperature perturbations themselves. One good way to address this issue is to use lower hybrid current drive[12] to decouple the $T_e(r)$ and $J(r)$-profiles from each other by nulling the loop voltage, and then proceed to study the latitude for independent variations of $T_e(r)$.

1.2 Heat Transport

According to Eq. (1), the gross energy confinement time τ_E of a profile-consistent tokamak plasma is determined by

$$\tau_E \propto [r_c^2/\chi_m(r_c)] \ [\langle n\rangle/n(r_c)]. \tag{2}$$

Since the magnitude of $T_e(r)$ is calibrated by the power flow through the outer shell, only the local value of $n\chi_e$ enters in Eq. (2). The plasma energy content, on the other hand, depends on an averaged density $\langle n\rangle \propto \int_0^a dr\ r\ T_e(r)/T_e(o)$ that emphasizes the plasma core. [For simplicity, this discussion has been ignoring the contribution of the plasma ions. Note that, since $T_i(r)$ has no direct relation to $J(r)$, the ion loss channel behaves somewhat independently, especially in unthermalized plasmas.]

From Eq. (2), it follows that "empirical confinement scaling laws" for tokamaks refer only to the scaling of transport in the outer plasma shell. This conclusion seems plausible, since changes at the edge of the tokamak plasma are sometimes found to have powerful impact on the empirical τ_E-value -- as in the H-mode[10] and Z-mode[13] experiments. Another consequence of Eq. (2) is that τ_E is unlikely to depend on the microscopic nature of the power input into the plasma core (i.e., whether the heating is ohmic, auxiliary or thermonuclear); direct interaction with the outer plasma shell, however, may well permit certain auxiliary-heating methods to enhance $\chi_m(r_c)$, thereby causing exceptionally strong degradation of τ_E.

As mentioned in the introduction to Section 1, an issue of particular physical interest is whether the locally determined $\chi_m(r)$ might not turn out to be an adequately competent Δ'-stability solver in its own right, thus making unnecessary the inclusion of a globally determined $\chi_s(r)$ -- except for occasional vigorous responses to gross Δ'-violations. For high q(a)-values, where the Δ'-constraint is not severely restrictive, a happy coincidence of this sort cannot be ruled out. For $q(a) < 3$, the implausibility of a coincidence increases -- unless the "local" χ_m at least takes some notice of the low-order rational surfaces. The identification of a Δ'-unrelated local transport mechanism that prescribes a specific $T_e(r)$-profile, though apparently being quite permissive in regard to variations of n(r), does present an interesting challenge to plasma theory -- especially since the

$T_e(r)$-profile must remain invariant over the whole range from low-density to high-density ohmic heating, as well as auxiliary heating. If we cannot invoke the sensitivity of χ_m to $d(nT)/dr$ or to $d \log T/d \log n$, there are not many interpretations left, except possibly in terms of $d\,\eta(T_e)/dr$.

The resistivity-gradient-driven rippling mode[14] would have an altogether catastrophic effect on tokamak confinement, were it not for the electron thermal conductivity along magnetic field $\chi_{e\parallel}$, which classical theory predicts to become extremely large at high T_e. Significant tokamak transport due to the rippling mode can be ruled out, on this basis, except very near the plasma edge ($T_e \lesssim 50$ eV) -- but the possibility that $\chi_{e\parallel}$ may actually be limited by nonlinear magnetic or electrostatic effects (thermal barriers?) perhaps deserves closer scrutiny. The somewhat mysterious topic of nonideal modes driven by anomalous electron viscosity also offers some opportunities for complex nonlinear effects.[4]

2. Enhancement of Confinement

The confinement model of Section 1 implies that there are two multiplicative τ_E-enhancement factors: (1) increase of the MHD-stable energy content in the plasma core; (2) improvement of thermal insulation in the outer shell. Various opportunities for advances in these two areas are discussed below.

2.1 Increased Energy Content in the Plasma Core

MHD-kink-stability considerations tend to limit the poloidal field strength B_p; there is normally also a stability limit for β_p, thus constraining the maximum plasma energy content. Special shaping of the plasma cross section is known to be helpful in raising both B_p and β_p. Theoretically, an additional benefit could be obtained by suppressing the $m/n = 1$ modes through a combination of equilibrium shaping and feedback control.[15] One can then identify $J(r)$-profiles with $q(o)$-values substantially below unity that are stable against all other kink modes.[16] The application of the profile-optimization technique of Ref. 9 to this problem has yielded stable solutions down to $q(o) = 1/2$ with $q(a) \to 1$. (Passage down through the $q(o) = 2/3$ point during current rise, however, may present special problems.) The experimental reality of the sub-Kruskal-Shafranov operation in the tokamak core has been demonstrated by direct measurements of J(r), as described in Ref. 17.

The "*first-stability*" *approach to maximizing plasma energy storage* has the attraction of drawing on an extensive data base, both in regard to MHD stability and transport phenomena. The main disadvantage is that increasing the plasma current -- particularly by special poloidal-field shaping techniques -- is undesirable from the point of view of reactor engineering: it raises the cost of the tokamak coil system and tends to preclude the possibility of efficient steady-state current drive.

The "second-stability regime,"[18,19] which offers very high beta values on the basis of high q(a) and moderate plasma shaping, is more attractive from the point of view of reactor potential. The main drawback, of course, is the present lack of relevant experimental data. Very high transient beta values have indeed been found in fast-pulsed tokamak experiments.[20] The surprisingly large Shafranov shifts (caused by energetic runaway electrons), which were measured on TM-3,[21] may indicate another possible experimental approach. Looking to the future, the PBX-M bean-shaping experiments[22] are designed to pass continuously from the first to the second-stability regime at beta values of about 10%.

An *intriguing type of high-beta tokamak solution is a kind of hybrid* stability regime,[23] with a low-beta, high-shear, first-stability region on the outside and a high-beta, low-shear, second-stability region within the plasma core. The experimental feasibility and advantage of this option will be discussed in Section 3.

2.2 Improved Heat Insulation in the Outer Shell

Divertor experiments[10,24] clearly show that improved global τ_E-values can be achieved by architectural improvements in the outer plasma shell. In terms of the Δ'-stability model discussed in Section 1.1, the following physical interpretation can be offered. For a fixed total plasma current, divertor plasmas have two basically different Δ'-stable J(r)-profile options: the usual L-mode profile, where dJ/dr is forced to become small toward the plasma edge, since dT_e/dr is depressed by the normal pattern of radially increasing $\chi_m(r)$;

and the H-mode "pedestal profile," where dT_e/dr remains large at the plasma edge -- perhaps by virtue of the strong shear near the separatrix, which may be limiting χ_m. Figure 4 illustrates what happens to the profile competition of Fig. 3 if the region of dT_e/dr limitation (lying between the arrows in Fig. 4a) is shifted slightly away from $r = a$, so that no limit is imposed on the gradient at the very edge of the plasma. Now the H-type profile allows the highest amplitude $T_e(r) \propto [J(r)]^{2/3}$ and provides the best τ_E-value. [Note that the preceding discussion suffers from the inconsistency that the Δ'-analysis of Ref. 9 is one dimensional, while the existence of a separatrix calls for a two-dimensional tokamak configuration. According to Ref. 25, the impact of the separatrix on the one-dimensional kink-stability results may not be very great; in any case a mild generalization of the stability-comparison theorem of Ref. 4 suggests that the separatrix effect can only be further stabilizing. A true two-dimensional resistive-kink-mode analysis, however, would clearly be desirable to reach quantitative conclusions.]

While the H-mode phenomenon encourages attempts at concrete physical understanding, the experimental tokamak literature also offers numerous τ_E-improvement effects that may well be "real," but defy simple interpretation -- for example the injection of high-Z impurities[13] and the electrostatic biasing of the tokamak limiter. An experimental approach that might be helpful both for physical understanding and improved confinement, would be to take advantage of the multi-tile graphite-limiter technique to wire up alternate tiles as electrostatic sensors and feedback-controlled electrodes. If the presence of electrostatic convective cells at the plasma edge is contributing to anomalous transport, a suitable feedback-control scheme might prove cost-effective.

Yet another approach to the improvement of heat insulation in the outer shell is simply to lower the plasma density. In strongly heated tokamak regimes, χ_m is either insensitive to n or inversely proportional, as in the case of Goldston's $\chi_m \propto d\,\beta_p/dr$ (obtained by eliminating the heating-power dependence), so that the heat outflow diminishes as n^2 for a given dT_e/dr. This approach is discussed further in the next section.

3. Dense-Core Tokamaks

The substitution of pellet-fuelling for gas-fuelling has produced significant improvements in confinement in a number of tokamak experiments, notably Refs. 16 and 27. Recent pellet-injection experiments in TFTR[28,29] have achieved high central densities and surprisingly large ratios of $n(o)/\bar{n}$. As illustrated in Fig. 5, the relaxation of the central density hump is quite slow -- apparently corresponding to values of $n(o)\ \tau_p(o)$ of order $\gtrsim 3 \cdot 10^{14}$ cm^{-3} sec. These experimental observations have stimulated renewed interest in the $\langle n\rangle/n(r_c)$-factor contained in the τ_E-scaling formulation of Eq. (2).

Figure 6 outlines in simplified form a profile-shaping strategy that promises to achieve substantial enhancements of fusion power P_F relative to the plasma heat loss P_L. To appreciate the logic of this strategy, it is useful to carry out a Gedankenexperiment that begins with the TFTR high-temperature mode. Extrapolating from present experimental results,[30] full-power TFTR operation should be able to reach $T_i(o) \gtrsim T_e(o) \sim 10$ keV using a normal density profile with $n(o) \sim 5 \cdot 10^{13}$ cm^{-3} -- even if $\chi_m(r_c)$ continues to follow Goldston low-mode scaling. Introducing a central density hump n^* while maintaining the standard $T(r)$-profile should have no effect on the power outflow P_L, while increasing the fusion power P_F by a factor roughly proportional to $\int_0^a dr\ r\ n^2\ T^2$. We thus obtain an enhancement of $Q \equiv P_F/P_L$ by the factor

$$Q^*/Q \ = \ (n\tau_E)^*/n\tau_E \ = \ f_p\ [n^*(o)/n(o)]^2, \qquad (3)$$

where the proportionality constant $f_p < 1$ reflects the slightly different $rT^2(r)$-weighted integrals for P_F^* and P_F. If the central density in Fig. 6 is set at $n^*(o) \sim 2\text{-}3 \cdot 10^{14}$ cm^{-3}, as in the TFTR pellet-injection mode of Fig. 5, while $T(r)$ is kept the same as in the low-density mode, the enhancement factor indicated by Eq. (3) could amount to an order-of-magnitude increase of $n(o)\tau_E$: from $\sim 10^{13}$ cm^{-3} sec to $\sim 10^{14}$ cm^{-3} sec.

Based on the present confinement model and experimental evidence concerning tokamak particle transport, the $n(r)$ and $T(r)$-profiles shown in Fig. 6 seem a natural choice. In the central region 1, the density is very high, but since there are virtually no gradients, there is little transport. Region 2 is characterized by large d log n/dr, but central-region particle confinement is notoriously good in tokamaks -- at least in part because of a self-pinching phenomenon. In region 3 there are gentle gradients of n and T, with the temperature profile calibrated according to the model of Fig. 1 by the local magnitudes of χ_m and n at r_c. Finally, at the very edge of the plasma there is another region of large d log n/dr, but since the temperature is very low in region 4 the transport is limited.

To follow the plan of Fig. 6 in actual TFTR experiments, one would probably not start with the high-temperature regime, but rather would raise the central density of a low-$\bar{n}$ ohmic-heated plasma by pellet injection, and then apply auxiliary heating to both the inner and outer plasma while preserving a Δ'-stable $T_e(r)$ profile. Initial neutral-beam experiments show that $T_e(o)$ tends to lag behind in this process, so that some form of penetrating rf-heating power will be important. To extend the regime of Fig. 6 from a transient TFTR experiment to quasi-steady-state tokamak-reactor operation will be technologically challenging, but the combination of ultra-high-velocity pellet injection and efficient edge pumping should be able, in principle, to do the job.

Reaching $n\tau_E$-values of order 10^{14} cm^{-3} sec in TFTR by the dense-core strategy is marginally compatible with a Troyon-type beta-limitation, the relevant consideration being $[<\beta^2>]^{1/2}$, rather than the volume-average $<\beta>$. If one seeks to raise n* still further, or if the available heating power is enhanced by a significant thermonuclear contribution, so as to raise both T(o) and dT/dr at r_c, then MHD beta limitations will become a principal obstacle to further Q-enhancement. In this context, the idea of entering the second-stability regime within a centrally localized high-beta region (cf. Section 2.1) would fit in rather well. Relevant stability calculations are currently being carried out by A.M. Todd[23] and also by J.J. Ramos.[31] Internal kink-stability is expected to be the main beta-limiting factor, as well as the main driver of special requirements for the J(r)-profile.

While plans for entry into the second-stability regime must be considered quite speculative at this point, there are near-term prospects for testing the reality of the dense-core approach to the enhancement of tokamak confinement.

Neutral-beam-heating experiments using low-$\bar{n}$, high-n(o) TFTR plasmas will either demonstrate the projected improvement of $n\tau_E$ relative to normal low-mode scaling, or else will reveal new anomalies, beyond the present tokamak confinement model.

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Figure Captions

1. Illustration of the necessary compromise between the "natural" $T_e(r)$-profile and the constraint of Δ'-stability.

2. The search for Δ'-stable $J(r)$-profiles begins with curve (A) and seeks to eliminate the listed m/n-unstable modes, arriving at the stable profile (D).

3. Given a family of Δ'-stable $J(r)$-profiles H, L, and K with the same values of q(o) and q(a), one can identify the L-profile as having the highest $T_e(r) \propto J(r)^{2/3}$ on the basis of a common calibration: a constraint on the maximum allowable gradient dT_e/dr within the outer region between the arrows in (a).

4. When the profile comparison of Fig. 3 is repeated with the region of dT_e/dr-calibration narrowed as indicated in (a), the highest $T_e(r) \propto J(r)^{2/3}$ is reached by the H-profile.

5. Density and temperature profiles in the TFTR ohmic-heating regime, following injection of three pellets.

6. The dense-core tokamak concept is designed to maximize $n\tau_E$ by combining the Δ'-constrained $T(r)$-profile with an optimal choice of the unconstrained $n(r)$-profile.

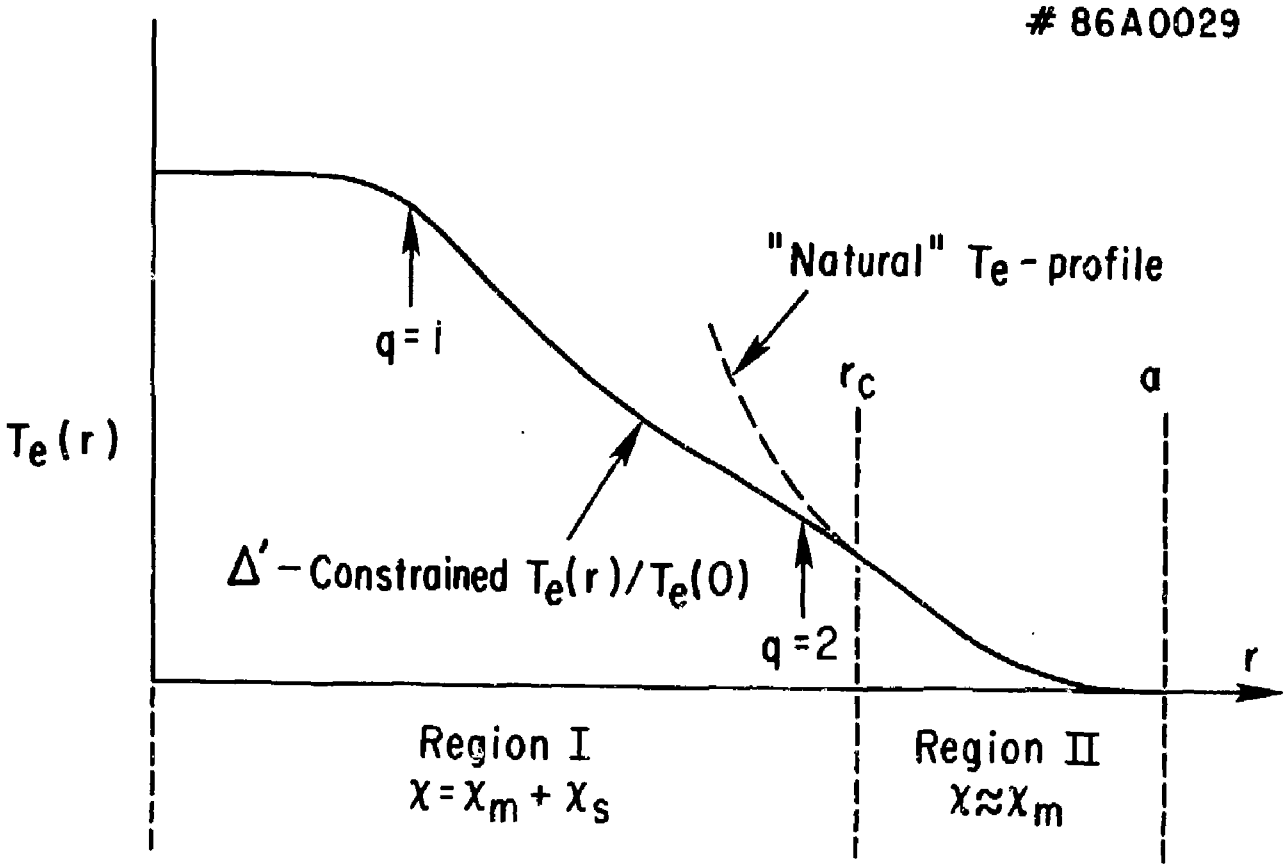
86A0029
$T_e(r)$
$q = 1$
"Natural" T_e - profile
r_c
a
Δ' - Constrained $T_e(r)/T_e(0)$
$q = 2$
r
Region I
$\chi = \chi_m + \chi_s$
Region II
$\chi \approx \chi_m$

FIGURE 1

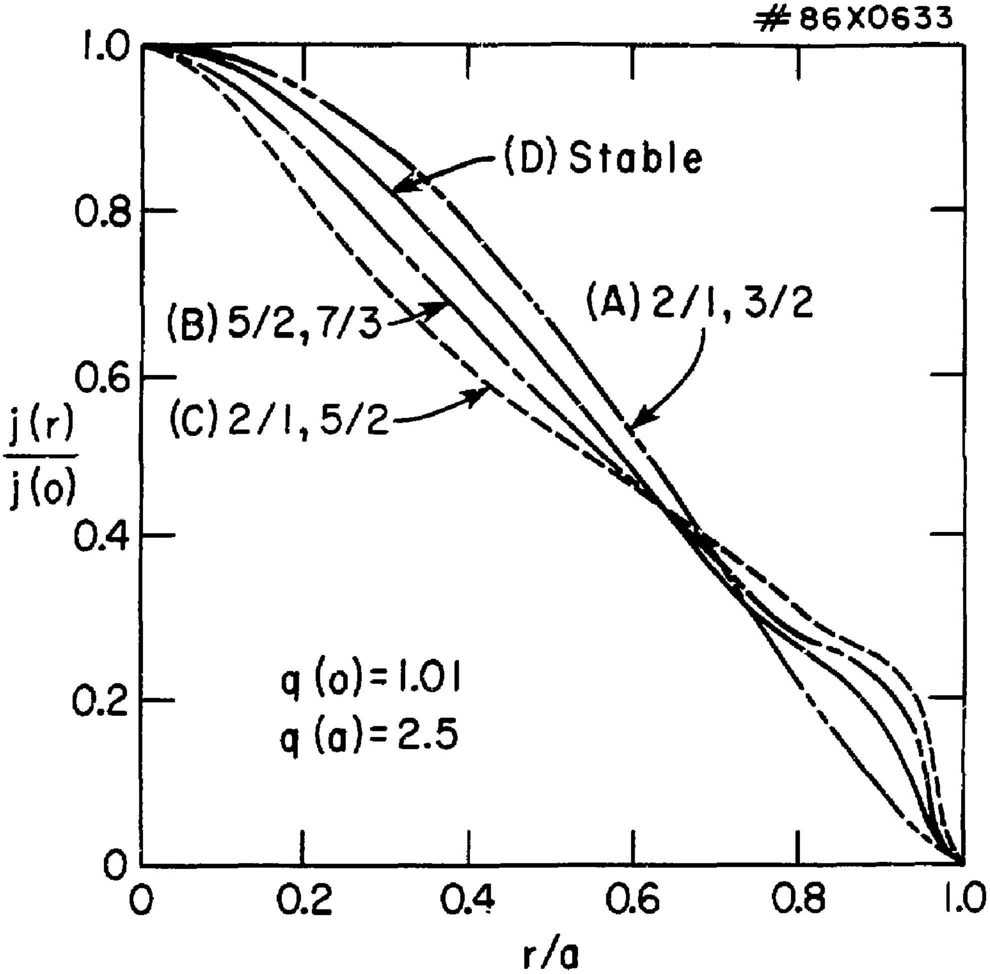
#86X0633
(D) Stable
(A) 2/1, 3/2
(B) 5/2, 7/3
(C) 2/1, 5/2
q (o) = 1.01
q (a) = 2.5
j (r) / j (o)
r/a
0
0.2
0.4
0.6
0.8
1.0

FIGURE 2

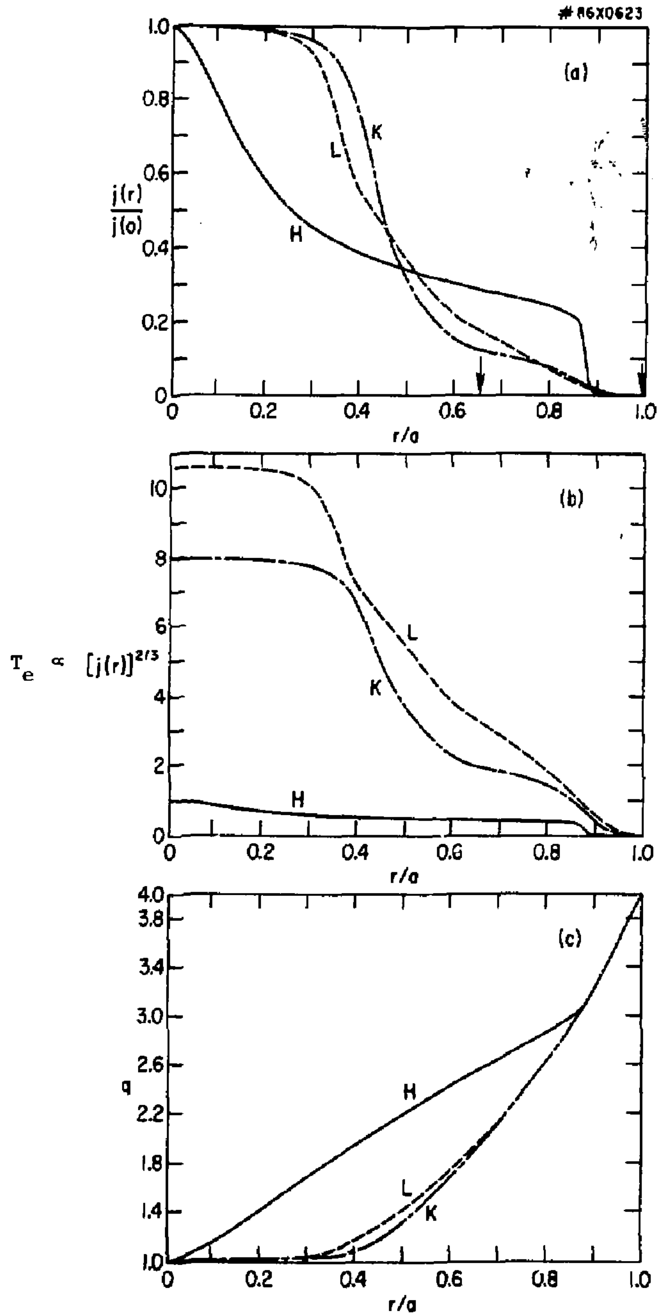
#86X0623
(a)
j(r)/j(o)
1.0
0.8
0.6
0.4
0.2
0
H
L
K
0
0.2
0.4
0.6
0.8
1.0
r/a
(b)
T_e ∝ [j(r)]^{2/3}
10
8
6
4
2
0
L
K
H
0
0.2
0.4
0.6
0.8
1.0
r/a
(c)
q
4.0
3.8
3.4
3.0
2.6
2.2
1.8
1.4
1.0
H
L
K
0
0.2
0.4
0.6
0.8
1.0
r/a

FIGURE 3

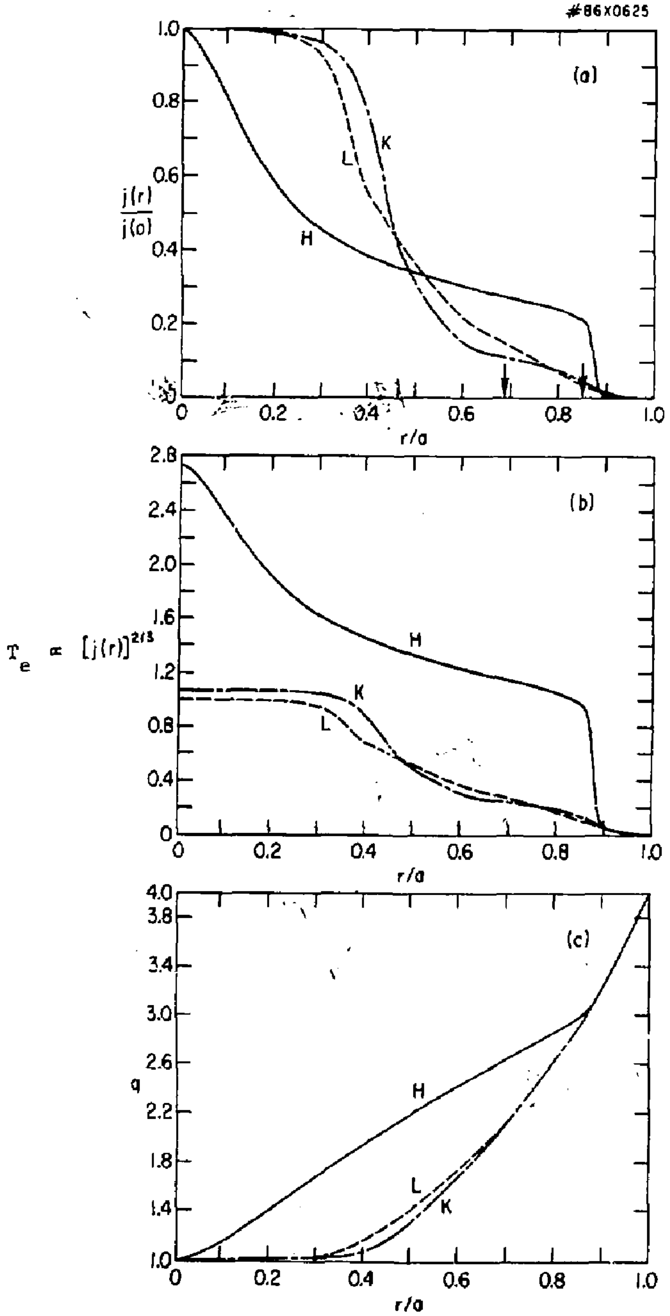
#86X0625
(a)
$\frac{j(r)}{j(o)}$
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
r/a
H
L
K
(b)
$T_e \propto [j(r)]^{2/3}$
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0
0.2
0.4
0.6
0.8
1.0
r/a
H
K
L
(c)
q
4.0
3.8
3.4
3.0
2.6
2.2
1.8
1.4
1.0
0
0.2
0.4
0.6
0.8
1.0
r/a
H
L
K

FIGURE 4

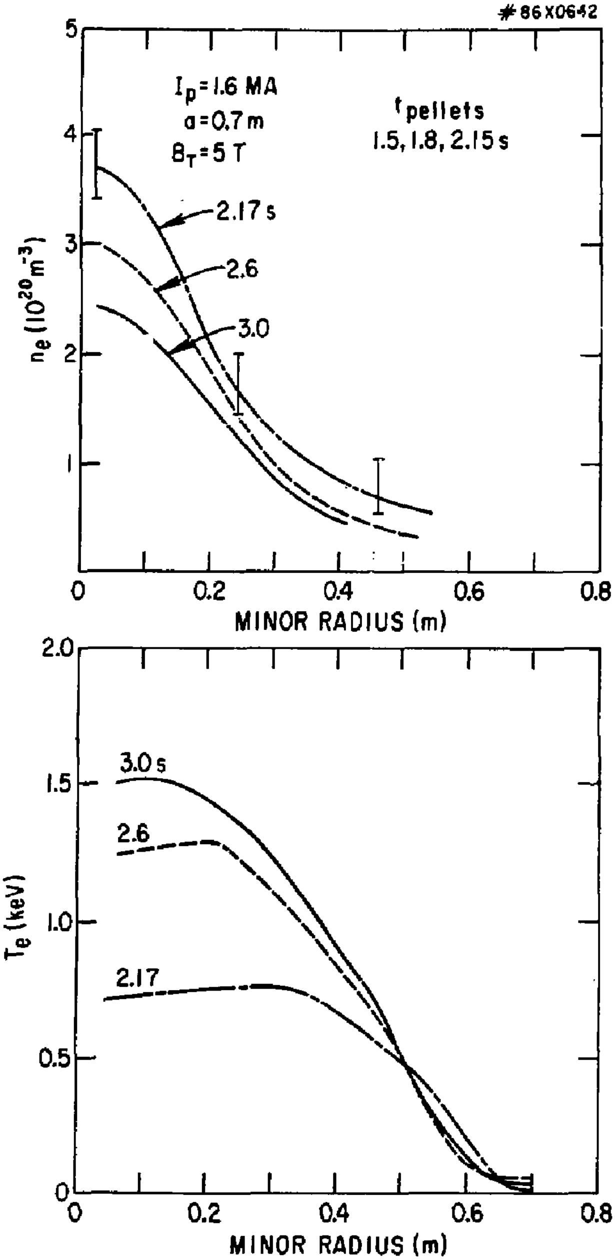
#86X0642
I_p = 1.6 MA
a = 0.7 m
B_T = 5 T
$t_{pellets}$
1.5, 1.8, 2.15 s
2.17 s
2.6
3.0
n_e (10^{20} m^{-3})
5
4
3
2
1
0
0.2
0.4
0.6
0.8
MINOR RADIUS (m)
3.0 s
2.6
2.17
T_e (keV)
2.0
1.5
1.0
0.5
0
0
0.2
0.4
0.6
0.8
MINOR RADIUS (m)

FIGURE 5

#86A0028

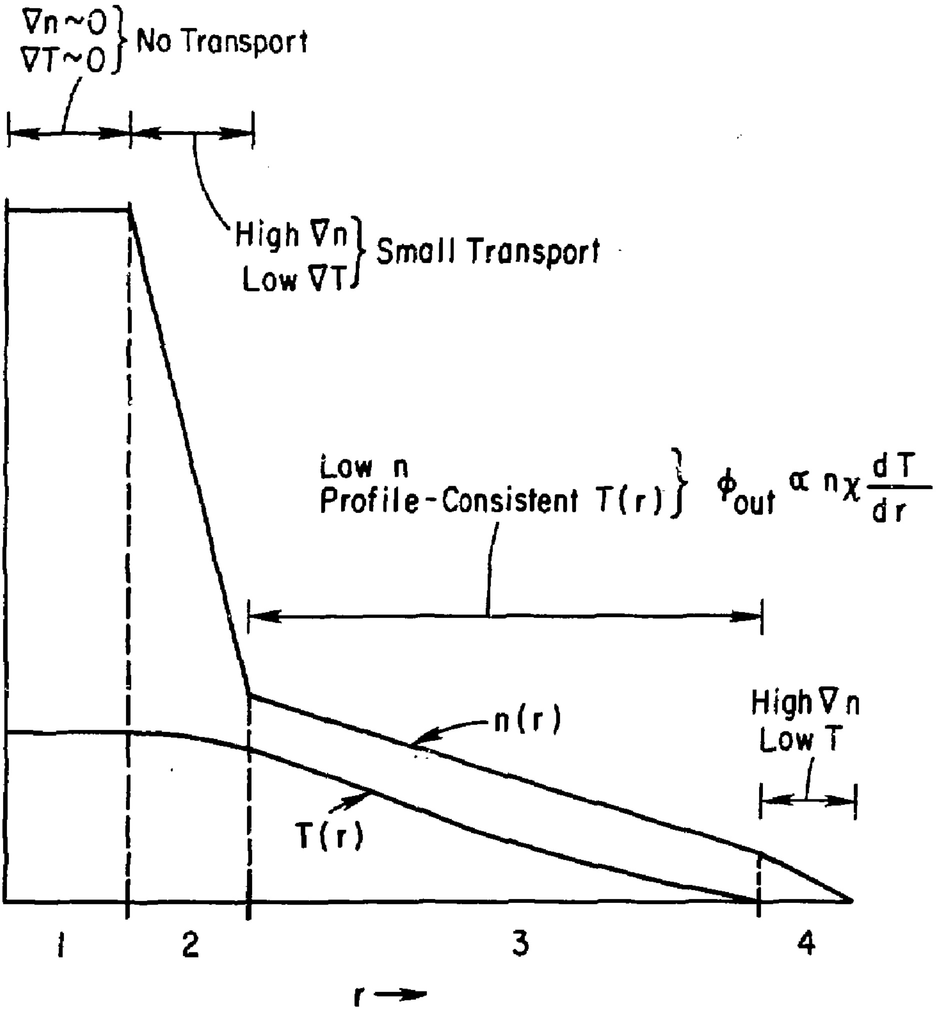

FIGURE 6

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