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INITIAL CONFINEMENT STUDIES OF OHMICALLY HEATED PLASMAS IN THE TOKAMAK FUSION TEST REACTOR

By

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ABSTRACT

Initial operation of the Tokamak Fusion Test Reactor (TFTR) has concentrated upon confinement studies of ohmically heated hydrogen and deuterium plasmas. Total energy confinement times (τ_E) are 0.1 - 0.2 s for a line-average density range ($\bar{n}_e$) of 1 - 2.5 x 10^{19} m^{-3} with electron temperatures of $T_e(o) \sim 1.2 - 2.2$ keV, ion temperatures of $T_i(o) \sim 0.9 - 1.5$ keV, and $Z_{eff} \sim 3$. A comparison of PLT, PDX, and TFTR plasma confinement supports a dimension-cubed scaling law.

The initial operation of the Tokamak Fusion Test Reactor (TFTR)[1] with a major radius (R) of 2.5 m and a minor radius (a) of 0.68 m offers an opportunity to study the confinement of ohmically heated plasmas and to test confinement size scaling developed from previous smaller tokamaks ($R \leq 1.5$ m and $a \leq 0.44$ m).[2-9] Confinement studies in ohmically heated discharges have been carried out with a toroidal magnetic field (B_ϕ) of 2.7 T, plasma currents (I_p) of 500-800 kA, and safety factors q(a) of 3.0 - 5.0, with fixed position carbon limiters. After vessel and limiter conditioning with pulsed and glow discharge cleaning, the line-average electron densities $\bar{n}_e = 0.9 - 2.5 \times 10^{19}\ m^{-3}$ were achieved with a peak Murakami parameter $\bar{n}_e R/B_\phi = 2.3 \times 10^{19}\ m^{-2}T^{-1}$.[10]

For a typical deuterium discharge, the time evolutions of the plasma current, surface voltage, and of the electron temperatures near the geometrical center of the outermost plasma flux surface at R = 2.48 m and at R = 2.22 m are shown in Fig. 1 ($\bar{n}_e = 2.7 \times 10^{19}\ m^{-3}$). The total discharge duration is 2.0 s, with the first 1.6 s shown here. In TFTR the feedback systems control the plasma current, position, and electron density. During the constant-current phase of the discharge, the loop voltage decreases to ~ 1 V with an e-folding time of approximately 0.3 s, which corresponds to the current penetration time due to the plasma conductivity.

The central electron temperature stops rising when the sawtooth activity begins, as in most other ohmically heated tokamaks. However, the temperature outside the q = 1 surface (r = 0.15-0.2 m from the magnetic axis) increases slowly with time. This increase in stored energy coupled with the falling loop voltage (and approximately constant Z_{eff}) results in an increase in the electron energy confinement time during the constant-current portion of the plasma discharge. These electron temperatures are ascertained from the measurement of the blackbody ordinary-mode fundamental electron-cyclotron emission by a calibrated fast scanning heterodyne receiver. This instrument provides a measurement of the temperature profile from the geometrical plasma center to the plasma inner edge at R = 1.82 m every 4 ms. The magnetic axis is near R ≅ 2.55 m. The peak temperature measurements are corroborated by temperature measurements obtained from pulse-height analysis (PHA) of the soft X-ray spectrum in the energy range 1 - 10 keV. Agreement of the two measurements is better than 20% for all plasma discharges during the initial operating phase of TFTR and typically $T_e(o) \sim 1.2 - 2.2$ keV.

Impurity K_α lines of chlorine, iron, nickel, copper, and the enhancement of the continuum due to impurity recombination and bremsstrahlung are observed in the soft X-ray spectrum. From the intensity of the K_α lines the concentration of these impurities is obtained. From these impurity concentrations and the enhancement of the continuum, the concentration of the light impurities (i.e., oxygen or carbon) and Z_{eff} are deduced. For the deuterium discharge shown in Fig. 1, the resulting Z_{eff} is 3.0 and is typically 2.5 - 4.0. Furthermore, the impurity line intensities provide an estimate of iron concentration $n_{Fe}/n_e < 10^{-3}$ and oxygen $n_O/n_e \sim 2 \times 10^{-2}$. The measurement of the radial profile of visible bremsstrahlung emission at 5230 Å provides a combined profile measurement of Z_{eff}, n_e, and T_e.[11] Assuming $Z_{eff}(r)$ is constant, Z_{eff} can be estimated using $\bar{n}_e$ and $T_e(r)$. These estimates of Z_{eff} agree with those obtained from PHA to within 20%. With the same assumption of a flat $Z_{eff}(r)$ profile, the density profile determined from the visible bremsstrahlung emissivity is generally found to be parabolic in shape, but sometimes has a flat center. The total radiation loss from the plasma is measured with a wide angle bolometer and is in the range of 50-75%.

Central ion temperatures were measured from the energy spectra of charge exchange neutrals, and by neutron counting in deuterium discharges with ^{235}U and ^{3}He detectors. Figure 2 compares these ion temperatures with a calculation based upon an analysis of the plasma energy balance that assumes neoclassical ion heat conduction.[12] The charge-exchange energy spectrum has been corrected for reabsorption of neutrals, and therefore the ion temperature is 15% higher than obtained directly from the slope of the measured energy spectrum. The deuteron density is estimated from $\bar{n}_e$ and Z_{eff} in order to determine the ion temperature from the neutron flux. The peak neutron flux in this discharge was 3×10^{11} n/s. Near equilibration of electrons and ions ($T_e \simeq T_i$) is observed at a density of $\bar{n}_e \sim 2 \times 10^{19}$ m^{-3} in this deuterium discharge. Because the electron and ion temperature difference is small and the uncertainty in the temperature measurements is ± 20%, it is possible to specify the ion confinement time only within the range of 0.5-2.0 s and the ion conduction loss to within 0-4 times neoclassical, assuming classical electron-ion heat transfer.[12]

Presently, there are a number of confinement scaling laws that are considered in the design of tokamaks. Jassby et al.[2] developed the size scaling $\tau_E \propto \bar{n}_e a^2 q^{0.5}$ for ohmically heated plasmas which was later simplified ($\tau_E \propto \bar{n}_e a^2$), and referred to as INTOR scaling.[13] More recently, a regression analysis of tokamak confinement data for ohmic heating by Pfeiffer and Waltz[3] suggested a strong major radius scaling for confinement $\tau_E \propto \bar{n}_e^{0.9} R^{1.91} a^{1.14} Z_{eff}^{0.14}$. The Alcator C group[8] studied the confinement of ohmically heated plasmas with different major and minor radii and essentially confirmed the size scaling of Pfeiffer and Waltz ($\tau_E \propto \bar{n}_e R^{2.04} a^{1.04}$).

The plasma power balance and energy confinement of TFTR have been analyzed by the time-dependent transport analysis code, TRANSP.[14] This code infers tokamak transport by analyzing the experimental data in terms of a one-dimensional magnetic-field-diffusion equation, and the particle and energy conservation equations. $T_e(r,t)$, $\bar{n}_e(t)$, $V_L(t)$, $I_p(t)$, and Z_{eff} are used as input data, $n_e(r)$ is taken to be parabolic, and the ion conduction loss is taken to be neoclassical.[12] Approximately 30 plasma discharges representing some 16 conditions were investigated with TRANSP.

Total energy confinement is defined as $\tau_E = (E_e + E_i)/(P_{OH} - \dot{E})$, where E_e and E_i are the total stored energy in the electrons and ions, respectively, P_{OH} is the net ohmic heating power corrected for inductive effects, and $\dot{E}$ is the time rate of change of the plasma energy. This definition does not remove radiation losses. (Removing them would give a higher confinement time estimate.) A variation of the plasma parameters within the known accuracy of the measurements indicates that the possible error in the total energy confinement time is ± 20%.

The TRANSP analysis of the TFTR plasma discharges indicated that the total energy confinement is 0.1 - 0.19 s for the density range $\bar{n}_e \sim 1\text{-}2.5 \times 10^{19}\ m^{-3}$. These confinement times are calculated at 1.6 s into the plasma discharge, so the plasma is near equilibrium and the inductive and time-rate-of-change corrections are less than 5%. The confinement characteristics of hydrogen and deuterium plasmas cannot be distinguished. This initial TFTR ohmically heated plasma confinement data base is combined with that of PLT[15,16] and PDX[17] to test the confinement predictions of various size scaling laws. PLT data are particularly helpful, because at high density, $\bar{n}_e > 8 \times 10^{19}\ m^{-3}$, confinement times were as long as 0.12 s. There is, therefore, an overlap in confinement times of TFTR and PLT plasmas. In addition, PLT at high density has values of $\bar{n}_e R^2 a$ and $\bar{n}_e a^2$, which are comparable to those in TFTR.

A comparison of this ohmic data base with $\bar{n}_e a^2$ is shown in Fig. 3 along with the INTOR scaling prediction. On this linear plot, $\bar{n}_e a^2$ scaling is not well supported and, in particular, INTOR scaling cannot predict the results.

A comparison of the data base with $\bar{n}_e R^2 a$ scaling is shown in Fig. 4. The solid line is the $\tau_E = 0.192\ \bar{n}_e R^{2.04} a^{1.04}$ (MKS) empirical scaling of the Alcator C group, which was derived from a fit to the confinement results of many tokamaks.[8] On the linear scale, the agreement is quite good. Specifically at $\bar{n}_e R^2 a \sim 6 \times 10^{19}$, both PLT and TFTR have the same confinement. However, PLT, TFTR, and PDX have nearly the same aspect ratios, R/a, and therefore, it is not possible to differentiate among R^2a, R^3, Ra^2, or a^3 scalings. It is not surprising that T-11 scaling[6] also fits the data ($\tau_E \propto \bar{n}_e R^{17/6} q^{7/6} (a/R)^{5/24} B^{-1/3}$). The TFTR-PLT-PDX data base is clearly inconsistent with dimension-squared scaling, but rather indicates a dimension-cubed scaling law. For densities up to 2.5×10^{19} m^{-3} the energy confinement of the TFTR plasmas does not saturate with increased density. The neoclassical Z_{eff} of plasmas with the same $\bar{n}_e$ in the PLT and TFTR are comparable. A comparison of the quantity $\tau_E/\bar{n}_e$ vs Z_{eff} for both tokamaks indicates no clear dependence of τ_E on Z_{eff}.

In conclusion, the TFTR tokamak has successfully operated during its initial period of ohmic heating experiments and has provided new information on plasma confinement. Tokamak plasma confinement has been longer than previously observed (τ_E up to 0.19 s). These discharges offer a favorable target plasma for neutral beam heating experiments, which are expected to begin in the summer of 1984. Future ohmic heating experiments with a movable limiter will investigate the explicit form of dimension-cubed size scaling and study confinement at higher densities and currents, and in larger plasmas ($B_\phi = 5$ T, $I_p = 2.5$ MA, and $a = 0.83$ m).[7,15,18]

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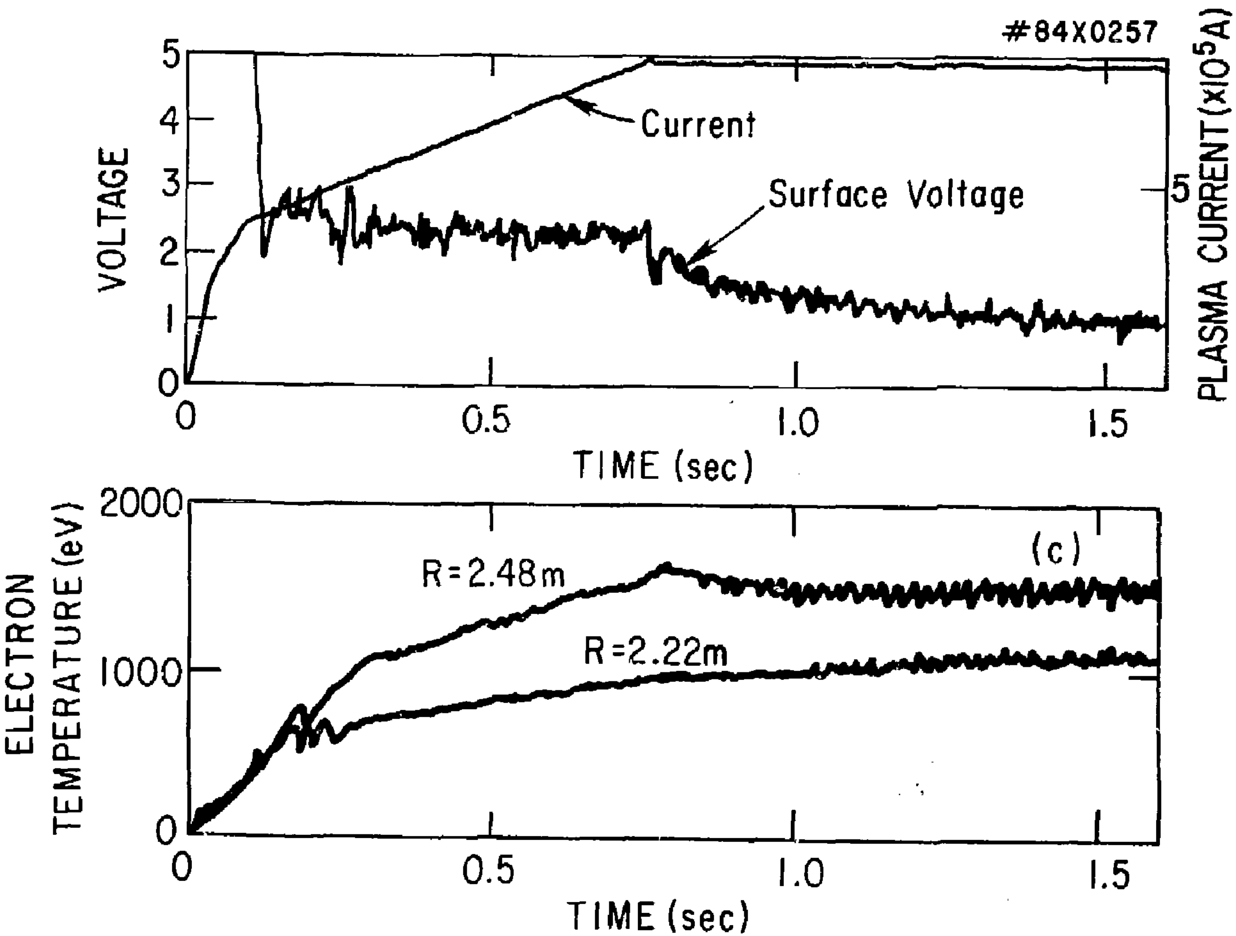
Figure Captions

Fig. 1 The time evolution of the surface voltage, plasma current, and the electron temperature at two different positions (R = 2.48 and 2.22 m).

Fig. 2 A comparison of the ion temperature ascertained from charge exchange and neutron-flux measurements and the ion temperature calculated from the plasma power balance assuming neoclassical ion conduction loss.

Fig. 3 Confinement time vs $\bar{n}_e a^2$ for PLT-PDX-TFTR ohmic confinement results. The predictions of INTOR scaling are included.

Fig. 4 Confinement time vs $\bar{n}_e R^{2.04} a^{1.04}$ for PLT-PDX-TFTR ohmic confinement results. The predictions of the Alcator C scaling law are represented by the straight line.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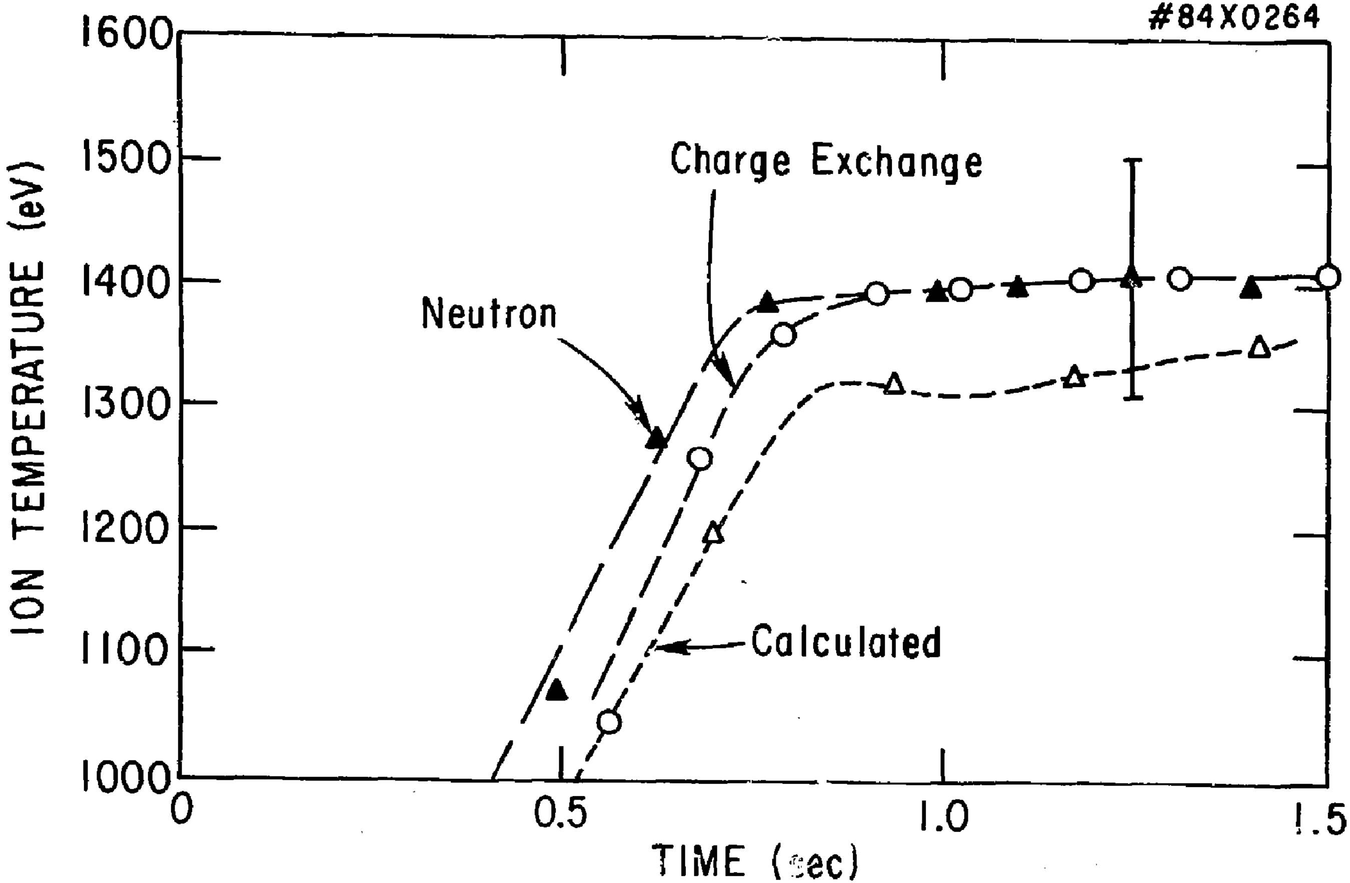
VOLTAGE
PLASMA CURRENT(x10^{5}A)
Current
Surface Voltage
TIME (sec)
ELECTRON TEMPERATURE (eV)
R=2.48m
R=2.22m
(c)
TIME (sec)

Fig. 1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1600
1500
1400
1300
1200
1100
1000
ION TEMPERATURE (eV)
0
0.5
1.0
1.5
TIME (sec)
Charge Exchange
Neutron
Calculated

Fig. 2

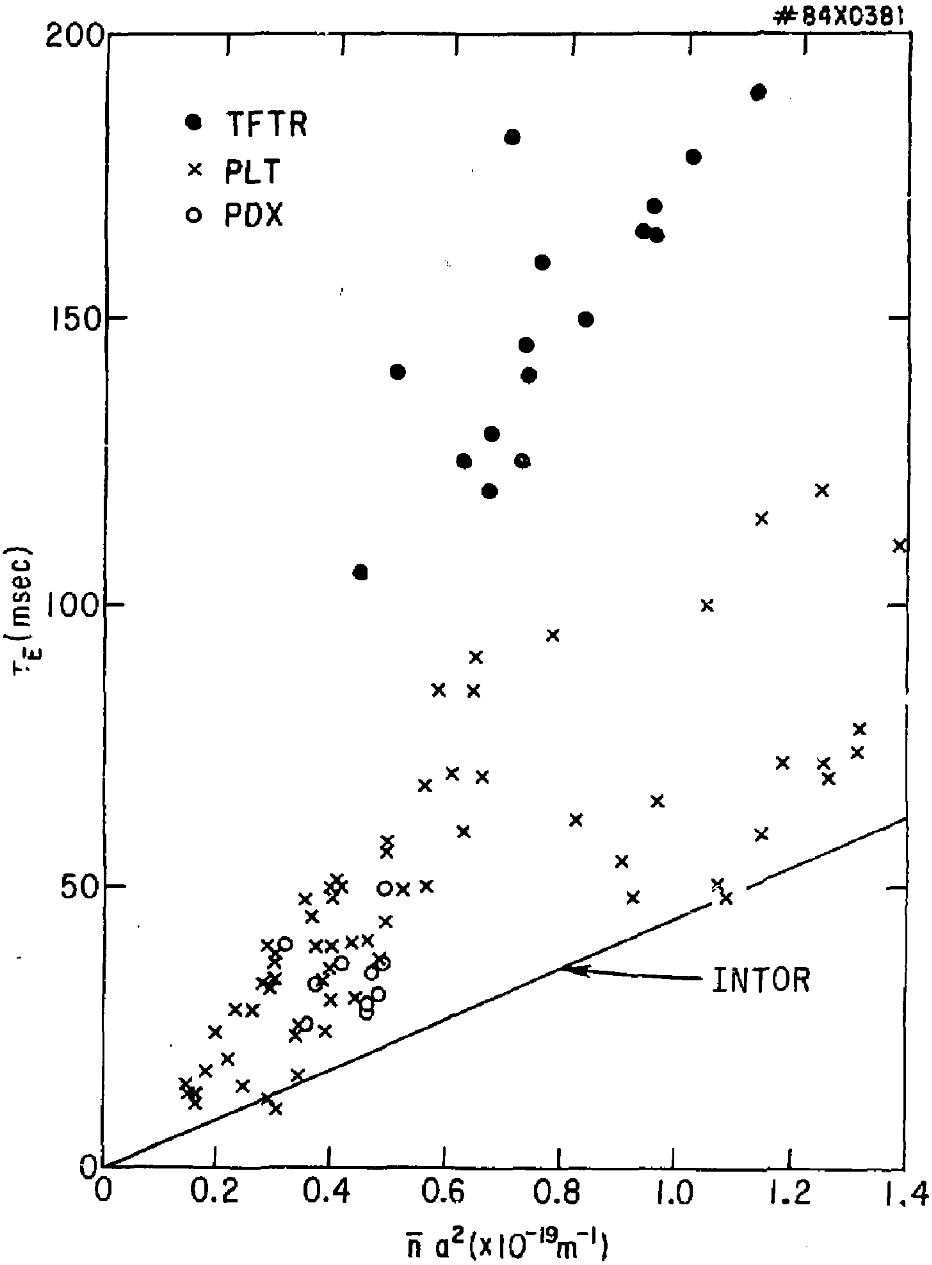
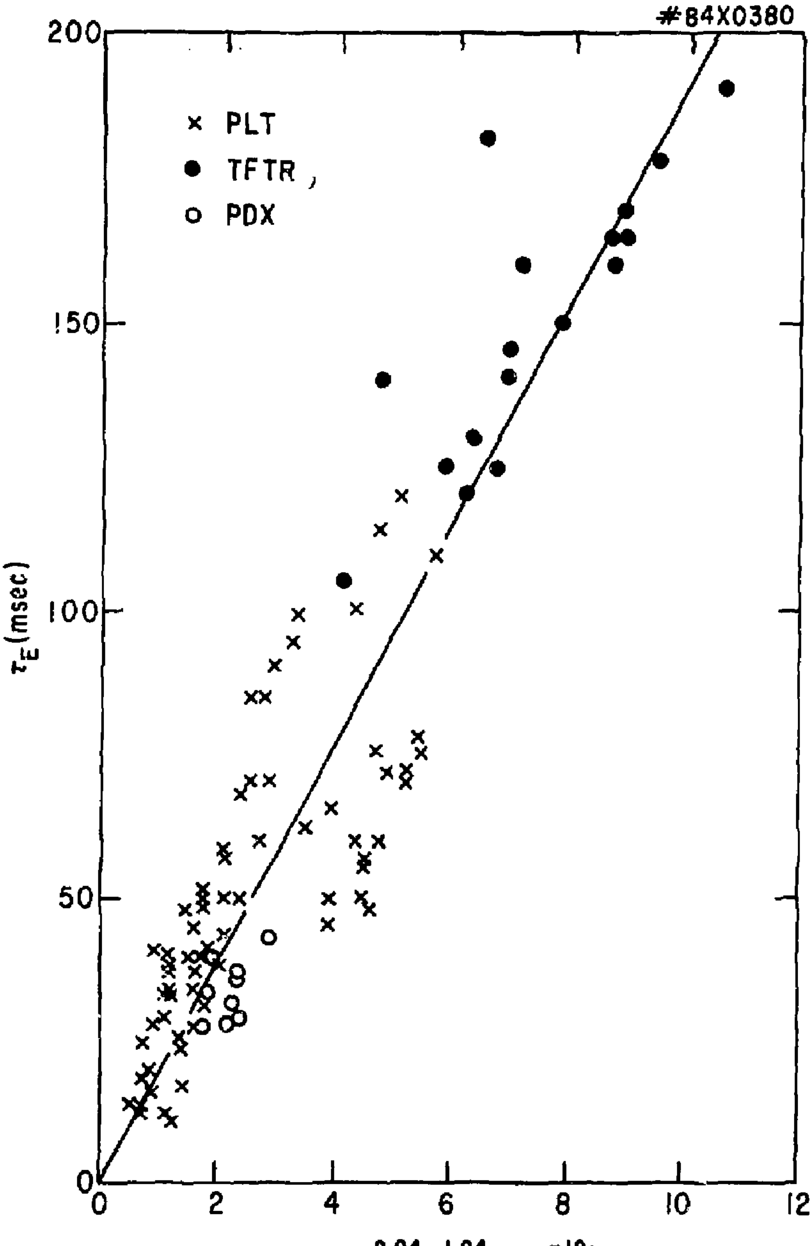

#84X0381
TFTR
PLT
PDX
INTOR
τ_E (msec)
$\bar{n}\,a^2 (\times 10^{-19} m^{-1})$
0
50
100
150
200
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Fig. 3



#84X0380
× PLT
● TFTR
o PDX
τ_E (msec)
200
150
100
50
0
0
2
4
6
8
10
12
$\bar{n}\,R^{2.04}\,a^{1.04}\,(\times 10^{-19})$

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