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EMPIRICAL SCALING FOR PRESENT
OHMIC HEATED TOKAMAKS

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EMPIRICAL SCALING FOR PRESENT
OHMIC HEATED TOKAMAKS

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ABSTRACT

Empirical scaling laws are given for the average electron temperature and electron energy confinement time as functions of plasma current, average electron density, effective ion charge, toroidal magnetic field, and major and minor plasma radius. The ohmic heating is classical, and the electron energy transport is anomalous. The present scaling indicates that ohmic heating becomes ineffective with larger experiments.

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INTRODUCTION

The construction of the Adiabatic Toroidal Compressor has been described previously,¹ and experiments on plasma compression,² neutral beam heating³, and stability and ohmic heating⁴ have been reported. In this paper, a summary is presented of the electron temperature and density measurements obtained with spectral analysis of Thomson scattered ruby light. In particular, empirical scaling laws are described for the average electron temperature and electron energy confinement time as functions of the plasma current, the average electron density and the effective ion charge. These empirical scaling laws are extended to include dependence upon minor and major plasma radius and toroidal field strength through a comparison of the various Tokamaks described in the literature.⁵⁻⁹ Finally, the local energy confinement time for a single discharge is assumed to have the same parametric dependence as that of the average confinement time obtained from numerous discharges, and it is shown that the predicted radial profile of the electron temperature agrees with the observed profile.

1. LASER SCATTERING EXPERIMENT

The experimental arrangement is shown in Figure 1. A Korad K1500 ruby laser is used to give a Q-switched pulse of 3 joules at $.69\mu$ and approximately 50 nsec halfwidth. The light scattered from a 1.5 cm length of the laser beam in the mid plane of the torus is collected over 5×10^{-2} sterad at an angle of 90° . The scattered light is resolved with a 40 cm Czerny-Turner diffraction

grating spectrometer into 8 plexiglass light guides which cover approximately $1000 \text{ \AA}$ on the blue side of the laser wavelength. Light in each channel is detected with an R.C.A. 8853 phototube which is electronically gated for 150 nsec. The phototube outputs are integrated, digitized and processed on an I.B.M. 1800 computer.

The phototubes are actually gated twice; once coincident with the laser pulse and once 10 μsec before the laser pulse in order to monitor the plasma light. Parasitic ruby light is determined on a separate laser shot with no plasma present. The 8 channels are calibrated relatively and absolutely with a tungsten lamp.

1.1 Computed Quantities

With the spectrometer signals corrected for parasitic scatter, plasma light and integrator zero level as described above, the raw data gives the one-dimensional distribution function for the electrons:

$$f(\Delta\lambda) = A \left(1 - \frac{3}{2} \frac{\Delta\lambda}{\lambda_R} \right) n \exp \left(- \frac{\Delta\lambda}{\lambda_O} \right)^2$$

where

$$A \equiv \left(\frac{m_e}{2\pi e T_e} \right)^{1/2}$$

$$\lambda_O^2 \equiv \frac{8e \sin^2 \frac{\theta}{2}}{m_e c^2} \lambda_R^2 T_e$$

and θ is the scattering angle of 90°

λ_R is the wavelength of the ruby laser

The factor including $\frac{3}{2} \frac{\Delta\lambda}{\lambda_R}$ is the relativistic correction term which accounts for the relativistic blue shift. This term is in agreement with that used previously,¹⁰ with the important difference that an additional wavelength correction is included due to the fact that a photomultiplier detector is strictly photon sensitive rather than energy sensitive.¹¹

A least squares fit was applied to the logarithmic approximation of the distribution function, $\ln f(\Delta\lambda)$ vs $\Delta\lambda^2$, to obtain a first approximation for an iterative least squares fit on the Gaussian distributing function. This fit then gave the electron temperature and density at the given radius and time.

To obtain radial profiles of the electron temperature and density, the laser beam was moved, shot-by-shot, along the major radius. Again a least squares fit was used to fit a trigonometric series to the measured points. The profile was then described by:

$$P(r) = \sum_1^N A_n \cos \left\{ (2n-1) \frac{(R-R_0)}{a} \frac{\pi}{2} \right\} \quad 1 \leq N \leq 9$$

Typically three terms were used and the same radius parameter (a) was used to obtain both density and temperature profiles. However, for some discharges, particularly gettered discharges,¹² it was necessary to use $a_T < a_n$. R_0 is the major radius of the plasma torus.

From these profiles various quantities were computed, such as:

$$\text{Poloidal } \beta: \quad \beta_\theta = \frac{16\pi^2}{\mu_0 I^2} \int_0^{a_T} n_e e T_e r dr$$

where μ_0 is $4\pi \times 10^{-7}$ Henry/m.

Electron Energy Confinement Time:

$$\begin{aligned}\tau_E &\equiv \frac{6\pi^2}{IV} R_O \int_0^a n_e e T_e r dr \\ &\equiv \frac{3}{8} \mu_O \frac{R_O}{R_M} \beta_\theta\end{aligned}$$

where R_M is the measured plasma resistance.

$$\text{Effective Ion Charge: } Z_{eff} \equiv \frac{\sum \langle n_i Z_i^2 \rangle}{\langle n_e \rangle}$$

This is obtained by assuming the plasma resistance is neo-classical¹³ and the average ion charge is independent of radius. An iterative procedure is used to solve for Z_{eff} in the implicit relation:

$$\frac{1}{R_M} = \int_0^a \frac{n_e^2 v}{\gamma(Z_{eff}) m_e v_{ei}} \left(1 - \frac{1.9 \left(\frac{r}{R_O} \right)^{1/2}}{1 + \gamma(Z_{eff}) v^*} \right) \frac{r}{R_O} dr$$

where v_{ei} is the classical electron ion collision frequency

$$\gamma(Z_{eff}) = \frac{.46 Z_{eff}}{1.08 + Z_{eff}} + .29 Z_{eff}$$

$$v^* = v_{ei} q \frac{R_O}{v_e} \left(\frac{R_O}{r} \right)^{3/2}$$

$$q = \frac{2\pi r^2 B \phi}{\mu_O I(r) R_O}$$

$$v_e = \sqrt{\frac{2eT_e}{m_e}}$$

The second term in the bracket above is the neo-classical correction due to trapped electrons which are excluded from carrying current. For all discharges discussed in this paper, the correction was small; amounting to $\leq 20\%$ increase in the plasma resistance compared with the classical value. Since v^* tends to infinity for both $r = 0$ and $r = a$, an average value was computed as:

$$\langle v^* \rangle = \left[\frac{2}{a^2 Z_{eff}} \int \frac{r dr}{v^*(r)} \right]^{-1}$$

For the discharges considered $1 \leq \langle v^* \rangle \leq 10$.

2. A.T.C. OPERATION

All data discussed in this paper was obtained with the plasma in the uncompressed position, i.e. plasma major radius of .87 m and minor radius of .17 m. The minor radius is determined by upper and lower rail limiters manufactured from either molybdenum or stainless steel. The toroidal field was 1.6T and the plasma current was varied between 30 and 100 kA. The base pressure was approximately 10^{-7} torr and the filling pressure was varied between 1 and 7×10^{-5} torr of either H_2 or D_2 . (There was no discernable difference in discharge parameters for the two gases.) The initial pressure determined the initial plasma density, but the electron density could then rise, fall, or remain steady with time, depending presumably, upon the condition of the limiters and/or vacuum walls.

Spectroscopically, the main impurity in the discharge was oxygen, with some iron, carbon and molybdenum also observed.⁴ The effective ion charge, as determined from the measured plasma resistance and electron temperature profile, was typically about 5. This is a factor of two higher than that obtained spectroscopically, but is in good agreement with the value obtained from pitch angle scattering of injected hydrogen.³ The effective ion charge could be reduced to 1 in discharges with titanium deposited on the limiters and vacuum wall.¹²

Typical radial profiles of electron temperature and density are given in Figure 2. These measurements were made at the time of peak current (30 msec). The accuracy of temperature measurement was typically $\pm 10\%$ and was limited by photon statistics. The accuracy of density measurement was also $\pm 10\%$ and was limited by reproducibility of the discharge. Figure 2 illustrates the typical profile shapes observed. The temperature profile was reasonably approximated by a $(1-[r/a]^2)^2$ dependence. (Discharges with low Z_{eff} tended to be contracted in minor radius, i.e. the minor radius used in the profile fit was less than the limiter value). The electron density profile was typically broader than the temperature profile and could be approximated by $(1-[r/a]^2)$. However, the electron temperature profile appeared to be independent of the electron density profile. Similar temperatures (peak and profile) have been reported for two discharges in which current, voltage and toroidal field were the same, but the average electron density differed by a factor of two.⁴ In Figures 3, 4, and 5, two discharges are compared which have similar average density

(Note line density curve of Fig. 3) but the peak electron density of Figure 5 is 50% higher than that of Figure 4. However, the temperature profile is similar in the two cases.

Figure 3 illustrates typical time evolution of A.T.C. discharges. The line density measured with a 4 mm microwave interferometer shows a fast initial rise which typically corresponds to half the neutral gas filling pressure. From this time, the average density can rise, fall or remain steady with no apparent effect upon the electron temperature. Figures 4 and 5 illustrate that the electron temperature profile is established early, at 15-20 msec, and then remains steady for 15-20 msec until the vertical field decays at 45 msec and plasma equilibrium is lost. Note that the temperature profile can show a strong axial peaking early in the discharge, as in Fig. 4, but this peaking rapidly relaxes to the typical profile shape.

3. A.T.C. SCALING

In this section we derive empirical scaling laws from approximately 80 ATC electron temperature and density profiles obtained with the Thomson scattering diagnostic. The range of machine parameters covered are $32 < I < 108$ kA, $.8 < \bar{n}_e < 3.5 \times 10^{19} \text{ m}^{-3}$, $90 < \bar{T}_e < 560$ eV, and $1 < Z_{\text{eff}} < 9$. For all discharges $a=.17$ m, $R=.87$ m and $B\phi=1.6$ T.

As with all Tokamak investigations,⁵⁻⁹ we find

$$\beta_{\theta} \propto \langle n_e \rangle. \quad (1)$$

In Fig. 6A, $\beta_\theta / \langle n_e \rangle$ is plotted against I for given values of Z_{eff} ; and, in Fig. 6B, $\beta_\theta / \langle n_e \rangle$ is plotted against Z_{eff} for given I . The result is

$$\beta_\theta \propto \frac{\langle n_e \rangle}{I^{3/2}} (Z_{eff})^{1/2} \quad (2)$$

Since β_θ is defined as

$$\beta_\theta \propto \frac{\langle n_e \rangle \langle T_e \rangle}{I^2} \quad (3)$$

this gives a relationship between $\langle T_e \rangle$, I and Z_{eff} for an ohmic heated Tokamak:

$$\langle T_e \rangle \propto (Z_{eff} I)^{1/2} \quad (4)$$

Since Z_{eff} is defined as

$$Z_{eff} \propto R_m \langle T_e \rangle^{3/2}, \quad (5)$$

then dependence 2 above also gives

$$\langle T_e \rangle \propto V^2 \quad (6)$$

These dependences of average electron temperature are plotted in Figs. 7 and 8. Figure 7A shows good agreement for $\langle T_e \rangle$ vs. $Z_{eff}^{1/2}$. Figure 7B is consistent with $\langle T_e \rangle \propto I^{1/2}$ but a stronger dependence upon I is possible. Figure 8 shows poor agreement for $\langle T_e \rangle \propto V^2$. High and low voltages (or temperatures) do not correlate with current, effective ion charge or electron density. There is a tendency for the low voltage, high temperature

discharges to have broad profiles and the high voltage, low temperature discharges to have narrow profiles.

It appears that ionization, radiation and charge exchange from recycling particles can introduce an energy loss which causes the plasma column to shrink from the limiter. Relations 4 and 6 should probably include this effective radius,

$$\langle T_e \rangle \propto (Z_{eff} I)^{1/2} / a_T \text{ and } \langle T_e \rangle \propto V^2 a_T^4.$$

The empirical parametric dependence of the average electron energy confinement time is given in Fig. 9.

$$\tau_E \propto \frac{\langle n_e \rangle \langle T_e \rangle^{3/2}}{I^{3/2} Z_{eff}^{1/2}} \quad (7)$$

This scaling is very similar to that reported previously⁴

$$\tau_E \propto \frac{n_e q(o)}{R_M} \propto \frac{\langle n_e \rangle \langle T_e \rangle^{3/2}}{I Z_{eff}} \quad (8)$$

Substituting dependence 4 in 7 to eliminate Z_{eff} , we have:

$$\tau_E \propto \frac{\langle n_e \rangle \langle T_e \rangle^{1/2}}{I} \quad (9)$$

This dependence upon $\langle n_e \rangle$ and I has been reported previously for high density discharges in the T4 machine.⁷

Note that the definitions of τ_E , and β_θ give

$$R_M \propto \frac{\beta_\theta}{\tau_E} \propto \frac{Z_{eff}}{\langle T_e \rangle^{3/2}} \quad (10)$$

This is consistent with our initial assumption that the plasma resistance is classical.

There is considerable literature on the heat loss from the electrons of an ohmic heated Tokamak. Artsimovitch suggests there must be an anomalous electron thermal conductivity.¹⁴ Our empirical scaling for this anomalous electron thermal conductivity is

$$\chi_e \propto \frac{I^{3/2} (Z_{eff})^{1/2}}{\langle n_e \rangle \langle T_e \rangle^{3/2}} \quad (11)$$

$$\text{or } \chi_e \propto \frac{I}{\langle n_e \rangle \langle T_e \rangle^{1/2}} \quad (12)$$

This interpretation of the electron energy confinement time neglects electron radiation losses. This omission is justified in present Tokamaks by recent bolometric measurements on A.T.C. which show the radiated power loss during the steady state of the electron temperature profile is $\lesssim 20\%$ of the total loss.⁴

The density and current dependences are very different from the "pseudo-classical" scaling obtained by Artsimovitch.¹⁴

$$\chi_{pc} \propto v_{ei} \rho_\theta^2 \propto \frac{\langle n_e \rangle Z_{eff}}{I^2 \langle T_e \rangle^{1/2}} \quad (13)$$

4. TOKAMAK SCALING

In this section, an attempt is made to generalize the above scaling laws by comparing Tokamak machines of different major and minor radius and toroidal field strength. A summary of machine parameters found in the literature is given in Table 1. The range of parameters available is $.80 < R_0 < 1.09$ m. $.06 < a < .23$ m. and $1.6 < B\phi < 5.0$ T. The list is restricted

to those papers which give sufficient experimental data for the calculation of Z_{eff} .

In Fig. 10, the electron energy confinement time is plotted against minor radius for the machines described in Table I. The temperature and current dependence has been removed by using relation 7 above. It is apparent that there is a strong dependence upon minor radius, and weak dependence upon toroidal magnetic field and major radius.

$$\tau_E \propto \frac{\langle n_e \rangle \langle T_e \rangle^{3/2}}{Z_{eff} I^{3/2}} a^3 \quad (14)$$

For power balance in an ohmic heated Tokamak with this empirical confinement time, we have

$$\begin{aligned} P_{in} &\equiv I^2 R_M = P_{loss} \equiv \langle n_e \rangle \langle T_e \rangle 3\pi^2 a^2 R_O / \tau_E \\ \text{or} \quad \frac{I^2 Z_{eff} R_O}{\langle T_e \rangle^{3/2} a^2} &\propto \frac{\langle n_e \rangle \langle T_e \rangle a^2 R_O I^{3/2} Z_{eff}^{1/2}}{\langle n_e \rangle \langle T_e \rangle^{3/2} a^3} \\ \text{i.e.} \quad \langle T_e \rangle &\propto \frac{(Z_{eff} I)^{1/2}}{a} \end{aligned} \quad (15)$$

This dependence is plotted in Fig. 11.

It is apparent that present ohmic heated tokamaks have the same scaling observed for the A.T.C. machine.

$$\langle T_e \rangle = \frac{(Z_{eff} I)^{1/2}}{10 a} \quad (16)$$

and

$$\tau_E = \frac{3 \langle n_e \rangle \langle T_e \rangle^{3/2}}{I^{3/2}} a^3 \times 10^{-16} \quad (17)$$

or

$$\tau_E = \frac{3 \langle n_e \rangle \langle T_e \rangle^{1/2}}{I} a^2 \cdot 10^{-17} \quad (18)$$

all in M.K.S. units.

These values are much lower than calculated with the numerical codes using pseudo classical transport coefficients. Furthermore, $\langle T_e \rangle$ would be reduced by a factor of approximately 2 in a clean hydrogen discharge and the confinement time reduced accordingly.

5. A.T.C. PROFILE

If it is assumed that the local energy confinement time $\tau_E(r)$ and thermal conductivity $\chi_e(r)$ have the same scaling as determined from the average quantities. Then the power balance during the steady-state portion of the A.T.C. discharge may be used to predict the radial temperature profile.

$$\text{Since } \frac{P_L(r)}{2\pi R_0} = -r n_e(r) e \chi_e(r) \frac{dT_e(r)}{dr} = \frac{VI(r)}{2\pi R_0}$$

$$\text{and } \chi_e = \frac{a^2}{\tau_E(r)}$$

$$\text{where } \tau_E(r) = 3 \times 10^{-17} \frac{n_e(r) T_e(r)^{1/2}}{I(r)} r^2$$

$$\text{then } \frac{dT_e(r)}{T_e^{1/2}} = 35 V r \frac{dr}{a^2}$$

$$\text{or } T_e = 80 V^2 \left(1 - \frac{r^2}{a^2} \right)^2, \quad \langle T_e \rangle = \frac{80V^2}{3}$$

This computed electron temperature profile is in agreement with the observed profiles shown in Figs. 2, 4 and 5. The computed average electron temperature scales with voltage as suggested above and is in agreement with the mean value of $\langle T_e \rangle$ vs. V^2 given in Fig. 8.

DISCUSSION

The values of Z_{eff} determined from resistance measurement, spectroscopic analysis and fast ion scattering times are all in agreement.³ Furthermore, with titanium gettering, Z_{eff} can be reduced to 1 in a hydrogen discharge and to 2 in a helium discharge.¹² This suggests that the plasma resistance is classical. It is however, necessary to consider the effective ion charge due to impurity ions in the discharge. In present tokamaks, the plasma resistance is enhanced by a factor of 1-10 over that of a hydrogenic plasma. The heat loss from an ohmic heated tokamak is anomalous. In the A.T.C. tokamak, the particle confinement time is approximately an order of magnitude longer than the electron energy confinement time, and this implies the anomalous heat loss results from an enhanced electron thermal conductivity. Theoretical considerations suggest the trapped electron mode is most likely to cause the enhanced thermal conductivity in present tokamaks.¹⁵ The results obtained here agree in magnitude, but do not agree in parametric dependence.

$$\text{Trapped Electron Mode: } \chi_e \propto \frac{\langle T_e \rangle^{7/2}}{\langle n_e \rangle Z_{eff} a^2 B_\phi^2}$$

Empirical Result: $\chi_e \propto \frac{I^{3/2} (Z_{eff})^{1/2}}{\langle n_e \rangle \langle T_e \rangle^{3/2} a}$

If the same transport process occurs in a larger ohmic heated tokamak as is observed in present tokamaks, then the electron temperature and confinement time can be estimated. The parameters of the P.L.T. device are:

$$\begin{array}{ll} I = 1 \text{ M.A.} & a = .45 \text{ m} \\ B_\phi = 4 \text{ T.} & R_O = 1.30 \text{ m} \end{array}$$

Note that B_ϕ and R_O are not changed appreciably from present tokamaks. From Figs. 10 and 11, we have:

$$\langle T_e \rangle \sim \frac{(Z_{eff})^{1/2}}{4.5} \times 10^3 \text{ eV}$$

$$\sim 450 \text{ eV for } Z_{eff} = 4 .$$

$$\text{Peak } T_e \sim 1400 \text{ eV}$$

$$\tau_E \sim 13 \langle n_e \rangle \times 10^{-23} \text{ sec}$$

$$\sim 13 \text{ msec for } \langle n_e \rangle \sim 10^{20} \text{ m}^{-3} .$$

Numerical simulation codes for tokamaks,¹⁶ which use an electron thermal conductivity enhanced by the trapped electron mode, predict a peak electron temperature of approximately 2000 eV and an energy confinement time of approximately 100 ms. The numerical codes include enhanced transport in the plasma core to simulate the M.H.D. activity which has been observed experimentally with X-ray techniques.¹⁷ The numerical codes also include loss effects due to recycling particles from the walls and limiters. These effects are ignored in the present analysis. Given the plasma minor radius, which if different from the limiter radius must result from a balance of ohmic power input and losses due to recycling at the plasma edge, and given the safety factor, q_a , is greater than two; then the electron thermal conductivity is assumed to dominate the entire profile.

7. CONCLUSION

Observation of power balance during the steady state phase of the A.T.C. discharge has given empirical scaling for the electron energy confinement time in terms of the average electron temperature and density, the effective ion charge and the plasma current. This empirical scaling is confirmed with data from other tokamaks.

$$\tau_E = \frac{3 \times 10^{-16} \langle n_e \rangle \langle T_e \rangle^{3/2}}{Z_{eff} I^{3/2}} a^3 \text{ sec.}$$

The range of values for major radius and toroidal magnetic field was small and further dependence upon these parameters is possible. Furthermore, due to the interdependence of τ_E , I and $\langle T_e \rangle$ in an ohmic heated tokamak, the above expression has not been proved unique. For example,

$$\tau_E = \frac{3 \times 10^{-17} \langle n_e \rangle \langle T_e \rangle^{1/2}}{I} a^2 \text{ sec.}$$

describes the radial power balance in A.T.C. (see section 5), and is consistent with the above expression, given that:

$$\langle T_e \rangle = \frac{(Z_{eff} I)^{1/2}}{10a} \text{ eV}$$

This final relation was confirmed both for A.T.C. data over the ranges $1 \leq Z_{eff} \leq 9$ and $30 \leq I \leq 100$ kA and for three other tokamaks over the range $.06 \leq a \leq .23$ m.

Empirically, the electron temperature is proportional to the square root of the current density for ohmic heating. Since the current density will not change appreciably in future devices due to limits on the safety factor and toroidal magnetic field, then it is apparent that large powers of auxiliary heating (of order 1MW for P.L.T.) must be used to raise the average electron temperature above the present value of about 1000 eV.

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TABLE I.

Device	a	R	B _φ	I	V	Z _{eff}	<n _e >	<T _e >	τ _E	Reference
	m.	m.	T.	(kA.)	(v.)		$\left(\begin{matrix} \times 10^{19} \\ m^{-3} \end{matrix} \right)$	eV	msec	
ST 1	.13	1.09	3.7	62	2.5	8.5	1.9	750	6.4	6
2	.10	1.09	4.4	42	3.1	4.5	1.9	470	3.4	5
3	.12	1.09	2.7	39	2.5	2	2.2	250	3.7	5
4	.11	1.09	3.5	45	4.3	6.5	1.5	430	2.0	5
5	.06	1.09	2.7	10	3.7	1	.8	140	.5	5
ATC	.17	.87	1.6	80	2.9	4	2.0	300	2.8	
TFR 1	.20	.98	2.0	100	4.0	8	2.4	(375)	(4)	9
2	.20	.98	4.0	200	3.3	11	3.4	(800)	(6)	9
3	.20	.98	5.0	300	3.0	9.5	4.4	(1000)	(8)	9
ORMAK	.23	.80	1.8	95	3.0	4.5	2.0	(230)	(4)	8

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Fig. 1. Schematic drawing of Thomson scattering experiment. (H) Q-switched ruby laser, (G) Movable lens and prism below fixed vacuum window, (F) Laser focal point and image of spectrometer slit, A.T.C. uncompressed plasma position, (A) Black glass laser beam dump, (B) Collecting lens, (C) Filter and black glass cutting off ruby and longer wavelength, (E) Grating spectrometer and (D) Light pipe and photomultiplier housing.

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Fig. 2. Electron temperature (open circle) and electron density (closed circles) as functions of major radius. Curves give typical A.T.C. profiles, $T_e = T_{eo} (1 - r^2/a^2)^2$ (solid line) and $n_e = n_{eo} (1 - r^2/a^2)$ (dotted line) where $T_{eo} = 1050$ eV, $n_{eo} = 2.7 \times 10^{19} \text{ m}^{-3}$, $a = .17$ m. and $r = R - R_0$.

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Fig. 3. Plasma current, loop voltage, and line density (4mm. microwave signal) as functions of time. Note that plasma density rises during pulse from initial values given by closed circles.

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Fig. 4. Discharge A. Electron temperature (left) and density (right) as functions of minor radius at time .010, .015 and .030 seconds (see Fig. 3).

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Fig. 5. Discharge B. Electron temperature (left) and density (right) as functions of minor radius at times .010, .015 and .030 seconds (see Fig. 3).

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Fig. 6. $\beta_{0e}/\langle n_e \rangle$ plotted against plasma current for various values of Z_{eff} (above) and $\beta_{0e}/\langle n_e \rangle$ plotted against Z_{eff} for given plasma current (below) i.e. $\beta_{0e} \propto \langle n_e \rangle Z_{eff}^{1/2} / I^{3/2}$.

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Fig. 7. Average electron temperature plotted against Z_{eff} for given plasma current (above) and average electron temperature against plasma current for given Z_{eff} (below).

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Fig. 8. Average electron temperature plotted against plasma loop voltage. ΔV represents uncertainty of voltage measurement due to noise on voltage signal. The minor radius of the electron temperature profile varied from .11 - .17 m.

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Fig. 9. Scaling of electron energy confinement time (τ). $\tau / \langle n_e \rangle$ against plasma current for given average electron temperature (above) and $\tau \cdot Z_{eff}^{1/2} / \langle n_e \rangle$ against average electron temperature for given plasma current (below) i.e. $\tau \propto \langle n_e \rangle \langle T_e \rangle^{3/2} / Z_{eff}^{1/2} I^{3/2}$.

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Fig. 10. Normalized electron energy confinement time plotted against plasma minor radius for various tokamak devices identified in Table I. $\tau_E = 3 \times 10^{-16}$ $\langle n_e \rangle \langle T_e \rangle^{3/2} / Z_{eff}^{1/2} (a^2/I)^{3/2}$.

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Fig. 11. Normalized electron temperature plotted against plasma minor radius for various tokamak devices identified in Table I. Note projected value for P.L.T. device. $\langle T_e \rangle = (Z_{eff} I / 100 a^2)^{1/2}$.

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