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OHMIC HEATING OF TOKAMAKS

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ABSTRACT

Ohmic heating in present generation tokamaks has proven to be efficacious to the extent that it raises the electron temperatures into the keV range and ion temperatures to several hundred eV. The ultimate temperatures reached have been dictated by the energy confinement time which at present is relatively short ($\lesssim$ 15 msec). This restriction should be relaxed in future devices in which the discharge duration will be comparable to the confinement time so that the ohmic heating rate should be primarily set by the thermal capacity of the plasma. If this proves to be the case, and if the current density profile can be suitably chosen, ohmic heating will provide a continual "slow" increase in plasma temperature throughout the discharge duration.

The current density profile will be strongly dependent on skin effect, stability, and particle influx at the plasma boundary. In present tokamaks, stability and particle influx are dominant but skin effect should play at least as dominant a role in the future machines. There is considerable concern regarding all three of these processes and schemes for avoiding their influence are being pursued. (It is likely that stability and particle influx will be of great importance in any heating scheme.)

Until now, the usual tokamak operation employing ohmic heating has been limited to $\beta_\theta = \bar{p}/B^2(a)/8\pi \lesssim 1$. Stepped ohmic heating current experiments suggest that equilibrium and stability can be maintained to at least $\beta_\theta \sim R/a$ if only the heat input could be increased. Predictions for straightforward enlargements of the conventional design of the tokamak suggest that β_θ will actually decrease. It is possible that selected magnetic geometries can improve the ohmic heating. However, it appears at this time that

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supplementary heating combined with ohmic heating will provide the higher β_e values desired for reactor-like operation in the next generation of devices, especially for the relatively short discharge duration times envisioned.

I - INTRODUCTION.

The current in a tokamak not only provides for plasma confinement and equilibrium but also supplies energy through ohmic heating directly to the electrons and indirectly to the ions. In present tokamaks this energy source has proven to be efficacious to the extent that it raises the electron temperature into the few keV range and the ion temperature to several hundred eV. Thus, the remote possibility exists that ohmic heating could suffice to heat the plasma of a future toroidal reactor device to ignition temperature. Consequently, considerable attention has been and is being given to the extrapolation of ohmic heating conditions to large scale tori.[1]

The dominating factors for ohmic heating are τ_E', the gross energy containment time, and the discharge duration time. In present tokamaks τ_E' is relatively short ($\lesssim$ 15 msec) and quickly limits the plasma temperature. Extrapolations to the reactor regime have been made by a number of authors (a few of which are listed in Ref. 2 - 9) who usually ignore the time factor, assume τ_E' scales neoclassically or pseudoclassically, and <u>wait</u> for ignition to occur under the prescribed conditions. However, extrapolation of τ_E' from the present regime is highly speculative. In fact τ_E' scaling according to either neoclassical or pseudoclassical or any other scaling has no firm experimental basis. As pointed out by Golovin,[2] intermediate size experimental devices are required to examine the τ_E' scaling.

The next generation of tokamaks (PLT, T-10, PDX) have an increase in minor radius a of ~ 3 over present devices and should give an increase in τ_E' of $\sim a^2 = 10$. (The a^2 scaling has usually been observed experimentally up to the present time.) This is an exciting prospect in that τ_E' could at last be dominated by bulk effects such as those considered in neoclassical and pseudoclassical energy transport in place of atomic effects such as ionization radiation, bremstrahlung, and recombination radiation (especially if impurities can be limited to the lighter species which should be fully stripped over the bulk of the discharge). If this turns out to be the case, the scaling law will probably become evident.

Thus it appears that the next generation of tokamaks will have τ_E' comparable to the discharge duration time so that both factors could influence the ohmic heating performance. The dominating features of ohmic heating over this time scale are :

1) $P_{OH} \propto 1/T_e^{3/2}$ for constant q (safety factor), etc..., so that T_e is strongly limited by the thermal capacity of the plasma,

2) q has a minimum limit set by instability onset, and

3) due to the increase of a, a strong skin effect is possible for the first time in a conventional tokamak.

In this paper, an impirical τ_E' approach will be made to obtain predictions for the ohmic heating performance in PLT. Then the influential properties associated directly with ohmic heating will be discussed :

1) MHD stability limit for q and effect on τ_E',

2) skin effect, and

3) ohmic heating optimization.

This will be followed by a discussion of the effect auxiliary heating could have in conjunction with ohmic heating and finally, by a brief look at an impurity effect common to all heating schemes.

Before discussing the PLT predictions, a brief montion of ohmic heating efficiency is in order. In the steady state, this may be defined as the energy per second delivered to the plasma particles divided by the A C line power (x 100). In present devices using delay line systems, this efficiency is ~ 45%. In principle, direct flywheel or AC-DC convertor systems could give $\gtrsim$ 90%.[10] It should be noted that the definition employed here for efficiency avoids putting any blame or credit on the ohmic heating for the energy confinement time achieved by the plasma; after the particles receive the energy, they are forgotten.

II - PLT OHMIC HEATING PREDICTIONS.

In order that reference can be made to reactor extrapolation, the profiles of Ref.2 will be assumed to apply for PLT after the initial skin phase (which is ignored for the present) :

$$T_e = T_i = T_o \left[1 - 9/10 \left(\frac{r}{a}\right)^2\right], \qquad (1)$$

$$n_e = n_o \left[1 - 1/2 \left(\frac{r}{a}\right)^2\right],$$

and all n_i constituents have the same radial profile as n_e. (The calculations which follow are insensitive to the exact profiles.) The pertinent PLT parameters are chosen to be $q = aB_\phi/RB_\theta = 3$ and $B_\phi = 50$ kG ($I_{OH} = 1.25$ MA), where $R = 130$ cm and $A \equiv R/a = 3$. As suggested by Eq.(1), operation will be assumed to be at sufficiently high densities and sufficiently low temperatures so that T_i is approximately equal to T_e.

The absolute maximum ohmic heating performance is obtained by assuming $\tau_E' \to \infty$. This gives

$$\frac{\partial W}{\partial t} = P_{OH} \qquad (2)$$

which for the profiles above can be integrated directly to give

$$T_o(t) = \left[T_o(o)^{5/2} + \left(\frac{5}{2} \cdot \frac{125\, Z'\, B_\phi^2}{3\pi^2 \sigma_o R^2 q^2 n_o \epsilon} \right) t \right]^{2/5} \qquad (3)$$

The units used here are the same as in Ref. 2, Z' is the appropriate factor taking into account the presence of impurities {assuming a single impurity with a concentration f times the number of singly ionized ions gives $Z' = Z_{eff} \times 2/\left[1 + (1+f)/(1+Zf)\right]$}, and ϵ is 1.6×10^{-19} J/eV. Equation (3) is plotted in Fig. 1 for a range of n_o values assuming $Z' = Z = 1$, or alternatively, for $n_o = 10^{14}$ and $Z' = 1, 2$, and 4. It is found that T_o increases slowly in time and attains rather modest levels over the expected discharge duration of 0.5 sec. This result is caused by the fall of P_{OH} with increasing temperature (Fig.1) and by the thermal capacity of the plasma [at higher densities the rate of increase is reduced (Eq.3)].

The temperatures attained after ~ 0.1 sec are independent of the reasonable starting T_o value range assumed just after the skin phase (10 to 500 eV). This result is attributable to the greatly enhanced P_{OH} at the lower temperature level (Fig. 1). Finally, the stored energy or β_θ is found to increase slowly on the experimental time scale as expected for the slow temperature rise.

Without energy losses the ohmic heating is rather slow and the temperature in PLT would be expected to reach a value less than 5 keV. With a finite confinement time the temperature must be less. Assuming a direct a^2 scaling from ST tokamak conditions places τ_E' in the 0.1 second range. It is informative to look at the effect of a constant τ_E' in this range on the ohmic heating performance. Figure 2 plots curves similar to those of Fig.1 for $\tau_E' = 0.1$ sec and 0.3 sec (the upper limit expected for the confinement time). T_0 now saturates in a time of the order of T_E to an equilibrium value in the range of ~ 1 to 3 keV for the conditions assumed appropriate for PLT. The saturated value of T_0 is given by

$$T_o(\infty) \doteq \left(\tau_E' Z' \frac{125 B_\phi^2}{3\pi^2 \sigma_o R^2 q^2 n_o \epsilon} \right)^{2/5} . \qquad (4)$$

An important consideration at this point is the reliability of the choice of a constant τ_E'. Figure 3, taken from Ref.1, shows the present state of the theory as regards the predicted energy containment time versus electron temperature in tokamaks. PLT falls in an unexplored region, but if the theory is correct the energy confinement time is not a strong function of T_e in the range of 1 to 3 keV.

It is of interest to consider the possibility that pseudoclassical scaling will extend into the PLT operating regime. Then two possibilities occur[11]:

1) thermal flow could dominate[12] and $\tau_E' \propto T^{1/2}/n$, or

2) particle flow could dominate[13] and $\tau_E' \propto T^{1/2} n$.

Figure 4 presents the calculations for these cases assuming $\tau_E' = 0.3$ sec at $n_0 = 5 \times 10^{13}$. (Note that this $n\tau_E'$ is not quite as optimistic as the projection of the pseudoclassical estimate in Fig. 3 but agrees with the lower trapped-electron level.) This figure clearly illustrates the potential for discovering the true scaling law for large Tokamaks on PLT. For case (1), the equilibrium temperature is strongly dependent on density, whereas for case (2), it is independent of density. (These results follow from Eq. (4) by inspection.)

All of the calculations discussed here point to a rather modest T_0 in PLT with ohmic heating alone. More elaborate calculations using advanced computer codes to more accurately represent the confinement theory provide the same conclusion.[14]

III - STABILITY AND SKIN EFFECT.

In this section, an attempt will be made to deduce the possible influence MHD instability and skin effect might have on the ohmic heating performance in PLT from consideration of their effects in present tokamaks. The MHD instability has two important effects on ohmic heating. It puts a lower limit on the magnitude of q and it reduces τ_E'. Fig. 5 shows a stability diagram for a constant current discharge on the ST tokamak.[15,16] The disruptive instability preceded by an m = 2 instability limits stable operation to $q \gtrsim 3$ for normal operating pressure in this case. (The same instability associated with a shrinking of the current channel occurs at high pressure at any q.[16]) Even without disruption in the presence of the m = 2 instability, the value of τ_E' is reduced as is illustrated in Fig. 6 which is derived from the data of Ref. 17 for the T-3 Tokamak.

Skin effect in present machines is not sufficiently strong to measure very accurately. However data do exist which show the qualitative skin time. Figure 7 illustrates that for the ST tokamak there is a skin phase of a few milliseconds during the buildup of the discharge current. Equilibrium position measurements of internal inductance ℓ_i[15] and Thomson scattering measurements of electron temperature[18] both indicate this.

The buildup phase is a complicated regime for which it is difficult to predict the skin time. Since it is quite probable that a well-defined current channel will be formed early in the current buildup of PLT, it would seem that the skin effect during the equilibrium of present tokamaks would be more pertinent. Some insight into this skin time is given by pulsing or stepping the I_{OH} level after the discharge has reached its steady state. Such an experiment was performed on the T-3 tokamak [19] giving the results of Fig. 8. β^* combines the changes in β_θ and in internal inductance ℓ_i (n h/cm) and should be proportional to I_1^2/I_2^2 if τ_E' and τ_{SKIN} are both >> 1 msec. Since other measurements of τ_E' indicate that it is indeed considerably longer than 1 msec, the failure of β^* to follow the theoretical curve is indicative of a short skin time (< 1 msec). A similar experiment was performed on the ST tokamak [20] with a similar result (Fig. 9). The position loop measurements (u) were analyzed taking into account the eddy currents in the vessel [21] and combined with the diamagnetic loop measurements (S) to determine β_θ and ℓ_i separately. The resulting time dependence for one current step is presented in Fig. 10. Clearly β_θ scales properly (τ_E'>> .6 msec) whereas ℓ_i does not ($\tau_{SKIN} \lesssim$ .6 msec). Finally, a very fast step (0.2 msec) resulted in the separate β_θ and ℓ_i plots of Fig. 11. Importantly, β_θ (loop measurements and Thomson scattering measurements) scales according to theory up to $\beta_\theta \sim$ R/a where instability insues (β_θ does not reach R/a possibly due to the plasma hitting the outside limiter) whereas ℓ_i does not follow the theoretical curve even for a 0.2 msec current step.

The electron temperature is too high in the plasma to permit such a fast skin time in the absence of some current dispersing mechanism . In this regard, MHD oscillations observed in the current step with azimuthal mode numbers m up to 6 might play a role in dispersing the skin current.[22] Also in the present case of a large change in plasma current, a dynamic calculation including heating by the surface current is required to correctly predict the skin time. Such a calculation has been attempted using neoclassical and pseudoclassical codes [23] and gives a voltage response to the step in current quite similar in form to that measured. However, the magnitude of the voltage as well as the temperature and density profile dependences on time do not agree with experiment. At this point, it is apparently necessary to accept the experimental finding and hope that τ_{SK} persists in being short in PLT.

An independent measurement of the resistivity profile in the ST tokamak has been made by measuring the ac impedance of the plasma versus frequency by superimposing a very small ac current on the ohmic heating current [24] . The analysis of the data in terms of the measured temperature profiles is rather involved and will not be entered into here (see Ref. 24). However, the essential results are that $\eta / \eta_{cl} \approx 1 + A \left(\frac{r}{a} \right)^4$ with A in the range of 4 to 6, and that full current penetration is obtained in ST for $f \lesssim$ 50 Hz (Fig. 12). The reason for the increase in resistivity at the surface is not known. But in the present context, the important observation is that η is classical over the bulk of the plasma and is likely to be also over the much larger central region of PLT.

Assuming that full current penetration can be obtained in PLT before the electron temperature exceeds $\sim$ 500 eV permits the calculation of current density profiles at different frequencies for the T_e profile of Eq. (1). The right plot in Fig. 12 suggests that full penetration should occur between 1 and 5 Hz. The larger frequency corresponds to a current buildup time of approximately 50 msec which is perhaps acceptable. However, an even faster buildup time may be required to hold down the temperature sufficiently due to the enhancement of ohmic heating at low temperatures as discussed earlier.

In the event that skin effect does pose a serious problem in PLT and other next-generation devices, a number of methods have been proposed to circumvent it. Figure 13 presents the simplest method ; by adjusting the vertical magnetic field, the plasma position can be programmed so that the radius a increases approximately as $\sqrt{I_{OH}}$ thereby keeping $\dot{j}_{OH}$ approximately constant. This same principle applies for moving limiters[25] which were proposed some time ago by Kadomtsev[2] and which will be available on PLT. However, it would be preferable to establish the current without having the current channel in direct contact with a metal surface so as to avoid excessive impurity influx. A magnetic limiter therefore would be optimal and will be a possible method for PDX[26]. Finally instabilities in the surface of the plasma may naturally disperse the current as suggested in the stepped-current experiments discussed above. However, this process may lead to overheating the limiter as detailed in Ref. 25.

IV - ENHANCEMENT OF OHMIC HEATING PERFORMANCE.

Ohmic heating of the plasma may be made more effective according to Eq.(4) by 1) increasing j_{OH} and
2) increasing plasma resistivity.

An increase in $\dot{j}_{OH}$ can be provided by
a) field shaping[27] (as in Doublet and PDX)
b) improving MHD stability with feedback or dynamic stabilization[28,29] so that q can be decreased, and
c) increasing B_ϕ (as in Alcator).

An increase in resistivity might be produced by
a) turbulence (Texas Tokamak, Alcator) and
b) by catalytic heating[30].

All of these methods have yet to be proven except for increasing B_ϕ which has a technological upper limit.

It is quite possible that many of them will succeed to some extent but since the plasma resistivity falls so rapidly with temperature it is not expected that they will greatly enhance the final temperature [Eq.(4)].

V - SCENARIO WITH SUPPLEMENTARY HEATING.

It is interesting to determine the effect an auxiliary heating source might have on the PLT plasma in conjunction with ohmic heating. This is determined by assuming that the auxiliary power goes directly into heating the plasma particles. Figure 14 shows the result of applying 5 MW of additional power until T_o exceeds 4 keV and then dropping the auxiliary power to a level which would hold T_o at 4 keV in the absence of ohmic heating. For τ_E' constant at 0.1 sec, the plasma is heated rapidly at lower densities, but 5 MW is insufficient for T_o to reach 5 keV at $n_o = 2 \times 10^{14}$. For $\tau_E' \propto T_e^{1/2}$ and equal to 0.1 sec at $t = 0.5$ sec in the absence of auxiliary power, 5 MW is sufficient to reach 4 keV even at 2×10^{14}. These results demonstrate first that 5 MW of auxiliary power can produce a significant increase in temperature for PLT and that this power should serve as another test for determining the τ_E' scaling law.

VI - IMPURITY INFLUX.

It is well known that the final density obtained in a tokamak is a function of the ohmic heating current and not of the filling pressure. This is illustrated in Fig.15 for the early operation of ST. The initial peak in density follows closely the base pressure value whereas the final value of density is almost independent of pressure (apparently the increment $\Delta \bar{n}_e$ is a constant). Over the years as the ST has "cleaned up", the level of the final density for a given I_{OH} has fallen as have the densities of impurities (especially O). However, it has remained true that at any given time, the final density is an increasing function of I_{OH}.

This dependence of n_e on I_{OH} is usually attributed to an increase in τ_p with an increase of I_{OH}.[31, 11] However, an alternative explanation is that the ion energy increases with I_{OH}, and hence the wall bombardment, so that the neutral influx is increased. If this latter explanation is correct, this effect could be extremely pronounced in PLT and next generation devices since as the ions become hotter the sputtering yields become important. According to recent measurements[32], the sputtering yields (atoms/ion) should increase ($\propto E_i^2$) by about two orders of magnitude in PLT over what they were in ST. If such an increase occurs, impurity radiation will dominate the power balance and hold the temperature down in PLT to below the levels presented earlier.[33]

VII - DISCUSSION.

The subject of ohmic heating is of interest to many researchers and is actively being pursued. It is not possible to cover all of its aspects in a 40 minute lecture and the ones I have discussed are sketched out only briefly. However, the material assembled here gives a general idea ot the prospects for ohmic heating in the next generation devices. It would appear that ohmic heating alone will continue to produce electron temperatures in the few keV range (but over a larger volume) and will at last provide ion temperatures which are also in the few keV range. The increase in size and in ion temperature make PLT and other next generation devices invaluable to the quest for a toroidal reactor system.

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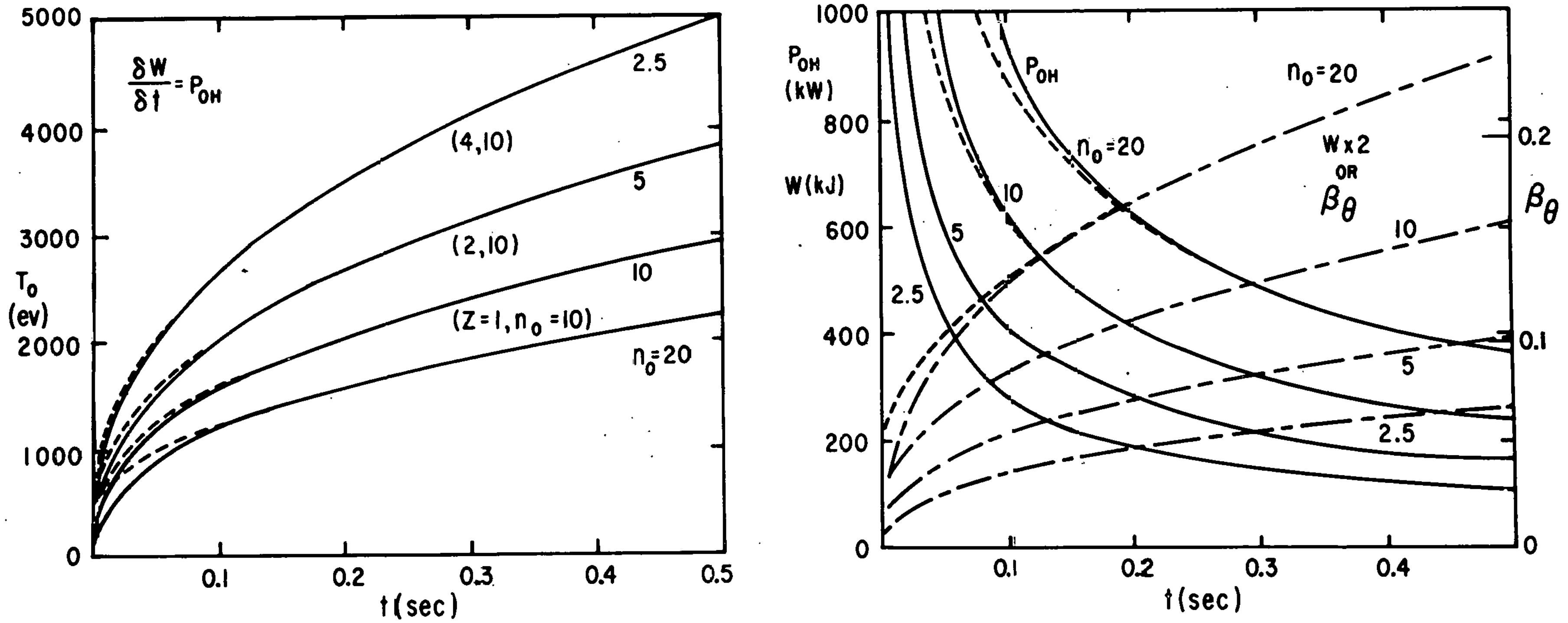

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Fig. 1. Ohmic heating of PLT plasma with $\tau'_E \rightarrow \infty$. Two initial values of T_o are assumed: 10 eV and 500 eV; n_o is in units of 10^{13} cm^{-3}; and Z=Z' values are for $n_o=10^{13}$ cm^{-3}. [B_ϕ = 50 kG, q = 3, R = 130 cm, A = 3(I_{OH} = 1.25 MA).]

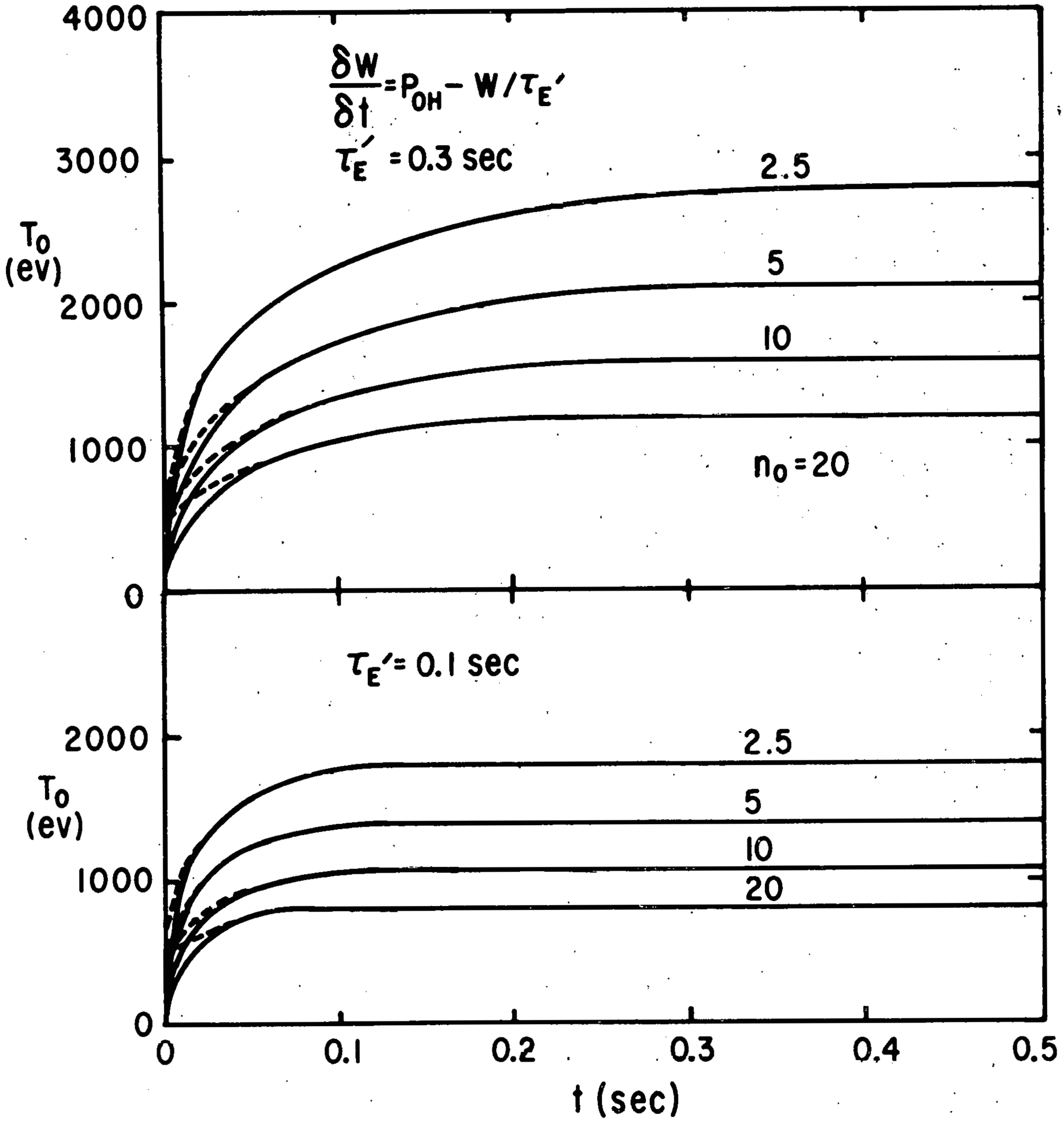

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Fig. 2. Ohmic heating of PLT plasma with $\tau'_E = 0.3$ sec. and 0.1 sec.

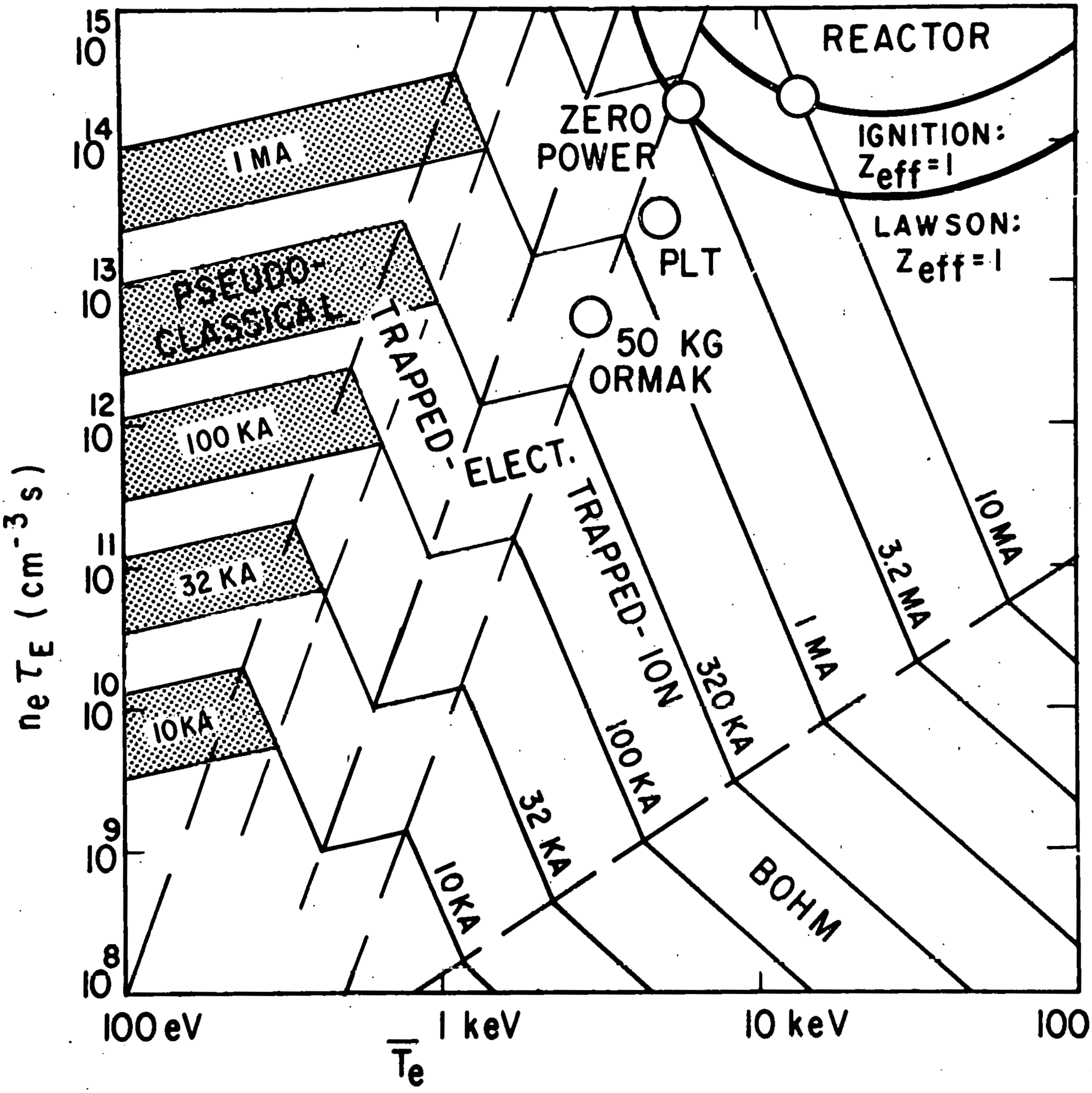

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Fig. 3. Theoretical temperature scaling of $n_e\tau_E$ as given in Ref. 1.

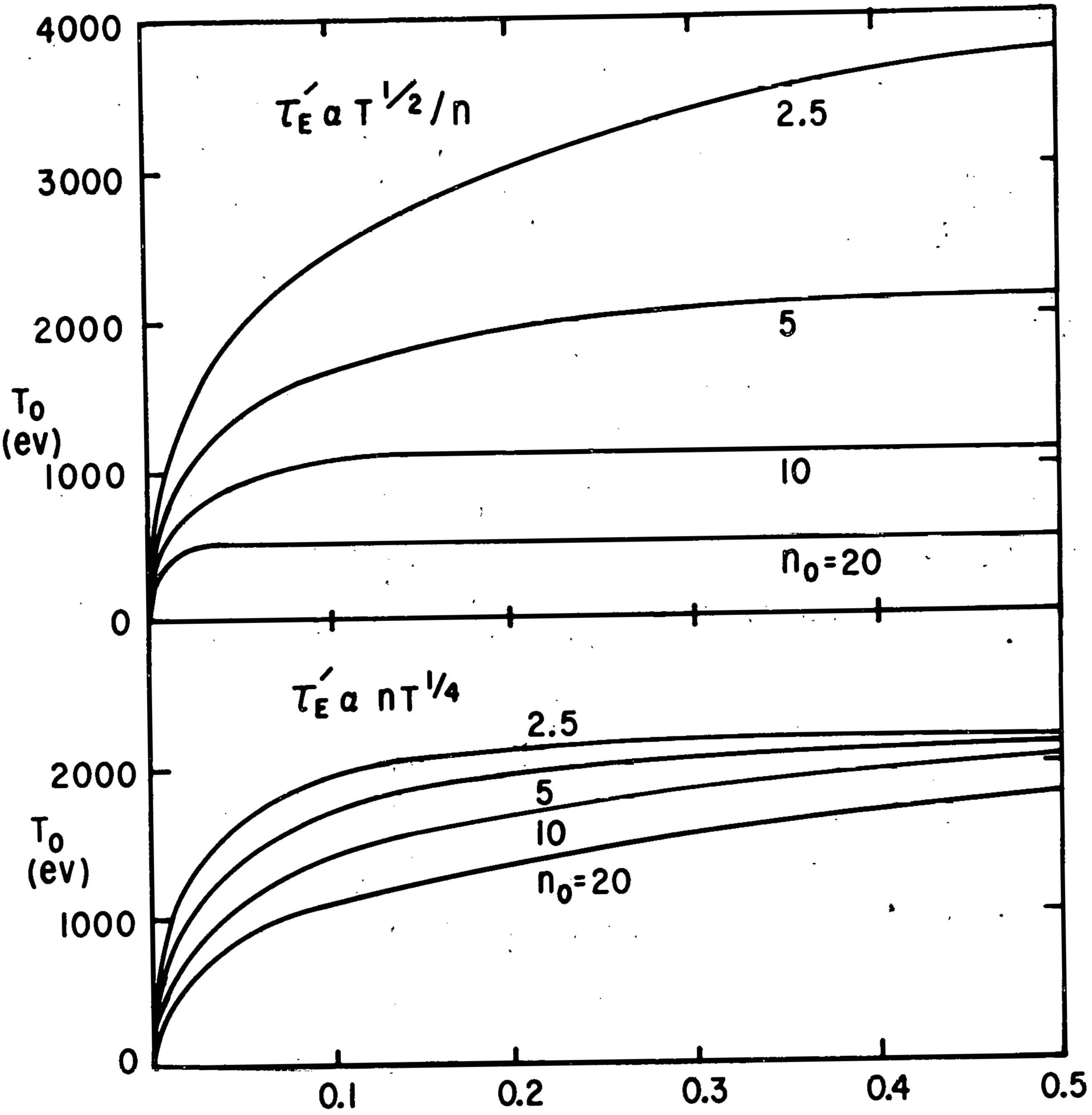

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Fig. 4. Ohmic heating of PLT plasma with τ'_E values corresponding to two pseudoclassical laws. $\tau'_E = 0.3$ sec at $n_o = 5 \times 10^{13}$ cm^{-3} for both plots.

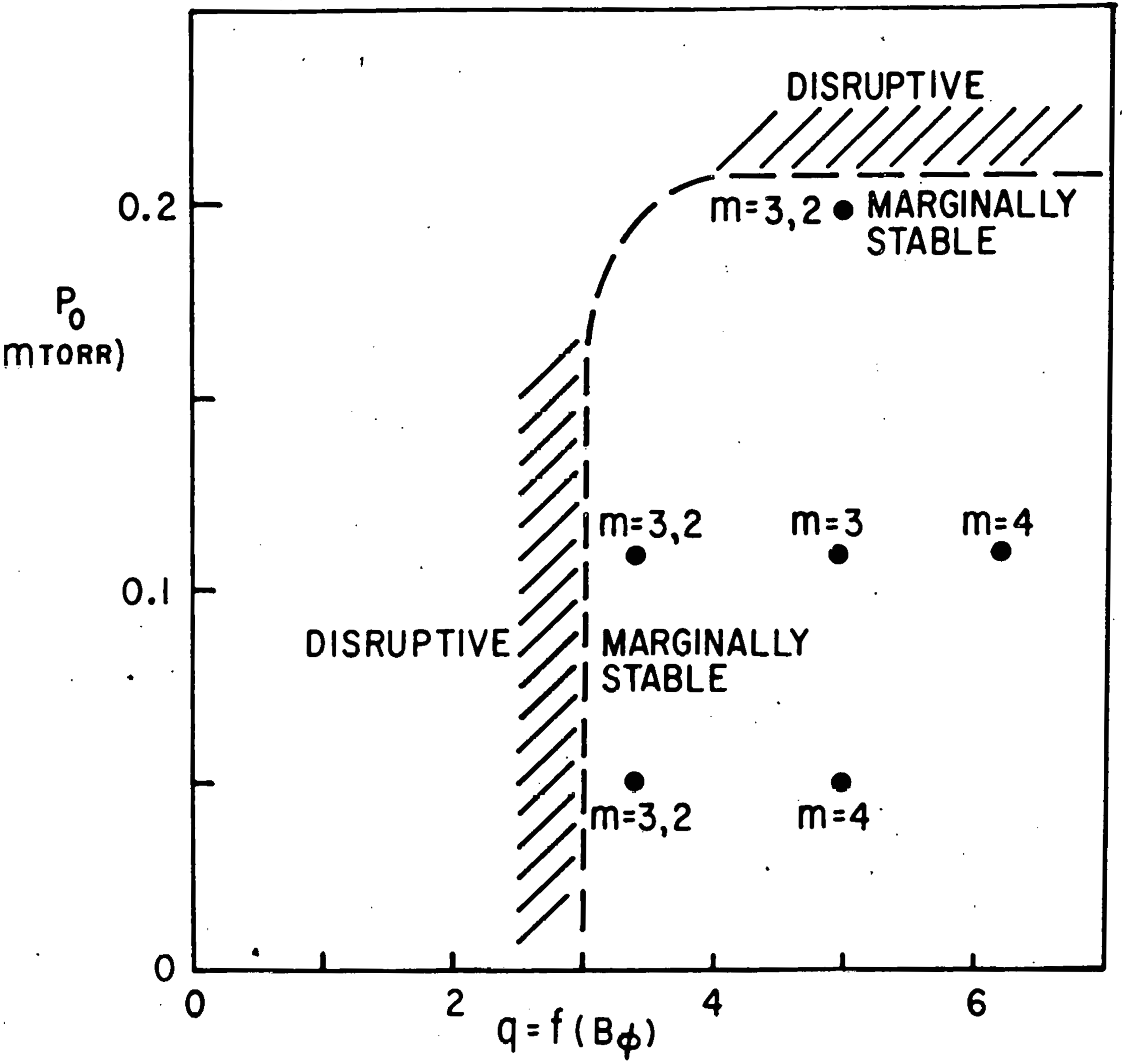

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Fig. 5. Stability diagram for ST tokamak plasma showing the low q limit for stable operation. [Helium discharges with I_{OH} = 42 kA, a ~ 11.5 cm (discharges of Table I in Ref. 15).]

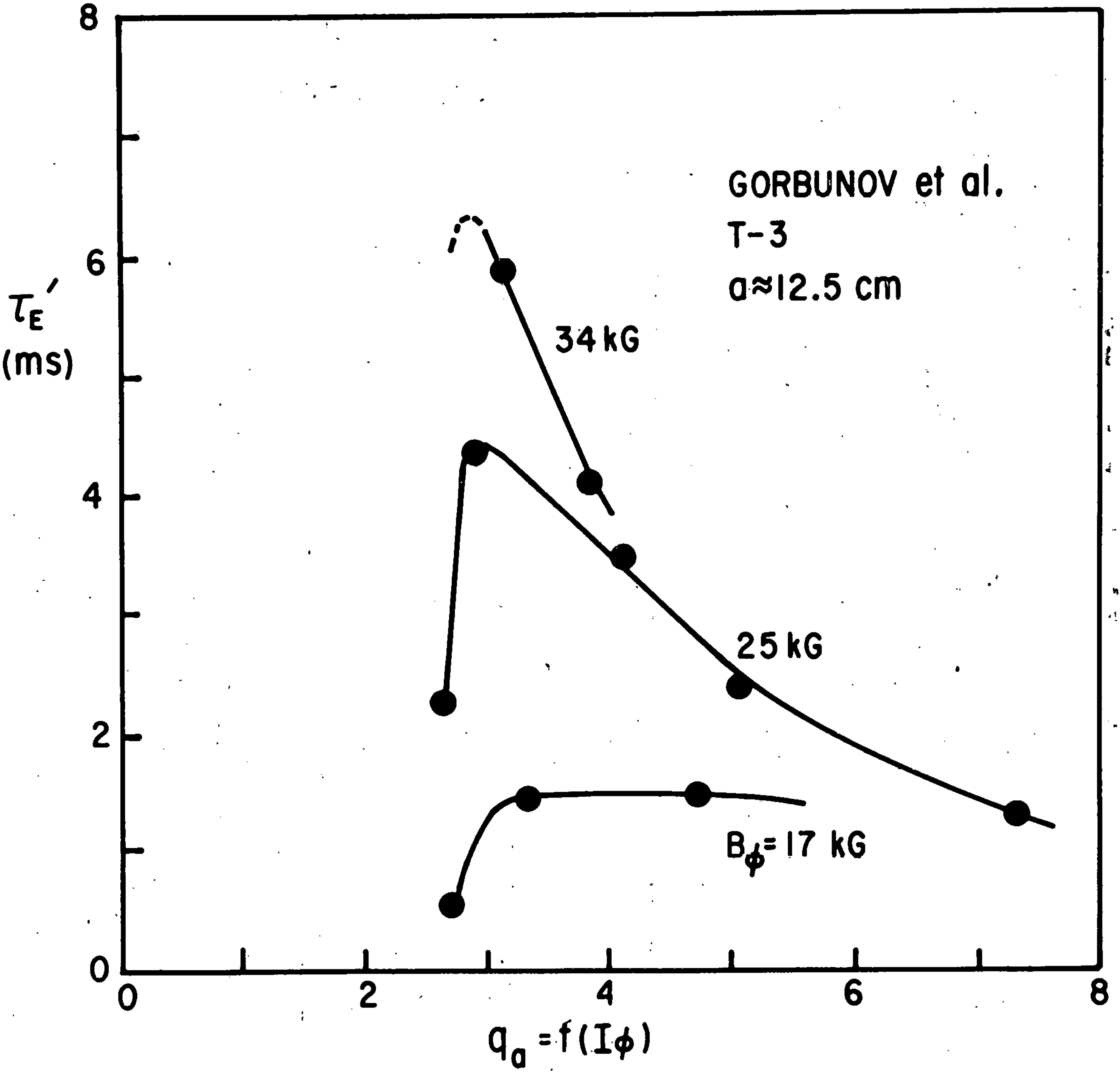

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Fig. 6. τ'_E versus q for the T - 3 tokamak derived from the data of Ref. 17. The diminution of τ'_E before the onset of the disruptive instability is clearly illustrated.

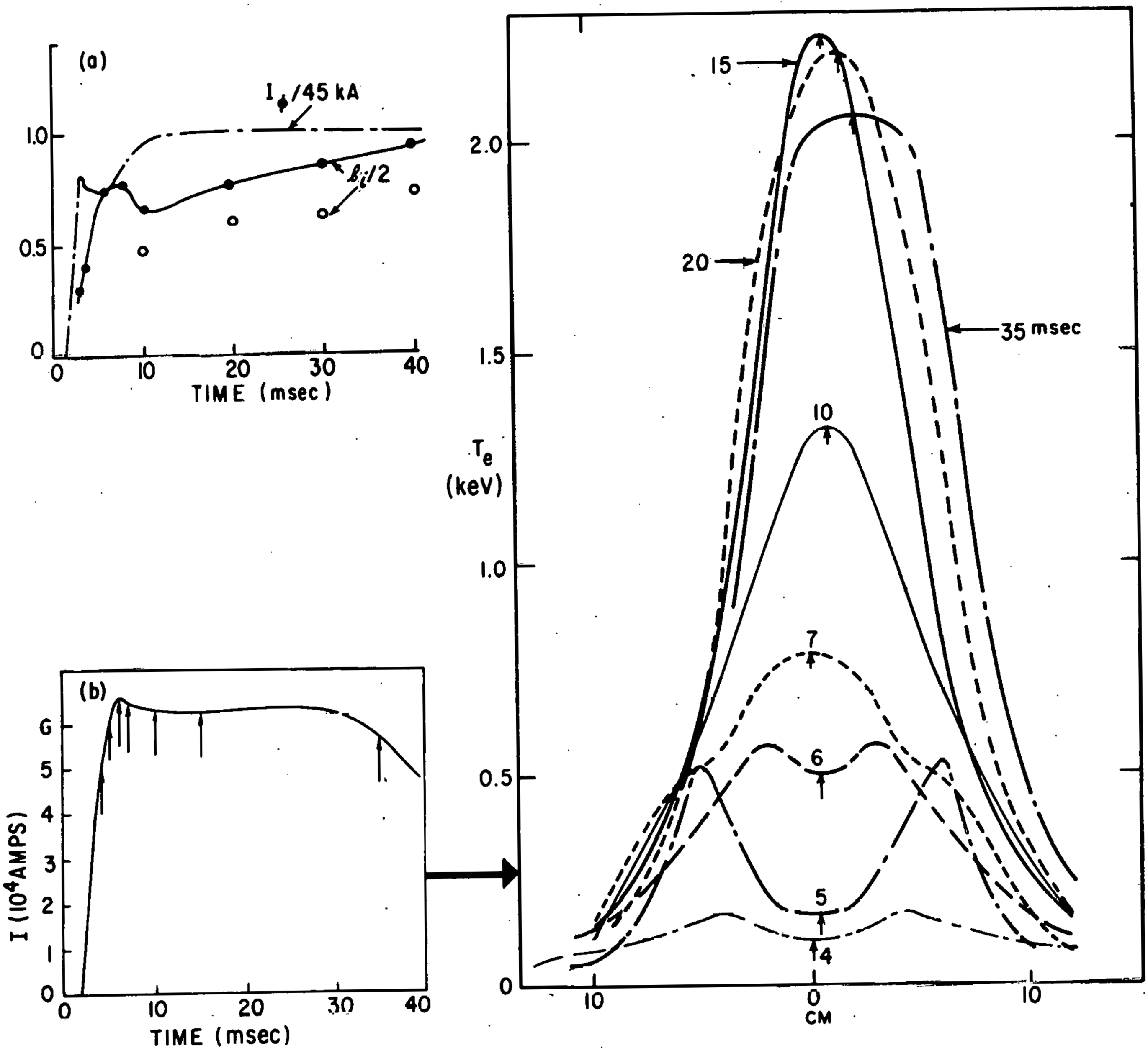

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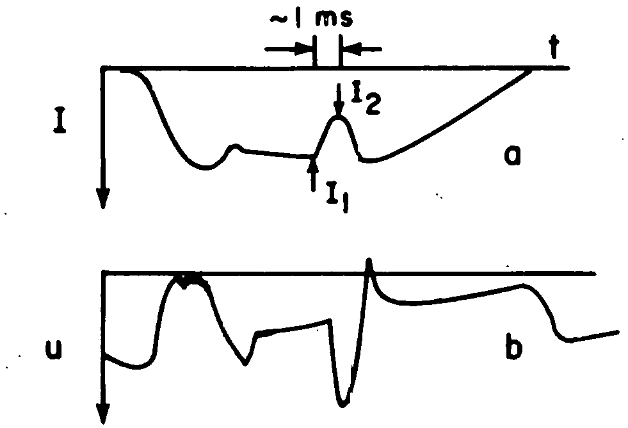
Fig. 7. Time evolution of discharges in the ST tokamak: (a) ℓ_i (nh/cm) is measured for a hydrogen discharge with $B_\phi = 34.4$ kG and a ~ 12 cm, and (b) Thomson scattering measurements are for $B_\phi = 43$ kG and a ~ 12 cm.



MIRNOV - T-3, JETP LETTS 12, 64 (1970)

$$\beta^* = \frac{R}{b}\left[\left(\frac{u}{U}\right)_2 - \frac{I_1}{I_2}\left(\frac{u}{U}\right)_1\right] + \left(\ln\frac{b}{a} + \beta + \frac{\ell_i}{2}\right)_1 \frac{I_1}{I_2} + \frac{\Delta I}{I_2}$$

$$L_{EXT} = 2\ln\frac{b}{a} = \frac{\Delta V}{\Delta I} \quad - \quad \text{Sounding}$$

$$\left(\beta + \frac{\ell_i}{2}\right)_1 = -\frac{R}{b}\frac{\Delta u}{\Delta U} - \left(1 - \frac{L_{EXT}}{2}\right) \quad \text{For small } \Delta I$$

For τ_E and $\tau_{SK} \gg 1_{\mathrm{msec}}$

$$\beta^*\ \text{Theory} = 2\ln\frac{b}{a} + \left(\beta + \frac{\ell_i}{2}\right)_1 \frac{I_1^{\,2}}{I_2^{\,2}}$$

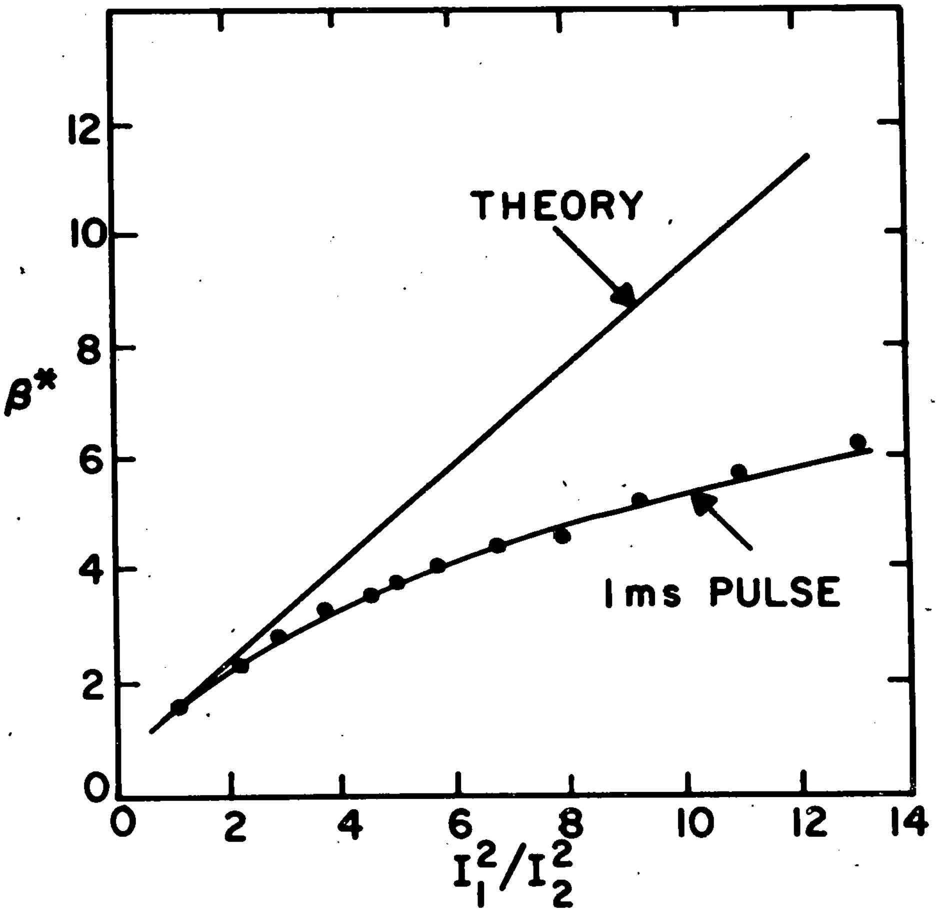


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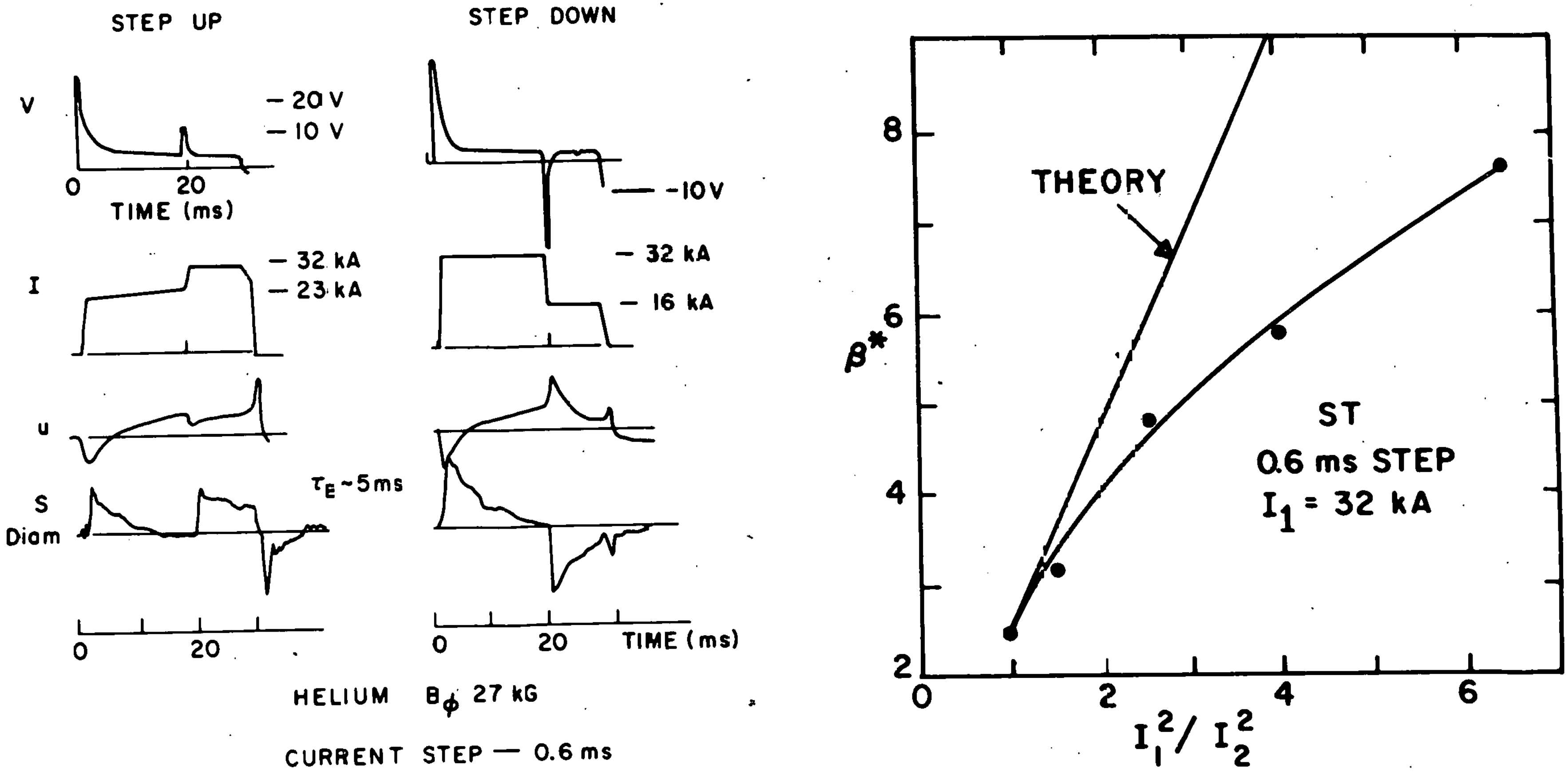
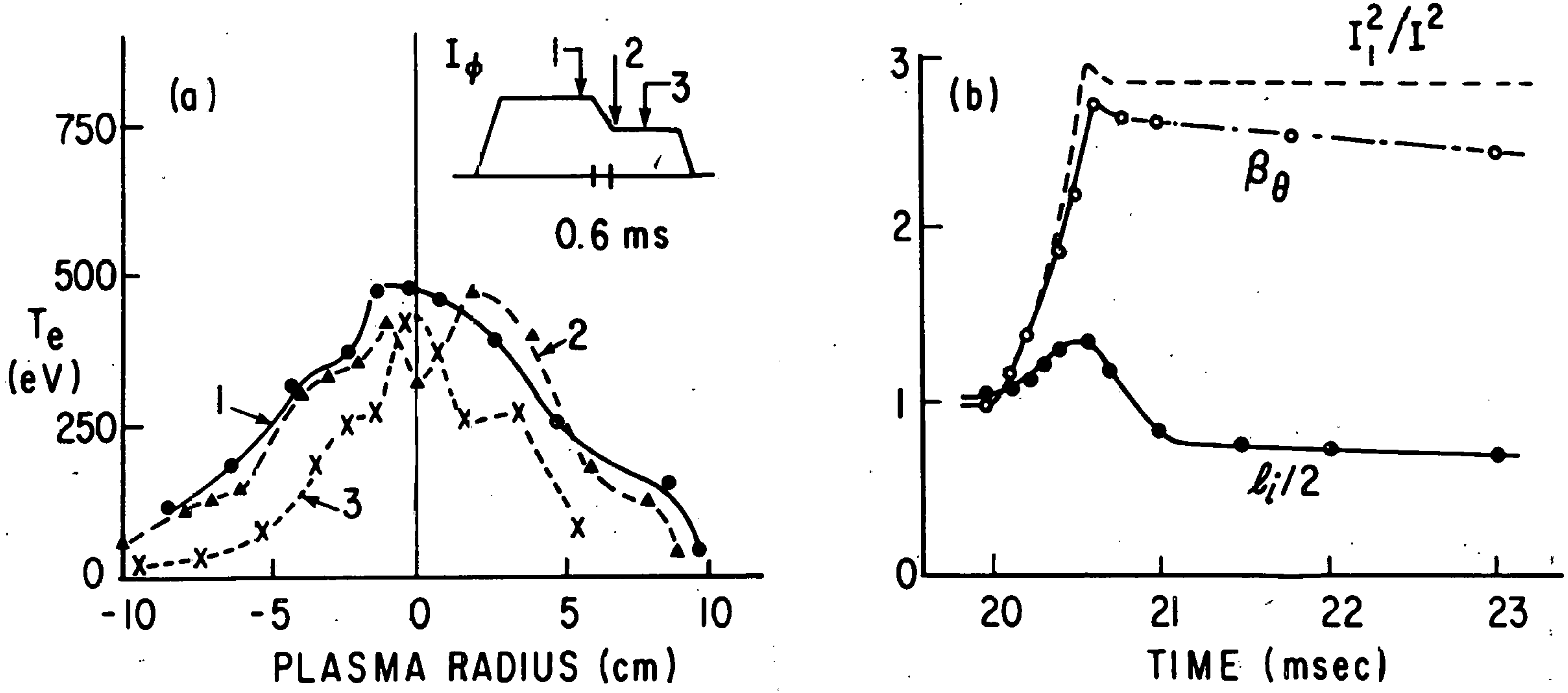
Fig. 8. Pulsed current experiment on the T - 3 tokamak as described in Ref. 19 - δI_{Max} occurs in ~ 1 msec.



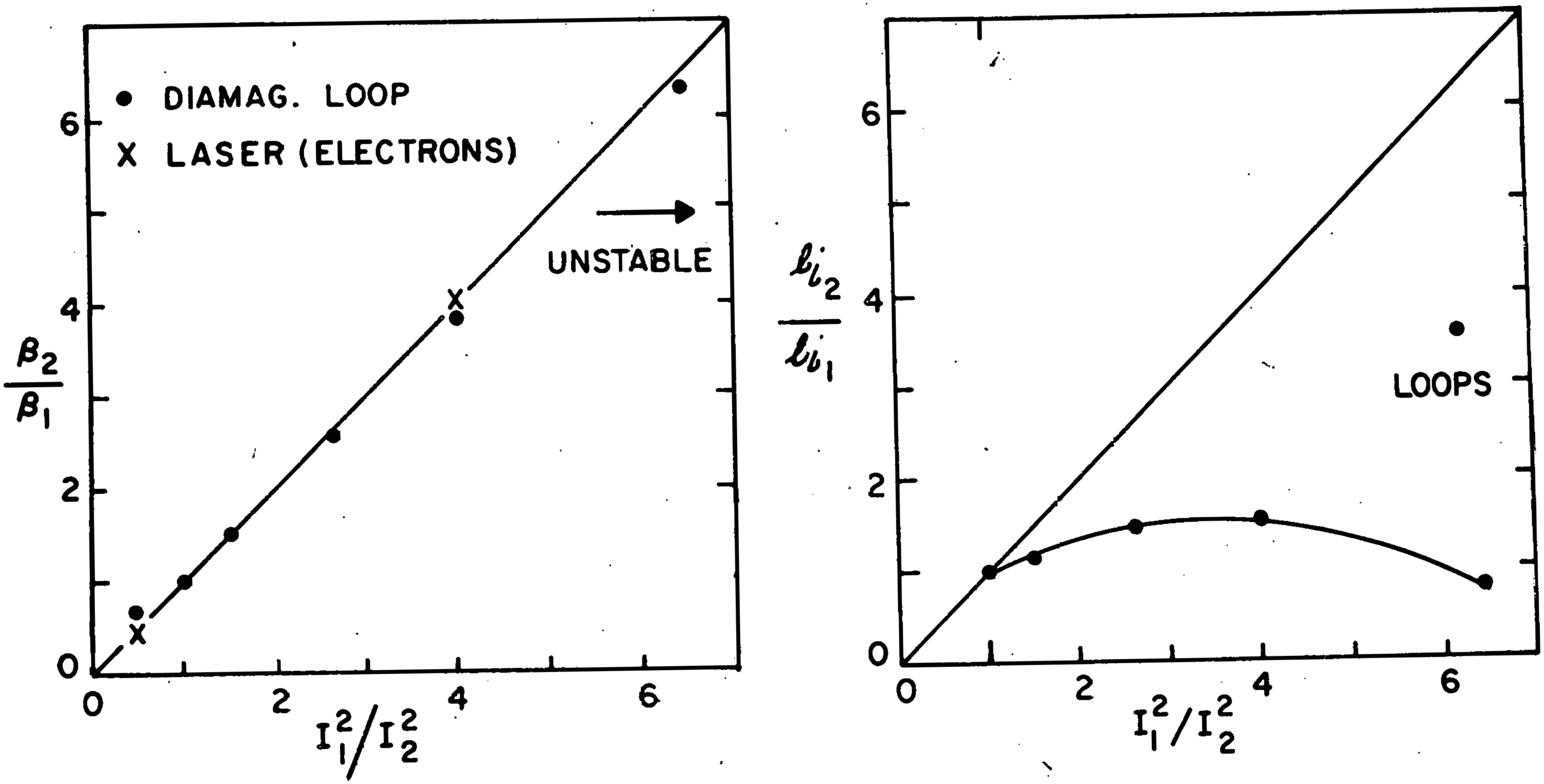
743581

Fig. 9. Stepped current experiment on the ST tokamak with the addition of the diamagnetic loop measurement - δ I occurs in 0.6 msec.



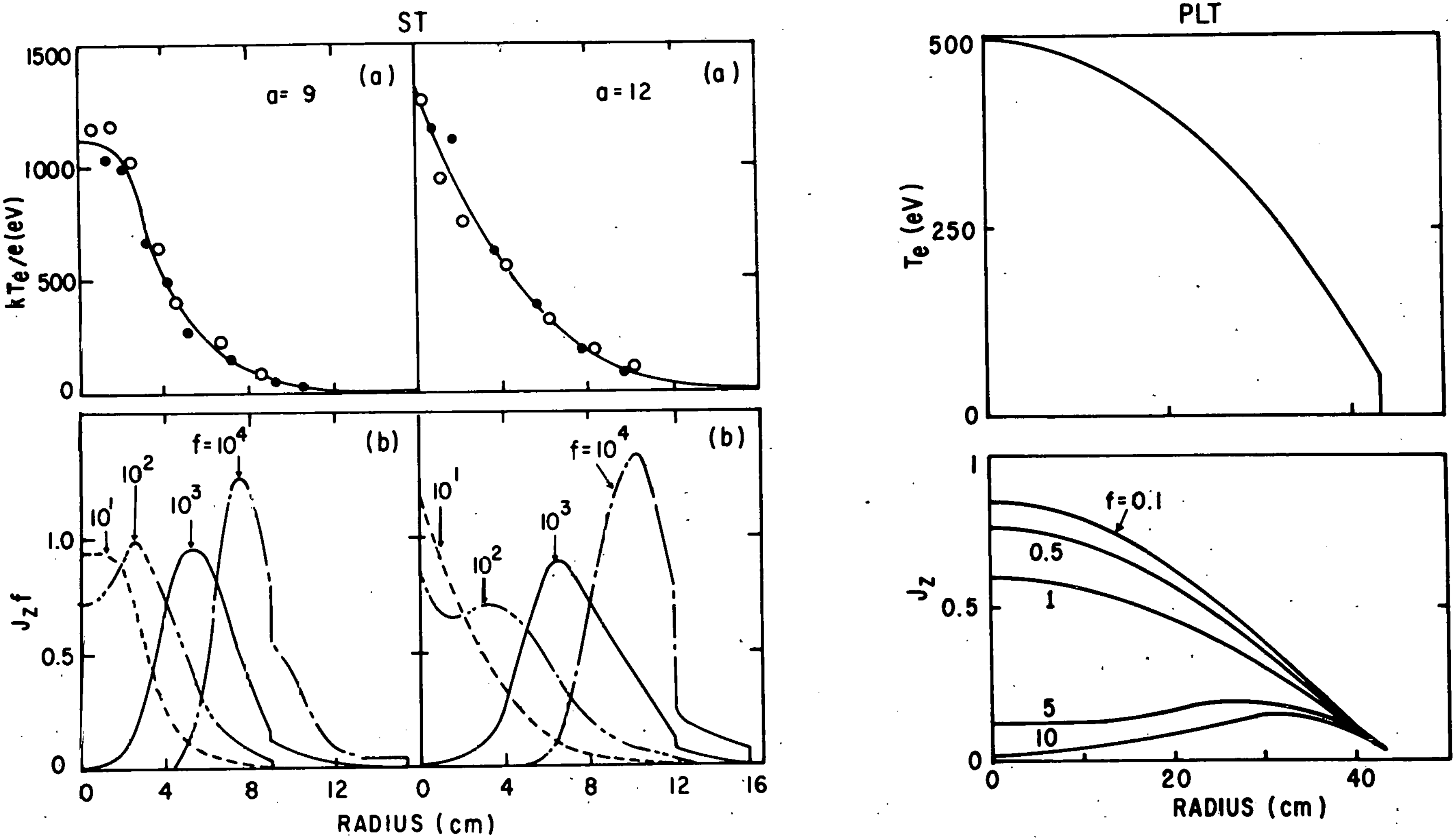
723255

Fig. 10. Temperature profiles before and after the step down in current of Fig. 9 and the time resolved behaviour of β_θ and ℓ_i.



723257

Fig. 11. β_ϕ ℓ_i scaling for a fast δI step (Δt = 0.2 msec) on the ST tokamak. (The initial conditions are those of Fig. 9 at I_{OH} = 32 kA).

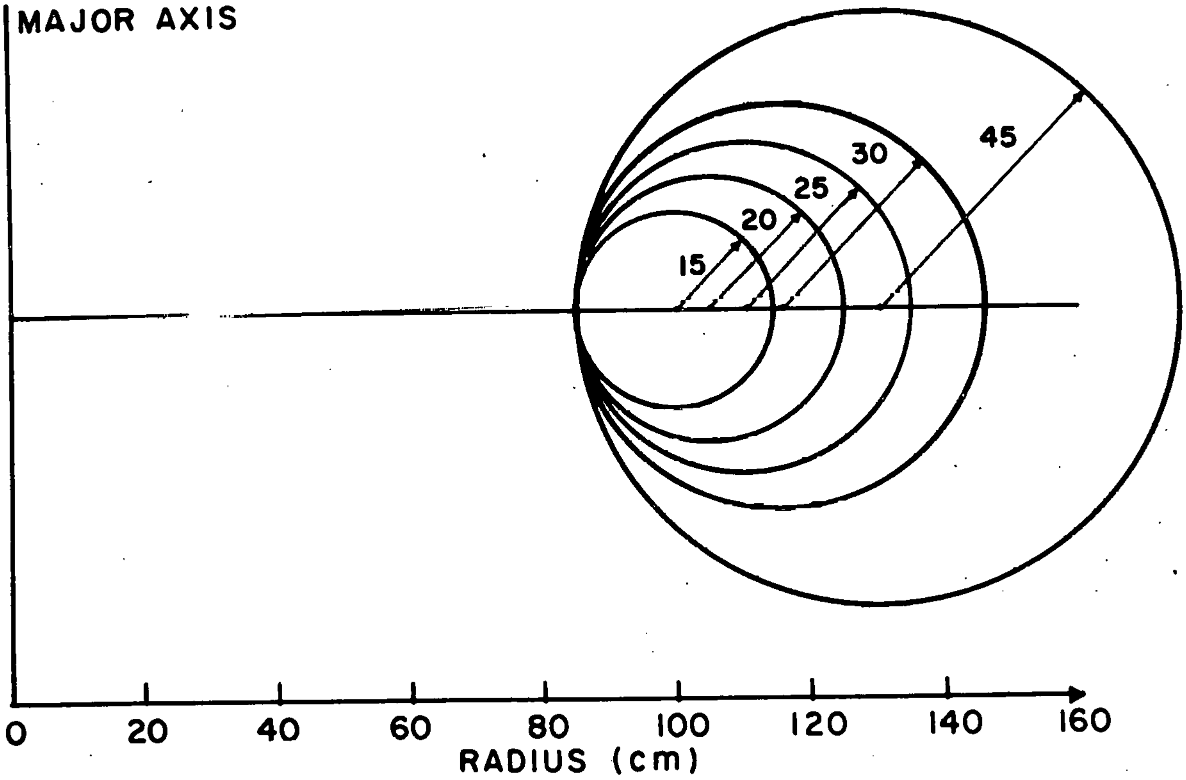


743586

Fig. 12. Current density profiles calculated for (a) Left plots: helium discharges on the ST tokamak (B_ϕ = 33 kG, I_{OH} = 30 kA) using the experimental temperature profiles and the ac impedance measurement of $\eta(r)/\eta_{cl}(r)$, and (b) Right plots: a PLT discharge with Z_{EFF} = 1.

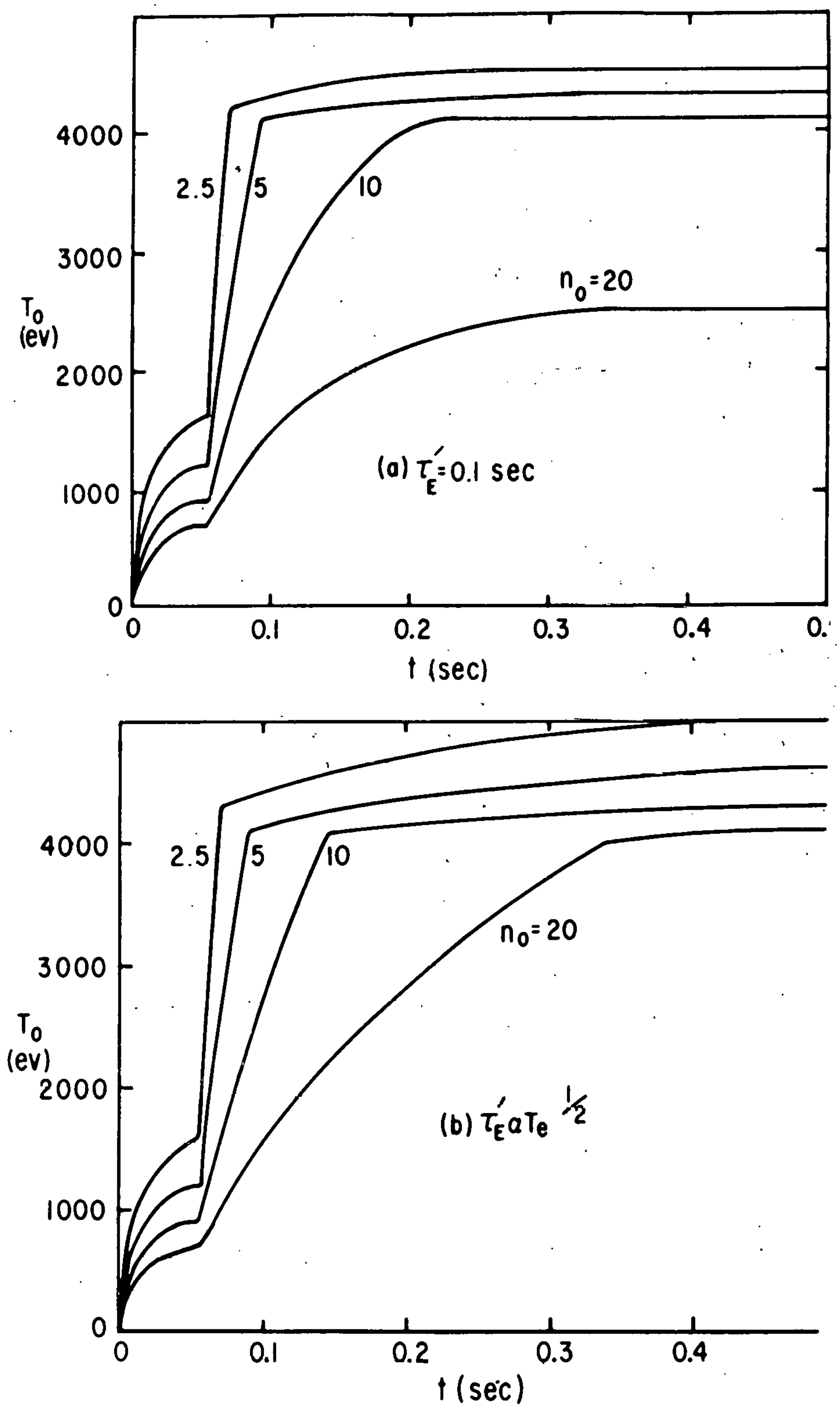
PLT Regimes with Reduced Apertures
[for fixed q(a) = 2.4]

r cm	R cm	B_ϕ kG	I kA
45	130	50	1600
30	115	57	900
25	110	59	690
20	105	62	490
15	100	65	300



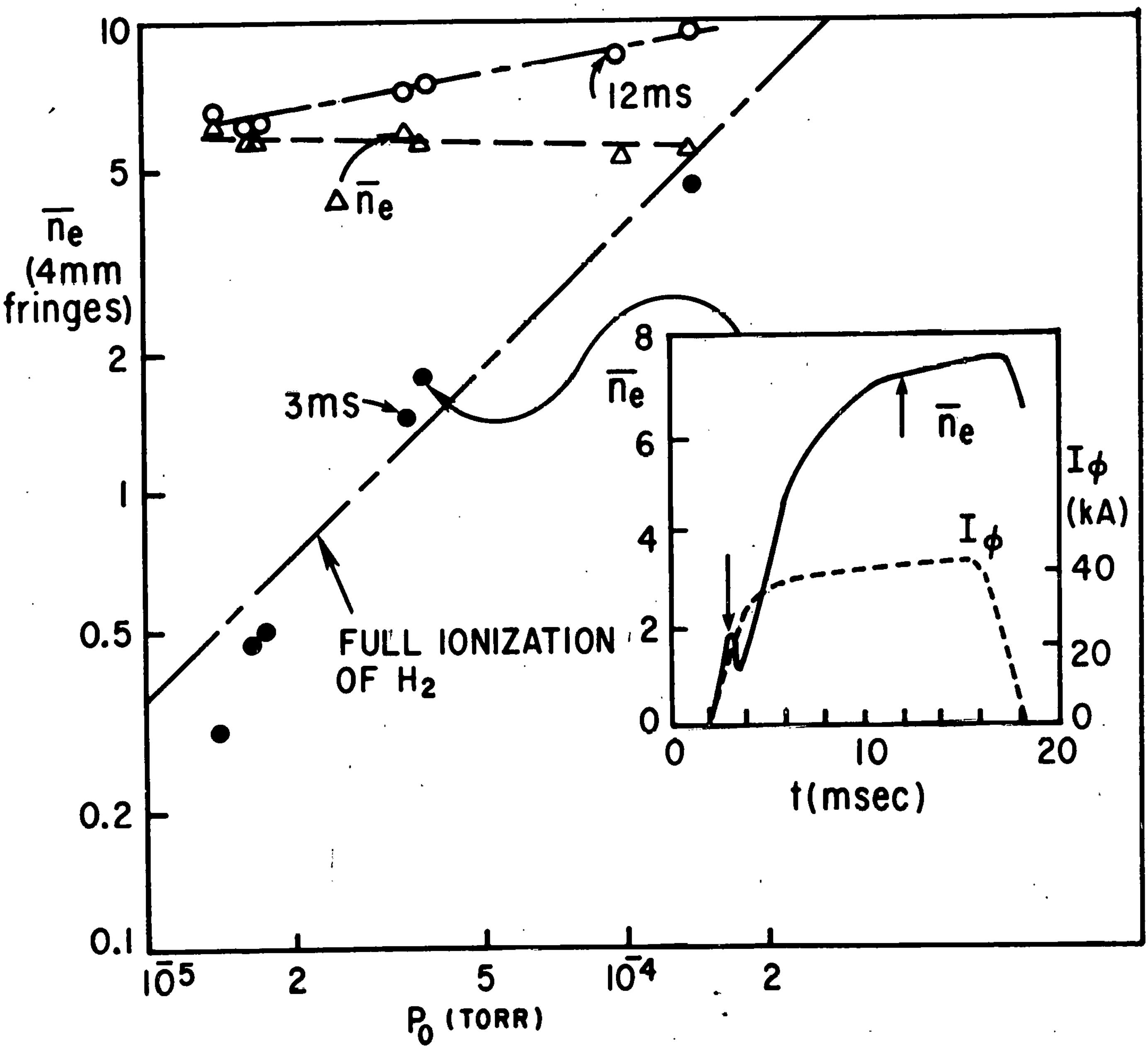
713570

Fig. 13. Plasma expansion method for avoiding skin effect.



753312

Fig. 14. Performance of auxiliary heating for (a) $\tau'_E = 0.1$ sec and (b) $\tau'_E \;\alpha\; T_e^{1/2}$ and equal to 0.1 sec in the absence of auxiliary heating for all values of n_o (units of 10^{13} cm^{-3}). An auxiliary power of 5 MW is applied until T_o reaches 4 keV at which time it is reduced to a level sufficient to maintain T_o at 4 keV in the absence of ohmic heating.



743587

Fig. 15. The dependence of electron density on filling pressure during the initial operating phase on the ST tokamak (B_ϕ = 33 kG).