Disruptive MHD Activity during Plasma Current Rise in Alcator A Tokamak

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ABSTRACT

During the current rise phase of the Alcator A discharge a series of disruptions occurs, related to MHD activity of poloidal periodicity m, at limiter q values approximately 1.6 m (m integral). The electron temperature profile is peaked at the center throughout. It is shown, however, that current diffusion with the experimental T_e profiles typically leads to hollow current profiles and that the disruptions appear to be related to the local minimum of q inside the plasma attaining near-integral values. Disruptions may be avoided by decreasing the rate of current rise. This leads to improved plasma conditions throughout the discharge.

1. Introduction

The current-rise phase of tokamak discharges, subsequent to ionization of the plasma but prior to the attainment of maximum current, involves significant nonclassical current diffusion processes. These processes are generally necessary to explain the absence of a dramatic skin effect in the spatial current profile.

Experimental evidence strongly supports the hypothesis that resistive MHD instabilities are responsible for the rapid current diffusion. On T-3 [1] and T-4 [2] a sequence of MHD oscillations with decreasing poloidal periodicity, m, was identified, associated with rising plasma current. Corresponding to the peak of each mode, a positive perturbation of the loop voltage occurred and the plasma internal inductance increased, indicating a narrowing of the current profile. Such sequences of positive voltage spikes have been observed on a number of tokamaks [1-4]. The relaxation of a hollow current profile was studied directly in LT-3 [5] and shown to be due to the growth, in this case, of an m=4 MHD mode in the presence of a local minimum of the safety factor, q, slightly below 4. This led to rapid current diffusion in the plasma and subsequent flattening of the current profile.

Thus a persuasive picture emerges as follows: as the current rises, a hollow current profile develops, which is known theoretically [6] to be unstable to tearing modes with m greater than the minimum q within the plasma. The fastest growing mode is that with the minimum possible m and so as q falls the dominant mode number m decreases in sequence. As each mode grows to a sufficient amplitude, magnetic reconnection occurs, causing rapid diffusion and flattening the current profile [7-9].

The present work reports a study of these phenomena on the Alcator A tokamak. We find that throughout most of the current rise phase the electron temperature profile remains peaked on axis. The characteristic series of relaxations is observed. However, the voltage spikes do not occur when the limiter safety factor, q_{ℓ}, is approximately integral, as has been reported elsewhere [2]. Instead, we find that relaxations occur, for typical parameters, when $q_{\ell} \approx (1.6 \pm .1)m$ with m the integral value of the related helical MHD mode.

An analytic criterion is derived in Section 3 for the formation of a hollow current profile and used to deduce the temperature evolution, assuming the plasma diffusion rises so as to maintain the profile only marginally hollow. The results are in good agreement with experimental observations.

A numerical integration of the current diffusion equation with prescribed temperature profiles is described in Section 4. It shows that the current profiles may be expected to be hollow, due to the skin effect, and that the typical ratio of limiter q to the minimum q value in the plasma is approximately 1.6. The MHD mode number, m, corresponds to this local minimum value of q, and thus the mode is internal, not localized to the plasma edge.

2. Experimental Observations

Our investigations of the MHD disturbances in the current rise phase have utilized a variety of diagnostics. Azimuthal and toroidal mode structure is deduced from the signals of two sets of magnetic pick-up coils. The first set consists of 12 discrete loops at a single toroidal location and spaced at 30° intervals in the poloidal direction. The second set is displaced 90° toroidally from the first and is comprised of 8 discrete coils at 45° intervals in the poloidal direction. Both sets are located at a radius of 13.5 cm, between the vacuum vessel (0.5 mm stainless steel bellows) and the copper shell (a_ℓ= 10 cm, $r_{copper\ shell}$ = 14 cm).

In addition to the standard loop diagnostics (e.g., voltage, plasma current, etc.), we have observed the electron cyclotron emission at the second harmonic using a tunable Fabry-Perot interferometer [10] to determine the temporal and spatial evolution of the electron temperature. Calibrating the electron cyclotron signal against Thomson scattering measurements gives us the absolute value of the temperature as well. Finally, the coupling of the MHD modes into the center of the plasma and the appearance of sawtooth oscillations is monitored from the soft x-ray emission ($E \geq 1$ keV) along the central chord using a collimated surface barrier detector.

Figure 1 illustrates the typical disruptive behavior in the current rise phase. Gas breakdown and the subsequent plasma current rise occurs approximately 1 ms after the application of large loop voltage. No pre-ionization is used and the initial plasma density is predetermined to be $\bar{n}_e \simeq 3 \times 10^{13} cm^{-3}$ by adjustment of the static gas fill pressure in the torus. During the first 7-10 ms the plasma density remains relatively constant owing to recycling from the cold walls; then it begins to increase as cold neutral gas is pulsed into the torus at about 7 ms. As the plasma current rises, a series of voltage spikes appears on the loop voltage. Associated with each of these individual disruptions is a sharp decrease in the rate of rise of plasma current, dI_p/dt, and an abrupt decrease in the central electron temperature, as illustrated by the sharp breaks in the trace fourth from the top in Fig. 1.

Electron cyclotron emission indicates that the sudden reductions in the electron temperature occur at all radii. Of importance also is the fact that the temperature profile is always peaked on axis during the current rise phase, increasing with time as shown in Fig. 2. Peaked temperature profiles such as these would thus tend to support skin currents only in the hottest portion of the plasma, well inside the limiter edge.

For large rates of current rise, disruptions begin shortly after breakdown and plasma formation. As shown in Fig. 3 the statistics for a large number of discharges studied indicate that the disruptions generally are not associated with an integral q surface at the limiter but tend to group around integral multiples of 1.6.

In view of the number of coils available, we have restricted our analysis to the slightly later stages when $q(a) \leq 12$ and MHD activity characterized by $m \leq 6$ can be discerned experimentally.

As the plasma current increases to the point where q_ℓ approaches 1.6 m, where m is an integer, a sudden increase in the MHD activity is observed on the magnetic loops. Simultaneous with the growth in MHD, a small amplitude oscillation at the MHD frequency is superimposed on a 1-3 volt increase in the loop voltage. When $q_\ell \approx 1.6$ m the loop voltage abruptly increases by up to 10 volts, accompanied by a short burst of hard x rays at the limiter and a sudden but moderate decrease in the electron temperature ($\Delta T_e \lesssim 20\%$). Disruptions of this nature tend to result in a slightly outward shift of the plasma and are characteristic of those early in the current rise state, i.e., for large m. Later disruptions for lower m tend to be more severe and have a different signature on the loop voltage. The positive voltage spike is often preceded by a large and very fast negative voltage spike. This results in a more dramatic decrease of the electron temperature, as indicated in trace 4 of Fig. 1, with reductions as large as 70% having been observed. Disruptions of this nature result in an abrupt inward shift of the plasma, as indicated in trace 2 of Fig. 1, the plasma returning to its pre-disruption position on the time scale of the electron temperature recovery. Plasma motion during these disruptions is most likely dominated by the poloidal β changes, as discussed in section 5.

As the plasma current continues to increase, the voltage and MHD activity decrease, the electron temperature recovers and continues to increase with the rising plasma current. As the plasma current approaches a value such that $q_\ell \approx 1.6$ (m-1) the sequence of events is repeated.

Although the modes tend to be quite distorted, a characteristic m value can be ascertained. In Fig. 4 we indicate the typical measured perturbations associated with each of the observed disruptions. During the early phase of the discharge there appears to be a general distortion of the perturbations toward the inside, which appears to be due to the significant inward displacement of the plasma column during the first 15 ms of the discharge. Later on as the plasma density and β increase, the column moves toward the outside slightly and the MHD modes are distorted toward the outside. In all cases the toroidal mode number is n=1.

The m of the final disruption is determined by the peak plasma current (minimum integral q value in the plasma) attained during the initial rise phase. In general, for Alcator A discharges with $q_\ell \leq 3.5$ at the end of the rise phase, the last MHD disruption is an m=2, n=1, mode. With this m=2 disruption (which is sometimes atypical in being the second of two with the same m) the central electron temperature does not fully recover to its previous level and sawteeth appear in the central temperature trace in Fig. 1. This implies that the m=2 disruption allows the current channel to peak rapidly on axis, forcing $q(o) < 1$. Thereafter the sawtooth disruption regulates the current and temperature profile evolution.

Experimentally we have found two ways of eliminating or at least reducing the severity of the disruptions during the current rise phase. The first method is to increase the static gas fill pressure and/or the immediate pulsing of cold neutral gas into the torus. A higher plasma density in the breakdown and subsequent current rise phase is then obtained. The available ohmic input power is approximately unchanged.

Power balance considerations then dictate that the rate of increase in the central electron temperature will be reduced for the higher density cases. This allows faster current diffusion, reducing the tendency to disrupt.

The second method is to change the rate of rise of the plasma current by reducing the voltage of the ohmic heating primary circuit. Using this technique we have been able to study these MHD disruptions for a broad range of current rise rates. In Fig. 5 we have plotted the value of dI_p/dt and I_p for which a disruption has been observed. Note the clustering of the disruptions around non-integral values of the limiter q. For large values of $\dot{I}_p$ and a given I_p the plasma exhibits MHD disruptive behavior. However, when the rate of current rise is lower, corresponding to parameters below the diagonal line in Fig. 5, the discharge evolves free of disruptions. We have found that thus changing the current rise rate has little influence on the rate of central temperature increase, at least until T_e attains values near those of the steady state.

3. Analytical Discussion of Hollow Current Formation

The observation of disruptions associated with modes which are internal to the plasma and the expectation that in the presence of a hollow current profile such modes will develop, leads us to consider the conditions of the formation of such a hollow current.

Determination of the complete current profile, even given a known temperature profile, $T_e(r,t)$, requires, in general, a full integration in time and space of the current diffusion equation. Such an integration, performed numerically, is described in Section 4. However, significant insight may be obtained analytically by restricting our discussion to the plasma center. This is possible since for all but very pathological temperature profiles the formation of a hollow current profile begins on axis (r=0).

We assume Ohm's law in the form

$$j(r) = \sigma(r)\cdot E(r) \tag{1}$$

so that at r = 0, where $\partial\sigma/\partial r = \partial E/\partial r = 0$, we have

$$\frac{\partial^2 j}{\partial r^2}\Big|_o = \frac{\partial^2 \sigma}{\partial r^2}\Big|_o E_o + \frac{\partial^2 E}{\partial r^2}\Big|_o \sigma_o \quad . \tag{2}$$

Maxwell's equations immediately give

$$\frac{\partial^2 E}{\partial r^2}\Big|_o = \frac{\mu_o}{2}\cdot\frac{\partial j}{\partial t}\Big|_o = \frac{\mu_o}{2}\,\frac{dj_o}{dt} \tag{3}$$

and taking $\sigma(r) \propto T_e(r)^{\frac{3}{2}}$ we also have

$$\frac{\partial^2 \sigma}{\partial r^2}\Big|_o = \frac{3}{2}\,\frac{\sigma_o}{T_{eo}}\,\frac{\partial^2 T_e}{\partial r^2}\Big|_o \quad . \tag{4}$$

Then the current is hollow if

$$0 < \frac{\partial^2 j}{\partial r^2}\Big|_o = \frac{3}{2}\,\frac{j_o}{T_o}\,\frac{\partial^2 T_e}{\partial r^2}\Big|_o + \frac{\mu_o \sigma_o}{2}\,\frac{dj_o}{dt} \quad . \tag{5}$$

This condition may be rewritten so as to display its physical meaning by defining a temperature profile scale length

$$a_T = \left[\frac{-1}{2T_o}\,\frac{\partial^2 T}{\partial r^2}\Big|_o\right]^{-\frac{1}{2}} \tag{6}$$

and then a skin time $\tau_\sigma = \frac{1}{2}\, a_T^2\, \sigma_o \mu_o$. In these terms the condition for a hollow current profile becomes

$$j_o / \left(\frac{dj_o}{dt}\right) < \frac{1}{3}\;\tau_\sigma \quad . \tag{7}$$

In words: the profile becomes hollow if the scale time for the current increase is shorter than 1/3 the resistive skin time in the plasma center.

Now we suppose that the MHD instabilities have a regulating effect on the plasma temperature such that it can never evolve far from the marginally hollow current state. We then deduce the temperature evolution from the current evolution as follows: Write

$$\tau_\sigma = 3\, C T_o^{\frac{3}{2}} \tag{8}$$

(so that C is a function only of a_T), then the marginal condition is

$$T_o = \left[\frac{1}{C}\, j_o / \frac{dj_o}{dt} \right]^{\frac{2}{3}} . \tag{9}$$

If we further assume that the current profile shape changes only slowly compared to the rise time, i.e.,

$$\left| \frac{j_o}{I} \cdot \frac{d}{d_t} \left(\frac{I}{j_o} \right) \right| << \left| \frac{1}{j_o} \frac{dj_o}{d\,t} \right| , \tag{10}$$

where I is the total current, then we may write

$$j_o \Big/ \frac{dj_o}{d\,t} \approx I \Big/ \frac{dI}{dt} , \tag{11}$$

which is quite accurate in our case, as confirmed in section 4, but may not necessarily be true in general. The marginal condition then gives T_o in terms of I:

$$T_o = \left[\frac{1}{C}\, I / \left(\frac{dI}{dt}\right) \right]^{\frac{2}{3}} . \tag{12}$$

As an example closely approximating the experimental situation on Alcator A, we take $I(t) = I_{pk}\,[1-\exp(-t/\tau_I)]$, (where I_{pk} is the peak plasma current attained in the rise phase and τ_I is the characteristic current rise time), in which case we obtain

$$T_o = \left[\frac{\tau_I}{C} \left(e^{t/\tau_I} - 1 \right) \right]^{\frac{2}{3}} . \tag{13}$$

In Figure 6 we plot the temperature evolution predicted from this equation taking the appropriate values: $a_T = 6$ cm, $Z_{eff} = 1$, $\ln \Lambda = 15$ and $\tau_I = 10$ ms. Also shown are experimental values of central temperature deduced from electron cyclotron emission for a discharge exhibiting MHD disruptions during the current rise phase. The agreement is remarkable, considering all of the uncertainties, up to 16 ms when the temperature begins to saturate. This saturation is indicative of transport effects taking over the dominant role in determining T_e and the plasma moving away from the marginally hollow state.

The criterion, Eq. (7), is rather insensitive to the current rise rate as such. For example, for linear current rise, Eq. (7) is independent of the value of dj_o/dt. However, the temperature is indirectly affected by the current via the energy balance in the plasma. It is easy to understand that if the current at any time is small enough there will be insufficient ohmic heating power to sustain the plasma temperature at the marginally hollow state. In this case no disruptions may be expected to occur.

4. Numerical Integration of the Current Diffusion Equation

A computer code was used to integrate numerically the 1-D current diffusion equation

$$\frac{\partial j}{\partial t} = \frac{1}{\mu_o r} \frac{\partial}{\partial r} \left[r \frac{\partial}{\partial r} \left(\frac{j}{\sigma} \right) \right] \tag{14}$$

in cylindrical coordinates, ignoring toroidal effects, using an explicit finite difference scheme. Classical Spitzer resistivity was assumed and the experimentally observed temperature was modeled by prescribing

$$T_e(r, t) = \Gamma_o t e^{-r^2/a_T^2} . \tag{15}$$

The boundary condition at the plasma edge consisted of prescribing the total current as

$$I(t) = I_{pk}(1 - e^{-t/\tau_I}). \tag{16}$$

Figures 7a and 7b show computed current and q-profiles respectively for typical disruptive current-rise conditions on Alcator A. A hollow current does indeed develop with an unstable local minimum of q well inside the plasma. It should be noted that the ratio of q at the limiter to the minimum q is between 1.5 and 1.8 during most of the rise phase. This corroborates the observation on Alcator A that the disruptions are internal.

In addition we have attempted to simulate MHD disruptions. This was done by anomalously increasing the resistivity by a factor of 10 and enforcing a large negative rate of change of electron temperature ($-10\Gamma_o$) whenever the current profile was hollow and the local minimum in q was near integral: $0 < (m - q_{min}) < 0.1$. The code was then allowed to continue on after each "disruption" with the normal resistivity and prescribed temperature rise rate. Whilst this scheme cannot be expected to reproduce the detailed dynamics of the disruption itself, it does model the salient features of the change in macroscopic parameters. Figure 8 shows typical results. When the minimum q is integral the current profile flattens and the process repeats itself with the minimum in q decreasing with each successive disruption. Again note that the disruptions are still internal, with the ratio of $q_\ell / q_{min} \simeq 1.6$, and that the current profile evolves in a marginally hollow manner, consistent with experimental observations. Moreover, we calculate the voltage at the vacuum bellows from the voltage at the plasma edge plus the inductive voltage due to the flux between the plasma and the liner. In Fig. 8c we compare the calculated loop voltage for the above given parameters with the experimentally measured loop voltage. The agreement is quite good with respect to both the magnitude and the temporal evolution of the loop voltage, demonstrating that no sustained large resistance anomaly is required to allow current penetration.

We have also verified with the code that for typical Alcator A profiles, $a_T < 7$ cm if the rate of temperature rise is ≤ 60 eV/ms, the growth of the current can occur without the formation of a hollow profile.

This simulation does not address the various transport and radiation losses which influence the temperature profile during the rise phase. However, the electron temperature profiles and other prescribed parameters are consistent with the Alcator A data, and the current diffusion equation is independent of loss mechanism. Thus we have shown that with the given parameters hollow current profiles will form even when T_e is peaked on axis. Moreover the ratio of q at the limiter to the minimum q is consistent with the observed q_ℓ values during disruptions on the assumption that the disruptions are associated with near-integer values of the minimum q and are thus internal.

5. Discussion

We have presented evidence to show that the MHD stability properties of the current rise phase of Alcator are dominated by the current profile shape well inside the plasma column. In particular a series of disruptions is observed arising from the formation of hollow current profiles. The electron temperature evolves, always peaked on axis, at a rate which appears to be governed by the hollow current profile formation, in such a way that a very strong current skin effect does not form.

The power balance within the plasma, as determined by current rise rate and electron density does not strongly influence the temperature rise rate as such. However, the severity of the disruptions necessary to dispose of any excess ohmic power and maintain the plasma near the marginally hollow state is determined by these power balance considerations. We have found this effect to be of vital importance for the operation of consistent well confined plasmas. The presence of strong disruptions in the current rise phase has been observed to degrade the plasma performance throughout the rest of the discharge. This degradation appears to be related to impurity content which probably arises from strong plasma interaction with the limiter or wall during severe disruptions.

The correct prescription for moderating the disruptions and thus achieving improved plasma conditions is to lower the current rise rate and increase the initial density, thus decreasing the ratio of ohmic power to rate of increase of plasma energy.

Our analysis has not addressed the detailed mechanisms occurring during the disruption. However several points should be noted in relation to our model and the experimental observations.

The shift of the plasma position during the disruption seems, at first sight, rather puzzling since we often observe in addition to very modest outward shifts more abrupt inward plasma motions (both are visible in Fig. 1). We note first, however, that the position is related to the plasma internal inductance ℓ_i through a term $\beta_p + \ell_i/2$ where β_p is the poloidal plasma beta. Thus an inward shift of the equilibrium implies a decrease in $\beta_p + \ell_i/2$. Fig. 9 shows the temporal evolution of β_p for the plasma of Fig. 1 calculated assuming parabolic density profile, gaussian electron temperature profile with width $a_T = 6.5$ cm and peak value as determined by cyclotron emission, and ion temperature equal to $0.5\ T_e$. Cumulative uncertainty in the absolute value of β_p may be as large as 50% due to uncertainties in T_i and n_e profiles. However the relative variations are probably accurate to better than 20%. It may be observed that the early disruptions, associated with slight outward shifts, have $|\Delta\beta_p| < 0.03$ so that a modest change in ℓ_i could account for the shift. The later, more severe, disruptions are accompanied by β_p changes of the order of -0.1, which can dominate over the change in ℓ_i leading to inward shifts similar to those in Fig. 1. For comparison the current profiles of Fig. 8 have $\ell_i \sim 0.9$ and $\Delta\ell_i \sim 0.05$ at a disruption.

The appearance of negative voltage spikes in addition to positive would suggest a negative derivative of plasma inductance. This might seem unexpected in a situation of relaxation of a hollow current profile. However, it is quite possible for the instantaneous rate of change of ℓ_i to be negative in this situation. For example, when widespread reconnection occurs the plasma might be expected to evolve towards a flat current distribution, whose ℓ_i is 1/2, less than the value 0.9 mentioned above. If such a negative $d\ell_i/dt$ did occur it would naturally help to explain any inward shift of the plasma. The time integral of the voltage excursion over a disruption is observed to be always positive even when sharp negative spikes are present. This suggests that the total inductance change is positive even though for brief periods $d\ell_i/dt$ may be negative.

The processes determining the temperature profile shape remain unclear, though it seems probable that a certain minimum level of MHD activity may be necessary to maintain the peaked temperature profile. We note however that definitely hollow temperature profiles have been observed in the early stages of other machines [11], and so it may be that processes other than MHD are responsible for the Alcator profile shape. For example, our quite high initial density (3-5 x $10^{13}cm^{-3}$) and associated recycling may be sufficient to keep the edge cool.

In attempting to apply our model to other machines a key relation is Eq. (12) predicting the temperature for marginally hollow profiles as a function of current and temperature profile scale length. Given this temperature as a function of time, strong disruptions may be expected if the ohmic power much exceeds that necessary to increase the plasma energy accordingly. As is expected for a diffusive process, the result is that to avoid severe disruptions the characteristic time of current rise should scale as linear dimensions squared.

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FIGURE CAPTIONS

Figure 1. Oscillograms of plasma parameters during current rise phase, showing (top to bottom) loop voltage, V_ℓ; plasma position; plasma current, I_p; central electron temperature, T_{eo} (from cyclotron emission); m = 3 pickup coil, m = 2 pickup coil. $B_T = 6$ T.

Figure 2 Electron temperature profiles measured during current rise deduced from $2\omega_{ce}$ radiation.

Figure 3 Frequency of occurrence of disruptions versus limiter q value for a sample of 123 disruptions. $B_T = 6$ T.

Figure 4 Loop voltage and measured poloidal field perturbations during current rise. The $\tilde{B}_\theta/B_\theta$ values were determined assuming no attenuation by the vacuum vessel. Auxillary measurements indicate the attenuation due to the liner may be as great as 50% for $\nu \approx 20$ kHz.

Figure 5 Location of disruptions with respect to plasma current, I_p, and its time derivative, $\dot{I}_p$. For discharges signicantly below the diagonal line, non-disruptive evolution is observed.

Figure 6 Experimental observations (points) of central electron temperature evolution and the theoretical evolution (line) for marginally hollow profile.

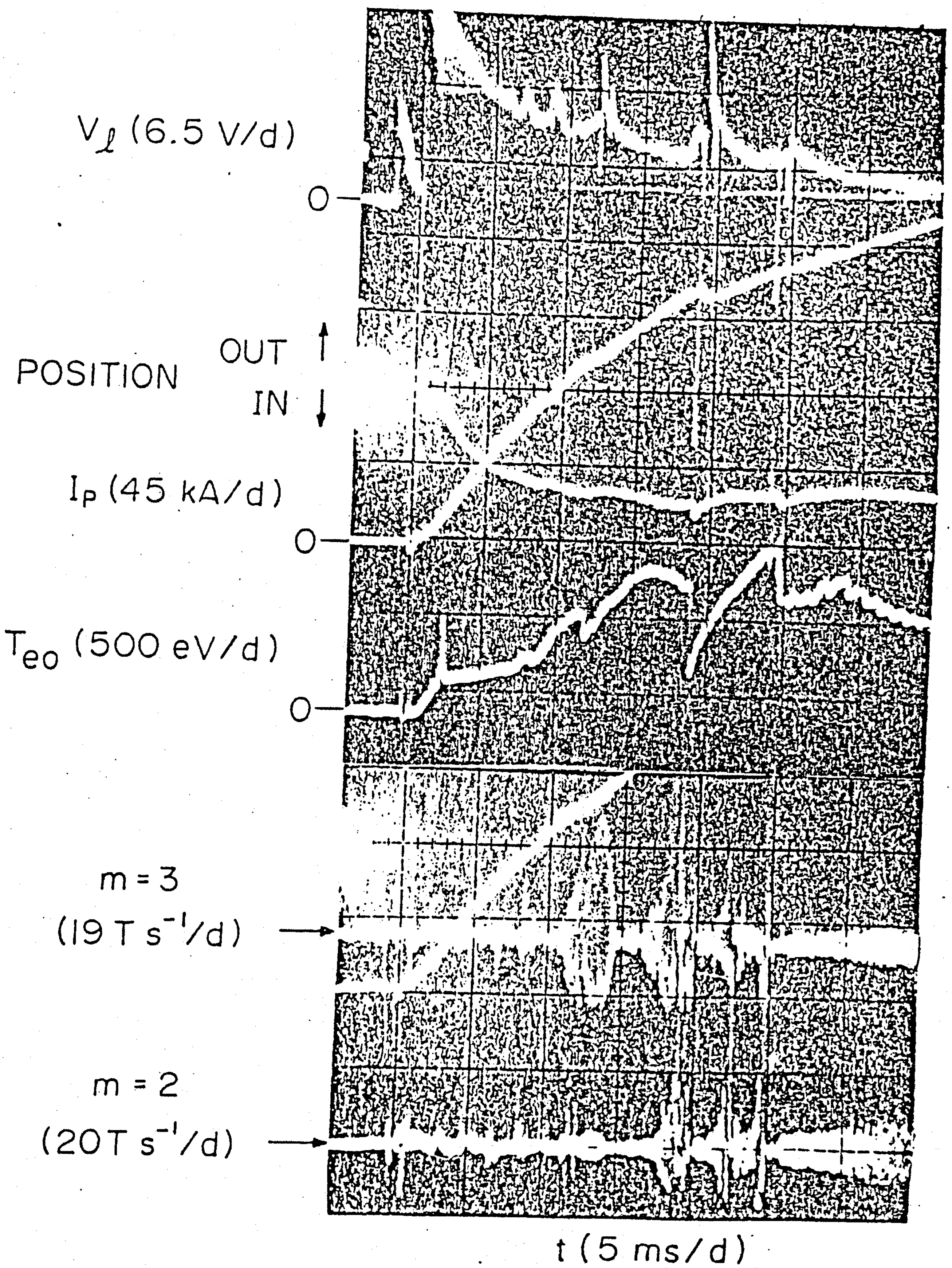
Figure 7 Results of computer simulation of current rise showing:
(a) current profile evolution, plotted at 1 msec spacings;
(b) corresponding q profiles: $B_T = 6$ T, $I_p = 200$ kA, $\tau_I = 10$ msec, $\Gamma_o = 80$ eV/ms, $a_T = 6.16$ cm. Disruptions were not modelled.

Figure Captions Cont.

Figure 8 Results of computer simulation for the case where B_T=6 T, I_p= 200 kA, τ_I= 15 msec, Γ_o= 80 eV/ms, a_T= 7.00 cm. Disruptions were modeled. (a) Current profile (b) q profile (c) Voltage (dashed line) compared with experimental results (solid line). The positive voltage spikes in the simulated disruptions have been truncated (with arrows).

Figure 9 β_p as a function of time for the discharge of Figure 1, $\bar{n}_e$ and T_{eo} are measured. $T_i = T_e/2$ is assumed. Cummulative errors may be as large as 50%, relative changes accurate to within 20%.

Fig 1



V_ℓ (6.5 V/d)
0
POSITION
OUT
IN
I_P (45 kA/d)
0
T_{eo} (500 eV/d)
0
m = 3
($19\ T\ s^{-1}/d$)
m = 2
($20\ T\ s^{-1}/d$)
t (5 ms/d)

Fig 2

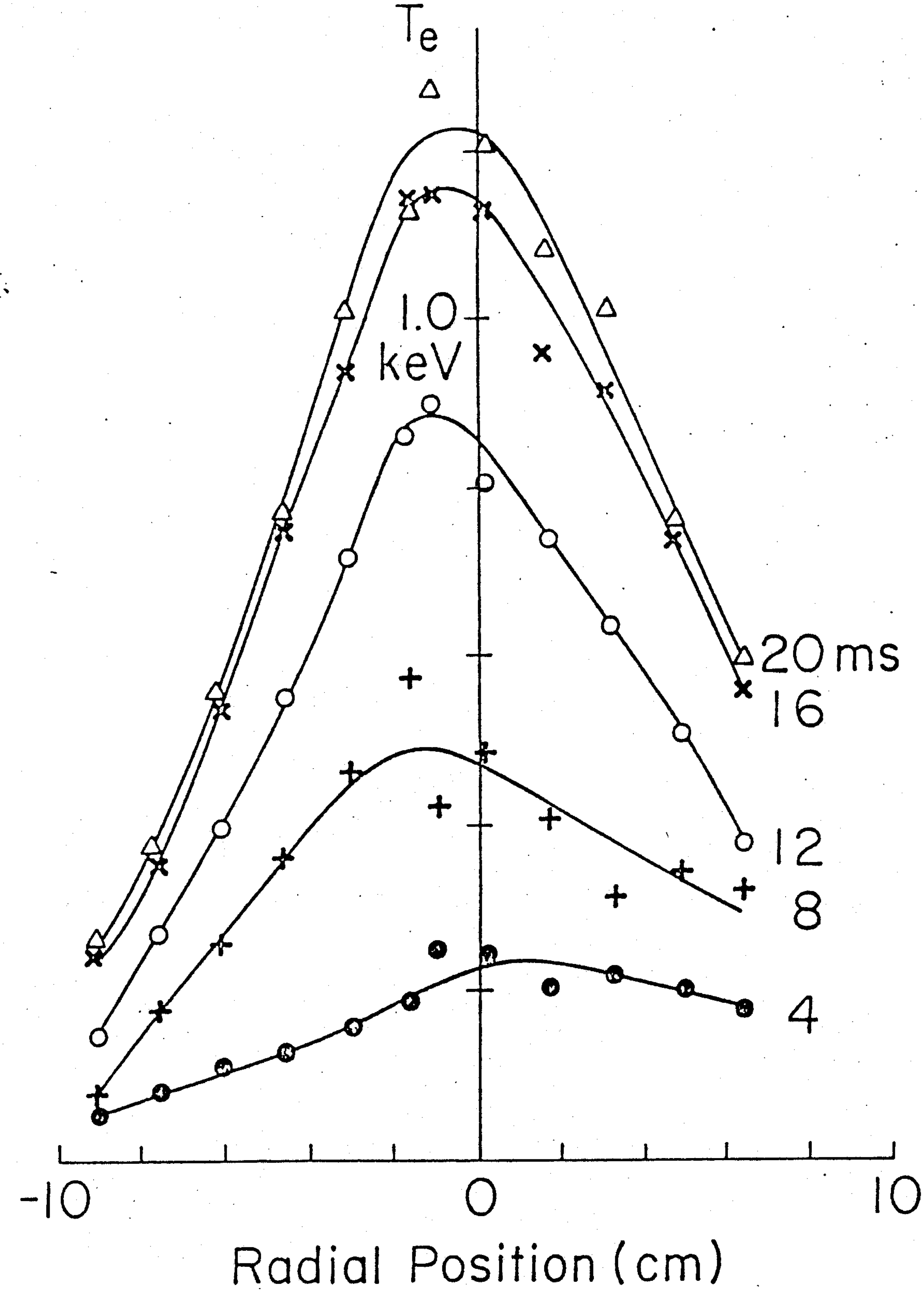


Fig 3

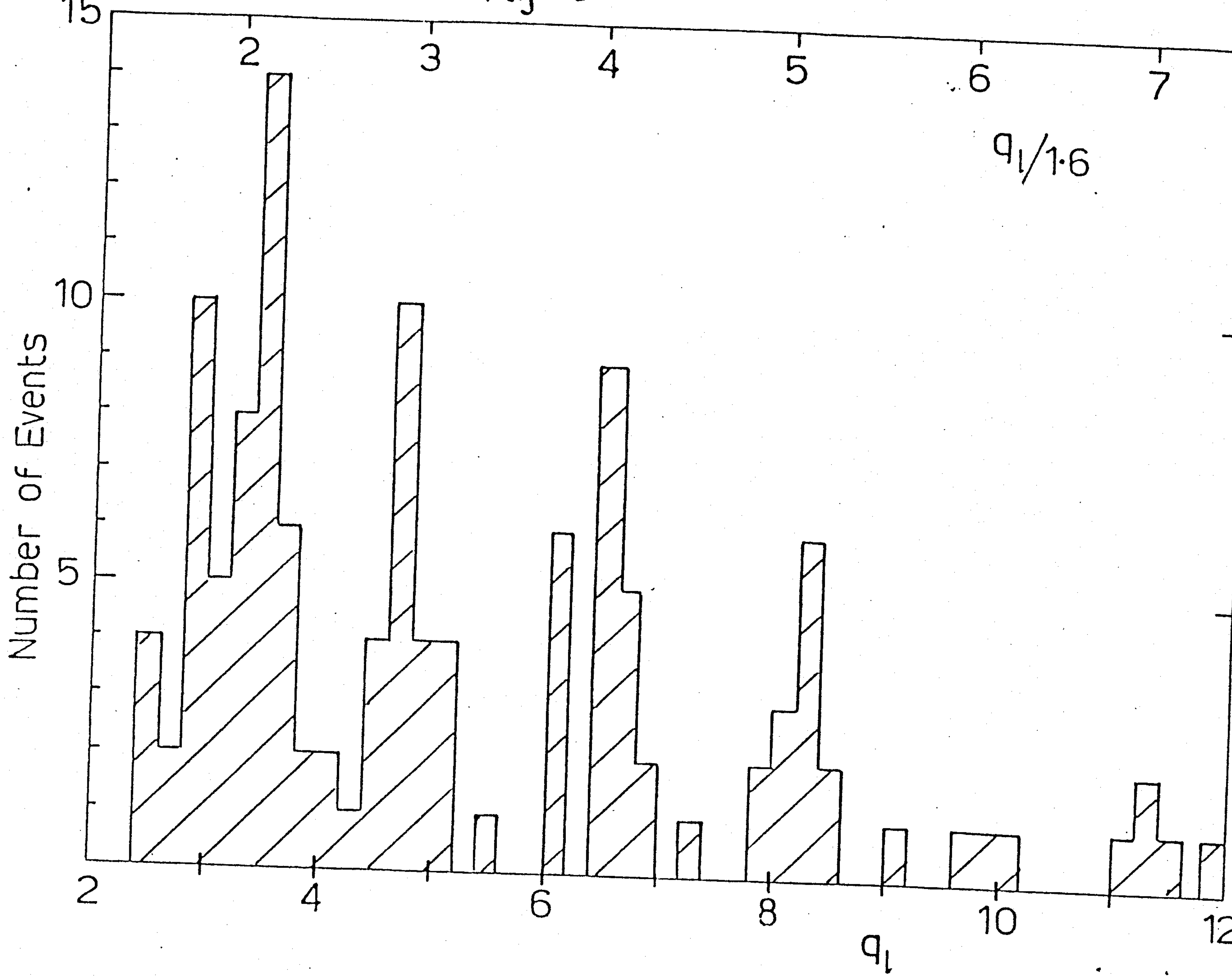
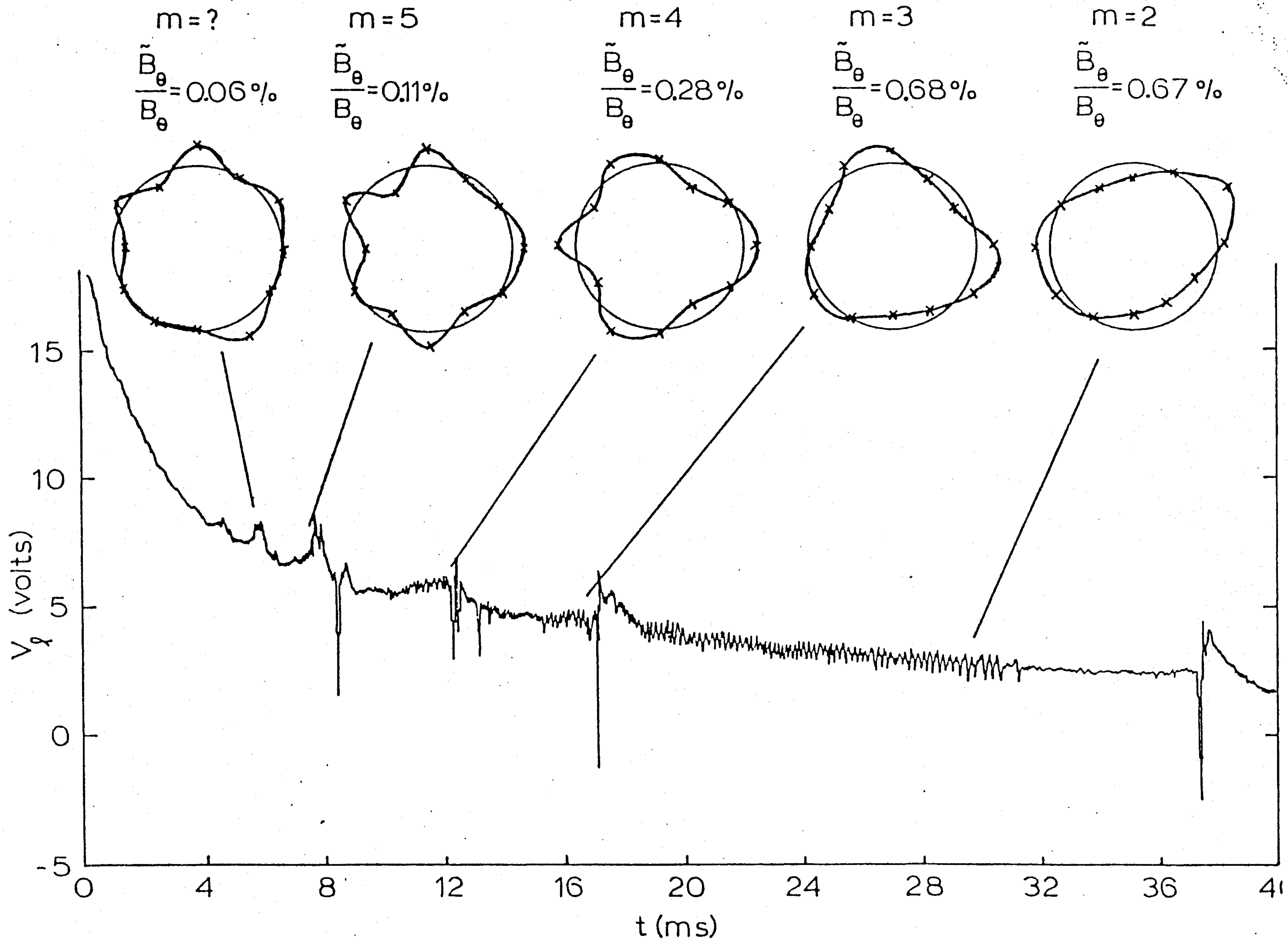


Fig 4



m = ?
$\frac{\tilde{B}_\theta}{B_\theta}$ = 0.06 %
m = 5
$\frac{\tilde{B}_\theta}{B_\theta}$ = 0.11 %
m = 4
$\frac{\tilde{B}_\theta}{B_\theta}$ = 0.28 %
m = 3
$\frac{\tilde{B}_\theta}{B_\theta}$ = 0.68 %
m = 2
$\frac{\tilde{B}_\theta}{B_\theta}$ = 0.67 %
15
10
5
0
-5
V_ℓ (volts)
0
4
8
12
16
20
24
28
32
36
40
t (ms)

Fig 5

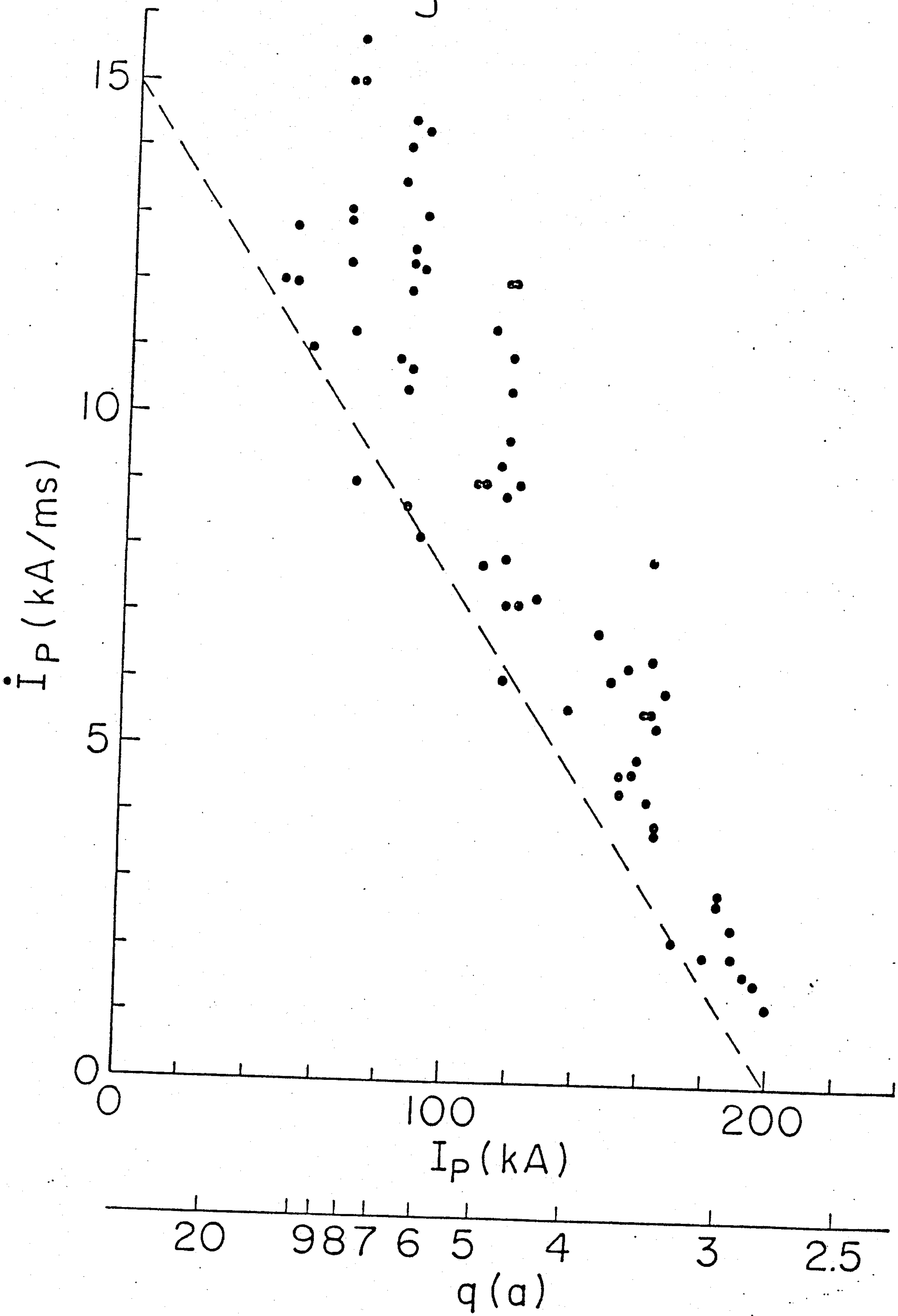


Fig 6

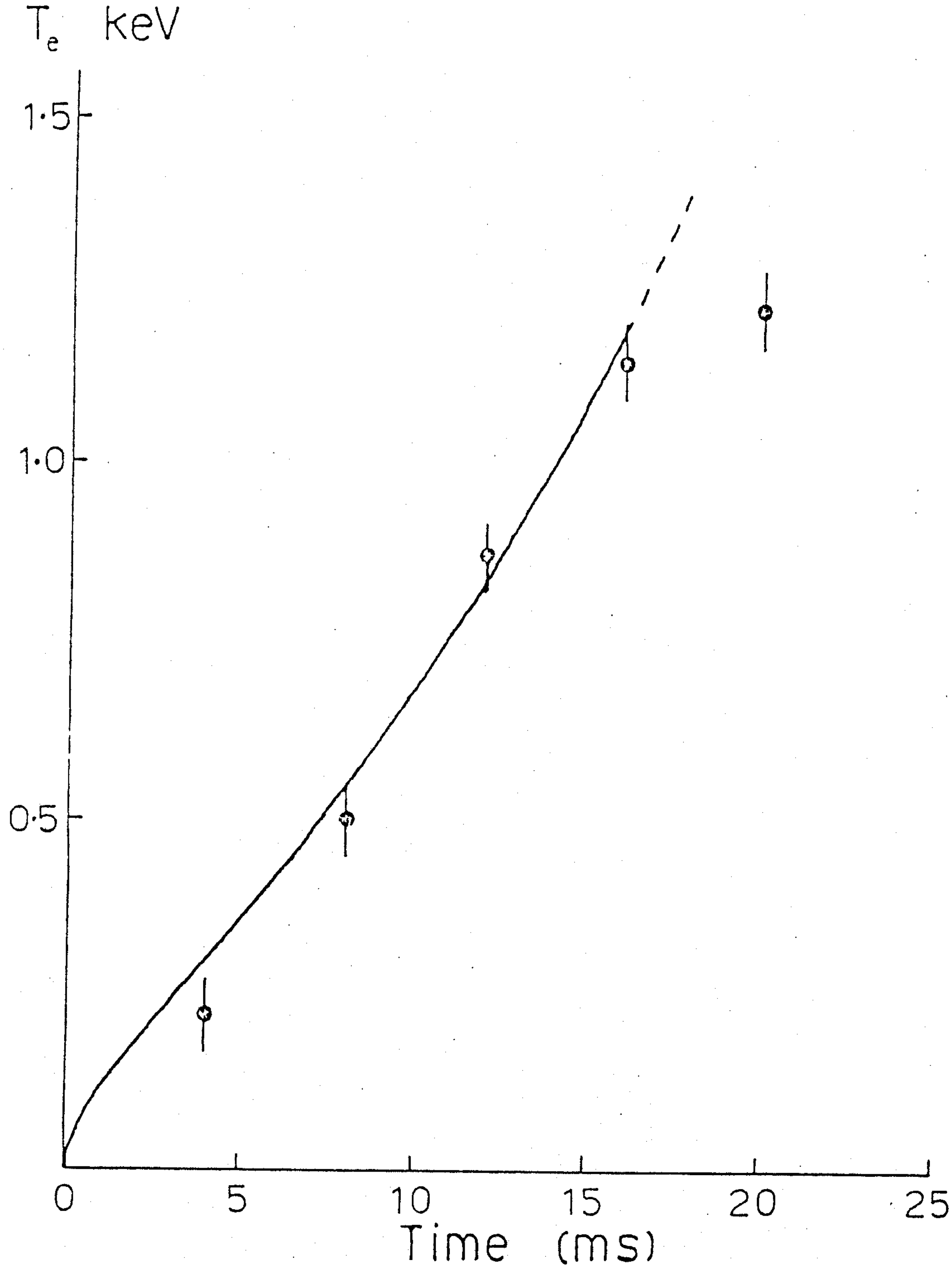


Fig 7(a)

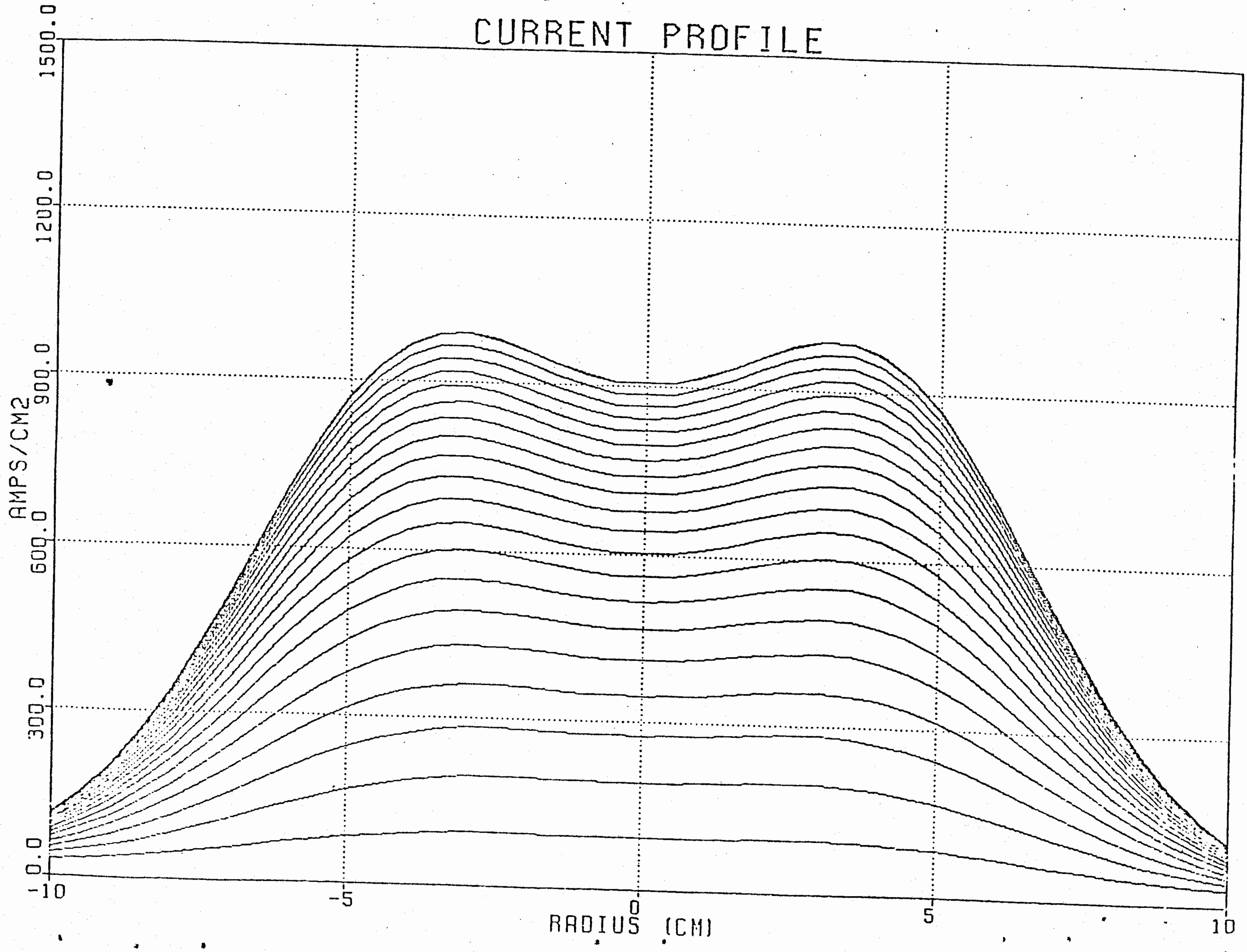

CURRENT PROFILE
AMPS/CM2
0.0
300.0
600.0
900.0
1200.0
1500.0
-10
-5
0
5
10
RADIUS (CM)

Fig 7(b)

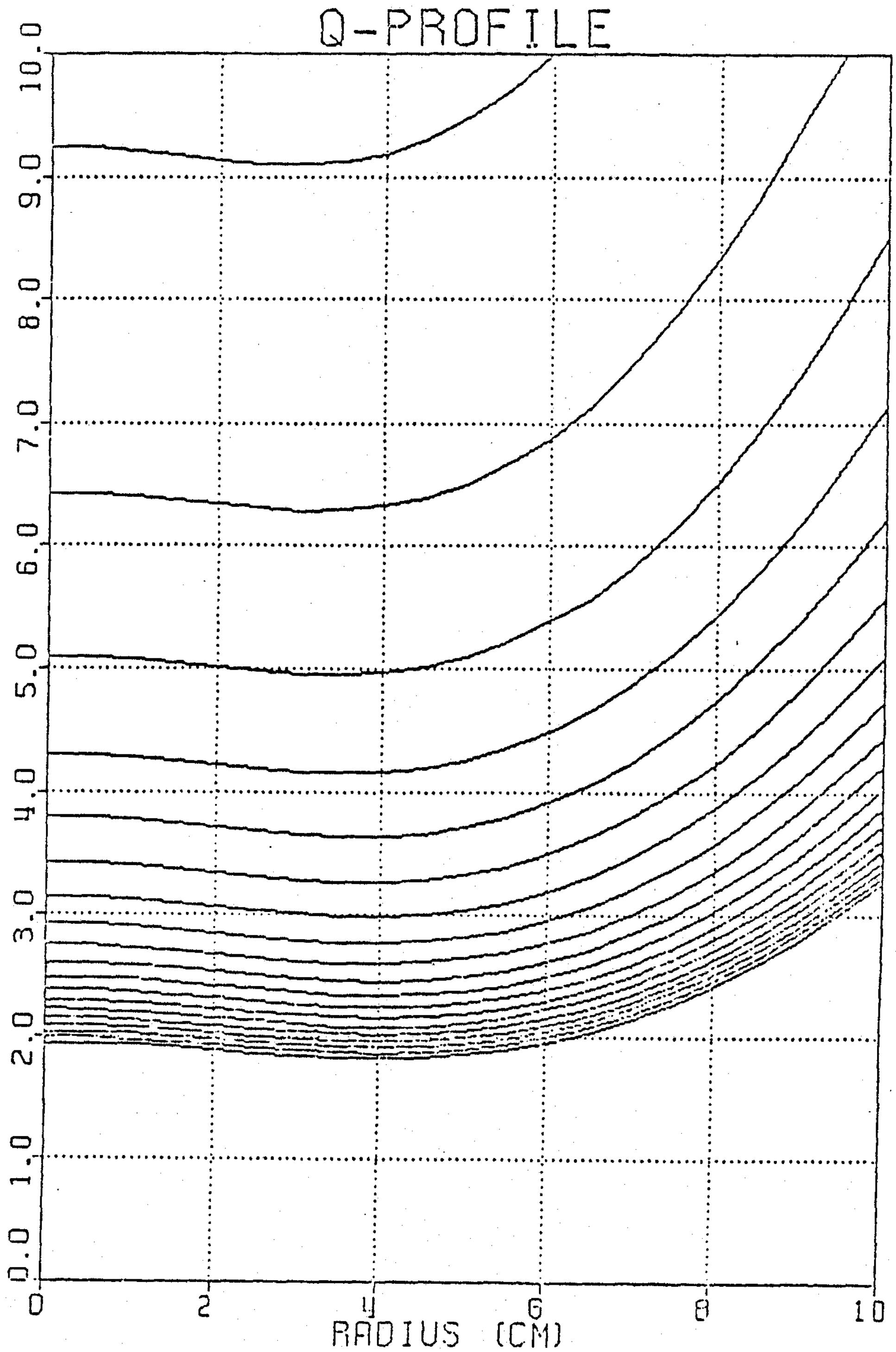


Fig 8(a)

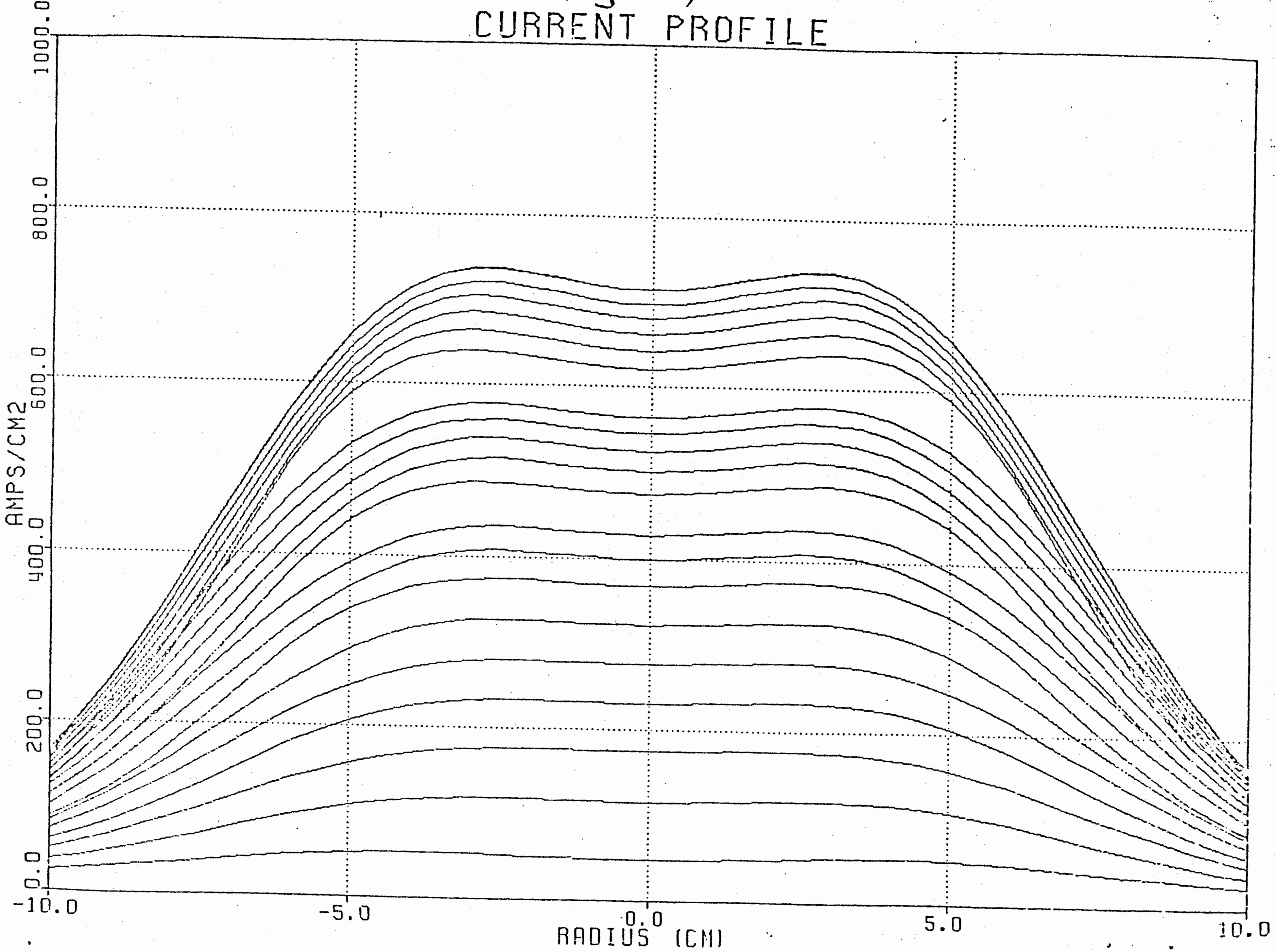
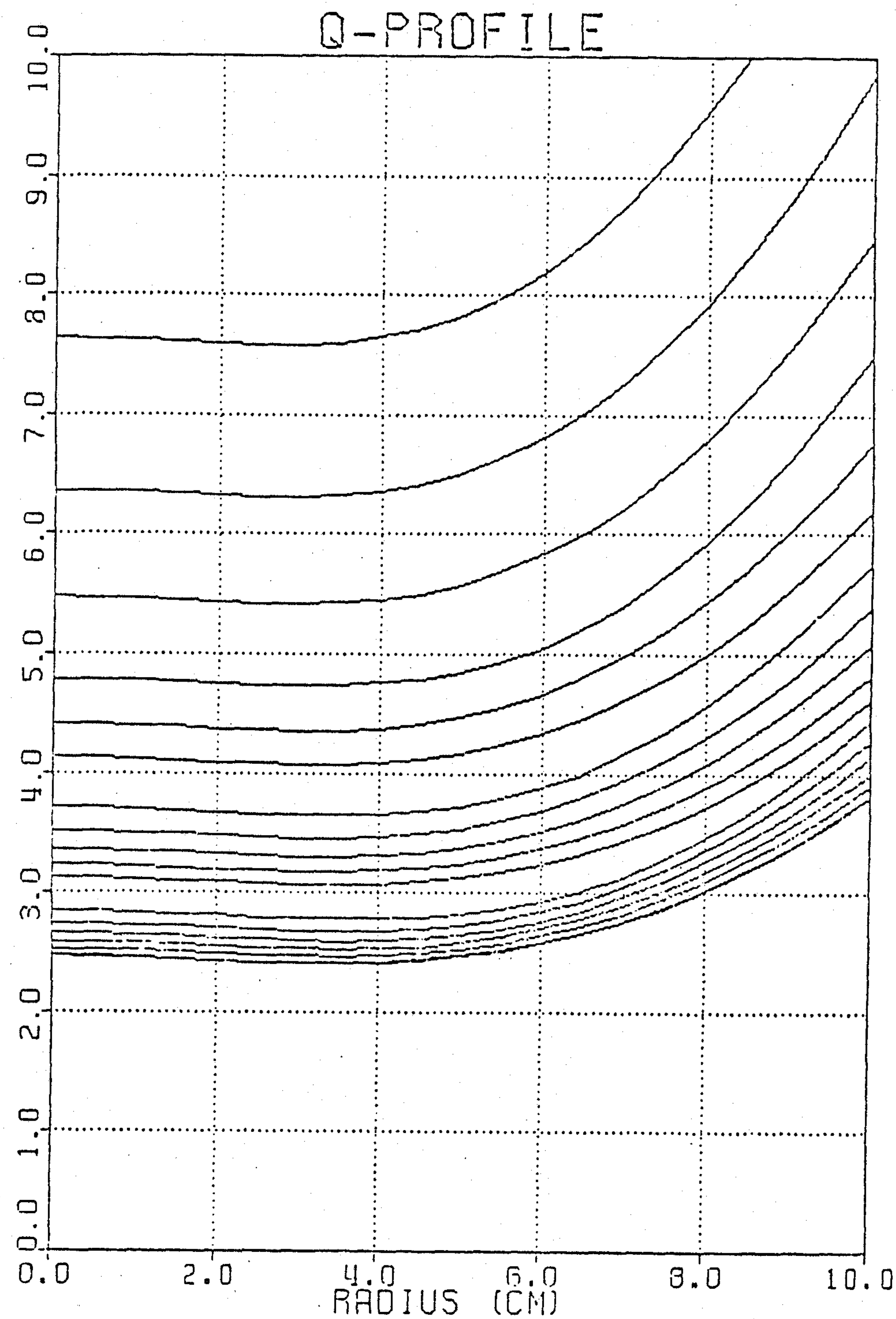
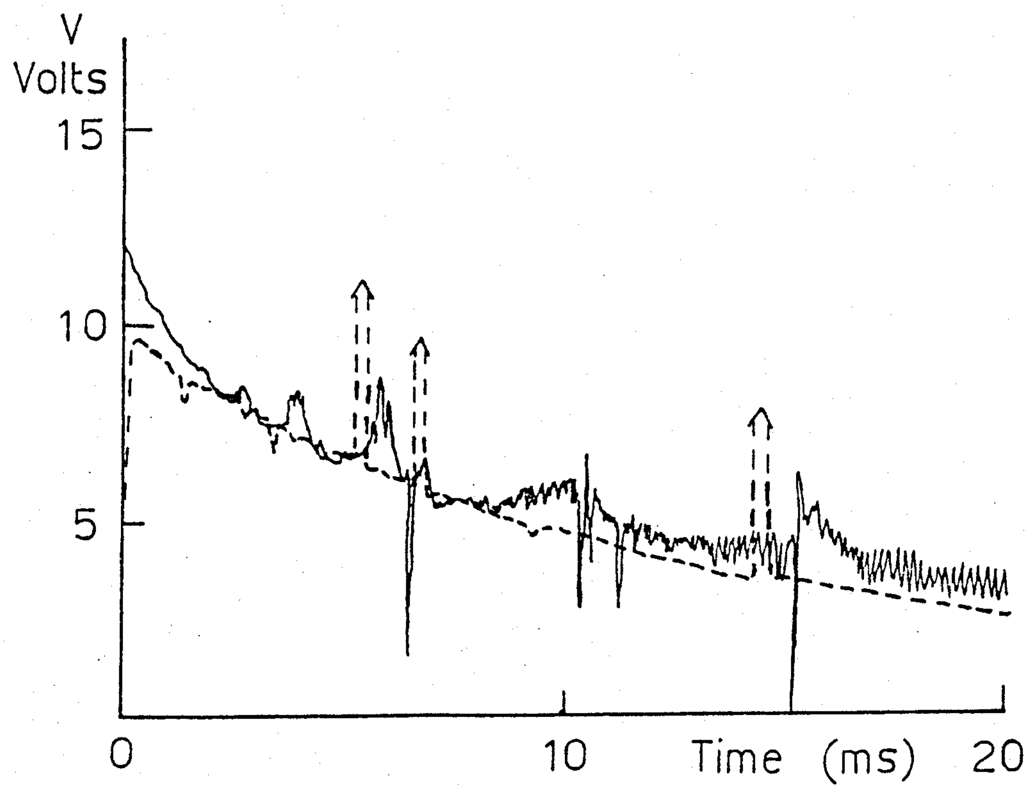
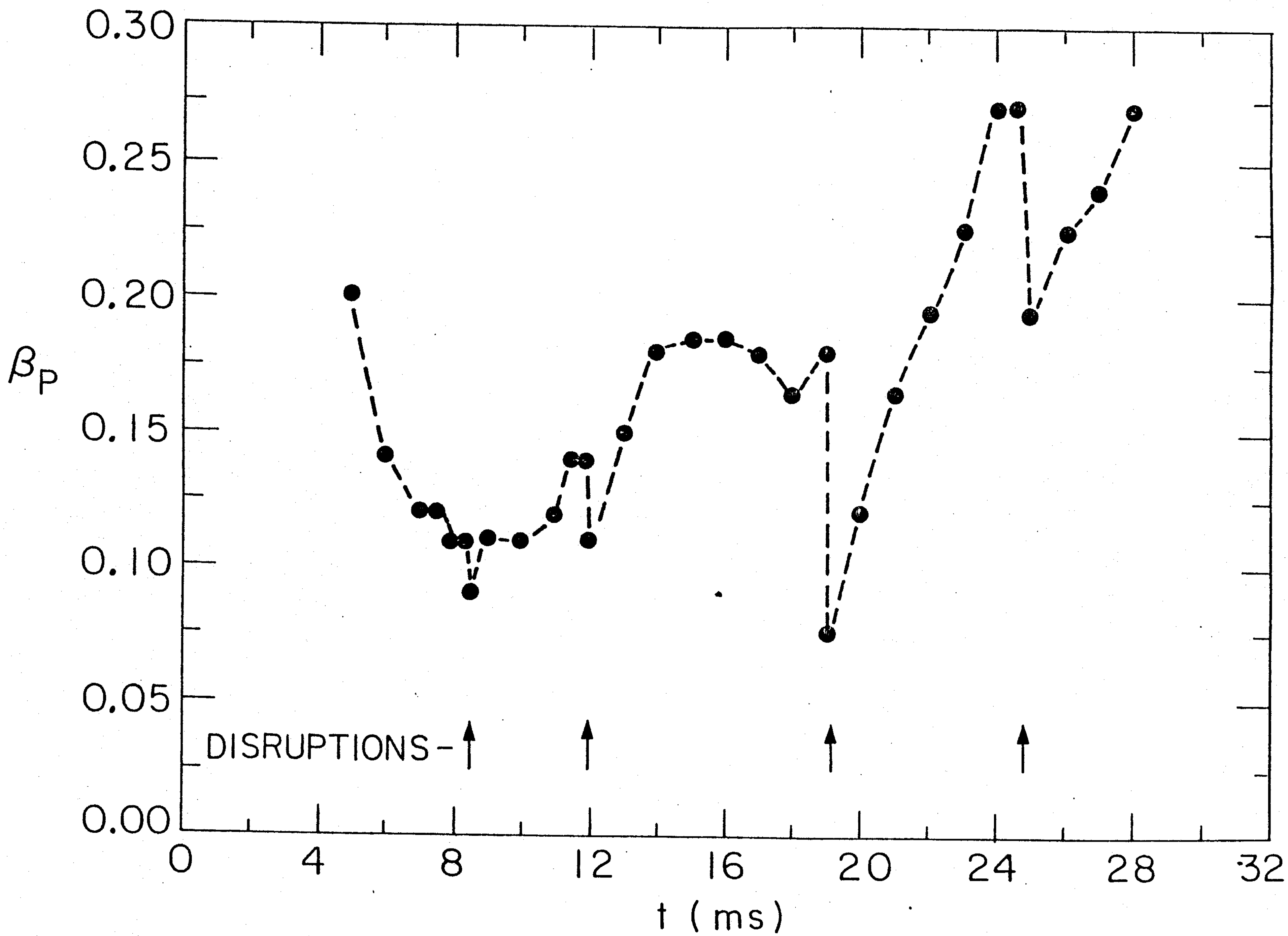

CURRENT PROFILE
AMPS/CM2
1000.0
800.0
600.0
400.0
200.0
0.0
-10.0
-5.0
0.0
5.0
10.0
RADIUS (CM)

Fig 8(b)


Q-PROFILE
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
0.0
2.0
4.0
6.0
8.0
10.0
RADIUS (CM)



V
Volts
15
10
5
0
10
Time (ms)
20


0.30
0.25
0.20
0.15
0.10
0.05
0.00
β_P
DISRUPTIONS
0
4
8
12
16
20
24
28
32
t (ms)