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Abstract

The sustainment of Ultra-low-q (ULQ) and Reversed Field Pinch (RFP) discharges longer than the vertical field penetration time constant of the shell in the HBTX1C device reveals new unstable modes arising from resistive shell instabilities. Their suppression in ULQ discharges has been achieved by controlling the value of the edge safety factor, q_a. The q_a boundary or current limitation often seen in Low-q Tokamak (LQ) and ULQ plasma is found to be related to a resonant mode with a growth rate that is fast compared to the vertical field time constant of the shell. The interaction of these two types of unstable modes results in stepwise plasma current behaviour in ULQ discharges. Resistivity anomaly in ULQ discharges is larger than that in RFP discharges and can be interpreted in terms of the low density and rapid particle recycling. Different plasma relaxation phenomena are observed in these regimes.

Introduction

The sustainment of the Reversed Field Pinch (RFP) and Tokamak equilibria requires different physics representation. The RFP plasma is a relaxed state plasma and its equilibrium field configuration can be described by the fully relaxed Taylor state [1]. Dynamo action [2] or electron flow along stochastic field lines [3,4] have been invoked to explain the maintenance of field reversal in steady state. Because of the continuous relaxation, RFP plasma can be described by magnetic helicity balance and transport [5]. To account for the Tokamak field profile, classical processes like non-isotropic resistivity, and radial flows suffice and relaxation arguments are usually not required; although sawtooth and profile consistency have been considered as relaxation phenomena [6,7]. The relaxation process in Tokamak increases heat transport. In contrast, the most discernible effect in RFPs is the generation of poloidal current drive. In experiments, the magnetic fluctuations in RFP [8] and Tokamak [9] display different characteristics. Typically, the magnetic field fluctuations in RFP are more stochastic and turbulent whereas in Tokamaks they are more coherent. RFP operations require a conducting shell to provide ideal and resistive MHD stability [10,11]. With a resistive shell, magnetic fluctuations are observed [12] to grow on the timescale of the vertical field penetration time constant of the shell (τ_w). In contrast Tokamaks are operated without a conducting shell at all. The metallic vacuum vessel which behaves as a resistive wall can have a stabilising effect on tearing modes through mode rotation [13].

The Tokamak and RFP discharges can be characterized by a common parameter, the edge safety factor $q_a = (a/R)(B_\varphi/B_\theta)$. In Tokamak operation, q_a is always positive and greater than unity. Normal Tokamak discharges have $q_a > 3$ and discharges with $1 \leq q_a < 2$ have been referred to as the Low-q Tokamak (LQ) [14]. RFP discharges have negative q_a values because of the field reversal which also removes the pitch minimum. The value of q_a is related to the reversal and pinch ratios by $q_a R/a = F/\Theta$. In between the Tokamak and RFP is the Ultra-low-q (ULQ) [15] operating regime with $0 < q_a < 1$. These ULQ states also exist transitorily in the RFP setting up phase when the plasma current is rising and the q_a value decreasing to below zero. Studies of the ULQ regime can improve the understanding of both Tokamaks and RFP plasmas, especially with regard to relaxation and thin shell stability in the latter.

In DIVA [16], low-q Tokamak discharges with $1 < q_a < 2$ were free from major disruption and their energy confinement was dominated by sawtooth oscillations. In ramping discharges in CLEO [17] i.e. discharges in which current was increased slowly in time, bursts of growing instabilities were observed and associated with helical modes m = 1, n = 1, 2, 3 and 4 as q_a passed through the values of 1, 1/2, 1/3 and 1/4. In the same device, LQ discharges were sustained for times longer than the shell vertical field penetration time constant [14]. In REPUTE [15], quasi-stable ULQ discharges with pulse length longer than the shell time constant have been obtained and the equilibrium magnetic field profile measured with an insertable magnetic probe. These measurements showed a q-profile with $dq/dr < 0$ in the major part of the plasma and a pitch minimum characterizing Suydam instability near the plasma edge. Unstable modes which are resonant at and localized around the pitch minimum have been detected [18]. Stepwise plasma current decay to certain discrete q_a values is a characteristic of the ULQ operation in thin shell devices. In OHTE, the magnetic field profile measurement in ULQ discharges [19] showed a q-profile increasing with radius with no pitch minimum.

Sustainment and Current Limitation

The HBTX1C [12] device (a/R = 0.26m/0.80m) has a resistive shell located at 1.15 times the plasma minor radius with vertical field penetration time constant of τ_W = 0.5 ms. The setting up procedure of the LQ, ULQ and RFP discharges are similar. After a uniform toroidal field is applied, the plasma current is raised in less than 0.5 ms to near its maximum value then sustained. The value of q_a after the current rise is determined by the plasma current and the initial toroidal field. When this ratio is sufficiently large, the edge toroidal field reverses itself naturally to form the RFP configuration. In normal RFP operation, the reversal is assisted by reversing the current in the external poloidal winding during the plasma current rise phase.

During the sustainment, it is possible to raise the q_a value either by decreasing the plasma current or by increasing the edge toroidal field. In a discharge where the toroidal field is sustained while the plasma current is allowed to decay, q_a is found to increase in discrete steps, taking sucessively values close to but rather larger than the major rational fractions such as 1/3, 1/2, 2/3 and 1. The current decay reflects this stepwise behaviour as shown in Figure 1. It is also possible to lower the q_a value to switch from one ULQ state to another provided $q_a < 1$. When q_a exceeds unity to form a LQ discharge it is not possible to return to the ULQ states with $q_a < 1$ using a slowly varying field, this confirming that $q_a = 1$ is a boundary, which at fixed toroidal field gives rise to current limitation often seen in LQ experiments [14].

With a constant edge toroidal field of $B_\varphi \simeq 130$ mT, increasing the loop voltage from 12 to 86 volts leaves the LQ plasma current unchanged at $I_\varphi \simeq 45$ kA (Figure 2). At low loop voltage, sawtooth oscillations and spikes can be seen on the plasma current and loop voltage traces respectively. Increasing the loop voltage results in stronger MHD activity observed on the edge coils and on the plasma current and the loop voltage. The duration of the discharge can be up to $\simeq 30\ \tau_W$ and is not dependent on the loop voltage.

Similar current limitation at fixed toroidal field also happens in ULQ discharges. The range of V_φ is 80 to 130 volts for the 210 kA, $q_a \simeq 1/2$ discharges. However, the q_a boundaries which correspond to the major rational fractions are not as firm as the $q_a = 1$ boundary. It is possible to raise the plasma current and to lower the value of q_a to pass through these soft limits. With sufficiently high loop voltage, quasi-stable $q_a \simeq 1/2$ and $2/3$ sustainment can last up to 15 τ_W and the duration is limited only by the circuit. As the loop voltage is reduced, the sustainment phase shortens (Figure 3). The $q_a \simeq 1/2$ sustainment at $I_\varphi = 210$ kA increases from 3 to 6 ms when the loop voltage varies from 95 to 115 volts.

Such q_a or current limits do not exist in RFP discharges. Each q_a value corresponds to a straight line passing through the origin in the F-Θ plane. In RFP discharges, the values of F and Θ do not fall onto a single straight line and the ranges of F and Θ, $-0.8 \leq F \leq -0.05$ and $1.4 \leq \Theta \leq 2.0$, correspond to a relative wide range of q_a values.

Resistive Shell modes and Termination

In RFP operation with resistive shell, the pulse length is normally < 10 τ_W and the values of F and Θ indicate a narrower $\mu = \underline{j}.\underline{B}/B^2$ profile than that in HBTX1B with conducting shell [20]. Analysis of m = 1 edge magnetic field measurement shows the presence of growing resistive shell modes. The most prominent m = 1 modes are the on-axis or the internal resonant modes with n = (-5 or -6), external non-resonant modes with n = (2 or 3). There is also significant activity with n = (10 or 11) and n = (~ -13). Typically, these resistive shell modes have normalized growth rate $\gamma\tau_W = 0.3 \pm 0.1$ and are phase-locked to the shell or rotate very slowly with $\omega\tau_W < 0.1$ [21]. They tend to have similar growth rate as illustrated in Figure 4 where the time behaviour of B_θ^2 is plotted. In this discharge, the dominant m = 1 modes are n = -5, 2 and 11. Following a turbulent setting up phase and a relatively quiescent period lasting about 0.5 ms, the unstable modes grow with similar growth rates for about two growth times before the discharge terminates.

The presence of the resistive shell modes can be seen in the edge radial magnetic field (B_r) signals. Figure 5 compares the radial field from an edge coil in the RFP, ULQ and LQ discharges with $\tau_W = 0.5$ as well as RFP discharges with $\tau_W = 80$ ms. The arrows indicate the sustainment period. The radial field that grows slowly to large amplitude observed in the resistive shell ($\tau_W = 0.5$ ms) RFP discharges is absent in the LQ and the strongly sustained ULQ discharges with high loop voltage; nor is it observed in conducting shell ($\tau_W = 80$ ms) RFP discharges.

In the $q_a \simeq 1/2$ and $q_a \simeq 2/3$ ULQ discharges with a lower sustaining loop voltage, there is a slowly growing (m,n) = (1,1) mode which would be resonant to a q = 1 surface, if such a surface exists within the plasma. The time behaviour of B_θ^2 in a $q_a \simeq 1/2$, $I_\varphi = 120$ kA discharge, as shown in Figure 6, reveals a significant level of (1,2) high frequency activity, and a (1,1) slowly growing mode. Stepwise plasma current transition begins at $t \simeq 5.8$ ms when the (1,1) mode amplitude reaches $\simeq 10\%$ of the edge mean field. However, with a high loop voltage maintaining the plasma current and q_a at its limiting value, the (1,1) mode is absent throughout the discharge, suggesting that its onset is related to the q_a value. Figure 7 shows the effect on the duration of the $q_a \simeq 1/2$ sustainment of increasing the edge toroidal field to raise the q_a value. The three cases labelled (a), (b) and (c) correspond to different and progressively larger levels of increase in the edge toroidal field. As the edge toroidal field is increased externally (at 2.6 ms in the figure), the value of q_a increases and the sustainment phase shortens. The shortening is related to the earlier onset of the (1,1) mode as shown in Figure 8 where the time behaviour of the B_θ^2 of the (1,1) mode corresponding to the discharges in Figure 7 is plotted. When q_a is raised more than ~10% of its limiting value, the (1,1) mode develops above the higher frequency activity and continues to grow to termination.

The (1,1) mode which has a growth time of 1 ms ($\gamma\tau_w \simeq 0.5$) and a rotational frequency of 300 Hz ($\omega\tau_w \simeq 0.9$) is similar to the resistive shell modes in RFP discharges. The latter, however, are not affected by the loop voltage. When a series inductor is added to a second Ohmic current-drive capacitor bank to provide a 'constant current source', the RFP pulse length is extended from 10 to 14 τ_w and the loop voltage increased from 70 volts to 140 volts. Yet, the growth of the resistive shell modes is not affected.

Anomalous Resistance and Relaxation

ULQ discharges with $q_a \simeq 1/2$ and plasma current up to 260 kA have been obtained. The average global parameters for the $q_a \simeq 1/2$ ULQ discharges at 210 kA plasma current are summarized in Table 1 together with those of RFP discharges at 180 kA plasma current for comparison. The averaged loop voltage of 67 volts in resistive shell RFP operation is higher than the 20 to 30 volts typical of conducting-shell operation in HBTX1B. Although ULQ plasmas have higher electron and ion temperatures, the plasma resistance is higher and energy confinement time shorter than in RFPs.

Typical $q_a \simeq 1/2$ discharges have $\Theta = 0.59 \pm 0.01$ and $F = 0.84 \pm 0.04$.

These values are consistent with those of a magnetic field configuration with parabolic profiles of $\mu = \underline{j}.\underline{B}/B^2$, T_e and n and 2% $\beta(0)$. With such profiles, the on axis plasma resistivity of a 210 kA discharge with $V_\varphi = 100$ V is 4.9 x 10^{-6} Ohm-m using global magnetic helicity balance and 5.8 x 10^{-6} Ohm-m according to magnetic energy balance [22]. The 17% difference between these two resistivities is smaller than the 30% to 50% typical of RFP profiles [23] indicating a lower fraction of the power flow coupled to fluctuations and, possibly, weaker dynamo activity in ULQ discharges.

The large electrical resistivities, which are more than 100 times the Spitzer resistivity of 3.5 x 10^{-8} Ohm-m for an 800 eV and Z = 1 plasma, may be explained by particle recycling [24]. Electron momentum can be dissipated through electron-ion collisions which leads to Spitzer resistivity $\eta_s = m_e/e^2 n\tau_{ei}$ with τ_{ei} being the electron-ion collision time or through particle loss which leads to a recycling resistivity $\eta_t = m_e/e^2 n\tau_p$ with τ_p being the particle confinement time. For densities and particle confinement times typical of these plasma e.g. n ~ 2 x 10^{18} m^{-3} and $\tau_p \sim 10^{-5}$s, the recycling resistivity $\eta_t \sim 2 \times 10^{-6}$ Ohm-m. Such recycling is also expected to channel input power into ion heating [24], which is consistent with the high ion temperatures (> 1 keV) that have been measured [25].

Increasing the loop voltage of LQ discharges generates more frequent sawtooth events (see Figure 2). The sawtooth current fluctuation is correlated to the (m,n) = (1,1) mode higher frequency activity as shown in Figure 9 where the plasma current, loop voltage and B_θ^2 of the (1,1) and (1,2) modes for a discharge with $q_a \simeq 1/2$ changing to $q_a \simeq 1$ are displayed. When the (1,1) mode grows with $\gamma\tau_w \simeq 0.5$ to large amplitude, the plasma current decreases from 95 to 55 kA and the sustainment changes from $q_a \simeq 1/2$ to $q_a \simeq 1$. During the $q_a \simeq 1$ sustainment from t = 3.5 to 6.9 ms, there is (1,1) mode activity with larger normalized growth rate of $\gamma\tau_w \simeq 25$. This fast growing (1,1) mode develops as the plasma current and q_a approach the $q_a = 1$ limit. When the mode amplitude reaches ~ 10% of the local mean field, the plasma current has a minor collapse. It can be seen that some of the excess power input above the minimum required to sustained a LQ discharge can be channeled through the sawtooth activity. For instance, the frequency and the amplitude of the sawtooth are ≃ 8 Khz and $\delta I_\varphi/I_\varphi \simeq 20\%$ corresponding to an energy flow of ~ 1.6 x 10^6 J/s which is about half of the excess power above $V_\varphi = 12$ V when the loop voltage is ≃ 80 V for a 50 kA discharge.

Correlation analysis on the loop voltage and the plasma current fluctuation in the LQ discharges, shown in Figure 10 in the form of coherence and phase spectra each averaged over 10 segments from 5 discharges, reveals a close to unity coherence (> 0.9) in the frequency range of 3 to 12 kHz. The high level of correlation and the phase angle of -90 degrees implies that the loop voltage fluctuation V_φ varies as $-dI_\varphi/dt$ i.e. a positive voltage spike corresponds to a drop in the plasma current. This causal relationship between the sawtooth collapse and voltage spike is more apparent at lower loop voltage when these events become infrequent (see Figure 2). The small collapse in the plasma current or relaxation takes place as q_a decreases from $1 < q_a < 2$ to the $q_a = 1$ boundary and does not result in termination.

In ULQ discharges, there is also a significant level of fluctuations in the plasma current and the loop voltage and the higher frequency magnetic activity is dominated by the (m,n) = (1,2) instead of the (1,1) mode (Figure 9). Correlation analysis shows that the loop voltage and plasma current fluctuations are highly correlated with coherence > 0.9 in the frequency range of 4 to 10 kHz and have the phase angle of -90 degrees similar to those seen in LQ discharges (Figure 10). Such strong correlation, however, is absent in RFP discharges. Instead, there is significant correlation at frequency below 2 kHz with a phase angle of zero degree implying that the loop voltage increases with plasma current at low frequency.

Discussion

Unstable m = 1 modes of two different timescales have been observed. The fast growing modes (compared to τ_w of the shell) observed in LQ and ULQ discharges are believed to be the resonant modes corresponding to the Suydam pitch minimum mode. Pitch minimum modes in ULQ discharges have been observed in REPUTE [15] where the equilibrium field profiles measured with an insertable magnetic probe reveal a pitch minimum near the plasma edge. The slowly growing (m,n) = (1,1) mode observed in ULQ discharges is non-resonant and has characteristics similar to the resistive shell modes seen in RFP discharges. Because $\omega\tau_w$ is larger than $\gamma\tau_w$ in ULQ discharges, the effect of mode rotation on stability cannot be ignored. In contrast, mode rotation in RFP discharges is negligible. The growth of these modes to large amplitude can limit the pulse length.

The q_a boundaries or current limitation at fixed toroidal field of LQ and ULQ plasma can now be explained in terms of the fast growing resonant modes. When the plasma current in a LQ discharge with $q_a > 1$ increases slowly to lower the value of q_a towards the unity boundary, the growing (1,1) mode developes to large amplitude and causes a rapid plasma current minor disruption. After the minor current disruption or relaxation, the plasma current restores to the previous lower level, the value of q_a increases to above unity and the (1,1) mode amplitude diminishes quickly. This cyclic process generates sawtooth oscillation on the plasma current and is similar to the sawtooth events seen in normal Tokamak discharges. The growth rate of this mode is quite different from the slowing growing resistive shell mode seen in both RFP and ULQ discharges. However, if the fast growing modes do not depend on the shell but on the metallic liner for stability, the normalised growth rate becomes $\gamma\tau_w \simeq 4$ for the bellows liner which has τ_w = 0.08 ms and is located at 1.03 times the minor radius. In the $q_a \simeq 1/2$ ULQ discharges, a similar resonant mode with (m,n) = (1,2) inhibits q_a from falling below the limiting value of 1/2. It is believed that these fast growing modes are resonant near the plasma edge and that the edge plasma parameters and plasma-wall interaction can have influence on their stability.

The characteristic stepwise plasma current decay in ULQ operation with a resistive shell can be understood in terms of the unstable modes. The fast growing resonant modes inhibit operation with q_a very close to the limiting values. The onset of the slowly growing non-resonant mode when q_a is more than 10% above the limiting value terminates the sustainment. Together they impose narrow ranges of operating values of q_a near each major rational fractions such as 1/2 and 2/3.

There is no q_a boundary or current limiting behaviour observed in the RFP operation. In the LQ and ULQ discharges, the resonant modes cause plasma current minor disruption or relaxation. The strong correlation between the loop voltage and the plasma current confirms the generation of positive voltage spikes by the plasma current collapse. The absence of such behaviour in RFP discharges suggests that the continuous relaxation prevents sawtooth current collapse. There is a wide spectrum of resonant modes observed in RFP experiments [20]. Their continuous interaction can provide a finer scale of relaxation and relieve the plasma from large sawtooth activity. In contrast, the growth of the resistive shell modes appears not to be affected by the relaxation process and their growth to large amplitude can lead to termination of sustainment. This may be related to the fact that the stability of the resonant modes has stronger dependence on the details of the internal field structure than that of the non-resonant resistive shell modes and is therefore sensitive to any current relaxation or rearrangement of the internal field profiles.

In both ULQ and RFP discharge, the loop voltage is higher than that expected from Spitzer resistivity but for different reasons. For RFP discharges, the large radial field associated with the resistive shell modes can lead to helicity loss and high loop voltage [5]. For well sustained ULQ discharges, the edge radial field is small and the high loop voltage can be related to the low density and short particle confinement time. For LQ discharges with excess loop voltage, at least half the power can channel through the plasma current sawtooth activity consistent with the result from DIVA [16] that the average energy confinement time in Tokamak discharges with $q_a < 2$ is dominated by sawtooth oscillation.

The results from HBTX1C and those from the earlier assembly HBTX1B having a conducting shell with τ_w of 80 ms shows that the growth of the resistive shell modes degrades RFP confinement properties. It is expected that ULQ confinement will benefit from having a conducting shell. Moreover, the suppression of the non-resonant resistive shell mode may allow a wider range of operating values of q_a and remove the stepwise plasma current decay behaviour.

Conclusion

Resistive shell modes growing on the vertical field penetration timescale of the shell have been observed in both ULQ and RFP operation in HBTX1C. Their growth to large amplitude limits the pulse duration. Mode rotation is more significant in ULQ than in RFP discharges. By maintaining the value of edge q to within 10% above its limiting value in ULQ discharges, the resistive shell mode can be suppressed. The q_a boundaries which exist in LQ and ULQ operation are related to the presence of a fast growing (compared to the vertical field penetration time constant of the shell) resonant mode. Its growth leads to minor plasma current collapse or relaxation but not major disruption. This fast growing resonant mode, together with the non-resonant resistive shell mode impose a narrow range of values of q_a near the major rational fractions for quasi-stable ULQ operation. Resistive anomaly is higher in ULQ than RFP plasma and can be related to the rapid particle recycling. Plasma current fluctuations similar to the sawtooth activity seen in LQ Tokamak discharges are present in ULQ but not in RFP discharges. It is suggested that the continuous relaxation in RFP prevents sawtooth current collapse.

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Parameters	ULQ	RFP
I_φ (kA)	210	180
V_φ (volt)	120	67
Pulse length (ms)	> 6	3.1
R (m-Ohm)	0.57	0.39
n_e ($\times 10^{19}$m^{-3})	< 0.5	2.2
T_e (eV)	800	210
T_i (eV)	1200	340
τ_E (ms)	0.13	0.15
Θ	0.59	1.65
F	0.84	-0.26

Table 1 Averaged global plasma parameters for ULQ and RFP discharges in resistive shell (τ_w = 0.5 ms) operations.

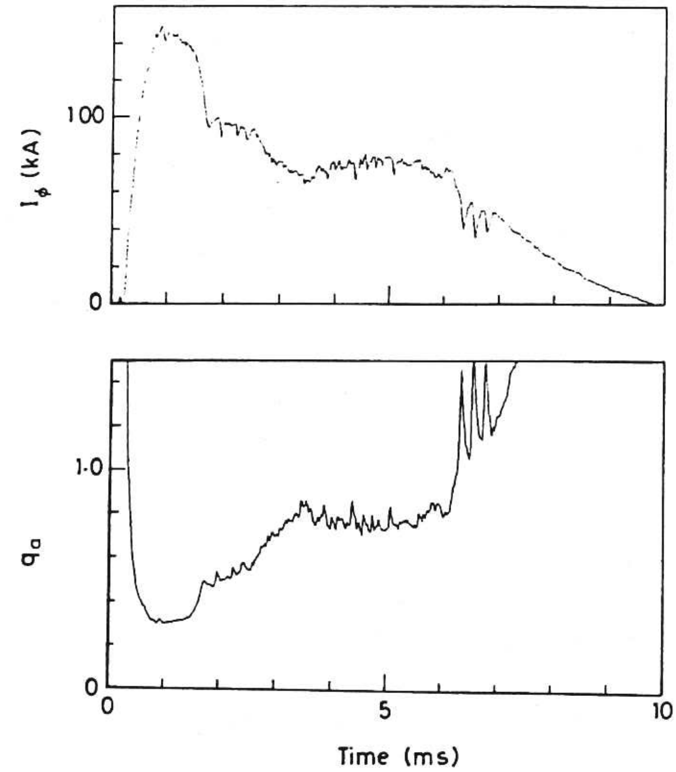

Fig. 1 The stepwise plasma current decay of a ULQ discharge. The current steps correspond to q_a values close to but rather larger than ⅓, ½, ⅔ and 1.

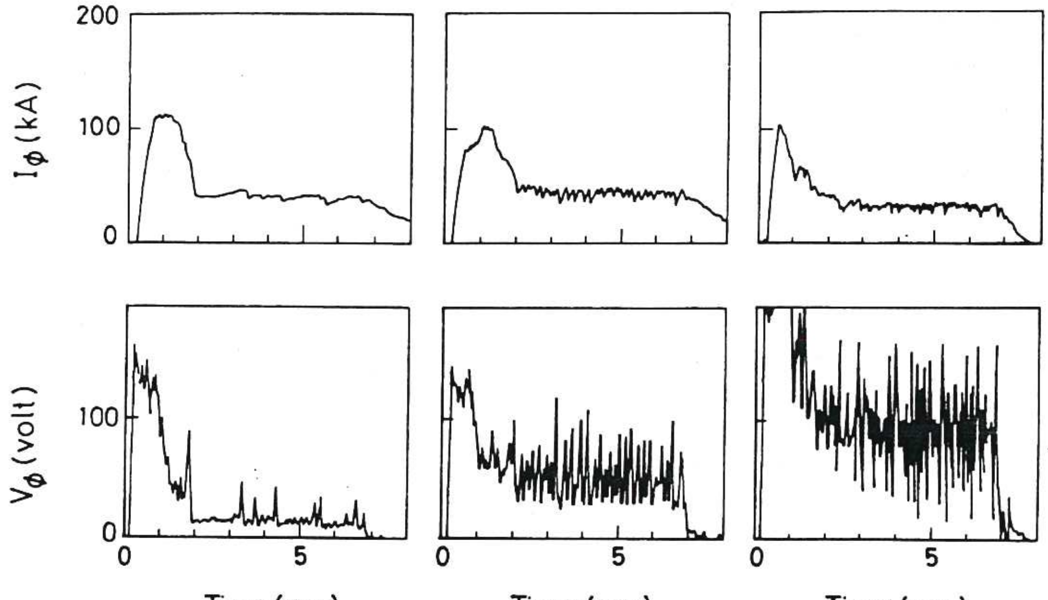

Fig. 2 Current limitation in a LQ discharge with $q_a \simeq 1$. Increasing the loop voltage from 12 to 86 volts yields more disturbances on the plasma current and loop voltage while the mean plasma current remains unchanged at $\simeq 45$ kA.

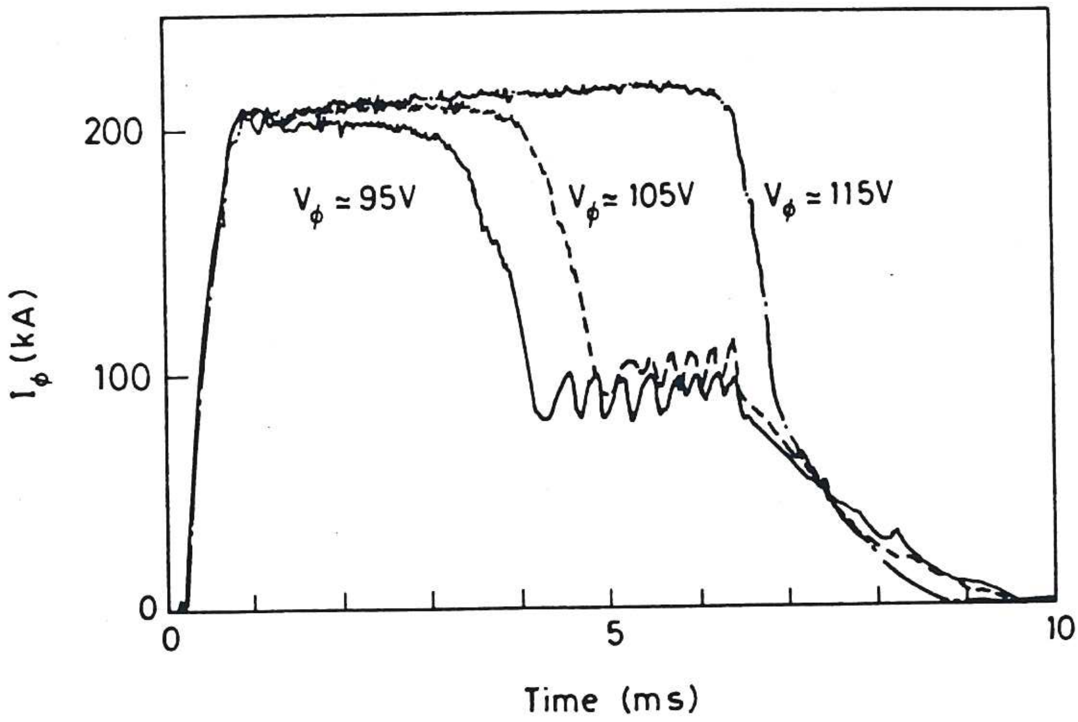

Fig. 3 The plasma current traces of $q_a \simeq ½$ discharges with different loop voltages. The pulse length increases with higher loop voltage.

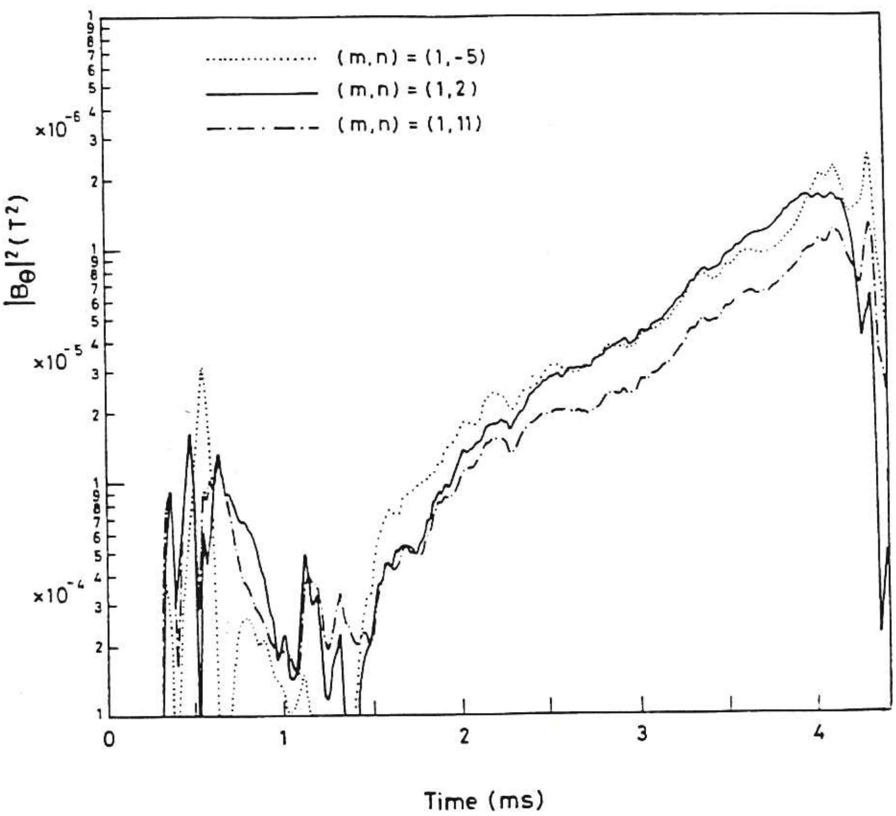

Fig. 4 The time behaviour of the dominant m=1 B_θ^2 in a RFP discharge showing a steady growth from t=2 to 4ms with a normalized growth rate of $\gamma\tau_w = 0.3$.

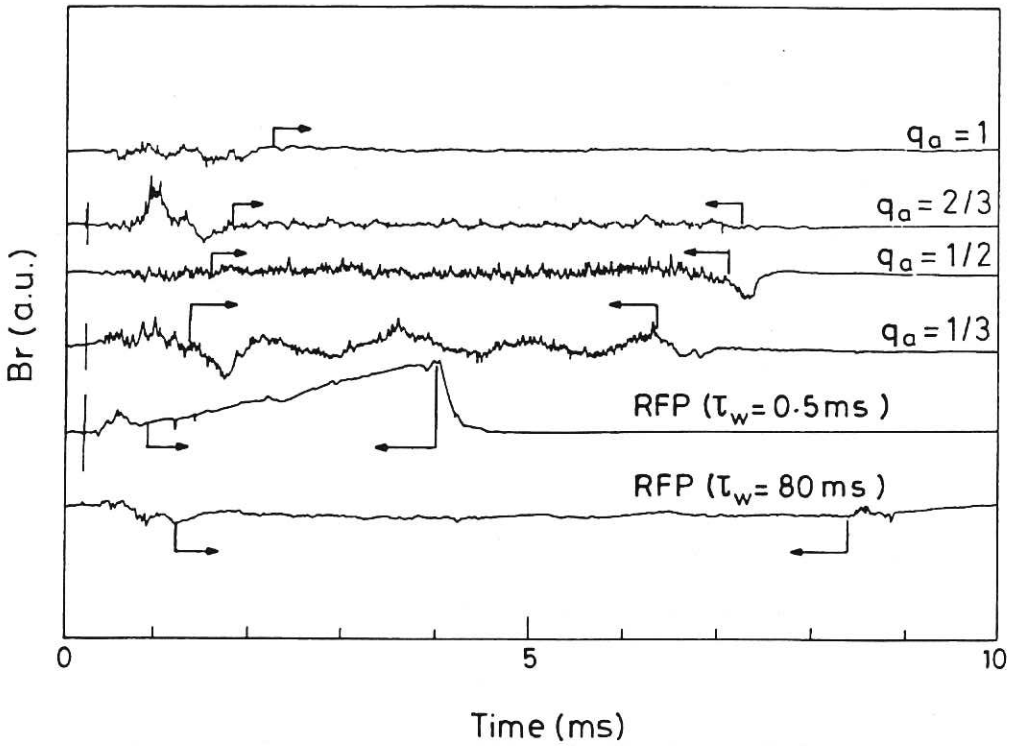

Fig. 5 The time behaviour of the edge radial field in LQ ULQ and RFP sustainment (indicated by the arrows). A slowing growing radial field is observed in the thin shell RFP discharge but not in the other discharges.

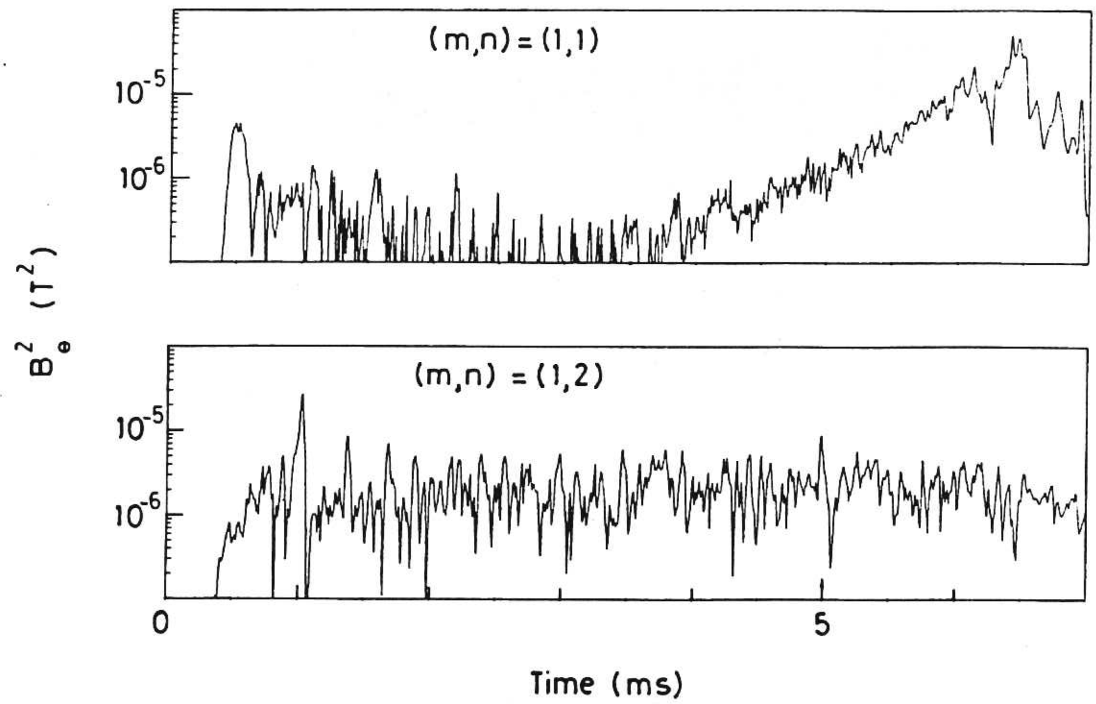

Fig. 6 The time traces of the B_θ^2 of the (m,n) = (1, 1) and (1, 2) modes in a $q_a \simeq$ ½ discharge showing a slowly growing (1, 1) mode and high frequency activity in the (1, 2) mode. The (1, 1) mode grows to $\simeq$10% of the mean field at termination.

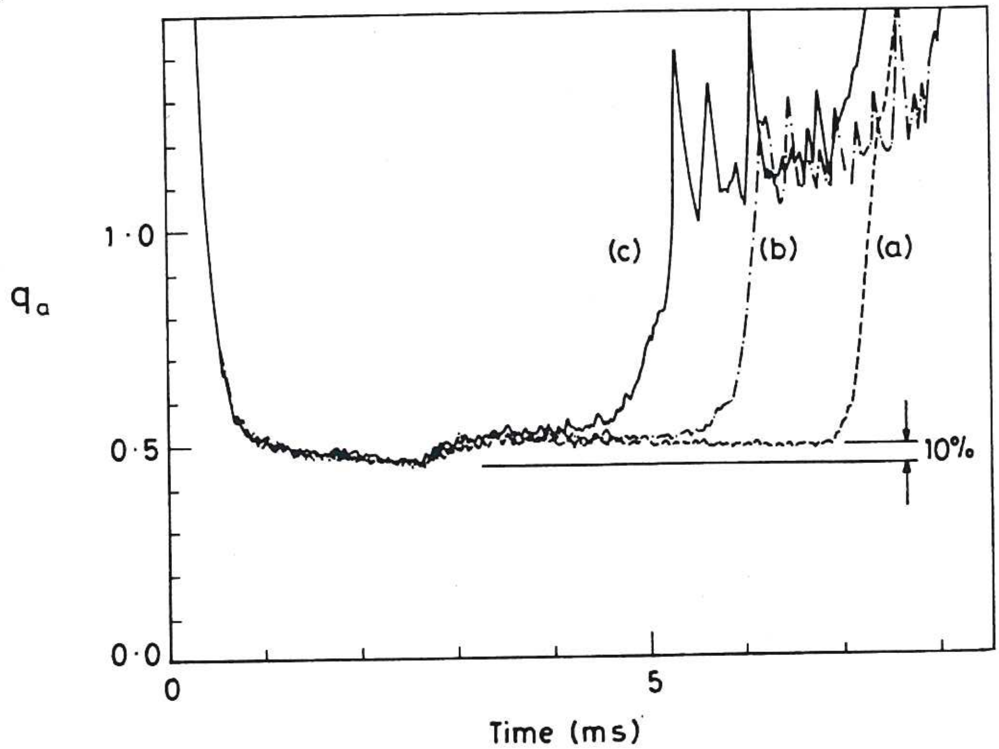

Fig. 7 The changes in pulse length and q_a values when the edge toroidal field is increased externally at 2.6 ms by progressively larger amount in cases (a), (b) and (c).

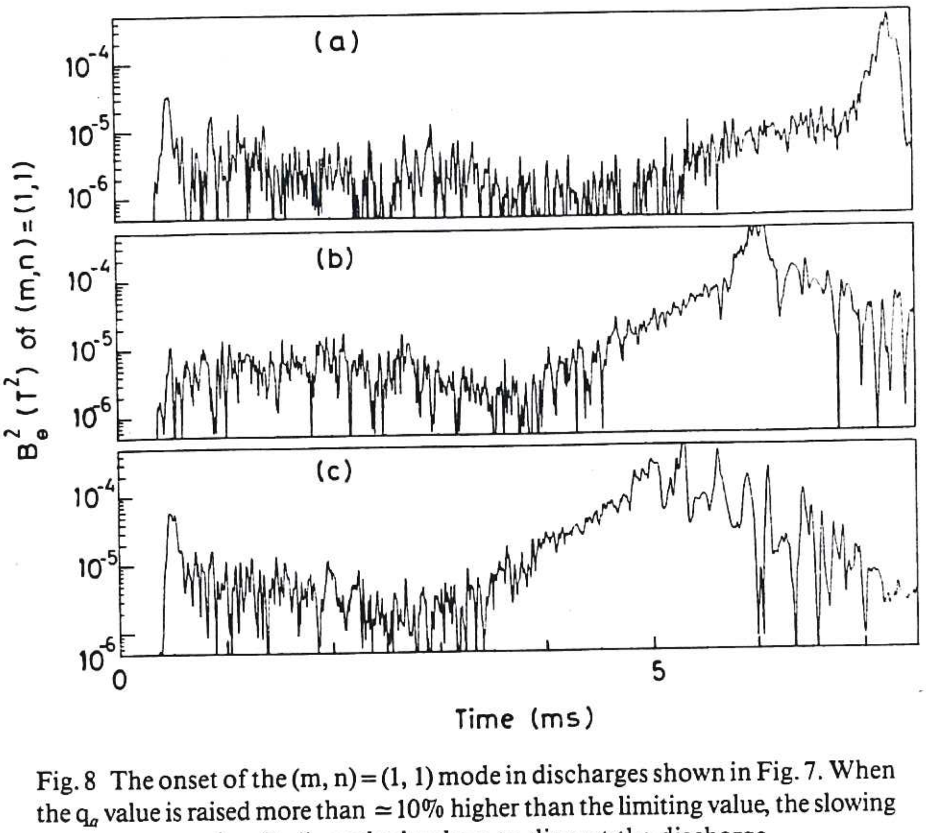

Fig. 8 The onset of the (m, n) = (1, 1) mode in discharges shown in Fig. 7. When the q_a value is raised more than $\simeq$ 10% higher than the limiting value, the slowing growing (1, 1) mode develops to disrupt the discharge.

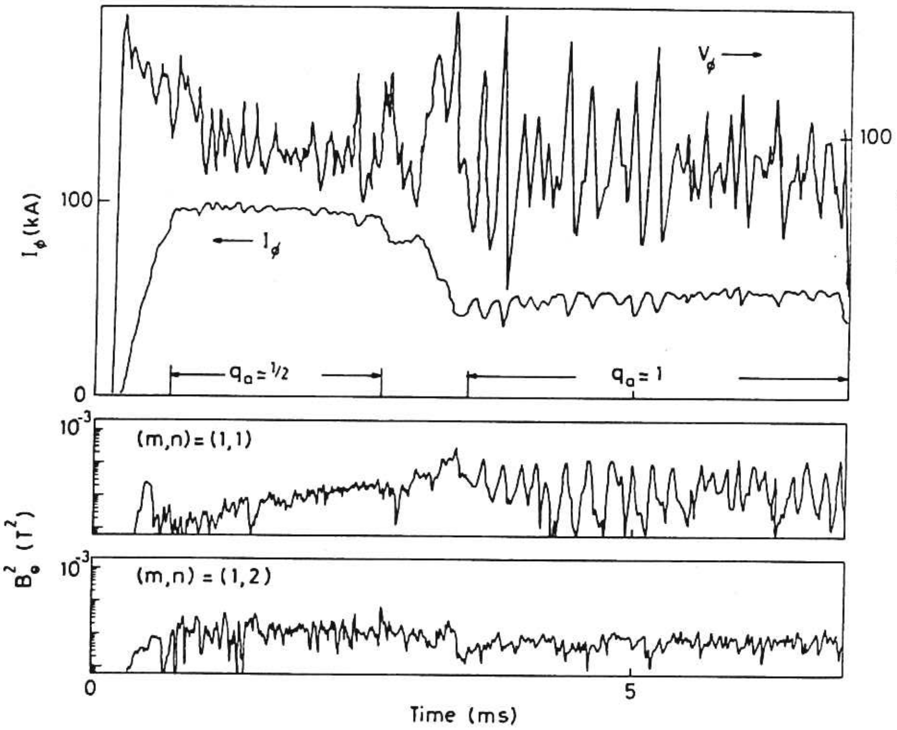

Fig. 9 The effect of the q_a limits on the behaviour of the plasma current, loop voltage and the (m, n) = (1,1) and (1,2) modes.

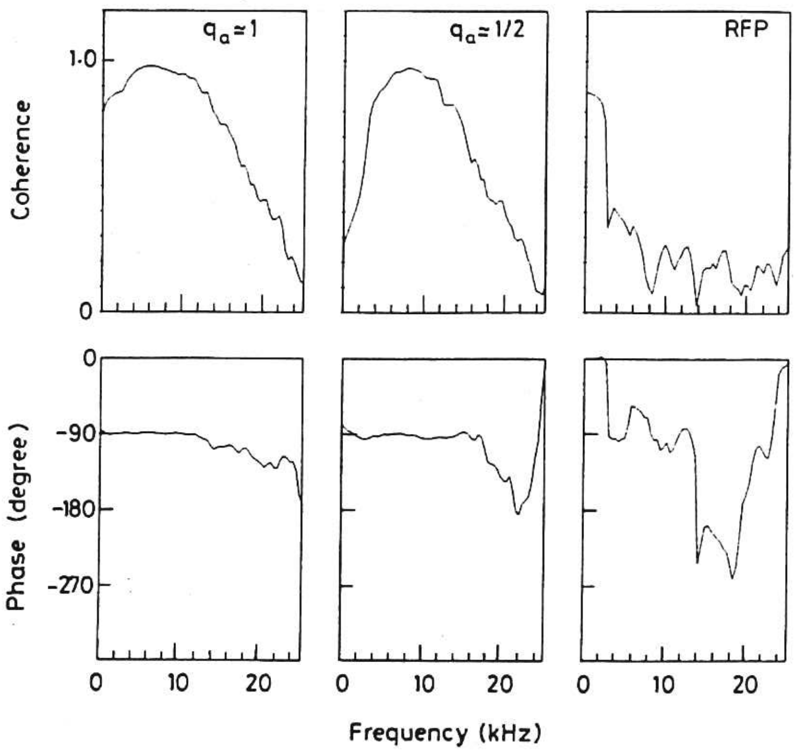

Fig. 10 The coherence and phase spectra of the correlation between the loop voltage and the plasma current. The -90° phase correlation is much weaker in RFP discharges.