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Over-relaxation phenomena during the set-up of RFP plasmas

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Abstract

Experiments on the Extrap T1 reversed field pinch [Phys. Scripta **49**, 224 (1994)] have shown that the formation of the RFP configuration is quite sensitive to the relative programming of the toroidal field and ohmic heating circuits. In this paper, new measurements of the evolution of the current density profile and of the spectral structure of the fluctuations during the set-up phase of RFP plasmas in the T1 experiment are presented. These measurements improve the understanding of the role of different spectral components in the dynamics of RFP formation. Under unfavourable (slow) set-up conditions, comparatively high energy is accumulated in $m = 1$ internal kinks prior to reversal of the edge toroidal field. At reversal, nonlinearly driven $m = 0$ modes trigger a rapid broadening of the $m = 1$ spectrum. This behaviour is associated with a violent suppression of the current density in the core leading to an over-relaxation of the discharge involving a hollowing of the parallel current density profile. The over-relaxation phenomenon increases the volt-second consumption and plasma/wall interaction during RFP set-up, and degrades the flat-top discharge performance.

I. INTRODUCTION

Reversed-field pinch (RFP) plasmas are formed by inducing a toroidal current in a weak, decreasing initial bias toroidal field. As the plasma current rises the toroidal magnetic field at the plasma edge decreases but the average toroidal field is sustained by the *dynamo*,[1] which converts poloidal flux, provided by the applied inductive drive, to toroidal flux. This process is generally believed to originate in the nonlinear evolution of internal $m = 1$ modes destabilised by parallel current gradients[2] (the perturbed fluid velocity **v** and magnetic field **b** can introduce the necessary modification of the mean electric field, through $\mathbf{v}\times\mathbf{b}$), and in radial diffusion of long mean free path electrons due to magnetic field stochasticity.[3] Prior to field reversal, when the helical structure of the current-path builds up, the loop voltage is relatively large and the magnetic fluctuation level is high. However, after reversal is achieved the discharge becomes comparatively quiescent and the loop voltage normally drops by about an order of magnitude. However, as previously reported,[4] the formation of the RFP configuration in the Extrap T1 experiment[5] can be quite sensitive to the relative programming of the toroidal field circuit (TFC), and ohmic heating circuit (OHC) during start-up. Although the loop voltage generally is high prior to reversal, under unfavourable conditions there can be an additional dramatic increase in the loop voltage when the edge toroidal field approaches zero and the reversal surface is introduced at the plasma boundary. The increased loop voltage coincides with an interruption in the discharge current rise, the generation of toroidal flux is suppressed and the reversal process is halted. This behaviour could be provoked[4] either by lowering the ratio of the OHC drive to the initial bias toroidal field during current ramp-up, or by prolonging the time between plasma initialisation and pre-programmed reversal, in both cases resulting in a slower set-up. Phenomenologically, the slow, unfavourable set-up discharges were observed reverse at lower pinch parameter, $\Theta = B_\theta(a)/\langle B_\phi \rangle$. A similar behaviour has also been reported from RFX.[6] In this experiment high recycling and higher electron density were found to have a reducing effect on this behaviour.

In this paper, we present an extended investigation of this phenomenon. New measurements of the evolution of the current density profile and of the spectral structure of the magnetic field fluctuations during the formation of RFP plasmas in T1 are presented. These results provide insight in the role of the different modal components in the dynamics of RFP formation. We shall denote normal set-up conditions: type A, and slow (unfavourable) set-up conditions: type B. We find that type B set-up conditions can lead to accumulation of comparatively high energy in internal kinks prior to reversal. These modes flatten the parallel current density profile, causing the discharge to approach reversal at lower values of the pinch parameter Θ. At the time of reversal nonlinearly driven $m = 0$ modes trigger a rapid $m = 1$ spectral broadening, which causes an over-relaxation of the discharge involving a strong suppression of the core current density and strongly hollow $\mu a = \mu_0 a \mathbf{j}\cdot\mathbf{B}/B^2$ profiles. This over-relaxation phenomenon leads to enhanced plasma wall interaction and increases the volt-second consumption during start-up. The flat-top discharge performance is also adversely affected by this phenomenon.

The paper is organised as follows. In Sect. II the Extrap T1 experiment and the diagnostics are described. Sect. III presents the global performance of type A and type B set-up conditions together with a detailed investigation of structure of the magnetic fluctuations and current density profiles for the two types of RFP formation. A summary of the main results and the conclusions are given in Sect. IV.

II. EXPERIMENTAL SET-UP

Extrap T1 is a small, high aspect ratio reversed-field pinch with the dimensions $R/a = 0.5$ m / 0.057 m = 8.8. The stainless steel bellows vacuum liner is surrounded by a segmented brass shell with average field penetration times of 0.5 ms for vertical magnetic fields and 0.3 ms for radial magnetic fields. The vacuum region between the plasma boundary and the conducting wall is 18% of the minor radius. The device is operated with toroidal plasma currents up to 115 kA, corresponding to average toroidal current densities exceeding 10 MA/m^2. In this regime, the T1 experiment has demonstrated high β values $\beta_\theta \geq 10\%$ and low normalised loop voltages $V_\phi a^2/R \approx 0.5$ Vm. Comprehensive reports on the T1 operational range and confinement performance can be found in Ref. 5. Typical pulse lengths are around 0.7 ms. The characteristic time between breakdown and reversal is about 0.05 ms, the rise time to maximum current is about 0.2 ms and the flat top period is about 0.4 ms. The plasma discharge is triggered after the maximum in the bias toroidal field pulse so that the toroidal field coil current is decreasing as the plasma current is rising. The OHC comprises a current ramp-up bank and a flat-top sustainment bank, which can be charged independently. The second stage in the toroidal field circuit is triggered after TF coil current reversal to sustain the constant current required for aided reversal operation at the desired Θ value during the flat-top phase of the discharge.

In the present study, the time evolution of the current density profile is reconstructed from internal magnetic probe measurements. The insertable probe is designed to measure B_ϕ, B_θ and B_r at eight radial positions. Errors associated with measurements of the internal magnetic field are estimated to be less than 4% and predominantly systematic. The magnetic field profiles are obtained by consecutively fitting sixth-order polynomials to the probe data. Since all three magnetic field components are measured by the probe, the shift of the magnetic axis can be estimated. The polynomials are shift corrected accordingly and the magnetic fields are expressed in a cylindrical system originating at the magnetic axis.[7] The current density profiles are obtained by analytical differentiation of the shift corrected polynomials. Details concerning the calibration of the probe and the profile reconstruction technique are given in Refs. 8, 9.

The spectral structure of the edge magnetic field fluctuations are studied using coil arrays located in the interspace between the liner and the shell. The poloidal mode structure of fluctuations in the edge toroidal field is studied with a array of eight coils distributed around the poloidal circumference. This array resolves the poloidal structure of fluctuations with poloidal mode number $m < 4$, with perfect resolution. For studies of the toroidal structure of the fluctuations an array comprising 19 pairs of $m = 1$ cosine and sine coils distributed over toroidal angle in a quadrant of the torus is available. With this array the helical spectrum of fluctuations in the edge poloidal field with toroidal mode numbers $-36 < n < 36$ can be resolved with a resolution of $\Delta n = \pm 2$. We choose the convention that $m \geq 0$ and that $n < 0$ corresponds to modes with helicities in the same direction as the equilibrium field inside the reversal surface. For the Fourier mode analysis the coils signals are band pass filtered to extract the frequency range of interest, i.e., for global MHD mode activity in T1, 4 kHz $< f <$ 200 kHz.[10,11]

The limited number of data acquisition channels available for this study inhibited recording of data from the insertable magnetic probe and the coil arrays simultaneously.

III. RFP START-UP EXPERIMENTS

Typical pulse data for a normal set-up, type A (—), and a slow set-up, type B (---), is shown in Fig. 1. The difference in set-up performance is provoked by triggering the bias toroidal field 10 μs later in the type B set-up, thereby increasing the initial bias toroidal field and extending the time between plasma breakdown and pre-programmed reversal. In a normal set-up, the transition to reversed field operation is smooth with no apparent disturbances on global signals. The plasma current and toroidal flux increase smoothly while the edge toroidal field decreases. When reversal is achieved the loop voltage starts to decrease. In the type B case, the toroidal current is suppressed prior to reversal and the generation of toroidal flux is stronger. When the edge toroidal field reverses the plasma current is strongly suppressed and the loop voltage increases dramatically. During this time interval $B_\phi(a)$ oscillates around zero before it finally reverses again and the RFP configuration is established. We note that the plasma losses appear to be larger during the type B set-up, as indicated by the continuing strong density pump-out during the event. Also, plasma wall interaction is enhanced during this period, as indicated by the increased Hα line radiation. In this connection we note that in RFX,[6] which has a graphite wall, the adverse effects of this phenomenon was found to be reduced by high edge recycling during the set-up phase. The onset of this phenomenon in Extrap T1 is quite reproducible. In fact, a gradual degradation of the pulse start-up performance can be provoked by changing the timing between the plasma circuit and the toroidal field circuit as described above.

The volt-second consumption during a type B start-up is significantly larger than for the normal set-up case and the plasma current remains at a comparatively lower level for the remainder of the pulse. In Table I, we show a comparison of pulse parameters corresponding to type A and type B set-ups with the OHC programmed for flat-top currents of 60 kA at $\Theta = 1.7$. The volt-second consumption during the current rise time (initial 0.25 ms) increases by about 30%. In addition, the flat-top plasma resistance V_{loop}/I_{ϕ}, increases by about 60%. We further note that the magnetic fluctuation level generally tend to remain higher throughout the type B set-up pulses.

In Fig. 2 we plot the evolution of the two discharges in the F-Θ plane. The Bessel function model BFM,[12] representing the relaxed states, is included for reference. The type B set-up discharge reverses at lower pinch parameter and exhibits a violent over-relaxation during the time period after the first reversal of $B_{\phi}(a)$, indicated by the F-Θ trajectory loop behind the BFM curve. During this time period the strong suppression of toroidal current is observed together with the dramatic increase in the loop voltage.

Fig 3 a) and b) show contour plots of the time evolution of the helical $m = 1$ spectral mode energies for two type A and type B set-up discharges. The contours represent surfaces of constant mode energy. We empirically find that type B set-up conditions can lead to accumulation of comparatively high energy in internal kink/tearing modes prior to reversal. This can be seen by comparing the evolution of the $m = 1$ spectra up to the dotted vertical lines ($\cdots$), which indicate the estimated time of $B_{\phi}(a)$ approaching reversal for the two discharges. In the type B case high energy internal modes are present, with toroidal mode numbers increasing gradually during initial current ramp-up as the central safety factor ($q = rB_{\phi}/RB_{\theta}|_{r=0}$) decreases. These modes resonate ($q = -m/n$) in the central part of the plasma. When the $m = 0$ resonance surface is introduced at the boundary a rapid $m = 1$ spectral broadening occurs. This can be seen in Fig. 3 a) as a spectral spread shortly after the initial reversal at $t \approx 0.045$ ms, and in Fig. 3 b) as a strong broadening both to lower and higher $|n|$ at $t \approx 0.055$ ms, followed by a second broadening around $t \approx 0.065$ ms. During the time periods of spectral broadening in Fig. 3 b) activity around $n = 0$ is evident, indicating the presence of equilibrium shifts. Note that the establishment of reversed-field operation, indicated by the dashed lines (- - -), is delayed until about 0.09 ms in the type B set-up case. We also find that discharges with type B set-up generally tend to have higher energies in the core resonant $m = 1$ modes throughout the pulses, which is reflected by the higher fluctuation level in Table I.

The spectral broadening phenomenon has a dramatic effect on the current profiles. The time evolution the experimental μ profiles for a type A and a type B set-up are shown in Figs. 4 a) and b). Note that, in the type B set-up case, the μ profile is weakly hollow in the central region prior to reversal, indicating stronger suppression of parallel current density $j_{\parallel}$ in the central region, which is reflected in the lower Θ value at the time of reversal. At reversal, $j_{\parallel}$ is strongly suppressed in the core and driven in the edge region. In the type B case the μ profile becomes strongly hollow during a significant period of time, indicating violent dynamo action. This is observed on global edge field diagnostics, F and Θ, as an over-relaxation, a loop of the F-Θ trajectory behind the BFM curve. This over-shooting of the flat, minimum energy, μ indicates a strong nonlinearity in the system. We note that the hollowing of the μ profile is consistent with a sudden dramatic increase in the fluctuation induced electric field $\mathbf{E}_f = -\langle \mathbf{v}\times\mathbf{b}\rangle$, which is of the shape to suppress $j_{\parallel}$ in the core and drive $j_{\parallel}$ in the edge region. We further note that a similar type of hollow μ profiles have been observed in numerical MHD simulations of RFP dynamics with a resistive boundary,[13] characterised by high fluctuation levels and strong dynamo action. In addition, we remark that the high loop voltage and the (presumably) increased stochastisation of the magnetic field associated with this event suggest that kinetic effects,[3] i.e. radial diffusion of long mean free path electrons, also may be important.

The behaviour of the $m = 1$, $m = 0$ and $m = 2$ modal energies (sum over all n) in the edge toroidal field corresponding to a type B case is shown in Fig. 5. Prior to reversal the $m = 0$ mode is essentially absent. At reversal $m = 0$ modes are driven to large amplitudes coinciding with the onset of $m = 1$ spectral broadening and the suppression of $j_{\parallel}$ in the central region. The $m = 2$ activity is clearly present prior to reversal and remains at high energy as long as the $m = 1$ energy is high, dropping to a comparatively lower level after reversal. It hence appears that the rapid $m = 1$ spectral broadening occurring at the time of reversal is triggered by the appearance of $m = 0$ modes nonlinearly driven to high amplitudes. It is interesting to note that of the two lowest order nonlinear convolutions of the $m = 1$ modes $(1, n_1) + (1, n_2) \rightarrow (2, n_1 + n_2)$ and $(1, n_1) + (1, n_2) \rightarrow (0, n_1 - n_2)$ only the first appears to be significant prior to reversal, but this convolution (the $m = 2$ convolution) apparently does not result in significant $m = 1$ spectral broadening. At least not when compared to the spectacular broadening after reversal when $m = 0$ modes are driven to large amplitudes in the type B set-up case. This observation lends experimental support to the numerical MHD simulation results reported in Refs. 2, 14, 15, i.e. that the $m = 2$ modes are primarily dissipative and effectively serve as an energy sink for the $m = 1$ dynamo. The present experimental results thus emphasise the role of the $m = 0$ modes in mediating nonlinear energy transfer between the $m = 1$ modes.

IV. SUMMARY AND CONCLUSIONS

The dynamics of RFP formation in Extrap T1 has been investigated. Previous experiments on RFX[6] and T1[4] have shown that the formation of the RFP configuration can be quite sensitive to the relative timing and programming of the toroidal field and ohmic heating circuits, and to the set-up electron density. We find here that under slow set-up conditions (characterised by too low OHC drive relative to the initial bias toroidal field, or too long time between plasma initialisation and pre-programmed reversal) comparatively high energy is accumulated in internal $m = 1$ modes prior to reversal of the edge toroidal field. These modes strongly suppress the core current density, which also is globally evident in a comparatively lower Θ value as the discharge approach reversal. At the transition to reversed-field operation, nonlinearly driven $m = 0$ modes trigger a rapid $m = 1$ spectral broadening. This phenomenon, which is associated with a dramatic increase in the loop voltage, results in an over-relaxation of the discharge involving violent suppression of the central current density and the development of strongly hollow μ profiles. This event is further associated with increased losses and enhanced plasma wall interaction during the formation phase. We note that the $m = 2$ mode is clearly present prior to reversal whereas the $m = 0$ mode is essentially absent. At reversal $m = 0$ modes are nonlinearly driven to large amplitudes coinciding with the onset of $m = 1$ spectral broadening. These results indicate that the $m = 0$ modes play a dominant role in mediating nonlinear power transfer between the $m = 1$ modes, and thus in the relaxation dynamics, while the $m = 2$ modes appears to be primarily dissipative, as back coupling from $m = 2$ (prior to reversal) is comparatively much less efficient. We note that the over-relaxation phenomenon, apart from increasing the volt-second consumption during start-up, also leads to higher flat-top plasma resistance and magnetic fluctuation levels, as compared to normal set-up discharges. Hence, in terms of optimising plasma performance there may be significant gain by carefully designing the set-up phase of the RFP configuration.

ACKNOWLEDGEMENTS

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TABLE I. Comparison of typical pulse parameters for type A and type B set-up plasmas, with the OHC programmed for flat-top 60 kA operation with $\Theta = 1.7$. The volt-second consumption refers to the initial 0.25 ms when the current is ramped to the flat-top value.

	Normal set-up Type A	Slow set-up Type B
Vs consumption during ramp-up	~ 0.10 Vs	~ 0.13 Vs
flat-top resistance V_{loop}/I_ϕ	~ 1.5 mΩ	~ 2.4 mΩ
flat-top RMS fluctuation level, $\delta B_\phi/B$	0.9 - 1.0 %	1.3 - 1.5 %

Figure Captions:

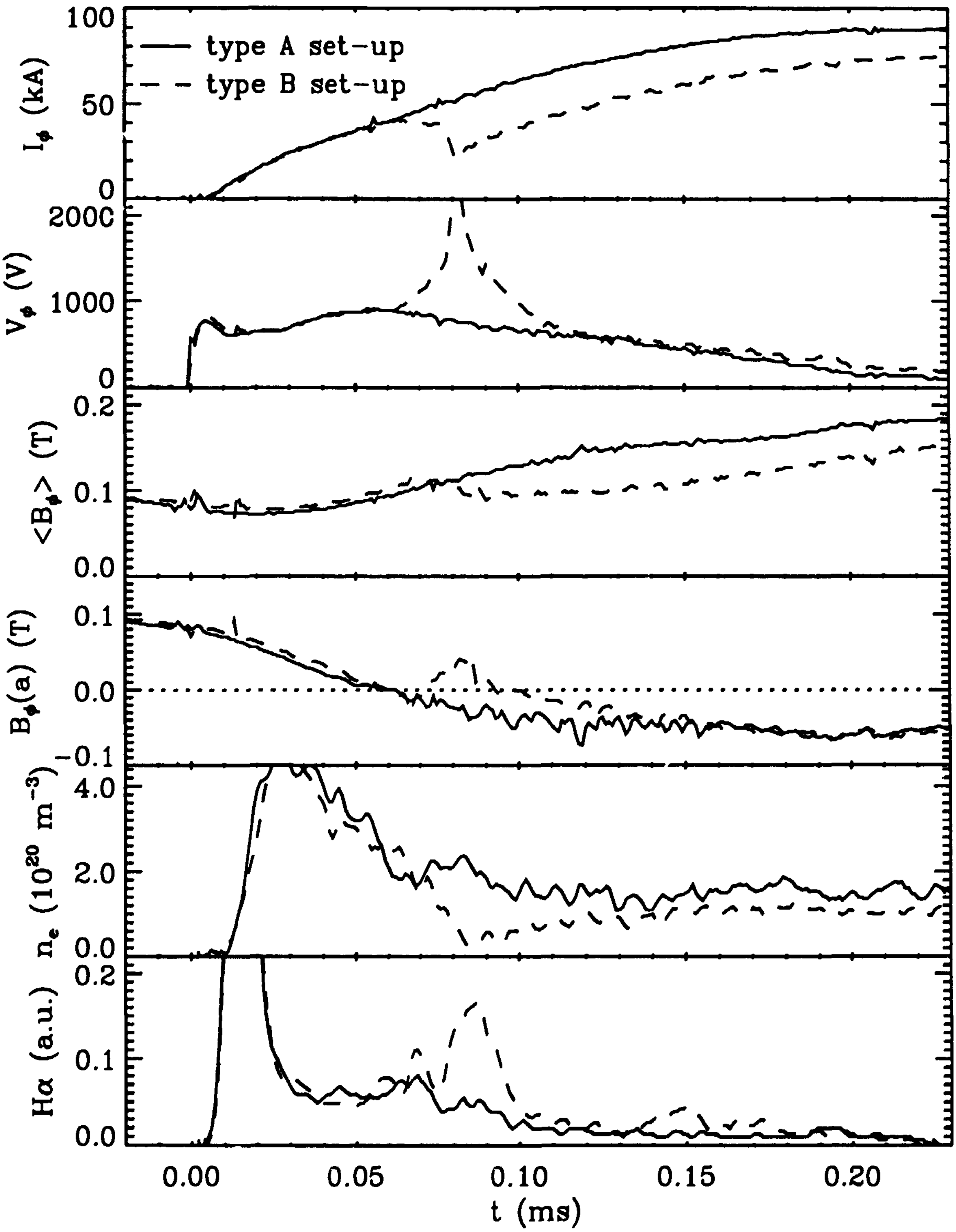
FIG. 1. Pulse data for two discharges with a typical normal, type A set-up (—) and a typical unfavourable, type B set-up (---). From top to bottom: toroidal plasma current I_ϕ, loop voltage V_ϕ, average toroidal field $<B_\phi>$ and edge toroidal field $B_\phi(a)$, line averaged electron density n_e, Hα line radiation.

FIG. 2. F - Θ trajectories during start-up for the normal, type A set-up (—) and the slow, type B set-up (---) discharges in Fig. 1. The Bessel function model BFM[12] representing the fully relaxed minimum energy states is included for reference. The discharge with the unfavourable, type B set-up exhibits a violent over-relaxation before the final RFP configuration is formed, indicated by the loop of the F - Θ trajectory below the BFM curve.

FIG. 3. Contour plot of the time evolution of the helical $m = 1$ spectrum during the formation of the RFP configuration for a) a discharge with a normal, type A set-up, b) a discharge with an unfavourable, type B set-up. The contours represent surfaces of constant mode energy. The dotted vertical lines (···) indicate the estimated time of $B_\phi(a)$ reversal for the two discharges. The dashed lines (---) indicate where reversed-field operation is established. Before reversal, comparatively high energy is accumulated in the (m, n) = (1, -5...-15) modes in the type B set-up case. In this situation, a dramatic broadening of the $m = 1$ spectrum occurs during reversal.

FIG. 4. Time evolution of the experimental $\mu a = \mu_0 a \mathbf{j}\cdot\mathbf{B}/B^2$ profile during the formation of the RFP configuration for a) a discharge with a normal, type A set-up, b) a discharge with an unfavourable, type B set-up. In the type B set-up discharge, the μa profile is flat prior to reversal. At the time of reversal parallel current is strongly suppressed in the core and enhanced near the edge, resulting in strongly hollow μa profiles.

FIG. 5. Time evolution of the energy in modes with poloidal mode number $m = 1$, $m = 0$ and $m = 2$ (includes all toroidal mode numbers) for a discharge with an unfavourable, type B set-up. The dotted vertical lines (···) indicate the estimated time of $B_\phi(a)$ reversal for the two discharges. The dashed lines (---) indicate where reversed-field operation is established. Prior to reversal the $m = 0$ mode is essentially absent. Around the time of reversal $m = 0$ modes are nonlinearly driven to large amplitudes, coinciding with the onset of $m = 1$ spectral broadening. The $m = 2$ mode is clearly present prior to reversal, but this convolution appears to play a comparatively less important role in the relaxation dynamics.



type A set-up
type B set-up
I_ϕ (kA)
100
50
0
V_ϕ (V)
2000
1000
0
$\langle B_\phi \rangle$ (T)
0.2
0.1
0.0
$B_\phi(a)$ (T)
0.1
0.0
-0.1
n_e (10^{20} m^{-3})
4.0
2.0
0.0
Hα (a.u.)
0.2
0.1
0.0
0.00
0.05
0.10
0.15
0.20
t (ms)

FIG. 1

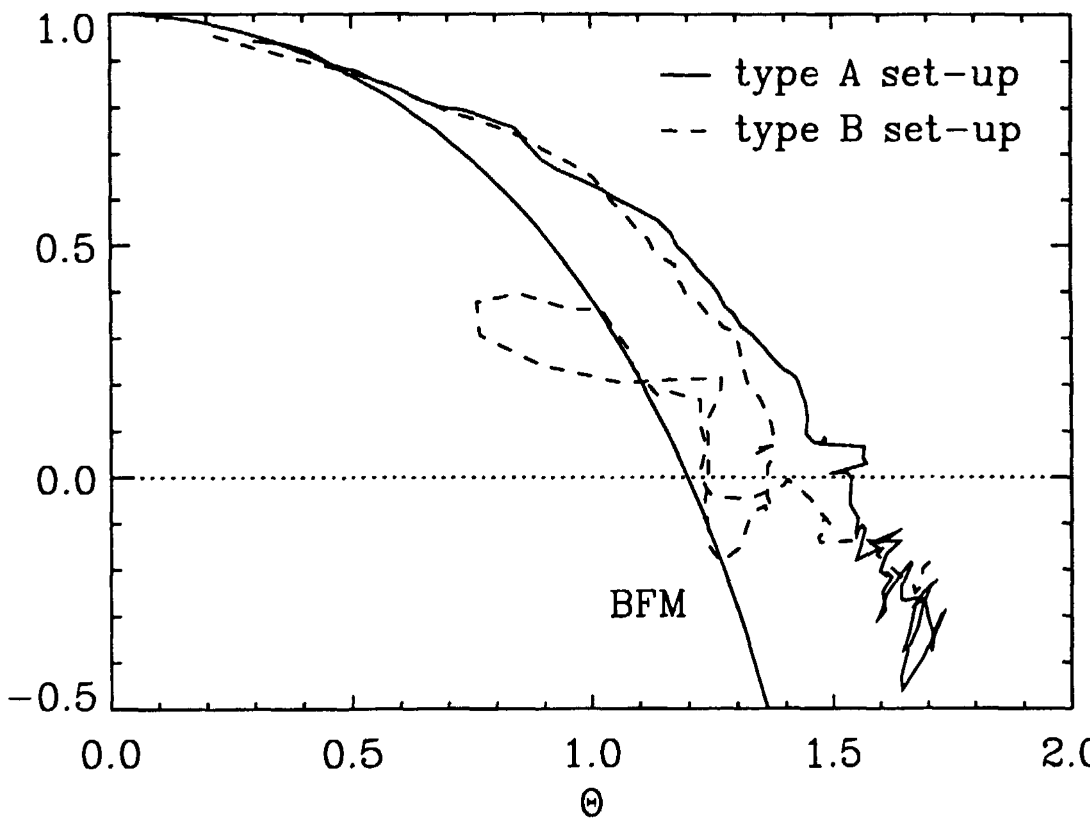


FIG. 2

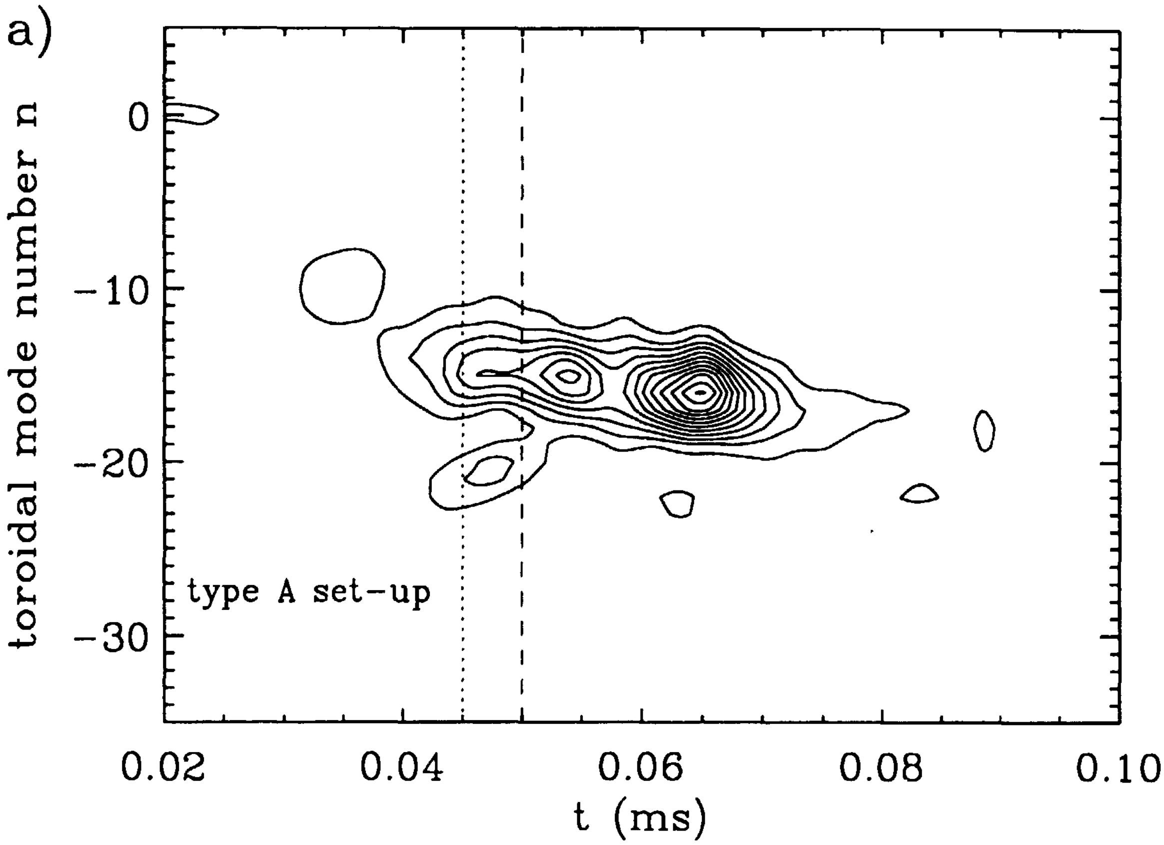

a)
toroidal mode number n
0
−10
−20
−30
type A set−up
0.02
0.04
0.06
0.08
0.10
t (ms)

FIG. 3a)

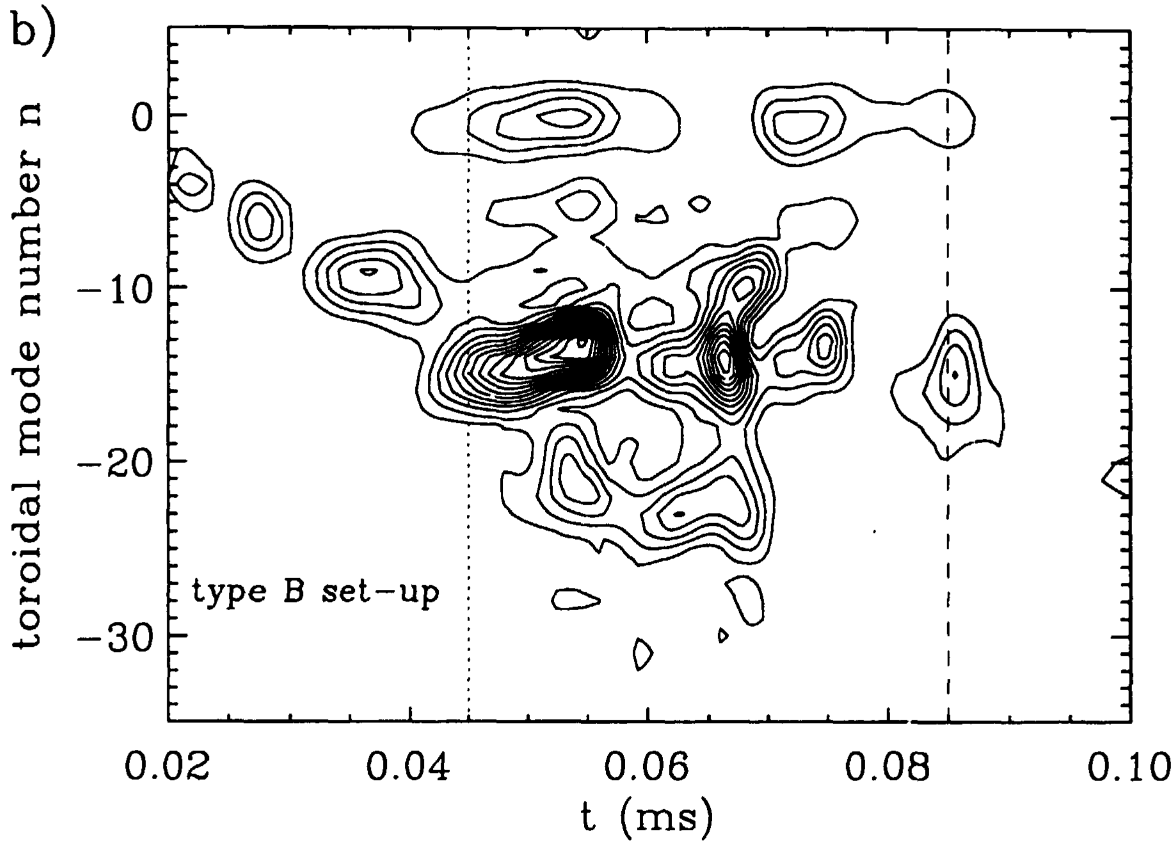

b)
toroidal mode number n
0
−10
−20
−30
type B set−up
0.02
0.04
0.06
0.08
0.10
t (ms)

FIG. 3b)

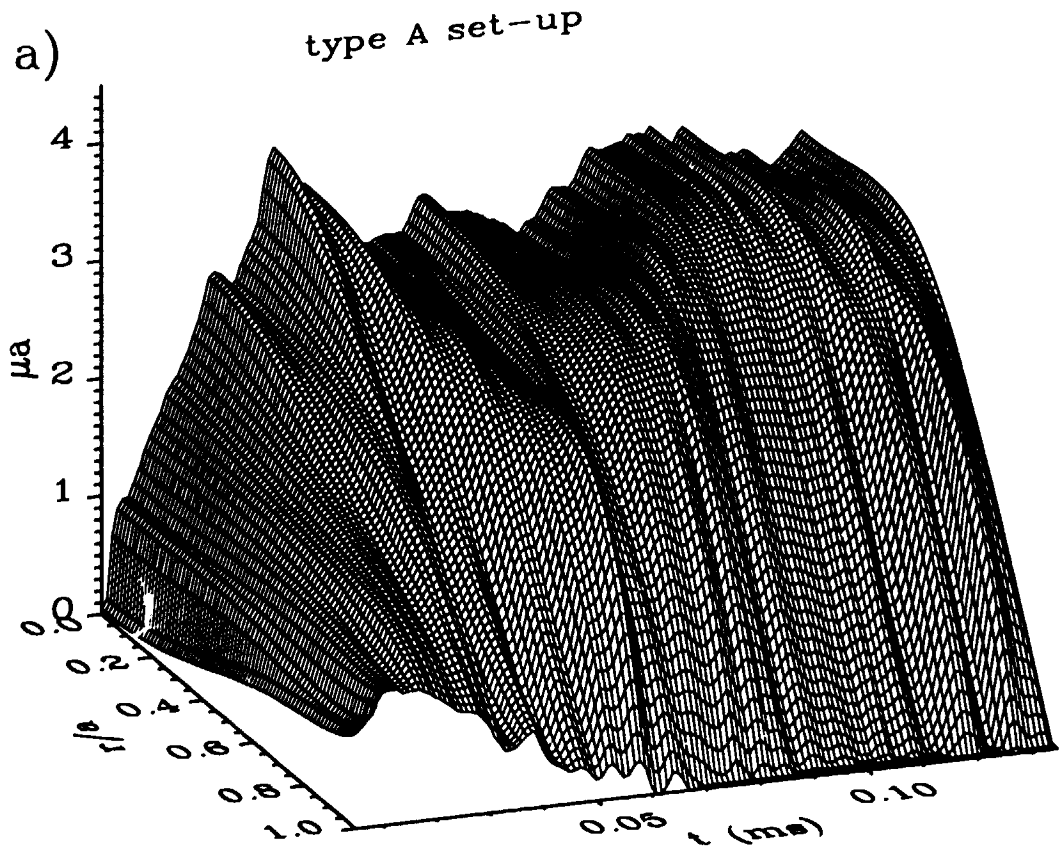


FIG. 4a)

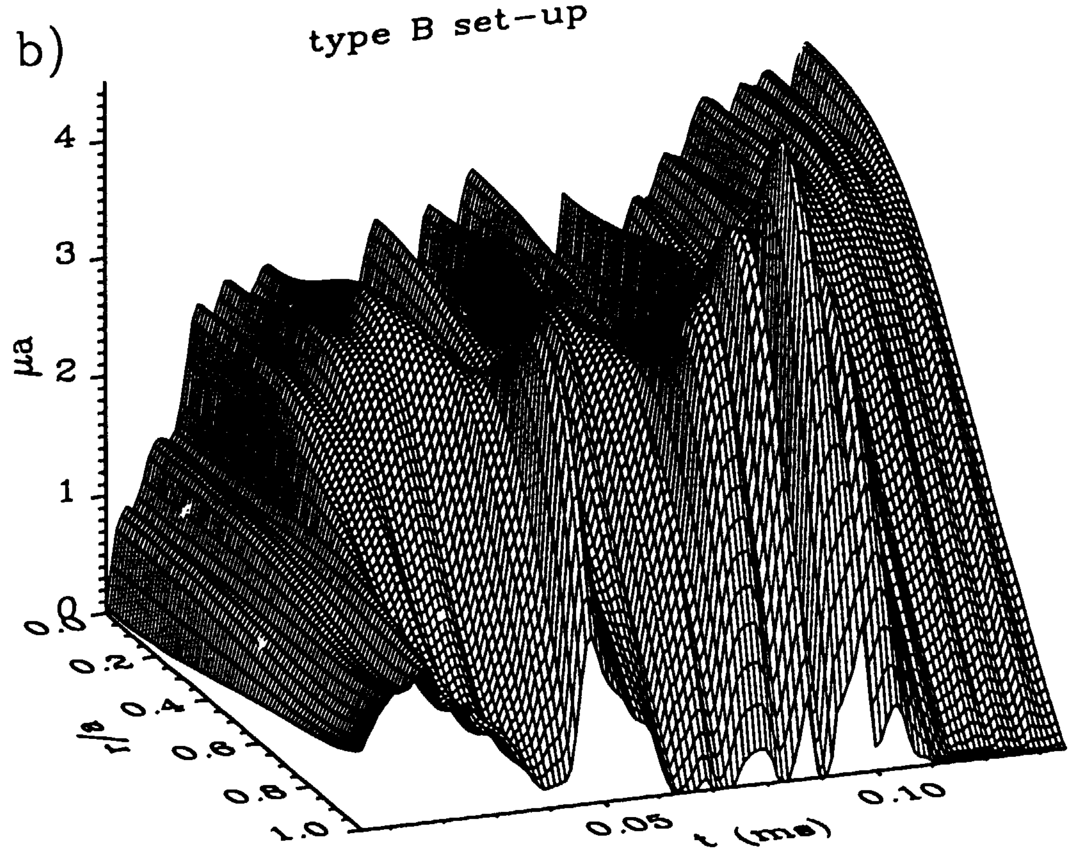


FIG. 4b)

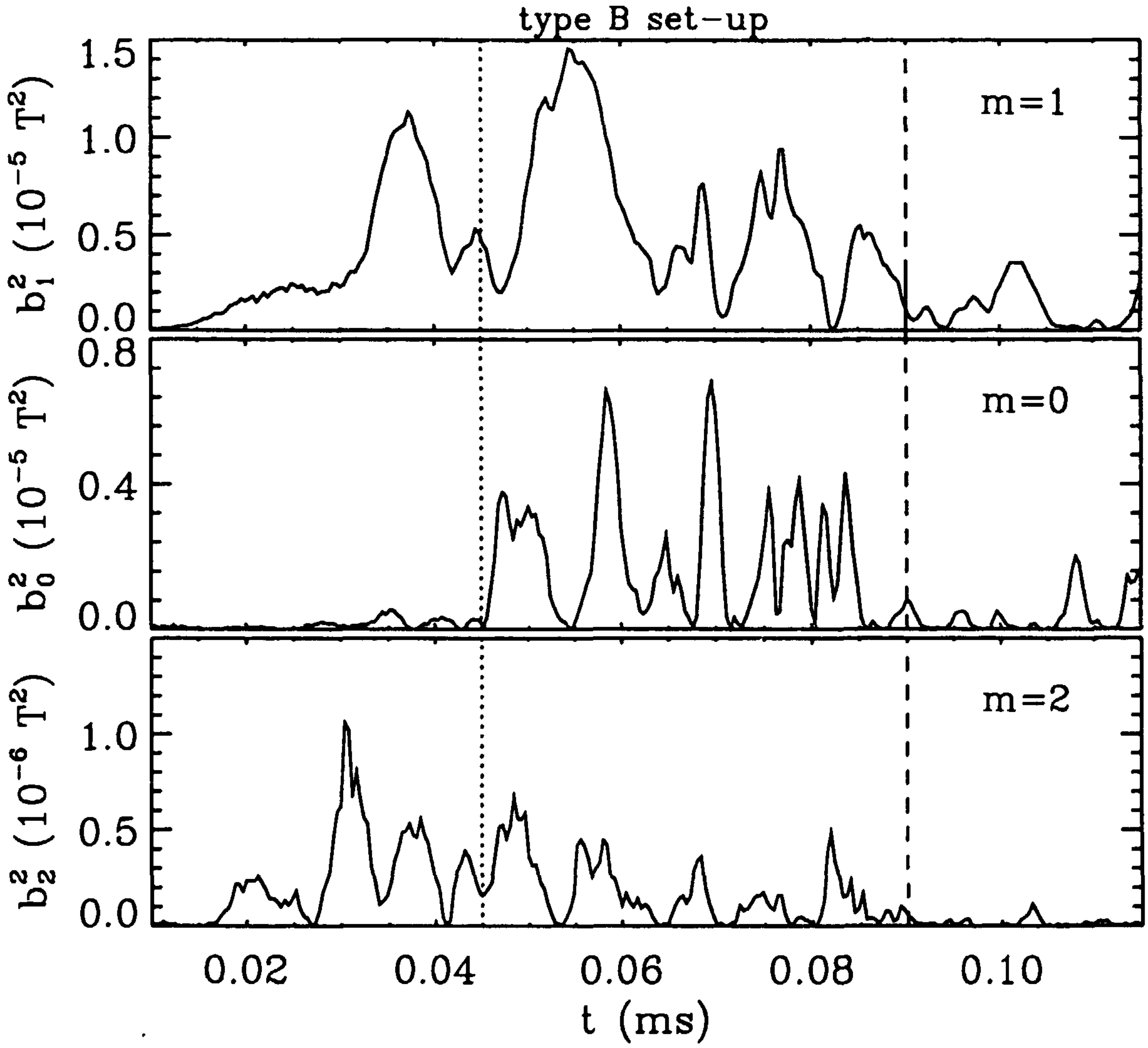

type B set-up
m=1
m=0
m=2
1.5
1.0
0.5
0.0
0.8
0.4
0.0
1.0
0.5
0.0
b_1^2 (10^{-5} T^2)
b_0^2 (10^{-5} T^2)
b_2^2 (10^{-6} T^2)
0.02
0.04
0.06
0.08
0.10
t (ms)

FIG. 5

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10 pages and 5 figures (in English)

Abstract

Experiments on the Extrap T1 reversed field pinch [Phys. Scripta **49**, 224 (1994)] have shown that the formation of the RFP configuration is quite sensitive to the relative programming of the toroidal field and ohmic heating circuits. In this paper, new measurements of the evolution of the current density profile and of the spectral structure of the fluctuations during the set-up phase of RFP plasmas in the T1 experiment are presented. These measurements improve the understanding of the role of different spectral components in the dynamics of RFP formation. Under unfavourable (slow) set-up conditions, comparatively high energy is accumulated in $m = 1$ internal kinks prior to reversal of the edge toroidal field. At reversal, nonlinearly driven $m = 0$ modes trigger a rapid broadening of the $m = 1$ spectrum. This behaviour is associated with a violent suppression of the current density in the core leading to an over-relaxation of the discharge involving a hollowing of the parallel current density profile. The over-relaxation phenomenon increases the volt-second consumption and plasma/wall interaction during RFP set-up, and degrades the flat-top discharge performance.

Key words: Extrap T1, reversed-field pinch (RFP), relaxation, dynamo, magnetohydrodynamics (MHD)