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Feedback Mechanism
for the
Precursors of Major Disruptions

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Abstract

A feedback mechanism for the exponentially growing low-frequency precursor oscillations of tokamak plasmas is proposed. It takes into account the interaction of the growing plasma pressure with the discharge walls.

It has been experimentally observed that the sawtoothing of the internal disruption phase /1/ abruptly ceases just before the onset of exponentially growing low-frequency precursor oscillations /2/,/3/. These oscillations, which lead to the onset of major current disruptions in tokamak plasmas, are shown, in an enlarged time scale, in Fig. 1(b), where the density oscillations (lower traces) are correlated with the soft X-ray emission along a central chord (upper trace). This letter proposes a feedback mechanism for the precursors shown in Fig. 1(b) by taking into account the interaction of the growing plasma pressure with the discharge walls.

The shot of Fig. 1 was obtained for a typical set of Pulsator discharge parameters, i.e. $B_\varphi = 27$ kG, $q(a_L) = 2.7$, $I = 80$ kA, $\overline{N}_e \approx 10^{14}$ cm^{-3}. As seen from the fringe shift of the $\lambda = 2$ mm wave in Fig. 1(a), the high-density regime, which is obtained by pulsed gas inlet, begins at t = 60 ms, one fringe shift corresponding to an average density of 5×10^{12} cm^{-3} along a probing chord passing through the center of the plasma. The density oscillations are well correlated with $\dot{B}_\Theta$ low-frequency oscillations (not shown here). These, however, cannot exibit the slow-growing d.c. perturbation, as the density does, since they are picked up with coils surrounding the discharge current poloidally. Contrary to the magnetic pick-up oscillations, the density exibits a correlation with the sawtoothing of the soft X-ray emission preceding the onset of the growing oscillations.

These oscillations have been ascribed to MHD m = 2 tearing modes occurring when the radial current distribution is such that the q = 2 surface is in the proximity of the limiter /2/,/3/,/4/,/5/. Under these conditions an abnormally flat temperature profile is observed /2/. In interpretations of the exponential growth of such oscillations /6/,/7/, they are associated with the existence of magnetic m = 2 islands, which can increase the radial thermal conductivity enough to cool the plasma interior. Owing to the increasing radial conductivity, a feedback mechanism exists whereby the islands grow to fill a substantial part of the tokamak cross-section /6/. By making contact with the limiter the growing islands cause the onset of the current disruption. In addition, a number of effects are suspected to contribuite to the major disruptions. As an example, non-linear coupling between the m = 2 and the weaker m = 1 internal modes (the latter also being associated with the corresponding m = 1 magnetic islands) can lead to large regions of ergodic field lines /6/,/7/. The following arguments show, however, the failure of the above standard model to explain experimental data, and the need for the proposed mechanism as a link between plasma-wall interactions and the MHD activity in the plasma interior.

The standard interpretation of the m = 0 soft X-ray sawtoothing of the internal disruption phase is that the plasma core is resistively heated until the safety factor drops below unity, causing the m = 1 tearing mode to become unstable, to grow with increasing rate, and ultimately to flatten the electron and safety factor profiles /8/,/9/. In Ref. /9/ the starting point for an explanation of the disruptive part of the sawtooth is that the m = 1 precursor appears to be the cause. However, as shown in Fig. 1(b), upper trace, the m = 1 oscillations, which are usually superimposed on the soft X-ray sawteeth, are not always observed. There are also discharges which do not even yield coherent, m = 2 external precursor oscillations before the onset of major disruptions. However, instead of m = 2 oscillations, one invariably observes increasing turbulence in the density fluctuations, indicating strong plasma-wall interaction before the onset of major disruptions. On the other hand it is not clear whether the flattening of the temperature profile is a consequence of the internal m = 1 tearing mode, as is usually claimed. Such mode, which is associated with the corresponding q = 1 magnetic island, should destroy the confinement of large regions of plasma before the onset of the m = 0 instability. The same applies to the m = 2 modes and q = 2 islands before the onset of major disruptions. Such destruction of confinement, however, is not observed. Furthermore, no experimental proof has been given for the existence of magnetic islands and the connection between the observed oscillations and the internal m = 1 and m = 2 MHD helical instabilities predicted by the theory /7/.

The MHD activity in tokamak plasma is usually interpreted as being dominated by the bulk properties of the electron distribution /9/. This is inferred from electron temperature measurements by Thomson scattering of laser light, before and after internal disruptions. However, these measurements, which are not very sensitive to the most energetic tail of the electron distribution, do not rule out the likelihood that the MHD activity may actually be dominated by the most energetic electrons and/or superthermals or runaways. In this contest the rapid flattening of the temperature profile at the onset of internal current disruption may be regarded as due to a rapid redistribution of the most energetic electrons. This hypothesis is sustained by the sawtoothing of both soft and hard X-ray emission /3/,/10/, which may be interpreted as due to outward spreading of the most energetic electrons from the center of the plasma. It should be noted here that the assumed sawtoothing symmetry about the q = 1 surface during the internal disruption phase is not experimentally proved. Moreover, the persistent flattening of the current profile which is observed during the precursor oscillations (just after the abrupt cessation of the last sawtooth) may, on the other hand, be interpreted as a progressive failure to replenish superthermal and runaway components, thus supporting the hypothesis of plasma collapse owing to depletion of superthermals or of the most energetic part of the electron distribution. The negative loop-voltage spikes observed in the predisruption and disruption phases may also be regarded as having been generated by a rapid redistribution of runaways, superthermals and/or the most energetic tail of the electron distribution, rather than by bulk electrons, as is usually assumed.

It should finally be noted that the asymmetrical tendency of the growing plasma pressure is conducive to progressive plasma interaction with the outer walls, which is the most likely cause of the observed disruptions. However, relatively little is known about the dynamics of plasma-limiter confinement processes, which should somehow be linked with the observed MHD activity involving superthermals, runaways and bulk electrons during disruptions. According to the following model, the missing link mechanism consist of resistive current displacement of bulk electrons owing to the gas produced by plasma-wall interaction or gas feed. Each time the growing off-centered plasma pressure approaches the outer limiter wall, the gas emitted by the plasma-wall interaction produces a layer of high resistivity

(3 to 10 times above the pure hydrogen plasma value /11/) which tends to displace the discharge current inwards. Owing to the smaller value of the Coulomb collision cross-section of the most energetic electrons in comparison with the Coulomb cross-section of the bulk electrons, the resistive current displacement can only force the latter inwards. This causes, however, destabilization of the discharge current ring owing to the immediate release of that part of the stored magnetic field energy which is associated with the inward displacement of the current. In fact, according to the expression for the self-inductance of the discharge current ring, $L_i = 4\pi R \left[\ln(8R/a) - 1.75\right]$, where a is the minor plasma radius, a smaller value of the major plasma radius R (corresponding to the inward displacement of the bulk-electron current) yields an excess of stored magnetic field energy $dW_m = (1/2) I^2 dL_i$ to be instantaneously depleted.

As will be seen, the release of this excess of field energy determines the flattening of the current profile by increasing the plasma radius, a, of the radial distribution of the most energetic electrons. In fact, assuming infinite conductivity for the current density of the most energetic electrons $J = \sigma E$ (i.e. by neglecting resistive dissipative effects) and by neglecting dissipative radiation effects, the excess of magnetic field energy dW_m can be associated with the behavior of the most energetic electrons by the fundamental MHD energy equation $dW_m/dt = \int v(JxB)dV = 0$, where the first term represents the rate of decrease of the stored magnetic field energy, while the second term represents the rate of doing work against the magnetic force JxB. The excess of magnetic field energy to be depleted is therefore that associated with the largest value of the conductivity, which is obviously that related to the most energetic electrons. In other words, the above energy equation represents a "sifting" effect of the MHD instability which spreads the most energetic electrons outwards from the bulk electrons of the plasma. This replaces the inward displacement of the bulk electrons until all runaways or most energetic particles are depleted. In short, by means of the proposed mechanism the current destabilization in the plasma interior can be excited from the plasma edge by several processes such as i) interaction of the growing plasma pressure with the outer walls, ii) gas feed, iii) drift waves, etc..

Following the above model, the feedback mechanism for the exponentially growing precursor oscillations is now illustrated on the basis of the typical succession of events given by or deduced from Fig. 1(b). After the last internal disruption at t = 97 ms in Fig. 1(b), upper trace, the sawtoothing of the soft X-rays is strongly attenuated.

This indicates that the flattening of the temperature profile, at the onset of the last disruption, persists until the onset of the major disruption at t = 100.4 ms. On the other hand, as seen in Fig. 1(b), lower traces, the low-frequency density oscillations start to grow shortly after the onset of the last disruption. The exponential growth of these oscillations is accompanied by an increased growth rate of the density. As the gas feed is constant, the increasing density may be ascribed to impurity gas produced by growing interaction of the plasma with the outer walls. Taking into account the above proposed model, this d.c. density perturbation alone can determine the conditions of persistent flattening of the temperature profile, i.e. through resistive inward displacement of bulk electrons from the outer plasma edge and through the consequent flattening of the radial distribution of the most energetic electrons. The increasing radial conductivity redistribuites on its own the O.H. field energy toward the region of plasma-wall interaction, thus determining the feedback conditions for the growing d.c. instability.

As is well known, the increasing density and temperature gradient at the outer plasma edge support low-frequency drift instabilities through ExB plasma rotation. Therefore, these exponentially growing low-frequency precursor oscillations should be regarded as merely an accompanying feature of the growing d.c. instability, not a cause of it. There are, in fact, discharges which do not yield coherent low-frequency precursors. The plasma-wall interaction is also demonstrated in Fig. 1(b), upper trace, by the positive pulses of soft X-ray emission just before the major disruption at t = 100.4 ms. These positive pulses, <u>not</u> being associated with enhanced electron temperature, must be due to high-Z impurity emission of soft X-rays. It should be finally noted that the proposed model is applicable to the internal and major disruption phases by taking into proper account the balancing of the outward JxB force of the poloidal field B_θ. This treatment, however, exceeds the scope of this letter and will be discussed elsewhere.

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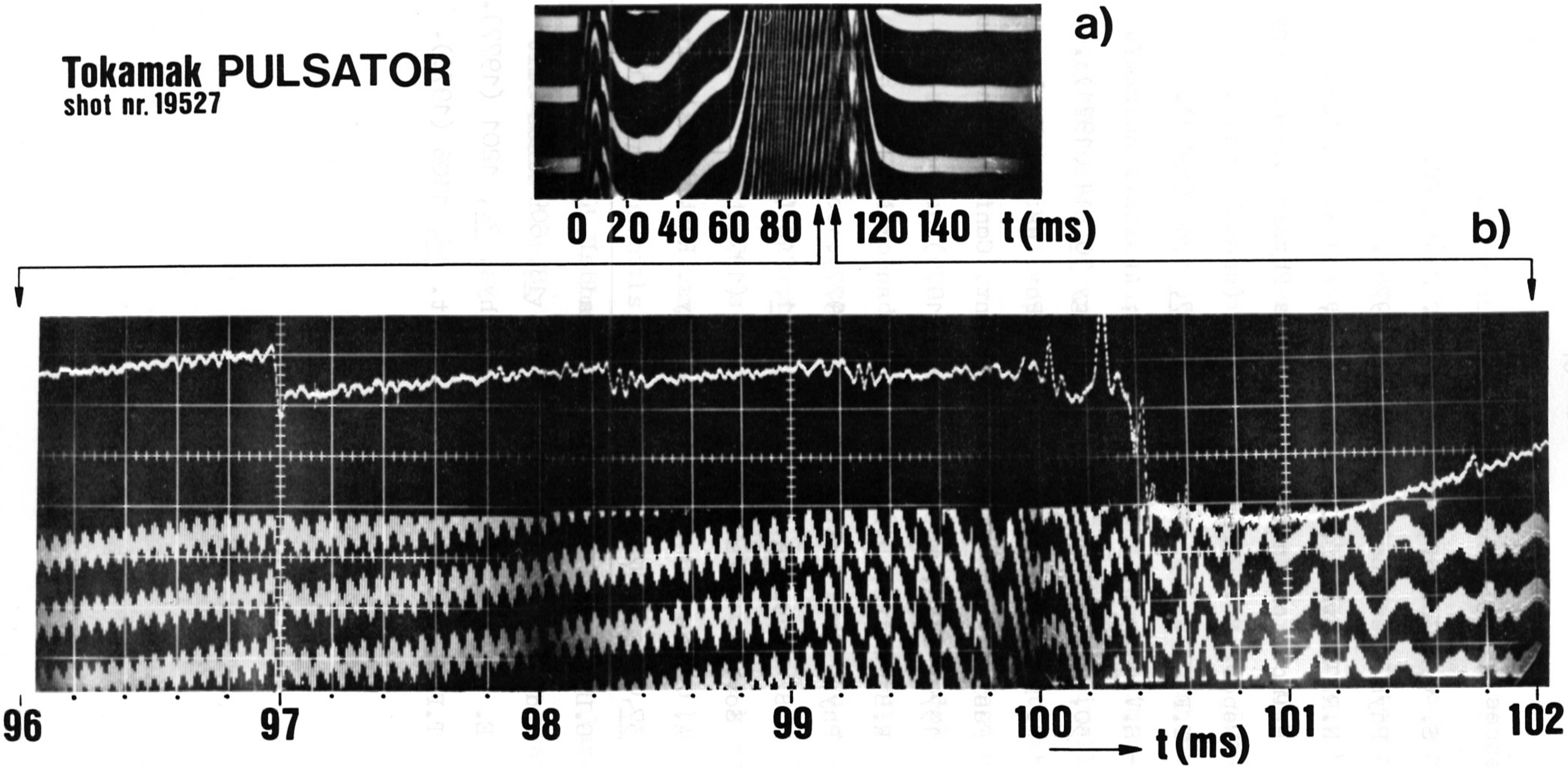

Fig. 1. Fringe shift (a) of $\lambda = 2$ mm waves and correlation measurements (b) of the $\lambda = 2$ mm fringe-shift (lower traces) with the soft X-ray emission (upper trace).