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Edge MHD activity in the ergodic divertor configuration of Tore Supra

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Abstract

On Tore Supra, the ergodic divertor (ED) is used to control particle and heat fluxes at the plasma edge. As it turns out, the ED has also the ability to affect the MHD stability of the plasma equilibrium. In the past, Tore Supra mostly took advantage of the ED stabilizing influence. However, recent attempts to operate the ED with optimal edge conditions happened to be limited by disruptive events. The interest in extending the operational domain is a clear motivation to understand how the observed MHD effects relate to the ED. A tentative analysis is reported in this paper.

Keywords: Tore supra; Ergodic divertor; Disruptions

1. Introduction

On Tore Supra ($R_0 = 2.36$ m, $a = 0.80$ m), the ergodic divertor (ED) has been successfully operated in various plasma scenarios. Operations with the ED are particularly dedicated to the study of particle and energy fluxes on plasma facing components with high additional power. By applying a static external magnetic perturbation, the ED destroys the outermost magnetic surfaces [1,2]. This edge stochastic boundary, referred to as the ergodic volume, leads to an enhanced electron transport in this region. This results in a lowering and flattening of the electron temperature in the ergodic region favourable to power exhaust and impurity control. In addition, the reduced edge electron temperature leads to a narrowing of the current channel [3]. The current redistribution is generally observed simultaneously with a stabilization of surface kink and tearing modes, in particular the (2, 1) tearing mode [4,5]. Another beneficial effect of the ED concerns the particle control. When the ED is applied, an increased impurity radiation and an efficient particle screening are observed inside the ergodic volume [6-8]. The screening property has been shown to be directly associated with a transient increase in the wall pumping capability. All these effects of the ED on the edge plasma open the way to investigate stable edge radiating layers during steady state discharges.

In a recent experimental campaign, some disruptive MHD activity has however seriously limited the operation at $q_{\mathrm{edge}} \approx 3$ for which optimum control of the edge plasma is achieved with the ED. Although MHD stability is not the main motivation for ED studies, the resonant magnetic perturbation (RMP) induced by the ED notoriously affects the MHD behaviour [4,5]. The understanding of the observed disruptive activity is therefore crucial to safely operate the ED with q_{edge} close to 3.

The Tore Supra ED and its principal characteristics are described in the first part of this paper together with the scenario where the disruptive MHD activity is observed. The MHD activity related to the ED is then analysed experimentally in details. Finally, the discussion reviews the present understanding of the considered phenomenon and suggests some further test-experiments to be done in the next Tore Supra experimental campaign.

2. Ergodic divertor characteristics and its effect on MHD

The ED generates a static radial magnetic field perturbation that resonates with the equilibrium magnetic field,

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to create an annular region where the magnetic field is stochastic. On Tore Supra, the ED consists of six identical coils designed for optimal major and minor plasma radii: $R_{ED} = 2.38$ m and $r_{ED} = 0.80$ m. Located on the low magnetic field side, these coils are equally spaced toroidally. Each coil extends over 120° poloidally and 14° toroidally. They generate an octopolar radial magnetic field perturbation δB_r^{ED}, with a maximum divertor current I_{ED} of 45 kA.

The magnetic perturbation spectrum of the ED is determined by the coil periodicity and extent. The main toroidal mode corresponds to the coil periodicity, i.e. $n = 6$. The coil toroidal extent (14°) leads to a spectral broadening $\delta n/n$ of the order of ± 4. Owing to both geometry and plasma dependent poloidal asymmetries, the poloidal spectrum must be analysed in the intrinsic frame of the equilibrium magnetic field. Therefore, the main poloidal mode number depends on the value of $\beta_p + l_i/2$. For the Ohmic discharges reported in this paper (Fig. 1), $\beta_p + l_i/2$ typically equals 0.7, which leads to a main poloidal mode number $m = 18$. The $\beta_p + l_i/2$ dependent intrinsic poloidal extent of the coils gives a spectral broadening $\delta m/m = \pm 0.3$.

Owing to the spectral broadening of the perturbation δB_r^{ED}, the extent of the stochastic layer generated by the ED (centered on the $q = m/n = 3$ surface) lies in the interval $2.15 < q = (m + \delta m)/n < 3.85$. The potentiality to extend the stochastic layer in the vicinity of the $q = 2$ surface is very important regarding MHD stability issues. This surface is indeed well-known for playing a leading role in most tokamak disruptive events.The (2, 1) MHD activity control by a RMP has been studied in various tokamaks using different kinds of RMP spectra. An example is given by Pulsator-I [9], where disruption control was investigated using a RMP with a substantially different spectrum (mainly lower m number, i.e. $m = 2$, $n = 1$) than on Tore Supra. Through the behaviour of the (2, 1) mode, the analysis indicates that a disruption is triggered when the RMP reaches a critical value δB_{hel}^*. Most interestingly, the MHD activity is stabilized for a RMP level lying between 60 and 95% of δB_{hel}^*. Since Pulsator-I results, similar stabilization/destabilisation observations have been made in experiments based on a large variety of RMPs [10–16].

On Tore Supra, the stabilization of the (2, 1) tearing mode has been achieved with the ED [4]. The ED has also been shown to allow faster current ramp-up, by avoiding early external-kink modes which otherwise later degenerate in lethal locked modes [5]. On the contrary, recent ED-operations at $q_{edge} \approx 3$ have been limited by a still unclear disruptive MHD activity. On Tore Supra, the interest in extending the operational domain with $q_{edge} \approx 3$ is a clear motivation for understanding how the observed MHD effects relate to the ED.

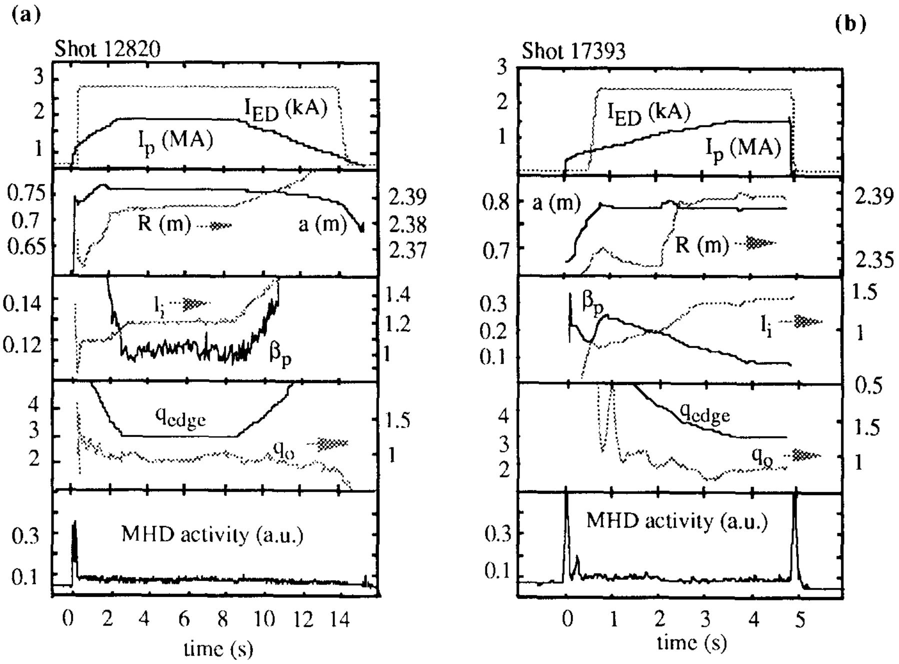

Fig. 1. Characteristics of the studied Ohmic ED discharges. (a) Shot 12820 ($B_T = 3$ T, $\langle n_e \rangle = 2 \times 10^{19}$ m^{-3}) is a typical MHD stable discharge. (b) Shot 17393 ($B_T = 3$ T, $\langle n_e \rangle = 1.75 \times 10^{19}$ m^{-3}) is a typical disruptive discharge.

3. ED-related MHD activity on Tore Supra

To understand the MHD activity in presence of the static magnetic perturbation produced by the ED, the magnetic modes involved in the triggering of the disruption process must be analysed in terms of their frequencies, mode numbers and amplitudes. On one hand, a RMP is likely to reduce the edge plasma rotation [15] and induces a detrimental mode locking above some critical amplitude. The current profile is the basic ingredient for the analysis of tearing mode stability. Transport analyses in the stochastic layer suggest that the current profile is affected by the ED in such a way that a substantial fraction of the longitudinal current is prevented from flowing in the layer and thus redistributed towards the plasma core. In the absence of edge current measurements on Tore Supra, this modification can be observed on the internal inductance l_i which provides a measurement of the current profile peakedness. The experimental analysis of these parameters (i.e. mode analysis and current profile through l_i) is therefore helpful in identifying the underlying cause for the observed disruptive MHD activity.

On Tore Supra, the MHD activity is monitored by magnetic pick-up coils located inside the vacuum vessel. Fluctuations of poloidal magnetic field δB_θ are recorded by an array of twelve Mirnov probes poloidally and an other of four toroidally, with a sampling time of 32 μs. A saddle coil is also used to detect radial magnetic field perturbation δB_r. In addition, during all the discharge duration, quasi-stationary or locked modes are monitored by a set of four saddle loops. To characterize MHD activity, Mirnov magnetic fluctuations are Fourier-analysed to identify the amplitudes, frequencies and the poloidal m and toroidal n wave numbers of each magnetic mode [17]. Singular value decomposition (SVD) analysis [18] is also used to complement the Fourier analysis results.

In all ED non-disruptive discharges, both Fourier and SVD analyses of Mirnov coil signals identify the presence of a (2, 1) dominant mode. This mode rotates at about 6 kHz in agreement with the $n = 1$ toroidal velocity measured by a combination of pick-up coils. This analysis also reveals the presence of a (3, 1) mode with a toroidal rotation frequency of 400 Hz. Such a slow rotation velocity is consistent with the edge location of this mode.

In disruptive discharges, MHD activity is detected prior to the disruption using the disruption trigger to acquire the data. In the predisruptive phase (i.e. 40 ms before the disruption) (Fig. 2), Fourier analysis reveals the presence of both (2, 1) and (3, 1) modes. They exhibit lower frequencies (158 Hz and 270 Hz, respectively) in comparison with the non-disruptive discharges (6 kHz and 400 Hz, respectively). 20 ms before the major disruption, the modes have a similar frequency of 150 Hz. The increasing amplitude of the radial component δB_r and the collapse of the plasma toroidal velocity suggest the presence in this phase of a quasi-stationary or locked mode [15,16,19].

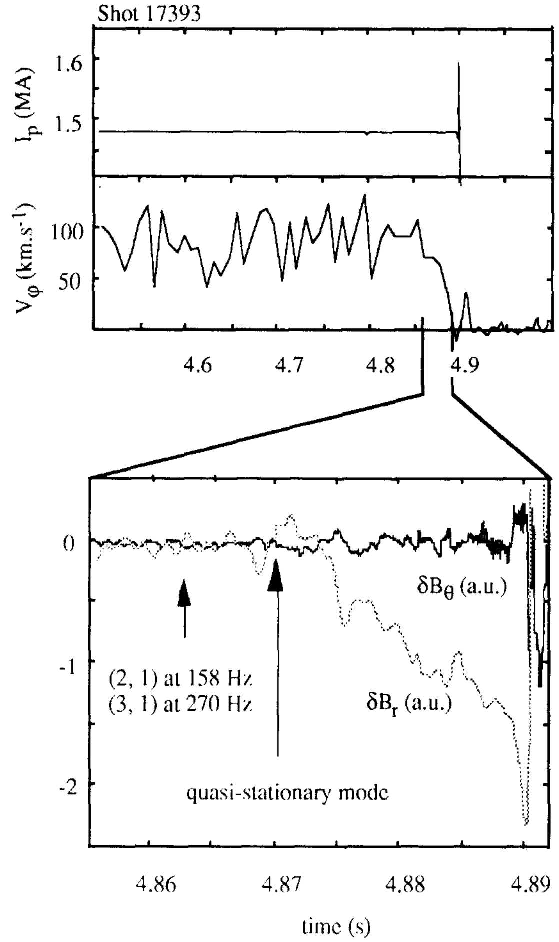

Fig. 2. For an ED disruptive discharge, the $n = 1$ toroidal velocity and both poloidal δB_θ and radial δB_r magnetic field perturbations in the predisruptive phase.

Since the stability of the observed (2, 1) mode cannot be studied with a detailed current profile, the analysis is made in terms of the global parameters l_i and q_{edge}.

The temporal trajectories of two non-disruptive discharges (12820 and 17397) and one typical disruptive discharge (17393) are indicated in the (q_{edge}, l_i) stability diagram [20] (Fig. 3). The lower and upper bounds of this diagram are associated with ideal external kink and low wave number tearing modes, respectively.

For non-disruptive experiments, the safety factor q_{ED} on the divertor is either around 3.3 with an internal inductance l_i lying in the range of 1.3–1.39, or around 3 with a lower internal inductance ($l_i < 1.2$). In both cases, the stochastic boundary is located outside $r \approx 0.63$ m. The disruptive discharges generally operate at q_{ED} values very close to 3 ($q_{ED} \approx 2.9$–3.1) and high internal inductance ($l_i > 1.3$). The inner limit of the stochastic layer is located

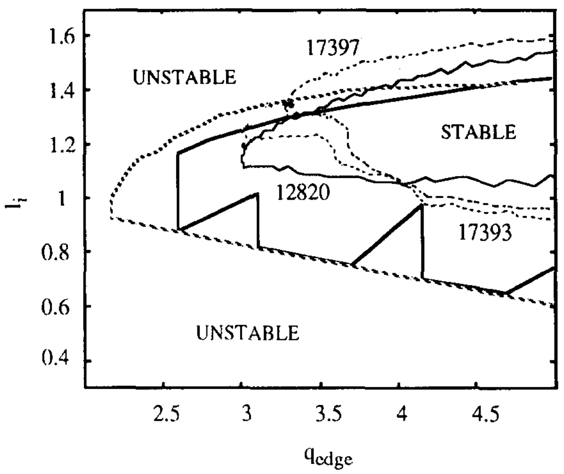

Fig. 3. Temporal trajectory of l_i and q_{edge} for three typical ED Ohmic discharges. Shots 12820 and 17397 are MHD stable whereas shot 17393 is terminated by a major disruption. Both Ohmic (plain line) and experimental ED (dashed line) MHD stability bounds are indicated.

between 0.6 and 0.65 m. The MHD activity remains at a low level until a disruption is triggered.

During the plasma current ramp-up of each discharge, the internal inductance l_i increases towards the upper bound. This behaviour is the signature of both the current diffusion and the reduction of the current density channel as the ergodic volume increases.

4. Discussion and conclusion

On Tore Supra, ED operations are part of the wide class of so-called 'RMP experiments' devoted to plasma edge and/or MHD activity control [10–16]. Because the ED-induced RMP consists of a 'broad' high-mode-number spectrum rather than a 'single' low-mode-number harmonic (as common in error-fields [15,16]), its MHD effects are quite subtle to analyse. On Tore Supra, the pre-disruptive signature of MHD activity during ED operations apparently relates to tearing modes: a clear (2, 1) component and a toroidally coupled (3, 1). None of these is part of the ED spectrum and as such, subject to a direct error-field-like interaction process. Nevertheless, the ergodic region created by the ED at the plasma edge typically extends down to the outer neighbourhood of the $q = 2$ surface. This likely affects the (2, 1) and (3, 1) modes in two ways consistent with the observations reported in the previous chapter: current profile modifications and mode braking.

Regarding current profile modifications, the analysis of Tore Supra discharge trajectories in the (q_{edge}, l_i) stability diagram indicates that the disruptive ED operations navigate close to the tearing-mode stability limit. This is primarily due to high l_i operation values which are indicative of peaked current profiles. While l_i is a relevant parameter to pre-programme discharges, it is too global to analyse specific stability issues. Detailed current-profile information are required, but they necessitate an improved modelling of ED-effects in the plasma edge, together with some edge current measurements not presently available on Tore Supra. In particular, the fact that potentially strong current gradients are expected at the transition between the ergodic layer and the plasma bulk i.e. in the neighhourhood of the $q = 2$ surface where the leading (2, 1) mode develops, places strong constraints on the analysis, owing to the extreme sensitivity to this parameter.

Magnetic data clearly indicate that a mode braking terminates the pre-disruptive phase. The present understanding is that the initially fast rotating (2, 1) mode locks to the slow rotating (3, 1) mode, via toroidal coupling [21] or some static external perturbation induced by the ED and/or the wall [22]. Because of limited Mirnov data acquisition and lack of additional diagnostics (no synchronized ECE nor SXR measurements in the past campaign), the available data do not allow to conclude about this scenario.

Other MHD-related ingredients may complement the analysis. For instance, the (2, 1) mode onset might be related to sawtooth relaxations which are known to affect it through profile redistribution and/or toroidal coupling. In any case, the ultimate goal is to provide clues for MHD-safe ED operational limits in terms of global parameters to be used for discharge programming.

By design, optimal conditions impose $a \approx r_{\text{ED}} = 0.8$ m, $R \approx R_{\text{ED}} = 2.38$ m and $q_{\text{edge}} \approx 3$ for the present Ohmic discharges at $\beta_p + l_i/2 \approx 0.7$ (the same programme has to be achieved with additional power i.e. higher $\beta_p + l_i/2$ and thus q_{edge}, in the next experimental campaign). For circular plasma shape, since q_{edge} is a function of minor (a) and major (R) radii and I_p/B_T, exclusively, this fixes the ratio I_p/B_T. Given $I_{\text{ED}} < 45$ kA and the requirement to achieve island overlapping to create the edge stochastic layer, the island-width variation as $(I_{\text{ED}}/B_T)^{0.5}$ finally imposes a maximum B_T and thus, a minimum I_p. For a given B_T or I_p, only density and current ramp-up scenario can be adjusted.

Another possibility is to operate the ED with 'non-optimal' parameters ($a \neq r_{\text{ED}}$, $R \neq R_{\text{ED}}$ and/or $I_{\text{ED}} < 45$ kA). For instance, the destabilizing influence of increasing R has been experimentally shown to be balanced by lowering I_{ED}. This leads to a (I_{ED}, R) stability diagram yet to be documented. Similarly, allowing q_{edge} values in the interval $2.5 < q_{\text{edge}} < 4$ (for edge ergodic layer), one can benefit from the supposedly destabilizing influence of lowering B_T to test the stability limit in the (I_{ED}, R) plane.

These scenarios will guide the investigations in the experimental campaign to come.

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