Stabilization of Tokamak Ohmic Discharges at the Density Limit by Means of the Ergodic Divertor

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The stabilization of both the $m=2$, $n=1$ tearing mode and a detached plasma has been obtained with the use of the ergodic divertor in Tore Supra Ohmically heated discharges at the density limit and for low plasma pressure. This has allowed us, for the first time, to define and to check a discharge piloting strategy to prevent density-limit disruptions and to create a stable edge radiating layer which dissipates 100% of the input power.

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In future thermonuclear reactors such as ITER (International Thermonuclear Experimental Reactor), the plasma-facing components will have to absorb tremendous power fluxes. Any inhomogeneity in the power flux or in the power deposition can cause damage to these components. For instance, in the case of conductive-convective power losses, the misalignment of first wall components can focus the power on salient surfaces [1]. The simplest way to get rid of this inhomogeneity is to maximize radiative losses at the plasma edge. Such an ideal radiating regime is directly achieved on tokamaks when the density limit is approached, inducing radiative phenomena such as MARFEs (multifaceted asymmetric radiation from the edge) and detached plasmas which radiate up to 100% of the input power [2,3]. This attractive scenario is counterbalanced by major disruptions occurring at the density limit and restricting the stable operating regime of present day tokamaks [4].

With long-pulse operation (>30 s), high auxiliary heating power (≤ 20 MW), and a first wall cooled by fully pressurized water (30 bars, 230 °C), Tore Supra already meets two major problems arising on future large tokamaks: the power exhaust and disruptions. For these reasons we are looking for specific operational strategies on Tore Supra to solve these problems. In this paper we report the results of experiments where for the first time the ergodic divertor (ED) [5,6] has been used to stabilize simultaneously the radiative structure of a detached plasma and the $m=2$, $n=1$ tearing mode (m and n are respectively the poloidal and toroidal numbers), both encountered in the predisruptive phase of density-limit disruptions. This allows us to avoid disruptions and to create plasmas with a stable edge radiating layer which is poloidally symmetric and dissipates 100% of the input power. These properties enlarge the application field of the ED, the first purpose of the ED being the screening of the plasma from the wall and the reduction of impurity contamination by increasing the transport in the ergodic layer.

The ED in Tore Supra allows us to destroy magnetic surfaces in an "ergodic layer" of about 0.1 m radial width at the edge. Each point in this layer is connected to the wall by a field line performing 3 to 12 toroidal turns. The Tore Supra ED is composed of six coils equally spaced toroidally. The poloidal and toroidal extensions of the coils are $\Delta\theta=120°$ and $\Delta\phi=11°$, respectively. This set of coils produces a total radial field perturbation δB_r^{ED} which is the sum of resonant components along field lines. The useful resonant components are the $16\leq m\leq 22$, $n=6$ modes; the broadband ED resonance is thus centered around a safety-factor value at the edge of $q_a\approx 3$. Magnetic island chains corresponding to neighboring modes $m,m\pm 1,m\pm 2,\ldots$ are created at rational surfaces at the plasma edge and overlap for $\langle\delta B_r^{\mathrm{ED}}/B_\theta\rangle \approx 10^{-2}$ (averaged along θ and ϕ), leading to the destruction of magnetic surfaces at the plasma edge and to a stochastic behavior of field lines. For discharge stability purposes, the ED has been designed so that the ergodic layer does not include the $q=2$ surface.

Measurements were made in circular, Ohmically heated plasmas of Tore Supra tokamak at low poloidal β ($\beta\approx 0.2$). To minimize the impact of disruptions, reduced discharge parameters ($R_0=2.4$ m, $a=0.75$ m, $B_t=3$ T, $I_p=1$–1.6 MA, $q_a=4$–2.5) were used. Plasmas were limited by an outboard graphite limiter (area ≈ 0.5 m^2). The total radiated power is estimated from an array of sixteen bolometers which monitors the plasma emission along vertical chords in one poloidal cross section $\Delta\phi=180°$ away from the limiter. An array of sixteen poloidal pickup coils provides the measurement of the amplitude and frequency of the rotating tearing mode. Furthermore, quasistationary or locked $m=2,3$, $n=1$ tearing modes are detected by a combination of four saddle loops. Electron temperature and density are measured by an electron-cyclotron-emission Michelson interferometer and by an infrared interferometer, respectively. The impurities are monitored by a grazing-incidence spectrometer. In these experiments, density-limit disruptions for deuterium plasmas without ED are reached at $Mq_a\approx 7\times 10^{19}$ m^{-2}T^{-1} ($M=\langle n_e\rangle R_0/B_t$ being the Murakami parameter and $\langle n_e\rangle$ the average volumic density) and follow the classical scenario of the radiative cooling of the plasma edge (Fig. 1) [4]. As the density is raised, the total radiated power increases and above a threshold it jumps up to 100% of the input power [Figs. 1(b) and 1(c)]. At this time the plasma detaches and its emission is localized in a poloidally and toroidally symmetric edge radiating shell. The observed jump in the calculated total radiated power does not correspond to a sudden increase of the actual radiated power but rather to the emissivity symmetrization when the plasma detaches (symmetry assumptions underly the total radiated power calculation). A shrinking of the electron temperature profile is observed during the detachment and corresponds for Ohmically heated plasmas to a shrinking of the current density profile. Consequently, the internal inductance of the plasma increases [Fig. 1(d)]. As the critical current density gradient on the $q=2$ surface is reached, the $m=2$, $n=1$ mode is destabilized and keeps growing up to a critical island width of about 10 cm. Then the mode locks and the disruption is triggered some 100 ms after [Fig. 1(d)] [7].

Experiments with the ED show two major effects on the plasma behavior (Fig. 2). First, in the outboard limiter configuration and for deuterium plasmas, the ED induces a large pumping out of the particles, leading to a decrease of the plasma density [Fig. 2(b)]. Any attempt to maintain the plasma density by gas puffing leads to a dramatic increase of the radiated power and to a disruption. So it is necessary to switch off the gas puff when the ED is applied. The density is then imposed by the transport coefficient in the ergodic layer and by the particle recycling coefficient. Two features suggest that the pumping effect corresponds to a trapping of deuterium inside the wall structures: (i) In helium plasmas, this pumping effect is not observed. (ii) For deuterium plasmas, when the ED is switched off, the density almost recovers its initial level without gas puffing [8,9]. It is found that the apparent particle confinement time τ_p^* varies by 1 order of magnitude with q_a (because of the resonance) and with the wall status, so that $0.35\ \mathrm{s} < \tau_p^* < 4\ \mathrm{s}$ while $\tau_p^* \geq 30$ s without the ED [6]. All of these data suggest that, when the density limit is approached, turning on the ED allows us to reach a more stable region in the operational domain [Fig. 2(b)]. Concerning the energy confinement time, one finds that it follows the Alcator law ($\tau_E \sim n_e a^2$), taking into account that the plasma radius is reduced by the ergodic layer thickness. This indicates that the confinement in the plasma core is not degraded by the ED.

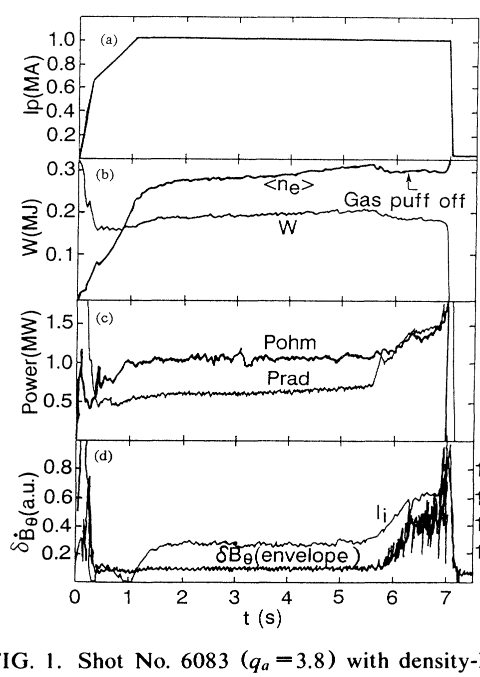

FIG. 1. Shot No. 6083 ($q_a=3.8$) with density-limit disruption (without ED) showing the plasma detachment at $t=5.5$ s [cf. (c)], $P_{\mathrm{rad}}=P_{\mathrm{Ohm}}$, and the growth of the $m=2$, $n=1$ tearing instability [(d)].

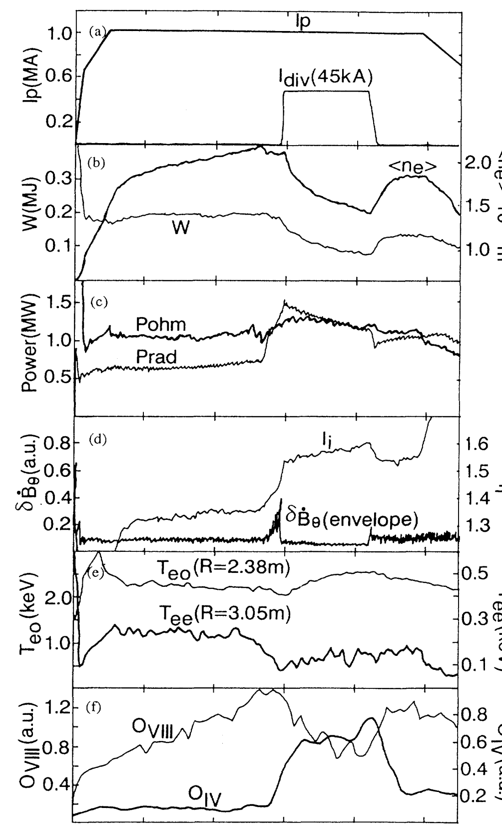

FIG. 2. Shot No. 6081 ($q_a=3.8$) with avoidance of density-limit disruption (with the ED). As the $\delta \dot{B}_\theta$ positive envelope reaches 0.4 V [cf. (d)], the ED is turned on [(a)] and the gas puff is switched off [(b)]. During ED phase, the MHD mode is stabilized [(d)], $P_{\mathrm{rad}}=P_{\mathrm{Ohm}}$ [(c)], and O VIII line decreases with the density while O IV increases [(f)].

The second effect observed in all experiments ($2.5 < q_a < 4$) is the stabilization by the ED of an unstable $m=2$, $n=1$ rotating tearing mode which actually does not lock [Fig. 2(d)]. In fact, the analysis of Mirnov coil signals, performed during the 100 ms following the ED turning on, shows that the $\delta \dot{B}_\theta$ component vanishes while the mode frequency presents a slight increase ($2\pi\omega_{m=2} \approx 1.5 \rightarrow 1.8$ kHz) as its amplitude decreases. In addition, no significant signal is recorded on the $\delta B_r(n=1)$ probes. This $m=2$, $n=1$ tearing mode stabilization may be attributed to a change of the current density gradient such that the linear Δ_2' becomes negative in the presence of the ED. The estimation of current density profiles using the induction law and temperature measurements is actually compatible with this scheme [7]. Indeed the ED tends to decrease the current density in the ergodic layer through the increase of the resistivity or through the connection of flux lines to the wall. This is consistent with the increase of the Ohmic power and the internal inductance [Figs. 2(c) and 2(d)]. Note that the two ED effects described above are independent: The $m=2$ stabilization is not an immediate consequence of the density decrease; it is also observed in helium plasmas for which the ED does not induce the pumping-out effect [7].

Combining the two ED effects, a strategy to prevent density-limit disruptions can be defined, at least for deuterium plasmas limited by the outboard limiter. Such a strategy requires a reliable trigger which precedes the disruption by a time interval of about 100 ms. This limitation is the characteristic rise time of the current in the divertor coils. Then the remaining limitation for reducing this time interval is the skin time of the plasma current which can be very short if the resistivity in the ergodic layer is large. As the algebraic growth rate of the $m=2$, $n=1$ mode in the predisruptive phase is lower than 10^2 s^{-1}, the mode amplitude can be used in these specific experiments to define a trigger. The trigger threshold has been chosen such that $\delta B_\theta / B_\theta \approx 2\times 10^{-3}$ (corresponding to an island width of $\delta_2 \approx 2$–3 cm) [Fig. 2(d)]. Note that usually on Tore Supra, the $m=2$, $n=1$ mode locks at an amplitude $\delta B_\theta / B_\theta \approx 8\times 10^{-3}$ ($\delta_2 \approx 8$–10 cm). The strategy to prevent disruptions is taken in three steps: (i) the $m=2$, $n=1$ mode amplitude threshold is reached. (ii) The gas puffing is switched off. (iii) The ED is applied. Then the $m=2$, $n=1$ mode is stabilized, the density decreases, and the disruption is prevented. An example of disruption avoidance is shown in Fig. 2. By contrast, Fig. 1 shows an ED-free experiment where the disruption occurs while the gas puff has been stopped for the same MHD activity threshold. Because of the large value of the apparent particle confinement time, stopping the gas puff delays the disruption only for several 100 ms [Figs. 1(a) and 1(b)].

In addition to the stabilization of discharges approaching the density-limit disruption, this strategy provides another unexpected result. The ED stabilizes the detached plasma which spontaneously appears near the density limit, corresponding to the growth of a thermal instability in the plasma boundary. Despite the density decrease, the ED keeps the radiation level close to 100% of the total plasma output power, $P_{rad} \approx P_{Ohm} - dW/dt$ (W being the stored kinetic energy) [Figs. 2(b) and 2(c)]. When the ED is applied we observe an inversion of the inward motion of the radiating layer, i.e., a relaxation of the radiating layer radius [Fig. 3(a)]. Note that this inward motion occurs without ED, the plasma detachment leading to a decrease of the effective plasma minor radius and to a shrinking of the electron temperature profile which gives rise to the $m=2$, $n=1$ mode [Fig. 3(b)] [10]. In that case, the effective plasma boundary is defined by the radius of the radiating layer. So when the ED is triggered, the shrinking process already under way is inversed and the radiating layer expands. The expansion rate is about 5 cm/s during the first 2 s following the ED switch on. This motion is fairly well illustrated by the local plasma emissivity profiles deduced from standard Abel inversion of bolometer data taking into account the magnetic equilibrium of the discharge [Fig. 3(a)]. During the expansion, the internal inductance is still slowly growing [Fig. 2(d)]. This indicates that with the ED the radiation comes from the ergodic layer where the current density is vanishing. This decoupling between the radiation and current density is probably the origin of the radiating-layer stability. Owing to the fact that P_{Ohm} in-

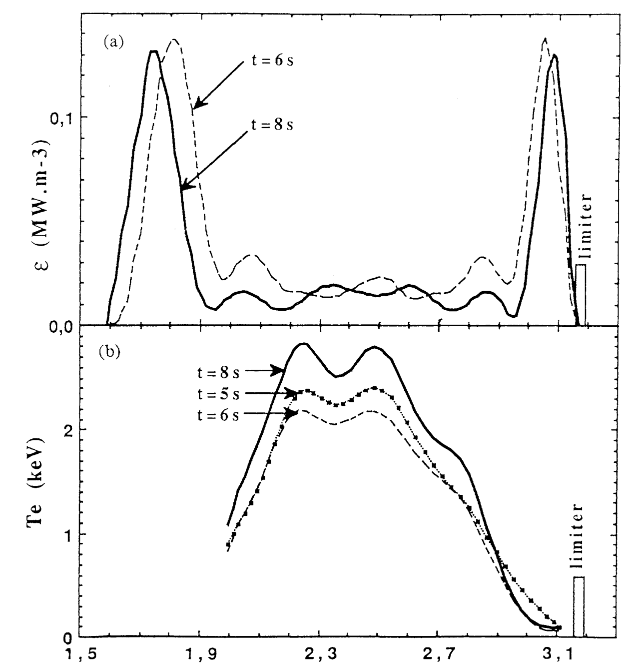

FIG. 3. Shot No. 6081. (a) Local plasma emissivity profiles ε showing the inversion of the inward motion of the radiating layer. (b) Electron-cyclotron-emission electron temperature profiles taken before the ED switch on and during the ED phase.

creases, the edge electron temperature T_{ee} in the ergodic layer falls below 100 eV with the ED, while the core electron temperature T_{e0} increases slightly [Figs. 3(b) and 2(e)]. T_{ee} is connected to the impurity behavior. In these experiments, the main impurity is oxygen and Fig. 2(f) shows the brightness of two oxygen lines, a "central line" O VIII and an "edge line" O IV radiating at 500 and 40 eV, respectively. The O IV emission is detectable only when the ED is on; it is correlated with the low ergodic-layer temperature. The O VIII line indicates that the oxygen concentration (the O VIII line brightness divided by $\langle n_e \rangle^2$) does not change in the plasma core while the O IV behavior shows that the oxygen recycling increases. As it is usual in ED experiments, the impurities do not accumulate [11].

To conclude, the experiments reported here have demonstrated that the pumping out of the plasma density and the $m=2$, $n=1$ tearing mode stabilization induced by the ED can be used to define a discharge piloting strategy which allows us to avoid density-limit disruptions. Furthermore, this successful strategy allows us to stabilize an edge radiating layer which is spontaneously created near the density limit. This stable radiating layer dissipates 100% of the plasma output power. The efficiency of this strategy has been experimentally demonstrated on Ohmically heated deuterium plasmas at low β, limited by the outboard limiter. The next step will be to extend our database experiments on ion cyclotron radio-frequency heating and lower hybrid radio-frequency current drive for giving an insight into the problem of thermal stability of the radiating layer in the presence of additional power.

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