Disruption Avoidance in the Frascati Tokamak Upgrade by Means of Magnetohydrodynamic Mode Stabilization Using Electron-Cyclotron-Resonance Heating

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Disruption avoidance by stabilization of MHD modes through injection of ECRH at different radial locations is reported. Disruptions have been induced in the FTU (Frascati Tokamak Upgrade) deuterium plasmas by Mo injection or by exceeding the density limit (D gas puffing). ECRH is triggered when the V_{loop} exceeds a preset threshold value. Coupling between MHD modes ($m/n = 3/2$, $2/1$, $3/1$) occurs before disruption. Direct heating of one coupled mode is sufficient to avoid disruptions, while heating close to the mode leads to disruption delay. These results could be relevant for the International Thermonuclear Experimental Reactor tokamak operation.

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Plasma disruptions represent a serious issue in tokamak operation and, consequently, methods for their avoidance are actively studied, especially in view of their application to future experimental reactors such as the International Thermonuclear Experimental Reactor (ITER). Some avoidance experiments were carried out in past years by applying electron-cyclotron-resonance heating (ECRH) during the disruption energy quench and the results varied depending on the device and on the disruption mechanism. In JFT-2M [1] the disruptions were induced by density limit at $q_{\text{edge}} = 3$ (H discharges) and avoidance was found with the ECRH power (P_{ECRH}) applied at $\rho_{\text{dep}} = \rho_{q=2}$ (ρ_{dep} and $\rho_{q=2}$ are the normalized minor radius of ECRH deposition and of $q = 2$, respectively). In RTP [2] (density limit disruptions, with Ne or He puff in He discharges) the condition was $0.7\rho_{q=2} < \rho < 1.1\rho_{q=2}$. In T-10 [3] (MHD induced with $q_{\text{edge}} = 3$ or $q_{\text{edge}} = 2$ and density limit, D puff in D discharges) disruption avoidance was found to be independent of ECRH deposition location, but an additional reduction in amplitude of MHD mode and in the requested P_{ECRH} was found if $\rho_{\text{dep}} > \rho_{q=2}$.

In this Letter we report on a set of experiments performed in the Frascati Tokamak Upgrade (FTU) in which it is found that MHD mode coupling plays an important role during the disruption evolution and can be exploited for disruption avoidance through localized ECRH injection. The nature of the coupling has not been investigated in this work. However, mode coupling in previous FTU observations has been already explained by a nonlinear dynamical model, including toroidal coupling with sideband modes [4]. The direct heating of one of the magnetic islands produced by MHD modes (either $3/2$, $2/1$ or $3/1$) prevents its further growth and also produces the stabilization of the other modes (indicating that those modes are toroidal sidebands of each other and their harmonics) and current quench delay or avoidance.

This phenomenology is important for the application of such disruption avoidance technique in future tokamak reactors, as it opens the perspective of more intervention options. For example, in density limit disruptions even though ECRH cannot be absorbed on the central $3/2$ mode (due the density cutoff), avoidance might be obtained by heating a more external coupled island where the density is below cutoff. In other cases, the strategy could be to deposit P_{ECRH} on the coupled island where less gyrotron power is needed (i.e.: where edge absorption is higher or the stabilization threshold is lower).

The experiments in FTU (circular cross section with major radius $R_0 = 0.935$ m and minor radius $a = 0.3$ m) have been carried out by inducing disruptions in D plasmas with $B_t = 5.3$ T either by injection of Mo through laser blow-off (LBO) at $I_p = 500$ kA or (for a limited set of discharges) by programming the gas injection system to increase the density above the Greenwald limit ($n_{\text{GW}} \sim 1.2 \times 10^{20}$ m^{-3}) at $I_p = 350$ kA. The trigger for firing the ECRH power ($\Delta t_{\text{ECRH}} = 100$ ms) is when the V_{loop} signal exceeds a preset threshold (usually 3.5 V). In FTU the transformer is feedback-controlled to keep I_p constant. Before the disruption, I_p decreases (due to the resistivity increase linked to the onset of the MHD activity) and the transformer feedback system reacts increasing the V_{loop}: therefore, P_{ECRH} is triggered in the energy quench phase. This allows clean and controlled experimental conditions, with P_{ECRH} fired at the same time in the disruption evolution, independently of other uncontrolled phenomena (impurity penetration time or density growth rate). The overall response time of the triggering system is <2 ms (1.5 ms for threshold electronics and 0.2 ms for gyrotron power supply). P_{ECRH} up to 1.2 MW, delivered by 3 gyrotrons at 140 GHz, was available in the experiments. The ECRH FTU launcher [5] is able to focus independently four beams from the center to $r/a = 0.85$ with a waist of 2.8 cm. The mirrors have been steered before every dis-

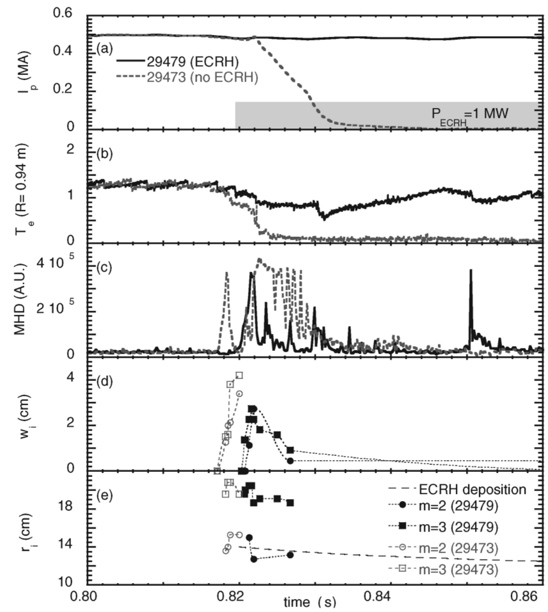

FIG. 1. Comparison of two discharges with Mo-injection: (a) I_p, (b) central T_e from ECE, (c) MHD (envelope of oscillations of $\dot{B}_\theta$, midplane, low field size), (d) width and (e) radius of $m = 2$ and $m = 3$ islands from soft x-ray tomography. The disruption is avoided in 29 479 by application of ECRH; the deposition location is shown in (e).

charge in order to change the deposition radius (same point for all used beams), while keeping constant B_t.

A typical disruption evolution in the Mo-injection discharges is shown in Fig. 1. At 0.8 s, during the I_p plateau when the electron density is $\sim 0.6 \times 10^{20}$ m^{-3}, the LBO system fires Mo (about 0.6 mg) into the plasma. The influx of impurities produces a high central concentration and a cooling of the edge (Fig. 2). As a consequence, the I_p profile becomes hollow and the I_p gradient increases in the outer region. From Mirnov coils fast-Fourier-transform (FFT) analysis it is found that MHD modes, either preexisting or not, grow in amplitude (Fig. 3). These modes quickly slow down and lock. Typically, the largest ones are 2/1 starting with frequency of $\sim$7 kHz and, just before locking, 3/2 (with twice the frequency of the 2/1). The current quench typically occurs within 5 ms after the mode locking. ECRH is triggered around the beginning of the MHD activity [$t_{\rm MHD}$, indicated by the abrupt rise of the MHD signal, Fig. 1(c)] and always before the locking of the modes. The comparison between a disruptive discharge (no ECRH, No. 29 473) and one in which the disruption is avoided ($P_{\rm ECRH} = 1$ MW, No. 29 479) is shown in Fig. 1. The MHD islands [$m = 2$ and $m = 3$ in discharge 29 473, see Fig. 1(d)] grow until the disruption occurs, while if ECRH is absorbed at one of the resonant surfaces [$m = 2$ in discharge 29 479, see Fig. 1(e)], both islands simultaneously stop growing and shrink [Fig. 1(d)], indicating the mode coupling. Note that, despite the reduction of the islands due to ECRH, the modes still lock. Therefore, the stabilizing effect of ECRH continues during the locked mode phase and leads to disruption avoidance. The mode locking time, however, is not affected by ECRH (Fig. 4).

The application of ECRH modifies the current quench starting time depending on the power deposition location

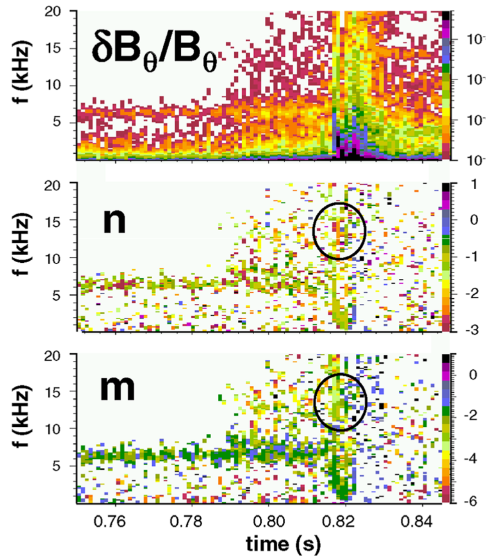

FIG. 3 (color online). Mirnov coils analysis for discharge 29 473 using phases of the various coils to extract the m (poloidal mode number) and n (toroidal mode number) of the modes. The circles indicate the time when the 3/2 mode is just visible.

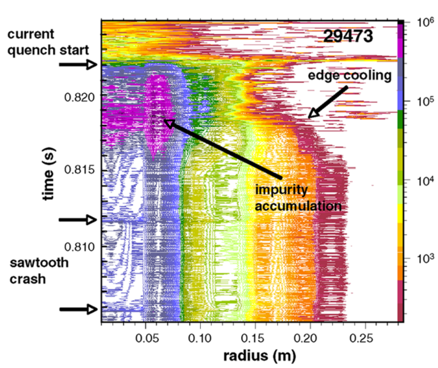

FIG. 2 (color online). Abel-inverted soft x-ray contours (discharge 29 473).

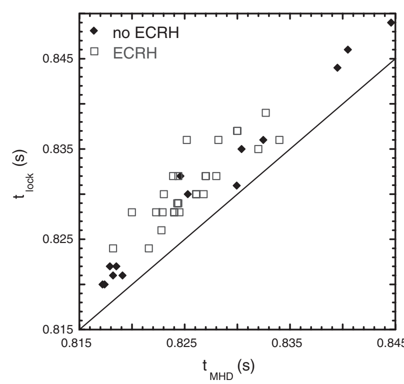

FIG. 4. Correlation between mode locking time ($t_{\rm lock}$) and MHD activity starting time ($t_{\rm MHD}$).

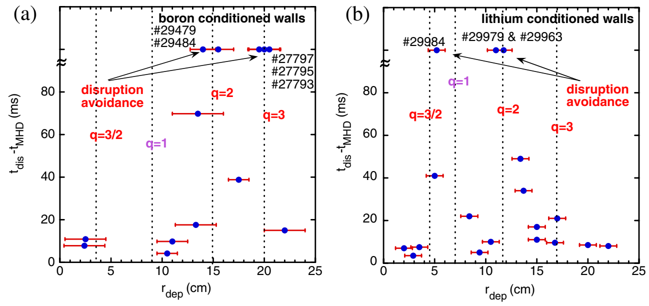

FIG. 5 (color online). Dependence of current quench time delay on ECRH deposition position for (a) boron- and (b) lithium-conditioned walls. The q values are obtained from island visualization through soft x-ray tomography (except for $q = 1$ determined from sawtheeth inversion radius).

(r_{dep}). A radial scan of the P_{ECRH} deposition has been carried out in the Mo-injection disruptions repeating the same discharge in exactly the same conditions of B_t, density, I_p, time of Mo-injection and V_{loop} triggering threshold and varying r_{dep} by steering the launching mirrors. A first set of experiments was performed with the tokamak walls conditioned with boron ($P_{ECRH} \sim 1$ MW), while a more fine scan has been performed in plasmas with lithium-conditioned walls ($P_{ECRH} \sim 0.8$ MW). The q profile is different in these two sets of discharges (broader in the first case, as confirmed by JETTO [6] transport calculations) and this is reflected in the different deposition locations (corresponding to rational q values) found for disruption avoidance. The results in both cases indicate that when P_{ECRH} is deposited close to the location of the MHD modes, the current quench time is delayed or the disruption is completely avoided. In Figs. 5(a) and 5(b) the time delay between the current quench and the start of the MHD activity is plotted vs r_{dep} (calculated with the ECWGB 3D quasioptical ray-tracing code [7] linked to the FTU equilibria and ECRH launching data) for the boron and lithium-conditioned walls cases: disruption avoidance is found in correspondence of the 3/1 or 2/1 and 3/2 or 2/1 islands, respectively.

Boron-conditioned walls discharges.—From the tomographic reconstruction of the soft x-ray horizontal camera (Fig. 6, discharge 29 473), the formation of $m = 2$ and $m = 3$ islands is observed at $t = 0.818$ s (the time at which the MHD signal also starts growing; see Fig. 1). In these discharges the systematic scan has been carried out for $r_{dep} > 10$ cm using 3 gyrotrons. The absorbed power for the $q = 2$ stabilized discharges (0.6 MW) enabled mode stabilization and disruption avoidance to be maintained even after switching off P_{ECRH}. The absorbed power for the $q = 3$ stabilized discharges was 0.25 MW: in this case, after the end of the power injection mode stabilization was lost and the discharge disrupted.

Lithium-conditioned walls discharges.—When P_{ECRH} is absorbed at the $q = 3/2$ (0.6 MW) the 2/1 mode grows, but the discharge does not disrupt (see discharge 29 984 in Fig. 7); when P_{ECRH} is absorbed at $q = 2$ (0.5 MW) the 2/1 mode does not grow and no disruption occurs even if the 3/2 is still present. In all avoidance cases the discharge continued until its natural end. These results show that the action of ECRH on one mode during the disruption also affects the evolution of the other coupled modes. Note that in the scan of Fig. 5(b) no $q = 3$ stabilization has been obtained as the absorbed power was only ~ 0.13 MW.

The standard Rutherford model [8,9], widely also tested in NTM stabilization experiments by EC heating [10], has been applied to estimate the evolution of the island width of the 2/1 mode for the discharges shown in Fig. 1, 29 473 (no ECRH) and 29 479 (with ECRH), and to provide indications on the level of power needed to produce disruption avoidance. The plasma parameters are taken from the experimental values; the growth rates and the tearing stability parameters Δ_0' are evaluated in such a way that the island saturation width extrapolated from measurements is matched: in particular, Δ_0' is calculated by balancing the Rutherford equation terms with the experimental saturation width. Destabilizing terms (such as $\Delta_0' > 0$ and bootstrap effects) and stabilizing ones (such as $\Delta_0' < 0$, curvature, polarization, EC heating and resistive wall effects) are included in the model. The EC absorbed power in the heating term is determined by ECWGB 3D. The results for discharge 29 473 are $r_2\Delta_0' = 0.24$ with $w_{sat} \sim 3.5$ cm at the resistive time $\tau_R = 0.007$ s (being r_2 the radial $q = 2$

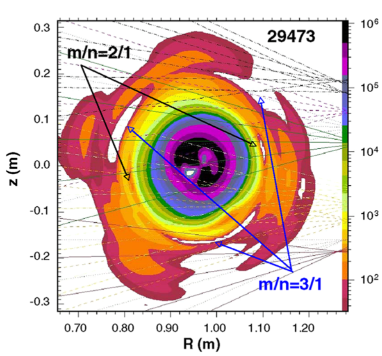

FIG. 6 (color online). Soft x-ray tomography at $t = 0.818$ s for discharge 29 473 (no ECRH); sight lines shown as dashed lines.

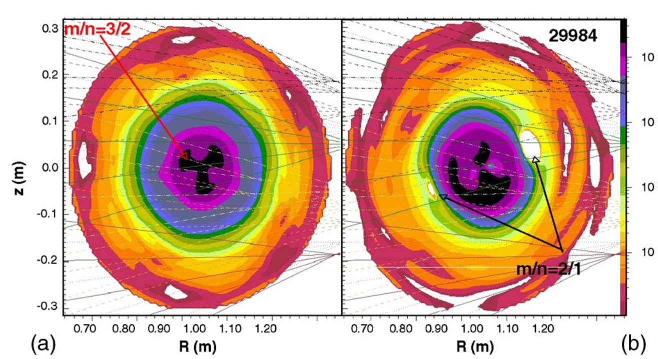

FIG. 7 (color online). Soft x-ray tomography at $t = 0.825$ s (a) and $t = 0.836$ s (b) for discharge 29 984 ($r_{dep} = 5.2$ cm).

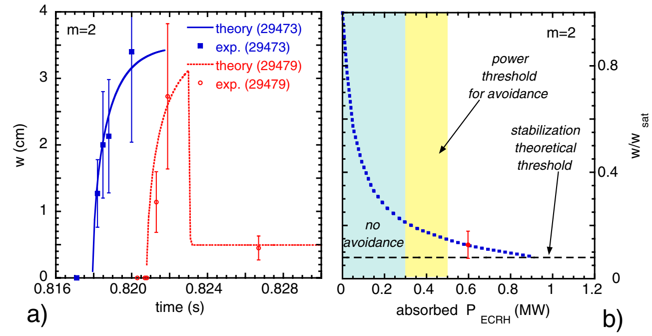

FIG. 8 (color online). Comparison between Rutherford model and experimental evolution of islands (a); calculation of $m = 2$ island width versus absorbed P_{ECRH} (based on experimental input data for discharge 29 479); also shown the experimental point measured during the stabilization phase [see Fig. 8(a)] (b).

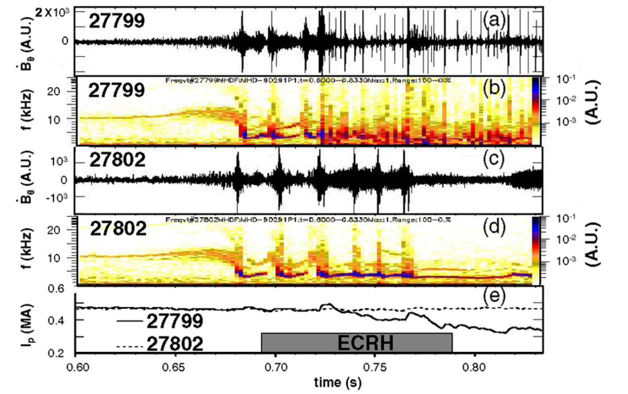

FIG. 9 (color online). Density limit disruptions: (a),(c) Mirnov coils traces; (b),(d) corresponding FFT analysis; (e) I_p with $P_{ECRH} = 0.8$ MW (dashed, 27 802) and without (solid, 27 799).

location), while for discharge 29 479 the following value is found $r_2\Delta_0' = 0.15$ with $w_{sat} \sim 3.4$ cm at $\tau_R = 0.008$ s. The positive values of Δ_0' indicate that these are conventional tearing modes. Figure 8(a) compares the experimental and theoretical 2/1 island width evolution for the two discharges. The mode stabilization has been obtained by using $P_{ECRH} = 1$ MW with 60% absorbed at $r = 14$ cm. An evaluation of the decrease of the $m = 2$ island depending on the level of the applied P_{ECRH} is shown in Fig. 8(b) (dotted line). The island has been experimentally stabilized by decreasing the $m = 2$ width down $\sim 13\% w_{sat}$ [red point in Fig. 8(b)] that is not far, within the experimental uncertainties, from the theoretically inferred marginal level below which the $m = 2$ cannot be destabilized [$\sim 8\% w_{sat}$, dashed line also shown in Fig. 8(b)]. In an identical discharge (29 486), but with less injected $P_{ECRH} = 0.7$ MW (2 gyrotrons, 0.3 MW absorbed at $r = 14$ cm), no disruption avoidance occurred. Note that for the *lithium-conditioned walls* discharges saved with 2 gyrotrons the absorbed power was higher (~ 0.5 MW at $r = 12$ cm). The range of $w/w_{sat} > 0.3$ (corresponding to an absorbed power < 0.3 MW) for which no avoidance was obtained is shown in Fig. 8(b) by the green shaded region: these results indicate that the minimum amount of power needed for $q = 2$ avoidance at $I_p = 500$ kA is 0.4 ± 0.1 MW [yellow shaded region in Fig. 8(b)].

The above results for Mo-injection disruptions are also confirmed by a few preliminary experiments so far carried out in density limit discharges at $I_p = 350$ kA. After crossing the Greenwald limit (corresponding to $n_e(0) \sim 2.1 \times 10^{20}$ m^{-3}) due to gas puffing, a disruption takes place in the standard way [11]. Some initial crashes are followed by mode locking, several mini crashes and finally a major disruption (see Fig. 9, discharge 27 799). The MHD activity is characterized by the presence of 3/2, 2/1, and 3/1 modes (located, respectively, at ~ 2 cm, at ~ 13 cm and ~ 15 cm). Two discharges are compared (Fig. 9): 27 799 (no ECRH) and 27 802 ($P_{ECRH} = 0.8$ MW at $r_{dep} = 2 \pm 1$ cm, $n_e^{cutoff} \sim 2.4 \times 10^{20}$ m^{-3}). In 27 802, before the second crash, ECRH is triggered by the V_{loop}: five more crashes follow without mode locking and no subsequent mini crashes are observed. The current quench, starting at $t \sim 0.73$ s in 27 799, is delayed after the end of ECRH injection. These observations indicate that stabilization of the 3/2 island by ECRH prevents the major density limit disruption, consistently with the frame depicted above for Mo-injection disruptions.

In summary, disruption avoidance and complete recovery of the discharge has been obtained in FTU by stabilization of MHD modes by means of ECRH injection in Mo-induced disruptions. The results are strongly sensitive to r_{dep}: direct heating of one of the coupled modes, affecting the evolution of the others, has been observed to be sufficient to avoid the disruption. A threshold absorbed $P_{ECRH} = 0.4 \pm 0.1$ MW has been found to be required at $I_p = 500$ kA for avoidance. More systematic P_{ECRH} and I_p scans during Mo-induced as well as density limit and low q disruptions are foreseen for an accurate determination of the best ECRH requirements for disruption avoidance.

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