

Disruption Control on FTU and ASDEX Upgrade with ECRH

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Abstract. The use of ECRH has been investigated as a promising technique to avoid or postpone disruptions in dedicated experiments in FTU and ASDEX Upgrade. Disruptions have been produced by injecting Mo through laser blow-off (FTU) or by puffing deuterium gas above the Greenwald limit (FTU and ASDEX Upgrade). The toroidal magnetic field is kept fixed and the ECRH launching mirrors are steered before every discharge in order to change the deposition radius. The loop voltage signal is used as disruption precursor to trigger the ECRH power before the plasma current quench. In the FTU experiments ($I_p=0.35-0.5$ MA, $B_t=5.3$ T, $P_{\text{ECRH}}=0.4-1.2$ MW) it is found that the application of ECRH modifies the current quench starting time depending on the power deposition location. A scan in deposition location has shown that the direct heating of one of the magnetic islands produced by magnetohydrodynamic (MHD) modes (either $m/n=3/2$, $2/1$ or $3/1$) prevents its further growth and also produces the stabilization of the other coupled modes and current quench delay or avoidance. Disruption avoidance and complete discharge recovery is obtained when the ECRH power is applied on rational surfaces. The modes involved in the disruption are found to be tearing modes stabilized by a strong local ECRH heating. The Rutherford equation has been used to reproduce the evolution of the MHD modes. The minimum absorbed power value found for disruption avoidance is 0.4 MW at 0.5 MA with deposition on the $q=2$ surface. In the similar set of experiments carried out in ASDEX Upgrade L-mode plasmas ($I_p=0.6$ MA, $B_t=2.5$ T, $P_{\text{ECRH}} = 0.6$ MW $\sim P_{\text{OHM}}$) the injection of ECRH close to $q=2$ significantly delays the $2/1$ onset and prolongs the duration of the discharge: during this phase the density continues to increase. No $2/1$ onset delay is observed when the injected power is reduced to 0.35 MW.

1. Introduction

Control of disruptions is one of the most challenging issues for ITER operation. It can be expected that the pre-disruptive ITER plasma conditions, for disruptions not originating from vertical displacement events (VDEs), but caused by radiation, density limits, locking of neoclassical tearing modes or pressure peaking in advanced scenarios, will be similar to those occurring in L-mode plasmas. This has been shown in JET experiments where high performance H-mode plasmas experience energy confinement deterioration at the disruption and therefore L-mode plasma conditions occur at the time of the thermal quench [1]. At present the most probable candidate foreseen for disruption control in ITER is the massive gas injection.

2. ECRH as a tool for disruption control

Even if at present the most probable candidate foreseen for disruption control in ITER is the massive gas injection, an additional possibility can be represented by the use of ECRH. This paper presents recent experiments performed in FTU and ASDEX Upgrade indicating how the disruption and its negative effects (surface melting/ablation of plasma facing components due to direct plasma heating, forces on structural components due to halo and eddy currents

and production of high runaway current) might be eliminated with the application of ECRH at specific radial locations. All experiments are based on the same concept of triggering a disruption in stationary L-mode plasma and then injecting ECRH power (P_{ECRH}) into the plasma (for a pre-set time interval) using a precursor signal as an automatic trigger. The effect on disruption is found to be strongly sensitive to the P_{ECRH} deposition location. FTU results (based mainly on disruptions induced by impurity injection and few density limit disruptions) show that the direct heating of one of the magnetic islands involved in the disruption prevents its further growth and produces the stabilization of the other coupled magnetohydrodynamic (MHD) modes avoiding or delaying the current quench. ASDEX Upgrade results (based on density limit disruptions) indicate that the involved MHD mode is stabilized when P_{ECRH} is deposited at the $q=2$ surface. The discharge duration is prolonged until the local density approaches the ECRH cut-off and the beam refraction moves the absorption away from the mode resonant surface. Both experiments give indications of the existence of a power threshold for mode stabilization to occur.

2.1. Experiments in FTU

Several experiments have been carried out in the last years in FTU ($R=0.935$ m, $a=0.3$ m) by inducing disruptions in 0.5 MA and 0.35 MA deuterium plasmas [2]. The toroidal magnetic field ($B_t=5.3$ T) is kept constant and the ECRH launching mirrors are steered before every discharge in order to change the deposition radius (all beams focusing at the same point). The loop voltage signal (V_{loop}) is used as disruption precursor to trigger automatically the ECRH power (P_{ECRH}): the duration of the ECRH pulse is pre-programmed (typically 30 ms). A dedicated set of experiments has been performed in order to select the better triggering threshold (FIG. 1). With the chosen value (-3.5 V, a factor 2 larger than the V_{loop} during flat top at $I_p=0.5$ MA) the ECRH power is injected few ms after the start of the T_e drop) and always before the mode locking time. Most disruptions have been produced at 0.5 MA by injecting Mo through laser blow-off (FIG. 2). Few disruptions have been obtained by puffing deuterium gas above the Greenwald limit: in these density limit disruptions, a lower I_p (0.35 MA) has been chosen in order to avoid the 140 GHz ECRH density cut-off ($\sim 2.4 \times 10^{20}$ m $^{-3}$). The analysis of Mirnov coils, fast ECE and soft x-ray tomography shows an intense MHD activity preceding the disruption: these modes grow up, quickly slow down and then lock.

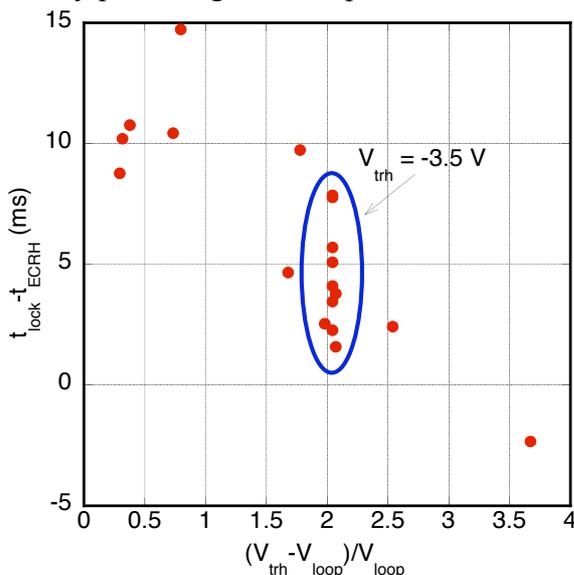


FIG. 1. Selection of best triggering threshold in FTU experiments.

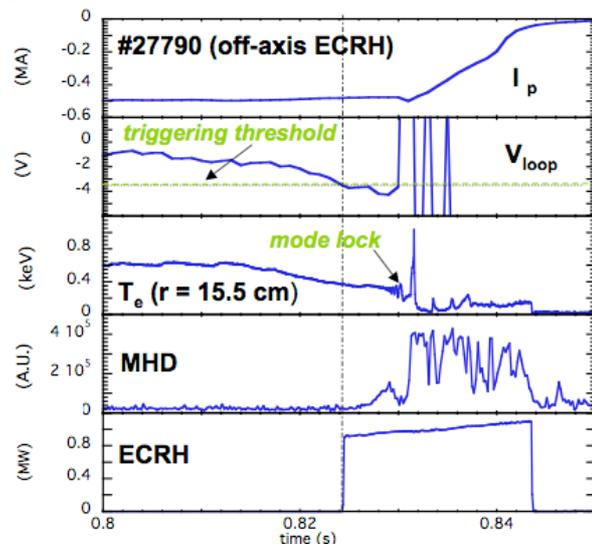


FIG. 2. Evolution of an FTU disruption induced by Mo injection at 0.8 s.

Usually, the largest one is the $m/n=2/1$. ECRH is triggered around the beginning of the strong MHD activity. The mode locking time (occurring around 5 ms before the current quench) is not affected by ECRH. A comparison of two discharges with/without ECRH is shown in FIG. 3. The application of ECRH modifies the current quench starting time depending on the power deposition location (r_{dep}). A fine scan in r_{dep} (carried out in disruptions induced by impurity injection) shows that 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 (FIG. 4). Disruption avoidance and complete discharge recovery is obtained when P_{ECRH} is applied on rational surfaces, whereas the current quench is progressively delayed when the r_{dep} is approaching a rational surface from the outer side. The injected P_{ECRH} has been varied in the range 0.4-1.2 MW. The fraction of absorbed power is calculated using the ECWGB 3D quasioptical ray-tracing code [3]. It has been found that absorbed P_{ECRH} levels sufficient to produce avoidance are 0.4 MW at 0.5 MA (deposition on the $q=2$ surface) and 0.8 MW at 0.35 MA (deposition on the $q=3/2$ surface).

A modified Rutherford equation (including asymmetric island parameters) and the island rotation frequency equation [4] have been used to study the evolution of the MHD modes. The modes involved in the disruption are found to be conventional tearing modes stabilized by a strong local ECRH heating. The results of the simulation are compared with the experimental data in FIG. 5: the effect of ECRH is that of reducing the growth of the width of the island which is subsequently slowed down and further reduced in amplitude by viscous and inertial torques.

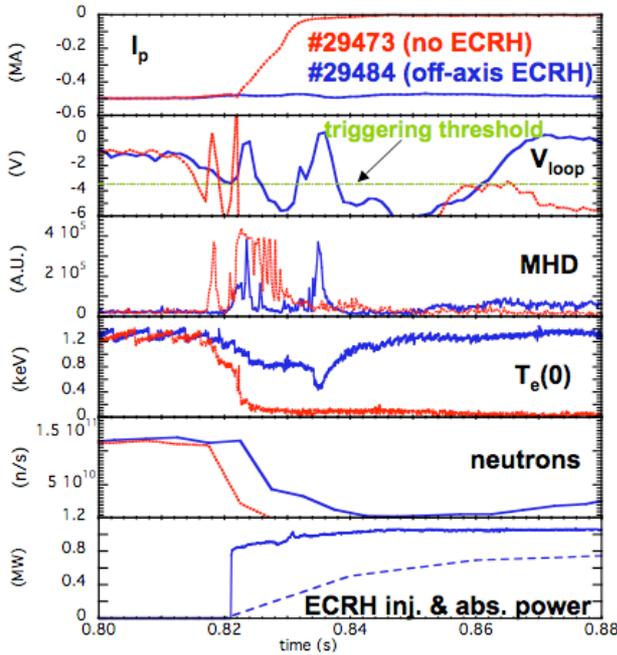


FIG 3. Comparison between two FTU discharges with/without ECRH. The disruption is avoided in discharge 29484 with ECRH injection on the $q=2$ surface.

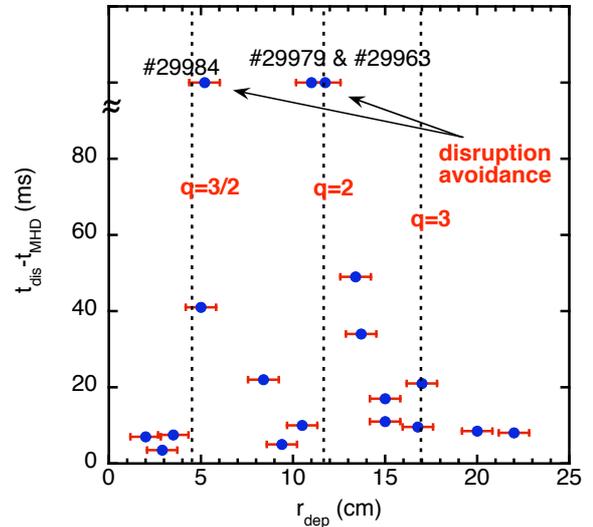


FIG. 4. FTU power deposition scan: current quench delay vs. r_{dep} (q values obtained from island visualization through soft x-ray tomography): t_{dis} = time of current quench; t_{MHD} =time of abrupt rise of MHD activity. The y-scale is interrupted above 80 ms in order to include also discharges with disruption avoidance.

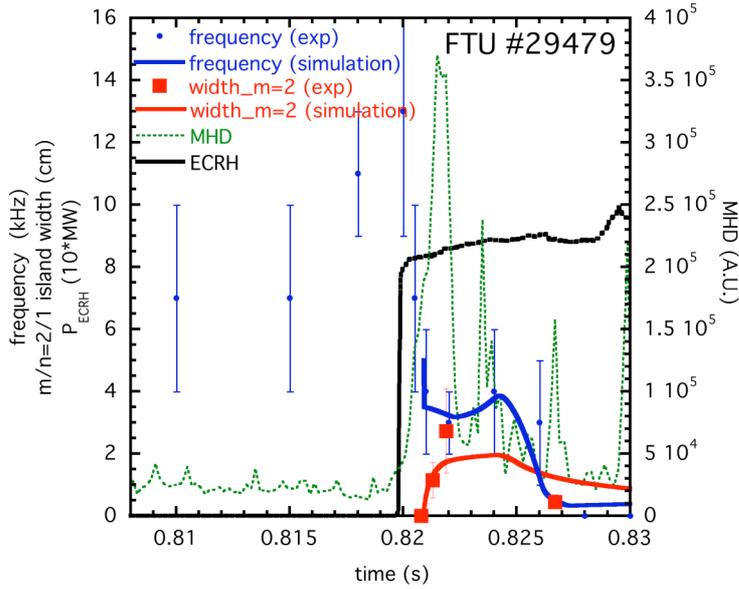


FIG 5. Time evolution of 2/1 mode frequency (determined from Mirnov coils), MHD (envelope of the oscillations of B_θ) and island width (determined by soft x-ray tomography) close to the mode locking time. The results of the simulation using the Rutherford model are also shown.

2.2 Experiments in ASDEX Upgrade

A set of experiments has been carried out during the 2008 campaign on ASDEX Upgrade to study the effect of localized ECRH injection on the evolution of disruptions, in order to confirm on a D-shaped plasma the results obtained on the FTU circular plasma. The experimental set-up has been as close to the FTU conditions as possible. Density limit disruptions have been induced in a reproducible manner by feed-forward gas puff rise in pure ohmic plasmas (0.6 MA, 2.5 T). The density increase triggers a MARFE followed by the appearance of MHD modes (3/1 and 2/1). The mode evolution follows the standard picture previously reported for density limit disruptions on ASDEX Upgrade [5]. The 3/1 mode appears first and then locks (FIG. 6). About 250 ms after the 3/1 locking a 2/1 develops and grows in amplitude; a series of bursts is observed until the final disruption (see the reference discharge in FIG.7(a)). The ECRH power has been set at ~ 0.6 MW (140 GHz) and vertically steered before every discharge in order to perform an r_{dep} scan. The real time trigger for P_{ECRH} is given when $V_{\text{loop}} > 1.85\text{--}1.88$ V (in a standard ohmic phase $V_{\text{loop}} \sim 1$ V). The ECRH trigger time occurs just in between the locking of the 3/1 and appearance of the 2/1. The effect of ECRH is to prolong the duration of the discharge. Moreover, when the power is deposited close to the $q=2$ surface, the abrupt growth of the 2/1 mode is significantly delayed in time (up to 120 ms, see FIG. 7(b)): during this phase the density continues to increase (above the Greenwald limit). As the density increases during the discharge, the refraction of the ECRH beam moves the absorption outwards, away from the $q=2$ surface and the mode resumes its growth. When r_{dep} is set outside the $q=2$ surface, the mode growth delay is progressively reduced, while for deposition locations corresponding to $q < 2$ no delay in mode growth is observed (FIG. 8). A power threshold effect seems to exist since when the injected power on the $q=2$ has been lowered from 0.6 MW down to 0.35 MW no delay effect has been observed (FIG. 8). Another point to investigate in further experiments and analysis is the role of the MARFE in the whole process.

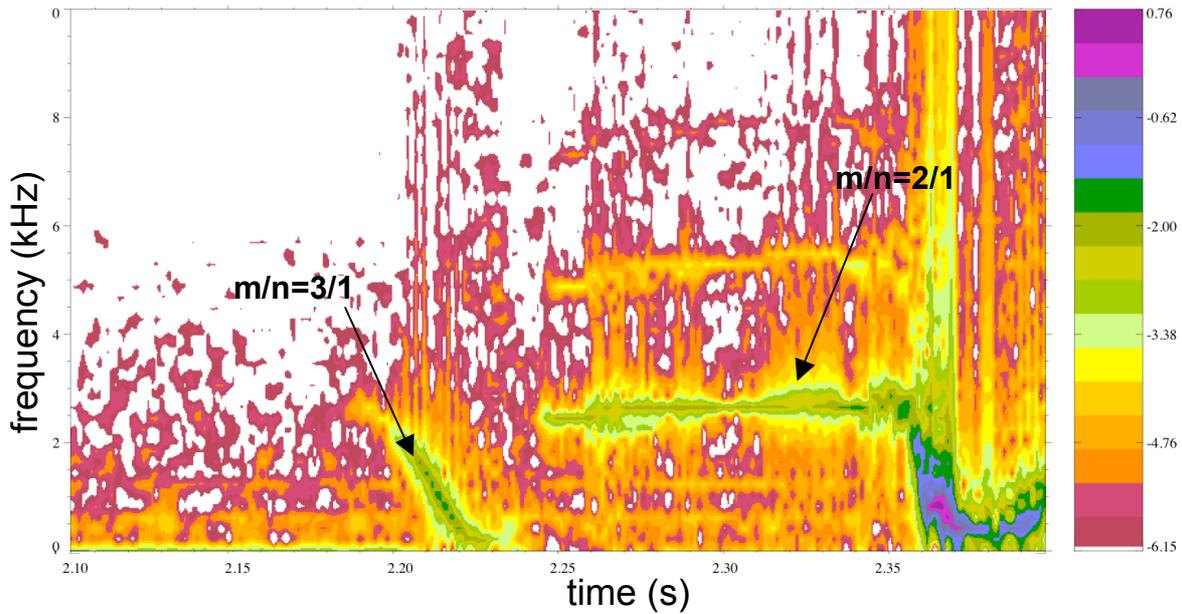


FIG. 6. ASDEX Upgrade density limit experiments: Mirnov coil spectrogram (discharge 23326).

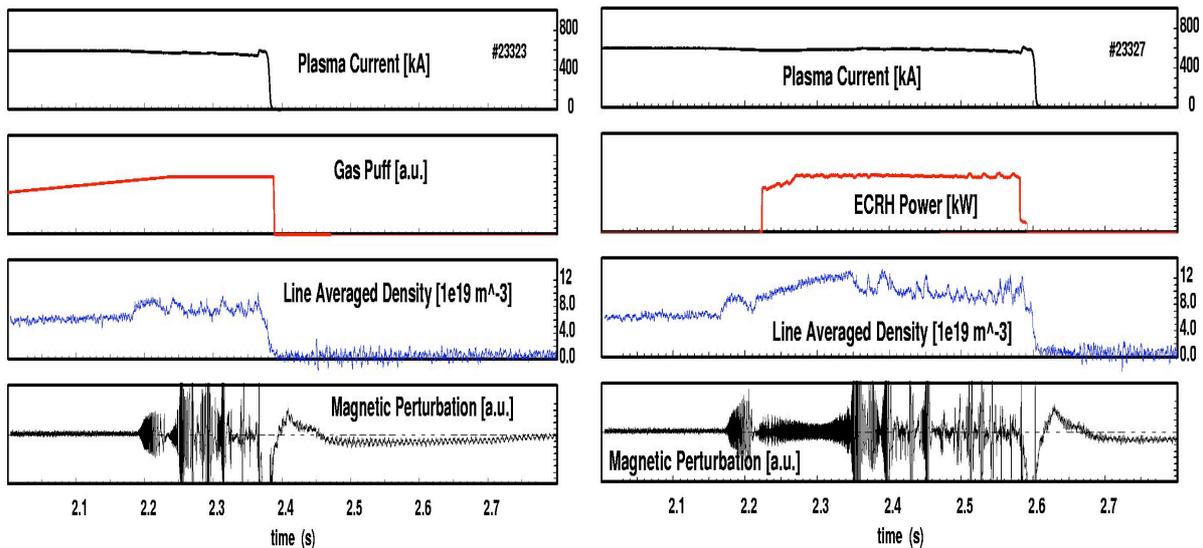


FIG. 7. ASDEX Upgrade density limit experiments: (a) reference disruption; (b) with ECRH injection on the $q=2$ surface.

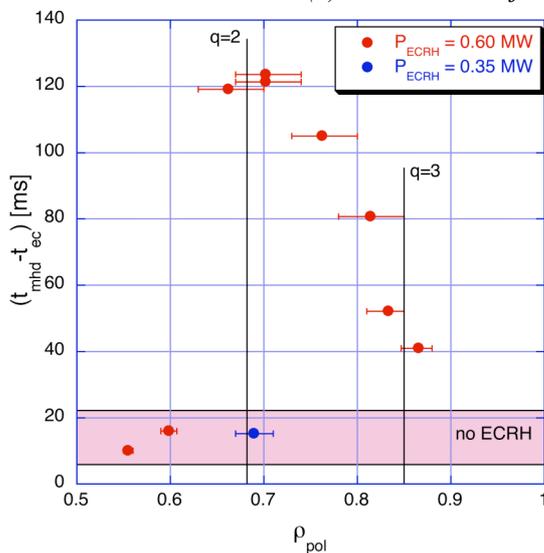


FIG. 8. ASDEX Upgrade power deposition scan: delay of MHD 2/1 mode onset with respect to ECRH injection time plotted versus the deposition location (preliminary TORBEAM [6] calculations; each point corresponds to a different discharge). The error bars are determined by using two different density profiles respectively at the beginning and end of stationary phase of the 2/1 mode.

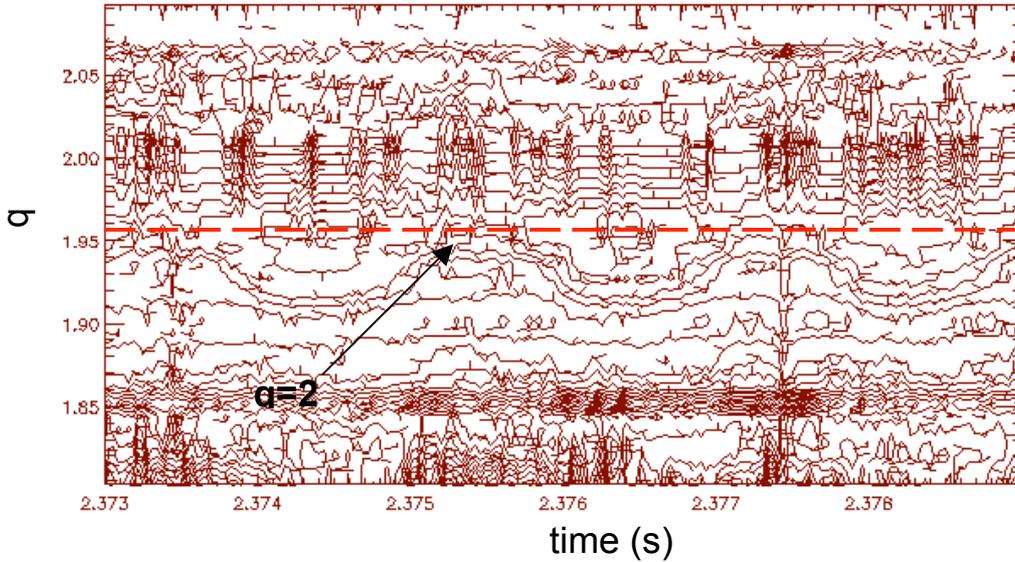


FIG. 9. ASDEX Upgrade density limit experiments: ECE contours showing 2/1 islands and $q=2$ position from equilibrium reconstruction (discharge 23327).

The evolution of the 2/1 island has been modelled in detail for discharge 23326 using the Rutherford equation as done with FTU data. The time evolution of the island width is provided by Mirnov coil measurements: the width absolute value is obtained from the fast ECE temperature contour plots (an example is shown in FIG. 9; in the time slice shown the 2/1 island is ~ 3 cm wide and its position agrees with the $q=2$ surface as determined by the magnetic reconstruction). The ECRH injection angle (with respect to the equatorial plane) is set to -4.5° for two identical discharges (23326 and 23327) and corresponds to $\rho_{\text{pol}} \sim 0.7-0.8$. The P_{ECRH} deposition profiles are shown in FIG.10: the absorption progressively moves outside the $q=2$ surface, due to the increasing density, and at 2.36 s the 2/1 mode explodes. The results of the Rutherford simulation, shown in FIG. 11, indicate that the P_{ECRH} is capable of stabilizing the 2/1 until it is absorbed on the $q=2$ resonant surface.

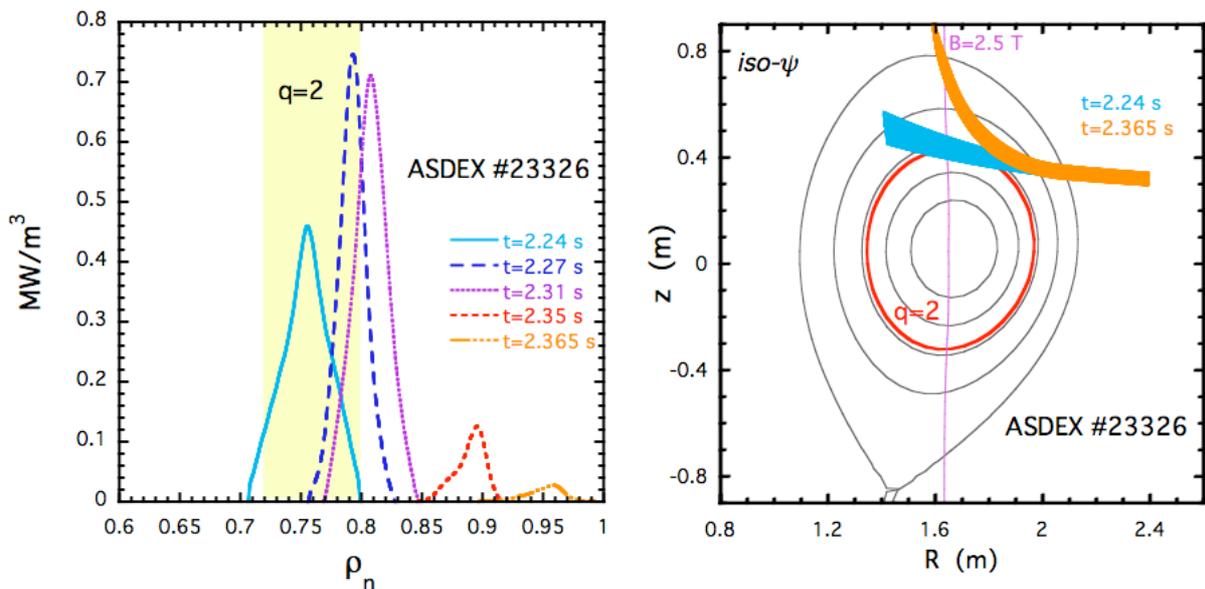


FIG. 10. Preliminary ECWGB 3D calculations for ASDEX Upgrade discharge 23326: (a) time evolution of P_{ECRH} deposition profiles; (b) ray-tracing at $t=2.24$ s and 2.365 s.

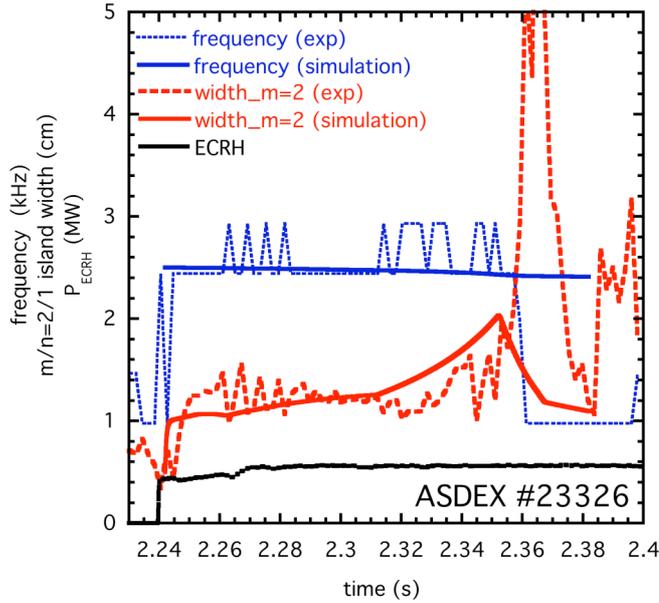


FIG. 11. Comparison of experimental and calculated time evolution of the 2/1 island width and mode frequency (ASDEX Upgrade discharge 23326).

3. Conclusions

The use of ECRH has been investigated as a promising technique to avoid or postpone disruptions in dedicated experiments in FTU and ASDEX Upgrade.

In FTU, the injection of ECRH has been found to modify the current quench starting time depending on r_{dep} . The direct heating of one of the magnetic islands produced by MHD modes 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. The mode coupling effects resulting from the FTU r_{dep} scans are interesting in view of a possible application of such ECRH control technique to ITER. Various schemes can be envisaged in order to suppress islands that are not directly heated by ECRH waves. In density limit disruptions, when ECRH cannot be absorbed on the central 3/2 mode due the density cut-off, avoidance might be obtained by heating a more external coupled island where the density is below cut-off. In other cases, P_{ECRH} might be deposited on the coupled island that requires less power for stabilization.

In ASDEX Upgrade the same type of experiments carried out in density limit disruptions confirm the FTU results as far as the mode stabilization of the 2/1 mode is concerned: the injection of ECRH close to $q=2$ significantly delays the 2/1 abrupt growth and prolongs the duration of the discharge. Mode control is then lost when the increase of the density (that was not feedback-controlled during this phase) moves the deposition of the power progressively outside the $q=2$ surface. Further dedicated experiments are needed to evaluate the effects when P_{ECRH} is deposited into the $q=3$ resonant surface.

The encouraging results obtained in these experiments suggest an ECRH-based disruption control technique in ITER as a possible alternative, with the further advantage, moreover, that no additional hardware would probably be needed as the use of ECRH ($P_{\text{ECRH}}=20$ MW) is already foreseen for plasma heating and neoclassical tearing modes stabilization.

References

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