

Disruption mitigation experiments in FTU using ECRH

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Introduction

Experiments carried out in various tokamaks in recent years to study the direct influence of ECRH on disruption evolution have produced somehow contradictory results: disruption avoidance has been obtained using ECRH, but the conditions varied depending on the machine and the disruption experiment conditions. In JFT-2M (the disruptions were induced with $q_{\text{edge}}=3$ & density limit, H gas) [1] avoidance during the energy quench was found with ECRH applied at $\rho_{\text{dep}}=\rho_{q=2}$ (ρ_{dep} = normalized minor radius of ECRH deposition). In RTP [2] (density limit disruptions, with Ne or He puff in He gas) the condition was $0.7\rho_{q=2}<\rho_{\text{dep}}<1.1\rho_{q=2}$ (energy quench case) and no ECRH deposition location dependence (current quench case). In T-10 (MHD induced with $q_{\text{edge}}=3$ and $q_{\text{edge}}=2$ & density limit, D puff in D gas, energy quench) [3], disruption avoidance was found to be independent of ECRH deposition location, but an additional reduction in amplitude of MHD mode and an extremely low ECRH power was needed when $\rho_{\text{dep}}>\rho_{q=2}$.

A set of experiments has been performed in FTU (D plasmas) in order to optimize disruption avoidance by ECRH (determination of the best timing of ECRH application and location of ECRH deposition, preparation for the use of a real time mode recognition algorithm for gyrotron triggering) and to study the underlying MHD mechanisms. The ECRH power has been applied during the current or energy quench of disruptions triggered either by injection of Mo through laser blow-off (LBO) in 500 kA discharges or by pre-programming the gas puff feedback system to provide \bar{n}_e above the density limit ($\sim 1.2 \times 10^{20} \text{m}^{-3}$) in 360 kA discharges. The ECRH power ($B_t = 5.3$ T, 140 GHz, ≤ 1.6 MW delivered by 4 gyrotrons [4]), injected both with on-axis and off-axis absorption, has been triggered by the V_{loop} signal exceeding a preset threshold [5].

Density Limit Disruptions

Two discharges have been analyzed in detail: #27799 and #27802 (**Fig.1**). The ECRH

power (0.8 MW from two gyrotrons) is injected with central resonance in #27802 at the end of the energy quench. The conditions of the plasma are the same in the two cases. Gas puffing, stopped by density feedback in #27799 at $t=0.78$ s and continuing in #27802 up to 1.1 s, causes a progressive cooling of the edge that, without application of ECRH in #27799, leads to a disruption. From the magnetics data (**Fig.2**), it is found that a low amplitude external $m/n=2/1$ mode is present (with ~ 10 kHz frequency), before density limit is reached, in both cases. Afterwards, a first mini-disruption occurs and the $2/1$ mode slows down in frequency (4 kHz). An $m/n=3/2$ mode at 7 kHz also appears. In #27802, before a second crash, ECRH is triggered by V_{loop} . This immediately produces a difference in the subsequent behaviour of the two discharges. In #27802 (ECRH), there are 5 more crashes and then the mini-disruption activity is stabilized; sawtooth activity is still present. The ECRH stops and after 300 ms the mini-disruption activity starts again. When ECRH is switched on again, the same cycle is repeated once more with a new stabilization. On the contrary, in #27799 (no ECRH), after the first 4 crashes the mode locks and several mini crashes occur leading to a major disruption. By looking at the soft-x ray tomography reconstruction just after the injection of ECRH in #27802 various features can be evidenced (**Fig.3b**): an $1/1$ mode and sawteeth are observed: therefore the q_{min} value is kept below 1. The $3/2$ mode is still present but very small. A small $2/2$ mode is seen in the outer plasma; $q=2$ is found at 12 cm ($\rho_{q=2}=0.4$). Instead in #27799 (**Fig.3a**), the $3/2$ mode (7 kHz) is clearly visible in the plasma and becomes stronger with time; sawteeth are not visible (the $1/1$ mode disappears at 0.71 s). Therefore, the shear is flat or slightly inverted; the $2/2$ mode is small but visible. In another density limit discharge (#27901), the ECRH power ($P_{abs}=10\%$) has been applied off-axis (at $\rho_{dep}=0.7$) and no disruption avoidance has been observed.

Mo-Injection Disruptions

In almost all these discharges, ECRH is triggered at the very beginning of the growth of the MHD mode, during the energy quench; the deposition ranges from $\rho_{dep}=0$ to $\rho_{dep}\sim 0.8$ and the power from 0.4 MW to 1 MW. In some cases the disruption is avoided by application of ECRH (**Fig.4**). By plotting the difference Δt_p between the time at which I_p reaches \sim zero level and the time of start of the mode growth versus ρ_{dep} it is seen that disruption avoidance occurs mainly around $\rho_{dep}\sim 0.7$ (**Fig.5(a)**). The analysis of the soft x-ray data gives indications on why off-axis injection at $\rho_{dep}\sim 0.7$ favors disruption avoidance. Three ECRH discharges (#27790, #27792 and #27793 whose deposition profiles calculated by ECWGB [6] are shown in **Fig.5(b)**) have been compared with #27791 (no ECRH): disruption avoidance occurs only

in #27793. Soft x-ray tomography has been performed during the growth of the MHD modes (**Fig.6**). In #27791 (no ECRH) large 2/1 and 3/1 modes are present as well as 3/2 and 1/1 in the center. The location of the $m=2$ mode is $\rho_{q=2} \sim 0.61$. The white regions of the 3/1 mode represent the O points of the island. A similar result is found in #27790 ($\rho_{\text{dep}} \sim 0.3$) and #27792 ($\rho_{\text{dep}} \sim 0.6$). In #27793 ($\rho_{\text{dep}} \sim 0.7$) the situation is different: the 2/1 island is smaller, indicating that when ECRH is deposited outside $\rho_{q=2}$ it may be acting on the 2/1 mode stabilizing it. Although a crash occurs at $t=0.831$ s, the discharge recovers and the disruption is prevented.

Conclusions

Avoidance of disruptions by applying ECRH has been obtained in FTU discharges. The optimum ECRH deposition location for avoidance (found to be on-axis for density limit and off-axis at $q=2$ for Mo-injection disruptions) seems to be linked to the q profiles (as inferred from MHD measurements) at the injection time. In the density limit disruptions, the injection has happened after the start of a considerable MHD activity (**Fig.1**): in this phase the q profile is flat or reversed and the low shear produces large islands in the core. The effect of ECRH might be that of forcing the q -profile to become once again monotonic, producing in turn a reduction of the islands' size and in the end disruption avoidance. In the Mo-injection disruptions, the time of ECRH application has occurred during the energy quench, before any strong MHD activity (**Fig.4**): here the q profile is still monotonic and, when ECRH is applied outside the $q=2$ surface, the 2/1 mode is suppressed leading to disruption avoidance.

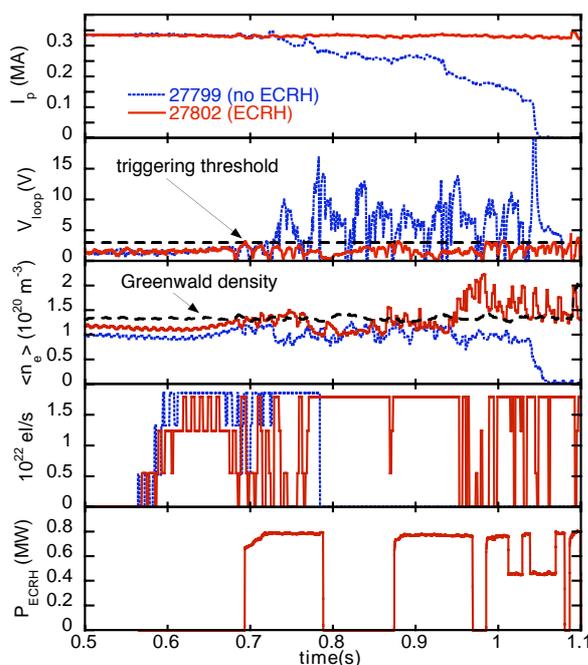


Fig.1: Density limit disruptions: from top time traces of I_p , V_{loop} , n_e , injected gas and ECRH power.

References

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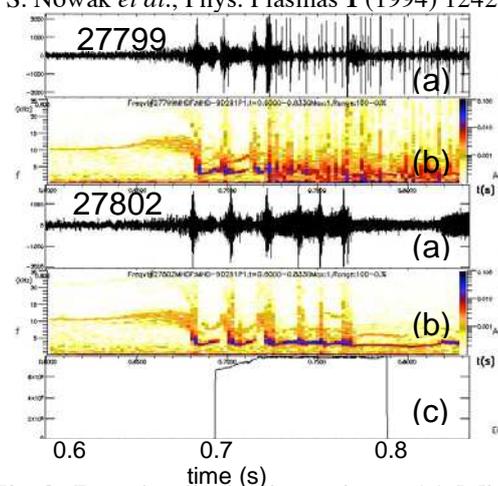


Fig.2: Density limit disruptions: (a) Mirnov coils traces; (b) correspondent FFT analysis; (c) ECRH power.

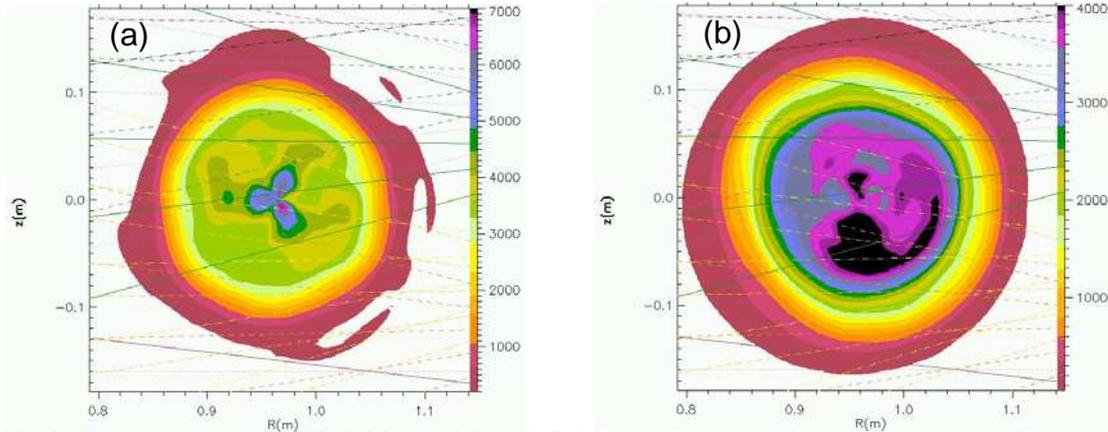


Fig.3: Tomograms: (a) #27799 $\Delta t=0.7115-0.7117$ s; (b) #27802 $\Delta t=0.7840-0.7843$ s.

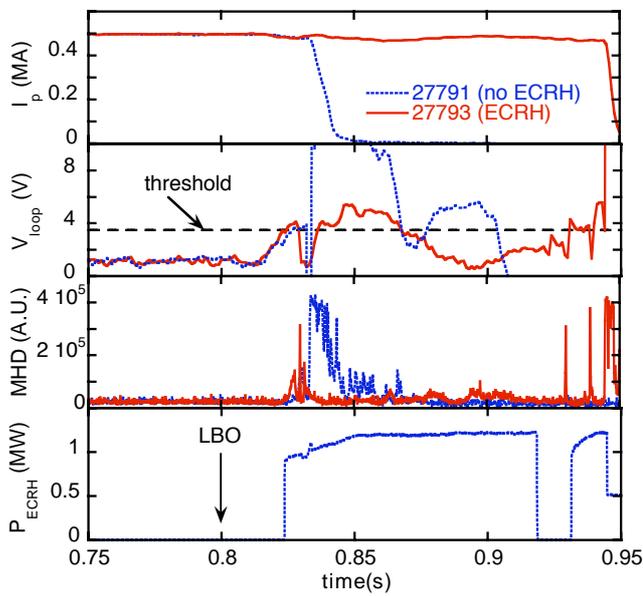


Fig.4: Mo-injection disruptions: time traces of I_p , V_{loop} , MHD activity (\dot{B}_{pol}) and ECRH power.

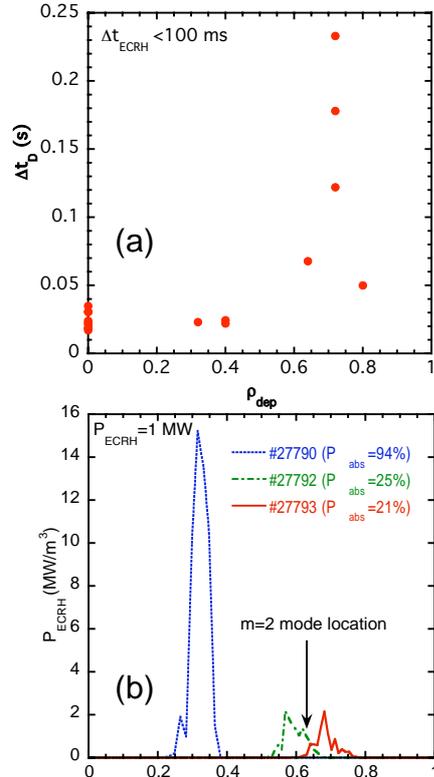


Fig.5: Mo-injection disruptions: (a) avoidance with off-axis ECRH; (b) ECRH deposition profiles

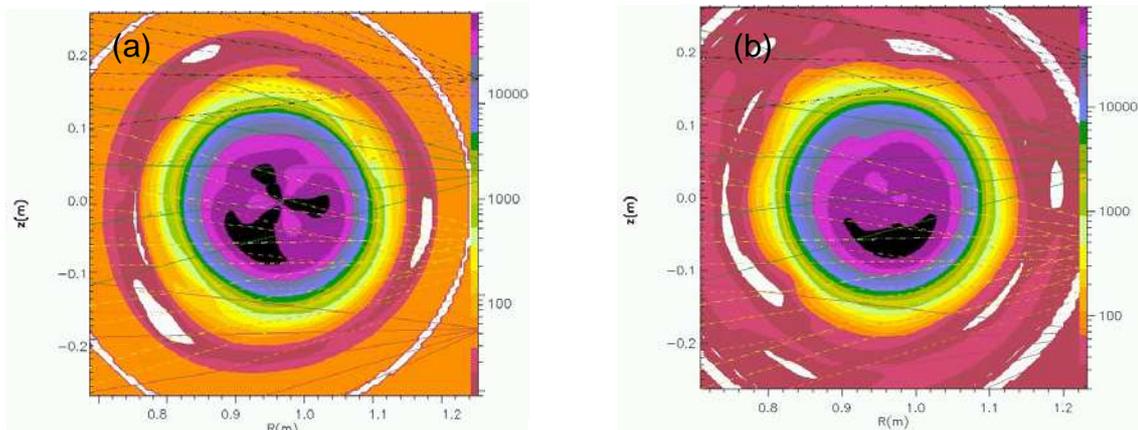


Fig.6: Tomograms: (a) #27791 $\Delta t=0.8308-0.8314$; (b) #27793 $\Delta t=0.8293-0.8296$ s.