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Disruption avoidance by ECRH power on FTU

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Introduction

Disruption control is one of the most challenging issues in ITER operation where two main types of disruptions are expected: *normal* disruptions (e.g.: due to excessive radiation, density limits, loss of NTM control leading to mode-locking, excessive pressure peaking in advanced scenarios, etc.) and vertical displacement events (VDEs). VDEs are not expected to lead to high runaway currents because by the time that the plasma disrupts, the edge q of the discharge drops to ~1.5-2.0. At these low q's large runaway losses are found in present experiments and, thus, no significant runaway currents can be produced. On the contrary, for *normal* disruptions a large efficiency of conversion of the poloidal magnetic energy into runaway electrons is expected and the associated runaway current may reach up to 10 MA (as the secondary electron runaway generation timescale is ≤ current quench timescale, typically several tens of ms in ITER). Approaching a *normal* disruption, except for ITB disruptions and other ideal MHD limits, the plasma experiences a considerable deterioration of the energy confinement, as shown initially in JET experiments [1]. Therefore, by the time of the thermal quench L-mode plasma parameters are found, even if during the high performance phase a high confinement H-mode is present. Such pre-disruptive plasma conditions are, thus, similar to those occurring in a circular limiter tokamak such as FTU.

Various approaches are currently investigated for disruption mitigation. Massive gas injection, which is being studied in several tokamaks, increases transiently the level of plasma radiation and density and achieves the conversion of the thermal energy into radiative energy that is deposited over a larger area than by convection/conduction and causes a fast plasma shutdown while avoiding runaway generation. It remains to be understood how this system can be applied to ITER as it may require a high gas pressure reservoir located very close to the plasma, which is difficult to install in ITER. Application of ECRH, currently investigated in FTU, is a promising technique to mitigate some of the problems associated with disruptions (avoidance of the current quench and, thus, of the associated runaway production and forces on components linked to halo and eddy currents). It has the further advantage that no new hardware would be needed for ITER as ECRH systems are already required for ITER (up to a total power of 20 MW), mainly for two purposes: plasma heating and neoclassical tearing modes (NTM) stabilization. In FTU the loop voltage measurement (V_{loop}), is used as disruption precursor to trigger automatically the ECRH power (P_{ECRH}) pulse for disruption avoidance [2]; in principle, the same method could be used in ITER.

Disruptions mitigation in FTU

Experiments have been performed on FTU (circular cross section with major radius R=0.935 m and minor radius a=0.3 m) in 500 kA discharges, at ITER-relevant parameters (B_t=5.3 T, central electron density ~ 10^{20} m^{-3}) with an accurate radial scan of the P_{ECRH} deposition localization (140 GHz, 0.4-1.2 MW). The ECRH FTU launcher [3] is able to focus independently four beams from the centre to r/a=0.85 with a waist of 2.8 cm; the mirrors can be steered before every discharge in order to change deposition radius (r_{dep}) while keeping constant B_t. Disruptions have been induced by impurity injection (Mo) by means of a laser blow-off system (LBO): an example is shown in **Fig.1**. At 0.8 s, during the current plateau when the line-integrated electron density is ~ 0.6×10^{20} m^{-3}, the LBO system fires Mo (about 0.6 mg) into the plasma. A large increase of the central impurity concentration is observed that is followed by the cooling of the edge plasma. From Mirnov coils FFT analysis it is found that MHD modes grow in amplitude until they quickly slow down and lock. Typically, the largest ones are 2/1 with frequency of 7 kHz and, just before locking, 3/2 (12 kHz). The current quench typically occurs within 5 ms after the mode locking (see discharge #29473 in **Fig.1**). On the contrary, when ECRH is applied (Δt_{ECRH}=100 ms) at one of the MHD mode locations (15 cm, corresponding to q=2, in the case of #29484, see **Fig.2**) the discharge recovers completely. Note, in particular, the re-heating shown by the electron temperature (T_e) and the neutron emission that, after dropping considerably, fully recover to the pre-LBO level in about 200 ms. Power deposition ray-tracing calculations have been performed by means of the ECWGB 3D quasi-optical ray-tracing code [4] linked to the FTU equilibria and ECRH launching data. The results of scan of the power deposition show the capability of EC waves to avoid disruptions only when the power is deposited on the q rational surfaces relevant for MHD activity (in correspondence of the 3/1 and 2/1 islands in **Fig.3**).

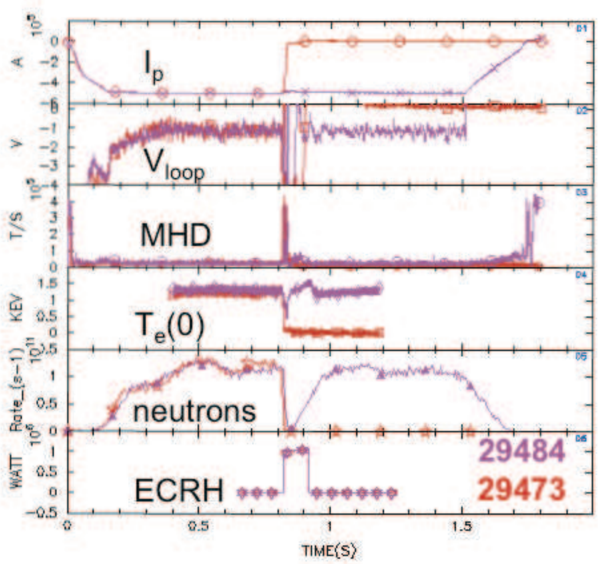

Fig.1: Disruption avoidance in Mo-injection discharges in FTU.

This fact suggests MHD as the final mechanism of disruption evolution, while plasma energy content replacement by ECRH does not seem to be crucial. When P_{ECRH} is deposited at the location of the modes the disruption is completely avoided, while the current quench time is only delayed if P_{ECRH} is deposited near to the resonant surfaces. The fact that the disruption can be avoided through stabilization of anyone of the coupled modes, as clearly evidenced in **Fig.3**, suggests that mode coupling can be efficiently used to suppress islands not directly heated by EC waves. This can increase the possibilities to use ECRH as disruption avoidance tool in future tokamaks.

The island width evolution (from soft x-ray tomography reconstruction) has been compared with the predictions of the standard Rutherford model [5] in order to provide an indication on the level of power needed to produce disruption avoidance. The results are presented in **Fig.4** for two cases (no ECRH: #29473; ECRH: #29479): using the coefficients inferred from the fitting of the experimental data, the minimum island width, below which the m=2 cannot be destabilized, is found to be 8% of the saturation width. This is the value reached by the stabilized island when 0.6 MW of EC power are absorbed at q=2.

Conclusions

Disruption avoidance and complete discharge recovery has been obtained in FTU by stabilization of MHD modes through ECRH injection in Mo-induced disruptions. The results are strongly sensitive to the power deposition location: direct heating of one of the coupled modes, affecting the evolution of the others, has been observed to be sufficient to avoid the disruption. The existence of a threshold in P_{ECRH} has not been systematically investigated so far: however, an absorbed P_{ECRH} of at least 0.4 MW has been necessary at I_p=500 kA for q=2 avoidance. As the determination of the power threshold for disruption mitigation with ECRH is a key issue in view of ITER application, systematic P_{ECRH} (as well as I_p) scans are foreseen in future FTU experiments. Such investigation will be carried out in Mo-induced, density limit and low q disruptions to determine the ECRH requirements for disruption avoidance.

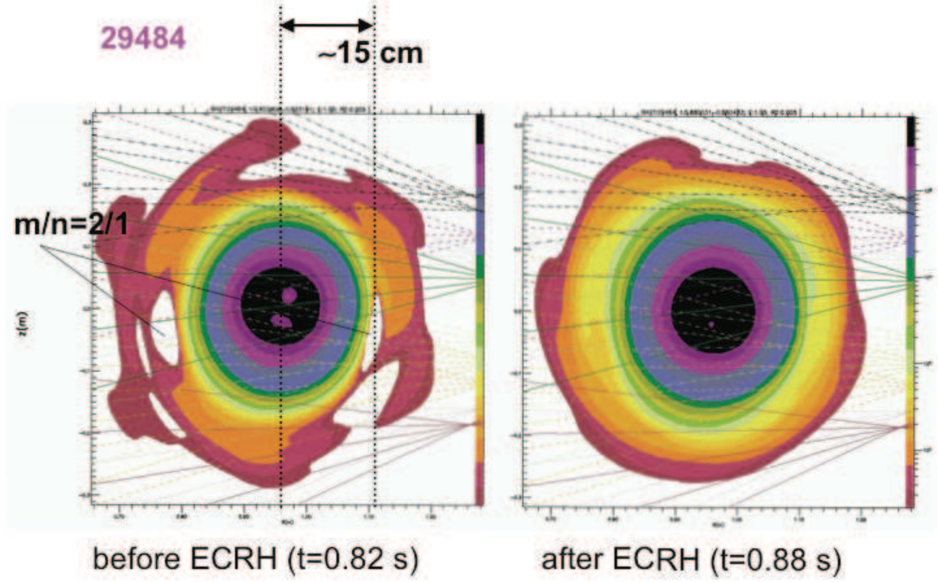

Fig.2: Localization of MHD islands from soft x-ray horizontal camera tomography in discharge #29484 (P_{ECRH}=1.0 MW, r_{dep}=15 cm).

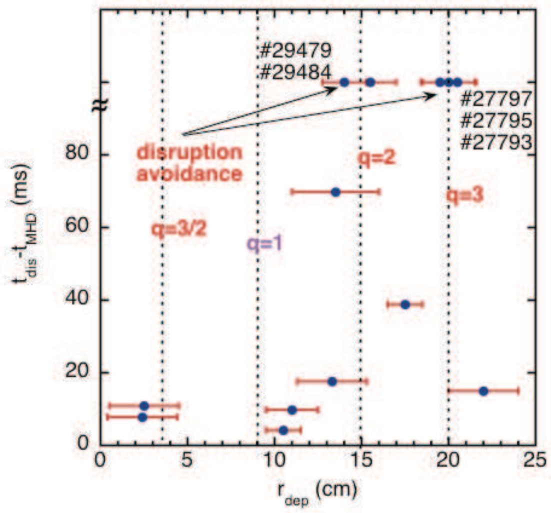

Fig.3: P_{ECRH} deposition scan: r_{dep} is evaluated using the ECWGB 3D quasi-optical ray-tracing code; t_{MHD} is the starting time of MHD activity and t_{dis} the disruption time.

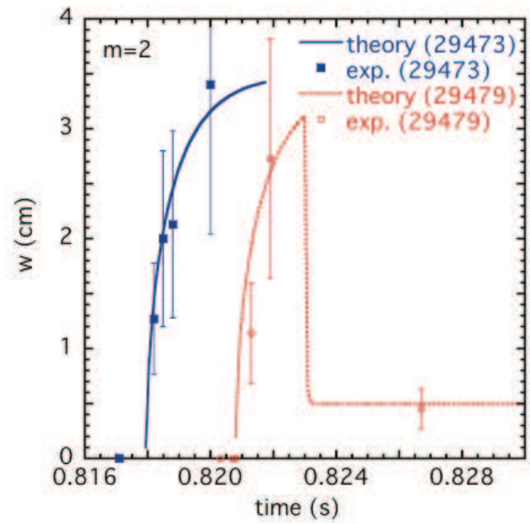

Fig.4: Comparison between experimental and theoretical (Rutherford model) evolution of islands (w=island width).

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