*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.143 (2004)*

MHD activity in EC-heated TCV plasmas with eITBs

G. Zhuang, A. Scarabosio, R. Behn, Y. Camenen, T.P. Goodman, M.A. Henderson, I. Klimanov, A. Martynov, O. Sauter, H. Weisen and TCV team
Centre de Recherches en Physique des Plasmas,
Association EURATOM-Confédération Suisse, EPFL, CH-1015 Lausanne, Switzerland

Scenarios leading to the formation of internal transport barriers (ITBs) are of interest for tokamak operation since they permit to obtain large bootstrap current fractions and considerable improvement in energy confinement [1]. In the case of dominating electron heating - e.g. by ECRH - the electron ITBs (eITBs) are influenced by the shape of the current density profile and the formation of q-profiles with reversed shear. In the TCV tokamak, combined application of ECH and ECCD (using up to six gyrotrons at 82.7GHz, 0.5MW each) has been used to form eITBs and improvements in energy confinement up to a factor of 6 above RLW scaling have been obtained [2]. However, current profile shaping and strong additional heating may lead to MHD activity with important consequences on performance and steady-state operation. During ITB experiments on TCV under various conditions, several types of MHD activities have been observed. In the following, their basic features will be described and the influence on plasma performance will be discussed.

For the studies presented here the MHD activity has been measured using sets of magnetic probes to record magnetic field perturbations and sets of detector arrays to record the plasma emission in the soft X-ray range (SXR). The magnetic probes are arranged in a toroidal array (16 probes) and a poloidal array (38 probes) permitting us to identify toroidal and poloidal mode numbers up to n=4 and m=8, respectively. The viewing chords of the X-ray detectors cover the poloidal cross section and permit tomographic reconstruction of the emissivity profiles. The signals from fans of chords have been analyzed to identify MHD activity in the central region of the plasma.

During eITB scenarios on TCV two basic types of MHD activities have been observed: tearing modes (TM) and kink-like modes at low m/n rational q-surfaces. The latter show the signature of periodic relaxation oscillations (PROs) with sawtooth-like features in the SXR signals. The tearing modes cause slowly oscillating perturbations (3-6kHz on TCV) of the fields measured by the magnetic probes.

In general, tearing modes (TMs) are associated with the appearance of magnetic islands at rational q-surfaces and are driven by current and pressure gradients. In our cases, the tearing modes are localized near q=m/n=2/1 and/or 3/1 surfaces outside the eITB in the region of positive magnetic shear. At the mode onset the values of β_N range from 0.6 to 1.4

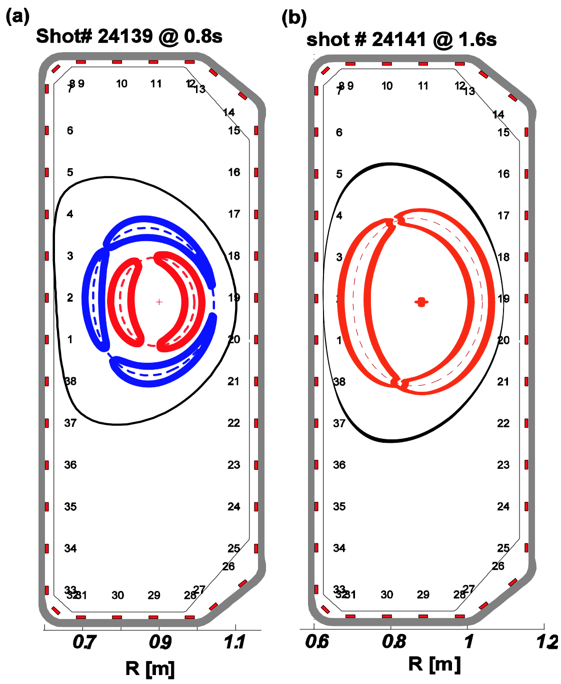

Fig.1 Magnetic islands reconstructed from the magnetic perturbation data. (a) m/n= 3/1 (blue) and 2/1 (red) modes (coupled); (b) single 2/1 (red) mode.

and the collisionality ν_{e*} varies from 0.003 to 0.01. Neither the double tearing mode nor the 3/2 mode have been observed. The magnetic islands as shown in Fig. 1 have been reconstructed from magnetic perturbation measurements using a model described in [3]. TCV #24139 (Fig.1a) is an example of a case where a 3/1 mode coexists with a 2/1 mode and both modes are coupled and rotate together, while in #24141 (Fig.1b) only the 2/1 island is present. The poloidal mode number *m* and the width of the magnetic island have been obtained from analysis of SXR data. The results from magnetic signals and SXR emissivity are in reasonable agreement.

The evolution of the saturated island size for the 3/1 and 2/1 modes respectively, is shown in Fig. 2. The island width of the 3/1 mode $w_{3/1}$ in #24139 increased during the current ramp up although β_p decreased. This implies the bootstrap current contribution to the mode is not important. In #24141, the width of the 2/1 mode $w_{2/1}$ changes in proportion to β_p (see. Fig. 2b). This linear dependence is expected for a typical neoclassical tearing mode (NTM). Detailed investigations showed that this 2/1 mode develops from a seed island, this does not seem to be the case for the 3/1 mode in #24139. The growth rate and saturation of the 3/1 mode island widths for #24139 have been calculated using the Rutherford equation in its form for classical TMs. It is found that the measured growth time scale τ_{tear} ~ 3ms would lead to an unrealistic value of the instability parameter ($\Delta' r_s$ ~75). Obviously, pure resistive tearing mode theory is not sufficient to explain this behaviour and mode coupling or other effects have to be included in the simulation to match the experimental time scale.

The influence on global confinement caused by the tearing mode is shown in Fig. 3 for # 24139. As the coupled 3/1 and 2/1 modes build up at 0.556s (see Fig. 3b), the global confinement (referred to RLW scaling) degrades significantly from 3.5 to 2.5, the eITB strength (identified by ρ_{*T}, according to

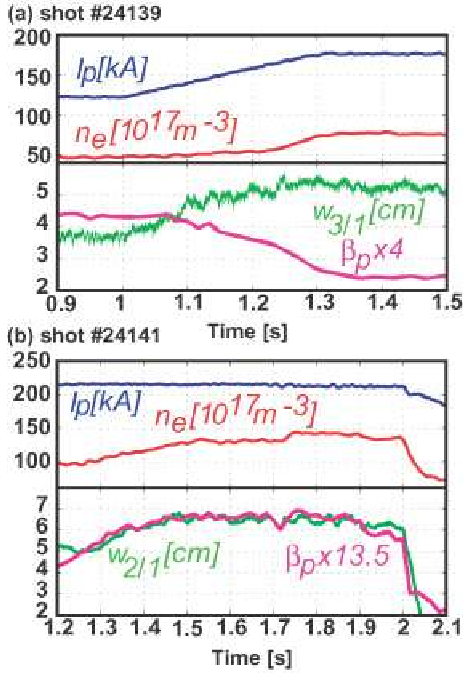

Fig. 2 Evolution of plasma current I_p, averaged density n_e, saturated magnetic island width $w_{m/n}$ and poloidal beta β_p for shots 24139 (a) and 24141 (b), respectively.

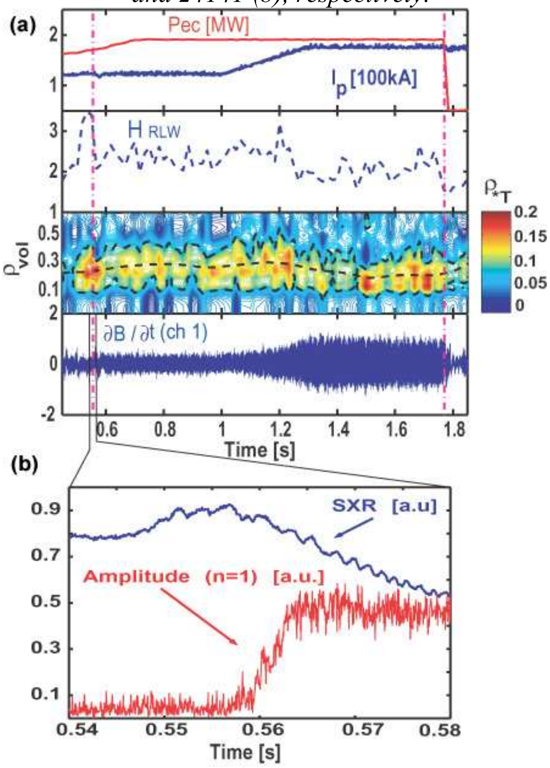

Fig. 3 (a) Evolution of I_p(blue), P_{ec} (red), the confinement H_{RLW}, the eITB strength ρ_{*T} (contour plot), and the mode amplitude (magnetic probe) for #24139; (b) The SXR signals and mode amplitude at time of drop in H_{RLW} (0.556s).

Tresset [4]) decreases but the radius of the weaken eITB stays at the same location even in the ramp-up phase of heating power. The growth of the mode amplitude is correlated with a gradual decrease of the SXR signal, indicating that the presence of the TMs is responsible for the degradation of the ITB and the energy confinement. As the mode amplitude increases further, the averaged H_{RLW} drops from 2.5 to 2 and the ρ_v radius of ITB shrinks from 0.3 to 0.2, which means that the high confinement phase is lost.

Apart from tearing modes, fast collapse events and PROs have been observed. The PROs show sawtooth-like signature with an inversion radius located close to the q=2 magnetic surface and a longer period than that of ordinary sawteeth. The PROs have been identified as kink modes driven by high local pressure gradients or by a global beta limit.

A paradigm of PROs is shown in Fig.4 for # 24696, and compared with a quiescent case (#24698). Both shots have quite similar plasma parameters except for the higher density and lower additional heating power of #24698. As seen from the SXR signals, the MHD activity in #24696 started at t=0.81s with a fast crash event (2/1 mode) which stabilized at 0.88s. Then PROs appeared with regular oscillations at a period of 16ms and stayed until the central EC heating power was turned off. Fig.4 shows that the degradation of the global confinement and the influence on the eITB introduced by PROs are much less pronounced than in the case of a TM. The averaged H_{RLW} of #24696 is ~2.5 and almost the same as that of #24698 (~2.6).

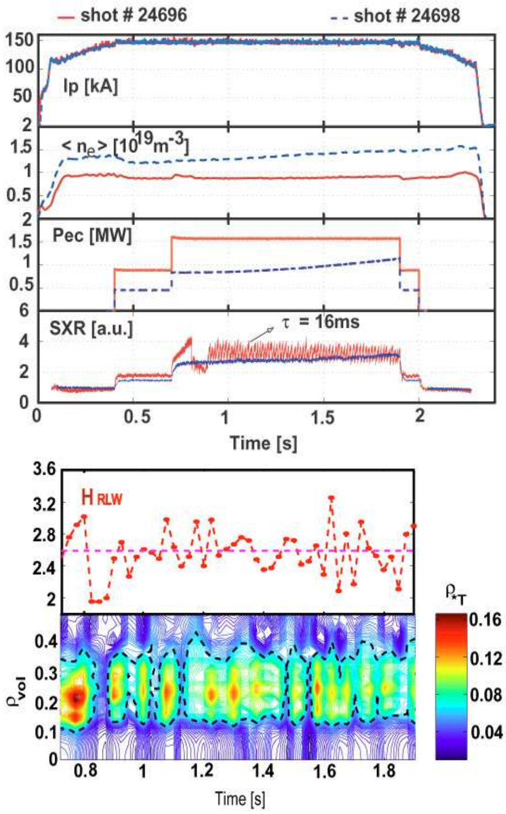

Fig. 4 ***Top***: *PROs as seen in SXR signal for shot # 24696, in comparison with quiescent case shot #24698.* ***Bottom***: *The confinement and eITB behaviour during the phase with PROs of shot #24696.*

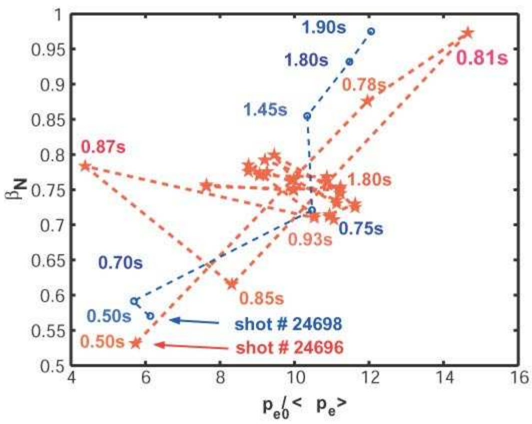

Fig. 5, Evolution of the experimental β_N and pressure peaking factor for shots #24696 (blue) and #24698 (red), respectively. In shot #24696, at 0.81s, the mode occurred leading to a rapid drop in β_N and peaking factor.

The evolution of the experimental β_N and pressure peaking factors (P_{e0}/<P_e>), as shown in Fig. 5, shows the difference between both shots. The peaking factor and β_N start to increase when the heating power is turned on. At 0.81s the peaking factor of #24696 reaches an extremely high value ~15 and causes a rapid collapse in the pressure profile and a large decrease in β_N. Due to the lower EC power the peaking factor of #24698 never reaches this limit.

For #24696 central counter ECCD is preceded by off-axis ECH, which results in broad temperature (T_e) profiles. However, after the injection of EC power (0.7MW) into the centre, T_e and pressure (P_e) become strongly peaked. The large pressure gradients, together with a broadened q profile (low magnetic shear), destabilize the ideal MHD modes. To compare and illustrate the effects of different heating scenarios, another example (TCV #23612) with different timing and deposition location of the EC power has been chosen (see fig.6). In case of #23612 off-axis ECH is deposited slightly inside the q=2 surface. At the same time (0.4s) central counter-ECCD begins with a power ramp reaching full power of 1.5MW at 0.7s. The T_e profiles evolve slowly and lead to a change of the current density profile on a resistive time scale. This can be inferred from the change in plasma internal inductance l_i. Increasing the central power injection causes the central T_e to rise, but the peaking of the pressure profiles does not exceed 12. During the whole heating phase a small amplitude mode is present, but does not degrade the performance, and the radius of the ITB stays near ρ_v=0.35. Therefore, good confinement (H_{RLW} ~ 4-4.5) is obtained at a rather high β_N ~ 1.4 (as indicated in Fig. 7).

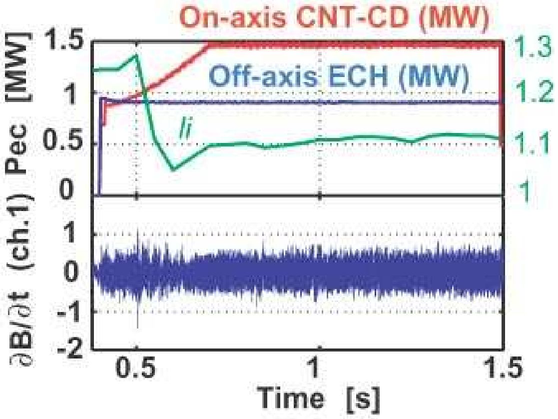

Fig. 6 The timing of EC power injection, plasma inductance l_i and MHD activities for shots 23612.

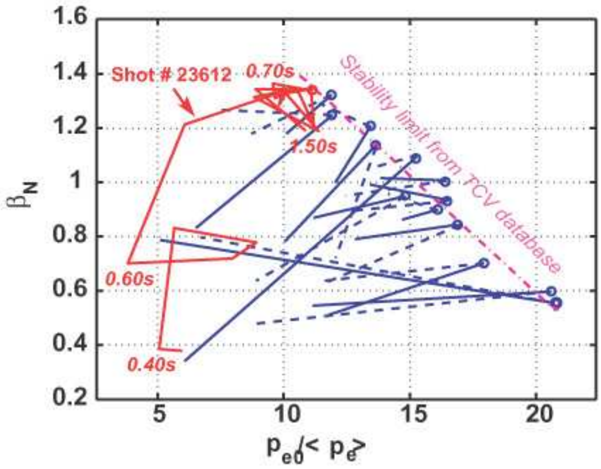

Fig. 7 The evolution of β_N and pressure profile peaking factors for a series of shots from the TCV database. In red the evolution for #23612 with the highest β_N. The symbol ('o') marks the onset of the MHD activity at the largest P_{e0}/<P_e>.
solid line: phase without MHD activity just before onset (~50ms);
dashed line: phase with MHD activity after onset (~50ms);
Magenta dashed-dotted line: experimental stability limit.

In general, the achievable β_N in tokamaks is limited by MHD instabilities driven by pressure gradients. As can be seen from these examples of EC heated plasmas with ITBs, attempting to reach higher β_N by increasing the heating power will not be successful unless too strong peaking of the pressure profiles can be avoided (see Fig. 7). Careful optimisations of EC power level and deposition location are necessary to achieve this goal.

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[2] R. Behn, et al, *Proc. 30th EPS conf. On controlled Fusion and plasma Physics,* St. Petersburg, 2003, P3.208
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[4] G. Tresset, et al, *Nucl. Fusion* 42(2002) 520

This work was partly supported by the Swiss National Science Foundation.