*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-1.111 (2007)*

ECCD perturbations aimed at MHD and ITB studies

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INTRODUCTION

One of the primary goals of present and future tokamak experiments is reaching and sustaining enhanced core confinement regimes, which should constitute the basis for the operation of a thermonuclear fusion reactor. In particular, internal transport barriers (ITBs) and MHD stability are found to be strongly linked to hollow j profiles, which in turn cause the safety factor profile "q" to be reversed in the centre [1,2]. In this aim, employing electron cyclotron current drive (ECCD) is a particularly attractive method to tailor the current profile: its high degree of power deposition localisation (~a few cm) allows for precise shaping of j even at low input power. The attractiveness of exploiting such kind of experiments on the Tore Supra tokamak resides in its long duration discharges (up to several minutes) which allow to reach and keep stationary regimes, as much as in its powerful RF power systems, in particular lower hybrid (LH), which can then sustain discharges in fully non-inductive current configuration (V_{loop}=0). Several series of dedicated discharges have been performed in the Tore Supra tokamak (major radius R=2.40 m, minor radius a=0.72 m, magnetic field B≅3.8 T, circular cross section), to investigate the effect of ECCD in a deuterium target plasma sustained by LHCD, in order to explore regimes affected by MHD phenomena [3] as well as electron internal transport barriers (eITBs) and investigate their stability limits. All shots have EC power P_{EC}~700 kW at 118 GHz, O-mode, 1st harmonic, supplied by two gyrotrons, delivering either co- or counter-EC current at different radial locations ($0.05<\rho_{ECCD}<0.52$). The current profile evolution has been reconstructed for all discharges by means of the integrated modelling code Cronos [4], linear stability analysis of MHD modes has been carried out using the Castor code [5]; modes frequency and structure, as well as experimental magnetic island width, could be evaluated based on the fast-acquisition ECE data (wavelet analysis as in [6]).

MHD TRIGGERING IN NEGATIVE SHEAR REGIMES

In reversed q scenarios, the MHD activity is found to be mainly linked to the double crossing of the 3/2 and 2/1 rational surfaces, and leads in some cases to MHD regimes (as defined in [3]). The temporal evolution of the q profile features two opposite patterns while the discharge is evolving towards the two different regimes ("stable" vs MHD). In all the shots, when an MHD regime sets in, the q profile is progressively shrinking, whereas during the "stable" shots its width is either constant or growing. We could observe that, for the triggering of these regimes, the presence or absence of rational surfaces in the plasma, as well as the superposition of two of them, is not a sufficient condition. Moreover, the values of

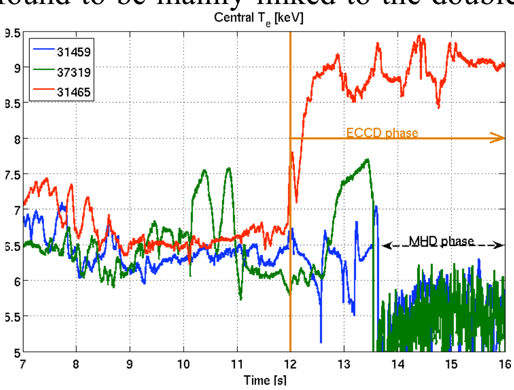

Fig. 1 : T_e evolution for shots #31459, 37319 and 31465. ECCD phase at 12 s (orange line), MHD regime signalled by the black arrow.

intersection widths are very erratic, thus no relationship can be inferred between this distance and the apparition of the unstable phase. We illustrate these statements in Figs.1 and2, where the temporal trace of T_e for three discharges, and the q profile evolution before the ECCD phase and just before the onset of the MHD regime are plotted, respectively (for the “stable” shot the same time slices are taken, as for the other two). Before the ECCD phase, the three discharges evolve very similarly (except for a barrier-like phenomenon around t=10.5 s in shot #37319, which will be discussed in the next paragraph); after t~12 s the red trace rises steadily, while the other two show big relaxations which eventually lead to an MHD regime. In the three discharges we observe a superposition of the q=3/2 and the q=2/1 surfaces: nonetheless the last one (#31465) remains stable until the end of the shot, while the other two trigger an MHD regime. When the amount of EC current (blue trace in Fig.2) driven outside the q_{min} position is greater, the q profile tends to shift downwards in that region, making the inner part move up and outwards: this results in an overall shrinking of the profile. On the contrary, when all, or most part of, the current is driven inside q_{min}, the q profile lowers locally, significantly distancing the inner crossing of one or both rational surfaces from the outer one, whose position remains unchanged. Therefore, operationally, a central ECCD location ensures the discharge stability, while, all shots with $\rho_{ECCD}>\rho_{q\_min}$ experience the MHD regime. In this case, if islands are located on the surfaces, they get closer and may tend to overlap. This can be an explanation for the violent crash which occurs at the onset of the MHD regime. The experimental confirmation of this hypothesis is given by the analysis of the temperature fluctuations in the fast acquisition range (~40 kHz ECE super-heterodyne). In Fig.3 we report the fluctuation amplitude of the mode detected just before the MHD regime and the q profile at t=11 s and t=13.5 s for shot #37319. The q profile for this time slice characterises the instability as an m=3/n=2 double tearing mode. The experimental island width at t=11 s is $W_{11\ s}$=6 cm, and it shrinks to $W_{13.5\ s}$=4.5 cm at the subsequent fast-ECE acquisition, but the q profile is shrinking too, thus another island appears on the 3/2 surface. Representing the island width evolution on the q rational surfaces for the two ECE acquisition times (as shown schematically in Fig.4, where the inner width is taken to be equal to the outer one) can indicate that the two island tend to superpose, leading to the complete reconnection which characterise the MHD regime triggered at 13.6 s. The calculation of the linear growth rates and theoretical islands position (Castor code) has confirmed this interpretation. A 2/1 and a 3/2 single-tearing modes are found at t=11 s, with growth rates $\lambda_{2/1}=4.2\cdot10^{-4}$ and $\lambda_{3/2}=4.5\cdot10^{-4}$ (normalised to the Alfvén time, with resistivity $\eta\sim7\cdot10^{-7}$ Ω·m, average of the computed Cronos resistivity over $0<\rho<0.9$). These growth rates rise to $\lambda_{2/1}=5.7\cdot10^{-4}$ and $\lambda_{3/2}=1\cdot10^{-3}$ at t=13.5 s, just before the MHD crash, confirming the higher instability of the shrunk q profile, and the predicted unstable modes are now an m=2/n=1 single tearing and an m=3/n=2 double tearing. The calculated islands evolution up until the MHD crash, plotted in Fig.5, predicts separate islands at 11 s and a superposition of the 3/2 mode at 13.5 s as it is found experimentally. In the counter-ECCD cases, the results about the q profile shrinking and the islands superposition are confirmed. Only the $\rho_{ECCD}<\rho_{q\_min}$ is documented so far, and the general result is that only a very central deposition ($\rho_{ECCD}<0.13$) perturbs the j profile too sharply, leading to an almost immediate triggering of the MHD phase. In all $0.14<\rho_{ECCD}<\rho_{q\_min}$ discharges, the injection of EC waves seems to stabilise the plasma: the T_e relaxations have a much smaller amplitude, while the modes generally become single tearings instead of double. Nonetheless, when two crossings on rational surfaces evolve away from each other, the plasma stays MHD stable, which is not the case when two intersections move closer.

ITB FORMATION

Employing an expanded database of ECRH and LH-only discharges, a study on eITBs formation has been preformed, which allowed to relate the manifestation of this phenomenon to a peculiar feature of the q profile evolution. The formation of a barrier is documented by means of the observation of a large rise in T_e, with a sharp change in slope at some radial location, as well as a decrease of the computed central electron heat transport coefficient χ_e, which gets back to a lower value when the higher confinement state is lost. The first general result we can report on is that the ITB starts when the q profile begins to feature a double crossing on the 3/2 or 2/1 surface. As illustrated in Fig.6, q_0 rises from below 1.5 progressively up to 2.5 or above, and at the times when an inner crossing appears, on q=3/2 or q=2/1, the temperature shows a significant increase (of hundreds of eV up to several keV). This happens while the other plasma parameters are apparently stationary, and can last for a few hundreds ms up to several seconds. When q_0 evolves in between 1.5 and 2, very often the higher confinement state is lost and χ_e increases, dropping off again at the subsequent passage above 2. This behaviour is kept also in the case of the time of triggering of the non-linear oscillations regime [7], which is understood, at present, as an intermediate state, i.e. an incomplete ITB transition. The generality of this result is illustrated in Fig.7: the times at which q crosses a rational surface is plotted against the times when a barrier starts (red squares). The presence of an inner crossing is taken when q_0=3/2 or 2. All the examined database aligns well on the diagonal, with the typical deviation being Δt=0.36 s. Nonetheless, we can affirm that a simple inverted q profile is not sufficient to drive the plasma into a barrier-like phenomenon: in Fig.7 the points corresponding to the magnetic shear becoming negative (black triangles) result very sparse. Moreover, no shear threshold can be found. The q_{min} values span the range [1.14÷1.57], without accumulating around any precise value, allowing for no correlation with the barrier formation (Fig.8). This tight correlation does not hold, though, for all the q profiles evolutions observed in the database: when a double crossing approaches, but no barrier is observed, some balance must be in act, between a possible stabilising factor linked to the crossing of the rational surface and the instabilities forming on those same surfaces, which degrade the higher confinement properties. Usually it is experimentally observed that a mode is detected during the shot, which disappears at onset of the barrier. The investigation of this issue is still under development.

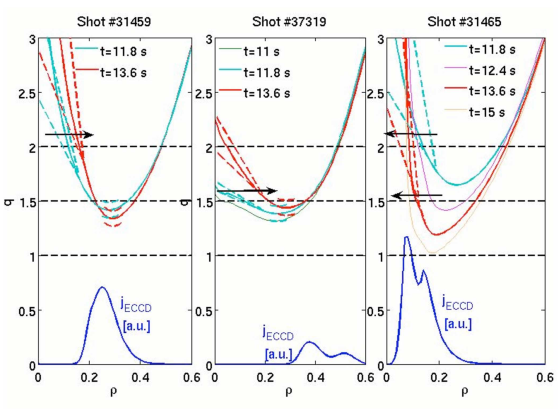

Fig. 2 : q profile evolution for the shots of fig.1. ECCD plotted in blue and error bars represented by broken lines.

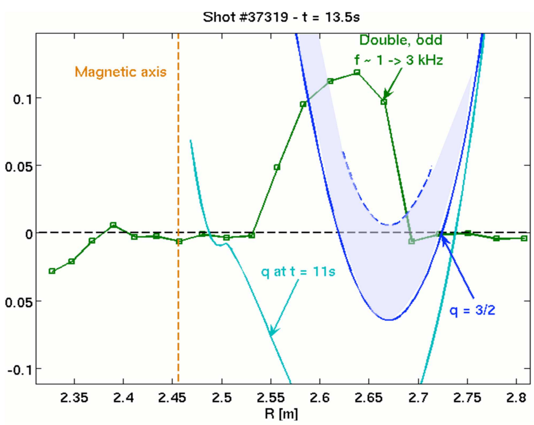

Fig. 3 : Mode structure evolution and relative q profile at t=11 s and t=13.5 s, for shot #37319.

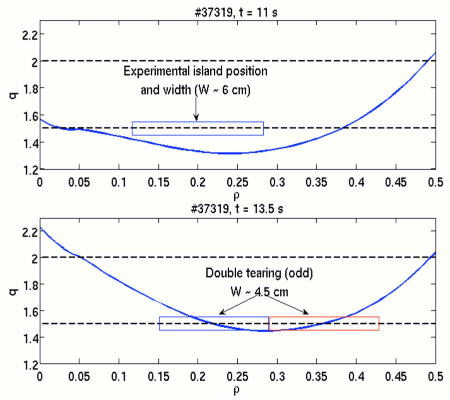

Fig. 4 : Experimental islands superposition based on reconstructed q profile at times 11 s and 13.5 s for shot #37319.

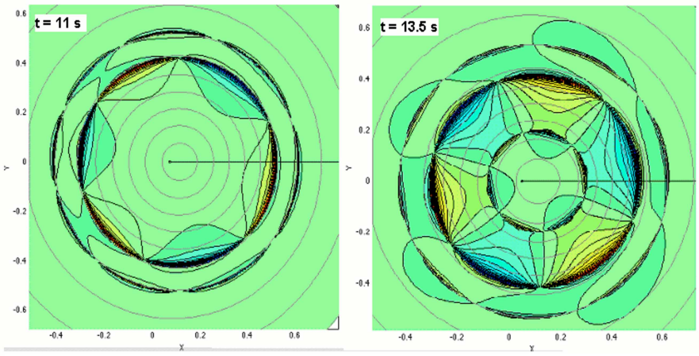

Fig. 5 : Evolution of islands positions computed in the linear stability regime. n=2 unstable modes at t = 11 s and t = 13.5 s for shot #37319.

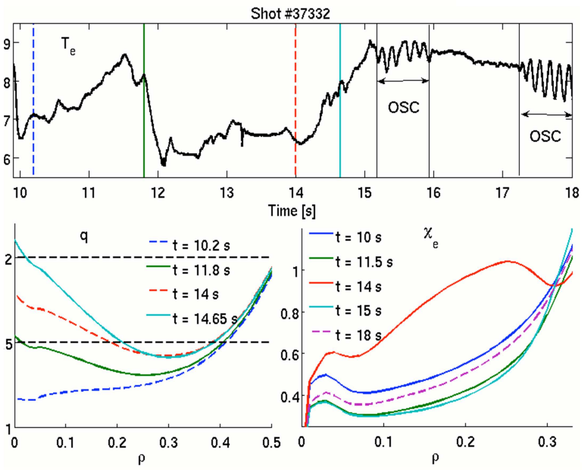

Fig. 6 : T_e evolution with barriers signalling (top), q profile double crossings (bottom left) and χ_e (bottom right) for discharge #37332.

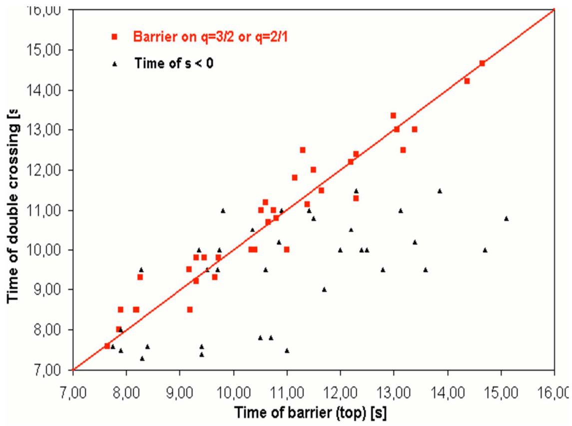

Fig. 7 : Correlation between time of barrier formation and time of q_0=3/2 or 2 (red squares), time of s < 0 (black triangles).

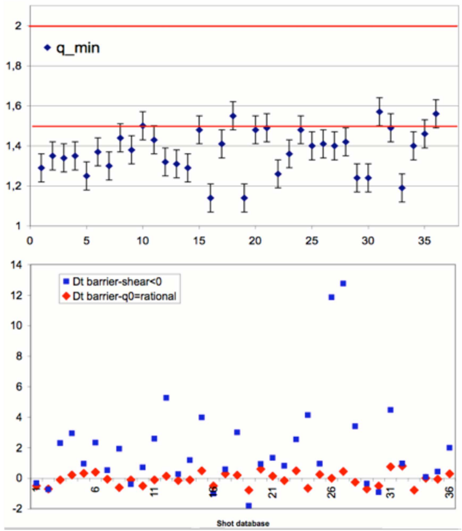

Fig. 8 : q_{min} values over the barriers database with error bars (top); time difference between barrier formation and q_0=3/2 or 2 (red diamonds), and time of s<0 (blue squares).

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