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Giant Oscillations of Electron Temperature during zero loop voltage discharges on Tore Supra

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1. Introduction

The capability of the Tore Supra tokamak to achieve long pulses with fully non-inductive current drive lead to the discovery of a stationary regime featuring periodic oscillations of the central electron temperature [1,2] (O-regime). Recent experiments have revealed the existence of a new phenomenon : intermittent oscillations of the electron temperature of much larger amplitude than the previous ones, hereafter named giant oscillations (GO). This paper reports on the first observation of this new plasma behaviour, which involves distinct mechanisms with respect to the O-regime.

2. Experimental conditions

Tore Supra is the largest operating tokamak device equipped with superconducting magnetic field coils (major radius R = 2.40 m , minor radius a = 0.72 m , magnetic field B = 3.8 T , circular cross section). In the experiments described here, steady-state operation is achieved by injecting about 3 MW of Lower Hybrid Current Drive (LHCD) in low density deuterium discharges at low plasma current ($n_{e0} = 2.0 \times 10^{19}$ m^{-3}, $I_p = 0.51$ MA). The level of LH power is controlled in real time in order to maintain a given value of the plasma current while the transformer current is kept constant (exactly zero loop voltage). The LH launched spectrum has its main peak at parallel refractive index $n_{//} = 1.8$, unless otherwise specified. This scenario typically provides access to the O-regime. The central electron temperature is $T_{e0} \approx 5-6$ keV, central ion temperature $T_{i0} \approx 1.2$ keV, and effective ion charge $Z_{eff} \approx 2.3$. The key diagnostic for the present study is a 32-channel super-heterodyne radiometer measuring the electron cyclotron emission (ECE) spectrum in the frequency range 78–110 GHz, around the fundamental cyclotron harmonic (ordinary mode, space resolution 2.5 cm , time resolution: 1–4 ms in standard mode, down to 8 μs during fast acquisition) [3]. The frequency range 92–110 GHz is not affected by super-thermal emission and therefore represents a precise measurement of the electron temperature profile in the central part of the plasma.

3. Description and interpretation of the giant oscillations

Giant electron temperature oscillations of the amplitude of about 3 keV have been observed during a stationary phase of standard low amplitude oscillations (up to 0.7 keV, frequency $\approx$ 8 Hz). The standard O-regime starts as I_p reaches 0.51 MA (t = 16 s on Fig. 1), which confirms the strong link of the phenomenon with the q-profile. After 1-3 s of stationary O-regime, a first giant oscillation occurs (t = 21.8 s on Fig. 1). Then other GO occur intermittently, either alone or in groups of successive events. They always start with a decrease of T_e in the plasma core (normalised toroidal flux coordinate $\rho < 0.2$) of duration $\approx$ 0.1 s, from typically 5 keV to 3.5 keV (Fig.1c). Then the electron temperature increases up to 6.5 keV, this level being significantly higher than the average T_e during the standard oscillations $< T_e > \approx 5$ keV. This impressive temperature excursion takes about 0.2 s. The high temperature is however not sustained, and the final phase of the GO may occur in two different ways : either there is a slow T_e decrease (duration ~ 0.1 s) back to the level of the standard oscillations, which then start again; or a sharp drop of T_e occurs (duration ~ a few ms) back to the minimum temperature level (~ 3.5 keV), followed by another giant increase. The latter case is at the origin of groups of successive giant oscillations (e.g. Fig. 1a. around t = 50 s).

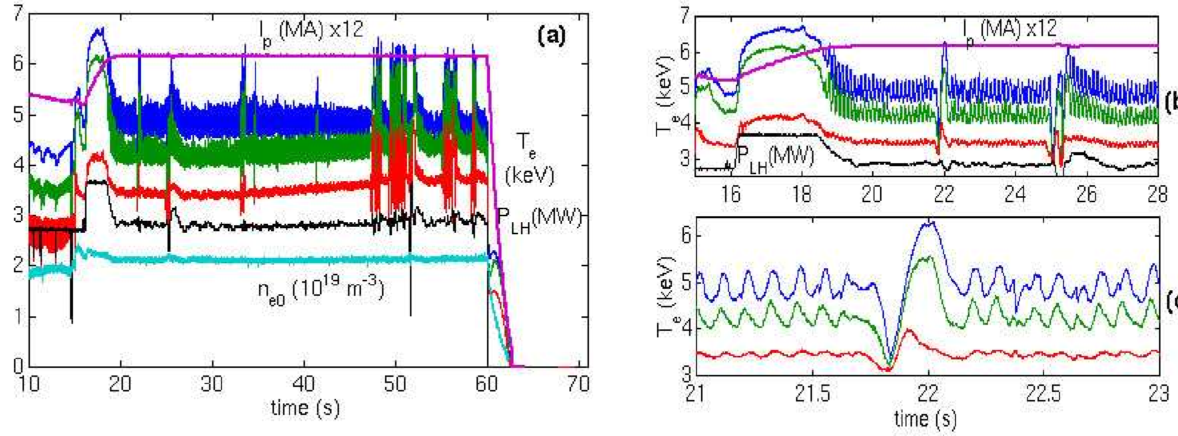

Fig. 1 : Time traces of Te (core ECE channels r < 0.2), plasma current Ip, LH power PLH and central electron density ne0, shot #33983. In this discharge, the toroidal field decreases slowly from Bt = 3.81 to 3.76 T between t = 34 and t = 55 s, which may influence the repetition rate of the GOs.

At $n_{//}$ = 1.8, there is no periodicity in the occurrence of the giant oscillations : they seem to be an intermittent phenomenon superimposed to the O-regime. The plasma behaves here as a two-cycle nonlinear oscillator, spontaneously alternating phases with standard and giant oscillations. When increasing $n_{//}$ (at zero loop voltage, thus increasing also slightly the LH power), the giant oscillations become more frequent (Fig. 2) and occur quasi-continuously above $n_{//} \approx 1.9$. They become almost periodic, with a frequency increasing continuously with $n_{//}$ from 4 to 15 Hz. The duration of the T_e increase phase becomes also shorter : 0.1 s at $n_{//}$ = 2.1 instead of 0.2 s at $n_{//}$ = 1.8. These sequences of several successive GOs at high $n_{//}$ (Fig. 2c) have some similarity to the large T_e relaxations that may happen in the fully developed hot core LHEP regime [4]. Within the high $n_{//}$ GO-regime, a quiet low T_e phase lasting about 2 s is even obtained, after which the GO restart (Fig. 2d). This clearly shows that the giant oscillation phenomenon is linked to the details of the current profile and can be controlled by external current drive actuators.

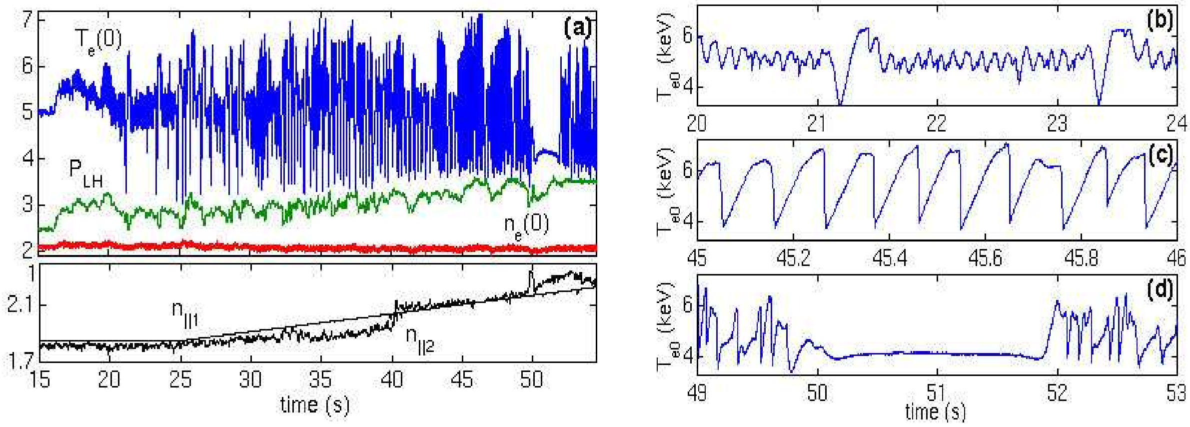

Fig. 2: Time traces of central electron temperature Te0, LH power PLH, parallel refractive index of the two LH launchers n//1 and n//2, and central electron density ne0, shot #33986.

In both the increase and decrease phase of GOs, the modifications of the temperature profile begin around $\rho \approx 0.2$ then propagate towards the centre : the T_e decrease starts with a flattening of the T_e gradient at $\rho \approx 0.2$ while the gradient remains large in the very core (Fig. 3a). Conversely, the T_e profile remains flat at the beginning of the temperature increase, which is built up through a continuous increase of the T_e gradient at $\rho \approx 0.2$ (Fig. 3b). According to current diffusion simulations, this position corresponds approximately to the minimum of the safety factor (q) profile that is slightly reversed in the plasma core owing the hollow LH power deposition profile, with $q_{\min} \approx 1.8 \pm 0.2$ localised at $\rho \approx 0.22$. This suggests that the mechanisms underlying the GO are linked to this particular shape of the q-profile, which is prone to trigger i) ITBs due to negative magnetic shear in the vicinity of a low order rational (q = 2) and ii) (m=2,n=1) tearing modes. While tearing modes are not systematically observed during the standard O-regime, they appear to be key players in the GO phenomenon. For instance, the fast T_e decrease (a few ms) which terminates several GOs has been identified as a multi-resonant large scale tearing mode (double or possibly triple) localised on the q = 2 surface. Fast ECE acquisition clearly shows how the mode develops progressively at the top of the GO (T_{e0} = 6.5 keV) from a quiescent phase to a large island leading to the ITB erosion and temperature collapse (Fig. 4). The triggering of GOs during the O-regime seems also linked to MHD activity on the q = 2 surface, since tearing modes are observed systematically just before or during the slow T_e decrease initiating all occurrences of a group of GO.

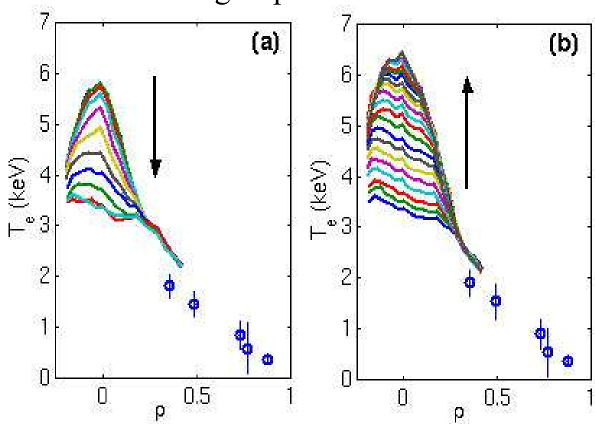

Fig. 3 : Dynamics of Te profiles during a GO at n// = 1.8 of shot #33986. (a) slow decrease phase starting from the O-regime level, t = 26.4 to 26.5 s; (b) increase phase up to the top of the GO, t = 26.5 to 26.7 s. Solid lines correspond to the ECE signal, displayed here every Δt = 0.01 s. Blue circles are time-averaged Thomson scattering measurements.

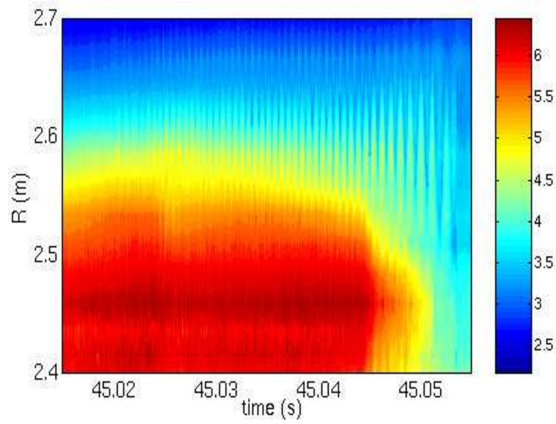

Fig. 4 : Color contour plot of Te (keV, fast ECE signal) showing the growth of a multi-resonant (m=2,n=1) tearing mode during the fast termination scheme of a GO (shot #33986).

In order to understand better the phenomenon of giant oscillations, the interpretive heat diffusivities have been estimated from a CRONOS simulation of shot #33986. The power deposition profile of LH waves, which are the main heating source in those discharges, has been estimated using fast electron bremsstrahlung (FEB) tomography [5]. The dynamics of the LH power deposition during the GO have been included in the calculation of the diffusion coefficient using multiple samples of FEB data in order to improve the signal to noise ratio (Fig. 5a). The effective heat diffusivity is calculated as $\chi_e^{eff} = -\Gamma_e / \nabla T_e$, where Γ_e is the time-dependent electron heat flux. The T_e decrease phase corresponds to a strong increase of χ_e^{eff} inside ρ = 0.2, and in particular in the region 0.15 < ρ < 0.2 (Fig. 5c). Conversely, the T_e increase corresponds to a significant improvement of the confinement occurring first around ρ = 0.22 before propagating towards the centre (Fig. 5d). At the top of the GO (t = 26.7 s, T_{e0} = 6.5 keV), the χ_e^{eff} profile features a clear drop inside ρ = 0.2 that is an evidence of a fully developed ITB.

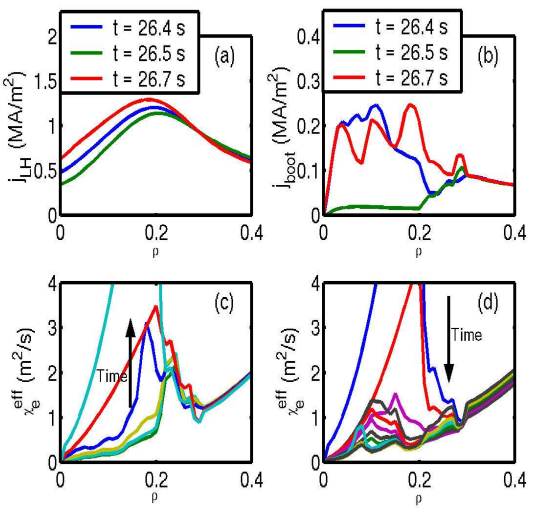

Fig. 5 : Dynamics of various profiles during a GO at $n_{//}$ = 1.8 of shot #33986 (same GO as in Fig. 3). (a) LH current density (deduced from Abel-inversion of the FEB signal, and renormalised using a given current drive efficiency), t = 26.4, 26.5 and 26.7 s. (b) bootstrap current density, same time slices as (a). Effective diffusivities during the decrease (c) and increase (d) phases of the GO, displayed every Δt = 0.02 s using the same color code as in Fig. 3.

The dynamics of the non-inductive current sources likely play an important role in the occurrence of the giant T_e increase : following the drop of T_e down to about 3.5 keV, both the LH power deposition and the bootstrap current profiles become more hollow than in the standard O-regime (Fig. 5a and 5b). This drives a slightly broader q-profile leading to a fully developed ITB inside ρ = 0.2. This interpretation is consistent with previous experiments on the hot core LHEP regime that showed that an ITB is triggered only when the non-inductive current drive source is broad enough [6,7]. It is also consistent with the fact that the giant oscillations become much more frequent at high $n_{//}$, i.e. when the LH power deposition is more hollow. Quite remarkably, it appears that the ITB triggering during the GO is a consequence of the initial T_e decrease, through the coupling between non-inductive current sources and the T_e profile. During the last phase of the GO (slow termination scheme), the non-inductive current sources peak again due to the high core temperature (Fig. 5a and 5b) and likely move q_{min} inwards, leading back to the standard oscillation regime in ~ 0.1 s.

4. Summary

The new phenomenon of giant oscillations is characterised by the spontaneous triggering of a fully developed electron ITB in the plasma core. This ITB is not sustained, either because the current profile relaxes towards the standard oscillation regime, or because a multiple tearing mode is triggered on the q = 2 surface. Owing to the particular shape of the q-profile that is slightly reversed with q_{min} just below 2, the plasma is at the threshold of a bifurcation between the triggering of MHD activity which is deleterious for the local confinement, and the formation of an ITB. The paradox of the giant T_e oscillation is that it is the initial deterioration of the confinement which drives the conditions leading to the ITB transition, providing the large amplitude of the GO (~50 % of the average temperature level). These experimental observations illustrate the complexity of the non-linear interactions between energy confinement, non-inductive current sources and MHD that may occur in a tokamak plasma at zero loop voltage. In addition to unveiling the physics of ITB and non-linear plasma dynamics, both the standard and giant oscillation regimes may be used to develop control algorithms that might be relevant for future fusion devices.

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