Giant Oscillations of Electron Temperature during Steady-State Operation on Tore Supra

F. Imbeaux, G. Giruzzi, P. Maget, J. L. Ségui, V. S. Udintsev, J. F. Artaud, D. Elbèze, G. Huysmans, E. Joffrin, D. Mazon, R. Sabot, and A. Sirinelli

Association EURATOM-CEA sur la Fusion, CEA/DSM/DRFC, CEA Cadarache, 13108 Saint Paul lez Durance, France

(Received 19 July 2005; published 1 February 2006)

During fully noninductively driven discharges in the Tore Supra tokamak, large spontaneous oscillations of the core electron temperature ($\Delta T_e/T_e > 50\%$) have been observed for the first time. They occurred during the standard O regime, which is itself characterized by periodic oscillations of much smaller amplitude. The "giant" oscillations appear to involve distinct mechanisms with respect to the O regime and provide a spectacular example of the complex nonlinear interactions between energy confinement, noninductive current sources, and MHD that may occur in a tokamak plasma during steady-state operation.

DOI: 10.1103/PhysRevLett.96.045004 PACS numbers: 52.55.Fa, 52.25.Fi, 52.35.Mw

A critical requirement on the route towards a magnetic fusion tokamak reactor is to increase the plasma discharge duration in order to minimize mechanical stress due to thermal cycling on the in-vessel materials. One possible solution to this problem is to achieve a steady-state plasma that would provide a constant and continuous energy production. For a tokamak, steady-state operation requires the driving of all the toroidal current by noninductive means, i.e., a combination of the self-generated bootstrap current and external sources. The interest for steady-state operation has increased during the past years and has opened a new range of physics issues. While the physics of the Ohmic discharges are rather constrained by resistive current diffusion, complex nonlinear interactions between the main plasma quantities (e.g., current, temperature, etc.) may occur in the case of dominant noninductive current drive. Indeed, the characteristics of the noninductively driven current are in general quite sensitive to electron temperature and density profiles and simultaneously the shape of the current profile may also affect the energy confinement. Such strong coupling mechanisms are at the origin of the steady electron temperature oscillations observed in steady-state discharges on Tore Supra (O regime) [1,2]. Various relaxation phenomena have been reported in other tokamaks [3,4] and stellarators [5–7], which are also characteristic of self-organizing mechanisms occurring in the absence of an Ohmic electric field. This kind of physics is expected to play an increasing role as tokamak scenarios progress towards steady-state operation. Of particular interest are self-organizing mechanisms that induce enhanced confinement and sustain it steadily. The steady electron temperature oscillations observed on Tore Supra belong to this issue, being ascribed to an incomplete transition towards an internal transport barrier (ITB). More recent experiments on Tore Supra 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 Letter reports on the first observation of this new plasma behavior, which involves distinct mechanisms with respect to the O regime.

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 with limiter). 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 at the plasma boundary). The LH launched spectrum has its main peak at parallel refractive index $n_{\parallel} = 1.8$, 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 $Z_{\mathrm{eff}} \approx 2.3$. The key diagnostic for the present study is a 32-channel superheterodyne 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) [8]. The frequency range 102–110 GHz is weakly affected ($\leq 15\%$) and the range 92–102 GHz is not affected by superthermal emission (in toroidal flux coordinate, respectively, $\rho = 0.2$ high field side to 0.05 low field side, and $\rho = 0.05$ to 0.4 low field side). This results in a slight asymmetry in the core T_e profiles. The dynamics of the fast electrons driven by the LH waves, which are the main heating and current source in these discharges, are observed by means of fast electron bremsstrahlung (FEB) tomography [9].

Giant electron temperature oscillations of an amplitude of about 3 keV have been observed during a stationary phase of standard low amplitude oscillations (up to 0.7 keV, frequency ≈ 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 [1,2]. After 1–3 s of stationary O regime, a first giant oscillation occurs ($t = 21.8$ s on Fig. 1). Then other GOs occur intermittently, either alone or in groups of successive events. They always start with a decrease of T_e in the plasma core (normalized toroidal flux coordinate $\rho < 0.25$) of duration ≈ 0.1 s, from typically 5 to 3.5 keV [Fig. 1(c)]. Then the electron temperature increases up to 6.5 keV, this level being significantly higher than the average T_e during the standard oscillations $\langle T_e \rangle \approx 5$ keV. This large 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 $\sim$ a few ms) back to the minimum temperature level (~ 3.5 keV), followed by another giant increase to the maximum level.

In order to investigate the sensitivity of the GO phenomenon to the current profile, a scan of the launched LH $n_\parallel$ has been carried out (Fig. 2). At $n_\parallel = 1.8$, 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 $n_\parallel$ (at zero loop voltage, thus also slightly increasing the LH power), the giant oscillations become more frequent (Fig. 2) and occur quasicontinuously above $n_\parallel \approx 1.9$. They become almost periodic [Fig. 2(c)], with a frequency increasing continuously with $n_\parallel$ from 4 to 15 Hz. At high $n_\parallel$, the GOs end much more often with a fast T_e decrease than at $n_\parallel = 1.8$. The fast decrease is systematically followed by another giant T_e increase, leading to a series of successive GOs. The duration of the T_e increase phase also becomes shorter: 0.1 s at $n_\parallel = 2.1$ instead of 0.2 s at $n_\parallel = 1.8$. Within the high $n_\parallel$ GO regime, a quiet low T_e phase lasting about 2 s is even obtained, after which the GO restart [Fig. 2(d)]. As $n_\parallel$ increases, the FEB emission is

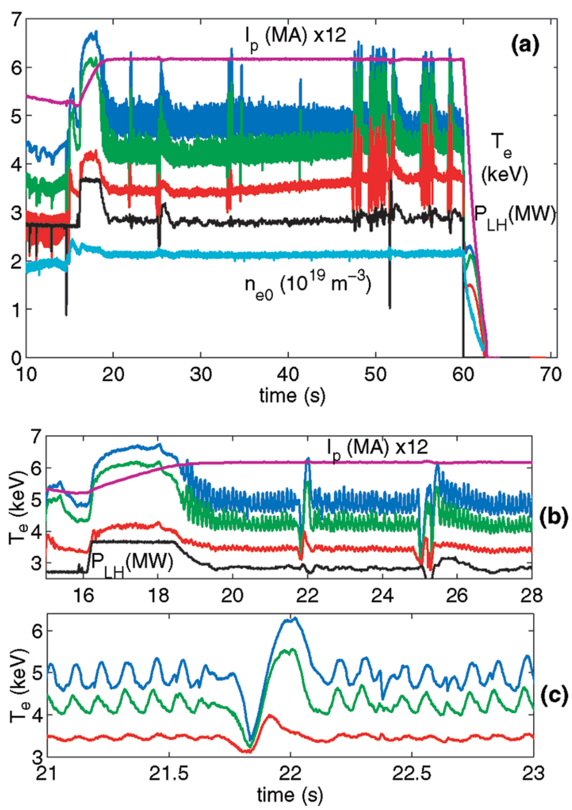

FIG. 1 (color). (a) Time traces of T_e (core ECE channels, blue: $\rho = 0$, green: $\rho = 0.1$, and red: $\rho = 0.2$), plasma current I_p (purple, multiplied by 12), LH power P_{LH} (black), and central electron density n_{e0} (light blue), shot #33983. In this discharge, the toroidal field decreases slowly from $B_t = 3.81$ to 3.76 T between $t = 34$ and $t = 55$ s, which may influence the repetition rate of the GOs. (b) Zoom on the start of the O regime for the same time traces. (c) Zoom on the first GO for the central ECE channels.

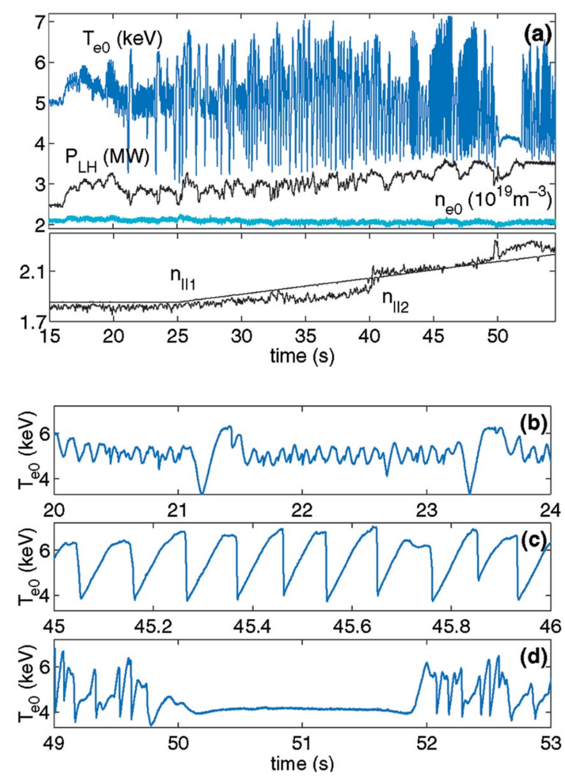

FIG. 2 (color). (a) Time traces of central electron temperature T_{e0} (blue), LH power P_{LH} (black, top), parallel refractive index of the two LH launchers $n_{\parallel 1}$ and $n_{\parallel 2}$ (black, bottom), and central electron density n_{e0} (light blue), shot #33986. (b)–(d) Zoom on various phases of the shot showing the different behavior of T_{e0} as $n_\parallel$ increases.

observed to decrease in the plasma core ($\rho < 0.4$), while increasing slightly outside $\rho = 0.4$, thus indicating a broadening of the LH power deposition. This leads to (i) a decrease of the electron heat source in the plasma core, in spite of the slight increase of the injected LH power, and (ii) changes in the current profile, since LHCD is driving 80% of the plasma current, which may affect the confinement properties of the discharge. Those two reasons may explain the slight decrease of the average central T_e observed after $t = 35$ s (Fig. 2). The sensitivity of the giant oscillation behavior to the LH power spectrum, and thus to the characteristics of the driven current, shows that the giant oscillation phenomenon is linked to the details of the current profile and can be controlled by external current drive actuators.

The dynamics of the T_e profile during a GO are shown in Fig. 3 ($n_\parallel = 1.8$ case). The corresponding interpretative electron heat diffusivities $\chi_e^{\rm eff}$ have been calculated taking into account the dynamics of the LH power deposition during the GO, estimated from the FEB measurements. The initial T_e decrease phase corresponds to a strong increase of $\chi_e^{\rm eff}$ inside $\rho = 0.2$, especially in the region $0.15 < \rho < 0.2$ [Fig. 3(b)]. Conversely, the subsequent T_e increase corresponds to a significant improvement of the confinement occurring first around $\rho = 0.22$ before propagating towards the center [Fig. 3(d)]. At the top of the GO ($t = 26.7$ s, $T_{e0} = 6.5$ keV), the $\chi_e^{\rm eff}$ profile features a clear drop inside $\rho = 0.25$, reaching even lower values around $\rho = 0.2$ than during the standard O regime ($t = 26.4$ s). This confinement improvement above the O regime level is characteristic of a fully developed ITB. This analysis shows that the GO phenomenon is due to a cyclic variation of the local heat transport properties inside $\rho = 0.25$.

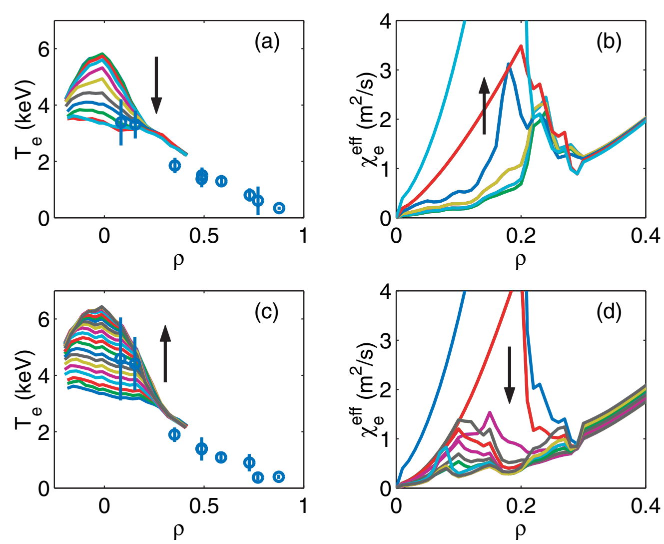

FIG. 3 (color). Dynamics of T_e and core $\chi_e^{\rm eff}$ profiles during a GO at $n_\parallel = 1.8$ of shot #33986. (a) and (b): slow decrease phase starting from the O regime level, $t = 26.4$ to 26.5 s; (c) and (d): increase phase up to the top of the GO, $t = 26.5$ to 26.7 s. On (a) and (c), solid lines correspond to the ECE signal, displayed every $\Delta t = 0.01$ s. Blue circles are Thomson scattering measurements, time averaged over 100 ms. On (a), the small T_e increase near $\rho = 0.25$ (small bump in the red profile at $t = 26.48$ s) shows the outward energy flow. On (b) and (d), the effective diffusivities are displayed every $\Delta t = 0.02$ s using the same color code as in the left column.

While tearing modes are usually not present during the standard O regime, they appear to be key players in the GO phenomenon. Indeed, the triggering of GOs during the O regime seems linked to MHD activity, since the growth of a large tearing mode on the $q = 2$ surface is observed systematically during the slow T_e decrease initiating all occurrences of a group of GOs (Fig. 4). Moreover, the fast T_e decrease (a few ms) which terminates several GOs has been identified as a multiresonant large scale tearing mode (double or possibly triple) localized on the $q = 2$ surface. This fast termination scheme, which gives birth systematically to another giant temperature increase, has the same phenomenology as the "$q = 2$ sawteeth" observed in reversed shear configuration in TFTR [10] and JET [11]. Nevertheless, the GO is not a pure MHD phenomenon: the giant T_e increase above the O regime level has to be related to non-MHD transport phenomena. Also, no MHD activity is detected on the regular ECE signals during the slow T_e decrease leading back to the standard O regime. This suggests that the final phase of a GO is driven by a distinct mechanism with respect to the initial phase.

The GO cycle thus appears as a succession of variations of the heat transport properties in the plasma core, some of them being due to tearing modes. The fact that the GOs are sensitive to the $n_\parallel$ of LH waves indicates that the q profile plays a key role in this phenomenon. According to current diffusion simulations, the q profile is slightly reversed in the plasma core owing to the hollow LH power deposition profile, with $q_{\rm min} \approx 1.8 \pm 0.2$ localized at $\rho \approx 0.22$. The mechanisms underlying the GO are likely linked to this particular shape of the q profile, which is prone to trigger

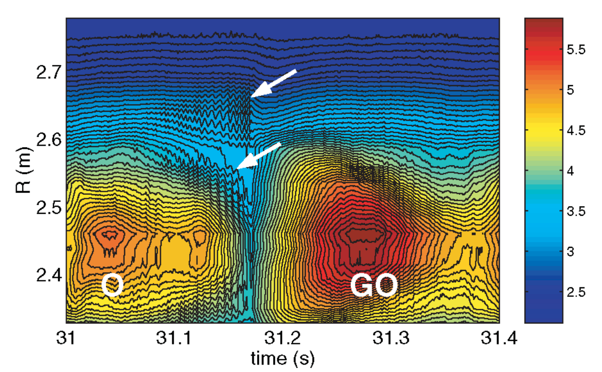

FIG. 4 (color). Color contour plot of T_e (keV) showing the growth of a large ($m = 2$, $n = 1$) tearing mode (between $t = 31.1$ and 31.15 s, magnetic islands around $R = 2.63$ and 2.55 m, indicated by white arrows) at the transition from the O regime to a GO event (shot #33982).

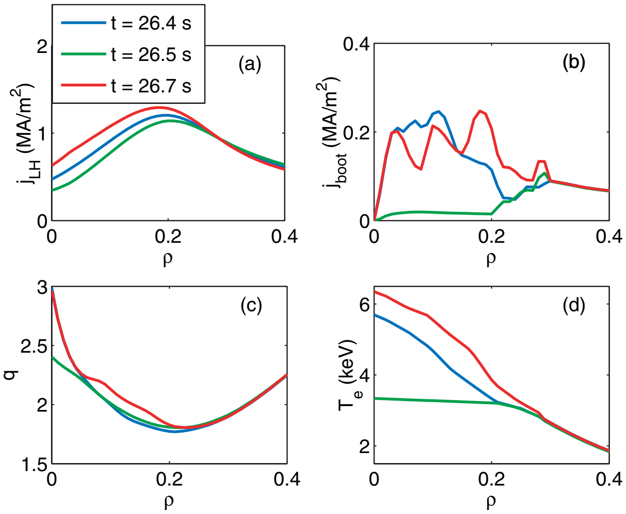

FIG. 5 (color). Dynamics of various profiles during a GO at $n_{\|} = 1.8$ of shot #33986 (same GO as in Fig. 3), at $t = 26.4$ s (blue, O regime just before the GO), 26.5 s (green, minimum T_e), and 26.7 s (red, top of the GO). (a) LH current density (deduced from Abel inversion of the FEB signal), (b) bootstrap current density, and (c) q profile deduced from current diffusion simulation, (d) electron temperature from ECE. Note that the q profiles should be taken with caution, owing to the presence of MHD activity during the various phases of the GO.

(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. At some point during the standard O regime, the oscillating q profile [1,2] meets the required shape that triggers the ($m = 2$, $n = 1$) tearing mode, which increases the heat transport level in the core. This is likely the starting point of the GO cycle. Then the subsequent giant T_e increase may be related to the dynamics of the noninductive current sources: following the initial slow T_e decrease 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. 5). This tends to drive a more hollow q profile [Fig. 5(c)], thus leading to a stronger ITB. This result of the current diffusion simulation is supported by fast ECE measurements that show the presence of a double tearing structure during the T_e increase phase, with a progressively decreasing distance between the two $q = 2$ surfaces. Thus the occurrence of a fully developed ITB during the GO might be a consequence of the initial T_e decrease, through the coupling between noninductive current sources and the T_e profile. Once formed, the ITB remains fragile owing to the possible triggering of a multiresonant large scale tearing mode and can be interrupted by fast T_e crashes. During the slow termination scheme of the GO, the noninductive current sources peak again due to the high core T_e (Fig. 5), leading back to the standard oscillation regime in $\sim$0.1 s. From the mathematical point of view, the whole GO cycle could be considered as the path taken by the coupled plasma variables to get back to the stable cycle (O regime) when the system is perturbed by some initial event (the initial slow T_e decrease driven by the $m = 2$, $n = 1$ tearing mode).

In summary, the new phenomenon of giant oscillations is characterized by the intermittent 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 ($\sim$50% of the average temperature level). These experimental observations illustrate the complexity of the nonlinear interactions between energy confinement, noninductive current sources, and MHD that may occur in a tokamak plasma at zero loop voltage. In a steady-state burning plasma, similar or even more complex nonlinearities are expected owing to the high fraction of bootstrap current and self-heating by fusion-driven alpha particles (which also can drive specific MHD phenomena such as toroidal Alfvén eigenmodes). Indeed, while being the dominant current and heat sources, those quantities strongly depend on the temperature profile. Therefore, large cyclic variations of the core temperature would have deep consequences on the whole plasma discharge, including its fusion reactivity. In addition to unveiling the physics of ITB and nonlinear plasma dynamics in steady state, both the standard and giant oscillation regimes may be used to develop control algorithms that might be relevant for future fusion devices.

[1] G. Giruzzi *et al.*, Phys. Rev. Lett. **91**, 135001 (2003).
[2] F. Imbeaux *et al.*, in *Proceedings of the 20th IAEA Fusion Energy Conference* (IAEA, Vilamoura, 2004), p. EX/P6-16.
[3] K. Hanada *et al.*, in *Proceedings of the 20th IAEA Fusion Energy Conference* (IAEA, Vilamoura, 2004), p. EX/P4-25.
[4] P. A. Politzer *et al.*, Nucl. Fusion **45**, 417 (2005).
[5] A. Fujisawa *et al.*, Phys. Rev. Lett. **81**, 2256 (1998).
[6] B. J. Peterson *et al.*, Nucl. Fusion **41**, 519 (2001).
[7] U. Stroth *et al.*, Phys. Rev. Lett. **86**, 5910 (2001).
[8] J.-L. Ségui *et al.*, Rev. Sci. Instrum. **76**, 123501 (2005).
[9] Y. Peysson and F. Imbeaux, Rev. Sci. Instrum. **70**, 3987 (1999).
[10] Z. Chang *et al.*, Phys. Rev. Lett. **77**, 3553 (1996).
[11] T. C. Hender *et al.*, Plasma Phys. Controlled Fusion **44**, 1143 (2002).