New Tokamak Plasma Regime with Stationary Temperature Oscillations

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During noninductively driven discharges in the Tore Supra tokamak, steady sinusoidal oscillations of the central electron temperature, lasting as long as 2 min, have been observed for the first time. Having no helical structure, they cannot be ascribed to any known MHD instability. The most plausible explanation of this new phenomenon is that the plasma current density and the electron temperature evolve as a nonlinearly coupled predator-prey system. This interpretation is supported by the numerical solution of coupled resistive current diffusion and heat transport equations.

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The present knowledge of tokamak plasma physics is mainly based on a very large set of discharges in which the plasma current necessary for the stability of the configuration is generated by an Ohmic electric field. A more limited database exists in which a substantial fraction of the plasma current is provided by the bootstrap effect [1], or by noninductive current drive [2]. In contrast, the database of tokamak plasma discharges in which the Ohmic electric field is negligible on the whole plasma cross section is still sparse. This type of experiment requires both a powerful noninductive current drive system and discharges lasting over several current diffusion times, which for large and hot tokamak plasmas can be of the order of tens of seconds. The physics of such discharges is expected to be substantially different from that of inductively driven plasmas, which are strongly constrained by resistive effects. In fact, the evolution of the main plasma quantities of this complex system (current, density, temperature, etc.) will be governed by different types of nonlinearities affecting, e.g., the absorption and current drive efficiency of the waves that sustain the noninductive current, the bootstrap mechanism, etc., as demonstrated by comprehensive computer simulations [3]. A systematic experimental investigation of plasma regimes at vanishing Ohmic field is now possible in the new configuration of the Tore Supra tokamak, equipped with a toroidal pumped limiter [4]. Several discharges of this type have been realized [5], showing, e.g., evidence of specific physics properties in the field of particle transport [6]. In this Letter, the discovery is reported of a new plasma regime, characterized by stationary sinusoidal oscillations of the electron temperature in the central region of the plasma, not related to MHD instabilities.

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 $B \approx 3.8$ T, circular cross section). Long pulse experiments have been performed in deuterium, at a plasma current $I_p = 0.52$–0.67 MA, central density $n_{e0} \approx 2.5 \times 10^{19}$ m^{-3}, central electron temperature $T_{e0} \approx 5$–6 keV, central ion temperature $T_{i0} \approx 1.3$ keV, and effective ion charge $Z_{\rm eff} \approx 2$. The current was generated by lower hybrid waves, launched by two couplers with power spectra peaked at $n_{\|} \approx 1.8$–2.0 and a total power of the order of $P_{\rm LH} \approx 3$MW. The key diagnostic for the present study is a 16-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 ~5 cm, time resolution: 1–4 ms) [7]. The range 92–110 GHz is not polluted by superthermal emission and therefore represents a precise measurement of the electron temperature profile in the central part of the plasma.

A typical observation of a new behavior of the ECE time traces is illustrated in Fig. 1. During a 3 min discharge, characterized by a stationary behavior of the plasma parameters and a loop voltage as low as 40 mV, the seven central channels of the ECE start to oscillate at $t = 51$ s [three of them are shown in Fig. 1(a)], without any change in other plasma parameters. The transition to the oscillating state, hereafter called O-regime, is shown by the enlarged view of Fig. 1(b): It is preceded by a slight broadening of the temperature profile, accompanied by irregular relaxations. Then, the central temperature jumps to a higher value and oscillations set in. The time sequence of this spontaneous temperature increase is typical of the transition to the hot core lower hybrid enhanced performance (LHEP) mode [8], routinely observed during lower hybrid current drive (LHCD) in Tore Supra [9–11]. In the LHEP mode, the electron transport is reduced in the central plasma region (normalized radius $\rho < 0.2$–0.3), owing to turbulence suppression associated with a negative magnetic shear. This time, instead, after the transition the temperature undergoes extremely regular, nearly sinusoidal oscillations [as shown by the further enlarged view of Fig. 1(c)], lasting 2 min, and surviving several perturbative events, such as impurity influxes and temporary loss of some LH power generators. These oscillations are not an instrumental effect of the ECE

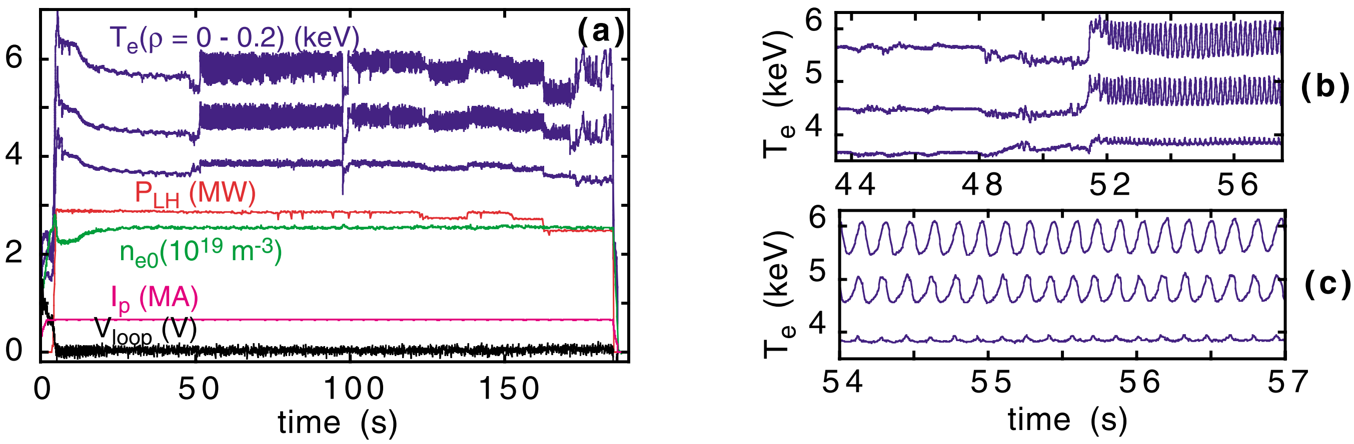

FIG. 1 (color online). Time evolution of various plasma quantities for Tore Supra discharge 30043. (a) From top to bottom: ECE channels No. 4, 6, and 7, LH power, central density, plasma current, and loop voltage. (b),(c) Enlarged views of the ECE channels.

diagnostic, since they are also observed on both soft and hard x-ray diagnostics, with the same frequency, and in phase with the ECE signals. The oscillating part δT_e may be peaked close to the magnetic axis at $R \approx 2.47$ m (as in discharge 30043 of Fig. 1), or it may be slightly hollow, as shown in Fig. 2, for discharge 30414. This figure shows that the oscillation has a purely radial structure, propagating from $\rho \approx 0.2$ to $\rho \approx 0$ at a velocity of the order of 4 m/s. Reconstruction of the perturbation in three dimensions [12] by means of soft x-ray tomography shows that the perturbation is poloidally symmetric. This absence of helicity, together with the very low frequencies involved (~ 10 Hz) and the fact that no correlation appears with the Mirnov coil signals, leads to the conclusion that this type of oscillation cannot be ascribed to any known MHD instability.

The O-regime has been observed in about 30 discharges of the 2002 campaign of Tore Supra, including the discharge with present record duration (4 min and 25 s) and injected energy (0.75 GJ). Many more discharges present phases with irregular cyclic behaviors of the electron temperature which could have the same physical origin, and that were already observed in the past [13]. Here the analysis is restricted to the most regular sinusoidal oscillations, observed for plasma current $0.5 < I_p < 0.7$ MA, and mostly for $V_{\mathrm{loop}} < 100$ mV. The maximum amplitude of the oscillations ΔT_e is plotted versus their frequency in Fig. 3, for all the O-regime discharges. The amplitude appears to decrease with frequency, although the data are affected by a large scattering, due to the variety of physical conditions in which the O-regime is observed (various LH $n_\parallel$ spectra, power, and density ramp-up or ramp-down phases, etc.). If a homogeneous set of discharges is chosen, characterized by the same value of $n_\parallel$ and no other heating power, the experimental points are much better aligned (full squares). The

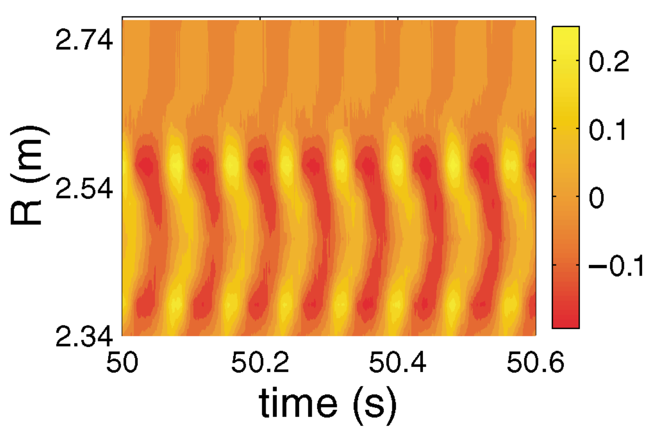

FIG. 2 (color). Color contour plots of the oscillating part of the ECE signal $\delta T_e = T_e - \langle T_e \rangle$ vs time and major radius coordinate, for discharge 30414.

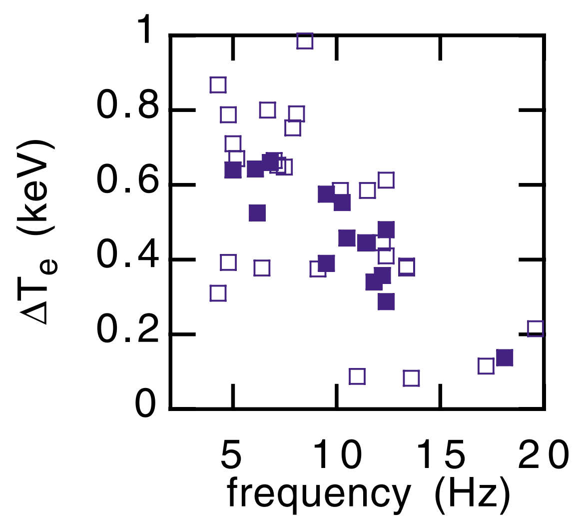

FIG. 3 (color online). Maximum amplitude of the oscillations vs their frequency for various phases of 29 discharges (open and full squares); selection of shots with LHCD only and $n_\parallel = 1.8$ (full squares).

oscillation amplitude is also found to decrease with the loop voltage and to increase with the radial width of the hard x-ray emission profile, which is related to the LH-driven current profile. All these clues, as well as the concomitance of the O-regime with LHEP transitions, point to a probable link with the shape of the current density profile j in the central part of the discharge. To check this hypothesis, localized perturbations of j between $\rho = 0$ and $\rho = 0.2$ have been applied to LHCD discharges at low density and loop voltage, using cocurrent and countercurrent electron cyclotron current drive (ECCD) at low power levels (0.4 MW, corresponding to a driven current $\sim$15 kA) and varying the toroidal injection angle by steps of 2° in order to scan the location of the current density perturbation. A transition to the O-regime has been obtained in two distinct conditions: cocurrent at $\rho \leq 0.1$ and countercurrent at $\rho \approx 0.2$, as shown in Figs. 4(a) and 4(b).

The whole of this experimental evidence leads to the plausible picture of the O-regime as an incomplete transition to an enhanced confinement regime of the LHEP type, with cyclic behavior of electron temperature and current density. The phenomena coupling j and T_e and which may be at the origin of these cycles are the following: (i) The turbulence responsible for heat transport is suppressed or reduced by effect of negative magnetic shear [14] and/or of the reduced density of rational safety factor q surfaces around a main rational value q_r [15]; thus, the electron heat diffusivity χ_e is a function of j through the magnetic shear and/or through the value of $q - q_r$; (ii) the LH-driven current density $j_{\rm LH}$ is an increasing function of both current and temperature, as experimentally observed [9,16]; (iii) both bootstrap current j_{bs} and resistivity η depend on T_e. Under these conditions, a possible mechanism for the coupled evolution of the j and T_e profiles is the following [3,13]:

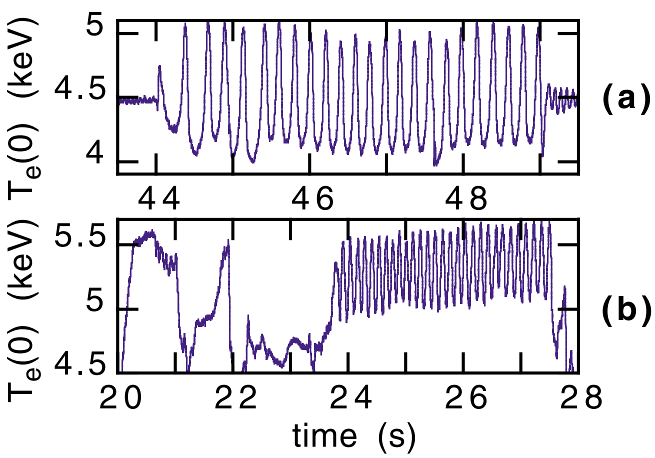

FIG. 4 (color online). Central ECE channel (No. 4) for two discharges with LHCD + ECCD. (a) Discharge 30559, co-ECCD at $\rho \leq 0.1$ between 44 and 49 s; (b) Discharge 30807, counter-ECCD at $\rho \approx 0.2$ between 20 and 28.2 s.

Whenever the magnetic shear becomes negative in the central part, the confinement is locally improved and T_e increases, then $j_{\rm LH}$ grows, the central q decreases, the shear turns positive again, T_e and $j_{\rm LH}$ decrease, and the cycle restarts. In the framework of theories involving the density of the rational q surfaces [17], a similar mechanism may be effective, the value of $q - q_r$ playing the role of the oscillator force. This physical picture can be cast into an oversimplified system of 0D equations, by reducing the resistive current diffusion operator $\nabla^2[\eta(j - j_{\rm LH} - j_{bs})]$ to a damping term $-\nu_j j(1 - \beta T_e)$ and by replacing the j-dependent temperature diffusion operator $\nabla \cdot [\chi_e(j)\nabla T_e]$ by a growth term $\nu_T T_e(1 - \alpha j)$ in order to mimic the transition towards an increased confinement state. This yields the following system (α and β being constants):

$$\frac{dT_e}{dt} = \nu_T T_e(1 - \alpha j), \qquad \frac{dj}{dt} = -\nu_j j(1 - \beta T_e). \quad (1)$$

These equations are known as the Lotka-Volterra equations [18,19]: They describe the coupled evolution of predator and prey populations living on the same territory, and notoriously admit periodic solutions. Many steadily oscillating phenomena in biology, chemistry, and physics are governed by equations of this kind [20].

Equations (1) have served as a guidance to understand the physical nature of the oscillations and the role of the nonlinearities. However, what remained to be proved was that the full transport equation system (including at least current and electron heat transport equations), applied to a parameter set as close as possible to experimentally measured data, had similar properties. To this end, the integrated modeling code CRONOS [21] has been used, which solves the 1D transport equations and self-consistently calculates the plasma equilibrium, bootstrap current, and the various heating and current source terms. Density and ion temperature profiles are taken from the measured values of discharge 30414. The LH-driven current density profile $j_{\rm LH}$ is assumed to be similar to the hard x-ray profile. Since the usual sophisticated wave and kinetic equations are not sufficiently stable numerically for describing such regular oscillations, an analytical nonlinear dependence of the local LHCD efficiency is introduced in the central region of the plasma ($\rho < 0.3$), i.e., $j_{\rm LH}(\rho) \propto j(\rho)T_e(\rho)$, as suggested by the predator-prey model. The electron temperature is predicted using a magnetic shear dependent diffusivity of the Bohm/gyro-Bohm type [22]. Oscillations start in the simulation when the initial LHCD current density source is slightly hollow, which is compatible with the uncertainties on its experimental determination. Simultaneous stationary oscillations of T_e and q have been obtained, as shown in Fig. 5. Note that the radial structure of T_e oscillations is similar to that displayed in Fig. 2, and that their amplitude, frequency, and propagation time are of the right

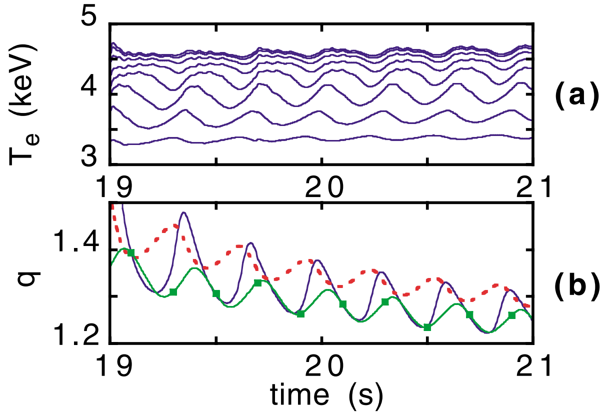

FIG. 5 (color online). Results of simulations by the CRONOS code. (a) T_e vs time at various radial positions $0 \leq \rho \leq 0.15$; (b) q vs time for $\rho = 0$ (solid line), $\rho = 0.04$ (dashed line), $\rho = 0.1$ (squares).

order of magnitude. The computed oscillations appear as a very localized region of negative shear and enhanced confinement propagating inwards, from the position of maximum time-averaged j_{LH} (absolute minimum of the q profile) towards the magnetic axis. Therefore, their time constants are related to the current diffusion time in the oscillating region ($\rho < 0.2$). The O-regime has also been simulated with a different transport model, i.e., assuming a region of very low transport around a given q value [23] and letting the core j_{LH} profile to oscillate as a whole. In this case, the oscillations are peaked at the plasma center. Depending on the width of the low transport q layer, the amplitude of the oscillations decreases with their frequency, as in the experiments.

In conclusion, experimental evidence and complex simulations converge to prove the existence of a plasma regime in which current density and electron temperature profiles behave as a predator-prey system, nonlinearly coupled by the effect of both wave-plasma interaction and turbulence suppression by particular shapes of the safety factor profile. With respect to the most common predator-prey systems observed in various science domains [20], this one has the distinctive feature of possessing a nonlinearity in a diffusive term. Oscillatory behavior is common in plasma physics, nevertheless regular sinusoidal oscillations have been observed only in conjunction with an extremely simple situation, i.e., the helical rotation of islands associated with MHD instabilities. The structure of the O-regime oscillations is not helical, thus the phenomenon is manifestly different. Cyclic pulsations of various plasma quantities which could be of a similar nature have been observed in stellarators [24–27] and tokamaks [28], but always as a succession of more or less regular crashes [29] rather than harmonic oscillations. The O-regime observed on Tore Supra, being linked to an incomplete transition towards an increased confinement regime in the plasma core, may provide a sharp test to various models describing the onset of internal transport barriers.

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