Non-linear electron temperature oscillations on Tore Supra: experimental observations and modelling by the CRONOS code

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Abstract. The recently discovered plasma regime characterised by stationary electron temperature oscillations [1,2], has been the object of further experimental investigation and extensive modelling by the integrated plasma simulation code CRONOS. The simulations have revealed the nature of the temperature oscillations, which originate from a non-linear coupling of temperature and current density profiles, of the predator-prey type. Various kinds of models are used inside CRONOS to produce oscillations which characteristics are close to the experimental observations. This phenomenon appears as a sharp test for transport theories, in particular those concerning the formation of internal transport barriers. Finally, recent experimental observations of the interplay between these stationary electron temperature oscillations and MHD activity are presented.

1. Introduction

This paper reports on experimental observations and modelling of regular and quasi-sinusoidal oscillations of the central electron temperature, in Tore Supra experiments. These oscillations appear spontaneously, sometimes after a long stationary period (of the order of 1 minute), in several non-inductive discharges sustained by Lower Hybrid Current Drive (LHCD), with a very low fraction of Ohmic current, or even at zero loop voltage [1,2]. They cannot be ascribed to any known MHD instability, since they do not present any helical structure and their frequency (3-20 Hertz) is very low compared to usual MHD phenomena. Therefore, they are interpreted as an interplay between current diffusion and electron heat transport, which occurs under specific conditions. In this paper, we describe various models that may reproduce such oscillations, and test them by numerical simulations carried out using the same plasma parameters as in the experiments. We show how the specific properties of this regime can be used to constrain electron heat transport and ITB formation models. Finally, we report also on recent experimental results about the co-existence of temperature oscillations and MHD activity.

2. Temperature oscillations with vanishing loop voltage

The typical scenario giving rise to the periodic electron temperature oscillations on Tore Supra (major radius R = 2.40 m, minor radius a = 0.72 m, magnetic field B ≈ 3.8 T, circular cross-section) uses the following plasma parameters : main gas deuterium, plasma current I_p = 0.5 – 0.7 MA (edge safety factor q_a = 9.7 – 6.9), central density $n_{e0} \approx 2.5 \times 10^{19}\ \mathrm{m}^{-3}$, central electron temperature $T_{e0} \approx 4\text{-}6\ \mathrm{keV}$, central ion temperature $T_{i0} \approx 1.3\ \mathrm{keV}$, effective ion charge $Z_{eff} \approx 2$. The current is 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 $P_{LH} \approx 3$ MW. The loop voltage can be either small (< 100 mV) or set exactly to zero by a feedback loop on the primary transformer. Figure 1 shows an example of the temperature oscillations obtained in this scenario, which last more than one minute. The analysis of the temperature profile measured by the ECE radiometer and soft X-ray tomography 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 (ρ denotes the normalised toroidal flux coordinate). The maximum amplitude of the oscillation may be located either on-axis (see Fig. 2, left), or off-axis (at $\rho \approx 0.2$, see Fig. 2, right). The absence of helicity, together with the low frequencies involved (~ 3-20 Hz) and the fact that no correlation appears with the Mirnov coil signals, lead to the conclusion that this type of oscillations cannot be ascribed to any known MHD instability.

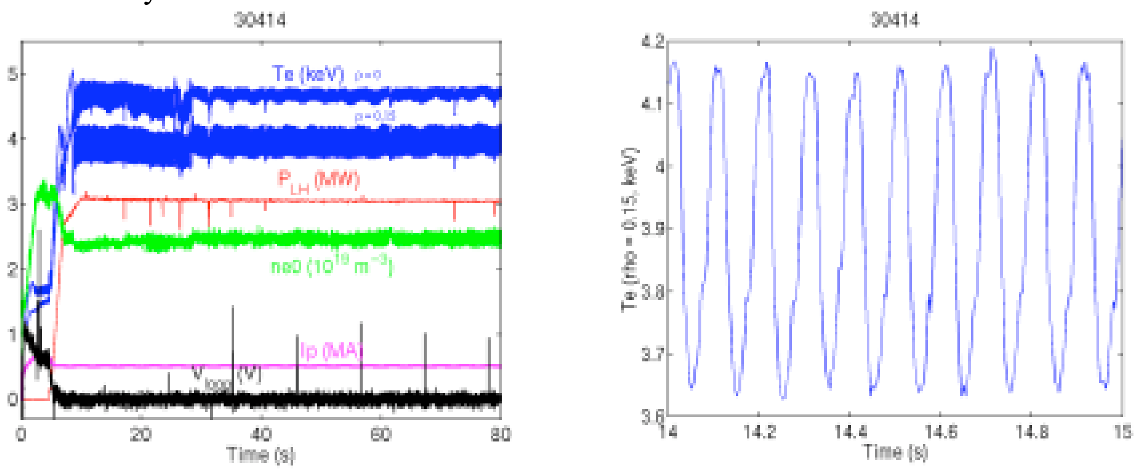


FIG. 1. Left : Time traces of the beginning of shot 30414 (shot duration is more than 260 s). Right : zoom on the Te oscillations (ρ = 0.15).

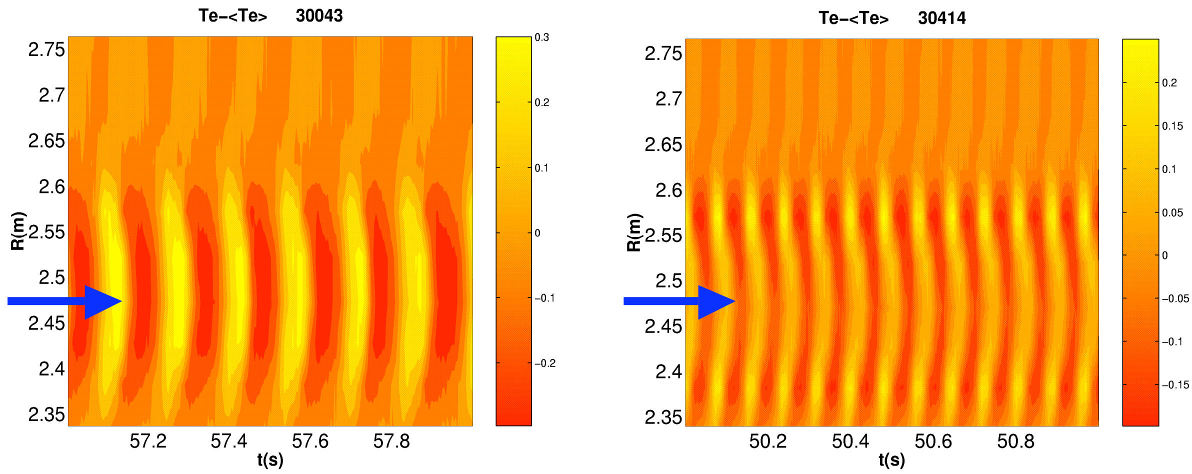


FIG. 2. Time traces of the amplitude of Te oscillations, from ECE radiometer. Left : TS shot 30043; Right : TS shot 30414. The blue arrow indicates the position of the magnetic axis.

Several observations suggest that this phenomenon depends on the shape of the plasma current profile : the oscillation amplitude is found to decrease with the loop voltage and to increase with the radial width of the hard X-ray emission profile related to the LH driven current profile. Moreover, comparison of nearly identical shots, with and without oscillations, shows, as the only significant difference, that in the case with oscillations the hard X-ray profile is flatter in the central part ($\rho < 0.2$). Also, oscillations can be triggered by tailoring the q-profile in the plasma core by means of co- or counter-Electron Cyclotron

Current Drive (ECCD). Finally, the onset of oscillations occurs usually just after a fast increase of the central electron temperature, typical of the transition to the hot core Lower Hybrid Enhanced Performance (LHEP) mode, routinely observed during LHCD in Tore Supra [3-5]. In the LHEP mode, the electron transport is reduced in the central plasma region (typically, $\rho < 0.2 - 0.3$), owing to turbulence suppression associated with a negative magnetic shear. All these observations suggest that the origin of the oscillation is linked to the interplay between the current profile and electron heat transport.

3. Models for the temperature oscillations

A coupling between electron heat transport and current profile may occur according to the following feedback process : (i) at the onset of a transport barrier, the local reduction of the electron heat diffusivity depends on the q-profile characteristics. (ii) the current sources, like LHCD, bootstrap, and inductive current, depend on the electron temperature profile. Assuming such dependences, the plasma transport equations can be turned into an oversimplified system of 0D equations by reducing the resistive current diffusion operator $\nabla^2[\eta(j - j_{LH} - j_{bs})]$ and the j-dependent temperature diffusion operator $\nabla\cdot[\chi_e(j)\nabla T_e]$ to damping/growth terms :

$$\begin{aligned} \frac{dT_e}{dt} &= \nu_T T_e(1-\alpha j) \\ \frac{dj}{dt} &= -\nu_j j(1-\beta T_e) \end{aligned} \tag{1}$$

In the equation describing the evolution of the electron temperature T_e, the growth term ν_T is positive in order to mimic the transition towards an increased confinement state, while the $-\alpha j$ damping term drives back to a low confinement state when the current profile ceases to be appropriate for stabilising the turbulence. In the second equation, the damping coefficient $-\nu_j$ corresponds to the current diffusion, while the positive cross-term βT_e represents the increase of local current sources with electron temperature. The system (1) is known as the Lotka-Volterra equations, which can for instance describe the coupled evolution of predator and prey populations living on the same territory, and notoriously admit periodic solutions [6-8]. Using this predator-prey picture as a guideline, we now investigate in more detail which kind of models can produce similar periodic solutions, in the framework of the full 1D transport equations for current and electron heat in a tokamak plasma. For this purpose, we use the CRONOS integrated modelling code [9], with plasma parameters corresponding to the shot #30414 (density profile, current drive conditions, ...).

3.1. Electron diffusivity dependence on current profile

Weak or negative magnetic shear is expected to stabilise the turbulence and to be at the origin of electron heat transport barriers, in particular in the hot core LHEP regime of Tore Supra [10,4]. Nevertheless, according to other theories, its effect is strongly enhanced in the vicinity of a low order rational q surface (where q is the safety factor), because of the low density of other rational q-surfaces around it [11].

In a first simulation, we test a model which mimics the reduction of heat transport around a rational q-surface : the diffusion coefficient, originally given by the Bohm-gyro-Bohm model [12], is divided by 10 around a given q value (which, in theory should be a low-order rational, but is not in the present simulation in order to avoid a tedious fine tuning of the simulation parameters, see Figure 3). The LH-driven current density and power deposition profiles are taken from the typical hard X-ray emission measured in Tore Supra steady-state discharges, i.e. slightly hollow with a maximum at $\rho = 0.2$. Outside $\rho = 0.3$, these profiles are kept constant throughout the simulation. Inside $\rho = 0.3$, the LH-driven current density j_{LH} is modulated proportionally to both the central temperature and current density ($j_{LH} \propto T_{e0} \cdot j_0$), and the LH power deposition p_{LH} to the central temperature only, in order to introduce a coupling mechanism in the same form as equations (1). Temperature oscillations are hence obtained, due to the following mechanism : as q goes up, the radial width of the good confinement zone increases, because the zero shear region lies below the enhanced confinement q sideband when the simulation starts. As a consequence, T_{e0} grows. Then, this increases j_{LH}, the current density also starts to increase and q decreases. Conversely, this reduces the width of the good confinement region, which causes T_{e0} to decrease, j_{LH} does the same and finally q will increase, starting the whole cycle again. In our simulation, we obtain periodic T_e oscillations with frequency 11 Hz and amplitude 130 eV, which is of the same order of magnitude as in the experiments (Fig. 3). However, there is no sign of propagation of the temperature modulation, since the profiles move as a whole inside $\rho = 0.3$. For the same reason, the magnetic shear is frozen. Therefore, the change in diffusivity is really due to the variation of the distance of the minimum q to a given (rational) value and reflects the topology aspects of the rational q theory fairly well [11]. Note also that this model provides periodic oscillations only if the minimum q is below the low order rational. This feature can be used as a test of the model relevance on experiment.

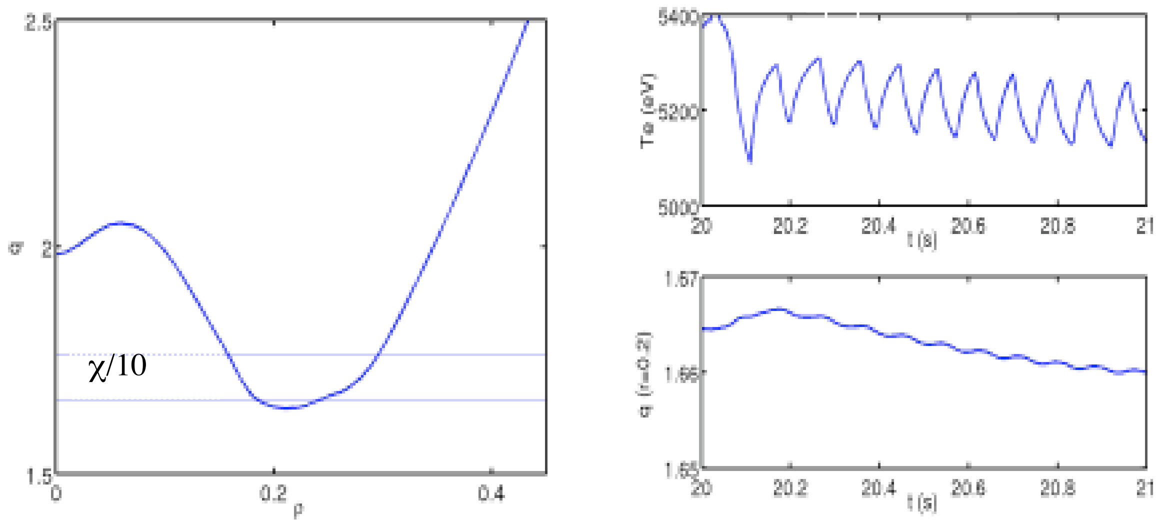


FIG. 3. Simulation involving the q band of enhanced confinement and $j_{LH} \propto T_{e0} \cdot j_0$. *Left : Zoom on the q-profile, the q band is indicated by the two horizontal lines. Right : Time traces of central* T_e *and q* ($\rho = 0.2$).

In a second simulation, only the effect of magnetic shear is considered, so the q band of enhanced confinement is removed. The Bohm-gyro-Bohm model includes a "shear function", which reduces transport when $s \le 0$ [4]. We use the original function of the model, though amplifying its effect by applying it also to the gyro-Bohm term. Then, in order to allow modulation of the magnetic shear, the LH current density profile varies now locally as $j_{LH}(\rho) \propto T_e(\rho).j(\rho)$, inside $\rho = 0.3$. An important condition for the oscillations to occur is to start from a weakly reversed q-profile. Indeed, the amplitude of the shear modulation is quite small ($\Delta q \sim 0.1$, $\Delta s \sim 0.3$), according to the simulation. Therefore, if the q-profile is either monotonic or too strongly reversed, the variations of j_{LH} are not sufficient to induce a periodic modulation of the strength and position of the barrier, and the system evolves to steady state. Note that this point is in agreement with the experimental observations, which suggest that the oscillations start just at the onset of a transport barrier, i.e. when the magnetic shear is neither monotonic nor deeply reversed. The periodic oscillations obtained with this model are shown on figure 4. This time, the magnetic shear is modulated, and the variations of T_e are due to a propagation of the minimum magnetic shear from $\rho = 0.1$ towards the centre. This propagation is very similar to the experimental observations (see Figure 2, right), moreover the maximum amplitude of the modulation is located slightly off-axis, as in some experimental cases (like shot #30414). The frequency of the T_e perturbation is 3.3 Hz, the maximum amplitude (at $\rho = 0.1$) is 300 eV. Therefore this model produces oscillations in fair agreement with the characteristics found in the experiment, having the same order of magnitude in amplitude and frequency, and very similar profile dynamics.

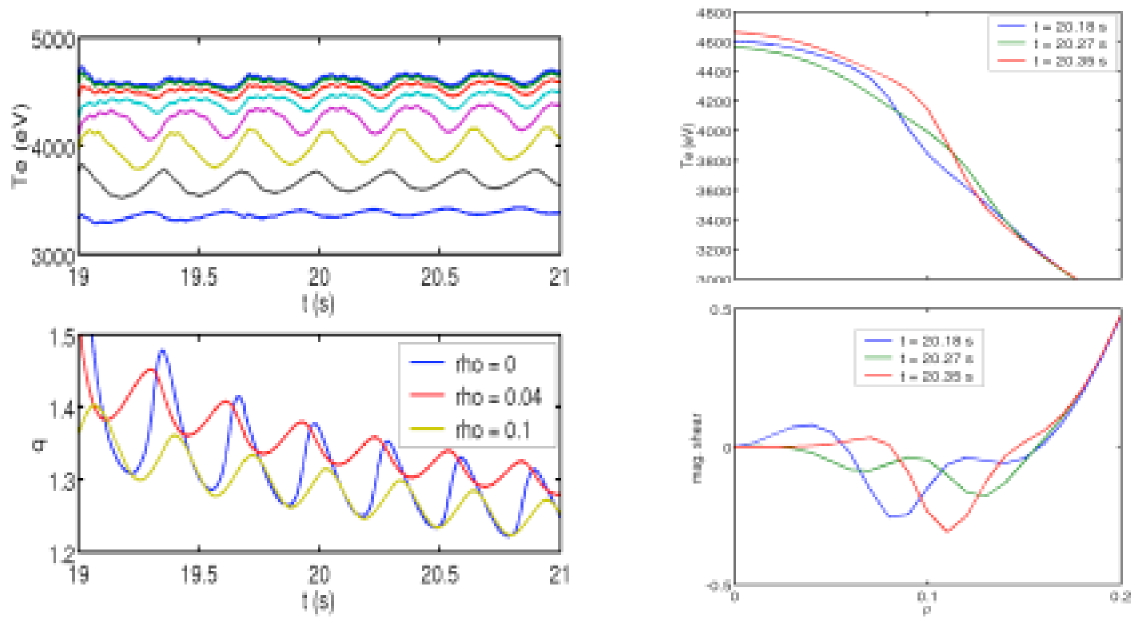


FIG. 4. Simulation involving magnetic shear and $j_{LH}(\rho) \propto T_e(\rho).j(\rho)$. Left : Time traces of T_e (ρ = 0 to ρ = 0.15) and q (ρ = 0, 0.04, 0.1). Right : Zoom on the T_e and magnetic shear profile (0 < ρ < 0.2) at various time slices.

3.2. LH current dependence on temperature and current density profile

Until now, we have used a direct proportionality of j_{LH} to j and T_e, since such an expression was suggested by similarity to the predator-prey equations. Such a trend can be qualitatively justified, since (i) the local LH absorption and current drive efficiency are expected to increase with the electron temperature [13,14], and (ii) the global LH current drive efficiency is found to increase with the total plasma current [3]. However, we have no rigorous way to derive a cross-term expression like $j_{LH}(\rho) \propto T_e(\rho).j(\rho)$. The proportionality between j_{LH} and j is particularly difficult to justify, since the plasma current profile influences the wave propagation in a complex way [15,16]. Therefore we have tried to find a mechanism based on LH Ray Tracing and Fokker-Planck simulations that would provide a predator-prey like feedback between electron temperature and plasma current.

The main current source being the LH-driven current, the $j_{LH} \propto T_e.j$ formula has the effect of providing an exponential growth of the current density when the electron temperature is high enough to dominate the losses due to current diffusion. This is indeed very similar to the role of the cross-term of equation (1) for the predator. Ray-Tracing coupled to Fokker-Planck calculations carried out using the DELPHINE code [15] with parameters close to the experimental conditions yields the following parametric dependence :

- for the low *Te* half-period of the oscillation : peaking the j profile results in a more peaked LH driven current (positive feedback of j_{LH} on j). Similarly, flattening the j profile leads also to flatter j_{LH} profile.
- with higher *Te* (ITB formed at $\rho = 0.25$) : flattening the j profile increases central deposition (negative feedback of j_{LH} on j).

If we now consider the peaking of the current profile as the predator, this behaviour is typically what we are looking for : depending on the prey level (T_e value), we have either exponential growth (positive j_{LH} - j feedback) or decay (negative j_{LH} - j feedback) of the predator. We have introduced this mechanism in the CRONOS simulations by assuming that the LH driven current and power deposition profiles inside $\rho = 0.3$ are gaussians with a maximum located at ρ_{LH} given by :

$$\begin{aligned} \rho_{LH} &= a + b\frac{j(\rho=0.2)}{j(\rho=0.1)}, \qquad T_e(\rho=0.15) < T_{e,crit} \\ \rho_{LH} &= c + d\frac{j(\rho=0.1)}{j(\rho=0.2)}, \qquad T_e(\rho=0.15) \geq T_{e,crit} \end{aligned} \tag{2}$$

The LH current density gaussian is then multiplied by the local T_e, which is justified by the expected increase with T_e of LH waves absorption and current drive efficiency. For the heat transport equation, we keep the model involving the magnetic shear. The role of the heat transport reduction here is to increase T_e in the very core as ρ_{LH} moves outwards, which triggers the crossing of $T_{e,crit}$ and then pushes ρ_{LH} back towards the centre. When T_e has reached its maximum in the centre, the negative j_{LH} - j feedback pulls ρ_{LH} back outwards, and the whole cycle can start again.

In the simulation shown fig. 5, $T_{e,crit}$ = 3560 eV, and the variables *a, b, c,* and *d* are chosen so that ρ_{LH} is continuous when T_e increases above $T_{e,crit}$. Unfortunately, it is not possible with the analytical expressions (2) to enforce at the same time continuity of ρ_{LH} when T_e drops back below $T_{e,crit}$. Quasi-periodic oscillations are obtained, with amplitude 800 eV and frequency 3.2 Hz. This is still of the same order of magnitude as in the experiments. The oscillations are clearly asymmetric, owing to the particular analytical formulas used. However, the physical mechanism in itself does not prevent a priori to get sinusoidal oscillations, if more complex expressions are used.

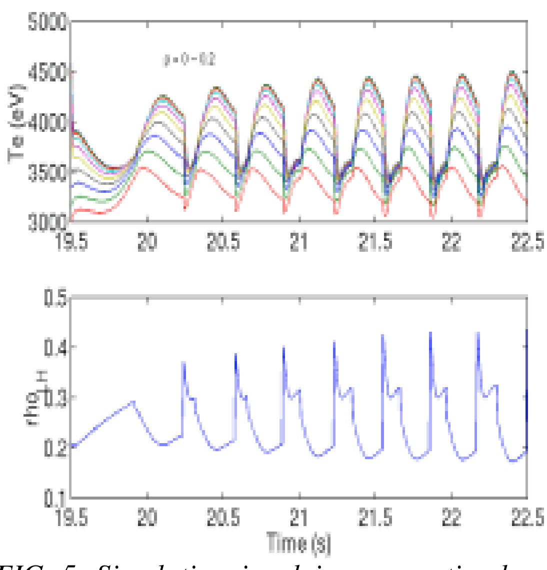
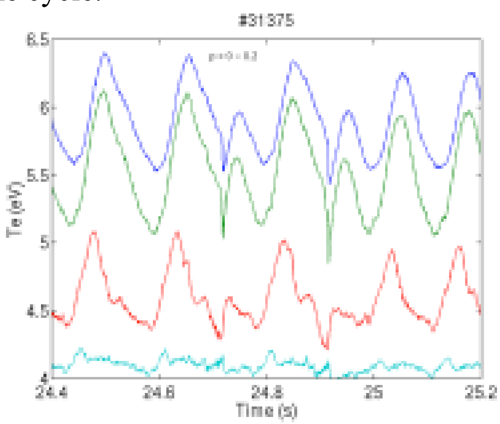


FIG. 5. Simulation involving magnetic shear and ρ_{LH} given by equations (2). .Top : Time traces of T_e (ρ = 0 to ρ = 0.2). Bottom : ρ_{LH}.

In order to have a fully consistent modelling of LH wave propagation and absorption, we have tried to directly couple DELPHINE calculations at high rate (every 5 ms) to the CRONOS transport simulation. This time-consuming simulation has been carried out for several seconds of plasma time. The main difficulty in this calculation is the high level of random numerical noise in the prediction of the LH power deposition, owing to the extreme sensitivity of ray-tracing calculations to the j and T_e profiles. Some oscillations-like structures appear at the beginning of the simulation on the T_e dynamics (amplitude ~ 500 eV, duration ~ 0.5 s), but they are not periodic. The T_e drops in those structures are due to periods during which the position of the j_{LH} and p_{LH} maximum is on average more off-axis (ρ_{LH} ~ 0.23), while the high T_e phase corresponds to ρ_{LH} ~ 0.18. Further investigations are needed to understand whether ray-tracing/Fokker-Planck codes contain the proper fine dependences that play a role in the temperature oscillations.

4. Co-existence of temperature oscillations and MHD

We report here recent experimental observations of MHD events that co-exist with the electron temperature oscillations of purely radial structure. This has been observed in the same kind of discharges, but this time rigorously zero loop voltage was imposed by a feedback loop on the transformer. In discharge #31375 (Fig. 6, left), a small MHD collapse (likely a m/n = 2/1 tearing mode) appears during the T_e decrease of the periodic cycle. It causes only a small perturbation to the cycle, and the electron temperature continues to oscillate. The crash occurs several times during the discharge, always in the same phase of the cycle. This phenomenon is an evidence of the fact that (i) the current profile is indeed evolving periodically, as the temperature, and (ii) its shape is different during the T_e increase and decrease phases. This latter observation supports models that involve the radial structure of the profiles, like the one based on magnetic shear described at the end of section 2. Indeed, in the simulation shown in Fig. 4, the shear is different in the T_e decrease and increase phases of the cycle.



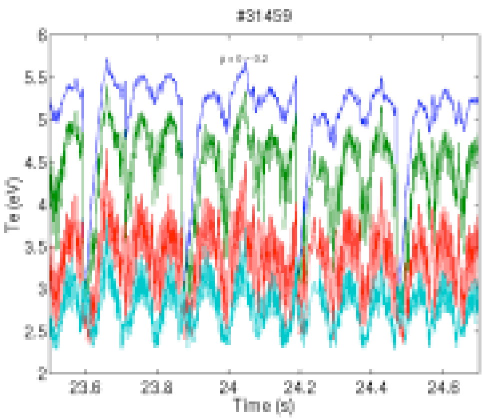


FIG. 6. Time traces of T_e (ρ = 0 to ρ = 0.2), measured by ECE radiometer. Left : Tore Supra shot #31375. Right : Tore Supra shot #31459.

In discharge #31459 (Fig. 6, right), a very strong interplay between MHD and oscillations is observed, and 3 characteristic frequencies can be distinguished : fast MHD crashes occur at high frequency (140 Hz) during stationary T_e oscillations (12 Hz). Then, every 3 to 4 oscillation cycles, there is a strong MHD crash, from which the whole dynamics still recovers ! Such a complex behaviour is at the moment understood only qualitatively. Nevertheless, it shows the important role of the details of the current profile in this phenomenon, as well as its robustness, once it is triggered. It is possible here that the large MHD crashes help to maintain a flat q-profile in the core, which has been identified as a critical feature for the triggering of oscillations in the modelling involving the magnetic shear effect.

5. Conclusions

This regime with stationary electron temperature oscillations is the result of a two-ways coupling between electron heat transport and current diffusion. It likely sets in when some turbulence stabilisation starts to develop near the plasma core, without reaching a stationary ITB state. Using dedicated experiments in the vicinity of this regime, it should be possible to determine which conditions on the current profile provide turbulence stabilisation. Therefore this regime provides a way for an experimental characterisation of ITB formation, as well as a sharp test to the transport models describing its underlying mechanisms.

In the present Tore Supra experiments, the onset of the T_e oscillations is likely linked to the almost full LH current drive, which introduces a strong dependence of the current diffusion on the temperature and q profiles. Nevertheless, this kind of dependence is not unique to LHCD : the bootstrap current for instance depends also on the pressure and q profiles. Therefore, it might be possible for similar T_e oscillations to exist in very different regimes, for instance in steady-state scenarios with high bootstrap fraction. Further work will be dedicated to the active real time control of this oscillation regime, using localised current drive.

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