High Power Lower Hybrid Current Drive Experiment in TORE SUPRA Tokamak

Y. Peysson and the Tore Supra team*

Association Euratom - CEA pour la Fusion Contrôlée
CEA Cadarache - 13108 S[t] Paul les Durance - France

e-mail contact of main author: yves.peysson@cea.fr

Abstract. A review of the Lower Hybrid (LH) current drive experiments carried out on the TORE SUPRA tokamak is presented. This work highlights the issues for an effective application of the LH wave at high power in reactor relevant conditions. Very promising performances have been obtained with the new launcher that is designed to couple up to 4 MW during 1000 s at a power density of 25 MWm^{-2}. The heat load on the guard limiter of the antenna and the fast electron acceleration in the near electric field of the grill mouth remain at a low level, while the mean reflection coefficient never exceeds 10%. The powerful diagnosis capabilities of the hard x-ray (HXR) fast electron bremsstrahlung tomography has led to significant progresses in the understanding of the LH wave dynamics. The role of the fastest electrons driven by the LH wave is clearly identified. From HXR measurements, an increase of the LH current drive efficiency with the plasma current is predicted and confirmed by a direct determination at zero loop voltage. LH power absorption is observed to be off-axis in almost all plasma conditions, and its radial width clearly depends of antenna phasing conditions. A correlation between the HXR profiles and the onset of an improved core confinement is identified in fully non-inductive discharges. This regime ascribed to some vanishing of the magnetic shear is found to be transient and usually ends when the minimum of the safety factor becomes very close to 2, leading to a large MHD activity. Experimental observations and numerical simulations suggest that LH power is absorbed in a few number of passes. However, besides toroidal mode coupling, additional mechanisms may likely contribute to a spectral broadening to the LH wave.

1. Introduction

Current profile shaping by non-inductive means is a crucial step towards the achievement of steady-state controlled thermonuclear fusion by magnetic confinement in a tokamak [1]. This challenging problem is addressed in TORE SUPRA by an extensive use of the Lower Hybrid (LH) wave, which is so far the most efficient method for this type of studies, even if some fundamental aspects of the wave dynamics in the plasma are still unclear [2]. In particular, experimental observations have not yet allowed to distinguish unambiguously between the various possible mechanisms for spectral broadening, leading to

* J. M. Ané, T. Aniel, G. Antar, J. F. Artaud, S. Balme, V. Basiuk, M. Basko, P. Bayetti, B. Beaumont, A. Becoulet, M. Becoulet, V. Bergeaud, G. Berger-By, M. Berroukeche, B. Bertrand, P. Bibet, J. M. Bottereau, F. Bottiglioni, C. Bourdelle, R. Bregeon, S. Bremond, R. Brugnetti, J. Bucalossi, Y. Buravand, C. E. Bush, A. Cambe, H. Capes, M. Chantant, P. Chappuis, E. Chatelier, M. Chatelier, X. Chen, L. Chiarazzo, D. Ciazynski, F.Clairet, L. Colas, J. J. Cordier, Y. Corre, L. Courtois, B. Couturier, P. Da Silva Rosa, C. Darbos, B. de Gentile, C. De Michelis, P. Decool, R. Dejarnac, C. Desgranges, P. Devynck, L. Doceul, H. Dougnac, J. L. Duchateau, R. Dumont, A. Durocher, A. Ekedahl, D. Elbeze, L. G. Eriksson, A. Escarguel, F. Escourbiac, J. L. Farjon, P. Fazilleau, C. Fenzi, M. Fois, D. Fraboulet, P. Froissard, L. Garampon, X. Garbet, L. Gargiulo, P. Garin, E. Gauthier, A. Geraud, F. Gervais, P. Ghendrih, T. Gianakon, R. Giannella, C. Gil, G. Giruzzi, P. Gomez, M. Goniche, G. Granata, V. Grandgirard, B. Gravil, C. Grisolia, A. Grosman, D. Guilhem, B. Guillerminet, R. Guirlet, J. Gunn, Y. He, R. Hemsworth, D. Henry, P. Hertout, G. T. Hoang, J. Hourtoule, J. How, T. Hutter, G. Huymans, F. Imbeaux, J. Jacquinot, R. Jimenez, E. Joffrin, J. Johner, J. Y. Journeaux, F. Kazarian, D. Lafon, J. Lasalle, F. Laugier, C. Laviron, F. Leroux, P. Libeyre, M. Lipa, X. Litaudon, T. Loarer, P. Lotte, A. Maas, P. Magaud, R. Magne, G. Martin, A. Martinez, L. Masse, R. Masset, P. Massmann, M. Mattioli, G. Minguella, F. Minot, J. H. Misguich, M. Missirlian, R. Mitteau, P. Monier-Garbet, D. Moreau, J. P. Morera, D. Moulin, M. Moustier, C. Munnier, F. Nguyen, S. Nicollet, M. Ottaviani, M. Pain, G. Pastor, B. Pégourié, Y. Petrov, Y. Peysson, P. Platz, C. Portafaix, M. Prou, A. Quéméneur, R. Reichle, J. D. Reuss, G. Rey, F. Rochard, B. Rothan, R. Sabot, F. Saint-Laurent, F. Samaille, A. Santagiustina, B. Saoutic, T. Schild, J. Schlosser, B. Schunke, J. Simoncini, A. Simonin, P. Spuig, F. Surle, M. Tena, J. M. Theis, R. Trainham, G. Tresset, A. Truc, E. Tsitrone, B. Turck, J. C. Vallet, D. van Houtte, V. Waller, J. Weisse, M. Zabiego, X. L. Zou, E. Zucchi, K. Zunino.

large uncertainties in the possibility of controlling the radial wave power deposition by external launch conditions. Simulations based on conventional toroidal ray-tracing coupled with two-dimensional relativistic Fokker-Planck and accurate plasma equilibrium reconstruction solvers have reached a very sophisticated level.However, their ability to reproduce numerous aspects of the observed phenomenology remains poor on the whole, especially concerning the location where the LH wave is absorbed [3]. In this context, the diagnosing capability of the fast electron population which is pulled out from the thermal bulk by resonant interaction with the LH wave has been considerably improved, by a tomography of the non-thermal bremsstrahlung emission on TORE SUPRA [4]. In addition to this instrumental effort, a new LH launcher has been installed in TORE SUPRA, which incorporates the latest technological developments for high power coupling in steady-state conditions [4,5]. Well diagnosed non-inductive discharges have been therefore carried out routinely in various plasma conditions, thus opening promising perspectives for a better understanding of the LH wave propagation and absorption in tokamak plasmas.

In this paper, selected results concerning important topics of the LH physics are addressed. In Section 2, the performance of the new LH antenna is summarised. The current drive efficiency is investigated in Section 3, with a particular emphasis on the role played by plasma equilibrium. Parametric dependence of the LH power absorption profile is addressed in Section 4, as well as the link between current profile shaping, plasma performance and the onset of MHD activity, this latter point being crucial for the successful achievement of high energy confinement steady-state discharges.

2. Towards steady state high power coupling

Designed to inject up to 4 MW of LH power during 1000 s [4,5], the new launcher has been successfully tested up to 3 MW during the last experimental campaign, which is close to the limits of its generator plant capability. As shown in Fig. 1, it is based on the multijunction concept, and the characteristics of the power spectrum is similar to that obtained with the previous type of antenna [5]. The directivity is 70% for $n_{//0}$ = 2.0, and by an appropriate

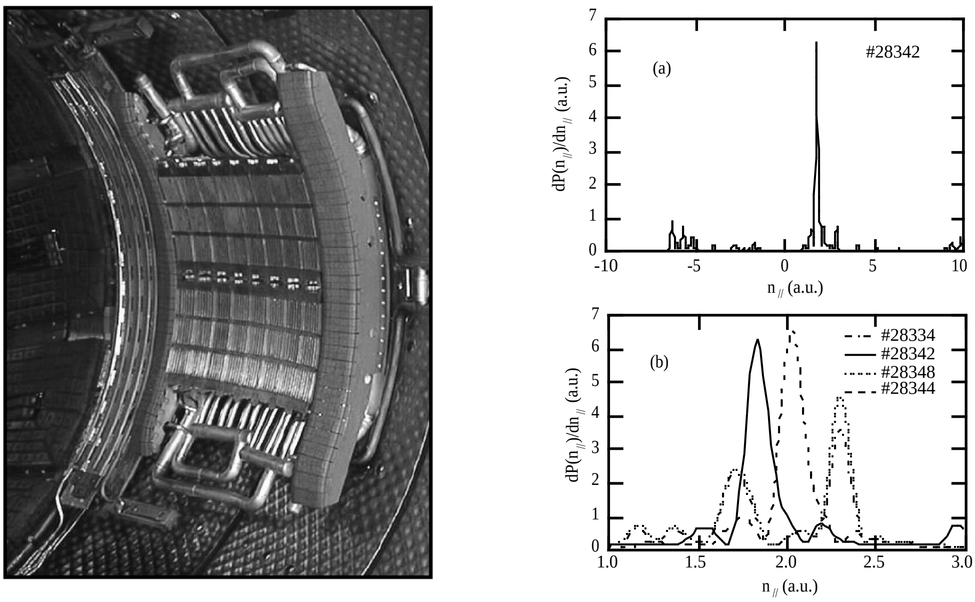

FIG. 1. (a) Picture of the new LH antenna installed in TORE SUPRA with its actively cooled lateral protections, (b, c) LH power spectra launched by the two antennas as calculated by the SWAN code [5], using measured waveguide phasing. All discharges correspond to full non-inductive current drive.

waveguide phasing, $n_{//0}$ can be varied from 1.7 to 2.3. The surface of the antenna has been increased so that power density never exceeds 25 MWm^{-2}, a limit which corresponds to reliable steady-state operation [6]. It is also protected by actively cooled guard limiters, designed for a convected flux of 10 MWm^{-2}, according to the level estimated for the next upgrade of TORE SUPRA [7]. As expected, the temperature of the antenna is considerably reduced with respect to that of the old antenna at similar power level on the two launchers, which confirms that operational margins have been strongly improved by the new design. The heat load that results from local acceleration of electrons in the near electric field of the new antenna is also reduced by a factor 2, as expected from theory [8]. Coupling properties have been tested in various plasma conditions, and the mean reflection coefficient never exceeds 10% [4]. It remains unchanged with the feeding phase, as a consequence of the passive waveguides inserted between the modules. Moreover, the mode converter is weakly affected by uneven poloidal loading in front of the antenna, a behaviour which is promising for extreme coupling conditions. Finally, at very low plasma densities, a poor coupling (15%) is observed on the outermost modules which results from an excessive distance between the guard limiter and the antenna. This problem will be rectified for the next campaigns.

3. Current drive efficiency and plasma equilibrium

The mean current drive efficiency η is deduced from a large database in deuterium and helium plasmas at B_t = 3.9 T, where the plasma current I_p varies from 0.4 to 1.2 MA, the central line-averaged density n_l from 1.3 to 4.5 10^{+19} m^{-3} and the LH power P_{LH} is ranging between 0.2 to 5 MW. From a fit of the relative drop of the loop voltage [9], η in quiescent conditions is estimated to be 0.65 10^{+19} $AW^{-1}m^{-2}$, in very good agreement with the mean level obtained at zero loop voltage. The waveguide phasing has a negligible effect on η, even if the ohmic current is fully replaced. MHD activity, in the form of a magnetic island extending over up to 20% of the plasma minore radius, leads to a reduction of the current drive efficiency of the same order at I_p = 0.8 MA, as shown in Fig. 2. Measurements of the HXR bremsstrahlung emission show that it results from the localised loss of the fastest electrons driven by the LH wave [4], around the q=2 surface, where the magnetic island develops (see Fig. 6, next section). From the scaling of the line-integrated HXR emission which is proportional to I_p and the ratio P_{LH}/n_l at all plasma radii, the current drive efficiency is expected to increase significantly at higher plasma current. Such a tendency is directly confirmed in discharges at zero loop voltage, as shown in Fig. 2. This result is ascribed to an enhanced downshift of $n_{//}$ as the LH wave propagates in the plasma during its first pass, leading to a resonant interaction with faster and less collisional electrons (Fig. 3). In

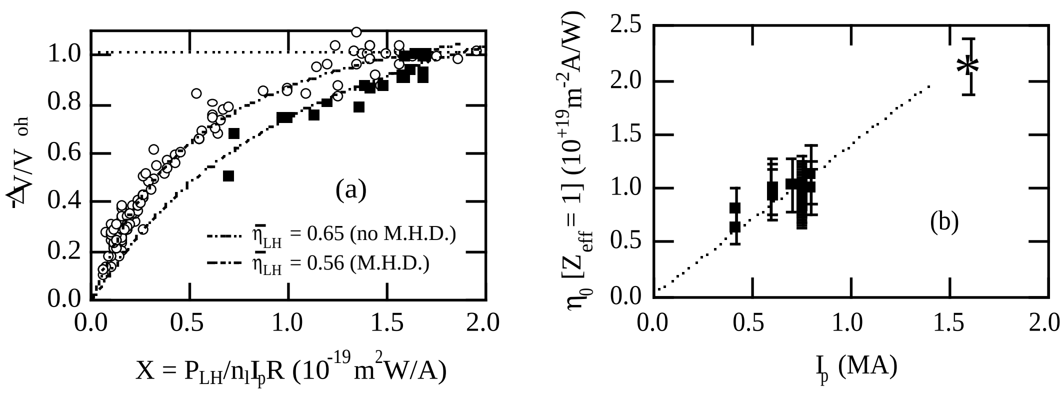

FIG. 2. (a) Relative drop of the loop voltage in LH discharges, (b) Zero loop voltage LH current drive efficiency, normalised to Z_{eff} = 1, vs. the plasma current I_p. The value at I_p = 1.5 MA is published in Ref. [10].

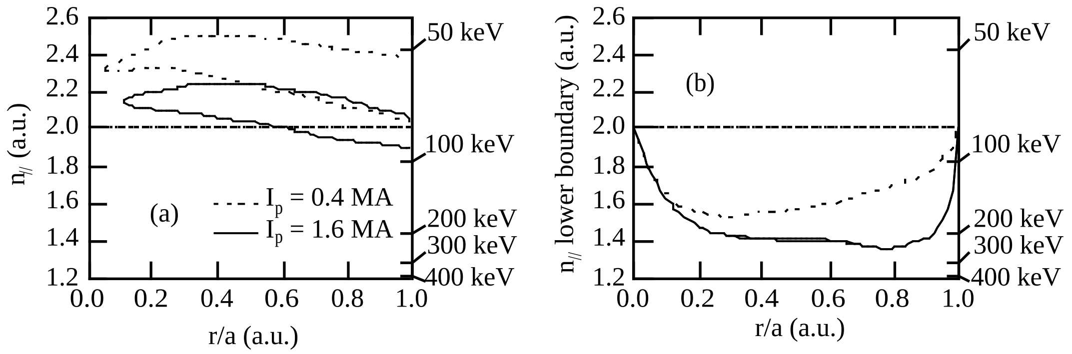

FIG. 3. (a) Variation of $n_{//}$ along the LH ray trajectory (first pass), and (b) low-$n_{//}$ propagation boundary of the LH wave for two different values of the plasma current ($n_{//0}$ = 2). All other plasma parameters are kept constant, and correspond to full current drive LHEP discharges. The right axis in both figures indicates parallel kinetic energies of the electrons which interact resonantly with the LH wave.

cylindrical geometry, the low-$n_{//}$ wave propagation domain boundary, defined by the condition $n_{//} \geq n_{//\min} \propto \dfrac{n_{//0}}{1+\left(\omega_e/\omega\right)/q}$, exhibits a similar behaviour as the plasma current is increased, as shown in Fig. 3., where q is the safety factor, ω_e the electron plasma frequency and ω the LH frequency [11]. If the upper limit of the quasilinear diffusion coefficient in the velocity space is assumed to be given by the resonance condition $v_{max} = c/n_{//min}$, it is possible to reproduce quantitatively by 2-D relativistic Fokker-Planck calculations the observed rise with I_p of the HXR emission at high energies, as well as the photon temperature which characterises the energy spectrum. Such a dependence may not be reproduced by a simple variation of T_e, according to the well known relation $n_{//} \geq 6.5/\sqrt{T_e}$, which corresponds to the lower boundary of the quasilinear diffusion domain, $v_{//min} = 3\text{-}4v_{th}$, where v_{th} is the thermal velocity. The increase of the current drive efficiency with I_p in fully non-inductive conditions, which has been already observed on JT-60U [12], emphasises the role played by the plasma equilibrium on the possibility to pull out a tail of fast electrons at very high energies by the LH wave. Such a result provides interesting perspectives for an effective improvement of the current drive efficiency at the level required for a fusion reactor, as well as guidelines for the achieving full current drive operation [4]. Nevertheless, natural limitations may be foreseen, especially related to the MHD activity which usually strongly affects fast electron dynamics. However, this detrimental effect may have only limited consequences in large devices if it remains localised in a narrow region of the plasma, as observed on TORE SUPRA. Finally, the picture that emerges from the experiment leads to conclude that the parametric scaling of the current drive efficiency with $\langle T_e \rangle$ is only an indirect consequence of the enhanced energy confinement at high I_p, and not a signature of a weak LH damping rate [4].

4. Current profile control and improved plasma performance

As shown in Fig. 4, significant modifications of the HXR emission profile are obtained by changing the waveguide phasing. When $n_{//0}$ = 1.8 for both antennas (Fig. 1), LH power absorption is peaked at $r/a \leq 0.2$ with a rather narrow profile width. In this case, full non-inductive current drive regime have been achieved in steady-state conditions, without onset of an MHD activity. With 4.7 MW of LH power, the ohmic current has been fully replaced during 9.5 s at I_p = 0.8 MA, with an efficiency of 0.85 $AW^{-1}m^{-2}$, as measured several years ago for a similar ratio P_{LH}/n_l, though at lower input power [6]. When the power-averaged $\langle n_{//} \rangle$ value is increased, taking into account contributions of both antennas for calculating the launch power spectrum, HXR emission profiles are only slightly shifted off-axis, but essentially become broader (Fig.4). There is no clear difference between compound and pure spectra corresponding to similar $<n_{//}>$, whatever the loop voltage level. This parametric dependence indicates that memory of initial conditions is not fully lost, in agreement with conventional toroidal ray-tracing and Fokker-Planck calculations, which show that full absorption of the LH wave takes place in less than 2-3 passes only [13]. However, simulations usually fail to describe the observed phenomenology, though some tendencies are qualitatively recovered, like the role played by I_p on LH power deposition [2,3,13,14]. Predicted profiles are too narrow, and the progressive off-axis shift of the maximum as a function of $<n_{//}>$ is not well reproduced. On the other hand, modifications of HXR profiles by changing $<n_{//}>$ at launch exhibit some interesting analogies with calculations that take into account of plasma fluctuations in the LH wave dynamics [15]. Detailed investigations will be carried out to clarify this crucial point, since in this case, extrapolation of the current profile control capabilities by the LH wave for a reactor may strongly differ from the usual predictions done using conventional toroidal ray-tracing calculations, where the spectral gap is bridged by toroidal mode coupling only. It is worth noting that the confidence in the determination of the LH power deposition is high, since measured profiles by the HXR tomography at different time slices are fully consistent with time evolutions of the loop-voltage, the internal inductance of the plasma, and also the onset of a transient hot-core regime followed systematically by a large MHD activity when current profile modifications lead to a broad vanishing magnetic shear region, with q_{min} close to 2, as shown in Figs. 4, 5 and 6 [4,16]. The fact that strongly hollow HXR profiles may be sustained in a steady-state manner is moreover a clear confirmation of weak fast electron transport [17], except in a narrow region where MHD activity is large, as shown in Fig. 6. This latter result demonstrates the robustness of the collisional relaxation in the fast electron dynamics over the radial transport mechanism. The LHEP regime [18], characterised by the spontaneous rise of T_{e0} one or two seconds after the LH power is switched on, has been routinely obtained in full current drive regime. Such discharges have been obtained with $<n_{//0}> \geq 1.9$, the magnetic shear being weak over a wide region. As shown in Fig. 5, HXR measurements provide, for the first time, a direct experimental evidence of an improved core confinement. At high energy, the HXR emission profile remains unchanged and hollow despite the strong rise of the core electron temperature, which is consistent with the peaking of the HXR emission in the lowest energy channel [4]. The local reduction in the electron transport is fully confirmed by the CRONOS code [19], which calculates self-consistently the radial diffusion of the electric field inside the plasma and the bifurcation of the electron transport as a consequence of the link

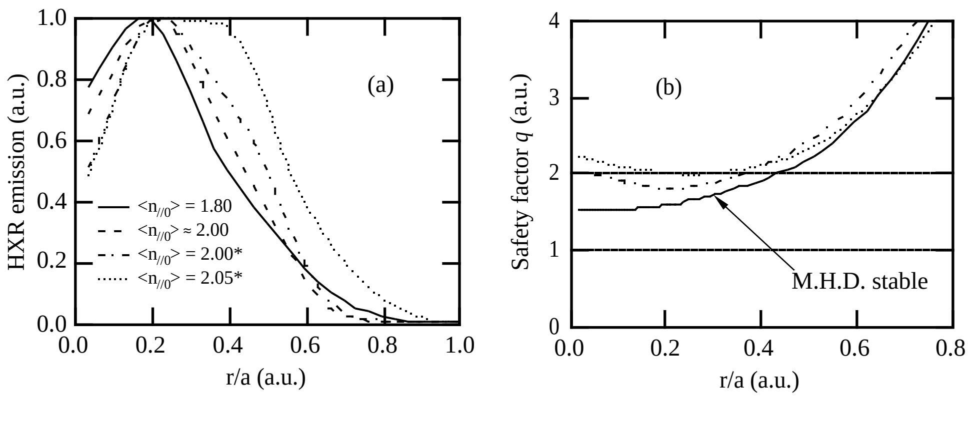

FIG. 4. (a) HXR emission in the photon energy interval 60-80 keV and (b) the corresponding safety factor profile q calculated by CRONOS code, for different launched power spectra indicated in Fig. 1 [19]. The asterisk indicates that LH power has been launched with different spectra by the two antennas.

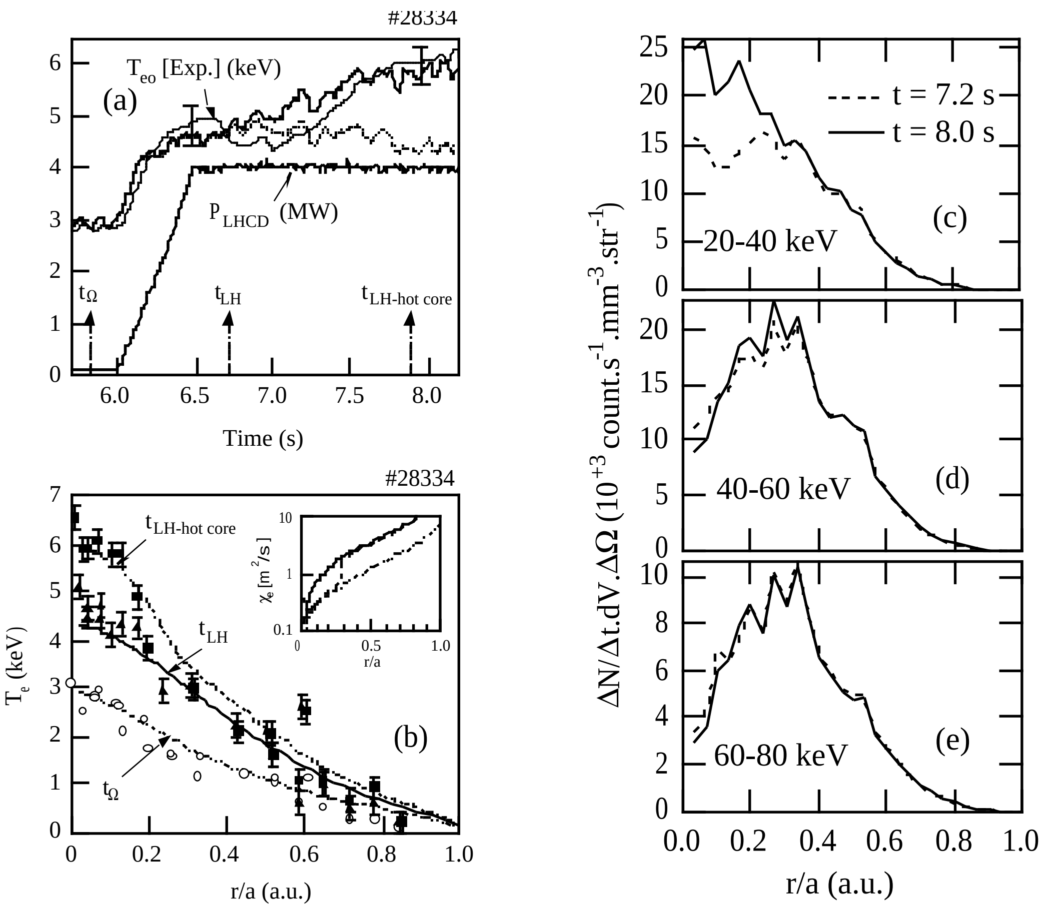

FIG. 5. (a) Time evolution of the LH power, the central electron temperature (thick line: exp., thin [dotted] line: simulations with [without] magnetic shear corrections in transport calculations). (b) Experimental and calculated electron temperature profiles at three different times, and corresponding heat conductivity χ_e profile (insert). In the CRONOS simulations [19], LH power absorption is given by HXR profiles in the photon energy range 60-80 keV. (c,d,e) HXR emission profiles before and during the hot-core LHEP regime, at different photon energies.

between the *q*-profile and the electron heat diffusivity [4,16]. The LH current source is directly determined at all time steps from experimental HXR profiles between 60 and 80 keV, by an appropriate normalisation to the LH power level. The reduction in the electron transport takes place in the region where the magnetic shear vanishes, in agreement with HXR and T_e profile observations (Fig. 5). Nevertheless, even if code predictions are quantitatively accurate, the role played by the magnetic shear and the concommittent vicinity of the q=2 surface is still unclear. Indeed, from turbulence growth rate calculations, it seems that the estimated flattening of the magnetic shear does not contribute significantly to a stabilisation of the modes which have a large radial structure, like trapped electron and ion modes, or circulating ion modes [20]. Moreover, ETG modes are expected to be fully stable. For all LHEP discharges, the calculated turbulence growth rate turns out to be weak, of the order of 10^{+4} s^{-1} which corresponds to stable plasma conditions. This may indicate that confinement improvement is marginal, as suggested in a similar regime in the T-10 tokamak [21]. In this case, the stabilising role played by the E×B shear due to enhanced electron ripple losses when LH power deposition is off-axis may be critical [22,23]. Improved performance observed during the 1999 experimental campaign systematically ended by dramatic losses in the core electron confinement, induced by some sudden MHD activity [3]. Both the growth rate of the unstable mode and its radial structure (initially global, then progressively reconnecting at the

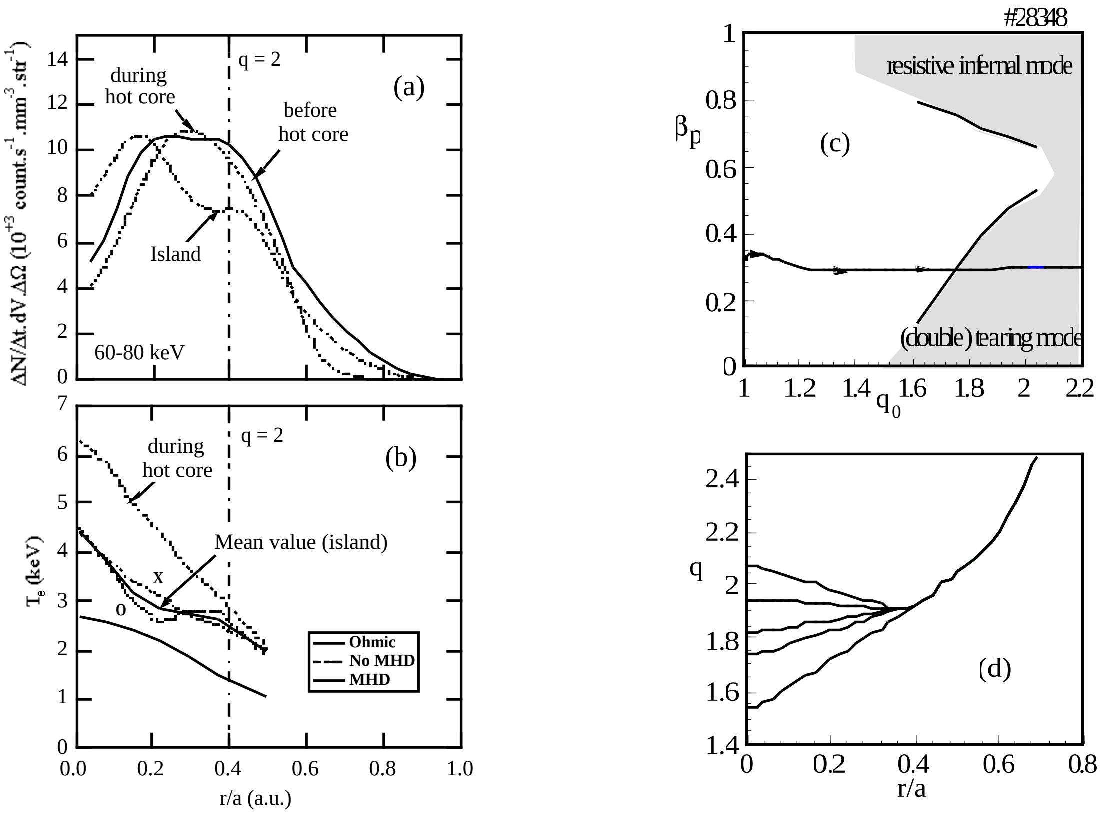

FIG. 6. (a) HXR emission and (b) electron temperature profile evolutions of a hot-core LHEP discharge, in the quescient and MHD phases. (c) MHD stability path of the corresponding discharge for different values of the central safety factor, as given in (d) and determined by the CASTOR code [24].

q=2 surface), as measured by the ECE diagnostic and calculated with the CASTOR code [24], point at the associated mode being the m/n=2/1 tearing mode, driven unstable by the evolution of the current profile. The observed features of this mode relate to the existence of an extended core region ($r/a < 0.4$) with weak shear and q_{min} slightly less than 2, as reconstructed from experimental data taken at the onset of MHD. In the absence of any dedicated feedback system (e.g. ECRH/ECCD) to eliminate the magnetic island, extending over up to 20% of the minor radius in the saturated regime, as visible from both ECE and HXR measurements (Fig. 6), performance recovery was not possible. CASTOR calculations show that the tearing mode limit could be by-passed by increasing pressure ($\beta_p < 0.35$ in the 1999 campaign), through combined LHCD/ICRH operation as planned in TORE SUPRA [7]. The MHD-stable window calculated by CASTOR, bounded by the 2/1 tearing mode at lower β and n=1 resistive infernal modes at higher β, can however dangerously narrow under unfavourable conditions (see Fig. 6). This points at strong requirements in terms of current-profile control capabilities in order to find a reliable path towards steady-state improved performance.

5. Conclusion

With a new launcher dedicated to high power long pulse operation and improved diagnosis capabilities provided by the HXR tomography, significant progress has been made towards the achievement of fully non-inductive current driven plasmas in TORE SUPRA. The important results concern, (i) the current drive efficiency which turns out to increase with the plasma current, (ii) the clear evidence that LH power absorption may be controlled to some extent by waveguide phasing, and (iii) the first direct experimental identification of the LHEP hot-core mode. The overall consistency between available data and the behaviour of the plasma gives strong confidence in the determination of the LH power absorption profile, and its consequences on the MHD stability. Several experimental details suggest that the contribution of plasma fluctuations to the LH wave dynamics in toroidal devices could be not negligible. Finally, the experience gained over the recent campaign, with appropriate diagnostics and modelling tools made available, suggests that accurate current-profile control will be necessary to insure MHD-safe operation in the generic scenarios where the fragile step of operating with $q_{min} \approx 2$ lies on the path to steady-state advanced discharges (as also recently experienced in AUG [25] and T-10 [21]). Interesting possibilities may be foreseen by using the electron cyclotron resonance heating and current drive system in conjuction with the LH wave, as done recently on FT-U [26].

Acknowledgements

The first author would like to thank V. Basiuk, P. Bibet, C. Bourdelle, L. Delpech, A. Ekedahl, V. Fuchs, X. Garbet, G. Huysmans, F. Imbeaux, X. Litaudon and M Zabiego for their clarifying discussions.

References

[1] TAYLOR, T., Plasma Phys. Controlled Fusion **39** (1997) B47.
[2] PEYSSON, Y., Proc. 13th Top. Conf. On Radio Frequency Power in Plasmas edited by S. Bernabei and F. Paoletti (Annapolis, USA) **485** (1999) 183.
[3] PEYSSON, Y. , THE TORE SUPRA TEAM, to be published in Plasma Phys. Control. Fusion.
[4] PEYSSON, Y., IMBEAUX, F., Rev. Sci. Instruments **70** (1999) 3987.
[5] BIBET, P., et al., 1998 Proc. 20th Symp. Fus. Technology (Marseille, France) Vol 1, p 339.
[6] PEYSSON, Y., et al., Proc. 16th Int. Conf. On Fusion Energy (Montréal, Canada) **IAEA-CN-64/E-4** (1996) 265.
[7] BECOULET, A., Proc. 13th Top. Conf. On Radio Frequency Power in Plasmas edited by S. Bernabei and F. Paoletti (Annapolis, USA) **485** (1999) 302.
[8] FUCHS, V., et al., Phys. Plasmas **3** (1996) 365.
[9] GIRUZZI, G., et al., Nucl. Fusion **37** (1997) 673.
[10] MOREAU, D., THE TORE SUPRA TEAM, Phys. Fluids **4** (1992) 2165.
[11] PAOLETTI, F., et al., Nucl. Fusion **34** (1994) 771.
[12] IKEDA, Y., et al. Proc. 15th Conf. On Plasma Phys. Controlled Fusion (Seville, Spain, 1995).
[13] IMBEAUX, F., EURATOM-CEA Report EUR-CEA-FC **1679** (1999).
[14] IMBEAUX, F., PEYSSON, Y., Phys. Rev. Letters **84** (2000) 2873.
[15] VAHALA, G., et al., Phys. Fluids **4** (1992) 4033.
[16] LITAUDON, X., et al., submitted to Plasma Phys. Control. Fusion.
[17] PEYSSON, Y., Plasma Phys. Controlled Fusion **35** (1993) B253.
[18] MOREAU, D., et al., Proc. 14th Int. Conf. On Fusion Energy (Würzburg, Germany, 1992) **IAEA-CN-60/A3-1** 649.
[19] LITAUDON, X., et al., Plasma Phys. Control. Fusion **36** (1996) 1603.
[20] BOURDELLE, C., et al., EURATOM-CEA Report EUR-CEA-FC **1703** (2000) 73.
[21] ALIKAEV, V. V., et al., Plasma Phys. Reports **26** (2000) 177.
[22] PEYSSON, Y., et al., Phys. Plasmas **3** (1996) 3668.
[23] WHITE, R. B., et al., EURATOM-CEA Report EUR-CEA-FC **1703** (2000) 173.
[24] KERNER W., et al., J. Comput. Phys.**142** (1998)271.
[25] GÜNTER, S., et al., Nucl. Fusion **40** (2000) 1541.
[26] PERICOLI-RIDOLFINI, V., et al., this conference.