

LOWER HYBRID WAVE COUPLING AND CURRENT DRIVE EXPERIMENTS ON TdeV

C. Côté, A. Côté, Y. Demers, P. Jacquet, D. Pinsonneault, N. Richard,
M. Shoucri, G. Abel, R. Décoste, V. Fuchs, J.-L. Lachambre, D. Lafrance,
G. Le Clair, G. W. Pacher, B. Quirion, I. P. Shkarofsky, and M. St-Onge
Centre canadien de fusion magnétique, Varennes, Qc, Canada J3X 1S1

1. INTRODUCTION

The *Tokamak de Varennes* has recently been upgraded to operate at higher B_T fields with an improved single-null divertor ($R=.83\text{m}$, $a=.21\text{m}$, $I_p<250\text{kA}$, $B_T=1.96\text{T}$). These upgrades combined with the addition of an ECRH system in late 1997 have made possible the study of LH antenna coupling and current drive in a broad range of operating regimes. The experiments described in the next two sections, done at relatively high densities ($\bar{n}_e=5.0\text{-}7.5\times 10^{19}\text{ m}^{-3}$, $I_p=220\text{kA}$), involve H-modes and wave coupling, while the ones described in the last two sections, done at lower densities ($\bar{n}_e=1.2\text{-}1.9\times 10^{19}\text{ m}^{-3}$, $I_p=160\text{kA}$), involve LHCD efficiency in the presence of EC waves and synergy effects. The TdeV LH system can launch up to 1 MW into the plasma at 3.7 GHz through a multijunction antenna [1]. The EC system can deliver 600 kW from the low-field side at 110 GHz (2X-mode) [2].

2. H-MODE WITH LOWER HYBRID HEATING

H-mode plasmas with type III ELMs were triggered and sustained in stationary state with LH heating only. Time traces are shown in Fig. 1. The H factor, defined as the ratio of the diamagnetic energies in H and L-mode, was 1.4 for the shot shown, which had the ion ∇B drift towards the active divertor. In this configuration, the LH driven current (I_{LH} is small at such high \bar{n}_e) is in the opposite direction to I_{OH} . The peak in the $N_{||}$ spectrum for these LH-generated H modes was set near the maximum of its range on TdeV, at 3.0, to help wave penetration. The waves still need a small $N_{||}$ upshift, to $N_{||}=3.5$, to access the plasma center at $n_e \sim 1\times 10^{20}\text{ m}^{-3}$.

Remarkably, the L-H transition power threshold at $\bar{n}_e=7\times 10^{19}\text{ m}^{-3}$ was found to be 350 kW (130 kW of LH and 220 kW of ohmic heating), well below the ITER DB2 H-mode Threshold Power Scaling [3]:

$P_{th}=0.65 n_e^{.93} B_T^{.86} R^{2.15}$, which gives 557 kW. It should be mentioned however that there is a strong edge density threshold (with a

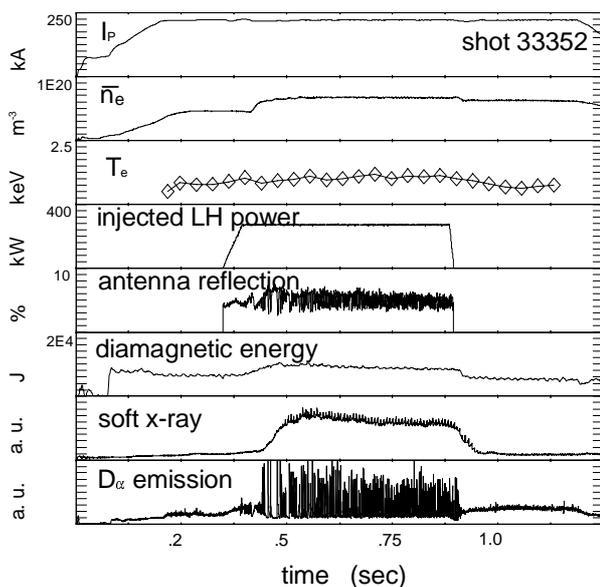


Fig. 1: Selected time traces for a H-mode shot produced with LH heating only.

corresponding line averaged $n_e \sim 5.5 \times 10^{19} \text{ m}^{-3}$) below which no L-H transition is observed with the available P_{LH} . Furthermore, generating stationary H-modes with LH at line averaged densities higher than $8 \times 10^{19} \text{ m}^{-3}$ is quite challenging because of the limited penetration and absorption of the waves at such high densities compounded by the increase in the power lost to edge plasma electrons accelerated at the antenna mouth. So far then, the range of densities for which a stationary H-mode was produced with LH only has been rather limited.

H-modes on TdeV were first obtained with ECRH. This was accomplished with similar power and density thresholds as described above but with a wider range of densities for which stationary H-modes could be generated. It was also found that for a given RF power, the L-H transition is controlled by the value of n_e near the separatrix rather than the line averaged n_e [4]. An edge interferometer chord is therefore used for the density feedback loop in order to produce stationary H-mode shots. This technique, together with the knowledge of a rather high density threshold for H-modes on TdeV, helped set the right conditions for obtaining an H-mode with LH heating only. Another essential element was good wall conditions resulting from regular boronization. Also, after He glow discharge cleaning, the helium level needed to be monitored closely as it prevented the L-H transition when too much of it had accumulated on the walls.

3. ANTENNA COUPLING IN L AND H-MODE PLASMAS

In general, LH antenna coupling deteriorates when going from L to H-mode in similar plasma conditions. The reflection coefficient at the grill, strongly modulated by the ELMs, can increase by a factor of two in H-mode plasmas because of the steepening of the density gradient near the separatrix and the resulting lower SOL density. This steepening can easily be seen in Fig. 2 which shows density profiles around the separatrix in L and H-mode obtained from reflectometry. The measurement for the H-mode case averages over the ELMs.

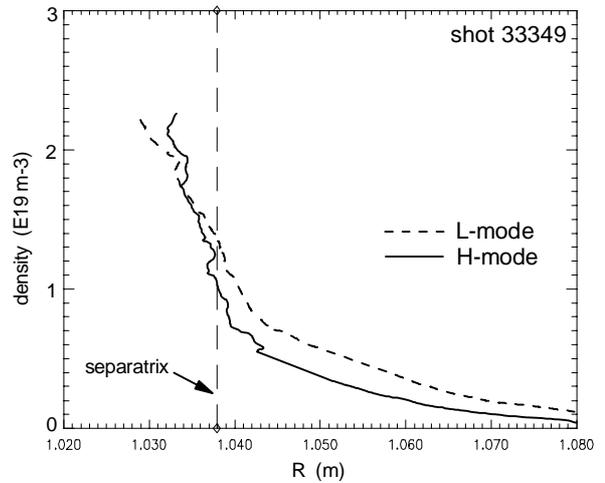


Fig. 2: Edge density radial profiles from reflectometry. Plasma parameters as in Fig. 1.

The degree to which the H-mode affects the reflection coefficient varies according to several factors: the distance d between the LH antenna and the separatrix, the direction of the ion ∇B drift, the ELM frequency and amplitude, the distribution of power between the LH and EC systems, the launched N_{\parallel} , etc. Fig. 3 shows as an example the modulation induced by the ELMs on the reflection coefficient for the shot introduced in Fig.1 (d here was 2.5 cm). Strong correlation is seen between the ELMs represented by the D_{α} emission, the antenna reflection coefficient, and a rough measure of the density near the antenna mouth as monitored by a Langmuir probe located on the antenna face and operating in the ion saturation current mode.

Good coupling at large antenna-separatrix separation is required for ITER-like machines

to minimize the scrape-off layer (SOL) heat flux reaching the antenna structure upon large excursion of the outer separatrix radius. In regards to H-mode plasmas, there is an additional incentive to increase the separation d : the fact that edge perturbations (acceleration of SOL electrons, ponderomotive effects, vortices, etc.) induced by high power LH waves launched near the separatrix can be detrimental to the H-mode and in fact has prevented TdeV so far from obtaining well controlled H-modes with LH heating above $P_{LH}=400$ kW.

When increasing d from 1 to 4 cm in high density L-mode plasmas, the reflection coefficient initially increases but then levels off at around 10% (this corresponds to an initial reflection coefficient of 30% in the small waveguides but this 30% is partially cancelled by the built-in 90° phasing between adjacent waveguides in each module). Antenna conditioning is needed to allow arc-free operation after moving the antenna. A series of L-mode shots was also made with the antenna 10 cm away from the separatrix, giving values close to 10% for the reflection coefficient. For these shots however, an influx of impurities was observed at high LH power, probably caused by electrons accelerated at the antenna mouth and hitting machine structures not conceived to handle such a power flux. This made subsequent attempts to study long distance antenna coupling in H-mode plasmas very difficult. A new moveable antenna guard limiter should help control this problem during the next campaign. Also, for large d coupling, ray-tracing calculations need to be done to see how many rays can move radially inside the separatrix before hitting the walls as they follow their trajectory around the torus.

4. LHCD EFFICIENCY VERSUS ELECTRON TEMPERATURE

A series of L-mode shots at $I_p=160$ kA and $\bar{n}_e=1.9 \times 10^{19} \text{ m}^{-3}$ was used to measure the LHCD efficiency, η_{LH} , versus $\langle T_e \rangle$. The electron temperature was changed using EC heating, with the waves launched perpendicularly toward the magnetic axis, giving central heating without any ECCD. The LHCD efficiency was obtained using the technique of Yoshioka, *et al* [5] to take into account the effect of the small residual electric field ($V_{loop} < 0.16$ V) and to obtain the equivalent efficiency at zero loop voltage. Changes in T_e and Z_{eff} were also taken into account. The results

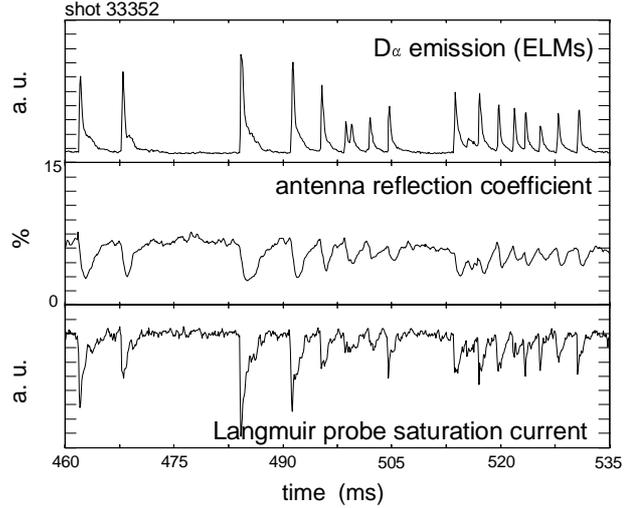


Fig. 3: Effects of ELMs on n_e outside the separatrix and on the LH antenna reflection coefficient.

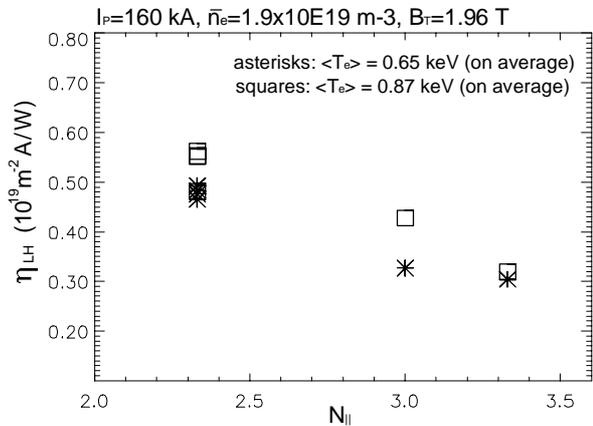


Fig. 4: Experimental data on LHCD efficiency vs N_{\parallel} for two different values of $\langle T_e \rangle$.

The results

are shown in Fig. 4 were η_{LH} is seen to increase by 20-30% in the $N_{||}$ range 2.3-3.0 when $\langle T_e \rangle$ goes from ~ 0.65 keV to ~ 0.87 keV. The improvement in η_{LH} comes from the reduced amount of $N_{||}$ upshift needed for absorption at higher $\langle T_e \rangle$ and, to a lesser degree, from the reduced plasma collisionality for higher $\langle T_e \rangle$ and lower n_e (if the absorption occurs at larger radius).

5. CURRENT DRIVE SYNERGY WITH COMBINED LH+EC OPERATION

To determine if the non-inductive current driven by a combination of LH+EC waves was higher than the sum of the currents driven by each system separately, a technique requiring a series of 4 shots was used. Those were all low density L-mode plasmas with $I_p=160$ kA. Two shots with EC waves only ($P_{EC}=500$ kW) at two values, $\phi=0^\circ$ and $\phi=20^\circ$, of the toroidal launch angle are first made to determine the current driven by the EC system only at $\phi=20^\circ$ ($\phi=0^\circ$ corresponds to a launch perpendicular to the magnetic axis which produces no EC current drive). These two shots are then repeated adding LH power; the shot with $\phi=0^\circ$ gives the current driven by the LH system only, and the shot with $\phi=20^\circ$ is the shot with possible LHCD+ECCD synergy. The LH $N_{||}$ was set at 2.3. The loop voltage, used to get I_{ohm} , was otherwise small enough to neglect the Yoshioka correction to η_{LH} for nonzero V_{loop} . Also, $\langle T_e \rangle$ was similar for all the shots, being determined mostly by the 500 kW of EC power. The ECCD efficiencies for shots without any LH ($\eta_{EC}=I_{EC} \bar{n}_e R / P_{EC}$) were of the order of $0.1 \times 10^{19} \text{ m}^{-2} \text{ A/W}$.

Two different conditions were tried: the first with the EC waves launched to reach the resonant surface near $z=0$ cm, and the second with the waves launched to reach this surface near $z=5$ cm. A synergy effect was observed in the first case ($z_{dep}=0$ cm) with the combined systems driving $\sim 8\%$ (11.5 kA) more current than the sum of the currents for each system used separately in CD mode (115 kA of I_{LH} and 25 kA of I_{EC}). For the $z_{dep}=5$ cm case, an anti-synergy effect was observed with the combined systems driving $\sim 10\%$ (16 kA) less current than the sum of the currents for the RF systems used separately (118 kA of I_{LH} and 40 kA of I_{EC}). Besides the deposition radius, the only difference between these cases was $\bar{n}_e = 1.8 \times 10^{19} \text{ m}^{-3}$ in the first case and $\bar{n}_e = 1.2 \times 10^{19} \text{ m}^{-3}$ in the second case. More experiments are planned and will shed some light on these intriguing preliminary results.

Simulations have shown that good synergy can be produced when combining LH and EC waves in certain regions of physical and parameter space [6]. More simulations involving the whole plasma volume are however needed for direct comparison with experiments.

REFERENCES

- [1] Y. Demers, *et al*, EPS Conf. on RF Heating, Brussels, July 1992, Vol. **16E**, p. 73 (1992).
- [2] R. Magne, *et al*, Proc. 19th SOFT, Lisbon, 16-20 Sept. 1996, p. 525 (1997).
- [3] J. A. Snipes, *et al*, Proc. 24th EPS Conference, Berchtesgaden, Vol. **21A**, p. 961 (1997).
- [4] G. W. Pacher, *et al*, 13th PSI Conference, San Diego (1998), to be publ. in J. Nucl. Mat.
- [5] K. Yoshioka, *et al*, Phys. Fluids **31**, 1224 (1988).
- [6] M. Shoucri, *et al*, Paper E-91, this conference.