

LONG DISTANCE COUPLING OF THE LOWER HYBRID WAVES ON TORE SUPRA

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1. Introduction

The Lower Hybrid (LH) couplers on reactor like tokamaks will have to be situated far away from the main plasma, to reduce the heat load they receive. On ITER for example, the LH couplers, as well as any component inside the vacuum vessel, will be situated at the first wall, 5 cm behind the poloidal limiter [1]. The total distance between the couplers and the separatrix, d_{cp} , will be ~ 15 cm during the burn phase. Extrapolating roughly from simulations of the plasma edge of ITER [1], it is easily seen that, at this radial position, the plasma density is likely to be less than the cut-off density ($n_{e,cut-off} \sim 3 \times 10^{17} \text{ m}^{-3}$ for 5 GHz) necessary for good coupling of the LH waves. The density in front of the grill, $n_{e,grill}$, will have to be increased locally, if we want to couple efficiently the LH waves. On Tore Supra, long distance shots have been achieved with good coupling for d_{cp} up to 14.8 cm [2]. This paper shows the detail of these experiments, and emphasises the importance of $n_{e,grill}$ on the coupling of the LH waves, bringing out the need to control actively the plasma in front of the grill.

2. Description of the experiments

Tore Supra ($R = 2.35$ m, $a = 0.75$ m) was used in the limiter configuration, with toroidal magnetic field $B_T = 2.1$ T and 4.0 T, plasma current $0.8 \text{ MA} < I_p < 1.2 \text{ MA}$, and line averaged plasma density $2.0 \times 10^{19} \text{ m}^{-3} < n_e < 3.8 \times 10^{19} \text{ m}^{-3}$. During LH coupling experiments on Tore Supra, d_{cp} is typically in the range of 2 cm to 5 cm. It represents a compromise between operational constraints and good coupling. For the long distance experiments, d_{cp} is larger than 5 cm, up to 15 cm. In contrast with other experiments [3], the long distance shots were made with high power densities (25 MW/m^2). The SOL plasma density profile, $n_{e,SOL}$, is measured by a reciprocating probe, at four different times during the shot. The probe is not connected magnetically to the LH grills during these experiments. The density in front of the grill, $n_{e,grill}$, behaves differently than $n_{e,SOL}$ during LH. It is measured with Langmuir probes imbedded in the LH grills. There are 3 probes on each launcher, situated on the midplane, at different toroidal locations. Their connection length with the outboard limiter is ~ 6 m. The

cut-off density is $\sim 2 \times 10^{17} \text{ m}^{-3}$ for a frequency of 3.7 GHz, and the Langmuir probe measurements confirm that RC increases rapidly when $n_{e,\text{grill}}$ gets lower than that value. Different scenarios were used to study the long distance coupling. d_{cp} was increased during the shot, either by moving the couplers, or by moving the plasma away from the couplers. In some cases, d_{cp} was fixed at a value $\geq 12 \text{ cm}$ during the whole shot. Good coupling was achieved in all three scenarios.

3. Experimental results and discussion

Figure 1 shows one example of a long distance shot, where d_{cp} was changed from 3 to 13 cm (Fig. 1-d), with total P_{LH} (Fig. 1-b) at 3 MW. The density at the grill (only one signal is shown for clarity, on Fig. 1-e) increases by a factor of 1.8 during LH. Its value remains higher than $n_{e,\text{cut-off}}$, as long as the total $P_{\text{LH}} > 700 \text{ kW}$. The mean reflection coefficient for each coupler, RC1 and RC2, (Fig. 1-c), remain low ($\leq 10\%$) during most of the shot. They show a gradual increase with d_{cp} , because of the diminution of $n_{e,\text{grill}}$. Towards the end of the shot, $n_{e,\text{grill}}$ decreases rapidly with P_{LH} , and RC shows a sharp increase as a result. The efficiency of current generation ($0.8 \times 10^{19} \text{ Am}^{-2}\text{W}^{-1}$ for this shot), has been calculated by taking into account possible changes in V_{loop} (Fig. 1-b shows that it does not change during LH in this case), Z_{eff} and the central plasma temperature. It does not change with d_{cp} , despite the changes in RC. This denotes a good performance of the multijunction antenna. Figure 2-a shows an example of the SOL plasma radial density profile, measured by the reciprocating probe, for $P_{\text{LH}} = 4 \text{ MW}$. $n_{e,\text{SOL}}$ increases slightly with LH, by a factor of ~ 1.17 , while the change in $n_{e,\text{grill}}$, at the lowest value of d_{cp} , is ~ 1.8 . The decay length ($\lambda_{n_{e,\text{SOL}}} = 3 \text{ cm}$) does not change when P_{LH} is applied, nor when $d_{\text{cp}} \dots$

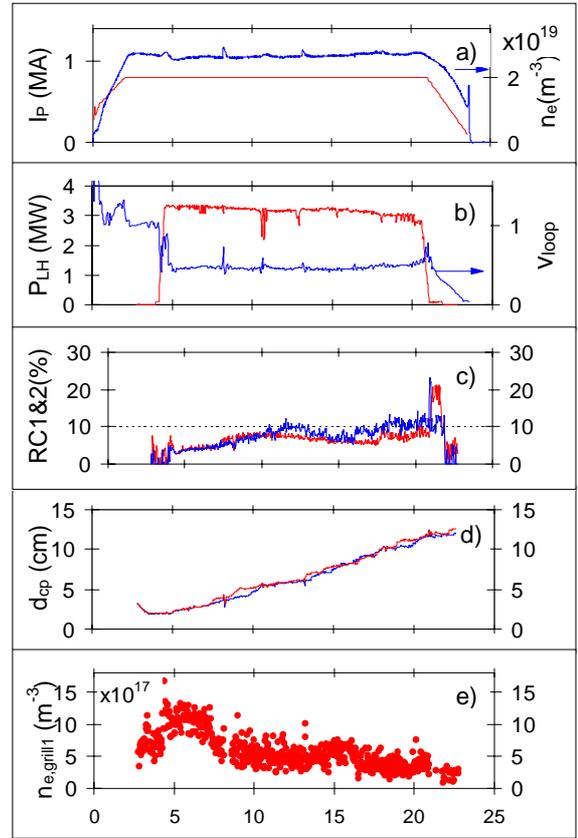


Figure 1. Time evolution of a long distance shot, a) plasma current and line averaged density, b) total LH power and v_{loop} , c) reflection coefficient of C1 and C2, d) distance to separatrix, e) $n_{e,\text{grill}}$.

It is important to note that, at distances from the separatrix larger than ~ 10 cm, $n_{e,SOL}$ is less than $n_{e,cut-off}$. For the same shot, the profile of $n_{e,grill}$ has been measured by the Langmuir probes on the coupler, as the couplers radial position was changed (Fig. 2-b). We see that, in comparison to the fit of the data of Fig. 2-a, the profile of $n_{e,grill}$ is flat. Moreover, the value of $n_{e,grill}$ remains higher than $n_{e,cut-off}$, even at $d_{cp} > 10$ cm, which explains the good RC ($\leq 9\%$) obtained during that shot. From these results we draw two conclusions. Firstly, good coupling at $d_{cp} > 10$ cm is made possible by an increase in density induced by P_{LH} . That increase is given by $\Delta n_{e,grill} = 1.5 \times 10^{17} \times P_{LH}$ [2] for the shots analysed. Secondly, the change in density is local, limited to the plasma in front of the grill. Those results are in agreement with the hypothesis that P_{LH} ionises the neutrals in front of the grill.

Before continuing, we want to point out that many shots have been obtained with good coupling, in the different scenarios. Figure 3 indicates that many long distance shots have been obtained with $RC \leq 10\%$, for d_{cp} up to 14.8 cm. However, it also shows that, at distances larger than 10 cm, it is not always possible to maintain good coupling, as shown by the $RC > 10\%$. A more detailed investigation of the shots shows that the deterioration in coupling is linked to a diminution of $n_{e,grill}$, to values lower $n_{e,cut-off}$. The efficiency for those shots was in the range of 0.6×10^{19} to $1.2 \times 10^{19} \text{ Am}^{-2}\text{W}^{-1}$. Again, for the shots with $RC \leq 10\%$, it does not change when d_{cp} increases. If we suppose that the augmentation in $n_{e,grill}$ is caused by the ionisation of neutrals in front of the grill, then the coupling should be related to the quantity of neutrals available. A qualitative indication of the neutral pressure is given by the intensity of the H_α signal from the edge of the plasma. Going back to Figure 3, we note that the RC are generally higher at large d_{cp} for the day identified as having the lower H_α signals. The H_α intensities for those shots are almost twice lower than for the other two days, for similar LH power levels. On Tore Supra, the sources of neutrals are gas injection, and recycling from the first walls and components. Tore Supra has a high recycling rate, which is an advantage for the long distance shots. However, the degradation of coupling sometimes seen indicates that

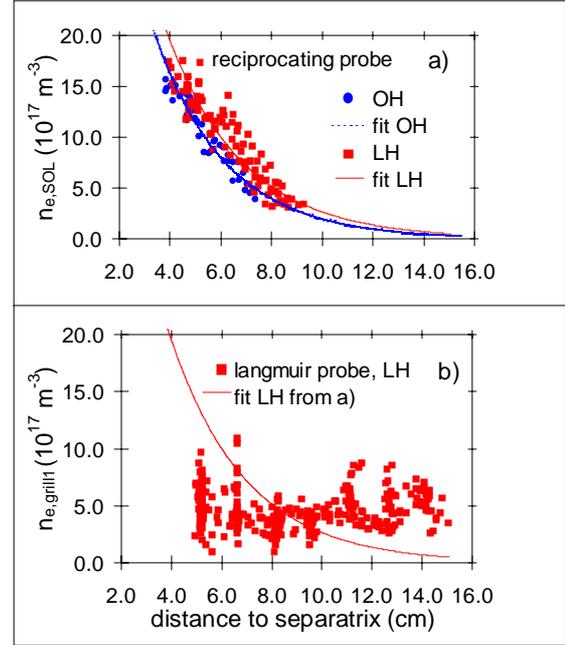


Figure 2. Density profile of the SOL plasma, as a function of the distance to the separatrix, a) measures from the reciprocating probe, at 3 times during the shot, with and without LH b) measures from a Langmuir probe on C1, with LH, compared to the fit of the LH data in a).

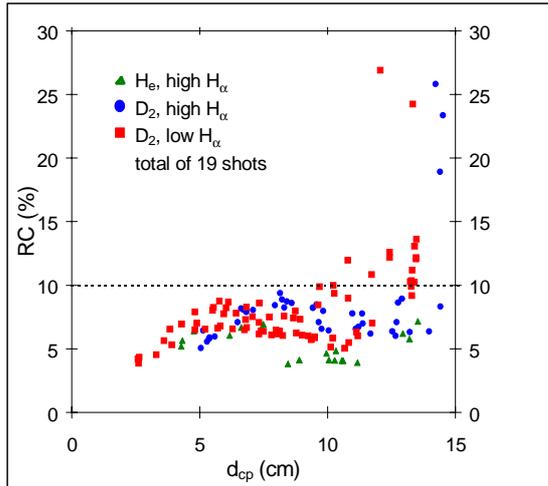


Figure 3. Mean reflection coefficients for 19 shots realised in different scenarios of long distance coupling. The symbols identify 3 different days of experiments. Low H_{α} means that the intensity of the H_{α} signals from the edge were lower than for the other two days.

an active control of $n_{e,grill}$ is needed. For some of the shots described here, gas puffs were done during LH. No change was seen on RC, but the location of the gas injection was not magnetically connected to the grills. Recent experiments on JET [4] show that gas injection from an injection system magnetically connected to the grills is more efficient.

4. Conclusion

Good coupling of the LH waves for distance to plasma up to 14.8 cm have been realised on Tore Supra, without loss of current generation efficiency. The coupling is made possible by a local increase of $n_{e,grill}$ induced by P_{LH} . However, the experiments indicate that an

active control of the density in front of the grill is needed. One of the coupler on Tore Supra has been recently equipped with a gas injection system, which allows to inject gas locally, in front of the grill. Coupling experiments will test its use as a mean to control $n_{e,grill}$ during LH. Finally, modelling of the interactions between the electric field of the coupler, and the SOL plasma and neutrals is needed to identify the predominant parameters conducting to neutrals ionisation.

References

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