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LHCD coupling during H-mode and ITB in JET plasmas

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Abstract. Good coupling of the LH power during the whole internal transport barrier (ITB) phase has been achieved in JET by fitting the plasma shape to the LH antenna shape and by injecting CD₄ gas from a pipe near to the LH grill. No adverse effect on the edge pedestal or on the ITB quality, or significant impurity influx is observed. The key is the low ionization potential of all the CD₄ dissociation chain, which is completed inside the SOL. Promising perspectives are open for injecting safely LHCD with more power during an ITB.

1. INTRODUCTION

Lower hybrid current drive (LHCD) preheating makes it easier to establish an internal transport barrier (ITB) in JET [1]. The LHCD effects (f_LH = 3.7 GHz) also during the ITB, were not investigated in the past, because of the poor LH coupling. Indeed the H-mode, which usually accompanies an ITB at JET, originates steep density profiles in the scrape-off layer (SOL). Very low plasma density are then found in front of the LH antenna, possibly smaller than the cut-off value =1.7x10¹⁷ m⁻³. The occurrence of strong interactions prevented from putting the antenna closer to the plasma, for the antenna safety and for the plasma performance, which is degraded by the consequent large impurity influx. In addition, the ELMs (edge localized modes) caused large unbalanced reflections, with frequent trips of the LH system and considerable reduction of the average coupled power [2]. These problems were faced with: 1) installing a real-time control of the LH launcher position under reliable safety limits, which is still in progress; 2) reviewing the protection system: averaging the reflected signals over ~20 µs has largely reduced the ELMs problem also for large or type I ELMs; 3) improving the plasma homogeneity along the poloidal profile of the LH antenna by fitting at best the plasma shape to the antenna shape; 4) injecting proper
gases from pipes near the LH launcher to actively control the local SOL characteristics. The latter two points are the objects of the present work.

2. EXPERIMENT

Standard ITB plasmas showed a large variation along the poloidal angle \( \theta \) of the gap between the plasma and the protection limiter, whose shape is identical to the LH antenna. This disuniformity has been reduced in an optimized plasma shape from 5 cm to less than 8 mm, while the X-point position is left unchanged for a good ITB mode. Consequently, the plasma-limiter equatorial distance has also been shortened by 1.5-2 cm, and brought to <2 cm during LH preheating, and to 3.5 cm during the high power phase (\( P_{\text{lo}} \) > 17 MW). The more regular poloidal pattern of the reflected power and the better coupling so obtained, no more limit the full exploitation of the whole LH antenna during ITBs. But small differences due to the not yet full optimization of the plasma shape and to the variation of the magnetic connection length with \( \theta \) still exist. Both radiation and impurity influx from the limiter or the antenna increase only negligibly during the LH pulse, even with the antenna placed only about 5 mm behind the limiter. Fig 1 shows the time traces of UV emission of FeXXIII and CIII for a shot when also CD4 is puffed.

The synthesis of previous results on improving the LH coupling by puffing \( \text{D}_2 \) from a pipe near to the grill [3] and on modifying the SOL properties by methane injection in L-mode [4], suggested to puff CD4 close to the LH antenna also in a ITB mode. The results are encouraging: good coupling is again achieved but with no unwanted effect on the quality of the H or ITB mode. Rather an interesting ELMs behavior is observed, as shown below. Accumulation of carbon on the walls during an experimental day is also negligible, nor is recognized the day after. CD4 has been puffed at rates from

![Figure 1](image1.png)  
**FIGURE 1.** CD4 puff in an H-mode. The third frame is the difference in the radiation losses between the central and a peripheral chord. The interaction plasma-LH antenna is negligible, despite proximity

![Figure 2](image2.png)  
**FIGURE 2.** Improvement of the reflection coefficient upon CD4 puffing, for the three grills of the LH antenna and for the total reflection coefficient.
FIGURE 3. No unwanted effect of CD₄ puffing on the quality of an H-mode. Rather it appears to control the ELM activity reducing their amplitude and increasing their frequency.

FIGURE 4. Two shots (Iₚ=2.3 MA, Bₜ=2.6 T), identical except for LHCD during ITB. In #51490 (LHCD), the crashes of Tₑ occurring with large ELMs, are recovered. The barrier is visible on Tₑ profiles during the whole main heating.

about 3 to 11×10²¹ el/s for longer than 4 sec. The optimum coupling is at ~8×10²¹ el/s with a ±30% of tolerance. Fig. 2 compares the time evolution of the LH coupling for a shot with CD₄ puff and one without it: the total reflectivity drops from about 10% to 5%, with major improvements on those grill rows already poorly coupled. The smaller signal noise is due not only to the less number of trips, but also to the stabilization operated by the modified SOL. Lowering reflectivity in a multijunction grill, as in JET, is beneficial to preserve the spectrum of the parallel index of refraction. Fig. 3 shows how the ITB most important features do not change upon even strong CD₄ puffing. Rather, a desired reduction of the ELMs amplitude and an increase of their frequency can be understood. As a consequence, we could couple during an ITB the maximum power allowed by the present conditioning of the launcher, i.e. Pₐₔ>3.5 MW.

Clear positive effects of LHCD on an ITB, even still preliminary, are shown in Fig. 4 (Iₚ=2.3 MA and Bₜ=2.6 T). The ITB time length is prolonged for several seconds to the end of the main heating (up to ~10 s for #53521). Also an electronic barrier is built up and recovering from partial or total crashes of the barrier associated with large ELMs is easier. In that phase, beside the control of the X-point position, also a low Dₑ emission appears preferable, in agreement with previous experiments [2]. This can be obtained with a proper plasma-limiter distance, requirement which is no more in contrast with a good LH coupling, just thanks to CD₄ injection.

3. DISCUSSION

The low ionization potentials of methane and of all the neutral fragments of the dissociation chain, are the main reason why the effect of the CD₄ puffing is mostly contained within the SOL. They are substantially smaller than H₂: between 9.8 eV for CD₃ and 12.5 eV for CD₄, with 11.3 eV for C. The total ionization rate is much larger
than for H\textsubscript{2} already in the wall proximity, about 7 times at temperatures T\textsubscript{e}>20 eV, and much more at lower temperatures. The various fragments then, should be driven to the divertor along the field lines, without entering the main plasma. The almost zero velocity of the C atoms at their birth, is the significant difference from carbon sputtered from the walls. In his study of the transport of puffed methane in a tokamak, [5] Langer shows how all the ionization processes should be completed within a short radial distance from the walls. The exact extent is determined by the edge parameters. Dedicated experiments in JET [6] suggest a prompt ionization within the SOL, because the SOL density increases mostly inside the flux bundle linked to the gas source. The measured profiles [4] show a sort of sub-layer similar to that predicted by Stangeby [7] when ionization dominates as source of electrons in a limited part of the SOL.

In H-mode the probes do not record as clearly as in L-mode the SOL density increase, evidenced by the large improvement of the LH coupling. Apparently, ionization does not occur in the same place, but in front of the antenna. The protection limiter aside the launcher could screen the Langmuir probe from the released electrons. The neutral gas however must be allowed to diffuse until the near-by LH launcher and be directly ionized there. Such diffusion is well consistent with the very low plasma density measured in H-mode near to the walls, and with the ionization rates given in Ref [5]. In L-mode instead, it would be promptly “blocked” by ionization in front of the pipe. The LH electric field in front of the antenna gives the electrons enough energy, about 5 eV, to increase enormously the CD\textsubscript{4} ionization rate there.

Finally, CD\textsubscript{4} puffing does not affect the plasma density, contrarily to D\textsubscript{2} puffing [3], because the equivalent D\textsubscript{2} rate is 7.5 times slower. A reduction by 2/3 comes from the release of one D atom in only two out of the three main CD\textsubscript{4} reaction channels [5]. Furthermore the CD\textsubscript{4} molecular flow is 5 times smaller for equal electron injection rates, as adopted in the two experiments.

4. CONCLUSIONS

The successful coupling of LH power during the main ITB phase is mostly due to the injection of CD\textsubscript{4} form a pipe near to the grill. The plasma-limiter distance could be further increased still preserving a good LH coupling, if requested to reduce the plasma-wall interaction. Carbon influx is negligible, and no other indication against this method in JET exists. Rather, the increase of the ELMs frequency and the reduction of their amplitude pushes CD\textsubscript{4} as a competitor of argon, which is unable to improve the LH coupling. Other gases more appealing for a reactor should be attempted, provided they have low ionization potentials along all the dissociation chain, as SiH\textsubscript{4} for example. Finally, the encouraging effects of LHCD on the main heating phase of an ITB, open the prospect at JET to full explore this effect up to the maximum allowed LH power.

REFERENCES