Improvement of LH-power coupling in H-mode and ITB plasmas on JET

Y. Sarazin[1], V. Pericoli-Ridolfini[2], Y. Baranov[3], C.D. Challis[3], A. Ekedahl[1], S.K. Erents[3], G. Granucci[4], F. Imbeaux[1], E. Joffrin[1], X. Litaudon[1], P.J. Lomas[3], J. Mailloux[3], G.F. Matthews[3], S. Podda[2], E. Righi[5], F. Rimini[1], A.A. Tuccillo[2], and contributors to the EFDA-JET workprogramme

1 *Association Euratom-CEA, CEA Cadarache, DRFC, 13108 Saint-Paul-Lez-Durance, France*
2 *Associazione Euratom-ENEA sulla Fusione, Frascati, C.P. 65, 00044 Frascati, Rome, Italy*
3 *Euratom-UKAEA Association, Culham Science Centre, Abingdon, Oxon OX14 3DB, UK*
4 *Associazione Euratom-ENEA-CNR sulla Fusione, Istituto Fisica del Plasma, Milan, Italy*
5 *EFDA Close Support Unit, D-85748 Garching, Germany*

Introduction

Lower Hybrid (LH) power is certainly the most efficient tool to drive non-inductive current in a tokamak discharge. As such, this heating scheme offers a powerful way to modify the q-profile. On JET however, LH has long suffered for bad coupling efficiency, with Reflection Coefficient (RC_{LH}) of up to 20-30% during the main heating phase of the pulse [1]. As a result, the roughly 7 MW of available electron heating have essentially remained weakly used. Especially in Optimized Shear (OS) scenarios, its use has long been restricted to the preheat phase. In this framework, the power needed to trigger an Internal Transport Barrier (ITB) regime appeared recently to be strongly reduced when early LH was used. Indeed, when applied early in the discharge, LH power tends to flatten or even reverse the q-profile, as a consequence of both heating and current drive effects [2]. Such encouraging results pushed forward the routinely use of LH as both electron heating and current drive method in ITB plasmas. This has motivated the development of an experimental set-up allowing for better LH-power coupling in various plasma configurations during the main heating phase, and especially in OS scenarios.

On JET, in the MarkII-GB divertor configuration, OS plasmas usually exhibit a H-mode edge, characterized by very steep Scrape-Off Layer (SOL) density profiles. In this case, the density in front of the LH grill can drop below the cut-off density, which is $n_{e,cut\text{-}off} \approx 1.7\ 10^{17}\ m^{-3}$ at f_{LH}=3.7 GHz. Such a case is exemplified on Fig.1. Here, density profiles are recorded at two different times in the SOL by means of reciprocating Langmuir probe measurements. The launcher radial extension refers to the different distances between the plasma and the various rows of the launcher (0.8m of vertical extension). It turns out that density drops below $n_{e,cut\text{-}off}$ in H-mode, leading to very high reflection of the wave. Furthermore, the occurrence of strong plasma-antenna interactions prevents from moving the antenna too close to the plasma, for safety reasons, and so as to keep the resulting impurity influx as low as possible. Finally, large Edge Localized Modes (ELM) also reduce the coupled power due to frequent trips generated by strong imbalance in reflected power [3]. Several issues have been investigated to face these problems: *(i)* Installing a real time control of the launcher position under reliable safety limits, namely radiated power in front of the launcher and Iron influx, allows one to work at a minimum plasma-launcher distance; *(ii)* Relaxing the protection system, by averaging the reflected power over a longer duration, and especially by increasing the threshold of specific trips, has significantly reduced the number of trips; *(iii)* Improving the plasma shape with regard to that of the launcher tends to homogenize the coupling conditions on the various rows; *(iv)* Injecting gas from a gas pipe magnetically connected to the launcher increases the density in the scrape-off layer (SOL), hence possibly exceeding the LH cut-off density. Here are reported successful results obtained with the two latter methods.

Plasma shape optimization

In experiments where the detailed shape of the plasma is a degree of freedom, it is worth fitting it to the one of the launcher. This optimization helps at least in two ways. First, for a given plasma-launcher distance, the various rows are then likely to have a similar RC_{LH}. Such a matching is likely to reduce the number of trips of the plant due to imbalance reflection between the various rows. Secondly, since the plasma flux reaching the limiters is then poloidally homogenized, it allows one to operate with a smaller distance without strong radiation from the launcher. As a result, the distance between the separatrix and the poloidal limiter can be maintained as small as about 4cm with the grill only 6mm in the limiter shadow. These conditions are maintained both in the preheat and in the main heating phase of OS plasmas, with a total power in excess of 20 MW.

A standard procedure has been developed to better match the shape of the separatrix to the one of the antenna. It essentially consists in two tools. On JET, the plasma magnetic axis is approximately 0.3m above the equatorial plane in standard plasmas, while the LH launcher is symmetric against it, extending from about ±0.4m. As a result, the lower part of the grill is usually farther from the plasma than the upper part by a few centimeters. Increasing the current (opposite to I_p) in the divertor poloidal coil located in the low field side leads to a movement of the X-point toward the inner target (high field side). Maintaining the plasma-limiter distance constant, the outer lower part of the separatrix then bends up, and gets closer to the lower rows of the LH launcher. A drawback is that this may also lead to a worse matching of the upper rows. In this case, decreasing the top outer gap may counterbalance this effect. Such latter technique leads to more elongated plasmas.

The shape optimization can be quantified by measuring the dispersion σ in the plasma-launcher distances, at various poloidal angles. The smaller σ the better. As seen on Fig.2, the well matched OS plasma #51552 exhibits an improvement by a factor of about 3 with regard to σ as compared to a standard OS configuration of last campaign (#49651), and a factor of about 7 as compared to non optimized high β_p ITB plasmas (#51930).

Gas injection

So as to increase density in front of the launcher, a Gas Injection Module (GIM 6) is installed on JET close to the LH antenna since 1996 (at a distance from the launcher of about 1.2m toroidally and 0.5m radially). Injecting Deuterium from this long pipe, magnetically connected to the launcher, has already proven very efficient in improving LHCD coupling, especially at large plasma-launcher distances [4, 5]. Despite its ability to improve efficiently LHCD coupling when injected from GIM 6, Deuterium has been found however to have a deleterious effect on ITBs. Indeed, the amount of D_2 needed to increase the coupling seems to lead to an increase in ELM activity, and to a further destruction of the barrier [3]. While Argon injection has been used routinely in ITB scenarios to increase radiative losses and subsequently to reduce ELM magnitude [6], of deleterious effect on ITBs [7], it has not been seen to improve LH coupling. Moreover, ion temperature and toroidal velocity measurements from charge exchange spectroscopy are not accurate in the presence of Argon.

Alternatively, methane (CD_4) injection in JET L-mode plasmas has been found to lead to a larger increase in electron density in the SOL than D_2, while electron temperature and density remain unchanged at the separatrix, suggesting the plasma core is essentially unaffected [8]. Surprisingly, the short ionization mean free path of CD_4 compared to D_2 does not seem able to account for these observed differences. Indeed, EDGE2D-U/NIMBUS code simulations suggest instead that an increase in SOL transport in CD_4 ionization zone – consistent with turbulence measurements – can lead to a rise in the peripheral density [9]. Such results have pushed forward the use of CD_4 injection from GIM 6 in ITB plasmas. The main result is that a level of about 8.10^{21} el./s of CD_4 allowed one to couple a maximum of 3.8 MW of LH-power to ITB plasmas, with a reflection coefficient dropping typically from 8% to 4%. An average of about 3 MW of LH has been coupled during the main heating phase (8 sec) of an OS scenario. No adverse effect is observed on the pedestal or bulk plasma characteristics, and similar performances are obtained in terms of temperature profiles and neutron yield. Also, no significant increase in radiation or impurity influx is generally observed from either the limiter or the launcher, and the accumulation of either methane or carbon on the walls looks negligible. Figure 3 exemplifies the improvement in LH-power coupling due to methane injection at medium total power (15 MW) in an OS plasma. Also evident on this figure, the increase in RC_{LH} when ICRH is used at the same time at a sufficiently high power. Such a deleterious cross-talk between both heating schemes is sometimes observed on JET, and is found to involve those ICRH antennae magnetically connected to the LH launcher. A tentative explanation involves ICRH-generated convective cells at the edge, which may alter edge plasma conditions. At present, the injected LH-power appears essentially limited by the status of the system and the grill conditioning, and no longer by plasma conditions. In addition, and similarly to Argon injection, CD_4 appears to reduce the ELM frequency and (to a less extent) to reduce ELM magnitude for P_{add}>14MW, as shown on Fig.4. Indeed, ELM frequency ranges from ~37 Hz up to ~68 Hz, while ELM magnitude (defined here as maxima in the D_α emission) is almost divided by a factor of two, when CD_4 injection rate increases from 0 to 8 10^{21}el/s. The intrinsic physical mechanism leading to such a modification of the ELM dynamics is still unclear. Possible explanations include larger radiative losses in the core (though not always observed), increase in edge resistivity, and modification of edge plasma current, which is thought to play a prominent role in type-III to type-I ELM transition [10]. These promising results push forward the use of CD_4 instead of Ar, hence allowing for accurate T_i and v_φ measurements, small amplitude type-III ELMs together with a good LH-power coupling.

Conclusion

Such encouraging results have already led to a much more frequent use of LH heating on JET at powers $P_{LH} \geq$ 3MW and on durations $\tau_{LH} \geq$ 4s. Good coupling conditions have been achieved during the main heating phase of OS H-mode plasmas at a total power in excess of 20 MW, with RC_{LH} smaller than 5-6%. Last but not least, a good LH coupling during the high power phase opens the prospect for a partial control of the q-profile, and hence of the ITB itself [11], as well as it makes LH a powerful tool for full current drive scenarios [12].

Acknowledgements:

Such improvements would not have been possible without the work and the strong involvement of the LH system group, namely P. Finburg, C. Fleming, P. Haydon and D. Pledge.

This work has been conducted under the European Fusion Development Agreement.

References:

[1] F.X. Söldner *et al.*, *Plasma Phys. Control. Fusion* **39**, B353 (1997)

[2] C.D. Challis *et al.*, to appear in *Plasma Phys. Control. Fusion* (2001); T. Tala *et al.*, this conference

[3] E. Joffrin *et al.*, *JET report* JET-R(99)09 (1999)

[4] A. Ekedah *et al.*, Radio Frequency Power in Plasmas (Proceedings 12th Topical Conference, Savannah, 1997), AIP Conf. Proceedings **403**, 169 (1997)

[5] M. Goniche *et al.*, *JET report* JET-R(97)14 (1997)

[6] C. Gormezano, *Plasma Phys. Control. Fusion* **41**, B367 (1999)

[7] Y. Sarazin *et al.*, Proceedings 27th EPS Conf., Budapest (2000), ECA Vol. **24B**, 253.

[8] J.D. Strachan *et al.*, to appear in *Journal of Nuclear Mat.* (2001)

[9] G.F. Matthews *et al.*, this conference

[10] M. Bécoulet *et al.*, this conference

[11] J. Mailloux *et al.*, this conference

[12] X. Litaudon *et al.*, this conference

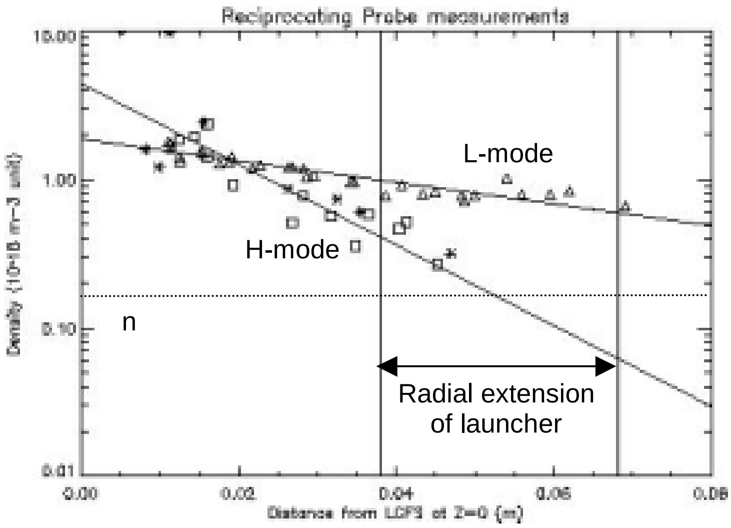

Fig.1: *Density decay in the SOL in L-mode (triangle) and in ELMy H-mode with LH-power (stars) and without LH-power (square) (Pulses #47878 and #47895). Reciprocating Langmuir probe data.*

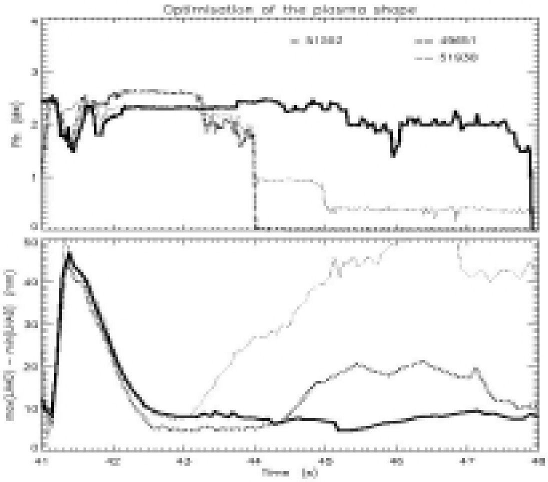

Fig.2: *Various plasma shapes: optimized (#51552), standard ITB (#49651), high β_p ITB (#51930). Bottom: σ (see text).*

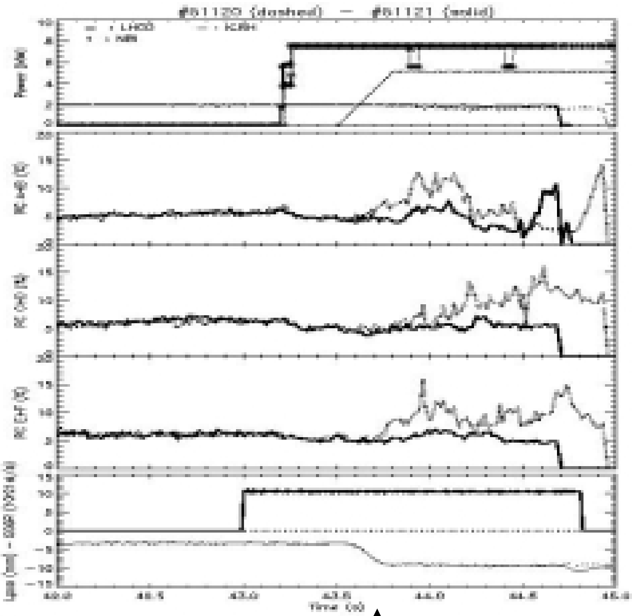

Fig.3: *Effect of CD_4 injection from GIM 6 on LH coupling in OS plasmas: #51120 without CD_4 (dashed), #51121 with CD_4 (solid).*

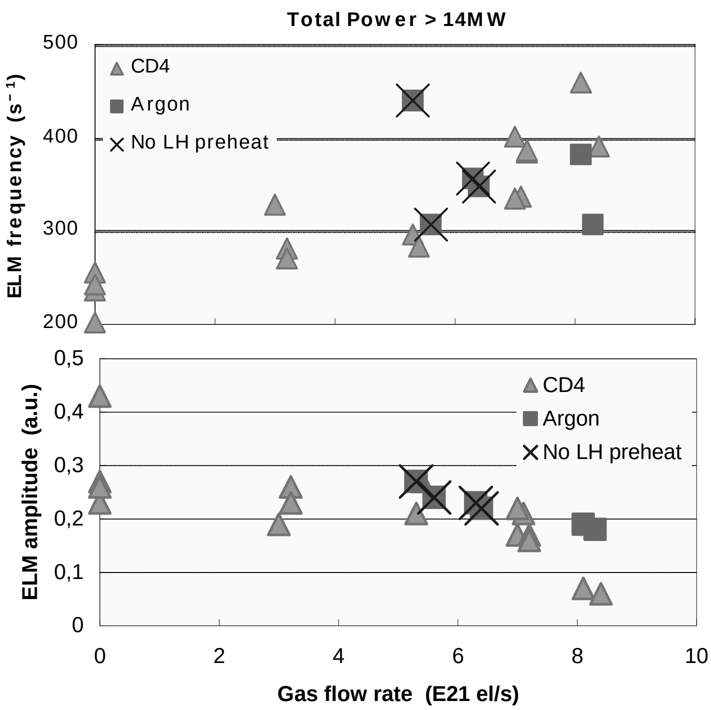

Fig.4: *Effect of gas (D_2 and CD_4) injection (from GIM 6) on ELM frequency and ELM magnitude for pulses with P_{tot}>14MW. ELM frequency increases while ELM magnitude decreases when gas injection rate increases.*