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ABSTRACT.
A significant step towards demonstrating the feasibility of coupling Lower Hybrid (LH) waves in ITER has been achieved in the latest LH current drive experiments in JET. The local electron density in front of the LH launcher was increased by injecting gas (D_2 or CD_4) from a dedicated gas injection module magnetically connected to the launcher. P_{LHCD} = 3MW was coupled with an average reflection coefficient of 5%, at a distance between the last closed flux surface and the launcher of 10cm, in plasmas with an internal transport barrier (ITB) and H-mode edge, with type I and type III ELMs. Following a modification of the gas injection system, in order to optimise the gas localisation with respect to the LH launcher, injection of D2 proved to be more efficient than CD_4. A D2 flux of 5-8×10^{21} el/s provided good coupling conditions at a clearance of 10cm, while when using CD_4, a flux of 12×10^{21} el/s was required at 9cm. The plasma performance (neutron rate, H-factor, ion temperature) was similar with D_2 and CD_4. An additional advantage with D_2 injection was found, as it reduced the amplitude of the ELMs, which further facilitated the LH coupling. Furthermore, preliminary results of the study of the behaviour of electron density profile in the scrape-off layer during injection of C_2H_6 and C_3H_8 are reported. Finally, the appearance of hot spots, resulting from parasitic absorption of LHCD power in front of the launcher mouth, was studied in the long distance discharges with near gas injection.

1. INTRODUCTION
Coupling of Radio Frequency (RF) waves in H-mode plasmas with large amplitude ELMs is a problem in existing tokamaks, both for Lower Hybrid (LH) Current Drive (CD) systems, as well as for Ion Cyclotron Resonance Frequency (ICRF) systems. The steep density gradient associated with the H-mode can bring the density in front of the antennas below the cut-off densities needed for efficient coupling. In addition, the presence of ELMs causes perturbations at the edge that give very rapid variations in loading in front of the antennas. Large efforts are placed on finding methods for improving the coupling of these RF systems in these conditions, in view of operation in future devices, like ITER.

For the LHCD system in JET, gas puffing in the vicinity of the launcher has proven efficient for increasing the local electron density, thereby improving the coupling of the LH waves. The launcher is equipped with a dedicated gas injection pipe, located in the outer wall 1.2m from the launcher. Before the experiments reported here, the gas injection system was modified back to its original design, as used in the initial experiments before 1997 [1]. In the experiments carried out with D2 injection in 1997-1999 [2, 3] and with CD_4 injection in 2000-2001 [4, 5], the gas injection system had two extra holes added in the upper part of the pipe. When comparing the efficiency of improving the LH coupling using D2 injection with the two designs, it appeared that the original design (with eight holes, rather than ten holes) gave a better localisation of the gas injection with respect to the launcher.

2. EXPERIMENTAL SCENARIO
A dedicated experiment was carried out in the JET tokamak in spring 2003, in order to demonstrate the feasibility of coupling LH waves under ITER relevant conditions, i.e. at large distance between

the Last Closed Flux surface (LCFS) and the launcher, and with type I ELMs. The plasma scenario was based on a configuration at IP=1.5MA and BT=3T, used in experiments aimed at achieving internal transport barriers (ITBs) in steady state conditions [6]. The scenario has a fast current ramp-up with 2-2.5MW LHCD, in order to produce a target q-profile with reversed shear, before the application of Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Frequency (ICRF) waves. Full NBI power (~16MW) was requested in these experiments in order to produce type I ELMs. The ICRF power was maintained at a moderate level, and the ICRF antenna located next to the LH launcher was not used, as this antenna in particular can degrade the LH coupling when operating simultaneously [7].

The LH coupling obtained in these discharges without near gas injection is shown in Fig.1. The launcher was retracted 2cm behind the poloidal limiter while the LCFS was held at 5cm from the limiter. The LHCD power was stepped down at 4s and the re-applied at 5s, due to diagnostic purposes. However, the low level of LHCD power coupled at 5s and onwards was due to poor coupling, i.e. too low density in front of the launcher. The low coupled power level and the ragged power signal is caused by a launcher protection system that switches off the power on a klystron if the difference in the reflected powers in the two multijunctions powered by the klystron is too large. Fig.2 shows the result when adding CD_4 injection near the LH launcher, at a rate of 8×10^{21}el/s, in an otherwise identical discharge. P_{LHCD}=2.5MW could be maintained during type I and type III ELMs. At the end of the discharge the gas injection rate was stepped down. This resulted in an increase in average power Reflection Coefficient (RC) and a decrease in coupled LHCD power, as this rate was not sufficient to maintain sufficient electron density in front of the launcher.

All discharges in this experiment had a second current ramp-up in the later phase of the pulse. This was programmed in order to be able to study the appearance of hot spots in the divertor region, caused by the acceleration of particles in front of the LH launcher, as described later. It can be noted that at the start of the second current ramp-up which takes place at 7.0s in Fig.1 and Fig.2, the ELM behaviour changes from type I to type III and the neutron yield increases, due to the formation of an ITB. It has been found that a large fraction of current at the edge, as obtained during a current ramp, can have some effect on the ELM activity [8].

3. LONG DISTANCE LH COUPLING WITH CD_4 AND D_2

In the subsequent discharges, the LH launcher was placed closer to the poloidal limiter (0.5cm in the shadow of the limiter), while the LCFS was moved further away from the limiter. The result of a discharge with CD4 injection near the launcher, in which the LCFS was 9cm from the limiter, is shown in Fig. 3. The second current ramp-up was delayed until 48.0s in this discharge, in order to maintain the type I ELM activity, as required for the LH coupling experiment. The long distance discharges were then repeated with injection of D_2 from the gas injection pipe near the launcher. The result of one of these discharges is shown in Fig.4. P_{LHCD} = 3MW was coupled with an average reflection coefficient of 5%, at a distance between the LCFS and the launcher of 10.5cm. When using D_2 injection, the amplitude of the ELM was smaller compared to the discharges with CD_4 injection, which was beneficial for coupling, both of LH waves and ICRF waves.

The decrease of the ELM amplitude was not the main factor for reducing the LH reflection coefficient in the discharges with D_2, compared to CD_4. A detailed comparison of the reflected power signals during CD_4 and D_2 injection, at similar ELM amplitude, revealed that the reflected power signals were lower and had less fluctuation in the pulses with D_2 injection. This suggests that the electron density in front of the launcher was higher when using D_2 injection, even though the injected rate of electron/s was lower in the discharges with D_2. The measurements of the electron density profile in the Scrape-Off Layer (SOL), taken by a reciprocating Langmuir probe magnetically
connected to the LH launcher, confirm that the electron density in the SOL was higher when using 8×10^{21} el/s D_2 compared to 12×10^{21} el/s CD_4. This can probably be explained by the fact that deuterium recycles at the plasmas edge, which further increases the electron density.

4. PLASMA BEHAVIOUR WITH CD_4 AND D_2

Several pulses were carried out with CD4 injection at 10-12$\times10^{21}$ el/s and with D_2 injection at 7-8$\times10^{21}$ el/s. Similar plasma performance was obtained with the two gases, as inferred from plasma parameters, such as neutron yield, ion temperature, and H-factor. Comparisons of the electron density profiles and the ion temperature profiles from otherwise identical discharges, one with CD_4 injection and one with D_2 injection, are shown in Fig.5 and Fig.6. Both figures show that an ITB was produced in the discharge with D_2 injection. This behaviour is in contrast to the results obtained in the earlier Optimised Shear experiments in 1998-1999, in which D_2 injection at 8×10^{21} el/s rather provoked type I ELMs and caused a degradation of the ITB [2, 3]. In addition, the LH reflection coefficient could not be maintained at a sufficiently low level without reducing the distance between the LCFS and the launcher to 5cm, or less. These results initiated the use of CD_4 injection near the LH launcher in order to improve LH coupling and still maintaining the ITBs [4, 5]. The reason to which D_2 injection has become efficient for improving the LH coupling in these latest experiments is most likely the change in the gas injection design, from ten holes to eight holes, which improved the localisation of the gas injection in the area magnetically connected the launcher. What concerns the behaviour of the ITB with D_2 injection in the latest and in the earlier experiments, it should be noted that the experiments were carried out in different plasma configurations. The earlier experiments (in the Optimised Shear configuration) used a flat q-profile, while the present ITB experiments use a q-profile with reversed shear. It has been found that this latter configuration is quite robust towards gas injection [9].

5. ELECTRON DENSITY IN THE SCRAPE-OFF LAYER DURING INJECTION OF DIFFERENT GASES

CD_4 was chosen as an alternative gas to D_2 to be used for LH coupling improvement, because its ionisation cross section is higher than that of D_2 and because CD_4 does not cause an increase in the separatrix density or in the main plasma density [10]. C_2D_6 or C_3D_8 should be even more efficient for increasing the electron density in the SOL, since their ionisation cross sections are even higher than that of CD_4. This was investigated in a specific experiment using the same plasma scenario as presented above, and using injection of C_2H_6 and C_3H_8 near the LH launcher. In order to compare the results obtained with the four gases (D_2, CD_4, C_2H_6 and C_3H_8), the corresponding electron density profiles were normalised to the same rate of electrons/s (4×10^{21}el/s). This is shown in Fig.7. CD_4, C_2H_6 and C_3H_8 seem to follow their respective ionisation cross sections at ~25eV. The density obtained with D2 is higher than what expected from its ionisation cross section, probably due to the recycling effect.

6. STUDY OF LH GENERATED OF FAST PARTICLES IN FRONT OF THE LH GRILL

Parasitic absorption of LH power in front of the launcher can lead to acceleration of fast particles, which travel along the magnetic field lines and impinge on components magnetically connected to the launcher, causing localised hot spots. Since the power involved in the parasitic absorption depends on the electron density in front of the launcher [11, 12], it is possible that this effect can become significant when using local gas injection near the launcher. The second part of the discharges in the LH coupling experiments was therefore dedicated to this study. A current ramp-up was programmed in order to change continuously the angle of the magnetic field line so as to ensure that, at some point during the ramp, there would be a magnetic field line connection between the launcher and the specific region of the divertor, which was monitored by CCD cameras. The CCD images of the LH produced hot spots were then analysed in order to obtain a qualitative picture of the dependence of the hot spots. A preliminary analysis of the data obtained in this experiment and in earlier LHCD experiments using local gas injection is shown in Fig.8. It can be seen that the relative brightness of the hot spots decreases when increasing the distance between the LCFS and the launcher, which is a very encouraging result in view of the long distance operation with LHCD. Note that, since only CCD cameras were used, no quantitative estimate of the power involved was made in the JET experiments. However, experiments in Tore Supra have shown that only <2% of the LHCD power is involved in this parasitic absorption, in conditions where the electron density in front of the launcher is less than 1×10^{18} m^{-3} [12]. Finally, it is important to note that, although these hot spots can be potentially dangerous in present experiments with conventional LH launchers, as they can involve very localised heat loads, this effect will be negligible for the Passive Active Multijunction (PAM) launcher, as foreseen in ITER [13].

SUMMARY

Very encouraging results regarding coupling of LH waves under ITER relevant edge conditions have been obtained in recent LHCD experiments in JET. 2.5MW LHCD power was coupled at a distance between the LCFS and the launcher of 9.5cm during type I ELMs, while 3MW was coupled at a distance of 10.5cm during type III ELMs.

At comparable injected electron/s rate, D_2 injection near the launcher proved more efficient than CD_4 for improving the LH coupling. This can probably be attributed to the recycling effect of the deuterium, which further increases the electron density, as confirmed by the reciprocating Langmuir probe measurements. In addition, D_2 injection reduced the amplitude of the ELMs, which is beneficial for the coupling of LH waves, as well as ICRF waves.

Internal transport barriers could be maintained in the discharges with D_2 injection, and the plasma performance was comparable in the discharges with CD_4 injection and D_2 injection. The reciprocating Langmuir probe measurements in the experiments with injection of C_2H_6 and C_3H_8 near the LH launcher show that higher electron densities in the SOL are obtained with C_2H_6 and C_3H_8, compared to CD_4. This is in agreement with their corresponding ionisation cross sections.

Preliminary results of the study of LH generated hot spots due to fast particle generation in front of the LH launcher, indicate that the brightness of the hot spots are weaker when operating at large LCFS-launcher distance.

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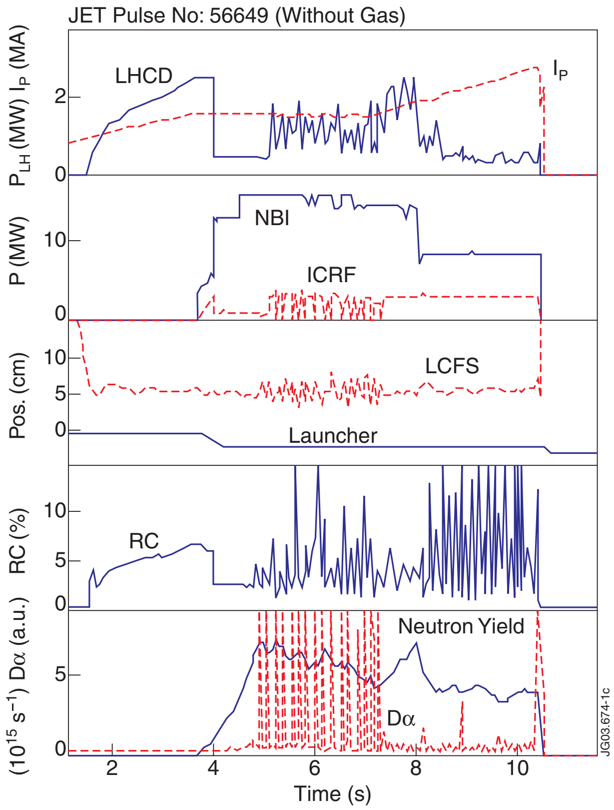

Figure 1: Poor LH coupling on type I and type III ELMs without near gas injection.

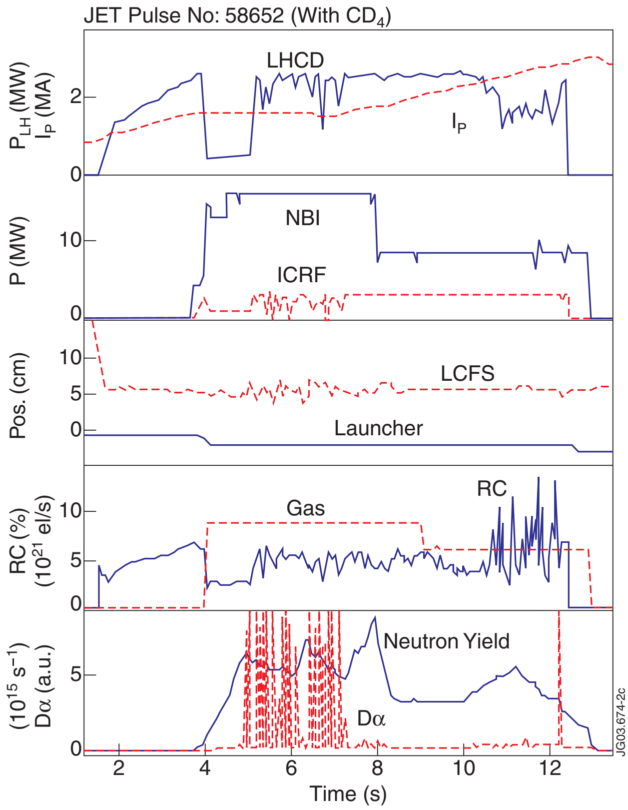

Figure 2: LH coupling improved by using injection of CD_4 near the LH launcher

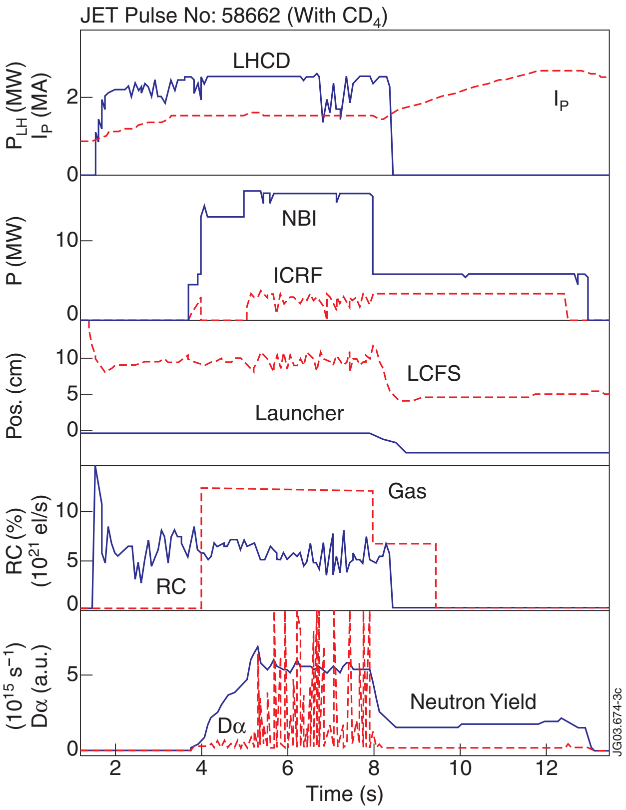

Figure 3: Long distance coupling during type I ELMs, using CD_4 injection (12×10^{21} el/s) near the LH launcher.

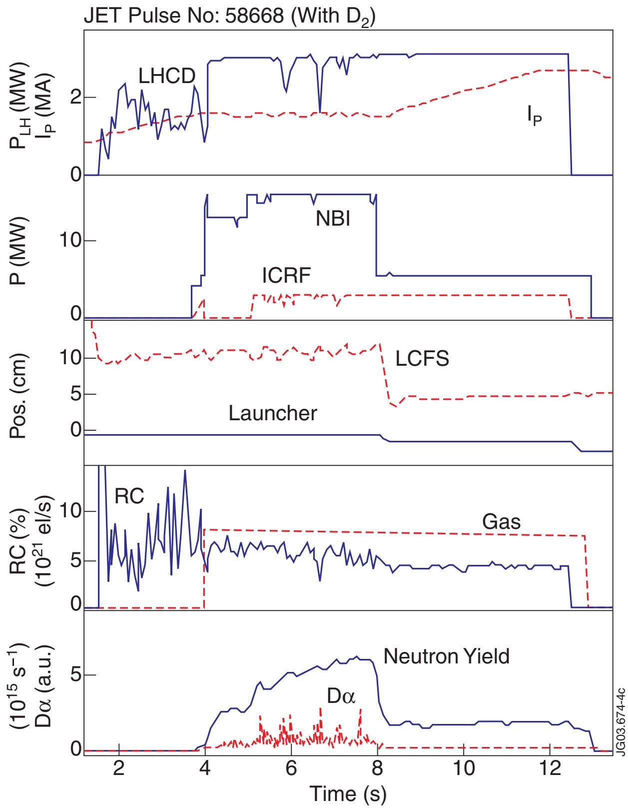

Figure 4: Long distance coupling with D_2 injection near the LH launcher. The amplitude of the ELMs reduced when using D_2.

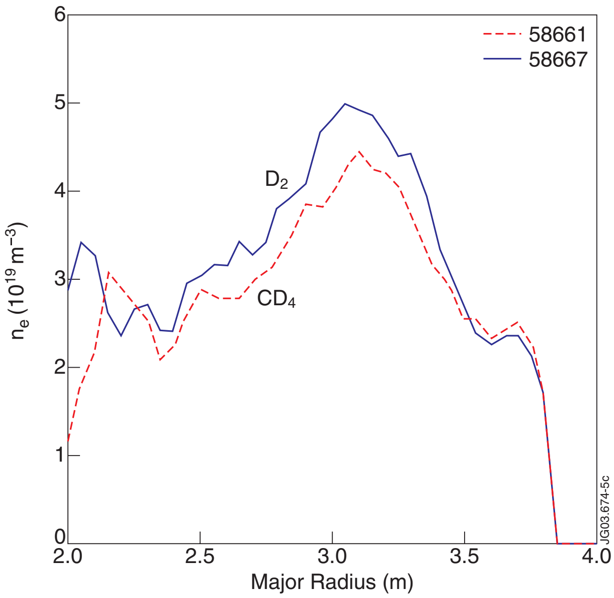

Figure 5: Electron density profiles in a discharge with D_2 injection (solid line) and with CD_4 injection (dashed line).

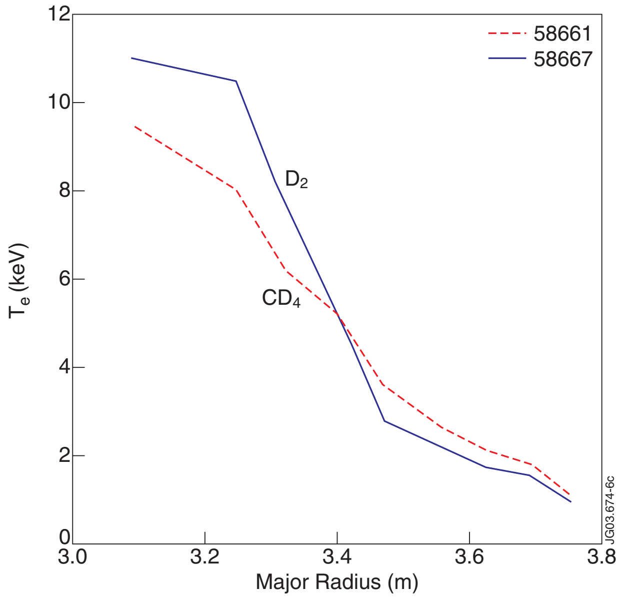

Figure 6: Ion temperature profiles in a discharge with D_2 injection (solid line) and with CD_4 injection (dashed line).

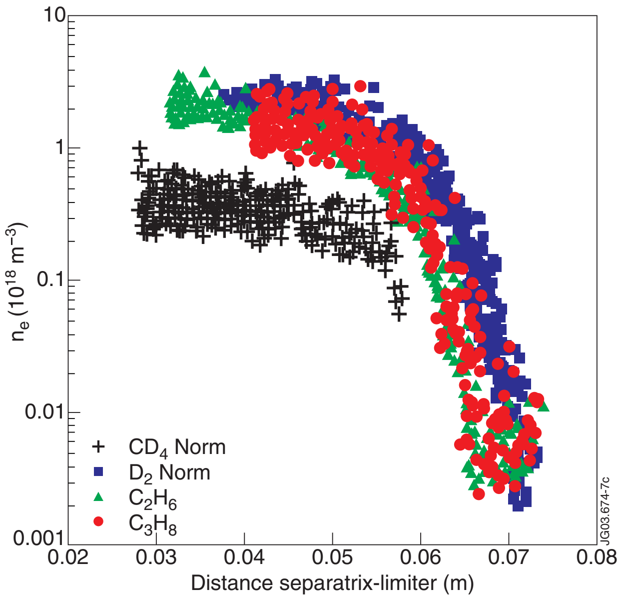

Figure 7: Electron density in the scrape-off layer normalised to the same electron/s rate (4×10^{21} el/s) during injection of different gases from the gas injection pipe near the LH launcher.

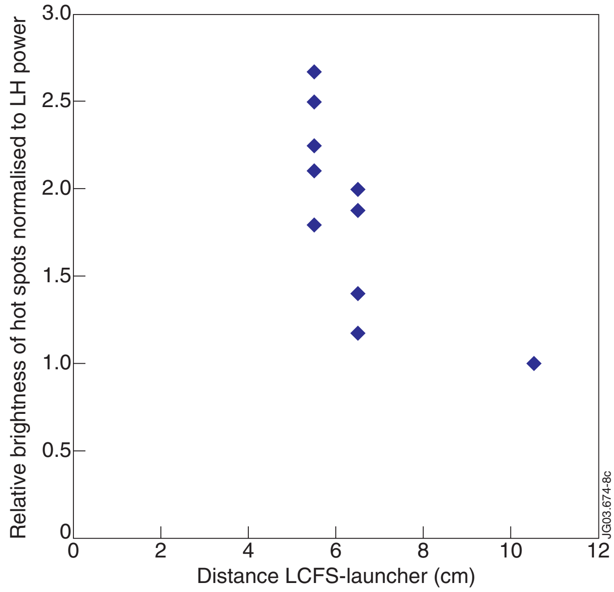

Figure 8: Relative brightness of hot spots as a function of the LCFS-launcher distance for several discharges with CD_4 or D_2 injection near the launcher, and LHCD power in the range 1-3MW.