EFDA–JET–CP(04)07-25

J. Mailloux, A. Ekedahl, G. Granucci, M. Goniche, V. Petržílka, K. Rantamäki, P. Andrew, J.-F. Artaud, Yu. Baranov, V. Basiuk, I. Coffey, K. Erents, E. Joffrin, K. Kirov, X. Litaudon, P. Lomas, G. Matthews, D.C. McDonald, V. Parail, V. Pericoli-Ridolfini, F. Rimini, R. Sartori, C. Silva, M. Stamp, A.A. Tuccillo, F. Záček and JET EFDA Contributors

ITER Relevant Coupling of Lower Hybrid Waves in JET

ITER Relevant Coupling of Lower Hybrid Waves in JET

J. Mailloux[1], A. Ekedahl[2], G. Granucci[3], M. Goniche[2], V. Petržílka[4], K. Rantamäki[5], P. Andrew[1], J.-F. Artaud[2], Yu. Baranov[1], V. Basiuk[2], I. Coffey[6], K. Erents[1], E. Joffrin[2], K. Kirov[7], X. Litaudon[2], P. Lomas[1], G. Matthews[1], D.C. McDonald[1], V. Parail[1], V. Pericoli-Ridolfini[8], F. Rimini[2], R. Sartori[7], C. Silva[9], M. Stamp[1], A.A. Tuccillo[8], F. Žáček[4] and JET EFDA Contributors*

[1]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon Oxon OX14 3DB, UK*
[2]*Association Euratom-CEA, CEA Cadarache, 13108, St Paul-lez-Durance, France*
[3]*Associazione EURATOM-ENEA sulla Fusione, IFP-CNR, Milan, Italy*
[4]*Association Euratom-IPP.CR, Praha, Czech Republic*
[5]*Association Euratom-Tekes, VTT Processes, Finland*
[6]Queen's University, Belfast, BT7 1NN, UK
[7]*Max-Planck-Institut für Plasmaphusik, EURATOM Association, Garching, Germany*
[8]*Associazione Euratom-ENEA sulla Fusione, Centro Ricerche Frascati, Frascati, Italy*
** See annex of J. Pamela et al, "Overview of JET Results ", (Proc.20 th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).*

Preprint of Paper to be submitted for publication in Proceedings of the
20th IAEA Conference,
(Vilamoura, Portugal 1-6 November 2004)

ABSTRACT.

Lower Hybrid (LH) is a highly desirable tool for ITER, particularly for the steady state and hybrid scenarios that rely on forming and maintaining a specific q profile. However, coupling of the LH waves in ITER represents a challenge because the launcher, flush with the outer wall, will be at least 12cm away from the Last Closed Flux Surface (LCFS), where the electron density, n_e, is predicted to be below the cut-off density. Also, the plasma will be in H-mode with ELMs that could trigger trips of the protection systems, resulting in reduction of the averaged power. To study solutions to improve coupling of LH waves in these conditions, experiments were performed in JET using plasmas with Internal Transport Barrier (ITB) and H-mode, with distance between the LCFS and the limiter, D_{PL}, up to 10 cm. To increase n_e in front of the launcher, $n_{e,grill}$, CD_4 or D_2 is puffed from a specially designed pipe, recently modified to optimise the gas flow. When no gas is puffed, the LH coupling is poor during the high power phase, indicating that $n_{e,grill}$ is below the cut-off density. With CD_4 puffing, the coupling improves dramatically, and 2.5MW of LH power is coupled with D_{PL}= 9cm and type I ELMs. Measurements with a reciprocating Langmuir probe show that $n_{e,grill}$ is at, or slightly above, the cut-off density, in this case. With D_2 puffing, preferable to CD_4 for ITER because of concerns about T co-deposition, 3MW was coupled successfully with D_{PL} up to 10cm. The ELMs are smaller with D_2, but the improvement in coupling can not be attributed only to this. The use of D_2 or CD_4 was explored further in other plasmas with ITB and H-mode. In all the scenarios, the coupling is better with D_2 than with CD_4. Moreover, the ITB existence and performance are not affected by the D_2. To help understand the processes leading to the increase in $n_{e,grill}$, C_2H_6 and C_3H_8 were compared to CD_4 and D_2 in the same scenario. n_e scales with the ionisation cross-section in the case of the hydro carbon gases, but is higher than expected for the D_2, possibly because of higher D_2 recycling from the walls. In a few shots with LHCD in JET, bright spots on components magnetically connected to the LH launcher have been observed with a CCD camera. These are probably caused by fast particles created parasitically in the SOL in front of the launcher, as has been observed in other machines. This paper also presents results from experiments investigating LH counter current drive in JET, in plasmas with reversed magnetic field and plasma current. Simulations indicate a current drive efficiency of a similar magnitude than in the co current drive case.

1. INTRODUCTION

Control of the q profile has become increasingly important to achieve and maintain plasmas with Internal Transport Barriers (ITB). Lower Hybrid (LH) waves have been used successfully in several tokamaks for this purpose, see for example [1 - 4]. LH is thus a highly desirable tool for ITER, particularly for the steady state and hybrid scenarios that rely on forming and maintaining a q profile with low or negative magnetic shear. However, coupling of the LH waves in ITER represents a challenge because the launcher, flush with the outer wall, will be at least 12cm away from the last closed flux surface. At this location, the electron density, n_e, is predicted to be below the cut-off density, $n_{e,cut-off}$, for waves at 5GHz ($3.1\times10^{17}m^{-3}$). As the plasma will be in H-mode, ELMs could be triggering trips of the protection system, resulting in large reduction of the averaged power. It is crucial to investigate solutions to improve coupling of LH waves in these conditions. Because of its size, JET can operate with a distance between the last closed flux surface (LCFS) and the poloidal limiters (d_{PL}), of up to 10cm, i.e. of similar order to that in ITER. Moreover, it can provide plasmas with core and edge transport barriers, with different types of ELMs, and low electron density in the scrape-off layer ($n_{e,SOL}$). This makes it ideally suited for testing ITER relevant heating and current drive systems, and to study their use in ITER relevant scenarios.

This paper is organised as follow. Section 2 briefly presents the LH system in JET. Section 3 describes the ITER relevant coupling experiments, including the comparison of different gases and the coupling of LH waves in plasmas with high triangularity. Section 4 summarises the observation of hot spots on components magnetically connected to the LH launcher. Section 5 describes LH counter current drive experiments that were done in plasmas with reversed magnetic field, B_T, and plasma current, I_P, including modelling of the current drive components. Finally, some conclusions are given, along with the experiments and modelling required to continue this work and to extrapolate it to ITER.

2. EXPERIMENTAL SET-UP

The LH system in JET comprises 24 klystrons at 3.7GHz, feeding a launcher composed of 12 rows of 32 small waveguides, though 48 multijunctions. The parallel refractive index of the main wave, $N_{//}$, is 1.84 in the experiments described here. Figure 1 shows the launcher inside JET, along with the nearest poloidal limiter and the specially designed gas pipe (GIM6) used to puff gas near the launcher to increase n_e locally. The gas pipe has been recently modified to optimise the gas flow near the launcher. The launcher position can be varied during the pulse, but is kept at a larger major radius than the poloidal limiters, typically at 0.5cm to 2.5cm behind. Reflection coefficients, RC = 100*(reflected power/forward power), are used to judge the LH wave coupling. RC must be well below 10% for good coupling. In this paper, global reflection coefficients are used, for the 4 top rows (RC_{TOP}), the 4 middle rows (RC_{MID}) and the 4 bottom rows (RC_{BOT}). RC for the different rows can behave differently, depending on the plasma shape, the connection lengths, the distance between the limiter and the launcher, (d_{LL}) and d_{PL}. Progress in improving the coupling of the LH wave in scenarios where the density in front of the grill is near or below the cut-off density ($n_{e,cut-off} = 0.17x10^{18}$ m^{-3} for waves at 3.7GHz) in JET has been described in [5].

3. ITER RELEVANT COUPLING EXPERIMENTS

Dedicated experiments to study LH coupling with large d_{PL} (≤10.3cm) and ELMs were performed in JET using ITB plasmas with H-mode edge, with B_T = 3.0T and I_P = 1.5MA [6]. The LH power is applied early in the pulse to shape the q profile, and during the high power phase (with Neutral Beam Injection, NBI = 13-16MW, and Ion Cyclotron Radiofrequency Heating, ICRH = 2-3MW), to slow down the q profile evolution. In that phase, both an ITB and an edge transport barrier can co-exist, with type III or type I ELMs. The distance between the launcher and the poloidal limiter was kept small (d_{LL} = -0.5cm to -1.0cm) since in ITER the LH launcher will be flush with the wall rather than far behind a poloidal limiter. When no gas is puffed from the gas pipe near the launcher, the LH coupling is poor during the high power phase, with high reflected powers and numerous trips of the protection systems, indicating that the density in front of the launcher, $n_{e,grill}$, is below $n_{e,cut-off}$.

When CD_4 is puffed near the launcher, the LH coupling improves dramatically. In addition, the number of trips is greatly reduced. Measurements of $n_{e,SOL}$ with a reciprocating Langmuir probe (RCP) magnetically connected to the area in front of the launcher indicate that the density in front of the grill is at, or slightly above, the cut-off density in this case. As in [5], the amount of gas puffed with GIM6 does not result in an increase of n_e inside the LCFS. Figure 2 shows that even with d_{PL}= 9.2cm and type I ELMs, 2.5 MW of LH power is coupled successfully, with an average overall RC = 5.6%.

For ITER, D_2 puffing is preferable to CD_4 since the latter introduces C, which raises concerns about T co-deposition. D_2 puffing was tested in plasmas with d_{PL} up to 10.3cm, and LH power up to 3MW was coupled successfully, as shown in Figure 3. The average RC is 5.7% in this case, i.e. similar to the shot with CD_4, even though d_{PL} is slightly larger. On all shots with D_2, the ELMs are smaller than with CD_4, because D_2 affects the edge differently. Measurements of the SOL plasma with the reciprocating Langmuir probe in plasmas with d_{PL} = 7cm show that $n_{e,SOL}$ is higher with D_2 ($8x10^{21}$e/s) than with CD_4 ($10x10^{21}$e/s) (the amount of gas is given in equivalent electrons/s). Moreover, the fluctuations in the reflected power typically measured during ELMy plasmas are smaller with D_2 than with CD_4, when comparing shots with similar ELMs.

Figure 4 shows the average reflection coefficient for the top, middle and bottom rows, as a function of the gas injected, for all shots with d_{PL} > 8cm and distance between launcher and poloidal limiter = -0.5cm (the minus sign indicates that the launcher is behind the limiter). RC on all rows improves when CD_4 or D_2 is used, but the largest improvement is seen on the bottom rows, possibly because the connection lengths of the flux tube in front of these rows are longer than for the rest of the launcher, which can result in a higher $n_{e,SOL}$.

These results demonstrate that with gas puffing near the launcher, it is possible to couple LH waves in conditions similar to those expected in ITER (i.e. large d_{PL} and ELMs). Note that the amount of LH power coupled up to now in these scenarios does not represent the limit achievable, but rather what could be achieved in the experimental time allocated.

3.1. COMPARISON OF D_2 AND CD_4 IN OTHER ITB PLASMAS

The effect of D_2 in comparison to CD_4 has been investigated further by comparing their use in other experiments with ITB and H-mode, but with the d_{PL} typically used in ITB experiments (5-6 cm). In all the scenarios analysed, the LH wave coupling is better with D_2 puffing than with CD_4, even when the launcher position is further away from the last closed flux surface.

In addition, the ITB existence and performance are not affected by the D_2, even though the edge density is generally slightly higher than with CD_4 in these experiments. In contrast, in previous ITB experiments, the ITB was lost when D_2 was puffed in quantity sufficient to improve the LH coupling [5]. This is partly because the present scenarios are more robust towards gas injection, but is also due to the optimisation of the gas pipe design. In comparison to the previous design, smaller amounts of D_2 are required to obtain similar coupling improvement.

3.2. COUPLING IN ITB PLASMAS WITH HIGH TRIANGULARITY

The experiments described above have a relatively low upper and lower triangularity (typically δ_{up} ~ 0.18 and δ_{lo} ~ 0.30 respectively). Previous experiments in JET have shown that the LH coupling is sensitive to the plasma shape [5]. ITER plasmas will have high δ, hence it is important to assess the LH coupling in that type of configuration. This was done in ITB plasmas with high triangularity (δ_{up} and δ_{lo} up to 0.48 and 0.41 respectively), but with small d_{PL}, and with the launcher far behind the limiter ($d_{LL} = -2.5$cm). Low LH power, ~ 2MW, was used, in plasmas with up to 20MW of NBI and up to 5MW of ICRH. Figure 5 shows that RC averaged over all rows decreases as a function of the plasma triangularity (the average δ is used because δ_{up} and δ_{lo} are varied together). The two points with the lowest δ are from two other ITB experiments with slightly smaller additional power levels and same d_{LL}.

The shots in figure 8 cover a range of plasma parameters. The amount of D_2 puffed from GIM6 varies between $3.9\times10^{21} - 6.8\times10^{21}$ e/s, the distance between LCFS and the limiter, between 3.1 - 5.5cm, and the line integrated edge density (inside the LCFS), between $2.0\times10^{19} - 3.4\times10^{19}$ m^{-2}. However, the correlation of RC with these parameters is weak when compared with δ, indicating that the triangularity is a more relevant scaling parameter. Since the main factor determining the coupling is the electron density in front of the grill, this result suggests that $n_{e,SOL}$ increases with δ. No $n_{e,SOL}$ measurements are available for these shots.

Figure 8 also shows that RC for the different rows behaves differently. The largest effect is seen on the middle and top rows, probably because the distance between the LCFS and these rows decreases with δ in the shots shown here. The behaviour of RC on the bottom rows is more complex, because the connection lengths in front of these rows can change significantly with small changes in the plasma configuration and location. In comparison to plasmas with lower δ, but with similar d_{PL} and launcher position, less D_2 from GIM6 is needed to improve the LH coupling. This could be because high δ plasmas use larger amount of gas puffing throughout the high power phase to control the edge and maintain small ELMs [7]. Additionally, the larger connection lengths in the SOL, in front of the poloidal limiter, that occur in high δ plasmas could have a beneficial effect on $n_{e,SOL}$.

3.3. INVESTIGATION OF THE IONISATION PROCESS

The effect of different gases on the coupling of the LH wave was explored to help understand the processes leading to the increase in $n_{e,SOL}$ [8]. C_2H_6 and C_3H_8 were chosen because of their high total ionisation cross-section. They were compared to CD_4 and D_2 in the scenario used for the ITER relevant coupling experiment, described at the beginning of section 3, with d_{PL} = 7 cm. Similar coupling, i.e. with average RC ~ 5-6%, was obtained in all cases. Additionally, ITBs with similar performance to that obtained in ITB plasmas with CD_4 or D_2 were obtained with C_2H_6 and C_3H_8.

Figure 6 shows $n_{e,SOL}$ measured with a reciprocating Langmuir probe for the different gases. It scales with the ionisation cross-section in the case of the hydro carbon gases. However, when D_2 is puffed, $n_{e,SOL}$, especially in the outward part of the profile, is higher than what would be expected based on its ionisation cross-section alone. This effect is not completely understood, but is likely to be due, at least in part, to a higher D_2 recycling from the walls.

The possible role of the electric field at the grill mouth of the launcher in the ionisation process has not been fully investigated yet. However, reciprocating Langmuir probe measurements for one pulse with D_2 puffing and without LH power show $n_{e,SOL}$ is smaller in the region behind the poloidal limiters than in the case with LH power, indicating a possible effect of the LH power in the ionisation of the D_2.

4. BRIGHT SPOTS ON COMPONENTS MAGNETICALLY CONNECTED TO THE LH GRILL

In Tore Supra [9] and TdeV [10], bright spots have been observed on components magnetically connected to the LH grill. They have been attributed to fast electrons accelerated in the SOL plasma by the high $N_{//}$ components the LH waves [11], [12], which are caused by the small scale length structures of the grill.

In recent experiments in JET, bright spots in the divertor apron have been observed with a CCD camera in the region magnetically connected to the LH grill [13], figure 7. They are related to the LH power since they disappear as soon as the LH power stops. The bright spots have been seen in a limited number of shots up to now, probably because, in the magnetic configurations typically used, the region of the divertor magnetically connected to the LH grill is not seen by the CCD camera. An absolute value of the temperature reached at the location of the bright spots is not available, however, their relative brightness has been used to qualify the bright spots [13]. The brightness increases with the LH power, which is consistent with observations reported in other machines [9], [10], and with the theoretical analysis and simulations [11], [12]. The brightness decreases when d_{PL} increases, which is favourable for ITER.

5. LOWER HYBRID COUNTER CURRENT DRIVE EXPERIMENTS

The direction of the main LH wave launched in JET is fixed because it is determined by the phase difference between the small waveguides of the launcher, which in turn is created by mechanical phase shifters inside the multijunctions. The main LH wave provides co-current drive in the configuration normally used in JET. Recent experiments with reversed B_T and I_P in JET have given a rare opportunity to investigate the LH wave current drive efficiency in the direction counter to I_P.

The experiments were done with 2.9MW of LH power, during flat top $I_P = -1.45$MA, $B_T = -3.1$T, and with line averaged density $n_e = 1.0\times10^{19}$ m^{-3} and central $n_{e0} = 1.6\times10^{19}$m^{-3}. The results were compared to those in plasmas with normal B_T and I_P, with similar, but not identical, plasma parameters (I_P = 1.3MA, P_{LH} = 3.3MW). Figure 8 shows the time evolution of the shots in co and counter direction. The change in surface loop voltage, vloop (Fig. 8-d), is smaller in the counter current case, but the core T_e (fig.8-e) is higher. The evolution of the internal inductance, l_i (Fig.8-e), reveals that the current profile is evolving differently in the co and counter current cases. l_i decreases when P_{LH} is applied in the co-current case, indicating that the current profile is broadening. In contrast, l_i increases in the counter-current case, which indicates that the current profile is becoming more peaked. In addition, sawteeth are observed from ~ 49s in the two shots with counter LH current, indicating that q has reached 1. No q = 1 sawteeth are seen in the shot with co LH current.

The code CRONOS [14], which couples the diffusion equation to a 2-D equilibrium code, has been used to estimate the amount of LH current driven in shot 59671 (counter) and 57326 (co). To reproduce the measured T_e, internal inductance, l_i, and surface loop voltage, v_{loop}, in the counter CD case, a current drive efficiency of ~ 1×10^{19} A.W^{-1}.m^{-2} is required, with a central, wide, LH power deposition. This current drive efficiency is of the same order of magnitude than that found in the co-current case. However, the LH power deposition in this case is off-axis, at r/a ~ 0.4.

The sensitivity of the Cronos results to the initial conditions has been assessed, including z_{eff} and the T_e profile, to validate the results. In particular, if a current drive efficiency = 0 is assumed, a T_e lower by more than 35% than the measured T_e has to be assumed to reproduce the measured l_i and v_{loop}.

CONCLUSION AND FURTHER WORK

Dedicated experiments in conditions similar to those expected in ITER, i.e. large d_{PL} and ELMs, have shown that it is possible to couple the LH wave successfully by puffing gas near the launcher to increase $n_{e,SOL}$. They have also shown that D_2 can be used to improve the LH coupling without detrimental effects on the ITB. In addition, good coupling has been obtained in plasmas with ITER relevant triangularity, although with low d_{PL}. The investigation of the processes leading to the increase in $n_{e,SOL}$ has started. A better characterisation of the SOL plasma with gas puffing is needed however, including the effect of the connection lengths and the possible effect of the LH power on the ionisation process. This experimental characterisation should also include an investigation of the parasitic loss of LH power in the SOL. Simulations predict that the amount of LH power in parasitic high $N_{//}$ will be negligible in ITER [12]. However, theoretical predictions of non-linear edge n_e variations and n_e fluctuation effects on LH waves [15] indicate that this could be a concern, which needs investigation. The LH counter CD experiment provides results that can be used in the process of validating LHCD modelling codes.

As described, for example, in [2], LHCD is a key tool for the development of advanced tokamak scenarios in JET and other machines. Additionally, fully non-inductive scenarios for ITER rely on a large component of externally driven non-inductive off-axis current [16] which LH waves can provide. Hence a LH system is highly desirable for ITER. The demonstration of long distance coupling in plasmas with large ELMs in JET represents a major advance towards the validation of the LH system on ITER. Further work is required for extrapolating in detail the coupling results presented here to ITER, including the optimisation of a gas puffing system.

ACKNOWLEDGEMENTS

This work was performed under the European Fusion Development Agreement, and funded partly by the UK Engineering and Physical Sciences Research Council and by Euratom.

REFERENCES

[1]. S. Ide *et al*, Plasma Phys. Control. Fusion **44** (2002) L63

[2]. X. Litaudon *et al*, Plasma Phys. Control. Fusion **44** (2002) 1057

[3]. V. Pericoli-Ridolfini *et al*, Plasma Phys. Control. Fusion **46** (2004) 349

[4]. X. Litaudon *et al*, Plasma Phys. Control. Fusion **43** (2001) 677

[5]. V. Pericoli-Ridolfini *et al*, Plasma Phys. Control. Fusion **46** (2004) 349

[6]. A. Ekedahl *et al*, 31st EPS Conference on Control. Fusion and Plasma Phys., London, UK, 2004 and submitted to Nuclear Fusion

[7]. F. Rimini et al, this conference, paper EX/P3-11

[8]. G. Granucci *et al*, 30st EPS Conference on Control. Fusion and Plasma Phys., St Petersburg, Russia, 2003

[9]. M. Goniche *et al*, Nuclear Fusion **28** (1998) 919

[10]. J. Mailloux *et al*, J. Nucl. Mater. **241-243** (1997) 745

[11]. V. Fuchs *et al*, Phys. Plasmas **3** (1996) 4023

[12]. K. Rantamaki *et al*, Nuclear Fusion **40** (2000) 1477

[13]. K. Rantamaki *et al*, 30st EPS Conference on Control. Fusion and Plasma Phys., St Petersburg, Russia, 2003 and submitted to Plasma Phys. and Control. Fusion

[14]. V. Basiuk *et al*, Nucl. Fusion **43** (2003) 822

[15]. V. PetrzÌlka *et al*, 30st EPS Conference on Control. Fusion and Plasma Phys., St Petersburg, Russia, 2003 and IAEA 2000

[16]. B.J. Grĕen *et al*, Plasma Phys. and Control. Fusion **45** (2003) 687

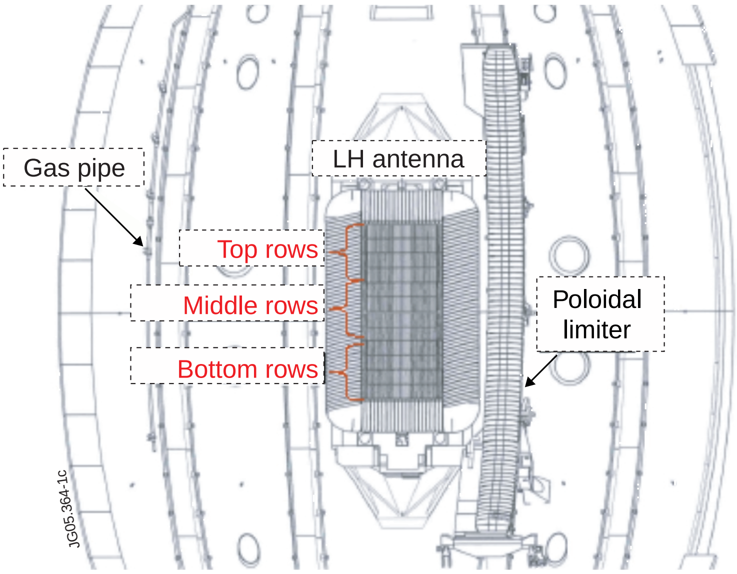

Figure 1. Drawing of the LH launcher in JET, the specially designed gas pipe and the nearest poloidal limiter.

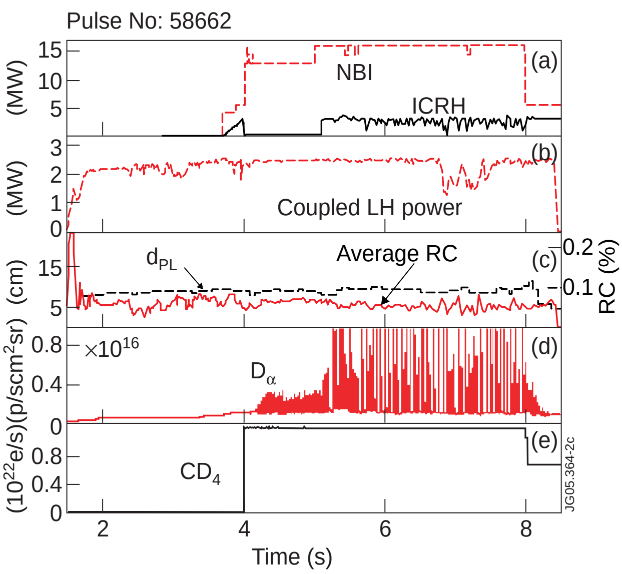

Figure 2. Time evolution of a) NBI and ICRH power, b) LH power, c) distance plasma-limiter in black and average RC in blue, d) $D_\pm$ signal and e) gas injection for Pulse No: 58662 with (CD_4).

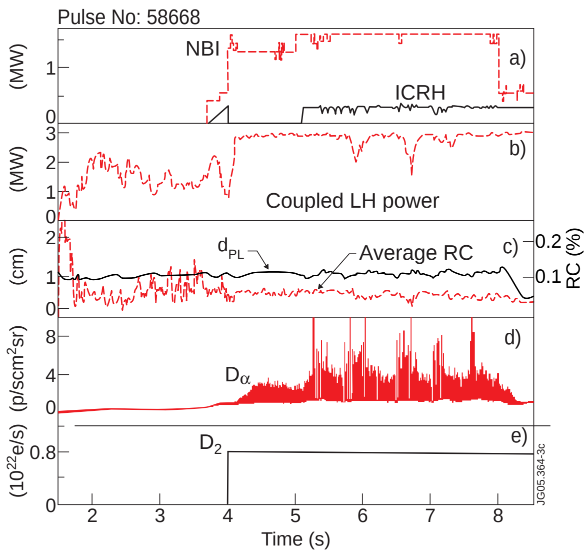

Figure 3. Time evolution of a) NBI and ICRH power, b) LH power, c) distance plasma-limiter in black and average RC in blue, d) $D_\pm$ signal and e) gas injection for Pulse No: 58668 (with D_2).

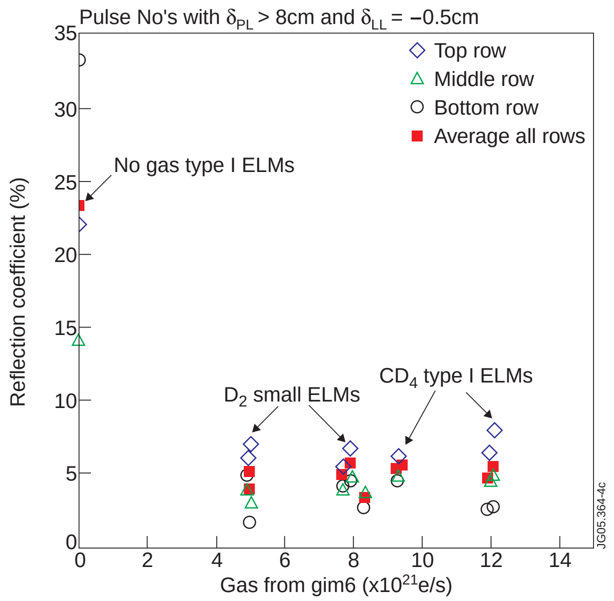

Figure 4. RC_{TOP} (diamonds), RC_{MID} (triangles), RC_{BOT} (circles) and RC averaged over all rows (squares) as a function of the gas injected in shots with d_{PL} > 8cm

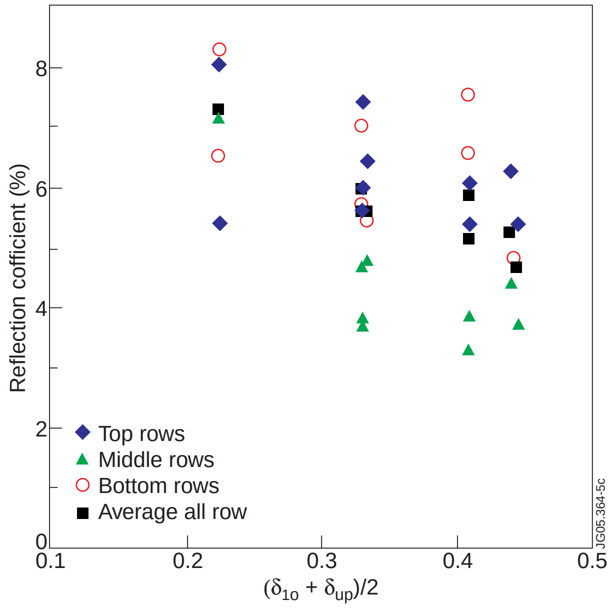

Figure 5. RC_{TOP} (diamonds), RC_{MID} (triangles), RC_{BOT} (circles) and RC over all rows (squares) as a function of the average δ.

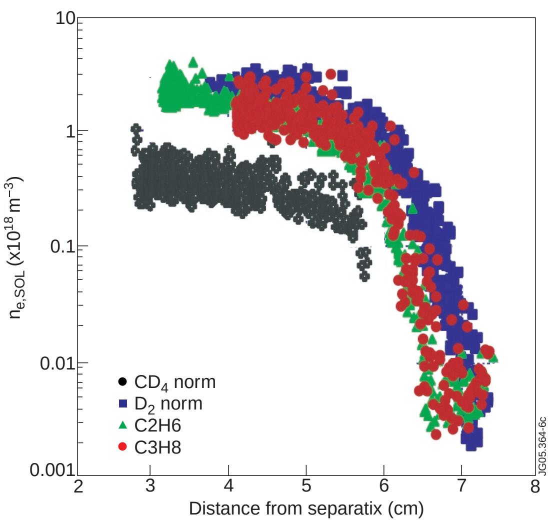

Figure 6. $n_{e,SOL}$ for CD_4 (diamonds), D_2 (squares), C_2H_6 (triangles) and C_3H_8 (circles) normalised to gas rate.

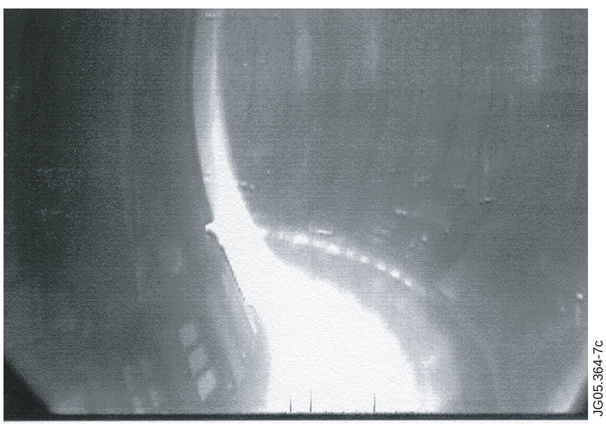

Figure 7. Bright spots on the divertor apron during LH power in JET.

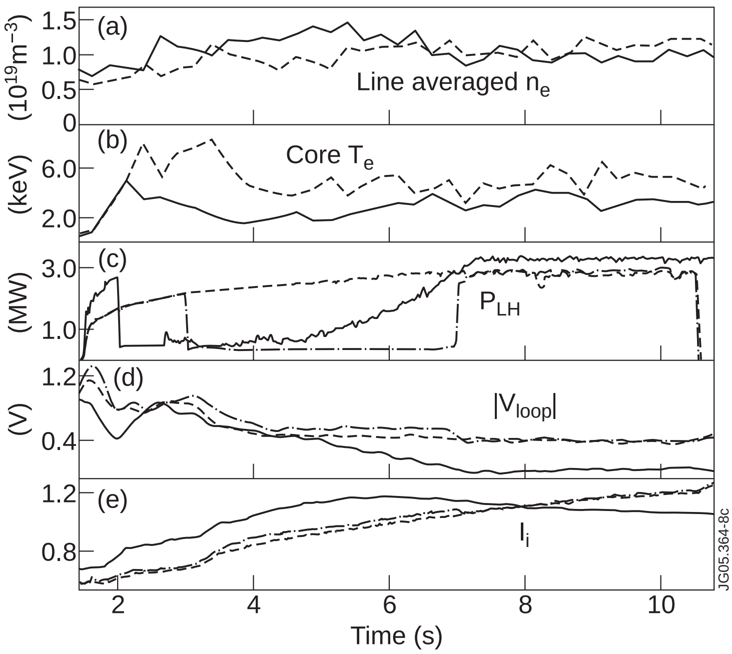

Figure 8. Evolution of plasma parameters for shots with P_{LH} in co (57326, full line) and counter (59671, dashed, and 59669, dashed + dotted lines) current drive direction.