EUROfusion

EUROFUSION WPJET1-PR(16) 15936

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Preprint of Paper to be submitted for publication in
Nuclear Fusion Letter

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Lower Hybrid Current Drive effects on JET plasma rotation

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*See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 13 -18 October 2014, Saint Petersburg, Russia

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Abstract

This paper reports on observations of rotation in JET plasmas with Lower Hybrid Current Drive. Lower Hybrid (LH) has a clear impact on rotation. The changes in core rotation can be either in the co- or counter-current directions. Experimental features that could determine the direction of rotation were investigated. Changes from co- to counter-rotation as the q-profile evolves from above unity to below unity, suggests that magnetic shear could be important. However, LH can drive either co or counter rotation in discharges with similar magnetic shear and at the same plasma current. It is not clear if a slightly lower density is significant. A power scan at fixed density, shows a lower hybrid power threshold around 3MW. For smaller LH powers, counter rotation increases with power, while for larger powers a trend towards co-rotation is found. The estimated counter-torque from the LH waves, would not explain the observed angular frequencies, neither would it explain the observation of co-rotation.

1 Introduction

Intrinsic plasma rotation of plasma, that flows mainly along the magnetic field lines, has been measured on virtually all tokamaks, nevertheless understanding its origin remains a challenge. Documenting experimental trends is still required in view of trying to predict the level of rotation that will exist in ITER [1]. Rotation in the absence of deliberate momentum input has been observed at JET in plasmas with Ohmic Heating (OH), Lower Hybrid (LH) and with Ion Cyclotron Resonance Heating (ICRH) [2, 3]. This paper reports on observations of rotation in JET plasmas with LH. The results from JET will complement intrinsic rotation experiments with LH in smaller size tokamaks such as CMOD [4-6] and Tore-Supra [7].

The JET Lower Hybrid Current Drive (LHCD) system has been mainly used for driving current and controlling the profile of the safety factor, q, in advanced plasma scenarios, such as plasmas with reversed magnetic shear and hybrid discharges [8]. The effect that LH has on plasma rotation has been measured in L-mode plasmas as the q-profile evolved from reversed shear to monotonic q-profiles, for LH powers, P_{LH}, up to 4.2 MW. Rotation was analyzed in experiments where LH was added to Neutral Beam Injection (NBI) and in no-NBI experiments dedicated to studying the intrinsic rotation. The former (discussed in section 3.1) shows the impact of lower hybrid waves on NBI induced rotation. For the intrinsic rotation study (presented in section 3.2), two types of experiments were analyzed depending on the phase in which LH was used, namely: (i) LH applied early, in the discharge pre-heating phase, when the plasma current, I_p, is still being ramped-up and the safety factor at the magnetic axis is larger than unity, $q_0>1$; and (ii) LH applied later on in the discharge with fully relaxed current profile. Dedicated intrinsic rotation measurements with LH-only and with q>1 were obtained in one discharge, previously reported in [2]. Newer intrinsic rotation data comes from experiments with LH applied when the plasma current has fully penetrated and, the q-profile was monotonic with $q_0<1$ (section 3.2 b). In the latter, rotation measurements where obtained in OH and LH phases, thus providing information on how LH alters the rotation of Ohmic plasmas. All the experiments, discussed here, were done with the previous JET CFC-wall.

Toroidal rotation was measured with Charge Exchange Recombination Spectroscopy (CXRS) of CVI line [9]. For intrinsic rotation studies, a diagnostic NBI blip, a low power, short duration NBI pulse from a normal Positive Ion Neutral Injector (PINI) was used [10]. This provided measurements of toroidal angular frequencies and ion temperatures in 12 radial positions that covered from the plasma center (typically at R~3m) to close to the edge (R~3.8), with a time resolution of 10 ms. At JET, NBI drives momentum in the co-current direction. For the purpose of intrinsic rotation measurements, the data was taken at the first available CXSR measurement collected at about 10 ms after NBI power application. The momentum input from NBI is negligible in this short time interval [11].

2 The JET Lower Hybrid Current Drive System

The LH current drive system at JET [12] is capable of launching about 6MW in L-mode plasmas

at 3.7 GHz. The microwave power is coupled into the plasma by a phase-array antenna at octant 3 also commonly referred to as a launcher, which is fed via a complex waveguide structure by the available 24 klystrons. The spectrum of the launched lower hybrid wave, which is measured as the radio frequency power density versus the parallel refractive index $N_{||}$, can be changed by phase shifting (or phasing) the power delivered by each klystron. Most commonly used phasing modes provide relatively narrow RF power spectrum peaked at about $N_{||}$=1.84. In some of the experiments discussed here an alternative phasing was used with spectrum peaked at about $N_{||}$= 2.1. Waves are launched in counter direction thus driving co-current drive. The direction of the LH wave propagation, the plasma current, I_p, and LH driven current drive are shown in figure 1.
LH waves power deposition and Current Drive (CD) used in this study are calculated by means of a new Ray Tracing (RT) / Fokker-Planck (FP) code [13]. The RT code works in real 2D geometry accounting for the plasma boundary and the launcher shape. LH waves with different $N_{||}$ spectra in poloidal direction can be launched thus simulating authentic antenna spectrum with rows fed by different combinations of klystrons. A relativistic bounce-averaged FP code is used to calculate the LH wave power absorption and CD efficiency. The quasilinear diffusion coefficient is calculated according to the procedure described in [13-14].

3 Rotation Studies with Lower Hybrid

3.1 LH effect on NBI rotation

The clear effect that LH has on plasma rotation has been observed in discharges where LH is added to continuous NBI heating. Figure 2 compares a discharge with continuous 1.5 MW of NBI heating, with a discharge where 2 MW of LH has been added to NBI. Here the NBI power from two different injectors have been alternated for measurements of Motional Stark Effect (MSE), used to calculate the q-profile, and CXRS measurements, for obtaining the rotation profiles. In these pulses, at the time the CXRS measurements started, the plasma rotation has already been influenced by the tangential NBI PINI used for the MSE measurements, figure 2. The typical observation with NBI heating is the toroidal velocity increasing with time in the co-current direction (positive sign in the figures). This is observed in the discharge with NBI-only (figure 2, traces in blue). Adding LH affects the rotation of the whole plasma, the effect being most significant in the core as shown for R=3.1m. Early in the discharge with LH+NBI (figure 2, traces in red), when magnetic shear is reversed and q is above unity, co-current rotation is slightly increased, however as the q-profile evolves into a monotonic profile, co-rotation decreases. At the later time when the central safety factor is close to unity, the central plasma velocity is 80 km/s in the discharge with NBI-only and 50 km/s in the discharge with LH+NBI. These two pulses were performed so that to have the same density and the same total plasma current. In the NBI phase, in particular in later phases when rotations are clearly different the densities are similar in both discharges. The main observed difference being the evolution of the q-profiles and an increase in core electron temperature of 50%. Since the plasma current is controlled, the internal induction, l_i, is reduced in the discharge with LH due to the larger non-inductive current.

3.2 Intrinsic rotation

Intrinsic rotation was studied in discharges with LH-only (except for NBI blips for the CXRS diagnostic). The rotation near the edge is always in the co-current direction, similar to observations in other JET L-mode plasmas [3], however in the core both co-current and counter-current rotation has been found. Typical values of the angular frequency near the edge of up to 4 krad/s with central values in either direction of up to 9 krad/s have been observed (1krad/s is equivalent to a velocity around 3 kms/s in the centre and 4 km/s at the edge). In the case of core counter-rotation the direction of rotation changes at mid-radius, as observed in JET discharges with Ohmic heating and in some cases with ICRF heating [2, 3]. As seen in the previous section, the LH effect on rotation may depend on the q-profile, so here it may be useful to separate intrinsic rotation observations when the plasma current is has not yet fully penetrated, with q above unity, and observations when central q is below unity.

In 2007 in order to investigate the possible influence of the q-profile and of core MHD instabilities on rotation in plasmas with RF heating, 2 MW of LH were used during the current ramp up to create plasmas with slightly reversed shear and q>1, as reported in [2]. Rotation measurements in a discharge with LH-only and central q~2 showed the whole plasma rotating in the direction of the plasma current. In recent experiments, LH was applied during the plasma current flat top, when the central q was just below unity consistent with the observation of sawtooth instabilities. In all discharges with $q_0<1$, except one, the rotation profiles were hollow with the core counter-rotating. In the following, pairs of discharges rotating in different directions are compared.

Figure 3 shows the angular frequency profile observed in the discharge with central q above unity with a discharge with similar average density and ion temperature, but with LH applied when the central q was below unity, as indicated by the presence of sawtooth activity. The observation of core co-rotation when LH was applied early in the discharge, and counter rotation in a later phase, appears to be consistent with the observation of decreasing co-rotation as q decreased seen in the discharge with LH+NBI in figure 2 (red traces). Both figures 2 and 3 indicate that magnetic shear might be an important factor for determining the direction of rotation in JET plasmas with LH. The calculated absorbed LH power profiles for the pair of discharges in figure 3 show that LH power reaches the plasma core in both cases. Although, sawteeth crashes are not present in the discharge with co-rotation, sawteeth are not thought to be determining the direction of plasma rotation with LH, as co-rotation is also observed in discharges with sawtooth, as described in the following paragraph.

Core co-rotation has also been observed in a discharge with monotonic q-profile with central value $q_0<1$. Figures 4-5 compare two discharges with P_{LH}=3.4 MW applied during the plasma current flat-top. These two discharges were supposed to be identical, but an unexpected influx of impurities, verified as an increase of around 10% in Zeff, leads to a small difference (up to 20%) in the density. Rotation was measured in the Ohmic plasmas before LH was applied and during LH. The time evolution traces of the central angular frequency (figure 4) show similar counter-rotation in the Ohmic phase (evolving into co-rotation during the NBI blip). During the LH

phase, counter-rotation increases in one case (blue traces), while the direction of rotation is reversed in the other (red traces). The difference between the rotation profile measured during LH and Ohmic phases (taking the rotation measurements at the beginning of the respective NBI blips), $\Delta\omega=\omega_{LH}-\omega_{Ohmic}$, is shown in figure 5a. Co-rotation was observed in the discharge with the slightly lower density and lower collisionality. One should note that differences in collisionality were already present in the Ohmic phase, but no significant effect on Ohmic rotation was observed. The large effect on rotation was observed with LH, indicating that directly or indirectly this is caused by LH.

The LH deposition profiles and the current driven by LH are shown in figure 5b. At the lower density the power deposition is centrally peaked, #74871 red curve, while at higher density, #74870 blue curve, the power deposition profile is broader and more off-axis. A larger driven current is observed in the outer region of the counter-rotating discharge, indicating that there might be local differences in magnetic shear. Small differences in sawtooth observations, the sawtooth frequency was slightly larger in the discharge with co-rotation also indicate localized differences in magnetic shear. This cannot be verified in the absence of MSE measurements. EFIT reconstruction with polarimetry constraints gives nearly identical q-profiles, with a difference in q_0 less than 0.05.

In the following, we look at trends obtained from the whole database. The largest effects on rotation have been observed in the core of the plasma. In the following figures the peak rotation is shown, that in most cases is in the counter-direction. A typical hollow profile is shown in figure 3. The maximum rotation occurs near the center at a normalized radius r/a<0.3. The experiments, done mostly parasitically to other experiments, had a narrow range of average line densities of $1.6\text{-}2.3\cdot10^{19}$ m^{-3}, as shown in Figure 6. The two measurements during the current ramp-up, with $q_0>1$, with I_p=1.9-2.2MA, B_T=2.8 T, are indicated by open symbols. For discharges with LH applied during the current flat top, $q_0<1$, the majority have I_p=2 MA, B_T=2.3-2.5 T, with average line densities $1.9\text{-}2.0\cdot10^{19}$ m^{-3} (this subset of discharges will be show in more detail in figures 7a-c). A smaller set of four discharges, with average line density around $2.2\cdot10^{19}$ m^{-3}, have I_p=1.7 MA, B_T=2.9 T. Co-rotation was observed in discharges with lower average line densities, $\langle n_e\rangle \leq 1.9\cdot10^{19}$ m^{-3} and in discharges with q above unity. Since the number of discharges with density below $\langle n_e\rangle \leq 1.9\cdot10^{19}$ m^{-3} is limited it is not possible to see how the rotation changes with density. The two LH refractive indexes at the launcher, $N_{//}$=1.84 and $N_{//}$=2.1 are indicated, respectively, by blue kites and red circles. No significant difference in the range of rotation values has been seen with $N_{||}$.

Figures 7a-c shows a subset of the discharges with $q_0<1$ and $\langle n_e\rangle \leq 2.0\cdot10^{19}$ m^{-3}. All these discharges have configuration B_T=2.3-2.5 T and I_p=2 MA. We will focus here on the counter-rotation cases, with densities in the range $\langle n_e\rangle$ =$1.9\text{-}2.0\cdot10^{19}$ m^{-3} (shaded area in figure 6), but for comparison also show the co-rotation case with the lower density $\langle n_e\rangle < 1.6\cdot10^{19}$ m^{-3} (this is the co-rotating pulse in figures 4-5, indicated here by open symbols). All the counter-rotating cases are essentially the same Ohmic target plasma, with LH power scans up to 4.2 MW. In all these discharges, the core of both Ohmic and LH plasmas are counter-rotating. However, the LH effect

can be either to increase or decrease counter rotation. Figure 7a shows the peak rotation versus LH power. A power threshold P_{LH}~3 MW was found: for lower LH powers the rotation increases in the counter-rotation while at higher powers adding LH reduces counter-rotation. The overall trend is that counter-rotation increases as P_{LH} is increased, reaches a minimum at 3 MW, then decreases linearly with power. The same pattern is observed if one plots the difference $\Delta\omega=\omega_{LH}-\omega_{Ohmic}$, with counter-rotation increasing with respect to the Ohmic reference up to a power of around 2.5 MW; for higher LH powers, co-rotation increases with respect to the Ohmic reference. At 4 MW the difference between Ohmic and LH peak rotation is negligible.

4 Discussion

Two possible causes related to LH waves can affect the ion rotation: (i) direct momentum input from the waves or; (ii) in a more complex way as a result of non-inductive current impact on the magnetic shear which modifies the turbulence and thus affects the rotation [15]. Indirect changes in momentum transport can also occur due to LH heating leading to modification of bulk plasma profiles, in their turn again changing turbulence and MHD stability.

LH wave power deposition profiles and driven current profiles were calculated by means of a ray tracing / Fokker-Plank code for some of the pulses in the power range P_{LH}=2-3 MW. The calculated LH absorbed power was then used to calculate the LH driven torque and the expected angular frequency. At JET a toroidal angular momentum in the counter-current direction is injected by the lower hybrid. The parallel and the perpendicular components of the angular momentum are transferred from the waves to the electrons and after several collision times to the ions [16]. For a pulse with P_{LH}~2.5 MW, showing counter rotation, the torque driven by the LH waves is around 10^{-3} Nm/m^{-3}. Assuming a Prandtl number of unity, the angular frequencies originating from torque driven by LH waves are an order of magnitude smaller than the observed LH effect on the Ohmic angular frequencies. Thus the LH torque would not explain the observed counter-rotation. In addition, it is inconsistent with the trend of increased co-rotation as the LH power increases.

A change from co- to counter-rotation as the q-profile evolves from above unity to below unity, suggests that processes associated to magnetic shear could be important. Co-rotation in the plasma core was observed in plasmas with $q_0>1$ with a low shear in the core (see co-rotating case in figure 3). Most plasmas with $q_0<1$, showed counter current rotation. In the latter, evidence of the role of the LH driven current, comes from the observation of a trend of increasing co-rotation as the LH power increases and thus the LH driven current increases. As the subset of discharges in figure 7a have all similar densities and toroidal field, for a given N// value the driven current I_{LH} is proportional to P_{LH} [17]. The change in the internal inductance, li, as a function of LH power, indicates that for LH powers > 2.5 MW, non-inductive current increases with LH power (Figure 7b). In the set of discharges described here LH was not fully optimised for current drive, thus the central electron temperature doubled from an average Ohmic value of 1.7KeV to 3.6 KeV at the maximum power of 4.2 MW (figure 7c). Thus the change in current is due to an effect of increasing electron temperature as well as an increase in LH driven current. The

increase in non-inductive current is expect to decrease the core magnetic shear. This trend is suggested by sawtooth observations and from EFIT magnetic reconstructions that show that magnetic shear in the plasma core decreases as LH power increases. The core shear becomes lower than reference Ohmic values for LH powers larger than 2 MW. EFIT data shows that both the Ohmic Power and the loop voltage decreases as expected as the LH power increases.

Changes in q-profile can be inferred from changes in sawtooth stability. The sawtooth period increases with LH power, suggesting increased stability of the internal kink mode at lower magnetic shear. However, the region affected by sawtooth is also reduced as the region inside of q=1 decreased. In discharges with sawteeth the peak rotation is observed near the sawtooth inversion radius (similar to observations in TCV [18]). As the inner region affected by sawtooth is getting smaller, one might expect the peak counter-rotation to increase with LH power, this is observed at low LH powers, but it is inconsistent with the co-rotating trend at the higher LH powers. Whilst in figure 7, the trend towards co-rotation occurs together with an increase in sawtooth period, in the pair of discharges in figures 4-5, the case with co-rotation has a slightly higher sawtooth period. No clear association between sawtooth observations and rotation trends has been obtained. Note that the direction and magnitude of rotation in JET discharges with ICRH could not be explained by sawtooth activity [2].

Since LH is very effectively at providing heating, kinetic plasma profiles and their derivatives are changed, which will change momentum transport as well as the LH power deposition. Further analysis is needed to understand if small differences in density or density gradient (as observed in figures 4-5), or the increase in the ratio between electron and ion temperatures could be influencing the direction of the rotation. Co rotation was observed in low density discharges. Decreasing the density improves LH core accessibility. The LH power deposition and driven current profiles, for the discharges with $q_0<1$ in figure 5b, show that for the same LH power, counter rotation was observed in the case of a broad off-axis deposition, while co-rotation was seen with peaked deposition. Differences in the LH driven current are expected to have created local changes in the q-profile, supported by small changes in sawtooth observations. In experiments with electron cyclotron heating (ECH), in DIII-D [19] and AUG [20], that similarly to LH provide heating as well as driving current, rotation profile shape in the plasma core has been observed to depend on the power deposition profile.

Extensive research of rotation effects with LH have previously been made in C-MOD [5-6] and Tore-Supra [7], in both experiments the plasma core has been found to rotate in either co- or counter-directions, with magnetic shear and total plasma current being identified as important parameters in determining the direction of the core rotation. In both machines, at a fixed density there is a critical plasma current where the direction of rotation is reversed. In the JET experiments with lower hybrid, this cannot be verified since the plasma current range is too small. In C-MOD a correlation between direction of rotation and magnetic shear was found [21]. As observed in JET, in C-MOD co-rotation was seen in plasmas with central safety factor above unity, while most of the plasmas with sawtooth, indicating that $q_0<1$, showed counter-rotation. However, in JET, application of LH can drive either co or counter rotation in discharges with similar magnetic shear and at the same plasma current. Here co-rotation was observed at a

slightly lower density, suggesting a possible similarity with Ohmic rotation observations in several tokamaks [22-25] where a rotation reversal from co to counter direction has been observed at a critical density or as suggested by AUG data at a critical density gradient [24].
Gyrokinetic modelling of the effect of turbulence on neoclassical parallel velocity, heat flow and neoclassical poloidal electric field have shown that changing collisionality [26] as well as magnetic shear [15, 27-28] can change the direction of rotation in quantitative agreement with observations in some tokamaks. Changes of rotation associated to magnetic shear were observed, when LH was added to Ohmic plasmas, as well as when LH was added to NBI heated plasmas. In the case with NBI, the change in the toroidal rotation may be the result of enhanced turbulent diffusion of the momentum injected by NBI due to a change in the magnetic shear, whereas in the case without NBI, both the turbulent diffusivity and the intrinsic momentum flux may have changed. Momentum transport modelling of the discharges discussed here, to be performed in the future, should take into consideration the effect of LH on q profile and magnetic shear, as well as kinetic profile changes, in particular the large increase in electron temperature with LH power.

5 Conclusions

When comparing pulses with and without LH a clear impact of LH on rotation is seen. The changes in core rotation can be either in the co- or counter-current directions. What experimental parameters might determine the direction of rotation in the plasma core has been investigated.
A change from co- to counter-rotation as the q-profile evolves from above unity to below unity, suggests that processes associated to magnetic shear could be important. For pulses with monotonic q profiles, with $q_0<1$, a power scan at fixed density, shows a power threshold around $P_{LH}\sim3$MW. For smaller LH powers, counter rotation increases with power, while for larger powers a trend towards co-rotation is found. An observed correlation with a decrease in the internal inductance indicates that the co-rotation trend is related to an increase in non-inductive current.
The possibility that the observed core-rotation might be related to LH core accessibility has been investigated and the effect that the LH waves deposition profile might have on rotation has been assessed. The power deposition has been calculated with a ray tracing code coupled to a Fokker Plank code. The estimated counter-torque from the LH waves, would not explain the observed angular frequencies, neither would it explain the observation of co-rotation.

Acknowledgements
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. M. F. F. Nave has also received financial support from “Fundação para a Ciência e Tecnologia” through contracts UID/FIS/50010/2013 and IF/00483/2014/CP1214/CT0008. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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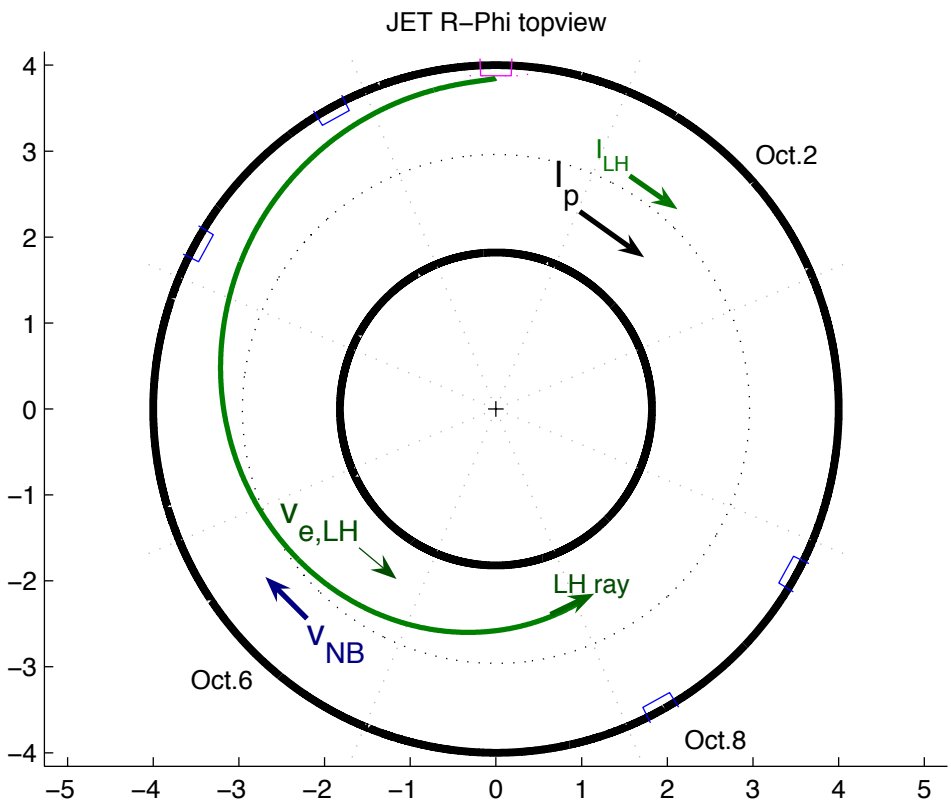


Figure 1 - JET schematic view from top showing the directions of the plasma current I_p, the LH driven current I_{LH}, the direction of propagation of LH waves, NBI driven velocity v_{NB} and the direction of the velocity of the fast electrons generated by LH, $v_{e,LH}$.

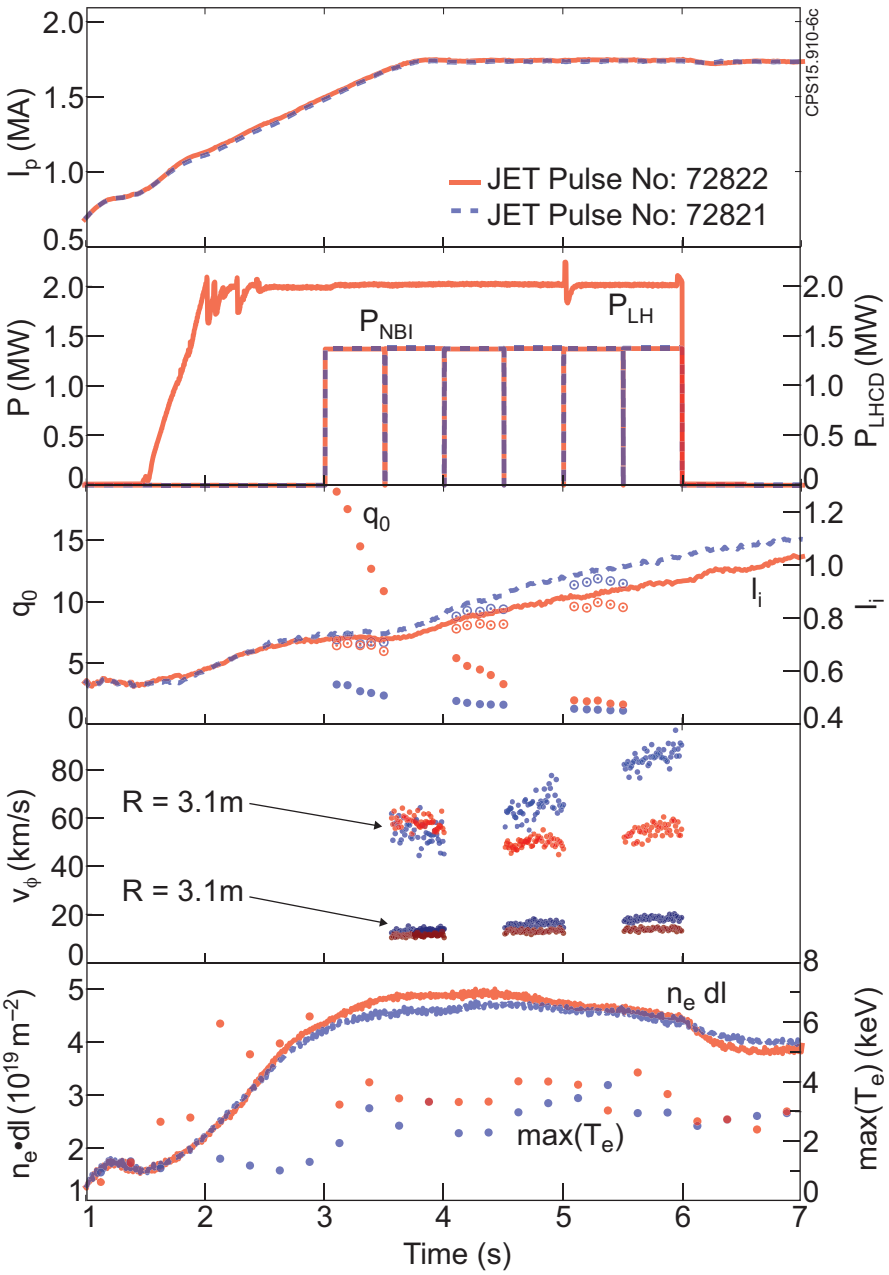


Figure 2 - Comparison of two JET pulses, 2.65T/1.7MA low density, $\langle n_e \rangle \sim 1.8e19m^{-3}$, with LH (red) and without LH (blue). The boxes show from top to bottom: (i) Total plasma current I_p, (ii) Continuous application of P_{NBI} in both pulses, consisting of alternate blips for measurements of MSE and CXRS and application of P_{LH} in one pulse; (iii) Central safety factor, q_0, and internal inductance, l_i, using magnetics and MSE data, (iv) central and edge toroidal velocity from C^6 CXRS and, (v) integrated line density through the plasma centre and maximum electron temperature.

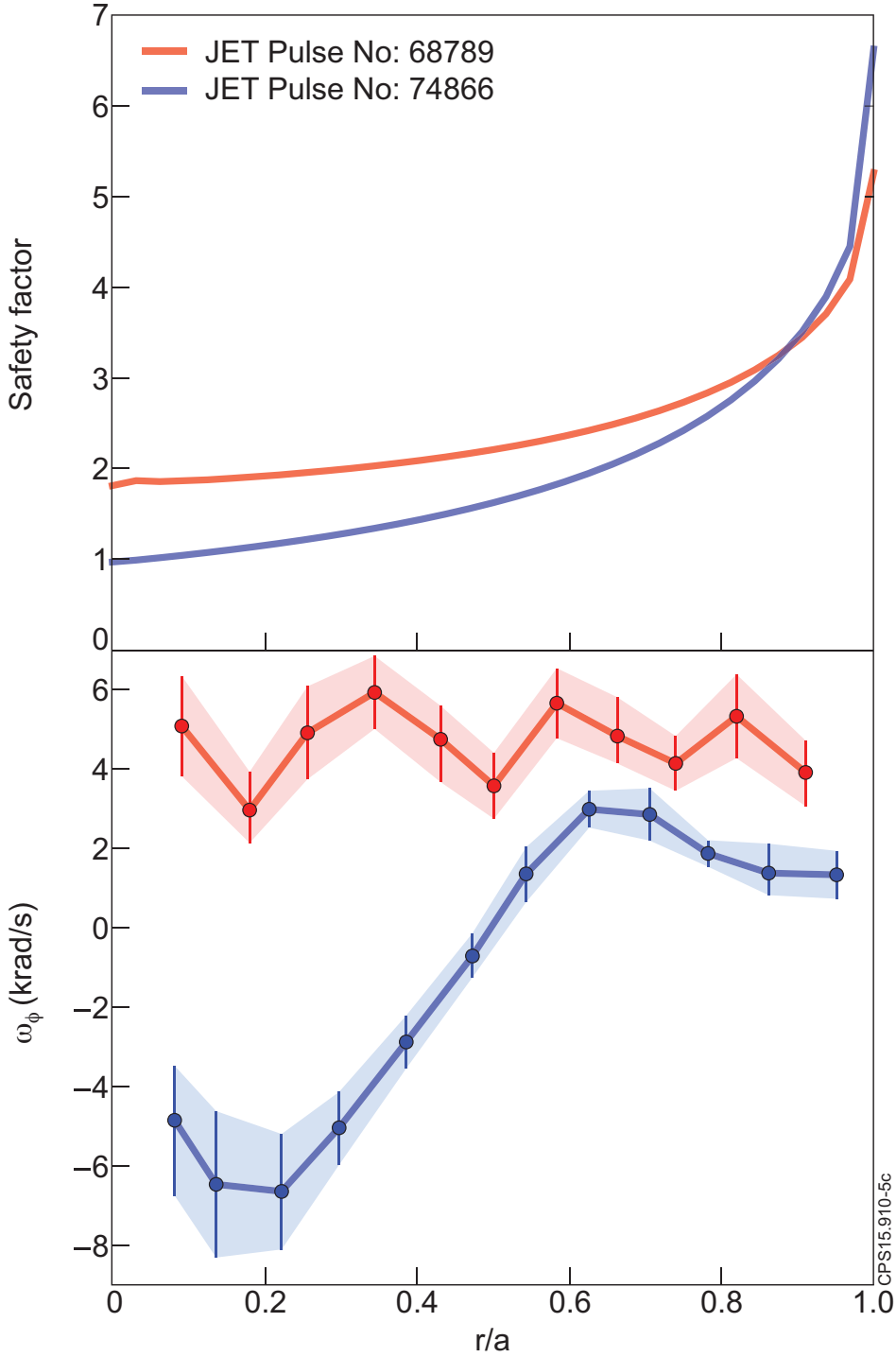


Figure 3 - Plasmas with LH applied during the I_p-ramp (Pulse 68789 with P_{LH}~1.8 MW, I_p=2.2 MA, B_T=2.8 T, $\langle n_e \rangle = 1.94 \cdot 10^{19}$ m^{-3}) and applied later during Ip flat-top (Pulse 74866 with P_{LH}=2.5 MW, I_p=2.0 MA, B_T=2.5T, $\langle n_e \rangle = 1.95 \cdot 10^{19}$ m-3). $N_{//}$=1.84 in both cases). (top) Safety factor profiles and (bottom) C^6 angular frequency profiles (measured at the beginning of NBI blips). The shaded area shows the CXRS fitting uncertainly.

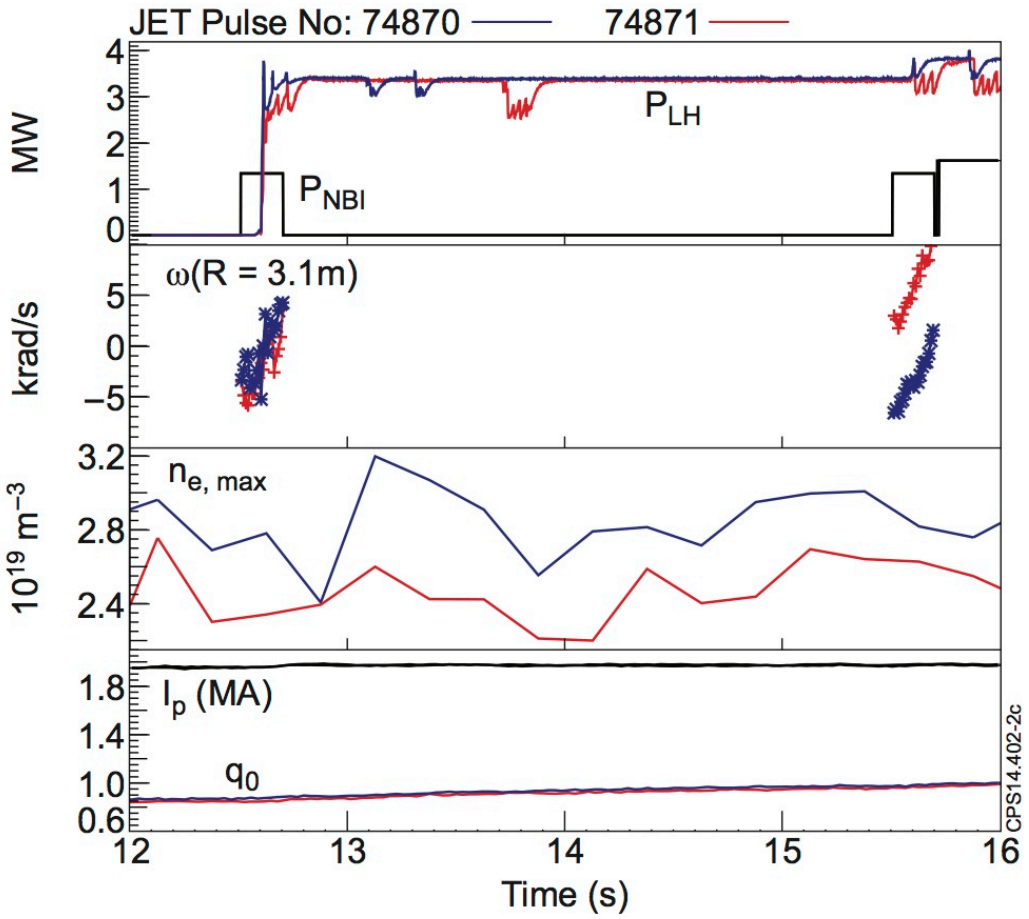
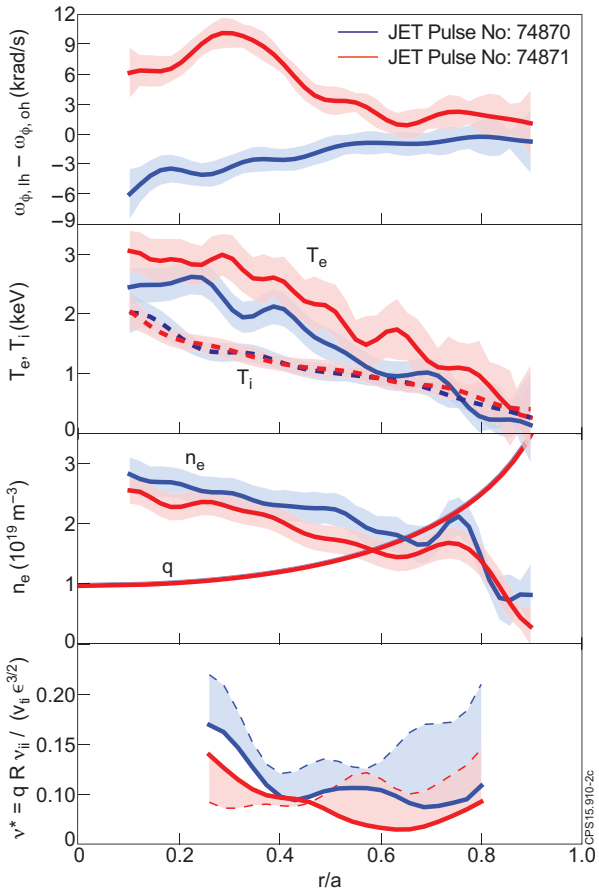


Figure 4 – Plasmas with monotonic q –profiles at the same I_p=2MA, B_T=2.45T. (i) P_{LH}=3.5 MW, short pulses of P_{NBI} to measure CXRS, the 1st NBI blip in the Ohmic phase, the 2nd blip in the LH phase, (ii) C^6 angular frequency near the centre (R=3.1 m), (iii) Maximum n_e from LIDAR, (d) I_p and EFIT q_0.

(a) *(b)*



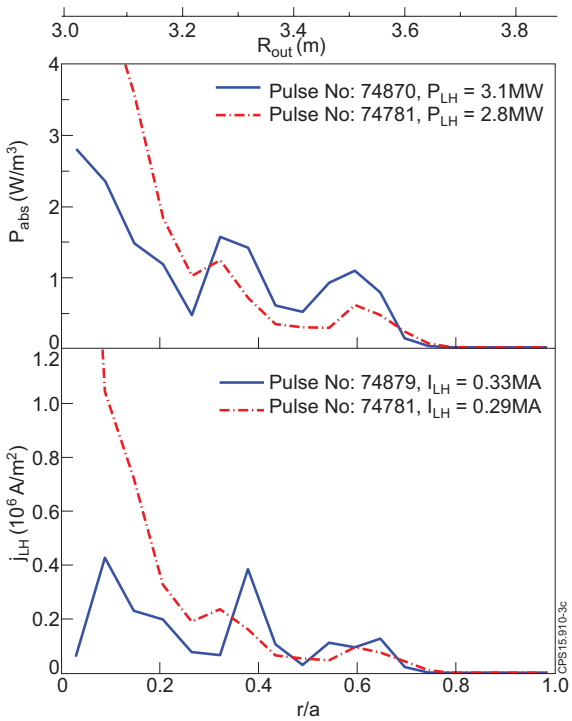


Figure 5a – Plasma profiles just before or at the beginning of the 2nd NBI blip at 15.515s. From top to bottom: (i) ω_{LH}-ω_{Oh}, the difference between the C^6 angular frequency profiles measured with LH, t= 15.515 s at the beginning of the 2nd NBI blip, and without LH, t=12.515s at the beginning of 1st blip, (ii) LIDAR T_e and CXRS T_i, (iii) LIDAR n_e profiles and EFIT q profiles, (iv) normalised collisionalities.

Figure 5b– (i) Absorbed LH wave power density profiles and (ii) current driven profiles versus normalized minor radius for pulses shown in figures 4 and 5. The LFS major radius, R_{out}, mapped to the corresponding r/a for these two pulses is provided on the top of the graph. Note that the LH power deposition profiles in the very core, inside r/a<0.05, are not very accurate.

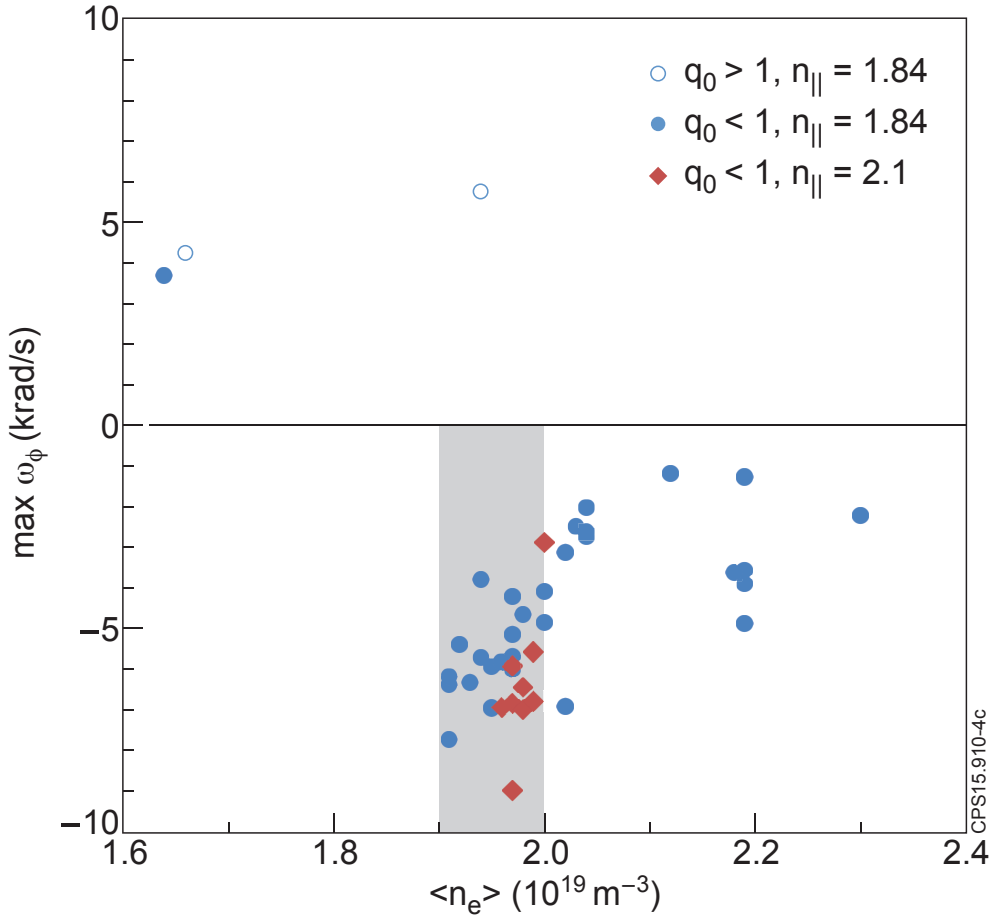


Fig 6 – Peak angular frequency, measured near the plasma centre during LH application versus the average line density (defined here as the integrated line density through the plasma centre divided by the cord length). Blue circles and red kite symbols indicate respectively, n// at the launcher of 1.84 and 2.1. The two measurements for plasmas with q_0~2 are indicated by open blue circles, all the others have q_0<1. The shaded area with average densities in the narrow range 1.9-2.0 10^{19} m^{-3} shows the subset of counter rotating plasmas discussed in the next figures.

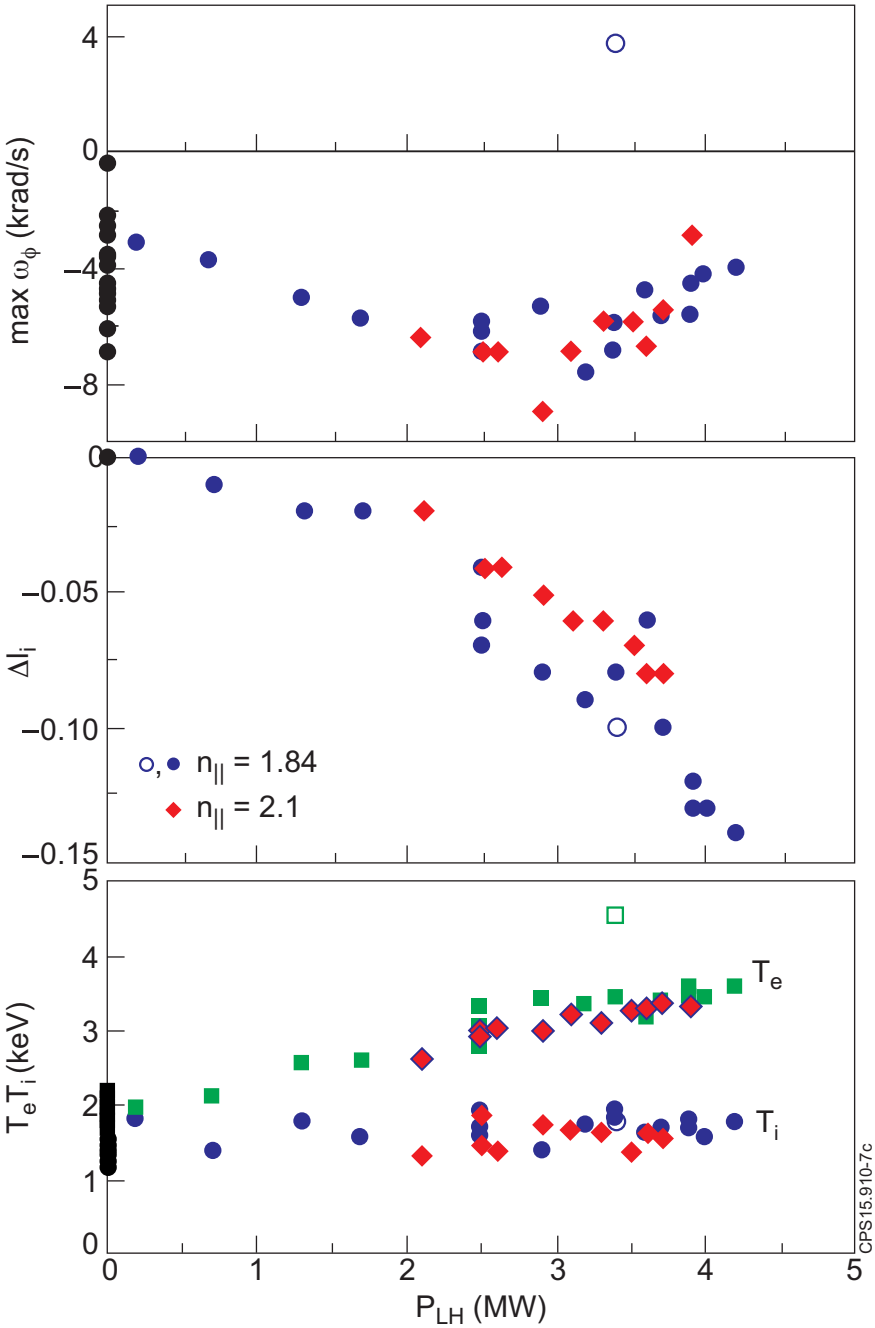


Fig 7 – (i) Peak angular frequency versus LH power for the discharges with $q_0<1$, with average line densities $<n_e> \leq 2.0\cdot10^{19}$ m^{-3}, B_T=2.3-2.5 T and I_p=2 MA. All the counter-rotation cases have a narrow density range $<n_e>$ =1.9-2.0·10^{19} m^{-3}. For comparison, the co-rotation case with the lower density $<n_e>$ ~1.64·10^{19} m^{-3} is shown with open symbols.
(ii) Change in li, ie the difference between li in the Ohmic and the LH phases, versus LH power. The average Ohmic li value is 1.2.
(iii) Maximum electron and ion temperatures versus LH Power.