JET–R(99)09

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February 2000

ABSTRACT

Lower Hybrid Current Drive (LHCD) is the most efficient tool to generate non-inductive current in tokamak plasmas. In JET, significant modifications of the current profile have been recently achieved in coupling up to 3MW of LH power in optimised shear discharges. However, the improved particle confinement during optimised shear plasmas results in a sharp decrease of the electron density in front the launcher close or below the cut-off density (ne=1.7.10^{17} m^{-3} for f_{LH}=37GHz) and makes difficult the coupling of the LH power. Deuterium gas near the launcher can help to improve the coupling, but has also the effect of increasing the ELM activity leading to the erosion of the internal transport barrier (ITB). Future development of lower hybrid launcher should include the constraints imposed by scenario such as the optimised shear.

INTRODUCTION

In JET, the full Lower Hybrid Current Drive system is in operation since 1994. Up to 6MW have been successfully coupled for about 10s and up to 7.3MW for several seconds in L-mode plasma. The system has been used in various scenarii to optimise the current profile such as hot-ion-modes [1] and optimised shear [2]. In the latter, LHCD has been used both to assist the start-up of the discharge and to drive edge current during the subsequent high power heating and performance phase. However, in this last phase, it appears that the reflection coefficient of the LH wave is very high (more than 20%), making difficult the coupling of more than 1MW of reliable power.

This paper focuses on the edge operating conditions to couple the LH-wave during optimised shear discharges. The effect of the ELMs is specifically addressed and the edge density profile decay is measured in the scrape off layer using a Langmuir probe. Then the experimental results of gas injection to control the edge density is described in detail. In the conclusion we will suggest possible ideas of development to improve the coupling during extreme conditions like those observed during optimised shear discharges.

1. THE LHCD SYSTEM ON JET AND EXPERIMENTAL SET-UP

On JET, the LHCD plant is equipped with 24 klystrons of 650kW each and operating at 3.7Ghz. The N// spectrum peaks at 1.84 for 0° phasing between adjacent multi-junctions. The launching antenna is made of 48 multi-junctions each dividing the power into eight wave guides [3]. The launcher can be moved radially behind the guard limiter and during the discharge with a stroke of 150mm.

Extensive programme of conditioning can be carried out to reduce the probability of arcing in the multi-junction and therefore to improve the achievable coupled power [4]. For this purpose, the vessel can be baked up to 350°C and the power can be applied with a high repetition rate.

A special gas pipe has also been installed 120cm toroidally from the launcher to modify the edge conditions in an attempt to improve the LH-coupling. This pipe injects any kind of gas

(Deuterium or impurity) along the vertical extent of the launcher. The pipe is 1.2m long and equipped with 10 holes of increasing aperture magnetically connected with all rows of the antenna. The injection rate and the timing can be adjusted during the operation. During the operation, it is usually limited to 8.10^{21} electrons per second to prevent the erosion of the launcher by charge exchange when the neutral density is too high.

During the operation, the fraction of reflected power is the first criterion to determine the maximum LHCD power that can be achieved. The reflection power is measured in real time in both arms of each multi-junction. From this, the reflection coefficient is experimentally determined for each klystron as:

$$(P_{ref}\ A + P_{ref}\ B)/P_{input}.$$

where A and B indexes denote each arm of the klystron.

This measurement is systematically recorded during the operations and used by the LH-system to trip the power in bad coupling conditions. In particular, systematic measurements have shown [5] that high standing wave amplitude in the wave-guide and unbalanced reflected power are the most dominant causes for the power to trip. Even when the system is well tuned, several reasons can produce high level of unbalanced reflected power during plasma operation. Perturbation of the edge density in ELMy H-modes [6] or connection with the ICRH antenna are known in JET to cause substantial increase of the reflected power and therefore of the unbalanced reflected power. Also, power from one module can be reflected back into the neighbouring wave-guides of other klystrons. This feature is often observed when the reflection coefficient is high.

2. LOWER HYBRID WAVE COUPLING DURING OPTIMISED SHEAR SCENARIO

Reflection coefficient measurement in Optimised shear discharges

During optimised shear scenario at 3.4T, the LHCD wave is first applied at low power (1MW) for about 1s in the initial phase of the plasma to assist the plasma breakdown and to slow down the current diffusion (Fig.1). During this initial phase the last closed flux surface is still far from the launcher (6 to 7 cm) and still evolving. The plasma is in L-mode at low density ($n_e=1.10^{19}$ m^{-3}) and low current (Ip=0.6MA). Despite these unfavourable conditions the LH-coupling behaves in a good manner and shows reflection coefficients of a few percents. These relatively good coupling conditions in limiter plasmas [6] are probably linked to the large magnetic connection length in this configuration. In this regime, the density decay length λ_{SOl} is large and therefore the plasma density is still sufficiently high in front of the launcher to couple the LH-wave. This pre-heating procedure is very reliable and doesn't seem to suffer from side effect like the generation of fast electron beam at the plasma edge.

LH-power is then applied as the ITB (Internal Transport Barrier) is formed and when the plasma current reaches its plateau. The use of the LH-power aims to maintain a significant amount of non-inductive off-axis current to the edge inductive current generated during thecurrent ramp-up. By this mean a large low shear region can be sustained in the plasma core to extend the ITB phase duration.

With the MarkIIGB divertor, the optimised shear scenario is achieved in ELMy H-mode phase with type III ELMs (fig.1). It often terminates by the transition to the L-mode after a few larger ELMs eroding the barrier and eventually destroying it. The LH-power is applied during the barrier during the ELMy H-mode, and extends after the transition from H to L mode terminating the ITB phase.

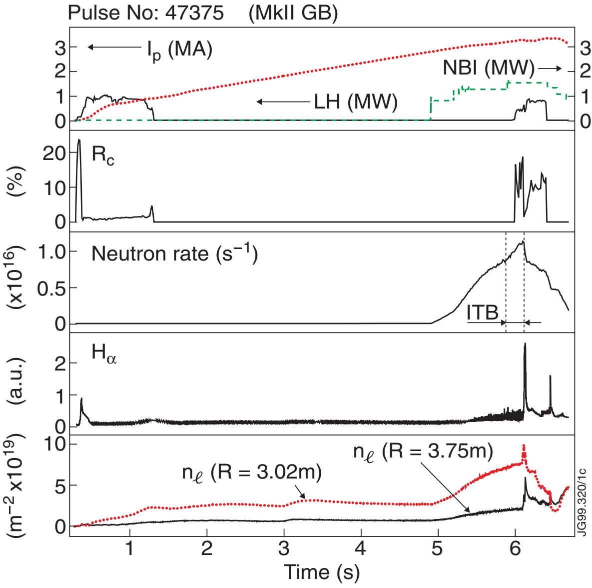

Fig.1: Typical Optimised shear scenario in JET with the MarkIIGB divertor and with the LHCD power in the breakdown and during the internal transport barrier.

In the case of the MarkIIA divertor (fig.2), the ITB is formed during the L-mode phase and then an ELM-free H-mode is triggered. For this particular discharge, the LH-power was applied during the whole discharge and was stopped when the H-mode starts to study the coupling behaviour during the ITB build-up.

During the L-mode phase either before or after an ITB phase, the reflection coefficient is relatively low (10%) (after t=6.2s on fig.1 and between 6s and 6.5s on fig.2).

When the ITB is triggered in L-mode (MarkIIA at t=6.6s on fig.2) or in ELMy H-mode (MarkIIGB at t=5.8s on fig.1), the average level of Rc goes up to 20% and therefore, the LH power cannot be coupled reliably.

In both cases the antenna is standing 3 to 4 cm from the plasma, in the shadow of the limiter by 5 to 10mm.

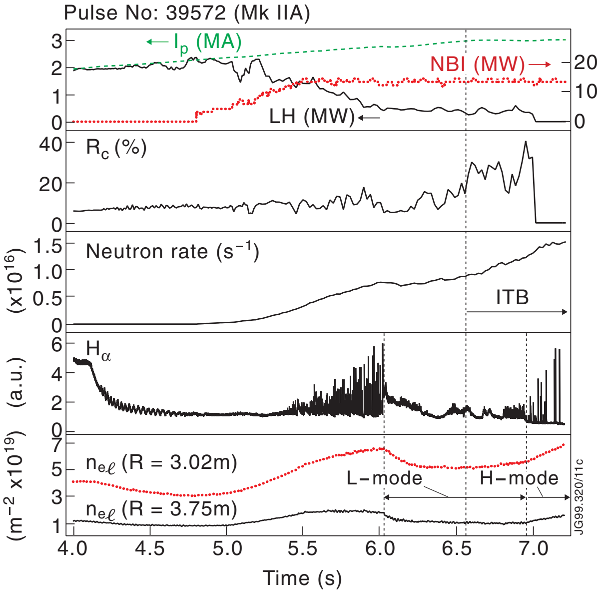

Fig.2: Reflection coefficient behaviour during a typical optimised shear discharge with the MarkIIA divertor.

ELM effect on the reflection coefficient

For both divertors (MarkIIGB and MarkIIA), the average reflection coefficient shows large excursions during the type III ELMy H-mode at t=6s and t=5.8s respectively. This behaviour is caused by the large number of power trips triggered by the LH-system. These power trips are being triggered by the excursion of the reflected power when going from the ELM event to the ELM-free phase in-between ELMs.

To illustrate the effect of the ELMs on coupling, fast acquisition data of in the lower and upper arm of the line coming from the multi-junction have recorded the reflected power of klystron E3 (fig.3a). From this figure, we note the following observations:

The average level of the reflected power is very different between the upper arm and the lower arm (8 or 9 kW for lower arm and 3 to 4kW for upper arm). In addition, the reflected power variation in each arm is clearly correlated with the ELMs. The power shows excursions between 15 and 3 kW for the lower arm and 8 to 1 kW in the upper arm. The reflection coefficient varies from a few percents to almost 30%. We also note that the ELMs have actually the effect to decrease the reflected power in both arms. This observation is true for all klystrons.

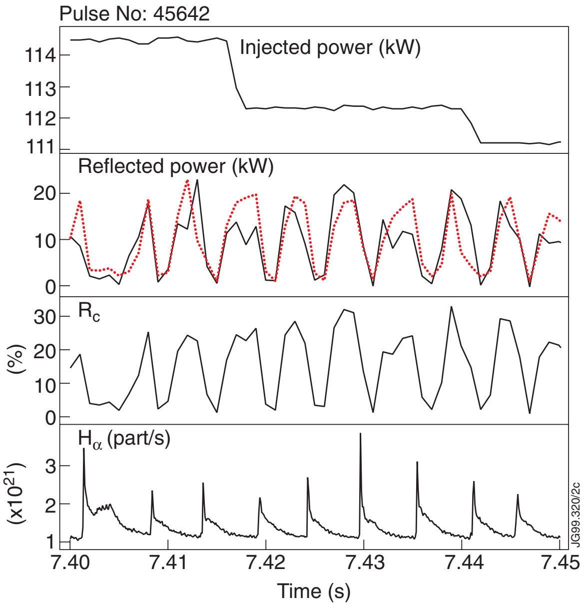

Fig.3a: Correlation of the reflection coefficient of the LH-wave with the type III ELM activity (MarkIIGB divertor).

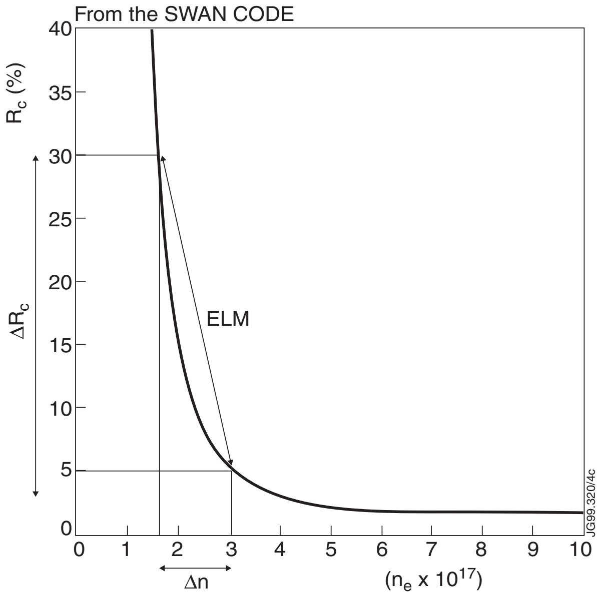

Fig.3b: Trajectory of an ELM along the reflection coefficient versus density curve.

The strong observed excursion of the reflected power in both arms could explain the triggering of power trips. For large ELMs, the excursion in reflected power can reach very high value and power trips are likely to be triggered. These power trips occur mainly when the unbalance between the reflected powers in upper and lower arms is too large.

Since the effect of the ELMs is essentially to expel particles from the edge of the plasma, the edge density should increase during the time of an ELM. Looking at the dependence of the reflection coefficient with the density (fig.3b) as computed with the SWAN code [7] and backed up by experimental results [6], an increase of the edge density in front of the launcher should have a beneficial effect on the reflection coefficient for densities less than 4.10^{17} m^{-3}. The minima observed on the reflection coefficient at the time of the outward particle bursts caused by the ELMs (fig.3a) are indeed confirming this analysis.

A first rough estimate of the density in front of the launcher is made possible with the use of the curve of fig.3b. The excursion in reflection coefficient (from 5 to 30%) appears to correspond to a density variation in front of the launcher from 2 to 3$10^{17}$ m^{-3}. This density is close to the cut-off density of the lower hybrid wave (1.7 10^{17} m^{-3}). This density variation is consistent with the number of particles expelled per ELMs as estimated from the D_α signal (fig.3). Assuming that the ELM duration is approximately 200µs, an outflux of 2.10^{21} particles corresponds to a density variation of about 1.10^{17} m^{-3}.

This first estimate of the density led the study towards the measurements of the behaviour of the density in the vicinity of the launcher.

3. EDGE DENSITY BEHAVIOUR DURING OPTIMISED SHEAR DISCHARGES

Scrape of layer density measurement (MarkIIGB)

To quantify more precisely the edge density profile in the scrape off layer, Langmuir reciprocating probe measurements have been made before (at t=42.5 s) and during the ITB phase at t=45s (fig.4). In JET, Langmuir probe is located in the top of the vessel at R=2.45m and Z= 1.75m. For these experiments, the probe stroke extended from -100mm to the separatrix. The density is deduced from the measured saturation current assuming that Ti=2.Te for the calculation of the sound velocity. The results are showing a strong steepening of the edge density gradient between the phase at t=42.5s in L-mode and the ITB phase in ELMy H-mode at t=45s (fig.5). The density decay length λ_{sol} decreases from 57mm to 16mm. Assuming a diffusive radial transport of characteristic coefficient $D_\perp = \lambda_{\mathrm{SOL}}^2 . C_s / L_{||}$ (where C_s is the acoustic speed and L the parallel connection length), this drop of λ_{sol} corresponds to a reduction of radial transport by a factor of 7. It should be noted that those measurements are made outside the launcher protection limiter frame. The actual density in the vicinity of the front end of the grill antenna (5 to 10mm behind

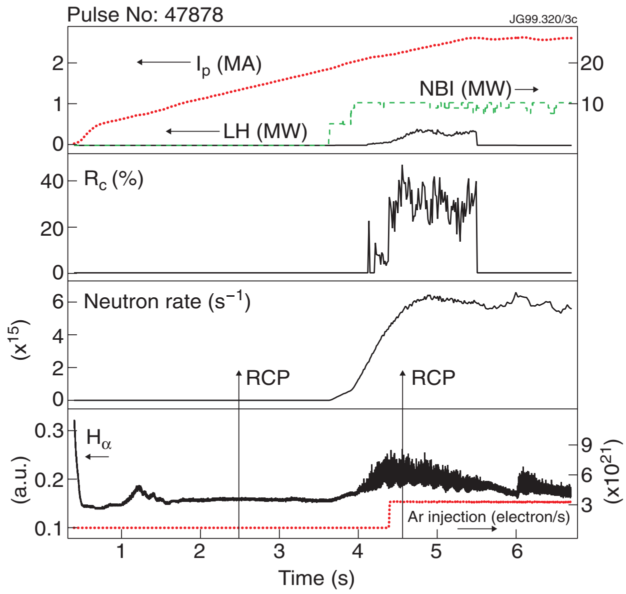

Fig.4: Measurement of the density in the SOL with the reciprocating probe before and during optimised shear discharges

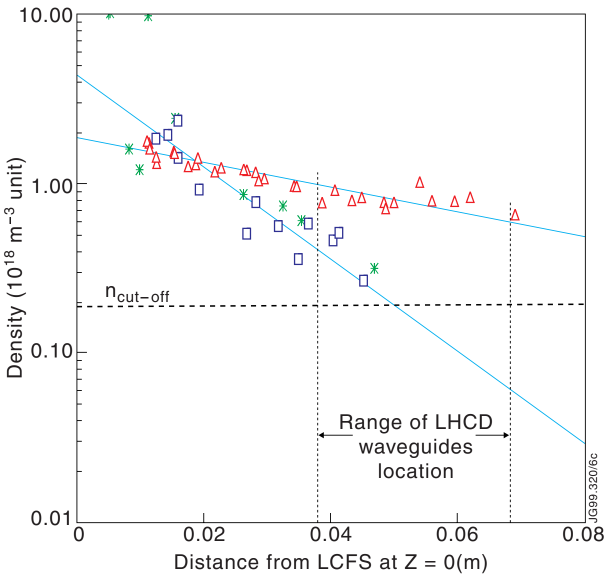

Fig.5: Density decay outside the separatrix in L-mode (triangle) and in ELMy H-mode with LH-power (stars) and without (square) (pulse No 47878 and 47895).

the limiter frame) is likely to be much lower. Using the prediction from the coupling code SWAN (fig.3b), the reflection coefficient in the range from 1% to 30% can be approximated to a very good accuracy as:

$$Rc = \frac{a}{n_{eL}^{b}} + c \text{ with } n_{eL} = n_{e.LCFS} \cdot e^{-\frac{d}{\lambda_{SOL}}}$$

where a and b mainly depend on the density decay length λ_{sol} in the scrape-off layer and d is the distance from the Last Closed Flux Surface (LCFS). c gives the minimum reflection that can be achieved and depends on the vacuum gap length in front of the launcher [6,7]. The experimental reflection coefficient (30% ±10% on fig.4) can be matched with these formulae using a vacuum gap of 4mm. This value is large in comparison with the actual gap size (1.5 to 2 mm) between the wave-guides and the picture frame limiter. This difference can probably be explained by the existence of secondary limiting surfaces behind which the density decay length is far steeper than λ_{sol} [6]. Slight variation of the picture frame alignment could explain that c=4mm is required to reproduce the observed reflection coefficient.

Effect of the ITB on the plasma edge density.

As noted on fig.2, it appears that the reflection coefficient is significantly rising when the ITB is formed in the MarkIIA divertor. At this time, the plasma is still in L-mode phase unlike the ITB with the MarkIIGB divertor. Consequently, the edge plasma is likely to be characterised by a high radial transport (see previous paragraph) and a long density e-folding length that should be favourable for the coupling of the LH-wave. It therefore suggests that the barrier formation has some strong consequences on the edge density behaviour by changing the particle transport properties.

To check this point experimentally, the behaviour of the density at the barrier formation has been investigated in discharges with prompt barriers with both the MarkIIA and MarkIIGB divertor. For these kinds of barrier, it is indeed expected that the particle transport at the edge is sufficiently modified by the ITB to be measured by the edge interferometer channel and the H_{α} spectroscopy.

Figure 6 shows the typical behaviour of the particles at the edge in an ITB discharges. When the barrier forms, the edge density is decreasing by almost 50% as well as the particle flux to the wall and the ELMs amplitude is decaying. Assuming a constant central particle influx (essentially provided by the neutral beams), the onset of the barrier is reducing the particle diffusion towards the edge. This temporary reduced flux from the centre has the consequence to decrease the fuelling of the edge reservoir of particles. Assuming that this reservoir is undergoing constant particle flux losses (by pumping), this process has therefore the effect to lower the edge density as fig.6 shows.

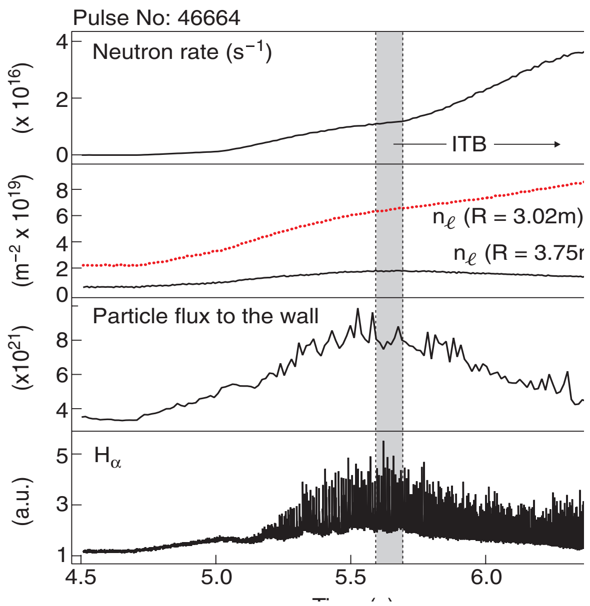

Fig.6: Effect of the ITB formation on the edge density at 3.75m and on the particle flux to the wall (MarkIIGB).

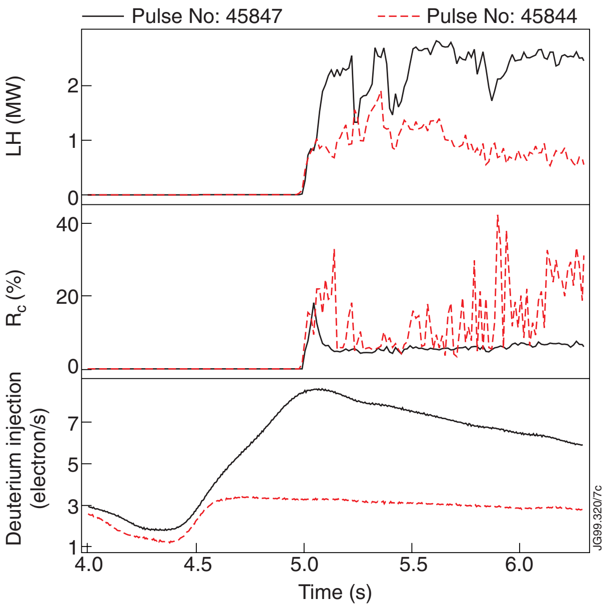

Fig.7: Effect of the deuterium gas injection on coupling coefficient.

The changing condition of particle transport when the barrier forms can be another contributor to the observed bad coupling of the LH-wave. In the MarkIIGB case this effect adds up to the decrease of λ_{sol}. In the case of the MarkIIA divertor, it seems to contribute dominantly to the high reflection coefficient level during the internal transport barrier phase.

4. OPTIMISED SHEAR OPERATION WITH GAS INJECTION

Effect of deuterium gas injection on coupling

The above observations on coupling during ELMs and the behaviour of the edge density gradient has motivated the use of gas injection in front of the launcher using the special pipe described in section 1.

Operation with gas injection has been attempted by gradually injecting deuterium gas during the LH power pulse. Figure 7 shows the comparison of two identical discharges with different gas injections level. The reflection coefficient is still showing large excursions during the ELMy phase when the injection is low. For higher injection rate (more than 5.10^{21} electrons per seconds), the effect of the ELMs is smoothed down, the reflection coefficient remains at a very low level (5%) during the ELMy H-mode and more power can be coupled. This also suggests that the injection rate required to reduce the reflection coefficient, must be at least 610^{21} electrons per seconds.

The other important parameter of the gas injection is the timing. If the valve is opened at the time when the power is applied, the gas has not the time to diffuse radially in front of the launcher and the reflection coefficient remains high for almost one second during the power pulse. The timing has therefore to be set up 0.5 to1 second before the power to allow the gas to diffuse and to be ionised. In the example of fig.7, the gas valve is opened at t=4.5s and the power began to ramp up at t=5s. The maximum of injection rate is reached at t=5s just when the power starts. The level of gas required to achieve good coupling may depend on the plasma conditions. With the available data, it is not yet possible to predict the required level of gas for a given plasma. However, appropriate and well-timed gas injection does improve effectively the LH wave coupling in ELMy H-mode scenario.

Using this technique (8.10^{21} electrons per seconds timed 0.5s before the power) up to 3MW of LHCD power has been coupled to the plasma (discharge 45847). For this particular discharge, significant change of the current profile is also observed on the poloidal flux evolution of the discharge.

Effect of Deuterium gas injection on the internal transport barrier.

However, strong deuterium gas injection in the plasma edge is also deleterious to the ITB quality. Figure 8a present one discharge with argon fuelling between 5s and 8s compared with another where argon is replaced by deuterium at 6s. As the deuterium gas is injected the edge density is increasing but the edge temperature remains constant (fig.8b). The pedestal pressure is increasing, resulting in steeper edge pressure gradients and the onset of ELM activity from type III ELMs to larger ELMs and then to an ELM free H-mode phase. This growing ELM activity with the gas injection affects the pedestal in such a way that it erodes the internal transport barrier and eventually destroys it, leading to a roll over of the neutron reaction rate.

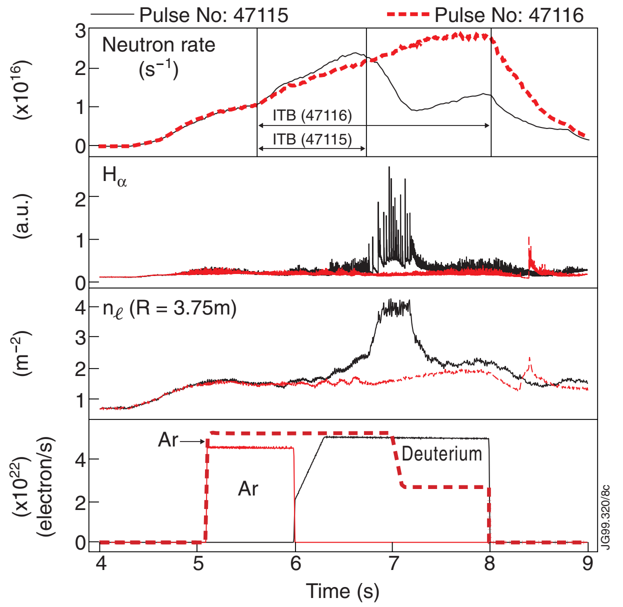

Fig.8a: Effect of deuterium gas injection on the internal transport barrier.

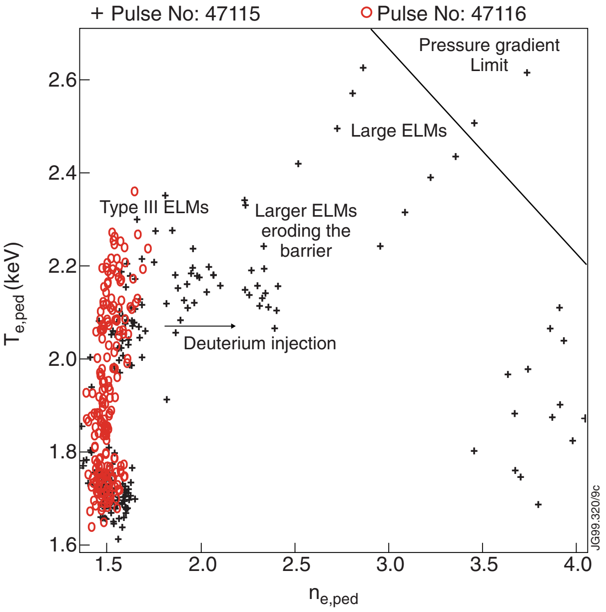

Fig.8b: Behaviour of the pedestal pressure (ne_{ped} vs Te_{ped}) when deuterium gas is injected

Other gases have also been attempted, such as Argon, to radiate the pedestal energy and therefore to reduce the ELM activity. This scheme has been very successful to extend the duration of the internal transport barrier [8] and to reduce significantly the ELM amplitude, but the reflection coefficient of the LH-wave has not shown any significant improvement.

5. CONCLUSION AND DISCUSSION

The optimised shear experiments with Lower Hybrid have revealed the difficulty to couple the wave in optimised shear plasmas both with the MarkIIGB and the MarkIIA divertors.

From the coupling and edge density measurements, we conclude that both the modified particle transport and the short density decay length during the ITB H-mode phase can reduce the density to a level close to the cut-off density of the lower hybrid wave (1.7 10^{17} m^{-3}). These effects are the two contributors explaining the high average reflection coefficient (above 20%) observed during the ITB and make difficult the use of the lower hybrid wave if an independent method of local density control is not developed.

The plasma-launcher distance can also play a major role in the optimisation of the coupling during the ELMs. As already specified, for all experiments analysed in this paper, the launcher sits at approximately 5 to 10mm in the shadow of the guard limiter. Reducing this distance provokes enhanced plasma-launcher interaction, resulting in impurity influx and excessive radiation level in the plasma edge. Varying the plasma-launcher distance is therefore very limited as a parameter to improve coupling.

Since lower hybrid is the most powerful tool to generate large fraction of non-inductive current, coupling of the LH wave is determinant in the ultimate goal of sustaining reversed shear current profile in steady state.

For the advanced tokamak scenario, the LH wave propagation requires the presence of plasma in the vicinity of the LH-launcher with a density above the cut-off density. As shown previously, gas injection alone does not seem to be sufficient to produce the required density in front of the launcher. In addition, the large quantity of required gas tends to increase the pedestal energy and the ELM activity leading to the erosion of the barrier. Gas injection technique could envisage either a direct injection through one of the wave-guide of the launcher or a mean to control the ionisation length of the neutrals such as ECRH for example. Recent experiments on JT60-U and Tore Supra have indeed shown that the reflected power could decrease with the LH-power. This is suggesting that the LH-wave may modify the ionisation length in front of the launcher. By raising the electron temperature in front of the launcher, the LH-wave can increase the dissociation processes of hydrogen neutrals and therefore produce a higher density improving the coupling conditions.

For advanced tokamak operation during the high performance phase, future design of lower hybrid launcher will have to take into account an independent control of the plasma density (and therefore of the ionisation) in front of the launcher.

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