Operation of the 3.7 GHz LHCD System in JET

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ABSTRACT

The Full Lower Hybrid Current Drive (LHCD) system has come into operation in JET during the 1994/95 experimental campaign. 7.3MW has been coupled to plasma, using 8.2MW of generator power. Long pulses with power in excess of 6MW have resulted in a maximum injected energy of 67MJ. Full current drive at plasma currents up to 3MA have been achieved with LHCD alone[1].

INTRODUCTION

The JET LHCD system is supplied by 24 klystrons operating at 3.7 GHz, capable of delivering 12MW for 20 seconds [2]. The launching structure (launcher) consists of 48 multijunctions, each dividing the power into eight 9mm by 72mm waveguides at the launcher-plasma interface [3]. The launcher can be moved radially during JET pulses with a stroke of 150mm, and with a typical response time of 0.3 seconds for a 10mm step [4]. An 80000 litres/second dedicated cryopump is situated on top of the launcher vacuum vessel, and the vessel can be baked at up to 350°C. The key elements determining the achievable coupled power are the conditioning state of the launcher and the reflection coefficient. Full current drive with LH only has been achieved at high power (>6MW) in the range 1-3MA. In conditions close to full LH current drive, sawtooth stabilisation followed in some cases by a strong increase in the central electron temperature has been achieved at 3MA [1].

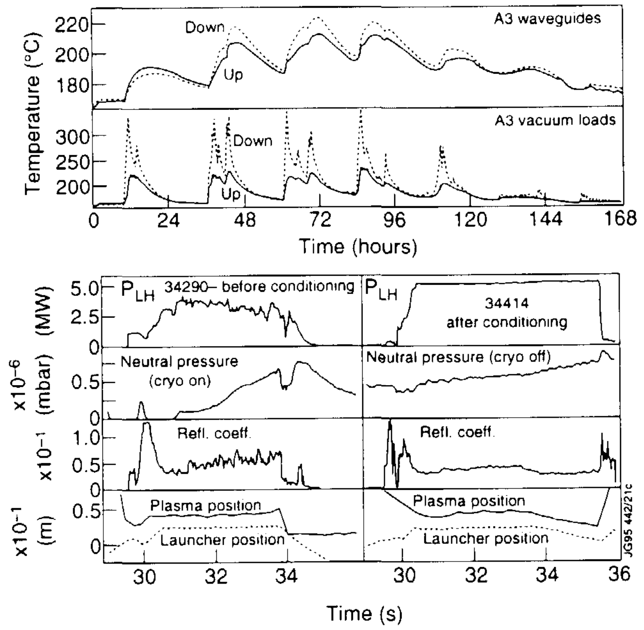

Fig. 1 Conditioning. Top: Temperatures of vacuum loads and multijunctions for 2 multijunctions situated above each other. Both multijunctions are powered by the same klystrons (A3) Bottom left: Shot 34290 (before conditioning). Bottom right: Shot 34414 (after conditioning).

CONDITIONING

In order to improve the power handling capability of the LH-antenna, an extensive programme of conditioning was carried out. The vacuum vessel around the launcher was heated to 350°, and then 3 second pulses of RF-power were applied to the antenna, radiating into vacuum, with a high repetition rate. During this RF-conditioning the temperature of the launcher increased significantly. Fig. 1. shows the result of several days of such conditioning. It is seen that the LH-power was unsteady due to arcs in the multijunctions and that the pressure in the LH vacuum vessel increased strongly during the first pulse, whereas no such problems were seen after the conditioning.

COUPLING

The LH coupling is quantified by the reflection coefficient at the input to the multijunctions. The measured reflection has been compared to the reflection R_c computed by the SWAN code [5]. The reflection coefficient calculated by the code can be approximated in the range from 1% to 30% with very good accuracy by:

$$R_c = \frac{a}{(n_{eL})^b} + c \tag{1}$$

where a and b depend on the density decay length λ_{sol} in the scrape-off layer (SOL). c gives the minimum reflection that can be achieved. n_{eL} is the electron density immediately in front of the antenna. Introducing a vacuum layer of 0-5mm in front of the launcher in the calculations, results in values of c of 0.2-32%. The above approximation is valid only for plasma densities at the antenna $n_{eL}<1.5 10^{18}$ m^{-3}. For higher values of n_{eL} the reflection increases for increasing density. In all relevant cases the density at the antenna is low enough for the above criteria to be satisfied and very high densities are required to introduce significant errors. The value of n_{eL} is determined from the following formula.

$$n_{eL} = n_{eLCFS} \cdot e^{-\frac{d_{LP}}{\lambda_{SOL}}} \tag{2}$$

where: n_{eLCFS} is the density at the last closed flux surface (LCFS). In the experimental results this is taken as 0.4 times the central line average density. d_{LP} is the distance from the LCFS to the launcher, as found from the EFIT boundary reconstruction code and the position of the launcher. λ_{sol} depends on the configuration and plasma current and on whether the plasma is in L-mode or in H-mode. The values of λ_{sol} given in this paper are chosen in order to fit the calculated R_c, using the above formulas, to the measured reflection coefficient. Fig. 2 shows the dependence of the reflection coefficient on the launcher-plasma distance, for 3 different series of experiments.

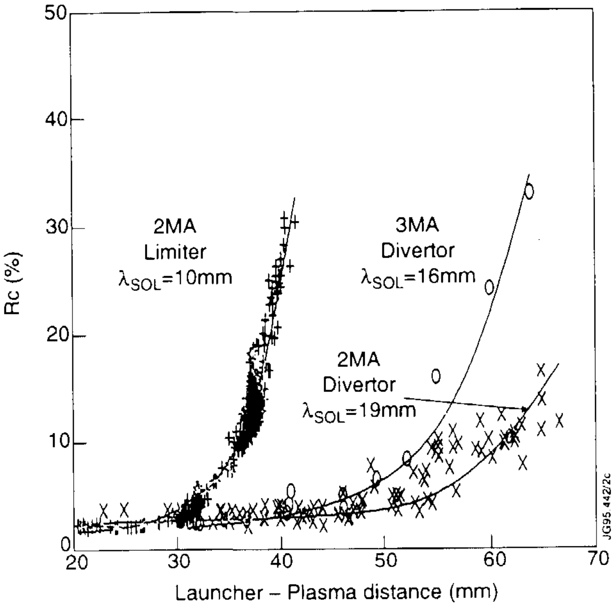

Fig. 2 Reflection coefficient versus plasma-launcher distance. + : 2MA Limiter Plasmas. : 3MA single null X-point plasmas. : 2MA single null x-point plasmas. The full lines are computed from (1)-(2), with = λ_{sol} =10mm, 16mm and 19mm respectively. All data are for L-mode.

All the points in Fig. 2 refer to the upper row of multijunctions in the antenna. The observed reflection for all 3 series agrees well with (1)-(2), using $c = 1\%$ corresponding to a 1mm vacuum layer in front of the launcher. The variation in λ_{sol} is in qualitative agreement with the following very simple estimate :

$$\lambda_{sol} = (2D_{\perp} \cdot \frac{L_c}{C_s})^{\frac{1}{2}} \tag{3}$$

where L_c is the connection length, $D_{\perp}$ the cross-field diffusion coefficient and C_S the speed of sound in the SOL [6]. The larger value of λ_{sol} for the divertor plasmas as compared to the limiter plasmas is caused by the difference in L_C for the 2 cases. The difference between the 3MA and 2MA plasmas on the other hand is caused by the increase in $D_{\perp}$ with decreasing plasma current. When the same comparison is carried out for the other rows of multijunctions in the antenna different values of c have to be used, corresponding to vacuum layer thicknesses between 1mm and 2 mm. The need to introduce a vacuum layer in the computations in order to achieve good agreement with the experimental results, can probably be explained by the existence of secondary limiting surfaces, behind which the density decay length is far steeper than λ_{sol}. The picture frame limiter, surrounding the launcher and protruding a few mm in front of it, is a good candidate. A slight variation in the alignment of this picture frame could explain the variation in vacuum layer thickness along the grill.

H-mode

The H-mode in JET is in general characterised by a succession of ELM-free and ELMy phases, with the period between ELMs varying from a few milliseconds up to seconds. LH-power has been coupled into a wide range of such plasmas, although H-modes with LH alone have not been observed. Fig. 3 shows the measured and calculated reflection coefficient for one such shot.

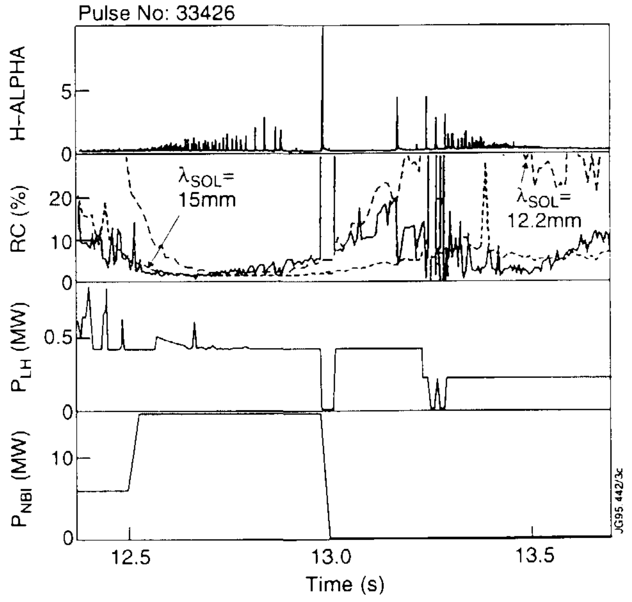

Fig. 3: LH-coupling into a long ELM-free period. 1: H . 2: LH-reflection coefficient, measured (full line), calculated assuming λ_{sol}= 15mm and 12.2mm respectively(dashed lines). 3: LH-power. 4:NBI-Power.

A 250 ms ELM-free phase starts when the NBI power is switched off. This period is terminated by an ELM, after which a series of ELMs occur at higher and higher frequency until the plasma has returned fully to the L-mode. The reflection coefficient follows the λ_{sol}=12.2 mm calculation very well during the long ELM-free period. When ELMs occur the reflection drops down to the level corresponding to λ_{sol}=15 mm. The large ELM, terminating the longest ELM-free period, results in a decrease in reflection from 20% to less than 5%. During the following shorter ELM free periods the reflection does not increase fully up to the λ_{sol}=12.2 mm calculation.

During JET radiative divertor experiments the ELM frequency is very high (Grassy ELMs). The ELMs are clearly visible on the LH reflection coefficient. The reflection coefficient decreases to very low values of the order of 0.2%. In this case agreement with (1)-(2) is obtained by assuming that λ_{sol}=19mm and that no vacuum layer exists in front of the launcher. In almost all other cases the assumption of a vacuum gap is necessary to explain the data. A possible explanation is that, in this case large numbers of particles are ejected from the plasma during the ELMs resulting in high plasma density even behind the secondary limiting surfaces.

In summary: 1: During ELM-free H-modes the density decay length decreases by several mm (3mm for the case shown). This can cause the reflection coefficient to increase sharply. 2: As long as the plasma-antenna distance is kept sufficiently small good coupling can be achieved during ELM-free H-modes. 3: The expulsion of particles during an ELM increases the density strongly at the LH-antenna, reducing the reflection substantially. 4: During "grassy " very high frequency ELMs, which is an ITER relevant situation, exceptionally good coupling is achieved. Thus coupling of LH-power to H-modes is clearly possible, the main problem being the very fast variation in density at the antenna associated with ELMs. It has to be noted that breakdowns start appearing at the front of the antenna causing large impurity influxes into the plasma when high power is injected while the density at the antenna is large enough to achieve R_c<2%.

Gas Injection

In an attempt to improve the LH-coupling by injecting gas close to the LH-antenna, a special gas introduction pipe was installed 0.5m from the antenna. From this pipe it is possible to inject gas along the complete vertical extent of the antenna. To asses the improvement in coupling achieved using this LH gas pipe, the following experiment is carried out: In a pair of shots, gas is injected from the LH gas pipe in the first shot, and from a gas injection module, situated in the divertor region toroidally opposite the LH-launcher in the second shot. The gas flows and the central line average densities for the 2 shots are equal. The experiment is repeated for different antenna-plasma distances, for different LH power levels, and for different amounts of injected gas. No significant difference between the reflections in the 2 cases can be observed in any of the comparisons. On the other hand a clear improvement in the coupling is seen when the amount of injected gas is increased, independently of which injection module is used. The decrease in reflection coefficient when the gas flow is doubled corresponds to an increase in λ_{sol} from 11 mm to 14 mm.

Power Handling

Fig. 4. shows the coupled power from one klystron for all shots where this klystron is operated as a function of the reflection coefficient. It is seen that the maximum power which can be achieved depends critically on the reflection coefficient. Power above 400 kW can only be achieved for reflection coefficients below 3%, corresponding to a reflection at the front of the grill below 17%. The achievable power is clearly limited by the maximum field in the waveguides, with the limit being ~500V/mm [7].

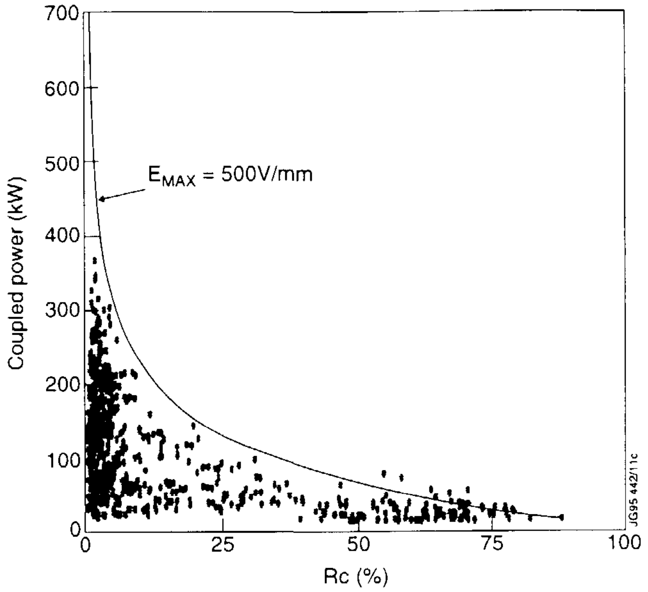

Fig. 4: Power handling versus reflection coefficient. The curve corresponds to a maximum electric field of 500V/mm.

Position Control

A low reflection coefficient is essential in order to achieve maximum power coupled to the plasma. On the other hand the density at the front of the antenna must not be too large since this induces breakdowns at the grill mouth, with large impurity influx into the plasma as a consequence. For coupling of more than 6MW to the plasma the reflection coefficient has to be kept between 2% and 4%. During JET pulses the reflection coefficient is kept constant at the desired value, by controlling the position of the launcher with a feedback loop. The non-linear reflection versus position curve (Fig. 2.), results in a loop gain in the feedback loop which is dependent upon the requested coupling. This in turn makes the loop unstable when too large reflection is requested, while the response becomes very slow when low reflection is requested. For the next campaign a more sophisticated controller will be employed in which the coupling curve is linearized, making the loop gain independent of the requested reflection. Fig. 5 shows how the feedback system has been instrumental in obtaining the highest coupled power achieved at JET till date.

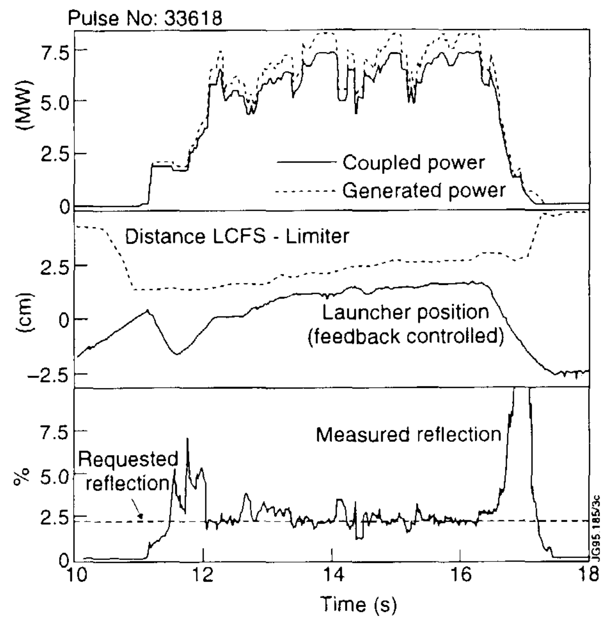

Fig. 5: 7.3 MW coupled power, with 8.2 MW Generator power.

Fig. 6 shows the feedback being used to keep the reflection constant for more than 5 seconds during an ELMy H-mode. The system reacts to the ELMs by retracting the launcher immediately when an ELM occurs and then moving it slowly forward as the H-mode develops. The power level is kept relatively low, to avoid breakdowns induced by the ELMs appearing before the launcher position system can react. Electronic systems aimed at overcoming this problem are under development.

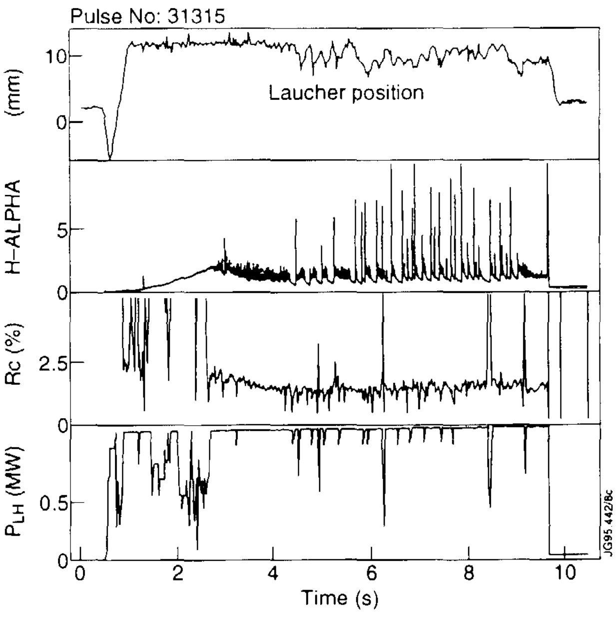

Fig. 6: Launcher moving under feedback control. 1: Launcher Position 2: H signal showing H-modes and ELMs. 3: Reflection coefficient.

REAL TIME POWER CONTROL

A new system has been implemented at JET to control the power from NBI, ICRH and LH in real time, using measurements from certain diagnostics as control quantities.

Controlling the injected powers in this way is essential for JET and ITER type machines. This system has been tested for LH, attempting to control the surface loop voltage of the plasma. Fig. 7. shows such an experiment, where a loop-voltage of 0.075 V is requested. The loop is seen to be somewhat underdamped, with the loop-voltage oscillating around the requested value.

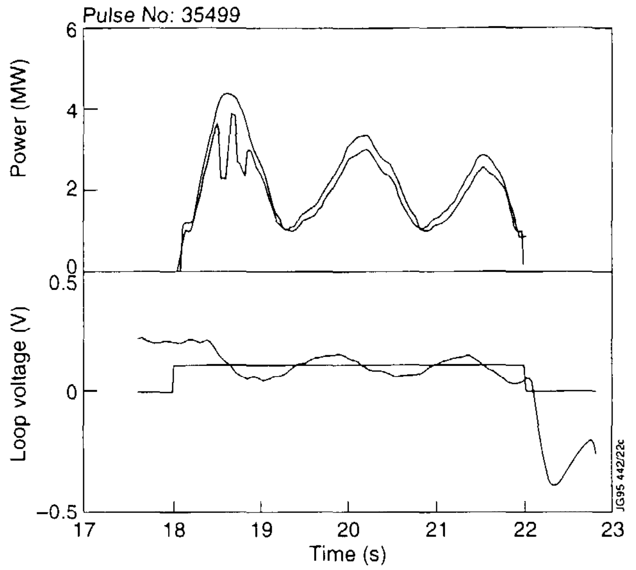

Fig. 7. Feedback control of the loop voltage. Top. Demanded and delivered LH-Power. Bottom: Requested and achieved loop voltage.

CONCLUSIONS.

In JET a maximum LH power of 7.3MW has been coupled to the plasma. This has been achieved by improving the conditioning state of the launcher, through electrical and RF baking and use of the dedicated cryopump, and by optimising the coupling of the LH waves to the plasma, by moving the LH-launcher under feedback control. The LH-coupling is seen to be in good agreement with the predictions of the SWAN code provided a vacuum layer of 1-2mm in front of the antenna is introduced in the computations. Coupling to both ELMy and ELM-free H-modes is feasible, although the large increase of density in front of the antenna associated with ELMs can cause problems at high power levels. Using a local gas introduction pipe near the LH-launcher has not shown any significant improvement in the coupling, as compared to using a remote gas introduction module, although the introduction of gas from either module is seen to improve the coupling significantly. The LH power can be varied in real time under feedback. This capability has been used preliminarily to control the plasma surface loop voltage.

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