LHCD Operations in JET and Developments for Fusion Applications

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Abstract: The full Lower Hybrid Current Drive (LHCD) launcher in JET has been completed and installed. Up to 6 MW has been coupled to the plasma and 2 MA full current drive was achieved with 4 MW of LH power. Coupling is improved by using active feedback control on the launcher and plasma position. A new launcher design concept, called Hyperguide, has been developed and tested successfully in JET to replace eventually conventional launchers using multijunctions for next step machines like ITER.

1. INTRODUCTION

The Lower Hybrid Current Drive (LHCD) system on JET consists of 24 klystrons with a total power of 12 MW for 20 seconds at 3.7 GHz. 3 different $N_{//}$ spectra can be launched simultaneously with the main peak ranging from 1.4 to 2.3 [1].

Three systems for controlling the coupling in real time have been implemented: the launcher position and the plasma position, which can both be controlled under feedback with the reflected coefficient as input signal, and a gas feed to modify the plasma edge density at the grill mouth.

In order to improve the conditioning speed of the launcher made of 48 multijunctions and the grill made of 384 reduced waveguides, an automatic grill conditioning technique and a cryopump installed on top of the launcher vessel have been used.

A new design concept for the launcher, called Hyperguide, has been developed on JET to simplify the design and improve the power handling capabilities of LHCD launcher for present and next step machines like ITER.

2. LHCD OPERATIONS IN JET

Operations on a variety of plasmas both in limiter and divertor configurations with central density ranging from 1 to 4 $10^{19}m^{-3}$ have been performed. Above 6 MW of power have been coupled to an X-point plasma and a maximum of 55 MJ of energy was injected with combined ICRH heating.

2.1 Current Drive Experiments

Up to 2 MA was driven with 4 MW of LH power resulting in a current drive efficiency $\eta=0.21$ 10^{20} $AW^{-1}m^{-2}$ (figure 1). Transformer recharging was also achieved in 1 MA discharges through loop voltage reversal with 4 MW of LH power.

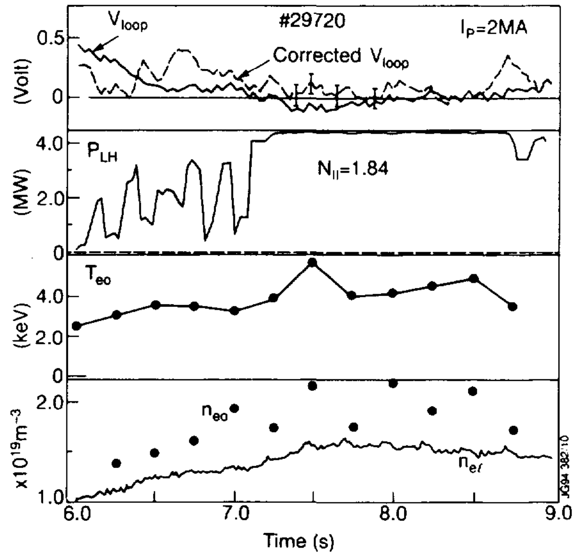

Figure 1: 2 MA Full CD shot

2.2 Coupling

Figure 2 shows the variation of the reflection coefficient with the distance between the separatrix and the limiter. Good coupling is achieved with the plasma up to 6 cm away from the limiter.

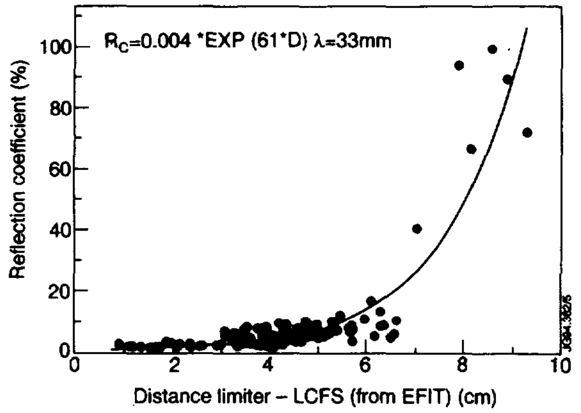

Figure 2: Reflection coefficient with distance separatrix-limiter

The effect of the plasma and launcher position on the coupling is indicated in figure 3 where the plasma is moving away from the limiter when LH is applied. Once the launcher reaches its preset position the coupling degrades. Improved coupling has been since achieved with active feedback control.

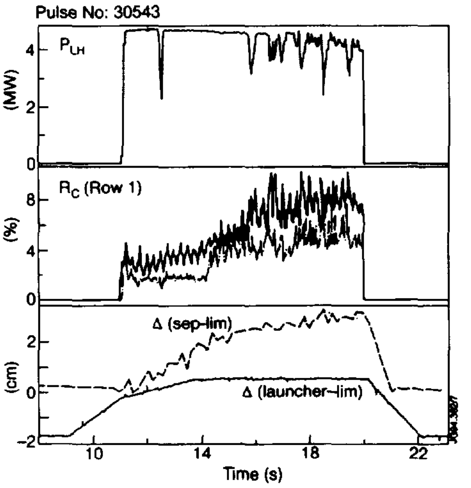

Figure 3: Rc function of Plasma and launcher position

Coupling on H-mode plasma is more difficult for LH as the density gradient is much steeper than in L-modes. However successful coupling on ELM'y H-modes has been achieved as shown in figure 4. Reduced reflection can be attributed to the strong density increase during the H-mode phase.

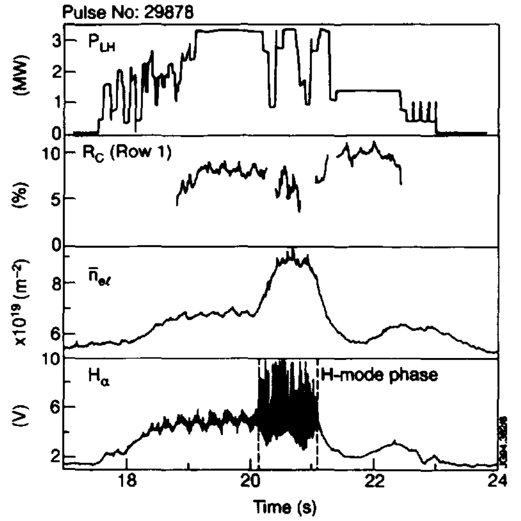

Figure 4: LH Coupling on H-mode plasma

2.3 Launcher conditioning and power optimisation

In order to increase the conditioning speed of the launcher, an automatic grill conditioning system has been developed. The klystrons are being pulsed in vacuum for 3 seconds with a 1:30 repetition rate. Depending on the number of trips on each generator, such as arcs, RF trips (VSWR, unbalanced reflection at the launcher, window arc prevention trips...), the power is incremented or decremented by 5 kW for the following pulse. Using this system, all klystrons were pulsed up to 200-300 kW in vacuum and no arcs were observed at the windows.

After one day of conditioning, the temperature at the grill mouth can increase by 100-200°C. The evolution in power transmission capability is indicated in figure 5 where the temperature increase rate of the load multijunctions, proportional to the average input power in the multijunction, is plotted versus the operation time. The gas released during conditioning is pumped by a 80000 l/s cryopump installed on top of the launcher vessel, keeping the pressure inside the launcher below 10^{-7} mbar.

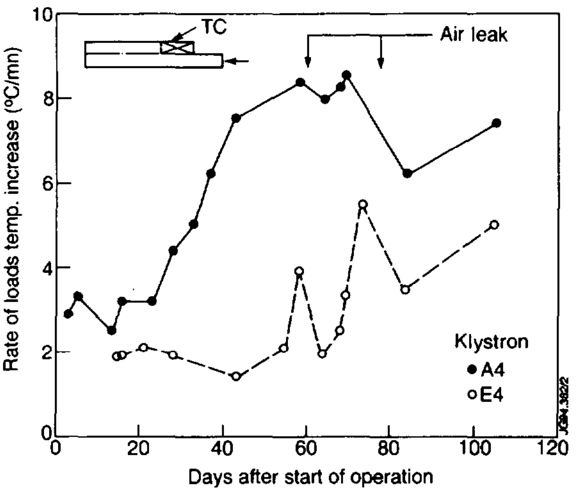

Figure 5: Temperature increase rate during grill conditioning

The pressure increase in the launcher as a function of the multijunctions temperature increase (measured at the 2 wg section) is indicated in figure 6 for cases with and without the cryopump.

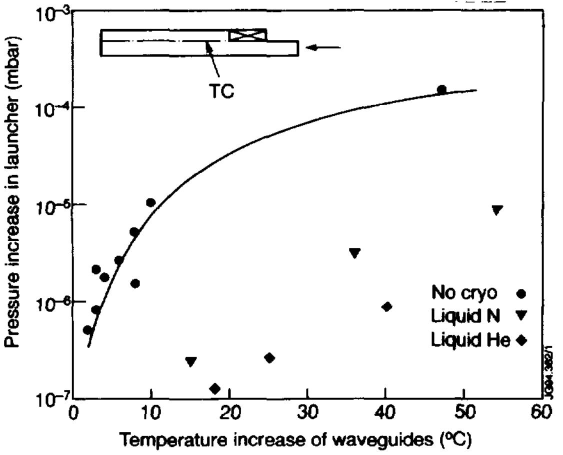

Figure 6: Pressure increase during conditioning

A power optimisation software has also been successfully used to increase the launched power during plasma pulses and determine the maximum operating power possible for a given set of plasma conditions.

3. HYPERGUIDE CONCEPT

For next step machines like ITER, a conventional launcher made of multijunctions is clearly impractical as it would require thousands of waveguides facing the plasma. The gas accumulation inside the launcher would limit the power handling capabilities of the antenna. A new design concept called Hyperguide [2], which is much lighter, simpler and cheaper to manufacture, has been developed in JET to overcome these difficulties.

The Hyperguide is an overmoded waveguide providing nearly total power transmission between an emitter plate, fed by standard waveguides operating at the fundamental $TE_{0,1}$ mode or mode converters operating at $TE_{0,m}$, and a receiver providing the slow wave launching structure facing the plasma. The main propagating mode in the Hyperguide is $TE_{0,N}$ where $N=m*n$ with n the number of waveguide rows emitting a $TE_{0,m}$.

3.1 Low Power Testbed

A low power testbed has been developed to simulate the behaviour of a full scale Hyperguide for JET (figure 7).

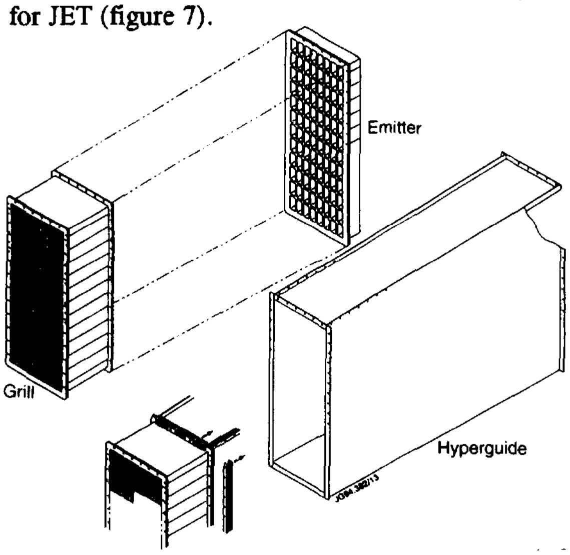

Figure 7: Low Power JET Hyperguide Testbed

It is made of 4 parts: the generators, providing up to 100 CW at 3.7 GHz, and splitting network, the emitter plate, made of 8x12 WR284 standard waveguides, a 1.5 m long tapered Hyperguide and finally the grill mouth, made of 24x12 reduced waveguides coupled to a RF load array, providing a return loss better than 30 dB in each waveguide. Various scenarii with homogeneous and inhomogeneous power and phase distribution at the emitter plate have been studied. For each case, the results have been compared with numerical predictions for a straight Hyperguide from a code called HYPER based on mode matching at the Hyperguide interfaces.

In the ideal case where homogeneous power and phase distribution is used at the emitter plate, the measured forward phase inside the reduced waveguides of the grill indicate that 180^0 phasing between rows is preserved. The measured power distribution in the grill mouth indicate that a transmission coefficient Qt (Qt=Total TE0,1 power in grill / Incident Power from emitter) better than 0.9 is achieved, which is in agreement with the numerical prediction.

Figure 8 shows the measured and predicted power distribution at the grill when the first 4 rows of the emitter are switched off. Good agreement is obtained even when strong inhomogeneous power is used to feed the Hyperguide. In this case the experimental Qt=0.6.

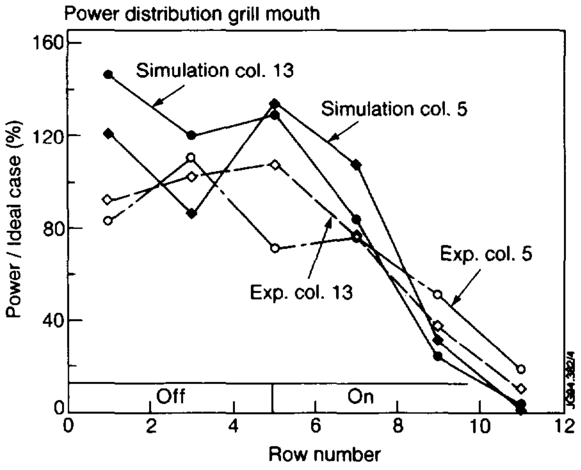

Figure 8: Power distribution when 4 rows are off

3.2 Future developments

The Hyperguide testbed results indicate that the Hyperguide concept is a viable solution for the design of a new launcher on JET and future applications on ITER.

A LHCD system using 2 launchers of 8 Hyperguides operating in $TE_{0,6}$ mode to launch around 50 MW at 5 GHz in ITER [3] has been proposed (figure 9).

The Hyperguides are fed by $TE_{0,3}$ mode converters and the grill mouth is made of alternate active-passive waveguides to provide space for cooling channels [4]. In this case the estimated Qt in each Hyperguide for zero reflection from the plasma is 0.9 and the power distribution inhomogeneity in the grill Qd=(Pmax-Pmin)/Pmean=1.24.

4. CONCLUSION

First operations with the full LHCD system on JET have demonstrated that LH is an efficient tool for current drive and profile control on large size Tokamaks. A new launcher concept called Hyperguide has been developed and tested successfully in JET. It is proposed to use this concept as part of an ITER LHCD Launcher.

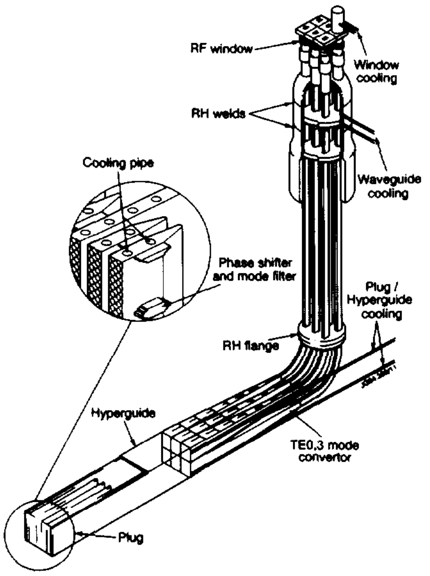

Figure 9: LHCD Launcher design for ITER

5. REFERENCES

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