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Theoretical and Experimental Analysis of the LHCD Power Coupling in JET Optimised Shear Plasmas

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ABSTRACT

In recent LHCD experiments in JET, a large effort has been placed on improving the coupling of the Lower Hybrid waves in Optimised Shear plasmas, i.e. in conditions with internal transport barriers or H-modes. Good results have been obtained by using gas puffing with CD_4 near the launcher. Results from coupling experiments have been compared with the SWAN coupling code, which has recently been extended to take into account the poloidal cut of the launcher mouth. The launcher mouth is composed of twelve rows of waveguides, all with different electrical lengths. By introducing the scattering matrices for all rows and calculating the resulting power splitting in the multijunctions, a more realistic model for the coupling is obtained.

INTRODUCTION

The control of the plasma current profile is an important aspect of the Optimised Shear scenarios in JET [1]. The tool for off-axis non-inductive current drive is the Lower Hybrid Current Drive (LHCD) system, which operates at 3.70GHz and launches slow waves with $n_{\|}$ in the range 1.4-2.3 [2]. Earlier attempts of using LHCD during the high power phase of the Optimised Shear plasmas exhibited problems with coupling of the LHCD power, due to the very low electron density in front of the launcher during the internal transport barrier (ITB) phase [3]. Attempts to improve the coupling with strong gas puffing ($\Phi \approx 8\times10^{21}$ el/s) of D_2 near the launcher caused a degradation of the ITB. The LHCD coupling experiments carried out at JET in 2000-2001 have therefore focused on improving the coupling and increasing the LHCD power during the ITB phase [4, 5]. Some results are given at the end of the paper. As a part of the coupling experiments we have analysed the reflection coefficients, *RC*, on the multijunction rows (mainly in L-mode plasmas) and compared them with new SWAN code calculations, in order to improve the understanding of the coupling behaviour. The calculations and comparison with experiments are described in the following section.

COUPLING ANALYSIS

The JET LHCD launcher is composed of six rows of eight multijunctions. The 48 multijunctions are fed by 24 klystrons. Each multijunction contains two poloidally stacked rows of four waveguides facing the plasma. The poloidal power splitting inside a multijunction is done via a hybrid junction, in which the fourth port is connected to a vacuum load. Before the LHCD launcher was installed on JET, the front end was modified in order to match the poloidal shape associated with divertor plasmas. As a result, the electrical lengths of the two 4-waveguide sections inside the same multijunction are not the same. This alters the power splitting in the hybrid junction.

The SWAN code calculations, which are based on 4-waveguide multijunctions without a hybrid junction, have previously been done using the 4-waveguide scattering matrix of the original multijunction [6] prior to the launcher modification. In the new calculations, the 4-waveguide scattering matrices have been corrected for the twelve rows of waveguides, and the SWAN code has been run independently for each case. These calculations yield the power reflection coefficients and phase

(R_n, φ_n, n=1..12), as seen from the hybrid junctions inside the multijuntions towards the 4-waveguide sections. The power fraction absorbed in the vacuum loads, $R_{vl,m}$, and that reflected back into the transmission lines, $R_{wg,m}$, can then be calculated for each row of multijunctions (m = 1..6). Rwg,m can subsequently be compared to the measured reflection coefficients at the input to the multijunctions. $R_{wg,m}$ and $R_{vl,m}$ are given by:

$$R_{wg,m} = \frac{1}{4}\left(R_{2m-1} + R_{2m} + 2\sqrt{R_{2m-1}\,R_{2m}}\cos\left(\varphi_{2m-1} - \varphi_{2m}\right)\right)$$

$$R_{vl,m} = \frac{1}{4}\left(R_{2m-1} + R_{2m} - 2\sqrt{R_{2m-1}\,R_{2m}}\cos\left(\varphi_{2m-1} - \varphi_{2m}\right)\right)$$

Comparisons of the calculated and measured reflection patterns was initially made in L-mode plasmas, at low power and at different values of phase difference between adjacent multijunctions, $\Delta\phi$. Somewhat better agreement between calculations and measurements is achieved with the new calculations, as seen in Fig.1, which shows the result for the middle multijunctions rows (m=3, 4) at waveguide phasing $\Delta\phi = 0$, which corresponds to $n_{//} = 1.84$. For the calculations of Fig.1 we used an electron density in front of the waveguides of $n_e = 3\times10^{17}$ m^{-3}, as found from reciprocating Langmuir probe data, and a vacuum gap, d_{vac}=1mm, in front of the waveguides. Figure 1 also illustrates that different coupling behaviour can be expected on different multijunction rows, due to the poloidal cut of the launcher mouth. Figure 2 shows good agreement between measured and calculated values of the average reflection coefficient as a function of $\Delta\phi$ for the two bottom rows of multijunctions (m = 5, 6). This verifies that the phase settings and, as a consequence, the launched n//-spectrum are correct [7]. The result of the phase variation experiment for the middle rows was also in agreement with theory. The data for the top rows (m = 1, 2) are not complete, but the existing data show poor agreement with calculations, probably due to the damage to the upper part of the launcher mouth. Comparisons of the reflection patterns were also done for H-mode plasmas, but these did not show as good agreement as the L-mode cases.

COUPLING IN OPTIMISED SHEAR EXPERIMENTS

Significant progress has been made in the latest experiments with LHCD in the high performance phase of Optimised Shear plasmas. An important factor has been gas injection near the launcher with CD_4. In contrast to D_2, the CD_4 could improve the coupling without any obvious degradation of the quality of the ITB [4, 5]. Figure 3 demonstrates both the effect of CD_4-injection on the coupling, as well as the effect of current profile control by LHCD on the ITB-behaviour. With CD_4 (Pulse No: 53521), the LHCD power was maintained at 2.9MW during the ELMy period and, as a result, the ITB could be sustained during the whole duration of the high power heating phase. Without CD_4 (Pulse No: 53514), the degradation of the coupling and the resulting decrease in LHCD power caused the q-profile to evolve more rapidly, which invoked a disruption.

A synthesis of the global coupling improvement in ITB and H-mode plasmas with CD_4 is given in Fig.4. RC≈5% has been obtained at an average distance of 6cm from the last closed flux surface

(LCFS) to the launcher. The launcher was always retracted behind the poloidal limiters by 0.5-1cm. The improvement in coupling was pronounced on the bottom rows, which are generally the most sensitive to perturbations at the edge, like ELMs. The coupling on ELMs or in plasmas with unequal loading can be made difficult by the existing launcher protection system, whose aim it is to detect arcs in the multijunctions by acting on the difference and the ratio of the reflected power in the upper and lower multijunction fed by the same klystron. The new SWAN calculations (Fig.1) show that different reflection patterns can be expected on two multijuntion rows fed by the same klystrons. (Eight klystrons feed rows 1&2, 3&4 and 5&6, respectively.) It may therefore not be useful to compare the reflected powers in multijunctions fed by the same klystron too rigorously. It has now been decided to increase the limits on the launcher protection system in order to avoid excessive interrupts. This is also justified by the fact that a new launcher protection system, which uses spectroscopic and radiated power measurements that are sensitive to arcs at the launcher mouth, has been implemented.

SUMMARY

From the promising results obtained in the recent LHCD experiments at JET, together with proposed modifications to the launcher protection system and to the gas injection system, the hope is to be able to increase the coupled LHCD power on ITB and H-mode plasmas. The goal is to reach a power density of $25MW/m^2$, which corresponds to 6MW at RC≈5%. It is also of particular interest to investigate the coupling capability in H-modes at large LCFS-launcher distance, as required for ITER.

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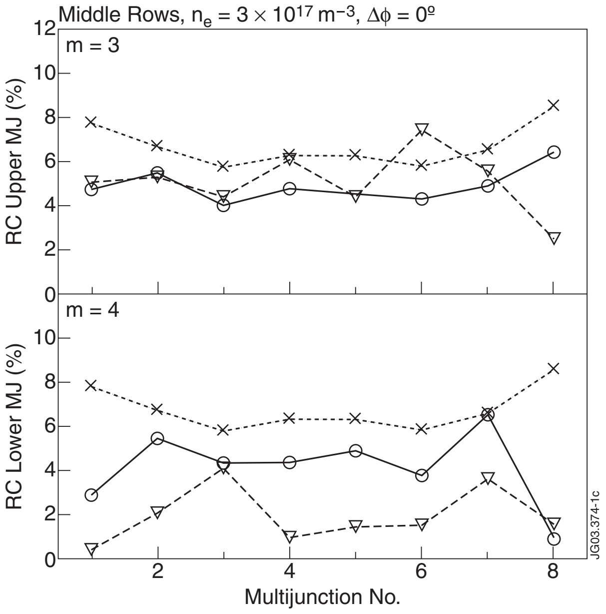

Figure 1: Reflection patterns on rows m=3&4. Experimental data (dashed), new SWAN results (solid), old SWAN results (dotted).

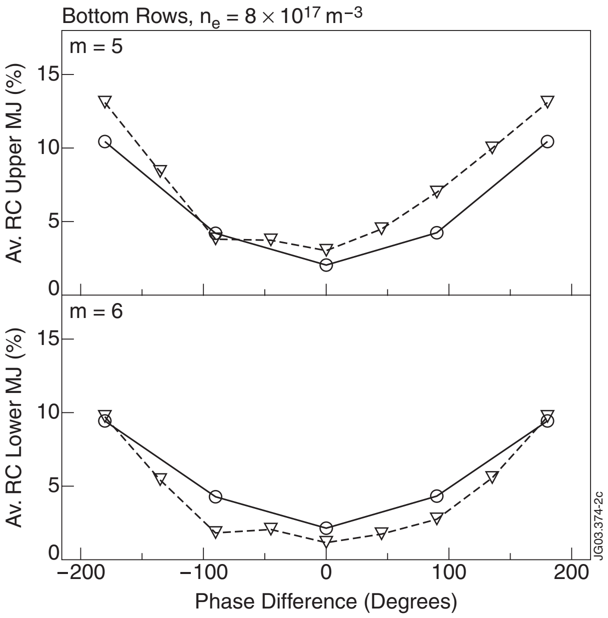

Figure 2: Average RC on rows m=5&6 versus Δϕ. Experimental values (dashed), new SWAN calculations (solid).

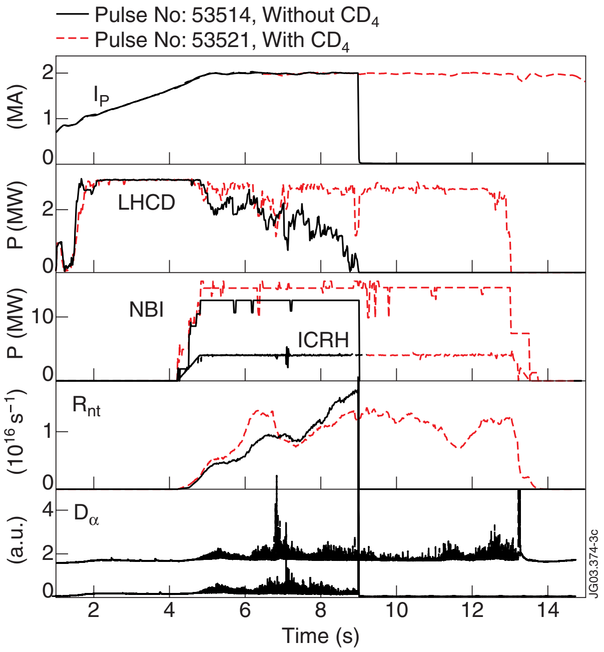

Figure 3: Effect of LHCD on the evolution of the ITB. CD_4-injection with Φ =8×10^{21} el/s was used in Pulse No: 53521.

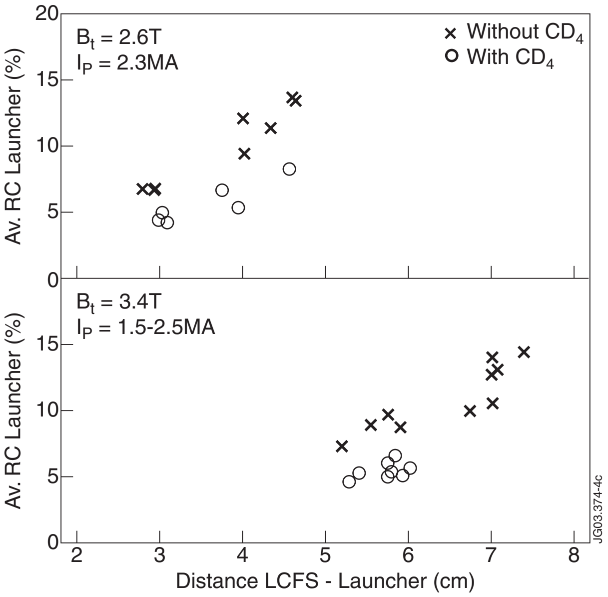

Figure 4: Average RC on the whole launcher in plasmas with ITB or H-mode, without and with CD_4 (Φ ≈ 6-10×10^{21} el/s).