First Results of Coupling and Edge Plasma Interaction Experiments with the New Advanced LHCD Launcher in Tore Supra

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1. Introduction

The results of the first experiments with the new Lower Hybrid Current Drive (LHCD) launcher in Tore Supra are presented. This new launcher, which is based on new advanced technological concepts [1], has been designed to inject 4MW at frequency 3.7GHz during 1000s, as required for the Tore Supra CIEL project [2]. Its radiating surface is increased by a factor of two compared with the old type of LHCD launcher. This leads to a maximum power density of 25MW/m^2 and a maximum electric field at the grill mouth of about 450kV/m, values that have been found to give reliable operation of LHCD systems [3, 4]. The launcher is composed of 16 modules with TE_{10} to TE_{30} mode converters, three-waveguide poloidal junctions and multijunctions. The launcher mouth has six rows of small waveguides, each row having 48 active waveguides and nine passive ones. The $n_{//}$-spectrum can be varied between 1.7 and 2.3 by varying the phase difference between modules. The launcher mouth is equipped with side protections, designed to withstand a power flux of 10MW/m^2 [5].

The new launcher was brought into operation in the second part of the 1999 experimental campaign at Tore Supra. In spite of a short experimental and conditioning time, the power coupled to plasma has reached 3MW, which is close to the limit of its actual generator plant. 2.6MW for 10s has been achieved, Fig. 1, with values of 420kV/m and 18MW/m^2. An average power reflection coefficient of 8% has been maintained at a plasma–launcher distance of 6cm. The discharge shown in Fig. 1 is also one of the first with combined operation of LHCD and electron cyclotron resonance heating (ECRH) in Tore Supra [6].

2. Coupling Properties

LHCD experiments have been carried out in plasmas with $B_T \approx 3.9$T, I_P varying between 0.4MA and 1.4MA and $\langle n_e \rangle$ varying between $1\times10^{19}m^{-3}$ and $4\times10^{19}m^{-3}$. On the old multijunction launcher, the reflection coefficient of the wave is a quite strong function of the phase difference between modules, as predicted by the SWAN-code [7]. On the new launcher the coupling remains constant as the phase shift is varied. The SWAN-code also predict a very small variation [8], due to the effect of the passive waveguides between the modules.

The large poloidal and toroidal extent of the new launcher may lead to a greater sensitivity to the shape of the magnetic field lines at the plasma edge. In particular, a difference in electron density in the poloidal direction in front of the launcher mouth can cause an imbalance within the three rows of the multijunction, which in turn can perturb the functioning of the mode converter. Displacing the plasma vertically by ± 5cm during the pulse tested the sensitivity to this effect. The distribution of the power reflection coefficients (RC) is shown in Fig. 2. Very good coupling is obtained on the central modules (RC ≈ 3%), and no effect is seen when the plasma is displaced vertically. However, the outermost modules usually suffer from a high reflection coefficient, and a vertical displacement of the plasma does alter their coupling.

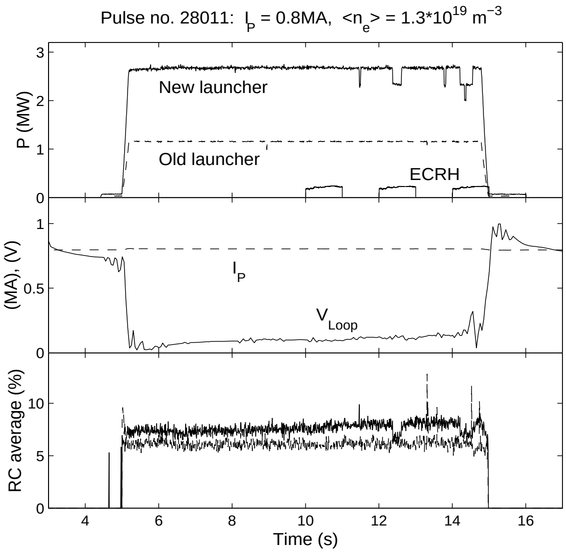

Fig. 1: Discharge with LHCD+ECRH. The injected energy on the new launcher reached 26MJ.

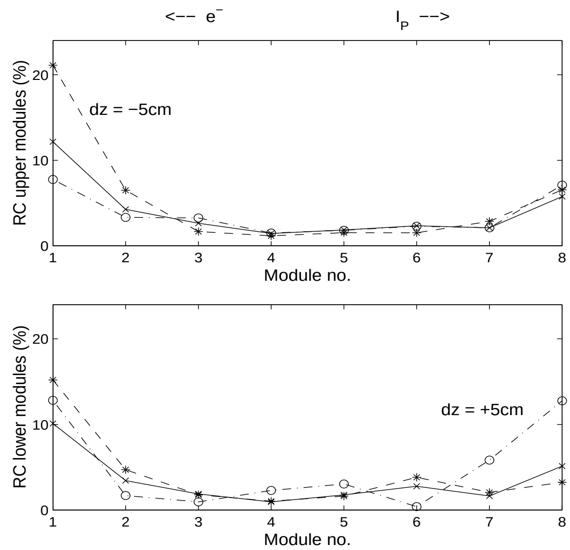

Fig. 2: Relf. coeff. on each module on the new launcher during poloidal displacement of the plasma.

The high reflection coefficient on the modules in the corners of the new launcher indicates that the electron density in front of these modules is low, i.e. close to the cut-off density ($n_{co} = 0.17\times10^{18}m^{-3}$). Indeed, the density measured by the Langmuir probes mounted in the corners of the grill mouth of the new launcher is lower than the density measured by a probe mounted in the centre of the grill mouth of the old launcher. The coupling on the outermost modules is found to improve with increasing electron density, i.e. the reflection coefficient decreases from ~20% at $\langle n_e\rangle \leq 2\times10^{19}m^{-3}$ to 5% at $\langle n_e\rangle = 4\times10^{19}m^{-3}$. Increasing the electron density in the scrape-off layer by the electric field of the LH wave has also shown to be beneficial for the coupling on the outermost modules. Fig. 3 shows two pulses at different LH power levels in ergodic divertor plasmas at relatively low density, $\langle n_e\rangle = 2\times10^{19}m^{-3}$, but in a high recycling regime. The recycling is measured by a set of dedicated fibre optics, collecting the D_α emission emerging from the area in front of the new launcher. Since the D_α emission is proportional to the electron density times the neutral particle density, the signal gives a measure of the electron density in front of the launcher. At high LH power, the D_α emission increases and the coupling is improved. This effect is not observed in low recycling conditions. These results indicate that the near gas injection pipe on the new launcher might be efficient for improving the coupling in low recycling regimes. The gas injection experiments with the new launcher remain to be done.

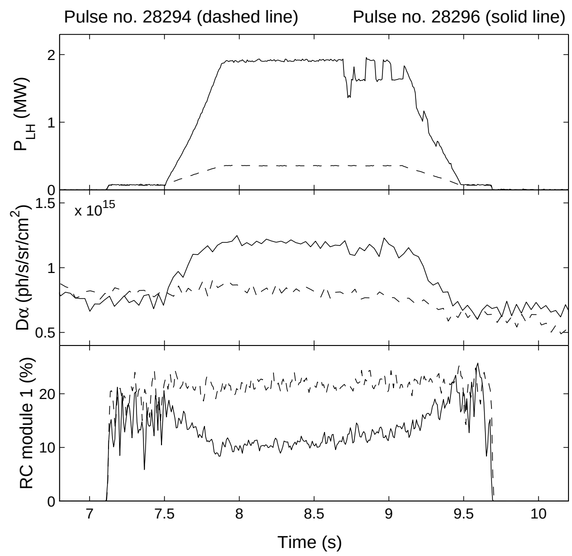

Fig. 3: Refl. coeff. on module 1 and D_α emission in discharges with different LH power levels.

3. Plasma Edge Interaction

Acceleration of electrons in the edge plasma by the electric field of LHCD launchers has been observed in various tokamaks [9]. Electrons are accelerated up to energies in the range of ~1keV by the LH electric field contained in the high-$n_{//}$ part of the wave spectrum ($n_{//} > 20$). These high-energy electrons can cause hot spots on components magnetically connected to the launcher. For the new Tore Supra launcher this deleterious effect is expected be reduced, because of its lower power density and thereby lower electric field. For the same power on the new and the old launcher, the power density on the new launcher is reduced by a factor of two and the electric field strength by a factor of 1.4. Another beneficial factor adopted on the new launcher is the rounding of the tips of the waveguide walls [10].

The effect of the electron acceleration was investigated by measuring the temperature increase with an infrared camera of the side protection of an ICRH antenna, magnetically connected to the two launchers. The launchers were pulsed one after the other, while maintaining identical plasma conditions. The results yield a decrease of the heat flux by about a factor two for the new launcher at a given power, Fig. 4. The effect of the edge electron acceleration depends not only on the electric field, but also on the electron density in front of the launcher [9]. Since the coupling was similar on the two launchers (Fig. 4), the electron densities could be considered to be similar.

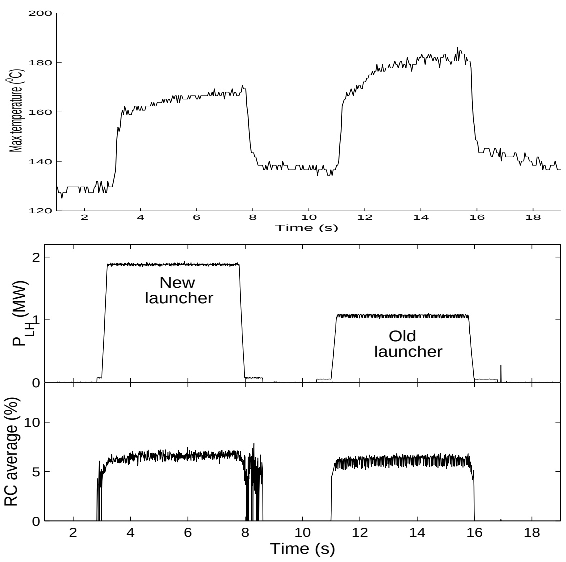

Fig. 4: Temperature increase during LHCD of an in-vessel component magnetically connected to the two launchers.

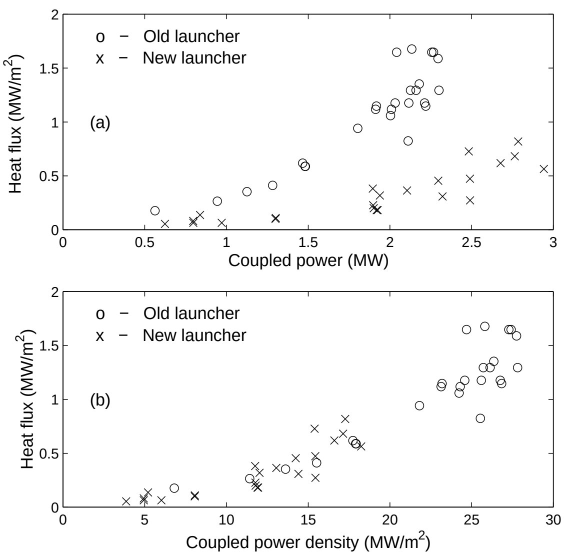

Fig. 5: Heat flux on the launcher side protections versus coupled LH power (a) and coupled LH power density (b).

The effect of electron acceleration has also been evaluated by comparing the temperature increase of the side protections on the launchers as a function of power. Fig. 5 shows the approximate heat flux, deduced from the measured temperature increase. Since the protections on the old and the new launcher have different thermal properties, the temperature increase can not be compared directly. An estimate of heat flux Q, can be obtained by taking $Q(MW/m^2) = \Delta T(°C)/170$ for the old launcher and $Q(MW/m^2) = \Delta T(°C)/110$ for the new launcher, where ΔT is taken at steady-state. According to this simple relation, it is seen that the measured heat flux on the new launcher is well reduced with respect to the old launcher, Fig. 5a. The heat flux can roughly be correlated with the power density, Fig. 5b.

The heat flux on the old launcher, caused by the edge electrons accelerated by the LH electric field, has been calculated in [11]. The calculations give Q = 1.5MW/m^2 for a coupled LH power density of 26MW/m^2 at $n_{e,edge} = 1\times10^{18}$m^{-3} and $T_{e,edge}$ = 25eV. The calculated value of Q is in agreement with the measured heat flux on the old launcher (Fig. 5b).

4. Current Drive Efficiency

Full current drive up to 0.8MA and improved electron confinement have been obtained in the recent experiments [12, 13], using a total LH power in excess of 4MW. The current drive efficiency is found to be very low in these experiments, $\eta_0 \approx 0.065\times10^{20}$m^{-2}A/W, but analysis suggests that the efficiency increases with plasma current [12]. The current drive efficiency of the new launcher has been verified by comparing the loop voltage drop for the old and the new launcher, using similar $n_{//}$-spectra, i.e. $n_{//0}$ = 1.9 for the old launcher and $n_{//0}$ = 2.0 for the new launcher. The loop voltage drop is the same for the two launchers. This is another experimental result that confirms the proper functioning of the new launcher design.

5. Summary

Promising results have been obtained in the first experiments with the new LHCD launcher in Tore Supra. Nearly the full available power has been reached, i.e. 3MW coupled to the plasma. Very good coupling is obtained on the central modules of the launcher (RC ≈ 3%). The reflection coefficient is higher on the outermost modules, but the coupling on these is improved as the electron density in front of the launcher is increased. For a given power, the heat flux associated with acceleration of edge electrons in the LH electric field is reduced by about a factor two for the new launcher. The results obtained give hope that the new launcher design will fulfil the requirements needed for providing non-inductive current drive in quasi continuous operation at improved performance in Tore Supra.

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