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Coupling studies of the C3 Tore Supra LH multijunction

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Non-inductive heating and current drive in Tore Supra relies heavily on the use of Lower Hybrid (LH) waves. Its most recent LH launcher, dubbed C3 [1]-[4], has been in use reliably since 1999, with well proven results, being also vital in the most remarkable achievements of this machine (6 min pulse length with the current fully driven by LH wave). Still, measurements which have been lurking for some time now [5], point to the emergence of a few unexpected/unexplained phenomena in its coupling and thermal behaviour. The purpose of this work is to shed some light into these matters – even if they are believed to bear no consequences to the overall performance – by comparing experimentally derived data with theoretical/numerical simulations, in which different plasma scenarios are explored.

The C3 launcher, whose detailed description of both its components and construction is given elsewhere [1], [3], was designed to inject 4 MW at 3.7 GHz with a power density of 25 MW/m^2, to withstand a plasma radiated flux of 0.15 MW/m^2 and provided with a guard limiter on each side that can withstand 10 MW/m^2, to reduce the fraction impinging on the launcher [3]. It consists of 16 identical modules set up in two rows of eight, being able to radiate a $N_{||}$ spectrum whose main peak may be made to vary between 1.7 and 2.3. Save for a difference in length stemming from the mouth's toroidal and poloidal shaping, each module is identically constructed having: a $TE^{□}_{10}$ to $TE^{□}_{30}$ mode converter (MC) at the module's input, a 3-waveguide H-plane junction, three 3-waveguide E-plane (0 π 0) multijunctions, nine E-plane (0 $\pi/2$) bi-junctions, creating a 1-input and 3×6-output device. At the launcher's output there is in each row a $\lambda_g/4$-deep passive waveguide inserted between consecutive modules and another at each end, λ_g being the guide wavelength. This leads to a launcher with 6 rows of 8×6 active and 9 passive waveguides. Each module is actively cooled by demineralised water (30 bar, 150°C, 3 m/s) flowing through four pipes (ϕ=8mm) running horizontally along its top and bottom sections (see Fig. 6) and ending at less than 4cm from the plasma. The launcher is equipped with four Langmuir probes near its corners and with thermocouples on the left- and right-most output waveguides, one in each row (at their mid planes).

In the present studies, the fully detailed antenna geometry – from the MC's input to the antenna's output, including the internal phase shifters as well as the toroidal and poloidal shape of the mouth – is taken into account in the scattering matrix computations for each module performed with HFSS® [6], whereas the coupling properties, previously handled with recourse to SWAN [7], were here studied with a more recent code developed at Cadarache by S. Berio [8] and carried now by one of the authors (D. Voyer): ALOHA (Advanced LOwer Hybrid Antenna). Even though ALOHA is still based on the plasma model as used in SWAN (i.e. a vacuum gap, followed by a steep density step and by a density slope), ALOHA is 2-D in nature – unlike SWAN – in the sense that it considers waveguides with finite heights and allows for the treatment of the entire (upper or lower) half of the antenna, passive guides included, while admitting independent plasma scenarios to be set-up in each row and taking into account cross coupling – through the plasma – between rows. Yet, presently it is limited to densities above the cut-off density, n_{co}, like SWAN. Its extension to $n_e < n_{co}$ is ongoing.

1. Coupling studies

Poor coupling on the C3's outermost modules, i.e. higher reflection coefficients (RC), which improve with increasing n_e – whereby RC decreases – have been previously reported [**4**],[**5**]. In the present studies, a typical shot was selected in trying to reproduce this: shot n°32294, with I_p=500kA and n_e=1.5×10^{19}m^{-3} whereas at the C3's Langmuir probes, Lp3 and Lp4, n_{e3}=1.5×10^{17}m^{-3} and n_{e4}=6×10^{17}m^{-3}, putting it between somewhat below and well above the cut-off density, n_{co}=1.7×10^{17} m^{-3}. The scattering matrices of each of the 16 modules, as computed by HFSS, were supplied to ALOHA as input parameters, together with the feeding conditions. The computed power RC (in %) and the corresponding phases (in degrees) for various scenarios of n_e (2.0 to 6.0×10^{17}m^{-3}) and ∇n_e (so that $n_e/\nabla n_e$=0.4 and 1.0cm) are compared to the experimental data as well as to SWAN calculations in Fig. 1 vs. the module number. These results show that not only does ALOHA reproduce overall quite remarkably the reported experimental tendency of the external modules in overshooting the power RC of the central ones for n_e near n_{co} but, what is more, indicate already that the coupling of these modules improves with increasing n_e. Clearly, lower densities are required to improve fitness and to support this note the difficulty to accurately measure n_e and its non-homogeneous nature, as revealed by the Langmuir probes on the C3 (down from $n_e \lesssim n_{co}$) and confirmed by those at the other LH launcher, the C2, which are as reported, indeed, somewhat higher [5].

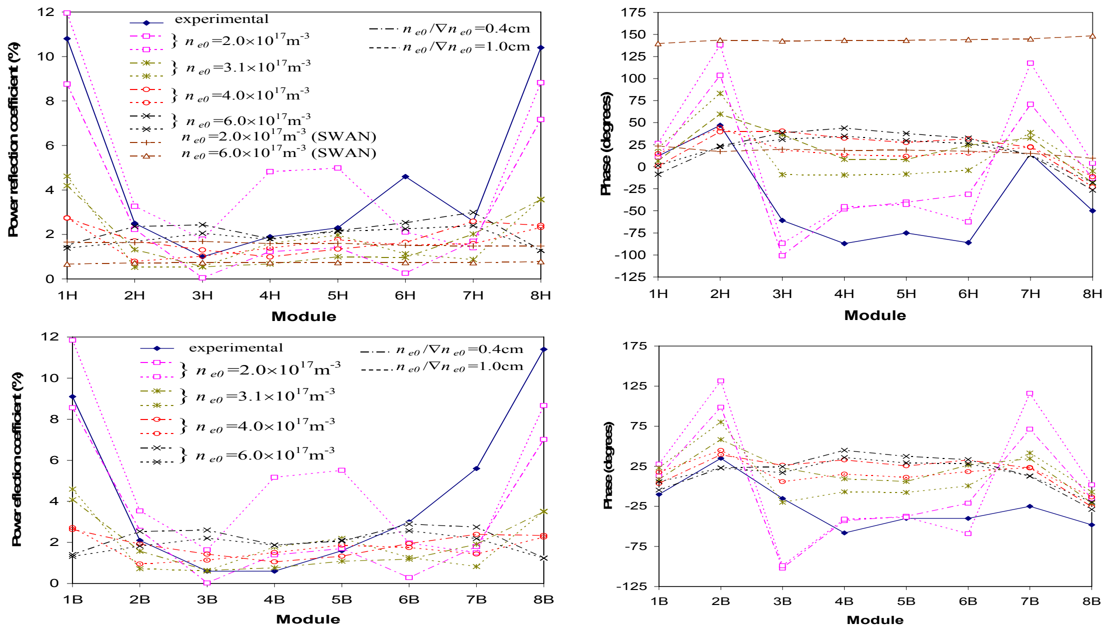

Fig. 1. Experimental and theoretical (from ALOHA and SWAN) power coupling coefficients (amplitude and phase) for TS shot no.32294, upper (H) and lower (B) modules, with $n_e/\nabla n_e$=0.4 and 1.0cm.

It has also been found experimentally that during long pulse operation the C3's power RCs increase steadily (Fig. 2 insert). A possible explanation could be linked, it was thought, to dissimilar (thermal) expansions among the transmission lines of different lengths that carry the rf power to the launcher thus, resulting in an effective variation of the feeding phase at the launcher's input during such long shots. This was tested using shot n° 32299 (I_p=500kA and n_e=1.5×10^{19}m^{-3}) where this occurrence is clearly visible. The results in Fig. 2 for the power reflection coefficients at time t=10s, t=110s and t=300s show no such behaviour taking place between t=110s and t=300s (with equal n_e). The difference between t=10s and t=110s is rather a reflex of the different density scenarios at these two times. The explanation for this behaviour could be due to a thermal shift in the antenna's transfer function. Yet, these results indicate also that coupling remains constant as the feeding phase is varied. In this case there was also a non-negligible degree of uncertainty in the data from the C3's Langmuir probes.

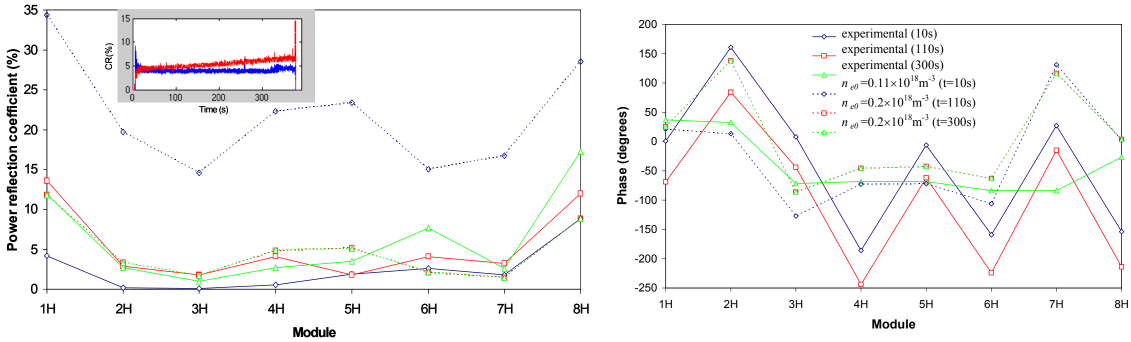

Fig. 2. Power RC during a long shot (n° 32299): amplitude [in red on the insert, experimental drifting of RC with time] (left) and corresponding phase (right) at times t=10s, t=110s and t=300s.

The effect of different poloidal profiles of n_e on coupling was also tested. As depicted in Fig. 3 increasing n_e, even if partially and differently in each row, has a more pronounced bearing on the outer modules. Indeed, as previously reported, displacing the plasma vertically during the pulse has no effect on coupling for the central modules, whereas on the outermost ones it improves as the electron density in front of the launcher increases **[5]**. The impact of ∇n_e, from 1.7 to 8.5×10^{19}m^{-4}, was tested at n_e=5n_{co} corresponding to L=n_e/∇n_e from 5cm to 1cm. As portrayed in Fig. 4 and in accordance with earlier work **[2],** the influence on coupling is negligible. It was found out experimentally that the phase with which the modules are fed has also little relevance on coupling **[5]**; this was reproduced reasonably well with ALOHA for shot no.35493 during which four different phases were used, as shown in Fig. 5.

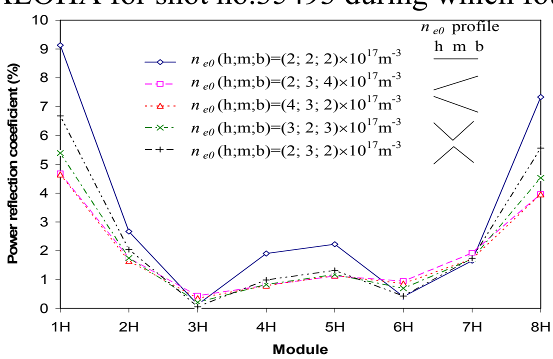

Fig. 3. Effect on RC of different n_{e0} in each row: h, m, b (high, middle, bottom) with n_e/∇n_e=0.4 cm.

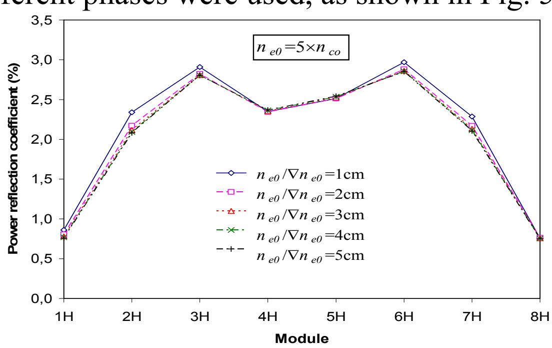

Fig. 4. Effect of n_e/ ∇n_e at n_{e0}=5×n_{co}.

2. Thermal studies

The thermal studies were focused on the four outermost modules (1H, 8H, 1B, and 8B) where thermocouples are installed. Experimental data was pointing towards anomalous temperature increases in the upper- and lower-row waveguides compared to the middle ones, in conflict with the design of the water cooling circuits of the launcher, which run along the top and bottom part of each module. Based again on shot n° 32299 (water at 115 °C and 3 m/s) with recourse to ANSYS® no such behaviour was revealed vs. time and in particular at t=308s, nor was it found with ALOHA via computation of $|J|^2$ using various and different plasma scenarios in each row. This is now believed to be due to problems in the measurements.

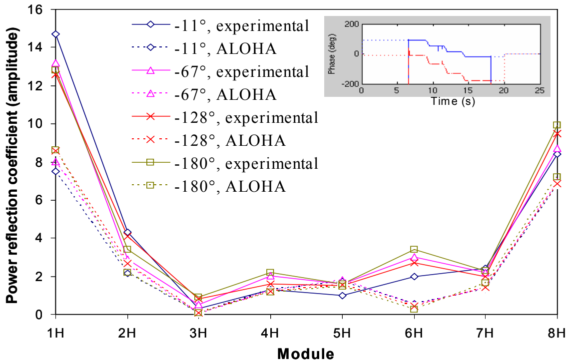

Fig. 5. Impact of the feeding phase (red on insert).

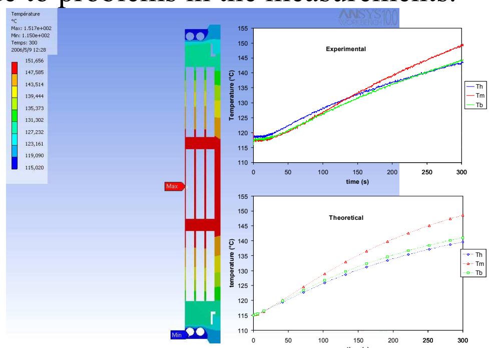

Fig. 6. Temperatures for (a half) module 8H: at t=308s; measured and computed vs. time (insert).

3. Conclusion

Using ALOHA in tandem with HFSS it was possible: to reproduce globally quite well the overshooting found experimentally in the power coupling reflection of the external modules of the C3 LH launcher; to confirm that for these modules coupling improves with increasing density; to verify that coupling remains constant as the feeding phase is varied; to corroborate that coupling on the outermost ones should improve by displacing the plasma vertically. Yet, no link was established between the dissimilar thermal expansions among the transmission lines and the measured RC drifting during long shots, just like no anomalous temperature increase is expected in the upper- and lower-row waveguides of the outermost modules.

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