Coupling properties and edge plasma interaction characteristics of the new Tore Supra Lower Hybrid Antenna

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1/ Introduction

A significant part of the non-inductive current in Tore Supra will be driven by a new launcher, to be installed in September 1999. The antenna phase 2 is made of 6 rows with 48 active waveguides and 9 passive ones in each [1]. Passive waveguides are inserted at every 6th active one. This grill has been designed in the frame of the CIEL project [2]. It will inject 4 MW at 3.7 GHz at a safe power density of 25 MW/m^2 for a pulse length of 1000 s. The radiated spectrum peaks at $N_{//} = 2.03$ with a possible variation of $\pm$ 0.35 and a FWHM of 0.35. In order to prepare for operation with this grill, the coupling properties and the power directivity of the radiated spectra have been studied as a function of :

- the electron density and electron density gradient,
- the feeding phase shift between the 8 antenna modules,
- the geometry of the antenna.

Furthermore, the interaction of plasma edge electrons with the antenna is analysed and a comparison with the previous Tore Supra [3] antenna is made. This is done for a range of plasma parameters and feeding phase.

2/ Antenna description

The antenna is made of 2 rows with 8 modules in each made of :

- a TE_{10} to TE_{30} mode converter which feeds a 3 waveguides H plane junction in order to divide the power into 3 poloidal sections.
- In each row there is a 3 waveguides (0 π 0) multijunction of length l_s which then feeds E plane bijunctions (0 $\pi/2$) of length l_t.

The toroidal geometric periodicity Δ is 10 mm, leading to a waveguide width of 8 mm. Passive waveguides are inserted between the modules.

In order to optimise the coupling properties , the effect of the multijunction lengths has been studied using SWAN code. The results are $l_s = n\,\lambda_g/2$, n = 1,2,... and λ_g being the waveguide wavelength and $l_t = (2n + 1)\,\lambda_g/2$.

The optimum passive waveguide depth is $\lambda_g/4$, a value which maximises the amplitude of the passive waveguide electric field, at the plasma antenna interface.

The phase shift leading to the radiated spectrum with the best directivity and a main peak at 2.03 is the one which corresponds to a linear increase of the phase by 90 degrees in the toroidal direction between neighbouring waveguides in a module, and about $\varphi = -90$ degrees between the modules due to the passive waveguide width of 11 mm.

3/ Coupling properties

The scattering matrix of the multijunction is calculated with a code based on the moment method in rectangular geometry. The first part of the multijunction includes a section which is larger than $\lambda_g/2$. Thus there are two propagating modes ; LSE_{10} and LSE_{11} which are both considered in the computation. On the other hand, the poloidal cross-coupling through the mode converter is neglected.

This matrix is inserted in the SWAN code where the plasma is modelled as an electron density step, n_e, followed by a gradient ∇n_e. In the following the ratio $n_e/\nabla n_e$ is denoted by L.

The reflection coefficient and the power directivity have been studied as a function of 3 different parameters : the feeding phase shift between modules, φ, the electron density n_e, and the gradient ∇n_e .

a/ Variation with the feeding phase shift.

For $n_e = 8.5\ 10^{11}$ cm^{-3} and L = 1 cm, the power directivity, η_p , remains at 74% for φ varying from –180 to 0 degrees. The small variation of η_p is explained by the existence of a E plane oversized part at the input of the multijunctions and of the passive waveguides.

The reflection coefficient is given in Figure 1. The mean reflection coefficient at the mouth of the active waveguide is Ract, at the input of the module it is Rmoy. R1, .., R8 are the power reflection coefficients at the input of the multijunctions. Due to the self matching properties of the (0 $\pi/2$) multijunction, it is expected that on matched load Rmoy equals $Ract^2$. However, that is not true in the present case, due to cross-coupling through the plasma between active waveguides.

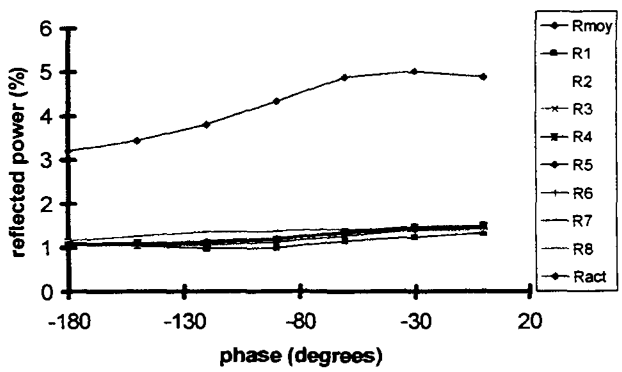

Figure 1 : Power reflection coefficient versus feeding phase φ, for $n_e = 8.5\ 10^{11}$ cm^{-3}, L = 1 cm

b/ Variation with the electron density

The density scan has been carried out for φ = -90 degrees and L = 1 cm for densities between the electron cut-off $n_{ec} = 1.7\ 10^{11}$ cm^{-3} and 10 n_{ec}. The power directivity equals 62% at low density and is then fairly constant from 3 n_{ec}. In Figure 2, the reflection coefficient at the input of the multijunction is mimimum around 2 n_{ec}. The power reflection coefficient at the input is higher near n_{ec} and smaller at large density due to the change of the cross coupling. In accordance with this, the maximum amplitude of the electric field decreases from 3.6 to 2.2 times the amplitude of the incident wave, whilst the average expected value $(1+ \sqrt{Rmoy})^2$ changes from 2.5 to 1.4.

c/ Variation with the electron density gradient

The density gradient scan was done at n_e = 8.5 $10^{11}cm^{-3}$ and φ = –90 degrees between 1.5 to 8.5 10^{11} cm^{-4} corresponding to L changing from 5.6 cm to 1cm. The effect on the power directivity and on the coupling is negligible.

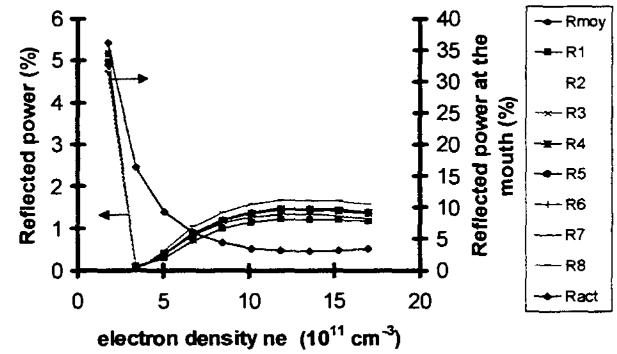

***Figure 2** : Coupling versus the density for φ = -90 degrees, L = 1 cm*

4/ Interaction of plasma edge electrons with the antenna

The acceleration of electrons in the near field of the launcher observed in many experiments is one of the main drawbacks of the LHCD grill [4], [5]. The induced flux on the guard limiter observed in Tore Supra can reach 10-30 MW/m^2. One explanation is based on the presence of power in the high $N_{//}$ part of the radiated spectrum. That can be reduced by using septa with rounded corners [6]. Here, we study the electron energy gain for the antenna phase 2 as a function of the power and n_e . The effect of rounded corners is also examined.

To carry out this analysis, we use the electric field calculated by SWAN. With the rounded corners, the amplitude vs the geometry is modified . The edge plasma temperature is assumed to be 40 eV. For an ensemble of 1000 electrons, a Monte-Carlo method is used to compute the mean energy of passing and reflected electrons respectively E+ and E-. The number of reflected electrons is denoted n- , of passing electrons n+.

a/ Effect of the power

For a case with n_e=8.5 10^{11} cm^{-3}, L=1cm and φ = -90 degrees, as the power is increased from 0 to 250 kW per module (4 MW for the total antenna), the electric field increases and the energy E+ reaches 1500 eV, see Figure 3.

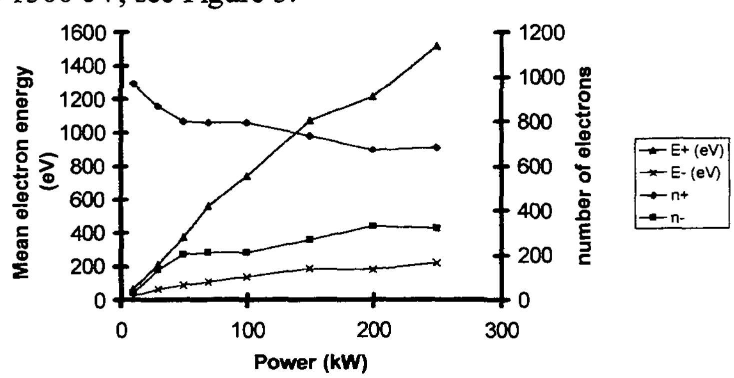

***Figure 3** : Mean energy and number of the electrons accelerated in the near field*

b/ Effect of the electron density

With increasing electron density, the coupling improves and therefore the electric field amplitude decreases. Therefore, the average energy of the electrons decreases. Due to the increase in density , the power flux computed with the obtained distribution function which does not take into account plasma effect, grows almost linearly from 50 MW/m^2 at n_e=n_{ec} to 320 MW/m^2 at 10n_{ec}. In the computation of the flux, a factor $n_e W_e/T_e$ is applied to take into account the ponderomotive force, with W_e the average energy and T_e the temperature [7]. The comparison of antenna phase 2 with the previous antenna shows that the highest energy near n_{ec} is respectively 3.7 keV and 4.5 keV, and at 10 n_{ec} it is 1.2 keV and 2.2 keV for the same amount of power (4 MW) (figure 4). The factor between the electric field amplitudes is 1.4.

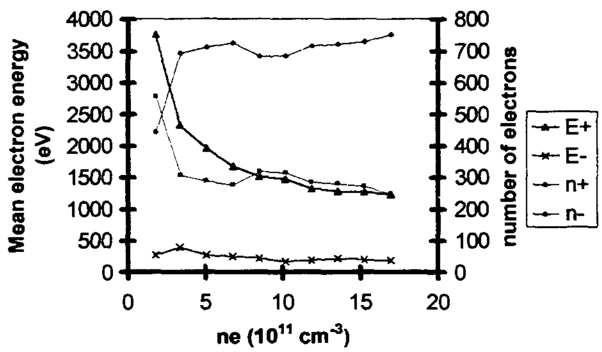

***Figure 4** : Mean electron energy and number with the electron density*

c/ Effect of rounded septa corners

Under the same conditions as in a/, we calculate the energy and the power flux versus the electron density for rounded septa corners. The septum thickness is 2 mm between waveguides and 3 mm between modules. The maximum energy obtained is 100 eV, leading to a power flux varying from 10 to 50 MW/m^2. To withstand this flux, the face of the CFC tiles of the guard limiter has been shaped to have a magnetic field grazing angle smaller than 10 degrees. This lowers the intercepted power flux level to less than 10 MW/m^2.

5/ Conclusion

We have shown that the coupling properties of antenna phase 2 are expected to be good over a wide range of parameter : n_e, φ, ∇n_e; with the advantage that the new launcher will allow the injection of twice the power of the previous one at a safe power density.

References

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