Coupling properties of Tore Supra's ITER-like LH PAM launcher

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INTRODUCTION

A new LH antenna has been designed for Tore Supra, in parallel with the transmitter refurbishing in the Cimes project frame [1], based on a novel launcher concept: the Passive-Active-Multijunction (PAM) [2]. The main objective for this device is twofold: to be able to launch 2.7 MW at a power density of 25 MW/m^2 for a central frequency of 3.7GHz, delivering a highly directional slow-wave spectrum with a refraction index $N_{||}$ peaked at 1.7 that, in conjunction with the preceding LH antenna will allow the injection of 6 to 7MW CW in order to perform long pulse operation i.e. 1MA in a 1.5×10^{19}m^{-3} fully RF driven plasma; to test the PAM in quasi CW operation in complement to the previous plasma experiments carried out on FTU plasma [3]. The main PAM specificity is to achieve an efficient coupling around the cut-off electron density. The purpose of this work is to study the coupling properties of the TS PAM launcher depending on both the plasma parameters and the antenna design. The antenna geometry is taken into account in the scattering matrix computation that has been evaluated with HFSS$^{®}$ (High Frequency Structure Simulator) [4], whereas the coupling properties to the plasma have been studied using the SWAN (Slow Wave ANtenna) code [5] which has been extensively validated [6], [7] – the FTU PAM experimental results providing the latest of its strong validations [3].
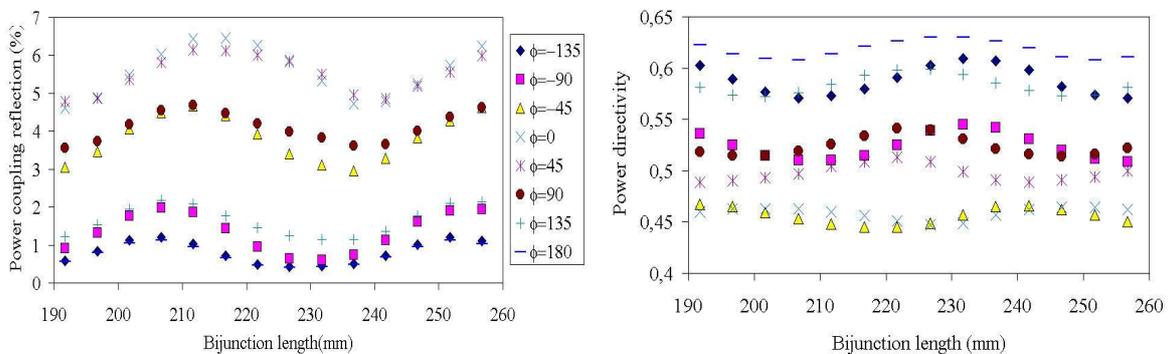
MODEL OF THE PAM AND RESULTS

The PAM concept was proposed in ref. [2] and in essence is based on the multijunction [7] but making use of an alternating active/passive waveguide structure in which the passive waveguides are fed by cross coupling through the plasma. The passive waveguides, whose depth is a mere λ/4 long, allow the insertion of an efficient water cooling system at its back. What is more, the PAM will be able to couple the wave at low density where the cross coupling between active and passive waveguides is higher, thus, permitting to place the antenna in an area where the thermal loads are smaller. For Tore Supra, it uses an array of 96 active and 102 passive waveguides, distributed in 6 rows of 8 modules made of E-plane 270° bijunctions each. There are 16 active and 17 passive waveguides in each row, yet only half of them have been considered in the present computations, see Fig. 1.
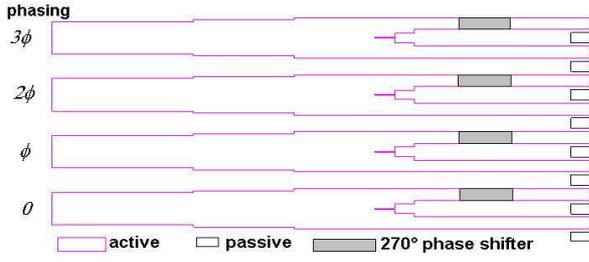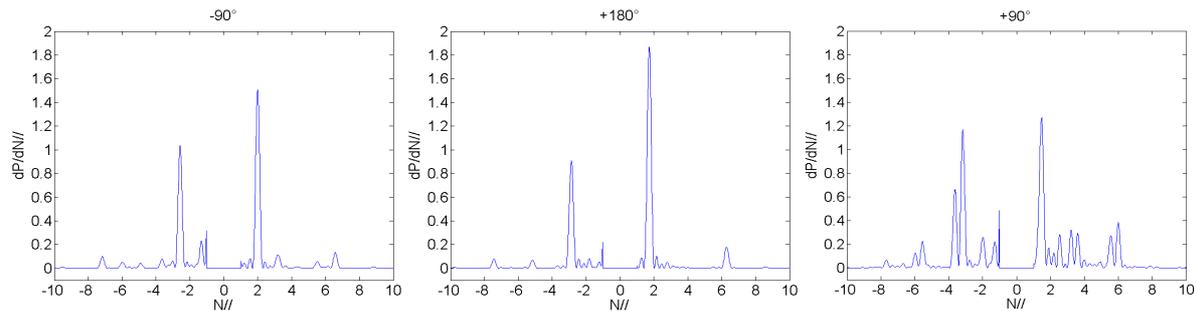
Fig. 1. Conceptual (top) view of four of the PAM bijunctions with the phase shifters and passive waveguides.

The first study has been to optimise the multijunction length, or to be precise the length l of its basic component, the *E-plane bijunction*, in terms of the coupling properties, given its strong impact on the antenna overall radiating properties. HFSS was used to calculate the scattering matrix of this basic geometry, confirming that the transmission coefficient is −3dB as expected and that the input standing wave ratio for the TE_{10}, TE_{01}, TE_{11} and TM_{11} propagating modes is lower than −35dB. The power coupling reflection coefficient R and the power directivity of the multijunction were then determined with SWAN as a function of the bijunction length l and the feeding phase between the different modules, ϕ (the scattering matrices are issued by HFSS) and include not only the effect of plasma loading but also of the passive waveguides in the alternating active/passive scheme of the PAM (Fig. 1), using a plasma model with a steep density step followed by a slope that has been considered with $n_e =3.4\times10^{11}$cm^{-3} and $\nabla n_e=3.4\times10^{11}$cm^{-4}, respectively, leading to $n_e/\nabla n_e =1$cm. From the results in Fig. 2 a length l_{opt}=231mm and a phase shift $\phi =180°$ emerge as the best compromise, achieving the minimum reflection (0.4%) and the maximum directivity (63%), together with a radiated spectrum having its main peak at $N_{||}$=1.72, see Fig. 3. Regarding the radiated spectrum flexibility (which in this design is achieved by changing the feeding phase ϕ), when the optimised length l_{opt} is used with $\phi =180°+\Delta\phi$ and $\Delta\phi$ is made to vary between −90° and +90° (taking $n_e =3.4\times10^{11}$cm^{-3} and $\nabla n_e =3.4\times10^{11}$cm^{-4}), SWAN reveals a $N_{||}$ flexibility between −0.24 and +0.28 relative to the nominal value of $N_{||}$=1.72 ($\phi =180°$), see Fig. 3.
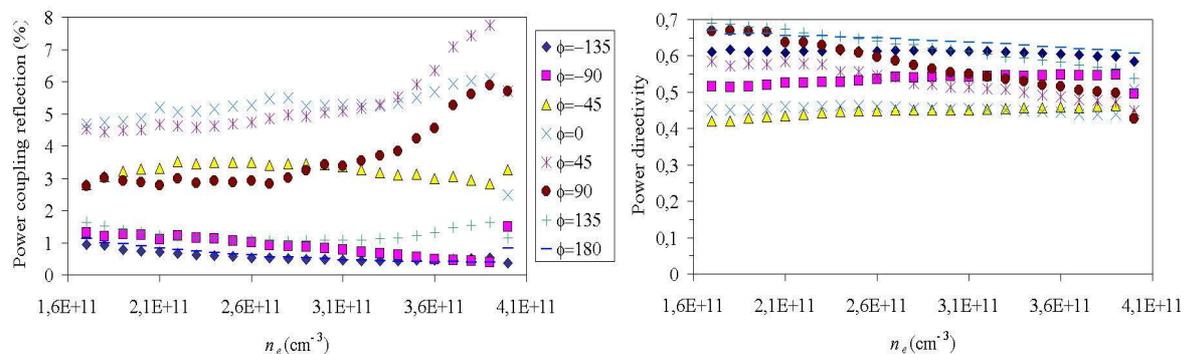

Fig. 2. Coupling properties of the PAM as a function of the bijunction length l for $n_e =3.4\times10^{11}$cm^{-3} and $\nabla n_e =3.4\times10^{11}$cm^{-4}, with the feeding phase ϕ as a parameter: mean power reflection coefficient (left) and power directivity (right).

Fig. 3. PAM radiated spectrum in N$_{||}$ for the optimised bijunction length (l_{opt}=231mm) when the feeding phase is −90° (left), 180° (centre) and +90° (right) with n_e =3.4×10^{11}cm^{-3} and ∇n_e =3.4×10^{11}cm^{-4}.

SWAN was subsequently used to study the effect of the electron density on the coupling properties of the optimised bijunction with ϕ as a parameter and keeping $n_e/\nabla n_e$=1cm. As illustrated in Fig. 4 a good coupling is expected down to the electron cut-off density n_{ec}=1.7×10^{11}cm^{-3} which is reached with very low reflection, in particular when ϕ=180° for which $R(n_{ec})$=1.13%, whereas for higher densities, in particular at n_e=3.4×10^{11}cm^{-3}, it is kept well below 1%. For the power directivity, again at ϕ=180°, a slight increase to 67% is expected as the density descends to n_{ec}, being maintained above 60% in the entire scanned region. Moreover, ϕ=180° achieves the best overall results except for densities close to n_{ec} where ϕ=+135° and −135° may show very slight specific advantages. It should be remarked that the standard multijunction achieves a higher maximum power directivity: around 72%.

Fig. 4. Coupling properties of the PAM as a function of n_e (with ϕ as a parameter and $n_e/\nabla n_e$=1cm): mean power coupling reflection (left) and power directivity (right).

The impact of a vacuum gap interposed between the launcher's mouth and the plasma, with widths ranging from 0 up to 1cm, was also explored considering n_e=n_{ec}=1.7×10^{11}cm^{-3} and $n_e/\nabla n_e$=1cm. The results shown in Fig. 5 reveal that for ϕ=180° this design may easily achieve reasonable performances for gaps up to 0.4 cm, at which the power coupling reflection and directivity are 6% and 62%, respectively. Concerning the power coupling reflection alone, ϕ=−135°, −90°, +90° and +135° could attain even better results. Yet, only

ϕ=+135° and +90° improve the directivity over that of +180°, reaching more than 70% for a gap between 1 and 4mm with a power reflection coefficient below 5%, whereas −135° and −90° lead to a degradation of performance. Therefore, only +135° and +90° are capable of improving reflection and directivity simultaneously.
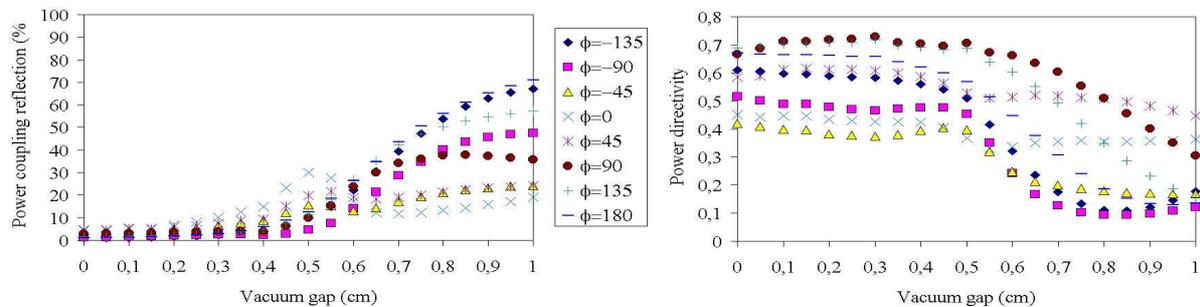
Fig. 5. Mean power reflection coefficient (left) and power directivity (right) for the PAM as a function of the vacuum gap width (with ϕ as a parameter and $n_e/\nabla n_e$=1cm).

CONCLUSIONS

This study has shown that from the stand point of the coupling properties, the PAM concept shows a potential for performances that are on a par with the more classic multijunction designs over which it even represents an improvement in terms of the coupling properties near the cut-off electron density, even if the power directivity is generally somewhat smaller than an independently fed classical launcher. The total injected power capability has to be experimentally assessed on long pulse discharge.

ACKNOWLEDGEMENTS

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