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Experimental test of an ITER-like Passive Active Multijunction Lower Hybrid RF launcher on the FTU tokamak

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The first experimental tests on the Lower Hybrid (LH) launcher similar to that foreseen for ITER have been carried out successfully on the FTU tokamak. The design of this antenna, called PAM (Passive Active Multijunction), developed in cooperation with the EURATOM-CEA association since several years, fulfils the following requests. 1) It can operate in the full shadow of the vessel port to avoid damage from the large particle flow inside the scrape-off layer (SOL) plasma. 2) It can tolerate the heating due to the perpendicular energy and neutron fluxes; 3) It preserves a level of power handling and current drive (CD) efficiency acceptable for ITER. Points 1 and 3 imply solving the problem of good power coupling to the main plasma in conditions of almost vanishing plasma in front of the grill. The proposal was to locate cooling ducts in between the LH fed waveguides in the final part of the launcher, except at the front end, where the usual periodicity of a multijunction (MJ) is restored by interposing passive waveguides between the active ones [1]. In this way the $N_{||}$ spectrum ($N_{||}$ is the parallel index of refraction) and hence the CD performances can be made similar to a usual MJ, provided a strong cross coupling exists between the active and passive waveguides. This in turn occurs if the plasma density in front of the grill is close to the cut-off value or if a thin vacuum layer is present, so that the almost vanishing plasma existing in the shadow of the port should not inhibit a good power coupling, as instead occurs either for a MJ or a conventional grill.

In the present work are detailed, within the limits of the allowed space, the experiments performed in FTU, which were focussed mainly to validate the PAM concept. The general layout of the FTU PAM and the main technical solutions adopted are instead described in a recent paper [2].

The PAM features most relevant for ITER, foreseen by the simulation codes, have been validated. The power density achieved in the FTU experiment in almost steady state conditions has been 85 MW/m^2, close to the design value of 95 MW/m^2. The value envisaged for the ITER launcher, equal to 33 MW/m^2, corresponds to 52 MW/m^2 on FTU when the difference between the frequencies in FTU, 8 GHz, and ITER, 5 GHz, is taken into account, and therefore is more than 1.5 times below. A pulse with an average power of 245 kW (the power scaled from the ITER request is 170 kW) can be injected for the maximum time allowed by the LH power system, namely >0.9 s, without any fault in the transmission lines or in the grill mouth. Even higher power is coupled to the plasma for shorter times: 260 kW (design value =270 kW) with a 0.2/0.08 s ON/OFF cycle on 0.92 s total duration, and more than 300 kW on a single pulse 0.07 s long. The limitation in the first case was only due to the concern that strong outgassing inside the waveguide could trigger some arching, while the second case was indeed limited by the outgassing, but no more time was left to condition further the waveguides.

Conditioning the section of the PAM in connection with the main FTU vacuum, even if essential to avoid unwanted gas release inside the waveguides, has not required lengthy or particular techniques. Feeding the waveguides with LH power during the plasma discharges for one day, without a previous baking at 200 °C, has been enough for operating at the power level equivalent to the ITER request, i.e. 170 kW. However this procedure has a sort of local character, since it had to be repeated after changing either the antenna position respect to the vessel, or the pattern of the total magnetic field, namely the plasma current I_p and/or the toroidal magnetic field B_T. A 200 °C baking, cleaning thoroughly the wave guide surface, should minimize this disadvantage.

After a proper conditioning has made negligible the outgassing from the waveguide walls caused by the LH electric field, very good coupling is always achieved. The average power reflection coefficient R_c stays below 2%, even with the grill mouth retracted 2 mm inside the port shadow, with density in front of the launcher ($n_{e,PAM}$) very close to the cut-off value ($n_{e,c.o.}=0.79 \cdot 10^{18}$ m^{-3}). In Fig. 1 R_c is plotted versus $n_{e,PAM}$, taken as an average from the measurements of 4 Langmuir probes located aside the grill. Despite its low absolute level, R_c never reaches the level ≈0.5%, predicted by both SWAN-2D [3] and GRILL-3D [4] codes. The latter code, however, foresees the R_c increase near the cut-off density, experimentally observed, differently from SWAN 2D. Finer comparisons, as to consider R_c for different $N_{||}$ spectra or its pattern along one grill row, are difficult because of the strongly varying density in front of the antenna. This, directly sampled by the Langmuir probes, is mainly caused by the uneven length of the field lines in the scrape-off plasma (SOL), which is particularly developed close to the wall because of the field distortion by the magnetic ripple.

The performance of the PAM antenna in terms of the current drive (CD) efficiency (η_{CD}) is shown in Fig. 2. Here the most relevant quantities are plotted versus time for a discharge where different phases must be considered. The first one is with the PAM only excited, the second is a reference ohmic segment, the third a LH pulse from a conventional grill alone, named G4, followed then by a superimposition of the PAM power onto the G4 grill. The conventional grill is set to launch a $N_{||}$ spectrum similar to the PAM: the peak value is the same, $N_{||,pk} \approx 2.24$, but the directivity, i.e. the fraction of the total power launched in the CD direction, is larger, 80% against 65%. The magnitude of the LH driven current is deduced from the evaluation of the ohmic current, considering the residual loop voltage and the resistivity change due to the variation of the impurity content (Z_{eff}) and of the electron temperature, as described in [5]. The greater CD efficiency for G4 is due not only to the higher directivity but also to the higher coupled power, which in turn raises $\langle T_e \rangle$ (volume averaged electron temperature) and consequently η_{CD} [5]. As expected, the present η_{CD} magnitude, $\leq 0.2 \cdot 10^{20}$ m^{-2}A/W, is lower than usual in FTU ($\eta_{CD} \approx 0.25 \cdot 10^{20}$ m^{-2}A/W [6]), when $\langle T_e \rangle$ is ≥0.8 keV and the LH waves phase velocity is higher, $N_{||,pk} \approx 1.8$. On many shots basis the CD properties of the PAM are illustrated in Fig. 3, where the LH driven fraction I_{LH}/I_p is plotted versus the parameter h, $h=P_{LH}/(\overline{n}_e \cdot I_p \cdot R) \cdot 6/(Z_{eff}+5)$, with which is linked by the linear relation $I_{LH}/I_p = h \cdot \eta_{CD}(Z_{eff}=1)$ [5], according to the definition of $\eta_{CD}(Z_{eff}=1)$. P_{LH} is the total LH coupled power, $\overline{n}_e$ is the line averaged plasma density and R=0.935 m is the FTU major radius. B_T and I_p are fixed to 7.1 T and 0.35 MA respectively, while $\overline{n}_e$ ranges in 0.3-$0.55 \cdot 10^{20}$ m^{-3}. Evaluations have been made for the phases with PAM alone, with G4 alone, with the combination of two, and also for the incremental effect of the PAM on the G4 only phase, denoted by different symbols. No distinction appears between the various situations, within the experimental errors, i.e. the PAM CD capability is well aligned with that of a conventional grill and its CD contribution is additive to that of other grills, as for the normal operations. The apparent deviation from the FTU usual linearity is reduced, but persists, if the waves directivity, neglected for these data points, is taken into account. This can be accounted for by the non negligible contribution of the residual electric field in cases of quite low collisionality, i.e. low density, and little power as for the discharge shown in Fig. 2, as pointed out in Ref [5].

With a fast electron bremsstrahlung (FEB) camera, recently installed, the features of the HXR (hard x-ray) emitted by the LH generated fast electron tail have been studied with the aim to gain information on the power radial deposition profile and on the extension of the tail in the velocity space. This latter point is essential to investigate the PAM flexibility in the $N_{\|}$ spectrum, which otherwise is hard to derive from the macroscopic plasma parameters as the loop voltage. To detect some effect at our low available powers, a large variation of the spectrum is required, but this also changes the waves directivity to the point that the corresponding η_{CD} variation is almost balanced. For the particular FTU PAM design, varying the phase shift between adjacent MJs from the optimum value $\Delta\Phi=135°$ ($N_{\|,pk}\approx2.24$) to $\Delta\Phi=0°$ ($N_{\|,pk}\approx1.7$) reduces the directivity from 65% to 53%, approximately.

The HXR signals, detected along the central chord in distinct energy windows, are compared in Fig. 4 for two discharges with same $\bar{n}_e\approx0.53\cdot10^{20}$ m^{-3}, but different $N_{\|,pk}\approx1.7$ and ≈2.4 ($\Delta\Phi=180°$). In both phases, with PAM alone (top) and PAM+G4 (bottom), the faster spectrum does create a faster tail. The relevant energy range, E_{ph}>120 keV, just pertains to an electron traveling at the phase velocity of a LH wave with $N_{\|}\approx1.7$ (relativistic $\gamma=1.235$). The most significant difference between top and bottom of Fig. 4 is the level of the residual loop voltage, V_{loop}, equal to 0.64 and to 0.46 V respectively, for both discharges. This difference, however, affects only negligibly the FEB spectrum, and then any determinant effect of the electric field on the fast electron tails can be ruled out. Indeed, we are in a density range where collisionality usually drops this kind of effects in FTU (the Dreicer electric field for electrons with the same velocity as a $N_{\|}\approx1.7$ LH wave is located at 2.6 V). In addition, the preserved V_{loop} value in the two shots is consistent with a balance between the variation of the CD efficiency and of the directivity, when changing $N_{\|,pk}$, as anticipated above.

Concerning the LH power radial deposition profile, the FEB profiles are consistent with the calculation of the fast ray-tracing code (FRTC) [7], for the $N_{\|}$ spectrum given by the grill codes, at line averaged densities $\bar{n}_e$>$0.4\cdot10^{20}$ m^{-3}. Below, the radial diffusion of the fast electrons makes the FEB profiles broader than those of the LH deposition.

Finer, yet important, effects as that of the edge density on the spectrum directivity have also been investigated, but the present low power level and the limited directivity of the FTU PAM sample do not allow any conclusive statement.

In conclusion, the PAM concept, proposed as LH wave launcher for ITER to overcome the heavy environment, has been validated by the tests carried out on FTU on the physics side and for some technical aspects also. Very good coupling is obtained with the launcher fully retracted into the port, as it will be for ITER, and with an almost evanescent plasma in front of the grill, even though a sort of offset to the reflection coefficient must be added respect to the code predictions. Taking into account the lower power directivity, the CD efficiency is not degraded respect to a conventional grill launching a similar $N_{\|}$ spectrum, and evidence of flexibility in managing the $N_{\|}$ spectrum has been given. From the technical side the power handling capability is well above the minimum required for ITER: instead of 33 MW/m^2, 50 at least is a possible target value, according to the usual frequency scaling. Conditioning the waveguides, even though essential for using the PAM, does not require lengthy or particular techniques and importantly is not lost over long time. All these features give reasonable confidence in applying the PAM technique to ITER, even though other very crucial aspects will be in the near future investigated on Tore Supra tokamak at Cadarache, CEA, France. In particular it will be studied the response to a very prolonged RF excitation and high energy fluxes, up to 1000 s, which is of the order of the time scale of the particle wall saturation and of the thermalization of the whole device, together with the issues not cleared by the FTU experiment, due to the low power and directivity.

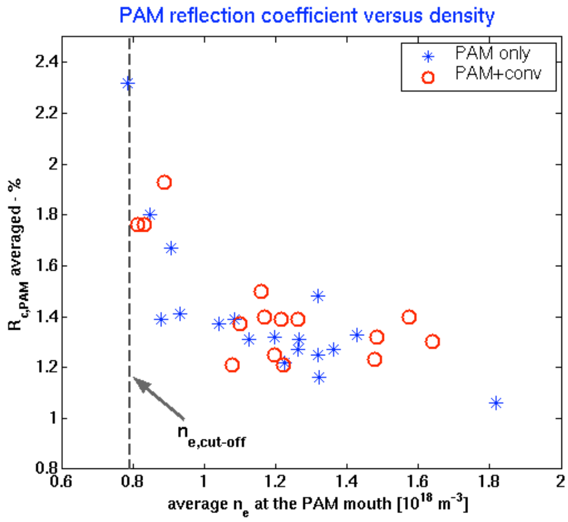

*Fig. 1 – Coupling characteristics of the PAM antenna shown as a plot of the power reflection coefficient versus the density at the grill mouth, as measured by Langmuir probes mounted aside the grill. * Symbols stand for PAM working alone, O symbols stand for PAM and a conventional grill simultaneously excited*

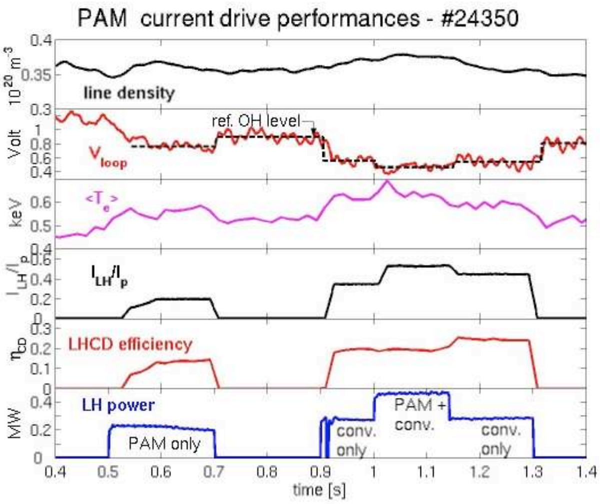

Fig. 2 – Current drive effects of the PAM antenna compared with those of a conventional grill. Time traces of: a) line averaged density, b) loop voltage, c) volume averaged electron temperature, d) ratio of the LH driven to the total plasma current, e) estimate of the CD efficiency, f) coupled LH power

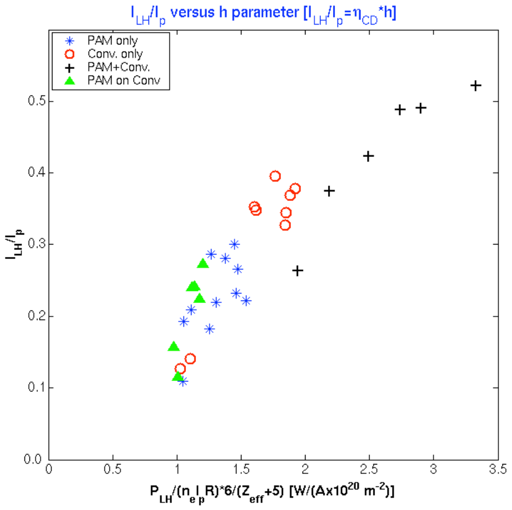

Fig. 3 – Fraction of the LH driven current versus the quantity h defined in the text. B_T=7.1 T, I_p=0.35 MA, $\bar{n}_e$=3.2-5.5·10^{19} m^{-3}. Triangles describe the incremental effect of the PAM on the conventional grill alone phase

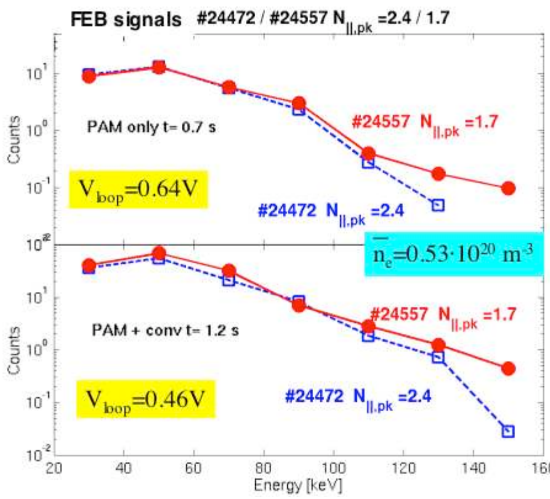

Fig. 4 – FEB signals detected along the central chord. Two different phasing of the PAM are compared for the PAM only and PAM+conventinal grill phases. B_T=7.1 T, I_p=0.35 MA, $\bar{n}_e$=5.3·10^{19} m^{-3}, V_{loop}=0.64 V (top) and =0.46 V (bottom)

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