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Plasma Dielectric Properties and ICRF Antenna Impedance Matrices.

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Ion Cyclotron Range of Frequencies (ICRF) waves will be coupled to ITER plasma with arrays of radiating straps. Such arrays are fully characterized by input impedance matrix **[Z_{ij}]**, relating RF voltage V_i on strap feeder i to RF current I_j on feeder j, thus summarising all antenna coupling properties. Modelling **Z** precisely has recently become a priority : both experiments with the new Tore Supra (TS) ITER-like antenna and modelling for JET-EP [1] suggest that the new "conjugate-T" matching scheme foreseen for ITER [2] is sensitive to strap cross-talk, i.e. to off-diagonal Z_{ij} elements. However no numerical tool is presently able to account accurately both for the geometrical details of the wave launching structure and for the dielectric properties of a realistic plasma. Simulation would be substantially simplified if the plasma could be reduced to a high permittivity dielectric medium, as in [1]. Yet both measurements and modelling in other contexts [3,4] suggest that some information is always lost in such reduction. This paper investigates the impact on the structure of **Z** of some dielectric properties specific to a plasma, with emphasis on the coupling imbalance between identical straps. All these properties are studied theoretically and numerically on the test 2×2 array in figure 1, both representative of the new TS antenna, and a pedagogical example since asymmetry between straps comes only from the plasma.

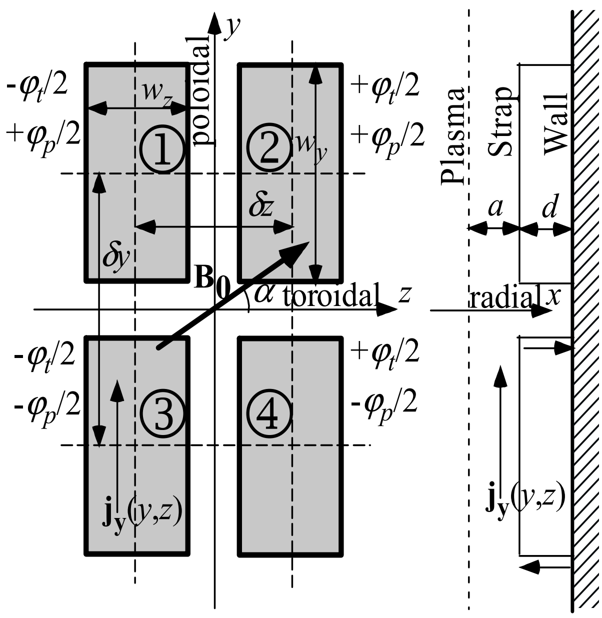

Figure 1 *: sketch of the test antenna studied in this paper. For numerical scan,* $w_z=0.147m$, $w_y=0.264m$, $\delta y=0.36m$, $\delta z=0.28m$, $a=5cm$, $d=16.5cm$. RF frequency 48MHz, $B_0=2.41T$, *pitch angle* $\alpha=7°$.

1. THEORY ON IMPEDANCE MATRIX SYMMETRY

Table 1 summarizes the general form of matrix **Z** for the test antenna radiating on several media. For symmetry reasons both in the antenna geometry and in the medium **Z** contains only 4 independent terms in the case of a diagonal dielectric tensor. Whenever a symmetry disappears in the medium new terms, and thus extra information, are added to **Z**. With plasma gyrotropy the up-down symmetry of the RF coupling problem is lost, so that $Z_{13} \neq Z_{31}$, $Z_{14} \neq Z_{41}$ (with strap numbering as in fig. 1, highlighted elements in table 1). Tilting magnetic field $\mathbf{B_0}$ with respect to the toroidal direction further breaks toroidal symmetry. Violating reciprocity relations $Z_{ij} \neq Z_{ji}$ allows identical straps, fed with phase 0 or π, to radiate different powers. Such behaviour cannot be reproduced with a diagonal dielectric tensor.

Diag. dielectric, toroidal $\mathbf{B_0}$	Magn. plasma toroidal $\mathbf{B_0}$	Magnetized plasma tilted $\mathbf{B_0}$
$\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{12} & Z_{11} & Z_{14} & Z_{13} \\ Z_{13} & Z_{14} & Z_{11} & Z_{12} \\ Z_{14} & Z_{13} & Z_{12} & Z_{11} \end{bmatrix}$	$\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{12} & Z_{11} & Z_{14} & Z_{13} \\ Z_{31} & Z_{41} & Z_{11} & Z_{12} \\ Z_{41} & Z_{31} & Z_{12} & Z_{11} \end{bmatrix}$	$\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{13} \\ Z_{31} & Z_{32} & Z_{22} & Z_{12} \\ Z_{41} & Z_{31} & Z_{21} & Z_{11} \end{bmatrix}$
4 independent elements /16	6 independent elements /16	10 independent elements /16

***Table 1**. Symmetries of **Z** matrix for test antenna radiating on several media. Strap numbering : see figure 1.*

Some matrix asymmetries are bounded however. If we prescribe that the medium can only absorb waves without re-emitting them, the total active power radiated by the array should be positive in all cases. Applying such prescription to straps i and j with phasing ±π/2 yields $|X_{ij}-X_{ji}| \leq (R_{ii}+R_{jj})$, where $\mathbf{Z}=\mathbf{R}+i\mathbf{X}$. No equivalent bound exists for $|R_{ij}-R_{ji}|$. Moreover, assuming that the RF current profiles are the same along straps i and j, the spectral contribution to $X_{ij}-X_{ji}$ of a plane wave with wavevector **k** differs from that of $R_{ii}+R_{jj}$ by the oscillating factor $\sin(\mathbf{k}.\boldsymbol{\delta}\mathbf{r_{ij}})$, where vector $\boldsymbol{\delta}\mathbf{r_{ij}}$ separates the straps centres (see fig. 1).

2. QUANTITATIVE NUMERICAL EVALUATION OF Z ASYMMETRIES.

The ICANT antenna code [5] now accommodates tilted $\mathbf{B_0}$ magnetic field [6]. A procedure was devised for extracting **Z** from ICANT output for any array of 4 straps on any medium. As no symmetry on **Z** is postulated *a-priori*, 16 complex Z_{ij} have to be computed. Each ICANT simulation yields 4 complex powers radiated by each strap so that 4 runs with proper poloidal and toroidal phasings (φ_p,φ_t) are sufficient to reconstruct **Z**. (φ_p,φ_t)=(0,0), (0,π), (π,0) and (π/2,π/2) were retained. As a validation, the symmetries of **Z** for the test antenna were verified with 10^{-10} relative precision in all media, and the main trends of $(X_{ij}-X_{ji})$ and $(R_{ij}+R_{ji})$ for bare straps (including majoration by $(R_{ii}+R_{jj})$) were recovered by an analytic formula, assuming flat RF current profiles along straps and feeders (see fig. 4). A density scan was performed on an homogeneous plasma for the test array of figure 1.

In the scan both toroidal and poloidal imbalance on active power could reach ±15% for (φ_p,φ_t)=(0/0), ±25% for (φ_p,φ_t)=(0/π), and ±50% for (φ_p,φ_t)=(π/0). Imbalance on reactive power did not exceed ±2% for all 3 phasings and was essentially poloidal. Figure 2 and 3 show that power equipartition was approached both at low n_e where the plasma behaves like vacuum, and at high n_e where it is like a mirror. Asymmetries are sensitive to surface waves : small n_e changes cause power redistribution between straps while the total RF power is a smoother function of density. Such fluctuations should attenuate on inhomogeneous plasma.

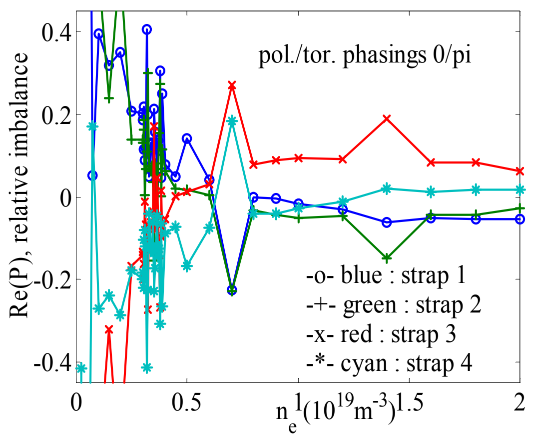

Figure 2 *: n_e scan, imbalance on active RF power for phasing (φ_p,φ_t)=(0/π). Strap numbering as fig. 1*

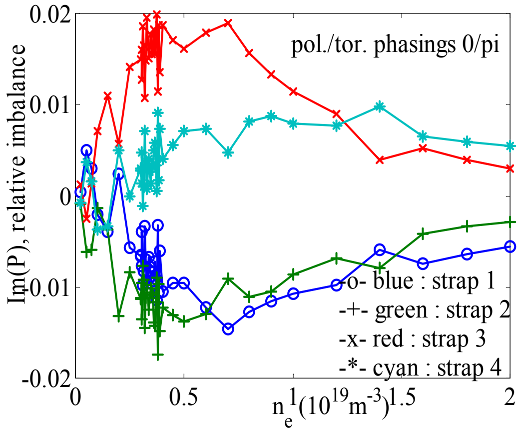

Figure 3 *: n_e scan, imbalance on reactive power for phasing (φ_p,φ_t)=(0/π). Strap numbering as fig. 1.*

Figure 4 and 5 quantify the off-diagonal matrix elements as a function of n_e. Figure 4 confirms that $|X_{ij}$-$X_{ji}|/(R_{ii}+R_{jj})<1$. Yet $(X_{ij}$-$X_{ji})/(X_{ij}+X_{ji})$ can reach 30%. $(R_{ij}$-$R_{ji})$ is not bounded *a-priori* and can be of the same order as $(R_{ij}+R_{ji})$ so that R_{ij} and R_{ji} can be quite different (fig. 5). Asymmetries vanish both at low and high n_e, due both to the plasma dielectric properties and to the oscillations of factor sin(**k.δr**$_{\mathbf{ij}}$) over the spectral coupling domain.

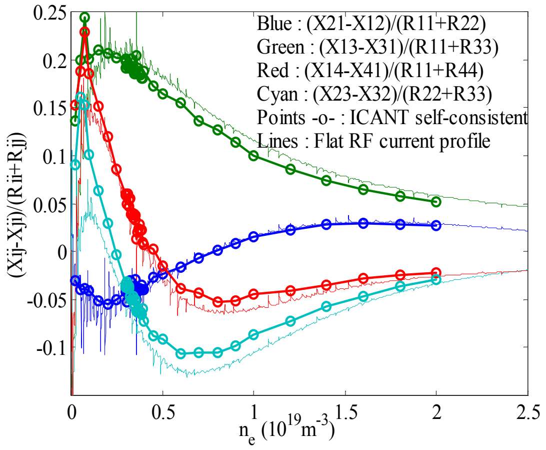

figure 4 *: n_e scan, off-diagonal X_{ij} asymmetries.*

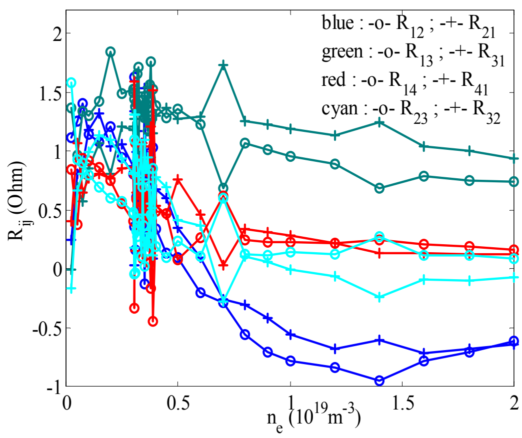

figure 5 *: n_e scan, real off-diagonal matrix elements.*

As observed on NSTX [3] the effect of tilting $\mathbf{B_0}$ is clearly visible on figures 4 & 5 : $(Z_{14}$-$Z_{41})$ and $(Z_{23}$-$Z_{32})$ are quite different, and $(Z_{12}$-$Z_{21})$ oscillation amplitude is comparable to $(Z_{23}$-$Z_{32})$. For similar reasons as on fig. 2 and 3, the antisymmetric part of **Z** varies a lot under small n_e variations while its symmetric part ($Z_{ij}+Z_{ji}$) is a smoother function of density.

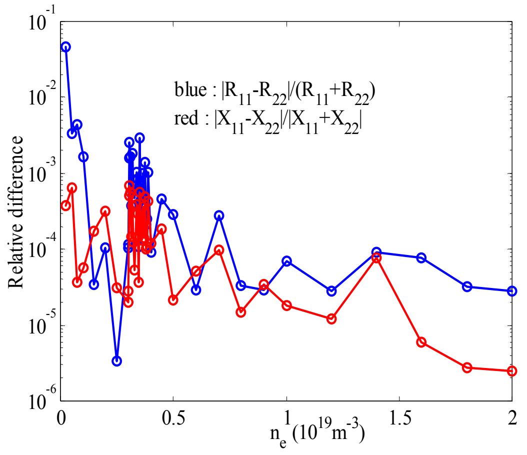

***Figure 6** : asymmetry on diagonal matrix elements*

Similar fluctuations were also obtained with the analytic formula (see spikes on figure 4).

When $\mathbf{B_0}$ is tilted $Z_{11} \neq Z_{22}$ is predicted. Figure 6 shows however that the asymmetry remains small, particularly on X_{ii}. It fluctuates with n_e, but vanishes at high n_e. Test runs indicate that the asymmetries evidenced in fig. 2-6 persist somehow when straps are put in independent metallic boxes.

3. SUMMARY AND OUTLOOK

Symmetries of the medium, e.g. gyrotropy and tilted $\mathbf{B_0}$, influence symmetries of the impedance matrix **Z**. At best an appropriate diagonal dielectric tensor can reproduce the total RF power radiated by identical straps fed with phasing 0 or π (i.e. symmetric part $Z_{ij}+Z_{ji}$). Yet this power is equally balanced between straps, while asymmetries ($Z_{ij}-Z_{ji}$) specific to real plasmas cause power imbalance. ICANT provides for the first time a numerical tool to quantify these asymmetries self-consistently. This was done on a 2×2 test array of identical bare straps. Significant imbalance was obtained between active powers, less than 2% on reactive power. Effect of tilting $\mathbf{B_0}$ by 7° was found negligible on diagonal terms (i.e. $Z_{ii} \approx Z_{jj}$ for identical straps i and j) and of the same order as gyrotropy for off-diagonal Z_{ij}. Although $|X_{ij}-X_{ji}|$ is bounded by $(R_{ii}+R_{jj})$, $(X_{ij}-X_{ji})/(X_{ij}+X_{ji})$ can reach several 10%. R_{ij} and R_{ji} can be totally different. In ITER-relevant plasma conditions at high density **Z** asymmetries are reduced. A lot of work is still needed to get more realistic **Z** simulations, and primarily include a strap environment (box, screen,…), but this first study suggests that both the wave launching structure and the plasma have to be described precisely to yield reliable results.

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