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Coupling Resistance of the JET ICRH A2 Antennas in the Divertor Configuration Mark II GB

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Abstract. On JET the coupling resistance averaged over the four straps of the A2 antennas in the Mark II GB divertor configuration was analyzed with particular emphasis on the plasma shape dependence. The measured values were compared with models for the coupling resistance of different levels of sophistication with the ultimate goal of supplying recipes on how to improve the coupling. For a given frequency and given plasma mode (L, H, etc.) the midplane distance between the antenna and the last closed flux surface was found statistically to be the most important element. The shape dependence itself was not pronounced. However, the statistical nature of the analysis does not preclude that the loading in any given discharge can be improved by slightly modifying the shape. In first experiments CD₄ gas puffs showed a 12% increase in loading of those antennas with field line connection to the gas valve.

INTRODUCTION

The plasma shape influences the plasma confinement properties in a variety of ways that are being investigated. In particular, plasmas with high triangularity have desirable properties. However, heating such plasmas with radio waves in the ion cyclotron range of frequencies (ICRF) might pose a problem if the antenna coupling resistance is low as is expected for plasmas whose poloidal shape is not well fitted to the poloidal shape of the antennas. From the actual impedance measurement of each antenna strap at some distance from the antenna the antenna coupling resistance, R_{ant} , is inferred to be the termination resistance of a section of transmission line with characteristic impedance, Z_0 , in a simple equivalent circuit. The RF power dissipated in this resistance approximately equals the power launched from the antenna into the plasma. For a given maximum voltage, V_{max} , sustainable in the transmission line the maximum launched power, P , is then given by

¹ See appendix of J. Pamela, "Overview of recent JET results", Proc. IAEA Conf. on Fusion Energy, Sorrento, 2000.

$$P \approx \frac{V_{\max}^2}{2Z_0} \cdot \frac{R_{\text{ant}}}{Z_0}.$$

Most ICRF heating systems are limited by the maximum voltage sustainable in the antennas and transmission lines. Thus for reliable operation it is necessary to increase the antenna coupling resistance.

The influence of the plasma shape on the antenna coupling resistance has been investigated statistically for the A2 antennas on JET in the divertor configuration Mark II GB with particular emphasis on configurations with high triangularity, taking into account the shots between 46670 and 52570. The antenna coupling resistance depends critically on the edge density profile. Unfortunately, on the JET the edge density profile measurements are not provided by a standard diagnostic. Therefore it was attempted to correlate the measured coupling resistance of antenna A with global plasma parameters which were thought to be related to the plasma edge profile. The geometric fit of the antenna to the plasma was quantified using different methods. The used antenna coupling resistance is the average value over all four straps of one antenna time-averaged over 200 msec. Since no dedicated experiments were done for this study a simple antenna model was developed in order to be able to compare different shots.

ANTENNA MODEL

The proposed antenna model assumes that the antenna coupling resistance depends on the distance, d , between the antenna current straps and the location where the plasma density equals the fast wave cutoff density, n_{cut} . The cutoff density is approximately proportional to $\langle k \rangle^2 / \omega$. Since the RF field decays exponentially away from the antenna in the evanescent region with a decay length approximately equal to the $\langle k \rangle$ value of the maximum of the antenna spectrum, one obtains $R_{\text{mod}} \propto e^{-2\langle k \rangle d}$. The plasma edge density profile in the scrape-off layer (SOL) is assumed have an exponential decay with a decay length λ_{SOL} . For most fusion experiments the fast wave cutoff density is reached in the scrape off layer. Then one obtains after some simple manipulations:

$$R_{\text{mod}} \propto \frac{n_{\text{LCFS}}}{n_{\text{cut}}} \cdot e^{-2\langle k \rangle \lambda_{\text{SOL}}} \cdot e^{-2\langle k \rangle d_{\text{LCFS}}},$$

where n_{LCFS} is the density at the last closed flux surface (LCFS) and d_{LCFS} is the distance between the antenna current strap and the LCFS. This distance can vary poloidally for different plasma shapes, thus it is necessary to describe the geometric fit of the antenna to the plasma. Four different geometric fit parameters are proposed that replace the last exponential in the Eqn. above. In the following $d(z')$ is the distance between the antenna current strap and the LCFS at different vertical positions z' with $d_{\text{ROG}} \equiv d(z'=0)$, L is the total length of the antenna in z , $l(z)$ is the normalized poloidal current distribution in the antenna strap. Fit0 does not take the poloidal variation into account and simply uses the midplane distance, Fit1 uses the average antenna distance, Fit2

averages over the actual antenna RF field at the LCFS assuming a poloidally constant antenna current and Fit3 assumes a poloidal variation of the antenna current.

$$\begin{aligned} \text{Fit0} &\equiv e^{-2\langle k \rangle d_{\text{ROG}}} & \text{Fit2} &\equiv \frac{1}{L} \int e^{-2\langle k \rangle d(z')} dz' \\ \text{Fit1} &\equiv e^{-2\langle k \rangle \left[\frac{1}{L} \int d(z') dz' \right]} & \text{Fit3} &\equiv \frac{1}{L} \int |f^2(z')| \cdot e^{-2\langle k \rangle d(z')} dz' \end{aligned}$$

A simple (linear) relation between the antenna coupling resistance of the model, R_{mod} , and the experimentally measured coupling resistance, R_{ant} , can only be assumed for fixed frequency and phasing since in the antenna model neglects the frequency and phasing dependence of the antenna electrical properties. The model could be improved by incorporating the measured 4×4 scattering matrix of the 4 strap antenna [1]. Also, averaging the coupling resistances of different straps is a crude simplification. However for typical day-to-day ICRH system operation, above definition of an antenna coupling resistance is considered a useful, albeit somewhat empirical quantity that is closely related to the expected performance.

COMPARISON OF EXPERIMENTAL DATA WITH MODELS

The analysis is based on a data base of about 1000 plasma shots with ICRH at frequencies between 25 and 60 MHz and antenna phasings of $(0|\pi|0|\pi)$, $(0|\pi/2|\pi|3\pi/2)$, $(0|\pi|\pi|0)$ and $(0|\pi/2|\pi|3\pi/2)$. The distance between the antenna current straps and the LCFS is determined from EFIT. According to that the distance in the horizontal midplane varied between 0.01 and 0.14 m, the plasma elongation between 1.55 and 1.78 and the triangularity between 0.1 and 0.5. The density at the LCFS is approximated with the line-averaged density measured closest to the LCFS ($R=3.75\text{m}$). The value of $\langle k \rangle$ was derived from experiments where d_{ROG} was changed while the other parameters were kept constant: $\langle k \rangle = 8\text{m}^{-1}$ for antenna phasing $(0|\pi|0|\pi)$ and $\langle k \rangle = 7\text{m}^{-1}$ for antenna phasing $(0|\pi/2|\pi|3\pi/2)$.

Fig. 1a and b show the antenna coupling resistance versus Fit0 and Fit2, resp., for a subset of the shots with $(0|\pi|0|\pi)$ phasing, L-mode plasmas and triangularity $\delta > 0.22$. The expression $y = a_0 + a_1 \cdot x^{a_2}$ was fitted to the scatter of points. The normalized variance given by $\sigma^2 \equiv \langle (y_{\text{data}} - y)^2 \rangle / \langle y^2 \rangle$ describes the goodness of the fit. It is found that the normalized variance is about equal for Fit0 and Fit1 and about 20% lower for Fit2 and Fit3. Similar results are obtained also for lower triangularities, different frequencies and phases. In general, however, the quantities that describe the fit of the plasma to the antenna lead only to a slight reduction of the data scatter. Thus it is concluded that, at least statistically, the reduction in antenna coupling is weak for highly triangular plasmas. The coupling resistance is dominated by the midplane distance between current strap and LCFS, d_{ROG} .

Fig. 2 a and b show a plot of the antenna coupling resistance versus the proposed antenna model. There the density decay in the scrape-off layer was modeled to be

$\lambda_{\text{SOL}} = 0.01\text{m} \cdot \sqrt{q_{95}/5}$. The model has some predictive qualities, at least for L-mode discharges. The pronounced scatter for ELMy H-mode discharges might be partially due to the time-averaging over 200msec. Even though this model does not include a frequency or phasing dependence of the electric properties of the antenna, it is all the more surprising that it yields reasonable results.

In some preliminary experiments it was attempted to improve the ICRH coupling with additional CD₄ gas pulses. The results show only a modest increase of the antenna coupling resistance of about 0.2 Ω (12%) if there was a magnetic field line connection between the location of the gas valve and the antenna.

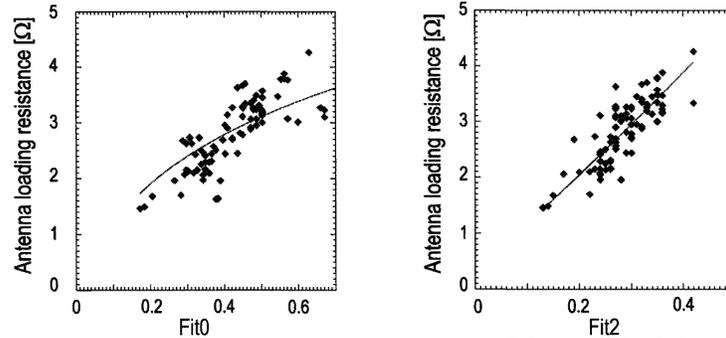


FIGURE 1. Measured antenna coupling resistance versus fit parameters Fit0 (a) and Fit2 (b) for L-mode, 0π0π phasing and 42 MHz.

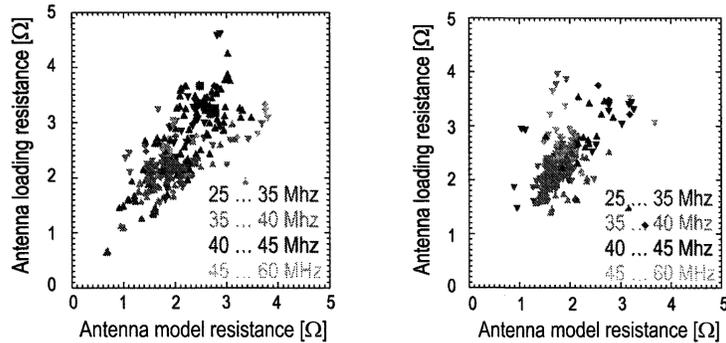


FIGURE 2. Measured antenna coupling resistance versus antenna model for L-mode (a) and ELMy H-mode (b).

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