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Simulating the JET ITER-like Antenna circuit

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§See Appendix F. Romanelli et al., Fus. En. Conf. 2008, (Proc. 22th Int. FEC Geneva, 2008) IAEA (2008)

Abstract.
A set of simulation/interpretation tools based on transmission line theory and on the RF model developed by M. Vrancken [2] has been developed to study the ITER-like Antenna (ILA) at JET. For given tuning element settings, the unique solution of the equations governing the ILA circuit requires solving a system of coupled linear equations relating the voltages and currents at the antenna straps and other key locations. This computation allows cross-checking predicted values against measured experimental ones. Further more, a minimization procedure allows improving the correspondence with the quantities measured in the circuit during shots, thus coping with unavoidable errors arising from uncertainties in the measurements or from inaccuracies in the adopted RF model. Typical applications are e.g. fine-tuning of the second-stage of the ILA circuit for increased ELM-resilience, cross-checking the calibration of the measurements throughout the circuit and predicting the antenna performance and matching conditions in new plasma scenarios.

Keywords: RF antennae, transmission line, matching
PACS: 41.20.Jb,52.50.Qt,84.40.Az,84.70.+p

INTRODUCTION

The ITER-like antenna (ILA) [1] has 8 straps connected in pairs to form 4 resonant double loops (RDLs). Each RDL (see Fig.1) has a capacitive and an inductive branch, whose reactances are set by variable capacitors to be approximately complex conjugate. In this way, Z_T (the effective impedance of each RDL defined at the T-point where the separate branches meet) is dominantly real. Moreover, this configuration features a relatively flat Z_T response as function of the branch resistances and therefore is very attractive for ELM resilient operation. During experiments, a real time matching algorithm steers the capacitor of each branch ensuring the system stays close to the predetermined Z_T value independent of the plasma loading. Variable second stage elements (stubs and phase shifters) allow adjusting the electrical length of the feeding transmission line to ensure that the generator is matched to the imposed Z_T value. These tuning elements are frozen during the plasma pulse and have to be adjusted on a shot-to-shot basis. In ELMy H-mode discharges the antenna loading varies significantly in very short time intervals, however. Therefore, ELM resilient operation relies on a combination of using low Z_T values together with off-matched second stage settings.

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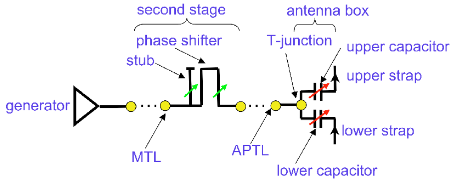

FIGURE 1. Schematic drawing of 1 of the 4 ILA RDLs, indicating the variable elements used for tuning the circuit.

THE ILA CIRCUIT SIMULATOR

The characteristic impedances Z_o and equivalent electrical lengths L of various components of the ILA circuit were invoked from detailed modeling [2]. Using the 2×2 'propagation' matrices $\bar{\bar{\mathbf{B}}}(Z_o, L)$ and - if needed - the 4-point junction coupling matrices representing the 3dB combiners (which were present at the outset of the ILA commissioning but were removed at a later stage to allow steering the relative phases of the RDLs) one can formally propagate the solutions of the telegrapher's equations along the transmission lines from the generator up to the APTL (Antenna Pressurized Transmission Line). Assuming the forward voltages at the generator as well as the voltages near the capacitors to be known, the voltages and currents at any position along the circuit can then be determined since the 3×3 T-junction scattering equation allows to determine the reflected voltage at the generator and the currents at the straps. Alternatively, rather than at the generator, the (forward) voltage at another reference point along the transmission line, e.g. at the APTL, can be assumed to be known.

Making use of the impedance matrix $Z_{8\times8}$ linking the voltages and currents on all 8 ILA straps is appealing from a diagnostic point of view: The wave pattern in the whole circuit then is uniquely defined by just 1 voltage per RDL. The actual $Z_{8\times8}$ accounting for the plasma is not known, however. In practice, two different $Z_{8\times8}$ are available: one can either use the $Z_{8\times8}$ obtained from TOPICA simulations or one can rely on test bed water load measurements using salted water as a dielectric [2, 3]. As the inductive near-field effects dominate the resistive effects, using these $Z_{8\times8}$ allows assessing the ILA behavior in a new regime prior to actually experimentally exploring it.

The ILA simulator can be run in 2 modes: Either the values of the various tuning elements are assumed to be known, in which case the voltages and currents at key places along the lines can be determined. Alternatively, some of these settings are assumed to be known only approximately, in which case their actual values can be determined using a minimization procedure that implements the simulator as a subroutine. Various minimization strategies can be opted for: finding the capacitor settings for a given experimental Z_T, finding the circuit element settings that ensure the actual phasing at the straps, ... Figure 2 shows an example of the simulator's output for $42MHz$ L-mode shot # 75329 for which up to $4.76MW$ of ILA power have been coupled to the plasma. On top of it giving a possibility to correct for unavoidable measuring errors, the main interest of the minimizer is that it allows to provide settings for the matching elements. The second stage setter - discussed next - is a key application.

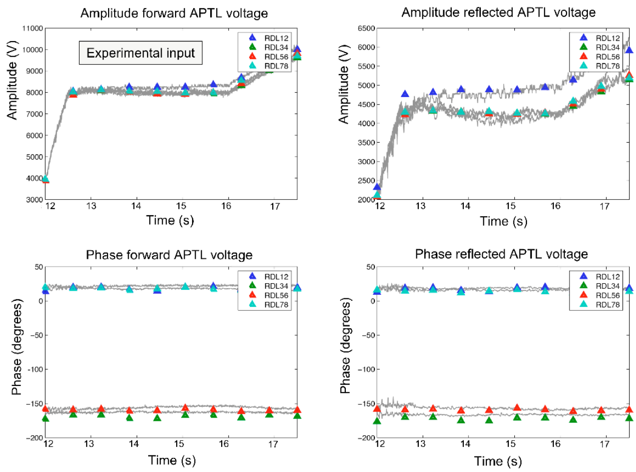

FIGURE 2. Amplitude (top) and phase (bottom) of the forward (left) and reflected (right) voltages at the APTL for shot # 75329. Symbols are simulated data; full lines are measured data. The top left data is assumed known while the other data is output. The APTL phases are slightly changed by the minimizer to ensure having the proper experimental phases at the straps.

THE SECOND STAGE SETTER

When the reflection coefficient Γ (the ratio of the voltages of the reflected and the incoming waves in the transmission line) is close to 1, a protection system turns the generator off to avoid it to be damaged. Hence, it is necessary to have a procedure allowing to adjust the second stage tuning elements in order to minimize the reflected power for an imposed impedance at the T-junction, Z_T. For second stage settings corresponding to a particular Z_T, small variations in the plasma load are compensated by adjusting the capacitor values, keeping the system as close as possible to its matched solution ($\Gamma \approx 0$ i.e. a voltage standing wave ratio $VSWR = [1+|\Gamma|]/[1-|\Gamma|]$ of about 1). This, though, is only senseful when the changes in the plasma load are relatively slow, as is the case in L-mode operation or the inter-ELM phase of an H-mode. In that case the parametric plot $(Re[Z_T(t)], Im[Z_T(t)])$ shows a more or less well localized 'cloud' of points which - for proper second stage element settings - can be centered on the desired Z_T (see Fig. 3). In H-mode the Z_T excursions are large and happen on a time scale that is too fast for the matching system to cope with the changing plasma load: aside from a fairly well localized cloud corresponding to the inter-ELM phase, the parametric plot now shows excursions in $|Z_T|$ of several Ohm. In such case aiming for the matched solution at the average Z_T is not adequate. Rather, the second stage settings must then be chosen off-matched to ensure the whole cloud lies inside the contour line of VSWR at which the trip level is set. Commonly second stage settings can be found to minimize the number of trips, but when too large Z_T excursions occur trips cannot be avoided.

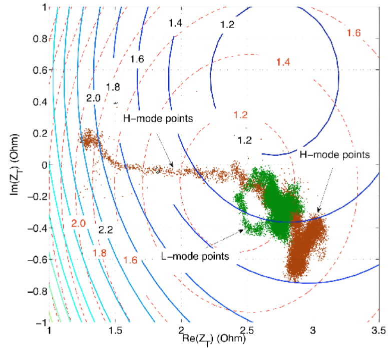

FIGURE 3. Z_T data points for H-mode shot # 77851 showing the need to set the second stage to a different Z_T to avoid too large VSWR during ELMs. The full contour lines correspond to the experimental values of the second stage elements; the dashed lines are for improved values, aiming at $Z_T \approx 2.4 - 0.1i\Omega$. For comparison the L-mode shot # 77852 cloud is shown.

CONCLUSIONS

A transmission line model tool has been developed to monitor and predict the voltages and currents in the ILA [1] circuit. It allows to perform consistency checks on the data and to determine the sensitiveness of the standing wave pattern in the lines to isolated or combined modifications of the tuning elements. The simulator is based on an RF model of the RF circuit [2] can be operated in a predictive or an interpretative mode, either using given (commonly experimentally read) data or adopting a minimization procedure to correct for unavoidable inaccuracies of the measurements. The ILA simulator has been used to cross-check and provide the coefficients of the scattering matrix arc detection system [2, 4], to identify calibration inaccuracies and to adjust second stage settings both in L- and H-mode operation.

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