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** See annex of M. Watkins et al, "Overview of JET Results ",*
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ABSTRACT

The RF characteristics of the JET-ITER Like (JET-IL) antenna relevant for operation on plasma have been assessed using full wave three Dimensional (3D) electromagnetic CST® Microwave Studio (MWS) simulations, measurements of the full 8-port antenna strap array S/Z-matrix, and RF circuit modeling. These efforts are made in parallel with the high voltage testing of the antenna inside a vacuum tank and the hardware implementation of a RF (Radio Frequency) matching feedback control system prior to installation of the antenna on the JET tokamak.

INTRODUCTION

The RF characteristics of the JET-IL antenna have been assessed using full wave three Dimensional (3D) electromagnetic MWS simulations and measurements of the full 8-port S/Z-matrix strap array of the antenna loaded with a tank filled with salty water at variable distance. These results are combined in RF circuit simulations which support the ongoing testing of the JET-IL antenna on testbed of which the first results are discussed below from an RF point of view.

ANTENNA STRAP ARRAY 8X8 S-MATRIX MEASUREMENTS AND SIMULATIONS

The full 8 port antenna strap array S-matrix of the antenna “loaded” with a water tank with salty water (5g/l) at variable distance [1] was measured with a NetWork Analyser (NWA) with appropriate measurement adaptors on all antenna ports and a metal wiregrid shield around the antenna as depicted in Fig. 1. The shield increases the accuracy of the measurements by improving the “grounding” of the antenna and reducing the stray fields reaching the back of the antenna housing. Fig. 2 compares the measured results to the MWS simulated results. The antenna loading as well as the inter-strap mutual coupling levels increase with decreasing distance to the load as expected intuïtively. The measured loading and mutual coupling levels are slightly less favourable than the simulated ones. The worst measured inter-strap cross talk is the poloïdal one between straps 2 and 3 at a -20dB level.

VACUUM MATCHING AT HIGH VOLTAGE TESTING

The measured and de-embedded 8-port S-matrix of the antenna strap array is imported into a RF transmission line and lumped element circuit model of the complete testbed setup. This allows to calculate the analytical solutions for the capacitor settings to achieve a desired T-point impedance Z_T, and the settings for the second stage matching phase shifter and stub in order to verify the real time RF measurements. In Fig. 3, the configuration during the high voltage testing of the Right Upper (RU) Resonant Double Loop (RDL) with the antenna assembled inside a separate vacuum tank is shown. The other RDLs are not powered in this case, and the feed lines are short circuited at the vacuum window flanges. Prior to connecting the feed line to the JET A1 generator for high voltage pulsing, the desired Z_T was found experimentally by manually adjusting the capacitor positions and using an Agilent® ENA E5070B NWA to calculate Z_T from the APTL (Antenna Pressurised Transmission Line) directional coupler measurements. It was found experimentally that the presence of the metal vacuum vessel has a considerable influence on the RF response of the antenna. The quality factor Q of the antenna in open air is increased considerably by the presence of the metal enclosure as depicted in Fig. 4, where the measured Z_T is compared to the one calculated from the measured S/Z-matrix in open air and by applying a scaling factor

$$\frac{Q_{simulated}}{Q_{measured}} = \frac{R_{simulated}}{R_{simulated}} \approx 0.6 \tag{1}$$

to the real part of the measured Z-matrix to obtain $Z=0.6*R_{measured}+jX_{measured}$ which gives better correspondence between measured and simulated results. Finding the matching solution of the narrow band vacuum resonator with the NWA is quite laborious and difficulties in reproducing the match due to only slight changes in the testbed setup were experienced. This difficulty was removed by the development of the automatic electronic RF feedback matching system as described below. The results of the high voltage testing itself are discussed in [2].

RF FEEDBACK CONTROL OF IMPEDANCE MATCH OF COUPLED RDLS

Figure 5 shows the block diagram of the automatic RF matching feedback control system which is intended to find the matched condition of all 4 RDLs and track it on a characteristic timescale of about 100ms during a plasma L- to H-mode transition. The matched condition is determined either by imposing 4 desired complex impedances at the conjugate T-points, or by imposing 4 desired complex ratios between the strap voltages within each RDL. The T-point impedance is calculated real time from the APTL directional coupler measurements [3],[4], while the RF probes measure directly the strap voltages. In the present test setup of Fig. 5 (only one RDL shown), a 0.2Watt 23-51MHz 50Ω RF signal is injected at the level of the service stub onto the 30Ω APTL to power the left and right upper RDLs of the JET-IL antenna “loaded” by the water tank in open air. The -80dB forward and reflected directional coupler signals have to be amplified by 60dB RF amplifiers to fall within the linear operating range of the ensuing processing electronics. The RFCM (Radio Frequency Conversion Module) downconverts the RF signals to an Intermediate Frequency (IF) of 1.3MHz. These IF signals are digitized to 12-bit amplitude and 10-bit phase signals by the APDM (Amplitude and Phase Detection Module) and routed to a National Instruments® PXI real time processor which runs the Labview® monitoring and control software. At present, the T-point impedance Z_T is controlled through the control algorithm error formulas [5]

$$\begin{aligned} \Delta C_k &= +sign_{kl}.Re\,(e^{j\alpha_{kl}}\,(Z_T(C_k, C_l) - Z_{Tkl})) \\ \Delta C_l &= + \qquad\quad Im\,(e^{j\alpha_{kl}}\,(Z_T(C_k, C_l) - Z_{Tkl})) \end{aligned} \tag{2}$$

for (k,l)=(1,2)=(5,6), where the choice of $sign_{kl}$ for the ΔC_k and the angles α_{kl} follow from the topology of the T-point impedance Z_T as a function of C_k, C_l and are parameters set by the knowledgeable operator. From these signals a PID (Proportional, Integral, Derivative) controller within the Labview® software generates 0-10V DC command signals for the J1B electronic processing cubicle that controls the AHSCS (Actuator Hydraulic Supply and Control System) with 4/20mA command signals. The The hydraulic fluid at 70bar absolute and 30bar differential pressure to the hydraulic actuators that adjust the vacuum capacitors closes the signal feedback loop. Figure 6 shows the (non optimized P=0.01, I=0.002, D=0) response of the capacitors when launched from the outer positions $[C_k, C_l]$=[140pF,70pF] preset during the first 5s, and under feedback control during 10s with parameters $Z_{Tkl}=2.8+j0.5\Omega$, $\text{sign}_{kl}=-1$, $\alpha_{kl}=-60°$ to find and hold one of the two existing conjugate solutions of the single RDL matching problem (d=0cm). The dashed lines show the convergence of the single RDLs when the capacitors of the other RLD are completely retracted to 50pF off resonance positions such that mutual interference can be neglected. The solid lines show that the coupled response with the influence of toroïdal mutual coupling between the RDLs leads to a convergence to slightly different end solutions. The ΔC of more than 30pF for this example is considerably larger than the expected variation of around 5pF with an L- to H-mode transition for which the shift of the solution can be tracked within 100ms by adjusting the PID settings of the feedback loop. Further work to implement the strap voltage control is in currently in progress.

ACKNOWLEDGMENTS

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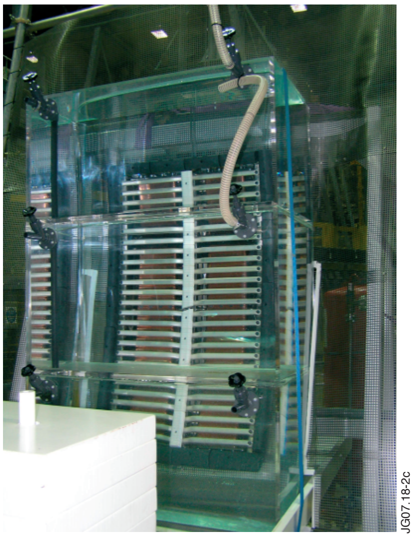

Figure 1: JET-IL antenna with metal wiregrid shield "loaded" by moveable tank with salty water.

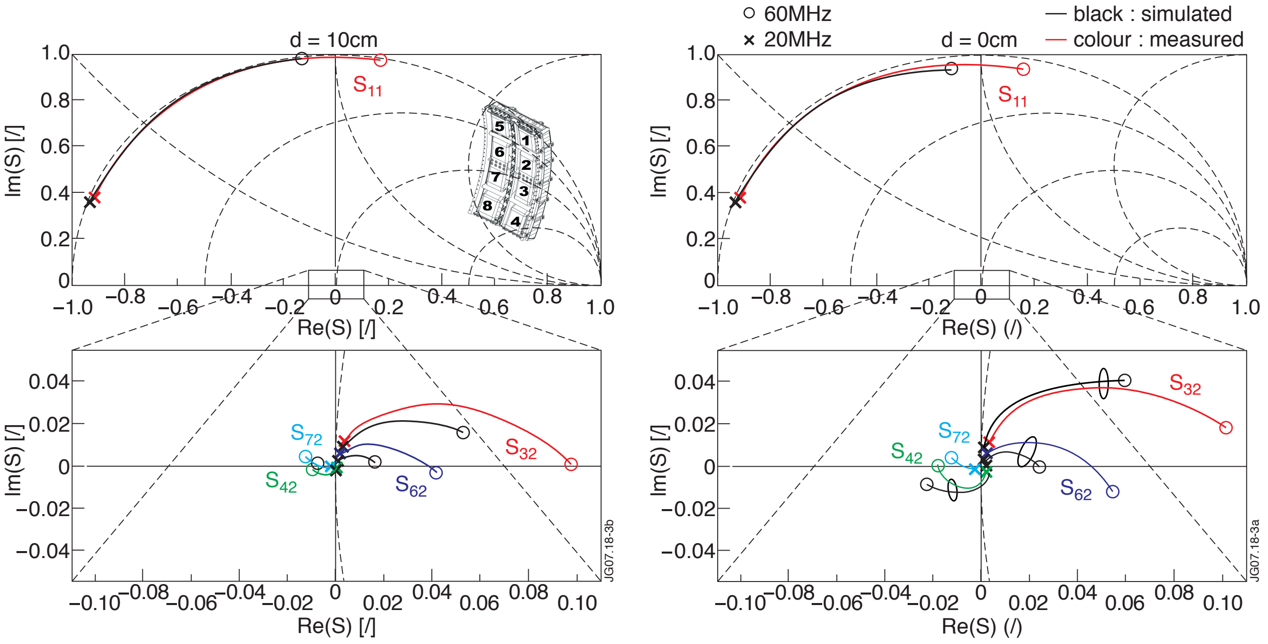

Figure 2: Measured and de-embedded versus MWS simulated S-parameters (50Ω reference impedance) of the 8x8 antenna strap array matrix in the 20-60MHz frequency range, for distances d=0cm and d=10cm.

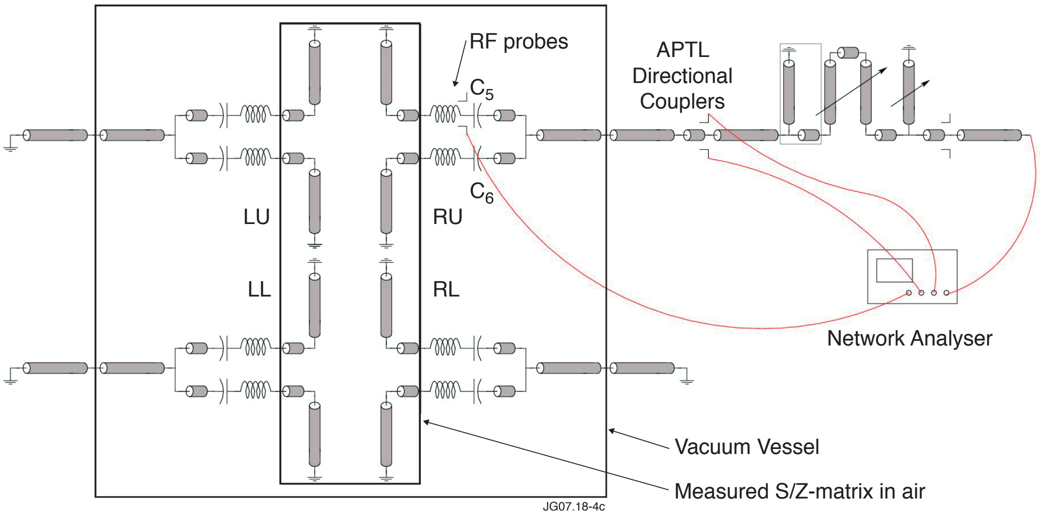

Figure 3: RF transmission line and lumped element circuit model of the testbed setup for high voltage testing of RDL RU.

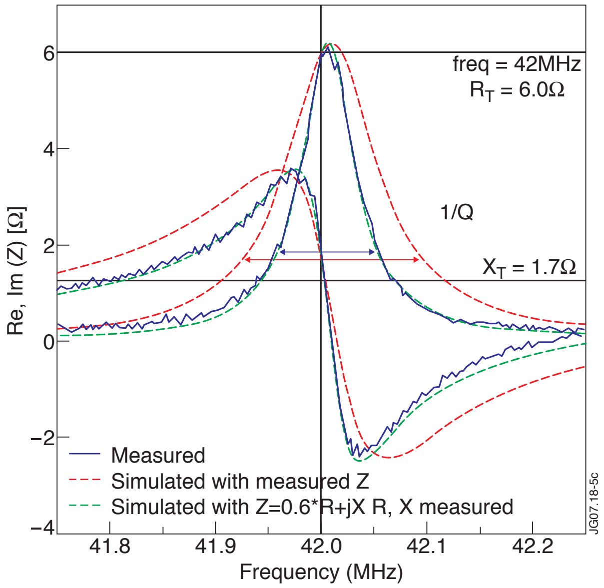

Figure 4: Measured vs simulated impedance at the conjugate T-point.

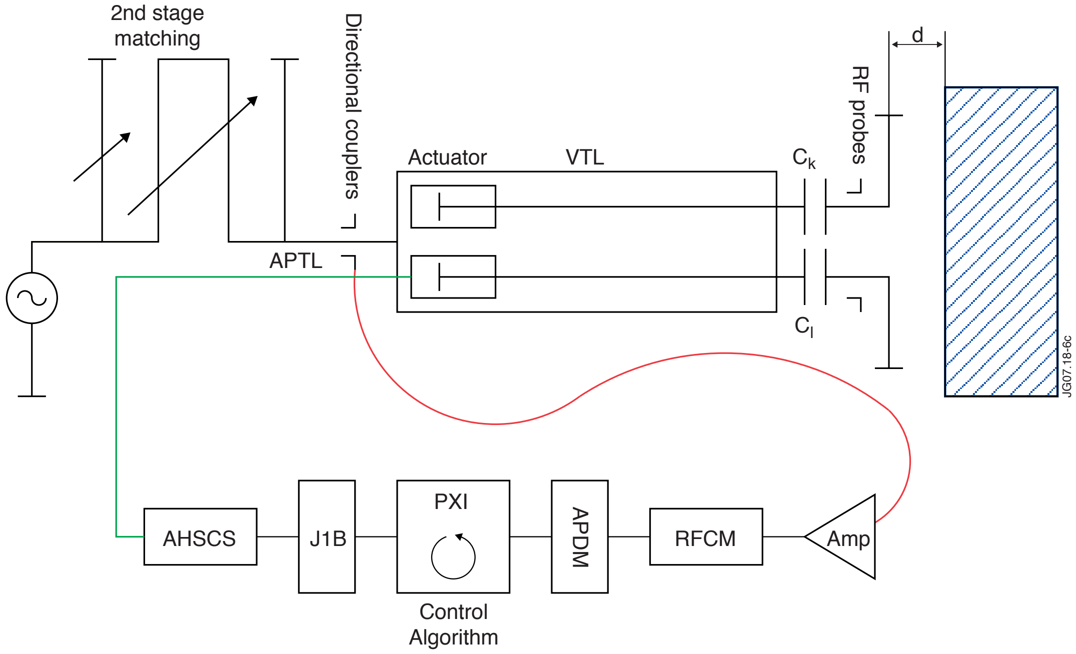

Figure 5: RF feedback control system for achieving and maintaining the impedance match at the conjugate T-point with variations of the loading of the antenna.

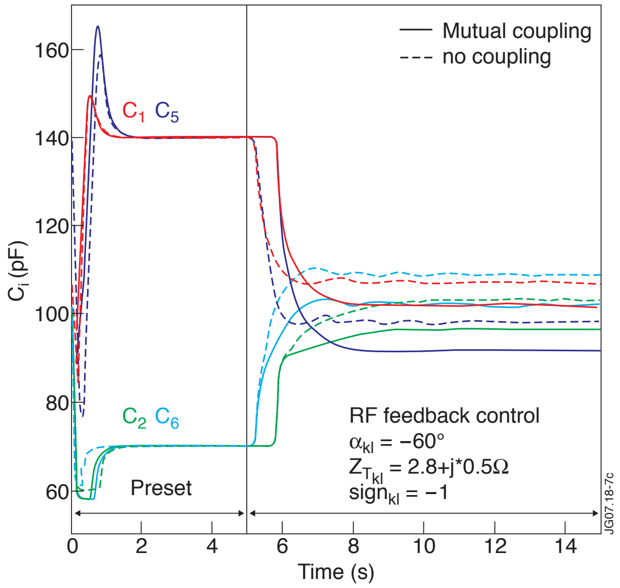

Figure 6: Movement of 4 capacitors by feedback system with and without mutual coupling between the two top RDLs.