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Abstract. The ITER-like Antenna (ILA) for JET [1] is a 2 toroidal by 2 poloidal array of Resonant Double Loops (RDL) featuring in-vessel matching capacitors feeding RF current straps in conjugate-T manner, a low impedance quarter-wave impedance transformer, a service stub allowing hydraulic actuator and water cooling services to reach the aforementioned capacitors and a 2nd stage phase-shifter-stub matching circuit allowing to correct/choose the conjugate-T working impedance. Toroidally adjacent RDLs are fed from a 3dB hybrid splitter. It has been operated at 33, 42 and 47MHz on plasma (2008-2009) while it presently estimated frequency range is from 29 to 49MHz.

At the time of the design (2001-2004) as well as the experiments the circuit models of the ILA were quite basic. The ILA front face and strap array Topica model was relatively crude and failed to correctly represent the poloidal central septum, Faraday Screen attachment as well as the segmented antenna central septum limiter. The ILA matching capacitors, T-junction, Vacuum Transmission Line (VTL) and Service Stubs were represented by lumped circuit elements and simple transmission line models.

The assessment of the ILA results carried out to decide on the repair of the ILA identified that achieving routine full array operation requires a better understanding of the RF circuit, a feedback control algorithm for the 2nd stage matching as well as tighter calibrations of RF measurements.

The paper presents the progress in modelling of the ILA comprising a more detailed Topica model of the front face for various plasma Scrape Off Layer profiles, a comprehensive HFSS model of the matching capacitors including internal bellows and electrode cylinders, 3D-EM models of the VTL including vacuum ceramic window, Service stub, a transmission line model of the 2nd stage matching circuit and main transmission lines including the 3dB hybrid splitters.

A time evolving simulation using the improved circuit model allowed to design and simulate the effectiveness of a feedback control algorithm for the 2nd stage matching and demonstrates the simultaneous matching and control of the 4 RDLs : 11 feedback loops control 21 actuators (8 capacitors, 4 phase shifters and 4 stubs for the 2nd stage matching, 4 main phase shifters controlling of the toroidal phasing and the electronically controlled phase between RF sources feeding top and bottom parts of the array and determines the poloidal phasing of the array which is solved explicitly at each time step) on (simulated) ELMy plasmas.

Keywords: ICRH, Antenna, Launcher, Power, Simulation
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THE CIRCUIT MODEL

A comprehensive circuit and simulation model (*FIG. 1*) of the ILA has been written in python 3.4 [2]. The ILA strap array coupling to the plasma is estimated with Topica [3] for plasma profiles of pulses JPN 81856 (L-mode) and JPN 84476 (H-mode) on JET with the Beryllium wall configuration [4]. Antenna strap impedance matrices were evaluated for different shifted positions of these profiles (0, 1, 2 and 3 cm away from the antenna). A $65m\Omega$ resistance was put in series to the 8 strap input ports to simulate the RF losses in the ILA.

The ILA in-vessel matching capacitor including all internal details of the capacitor such as electrode cylinders and bellows have been simulated using HFFS [5] for a large set of variable electrode positions [6]. The conjugate T-point, where a pair of matching capacitors are connected in parallel, the low impedance quarter wave (at 42.5 MHz)

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[1] See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

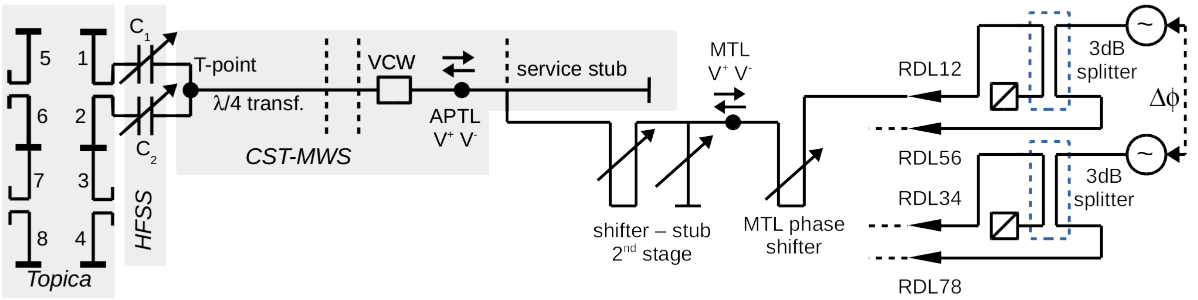

FIGURE 1. Schematic view of the circuit model showing the ILA strap array, the components of RDL$_{12}$ and the "3dB" hybrid splitters and RF sources feeding the top and bottom RDLs

transformer, the Vacuum Ceramic Window (VCW) and the Service Stub (SS) were simulated with CST-MWS [7]. The 2^{nd} stage phase shifter and stub as well as the Main Transmission Line (MTL) and the main phase shifters were simulated as ideal Transmission Line components and the "3dB" hybrid splitter feeding torodially adjacent Resonant Double Loops (RDL) was simulated as a coupled transmission line with a coupling factor of 2.72 dB, coupled length of 1.685m. The "3dB" combiners allowing to feed the "3dB" hybrid splitters from two nominally 2MW RF sources have not been included in the circuit model.

The circuit includes 20 variable feedback controlled actuators : 8 capacitors controlling the 4 RDLs T-point impedance, 4 2^{nd} stage stubs and 4 2^{nd} stage phase shifters controlling the MTL matching and 4 MTL phase shifters controlling the phases of the voltage probes of the inner straps' (near the antenna equatorial mid-plane; i.e. straps 2 and 6 for the top RDLs and 3 and 7 for the bottom RDLs) of torodially adjacent RDLs. In this model the phase between poloidally adjacent RDLs is not implemented as a feedback loop but is set exactly (if possible) to the prescribed (possibly time dependent) value by solving the circuit and finding the phase difference between the 2 RF sources ($\Delta\phi$ in *FIG. 1*) to realize the prescribed phase difference between the voltage probes of the straps 2 and 3 or 6 and 7. The reason for this is that in reality on JET the RF source phase control loop is very fast as it was designed to track ELM load transients using SLIMPs [8].

The capacitor actuators' response time was adjusted to measured data for the step-response of the hydraulic actuators. The phase shifters (2^{nd} stage and MTL) as well as the 2^{nd} stage stubs are implemented with a small dead band as well as a switch over point between fast and slow movements (resp. 165 mm/s and 16 mm/s (phase shifters) and 50 mm/s and 10 mm/s (stubs)).

Power level dependent VSWR tripping with a time off and reapplication of power is also included in the simulation. Arcs can be simulated as a small inductance inserted along the low impedance quarter wave transformer, appearing at a given time in the simulation.

MATCHING ALGORITHMS

Capacitor Matching Algorithm. The algorithm which uses the APTL directional couplers (*FIG. 1*) to estimate the impedance of the T-point, is slightly improved from the original one [9] which only takes into account the orientation of the isolines for the resistance and reactance of the T-point in the plane of the two matching capacitors. It was however observed that the spacing of the isolines of the resistance and reactance are quite different. Therefore it is proposed the rewrite the formulas for the error estimates for the capacitors in a matrix form shown below. The approximate form is equivalent to the original form depending on α and s = +1 or -1 for a scaling of real and imaginary parts of Z_T, K_{RI}, of 1. The matrix of the partial derivatives can be estimated from the circuit simulation using Topica impedance matrices for a given plasma by looking at the variations of the T-point impedance vs. the capacitor values about a found matching solution.

$$\begin{bmatrix}\delta C_m\\ \delta C_n\end{bmatrix} = \begin{bmatrix}\partial_{C_m} Re(Z_{T_{mn}}) & \partial_{C_n} Re(Z_{T_{mn}})\\ \partial_{C_m} Im(Z_{T_{mn}}) & \partial_{C_n} Im(Z_{T_{mn}})\end{bmatrix}^{-1}\cdot\begin{bmatrix}\Delta Re(Z_{T_{mn}})\\ \Delta Im(Z_{T_{mn}})\end{bmatrix} \approx \begin{bmatrix}-s\cdot cos(\alpha) & s\cdot sin(\alpha)\cdot K_{RI}\\ -sin(\alpha) & -cos(\alpha)\cdot K_{RI}\end{bmatrix}\cdot\begin{bmatrix}\Delta Re(Z_{T_{mn}})\\ \Delta Im(Z_{T_{mn}})\end{bmatrix}$$

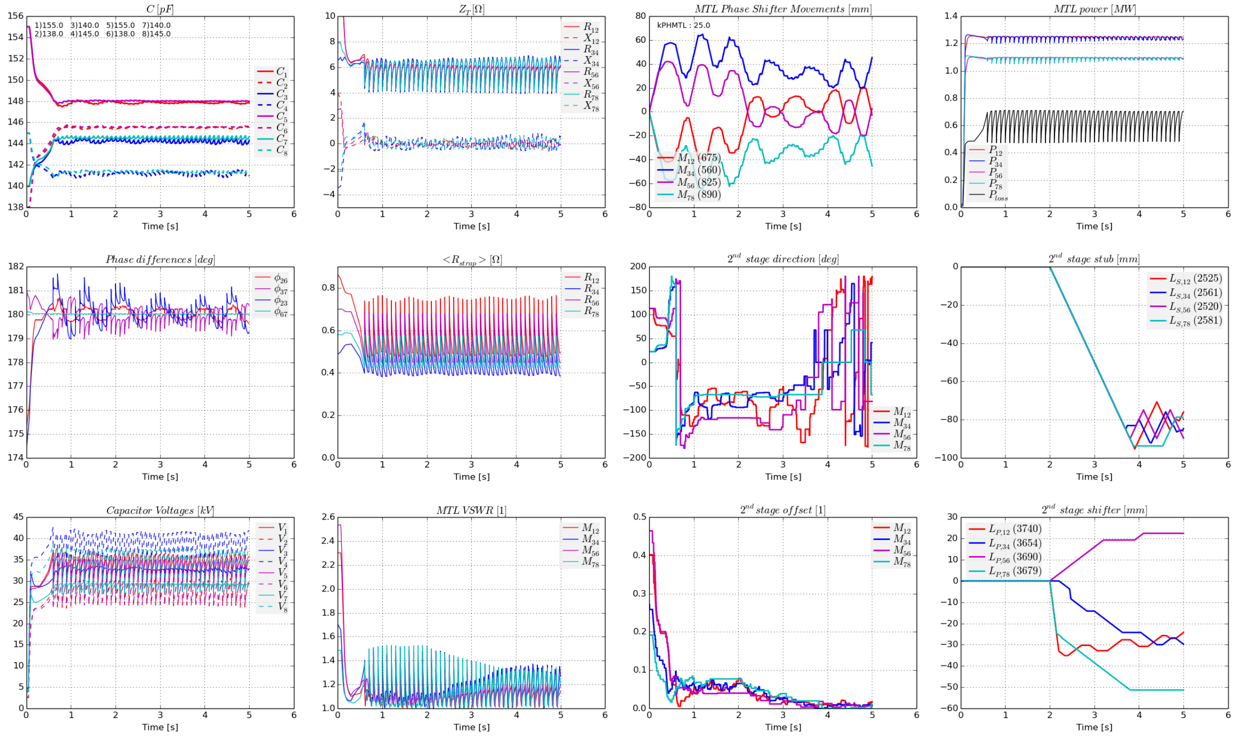

FIGURE 2. Simulation of ILA operation on an ELMy H-mode plasma

2^{nd} Stage Matching Algorithm. The algorithm works on 2 time scales. On a time scale fast enough to resolve the ELM transitions, typ. 2-5 μs, the reflection coefficients in the MTLs are recorded in a relatively crude 2D map of typically 8 phase bins and 15-20 amplitude bins. The recording is done by filling an integer proportional to the tracking time interval the algorithm should consider. At each fast cycle the non-zero elements of the map are decremented by one. E.g. if a tracking time of 200 ms is desired and the fast cycle is every 2 μs, then the initial integer will be 100000.

On a much slower time scale commensurate to the movement of the 2^{nd} stage phase shifters and stubs, typically 5-10ms, an average reflection coefficient is estimated from (remaining) non-zero entries in the 2D reflection map, and the normalized admittance, y_{MTL} at the MTL side of the 2^{nd} stage stub is found. $Re(y_{MTL})$ controls the 2^{nd} stage phase shifter and $Im(y_{MTL})$ controls the 2^{nd} stage stub.

RESULTS

For the simulation at 42 MHz shown in *FIG. 2* the time evolution of the ILA impedance matrix, reflecting that of the plasma, are achieved by starting from an L-mode impedance matrix with the plasma at the reference position (0 cm) and from 0.3s to 0.6s the L to H transition is simulated by a linear interpolation of the initial L-mode matrix to an H-mode matrix shifted by 2 cm away from the antenna. Starting at 0.6s the ELMs are simulated as a repetitive sequence of fast (1ms) transitions from the H-mode matrix to the L-mode matrix followed by a 99ms sort of exponential relaxation back to the H-mode matrix. At 5s the pulse is terminated.

The requested T-point impedance is 6+0jΩ and the simulation time step is 1ms. The requested phasing is 180°toroidal (between straps 2 and 5 for the top RLDs and 3 and 7 for the bottom ones) as well as poloidal (between straps 6 and 7).

The actuators, capacitors, phase shifters and stubs are put at sensible starting positions. In particular the 2^{nd} stage phase shifters and trombones were not started from their ideal positions (i.e. matching exactly the requested T-point impedance to 30Ω) but were randomly offset by up to 3cm.

The capacitors start matching at 50ms and the MTL phase shifters start tracking the phase at 50ms. In this simulation, the 2^{nd} stage starts looking for the optimal setting from 2s onwards allowing to present the effect of the algorithm; in reality the 2^{nd} stage could start matching as soon as the capacitors are close to their matched positions in typ. 0.5s. The simulations show clearly the effect of the 2^{nd} stage matching algorithm despite that the present set of Topica ILA impedance matrices only exhibit modest coupling variations due to ELMs (somewhat less than a factor 2).

Importantly the simulation shows that the MTL phase shifters are able to control the toroidal phasing of the ILA array and the phase errors are kept to about 1°. This is necessary to avoid drifting capacitor matching solutions observed when the phase is not feedback controlled[1]. Other simulations have also shown that it is possible to drive the ILA with a toroidal and poloidal phase different from 180°.

The poloidal phasing control is not feedback controlled (see above) in these simulations but it is interesting to observe that simulations have shown that there is not always a (real) solution (to the quadratic equation which is solved for $\Delta\phi$) in the case of transients from (very) low to high coupling (e.g. as in the case of an ELM). In the numerical simulation the negative discriminant is set to zero; what would happen for the phase feedback control in reality is unclear at present.

Simulations have also revealed that the observability by the VSWR arc detection of arcs simulated as a 20nH inductance near the T-point is dependent on whether the full array is powered or not : for a top or bottom half the visibility for a T-point impedance of 6Ω is sufficient, however for full array operation the T-point impedance should be about 10Ω.

The improved capacitor matching algorithm is faster in stabilizing capacitor oscillatory movements near the matching solution. It remains to be seen if the matrix of partial derivatives estimated from the Topical impedance matrix is close enough to the real experimental dependencies to warrant the improvement.

It was also shown that by reducing the error response coefficient for the capacitors by a factor of 5, the matching control is able to match the ILA upper RDLs or the lower half RDLs separately, which simplifies to some extend the ILA HV conditioning procedures.

Although most of the simulations have been carried out for 42MHz, full array simulations at 29MHz on ELMy plasmas and at 47MHz on stationary plasmas have shown the algorithms to work as well (both not realized experimentally in 2008-2009 due to lack of time before the one of the matching capacitors was damaged). However. simulated operation at 47 and 49MHz on ELMy plasmas have only been stable on separately powered top or bottom RDLs.

The one striking discrepancy of the simulation results with respect to the experiments in 2008-2009 is the value of the matching capacitors for the lower half of the array : $\Delta C_{3,7} \approx$ 5pf; $\Delta C_{4,8} \approx$ 11pF, while for the upper half the correspondence is rather good : $\Delta C_{1,5} \approx$ 2pF; $\Delta C_{2,6} \approx$ 1pF. It is not clear at present what causes this discrepancy.

Further work will consist of exploring the operating frequencies from 29 MHz to 49 MHz and establish a set of starting configurations for the capacitors, phase shifters and stubs.

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