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RF Matching Feedback Control Systems on the JET ITER-Like Antenna

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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT.

Ion Cyclotron Resonance Frequency (ICRF) antennas achieve maximum power transfer from RF generator to plasma load by establishing an impedance match. The JET ITER-Like Antenna (ILA) consists of 4 mutually coupled resonators that need to be matched simultaneously and whose resonant states need to be accurately controlled by several available actuators to couple maximum power and to achieve optimal ELM resilience. The operation of the matching system is described. Experimental operation revealed some phenomena and sensitivities that did not surface from simulation alone and that should be taken into account for the design of future ICRF antennae systems.

1. INTRODUCTION

The RF operation of the ILA [1] is controlled by several feedback systems as depicted in Fig. 1. In the experiments, firstly the 4 complex T-point impedances Z_{Tkl} ((kl) = (12), (34), (56), (78)) were feedback controlled by adjusting the capacitors C_k, C_l. The imaginary part of Z_{Tkl} was set iteratively on a shot by shot basis to achieve equal voltage amplitudes on the capacitors/straps $\mathrm{Abs}(V_k/V_l) = 1$ within each RDL (not discussed further below). Secondly, the phase shifter and stub lengths l_k,l_l ("second stage" elements) were manually adjusted to achieve an "offset" match as described in the next section. Finally, the relative generator phasing was put under automatic real-time feedback control as described below. The target settings of this feedback loop were then adjusted to achieve equal amplitude of all voltages in the array as described in the last section. The experimental accuracies on the settings range from about ±0.1pF on the capacitor values (±20μm actuator position), ±5cm on trombone and stub lengths and $\pm5^o$ on the imposed generator phasing.

2. THE SECOND STAGE "OFFSET" MATCH

Figure 2(a) shows the time evolution of 3 signals important for setting the second stage elements. Figure 2(b) shows the measured T-point impedance Z_T in the complex plane during L- and H-mod, and circles of constant Voltage Standing Wave Ratio (VSWR) = 2.0 for two sets of lengths l_s, l_t. If the second stage is set to match Z_T during L-mode or H-mode between ELMs, the VSWR limit will be exceeded with the ELM excursions. A retraction of the stub by 15cm targets the average Z_T reached during the ELM excursions and avoids exceeding the generator VSWR limit.

3. THE INNER STRAP PHASE FEEDBACK CONTROL

Operation of the ILA on testbed and plasma (in its original layout [1]), showed that the forward voltage phase on the feed line could not be set manually accurately enough to stabilise the capacitor voltage distribution in time, as can be seen in Fig.3(a). Although the Z_{Tkl} remain constant, small phasing errors lead to power transfers between RDLs that causes the capacitors C_k and their voltages V_k to drift in time. Simulation shows that the drift is the start of a general evolution towards a steady state solution with fixed Z_{Tkl} but assymetrical voltages V_k. To operate the antenna stable and within safe voltage limits, the 3dB combiners and splitters (see Fig 2 of [1]) were removed and the existing JET RF plant generator phase control systems [2] were re-used to feedback control the 4 inner strap voltage phases (ψ_2, ψ_3, ψ_6, ψ_7). Initially, the relative generator phases Δ_{34}, $\Delta_{56,}$ Δ_{78} were set such that the inner strap voltage phase differences are $\psi_3 - \psi_2 \approx \psi_6 - \psi_2 \approx \psi_7 - \psi_3 \approx \pi$. The improvement with this modi-fication can be seen in Fig. 3(b). As a downside of these modifications, problems were often experienced running the full antenna array with 4 interacting generators. Generators not all starting simultaneously and/or the appearance of oscillations of growing amplitude during power ramp up (suspected to be related to the phase feedback control) caused excessive tripping and termination of these full array pulses.

4. THE RELATIVE GENERATOR PHASING

On previous RF measurements on the individual strap feeders, with the antenna facing a salty water load [3] closely fitting the Faraday screen curvature, similar values of the individual port impedances Z_{ii} were obtained. With the antenna operating on plasma, measurements of the full scattering parameters are no longer available. An effective resistive loading R_{Ckl} per RDL at the position of the capacitor voltage RF pickup probes can still be calculated as depicted in Fig. 4. With the relative generator phasing initially set such that $\psi_3 - \psi_2 \approx \psi_6 - \psi_2 \approx \psi_7 - \psi_3 \approx \pi$, the measured effective loading of the upper half of the antenna was higher than for the lower half (see Figure 6, 11-14s).

This difference is caused by the triangularity of the plasma putting the plasma separatrix on average ~3cm further away from straps of the lower RDLs as compared to the upper ones. To achieve maximum power transfer and optimal ELM resilience, all voltages over the antenna strap array should be made equal in amplitude. This can be done by using the reactive mutual coupling with the proper imposed phasing of the generators to create a power transfer between the upper and lower RDLs, as demonstrated during JET Pulse No. 75173 in Figure 6. The relative inner strap phasing from 11-14s was obtained experimentally to equalize the effective resistive loading within upper half R_{C12}=R_{C56} and R_{C34}=R_{C78} within lower half of the ILA separately. From 14/16/18s, the inner strap up/down phasing $\psi_3 - \psi_2 \approx \psi_7 - \psi_6 \approx \pi + \Delta$ is varied by sweeping î from 0^o/$+15^o$/-15^o from these initial values and one sees the corresponding change in effective load resistance and capacitor voltage until they are all equalized near the end of the pulse with $\Delta = -15^o$.

CONCLUSIONS

This paper described the RF matching system of the JET-ILA in its final configuration on plasma. After removal of the 3dB combiners/splitters, introduction of the inner strap phase control, offsetting the second stage match, adjusting $\mathrm{Im}(Z_{Tkl})$ and the generator phasing to equalize the voltage amplitudes over the entire strap array, the general operating conditions for the ILA physics experiments were established, the results of which are fully reported in [4].

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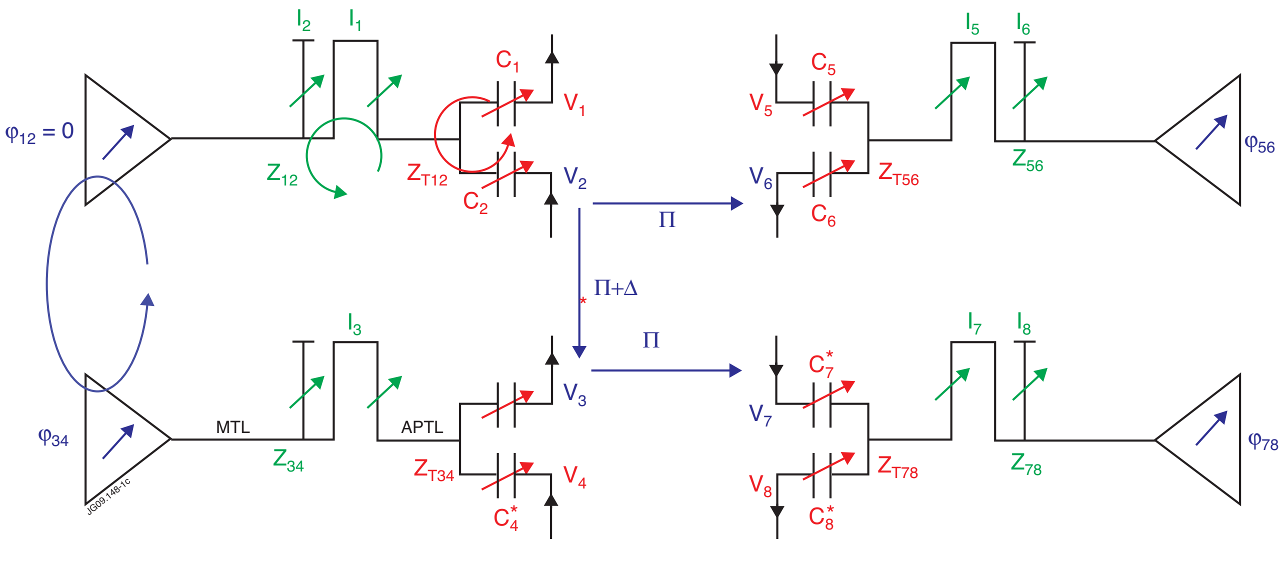

Figure 1: Overview of JET-ILA RF matching feedback control system on final installation (to be compared with original installation Fig.2 in [1]).

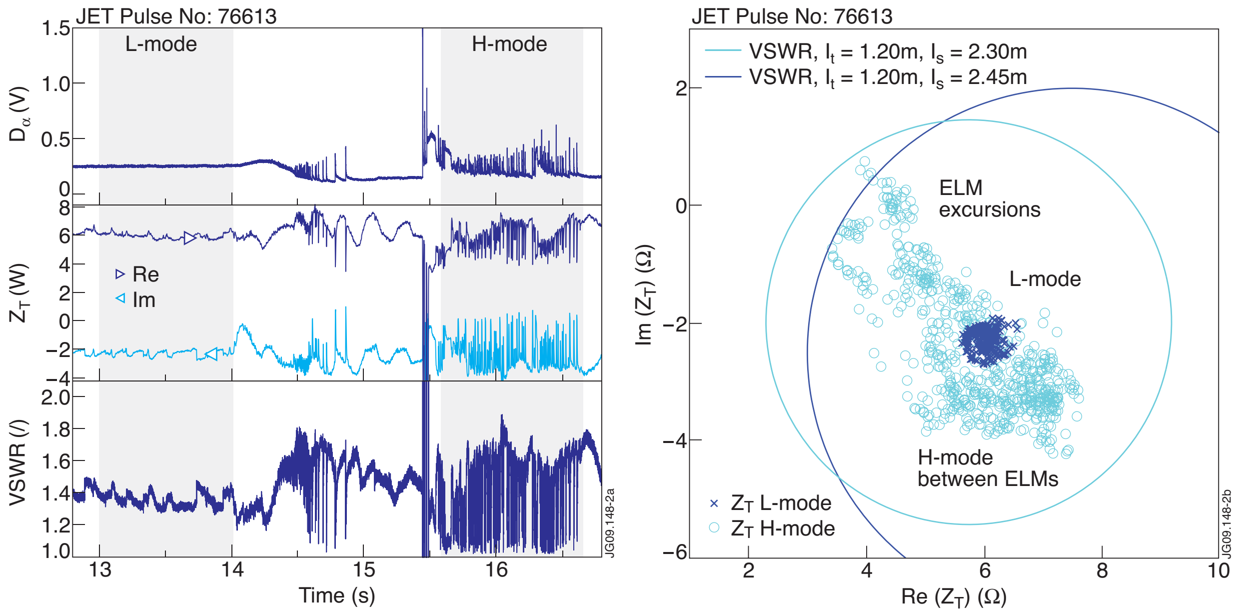

Figure 2: (a) Time evolution of D_α ELM signal, Z_T and VSWR during L-mode and ELMy H-mode on JET Pulse No: 76613. (b) Measured T-point impedance during L-mode (13-14s) and ELMy H-mode (15.7-16.7s) in the complex plane with overlayed circles of VSWR=2.0 for two sets of length l_t, l_s.

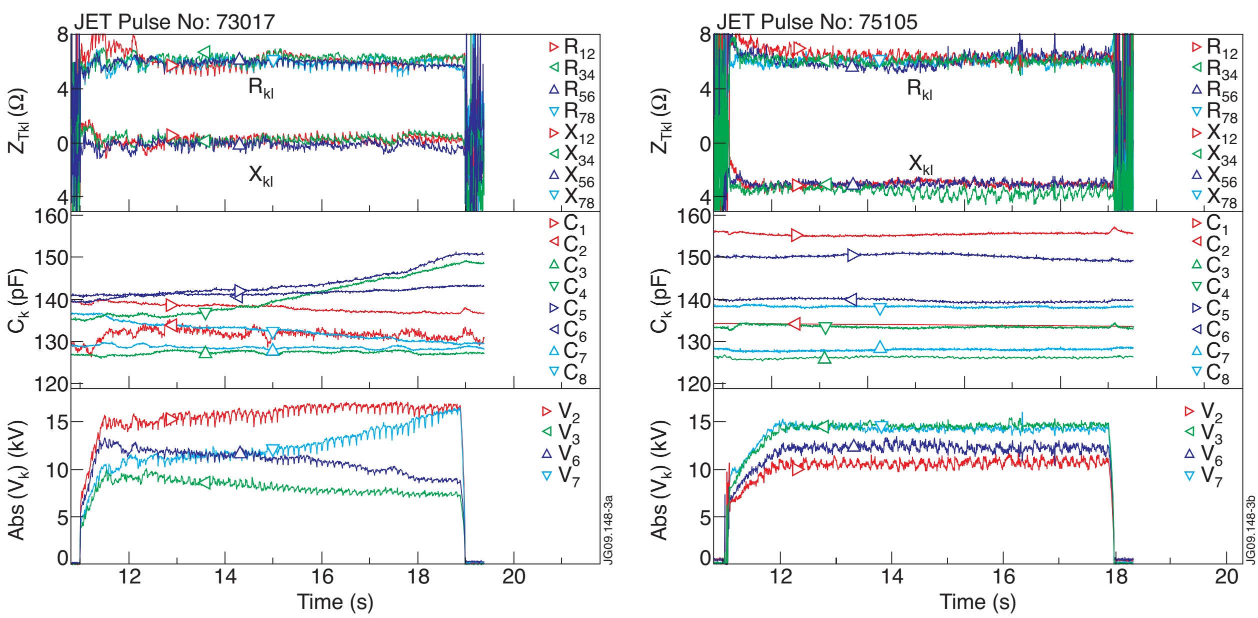

Figure 3: Time evolution of T-point impedances Z_{Tkl}, capacitor values C_k and voltages V_k on (a) JET Pulse No: 73017 without, (b) JET Pulse No: 75105 with inner strap phase control feedback.

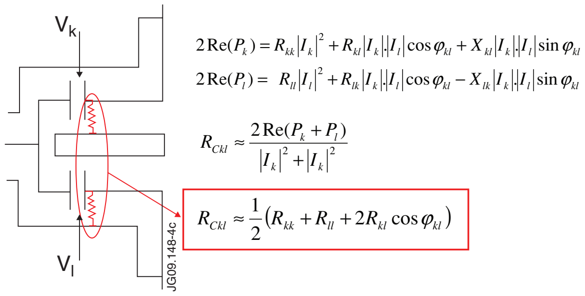

Figure 4: Definition of effective resistive loading R_{Ckl} at the capacitor probe position in a Resonant Double Loop (RDL) of the ILA.

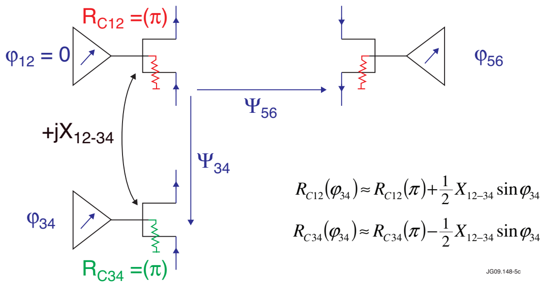

Figure 5: The resistive loading in an antenna array depends on plasma load and power transfer between the generators due to reactive cross talk.

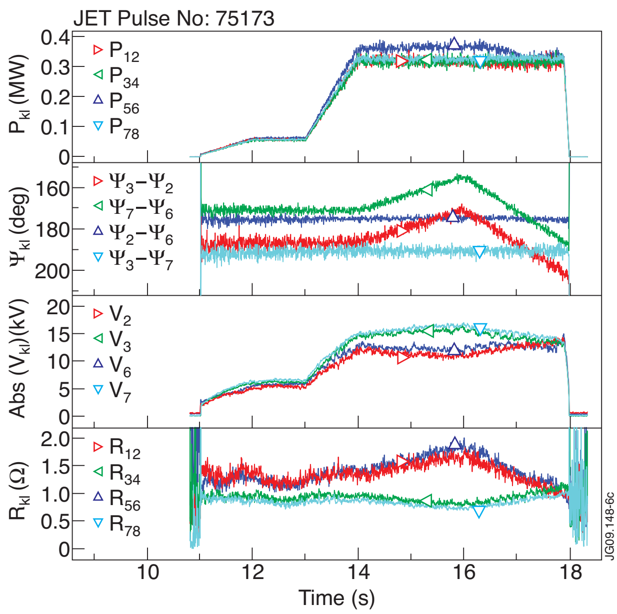

Figure 6: Time evolution of forward power, inner strap phase difference, capacitor voltage and effective load resistance on JET Pulse No: 75173.