JET ILA Full Array and Polychromatic Operation

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The JET ICRH ILA is an Ion Cyclotron Resonance Heating (ICRH) antenna composed of four resonant double loops (RDLs) arranged in a 2 toroidal by 2 poloidal compact array. It has been operated at 33, 42 and 47MHz in 2008-2009. Improved RF models, more accurate calibrations of the RF measurements and new control algorithms have since then allowed reliable and routine operation of the antenna in an extended range of frequencies from 29 to 51MHz, but mostly on half array. Some full array pulses were achieved but without all control loops implemented.

All control algorithms (first and second stage matching, toroidal and poloidal phasing, totalling 22 feedback loops) have now been implemented and recently allowed to operate the full array at 33MHz and 42MHz up to 4MW. It also allowed for the first time to perform a poloidal phase scan of the antenna at 37MHz, with dipole toroidal phasing.

Although full array operation has mostly proven reliable at 33MHz, it has proven unstable at 42MHz in several occasions due to the high level of mutual coupling between the different RDLs inherent to a compact array. To decouple the control of the top and bottom halves, first tests were successfully performed with polychromatic – or dual frequency – operation of the ILA (operation at 2 different frequencies around a central frequency).

Keywords: JET, ICRF, ICRH, ILA, Polychromatic, Dual Frequency

1. Introduction

The JET ICRH ILA is a compact Ion Cyclotron Resonance Heating (ICRH) antenna composed of four resonant double loops (RDLs) arranged in a 2 toroidal by 2 poloidal array. Each RDL consists of two poloidally adjacent straps fed through in-vessel matching capacitors from a common Vacuum Transmission Line (VTL). Two toroidally adjacent RDLs are fed through a 3dB combiner-splitter (Fig. 1) from two 2MW amplifiers [1].

Section 2 briefly introduces the different feedback control loops that were implemented to control the full antenna array. Section 3 illustrates the use of all feedback control loops to operate the full antenna array and highlight some of the control issues encountered. Finally in Section 4 a potential method to tackle the full array control instability issues, using polychromatic heating to decouple the control of both halves, is introduced and tested.

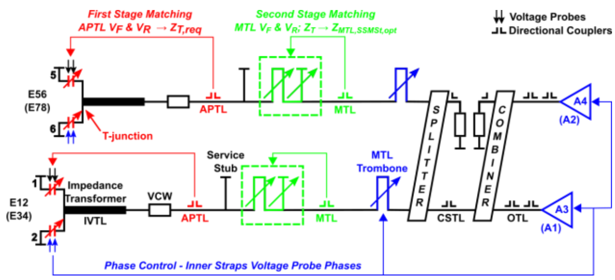

Fig. 1. Schematic of the JET ILA RF circuit (upper half; similar circuit for the bottom half) featuring the different control loops: first stage (Z_T), second stage (SSM), toroidal and poloidal phase controls. IVTL = Inner Vacuum Transmission Line, APTL = Air Pressurised Transmission Line, MTL = Main Transmission Line, CSTL = Combiner-Splitter Transmission Line, OTL = Output Transmission Line, VCW = VaCuum Window, A1…A4 are the four 2MW amplifiers.

2. Antenna Feedback Controls [2]

Figure 1 displays the JET ILA RF circuit for the two upper RDLs (the two lower RDLs have a similar circuit) as well as the antenna array feedback control loops.

The first stage matches the 4 complex conjugate-T point impedances (Z_T) – estimated from the Antenna Pressurised Transmission Line (APTL) directional coupler forward and reflected voltage measurements combined to a numerical RF model of the circuit – to the requested values $Z_{T,req}$ by adjusting the 8 in-vessel variable capacitors in each RDL branch (4 feedback loops; 8 actuators).

The Second Stage Matching (SSM) circuit adjusts the lengths of the 4 SSM stubs and of the 4 SSM trombones (4 feedback loops; 8 actuators) in order to minimize the Main Transmission Line (MTL) Voltage Standing Wave Ratio (VSWR) excursions during the ELM cycles in ELMy plasmas (offset match).

The phasing of the antenna array is controlled by controlling the phase of the voltage probe signals of the four inner straps (straps number 2, 3, 6 and 7).

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The toroidal phase between two toroidally adjacent RDLs is controlled by acting on the 4 MTL trombones located at the output of the 3dB combiner-splitters (2 feedback loops; 4 actuators).

Finally, the poloidal phase, i.e. the phase difference between poloidally adjacent RDLs is controlled with respect to a separate phase reference and is adjusted by acting on the 4 amplifiers' output phases. Two amplifiers are feeding one 3dB combiner-splitter thereby constraining these two amplifiers' output phases (poloidal phasing constrained by 3dB combiners: 2 feedback loops; 2 independent actuators).

The matching and phasing of the whole array is consequently controlled by 12 feedback loops driving 22 actuators: the 8 variable in-vessel capacitors, the 4 SSM trombones, the 4 SSM stubs, the 4 MTL trombones and the 4 amplifiers' output phases constrained by the two 3dB combiners.

3. Full Array Operation

The JET ILA has been operated at 33, 42 and 47MHz in 2008-2009 [1]. Improved RF models, more accurate calibrations of the RF measurements and new control algorithms have since then allowed reliable and routine operation of the antenna in an extended range of frequencies from 29 to 51MHz, but mostly on half array [3]. Some full array pulses were achieved but without all control loops implemented.

All control algorithms (first and second stage matching, toroidal and poloidal phasing) have now been implemented and recently allowed to operate the full antenna array in a fully controlled way at 33MHz and 42MHz up to 4MW, limited by the available generator power. Fig. 2 displays an example of a 4MW fully controlled pulse at 33MHz: the T impedances (Z_T=6+0jΩ) and MTL VSWR are well controlled for all RDLs; top and bottom toroidal phases are 180° and the poloidal phase (i.e. the phase between the top and bottom RDLs inner straps capacitor voltage) is ~165° to balance the voltages on all straps. The toroidal and poloidal phase controls are performed by monitoring the inner straps capacitor voltage phases. Two poloidally adjacent inner straps have a common ground plane in the middle of the antenna. Consequently, a 180° poloidal phase on the capacitor voltages of the inner straps correspond to currents in phase in these straps.

The implementation of all controls also allowed for the first time to perform a poloidal phase scan of the antenna (37MHz – 500kW), with dipole toroidal phasing (Fig. 3): the poloidal phase between the top and bottom RDLs inner straps was varied from the usual φ_{pol}=180° (currents in phase as the inner straps have a common ground in the mid-plane, Fig. 3 left) to 135°, 225° and 270°. When moving the poloidal phase away from 180°, power transfer starts to occur between upper and lower RDLs. For φ_{pol}=135° (Fig. 3 second from the left) there is power transfer from the lower to the upper half; the lower half is coupling partly to the upper half and the lower half capacitor voltages are consequently lower than the upper half strap ones. The intra-RDL strap phase difference from the lower half straps (φ_{34} and φ_{78}) are moving away from 180° (high coupling case) whereas the intra-RDL strap phase difference from the upper half straps (φ_{12} and φ_{56}) are moving toward 180° (low coupling case). For φ_{pol}=225° and 270°, the opposite is true and there is power transfer from the upper half to the lower half (Fig.3 – two right figures).

Although full array operation has mostly proven reliable at 33MHz, it has proven unstable at 42MHz in several occasions, due to the high level of mutual coupling between the different RDLs inherent to a compact array. In the worst case, the capacitors of one RDL are running away. The cause of the instability is not yet clear, but it translates into a sequence of concomitant events: some capacitors are moving away from their match point, the phases are deviating from the – generally dipole – request and power transfer between RDLs grow stronger, contributing to grow the instability further.

Further work on the control algorithms is needed to improve the reliability of full array operation at all frequencies. For example, the first stage (capacitor) control is currently done RDL by RDL; an algorithm could be developed and tested to include cross-coupling effects (i.e. including the impact of the position of the capacitors of one RDL on the control of the T impedances of the other RDLs).

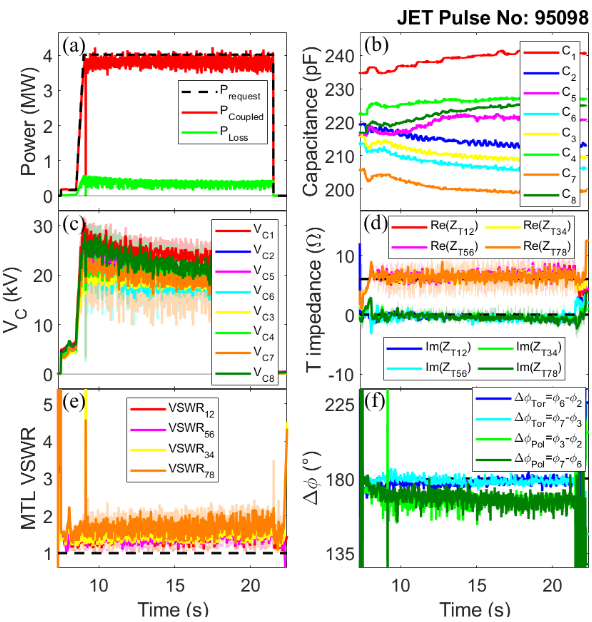

Fig. 2. 4MW Full array pulse at 33MHz. (a) Coupled and loss power (b) Capacitances (c) Capacitor voltages (d) T Impedances (e) MTL VSWR and (f) Toroidal and Poloidal phases.

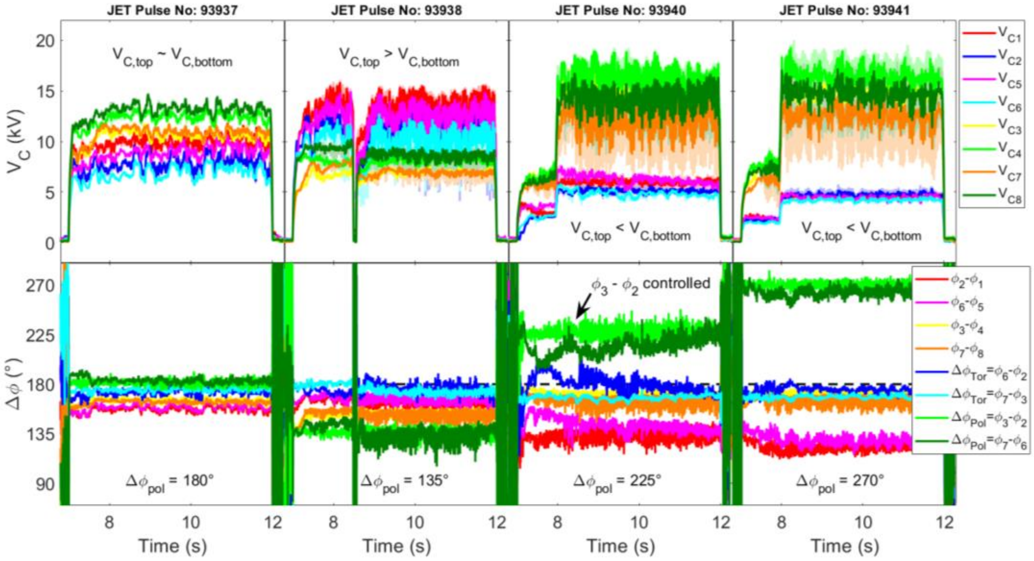

Fig. 3. Poloidal phase scan at 37MHz – 500kW. Top: capacitor voltages. Bottom: intra-RDL, toroidal and poloidal phases. The poloidal phase is controlled by the capacitor voltage probe phase measurements of straps 2 and 3.

4. Polychromatic or Dual Frequency Operation

As half array operation has proven more stable than full array operation, and in order to decouple the control of the upper and lower halves of the antenna, first tests were performed with operation of both halves at two slightly different frequencies around a central frequency ($f_0 \pm \Delta f$, with Δf=0.5MHz) in a new scheme called polychromatic or dual frequency operation. This not only allows to operate the whole array in a more reliable way but also has the potential to operate the whole array at the frequency band edges (29MHz and 51MHz), which is not possible with the full array. Indeed, the capacitor positions tend to spread out in the single frequency full array operation as compared to half-array operation and some capacitors are therefore reaching their end of range position. This is not the case with dual frequency, where control is closer to half array operation.

First dual frequency operation tests were successful with reliable operation proven at 33, 42 and up to 2MW at 51MHz, where single frequency full array operation is not accessible.

Fig. 4 displays a comparison between a single frequency full array pulse at 33MHz (Fig. 4 left) and a whole array dual frequency pulse operated at 32.75MHz and 33.25MHz for the top and bottom halves respectively (Fig. 4 right). For the same power – 1MW – the same voltages are reached. The voltages are however better balanced in the dual frequency operation (less spread on the voltages) but some low-frequency (~13Hz here) oscillations appear on the signals.

All RF measurement signals are filtered for the operating frequency. In the case of the dual frequency operation, the signals are filtered for the main frequency of operation of the considered half. The secondary frequency contribution is not measured. If this is adequate for the control of the antenna, it is not necessarily for its protection.

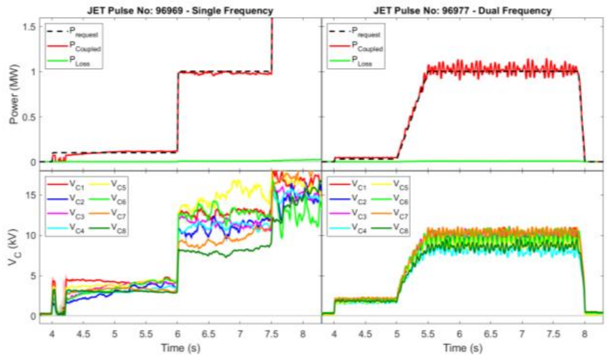

Fig. 4. Comparison between a single frequency full array pulse (left) and a dual frequency whole array pulse (right). Top: coupled and loss power. Bottom: capacitor voltages.

Fig. 5 displays the voltage measured by the capacitor voltage probes and filtered for the main operating frequency (V_C) as well as the wideband voltage estimated from the capacitor over-voltage protection circuit ($V_{C,ALM2}$). This last one is based on diode rectification and is an estimate of the total voltage considering contributions from all frequencies. In the case of the single frequency full array operation (left), both signals are about the same amplitude, $V_{C,ALM2} \sim V_C$, whereas for dual frequency operation, $V_{C,ALM2}$ may reach 2 x V_C, meaning that the secondary frequency contribution to the total capacitor voltage is of the same order of magnitude as the main frequency contribution. The operation of the antenna in dual frequency will consequently be limited by the maximum total voltage allowed at the capacitor (typically 42kV) at a lower power than could be achieved by single frequency full array operation.

Although dual frequency whole array operation will be limited to lower powers than full array single frequency operation due to the voltage limit, it has the benefit of larger reliability so far. It also has some benefits against half-array operation, as it could provide slightly more power, but essentially allows to operate the amplifiers with lower power requests from the amplifiers (4 amplifiers used instead of 2).

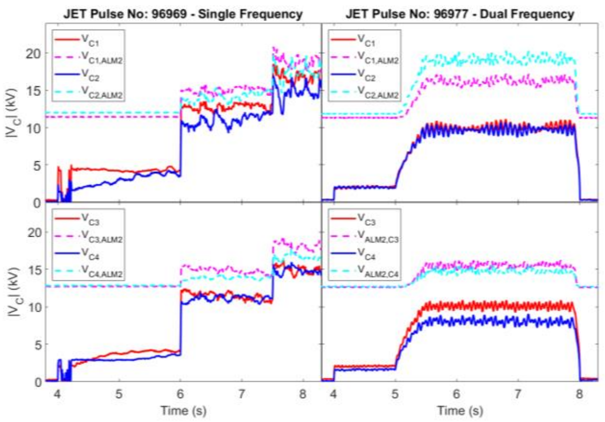

Fig. 5. Comparison between single frequency full array pulse (left) and dual frequency whole array pulse (right). Capacitor voltages of straps 1 and 2 (top) and 3 and 4 (bottom). Plain: capacitor voltage measurement at main frequency (V_C); dashed: diode-rectified wideband capacitor voltage measurement ($V_{C,ALM2}$).

It was also checked that the S-Matrix Arc Detection (SMAD) system, which works based on a single frequency at the moment, was still fully adequate to protect the antenna. The SMAD error is indeed not very sensitive to the frequency and a Δf=0.5MHz only introduces a small correction on the imaginary part of the error. The antenna is hence adequately protected against T-point arcs using the dual frequency scheme.

The forward and reflected voltages measured by directional couplers in the amplifier Output Transmission Line (OTL) showed that the secondary frequency forward and reflected signals were of the same order of magnitude and could reach up to half of the main frequency forward voltage. Hence, an RF amplifier operating at a main frequency sees a significant level of signal at the secondary frequency produced by another amplifier, through the large cross-talk inherent to the compact array design.

Spectrum analyser measurements on the so-called 'mushroom' probe in the end-stage cavity of the amplifier furthermore revealed that the peaks at the main and secondary frequencies were of the same order of magnitude, confirming the significant level of secondary frequency signal present at the level of the generators.

Although no issues were found operating the dual frequency scheme up to 2MW at 51MHz (where the cross-talk is maximum) for the whole array, instabilities could nevertheless arise at larger powers and generator protection, more generally, must be addressed should this scheme of operation be further developed.

Finally, it is to note that toroidal phase drifts were observed with dual frequency operation, the Main Transmission Line (MTL) trombones moving throughout the pulse to keep the requested dipole toroidal phases.

5. Conclusions

First operation of the JET ILA with all implemented control feedback loops (12 control feedback loops controlling 22 actuators) has been achieved. It allowed fully controlled full array operation up to 4MW at 33MHz and 42MHz. It also allowed for the first time to operate a poloidal phase scan (at 37MHz – 500kW) showing that there is power transfer from one half of the antenna to the other when the poloidal phase moves away from the reference 180° (i.e. strap currents in phase).

Some instabilities however were observed in some occasions when running the full array leading to capacitor runaway, due to the large cross-talk inherent to the design of the compact antenna array. Further work on the control algorithms is needed to improve the reliability of full array operation at all frequencies.

Considering the higher reliability of half array operation, another whole array operation option has been investigated: operate both halves at slightly different frequencies around a central frequency ($f_0 \pm \Delta f$, with Δf=0.5MHz) in order to decouple the top and bottom half controls.

First tests were successful, and the whole array could be operated up to 2MW at 51MHz, where single frequency full array operation is inaccessible.

Unfortunately, it has been observed that the secondary frequency contribution to the capacitor voltage could be of the same order as the main operating frequency contribution, therefore limiting the operation to lower powers than could be achieved by single frequency full array operation. Also, spectrum analyser measurements of signals in the end-stage cavity show peaks of similar amplitude for the main and secondary frequencies. Impact on generator protection must be assessed. However, even with the observed voltage limitation, dual frequency may be helpful to operate the whole array with reduced request from the amplifiers compared to half-array operation and more reliably than with single-frequency operation.

Acknowledgments

This work has been carried out within the framework of the Contract for the Operation of the JET Facilities and has received funding from the European Union's Horizon 2020 research and innovation programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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